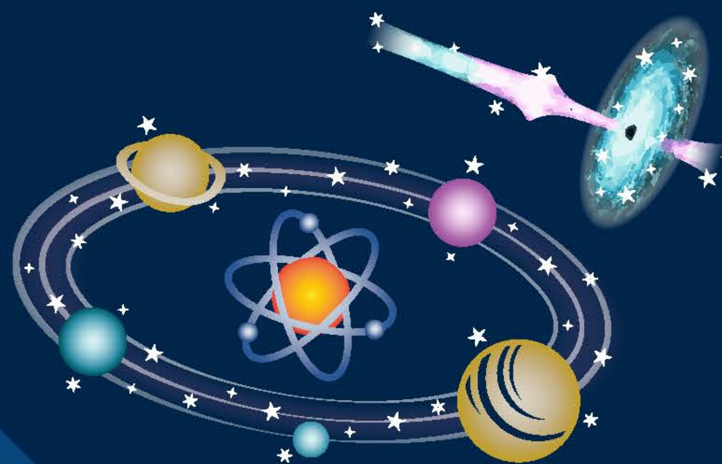
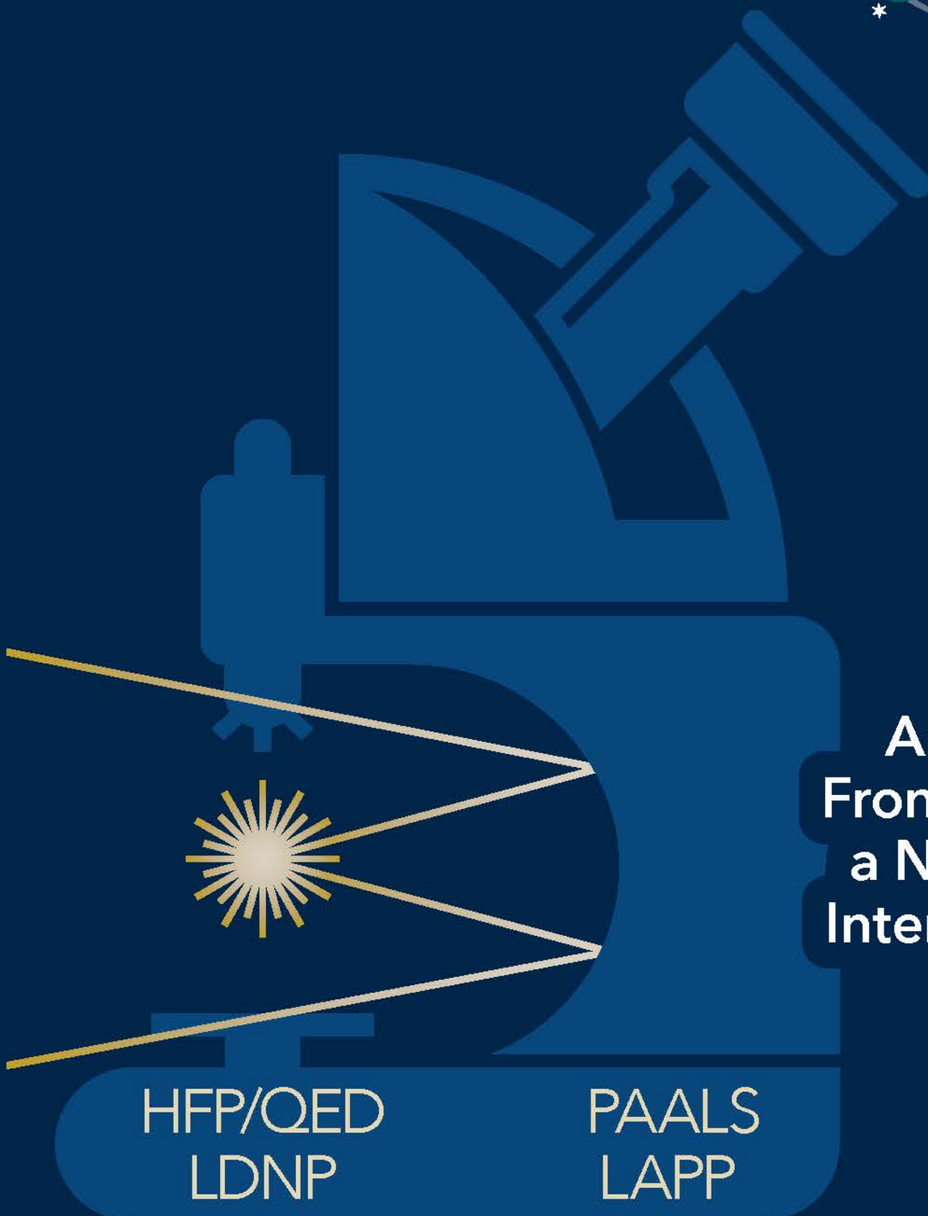
Multi-Petawatt Physics Prioritization

MP3





An International Focus on Frontier Science Enabled by a New Generation of Ultra-Intense and Powerful Lasers

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WORKSHOP REPORT

April 20-22, 2022 • Sorbonne Université, Paris, France

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Multi-Petawatt Physics Prioritization Workshop Report

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Table of Contents

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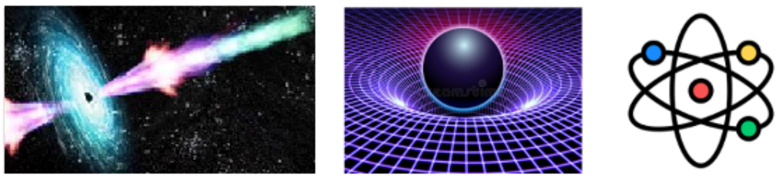
Multi-Petawatt Physics – Extreme Laboratory Science



Executive Summary

This Multi-Petawatt Physics Prioritization (MP3) Workshop Report captures the outcomes from a community-initiated workshop held April 20-22, 2022 at Sorbonne Université in Paris, France. The MP3 workshop aimed at developing science questions to guide research and future experiments in four areas identified by corresponding MP3 working groups:

- high-field physics and quantum electrodynamics (HFP/QED),
- laboratory astrophysics and planetary physics (LAPP),
- laser-driven nuclear physics (LDNP), and
- particle acceleration and advanced light sources (PAALS).

The PAALS working group focused on the unique laser-driven particle and photon sources that will enable the science questions (SQs) identified by other working groups.

A year-long series of virtual working group and all-hands meetings reviewed concepts, developed science themes, and evolved SQs derived from 97 white papers solicited from 265 registered MP3 community members. The combined in-person and Zoom participation for the MP3 workshop totaled 154 people. Participants enjoyed seeing long-time colleagues and meeting new ones in person after a long hiatus imposed by the COVID-19 pandemic.

Science Theme 1: Highest-energy phenomena in the universe – High-power laser facilities now enable unprecedented focused intensities and field strengths in the laboratory. Experiments using multi-petawatt laser pulses promise access to extraordinary field strengths exceeding the threshold where quantum-electrodynamics (QED) effects play an important role in the dynamics of the system.

- SQ1A – How might multi-petawatt lasers reveal the physical mechanisms that produce the most energetic particles and brightest events in the universe?
- SQ1B – How does light transform into “plasma fireball” composed of matter, antimatter and photons?

Science Theme 2: The origin and nature of space-time and matter in the universe – Current and future facilities can create matter and radiation at extreme conditions so that on a tiny scale one may replicate a huge variety of environments known to exist in the visible universe. Some experiments do not produce results predicted from first-principles calculations showing the importance of testing theoretical predictions. Multi-petawatt lasers can generate these conditions of ultra-high temperature, pressure, and acceleration, as well as new diagnostic probes to interrogate them.

- SQ2A – How do complex material properties and quantum phenomena emerge at atomic pressures and temperatures relevant to planetary cores?
- SQ2B – How can multi-petawatt lasers study black hole thermodynamics through the link between gravity and acceleration?
- SQ2C – How does the electromagnetic interaction behave under extreme conditions?

Science Theme 3: Nuclear astrophysics and the age/course of the universe – Nuclear physics using intense lasers can open new frontiers in scientific research. Laser-driven sources of energetic particles, such as protons and neutrons, and photons can induce nuclear reactions, probe nuclear physics, and enable practical applications.

- SQ3A – What can be learned about heavy-element formation using laser-driven nucleosynthesis in plasma conditions far-from-equilibrium?
- SQ3B – How can high-flux gamma sources generated from multi-PW lasers be used to explore hadronic physics (low-energy QCD)?

High-energy particle and radiation sources based on multi-petawatt lasers with unique capabilities for addressing the science questions posed in this report constitutes a core area of research, as well as enabling new applications based on these sources.

Chapters 2, 3, and 4 address the MP3 science themes and each of the SQs using a common approach: (1) road mapping science goals and flagship experiments for each SQ using and building on existing capabilities; and (2) identifying any missing critical needs, like diagnostics, theory, computation. Chapter 5 outlines underlying research to produce needed high-energy particle and photon sources, while Chapter 6 summarizes collaborative frameworks and joint strategies to realize needs for meeting roadmap goals, and Chapter 7 presents a vision for next-generation facility capabilities.

1 Introduction to the Multi-Petawatt Physics Prioritization (MP3) Workshop

Multi-petawatt laser systems can produce light pressures in the exa-Pascal regime, copious amounts of photons and extremely bright beams of energetic particles up to multi GeV energies including X-rays, electrons, ions, neutrons, or antimatter. These novel capabilities enabled by multi-PW lasers, described in a series of recent reports shown below, open new frontiers in research and development, such as high-field physics and nonlinear quantum electrodynamics (QED), laboratory astrophysics, and laser-driven nuclear physics.

1.1 MP3 Workshop Charge, Organization and Process

The top-level charge of the Multi-Petawatt Physics Prioritization (MP3) workshop, sponsored by the National Science Foundation, includes:

- defining key science goals and flagship experiments;
- identifying joint strategies for developing diagnostics; and
- discussing a vision for the optimal next-generation facility.

The MP3 workshop process employed an atypical approach adapted to the circumstances of the COVID-19 pandemic. It used virtual networking tools to engage a broad range of global experts to prepare for the in-person workshop. The chairs first established the MP3 process and tools, and then recruited and engaged working group (WG) leaders in January to March 2021. The process organized around four topics:

High-Field Physics and Quantum Electro-Dynamics (HFP/QED)
Alexey Arefiev (UCSD)
Tom Blackburn (U. Gothenburg)
Stepan Bulanov (LBNL)
Dmitri Uzdensky (CU Boulder)

Laboratory Astro/Planetary Physics (LAPP)
Gianluca Gregori (Oxford)
Hye-Sook Park (LLNL)
Eva Zurek (U. Buffalo)

Particle Acceleration and Advanced Light Sources (PAALS)
Sudeep Banerjee (ASU)
Gennady Shvets (Cornell Univ.)
Scott Wilks (LLNL)

Laser-Driven Nuclear Physics (LDNP)
Calvin Howell (Duke Univ.)
Markus Roth (TU Darmstadt)
Kazuo Tanaka (ELI-NP)

The chairs solicited white papers addressing the WG topics and invited participants to join one or more WGs that aligned with their interests by signing up for the MP3 mailing list. The MP3 mailing list includes 265 individuals self-identifying in the HFP/QED (118), LAPP (91), PAALS (132), and LDNP (71) working groups. The MP3 mailing list includes participants from Europe (135), North America (110), and Asia (22). White paper submissions totaled 97 that aligned with the HFP/QED (51), LAPP (27), PAALS (42), and LDNP (13) working groups.

WG leaders led a series of April to June 2021 virtual WG meetings where participants discussed the white papers and identified preliminary science questions that were summarized at a "working group cross-check meeting" in June 2021. Chairs and WG leaders refined these science questions during a summer break in the process and presented distilled questions into three science themes that were presented at an "MP3 all-hands" meeting in early November 2021 and further refined.

1. **Highest-energy phenomena in the universe**
   - How might multi-petawatt lasers reveal the physical mechanisms that produce the most energetic particles and brightest events in the universe?
   - How does light transform into a "plasma fireball" composed of matter, antimatter, and photons?
2. **The origin and nature of space-time and matter in the universe**
   - How do complex material properties and quantum phenomena emerge at atomic pressures and temperatures relevant to planetary cores?
   - How can multi-petawatt lasers study black hole thermodynamics through the link between gravity and acceleration?
   - How does the electromagnetic interaction behave under extreme conditions?
3. **Nuclear astrophysics to understand the age of the universe**
   - What can be learned about heavy-element formation using laser-driven nucleosynthesis in plasma conditions far-from-equilibrium?
   - How can high-flux gamma sources generated from multi-PW lasers be used to explore Hadronic Physics (Low Energy QCD)?

COVID-19 pandemic surges led to postponement of the three-day, in-person workshop until April 20-22, 2022. Additional working group meetings prepared material for consideration at the workshop, including summaries of the working group findings and a draft workshop report.

The first day of the MP3 workshop started with a plenary session to kick off the workshop with opening remarks by the chairs. It included plenary sessions to report the WG findings and draft recommendations by WG leaders for all three science themes after an opening keynote talk, as noted in Table 1. The second day started with a plenary session summarizing key points from Day 1 and charged breakout groups with the goals for parallel, all-day breakout sessions. Each breakout group reviewed the draft workshop report materials in three areas:

1. roadmap each MP3 science question using and building on existing capabilities, and defining any new needs;

2. identify any missing critical needs (diagnostics, theory, computation, etc.); and
3. develop collaborative frameworks to realize them for meeting roadmap goals.

The third day started with a plenary session summarizing key points from Day 2 that was followed by an open discussion for any long-term needs beyond what can be realized with existing or upgraded facilities. Workshop chairs and working group leaders met after closing the workshop to define the process for finalizing the workshop report. Working group leaders updated summary material and forwarded it the co-chairs for review. Two co-chairs were assigned primary writing and editing duties for each section. Upon completion, all sections were reviewed by all chairs and distributed to working group leaders for their feedback. Chairs resolved any concerns that were identified during this review.

Topic	Speaker
Multi-petawatt science and underlying physics	**Keynote:** Prof. Stuart Mangles (Imperial College London)
Highest-energy phenomena in the universe	**Summary:** Prof. Thomas Blackburn, (Univ. Gothenberg, Sweden), & Prof. Dmitri Uzdensky, (Univ. Colorado, Boulder, USA) **Plenary:** Prof. Mattias Marklund (Univ. Gothenberg, and Secretary General for Natural and Engineering Sciences, Swedish Research Council, Sweden)
Probing matter and space from the microscopic scale to their emergent (collective) behavior	**Summary:** Prof. Gianluca Gregori, (Oxford University, UK) **Plenary:** Prof. Luís Silva (Inst. Superior Técnico, Portugal)
Nuclear astrophysics to understand the age of the universe	**Summary:** Dr. Klaus Spohr (ELI Nuclear Physics, Romania) **Plenary:** Prof. Norbert Pietralla (TU Darmdstadt and Managing Director of the Inst. for Nuclear Physics, Germany)

Table 1: Speakers who presented in the MP3 workshop plenary sessions

1.2 Overview of the global MPW status

Multi-petawatt physics experiments using ultraintense lasers have started emerging now that laser technology has recently crossed the multi-petawatt threshold. Ref. [1] provides a recent overview of petawatt- and exawatt-class lasers worldwide and includes Fig. 1 that illustrates the technological progress leading to this new regime.

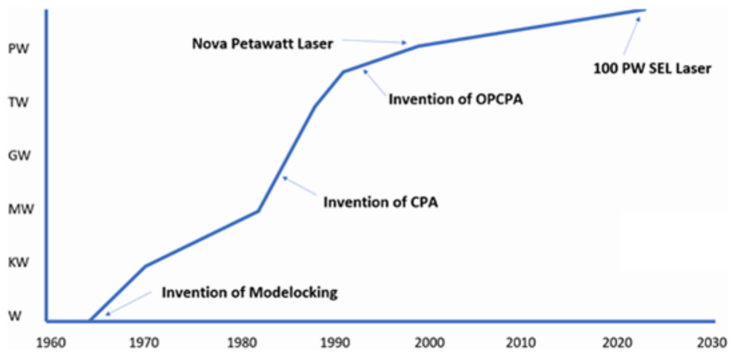


Figure 1: Record ultra-short-pulse laser peak powers at since the invention of the laser. [From Ref. [1]]

Numerous petawatt-class lasers have operated around the world (see Fig. 2). The development of chirped-pulse amplification (CPA) by Strickland and Mourou [3] in 1985 enabled rapid progress in the ensuing decades. Implementation of optical parametric chirped-pulse amplification (OPCPA) continued this progress with ever increasing peak powers since it can support broader bandwidth for shorter pulses, as well as higher pulse energies. The pace of advances slowed as technological limits arose, most notably due to the large diffraction gratings required to compress highly energetic, ultrashort laser pulses. Commissioning lasers and experimental systems to full specifications takes careful and deliberate steps, especially as the facility scale increases.

Table 2 notes multi-petawatt laser facilities that have come online, started construction, or planned/proposed along with their ultimate MPW peak power and the start or expected year operating.

Chapters 2-4 of this workshop report present science questions and grand challenges in three research themes enabled by this new generation of ultra-intense and powerful lasers – high-field physics and quantum electrodynamics (HFP/QED), laboratory astrophysics and planetary physics (LAPP), and laser-driven nuclear physics (LDNP). Chapter 5 presents research and development required to produce particle acceleration and advanced light sources (PAALS) using multi-petawatt lasers needed for the grand-challenge experiments. Research will exercise the petawatt and the multi-petawatt laser facilities existing now and those to come.

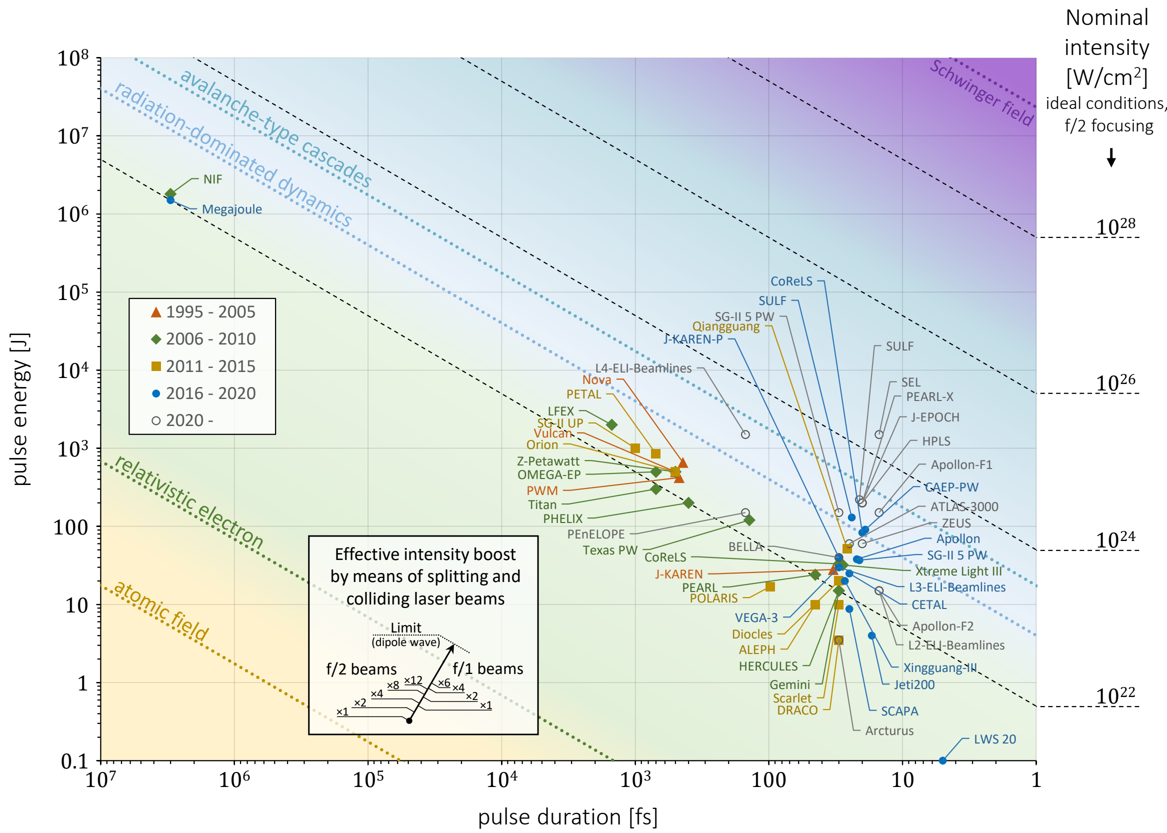


Figure 2: The existing, being built, and planned laser facilities in the (pulse energy, pulse duration) plane, according to Ref. [1] and the data from individual facilities. In order to illustrate the potential reach of these facilities, the nominal peak intensity levels (marked with dotted lines) are estimated (the laser pulse is assumed to be Gaussian temporally and spatially, with a wavelength of $\lambda = 1$ μm and focused by an $f/2$ off-axis parabola). The intensification due to the splitting of the laser power among the specified number of beams and colliding them so that the electric field is summed up coherently is shown in the insert. Reproduced from Gonoskov et al., [2].

Facility (country)	MPW Peak Power	Laser Technology	Year
Operating (actual start of MPW operations)			
CORELS (South Korea)	4.2 PW (83 J/19 fs)	Ti:sapphire CPA (0.1 Hz)	2017
SULF (China)	12.9 PW (551J/23 fs)	Ti:sapphire CPA (shot/min)	2019
ELI-NP HPLS (Romania)	10.2 PW (230 J/23 fs)	Ti:sapphire CPA (shot/min)	2022
Under construction / commissioning (expected full commissioning year)			
Apollon (France)	10 PW (180 J/18 fs)	Ti:sapphire CPA (shot/mins)	2023
ELI-ALPS HF (Hungary)	2 PW (34 J/17 fs)	Ti:sapphire CPA (10 Hz)	2023
NSF ZEUS (USA)	3 PW (75 J/25 fs)	Ti:sapphire CPA (shot/min)	2023
ELI-Beamlines L4 (Czechia)	10 PW (1.5 kJ/150 fs)	OPCPA-glass (shot/mins)	2023
Planned / Proposed (expected full commissioning year)			
SEL (China)	100 PW (1.5 kJ/15 fs)	All-OPCPA (shot/mins)	~2027
EP-OPAL (USA)	2×25 PW (500 J/20 fs)	All-OPCPA (shot/5 mins)	~2029
Vulcan 20-20 (UK)	20 PW (400 J/20 fs)	All-OPCPA (shot/5 mins)	~2029

Table 2: Multi-petawatt lasers worldwide.

2 Science Theme 1: Highest energy phenomena in the universe

2.1 Science Question 1A: How might multi-petawatt lasers reveal the physical mechanisms that produce the most energetic particles and brightest events in the universe?

2.1.1 Introduction

Extremely energetic, ultrarelativistic particles pervade the Universe and produce very high-energy gamma-rays.

Extremely energetic ultrarelativistic particles, often with power-law distributions covering several decades in particle energy, pervade the Universe and emit high-energy gamma-rays. Astrophysical systems producing these particles usually involve relativistic compact objects – neutron stars (NSs) and black holes (BHs) — and their relativistic plasma outflows, such as pulsar magnetospheres and pulsar wind nebulae or spectacular relativistic jets driven by supermassive BHs in active galactic nuclei (AGN), including blazars; they can also involve dramatic cosmic stellar explosions, like supernovae (SN) and Gamma-Ray-Bursts (GRBs). Perhaps the most notable example of extremely energetic particles is cosmic rays (CRs) — ultra-relativistic protons with energies up to 10^{20} eV. While most CRs with moderate energies $\lesssim 10^{15}$-10^{16} eV are believed to be produced by Galactic sources such as SN shocks, the most energetic particles, including, ultra-high-energy CRs (UHECRs, $E \gtrsim 10^{18}$ eV), require extragalactic origin, with AGN jets and GRBs being the most plausible sources.

In addition to direct detection of CRs on Earth, extremely relativistic charged particles can also manifest themselves observationally in other ways. For example, accelerated electrons and positrons can produce very high-energy gamma-ray emission, e.g., the TeV emission observed from SN shocks or ultra-rapid TeV flares from blazars, or as MeV-GeV emission, also often rapidly flaring, from many classes of astrophysical NS or BH objects. In addition, multi-PeV CR protons in, e.g., AGN jets are capable of producing, via various hadronic processes, PeV neutrinos that are detected with the NSF's IceCube neutrino observatory. Along with Cosmic Rays (and also gravitational waves), these neutrinos open up the rapidly developing frontier of Multi-Messenger Astronomy.

How these particles are accelerated in Nature to their extremely high energies has been an outstanding scientific question in Plasma Astrophysics over many decades, driving copious observational, theoretical, and computational research. It is generally believed that relativistic particles are accelerated by nonlinear *collective plasma processes*; the most important examples are magnetic reconnection, collisionless shocks, and turbulence, taking place in highly dynamic relativistic plasma environments around NSs and BHs. These plasma processes are complex: they are nonlinear, often involve nontrivial kinetic physics requiring full 6D phase-space treatment, and are typically characterized by huge (many orders of magnitude) scale separations between global macroscales and fundamental kinetic plasma microscales. All these aspects make numerical modeling and developing theoretical physical understanding of these processes and of their associated particle acceleration a profound challenge of modern plasma physics.

Laboratory studies of these astrophysically relevant collective plasma processes could in principle be of great help, as they could provide invaluable fundamental physics insights into the underlying mechanisms of relativistic particle acceleration and strongly impact astrophysics and fundamental plasma physics research. Dedicated experimental campaigns, including those employing powerful lasers, have started and show great promise, especially in regard to developing the necessary experimental platforms and diagnostics with some already starting to yield unique physics insights.

First-principles, kinetic (particle-in-cell, or PIC) numerical simulations and analytical theory have shown that nonthermal particle acceleration to extremely high relativistic energies becomes especially effective (resulting in harder power laws, greater high-energy cutoffs) when the underlying collective plasma processes occur in the so-called *relativistic regime*, in which magnetic energy density greatly exceeds the rest-mass energy density of the plasma. Most of today's laser-based experiments studying basic collective plasma processes (such as those using Omega-EP, NIF, Vulcan, etc.) employ relatively long pulses with only modest intensities making it difficult to achieve relativistic plasma conditions, which makes them not very well-suited for studies of relativistic plasma processes.

Experiments using ultra-intense, short-pulse lasers available today already access the relativistic-electron regime and enable pilot laboratory studies of collective plasma processes in semi-relativistic plasmas (relativistic electrons but sub-relativistic ions) under the conditions similar to those in accreting BH coronae, although only at the electron scales.

Direct experimental investigation of truly relativistic collective plasma processes initially requires using a relativistic electron-positron pair plasma as its basic platform, since making ions relativistic in an electron-ion plasma is even more difficult. *Creating a relativistic pair plasma in the lab* represents a top priority for High-Energy-Density plasma physics in general and for the next generation of laser facilities in particular. Both collisionless and optically thin relativistically hot pair plasma, and a dense, optically thick, collisional photo-leptonic fireball (see SQ 1B) would be of great interest from the astrophysics point of view.

Just creating a cloud of relativistic electrons and positrons is not enough. In order for such a platform to be useful for studies of collective plasma phenomena, the relativistic pair plasma needs to be "macroscopic", — i.e., have a sufficiently large spatial extent and sufficiently long life time, — so that it could, in fact, be capable of exhibiting collective behavior. In particular, the plasma size should exceed the basic plasma kinetic scales such as Debye length, collisionless skin depth, etc., preferably by a factor of 10 to 100. Accessing this demanding regime requires not just a very high ($\gtrsim 10^{23}$ W/cm^2) laser intensity, but also a large (kJ) overall laser pulse energy that could enable a sufficiently large transverse spot size (mm) and long duration (ps). Next-generation multi-PW lasers coming on-line in the next decade can achieve this ambitious goal, as discussed below.

One particularly interesting key aspect of this quest, especially important for studies of high-energy particle acceleration by astrophysically-relevant plasma processes, is the need to generate very strong magnetic fields that are coherent and long-lasting on macroscopic scales. Indeed, charged particle acceleration is ultimately accomplished by the electric field, whose magnitude, in a macroscopic plasma exhibiting relativistic bulk motions, can approach a sizable fraction (e.g., ~ 0.1 in collisionless relativistic reconnection) of the magnetic field. The maximum attained particle energy, which is limited by the work done by the electric field on the particle, is thus controlled by the product of the electric (and hence magnetic) field strength and its coherence scale. Likewise, the same product controls the maximum energy of particles that can be confined by the magnetic field within the system. For example, accelerating electrons in magnetic reconnection to $\gamma = 100$ over a $10\,\mu$m accelerating length by an $E_{\rm rec} \simeq 0.1 B_0$ reconnection electric field would require a reconnecting magnetic field of at least $B_0 \gtrsim 10^6\,{\rm T} = 10^{10}\,{\rm G}$ (ignoring radiation losses). Producing coherent fields of such strength is not really feasible now, but should be possible with future next-generation lasers reaching intensities of order $10^{24}\,{\rm W/cm}^2$, requiring laser power [assuming a $(10\,\mu{\rm m})^2$ active spot area] of order 10^3 PW or an exawatt (EW) (see § 2.1.5).

Strong coherent plasma magnetic fields of $10^5 - 10^7$ T $= 10^9 - 10^{11}$ G, which are needed to study relativistic particle acceleration via collective plasma processes and which are expected to be produced in such next-generation multi-PW class laser facilities, are impressive even by astrophysical standards. They exceed the fields expected near accreting stellar-mass BHs in X-ray Binaries such as Cyg X-1 (up to 10^8 G) and super-massive BHs in AGN (10^4 G). They also exceed the magnetic field at the light cylinder of the Crab pulsar (10^6 G) or near the surface of weakly-magnetized NSs in X-ray bursters ($10^8 - 10^9$ G), although they are still much weaker than the surface magnetic fields of most normal NSs, such as regular radio- and X-ray pulsars (10^{12} G), and, by an even larger margin, those near magnetars ($10^{14} - 10^{15}$ G). At the same time, $10^9 - 10^{11}$ G are expected in the intermediate ($r \sim 10 - 100 R_{\rm NS}$) zone of magnetar magnetospheres, a hypothesized site of Fast Radio Bursts (FRBs); thus, investigating in the lab relativistic pair plasma behavior in the presence of fields of such strength may be instrumental for understanding this enigmatic phenomenon.

2.1.2 Roadmap: progress using current facilities

Main idea: *Current facilities have the capability, for the first time, to study electron-scale collective plasma processes (like magnetic reconnection) in the semi-relativistic regime, where the ions are subrelativistic but electrons can become ultra-relativistic, with some radiation effects. This regime is of great interest in high-energy astrophysics, specifically, for understanding electron energization processes in accretion flows and coronae around accreting black holes. However, these experiments will not yet be able to achieve QED plasma conditions, necessary for the creation of macroscopic pair plasmas.*

Current state-of-the-art, ultra-intense laser facilities (see Table 2, and a detailed list in Ref. [2]), employing ~ 1 PW-power laser beams tightly focused onto $\sim 1\ \mu m^2$ (comparable to laser wavelength) spots, achieve intensities of order $10^{23}\,{\rm Wcm}^{-2}$. This corresponds to a classical relativistic nonlinearity parameter of $a_0 \sim 200$, corresponding to a laser magnetic field of about 2×10^6 T. Assuming for simplicity that the resulting coherent magnetic field generated in the plasma is about 5 times weaker than the laser field, we can reasonably hope to be able to generate plasma fields of 4×10^5 T $= 4 \times 10^9$ G. This may enable one to accelerate electrons in a magnetic reconnection scenario, to moderately relativistic energies with a Lorentz factor of a few; however, the small hot spot size, limited by the available laser power, will not be large enough to create a macroscopic pair plasma. Nevertheless, these intensities, when used in a laser-solid-target experiments, will allow researchers to produce a small-scale, relativistically hot electron plasma embedded in a sub-relativistic, essentially stationary or slowly moving quasi-uniform ion background. This, in turn, will enable important pioneering studies of collective nonlinear processes like shocks and magnetic reconnection on small (namely, electron kinetic) scales in the semi-relativistic regime [e.g., WP-81], opening new vistas in laboratory plasma astrophysics research and laying down the groundwork for future experiments with relativistic pair-plasma fireballs.

2.1.3 Roadmap: theoretical understanding

The growth in theoretical understanding over the next decade will continue benefiting from state-of-the-art 2-D and 3-D simulation studies of collective plasma processes in the relativistic and radiative regimes. Such studies have recently become possible thanks to the advent of novel radiative-PIC and radiative-QED PIC codes, such as EPOCH, OSIRIS, PICLS, Zeltron, Tristan v2, and Smilei. These codes can simulate complex kinetic plasma processes from first principles, while taking into account all relevant "exotic" radiation and QED physics. Codes like EPOCH, OSIRIS, Smilei, and Tristan v2 include the basic QED processes of nonlinear Compton scattering and nonlinear Breit-Wheeler pair production, whereas PICLS and OSIRIS also include effects related to photon-photon scattering and vacuum polarization, respectively. These novel capabilities, combined with ever-growing computing resources, will put understandings of astrophysically-relevant collective plasma processes in relativistic and radiative plasmas on a rigorous, firm theoretical basis. The parameter regime of interest, motivated by astrophysical applications, is, however, very broad and multi-dimensional; thus, exploring it comprehensively with rather expensive large-scale 3D kinetic simulations, and then analyzing these simulations, will require very substantial resources, both in terms of computing allocations and human time. This requires the community to develop a systematic, organized approach to such computational studies, which will require coordination between different research groups.

In addition to numerical simulations, further progress will require concerted theoretical (analytical) efforts, to guide both numerical simulation campaigns and experimental explorations. WP-8 is an example of new schemes to generate extreme electric and magnetic field conditions. Analytical theory will push the frontiers of understanding plasma-astrophysical particle-acceleration processes into new, so far relatively unexplored, extreme plasma regimes where familiar collective plasma processes interplay in nontrivial ways with radiative and QED physics. Analytical theory will also play a key role in building bridges between laboratory laser-plasma experiments, fundamental plasma physics, and phenomenological models of extreme astrophysical plasma environments around NSs and BHs.

2.1.4 Roadmap: flagship experiments requiring new capabilities

Main idea: *New capabilities at existing facilities will feature more complex experimental configurations involving multiple beams. The resulting increased flexibility will enable studies of diverse physical regimes with a broader coverage of the parameter space. In addition, the new capabilities will open up access to the radiation-dominated regime of collective plasma processes, including some QED effects like radiation recoil.*

In the next few years, upgraded capabilities at existing laser facilities, such as new beam lines, and intensity and/or power upgrades, the ability to shoot fixed plasma targets, will add flexibility to the experimental configurations, such as arrangements involving multiple laser and particle beams. Among other benefits, these enhancements will raise the available laser beam power up to around 10 PW, allowing one to reach intensities of order $10^{23} - 10^{24}\,\mathrm{W\,cm^{-2}}$, depending on the focusing. This, in turn, will open the new radiation-dominated regime of plasma processes to direct experimental exploration [e.g., WP- 77]. In this regime, the emitted radiation is not just a passive tracer of the plasma dynamics and energetics (still extremely useful for diagnostics) but also strongly affects them. The interplay between quantum (e.g., quantum recoil on emitting particles) and collective effects will significantly determine the dynamics of the plasma, opening for the first time the possibility to investigate such interactions in the relativistic regime.

In terms of experiments aimed at producing strong coherent plasma magnetic fields, the commissioning of the L4 laser at ELI Beamlines poses an important milestone. The combination of longer pulse duration (150 fs vs. 30 fs) and high intensity ($\sim 10^{23}\,\mathrm{W\,cm^{-2}}$) will enable generation of volumetric plasma magnetic fields in the MT range, enabling meaningful reconnection experiments in new, strongly radiative regimes relevant to many extreme astrophysical systems described in § 2.1.1. Reconnection experiments require configurations with at least two laser pulses, which introduces additional demands for laser facility capabilities; these demands, however, will be met with the planned upgrades to the above-mentioned facilities in the next few years.

Volumetric laser-plasma interactions leading to generation of strong plasma magnetic fields coherent over relatively large scales are also likely to require specifically designed targets. These might be foam targets with a density that guarantees relativistically induced transparency for the expected laser intensity. Structured targets might be introduced to improve control over the laser-plasma interaction. Currently, such targets are expensive, so new target fabrication capabilities will need to be developed to address the cost. This aspect becomes even more important for high repetition rate laser facilities.

2.1.5 Roadmap: flagship experiments requiring next-generation facility capabilities

Main idea: *Flagship experiments on next-generation laser facilities will create a revolutionary experimental platform — macroscopic (i.e., plasma size exceeding kinetic scales) relativistic pair-plasma fireballs — used to study collective plasma processes in the truly relativistic regime.*

Next-generation laser facilities (Chapter 7) — those reaching laser power of several tens, perhaps up to a hundred, of PW — will create relativistically hot pair-plasma fireballs via the avalanche-type electromagnetic cascade process using two or more very powerful laser beams [e.g., WP-71, WP-77]. Creating such pair-plasma fireballs of macroscopic size will be a great scientific breakthrough on its own right. How to achieve it using multi-PW-class lasers is described in Science Question 1B (§ 2.2), but here we shall briefly discuss how to use these fireballs to build a new experimental platform for laboratory studies of relativistic collective plasma processes [e.g., WP-72], and the associated particle acceleration, and what progress can be expected from such studies.

Most promising schemes will require creating two such fireballs (and hence several, at least 4 beamlines) and make them interact with each other by bringing them into direct contact (e.g., colliding them with each other). This is particularly useful for setting up laboratory studies of magnetic reconnection and shocks — the two plasma processes that are broadly regarded as the most important astrophysical mechanisms of nonthermal particle acceleration. Lasers have already been used for studies of these processes in traditional, non-relativistic electron-ion plasmas, so some of the key guiding design principles of such experiments are understood. Extending them to studies of similar processes but in the relativistic pair-plasma regime should not cause much difficulty, especially for shock studies, provided that pair plasmas of sufficient size (preferably tens of hundreds of skin depths) can be created. If the two lasers involved in the creation of each fireball are asymmetric, then the resulting fireball can be made to fly with a relativistic speed; colliding two such fireballs can set up a scenario for studying a relativistic shock, mimicking processes that occur at the pulsar-wind termination shock or in the internal shock model of GRB prompt emission.

2.1.6 Broader Impacts

The study of relativistic plasma with the parameters relevant to astrophysical phenomena would require significant technological advancement of the high intensity high power laser facilities. Some initial progress can be achieved at current facilities, but in order to move forward, new capabilities at existing facilities need to be introduced and, ultimately, next-generation facilities built. This can not be achieved without concentrated efforts by scientists and engineers, academic institutions, and industry partners. It will require much broader efforts to train a new generation of specialists who will build and then use these facilities to answer the scientific question outlined in this report. New capabilities and new facilities mean not only more powerful lasers, but new and more precise diagnostic tools (Chapter 6) able to cover much wider parameter space, and new advanced targets. Last but not least, the efforts will build a robust collaboration between laser scientists, astrophysicists, and those working in the emerging field of QED plasma.

2.1.7 Recommendations

Since the collective plasma processes in the semirelativistic regime, where ions are subrelativistic but electrons ultra-relativistic with some radiation effects, prove of great interest in high-energy astrophysics for understanding electron energization processes in accretion flows and coronae around accreting black holes, they should be studied at current facilities capable of carrying out such experiments. New capabilities on existing facilities will enable more complex experimental configurations involving multiple beams to provide increased flexibility and enable studies of diverse physical regimes with a broader coverage of parameter space. In addition, the new capabilities will open up access to the radiation-dominated regime of collective plasma processes, including some QED effects like radiation recoil. Flagship experiments on next-generation laser facilities will create relativistic pair-plasma fireballs and use them to study collective plasma processes in the truly relativistic regime. These experimental efforts will require accompanying theoretical and simulation advances.

These conclusions are based on the white papers received: the importance of the study of pair plasmas was emphasized in WPs-[25,26,59,64,72,77], the study of magnetic reconnection in WPs-[65, 81], the study of instabilities/particle acceleration in WP-69, and shocks in WP-74.

2.2 Science Question 1B: How does light transform into a "plasma fireball" composed of matter, antimatter and photons?

2.2.1 Introduction

The creation and acceleration of high-energy particles in astrophysical environments usually require strong electromagnetic fields, highly relativistic plasmas, and interactions governed by quantum electrodynamics (QED). QED is the best verified quantum field theory with astonishing agreement between theoretical predictions and experiments, and it represents one of the cornerstones of the Standard Model of particle physics; however, one sector of this theory has remained quite undeveloped compared to everything else: the interaction of charged particles and photons with strong electromagnetic fields, which is quite different from the usual single-particle scattering and decay processes [2, 4–6] and which is usually referred to as strong-field QED (SF-QED). The basic building blocks of the description of such interactions are well known for many years [7], but the consistent theoretical description of the interaction, which can be verified experimentally, is still under development [5]. Moreover, the number of experimental campaigns addressing the challenges of particle interactions with strong electromagnetic fields has been quite limited (see, e.g., [8–11]), which hopefully will change soon with the advent of MPW lasers.

The electromagnetic (EM) field is considered strong in QED when it is on the order of thw critical (Schwinger) field of QED, E_{cr}. This field produces work of $mc^2 = 0.51\,\text{MeV}$ over an electron Compton length $\lambda_c = \hbar/mc = 3.9 \times 10^{-11}$ cm, $E_{cr} = m^2c^3/\hbar e = 1.32 \times 10^{16}$ V/cm. Such fields can produce an electron-positron pair from vacuum, the so-called Schwinger effect. However, the critical QED field does not only characterize the Schwinger effect, but also provides a scale for the onset of quantum field theory effects in charged particle and photon interactions with electromagnetic fields. For example, the probabilities of the nonlinear Compton scattering ($e \rightarrow e\gamma$) and nonlinear Breit-Wheeler pair production ($\gamma \rightarrow - > e^+e^-$) are characterized by two parameters $\chi_e = \sqrt{|F_{\mu\nu}p^\nu|^2}/mcE_{cr}$ and $\chi_\gamma = \sqrt{|F_{\mu\nu}k^\nu|^2}/mcE_{cr}$, where $F^{\mu\nu}$ is the tensor of the strong EM field and p^ν and k^ν are the four-momenta of the electron and photon, respectively. These probabilities acquire optimal values at $\chi_{e,\gamma} \sim 1$. Both χ_e and χ_γ are the products of EM field tensor and the particle momentum normalized to the critical field. An electron in a strong field provides a straightforward interpretation of χ_e, which is the EM field strength in electron rest frame normalized to E_{cr}:

$$\chi_e = \frac{\gamma E}{E_c r} = 0.3 \left(\frac{E}{500 \text{ MeV}}\right) \left(\frac{I}{10^{22} \text{ Wcm}^{-2}}\right)^{1/2}, \tag{1}$$

where the laser intensity and the amplitude of the vector-potential of the EM field are connected in the following way:

$$a_0 = \frac{eE}{mc\omega} = 85 \frac{\lambda}{\mu\text{m}} \left(\frac{I}{10^{22} \text{ Wcm}^{-2}}\right)^{1/2}. \tag{2}$$

Thus, these parameters literally compare EM field strength to the critical one, indicating the importance of quantum corrections to the particle dynamics, radiation emissions, and pair production in EM fields.

Strong EM fields can be found in different interaction setups, including close proximity of compact astrophysical objects, such as magnetars and central engines of GRBs, high-Z nuclei, dense particle beams in the interaction points of high energy particle accelerators, aligned crystals, and in the foci of high-power lasers. Whereas some of these environments provide fields of critical value, others provide fields that are below and need to be combined with high-energy particle beams (below critical fields may appear of critical strength in the reference frame of the relativistic particle beam) or fixed plasma targets to probe SF-QED effects. For example, the case for aligned crystals and in the foci of high power lasers. The latter seems to be the most attractive option due to its flexibility from the point of view of providing different interaction configurations, especially, at the multi-PW level.

While many phenomena in SF-QED have attracted a lot of attention over the last several decades, one stands really apart from the others: the so-called electromagnetic cascade, which is a multi-staged process of initial particle and/or laser pulse energy transformation into secondary electrons, positrons, and photons. Here the dynamics of particles is dominated by photon emission and pair production, the laser pulse properties might be severely affected by emerging electron-positron-photon plasma. This is the intersection of SF-QED and relativistic plasma physics. It is exactly here, where SQ1B comes from: "How does light transform into plasma fireball composed of matter, antimatter and photons?" The most general answer to that would be "through the electromagnetic cascade." There are two types of cascades, usually associated with either longitudinally or transversely dominated motion of electrons, positrons, and photons with respect to the laser pulse propagation direction. The former is referred to as a shower-type cascade, while the latter as an avalanche-type cascade.

A typical setup for a shower-type cascade is a head-on collision of a high energy particle beam with a laser pulse with $\gamma \gg a_0$. In this case the laser works as a target for the particle beam. As the particles interact with the laser field they experience Compton and Breit-Wheeler effects leading to beam energy transformation into secondary electrons, positrons, and photons, which are mainly streaming in the same direction as the initial particle beam.

A typical setup for an avalanche-type cascade is the interaction of two or more colliding laser pulses with a fixed target. In this case the lasers not only accelerate charged particles, but also provide conditions for Compton and Breit-Wheeler effects, and then re-accelerate electrons and positrons either after a photon emission or after being produced in a Breit-Wheeler process. Due to the re-acceleration, the avalanche-type cascade is significantly more effective in producing secondary particles, when comparing to the shower-type cascade. This process can produce a plasma fireball consisting of matter, antimatter, and photons. Theoretical estimates show that an avalanche-type cascade starts when the interaction enters the radiation dominated regime, which can be defined as the electron (or positron) being able to emit almost all of its energy via a single Compton process. This occurs at laser intensities approaching 10^{24} W/cm^2. Multi-PW laser facilities are needed to reach such intensities; however, as was repeatedly emphasized in the literature (see [2] for details), the availability of tens of PW of laser power is not enough to observe the cascade. The electromagnetic field should be structured in a way that enhances the emission of photons and production of electron-positron pairs, as well as the re-acceleration. The multiple colliding laser pulses seems to offer the most advantageous and robust scheme to satisfy this requirement.

2.2.2 Roadmap: progress using current facilities

As mentioned above, strong EM fields can be found in different interaction setups. Here we consider those that need to be combined with high-energy particle beams to observe quantum behavior. Experiments using aligned crystals were reported recently [12, 13]. Experiments using the beams of particle colliders are being proposed [14] but can not be carried out yet due to the lack of accelerators with necessary parameters. Therefore, experiments involving high-power lasers provide the best immediate path forward for studying SF-QED effects. It was already demonstrated at SLAC (E144) [8, 9] and at CLF (GEMINI) [10, 11] that a high-energy electron bunch interacting with a counter-propagating laser will not only loose a lot of energy due to radiation but this radiation needs to be described in the SF-QED framework. The parameter χ_e was approximately 0.3 for the E144 and 0.2 for GEMINI experiments. The main difference between the SLAC and CLF experiments was that the former used the conventional SLAC accelerator to produce high energy electrons, while the latter resorted to the all-optical scheme, where the lasers are used to both accelerate electrons via laser wakefield acceleration (LWFA) and to scatter off the accelerated electrons.

Building on these results, many facilities are planning experiments that aim to increase χ_e or χ_γ well above unity to reach into previously inaccessible quantum regime and track the transition of the radiation reaction from classical to quantum description. For example, SLAC is running the E320, and DESY is planning the LUXE experiment [15] using conventionally accelerated 10 or 17.5 GeV electron beams in collision with tens of terawatt laser pulses. The University of Michigan ZEUS facility will use two laser pulses (with 2.5 PW and 0.5 PW), one to accelerate electrons (either $\gtrsim 10$ GeV or several GeV) and one to provide the electromagnetic field (intensity 10^{21} W/cm^2 or 10^{23} W/cm^2). Other laser facilities with active SF-QED study program include J-Karen in Japan, Apollon in France, CORELS in Korea, CALA in Germany, ELI-NP in Romania, and ELI-BL in

Czech Republic (for an expanded list see Ref. [2] and Fig. 2).

These experiments at current facilities all share the same features. First, the experimental setup utilizes PW-class lasers colliding with GeV-class electron beams. Second, the transition of the radiation reaction description from classical to quantum will be studied. Third, the proposed experiments are supposed to test the validity and the applicability limits of different theoretical and computational models used now. Other possible applications of the laser pulse collision with a high-energy electron beam include but are not limited to gamma-ray sources, positron sources, and strong magnetic field generation for astrophysical studies (see Fig. 3).

2.2.3 Roadmap: theoretical understanding

Theoretical understanding of SF-QED processes is based on a number of approximations, including plane wave, external field, and local constant field ones. Most of them result from an inability to obtain solutions of Dirac's equation in any EM field configuration other than a plane wave, which prevents us from carrying out analytical calculations to quantize the strong field to account for the backreaction of the SF-QED processes on the field itself, and to calculate radiative corrections and multi-staged processes. In addition, one can identify the limits where SF-QED methods should fail, but were not able to formulate a self-consistent approach how to go beyond these limits.

In most cases we rely on the separation of scales, assuming that SF-QED processes happen instantaneously, i.e., their formation lengths are much smaller than the characteristic temporal and spatial scales of strong fields. This allows to consider the motion of charged particles and photons in strong fields according to the classical equations of motion between SF-QED processes (either a photon emission by a charged particle, or an electron-positron pair production by a photon). Such approach turned out to be extremely advantageous for computer modeling of SF-QED processes in different field configurations with the majority of the results obtained with the help of PIC-QED codes.

That is why any new high power laser facility should be accompanied by a robust theoretical/simulation effort. The immediate theoretical goals are to go beyond the mentioned above approximations and develop a theoretical framework for the analysis of shower- and avalanche-type cascades, which should involve the ability to calculate rates for multi-staged processes and to take into account the backreaction of the SF-QED processes on strong EM fields.

2.2.4 Roadmap: flagship experiments requiring new capabilities

It is well understood that the current facilities are quite limited in their studies of the SF-QED effects. That is why many of these facilities plan to acquire new capabilities, like new beamlines, intensity and/or power upgrades, the ability to shoot fixed plasma targets, etc. From the point of view of EM cascades development studies new capabilities should involve a multi-GeV, laser-driven source of electrons to collide with a second intense laser pulse to study shower-type cascades. The avalanche-type cascades would require approximately 20 PW of laser power in the form of colliding laser pulses to become observable. So this task might be more appropriate for the next generation laser facilities; however, the avalanche "pre-cursors" can be observed at lower power levels corresponding to current facilities with new capabilities [16]. These "pre-cursors" are characterized by the enhanced energy absorption from the laser pulse (or pulses) by charged particles, which hints towards energy loss due to photon emission and energy gain due to the re-acceleration.

The interaction setups relevant for the cascade studies can also be used to generate gamma-ray sources, positron sources, and strong magnetic fields (see Fig. 3).

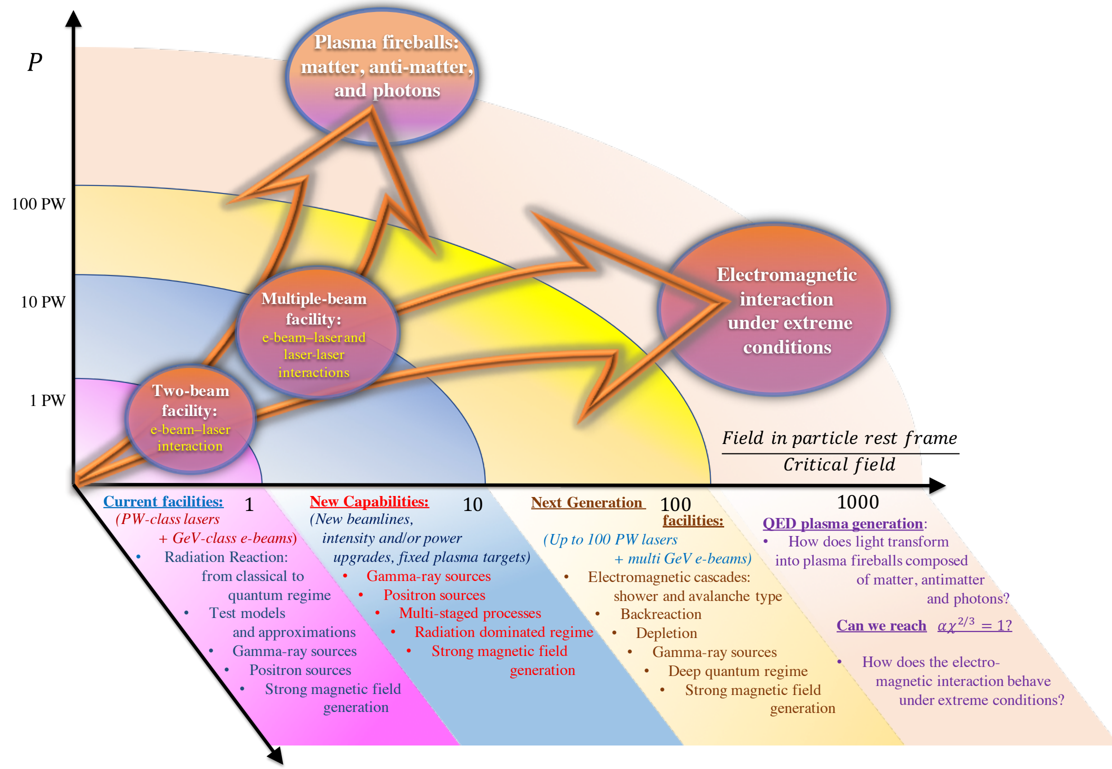


Figure 3: Timeline of the HFP/QED studies leading to answering SQ1B and SQ1C envisioned as a three-stage process starting with "current facilities" operating at PW level, then using "new capabilities" to reach new regimes of interaction at up to 10 PW level, and then "next generation" facilities to study the most fundamental SF-QED phenomena at laser power level approaching 100 PW.

2.2.5 Roadmap: flagship experiments requiring next generation laser facilities.

The main experimental goal of the next-generation laser facilities from the point of view of SQ1B will be the observation and study of the avalanche-type cascade in order to advance our understanding of "how does light transform into plasma fireball composed of matter, antimatter and photons?" This would require a multi-beam, multi-PW facility of the type shown in Fig. 4.

Such a facility design arises naturally from laser-driven particle acceleration. It is due to the fact that one of the more efficient ways of accelerating electrons and positrons is laser wakefield acceleration, which uses a staged approach [17]. This means the utilization of many laser pulses, each powering its own acceleration stage. Alternately, these pulses can instead be simultaneously focused to produce a multi-beam configuration yielding the highest intensity.

Due to the exponential growth of the number of electrons, positrons, and photons, the avalanche-type cascade provides a natural environment for the study of backreaction of produced lepton-photon plasma on the laser electromagnetic field and subsequent laser energy depletion. This is the

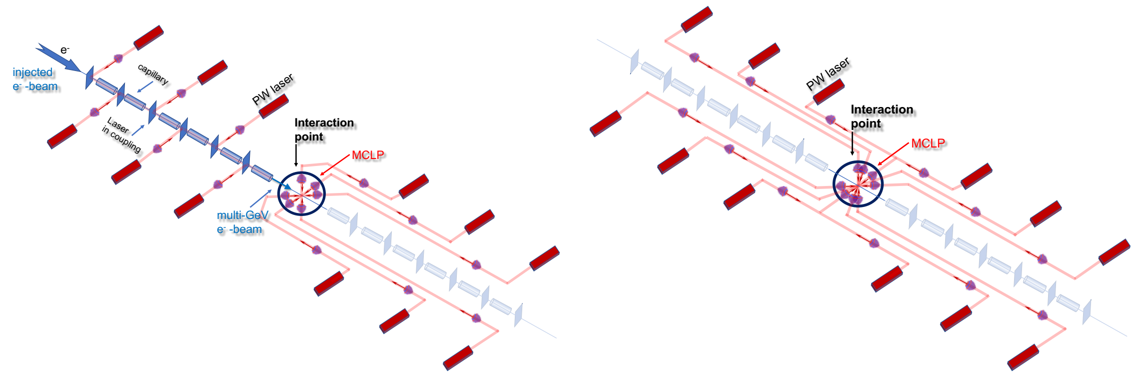


Figure 4: A multi PW laser facility, which can operate in two modes: electron-beam interaction with high intensity laser pulses for the study of shower-type cascades (left), and ultimately SQ1C and all the laser pulses are brought to the interaction point to generate highest intensity possible for the study of avalanche-type cascades and ultimately SQ1B (right). Reproduced from Zhang *et al.* [5]

domain of QED plasma physics, which is highly relevant for the astrophysical studies and almost unexplored by theory, simulations, and experiments. The coupling of high-energy physics processes with collective plasma effects will likely challenge our understanding of this state of matter and lead to significant scientific discoveries.

2.2.6 Broader Impacts

Significant scientific and technological efforts must be undertaken to answer the question, "how does light transform into plasma fireball composed of matter, antimatter, and photons?" To reach the required laser parameters, next-generation facilities need to be built that are equipped with advanced targetry, laser controls, detectors, and computational capabilities. They will also require the next generation of scientists and engineers trained at existing and upgraded facilities.

The obvious connection of this scientific program is to the astrophysical studies (WP-86), since the parameters of generated electromagnetic fields, plasma densities, and particle energies are of relevance to that field. Different particle and radiation sources can become available as we explore the parameter space of laser plasma interactions towards high energies and high intensities.

Last but not least, the possible design of a next generation, multi-PW laser facility (see Fig. 4) can lead to an electron-positron collider for high energy physics studies.

2.2.7 Recommendations

The scientific question *"how does light transform into plasma fireball composed of matter, antimatter, and photons?"* lies at the heart of QED plasma physics studies. Though it can be addressed with the help of multi-PW laser facilities able to reach 10^{24-25} W/cm^2 intensities in a matter of tens of femtoseconds and accelerate charged particles to the energies exceeding 10's and 100's of GeV, this requires much progress. Current facilities need to study individual SF-QED processes to build up understanding of particle behavior in strong fields. These facilities need to be upgraded with new capabilities to make the study of the electromagnetic cascades possible. It will open up possibilities to study the plasma dynamics in a QED/radiation-dominated regime, where collective effects of the produced electrons, positrons, and photons begin to manifest themselves for QED plasma studies at next-generation, multi-PW laser facilities. The experimental effort should be accompanied by theoretical and computational advances, which would require to significantly expand the existing workforce and the resources available to it.

This conclusion is based on multiple MP3 white papers received: WPs-[12,23,24,31,40,54,60, 67,68,70,78,80] emphasize the importance of the study of particle dynamics in strong fields, WPs-[7,37,61,72,75] consider the study of plasma dynamics in strong fields, and WP-28 investigates the theoretical possibility of investigating the "duration" of the process of pair production using muti-petawatt lasers.

The production of particles from light is probably the most striking manifestation of the interaction among electromagnetic fields in vacuum, as predicted by QED. The community has also shown interest on another still untested aspect of light-light interaction in vacuum: Intense electromagnetic fields alter the dielectric properties of the vacuum, which, according to the predictions of QED, behaves as a birefringent medium. For instance, the WPs-[17, 19 and 62] propose different setups involving either optical or x-ray photons, as probes of the birefringence properties of the vacuum as induced by a super-intense optical laser beam (WPs[17, 19), and interferometric techniques already tested to study the dielectric properties of materials (WP-62). The elementary process responsible for vacuum birefringence is photon-photon scattering and the WPs-[30, 84] aim at measuring the corresponding cross section using multi-petawatt laser beams (WP-30), as well as at improving our theoretical understanding by using novel analytical techniques (WP-84).

The mentioned WPs agree on the fact that, according to existing and soon-available detectors, such processes cannot be observed without multi-petawatt laser beams. Moreover, experiments aiming at measuring such small cross sections, like that of photon-photon scattering and/or related processes require a high-quality vacuum (better than 10^{-7} mbar) and high-sensitivity photon detectors. Another key requirement from the detection point of view is the spatial/angular and temporal resolution,to be able to discern the photon-photon scattering from unavoidably high background. WP-17 discusses the possibility and the challenging aspects of co-locating a multi-petawatt laser with an x-ray free electron laser, a setup suitable also to observe vacuum birefringence.

3 Science Theme 2: The origin and nature of space-time and matter in the universe

3.1 Science Question 2A: How do complex material properties and quantum phenomena emerge at atomic pressures and temperatures relevant to planetary cores?

The interiors of planets (e.g. silicates, oxides, iron, ices and hydrogen) are subject to extreme pressures that dictate their crystal structures, and also alter the electronic shell structures of atoms. Such pressures therefore impact phase transitions, the dynamics of planetary interiors, and their evolution. Moreover, these conditions may be harnessed to create materials with new chemistry and unprecedented properties. Multi-petawatt laser facilities allow one to use convergent direct- or indirect-drive techniques to access pressures higher than those currently available using shock and ramp compression, as well as to employ advanced diagnostics including: femtosecond x-ray and electron diffraction, spectroscopy, and broadband reflectivity. New developments at multi-petawatt laser facilities will enable the experimental study of matter under the unchartered extreme pressures at which most of the known mass in the universe resides [WPs-87,88].

3.1.1 Introduction

The quantum unit of pressure, 29.4 TPa, is the pressure required to disrupt the shell structure of atoms, engage core electrons in bonding, and unlock a new regime where correlations of electrons and ions can grow to the macroscale at high temperatures. Most of the recently discovered extrasolar planets and stars have internal pressures approaching or exceeding such conditions. First-principles calculations have predicted remarkable behavior of matter at these conditions including transforming simple metals into transparent insulators, superionic phases, hot superconductors, unexplained bonding in dense plasmas, and more. We seek to harness the power of multi-petawatt lasers to create these quantum materials here on Earth, and to probe their structure and electronic structure via advanced diagnostics. The results will make it possible for scientists to model and understand the behavior of Earth and exoplanets.

One can create ultrahigh pressures using high-power laser facilities, such as the National Ignition Facility (NIF), to conduct material studies under extreme conditions. In the direct-drive configuration, the lasers irradiate the ablator material directly producing an ablation plasma. An approximate formula to calculate the ablation pressure in direct-drive laser experiments is [18]:

$$P_{DD}(\text{Mbar}) = 40\,(I_{15}/\lambda_{\mu m})^{\frac{2}{3}} \tag{3}$$

where P_{DD} is the direct-drive pressure in Mbar, I_{15} is the laser intensity in units of 10^{15} W/cm^2, and $\lambda_{\mu m}$ is the laser wavelength in μm. As an example, if one has a 351 nm ($\lambda = 1.053/3\ \mu$m) wavelength and deposits 10 kJ of laser energy onto a 1 mm diameter spot in 1 ns ($I = 2.5\times10^{15}$W/cm^2), the ablation pressure is $\sim$100 Mbar, i.e. 10 TPa.

To reach ultrahigh pressures without melting the sample, the compression must be ramped up along a quasi-isentropic path. The easiest way to compress a sample is to apply a strong shock; however, this method quickly reaches its limit as the sample follows the Hugoniot curve and melts if the shock strength is too high. Melting can be avoided by either staging the shocks or ramping the compression following a quasi-isentropic path. In this way, as the sample is gradually compressed to higher pressures, compression is achieved with minimal entropy generation; thus, the sample stays in a solid-state while reaching high pressure.

Another interesting line of study is to shock melt the sample first and then apply a ramp compression. There are several ways of creating a ramped compression: In gas gun experiments, one uses a graded-density impactor to shape the impact pressure profile; in laser experiments, one uses the laser pulse shape to control the pressure profile; or one can use a reservoir-gap configuration where a strong shock in a reservoir material releases a plasma across the gap and then stagnates on the sample, creating a ramp compression profile on the sample [19].

While the drive capability exists on existing facilities, the diagnostic capability is very limited especially probing lattice spacing using diffraction techniques. Laser-generated x-ray sources are commonly used in diffraction experiments at laser facilities. A subset of the lasers is used to heat a backlighter foil to generate helium-like, quasi-monoenergetic x-rays [20]. These laser-generated x-ray sources convert ∼1% of the laser energy into x-rays and usually include different emission lines and continuum bremsstrahlung components. The most dominant source is the He_α line emission with the spectral resolution of: $\Delta E_x/E_x < \sim 0.6\%$, where E_x is the backlighter x-ray energy.

Current capabilities limited to generating only ∼10 keV x-ray sources prevents probing very high pressure planetary core conditions. Diffraction of up to ∼MeV electrons or ∼20-100 keV x-rays would provide information about the long-range order of phase transitions at TPa pressures.

3.1.2 Roadmap: progress using current facilities

Recent exciting results have been obtained at the National Ignition Facility at LLNL and the Omega Laser Facility that are revealing the complexity of matter in extreme environments at which most of the known mass of the universe resides. These experiments show that the results of first-principles calculations do not necessarily reveal the phases that will be adopted at these conditions because they typically do not consider kinetic effects, or finite temperatures. For example, ramp compression of carbon [21], the fourth-most abundant element in the universe, probed by nanosecond-duration time-resolved XRD showed that it retains the diamond structure up to 2 TPa, in contrast to theoretical predictions. Other examples include measuring the melting curve of iron at conditions similar to those of super Earth cores [22], spectroscopic signatures of superionic phase of ice that may be the predominant form of H_2O throughout the universe [23], and phase behaviour of H-He mixtures [24].

3.1.3 Roadmap: theoretical understanding

First-principles calculations have revealed that molecules and their mixtures at extreme pressures exhibit entirely new and unprecedented behavior [25]. They have shown that the long-held belief that all matter, when sufficiently compressed, will assume a Thomas-Fermi-Dirac state where a sea of electrons surrounds ionic cores, and simple compact structures are assumed, is too simple. Elements that are metallic at 1 atm (such as sodium) become insulating with accumulation of charge in interstitial regions, which can be thought of as "quasi-atoms", the energy ordering of atomic orbitals is affected so that normally unoccupied orbitals become valence, and core or semi-core orbitals mix with the valence states. This allows core electrons to participate in bonding, and atoms may assume unprecedented oxidation states. Theoretical studies of hydrogen, a major constituent of planetary interiors, turns out to be extremely challenging because they must consider complex phenomena, such as quantum nuclear and anharmonic effects. Unsolved predictions for hydrogen include a high-temperature superconducting phase, a dense plasma ground state, Wigner crystallization, and a high-temperature plasma state of hydrogen isotopes. Density-functional theory has predicted “hot superconductivity” in hydrogen-rich alloys. Many first-principles calculations on complex materials performed at 0 K do not take into account anharmonic or quantum nuclear effects, nor strong correlations of the electrons. As computer power increases, and algorithms implemented to treat these effects efficiently, routine modelling of these effects will reveal new phenomena to be searched for experimentally.

3.1.4 Roadmap: flagship experiments requiring new capabilities

Recent advances in generating radiation sources using laser wakefield acceleration (LWFA) have led to the possibility of using them for diffraction [26, 27]. LWFA-driven electron or x-ray (from betatron or Compton scattering processes [26, 28]) probe beams can provide high flux over short femtosecond time scales. Collocation with terawatt, long-pulse (>30 ns) lasers with precise laser pulse shaping can ramp, shock, or shock-ramp compress materials to study planetary materials at the pressures, densities, and temperatures needed to make a meaningful impact on our understanding and modeling of terrestrial and gas giant planets.

LFWA-based probes produced by ultrashort-pulse lasers prove advantageous when x-ray free electron lasers (XFELs) or synchrotron sources cannot be collocated with the required long-pulse lasers drivers. The probe beams should be quasi-monochromatic ($\delta E/E \approx 1$) and have a duration of several femtoseconds [26]. Approximate requirements for the electron beam are energies of $\sim$100 keV to several MeV, a divergence of $< 0.1°$, and flux of $\sim$1 pC/pulse. Significant target design and development efforts will be necessary when using electron probes given their short and may require collimation of the electron beam to obtain the desired energy and spot size [29]. The x-ray beam should have energy of several 10’s to 100 keV to investigate the long-range coordination and $> 10^{11}$ photons/pulse to be competitive with XFELs. Extending these tools would benefit studies of ionization balances, line shapes, and opacities of warm dense matter (WP-27, WP-20) and would allow validation of theory and simulations (WP-80).

3.1.5 Roadmap: flagship experiments requiring next-generation facility capabilities

Current dynamic diffraction experiments in the HED realm cannot determine the structure of complex solids (10’s to hundreds of atoms per unit cell), or warm dense matter, which is now thought to have significant atomic or partially bonded coordination. Next-generation facilities, like EP-OPAL (Fig. 11), when combined with a compression facility, such as the Omega Laser Facility, could enable a high-energy, x-ray source that could reveal the first dynamic, complex solid-and-fluid structure determination for HED matter. Such a short-pulse, high-intensity source will open the door to very large Q scattering, thus revealing this long-range structural complexity. Much like the difference between graphite and diamond, this atomic arrangement will likely play a pivotal role in the behavior of such solids. Also, recent observations of partially bonded complex fluids in CO_2, SiO_2, $MgSiO_3$, carbon, all suggest these materials are highly viscous, nominally electrically conducting, and structurally complex, in a pressure-temperature regime where scientists imagined the atoms were more or less random and unbonded until recently.

Other flagship experiments that require a significant compression facility coupled to an intense, short-pulse laser capability, like EP-OPAL, include determining the most extreme structures of electrides (compounds composed of positively charged ionic cores, where localized electrons serve as anions), the quantum states of electron pairs (such as those comprising quasiatoms within electrides), the viscocity of warm dense matter, the chemistry of extreme matter (keV chemistry - where core electrons take part in bonding), the multiscale evolution of matter (going from cascade to turbulence), testing for Hawking radiation, and the breakdown of the vacuum continuum.

3.1.6 Broader Impacts

The findings will impact the field of chemistry, where it is traditionally assumed that only valence electrons are involved in chemical bonding, resulting in the development of new periodic tables for specific pressure regimes. Within materials science and energy-related research, the techniques will be useful to probe the long-range order and extraordinary properties of high-pressure, high-temperature superconducting and topological materials that contain a substantial fraction of light-element atoms. Higher flux x-ray or more sensitive electron diffraction probes could aid in their structural determination. The experimental observables will be used to benchmark theoretical developments in next-generation density functionals, methods that can be employed to treat anharmonic and quantum nuclear effects, and evolve crystal structure prediction techniques so they may be used at finite temperatures. Moreover, the explored matter states could help determine if white dwarf stars are in a glassy or crystalline state, which would affect their thermal conductivity, luminosity, and determine the age of the halo and disk in galaxies.

3.1.7 Recommendations

Upgrade existing high-compression facilities by implementing high-intensity lasers to produce relativistic particle beams and advanced light sources for creating and probing matter at atomic pressures and temperatures. These new capabilities will extend and expand forefront science already performed at major facilities, such as high-energy-density physics and laboratory astrophysics. Next-generation multi-petawatt lasers envisioned in Chapter 7 that exercise newly developed methods described in § 5.1, § 5.3, and § 5.5 will enable even deeper experimental studies of extreme material properties and quantum phenomena found across the universe.

3.2 Science Question 2B: How can multi-petawatt lasers study black hole thermodynamics through the link between gravity and acceleration?

In pursuit of a "theory of everything," gravitationally driven particle productions through quantum processes may hold keys to new breakthroughs. The physical mechanisms involved bring together general relativity, particle physics, and thermodynamics to the limits of our understanding of fundamental physics. Multi-petawatt laser facilities will enable one to access and control the unprecedented large acceleration that may lead to the laboratory observation of particle production in an accelerating frame for the first time. This would include the experimental confirmation of Unruh radiation, considered by many to be equivalent to Hawking radiation as a consequence of black hole thermodynamics and a pointer to quantum gravity. WP-51 introduced ideas on how high-power lasers can access physics beyond the Standard Model. WP-57 and WP-29 considered how to detect Unruh radiation in a laser experiment.

3.2.1 Introduction

It is well known that particle-production phenomena can occur in a curved or dynamic spacetime [30]. For example, thermal radiation can arise from particle production near the event horizon of a black hole, an effect commonly known as Hawking radiation [31, 32]. The expansion of the universe also occurs in curved spacetime described by the Friedmann-Lemaître-Robertson-Walker metric. Particle production occurs due to the varying gravitational field, [33–36]. Understanding particle production [37–39] during inflation [40, 41] will help to address fundamental questions in cosmology and may also be relevant for (non-thermal) production of supermassive dark matter in the early universe.

Particle production is a consequence of the mappings between the Fock (particle number) states associated with different reference frames, called the Bogoliubov transformation, a technique widely used in condensed matter, particle physics, and cosmology. The Bogoliubov transformation between a non-inertial frame to another reference frame results in particle non-conservation, which may arise from a curved spacetime or an accelerating frame in flat spacetime, both of which can be interpreted as gravitational particle productions through the equivalence principle. While these techniques are generally accepted, gravitational particle production has not yet been observed in the laboratory.

3.2.2 Roadmap: progress using current facilities

Recent advances in ultra-high intensity lasers [3] have stirred interest in the possibility of detecting both the Schwinger effect and testing non-perturbative QED effects [42–45] using facilities, such as the European Extreme Light Infrastructure [46], which will provide radiation beams of intensities exceeding 10^{23} W/cm^2. An electron placed at the focus of such beams would experience an acceleration comparable to what it would feel if placed near the event horizon of a 6×10^{18} kg ($= 3 \times 10^{-12}\ M_{\rm sun}$) black hole. For such low-mass black holes, the surface gravity is strong enough that pairs of entangled photons can be produced from the vacuum, with one of the pair escaping to infinity. The black hole can then radiate, and the spectrum of such radiation is a blackbody at the Hawking temperature.

3.2.3 Roadmap: theoretical understanding

Given the insurmountable difficulties in directly observing Hawking radiation, Unruh proposed, by virtue of the equivalence principle (of gravitational and inertial accelerations), that a similar effect could be measured by an accelerated observer [47].

While the scientific community generally believes that the derivation of Hawking radiation is sound, this is nevertheless made possible by several approximations that have not been tested. Similarly, while an accelerated observer experiences the equivalent Unruh radiation, it remains unclear what a detector in the laboratory frame will ultimately measure. Views are split, with some researchers believing the answer only comes from ordinary quantum field theory, while others pointing out that additional effects due to the acceleration must be included. A reason for these many opposing views is that an experimental proof of Hawking and Unruh radiation requires a deep knowledge of seemingly disparate fields such as gravity, non-equilibrium quantum field theory in curved space-time, and high-intensity lasers. Figure 5 is emblematic. Acceleration temperature is still a mystery now as it was then. High-power lasers may finally unlock what is needed to learn and address the meaning of acceleration temperature.

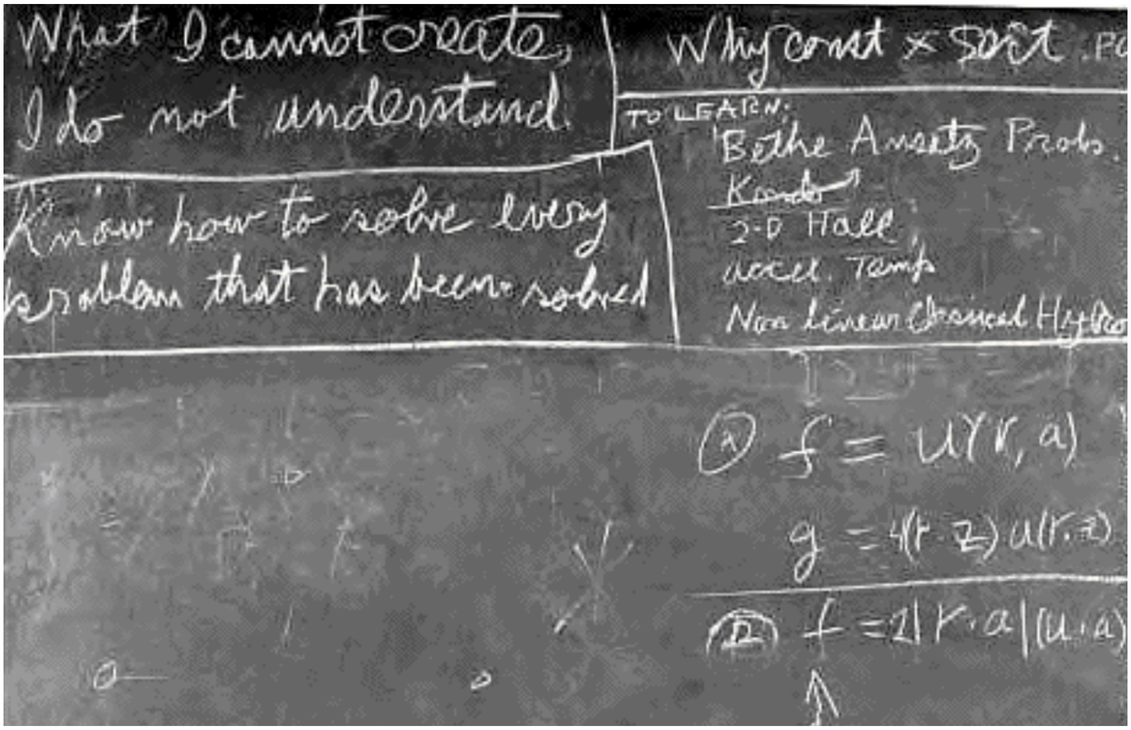


Figure 5: Photo of Feynman's blackboard left at time of his death. Note the section "To learn: Accel Temp". Courtesy from the California Institute of Technology.

The exact derivation of the Unruh effect is far from simple, but some physical intuition can be gained by considering an idealized two-level atom that is subject to a constant acceleration [48, 49]. In the accelerated state, higher-order processes by which a photon is simultaneously emitted and absorbed can also be considered. Since the acceleration incrementally changes the velocity of the atom, the frequency at which the photon is emitted can be slightly different than the frequency at which it is absorbed. If this change in frequency exceeds the linewidth of the atomic transition, the emitted photon disentangles with the absorbed one, and we are left with an atom in the excited state and a real photon being radiated away.

If the acceleration continues for a sufficiently long time, the process of emission and absorption of photons by the atom reaches a steady state. Equilibration requires that the duration of the acceleration to be at least comparable to the inverse of the Einstein coefficient for spontaneous emission (for the case of natural broadening of the lineshape). Unruh showed that the flux of emitted photons can be represented in terms of a blackbody function at a temperature

$$T_U = \frac{\hbar \dot{v}}{2\pi k_B c}, \tag{4}$$

which is the Unruh temperature, where $\dot{v}$ is the acceleration.

From the above considerations, we see that the key element in the realization of the Unruh effect is the atom having discrete energy levels. This can be understood as a system that can change its state or its internal energy. We call this system a *detector*. An elementary particle with internal structure, such as a proton or a neutron, would also be considered as a detector. The situation is less trivial for a particle without any internal structure, such as an electron. In this case, the interaction with the photon bath in the accelerated frame occurs through a continuous change in its momentum via Thomson scattering [50, 51]. These energy changes can be infinitely small, meaning that those small continuous transitions may require infinitely long times to equilibrate and consequently the power radiated by the Unruh effect at those frequencies is very small. Note, however, that a flip in the electron spin can also be considered as a change of its internal structure. In fact, the residual depolarization of electrons in storage rings has been claimed to be the result of the Unruh effect [52].

The power emitted by Unruh radiation is given by[53]

$$P_\nu = \frac{2}{3}\left(\frac{\hbar}{c^2}\right)\alpha^2\dot{v}^2, \tag{5}$$

where α is the fine structure constant. Assuming that the electron had sufficient time to thermalize, we indeed reproduce the classical Larmor formula for electromagnetic radiation, which can be seen as the limit power achieved by accelerated detectors with no internal structure [54]. Thus, the Unruh effect reduces to the classical Larmor radiation for accelerated electrons. This is correct if we consider only the lower order (classical) limit. In fact, the above formula was derived assuming that the electron carries no recoil; however, as photons are exchanged with the detector, the latter experience a finite recoil. Adding this effect, the power emitted by Unruh radiation now becomes [53]

$$P_\nu = \frac{2}{3}\left(\frac{\hbar}{c^2}\right)\alpha^2\dot{v}^2\left(1-\eta\frac{k_BT_U}{2mc^2}\right), \tag{6}$$

and η is a coefficient that depends on the details of the detector. For electrons, $\eta = 24$ [53]. The above formula shows that quantum corrections to the Larmor formula contain terms of order $\dot{v}^2 k_B T_U/mc^2$ [53, 55]. This is what should be understood as the Unruh effect for an accelerated electron (that is, a detector with no internal structure).

3.2.4 Roadmap: flagship experiments requiring new capabilities

Large accelerations can already be realised in the laboratory using existing high-intensity lasers. For example, lasers with intensity $I \sim 10^{19}$ W/cm^2 can accelerate electrons to a Unruh temperature of about 1 eV [56]. While, in principle, this can be measured in the laboratory, it is very challenging to separate the effect of Unruh radiation against other classical and quantum radiation processes involving acceleration of charged particles. For this reason, Unruh and others have instead adopted an alternative approach to exploit the mathematical analogy between trans-sonic flowing water [57], Bose-Einstein condensates [58] and other analogue systems [59], and the behaviour of quantum fields in the vicinity of a black hole horizon. While these experiments have successfully demonstrated the mathematical soundness of Hawking's solution, they may have fallen short in proving that the radiation is actually emitted by non-inertial bodies and that the underlying theory is indeed physically correct [60].

3.2.5 Roadmap: flagship experiments requiring next-generation facility capabilities

Unruh radiation has been a controversial subject in the literature [61]. For the case of accelerated electrons, distinguishing Unruh radiation from other processes is essential. Since Unruh radiation is thermal, it is very different from non-thermal Larmor radiation. But how to do this in practice is unclear. Likely, higher accelerations are needed. For intensities $I > 10^{23}$ W/cm^2, $T_U > 100$ eV, making it simpler to separate Unruh radiation from the optical background. A more direct observation of the Unruh effect would involve the acceleration of atoms; however, acceleration of atoms and ions is extremely challenging. Using radiation pressure acceleration [62], even at intensities $I > 10^{25}$ W/cm^2, we only expect $T_U > 10^{-3}$ eV. This temperature is already high enough to affect the ionization state of the bound levels in the accelerated ion. Measurement of the ionization balance or line emission spectral changes as a function of the acceleration, particularly for rotational/vibrational spectra of molecules, would provide possible avenues for the detection of Unruh radiation.

The detection of thermal radiation from an accelerated oscillator is not, by itself, sufficient to prove the Unruh effect. We will need to develop a unified new theoretical framework, based on which a convincing experimental test can be constructed and a reliable data analysis and interpretation can be carried out. Such a framework must be able to address the fact, for example, that in the laboratory acceleration is not constant (as assumed in Unruh's derivation) [47], and compare Unruh radiation against conventional QED processes [63].

3.2.6 Broader Impacts

The significance of the proposed research could hardly be overstated. It will lead to the first experimental test of the Hawking-Unruh radiation. The ability of doing so will already be a major scientific milestone marking a new era of experimentally testing quantum gravity that would have required an inconceivable 10^{19} GeV high-energy collider based on the standard particle physics approach.

This will shed important light on a wider range of fundamental scientific issues related to the (im)possibility of information loss and the smallest possible scale in nature, with crucial implications on the foundation of physics to justify whether quantum evolution is indeed the correct framework for all laws of physics and what would be the size of the basic building blocks of space and time. The project may further impact on application areas such as quantum computing (as a quantum process under unscreenable gravitational fluctuations) to drive the next generation of artificial intelligence.

The proposed research will yield important implications for classical and quantum theories of gravity by testing the equivalence principle. High-order acceleration with Unruh radiation as a special case are manifestations of gravitational particle productions rooted in the equivalence principle. Therefore, their direct detection are crucial in fundamental physics.

Moreover, the recently discovered double copy correspondence between QED/QCD and classical and quantum gravity [64, 65] can be employed to effectively perform strong-gravity experiments relating to black holes and graviton scatterings using new intense lasers.

3.2.7 Recommendations

The extreme conditions required for accelerating atoms or ions to directly observe the Unruh effect and address controversies surrounding Hawking-Unruh radiation depends on two next steps: (1) developing a new, unified theoretical framework for devising experimental tests and analyzing data; and (2) establishing next-generation multi-petawatt laser facilities that can produce intensities greater than $I > 10^{23}$ W/cm^2, $T_U > 100$ eV,

3.3 Science Question 2C: How does the electromagnetic interaction behave under extreme conditions?

3.3.1 Introduction

The creation of ultrastrong electromagnetic fields would enable exploration of QED, the most precisely tested component of the Standard Model, in an entirely new region of parameter space. The theory of QED has had great success in predicting interactions at increasing energies, thanks to perturbative approaches that exploit the small size of the fine-structure constant α; the same cannot yet be said for increasing *intensities*, where the number of particles participating in a single interaction is large and perturbative approaches fail. It is convenient to imagine the physical electromagnetic field divided into two components: a strong classical background and a quantized radiation field. In the region $a_0 \gtrsim 1$, it is necessary to take all orders of the interaction with the background field into account, using what we have already indicated as SF-QED, because the probability of a single interaction is increased by the high photon flux to $P \sim \alpha a_0^{2n}$, which is not necessarily small for larger n. Investigation of this regime is the subject of SQ1B. If the field strength is increased even further, the interaction with the radiation field itself also ceases to be perturbative. Ever higher orders of interaction, featuring virtual electron-positron loops, absorption and re-emission of photons, become as likely as lower orders of interaction. Perhaps even the identification of individual electrons or photons becomes impossible. No existing theory describes this regime, although encouraging progress is being made (see § 3.3.3). Experimental investigations could shed light on the fundamental structure of the electromagnetic interaction and the dynamics of extreme environments in the early Universe.

The theoretical argument underlying these points is the *Ritus-Narozhny conjecture*, which posits that the 'true' expansion parameter of strong-field QED is $\alpha\chi^{2/3}$ [66, 67], where χ is the quantum non-linearity parameter. This may be understood in the following way (see Fig. 6).

At large values of χ, perturbative strong-field QED predicts that photon emission rate is given by $P = \alpha m \chi^{2/3}$. Thus at $\alpha\chi^{2/3} \simeq 1$, the mean free path between emission events collapses to the scale of the Compton length $\lambda_c = 1/m$ and theory becomes strongly coupled (see [6, 68]). Theoretical analysis suggests that the conjecture holds, at least in the strong-field limit $a_0^3/\chi \gg 1$ [69, 70], as would be achieved with multipetawatt lasers. In order to explore this region experimentally, it is necessary to reach $\alpha\chi^{2/3} \gtrsim 1$ or $\chi \gtrsim 1600$. The quantum parameter achieved in the collision of an electron beam of energy E and a laser with peak intensity I is

$$\chi \simeq 1600 \left(\frac{E}{200 \text{ GeV}}\right) \sqrt{\frac{I}{10^{24} \text{ Wcm}^{-2}}}, \tag{7}$$

and therefore the region $\alpha\chi^{2/3}$ is well beyond the capability of currently existing laser facilities, and indeed that of currently existing conventional accelerators. Furthermore, the above expression optimistically ignores the effect of radiative energy losses: at such extreme intensities, electrons would radiate away a significant fraction of their energy in a single laser period, reducing their χ below the target value. Overcoming this means concentrating the electromagnetic field into as small a spatiotemporal region as possible (in principle, below the mean free path of a single photon emission). Various methods have been proposed to do so, including the use of beam-beam collisions [14], oblique-incidence electron-laser collisions [71], collisions with the attosecond pulses emitted during laser irradiation of a plasma mirror [72], or aligned crystals [73]. We remark also the highest field strength for fixed input power is achieved using a dipole wave (4π focusing via

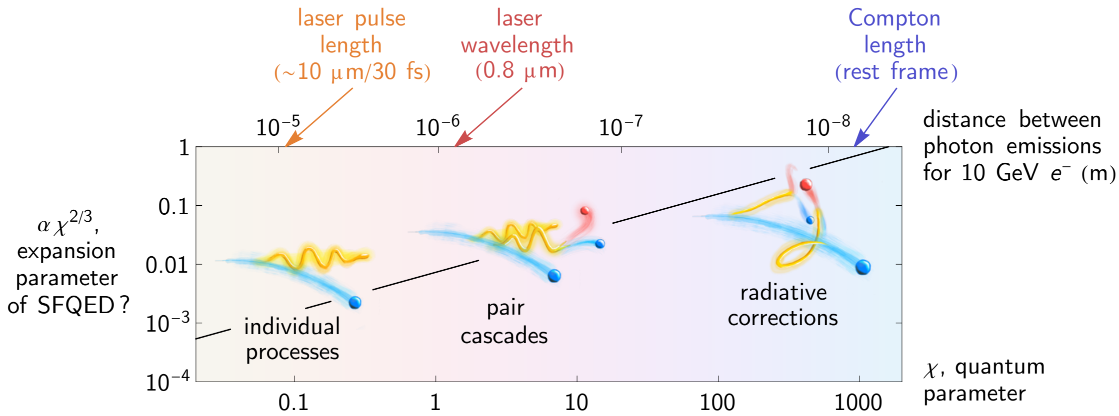


Figure 6: The acceleration induced by an electromagnetic field on an electron is quantified by the quantum parameter $\chi = E_{\rm rf}/E_{\rm cr}$, where $E_{\rm rf}$ is the background electric field in the rest electron frame. As the acceleration increases in strength, the distance travelled by an electron before it emits a high-energy photon decreases, allowing us to explore new kinds of physics with ultrashort lasers. At $\chi \simeq 0.1$, where one photon is emitted per laser pulse duration, it is possible to explore single-vertex processes of strong-field QED in detail. At $\chi \gtrsim 1$, the electron emits multiple photons per laser wavelength, leading to an electromagnetic cascade (see SQ1B). For the most extreme parameters, $\chi \gtrsim 1000$, the distance between QED events collapses to the scale of the Compton length and individual electrons and photons can no longer be identified.

coherent combination of multiple laser pulses) [74, 75] and that this too could be used as the target of a high-energy electron beam [76]. In Fig. 7 we show the electron-beam energy and laser power necessary to reach $\chi = 100$ and 1000, assuming a collision with a single-cycle optical pulse, a dipole wave, or an attosecond pulse from a plasma mirror.

The bounds we show account for radiative energy losses, using the scaling given in [71], and we also estimate what laser power would be necessary to reach a given electron-beam energy in LWFA [78]. It is clear that probing the extreme-field regime, $\chi > 100$ requires several lasers of multipetawatt power that also have (or can be used to generate secondary radiation with) ultrashort duration or XUV wavelengths.

3.3.2 Roadmap: progress using current facilities

It is possible at present to probe the onset of SF-QED effects at $0.1 < \chi < 1$, using 'all-optical' collisions between LWFA-electron beams and lasers at multi-laser facilities [10, 11], see review [79]. Collocation of an intense laser with a conventional electron accelerator facility [8, 9] is also being revisited [80, 81] (see WP-75). Such experiments will build our understanding of the basic processes of SF-QED, including tree-level processes of nonlinear Compton scattering and nonlinear Breit-Wheeler pair creation (see WP-12), and test the approximations used in simulations, including the locally constant field approximation (LCFA), an important component of the Ritus-Narzohny conjecture.

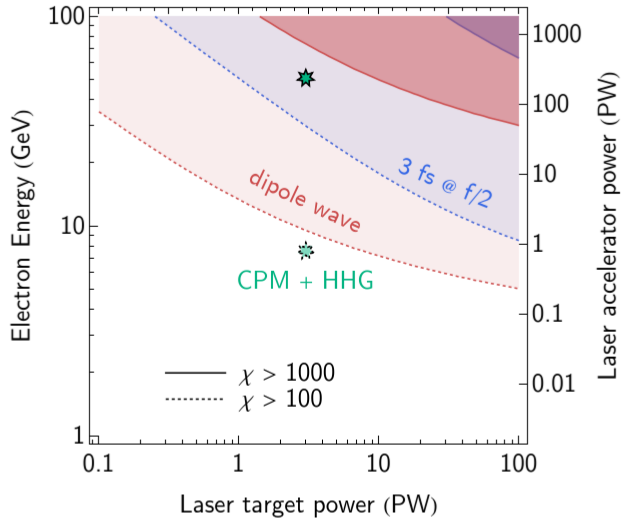


Figure 7: Requirements on the electron-beam energy and the laser power required to reach a quantum parameter of 100 (dashed lines) and 1000 (solid lines). The electron beam is considered to collide with: (blue regions) a single-cycle optical pulse ($f/2$ focusing); (red regions) a dipole wave (4π focusing, or the coherent combination of multiple laser pulses); or (green stars) the focused attosecond pulse from a curved plasma mirror (CPM+HHG) [77]. The bounds account for radiative energy losses during the collision, as estimated in [71]. The right-hand axis gives the laser power necessary to reach the given electron energy in single-stage LWFA acceleration, estimated using a plasma density of 3×10^{17} cm^{-3} [78]. More sophisticated field geometries and particle-acceleration schemes could lead to lower requirements on the necessary power: see chapter 5.

3.3.3 Roadmap: theoretical understanding

Our theoretical understanding of electrodynamics in strong fields takes as its starting point the separation of the electromagnetic field into a fixed, classical background and a fluctuating, quantized radiation field [6, 79]. It is possible to find exact, all-order, solutions for the interaction with the background for fields of particular symmetry, including plane electromagnetic waves [82]. What follows is a perturbative expansion of the interaction with the radiation field, in the so-called Furry picture [83], using the Volkov solutions to construct Feynman rules for the tree-level processes of photon emission $e \to e\gamma$ and electron-positron pair creation $\gamma \to e^- e^+$.

The non-trivial spacetime dependence of the basis states makes it difficult to obtain analytical results for higher order processes, although there has been much progress in the study of trident pair creation ($e \to ee^- e^+$), loop contributions, and chains of bubble diagrams [6, 45, 79]. If the interaction with the radiation field does indeed become nonperturbative for $\chi \gg 1$, as conjectured, then it may be necessary to develop new 'all order' methods for this interaction as well. For example, resummation techniques have been used to study the analogous breakdown of perturbation theory in the classical regime [84], to construct high-order predictions of quantum radiation reaction [85], and to compute the probabilities of nonlinear Compton scattering and nonlinear Breit-Wheeler pair production by taking into account that electrons, positrons and photons in a plane wave are unstable (electrons and positrons under radiation of photons) [86, 87]. How these techniques could be applied to more general field configurations or combined with numerical simulations requires research.

3.3.4 Roadmap: flagship experiments requiring new capabilities

Probing $\chi > 10$, while mitigating radiative energy losses, requires not only 10-GeV class electron beams but also ultrashort-duration electromagnetic pulses. One method to achieve very high fields is to use a relativistic plasma mirror as an optical-to-XUV converter (see §5.5.1). Intense, optical laser light incident on such a mirror drives nonlinear, relativistic oscillations of the plasma surface. These relativistic oscillations in turn temporally compress (over tens of attoseconds) and intensify the reflected light at each laser cycle, producing a broadband spectrum of high harmonics [88, 89]. The reduced diffraction limit for higher frequency radiation means that this secondary emission can be focused more tightly [90–93]. So far, the proof-of-principle experiments that have been carried out have not demonstrated light intensification [94–96].

Proposed implementations of relativistic plasma mirror focusing suffer from two major impediments. The first is a lack of robustness to laser-plasma imperfections: in realistic conditions, it was predicted that the maximum intensity achievable would actually be limited to 10^{24} W/cm^2, at most, with PW-class lasers [97]. The second comes from the high degree of experimental control required in most implementations, which may mandate sub-micron and/or sub-fs laser stability/alignment. Nevertheless, high-resolution numerical solutions now show that the natural curvature of the plasma mirror surface induced by the incident laser radiation pressure can very tightly focus the high harmonics at an unprecedented optical quality [77]. For a PW-class laser, intensities close to 10^{25} W/cm^2 could be reached at the plasma mirror focus. In combination with a 10-GeV electron beam [98], it would be possible to reach $10 < \chi < 100$. Testing SF-QED predictions would, however, require careful characterisation of the field's spatiotemporal structure, such that differences between theoretical predictions and measured spectra could be attributed with confidence to the underlying theory, as opposed to uncertainties in the interaction conditions.

3.3.5 Roadmap: flagship experiments requiring next-generation facility capabilities

Reaching the point where $\alpha\chi^{2/3} \simeq 1$ requires 100-GeV class electron beams (as shown in Fig. 7) and ultrashort electromagnetic pulses, in order to mitigate the extreme radiative energy losses expected. Only a next-generation facility would be able to achieve the electron energies required, either by colocation of an ultraintense laser (or laser-driven secondary source) with a new linear collider, or by the construction of a staged laser-driven plasma accelerator facility, as shown in Fig. 4. The electromagnetic field with which such an electron beam would be made to collide would need to be highly confined. Apart from the laser energy being used to drive a curved plasma mirror of the type describe in the previous section, it could be split and recombined into a dipole-wave structure, which would confine the electromagnetic field to a λ^3 volume. The essential idea is as follows [79]. If focusing a single laser pulse leads to a peak amplitude of $a_0^{(1)}$, splitting the laser into two beams of equal power and focusing them to the same point (from opposite directions) yields an increased field amplitude of $a_0^{(2)} = \sqrt{2}a_0^{(1)}$. Extending this concept to n 'multiple colliding laser pulses' (MCLP), arranged in counterpropagating pairs in a common plane (Sec. 7.1, Pf. 15), leads to an even higher amplitude of $a_0^{(n)} = \sqrt{n}a_0^{(1)}$ [74]. The theoretical limit, with 4π focusing, provides the strongest possible field strength for fixed total power P, $a_0 \simeq 780(P\ [\mathrm{PW}])^{1/2}$ [99–101].

Realizing a dipole wave by the use of six or twelve beams is discussed in the Appendix of [102]. Colliding a 10-GeV electron beam with such a field structure has already been proposed as a means of generating a high-flux of multi-GeV photons [76]. A 100-GeV class electron beam would ensure that the $\chi \gtrsim 1000$ region could be reached.

3.3.6 Broader Impacts

There may be connections between QED in electromagnetic fields of extreme intensity and other nonperturbative quantum field theories, such as QCD, although the theory of this regime of QED is at a much earlier stage of development. From a theoretical point of view, the long experience acquired in QCD can be exploited to investigate analytically and numerically also the fully non-perturbative regime of QED at $\chi \gtrsim 1000$. The experimental tools required to reach such high values of χ themselves represent significant technological development, from the creation and control of the ultrastrong electromagnetic fields themselves, to the generation of 10 to 100-GeV electron beams.

3.3.7 Recommendations

QED has proven the best-tested and most accurate physical theory so far, but unprecedented regimes will enable deeper investigations. Reaching the 'fully nonperturbative' regime ($\chi \gtrsim 1000$) demands entirely new methods of generating and focusing light at the highest intensity, as well as accelerating electrons to energies of the order of 10-100 GeV. Current and next-generation multi-petawatt laser facilities will play a decisive role to achieve the required conditions. For the sake of a clean signal, one needs to produce ultra-short, ideally few-cycle, pulses and it may be necessary to work in the XUV domain because optical lasers of such strength might drive pair cascades (see SQ1B) of such density as to shield the focus from incoming radiation. Accurate synchronization of laser and electron beams proves crucial so that the electrons cross the laser field at the maximal intensity. Experiments will require the detection of photons and/or electrons with energies on the scale of 100 GeV, which will require methods and know-how from the high-energy particle physics community. Corresponding advancements in analytic (resummation) and numerical (strong-field QED in a lattice) techniques are also required in order to possibly compare theory with experiments.

A proposal to reach ultra-high intensity and ultimately the Schwinger limit has been put forward in WP-11, whereas electron energies of the order of 20-30 GeV are envisaged in WP-22 by employing multi-petawatt lasers. WP-54 proposes an experiment on quantum radiation reaction employing a 60-PW laser beams a 10-GeV electron beam. Although a tight focusing is not required in this proposal, if the 60-PW beam can be focused down to a spot 1-2 wavelengths in size, sufficiently high values of the nonlinear quantum parameters could be reached so as to detect signatures of the fully-nonperturbative regime. Finally, the importance of studying plasma dynamics in the presence of supercritical electromagnetic fields has been pointed out in WP-79.

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4 Science Theme 3: Nuclear Astrophysics and the age/course of the universe

Nuclear physics using Intense lasers can open new frontiers in nuclear physics research. Laser-driven sources of energetic particles, such as protons and neutrons can induce nuclear reactions, probe nuclear physics, and enable practical applications. Exploring nuclear science at high temperature conditions is important to test models of astrophysical reaction rates (WP-55, WP-58). Scaling laser-driven Compton sources to MeV photon energies with extremely high fluxes and using their unique properties can excite and manipulate atomic nuclei. The MP3 workshop identified two frontier science areas enabled by new secondary radiation sources generated by multi-petawatt lasers: studies of nuclear astrophysics using intense neutron sources; and studies of the strong nuclear force in low-energy quantum chromodynamics (QCD) using tunable intense gamma sources.

4.1 Question 3A: What can be learned about heavy-element formation using laser-driven nucleosynthesis in plasma conditions far-from-equilibrium?

4.1.1 Introduction

All elements other than hydrogen result from fusing lighter elements into successively heavier elements, like carbon, oxygen, aluminum, iron, and nickel, which are synthesized in the cores of stars, like the sun. For example, two hydrogen atoms fuse to form helium, two helium atoms fuse to form beryllium, and three helium atoms fuse to form carbon.

Heavier elements, like copper, silver, gold, or uranium, form via nucleosynthesis in the helium- and carbon-burning shells of massive stars or via proton and neutron capture processes in supernova explosions. In almost every case, these nuclear fusion processes happen in a hot, dense plasma environment. Until now, Measurements of nuclear fusion reactions using accelerators do not include these plasma backgrounds. Significant discrepancies exist between the calculated abundance of elements based on the measured cross sections and those observed in astronomical measurements [103]. These discrepancies influence our understanding of stars and their evolution, as well as the use of these processes in fusion technologies.

In nuclear astrophysics, the **rapid neutron-capture process, also known as the r-process**, is a set of nuclear reactions responsible creating approximately half of all the "heavy elements" with atomic nuclei heavier than iron. The **proton "p-process"** and another slow neutron-capture "s process" account for the other heavy elements. The r-process also contributes to abundances of some lighter nuclides up to about the tin region and occurs in supernova explosions, while the heaviest elements are produced in binary neutron-star mergers. Figure 8 highlights the isotopes produced by these nucleosynthesis processes.

The r-process [106] proceeds at high temperatures (several giga-Kelvin, GK) and high neutron fluxes. Neutron captures occur on time scales comparable to the lifetime of excited nuclear quantum states. This sequence can continue up to the limit of stability of the increasingly neutron-rich nuclei, as governed by the short-range nuclear force. Figure 9 illustrates schematically how the r-process and beta decay create new heavy isotopes and elements. The r-process must occur where a high density of free neutrons exists, such as the material ejected from a core-collapse supernova [108] or decompression of neutron-star matter thrown off by a binary neutron star merger [109]. The relative contribution to the astrophysical abundance of r-process elements proves a matter of ongoing research [109].

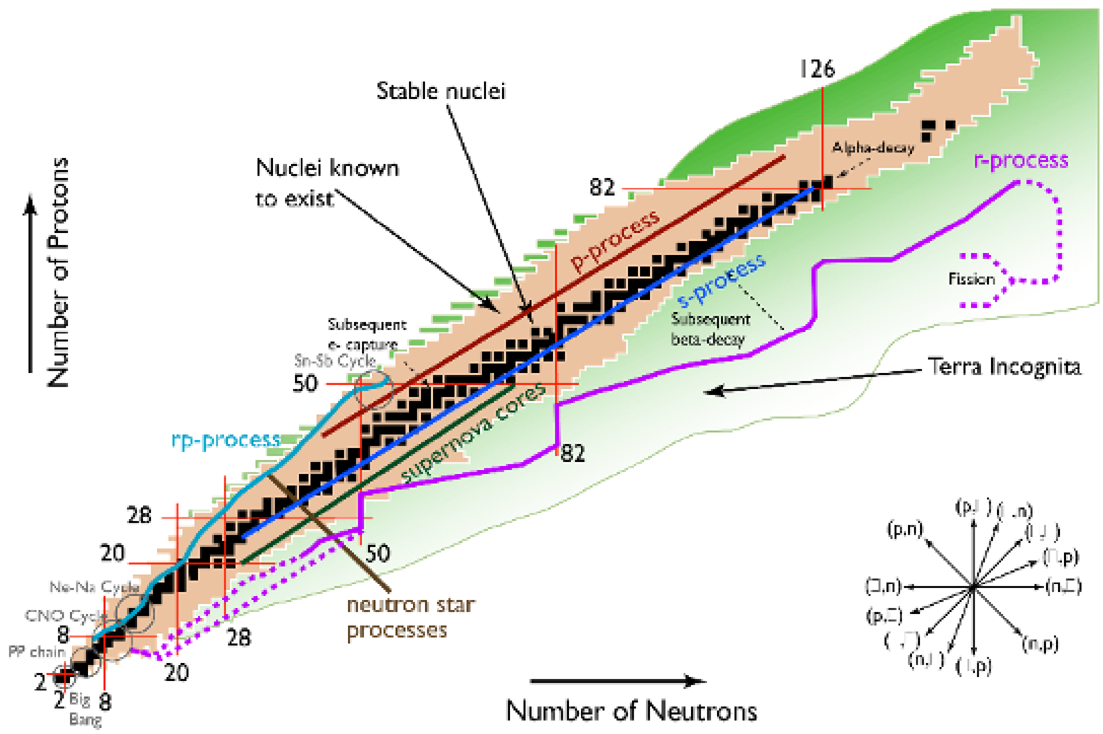

Figure 8: The chart of the nuclides in the (Z,N) plane [104]. Stable nuclides indicated by squares along with pathways of different astrophysical processes. The rapid neutron capture r-process drives nuclear matter far to the neutron-rich side and is interrupted by fission. The rapid proton-capture rp-process on the neutron-deficient side produces nuclides close to the proton drip-line; p-process deals with γn-processes [105]

Quantitative modeling of the r-process path requires knowing the neutron-capture cross sections of these excited nuclear states, or theoretical modelling benchmarked with experimental data on nuclei where this can be done. Research facilities dedicated to the production of neutron-rich radioactive ions, such as the Facility for Rare Isotope Beams (FRIB) [110] or the Facility for Antiproton and Ion Research (FAIR), [111] (WP-53), will investigate the structure of r-process nuclei to provide direct or indirect information on neutron capture on the nuclear ground states, but neutron-capture cross sections on excited nuclear states will not be possible, except for a few very specific long-lived isomers.

4.1.2 Roadmap: laser-driven nucleosynthesis using current facilities

Experimental demonstrations can produce sequential neutron-capture reactions on short-lived nuclear excited states by exposing target materials of interest to short-pulse laser-driven neutron beams with neutron fluences exceeding 10^{20} n/(cm^{2}s) [112, 113]. For ordinary neutron-capture cross sections (typically of the order of barns), a sufficient number of neutron-capture processes will produce isotopes with mass number A+1 in the ground state and in excited states and secondary-neutron captures on the unstable A+1 isotopes. These reactions will produce unstable A+2 isotopes that will eventually decay by beta- decay with typical half-lives of hours to their Z+1 isobars, typically odd-odd nuclides that are unstable by themselves and further decay to the Z+2 isobar, which

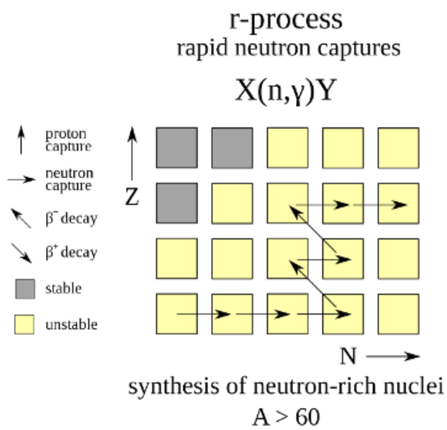

Figure 9: Schematic of nucleosynthesis r process. Successive rapid absorption of neutrons leads to unstable, neutron-rich nuclei with higher atomic weight, N. Beta decay increases the atomic number, Z, and lowers the neutron:proton ratio resulting in more stable nuclei. [107]

will be stable.

After being exposed to the short-pulse neutron burst, the target will be retrieved and put into a low-background counting station to measure its radioactive decay to determine the production of consecutive two-neutron captures. The lifetimes of the longest-lived and lowest lying levels will be known. The sequential double-neutron capture cross section could be measured as a function of the temporal length of the neutron burst, which would vary the contribution of subsequent neutron captures on excited states.

Current PW-class laser facilities can produce 10+ MeV-class proton beams suitable for high-flux neutron generation, including beams with more than 10^{11} protons above 1 MeV [114]. Achromatic divergence allows refocusing proton beams onto secondary proton-to-neutron converter targets with small spot sizes to generate intense neutron bursts [115].

Experiments can scale up stepwise using laser systems listed in Table 4.1.2 ultimately leading to experiments using the 10-PW lasers coming online at ELI-Nuclear Physics (ELI-NP) in Romania near Bucharest and ELI-Beamlines (ELI-BL) in the Czech Republic near Prague.

Table 4.1.2: Experimental steps moving from current to next-generation laser facilities

Laser Facilities	**Laser Parameters**	**Experimental Steps**
BELLA (LBNL) VEGA-3 (CLPU)	1 PW (30 J, 30 fs, 1 Hz)	• Optimize proton, deuteron acceleration & neutron production • Test neutron flux/angular dist. and source size • Develop and test "rabbit" and nuclear detection systems
L3 (ELI-BL) HPLS (ELI-NP)	1 PW (30 J, 30 fs, 10 Hz)	
L4 (ELI-BL) into E5 Hall	10 PW (1500 J, 150 fs, shot/1 min)	• Optimize ion acceleration and neutron production, scale for laser energy
HPLS (ELI-NP)	10 PW (230 J, 23 fs, shot/1 min	• Optimize proton acceleration to cut-off energies $E_\mathrm{p} > 100\,\mathrm{MeV}$
Next-generation facilities (Chapter 7)	$\geq$ 25 PW multi-kJ, multi-beam	• To be determined!

These experiments will require improving plasma and neutron measurements on well-understood CD_2 and cryogenic deuterium targets at current petawatt-level facilities. The high instantaneous fluxes encountered in these laser-plasma interactions will require state-of-the-art neutron and plasma diagnostics (§ 5). The L3 laser at ELI-Beamlines and the two 1-PW HPLS beamlines at ELI-NP offer performance similar to earlier PW-class experiments but at higher shot rates. Experiments using the two 10-PW HPLS beamlines at ELI-NP are expected to increase reaction rates by up to 10×. Longer pulses at the ELI-BL L4 beamline will deliver more laser energy and generate more protons and neutrons.

Intense proton sources developed to drive r-process experiments can also drive p-process experiments, and the extensive suite of photon and neutron diagnostics available at ELI-NP may enable searching for secondary nuclear reactions. Theory suggests an intricate coupling of the ground-state in ^{26}Al and its first excited isomer ^{26m}Al via higher-lying excitation levels resulting in a dramatic reduction of the effective lifetime of ^{26}Al, which will influence the abundance of this isotope in our Galaxy. It is estimated that a short burst of laser-driven protons with energies > 5 MeV can induce the ^{26}Mg(p,n)^{26}Al reaction that proves out of reach with current DC- and RF-accelerator systems. A multi-PW laser-driven experiment could lead to high and comparable spatial and temporal yields of the three lowest-lying states in ^{26}Al including the short-lived state at 417 keV. After such a p-process reaction, the yield ratios between the ground and the two lowest-lying excited states will represent thermodynamic imbalance. This condition can mimic thermodynamic equilibrium at high temperatures experienced in stellar conditions and serve as a first step towards investigating the interplay between those states in plasma environments that will inform studies of nuclei decay in astrophysical conditions.

Tight laser focusing combined with techniques to enhance laser temporal contrast [116] could enable new ion acceleration mechanisms, like magnetic vortex [117, 118] and radiation pressure acceleration (light sail), that could scale to multi-PW experiments at higher particle fluxes and energies to potentially access proton energies $> 100\,\mathrm{MeV}$ [119].

Ultraintense lasers can create hot, dense plasmas in which to measure fusion processes. The laser will create a billion-degree hot plasma and accelerate atoms to the required energies to cause them to fuse. By measuring the different escaping particles, it is then possible to understand both the plasma conditions and how they influence the fusion reactions. This data can then be used to improve nuclear and stellar models and improve our understanding of the universe, and possibly even help to develop controlled fusion technology here on earth, providing a clean energy source.

4.1.3 Roadmap: theoretical understanding

Fusion reactions between light nuclei in far-from-equilibrium plasmas, such as deuteron-deuteron fusion [$d(d,n)^3He$] reactions using laser-driven neutron sources with flux $> 10^{25}$ neutrons/cm^2/s, carry information about the plasma in the output neutron spectrum. Experiments can provide observables from plasma conditions to compare and improve theoretical understanding and computational models used to compute corrections to nuclear reaction rates. Numerical simulations will optimize laser and target parameters to maximize energy transfer to deuterons, the distribution of electrons and deuterons as inputs to the fusion cross sections and their plasma-dependent corrections, as well as reaction volume and confinement time. Continuous theory support during experiments will analyze and understand the data gathered and connect it with existing stellar and nuclear models.

4.1.4 Roadmap: flagship experiments requiring new capabilities

Experiments with existing PW-class systems have yielded 10^{11} MeV protons in single shots. Multi-PW lasers will extend this capability and access the currently elusive Radiation Pressure Acceleration (RPA) or even the Single-Cycle Laser Acceleration (SCLA) regimes that could herald the advent of “collective ion acceleration” reaching GeV proton energies. Developing high-repetition-rate lasers and targetry at multi-Hz rates would enable highly productive experiments with good statistics. The two-beam, 10-PW HPLS system at ELI-NP drives development of nuclear detection and analysis tools for fast and slow neutrons, ion characterization (Thomson parabola, $LaBr_3$ scintillation detectors for delayed γ photons, and activation methods), and γ-flash measurements with optical-based scintillator and image plate systems. Part of these detector systems are already in construction at PW-class sites such as ELI-NP.

4.1.5 Roadmap: flagship experiments requiring next-generation facility capabilities

Nuclear physics experiments benefit from high flux and high repetition rates for low-probability interactions to collect experimental statistics using ever larger single-beam laser systems. Figure 10 illustrates an alternate, modular approach for a next-generation facility that implements multiple state-of-the-art petawatt lasers.

The SHARC (Scalable High-power Advanced Radiographic Capability) laser concept [120] delivers 150-J, 150 fs laser pulses at 10 Hz. A concentric arrangement of SHARC lasers focuses on a ring of deuterated water jets to generate protons that interact with an inner-ring jet of liquid-lithium jets to produce a high-flux source of neutrons for irradiating samples that pass through the

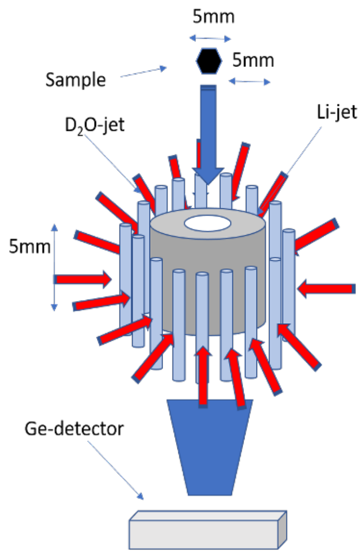

Figure 10: "Multi-SHARC" laser concept to produce a high-repetition-rate, high-flux neutron source for nuclear physics research.

central void. The lithium ring also works as a neutron reflector to confined the neutrons. Scaling from existing laser systems and experimental demonstrations leads to estimates of average neutron flux of 10^{24} n/s/cm^2 at 10 Hz with 10^{13} n/s in the inner void to irradiate samples before delivering them where detectors count decay reactions.

4.1.6 Broader Impacts

Laser-driven nuclear physics experiments described above entail scientific and technological advances with potential broader impacts. Understanding and controlling excited nuclear states and isomers offers the potential to identify and create unique signatures for identifying nuclear material by active interrogation, as well as understanding and realizing transmutation of actinides for nuclear waste disposal.

The broader impacts of laser-driven nucleosynthesis research can inform applied and fundamental research topics with societal impact that includes:

- the quest for a net-zero carbon emission energy source to combat global warming, such as novel approaches to inertial fusion energy that can profit from high-field effects [121], high-energy proton and ions [122], and isochoric heating [123];
- new methods for nuclear waste characterization [124]; and
- enhanced by in-situ studies of the FLASH effect for efficient cancer treatments [125].

4.1.7 Recommendations

Multi-petawatt laser systems offer new and powerful tools for nuclear astrophysics research. They provide ultrashort pulses that can recreate or at least mimic conditions that exist in the inner core of stars and were present at the time of the Big Bang. Plasma conditions will be far from equilibrium, but corrections can be applied to deduce the interaction to be measured experimentally in plasma for the first time. Experimental programs can start now with existing petawatt lasers and scale with the laser intensity to shed much-needed light (pun intended!) on the abundance of heavy elements by evaluating the r-process path, their creation and decay within the first moments at high $k_B T$ values after the Big Bang and stellar lifecycles (e.g., ^{26}Al). The study of multi-neutron absorption processes spanning over the relevant energy windows seems in reach due to the high temporal and spatial confinement of the produced neutrons. Recommendations include:

- Experimentally develop high-flux, high-energy particle (proton, neutron, deuteron) generation and characterization methods using existing laser facilities.
- Conceive and implement next-generation facilities (Chapter 7) with kJ laser pulse energies that increase particle energy and flux rates for experiments and applications.

4.2 Science Question 3B: How can high-flux gamma sources generated from multi-PW lasers be used to explore Hadronic Physics (Low-Energy QCD)?

4.2.1 Introduction: Nuclear physics with precision photon sources

The US and EU Nuclear Physics Long-Range Plans [126, 127] both identify the following as one of the central questions of nuclear physics: *"How does subatomic matter organize itself and what phenomena emerge?"*. Answering this question requires high-intensity gamma-ray beams with narrow energy spread ($\Delta E_\gamma/E_\gamma < 0.03$ FWHM) and high beam polarization, both linear and circular. A recent white paper [128] identifies the required beam parameters for pursuing the low-energy QCD research described in this section. Gamma-ray beams in two distinct energy ranges are needed: (1) $E_\gamma < 12$ MeV for studying hadronic parity violation in light nuclei via photonuclear reactions, and (2) $60 < E_\gamma < 300$ MeV for nucleon structure measurements via Compton scattering and charge-symmetry investigation using photo-pion production. In both energy ranges beam intensities greater than 10^{10} photons/s/cm^2 on target are needed. This required beam intensity is about a factor of $\times$ 100 the capability of current gamma-ray beam technology. The research opportunities and estimated beam parameters are summarized below.

Nucleon Low-Energy Electromagnetic Structure

In real Compton scattering on nucleons and light nuclei, electric and magnetic fields induce radiation multipoles by displacing a hadron's electric charge constituents and currents. The energy- and angle-dependence of the emitted radiation encodes in the form of the nucleon polarizabilities the strengths and symmetries of the interactions with the incident photon and between them. That is, the nucleon polarizabilities parametrize the stiffness of the responses of the nucleon's internal charge and magnetic constituents to applied electromagnetic fields. The difference in the magnetic polarizabilities between proton and neutron values is a salient contribution which narrows the mass gap between protons and neutrons. Additionally, the spin-polarizabilities describe hadronic birefringence caused by the electromagnetic field of the spin degrees, like in the classical Faraday effect. They therefore parametrize the response of the nucleon itself, complementing experiments at Jefferson Lab. Thus far, these quantities are not well known, often with error bars of 40% to 100%. Reference [128] identified that the parameters above allow extractions from data to the 20% level or better from "aspirational" uncertainties for the cross section of 3% and beam-target asymmetries of 0.03. This suffices to answer the fundamental questions raised.

The QCD Origin of Charge-symmetry Breaking

The mechanism for charge-symmetry breaking (CSB) in the nucleon-nucleon interaction is well established in terms of hadronic degrees of freedom, e.g., $\rho - \omega$ mixing in the meson-exchange interaction between identical nucleons [129]. Steven Weinberg postulated that the fundamental cause of CSB is the differences in the masses of the up and down quarks and in their electromagnetic interactions [130]. In this paper, Weinberg showed that the difference is the masses of the down and up quarks is proposal to the difference in the s-wave $\pi^0 n$ and $\pi^0 p$ scattering lengths. High-accuracy pion-photoproduction on the proton and light nuclei at energies above about 140 MeV will answer the question of how CSB emerges from QCD. The most relevant amplitudes are the photon-pion charge-transfer reactions (at 1% accuracy), as well as neutral pion photoproduction (to 7%). Data on the proton and the lightest nuclei at energies up to 300 MeV will elucidate the interplay of chiral physics and resonance physics in the transition from non-perturbative to perturbative quarks, and hence the emergence of the complex structures and interactions of nuclear physics from the deceptively simple QCD interactions between quarks and gluons.

Hadronic parity violation in few-nucleon systems

Hadronic parity violation (HPV) in light nuclei provides an important probe of two phenomena that are not well understood: *neutral-current nonleptonic weak interactions* and *nonperturbative strong dynamics*. While PV is well understood in quark-quark weak interactions, it is ultimately the interplay of different forces at different length scales that is responsible for hadronic PV phenomena. Neutral-current interactions are suppressed in flavor-changing hadronic decays, making hadronic PV between nucleons the best place to study neutral-current effects. Because parity-violating, nucleon-nucleon (NN) interactions manifest the interplay of nonperturbative strong effects and short-range weak interactions between quarks, they are sensitive to short-distance, quark-quark correlations inside the nucleon.

Weak NN interactions at low energy are suppressed by six to seven orders of magnitude compared to strong NN interactions making them difficult to observe. Unambiguous extraction of information about weak interaction among nucleons requires parity violating measurements in very light nuclei (e.g., the deuteron, the triton, and ^{3}He) where theory is under good control. These light nuclei can be calculated using two- and three-nucleon interactions formulated in terms of effective field theories (EFTs) that systematically incorporate the symmetries of QCD [131]. The EFT approach can consistently be applied to strong and weak nucleon interactions as well as to external currents.

Initial experiments will measure parity violation in photodisintegration reactions of few-nucleon systems, such as ^{2}H and ^{3}He. These experiments put stringent demands on the photon source-performance parameters because the parity violating asymmetry is extremely small ($\sim 10^{-7}$) and these measurements are optimally performed near the reaction threshold energy where sensitivity to parity-nonconserving interactions is greatest but the cross section is changing rapidly with energy. The most recent DOE-NSF Nuclear Science Advisory Committee (NSAC) Long-Range plan lists P-odd deuteron photodisintegration [126] near threshold as a priority NN weak interaction measurement. Table 4.2.1 lists the beam requirements to carry out such measurements – no photon beam facility currently can provide these parameters.

Table 4.2.1: P-odd deuteron photodisintegration beam requirements	
Photon Beam Parameter	Value
Energy	< 12 MeV
Flux	10^{10} photons/s
$\Delta E/E$	$< 1\%$ FWHM
Polarization	Circular ($> 97\%$)
Diameter	< 12 mm on target
Time Features	> 10 Hz pol. flip

4.2.2 Roadmap: progress using current facilities

Precision nuclear physics in the area of low-energy QCD requires beams of the range of 10^10 ph/cm^2/s at 10- to 300-MeV photon energies are needed with percent-level energy spreads. Measurements aimed at advancing topics in low-energy QCD described in this section have been performed during the last decade using conventional accelerator-driven laser Compton and tagged bremsstrahlung sources. The Compton-scattering experimental programs using the tagged bremsstrahlung photon beam at the Mainz Microtron ($E_\gamma > 150$ MeV) [132–135] and the quasi-monoenergetic phton beam from Compton source at the High Intensity Gamma-ray Source (HIγS), $E_\gamma < 110$ MeV [136, 137], have significantly contributed to improving the accuracy of the electric and magnetic dipole polarizabilities of the proton. Also, asymmetries for elastic Compton scattering from a polarized proton target using a circularly polarized photon beam were measured at the Mainz Microtron. These asymmetries were used to determine spin-dependent polarizabilties of the proton. In addition, photo-pion production measurements are carried out at the Mainz Microtron.

There are currently no research programs in low-energy QCD using photons produced by high-power fast pulsed laser systems. However, there is potential on the horizon for developing such photon beam sources. Compton backscattering gamma sources based on plasma accelerators have advanced with recent experiments at Lawrence Berkeley National Laboratory (LBNL) [98] and University of Texas, Austin [138] that have demonstrated electron beams of few GeV energies with 10^8 to 10^9 electrons/pulse, suitable for the required photon energies. Separate experiments at lower energy at University of Nebraska, Lincoln [139], University of Texas, Austin [140], Max-Planck-Institute for Quantum Optics (MPQ) [141], and LBNL [142] have demonstrated photon production efficiencies approaching a photon per electron, and electron energy spreads at the percent level [142–144]. Research and development underway aims to reach the required low divergence via either refocusing or advanced injection techniques [145, 146]. Integration of these results at current facilities could result in a source at the range of a few 10^7 photons/shot with the required energy spread and energy. The required areal flux could be achieved in mm-scale spots at the 1- and 10-Hz repetition rates available at current facilities or at higher laser powers in the multi-PW range at Hz rates. Multi-PW systems could also offer high single-shot intensities if multi photon processes are important.

4.2.3 Roadmap: Theoretical understanding

New theory efforts focused on this science will provide important input to experimental planning and ensure quick and efficient analysis of data. Such efforts are well-aligned with the recommended "Theory Initiative" of the 2015 NSAC Long-Range Plan and continue the strong tradition of synergy between theory and experiment in this area. A range of initiatives would ensure that the strong international theory community working on this physics stays fully engaged:

1. Workshops with small lead times and duration of up to a month.
2. Funding for long-term theory visitors, including sabbatical and summer stays.
3. Support for off-site Postdoctoral Researchers and Graduate Students to ensure continued scientific progress and workforce development.

In addition, computing resources must address the high-level computational needs of related theory projects. This contributes to the Long-Range Plan's recommendation of "new investments in computational Nuclear Theory that exploit US leadership in high-performance computing".

5 Particle-acceleration and high-energy-photon sources

Observing the emitted particles and photons or probing interactions with secondary beams of particles or photons, provides a way to understand and diagnose the physics involved in a laser-plasma interaction. Historically, as laser-pulse intensities were increased, certain laser-plasma interactions gave rise to accelerating structures that created beams of particles, and secondary sources of photons. Through careful tailoring of the interactions – choosing suitable laser pulse properties and target conditions – a wide variety of particle and photon sources have been engineered with many unique properties. These sources are compact compared to conventional sources, and have a huge range of potential applications across science, technology, engineering and medicine. They are also extremely useful, essential even, to enable and probe the new science questions presented in this report. Indeed, sometimes the physics investigated in the science questions may lead to new radiation sources. This makes the development of laser-driven sources of high-energy particles and photons a core area of multi-PW laser research. The "2020 roadmap on plasma accelerators" gives a forward-looking overview of these advanced accelerator concepts [26].

In response to the solicitation for white papers (WPs) the Particle Acceleration and Advanced Light Sources (PAALS) working group received thirty-six WPs that in part or in whole addressed the question of high-energy particle and radiation sources using the next generation of multi-PW lasers. The WPs covered all of the major sub-areas of research and addressed topics such as electron and proton acceleration, generation of neutron and positron beams, as well as approaches to generate keV to MeV energy x-rays. Additionally, several WPs focused on the diagnostic aspects. The need for high-repetition rate laser facilities and diagnostics to enable large data sets for statistics and to cover parameter space, as well as for active feedback and machine learning was highlighted in WP-21 and WP-10 as a need for high quality science.

In this chapter, the main mechanisms for generating these particle (electron, positron, proton/ion, neutron) and high-energy photon sources will be reviewed and the current state-of-art summarized, before introducing the future work that may be enabled by the multi-PW lasers. On the low-frequency side, instead, the interaction of kJ class lasers with solid and gaseous targets have been proposed in the WP-85 to generate unprecedented J-class THz pulses, which in turn can open up a new regime of relativistic optics. Diagnostic development goes hand-in-hand with the source development, and some of the ideas are described in chapter 6.

5.1 Particle sources: Relativistic electron beams and heating

Multi-PW laser systems will drive compact, high-energy electron accelerators that are predicted to enable energies up to 20–30 GeV for physics applications and also enable new sources of ultrafast, high-brightness x-rays for applications [147]. The electrons may gain energy from laser-driven plasma waves in a scheme known as Laser WakeField Acceleration (LWFA) [17, 148] that can generate multi-GeV, quasi-monoenergetic, high-charge, small-emittance, few-femtosecond duration electron beams, or directly from the laser fields (Direct Laser Acceleration or DLA) [149–152] that are well-suited for generating broadband x-rays with high-efficiency. DLA will likely be a key mechanism in transferring laser energy to the electrons for creating the extremely hot dense plasma in very strong magnetic fields that are required for addressing SQ1A. For other applications, such as the colliding beam experiments that will be the first steps to addressing SQ1B, the high-energy, small energy-spread LWFA electron sources are preferable. Other laser-to-electron heating mechanisms are important in different configurations, such as for solid target interactions typically used for producing laser-driven proton, ion and neutron beams.

5.1.1 Laser wakefield acceleration (LWFA)

In LWFA, an electron bunch "surfs" on the electron plasma wave (the "wakefield") generated by the ponderomotive force of an intense laser [17, 148]. The plasma wave has a strong longitudinal electric field that stays in phase with the relativistic driver so that relativistic particles may remain in phase with the accelerating field over long distances and gain ultra-relativistic energies. The accelerating electric field strength that the plasma wave can support can be many orders of magnitude higher than that of conventional metallic RF accelerators, which makes laser wakefield acceleration an exciting prospect as an advanced accelerator concept. LWFAs using PW-class, short pulse lasers are able to generate $\sim$ 8 GeV electron beams in underdense plasmas [98]. Not only can these compact, centimeter-scale accelerators generate high-energies, they can also have small energy spread (less that a few percent [138, 143, 153, 154]), small transverse emittance (0.1 mm mrad, [155–157]), short duration (few femtoseconds) bunch length [158], and high-charge (5 pC for the current record energy beam [98]); considerably higher for smaller energies [159, 160]). Despite these successes, it is still challenging to optimize all of the beam properties simultaneously. The rational for using multi-PW laser pulse is that, owing to the scaling of the critical beam power as $P_{\text{crit}} \propto 1/n_p \propto \lambda_p^2$ (where λ_p is the plasma wavelength), such pulses can be self-guided in a fairly tenuous plasma ($n_p < 10^{16} cm^{-3}$), resulting in a longer dephasing distance $L_{\text{deph}} \propto \lambda_p^3$ and higher beam energy $\gamma_b mc^2 \propto 1/n_p$ [17].

Once high-quality electrons beams have been formed, secondary sources of radiation, such as positron beams or high-energy photons can be generated. Of particular note, the electrons undergo transverse oscillations in the multi-PW-laser-driven plasma wave during and after their acceleration. These so-called betatron oscillations result in the emission of energetic (keV-MeV) photons (see § 5.5.3) that could be used for a variety of scientific applications.

LWFA using multi-Petawatt lasers

The MP3 science questions and realizing next-generation, all-optical light sources (WP-44) both require improvements to LWFA source brilliance, shot-to-shot reproducibility, conversion efficiency and repetition rate. A number of interesting new concepts were proposed in this area of research. Multi-PW laser pulses are expected to generate beams with energy exceeding 10 GeV (WP-47 and WP-22), i.e. the electron beams have large γ, such that the χ of an electron beam-laser counter-propagating interaction will be greatly increased (SQ 1B). Novel concepts were also proposed to overcome the limitations of traditional LWFA to enable even more compact accelerators. Approaches to overcome dephasing, where the electron beam outruns the accelerating structure and thereby limits the energy gain, include the combination of two obliquely incident pulses with tilted phase fronts using cylindrical mirrors to create line foci along the accelerated electron trajectory [161] or controlling the spatiotemporal structure of the laser pulse [162] (WP-2, and WP-92). Post-acceleration of LWFA beams is also proposed, through adding acceleration stages either optical, by transitioning to a beam driven stage (WP-76), or by combining electron bunch and laser pulse drivers [163]. WP-9 proposes using vacuum post-acceleration of relativistic electrons by a combination of THz electromagnetic pulses and constant magnetic fields to boost the energy of the electron beams.

Study of LWFA using multi-PW facilities promises more stable and better control of the electron beam characteristics, and higher energy beams beyond current scaling limits that would advance the understanding of laser-plasma acceleration for future high-energy physics colliders. The interaction of these multi-GeV electron beams with high intensity laser pulses will enable the study of nonlinear quantum electrodynamics (QED) addressed in SQ 1B and 2C. Use of these electron beams to generate positrons and x-rays are covered in § 5.2 and § 5.5.

5.1.2 Direct Laser Acceleration (DLA) and electron heating mechanisms

The mechanisms through which a laser pulse transfers energy to electrons can be complex and depends on the target and laser pulse conditions. Vacuum heating [164] or j $\times$ B heating [165] prove to be key mechanisms for solid target interactions at laser intensities $> 10^{18}$ W/cm^2, but intensity to electron temperature scalings are tricky because of the dynamic energy partition. For a laser pulse interacting with a solid-density target, heating of plasma electrons is the first and foundational step for several interesting secondary processes, such as positron generation, proton, ion and neutron beam generation, compact x-ray sources, or the creation of extreme field or pressure conditions. Understanding the key energy transfer step of laser-pulse energy to the electrons is therefore of vital importance.

For a laser pulse duration longer than the inverse of the plasma frequency in a low density plasma, or at higher densities with ultra-intense laser conditions, the plasma electrons quickly respond to the ponderomotive force of the laser to create a channel. Within this channel strong transverse electric fields are present, and as an electron beam is driven forward, large azimuthal magnetic fields form. These channel fields can enable considerable energy gain [166].

DLA and electron heating using multi-Petawatt lasers

DLA in underdense plasmas could be used to demonstrate high-energy, high-charge electrons beams for a variety of potential applications (WP-50). At ultra-high-intensities, DLA may play an ever increasing role in the energy transfer process as even solid-density targets will become transparent due to the relativistic heating [167] and radiation reaction will also influence DLA [168]. At high enough intensities, the radiation reaction force alters the electron trajectories, both as a loss mechanism into a bright photon beam (see below, WP-7) and by interfering with the dephasing from the laser fields [169]. For picosecond, kilojoule-class, multi-petawatt pulses, the energy distribution evolution will be affected by multiple interactions with the laser and self-generated fields, stochastic effects including collisions, re-circulation and radiation loss effects (WP-36). WP-42 and WP-45 both consider how the hot electron generation can be enhanced by magnetizing the plasma. WP-43 also noted that understanding how fast electrons behave in highly magnetized environments is of significance to laboratory astrophysics and may be beneficial for advanced inertial fusion schemes. WP-49 considers using nanowire foam targets to form uniformly heated, relativistic electron temperature conditions [170]. Schemes with multiple multi-petawatt pulses with overlapping focal spots are considered as a way to enhance the intensity and the laser energy coupling to the electrons and consequently proton acceleration (WP-82). WP-82 identifies that laser-driven magnetic reconnection [171] may play a role in this enhancement.

5.2 Particle sources: Positron generation

Addressing SQ1A requires a macroscopic relativistic plasma created from electrons and positrons is required. The current route to creating positrons uses high-Z targets and produces an electron-positron jet. Relativistic electrons are either produced through laser-solid interactions [172], or via LWFA [173]. As the relativistic electrons propagate through the high-Z material (typically gold), the high-energy electrons produce high-energy Bremsstrahlung photons. These photons interact with the high-Z nucleus and the photons decay into electron-positron pairs via the Bethe-Heitler process. These methods have been shown to generate almost charge neutral jets [173, 174], and confining the pairs in a magnetic bottle has been demonstrated [175, 176], although not yet at sufficient density and scale to be considered a pair plasma.

SQ1B has the ultimate aim of using strong fields to create a plasma fireball of matter (electrons), anti-matter (positrons) and photons. The diagnostic techniques developed for characterizing the positrons using the high-Z targets will benefit the experiments designed to study the routes to positron generation via strong fields.

Positron generation using multi-petawatt lasers

The ultimate goal of creating a pair plasma fundamentally requires sufficient positrons to be created, which translates back to the laser energy as well as the conversion efficiencies involved in each step of the process. The goal is to achieve a high pair density, volume and lifetime (WP-26). For example, the duration of the pair jet needs to be greater than the typical instability growth time of interest. For a Weibel instability, this means for a 1 ps duration requires a pair density $> 10^{15}$ /cm^3. Experimental data using the direct heating of a high-Z target has shown a quadratic scaling of positron yield with laser energy [174], making a case for high-energy multi-Petawatt lasers. Optimization and control of the pair plasma promises to be a unique laboratory platform to study extreme astrophysical phenomena (WP-64).

Beyond the scope of the science discussed in this report, future laser-driven colliders for high-energy-physics experiments are envisioned [177], requiring synchronized electron and positron beams. Multi-PW laser systems generating ultra-relativistic positron beams with femtosecond duration, and high spatial and spectral quality via LWFA would be an important step towards building plasma-based colliders. The initial stage of positron generation experiments will involve characterization of the positron beam properties such as the emittance, divergence and energy spread (WP-39). An important next step would show that these positron beams can subsequently be accelerated using plasma waves. Standard plasma waves defocus positrons, so WP-22 proposed creating azimuthally symmetric "donut-shaped" wakefields by manipulating the laser focus.

5.3 Particle sources: Proton and ion beams

The relative inertia of protons and ions compared to electrons means the laser fields do not directly interact with them over a single laser cycle. Once the laser heats the plasma electrons, the electrons move and expand to form electric sheath fields, the resulting currents form magnetic fields that can launch a collisionless electrostatic shock. These high-gradient (~TV/m), longer timescale secondary fields can accelerate protons and ions.

A number of ion-acceleration mechanisms that depend on target and laser conditions have been identified [178–180]. The most robust and well-studied is target normal sheath acceleration (TNSA) [181]. A solid foil is irradiated with the laser pulse, a hot electron cloud expands in all directions out into the vacuum. The sheath field on the rear surface of the target rapidly ionizes and then accelerates protons and ions from a thin layer typical composed of hydrocarbons. Protons are preferentially accelerated due to their higher charge-to-mass ratio, but special surface cleaning may allow improved acceleration of higher-Z ions. The energy spectra is broad and Maxwellian-like, with maximum proton energies up to ~ 100 MeV achieved [182–184]. The proton beams have a divergence of $< 30°$ and a very small transverse emittance [185], making the beams suitable for imaging applications [186]. Typical energy-conversion efficiencies from laser-energy into proton-beam energy are a few percent [187].

To boost maximum energies, the rear surface fields can be enhanced. The Break-Out Afterburner (BOA) acceleration mechanism uses relativistically induced transparency in exploding thin foil targets to enhance the sheath field through a relativistic Buneman instability [188]. Carbon ions with greater than 1 GeV have been accelerated in this way [189]. Magnetic Vortex Acceleration (MVA) [117, 118] is another mechanism where the rear surface field is enhanced by the laser pulse relativistically channeling through the target, confining and heating electrons so that they emerge as a huge current from a small region at the rear. The exiting electron current induces a magnetic field on the rear surface that acts to enhance the accelerating fields.

For many applications, a proton or ion beam requires a narrow energy spread. It is possible to perform a post-acceleration energy selection step on the TNSA proton beam, but this is not efficient. Alternative schemes have been developed to tune the accelerated ion spectra. Extensive theoretical and numerical simulation studies indicate that Radiation Pressure Acceleration (RPA) has the potential to achieve energies per nucleon beyond the GeV range [118, 190–194]. The required targets are very thin ($\sim$ 10's nanometers thick), so the light pressure of the high-intensity laser pulse moves the whole volume of electrons forward, and generates a large electric field that then accelerates the whole ion volume in a uniform potential, to create a quasi-monoenergetic spectra with high efficiency [195]. Experimentally realizing results predicted by numerical modeling proves extremely difficult for several reasons:

(1) RPA requires exceptionally high-temporal-contrast laser pulses to avoid pre-plasma formation expansion/destruction of the ultra-thin targets, even on a picosecond timescale. This proves particularly tricky to attain for the ultra-high intensities required. Enhancing the contrast usually requires plasma mirrors [116] that add significant complexity to the experimental set up.

(2) The ultra-thin foil targets are susceptible to instabilities, such as Rayleigh-Taylor, that are detrimental to the acceleration [196]. Various remedies, such as using multi-species or variable-thickness targets, are being explored [197, 198]. Furthermore, minimal heating of electrons is required, so circular polarization of the laser pulse is superior to linear.

(3) To achieve high intensities, tight focusing is currently required and the rapid deformation of the target enables efficient electron heating reducing the effectiveness of the acceleration [199, 200].

The laser interaction at the front surface provides at least two other possible ion acceleration mechanisms: skin-layer ponderomotive acceleration [201] or shock acceleration [202, 203]. The ponderomotive force of the laser exerts a pressure on the target electrons driving them away from regions of highest intensity into the target. The ions are unaffected by the laser fields directly, but respond to the electric field due to the electron displacement. Under optimum density conditions, a high-Mach-number electrostatic shock can be driven into the target that is capable of accelerating ions. Proof-of-principle experiments for this ion beam acceleration mechanism, Collisionless Shock Acceleration (CSA) [202, 204, 205], have accelerated quasi-monoenergetic ion beams [206, 207].

Proton and ion beams using multi-petawatt lasers
Multi-PW laser pulses bring significant improvements to the stability, efficiency and achievable energies of proton and ion beams. Enhancements to TNSA through temporally shaping the laser pulse and secondary effects, like relativistic transparency, are predicted to boost the maximum energy by a factor of 2.5-3 (WP-46). Multiplexing petawatt-class laser beams in different configurations [171, 208, 209] would enhance the laser coupling, matter heating, and particle acceleration (WP-82). Ideas for using laser-generated proton beams to produce isotopes that might be used as a nuclear battery were proposed (WP-59) which requires high-flux proton beams. Using the high-intensity and energy density laser pulses provides a potential route to creating highly ionized, high-Z plasmas and accelerated ions (WP-5).

Multi-PW laser pulses promise to better match the criteria required for RPA: high-intensity, high-contrast, with a sufficiently large focal spot. Recent theoretical work demonstrated that proton beams can be simultaneously accelerated and focused to a tiny volume when non-uniform thickness targets are used, and that ultra-high laser power (tens of PW) improves target stability with respect to Rayleigh-Taylor instability [198]. Likewise, dual RPA in a colliding ion beam geometry is proposed for a compact hadron collider (WP-73), or to generate TeraBar pressures (WP-90). How the QED process that will likely occur at the highest intensities will affect the ion acceleration mechanisms is also of considerable interest (WP-63). There is an experimental need for ultra-thin (possibly as thin as tens of nanometers) foils, and one leading contender for enabling relatively high repetition rates is liquid crystal targets [210]. WP-66 considered using helical laser beams to impart unique orbital angular momentum to ion beams, and it was suggested that the hollow intensity profile could be beneficial for RPA.

5.4 Particle sources: Neutron generation

Once high-energy electrons, protons, ions or photons (Secs. 5.1, 5.3, 5.5) have been generated, nuclear reactions may take place that create neutrons. This opens the door to compact, high-flux, high-energy neutron sources. Neutron beams can be generated through nuclear spallation, when beams of particles (typically GeV protons) pass through a "catcher" target made from a material with a large cross-section for the neutron generating reaction of interest. The beam-target reaction can upshift the neutron energy from the reaction center-of-mass energy. Examples of reactions that have been used are ^{2}d(d,n)3He [211, 212], ^{7}Li(p,n)^{7}Be [213], ^{7}Li(d,n)^{8}Be [214], ^{9}Be(d,n)^{10}B [215]. Electron-beam-induced nuclear reactions via Bremsstrahlung in copper (reactions ^{65}Cu(γ, n)^{64}Cu and ^{63}Cu(γ,n)^{62}Cu) can create a neutron beam with short pulse duration (< 50 ps) and high peak flux ($> 10^{18}$ n/cm^{2}/s)[216].

Neutron generation using multi-petawatt lasers
Scaling to multi-PW lasers opens the possibility to combine the high-flux of a conventional spallation source, the ultrashort nature of the laser pulse with the ability to collocate a compact facility with existing infrastructure (WP-1). The potential exists to produce directional, short-duration neutron sources with energies of up to 100's MeV.

5.5 High-energy photon sources

A variety of approaches exist to create compact and ultrashort XUV to x-ray light sources based on laser-plasma accelerators. Laser-based, high-energy photon sources have made tremendous progress and have huge potential. LWFA-based sources now produce keV-MeV photon sources with unprecedented spatial, temporal and spectral characteristics [147]. They are becoming standard tools for high-energy-density physics experiments and used for imaging [217], absorption spectroscopy [218], or diffraction (WP-48). These photon sources may have a much broader potential across STEM disciplines, with medical imaging [219] and material science [166] applications already demonstrated. This section briefly reviews the basic mechanisms for high-energy photon generation – high-harmonic generation, Bremstrahlung, emission of betatron radiation, radiation reaction, inverse Compton scattering (ICS), x-ray free electron lasers (XFELs) – along with their photon source properties and their potential using Multi-PW laser pulses.

5.5.1 Relativistic high-order harmonic generation (RHHG)

A high-intensity laser pulse focused onto an overdense target with a sharp density gradient induces the surface electrons to rotate in relativistic orbits [220, 221]. The relativistic motion causes them to emit temporally coherent photons at high-harmonics of the driving laser pulse fundamental frequency. The superposition of these coherent high-harmonics forms attosecond pulse trains. The photon spectrum can extend into the extreme ultraviolet and even x-ray energies. Science Question 2C discusses how RHHG or this can be considered a relativistic plasma mirror could be used to intensify the light energy (see §3.3.4).

A key challenge for creating efficient relativistic high-harmonic generation at high-intensity is preserving a steep density gradient on the target. Chirped Pulse Amplification-based laser systems have non-compressible energy component due to Amplified Spontaneous Emission (ASE) that forms a ∼nanosecond pre-pulse pedestal that the high-intensity short pulse sits on. A measure of the size of the pre-pulse is the intensity temporal contrast, the ratio between the pedestal intensity to the peak intensity. Even with advanced pulse cleaning techniques in the laser systems, best contrast ratios would be $\sim 10^{-11}$. To remove this pre-pulse laser energy, plasma mirrors can "clean" the pulse [116]. Double plasma mirrors typically can improve the temporal contrast by several orders of magnitude or more at the expense of some of the pulse energy.

RHHG using multi-petawatt lasers

Work by Edwards and Mikhailova examines how HHG might scale with intensity (excluding QED effects) [222]. Science Question 2C (§3.3.4) also requires the focusing properties of the naturally curved interaction surface to be tested and characterized, which will be challenging.

5.5.2 Bremsstrahlung radiation sources

High-energy electrons passing through a dense material, particularly a higher-Z material, can pass near to nuclei such that they are scattered by the fields and generate Bremsstrahlung photons. The Bremsstrahlung photon spectrum is continuous, up to a maximum photon energy being about that of the maximum electron energy. The Bremsstrahlung method is a straightforward technique for generating a lot of high-energy photons and has been demonstrated to have applications for imaging of high-energy-density materials. Using LWFA to generate the Bremsstrahlung source, spatial resolutions of better than 30 μm have been achieved [223].

Bremsstrahlung sources using multi-petawatt lasers

The brightness of Bremsstahlung sources increase with increasing laser-pulse peak power and LWFA electron beam energy that will translate directly to the highest photon energies achievable.

5.5.3 Betatron radiation sources

LWFA accelerates a highly relativistic electron bunch in a moving plasma wave, with longitudinal electric fields accelerating the beam forward. Transverse electric fields act to center the electron bunch and the electron bunch undergoes betatron oscillations that generate an x-ray beam. The properties of the x-rays closely resemble synchrotron radiation, a well collimated broadband beam in the 1-100 keV range. The duration of the LWFA electron bunch, and therefore the emitted x-rays, are a few-to-tens femtoseconds in duration, making them $\sim$ 1000-fold shorter pulse duration compared to conventional synchrotron facilities. Additionally, the betatron radiation has μm source size giving a high degree of spatial coherence that enables phase-contrast imaging [217].

Betatron sources using multi-petawatt lasers

Moving to multi-PW laser pulses will increase the energy of the electron beam created during LWFA. The synchrotron-like betatron spectrum peaks at the critical energy, $E_{crit} \propto \gamma^2$. Therefore the increase in electron γ expected from increasing laser power will shift the critical energy of the photon spectra to higher energies. WP-3 proposed a LWFA based scheme to create a tunable, ultra-bright γ beam ($> 10^{12}$ γ photons per shot with a brilliance of 10^{26} photons/s/mm^2/mrad^2 per 0.1% bandwidth) with energy conversion efficiency above 10% for photons above 1 MeV. A double stage process is used; first an efficient laser-driven stage, then a second higher density beam driven stage to increase the trapped charge, enhancing the betatron photons [224].

5.5.4 Photon sources from radiation reaction effects

A bright, directional photon beam is also created during during direct laser acceleration (DLA) of electrons [225] in a mechanism similar to the betatron source. The laser-induced oscillation of the electrons coupling with channel fields in the plasma act to confine the electrons in the laser focal region. Increasing the intensity of the laser pulses eventually gives rise to the onset of a regime where a large fraction of the energy gained by electrons, usually directly from the laser, is radiated into photons as the electrons oscillate.

Radiation reaction effects using multi-petawatt lasers

Numerical modeling studies have shown that plasma channels can sustain extremely strong azimuthal magnetic fields ($\sim$mega-Telsa for multi-PW conditions) that efficiently convert the electron energy into a dense γ-ray pulse (WP-7). Furthermore, the intensity increase for multi-PW conditions mean radiation reaction will begin to influence the DLA mechanism (see above). Similarly, optimizing the density profile of a solid target should lead to very efficient gamma beam sources (WP-41). These intense γ beams are a potential source for testing two-photon Breit-Wheeler pair production [163, 226], and photon-photon scattering [227].

5.5.5 Inverse Compton Scattering (ICS) sources

Inverse Compton Scattering of laser photons from a relativistic electron beam leads to an upshift in photon energy by a factor $4\gamma^2$, where γ is the electron relativistic factor. ICS promises collimated, ultrafast, tunable, and narrowband MeV and GeV photon beams. Even for modest electron beam energies, ICS sources are attractive because the scattered photon energies can be > 100 keV. A laser pulse scattering off a conventional RF-accelerator-generated electron beams is a well established x-ray source for many applications. All-optical approaches, using high-quality LWFA electron beams to perform ICS experiments have been demonstrated. Challenges for ICS include the need for a very high-quality (dense) electron beam, and overlapping the micron-scale electron bunch with the comparably sized laser pulse in space and time. The quasi-monochromatic photon energy can be tuned by controlling the electron and laser parameters [141]. Increasing the laser intensity requires additional efforts to retain the narrow energy spread. It has been shown that a chirped laser pulse can compensate for the ponderomotive line-broadening in the scattered radiation [228–232] (WP-14). Recent experiments have shown ICS schemes showing evidence for radiation reaction with photons with a critical energy > 30 MeV [233].

Inverse Compton Scattering using multi-petawatt lasers

Prospects for ICS using multi-PW laser pulses look excellent. Not only can LWFA potentially produce higher quality electron beams with higher γ values, but multi-PW lasers can deliver them with higher peak powers. Properties of the ICS output beam may be better controlled through the properties of the laser pulse, such as the spectral chirp (WP-14, WP-15), manipulating the focusing properties to create caustics [234], or using polarization gating techniques to generate MeV frequency combs [235] (WP-15). Using electron beam with a correlated energy spread may reduce the spectral bandwidth [236] (WP-15). WP-33 [237] proposed an alternative scheme using ultrahigh-intensity laser pulses with 10s of femtosecond duration to irradiate near-critical-density targets. Prospects for ICS beyond all-optical schemes include coupling a multi-PW laser to a meter-long, x-band linac to generate 20-keV x-rays for probing warm dense matter states (WP-52). WP-16 looks to ICS experiments as a way to inspect the conditions of the coherently emitting region of pulsars and fast radio bursts.

5.5.6 X-ray free electron lasers (XFELs)

X-ray free electron lasers (XFELs) have proven a revolutionary tool to probe ultrafast, and ultra small phenomena across STEM fields. An electron beam in an XFEL passes through an undulator (periodic magnets) that induces the beam to oscillate and emit radiation. The radiation then continues to interact with the electron beam so it forms mircobunches at the wavelength of the emitted radiation. These microbunches then begin to emit coherent, mono-chromatic radiation that reinforces the microbunching process. The energy extracted from the electrons generates a coherent x-ray beam. Conventional XFEL facilities require kilometer-scale electron accelerators, which limits their availability due to size and expense. This makes compact LWFA electron sources a desirable alternative to drive an XFEL and may even open the door to attosecond x-ray pulses. Making small-scale XFEL systems widely available can potentially transform science and applications (WP-89), but this requires an electron beam of exceptional quality with a narrow energy spread, small emittance, and high current. This challenges the limits of what LWFA can achieve, but a breakthrough experiment has recently demonstrated the use of a LWFA to drive a 27 nm wavelength FEL [238].

XFEL sources using multi-Petawatt lasers

Potential improvements at multi-PW laser facilities in electron beam current and stability will directly translate to the success of future LWFA-driven XFELs. Improvements to modeling and simulation are another tool that can further the optimize scheme for specific configurations (WP-4). A further challenge for LWFA driven XFELs is increasing the repetition rate to compete with conventional facilities, with the laser technology being a bottleneck (WP-4). Schemes for all-optical free-electron-lasers are being developed, that use LWFA electron beams, and they replace the magnetic undulator with the electromagnetic fields of a laser pulse [239–241]. This reduces the undulator period to the laser wavelength of the and shrinks the overall size of the FEL. One all-optical scheme uses traveling-wave Thomson Scattering (WP-91). A relatively long laser pulse with a few 100 to several 1000 cycles is required for FEL operation. The traveling-wave Thomson Scattering scheme creates the electron-laser overlap by passing the electron beam at angle to the a laser pulse with a compensating phase-front tilt.

5.6 Broader Impacts of laser based particle and high-energy-photon sources

New laser-driven particle acceleration technology could lead to better understanding of potential screening and high-field effects that may affect fusion cross sections relevant to fusion processes for future energy sources. Intense, high-charge proton beams would enable fast ignition and warm-dense matter studies, and multi-100-MeV ion beams for cancer radiotherapy treatments. Fundamental ion acceleration studies could develop sources using radiation pressure acceleration, magnetic vortex, single-cycle laser acceleration to generate ion beams with $> 1\,\mathrm{GeV}$ particle energies that could access even more extreme regimes of nuclear physics.

Enabling advanced lights sources represents one of the most promising applications of laser-wakefield acceleration of electrons, with applications in medicine, high-energy-density and material sciences, and national security [147, 242].

6 MP3 joint strategies for needed diagnostic capabilities

The new capabilities needed to answer the MP3 science questions with flagship experiments identified in Chapters 2-4 using high-energy particle and photon sources identified in Chapter 5 will require concerted efforts. Advancing ultrahigh-intensity scientific research depends on establishing a stable ecosystem that sustains existing laser facilities, upgrades them, and builds new ones to pursue new frontier science. Often, these efforts will exceed the capacity of any individual research institutes, or even national science and international organizations, so a key charge for the MP3 workshop included identifying common interests and joint strategies for developing **diagnostics needed for the flagship experiments**.

This chapter addresses this charge, as well as **new theoretical constructs and computational capabilities** needed to guide and interpret the flagship experiments, and **novel targets** that can relieve some laser constraints by tailoring laser-matter interactions to achieve desired results. Chapter 7 addresses next-generation lasers needed for advancing multi-petawatt laser-based science that could benefit from coordinated efforts. This MP3 workshop report does not explicitly treat next-generation experimental systems, ultrahigh vacuum, and other support systems, since these advances typically require engineering to meet requirements at each specific facility.

Research networks offer excellent opportunities to pursue joint strategies. **Laserlab Europe** [243], an integrated initiative of European laser research infrastructures, fosters new research and developments in a flexible and coordinated fashion beyond the national scale. It brings together leading organizations in laser-based inter-disciplinary research from 18 countries and its main objectives include: maintaining a sustainable inter-disciplinary network of European laboratories; strengthening research through Joint Research Activities; and offering access to state-of-the-art laser research facilities to researchers from all fields of science and from any laboratory in order to perform world-class research. **LaserNetUS** [244] the **Extreme Light Infrastructure European Research Infrastructure Consortium (ELI ERIC)** [245] provide similar benefits in the United State/Canada and across Europe, respectively.

The US National Science Foundation (NSF) recently announced funding of to develop an international "network of networks" to apply "extreme light" to advance the frontiers of science and engineering. The Ohio State University will lead development of this **Extreme Light in Intensity, Time, and Space (X-*lites*)** collaboration initiative. X-*lites* aims to promote collaboration among researchers around the world to make full use of new laser facilities to improve communications among, and promote broad participation at the frontiers of laser-driven science.

Adopting standards and sharing best practices promises a way to reduce both capital and operating costs, while improving performance and maximizing compatibility, interoperability, safety, repeatability, and quality. Adopting standards depends on setting performance specifications and timelines that can meet broad needs, as outlined in this report. Road maps can identify facilities required to meet established scientific research needs, as well as needed technologies that can benefit by taking a standards-based approach to research and development. Developing and implementing technical standards requires consensus and compromise among parties involved, including both users and suppliers. All parties can realize mutual gains by making mutually consistent decisions.

One of the greatest benefits from research networks would be enhanced **network effects**. In economics, a network effect (also called network externality or demand-side economies of scale) is the phenomenon by which the value or utility a user derives from a good or service depends on the number of users of compatible products. Network effects are typically positive, resulting in a given user deriving more value from a product as more users join the same network. Upon reaching critical mass, a "bandwagon effect" can result. [246]

Standards and coordination increase compatibility and interoperability, allowing information to be shared within a larger network and attracting more users of new technologies, further enhancing the network effects. Standardization can facilitate commoditization of formerly custom products and processes, which can lead to broader markets where only niche markets might otherwise exist. *De facto standards* can arise organically, but coordinating research and development to satisfy the broader needs of the community and aligning it with a coordinated strategy generally prove more effective. Nonrecurring engineering costs can be spread across multiple units and users. Proven designs can be easily adapted and extended to new applications while minimizing cost and development time.

Near-term upgrades to existing facilities can serve two important purposes: (1) they meet the ever-increasing demands of frontier science at established research centers, and (2) they provide platforms for developing technology required in new facilities. Pursuing upgrades at existing infrastructure proves essential to realize future opportunities, and cooperation among university, national laboratory and industry stakeholders, as well as retain, renew and grow the talent base.

6.1 Diagnostics

The diagnostics for multi-petawatt physics experiments present excellent opportunities for exercising joint strategies and realizing the benefits of network effects. Some diagnostics can port to multiple facilities by defining standard interfaces or just by providing adaptable space and services. In other cases that demand substantial diagnostic installations, such as those requiring heavy shielding, multiple facilities can leverage common designs and technology to minimize cost and schedule with the added benefits of improving the ability to compare experimental results and to support the equipment with common logistics.

- Laser pulse peak intensity on shot at full energy - measuring the intensity at focus represents a critical need for practically every ultraintense laser used for experiments. Typically measurements of the energy on target, the focal spot profile (taken at low power), and pulse duration by autocorrelation measurement are combined to estimate the peak laser intensity. WP-34 discusses the prospects and challenges of measuring extreme intensities using Nobel gas ionization states. WP-32 proposed a method using Thomson scattering of protons from within the focal volume to achieve an in-situ measurement for the intensities of $\sim 10^{24}$ Wcm^2 [247]. WP-13 proposed methods to generate electrons or electron-positron pairs with the desired density distribution at the surface of a thin flat foil target and detecting the number and angular distribution of electrons or positrons generated. The multiphoton Breit-Wheeler process, the dominant process responsible for pair creation, has a very sharp intensity threshold above $\mathrm{I} = 10^{22}$ W/cm^2. Below this threshold, no pairs are created and above the number of pairs increases with laser intensity. This sensitivity of detectable positron number on laser intensity makes this diagnostic very precise. Joint and/or coordinated development of this approach can start with demonstrations at PW lasers using electrons and proceed to MPW lasers that exceed the threshold.

- Colliding beam overlap - The colliding electron beam and laser pulse experiments required to study SQ1B will be challenging. Both beams will need to have extremely stable pointing stability to overlap the micrometer scale electron beam with the tightly focused laser beam. WP-83 considered the development of a performance metric to assist with the optimization process.

- High-energy X-ray diagnostics – Multi-petawatt lasers being developed or commissioned around the world will generate copious multi-MeV photons associated. WP-18 describes diagnostics to measure photons with energies greater than 100 keV. It also summarizes the requirements for successfully implementing these diagnostics on upcoming facilities. WP-38 considers the feasibility of using di-muon production as a diagnostic of the high-energy photons.

- Phase-based X- and gamma ray diagnostics – Novel phase-based diagnostics for laser-produced X-ray and gamma ray sources can measure pre-plasma electron density profiles. Phase-based (refraction and diffraction) measurements prove much more accurate and feasible at high photon energies than attenuation-based methods, because the real part of the complex index of refraction that determines the phase effects is orders of magnitude larger than the imaginary part determining the attenuation effects ($1/E^2$ scaling, versus $1/E^4$ energy scaling). Phase-based X-ray measurements are well suited for diagnosing the extreme gradients expected in the dense pre-plasmas produced by high-temporal-contrast, multi-PW laser pulses (gradient scale lengths of a few microns), as refraction-based diagnostics measure directly the plasma electron density gradients. One phase-based X-ray method proposed for diagnosing multi-PW laser experiments is grating-based Talbot-Lau X-ray Deflectometry (TXD). (WP-6)

- Laser-generated x-ray sources for diffraction experiments – probing the lattice spacing of matter at extreme conditions often uses diffraction techniques that prove limited. Lasers heat a backlighter foil to generate helium-like, quasi-monoenergetic x-rays [19]. These sources convert only $\sim$1% of the laser energy into x-rays that usually include emission lines with the spectral resolution $\Delta E_x/E_x \lesssim 0.6\,\%$, where E_x is the backlighter x-ray energy, along with continuum bremsstrahlung components. Current capabilities limit these x-ray sources to only 10 keV photons, which prevents probing very high-pressure planetary core conditions. Diffraction by up to $\sim$MeV electrons or $\sim$20-100 keV x-rays would provide information about the long-range order of phase transitions at TPa pressures needs to study complex material properties and quantum phenomena that emerge at atomic pressures and temperatures relevant to planetary cores (§ 3.1).

- Positron detection – the strong fields used to create a plasma fireball of matter (electrons), anti-matter (positrons) and photons described in § 2.2 will require diagnostics to study the routes to positron generation via strong fields.

- Intense proton and neutron sources for probes – Intense proton sources developed to drive r-process experiments with intense neutron fluxes described in § 4.1 can also probe magnetic fields in plasmas studied in Chapters 2 and 3, while the neutron sources can enable non-destructive imaging of dense materials and active interrogation for identifying nuclear materials. Joint and/or coordinated development of these sources at existing and upgraded PW and MPW facilities would advance many scientific areas.

- Electromagnetic pulse (EMP) – EMP generated by MPW laser-matter interaction will create a hostile environment and render many diagnostics vulnerable to disruption or even damage.

An ongoing Expert Group Laser-generated EMP Workshop supported by Laserlab Europe and held five times since 2018 provides a venue for collaboratively addressing these issues.

- High-count-rate diagnostics – many existing experimental approaches depend on single-photon or single-particle counting techniques to analyze and differentiate outcomes. Some MPW experiments enable new regimes that require operating in a high-intensity, low-shot-rate mode cannot apply these techniques because the experimental signatures comprise copious outputs. These will require diagnostic strategies that can record and distinguish signals with potentially large backgrounds both coincident and time-delayed with respect to the signal.

- Real-time data collection and analysis – fast and accurate data processing can provide improved experimental productivity and flexibility when coupled with high shot-rate or high repetition rate lasers, especially if machine learning can be applied to the large data sets that result.

- Machine learning for 3D reconstruction of high-density laser plasmas – WP-56 proposed to develop and demonstrate machine learning (ML) algorithms as a tool to reconstruct the 3D plasma plume using a high speed x-ray imaging from different lines of sight. The formation and time evolution of X-ray emission from the plasma formed when the laser pulse hits the target would be diagnosed so that the 2D radiographs are converted to 3D models. This will enable to identify the corresponding ion and proton acceleration phases based on plasma dynamics.

6.2 Opportunities for joint development strategies

Specific examples of diagnostics that would benefit from joint development strategies:

- Laser focal spot intensity
- X-ray and gamma-ray light sources for probes
- Gamma spectrometers for radiation up to E = 50 MeV via the conversion of gamma radiation by Li target into electron-positron pairs.
- Triggered LaBr3 arrays to measure delayed gamma radiation from produced isotopes with lifetimes above the ns-regime.
- Intense proton and neutron sources for probes
- Thomson parabolas for proton energies above 200 MeV.
- Time-of-flight MeV-neutron detection systems to measure neutron energy spectra.
- Electromagnetic pulse (EMP) detectors and mitigation schemes

7 MP3 vision for the optimal next-generation facility

The Adam Project (2022)
"It's not meant to be easy. That is the beauty of physics ... that is the beauty of life. We are meant to work on problems that our children will solve. You will die before your life's work is done."

The science questions identified and developed in Chapters 2-4 present grand challenges in three research themes – high-field physics, laboratory astrophysics and planetary physics, and nuclear physics – enabled by a new generation of ultra-intense and powerful lasers. Chapter 5 presents research and development required to produce high-energy particle and photon sources using multi-petawatt lasers needed for the grand-challenge experiments. Research in the three research themes can start using existing petawatt and a few multi-petawatt laser facilities now coming online, some with upgrades to provide additional capabilities, but all would benefit from a next-generation facility with performance possible beyond the current state.

Science enabled by multi-petawatt lasers depends on several important laser parameters: pulse peak power (or peak intensity), pulse energy, pulse duration, focal spot size, and repetition rate. These parameters relate in relatively simple ways physically, but advancing all of these parameters simultaneously presents challenges that will entail compromises and optimizing across them for different experimental applications.

- Peak power (intensity): Laser power and focusing conditions determine the attainable laser intensity and field strengths. The record intensity from CoReLS using a 4-PW laser with tight focusing (56 J, 20 fs, 0.9 μm focus, 0.68 Strehl ratio) stands at just over 10^{23} W/cm^2 [248]. Achieving significantly higher focused intensities requires higher pulse energy, shorter pulse durations, and/or tighter focusing.

- Pulse energy: Kilojoule-class, multi-petawatt lasers promise 10× to 100× improvements in pulse energy in a single beamline. Combining the output of multiple beamlines may provide a path to even higher energies. Higher pulse energy can yield higher peak intensities with ultrashort pulses for some physics experiments to achieve threshold conditions, like producing electromagnet cascades (§ 2.1.4, Fig. 3); or longer pulses with larger focal spots where peak intensity or power is not so important as the total number of secondary particles generated and accelerated, like solid-density neutron beams for laser-driven nucleosynthesis (§ 4.1).

- Pulse duration: Shorter pulses require laser systems that can deliver broader bandwidth and/or employ nonlinear compression techniques. Demonstrated nonlinear compression techniques have shown to up to 6× improvements, as described below, but realizing this kind of performance at very high pulse energies with large beams poses challenges.

- Focal spot size: Tighter focusing requires exquisite control and promises less than a factor of two given the CoReLS result; not much improvement is expected using conventional focusing schemes.

- Repetition rate: Increased experimental repetition rates provide a way to study low-probability events and reducing measurement uncertainties by producing large data sets and using statistical methods. Realizing higher shot rates and ultimately multi-Hz and even multi-kHz repetition rates requires technological advances in thermal management and high-average-power optics.

7.1 Opportunities to advance laser performance

The following highlights opportunities to advance laser parameters and offers a vision for next-generation, high-intensity lasers to address the frontier science goals.

Kilojoule-class, multi-petawatt lasers: Most of the petawatt and the few multi-petawatt lasers operating now employ titanium-doped sapphire (Ti:Sa) laser amplification, which has likely reached its maximum output energy due to technical limitations. Optical parametric chirped pulse amplification (OPCPA) pumped by high-energy laser systems promise to surpass this limit and potentially increase the bandwidth to produce even shorter pulses.

Several proposed facilities aim to deliver beamlines each delivering up to 25 PW (e.g. 500 J in 20 fs) and even possibly to 100 PW with advances in large optics required for larger beams. Figure 11 illustrates a concept proposed for an optical parametric amplifier line pumped by the OMEGA EP laser system (EP-OPAL) at the University of Rochester Laboratory for Laser Energetics (UR/LLE) [249]. This all-OPCPA system approach promises to achieve high energy and

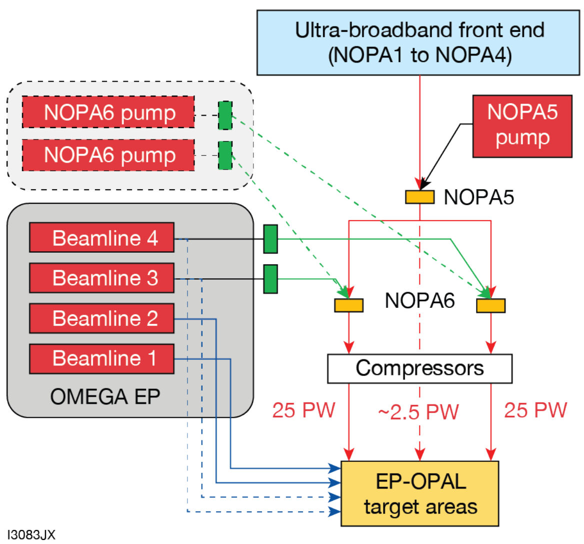

Figure 11: Schematic for EP-OPAL facility proposed by UR/LLE.

ultrahigh temporal contrast by leveraging multi-kilojoule beamlines to pump large-aperture, highly deuterated dihydrogen potassium phosphate (DKDP) crystals in a ultrabroadband phase matching configuration [250, 251]. Figure 12 shows a similar approach being pursued at the Shanghai Institute of Optics and Fine Mechanics (SIOM) for the Station of Extreme Light (SEL-100PW) that targets a 100-PW, 20-fs, 2 kJ beamline [252]. SEL-100PW will serve three end stations: Dynamics of Materials under Extreme Conditions (DMEC); Ultrafast Sub-atomic Physics (USAP); and Molecular Dynamics and Extremely fast Chemistry (MODEC).

Plasma amplification and plasma optics: As noted above, technical limitations of the

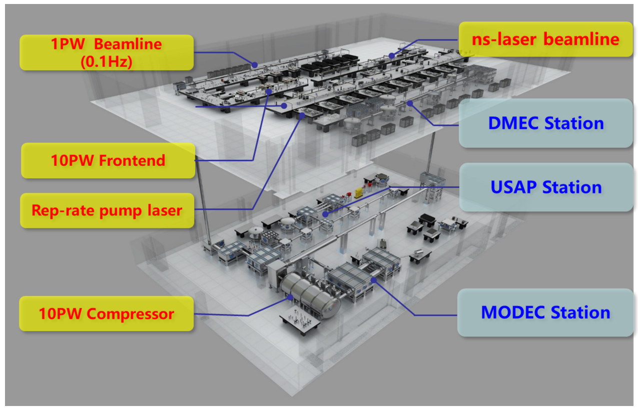

Figure 12: CAD rendering of SEL-100PW project underway at SIOM [252]

optic size that can be feasibly manufactured is a challenge for creating higher power pulses. An alternative is to consider plasma amplification methods of the laser pulse and plasma optic, to replace conventional gratings for example. WP-35 highlighted the possibility of using multi-PW laser facilities to explore pushing the potential of plasma optics beyond the academic and apply to real systems.

Coherent combination of multi-PW modules: Figure 13 shows a concept developed at the 2019 Brightest Light Initiative (BLI) workshop. It envisions an approach to realize exawatt peak

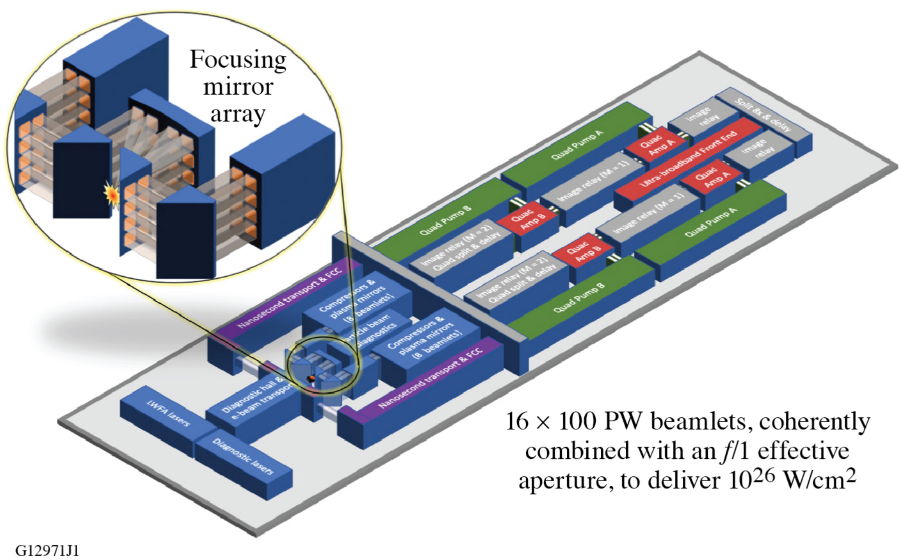

Figure 13: Concept layout for an exawatt laser facility with an array of coherently combined 100-PW beams with a 4×4 array of beamlines arranged to provide low-effective f-number focusing.

powers with an array of coherently combined 100-PW beams with low effective f-number focusing. The higher energy could be capable of reaching 10^{26} W/cm^2 with near-diffraction-limited focusing to an approximately 1 μm^2 spot.

Figure 14 illustrates the "Nexawatt" concept [253] that coherently combines the output of high-energy, chirped-pulse amplification where grating and focusing optic size and damage thresholds typically limit the maximum compressed pulse energy. This scheme divides final pulse compression into multiple channels where each channel completes compression of the pulse and focuses it on target. Maximizing performance depends on matching precisely the dispersion and timing of all the channels.

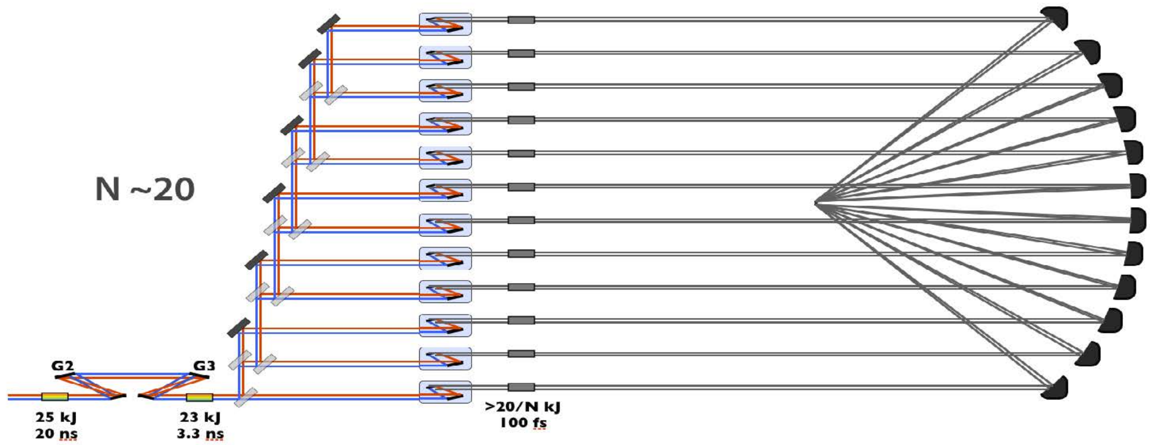

Figure 14: Schematic of Nexawatt concept [253].

Maximizing the electric field at a focusing point requires coherently combining multiple laser beams to reproduce a phase conjugated dipole radiation field. Figure 15 illustrates a "dipole focusing" concept [254–256], where a number of tightly focused laser pulses mimic such a dipole-like wave structure that can reduce the total power needed to reach a desired field intensity with a minimum dipole focusing volume, $V_{dp} \approx 0.032\,\lambda^3$ or $(0.32\,\lambda)^3$. A "double-belt" configuration with

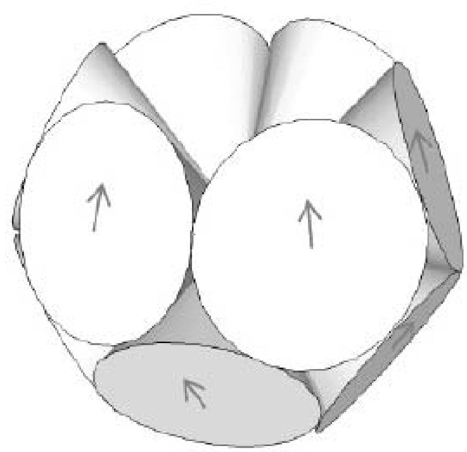

Figure 15: A "double-belt" focusing configuration using coherent beam combination and f/1 focusing optics can approach the ultimate intensity or field strengths possible with a given amount of laser power.

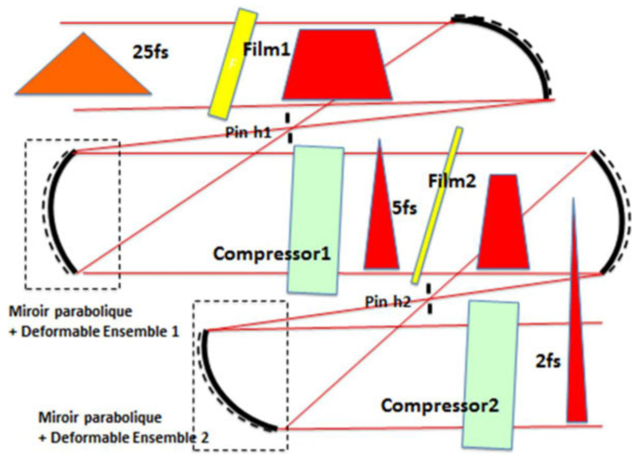

Figure 16: Nonlinear pulse compression: Thin-film compressor

12 beams using $f/1$ focusing optics can theoretically simulate a 10 PW electric-dipole wave with only 12 PW of laser power. This advanced form of coherent combination approaches the ultimate intensity or field strength possible with a given amount of laser power.

Higher repetition rates: Running any of the schemes noted above at higher repetition rates poses significant but surmountable technical challenges that can be met with appropriate research and development efforts. Lasers generate heat due to inherent quantum defects and this heat load can degrade performance or even damage the lasers without proper thermal management. Minimizing heat loads by using lower-quantum defects laser materials [257], and actively cooling the laser gain media [258] have enabled 10-Hz repetition rates at 100-J pulse energies that deliver kilowatt average powers. Scaling to higher pulse energies and repetition rates looks feasible but it will require investments and careful engineering. Figure 10 illustrates another approach to realize multi-petawatt lasers that can operate at high repetition rates. Many petawatt lasers working simultaneously can essentially run multiple experiments in parallel to produce high-energy particles and drive nuclear reactions that do not depend on laser pulse coherence with experimentally useful yields. This "multi-SHARC" concept could lead to otherwise unreachable peak neutron fluxes of 10^{21} n/s/cm^2 and average fluxes of 10^{13} n/s.

Shorter pulses using nonlinear mechanisms: Figure 16 shows an approach to shorten pulse durations using self-phase modulation of ultrashort pulses to broaden their spectrum and subsequently compress them [259]. It employs two stages of "thin-film" compressors that each might achieve several factors of compression to approach single-cycle pulses.

Figure 17 illustrates another approach that implements a relativistic mirror with focusing, where the light pressure of a few-cycle pulse interaction with a solid target distorts the target [259]. The plasma takes the form of a shaped mirror that reflects and compresses the pulse by a factor proportion to a_0, the vector potential, into the attosecond or even the zeptosecond regime.

7.2 Vision for a next-generation facility

A multi-petawatt laser facility would ideally combine every "trick in the book" noted above to achieve the highest peak intensity, pulse energy and repetition rate possible to address all of the

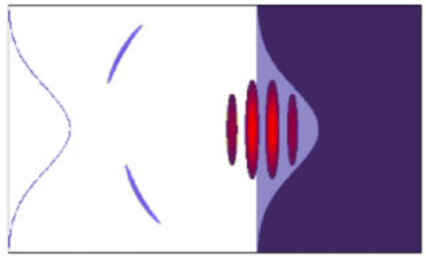

Figure 17: Nonlinear pulse compression: Relativistic mirror/focusing

MP3 science questions. Achieving this ultimate goal with a single facility looks unlikely because the laser requirements vary greatly, but a flexible and comprehensive approach could make significant progress towards it. The first next-generation facility would implement at least two multi-10+ PW laser beamlines required for science questions that involve colliding electron-laser or laser-laser beams. These beamlines would provide adjustable pulse widths and focusing geometries in different target areas optimized for specific types of studies. A prudent approach would also make provisions for coherently combining beamlines, as well as applying nonlinear pulse compression and advanced focusing schemes to extend their performance. The facility would implement state-of-the-art technologies, like actively cooled kJ lasers with shot per minute shot rates, and provide clear upgrade pathways to provide multi-Hz and even higher repetition rates. Each of these steps depend on commensurate improvements in target and experimental diagnostic capabilities.

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Appendices

A Workshop Participants and Additional Report Contributions

This appendix contains a list (alphabetical) of the registered participants of the workshop, both in-person participants (IP) and virtual participants (VP), as well as additional contributors to the final report.

A.1 Workshop Participants

In-Person participants:
Alexey Arefiev (UC San Diego, USA), Sudeep Banerjee (Arizona State University, USA), Tom Blackburn (University of Gothenburg, SWEDEN), Sergei V. Bulanov (ELI-Beamlines, CZECH REPUBLIC), Stepan S. Bulanov (Lawrence Berkeley National Laboratory, USA), Federico Canova (ELI ERIC, CZECH REPUBLIC), John Collier (Central Laser Facility, UK), Antonino Di Piazza (Max Planck Institute for Nuclear Physics, Heidelberg, GERMANY), Domenico Doria (ELI-NP/ IFIN-HH, ROMANIA), Roger Falcone (UC Berkeley, USA), Cameron Geddes (Lawrence Berkeley National Laboratory, USA), Evgeny Gelfer (ELI-Beamlines, CZECH REPUBLIC), Anna Grassi (Sorbonne Universitè (LULI), FRANCE), Mickael Grech (LULI, CNRS, Ecole Polytechnique, FRANCE), Gianluca Gregori (University of Oxford, UK), Harald Griesshammer (George Washington University, USA), Gabriele Maria Grittani (ELI-Beamlines, CZECH REPUBLIC), Wendell Hill (University of Maryland-College Park, USA), Anton Ilderton (University of Edinburgh, UK), Subhendu Kahaly (ELI-ALPS, HUNGARY), Masaki Kando (National Institutes for Quantum Science and Technology, JAPAN), Felix Karbstein (Helmholtz Institute Jena, GERMANY), Karl M. Krushelnick (University of Michigan, USA), G. Ravindra Kumar (Tata Institute of Fundamental Research, INDIA), Sebastien Le Pape (LULI, FRANCE), Rodrigo Lopez-Martens (ELI-ALPS, HUNGARY), Stuart P. D. Mangles (Imperial College London, UK), Mattias Marklund (University of Gothenburg, SWEDEN), Judith McGovern (University of Manchester, UK), Arseny Mironov (LULI, Sorbonne University, FRANCE), Karoly Osvay (University of Szeged, HUNGARY), Hye-Sook Park (Lawrence Livermore National Laboratory, USA), Rajeev Pattathil (Rutherford Appleton Laboratory, UK), Norbert Pietralla (TU Darmstadt, GERMANY), Ishay Pomerantz (Tel Aviv University, ISRAEL), Caterina Riconda (LULI - Sorbonne Université - CNRS, FRANCE), Hans Rinderknecht (Laboratory for Laser Energetics, USA), Carl Schroeder (Lawrence Berkeley National Laboratory, USA), Luis O. Silva (Instituto Superior Tecnico, PORTUGAL), Klaus Steiniger (Helmholtz-Zentrum Dresden-Rossendorf, GERMANY), Matteo Tamburini (Max Planck Institute for Nuclear Physics, Heidelberg, GERMANY), Elizabeth Tolman (Institute for Advanced Study, Princeton, USA), Ion C. Turcu (Rutherford Appleton Laboratory, UK), Dmitri Uzdensky (University of Colorado Boulder, USA), Henri Vincenti (Commissariat à l'Energie Atomique, FRANCE), Stefan Weber (Institute of Physics of the Czech Academy of Sciences & ELI Beamlines, CZECH REPUBLIC), Louise Willingale (University of Michigan, USA), Jonathan Zuegel (Laboratory for Laser Energetics, USA).

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A.2 Additional Report Contributors

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B Acronym Glossary

- AGN: Active galactic nucleus
- ASE: Amplified Spontaneous Emission
- BH: Black hole
- BLI: Brightest Light Initiative
- BOA: Break-Out Afterburner
- CPA: Chirped pulse amplification
- CR: Cosmic ray(s)
- CSA: Collisionless Shock Acceleration
- DC: Direct-current
- DKDP: deuterated dihydrogen potassium phosphate
- DLA: Direct Laser Acceleration
- DMEC: Dynamics of Materials under Extreme Conditions
- DOE: Department of Energy
- EFT: effective field theories
- ELI: Extreme Light Infrastructure
- ELI-BL: ELI-Beamlines
- ELI ERIC: Extreme Light Infrastructure European Research Infrastructure Consortium
- ELI-NP: ELI-Nuclear Physics
- EM: Electromagnetic
- EMP: Electromagnetic pulse
- EU: European Union
- EW: exawatt
- FAIR: Facility for Antiproton and Ion Research
- FRIB: Facility for Rare Isotope Beams
- GRB: Gamma ray burst
- HED: High-energy-density
- HFP/QED: high-field physics and quantum electrodynamics

- ICS: inverse Compton scattering
- LAPP: laboratory astrophysics and planetary physics
- LBNL: Lawrence Berkeley National Laboratory
- LCFA: Local constant field approximation
- LDNP: laser-driven nuclear physics
- LWFA: Laser wakefield acceleration
- MCLP: multiple colliding laser pulses
- ML: machine learning
- MODEC: Molecular Dynamics and Extremely fast Chemistry
- MP3: Multi-Petawatt Physics Prioritization
- MPQ: Max-Planck-Institute for Quantum Optics
- MPW: Multi-Petawatt
- MVA: Magnetic Vortex Acceleration
- NIF: National Ignition Facility
- NN: nucleon-nucleon
- NS: Neutron star
- NSAC: Nuclear Science Advisory Committee
- NSF: National Science Foundation
- OPCPA: optical parametric chirped-pulse amplification
- PAALS: particle acceleration and advanced light sources
- PIC: Particle-in-cell
- PV: parity violation
- PW: Petawatt
- QCD: Quantum chromodynamics
- QED: Quantum electrodynamics
- RF: Radio-frequency
- RHHG: Relativistic high-order harmonic generation
- RPA: Radiation Pressure Acceleration

- SEL-100PW: Station of Extreme Light
- SCLA: Single-Cycle Laser Acceleration
- SF: Strong-field
- SF-QED: Strong-field quantum electrodynamics
- SHARC: Scalable High-power Advanced Radiographic Capability
- SIOM Shanghai Institute of Optics and Fine Mechanics
- SN: supernovae
- SQ: Science Question
- STEM: Science technology engineering and medicine
- Ti:Sa: titanium-doped sapphire
- TNSA: target normal sheath acceleration
- TXD: Talbot-Lau X-ray Deflectometry
- UHECR: ultra-high-energy cosmic ray(s)
- UR/LLE: University of Rochester Laboratory for Laser Energetics
- US: United States
- USAP: Ultrafast Sub-atomic Physics
- WG: Working group
- WP: White Paper
- XFEL: x-ray free electron laser
- X-lites: Extreme Light in Intensity, Time, and Space
- XUV: Extreme Ultraviolet
- ZEUS: Zettawatt-Equivalent Ultrashort pulse laser System

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C White Papers

This appendix contains a list of the white paper author(s) and titles that were received for the MP3 workshop. Listed in the order they were received. The list is linked to the full text of each white paper as they were submitted.

1. Markus Roth, Marc Zimmer, Stefan Scheuren, Christian Rödel, *Laser Neutron Production entering the Spallation Mode*

2. J.P. Palastro, A. Arefiev, J. Bromage, M. Campbell, A. Di Piazza, M. Formanek, P. Franke, D.H. Froula, B. Malaca, W. Mori, J. Pierce, D. Ramsey, J.L. Shaw, T.T. Simpson, J. Vieira, M. Vranic, K. Weichman, J. Zuegel, *Novel Plasma Physics Regimes enabled by Spatiotemporally Shaped Laser Pulses*

3. Xing-Long Zhu, and Zheng-Ming Sheng, *Ultra-brilliant GeV gamma-ray emission with multi-petawatt lasers*

4. Henry P. Freund, *Advanced Light Sources with Polarization Control Based upon Laser-Based Accelerators*

5. Yasuhiko Sentoku, Natsumi Iwata, Mamiko Nishiuchi, Alexey Arefiev, *Dynamics of multi-petawatt laser driven high Z radiative plasmas*

6. D. Stutman, M.P. Valdivia, D. Kumar, M. O. Cernaianu, D. Doria, P. Ghenuche, N. Safca, *Phase-based X and gamma ray diagnostics for multi-Petawatt laser research*

7. Hans Rinderknecht, A. Arefiev, T. Toncian, M. Wei, T. Wang, G. Bruhaug, A. Laso Garcia, K. Weichman, J. Palastro, D. Doria, K. Spohr, M. Cernaianu, P. Ghenuche, J. Williams, A. Haid, T. Ditmire, H. Quevedo, and Dan Stutman, *Relativistically transparent magnetic filaments: a platform for high-field science and efficient gamma-ray sources*

8. Kathleen Weichman, M. Murakami, J.J. Honrubia, S.V. Bulanov, J.K. Koga, M.A.H. Zosa, A.V. Arefiev, and J. Palastro, *Microcavity implosions for the generation of extreme electric fields and ultrahigh magnetic fields*

9. Oleg B. Shiryaev, Michael Yu. Romanovsky, and Vladimir V. Bukin, *Vacuum post-acceleration of relativistic electrons by combinations of THz electromagnetic pulses and constant magnetic fields*

10. Stephane Branly, Franck Falcoz, Catalin Neacsu, Kaikai Zhang and Pierre-Mary Paul, *Status and future of high energy high average power lasers*

11. James K. Koga, Masaki Kando, Sergei V. Bulanov, Timur Zh. Esirkepov, Alexander S. Pirozhkov, Petr Valenta, Tae Moon Jeong, Georg Korn, Stepan S. Bulanov, *Relativistic Flying Mirrors for Fundamental Science and Applications*

12. T. Heinzl, A. Ilderton, and B. King, *Laser-Matter Interactions at the Intensity Frontier*

13. Zsolt Lécz1, and Alexander Andreev, *Positron detection for plasma and field diagnostics in high-power laser-solid interactions*

14. Balvsa Terzić, and Geoffrey Krafft, *Improving Performance of Inverse Compton Sources in High-Field Regime via Laser Chirping*

15. D. Seipt, M. Zepf, and S. G. Rykovanov, *Advanced Concepts for Monoenergetic γ-Ray Generation using Nonlinear Compton Scattering*

16. Shuta J. Tanaka, Keita Seto, Yasuhiro Kuramitsu, Yuji Fukuda, and Youichi Sakawa, *Experimental observation of induced Compton scattering*

17. Felix Karbstein, Holger Gies, Elena A. Mosman, Gerhard G. Paulus, Kai S. Schulze, and Thomas Stöhlker, *Co-location of a multi-petawatt laser with an x-ray free electron laser*

18. Deepak Kumar, Chris Armstrong, Florian Condamine, Thomas Cowan, Alejandro Laso Garcia, Tae Moon Jeong, Ondvrej Klimo, Paul McKenna, Alexander Pirozhkov, Sushil Singh, Dan Stutman, Vladimir Tikhonchuk, Roberto Versaci, June Wicks, *High energy X-ray diagnostics for interaction of a high repetition rate multi-petawatt laser with solid targets*

19. Holger Gies, Felix Karbstein, Jörg Schreiber, and Matt Zepf, *Quantum vacuum signatures in laser pulse collisions*

20. Hiroshi Sawada, *Relativistic Electron Isochoric Heating with Petawatt Femtosecond Lasers for Creation of Warm Dense Matter*

21. Peter V. Heuer, Hans G. Rinderknecht, Derek B. Schaeffer, Scott Feister, *The Role of High Repetition Rate Experiments in Advancing HEDP Science*

22. Karl Krushelnick, *Laser wakefield acceleration with Multi Petawatt lasers*

23. Matteo Tamburini, Antonino Di Piazza, Christoph H. Keitel, *The quest for precision measurements of strong-field QED effects*

24. Yan-Fei Li, Wei-Min Wang, Yu-Tong Li, *The interaction of a multi-petawatt laser pulse with an ultrarelativistic electron beam could be utilized to produce polarized positron-beam source or conduct confirmatory experiments on QED theory*

25. Bruce A. Remington, Hui Chen, *Relativistic astrophysical jets from accreting massive black holes in galactic centers*

26. Hui Chen, Frederico Fiuza, and Bruce Remington, *Laser produced relativistic pair plasmas in the laboratory*

27. Stephanie Hansen, and Brent Jones, *MP3 Opportunities for Benchmark-quality Lab-Astro Experiments*

28. Reinhard Alkofer, Matthias Diez, and Christian Kohlfürst *What are the time-scales of particle formation in the Schwinger effect?*

29. Ronnie Shepherd, Mark Sherlock, Max Tabak, Steve Libby, Yuan Shi, Nathaniel Roth, Hui Chen, Howard Scott, *Soft X-ray emission spectroscopy to search for Unruh radiation*

30. Wendell T Hill, III, Andrew Longman, Calvin Z He, Smrithan Ravichandran, José Antonio Pérez-Hernández, Jon I Apiñaniz, Roberto Lera, Luis Roso, and Robert Fedosejevs, *Direct Measure of Quantum Vacuum Properties*

31. Luis Roso, Andrew Longman, Calvin Z He, Smrithan Ravichandran, Jose Antonio Pérez-Hernández, Jon I Apiñaniz, Roberto Lera, Robert Fedosejevs, and Wendell T Hill, III *Radiation from the electron-positron virtual pairs accompanying laser driven electrons.*

32. Robert Fedosejevs, Andrew Longman, Calvin Z He, Smrithan Ravichandran, Jose Antonio Pérez-Hernández, Jon I Apiñaniz, Roberto Lera, Luis Roso, and Wendell T Hill, III, *In situ intensity gauge adapted for extremely-high intensities*

33. Ondrej Klimo, Stefan Weber, *Controlled γ-ray secondary source*

34. Marcelo Ciappina, Stefan Weber, *Atomic high-field diagnostic using multiple sequential ionization*

35. Caterina Riconda, Stefan Weber, *Plasma Amplification for High-Power Lasers*

36. N. Iwata, Y. Sentoku, A. J. Kemp, and S. C. Wilks, *Stochastic laser-plasma interaction with kJ-class petawatt laser light*

37. Timur Zh. Esirkepov, Akito Sagisaka, Koichi Ogura, Hiromitsu Kiriyama, James K. Koga, Masaki Kando, Danila R. Khikhluha, Ilia P. Tsygvintsev, Chris D. Armstrong, Deepak Kumar, Stepan S. Bulanov, Georg Korn, Sergei V. Bulanov, Alexander S. Pirozhkov, *Experimental Access to Laser-Driven Gamma Flare*

38. Calin Ioan Hojbota, Mohammad Rezaei-Pandari, Mohammad Mirzaie, Vishwa Bandhu Pathak, Doyeon Kim, Jeongho Jeon, Kiyong Kim, Chang Hee Nam, *Muon production for the detection of high-energy photons from laser-electron collisions*

39. G. Sarri, M. Streeter, L. Calvin, N. Cavanagh, *High-energy and high-quality positron beams from a laser wake-field accelerator*

40. G. Sarri, M. Streeter, L. Calvin, N. Cavanagh, K. Fleck *High-field quantum electrodynamics in the field of an intense laser*

41. Sergei V. Bulanov, Prokopis Hadjisolomou, Gabriele Grittani, Tae Moon Jeong, Georg Korn, Danila R. Khikhlukha, Pavel V. Sasorov, Petr Valenta, Kirill V. Lezhnin, Ilia P. Tsygvintsev, Vladimir A. Gasilov, Timur Zh. Esirkepov, Alexander S. Pirozhkov, James K. Koga, Masaki Kando, Tetsuya Kawachi, *High Power Gamma Flashes Generated in Multi-Petawatt Laser-Matter Interaction for Fundamental Science and Applications*

42. Thomas G. White, Matthew Oliver, and Tilo Döppner, *Measurements of Transport Properties in Warm Dense Matter with Multi-Petawatt Lasers*

43. K. Matsuo, M. Bailly-Grandvaux, S. Bolanos, D. Kawahito, C. McGuffey, M. Dozières, J. Peebles, J. R. Davies, M.S. Wei, W. Theobald, P.-A. Gourdain, J. Honrubia, J.J. Santos, and F.N. Beg, *Energy deposition in magnetized dense plasma by laser-driven relativistic electrons*

44. Matthias Fuchs *Next-generation Lightsources and Applications*

45. Lili Manzo, Matthew Edwards, Yuan Shi, *Enhancing hot electron generation via magnetized laser absorption*

46. J. Kim, D. Mariscal, B. Djordjevic, *Efficient laser-driven ion acceleration using temporally shaped high-intensity pulses*

47. C. B. Schroeder, C. Benedetti, E. Esarey, C. G. R. Geddes, J. van Tilborg, *Laser wakefield acceleration using multi-PW lasers*

48. Félicie Albert *X-ray light sources from laser plasma acceleration and their applications*

49. Andreas Kemp, S.C.Wilks, G.Grim, E.Hartouni, S.Kerr, G.Cochran *Development of a new laser-based platform capable of measuring nuclear reaction rates in hot plasmas*

50. Amina E. Hussein, *Multi-petawatt electron acceleration and strong magnetic field generation*

51. G. Gregori, S. Sarkar, R. Bingham, C. H.-T. Wang, *Going Beyond the Standard Model with High Power Lasers*

52. Pierre Gourdain, and Georg Hoffstaetter, *Using inverse Compton scattering from a short pulse laser to measure the properties of warm dense matter produced by pulsed-power drivers*

53. P. Neumayer, V. Bagnoud, *Research at the high-energy short-pulse laser system PHELIX user facility*

54. Keita Seto, Jian Fuh Ong, Yoshihide Nakamiya, Mihai Cuciuc, Stefan Ataman, Cesim Dumlu, Madalin Rosu, Ovidiu Tesileanu, Takahisa Jitsuno, and Kazuo A. Tanaka, *Radiation reaction experiment with 60 PW laser pulse and 10 GeV electron bunch*

55. Bruce A. Remington and Hui Chen, *High power laser experiments probing plasma nuclear science*

56. Alexandru Măgureanu, Viorel Nastasa, Deepak Sangwan, Bogdan Diaconescu, Dan G. Ghiţă, Marius Gugiu, Theodor Asavei, Zhehui Wang, Cătălin M. Ticoş, *Machine Learning for 3D Reconstruction of High Density Laser-Plasma*

57. Andrei Tudor Patrascu, *Unruh Radiation Detection*

58. K. M. Spohr, D. Doria, K. A. Tanaka, G. Bruhaug, C. Forrest, and H. Rinderknecht, et al., *Nuclear physics research in laser induced plasma with a multi-petawatt laser system: production and decay studies of cosmogenic 26Al*

59. K. M. Spohr, D. Doria, K. A. Tanaka, M. O. Cernaianu, D. O'Donnell, V. Nastasa, P. Ghenuche, P. A. Söderström, G. Bruhaug, C. Forrest, and H. Rinderknecht, *Laser-driven population and release of the 2.4 MeV isomer in 93Mo, towards a 'Nuclear Battery'*

60. Cesim K. Dumlu, Keita Seto, Stefan Ataman, Jian-Fuh Ong, Ovidiu Tesileanu and Kazuo A. Tanaka, *A Proposal for the Observation of Pair Production in Intense Field Regime*

61. M. Vranic, T. Grismayer, A. AreBiev, H. Chen, S. Corde, R. A. Fonseca, M. Grech, C. Joshi, A. G. R. Thomas, B. Martinez, S. Meuren, W. B. Mori, C. Riconda, C. Ridgers, D. Seipt, L. O. Silva, T. Silva, J. Vieira, L. Willingale, *Positron creation and acceleration with multi-petawatt lasers*

62. Stefan Ataman, Keita Seto, Cesim Dumlu, Jian-Fuh Ong, Andrei Berceanu, Ovidiu Tesileanu, Kazuo A. Tanaka, *MP3 all-optical vacuum birefringence experiment proposal*

63. Domenico Doria, A. Arefiev, M. O. Cernaianu, P. Ghenuche, K. Spohr, K. A. Tanaka, *Laser driven-acceleration of ion and energy scaling modification by competitive processes.*

64. Edison Liang, *High-Energy Astrophysics Experiments Based on Ultra-intense Lasers Irradiating Solid Targets*

65. Sergei V. Bulanov, Yan Gun Gu, *Magnetic field annihilation and charged particle acceleration in ultra-relativistic laser plasmas*

66. P. Ghenuche, M. O. Cernaianu, D. Stutman, F. Negoita, D.L. Balabanski, A. V. Arefiev, D. Schumacher, and, D. Doria, *Enhanced laser-plasma experiments with helical laser beams*

67. Edmond Turcu, *Electron-Positron Pair Production Interaction Chambers with Counter-propagating, Colliding multi-PW Laser Pulses*

68. M. Grech, L. Lancia, I. A. Andriyash, P. Audebert, A. Beck, S. Corde, X. Davoine, M. Frotin, A. Grassi, L. Gremillet, S. Le Pape, M. Lobet, A. Leblanc, F. Mathieu, F. Massimo, A. Mercuri-Baron, D. Papadopoulos, F. Pérez, J. Prudent, C. Riconda, L. Romagnani, A. Specka, C. Thaury, K. Ta Phuoc, T. Vinci, *Investigating strong-field QED processes in laser-electron beam collisions at Apollon*

69. C. A. J. Palmer, B. Reville, A. R. Bell, A. F. A. Bott, H. Chen, G. Gregori, D. Lamb, C. K. Li, J. Matthews, J. Meinecke, H-S.Park, R. Petrasso, S. Sarkar, A. Schekochihin, L. Silva, A. Robinson, P. Tzeferacos, and M. Vranic, *Exploring cosmic-ray physics with high-energy, high-intensity lasers*

70. Jian-Xing Li, Yue-Yue Chen, Yan-Fei Li, Karen Z. Hatsagortsyan, Christoph H. Keitel, *Generation of polarized high-energy lepton and photon beams*

71. Sergei V. Bulanov, Gabriele Grittani, Tae Moon Jeong, Martin Jirka, Georg Korn, Pavel V. Sasorov, Timur Zh. Esirkepov, James K. Koga, Stepan S. Bulanov, Francesco Pegoraro, *Nonlinear Electromagnetic Waves in Quantum Vacuum*

72. Matteo Tamburini, Brian Reville, Jim Hinton, Christoph H. Keitel, *Laboratory gamma-electron-positron plasma – a new frontier in strong-field QED and relativistic laboratory astrophysics*

73. Sergei V. Bulanov, Timur Z. Esirkepov, Stepan S. Bulanov, *Compact Hadron Collider with the Ion Accelerator Using the Laser Radiation Pressure*

74. J. Fuchs, W. Yao, V. Horny, K. Burdonov, C. Ruyer, L. Gremillet. X. Davoine, E. d'Humières, X. Ribeyre, S.N. Chen, D. Schaeffer, W. Fox, P. Heuer, *Towards investigating astrophysically relevant fast collisionless shocks*

75. Sebastian Meuren, David A. Reis, Roger Blandford, Phil H. Bucksbaum, Nathaniel J. Fisch, Frederico Fiuza, Elias Gerstmayr, Siegfried Glenzer, Mark J. Hogan, Claudio Pellegrini, Michael E. Peskin, Kenan Qu, Glen White, and Vitaly Yakimenko, *Research Opportunities Enabled by Co-locating Multi-Petawatt Lasers with Dense Ultra-Relativistic Electron Beams*

76. Vishwa Bandhu Pathak, Calin Ioan Hojbota, Mohammad Mirzaie, and Chang Hee Nam, *Electron acceleration beyond the single-stage laser wakefield acceleration*

77. J. Fuchs, V. Horny, K. Burdonov, V. Lelasseux, W. Yao, L. Gremillet. X. Davoine, E. d'Humières, X. Ribère, S.N. Chen, F. Negoita, P-A Söderström, I. Pomerantz, *Opening the experimental investigation of heavy elements nucleosynthesis through extreme brightness neutron beams generated by multi-PetaWatt-class lasers*

78. P. Zhang, S. S. Bulanov, D. Seipt, A. V. Arefiev, and A. G. R. Thomas, *Relativistic Plasma Physics in Supercritical Fields*

79. D. Seipt, C. P. Ridgers, M. Vranic, T. Grismayer, and A. G. R. Thomas, *Spin and Polarization in High-Intensity Laser-Matter Interactions*

80. Chris Fryer, Shane Coffing, Suzannah Wood, Chris Fontes, Todd Urbatsch, *Understanding Transients: Needs from the Laboratory Astrophysics Community*

81. Brandon K. Russell, Marija Vranic, Paul T. Campbell, Kevin M. Schoeffler, Alexander G. R. Thomas, Dmitri Uzdensky, and Louise Willingale, *Electron-only radiation dominated magnetic reconnection*

82. J. Fuchs, W. Yao, V. Horny, K. Burdonov, L. Gremillet, X. Davoine, E. d'Humières, X. Ribèyre, S.N. Chen, *Enhanced laser coupling, matter heating, and particle acceleration by multiplexing PetaWatt-class lasers*

83. B. Manuel Hegelich, Lance Labun, Ou Zhang, *Performance metrics for laser-electron colliders to aid design and discovery*

84. James P. Edwards, Misha A. Lopez-Lopez, Christian Schubert, *Photon-photon scattering in a plane-wave background*

85. G. Bruhaug, H. G. Rinderknecht, J.R. Rygg, G. Collins, Y. E, K. Garriga, X.C. Zhang, *Extreme THz Pulse Generation and Interaction with Matter*

86. M. Lyutikov, *Astrophysical analogues of laser-plasma interaction*

87. M. C. Marshall, D. N. Polsin, G. Bruhaug, G. W. Collins, and J. R. Rygg, *Ultrafast phase transformation studies in planetary materials to terapascal pressures using x-ray and electron diffraction*

88. Gilbert Collins, Tom Duffy, Danae Polsin, Scott Wilks, Gianluca Gregori, Eva Zurek, *Multi-Petawatt Laser Systems to Interrogate Matter at Atomic Pressures*

89. Henry Freund, *Discussion of XFELs & Laser-Driven FELs Petawatt Laser Initiative*

90. Ion Cristian Edmond Turcu, *Colliding Relativistic Light-Sails accelerated by Multi-PW lasers*

91. Klaus Steiniger, Alexander Debus, and Ulrich Schramm, *Petawatt Class Lasers for Realizing Optical Free-Electron Lasers with Traveling-Wave Thomson-Scattering*

92. Alexander Debus, Klaus Steiniger, Ulrich Schramm, *Scaling Laser-Plasma Electron Accelerators to 100GeV-scale Energies using TWEAC and Multi-Petawatt Lasers*

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MP3 White Paper 2021
Title: Laser Neutron Production entering the Spallation Mode

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Working Group(s): Laser-Driven Nuclear Physics

Abstract: Laser-driven neutron sources have gained significant interest as they would offer a compact and potentially mobile source for neutrons with unprecedented pulse parameters. Neutrons are of paramount interest to non-destructively assess the composition, shape, density and isotopic distribution in complex samples and therefore allow for testing objects from illicit cargo to ancient artifacts. The bottleneck for a widespread application is the limit in useable neutron sources. Bright sources are usually large scale, complex facilities, like nuclear reactors or large spallation sources, and small-scale neutron sources often lack the flux required for applications.
One significant drawback of most sources is the limit to the maximum neutron energy. Except for large-scale spallation sources the maximum neutron energy is limited either by the energy of the nuclear reaction (Q-value, e.g.14.4 MeV for DT) or by the low energy of the driving particle accelerator.
Multi PW laser systems could potentially serve as neutron sources that combine the high energy of a spallation source, the ultra-short pulse duration of a laser driver with the relative compactness of the facility that would allow to co-locate a bright neutron source to existing research or industrial facilities.

Scientific goal: We intend to simulate, design and test a multi-PW laser-driven neutron source, where the neutron generation mechanism enters the high-energy spallation regime. In contrast to TW lasers, or compact accelerator-driven sources, the MPW lasers could accelerate protons to a few hundred MeV over a distance of only a few millimeters. At these energies the neutron production asks for high-Z targets rather than the low-Z converters for lower energy drivers and the neutron number also could largely exceed the number of the incoming proton number (neutron multiplication). The resulting neutron emission is forward peaked, short pulsed and could yield neutrons up to 100's of MeV.

We like to explore this new source for applications, where the high penetration depth of the neutrons constitutes a new diagnostic tool for large-scale objects, or objects equipped with massive radiation shielding.

Tools required: For these experiments, we require a high energy, multi-PW laser system, an optimized target design as well as an integrated package of simulation tools from 2 and 3D PIC codes. These tools allow us to simulate the extreme laser-matter interaction on a spatial scale relevant to the experiment. The resulting ion spectra are exported into Monte Carlo particle transport codes for an assessment of the nuclear activation and radiation safety. On the diagnostics side we need to develop detectors to accurately detect high energy neutrons, while being resilient to hard X-ray and EMP impact from the laser matter interaction. The diagnostics should be able to provide spatial resolution and some temporal resolution matching the requirements for some example applications (see below).

Scientific impact(s): There are two main impacts to the scientific community. First is the development of a neutron source that is comparable in pulse strength to mile-long spallation facilities, but has orders of magnitude shorter pulse duration and thus much higher peak flux from a very small source. Second is the option to co-locate such a facility and time the neutron pulses very precisely to external sources.

Broader impacts: There is a wealth of applications that would be enabled by this new technology. Just as one example it can address a currently pressing problem in our society's nuclear legacy. Spent fuel dry-cast containers were designed to confine the radiation coming from the decay products in the fuel rods. It is a legal requirement to monitor the containers at all times in order to ensure all the nuclear material is accounted for, especially the significant amount of plutonium that has accumulated in the fuel. If the security chain is breached, the current law asks for opening and manual inspection of the fuel, which is currently impossible to do. Organizations, like to European Commission for Nuclear Safeguard and IAEA are looking for a technique to inspect a dry cast container with an external radiation source. This is a challenging task as these containers are designed to shield against ionizing radiation (e.g. wall thickness of a CASTOR dry cast container is around 45 cm of carbonized steel). Simulations have shown that 150 MeV neutrons could provide a signal to noise ratio sufficient to determine the presence of the individual fuel rods. In contrast to high energy X-rays they might also be able to distinguish between e.g. tungsten and high-Z material of fissile material. So far, no source is available to perform such a measurement at any of the storage sites. The problem becomes more prominent as the containers start to age and need to be opened for transfer of the material into containers designed for underground storage. As no one knows the status of fuel rods after decades of storage, there is a great desire to know the physical shape and integrity of the fuel after 30 to 40 years of intermediate storage prior to opening.

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White Paper

Submitted to the Multi-Petawatt Physics Prioritization Workshop 2021

Novel Plasma Physics Regimes enabled by Spatiotemporally Shaped Laser Pulses

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Introduction: Strong-field, collective quantum electrodynamics (QED) exists at the intensity frontier of laser-matter interactions—a frontier in which ripping electron-positron pairs from the Dirac sea may make targets a thing of the past [1]; where the vacuum can exhibit magnetization, polarization and birefringence [2]; and in which the analogy of Hawking radiation in electric fields, Unruh radiation, could provide insight into the life-cycle of black holes [3]. Compared to any other physical theory, perturbative QED predictions have been experimentally confirmed to unprecedented accuracy. Confirmations, or even focused experiments, in regimes of strong-field QED, on the other hand, remain remarkably uncommon. In principle, this regime can be accessed by accelerating an electron to its rest energy over a Compton wavelength, i.e., in an electric field (E) at the Schwinger limit ($E_{cr} = m_e^2 c^3/e\hbar$). In practice, these fields ($E_{cr} \sim 1.3 \times 10^{18}$V/m) lie well beyond the largest electromagnetic fields created on earth ($E \sim 1 \times 10^{15}$V/m), i.e., those created by high power lasers.

Fortunately, creative laser-plasma configurations can produce highly nonlinear QED environments at much lower field strengths ($E \ll E_{cr}$). This strategy has already proven successful in experimental demonstrations of nonlinear Thomson scattering [4], positron production [5–7], and radiation reaction [8, 9]. Despite these successes, the exotic theoretical and computational predictions of strong-field QED models have rapidly outpaced the experimental capabilities to test them.

Of particular interest are predictions of unique states of matter characterized by the interplay of collective plasma and high-field quantum processes. Here, the interaction of an intense laser pulse and a relativistic electron bunch can ignite a cascade of photon, positron, and electron creation, producing conditions relevant to extreme astrophysical objects [10–13]. Such phenomena lie at the intersection of plasma, astro, particle, laser, and accelerator physics, representing a unique opportunity for community wide collaboration and discovery.

Proximity to the strong-field QED regime is quantified by the invariant parameter $\chi = |F^{\mu\nu} p_\nu|/m_e E_{cr}$, with $\chi \approx 1$ roughly marking the transition from the linear to nonlinear regimes (e.g., $\chi = E/E_{cr}$ for an electron at rest) [12]. A nonlinear Thomson scattering (NLTS) geometry, in which a high intensity laser pulse counterpropagates with respect to an energetic electron beam, provides one of the possible configurations for maximizing χ [5]. Among others, two nonlinear QED processes can occur in this configuration: First, an electron emits an energetic photon with non-negligible recoil, i.e., radiation reaction (e), and, second, the emitted photon scatters from multiple laser photons, decaying into an electron-positron pair, i.e., multiphoton Breit-Wheeler (s) [12]. For these two processes, the relevant expressions for χ are given by

$$\chi_e = 2\gamma\left(\frac{\hbar\omega_0}{m_e c^2}\right)a_0 \qquad \text{and} \qquad \chi_s = 2\left(\frac{\hbar\omega_s}{m_e c^2}\right)\left(\frac{\hbar\omega_0}{m_e c^2}\right)a_0,$$

where γ is the relativistic factor of the electron, ω_0 the frequency of the laser pulse, a_0 the normalized vector potential of the laser pulse, and ω_s the frequency of the scattered photon.

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These expressions for χ reveal several paths for achieving nonlinear QED conditions. Specifically, maximizing χ requires maximizing the energy of each participant in the interaction (i.e., γ, ω_0, ω_s) and the photon density of the incident laser pulse ($U \propto a_0^2$). Multi-petawatt lasers can deliver pulses with large values of a_0 (>100) and drive plasma wakefields that can accelerate electrons to large values of γ ($> 10^4$). More importantly, however, these systems have the bandwidth to create a new paradigm in ultrashort pulse laser applications—spatiotemporal pulse shaping. The ponderomotive control afforded by spatiotemporal pulse shaping can greatly reduce the accelerator length required for a particular γ and increase the power and frequency of the scattered photons (ω_s). Both of which can put the nonlinear QED regime ($\chi > 1$) well within reach.

Spatiotemporal Pulse Shaping: By providing unprecedented control over the trajectory of an intensity peak and the distance over which it can be sustained, spatiotemporal pulse shaping can enable new physics regimes at the frontier of strong-field QED. Conventional optics rely on spatial shaping alone, e.g., through refraction or diffraction, which severely constrains their flexibility. Beyond this simple spatial shaping, spatiotemporal shaping provides the flexibility to structure the pulse with advantageous spacetime correlations [14–17]. For accessing regimes of nonlinear QED and maximizing χ, the spacetime structure must: (1) ensure that the pulse maintains a high intensity over an extended distance and (2) create an intensity peak with a controllable velocity. Both of these can be achieved by stretching the region over which a laser pulse focuses and adjusting the relative timing at which those foci occur.

As an example, the chromatic aberration of a diffractive optic and a chirp can be used to control the location and time at which each temporal slice within a pulse comes to its focus, respectively [14]. By adjusting the chirp, the velocity of the resulting intensity peak, and hence the ponderomotive force, can take any value. This includes an intensity peak that counterpropagates with respect to the phase velocity. This particular configuration enables a new regime of NLTS where the velocity of the pondermotive force can be tuned to control the electron trajectory and optimize the radiation properties [18]. Notably, the rate of emission and the emitted photon frequencies, and hence χ_s, can be much higher than in traditional NLTS.

An alternative technique employs an axiparabola to focus different radial locations in the near field to different axial locations in the far field and an echelon to adjust the relative timing of the radial locations [17]. Along with velocity control, the features of this technique—an extended focal range and a near transform-limited intensity peak in the far field—have enabled a novel regime of laser-wakefield acceleration (LWFA). Specifically, setting the velocity of the intensity peak in the plasma to the vacuum speed of light eliminates dephasing–a key design limitation in which electrons outrun the accelerating phase of the wakefield. Aside from requiring only one acceleration stage, this technique can achieve the same value of γ and χ_e in less distance than a traditional LWFA and in much less distance than a conventional linac.

Dephasingless Laser Wakefield Acceleration: Particle accelerators provide a looking glass into a subatomic world inhabited by the fundamental building blocks of the universe. Conventional accelerators, based on vacuum technology, continue to make impressive strides, routinely improving beam quality and achieving unprecedented energies. With each advance, however, conventional accelerators grow in size or cost. Laser-plasma accelerators promise to break this trend by taking advantage of the extremely large fields driven by high power, ultrashort laser pulse in a plasma.

In traditional LWFA, the ponderomotive force of laser pulse drives a plasma wave with a subluminal phase velocity: $\mathrm{v}_p = \mathrm{v}_g < c$, where v_g is the group velocity of the pulse [19]. As a result, high-energy electrons, travelling at near the vacuum speed of light ($\mathrm{v}_e \simeq c$), escape the accelerating phase of wakefield after a dephasing length, $L_d \propto n_0^{-3/2}$, where n_0 is the plasma density. Because the maximum accelerating field scales as $E_{\max} \propto n_0^{1/2}$, a lower plasma density will increase the maximum energy gain of electrons, $\Delta\gamma \propto n_0^{-1}$, but will greatly increase the length of the accelerator. As an example, a single-stage 1-TeV accelerator would require at least 200 m. Instead, the community currently envisions a TeV LWFA composed of multiple ~ 10 GeV stages. This approach, however, comes with its own set of challenges, such as precisely timing the injection of the electron beam and laser pulses into each of the stages.

Spatiotemporal pulse shaping allows for a different approach. A spatiotemporally shaped laser pulse can drive a plasma wave with a phase velocity equal to the vacuum speed of light ($\mathrm{v}_p = c$), eliminating dephasing and greatly reducing the accelerator length by allowing for operation at higher densities [17]. In addition, the

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stretched focal region eliminates the need for an external guiding structure or self-guiding, while the luminal phase velocity precludes wavebreaking and prevents the accumulation of dark current through self-trapping [20].

Scalings highlight the advantage of dephasingless laser wakefield acceleration (DLWFA). In the linear regime, the energy gain of a DLWFA (subscript D) scales as $W_D = \frac{\pi}{8} m_e c^2 (cL/\tau) a_0^2$, where L is the accelerator length and τ the transform-limited pulse duration. Maximizing the energy gain requires operating at the highest possible density, $n_{\max} = \pi^2 \varepsilon_0 m_e / e^2 \tau^2$, and increasing the length of the plasma as much as possible. This is in contrast to the scaling of a traditional LWFA (subscript T), which requires operating at lower densities to increase the dephasing length, and hence the energy gain: $W_T = \frac{\pi}{8} m_e c^2 (k_p L_d) a_0^2$, where $L_d = 2\pi\omega_0^2/c^2 k_p^3$, and $k_p = (e^2 n_0 / m_e c^2 \varepsilon_0)^{1/2}$ [19]. From the two scaling laws, the traditional LWFA only attains a fraction of the DLWFA gain over the same distance, $W_T = (\omega_0\tau/\pi)^{2/3}(2c\tau/L)^{1/3} W_D$, or must have a length $L_d = (\pi/\omega_0\tau)(L/2c\tau)^{1/2} L$ to attain the same energy gain. As an example, a DLWFA could accelerate electrons to 10 GeV in only 55 cm compared to 5.5 m for a traditional LWFA.

The scalings become even more impressive in the nonlinear bubble regime of LWFA. For a nonlinear DLWFA, $W_D = \frac{1}{2} m_e c^2 (cL/\tau) a_0^{1/2}$, where now $n_{\max} = \varepsilon_0 m_e a_0 / e^2 \tau^2$ in order to match (roughly) half the bubble radius to the transform-limited pulse duration. As before, operating at the highest possible density and increasing the plasma length maximizes the energy gain. The traditional LWFA must have a length $L_d = (3a_0/4)^{1/2}(\omega_0\tau)^{-1}(L/2c\tau)^{1/2} L$ to match the energy gain of a DLWFA and only reaches a fraction of the DLWFA gain over the same distance, $W_T = (4/3a_0)^{1/3}(\omega_0\tau)^{2/3}(c\tau/L)^{1/3} W_D$, where $W_T = \frac{1}{2} m_e c^2 (k_p L_d) a_0^{1/2}$ and $L_d = \frac{4}{3} a_0^{1/2} \omega_0^2 / c^2 k_p^3$ [21]. Here a DLWFA could achieve 100 GeV energy gains in only 50 cm compared to 8 m for a traditional LWFA. In either the linear or nonlinear regime, DLWFA allows for sizable values of γ, and hence χ_e, at distances compatible with multipetawatt laser target areas.

Nonlinear Thomson Scattering with Ponderomotive Control: The strong accelerations experienced by electrons in intense laser-plasma interactions unleashes a torrent of secondary radiation that spans the electromagnetic spectrum. Nonlinear Thomson scattering, in particular, can produce extremely high energy photons with a spectrum that can be tuned through the laser amplitude (a_0) and electron energy (γ). Aside from its application to studying radiation reaction and the nonlinear Breit-Wheeler process, i.e., electron-positron cascades, NLTS could provide a compact, low-cost alternative to sources based on conventional accelerators. Such as source could have far-reaching benefits in medicine, defense, and basic science, including probes for high-energy density materials.

In traditional NLTS, an electron radiates harmonics of the twice Doppler upshifted laser frequency, $\omega_N = 4N\gamma^2\omega_0/(1 + \frac{1}{2}a_0^2)$, over a characteristic bandwidth, $\omega_c = 3\gamma^2 a_0^3 \omega_0/(1 + \frac{1}{2}a_0^2)$, and at an angle $\theta \sim (1 + \frac{1}{2}a_0^2)^{1/2}\gamma^{-1}$ [22]. The denominator of both frequencies $(1 + \frac{1}{2}a_0^2)$ results from the ponderomotive deceleration of the electron as it passes through the rising edge of the laser pulse. While a high intensity laser pulse ($a_0 \gg 1$) can increase the radiated power ($P \propto \gamma^2 a_0^2$) and number of photons, it also causes a significant redshift in the emitted photon frequencies ($\omega_N \propto a_0^{-2}$) and a weaker scaling of the characteristic bandwidth (c.f., $\omega_c \propto a_0$ to $\omega_c \propto a_0^3$ in the linear and nonlinear regimes). Further, due to the stronger ponderomtive force, the electron undergoes larger longitundal oscillations in its average rest frame, which increases the angle of the emitted radiation ($\theta \sim a_0\gamma^{-1}$). This introduces a tradeoff between the number of photons, the spectral properties, and the angle of emission.

Spatiotemporal pulse shaping provides control over the velocity of the ponderomotive force (v_I), which can either compensate for the ponderomotive deceleration or ponderomotively accelerate the electron up to v_I [23]. For both of these cases, referred to as “drift-free” and “matched” NLTS respectively, v_I provides an additional parameter that can eliminate the tradeoffs of traditional NLTS [18]. In the drift-free case, compensation of the ponderomotive deceleration requires $\mathrm{v}_I = c^2/\mathrm{v}_e$. The compensation removes the $1 + \frac{1}{2}a_0^2$ dependence in the harmonic frequencies, bandwidth, and angle, providing $\omega_N = 4N\gamma^2\omega_0$, $\omega_c = 3\gamma^2 a_0^3\omega_0$, and $\theta \sim \gamma^{-1}$ and increases the scaling of the radiated power, $P \propto \gamma^2 a_0^4$. In the matched case, acceleration up to the velocity of the intensity peak requires $\gamma_I = \sqrt{2} a_0 \gamma$, where $\gamma_I = (1 - \mathrm{v}_I^2/c^2)^{-1/2}$. Here, the harmonic frequencies, bandwidth, angle, and power scale as $\omega_N = 4N\gamma_I^2\omega_0$, $\omega_c \approx 3\gamma_I^2 a_0^3 \omega_0$, $\theta \sim \gamma_I^{-1}$, and $P \propto \gamma_I^2 a_0^4$. Both of these regimes greatly improve the properties of the radiation by increasing the emitted frequencies, improving collimation, and boosting the radiated power.

The increase of the emitted frequencies in these new NLTS schemes significantly enhance the scaling of

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χ_s with respect to a_0. This could provide access to the nonlinear QED regime at either smaller values of a_0 or γ. In the latter case, this switches the burden from the accelerator to the laser—a situation ideal for a multipetawatt laser facility. Setting $\omega_s = \omega_c$, the expressions for χ_s in the limit $a_0 \gg 1$ are given by

$$\chi_s^T = 12\gamma^2\left(\frac{\hbar\omega_0}{m_e c^2}\right)^2 a_0^2 \qquad \chi_s^{DF} = 6\gamma^2\left(\frac{\hbar\omega_0}{m_e c^2}\right)^2 a_0^4 \qquad \chi_s^M = 6\gamma_I^2\left(\frac{\hbar\omega_0}{m_e c^2}\right)^2 a_0^4$$

for traditional (T), drift-free (DF), and matched (M) NLTS, respectively. As an example, for a 1 μm wavelength laser pulse, $\gamma = 200$, and $a_0 = 100$, $\chi_s^T = .03$ and $\chi_s^{DF} = 140$. With a spatiotemporally shaped pulse, even a mildly relativistic electron beam can place photon-photon scattering well into the nonlinear regime of QED.

Conclusions: Glimpses into the frontier of strong-field, collective QED have already revealed a teeming landscape of wonderous phenomena. The remaining territory, vast, uncharted and unmeasured, promises a host of opportunities to discover exotic phenomena that will inspire young scientists and public enthusiasts alike. Progress and scientific discovery in pursuit of this frontier will require a community approach to experiments, simulations, and theory, together with investments in multipetawatt laser facilities and simulation software. By providing flexible laser-plasma configurations and extremely high intensities, a multipetawatt laser could access unexplored regimes of strong-field QED and test the exotic predictions of the models. Such a facility could bring the mysteries of the cosmos, including black holes, pulsars, and magnetars, down to earth by creating new states of matter where collective plasma and strong field quantum dynamics co-exist. The new paradigm in laser-plasma physics, spatiotemporally shaped pulses, can facilitate these discoveries.

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MP3 White Paper 2021

Title: Ultra-brilliant GeV gamma-ray emission with multi-petawatt lasers

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Abstract: Bright X/γ-ray sources have opened up new frontiers in fundamental research and are widely applied in medicine and industry. So far, state-of-the-art X-ray sources are mostly generated by large-scale synchrotron facilities [1] and/or X-ray free-electron lasers (XFELs) [2]. Synchrotrons can produce bright X-ray sources, but require acceleration distance of hundreds of meters in order to generate GeV electron beams necessary to deliver hard X-rays. XFELs can deliver the brightest X-ray pulses with typical photon energies in the soft X-ray region, but it still relies on large-scale accelerators and undulators. Moreover, these sources are not sufficient to meet the needs of high energy applications, such as probing the nuclear structure and dynamics [3], exploring exotic quantum electrodynamic (QED) processes [4, 5], radiography of dense objects [6], etc., which require brilliant high-energy γ-rays. With the development of laser-plasma based accelerators or laser wakefield accelerators (LWFAs) [7], one can accelerate electrons to several GeV energies in the centimeter scale, enabling it to drive bright femtosecond X-ray sources via betatron radiation and multi-MeV γ-ray sources via nonlinear Thomson scattering or Bremsstrahlung radiation [8]. Despite promising proof-of-principle successes, these X/γ-ray sources produced with multi-100 terawatt (TW) lasers have low average photon flux and/or limited photon energies. Recent progress in the multi-petawatt (PW) laser technology [9, 10] offers the possibility for producing high-energy γ-ray sources with much higher brilliance. We propose an ultra-bright γ-ray beams with photon energies tunable up to GeV-level with a multi-PW laser pulse in a two-stage LWFA. Three-dimensional numerical simulations demonstrate that more than 10^{12} γ-ray photons/shot are produced with energy conversion efficiency above 10% for photons above 1 MeV, emitted with unprecedentedly high peak brilliance of over 10^{26} photons s^{-1} mm^{-2} $mrad^{-2}$ per 0.1% bandwidth.

Scientific goal: The main goal of this research is to develop high-flux bright γ-ray sources and extend their photon energies up to the GeV range based upon a two-stage LWFA driven by a multi-PW laser pulse [11]. In the first stage, a low-divergence, tens-nC, multi-GeV electron beam with a high beam density is generated in the bubble regime. The laser-to-electron energy conversion efficiency is up to ~40%. In the second stage with a higher plasma density, additional electron trapping and acceleration are found in the wakefields driven by the electron beam from the first stage and the remanent of the multi-PW laser pulse, resulting in even higher trapped charge and charge density. This leads to efficient γ-ray emission via betatron radiation with extreme brilliance, where QED effects start to play an important role. With such brilliant γ-rays, one may test electron-positron pair production with a second PW laser pulse [12-14].

Tools required: Experimental efforts are crucial to demonstrating the above proposed scheme and examining theoretical and numerical models. To realize the proposed scheme experimentally, laser facilities with peak power at the multi-PW level are required.

The scheme of two-stage LWFA and subsequent γ-ray emission is driven by a single PW laser pulse, which includes the high-intensity laser-plasma acceleration and extremely bright γ-ray emission. The main parameters of the required laser pulse are as follow: the peak intensity is in the range of 10^{21} W/cm^2, the pulse duration is about 30fs, and the focused spot size is about 10μm, corresponding to a peak power about 3PW. The structure of the plasma density profile is longitudinally tailored to form two successive stages, where one has a moderately low density (e.g., 0.02n_c) with a length ~1.5mm for efficient acceleration and the other has a relatively high density (e.g., 0.1n_c) with a length of a few hundred microns for efficient radiation.

Based upon the above experiment, new experiments could be carried to achieve copious GeV electron-positron pairs with the emitted high-energy γ-rays by introducing a second multi-PW laser pulse (e.g. 10PW). When the γ-rays collide with the second 10PW laser pulse, electron-positron pairs can be produced via nonlinear multi-photon Breit-Wheeler process. This makes it possible to investigate such nonlinear physical processes in the QED regime at a laser intensity of several orders of magnitude lower than the Schwinger field strength.

Scientific impact(s): The studies of LWFAs and subsequent radiation have been mostly limited to the sub-PW laser level and the involved physics is mainly classical. The proposed research could not only fill in the gap of high-intensity laser plasma acceleration and radiation in a new parameter regime, where unique electron beams with multi-GeV energy and high charge over a few tens of nC are generated, but also provide a source of GeV γ-rays with unprecedented high brilliance.

Broader impacts: This research can enable the development of compact ultrashort γ-ray sources with extremely high-brilliance reaching up to that of XFEL and high photon energy tunable up to the GeV level. Such powerful γ-ray sources may serve as a unique platform for a wide range of applications ranging from fundamental science (e.g., high-field physics, laboratory astrophysics, photonuclear and QED physics), medicine, industry to national security.

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MP3 White Paper 2021
Advanced Light Sources with Polarization Control Based upon Laser-Based Accelerators

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Abstract:
The intention here is to design and simulate various possible free-electron laser (FEL) light sources based on laser-based accelerators to determine what may be achieved. Interest is growing in x-ray light sources that produce ultra-short pulses with polarizations that can be tailored toward various applications. Laser-based accelerators are capable of producing short, intense electron bunches in the femtosecond and sub-femtosecond range which are needed to drive short pulse, x-ray FEL light sources with variable polarization states. Variable polarizations can be produced in FELs and simulated by using advanced modeling tools, taking user needs into account. Our primary simulation tool is the MINERVA code. MINERVA is a three-dimensional, time-dependent FEL simulation code which is computationally efficient and has demonstrated the capability to simulate ultra-short electron/optical pulses. In addition, it has the unique capability of simulating undulator lines and optical fields with arbitrary polarizations and treats harmonic generation self-consistently. In addition, MINERVA has been linked to the Optics Propagation Code (OPC) to simulate oscillators and to propagate the FEL output beyond the undulators. These codes will be used to simulate the performance at the fundamental resonance and harmonics for various short-pulse FEL configurations based on different advanced laser-based accelerator concepts and to determine the requirements on these accelerators for light source applications.

Scientific goal:
Small-footprint laser-plasma-based accelerators [1,2] offer the possibility of sub-femtosecond multi-GeV electron pulses. When used as drivers for free-electron light sources, they could produce intense attosecond x-ray pulses. This holds up the compelling opportunity for applications that are currently out of reach [3,4]. Tantalizing possibilities opened up by such sources lie in their spatial and temporal coherence, combined with the achievable ultrahigh intensity, broadly adjustable photon energy range, ultrashort pulse duration, and variable polarization. These sources could enable novel ultrafast experiments with attosecond temporal resolution [4], e.g.: site-specific X-ray-pump, X-ray-probe experiments [5], serial crystallography for structural dynamics [6], atomic-scale imaging on energy-selected molecular states, nanoparticles, and surfaces [7], with dynamic movies [8-10].

Our goal is to design/simulate possible x-ray FELs (XFELs) based on the characteristics of these laser-based accelerators to inform the required attributes of future laser-based accelerators and light sources to realize the goal of time-resolved X-ray applications with attosecond resolution.

The FEL physics dictates the requirements that these laser-based accelerators must satisfy [11]. As in conventional x-ray FELs such as the Linac Coherent Light Source (LCLS) at SLAC [12], peak currents in the kilo-Ampere range are needed to reach saturation in an undulator line several tens of meters in long. These accelerators employ ultra-short femtosecond-class laser pulses (FWHM) in which electrons are accelerated near the peaks of the laser pulse(s) with pulse lengths in the sub-femtosecond range. This implies that pico-Coulomb bunch charges will be needed to reach kilo-Ampere peak currents. Beam quality as measured by the thermal energy spread and the emittance are also important properties of the electron beam and rms energy spreads in the range of 10^{-5} – 10^{-4} and emittances in the sub-micron range are typical of x-ray FELs. These are stringent requirements even for conventional XFELs. The pulse format of the driving lasers is also an important consideration. For example, if the driving laser is single-shot or has a repetition rate of several Hz, then the XFEL must operate in Self Amplified Spontaneous Emission (SASE) mode or as a High-Gain Harmonic Generation (HGHG) cascade. However, recent advances in the technology of Ti:sapphire lasers have achieved kHz repetition rates [13] and this allows for the design of low-gain, high-Q oscillators or Regenerative Amplifiers (RAFELs) which are essentially high-gain, low-Q oscillators.

It is important to remark that while the character of the undulators needed for XFELs driven by laser-based accelerators will not differ markedly from those used in conventional XFELs, the length and cost of the accelerator will be significantly less. For example, the LCLS employs one-third of the SLAC 2-mile linac. Since it is a normal conducting, copper linac, it requires substantial rf-power. Many newer XFELs employ superconducting accelerating structures which require less rf-power but are still quite large and need large cryo-plants.

The tools/methods to be used rely on the MINERVA FEL simulation code [14-18] in conjunction with the Optics Propagation Code (OPC) [19,20] for modeling oscillators. In this regard, we will study designs, requirements, and sensitivities for SASE and HGHG cascades as well as oscillators (including RAFELs) at both the fundamental and harmonic resonances for ultra-short electron bunches and for different polarizing undulators. In short, this activity will study different system/FEL architectures suitable for a laser-plasma accelerator-based light sources.

FEL simulation codes have been validated against numerous experiments. Most of the commonly-used codes such as MINERVA [14-18], FAST [21], GENESIS [22], MEDUSA [23], GINGER [24] and the NPS code [25] use the slowly-varying envelope approximation which averages the wave equation over the wave time-scale. Thus, oscillations on the time-scale of the wave are not resolved and only the slower amplification of the wave is tracked. These codes require relatively little in the way of computational resources. Each of these codes, except for MINERVA and MEDUSA, impose a further average of the particle motion over the undulator period and integrate only two equations per particle: the energy and ponderomotive phase. Alternately, MINERVA and MEDUSA integrate the full Lorentz force equations for each particle and resolve the undulator motion. Hence, these two codes retain all harmonic components of the interaction and treat harmonic generation self-consistently and can simulate an arbitrary sequence of different polarizing undulators. Further, all of these codes, except for MINERVA, treat a fixed polarization of the optical field by means of a phasor representation of the field, while MINERVA follows the amplification of the *x*- and *y*-components of the optical field separately. In contrast to the SVEA codes, PUFFIN [26] is a Particle-in-Cell code that imposes no average over Maxwell's equations or the undulator period. Since it resolves the fast oscillation, it requires substantial computational resources and is not a practical design code. However, PUFFIN is capable of simulating arbitrarily short pulse interactions.

MINERVA has demonstrated the capability to simulate the essential features of an advanced XFEL. It has the ability to model both linear and nonlinear harmonic generation [14]. Under an SBIR program funded by the Department of Energy under contract DE-SC0018539, MINERVA/OPC was used to simulate/design an advanced XFEL RAFEL [16] using diamond pinhole Bragg mirrors. MINERVA has been run in comparison with PUFFIN [17] to determine the limits on the ability of an SVEA code to simulate ultra-short pulses. It was demonstrated therein that an SVEA code is able to simulate pulses as short as the cooperation length in the FEL. More recently, the capability to model arbitrary polarization states has been incorporated into MINERVA [11] by separately tracking the growth of the *x*- and *y*-components of the optical field. As such, MINERVA can simulate the evolution of an arbitrarily polarized optical field in an undulator line that may contain differently polarized undulator segments or by an undulator line that may include undulators, such as APPLE-II undulators [27], in which the polarization may be adjusted as desired. As a consequence, MINERVA/OPC is capable of simulating and designing the various configurations of an XFEL (SASE, HGHG, RAFEL, etc.) and studying the sensitivities of these designs to the various beam qualities associated with laser-based accelerators.

Tools required:

MINERVA and OPC use the Message Passing Interface for parallelized execution. The codes are efficient and portable and have been run on advanced laptops, desktops, workstations and clusters under all the relevant operating systems. Computing resources are available, and will be used, on clusters provided by the University of New Mexico Center for Advanced Research Computing which is supported in part by the National Science Foundation.

Scientific impact(s):

Modeling and simulation of the application of electron bunches from laser-driven accelerators will inform both the design of the accelerators and the light sources based on them. Our intention is both to set limits on what is needed to drive various light source configurations while illuminating how achievable electron beam characteristics will define which configurations will work best for light sources.

To the extent that this activity results in advanced light sources, it will result in new avenues of research that these sources make possible and will advance many areas of research in general.

Broader impacts:

Laser-driven accelerators are presented as a low-cost alternative to standard linacs that would be suitable to small-scale university-based researchers. Development of such tools in conjunction with new light source concepts will greatly expand the number of researchers able to access these machines and, hence, the research that is conducted using them.

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MP3 White Paper 2021
Title: Dynamics of multi-petawatt laser driven high Z radiative plasmas

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Abstract: Brief description, maximum of 250 words.

There has been a lot of recent interest in the acceleration of high atomic number (high-Z) ions. Although conventional sources of low-Z ions are already relatively compact, high-Z sources cannot achieve high energies and charge states, resulting in heavy-ion accelerator complexes being extremely large with unavoidable beam emittance growth. Laser-accelerated heavy ions can provide, in a compact space both high charge states and moderately high energies (>10MeV/nucleon) with good emittance [1], making them an attractive source of the front end of conventional heavy-ion accelerator systems.

It is challenging to highly ionize heavy metals, such as gold or silver, as inner shell electrons are bounded in deep potential wells, i.e., a silver atom has an ionization potential I_p > 5 keV for its L-shell and ~30 keV for its K-shell. The total ionization potential density of solid silver is $P_{ion} \sim 1.3$ peta-Pascal (PPa). A petawatt laser focused to an intensity $I = 10^{21}$ W/cm^2 has an energy density of 33 PPa, so that only a petawatt laser light can produce highly ionized high Z plasmas.

The energy transport in dense high Z plasma driven by the petawatt laser is quite complex where the plasma which is heated over keV temperature via collisional processes together with ionization and radiation transport. Since keV electrons' mean free path and optical depths of hard x-rays in solid silver are comparable, the keV silver plasma has vigorous energy transfer among electrons and photons. The plasma loses energy via radiations in picoseconds [2]. This means hard x-rays flush in picoseconds. Understanding the energy transport in high Z plasma is the key to make an efficient high Z ion acceleration and also a novel radiation source.

Scientific goal: Description of the goal and the methods that would be used.

Using the next multi-petawatt laser light with high repetition, create exotic hot heavy metal plasmas with a bigger volume, higher charge states, higher number of accelerated ions with higher energies than the current petawatt laser.
Understand the energy transfer among particles, photons and fields, and the energy transport in hot dense high Z plasmas with radiations. Make a theoretical model of the transport, and verify the model using PICLS simulations and experimental data.

Tools required: Parameters required for the experiment, or technical requirements/abilities of modeling tools, or theory development. Identify any facility/diagnostic/code developments that need to be made to achieve the goal.

- Current petawatt-class laser: J-KAREN-P, DRACO, ELI. Next multi-petawatt short pulse laser light: 10^{21}W/cm^2 with a few tens fs duration with wider spots (> 10um).
- Diagnostics: electron/ion particle distributions, hard x-rays.
- PICLS code: Multi-dimensional PIC + collisions, ionizations, radiations.

Scientific impact(s): What will the impact of achieving this scientific goal be?

Demonstrate the isochoric heating of heavy metals to produce keV solid density highly-ionized plasmas. Understand the ionization/plasma formation dynamics with the hard x-ray radiation transport properties.

Broader impacts: Highlight other areas / fields or benefits to broader society where this research could make an impact.

Provide heavy ion source in control for the conventional accelerator. Realize a novel intense hard x-ray source for bio-imaging, inactivation of bacteria/virus, especially with high-repetition laser systems.

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Phase-based X and gamma ray diagnostics for multi-Petawatt laser research

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Abstract:

The ultra-intense laser beams available in the recent years can create new states of matter characterized by extreme energy density and intense emission of high energy particles and radiation, on femtosecond time scale. To experimentally characterize the interaction of these lasers with matter, new types of diagnostics will be required. In particular, multi-PW lasers are predicted to create micron-sized, extremely intense, and directional sources of X-rays and gamma rays, with up to tens of percent of the laser energy being converted into radiation from tens of keV to hundreds of MeV. Determining the spatial extent of these high energy sources with conventional, attenuation-based X-ray methods will be difficult and uncertain. Additionally, standard laser interferometric diagnostics are limited to electron densities below the critical density, therefore diagnostic able to probe the plasma electron density close to the solid density (10^{23} cm^{3}) with high accuracy are needed to validate the PIC simulations and allow the understanding of the plasma parameters and its dynamics.

Scientific goal:

The Johns Hopkins Plasma Spectroscopy Group, in collaboration with researchers from ELI-NP in Romania, proposes to develop and test in experiments up to 10 PW at ELI-NP, novel phase-based diagnostics for the measurement of the X-ray and gamma ray laser produced sources, and for the measurement of the pre-plasma electron density profiles. Phase-based (refraction and diffraction) measurements are much more accurate and feasible at high photon energies than attenuation-based ones, because the real part of the complex index of refraction, determining the phase effects, is orders of magnitude larger than the imaginary part determining the attenuation effects ($1/E^2$ scaling, versus $1/E^4$ energy scaling).

Similarly, phase-based X-ray measurements are well suited for the diagnostic of the extreme gradients expected in the dense pre-plasma produced by high temporal contrast, multi-PW laser pulses (gradient scale lengths of few microns). This is firstly because the refraction-based diagnostics measure *directly* the plasma electron density gradients, and secondly because, as above, the X-ray refraction coefficients are much larger than the attenuation ones.

The main phase-based X-ray method we propose to utilize for the diagnostic of multi-PW laser experiments is Talbot interferometry, namely grating-based Talbot-Lau X-ray Deflectometry (TXD). For electron density gradient diagnostic, the method consists in measuring the small angular deflections caused by refraction in the plasma of X-rays emitted by a backlighter with a micron-period grating interferometer. Together with refraction, the X-ray absorption and scatter in the plasma are also measured, enabling additional diagnostics such as Z_{eff} profile [1], or microturbulence assessment. In addition to pre-plasma diagnostic, the method can serve for density profile and material mixing diagnostic in shock experiments, and for plasma expansion measurements in basic laser-matter physics studies. The method can be applied using betatron or inverse Thomson scattering X-ray sources as bright, fs-duration backlighters, since the phase-based techniques work well with broad X-ray spectra. Quasi-monochromatic TXD diagnostic is also possible using X-ray mirror reflectors.

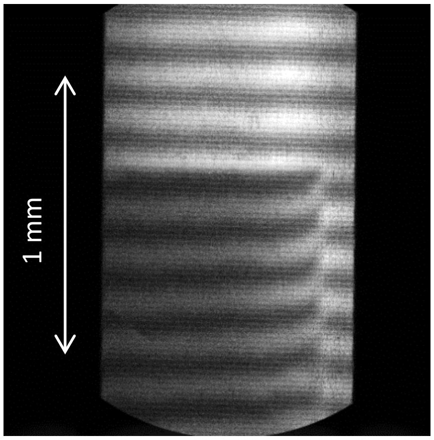

Fig. 1 Moire fringe pattern with 1 mm diameter, PMMA cylindrical test object, obtained with 8 KeV Cu K-alpha backlighting.

TXD has been developed at JHU for the past several years and is currently being implemented on MJ class laser experiments, as well as on pulsed power experiments [1,2]. For illustration, Fig. 1 shows the high contrast interferometer fringes obtained with an 8 keV Cu K-alpha backlighter.

For the diagnostic of the spatial extent of high energy X and gamma sources, the method consists in determining the transverse coherence length of the source, by measuring the visibility of the fringe pattern in a Talbot interferometer configuration. The key advantage of a coherence-based source measurement is that it can be accurately performed up to high photon energy, in principle reaching the gamma-ray energy range. This is supported by recent advances in the manufacturing of high aspect ratio X-ray optical elements. For illustration, Fig. 2 shows the high contrast fringe pattern obtained with a Glancing Angle Talbot-Lau interferometer [3], for an X-ray spectrum of 100 keV mean energy and extending up to 200 keV.

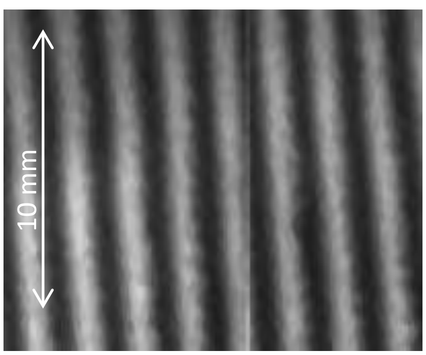

Fig. 2 High contrast Moire fringes obtained with Glancing Angle X-ray Interferometer and spectrum of 100 keV mean and 200 keV peak energy.

Tools required:

Key resources for the proposed effort are the know-how and X-ray optical systems available at JHU, and the 1 PW and 10 PW lasers and experimental setups at ELI-NP. In addition, an x-ray optics laboratory will be available at ELI-NP, and synchrotron beam time will be available at the Karlsruhe Institute of Technology. Simulative and theoretical capabilities will be available through existing JHU and ELI-NP collaborations in the US and in Europe. Following testing and validation of the proposed diagnostics on ELI-NP, they will become available to US PW facilities such as SCARLET, ZEUS, and the future OPAL. For the implementation of the TXD diagnostic, a betatron source can be used to generate the backlighter, typically consisting of a He gas cell of 5-10 mm at ~10^{19} cm^{-3} density and irradiated by a 20-100 TW ultra-short laser pulse. This will allow obtaining the required repetition rate with low debris and provide time-resolved measurements of the density distribution in the generated plasma. Adjusting the delay between the backlighter beam and the main pulse will also allow to probe the dynamics of the processes in the plasma.

Scientific impact:

Most of the theoretical predictions of the initial electron density profiles in laser produced plasma are based on PIC simulations which are typically indirectly validated from the measurements of the secondary generated sources. As the laser intensities exceeds 10^{21} W/cm^2, where an exponential growth of the gamma yield is also predicted [4,5], accurately measuring the electron density profiles and the spatial extent of the secondary photon sources will help understanding the laser–matter interaction and overcome the discrepancies between simulations and experiments. Lastly, accurately measuring through coherence based methods the extent of micron-scale hard X-ray and gamma-ray sources produced by high intensity lasers will help characterize the physics of the interaction, as well as enable to define the application potential of such sources.

Broader impacts:

The X-ray imaging with Talbot-Lau grating interferometers is a technique capable to image low-Z mater with improved contrast, thus having a broad range of applications, from material sciences, to biomedical sciences, and to non-destructive testing [6-8]. For biomedical applications for instance, the technique is studied towards an improved diagnostic of lung diseases, rheumatoid arthritis or osteoarthritis disease [3,7]. In conclusion, Talbot interferometry with laser produced X-rays and gamma rays can be a unique and versatile tool for many applications in a wide variety of fields.

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MP3 White Paper 2021
Relativistically transparent magnetic filaments: a platform for high-field science and efficient gamma-ray sources

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Abstract: High-power lasers enable a new regime of relativistically-transparent laser-plasma interaction physics. At relativistic intensities, the critical density of the plasma is increased by the effective electron mass, allowing the laser to interact with large volumes in a classically over-dense plasma that can sustain a higher relativistic current density. As an intense laser propagates through an over-dense plasma, it pushes the electrons forward, inducing a relativistic current filament that generates a quasi-static azimuthal field with strength comparable to the oscillating laser field. This system can be understood as a relativistic plasma rectifier for laser light that efficiently converts the oscillating electric and magnetic fields into a direct filamentary current and associated magnetic field. State-of-the-art simulations show that the azimuthal field strength reaches the mega-Tesla level in the multi-Petawatt regime. Such strong fields offer an exciting and previously unexplored opportunity to efficiently convert laser energy into a dense pulse of energetic gamma-rays. Plasma electrons serve as a mediator: the confining azimuthal magnetic field facilitates their energy gain from the laser, while, at the same time, their deflections within the magnetic field cause them to emit energetic gamma-rays. The extreme magnetic field strength and high electron energy boost the parameter characterizing the photon emission into the regime, where a single photon can carry an appreciable fraction of the emitting electron's energy. This feature ensures high efficiency of gamma-ray emission, and produces a unique and robust platform for the study of high-field physics.

Scientific goal: Intense laser fields can rapidly drive relativistic electron current filaments in plasmas, producing strong azimuthal magnetic fields.[1-6] For non-relativistic laser intensity, the cutoff density for laser propagation (the critical density) depends only on the laser wavelength λ_0, as: n_{cr} [cm^{-3}] ≈ 1.1×10^{21} / (λ_0 [μm])^2. At relativistic intensity, the limiting electron density scales linearly with laser amplitude, so the plasma remains transparent for $n_e < a_0 n_{cr}$, where $a_0 \approx 0.85 (I_0 [10^{18}\ \mathrm{W/cm^2}])^{1/2} \lambda_0$ [μm] is the normalized laser amplitude. (The laser amplitude is considered to be relativistic if $a_0 \geq 1$.) The maximum current density j that can be sustained in a plasma is also limited by the electron density n_e as $j < e\, n_e\, c$, due to the fact that the electron velocity cannot exceed the speed of light c. As such, in the interaction of a relativistically intense laser with a plasma, the limiting current density is increased by a_0 and ultra-strong magnetic fields may be produced. If a current filament of radius R carries a spatially-uniform axial current density $\alpha \equiv j / j_{cr}$ (normalized to the current density limit at the critical electron density $j_{cr} = e\, n_{cr}\, c$) when driven by an intense laser, the maximum resulting azimuthal magnetic field strength B is calculated relative to the laser field strength B_0 as: $(B / B_0) = \pi (R / \lambda_0)(\alpha / a_0)$.[2,3,7] This shows the importance of relativistic transparency in achieving a high azimuthal magnetic field: the maximum current density that can be driven in a relativistically transparent laser-plasma interaction is $\alpha \leq a_0$, which will produce azimuthal fields on the same order of magnitude as the laser field.

Simulations predict the robust acceleration of such relativistic current filaments and the associated production of strong azimuthal fields, as shown in Figure 1. These 3D-PIC simulations show that the direct laser acceleration (DLA) of an ultra-relativistic electron population is a threshold process, as opposed to a narrow linear resonance, that requires a certain current density in the plasma for given laser amplitude a_0.[3,4] In particular, a limiting value of $(\alpha / a_0) \gtrsim 0.01$ is needed to produce high effective acceleration gradients. For the portion of the electron population that matches the phase of the laser oscillation, this acceleration is extremely rapid: Figure 2 shows tracked electrons in a simulation with $a_0 = 50$ and $n_e = 1.5\ n_{cr}$ undergoing an acceleration of 10 MeV/μm, which is 10^5 times greater than a conventional electron accelerator.

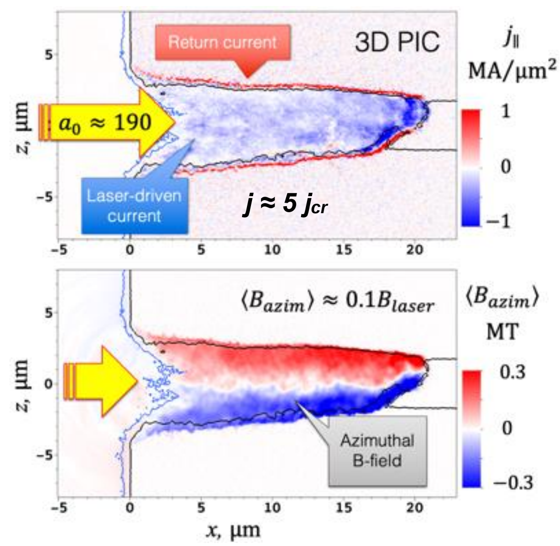

Figure 1: A high intensity laser pulse propagating in a relativistically-transparent plasma channel, $n_e = 20\ n_{cr}$, drives a strong current and generates a static magnetic field.

By oscillating in the confining magnetic filament, the relativistic electrons radiate photons in the MeV energy range. Figure 3 shows the spatial distribution and energy conversion efficiency into MeV photons for $a_0 = 190$ and $n_e = 20\ n_{cr}$, with peak laser power ranging from 1 to 10 PW. The photons are preferentially radiated into two forward-directed lobes, separated along the axis of laser polarization (Figure 3a). At 1 PW, each of these lobes contains 10^{11} photons with energy greater than 1 MeV [5]. For laser powers above 4 PW, the efficiency of conversion from laser energy into photons above 10 MeV exceeds 1% (Figure 3b). The goal of this work is to study the scaling of this predicted phenomenon in experiments, and to robustly and efficiently convert intense laser impulses into extreme fields and directed high-energy photon beams.

Tools required: The described experiments require laser intensity sufficiently high for relativistic transparency to occur. The characteristic radiated photon energy and power are predicted to increase as $\varepsilon \propto a_0^3$ and $P \propto a_0^4$, respectively, so multi-Petawatt laser pulses with tight focusing capability will be needed at a range of intensities from 10^{21} to above 10^{24} W/cm². Using optical lasers, a target density on the order of mg/cm³ is typically needed for relativistically transparent interaction. These densities have been demonstrated with aerogel foams.[8] At higher intensities ($\gg 10^{23}$ W/cm²), low-density liquid or solid targets become viable, such as liquid hydrogen (25 n_{cr} at λ_0 = 800 nm). The propagation of laser pulses in an overdense plasma has been shown to be unstable to filamentation and hosing

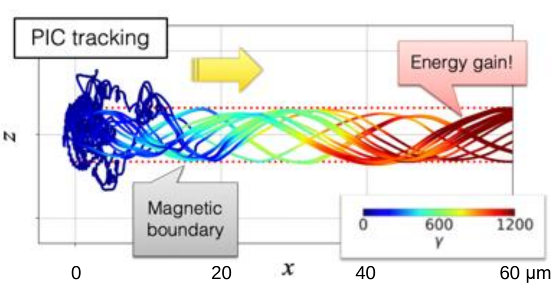

Figure 2: DLA of electrons at $a_0 = 50$ enhanced by a quasi-static magnetic field of a structured target in a 2D PIC simulation [3]. The dotted line is the magnetic boundary, $r_{MB} \approx \lambda_0\ (a_0/\alpha)^{1/2}$.

instabilities, which result in random variations in the direction of the accelerated electrons.[9,10] This can be remedied by the use of a low-density channel in a solid-density substrate. The channel wall prevents cavitation of the plasma and acts as a waveguide, enabling stable, high-intensity interaction over many Rayleigh lengths.[1] Initial targets have been demonstrated using 2-photon polymerization (2PP) and laser-drilling technology, but further development is needed to demonstrate control over material density and composition. To successfully inject intense laser light into a low-density microchannel target will require laser pointing stability on the order of the microchannel radius (< 3 μm). Compact and rapid spatial and spectral diagnostics for GeV electrons and 10's MeV photons are the primary diagnostics required. A microscopic measurement of the magnetic filament field structure will be highly beneficial: this will require the development of μm-scale charged particle radiography, or x-ray polarimetry using an FEL [11]. The need for high laser contrast is not yet established, but may prove critical to prevent the ablated pre-plasma from deflecting or defocusing the intense laser prior to interaction with the relativistically transparent bulk. Plasma mirrors will be used to address this issue.

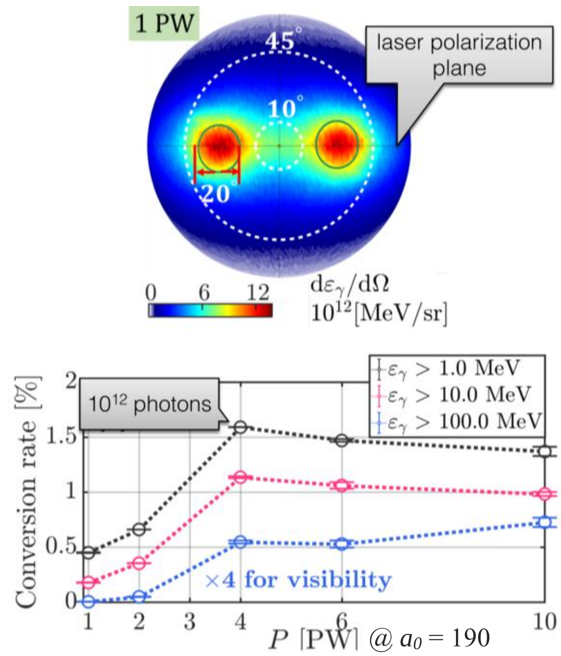

Figure 3: Photon emission (>1 MeV) projected onto a sphere, and power scan for three different photon energy cutoffs [5]. The conversion rate is for a single lobe (black circle) in the upper plot.

Scientific impact(s): This relativistic laser-plasma phenomenon will provide a unique window into the collective effects of strong-field physics. As laser intensity exceeds 5×10^{22} W/cm^2, field strength and electron energy will increase to the point that the magnetic field will exceed the critical field strength in the reference frame of the electrons, and radiation reaction (radiation friction) will begin to affect the electron orbits [6]. Even though the radiation friction is an energy loss mechanism, in the microchannel environment it is predicted to enhance the electron acceleration by interfering with dephasing. This interaction represents an integrated testbed for radiation friction in a plasma environment that will challenge models of QED reactions.

Both the photon yield and conversion efficiency are orders of magnitude higher compared to other laser-driven sources in this regime [12]. As the source is emitted on the same timescale as the driving laser pulse (τ ~ 100 fs), the photon flux is also extraordinarily high. These features make relativistically transparent magnetic filaments promising for the development of compact and efficient gamma-ray sources. The intense gamma sources will enable sensitive studies of QED phenomena such as Breit-Wheeler pair production [5, 13] and photon-photon scattering [14].

Broader impacts: The mega-Tesla fields in the laboratory will approach for the first time conditions relevant to extreme astrophysical environments such as neutron stars [15], potentially providing a unique platform for high-field laboratory astrophysics [16]. The high efficiency of MeV-photon production will additionally provide unique probes to advance photonuclear [17,18] and high-energy-density physics. An efficient and high-average-brightness gamma-ray source will have applications in radiation therapy [19] and radiosurgery [20].

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MP3 White Paper 2021
Microcavity implosions for the generation of extreme electric fields and ultrahigh magnetic fields

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Abstract: Microcavity implosions driven by multiple ultraintense laser pulses enable new regimes of strong electric and magnetic field generation. Laser irradiation of a target with an embedded micron-scale void generates a population of hot electrons which fill the void, driving implosion of the cavity. When the implosion is symmetric, the collapse of ions to the target center is accompanied by the generation of a strong electric field. In the case of spherical microbubbles, the resulting electric field is predicted to reach the extreme values needed to observe high-field phenomena such as vacuum polarization. Cylindrical microtube implosions, while less favorable for electric field production, generate strong axially-oriented magnetic fields, and can additionally amplifying applied fields, offering a path towards megatesla magnetic fields. The development of microcavity implosion platforms would introduce new capabilities in extreme electric field and ultrahigh magnetic field generation for both high-field physics and magnetized high energy density plasma experiments.

Scientific goal: The interaction of an ultraintense laser pulse with an opaque target produces a large population of hot electrons which can be leveraged to drive implosions in targets containing voids, as shown schematically in Figure 1. Implosion of the void is driven by charge separation between the hot electrons entering the void and the initially cold ions at the inner surface. When the void has a radially converging configuration such as a spherical bubble or a hollow cylinder, the imploding ion population can overshoot the electron density at the void center, generating a large, transient outward-directed electric field [1,2].

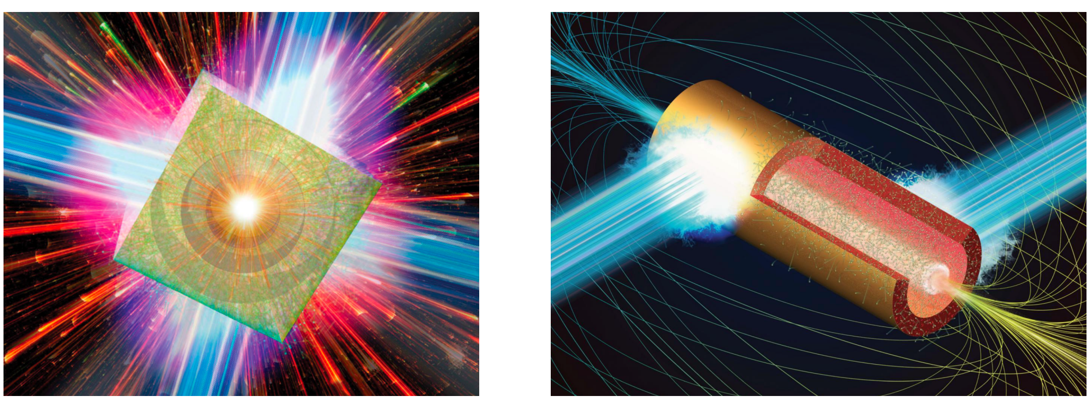

Figure 1: The implosion of a laser-irradiated microbubble (left) or microtube (right) target is accompanied by the production of extreme electric fields and can also deliver ultrahigh magnetic fields. [1,2,3]

In an imploding microbubble, the maximum electric field is predicted to scale as [2]

$$E_{max}/E_s \sim 0.7\tilde{n}_{e0}^2 n_{i0}^{-2/3} R_0^2 r_e \lambda_e,$$

where E_s is the Schwinger field, $\tilde{n}_{e0}$ is the initial hot electron density in the bubble, n_{i0} is the initial ion density, R_0 is the initial bubble radius, r_e is the classical electron radius, and λ_e is the Compton wavelength. For micron-scale bubbles, E_{max} can be more than an order of magnitude greater than the laser electric field E_L [2], as shown in Figure 2. When E_{max} reaches a few tenths of percent of E_s, vacuum polarization is predicted to noticeably affect the propagation of tens of MeV gamma-rays passing through the microbubble [4] (Figure 2). If order-of-magnitude stronger electric fields can be achieved (though, for example, increasing the electron density), pair production may also be possible within the microbubble [5].

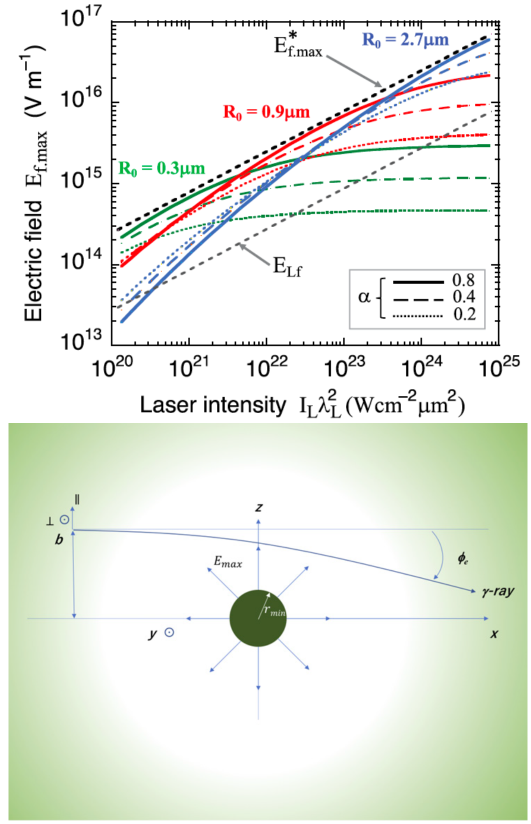

Figure 2: Microbubble implosions are capable of generating extreme electric fields (top), which could be sufficiently large to deflect a γ-ray probe (bottom). [2,4]

In addition to strong electric fields, strong magnetic fields can also be generated by micron-scale implosions [3,6]. Axial magnetic field production in an originally non-magnetized microtube target (Figure 3) is seeded by laser-induced spatial non-uniformities in the hot electron population. Magnetic field generation in this configuration may complement field generation by planar targets [7] as an experimental platform for magnetic reconnection. In addition, microtube implosions are capable of significant magnetic field amplification. The peak magnetic field which can be generated is predicted to scale as [3]

$$B_{max}\,[MT] \sim \left(\frac{Z}{6}\right)^{3/2}\left(\frac{A}{12}\right)^{-1/2}\left(\frac{n_{i0}}{10^{23}cm^{-3}}\right)\left(\frac{R_0}{3\ \mu m}\right)\left(\frac{\varepsilon_{hot}}{6\ MeV}\right)^{1/2},$$

where Z and A are the charge state and atomic mass of the ion species, and ε_{hot} is the average kinetic energy of hot electrons. Through this process, kilotesla-level applied magnetic fields may be amplified to the megatesla level [3] (Figure 3). The generation of such strong fields is of astrophysical relevance [8,9] and additionally probes fundamental phenomena in magnetized high energy density physics [10]. As an example of the latter, the surface magnetic field associated with laser irradiation of magnetized targets [11] is sometimes predicted to trigger magnetic field amplification in the opposite direction to the applied seed field [6].

The scientific goal of this work is to verify the aforementioned promising theoretical predictions and develop microcavity implosions as an experimental platform for accessing high-field, QED, and astrophysically relevant electric and magnetic fields.

Tools required: A fundamental requirement of the described implosion process is substantial hot electron generation. The predicted laser intensities required to approach the Schwinger limit or to produce megatesla magnetic fields are on the order of $10^{22} - 10^{23}\ W/cm^2$ [2,3]. These predictions will require further verification by fully self-consistent simulations accounting for the details of the laser-driven hot electron production. The presence of strong electric fields may be diagnosable via the generation of energetic ions from the implosion [1,2]. The production of the strong quasistatic magnetic fields needed to seed megatesla magnetic field generation is an area of active research, with currently accessible fields reaching up to the kilotesla level [12,13]. Megatesla magnetic field generation has been primarily designed around multi-kilotesla applied fields and additional modeling may ultimately be needed to match experimentally available applied magnetic field strengths.

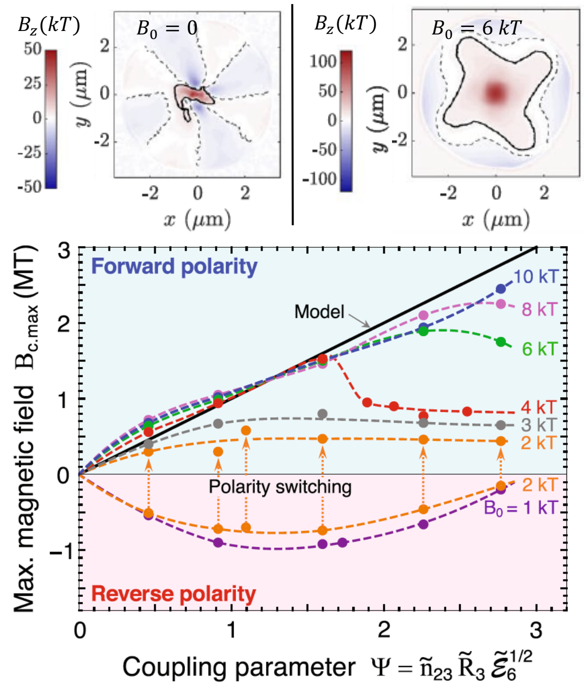

Figure 3: Microtube implosions generate strong magnetic fields and are capable of amplifying applied fields (top), with theoretical predictions suggesting that the amplified field can reach the megatesla level when the hot electron population is sufficiently large (bottom). [3]

Additional requirements include sufficient contrast to prevent substantial pre-filling of the void, and good implosion symmetry. Experimentally, symmetry would be aided by the availability of multiple high intensity laser pulses with multi-micron spot sizes. Advanced target design could also aid in the uniformity of the hot electron population and may allow for experiments to be conducted with two or fewer laser pulses. Microstructured targets with embedded voids have been fabricated via a variety of techniques [14-16], though are in some cases incompatible with side illumination. Additional modeling campaigns will be required to incorporate prepulse, symmetry, and other considerations specific to the facility and the final target design.

Scientific impact(s): Laser-driven microcavity implosions offer an emerging platform for the generation of extreme electric fields and ultrahigh magnetic fields. Electric fields in microbubble targets are predicted to be sufficiently strong to experimentally probe QED phenomenon including vacuum polarization [4] and potentially pair production [5]. Magnetic field generation in microtube targets [3,6] may provide a novel platform for magnetic reconnection studies. The amplification of an applied magnetic field in microtube geometry could additionally probe the fundamental physics of magnetized high energy density plasma [6,10], and is predicted to deliver laboratory magnetic fields as strong as those found in neutron stars [3,8].

Broader impacts: The development of platforms for the laboratory generation of extreme electric fields and ultrahigh magnetic fields will allow experimental testing of fundamental principles in QED [4,5], magnetized high energy density physics and laboratory astrophysics [7,10], and extreme astrophysical environments [8,9].

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Vacuum post-acceleration of relativistic electrons by combinations of THz electromagnetic pulses and constant magnetic fields

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Abstract. Recent theoretical studies have demonstrated considerable potential for the post-acceleration of relativistic electrons in vacuum with the help of monocyclic THz electromagnetic pulses of moderate power, particularly provided that those are augmented with constant magnetic fields. The directions of the electromagnetic wave propagation and electron injection should be completely or closely aligned to enhance the time of energy transfer from the field to the electron. According to available simulations, monocyclic THz pulses efficiently capture and drive fast electrons until they are released due to field-induced transverse displacement or overtaken by the electromagnetic radiation. While the unidirectional motion of the electromagnetic wave and the relativistic electrons facilitates longer overall capture of the particles by the field, protracted drift of an electron across the accelerating part of the monocyclic THz pulse may be achieved by calibrating the additional magnetic field. According to recent theoretical findings, under optimized parameters the additional electron energy gains due to post-acceleration may reach magnitudes ranging from several to tens of electron rest energies depending on the injection energy. The suggested scheme of post-acceleration of relativistic electrons by combinations of comparatively moderate-intensity THz electromagnetic pulses and constant magnetic fields may thereby provide significant enhancement to electron accelerators powered by relativistically intense laser radiation.

Scientific Goal

The acceleration of electrons with the help of relativistically intense laser pulses remains among the priorities of contemporary laser physics [1-5]. At the same time, progress in THz technology stimulates studies of the electron acceleration by moderate-intensity THz electromagnetic pulses which can be generated by relatively compact and low-cost systems but are originally intended to drive electrons to much lower energies [6-10]. Recent studies [11,12] suggest combining the two approaches in the framework of a scheme in which electrons are accelerated by relativistically intense laser pulses and, as the next phase, undergo post-acceleration by co-moving THz electromagnetic radiation. An approach to the post-acceleration of relativistic electrons by THz pulses is suggested in [11,12]. Relativistic laser-accelerated electrons are assumed to be injected into the THz field in a direction closely aligned with that its propagation to ensure longer interaction distance and, thereby, extraordinary efficiency of acceleration. The energy gain may be considerably enhanced by adding an optimally calibrated constant magnetic field to the scheme. The projected increases in the energies of post-accelerated electrons make 2-10 electron rest energies for the parameters of the most powerful of the currently available THz systems.

Tools Required

- Laser system outputting femtosecond optical pulses with intensities in the 10^{18}-10^{20} W/cm^2 range
- An advanced system generating THz pulses with 10-50 mJ energies and the duration around 1 ps duration

Scientific Impact

For optimal THz field parameters and given relativistic-level electron injection energies, the electron energy gains in the process of the suggested THz-driven post-acceleration may reach the magnitudes from several to tens of rest energies of the particle. The above warrants the conclusion that the scheme of vacuum post-acceleration of relativistic electrons with the help of THz pulses of moderate intensity may be cast into a key element of an efficient combined acceleration design.

Broader Impacts

The broader impacts of the implementation of the suggested THz electron post-acceleration scheme include the improvement of laser acceleration efficiency for basic research and various applications as well as the creation of a synchrotron based on THz acceleration, as proposed in [11].

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MP3 White Paper 2021

Status and future of high energy high average power lasers

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LAP: Laboratory Astrophysics

Abstract:

Laboratory Astrophysics distinguishes itself more and more as an important application that benefits from high energy laser developments. We identify three main trends that seem to crystalize progressively.

First, there is a need for more energetic laser sources to study vast regions of the phase space of matter still unexplored by extreme physics.

Then, at the same time, Big Data and Artificial Intelligence already offer promising possibilities to assist and accelerate the speed of exploration of this immense phase space. In order to fully take advantage of this trends, there is a deep need to increase the recurrence rate of the measurements and thus the repetition rate of the lasers. The latter will also allow for efficient active feedback loops.

Last but not least, lasers with ever more temporal and spatial pulse shaping capabilities will be required in order to precisely optimize the laser-matter interaction parameters.

We consider that the expectations for the next one-two decades will be for High Energy and High Average Power (HEHAP) lasers delivering average power up to 10 kW with energies between 100J and kJ. Surely this will be accompanied by challenges and developments downstream of the laser: target, radiation and diagnostics management but this is out of the scope of this paper.

Pulse durations ranging from ns down to fs are necessary to address such applications. In some cases the ns lasers are used as primary source of energy for ultrashort pulse lasers.

Beyond the need for new laser active materials to allow for higher energy, less thermal effects, better properties, our community will also have to improve by at least one order of magnitude the thermal extraction in laser medium.

Scientific goal:

Two main goals arise as for lasers to serve the Laboratory Astrophysics community: multi-PW femtosecond class lasers at 10-100Hz and 1-10kJ nanosecond lasers at Hz rep-rate.

1- Multi-PW femtosecond class lasers at 10-100Hz would be a tool for relativistic plasma.

The highest repetition rate to date for multi PW-class systems is 10Hz. To date a 1PW laser (30J / 30fs) at 10Hz and a 2PW laser at 10Hz (34J / 17fs) have already been manufactured by the Lawrence Livermore National Laboratory (USA) for ELI-L3 in Czech Republic and Amplitude (France) for ELI-ALPS in Hungary, respectively. Both of them are based on Ti:Sapphire technology.

In order to operate these PW lasers at 10Hz, notable breakthrough[(1), (2), (3)] in pump laser domain was necessary and has been demonstrated in the last 3 years; indeed kW-class lasers at 80J/150J-10Hz level have been manufactured in ns regime, two of them (LLNL and Amplitude) already being used as pump lasers.

In all cases, the challenges faced for such pump lasers have been approached with remarkable conceptual similarities but important difference in details. All geometries are based on large diameter, longitudinally cooled (i.e., the beam under amplification passes through the numerous cooling channels), split-thick disks for the amplifier modules. The large diameter eases the generation of high energy together with minimizing non-linear effect due to limited fluence on optical components. The split-disks configuration allows for efficient heat extraction through multiple & large facets. The high diameter-to-thickness ratio relies on the implementation of anti-transverse lasing cladding around the disks.

The first key challenge is the heat load management which scales-up with increasing average power. Two of these 3 lasers (Dipole by SFTC in Great Britain, HAPLS pump Laser by LLNL in USA) take advantage of the lower thermal load offered by diode pumping and are cooled by gas jet at various temperatures. The last one, the Premiumlite-YAG developed by Amplitude, can manage more than 7kW heat in the laser medium generated by inefficient but inexpensive flashlamps and is liquid-cooled. Liquid-cooling offers the advantage of a high capacity for heat extraction.

Repetition rates as high as 100 Hz and beyond can be reached taking all advantages of the aforementioned technologies: simulations suggest that by replacing the flash pumping by a diode pumping scheme we can sustain even more than the requested factor of 2 on the thermal load extraction (heat load divided by 5 with diode pumping but then multiplied by 10 by rep-rate increase from 10 Hz to 100 Hz). Hence,100J-class lasers at 100Hz are achievable, meaning 10kW average power. As a consequence, multi-PW level at 100Hz seems reachable but is still to be developed and demonstrated.

These multi-PW peak power and multi-kW average power lasers could be based on Ti:Sa or OPCPA laser technologies - both require ns pump lasers delivering ~100J in the green at up to 100Hz and with pulse shaping capability especially for OPCPA.

2- 1-10kJ nanosecond lasers at Hz rep-rate would address planetary, solar interiors, dwarf star studies at rep-rates more than 100 times faster than today.

Today most kJ lasers existing in labs are limited to one shot per hour or less, an obvious experimental bottleneck.

Based on the same liquid-cooled split disks flashlamps pumped technology (Premiumlite by Amplitude), but replacing ceramic YAG disks by Nd:phosphate glass disks in order to increase the stored energy, a kJ-class laser operating at more than 0.1Hz is under design at Amplitude.

100J have already been successfully demonstrated at 0.1Hz as a shock driver ready to be delivered to the European Synchrotron Radiation Facility (Grenoble, France). This kind of laser already includes pulse shaping capability, active spatial smoothing (SSD) in order to favour the optimum conditions of interaction.

One can extrapolate that a diode-pumped version could even operate in kJ regime at multi-Hz rep-rate resulting in the delivery of an unprecedentedmulti-kW average power at such a high energy but at the expense of much massive budget. Achieving this goal within 10 years seems feasible.

Tools required:

One of the biggest challenges for the HEHAP lasers of the future is heat management, which translates to the critical wavefront quality performance for the laser user. Second harmonic generation for Ti:Sapphire pumping, OPCPA pumping, far field optimization for shock driver all require high level control of wavefront quality. Wavefront improvement is the result of minimizing aberrations and improving active wavefront correction.

Currently we identify 4 key elements to overcome the major wavefront distortion problem expected in HEHAP lasers:

- the understanding via simulation of thermo-optical deleterious effects induced in the coolant at high heat extraction (indeed, the coolant can become a significant contributor to the aberration due to its residual absorption),

- the development of composite laser materials compatible with the thermal gradients involved: the objective is to minimize the highly aberrant contribution of the anti-transverse lasing cladding to the wavefront distortion. More complex laser ceramic, glass and crystal geometries will be required.

- the development of novel high energy and high average power (> 10J - 100Hz) SBS mirror for ns pump lasers. In some specific cases where ns pump lasers can be SLM, the SBS mirror is a tool of choice because it is self-optimizing and quasi-instantaneous. Thus, even shot-to-shot fluctuating aberrations can be compensated.

- the development of new laser materials with the lowest quantum defect and acceptable thermal, optical and gain saturation properties, so that their implementation in real lasers can be considered.

Scientific impacts:

Contribution to the demonstration of 100J and more at 10kW average power is the first important step towards the still more grand & ambitious goal of having lasers capable of delivering 100kW average power at tens of kHz. Indeed at 100kW, not only the average power will be higher but the thermal density to be extracted will be even higher. This will increase the requirement on the heat exchange coefficients to be reached and thus the complexity of the geometries of laser amplifiers. The increase in peak laser power has been phenomenal over the last 30 years, from 10TW to more than 10PW. The challenge of the coming decades is to accompany this trend by an increased average flow of photons in order to allow the drastic increase in scientific production that is about to be accessible with the emergence of Artificial Intelligence.

Broader impacts:

HEHAP PW lasers could also be the source of reference for compact electron accelerators, meaning that efforts to develop aforementioned laser could be mutualized.

Societal application like proton therapy [4] with laser-accelerated protons will require HEHAP PW lasers to precisely deliver the requested radiation dose to treat cancerous tumours in critical areas of the body. HEHAP PW lasers may be the key tools for this purpose.

Industrial applications are waiting for high-speed laser sources to become competitive: laser shock peening, laser bond inspection of composite materials could help lighten structures and play a key role in the green revolution by saving energy and raw material consumption.

The 10kW nanosecond lasers, if extrapolated to UV by addition of a THG crystal, could be promising candidates for other industrial applications: display and semiconductor industries would probably welcome more efficient and safer sources of photons than excimer lasers.

Another fascinating application is cleaning space debris with HEHAP laser in the near future.

We at Amplitude expect a bright future for HEHAP lasers with numerous applications in many different domains ranging from science, medicine, space to industry. We are already committed to having this as one of the main technological developments for the years to come and beyond.

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Relativistic Flying Mirrors for Fundamental Science and Applications

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Abstract:

With the advent of petawatt lasers the possibility to breakdown the vacuum generating electron-positron pairs has come closer to being a possibility, however, the expected focused intensities even with the next generation lasers is expected to be orders of magnitude too small. We propose considering combinations of high intensity lasers with high frequency seeds to induce the breakdown. The high frequency seed will be generated by using relativistic flying mirrors and laser solid target interactions. We expect that with this combination the vacuum breakdown could be achievable with next generation laser systems.

Scientific goal:

Petawatt (PW, 10^{15} W) lasers of the duration 10's of femtoseconds (fs, 10^{-15} s) have been and are being developed [1]. Focused laser ultra-high intensities 1~5.5x10^{22} W/cm^2 have currently been achieved [2-5]. Soon multi-PW lasers will be available producing intensities ~ 10^{23} to 10^{24} W/cm^2 [6-8]. These intensities are equivalent to the total power of solar radiation received by the Earth (~174 PW [9]) focused to a square ~10's of μm on each side (Figure 1).

Figure 1 Petawatt lasers.

However, even these extreme intensities are far below the threshold intensity, I_S, for electron-positron pair production from the vacuum $I_S = 2.3 \times 10^{29}\ W/cm^2$ [10-12].

Extremely short coherent light pulses with photon energies greater than optical levels focused to extremely small spots can be achieved from the interaction between plasma and ultra-short laser pulses via relativistic flying mirrors (RFM's) with relatively compact laser systems [13]. In this scheme the relativistic mirror is a breaking plasma wave generated by an ultra-short high power laser propagating in plasma [13]. A laser pulse counter-propagating to this mirror is up-shifted in frequency and shortened in length by the mirror [13] (Figure 2).

RFM's can generate tightly focused high frequency photon beams due to the naturally focusing nature of the mirror. The reflection from the mirror of low intensity counter-propagating optical laser pulses has been the main topic of study. However, at high intensity high order harmonics have been found to be generated in the up-shifted laser light [14,15]. Care must be taken if the intensity gets too high due to the significant back reaction on the mirror that can occur [16].

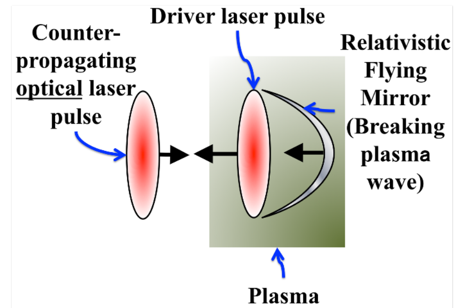

Figure 2 Relativistic Flying Mirror.

In addition at the intensities achievable it has been shown that greater than 30% of the laser energy can be converted into γ-ray photons when multi-PW lasers interact with high energy electrons [15-17] and solid targets [19-21] (radiation reaction dominant regime). Since the γ-rays are of the order of the laser pulse duration (10's of fs), these γ-ray sources generated from solid targets are expected to reach ultra-high PW levels and have photon energies in the 10's of MeV range [20,21].

By combining the three sources of high intensity lasers, RFM's and γ-ray sources generated from solid targets we consider that the vacuum breakdown could be achieved with the next generation PW laser systems.

Tools required:

As well as modelling the RFM's determination of the focused intensity is critical in verifying that the breakdown of vacuum has occurred due to the Schwinger mechanism. We consider two tools: (1) high field ionization [22] and (2) high energy electron beams [23]. This will require detailed modelling of the laser atom and laser high energy interactions. In particular due to the relativistic ionization intensities large computational resources will be needed to model the interaction as in [24]. We anticipate performing preliminary experiments with high Z atoms as model experiments for the vacuum breakdown as the ultimate goal.

Scientific impact(s):

The ultimate goal of achieving the breakdown of vacuum is of great importance, since to date it has not been achieved in large volumes with just light. Intermediate impacts include the verification of ionization rates of high Z atoms by ultrahigh intensity lasers.

Broader impacts:

Some of the basic physics problems include the possibility of an ultra-high luminosity low energy γ-γ collider [25] and laboratory astrophysics [26,27]. The many applications include the efficient generation of radioactive isotopes needed for medical imaging, high brilliance neutron and positron beams and nuclear assay [28].

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Laser-Matter Interactions at the Intensity Frontier
Working Group: HFP/QED

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High-intensity laser pulses can be used to test predictions of quantum electrodynamics. The nonlinear coupling that appears at high field strength can lead to a variety of phenomena. We suggest combinations of electron and/or high-intensity optical beams to explore a number of non-linear effects: Thomson/Compton scattering, radiation reaction and photon-photon scattering.

I. NONLINEAR THOMSON AND COMPTON SCATTERING IN LONG, INTENSE PULSES

A. Scientific goal

When electrons (charge e, mass m_e) interact with a laser beam of high intensity, multi-photon interactions between the electron and the laser lead to the emission of a non-laser photon with a characteristic frequency spectrum. The outgoing electron spectrum complements that of the photon: the light-front (longitudinal) momentum lost by the electron is gained by the photon and vice versa. The theory of strong-field quantum electrodynamics (QED) (reviewed e.g. in [1, 2]) predicts that the resulting spectra depend sensitively on the parameters involved [3], in particular the dimensionless laser amplitude, $a_0 = eE/m_e\omega$, where E and ω are the ambient laser electric field and frequency, respectively. We propose to measure this intensity dependence as precisely as possible, both in the classical (Thomson) and quantum (Compton) regimes. Which of the two is realised, is controlled by the initial electron energy, that is its gamma factor, γ_e. As a rule of thumb, for collisions with optical laser photons, the quantum regime is reached for $\gamma_e \gtrsim 10^3$, i.e. electron energies above 1 GeV [4]. (The transition between the two regimes is a research field in its own right, see Section II.)

The experimental study of the intensity dependence is still in its infancy [5–8]. The interpretation of results is made difficult by the fact that there is not much of a theory that goes beyond modelling the laser beam as a plane wave field. While theoretical efforts to overcome this problem are ongoing [9, 10], we suggest to turn the current limitation into a virtue: as nonlinear Thomson/Compton scattering is very well understood for the plane wave model, the laser beam used for the experiments should resemble a plane wave as much as possible. In this way, the detailed predictions available could be tested with high accuracy. Of particular interest are the red-shift of the linear Compton edge due to the intensity-dependent electron mass-shift [11], the positions and widths of the spectral lines, and features associated with the pulse envelope [12], and the dependency of photon polarisation [13, 14] as a_0 is varied. For instance, when $a_0 = 2\gamma_e$, the theory predicts an approximate line spectrum with vanishing widths [3].

B. Tools required

To make the plane wave model an approximate reality requires a high-intensity laser with long pulse duration and moderate focussing, but still capable of reaching intensities well above $a_0 = 1$. To test the dependence on a_0, it must be possible to achieve stable values for a_0 and fine-tune these over a useful range, say $0.1 < a_0 < 100$. On the electron side, one would want a stable beam with little energy spread and, ideally, the possibility to change the electron energy, say in the range of $10^2 < \gamma_e < 10^4$. This could be achieved with laser wake-field acceleration.

C. Scientific impact(s)

A successful experimental campaign along the lines above would confirm the validity of the current theory of high-intensity QED based on the plane wave model. It would form a solid base and motivation to then go beyond, both theoretically (e.g. by employing new numerical techniques) and experimentally (with increased focussing and reduced pulse duration).

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D. Broader impacts

The research proposed is of a fundamental nature. It will certainly hone both the analytical and practical skills of the scientists involved. There is some theoretical overlap with the physics of synchrotron radiation and wigglers/undulators which also generate radiation (spectra) through controlled acceleration of charges in electromagnetic fields, albeit of different type.

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II. QUANTUM RADIATION REACTION IN SHORT, INTENSE PULSES

A. Scientific goal

Recent experiments have observed QED effects in the collision of high-energy particles with high-intensity laser beams [1, 2]. These experiments, which marked a turning point for the research field, have in particular allowed the observation of 'radiation reaction' effects, that is, both the emission of high-energy radiation from accelerated particles, and the corresponding recoil on those particles due to the emission.

Radiation reaction provides an ideal testing ground for the study of non-perturbative phenomena [3] and the transition from classical to quantum physics; the reason is that classical radiation reaction has well-known unphysical properties, which can only be properly resolved by the inclusion of quantum effects. There is thus significant interest in accessing experimental regimes where quantum effects become more prominent [4].

B. Tools required

Increased laser intensity allows access to novel, even counter-intuitive, charge dynamics [5]. The combination of *high laser field strength and short pulse duration* offered by multi-petawatt systems can bring us closer to the regime in which purely quantum radiation reaction effects appear, including straggling [6] and quenching [7]. Here the fundmanentally probabilitistic, or stochastic, nature of quantum mechanics becomes manifest.

C. Scientific impact(s)

An improved understanding of radiation reaction, through precision experimental measurements, has implications for understanding high intensity quantum behaviour, which is a topic of significant current interest. It has been conjectured that a new, fully non-perturbative, regime of QED can be accessed using intense electromagnetic fields [8], the physics of which is currently inaccessible even theoretically. It has however recently been shown that proper inclusion of radiation reaction effects, even classically, is crucial for understanding this non-perturbative regime [9].

D. Broader impacts

Radiation reaction effects can be significant in diverse situations where e.g. strong fields lead to hard acceleration gradients. Examples include magnetar environments, heavy-ion collisions, and the collision point of high-bunch-density accelerators. Even if these environments are physically quite distinct, the underlying fundamental physics of radiation reaction, and the theoretical tools needed to model it, are common to all.

As such the continued theoretical and experimental study of radiation reaction in strong laser fields can have an impact on understanding a broad range of effects in various physical scenarios.

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III. PHOTON-PHOTON SCATTERING USING INTENSE LASER PULSES

A. Scientific goal

The fact that real photons can scatter off one another is a prediction from the early days of QED [1]. Photon-photon scattering has no classical analogue: it is a purely quantum phenomenon. Recent experiments at ATLAS have demonstrated this phenomenon using photons of low virtuality in ultra-peripheral collisions of heavy ions [2], but the observation that this occurs with real photons, has still yet to be made. One reason for this is the very small cross-section of the process when the centre-of-mass energy is much lower than the electron rest energy. One way to compensate for the rarity of events, is to use the high flux of photons provided by high-power optical laser pulses. By combining such laser pulses, a variety of phenomena can arise out of photon-photon scattering, such as: helicity flipping (vacuum birefringence) [3–5], frequency shifting [13], vacuum diffraction [8, 12] and reflection [6] (a more in-depth review can be found here: [11]). In particular, to maximise the discovery potential of such an experiment, one could perform the simultaneous measurement of, polarisation, momentum (scattering angle) and energy. It was shown by a basic calculation in [7] and more recently refined to focussed pulses with temporal envelopes in [9, 10], that by using at least *three* laser pulses, photons could be scattered into: i) a direction; ii) a polarisation and iii) a frequency, which is distinct from the background pulses. The EP-OPAL proposal would provide an ideal facility in which to perform such an experiment.

B. Tools required

An example three-pulse set-up is demonstrated in Fig. 1.

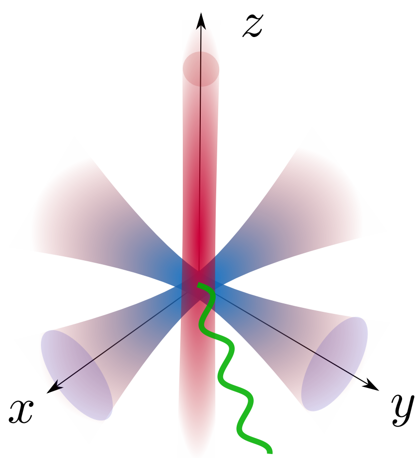

FIG. 1. A collision of three laser pulses can yield a signal of photon-photon scattering with a different scattering angle, frequency and polarisation. One example choice of wavevectors of the three laser pulses, k_1, k_2, k_3 and the signal, k', is given by

$$k' = \omega(3, 2, 2, -1)$$

$$k_1 = \omega(1, 0, 0, 1)$$
$$k_2 = 2\omega(1, 1, 0, 0)$$
$$k_3 = 2\omega(1, 0, 1, 0)$$

In order to calculate the scattered photon signal, an analysis based upon the Heisenberg-Euler Lagrangian, e.g. as performed in [9, 10], would suffice. Since the calculation can be phrased in the form of an integral, a numerical code would be a useful tool for calculating various configurations of the experiment. A full simulation that numerically solves differential equations would not be required for the signal. However, sources of background would be important to understand, and existing codes that calculate this, including e.g. GEANT4, would be useful.

In terms of experiment, the ability to measure the polarisation of few numbers of optical photons as well as their frequency would be necessary in order to combine the signals (polarisation, scattering angle and frequency) to confirm this effect.

C. Scientific impact(s)

A positive measurement of real photon-photon scattering would be a confirmation of a long-standing prediction of QED. It would provide experimental justification for the use of effective field theory methods to describe vacuum polarisation phenomena. Photon-photon scattering can be viewed as a process which becomes increasingly important, the more intense the laser pulses are that collide. Therefore, in order to fully understand collective phenomena at higher intensities, such as the development and control of QED cascades, photon-photon scattering and vacuum polarisation in general, is an important step.

D. Broader impacts

In the wake of the ATLAS experiments results, bounds were derived on physics beyond-the-standard-model (BSM) [14] employing the fact that many BSM models include a coupling to photons. Therefore, in the internal loop that couples the incoming and outgoing photon states, it is possible that BSM particles could couple and hence affect the total cross-section of real photon-photon scattering. A deviation from the QED prediction would therefore serve as *indirect* detection of BSM physics.

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Positron detection for plasma and field diagnostics in high-power laser-solid interactions

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Recent developments of powerful lasers allow us to achieve peak intensities where quantum electrodynamics starts to play an important role in the particle motion. The photon emission by relativistic electrons, crossing the field of a well-focused petawatt laser pulse, becomes non-classical and new effects have to be taken into account, such as radiation reaction or electron-positron pair creation. By detecting these energetic particles we can infer the actual laser intensity at the source where they were generated. This would allow the online, real-time measurement of laser intensity during the laser-plasma interaction which is not possible by other means.

Scientific goal: A simple diagnostic is needed to estimate laser pulse peak intensity during the experiment at full energy level near the area of ultra-intense laser-target interaction. Usually, the peak intensity in focal spot is determined from separately measured characteristics at significantly lowered pulse energy and may differ from the real maximal intensity due to several reasons. Some techniques for the characterization of laser parameters have been already proposed [1], however, they do not determine laser parameters in focal volume, thus there is an important task to find some method to determine laser peak intensity. Different indirect peak intensity diagnostics were already proposed, which is connected to laser ionization of noble gas in focal volume [2]. Others used laser pulse backscattering on a fast electron beam [3]. The method proposed in [4, 5, 6] is based on the measurement of energy spectrum of electrons, directly accelerated by a laser pulse from rarefied gas or an ultrathin foil in the beam waist. This allows one to directly connect laser pulse parameters to electron angular-spectral distributions. At ultrahigh intensity (> 10^{22} W/cm^2) this technique can not have a high accuracy mainly because of the radiation reaction, or photon recoil, which is less important in pair creation.

Recently [7], we proposed a simple diagnostic method of the laser intensity based on detecting the number and angular distribution of positrons generated from thin foil, which is usual target in many experiments. A moderate intensity laser pulse, or a prepulse, can produce the desired density distribution at the surface of a flat foil target. In such medium the electrons are directly accelerated by the field of focused ultra-intense laser pulse, which at some point gets reflected in the overdense region of the expanded plasma. In contrast with previous works, in our scheme a single laser pulse is sufficient to generate pairs instead of two counter-propagating pulses [8].
The dominant process responsible for pair creation in our conditions is the multiphoton Breit-Wheeler process which has a very sharp intensity treshold slightly above I = 10^{22} W/cm^2. Below this threshold no pairs are created and above the number of pairs increases extremely fast with laser intensity. This sensitivity of detectable positron number on laser intensity makes this diagnostic very precise.

Tools required:

A proof-of-principle experiment would require a prepulse which is responsible for the generation of a preplasma at the target front side with an exponential density scale length (L_n) equal to the half of the plasma wavelength [9]. The control of the preplasma scale length could be achieved by employing a longer pulse with lower intensity (∼10^{18} W cm^{-2}) or by controlling the prepulse which heats up the target surface and initiates the expansion. A contrast ratio on the order of 10^{-5} is sufficient for this purpose. If the isothermal semi-infinite plasma expansion model [10] is used, then the prepulse duration can be estimated as $t_p \approx L_n \sqrt{m_i/(ZT_h)}$, where T_h is the temperature of hot electrons generated by this laser pulse and m_i, Z are the ion mass and charge state, respectively. For the gold target and for 250 keV electron temperature the prepulse duration would be ≈500 fs. The dependence of the positron generation on the preplasma scale length has been studied in Ref. [9].

The main pulse, with petawatt (PW) power, will interact with a performed plasma at the target surface. The angle of incidence should be close to 30 degrees and P-polarization is recommended for more efficient electron acceleration. Tens of femtoseconds FWHM pulse duration is sufficient to generate high number of GeV electrons, which will interact with the reflected laser pulse. Analytical and numerical modeling of this process is presented in Ref. [9]. This concept is further developed in Ref. [7], where the intensity-dependent positron yield is derived analytically.

In experiments, it is important to know the propagation direction of particles in order to place the detector at the right position. Due to the high nonlinearity of the proposed three-step-process (electron acceleration, photon emission, pair creation) it is not possible to precisely predict the angular distribution of positrons. However, with the help of an analytical model the average angle of the observed non-trivial positron emission at the rear side of the target can be described by Eq. (5) from Ref. [7]. It is more advantageous to place the detector at ≈ 80 degrees with respect to the laser propagation direction because more positrons will propagate in that direction with lower energy (~ 100 MeV). Another important aspect, which must be taken into account for successful detection, is the aperture of the detector and its distance from the target. Since the number of positrons is quite limited, the detector should be placed close enough to be able to capture from an angular interval between 70° and 90° , where about 30 % of the positrons are collimated, according to [9]. A well calibrated electron spectrometer [11] could be used to separate the positrons originating from different laser cycles. From each cycle, where the intensity is high enough, different positron energy distributions are generated which could give information about the temporal shape of the laser pulse near the peak intensity. The measurement of laser intensity in the case of even higher power (> 10 PW) should be possible for incident angles larger than 20° . The nearly normal incidence introduces the possibility of cascades, which are difficult to control [12]. The overlap of incident and reflected fields should be limited in time and space in order to avoid the development of cascades and the abundant amount of positrons and to make use of the sub-cycle model presented in [7].

Due to the probabilistic nature of the quantum processes an improved statistical approach has been developed and implemented in the EPOCH code [9]. This allows the usage of moderate number of pseudo-particles in simulations, thus even 3D modeling is possible. This approach has been used in Ref. [13] as well for more accurate characterization of the generated photon and positron bunches.

Scientific impact(s):

The experimental realization of the proposed scheme would lead to the development of an in-situ measurement technique which enables the precise measurement of the peak intensity of a focused laser pulse with PW power. This would allow the better understanding of other mechanisms, for instance ion acceleration, which take place in such laser-foil interactions. On the other hand, the multiphoton Breit-Wheeler process is a fundamental high-field phenomena,which, to the best of our knowledge, so far has not been observed in laboratory overdense plasma physics. We are convinced that the proposed experiment can have an impact in the development of new QED theories, or in the confirmation of existing ones.

Broader impacts:

In the current work the probability of pair production is carried out in the local constant field approximation (LCFA), i.e. the background field is regarded as constant crossed field. However as several authors reported, see e.g. [14], the production rate may be enhanced due to the finite extent of laser field. Therefore the finite size effects should be taken into account in order to increase the accuracy of this method. These represent the basis for future research. At the ELI-ALPS facility the currently constructed PW laser system will provide pulses with less than 20 fs, which can be a promising candidate for testing those finite pulse effects. With a different target design [13] the generated positron bunches can be used also in attosecond physics as special diagnostic tools due to their ultrashort duration.

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Title: Improving Performance of Inverse Compton Sources in High-Field Regime via Laser Chirping

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Working Group(s): PAALS: Particle Acceleration and Advanced Light Sources

Abstract: When inverse Compton scattering occurs at high laser field strengths (amplitude of the normalized vector potential $a_0 \gg 0$), there is *ponderomotive* line-broadening in the scattered radiation [1]. This broadening, accompanied with the significant reduction of the spectral brilliance, is so deleterious that most inverse Compton sources (ICS) either remain at low laser intensities or pay a steep price to operate at a small fraction of the physically possible peak spectral output. In Ref. [2], we showed that the ponderomotive broadening can be eliminated by suitable longitudinal chirping of the incident laser pulse. The non-linear shape of the optimal chirping function makes it unlikely implementable experimentally. However, we suggested a practical realization of this compensation idea in terms of a chirped-beam-driven free electron laser oscillator configuration and showed that significant compensation can occur, even with the imperfect matching to be expected in these conditions. Furthermore, our recent, yet unpublished, study revealed that a substantial return in the bandwidth reduction and increase in peak spectral brilliance can occur even for a simple saw-tooth chirp, where the pulse is linearly chirped up from the front to the middle of the pulse and then linearly chirped down from the middle to the back. We propose a set of experiments to test the theoretically-predicted improvements in performance of the ICS operating in the high-field regime accomplished by our laser chirping technique. Demonstrating improvements even close to those theoretically predicted would lead to the technique's widespread adoption for existing and future ICS operating in the high-field regime.

Scientific goal: We are keenly aware that for this still-theoretical idea of laser chirping to take root, it needs to be experimentally tested. This is what we propose to our experimentalists colleagues to do – to test the improvement in the performance of ICS when the laser pulse is appropriately chirped. Experimentally what this may require, we are not sure. This is a question for laser experts, which should play an integral part in this proposal. As theorists, the best that we can do is convince our experimentalists colleagues that this experiment is worthwhile. We proceed to do that in the next couple of paragraphs.

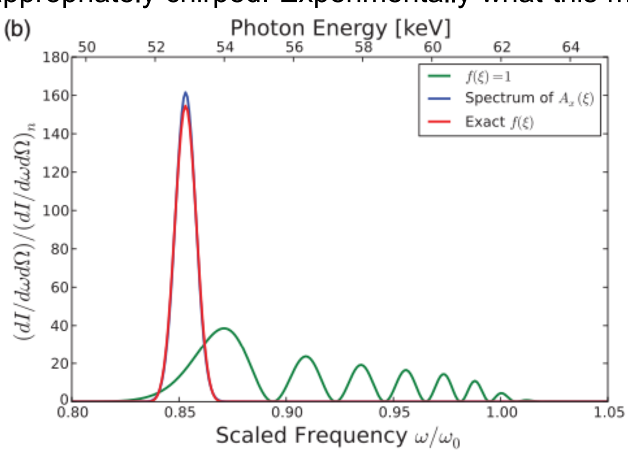

Figure 1: Unchirped (green) versus chirped (red) spectrum for ICS with $E = 51\,\mathrm{MeV}$ and $a_0 = 0.587$. Transform-limited spectrum (best physically possible) is shown in blue [2].

In Ref. [2], we showed that the optimal frequency modulation can perfectly restore the scattered bandwidth and peak spectral density. This is illustrated in Fig. 1: the undesirable effects of ponderomotive broadening, reduced peak spectral density and the non-linear subsidiary peaks resulting from a unchirped laser in high-field regime (green line) is perfectly compensated with optimal chirping (red line), all the way up to the best physically allowed scenario: transform limit (blue line). The increase in peak spectral density of scattered radiation from an ICS with a chirped versus unchirped laser is substantial, and it grows with the strength of the laser field. It stems from our finding [3], illustrated in Fig. 2, that for the unchirped laser pulse, in the linear regime ($a_0 \lesssim 0.2$), peak spectral density scales as the strength of the laser field squared ($\propto a_0^2$), while in the non-linear regime ($a_0 \gtrsim 0.2$), it scales only linearly with the strength of the laser field ($\propto a_0$). Laser chirping improves the scaling of the peak spectral density with the laser pulse substantially: optimal chirping almost perfectly recovers the square dependence ($\propto a_0^{1.9}$), while even simpler RF chirping does quite well ($\propto a_0^{1.7}$). Our preliminary studies reveal that similar type of return is likely possible with a simple saw-tooth chirping prescription. In any case, the improvement is likely to be quite substantial, exceeding an order of magnitude for medium-to-substantial laser field strengths.

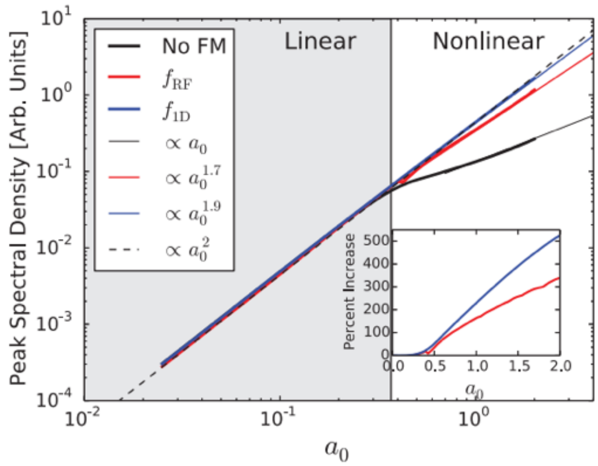

Figure 2: The peak spectral density of as a function of the field strength a_0. Spectra for an unchirped (no frequency modulation – "No FM") laser are shown in black, for a perfect chirp in blue, and for an RF chirp in red [3]. $E = 23$ MeV and $\lambda_0 = 800$ nm, $\tau = 15$ fs.

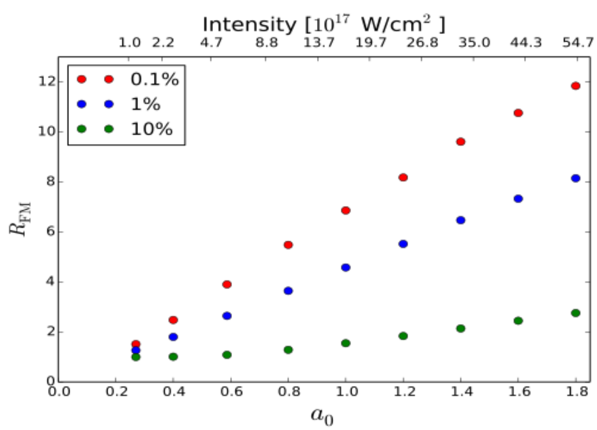

Figure 3: Peak spectral density from an ICS using an optimally chirped laser pulse, normalized to that of the non-chirped pulse as a function of the intensity (and the amplitude of the normalized vector potential a_0). Gaussian laser pulse is used with $\lambda = 1$ µm and an electron beam with $E_e = 163$ MeV and 0.1% FWHM energy spread (red dots), 1% (blue) and 10% (green) [4].

In Ref. [4], we demonstrated that the chirping of laser pulses in Compton sources at high laser intensities: (i) enables the use of higher order harmonics, thereby reducing the required electron beam energies; and (ii) increases the photon yield in a small frequency band beyond that possible with the fundamental without chirping. *This combination of chirping and higher harmonics can lead to substantial savings in the design, construction and operational costs of the new Compton sources*. This is of particular importance to the widely popular laser-plasma accelerator based Compton sources, as the improvement in their beam quality enters the regime where chirping is most effective. The effects of laser chirping on peak spectral density are substantial, as illustrated in Fig. 3.

Tools required: We envision closely working with the laser experts on carrying out the proposed activity. We have the requisite theoretical and computational tools [3] which are able to accurately simulate radiation spectra from collisions electron beams with arbitrarily chirped laser pulses. The project will have two stages:

Stage 1: Proof-of-concept for non-linear laser chirping. This stage requires a laser operating in the non-linear, high-field regime where $a_0 > 0.2$ (or intensity $I > 10^{17}$ W/cm^2). Chirping is more easily implementable when the laser pulse length contains multiple cycles $c\tau/\lambda_0 \gg 1$, where τ is the pulse duration, c the speed of light and λ_0 the laser wavelength. The crux of this stage would be for the experimentalists to assess whether non-linear chirping is possible. Any type of laser chirping where the pulse is chirped up from the front to the middle of the pulse and then chirped down from the middle to the back achievable in the lab will impact the scattered spectrum. Our group at Old Dominion

University would provide analytic and computational support – we can compute the impact of the experimentally-implemented chirp on the eventual radiate spectra from ICS.

Stage 2: Proof-of-concept ICS with a non-linearly chirped laser. This stage requires the integration of the chirped laser implemented in Stage 1 into a ICS: colliding the chirped laser with an electron beam. The requirements for the electron beam are not at all stringent. Even a laser plasma wakefield-produced electron bunches would serve the purpose, provided that the energy spread is below few percent [4].

Parameters required for the experiment, or technical requirements/abilities of modeling tools, or theory development. Identify any facility/diagnostic/code developments that need to be made to achieve the goal.

Scientific impact: The impact of the proposed effort would be substantial improvement in the performance of ICS operating in the high-field regime. Ultimately, it would contribute to making ICS of x-ray radiation an accessible, low-cost alternative to billion-dollar synchrotron machines.

Broader impacts: Proliferation of ICS into hospitals, industrial laboratories, and universities would have profound global impact. In medicine, x-ray dose could be reduced by orders of magnitude with dramatic improvements in imaging modalities and detectability of soft tissue structure including tumors. New cancer treatments modalities would be possible. In industry, it would speed-up drug discovery. In chemistry, biology and materials sciences it would enable ultrafast x-ray diffraction to understand structural changes on a femto- and picosecond time scales.

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Advanced Concepts for Monoenergetic γ-Ray Generation using Nonlinear Compton Scattering

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Abstract

Multi-PW lasers enable compact high, charge electron beams with GeV energies based on the LWFA approach and also provide high energy laser pulses required for an intense Inverse Compton Scattering (ICS) source. This combination forms the basis for narrow-band, highly efficient Inverse Compton scattering (ICS) sources in the hard X-ray regime opening the door to single shot measurements of ultrafast events in wide range of photon energies.

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The Inverse Compton Scattering (ICS) of laser light off high-energy electron beams is a well-established source of keV to MeV X- and gamma-rays for applications in medical, biological, and material sciences, and for nuclear physics. GeV photons could be used for high-precision pair production studies in strong-field QED [1] as well as nuclear and quark-gluon physics [2]. The main advantages of ICS photon sources is the possibility to generate, collimated, ultrafast, tunable, and narrowband MeV and GeV photon beams. Intense lasers interacting with the electron beam allow large numbers of photons - in the range of one photon per electron - to be produced. Until recently the high intensity lasers and thus photon emission rates approaching a photon per electron and narrow band emission contradicted each other.

This is due to the dependence of the emitted wavelength on the instantaneous laser strength parameter a_0 with the frequency of the Doppler-upshifted photons approximately given by

$$\omega = \frac{4n\gamma^2\omega_L}{1+\gamma^2\theta^2+a_0^2/2+4n\gamma\omega_L/m}\,,$$

where ω_L is the laser frequency, γ is the Lorentz factor of the electron beam, θ the scattering angle, m is the electron mass, and a_0 is the normalized vector potential. We use units in which $\hbar = c = 1$.

Apart from upshifting of the scattered radiation frequency, there is also the emission of higher harmonics n, and an intensity-dependent red-shift, which can be understood by a longitudinal dephasing due to the $\mathbf{v}\times\mathbf{B}$ force [3]. This ponderomotive slowdown of the electron relative to its initial velocity inevitably broadens the spectral lines of the backscattered harmonics.

This imposes limitations for generation of monoenergetic gamma-rays using ICS, and usually the emitted radiation is broadband, at high laser intensity when $a_0 > 1$ [4]. Operating narrowband ICS at high intensities requires additional efforts. Several schemes for the compensation of the nonlinear spectral broadening - for example by controlling the chirp of the laser - have been developed and investigated theoretically and pave the way to bright, narrowband ICS soruces and overcoming the past limations.

For instance it has been shown that by properly chirping the scattering laser pulses the ponderomotive a_0-dependent broadening of the backcscattered radiation can be compensated [5, 6, 7, 8, 9]. If the instantaneous laser frequency follows the laser pulse envelope proportional to the local intensity $\omega_L(\varphi) \sim 1 + a(\varphi)^2/2$ then the non-linear broadening is perfectly compensated for on-axis radiation. The synthesis of properly chirped pulses by spectral phase interferometry has been investigated [10], which allows to adjust the temporal pulse shape and the local laser frequency simultaneously to fulfill the compensation condition.

In close analogy to the natural focusing and universal diffraction patterns near optical caustics one can apply the theory of singularities of differentiable projection maps—also called catastrophe theory—to the inverse Compton scattering process. Higher dimensional caustics can lead to a the *spectral focusing* of the backscattered radiation to narrow peaks determined by higher dimensional stationary points of the corresponding phases of the transition amplitudes describing the radiation generation process [11].

Polarization gating techniques, which have been used before for instance in high-harmonic generation on solid density targets [12], could offer the opportunities to generate MeV frequency combs [13]. Moreover, the use of electron beams with a correlated energy spread to reduce the ICS spectral bandwidth has been proposed [14].

These and similar concepts harnessing all degrees of freedom such as the chirp, polarization, orbital angular momentum and other complex properties of the involved particles and beams should be developed further to achieve a new class of radiation source. Multi-petawatt lasers offer the opportunities to implement such narrowband MeV and GeV photon sources in an all-optical set-up. High laser power allows to generate multi-GeV electron beams with LWFA and very high beam charge, thus brighter photon beams. This would allow single-shot experiments to be performed with ultra-short, narrowband high-intensity photon beams.

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MP3 White Paper 2021
Experimental observation of induced Compton scattering

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Abstract: Induced Compton scattering (ICS) is a nonlinear interaction between intense electromagnetic radiation and a rarefied plasma. Some astrophysical phenomena, such as pulsar and fast radio burst, are potential sites at which ICS occur in nature, although ICS signatures have not been discovered so far because we still do not possess a concrete understanding of such nonlinear plasma interactions. Here, we propose an experimental demonstration of ICS in laboratories with the high-power lasers. The outcomes of this experiment can be a unique tool to study the pulsar magnetosphere, i.e., diagnosing a physical condition of the magnetosphere. ICS would also be a process to accelerate the scatterer electrons to relativistic energy and then be used as an electron accelerator.

Scientific goal:

The first discovery of a neutron star was made unexpectedly by radio observation, eventually named radio pulsars [1]. Because neutron stars are so compact, the radio emission mechanism must be a coherent process so that pulsars are laser transmitter in nature. Such a coherent radio emission has also been found from recently identified another class of object called fast radio bursts [2,3]. The mechanism of the coherent radio emission is a long-standing mystery of astrophysics, and we do not even know what kind of a physical situation can be realized around the emission region. Observations of pulsars themselves and also their surroundings in other wavelengths independently suggest that the pulsar magnetosphere is filled with strongly magnetized electron-

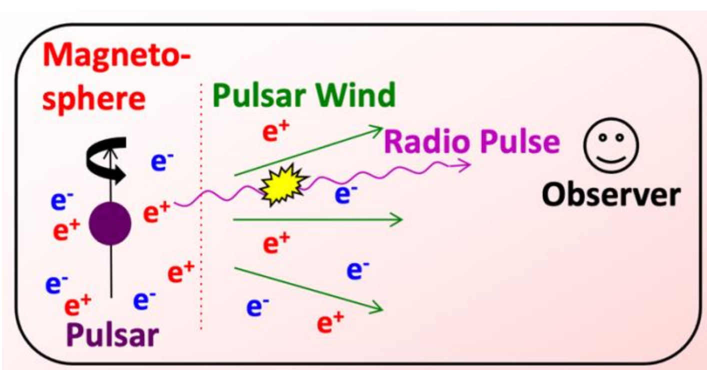

Fig. 1. Schematic picture of the induced Compton scattering at pulsar a magnetosphere. The pulsar magnetosphere is filled with electron-positron pairs and they are blown away from the pulsar by centrifugal force as a pulsar wind. The radio emission from the pulsar itself would interact with the pulsar wind plasma.

positron pair plasma. Quantum and also relativistic plasma dynamics is expected to play a role in the radio emission [4].

Induced Compton scattering (ICS) is one of nonlinear interactions between the bright radiation and plasma [5] expected to occur in the surroundings of pulsars and fast radio bursts [6] (Fig. 1). The scattering probability of ICS is amplified compared with (spontaneous) Compton scattering or Thomson scattering by a factor of $k_B T_b / m_e c^2$, where T_b is the brightness temperature of the radiation. The amplification factor can be much larger than unity for the above astrophysical situations and also for the laser facilities on the Earth. However, we still do not identify a consequence of the scattering. We recently predicted theoretically a characteristic signature of ICS in a spectrum of the scattered radiation [7] (Fig. 2) and the signature can be observed experimentally with the use of current short-pulse lasers [8]. First of all, we are going to demonstrate ICS with the use of a 1 PW laser. Then we explore a nonlinear phase of the interaction and application to astrophysics by using a higher-power laser.

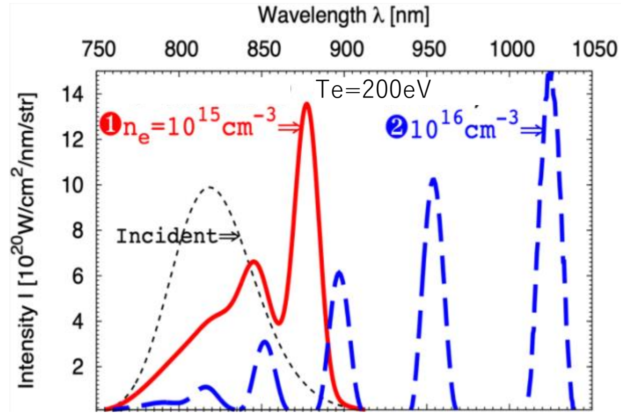

Fig. 2. Predicted spectra for a PW laser experiment, where the dotted black line is incident spectra, the red solid and blue dashed lines are spectra of scattered radiation taken from [7].

Tools required: Considering ICS at the Rayleigh range of a Gaussian beam, the scattering optical depth for ICS is

$$\frac{\tau_{\rm ICS}}{n_{\rm e}} = \frac{3}{16\pi^3}\sigma_T \frac{E_0}{\Delta t \Delta\nu m_e c^2}\frac{\lambda_0^3}{w_0^2}, \quad (1)$$

where $n_{\rm e}$ is the density of the scattering electrons, σ_T is Thomson cross section [8]. All the values on the right-hand side of equation (1), the total energy (E_0), central wavelength (λ_0), spectral width ($\Delta\nu$), pulse width (Δt), minimum beam waist (w_0), are the laser parameters. We require $\tau_{\rm ICS} > 1$ to observe the characteristic ICS signature (Fig. 2). Equation (1) is valid when the spectral width is greater than the Langmuir plasma frequency [9], i.e.,

$$n_{\rm e} < 6\ \times 10^{18}\ {\rm cm}^{-3}\ \left(\frac{\lambda_0}{820\ {\rm nm}}\right)^{-4}\left(\frac{\Delta\lambda}{50\ {\rm nm}}\right)^{2}, \quad (2)$$

so that, for $\tau_{\rm ICS} > 1$, we require short-F (small w_0), high energy laser. There is another competing (co-existing) process known as nonlinear Thomson scattering (NTS) whose optical depth is the Thomson optical depth multiplied by the square of the laser strength parameter, $a_0^2 \propto \lambda_0^2 E_0/\Delta t w_0^2$ [10], and then we obtain

$$\frac{\tau_{\rm ICS}}{\tau_{\rm NTS}} \approx 5\times 10^8 \left(\frac{\lambda_0}{820\ {\rm nm}}\right)^{4}\left(\frac{\Delta\lambda}{50\ {\rm nm}}\right)^{-1}\left(\frac{w_0}{1\ \mu{\rm m}}\right)^{-2}. \quad (3)$$

Considering other constraints, $\tau_{\rm ICS} > 1$ is marginal for the current high-power laser facilities, e.g., PW-class lasers. Higher energy (E_0), longer wavelength (λ_0), smaller F number (w_0) facilities can explore the frontier of ICS.

The target is an electron gas of $10^{15-18}\ \mathrm{cm}^{-3}$ and the gas jet target can be used. The element of the gas is not specified. The high contrast laser is favored in order for electrons at Rayleigh range not to be blown away.

The main diagnostic tool is a spectrometer. We need spatially resolved spectroscopy of the scattered (transmitted) laser radiation in order to specify the characteristic signal of ICS [7] (Fig. 2). The density of electron gas can be measured by interferometry or collective Thomson scattering measurements. We also obtain the temperature of the scattering electrons from collective Thomson scattering measurement. Because ICS is an additional scattering process to Thomson scattering of electrons, ICS induces an additional radiation pressure force to electrons and then electrons can be accelerated to relativistic energy. Calorimeter to measure the energy of electrons is also required in this purpose.

Scientific impact(s):

In order to identify the mechanism of the coherent emission from pulsars and fast radio bursts, we need to find a physical condition of an emitting region. The characteristic signature of the scattered radiation of ICS can be a unique tool to explore the physical condition of the emitting region. This will be a completely new approach to study the pulsar magnetosphere.

In the nonlinear phase of ICS, the backreaction of the scatterer, i.e., electrons, must be important and would change the predicted characteristic signature of ICS.

Broader impacts:

After the demonstration of ICS, further studies of the backreaction should be conducted both in experimentally and theoretically. In ICS, photons always lose their energy while electrons gain their energy by Compton recoil. ICS can more efficiently push electrons than Thomson scattering and then the electrons could be accelerated to relativistic regime by induced radiation pressure. This is a new acceleration process of electrons.

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Co-location of a multi-petawatt laser with an x-ray free electron laser (HFP/QED)

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The co-location and synchronization of a multi-petawatt laser with an x-ray free electron laser will facilitate worldwide unique pump-probe type experiments of quantum vacuum signatures, such as vacuum birefringence and x-ray photon scattering, at unprecedented accuracy. As signatures of quantum vacuum nonlinearity typically scale with positive powers of the peak field of the pump, the higher its intensity the larger the signal and the less laser shots are needed to achieve decent statistics. This will allow for the quantitative analysis of the long-standing prediction of vacuum birefringence arising from the leading vacuum-fluctuation-mediated effective coupling between four fields within quantum electrodynamics (QED). Moreover, it even has the potential to enable probes of quantum vacuum nonlinearity beyond leading order, and thus pioneer precision tests of QED in an uncharted regime.

I. SCIENTIFIC GOAL

Recent advances in laser technology open up the possibility to address fundamental physics questions at the high-intensity frontier. A particularly promising research opportunity will be the study of vacuum-fluctuation-mediated light-by-light scattering phenomena predicted by quantum field theory in controlled laboratory experiments. These provide classical Maxwell theory with nonlinear corrections.

The effective nonlinear interactions between macroscopic electromagnetic fields $(\vec{E},\vec{B})$ mediated by QED vacuum fluctuations are encoded in the renowned Heisenberg-Euler effective Lagrangian [1–3]. The latter can be expanded both in powers of $\{\vec{E}/E_{\rm cr},\, c\vec{B}/E_{\rm cr}\} \ll 1$, with critical electric field $E_{\rm cr} = m_e^2/e \simeq 1.3\times10^{18}\,{\rm V/m}$ (m_e is the electron mass), and in powers of the fine-structure constant $\alpha = e^2/(4\pi) \simeq 1/137$ counting the number of loops ℓ of the constituting Feynman diagram,

$$\mathcal{L}_{\rm int} = \frac{m_e^4}{360\pi^2}\Bigg[\underbrace{4\Big(1+\frac{40}{9}\frac{\alpha}{\pi}+\ldots\Big)}_{=:a}\frac{(\vec{B}^2-\vec{E}^2)^2}{4E_{\rm cr}^4} + \underbrace{7\Big(1+\frac{1315}{252}\frac{\alpha}{\pi}+\ldots\Big)}_{=:b}\frac{(\vec{B}\cdot\vec{E})^2}{E_{\rm cr}^4}+\ldots\Bigg]. \quad (1)$$

The leading effective interaction is a four-field coupling; the next-to-leading interaction couples six-field and is thus parameterically suppressed with $(E/E_{\rm cr})^2 \ll 1$. On the other hand, an ℓ-loop contribution to $\mathcal{L}_{\rm int}$ scales as $(\alpha/\pi)^{\ell-1}$; cf. [4].

A prominent quantum vacuum signature is vacuum birefringence [5]: as a consequence of the effective interaction of electromagnetic fields originally linearly polarized light traversing a strong-field region can pick up a small ellipticity, attributing a birefringence property to the quantum vacuum. This gives rise to signal photons $N_\perp$ scattered into an originally empty, perpendicularly polarized mode constituting the signature of quantum vacuum nonlinearity in experiment. The number of attainable signal photons [6] scales quadratically with the frequency of the probe and the intensity of the pump field, as well as linearly with the number of photons available for probing. This suggests using an x-ray free electron laser (XFEL) as probe and a high-intensity laser as pump [7]. Another advantage of using x-rays as probe is the availability of spatially-resolved single photon counting detectors.

In the past decade lots of progress was made in advancing x-ray polarimetry in the energy regime of $\mathcal{O}(10)\,{\rm keV}$ to polarization purities $\mathcal{P}$ on the 10^{-11} level [8–10]. Future high-precision x-ray polarimeters even have the potential to reach polarization purities $\mathcal{P} \lesssim 10^{-12}$ [11]. At the same time, the theoretical description of vacuum birefringence in the collision of XFEL and high-intensity laser pulses was significantly improved. It was in particular shown that vacuum birefringence in spatio-temporally inhomogeneous fields is generically accompanied by a scattering phenomenon resulting in a different far-field angular decay of the signal photons [12–14]. This scattering phenomenon is not limited to the vacuum birefringence signal, but rather amounts to a generic property exhibited by arbitrarily polarized probe photons traversing a spatio-temporally localized strong field region [15].

This can be used to improve the signal-to-background separation in experiment: the signal photons $N_p(\Omega)$ of

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polarization p emitted into a solid angle Ω are *discernible*, i.e, can be measured above the background of the driving laser photons $\mathcal{N}_p(\Omega)$ reaching the detector, if the criterion

$$N_p(\Omega) \geq \mathcal{N}_p(\Omega) \quad (2)$$

if fulfilled [16]. For instance, aiming at measuring the perpendicularly polarized mode in vacuum birefringence we have $p = \perp$ and $\mathcal{N}_\perp = \mathcal{P}\mathcal{N}$, where $\mathcal{N}$ is the total number of photons available for probing the effect [13]. For the number of signal photons attainable in a polarization insensitive measurement N one has to sum both sides of Eq. (2) over the two transverse photon polarizations, resulting in the criterion $N(\Omega) \geq \mathcal{N}(\Omega)$.

Our goal is to make use of these recent advances in both experiment and theory and bring them to fruition in a dedicated discovery experiment. While a petawatt-class high-intensity laser may be sufficient for detecting QED vacuum birefringence for the first time, only a multi-petawatt (multi-PW) pump will allow for quantitative studies of the effect with satisfactory statistics. This will enable measuring $N_\perp^{\rm dis}$ as well as $N^{\rm dis}$ emitted into a solid angle where both signals are discernible at unprecedented accuracy: for a relative angle of $\pi/4$ between the polarization vectors of the linearly polarized probe (photon energy $\omega = 12914\,\mathrm{eV}$ [8], waist $w_{\rm x}^{\rm HWHM} = 2.7\,\mu\mathrm{m}$) and pump (wavelength $\lambda = 800\,\mathrm{nm}$, pulse duration $\tau^{\rm FWHM} = 25\,\mathrm{fs}$, waist $w_0^{\rm HWHM} = 1\,\mu\mathrm{m}$) beams maximizing the birefringence signal, the integrated numbers of discernible signal photons can be estimated as [17]

$$\begin{Bmatrix} N_\perp^{\rm dis} \\ N^{\rm dis} \end{Bmatrix} \simeq \begin{Bmatrix} 7.7 \\ 6.9 \end{Bmatrix} \times 10^{-17} \times \left(\frac{W}{1\,\mathrm{J}}\right)^{2.2} \times \mathcal{N} \,. \quad (3)$$

Here, W denotes the pulse energy of the high-intensity laser, and we assumed a polarization purity of $\mathcal{P} = 10^{-11}$ for the measurement of the polarization-flipped signal. Correspondingly, for $\mathcal{N} = 10^{12}$ probe photons per shot, which amounts to a typical photon number delivered by an XFEL, and a pump pulse energy of $W = 100\,\mathrm{J}$, i.e., a $4\,\mathrm{PW}$ laser, we can expect $N_\perp^{\rm dis} \simeq 1.9$ and $N^{\rm dis} \simeq 1.7$ discernible signal photons per shot.

At the same time, the signal photon numbers scale as

$$\begin{Bmatrix} N_\perp \\ N \end{Bmatrix} \sim \begin{Bmatrix} (a-b)^2 \\ 2(a^2+b^2) \end{Bmatrix} , \quad (4)$$

with the numerical coefficients a, b of the Heisenberg-Euler Lagrangian (1). This directly implies that the experimental results for both $N_\perp^{\rm dis}$ and $N^{\rm dis}$ will allow for an individual extraction of the coefficients a and b. Standard birefringence experiments only provide access to the difference $b - a$; cf. the first line of Eq. (4).

For a sufficiently high number of repetitions of the experiment and thus large enough statistics, the co-location of a multi-PW laser with an XFEL will even facilitate measuring these coefficients at two-loop accuracy, and thus pioneer precision tests of QED in an uncharted regime.

II. TOOLS REQUIRED

The successful achievement of our scientific goal requires the close collaboration of beam scientists, computational physicists, experimentalists and theorists. This is absolutely essential for identifying the most prospective scenario for the actual experiment, taking into account all possible real-world complications such as inevitable shot-to-shot fluctuations and potential parasitic signals from residual rest gas atoms in the interaction volume of the pump and probe laser pulses as well as strategies for their evacuation. Moreover, concerted simulation campaigns of the particular scenario to be implemented in experiment are indispensable as precision tests require quantitatively accurate theoretical predictions of the signatures to be measured.

Due to the fact that both the directional emission characteristics of the signal photons and their absolute number depend sensitively on the details of the driving laser fields in the interaction region [18], diagnostics allowing to infer detailed informations about the spatio-temporal structure of the colliding laser fields for each shot would be desirable. A particularly interesting route towards achieving an improved signal-to-background separation in experiment, is the use of tailored laser beams in enhancing quantum vacuum signatures in experiment [19]: tuning the far-field and focus profiles of the driving laser beams accordingly, the signal to background separation can be significantly enhanced relatively to the estimates based on ordinary Gaussian beams quoted in Eq. (3). Implementing such tailored laser beams for quantum vacuum experiments necessitates the combination of ray tracing simulations, the measurement of far-field and focus properties as well as their controlled manipulation.

While we have already successfully developed both analytical [12–15, 19] and numerical approaches [16, 18] in this direction and exemplified their huge potential, we have not yet performed integrated simulations of an complete experiment. Achieving this requires embedding our vacuum emission solver [18] in simulation codes used to simulate other aspects of the experimental scenario, such as ray-tracing and particle-in-cell codes. Due to large computational demands of such simulations, access to high-performance computing infrastructure will be needed.

Figure 1 shows a sketch of a possible setup allowing for the head-on collision of high-intensity and XFEL laser pulses. Although XFELs provide polarized radiation, its purity is not sufficient to allow for the detection of the small vacuum birefringence signal predicted by QED. Devices that are able to detect the tiniest polarization changes are high-precision x-ray polarimeters, which we have developed in recent years [8–10]. As noted in Sec. I, these polarimeters already demonstrated polarization purities $\mathcal{P}$ on the level of 10^{-10}, and even have the potential to reach $\mathcal{P} \lesssim 10^{-12}$ [11]. Even a tiny rotation of the polarization plane of a few micro-radians induced by a sugar solution was detected using these devices [8]. Our high-

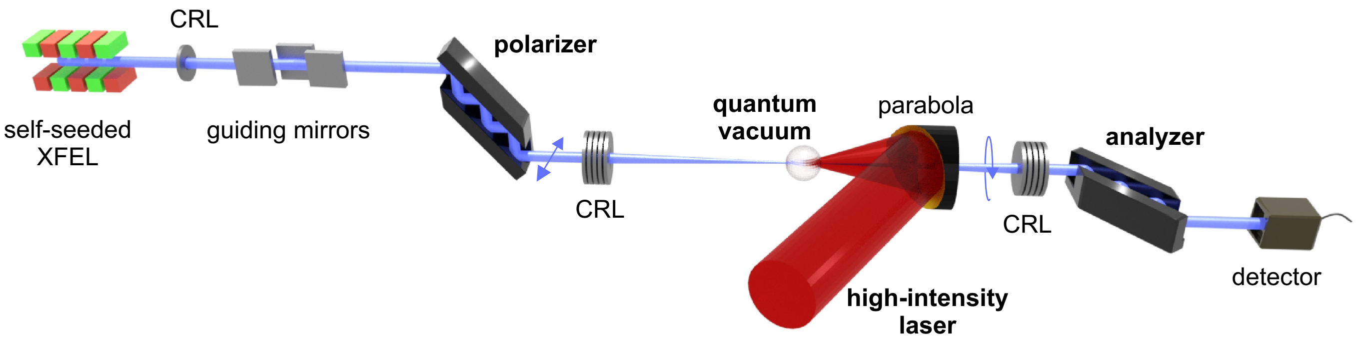

FIG. 1: Sketch of the experimental setup. The strong electromagnetic fields of a tightly focused multi-PW laser pulse induce a vacuum birefringence phenomenon, which is probed by counter-propagating XFEL pulses.

precision x-ray polarimeters base on multiple consecutive Bragg-reflections with a scattering angle of exactly 90° inside so-called channel-cut crystals. At this scattering angle the polarization component parallel to the scattering plane is suppressed with high efficiency.

In order to match the focal area of the multi-PW laser, x-ray optical components like compound refractive lenses (CRLs) are required. Since the purity of the polarization state degrades with increasing divergence [11], an additional optic behind the interaction region is needed to recollimate the beam. Both optics have to conserve the high degree of polarization. We have already successfully verified that such a focusing and recollimation scheme can be realized with amorphous lens materials, which leave the polarization unaltered.

III. SCIENTIFIC IMPACT

The quantum vacuum experiment put forward in the present contribution is expected to have a substantial scientific impact: up to date quantum vacuum nonlinearities in macroscopic electromagnetic fields, such as provided by high-intensity lasers have never be verified in a controlled laboratory experiment. Hence, a first confirmation in experiment would certainly have a huge impact. However, this might have changed when a multi-PW laser is coming online at an XFEL facility because various experimental activities are currently ongoing, cf., e.g. [20–23], and under preparation.

We emphasize that even in this case the perspectives of a precision measurement of quantum vacuum signatures enabled by the co-location of a multi-PW laser and an XFEL will make the experiment put forward in this proposal highly topical: it will enable probes of quantum vacuum nonlinearity beyond leading order ("at two loops"), and thus pioneer precision tests of QED in an uncharted regime.

Apart from that, we note the discovery potential of these kind of experiments for New Physics beyond the Standard Model of particle physics: any deviation from the Standard model prediction for the coefficients a and b of the Heisenberg-Euler effective Lagrangian could hint at the existence of new particle degrees of freedom beyond the Standard Model (BSM), such as, e.g., minicharged or axion-like particles [24–26]. On the other hand, the more precise the agreement of the experimentally determined values for a and b with the Standard model prediction (1), the more severe the constraints on the parameter space of such BSM particles.

IV. BROADER IMPACTS

Modified light propagation phenomena in the quantum vacuum subjected to macroscopic electromagnetic fields are also of substantial relevance in an astrophysical or cosmological context; cf., e.g., the recent claim of the relevance of vacuum birefringence for explaining the observed polarization degree of the light from an isolated neutron star [27]. The subsequent scientific debate [28] highlights the relevance and necessity of controlled laboratory tests of quantum vacuum nonlinearity.

Besides, the co-location and synchronization of a multi-PW laser with an XFEL will of course also open up interesting opportunities for more conventional pump-probe type experiments, such as, e.g., precise measurements of self-generated magnetic fields via Faraday rotation in high-intensity laser driven plasma [29, 30].

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High energy X-ray diagnostics for interaction of a high repetition rate multi-petawatt laser with solid targets

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Abstract: Multi-petawatt lasers being developed (or commissioned) around the world will lead to several new frontiers of physics. One of them is the generation of ubiquitous amounts of multi-MeV photons associated with the effect of radiation reaction when an intense laser pulse interacts with a solid target with a tailored pre-plasma profile[1, 2]. A measurement of high energy photons from such experiments in future will not only lead to quantify parameters of the interaction like focused intensity and electron energy distribution, but also to the development of laser based gamma ray sources for applications in nuclear physics and homeland security. This paper describes the diagnostics to measure X-ray photons with energies greater than 100 keV, i.e., above the atomic transitions, which our collaboration has focused on. It also summarizes the requirements for successful implementation of experiments utlizing these diagnostics on upcoming facilities. Special consideration is given to real time data collection and analysis from diagnostics, which makes them compatible with high repetition rate lasers.

Scientific goal: One of the primary goals of future experiments with multi-petawatt lasers will be to explore gamma-ray generation leading to radiation reaction force on electrons. The challenge for such experiments will be (a) measurement of high energy photon spectrum from the experiment, and (b) demonstrating a clear distinction from photons generated via bremsstrahlung and synchrotron effect. Presumably, such an experiment might include measuring bremsstrahlung spectrum from thick target with high atomic number as a control experiment, to compare with spectrum of photons from thin targets where the dominant mechanism would be synchrotron effect. However, photon spectrum measurements from solid target experiments is challenging. To the best of our knowledge, a spectrum (with a resolution $< 5\%$) of photons with energy greater than 100 keV has not been measured on solid target experiments, and hence there is an urgent need to develop such diagnostics.

Table 1 summarizes the energy range of some of the diagnostics being pursued by our research collaboration. It also provides a brief comment on the diagnostic. An example of filtered scintillator stack using LYSO crystal and Tungsten attenuators is shown in figure 1a. The cameras imaging the scintillators produce instantaneous data after each shot. Members of our collaboration are currently developing algorithms for reconstruction of photon temperature(s) from the data in real time. The stacks are compact and thus can provide real time estimate of photon temperature at

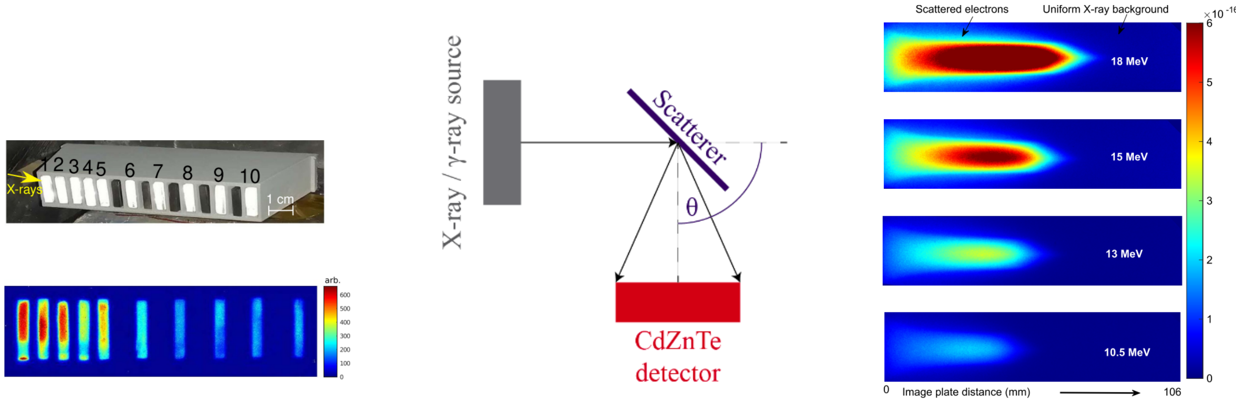
Diagnostic	Photon energy range	Comment
Filtered scintillator stacks	100 keV to 2 MeV	Image plate based spectrometers have been used on solid targets[3] and gas jet experiments[4]. Recently filtered scintillator based spectrometers were used for solid target experiments with petawatt class lasers[5, 6]. The measured signal showed good agreement with monte carlo simulations. Because of the coarse resolution of such spectrometers, reconstruction of incident photon energy distribution or laser generated electron energy distribution is challenging.
Thick single crystal sensors with sub mm spatial resolution	$50 - 1000$ keV	Pixelated detectors of CdZnTe have been used with substrates of about 1 cm thickness to measure gamma rays up to 2.6 MeV[7]. However the pixels were of the order of a mm, and thus made the detector undesirable to measure spectrum of photons. Recent upgrades to this technology has lead to sensors with pixel size of the order of 250 μm and substrates with thickness of 2 mm[8]. These sensors can detect gamma rays in a single photon counting mode upto ~ 1 MeV and have the potential of providing a high resolution photon spectrum from laser plasma experiments.
Forward Compton scattering spectrometer	$4 - 20$ MeV	A forward Compton scattering spectrometer was tested on a bremsstrahlung beamline of a linear accelerator[9]. However such spectrometers have a very low efficiency, and consequently have not been able to measure bremsstrahlung spectra from laser solid target experiments or narrow band spectrum from inverse Compton scattering[10].

Table 1: Summary of diagnostics for measuring high energy photons in the range of 100 keV to 20 MeV.

multiple spatial locations in experiments.

Compared to the scintillator stack spectrometers, pixelated high energy detectors can provide exact spectrum of photons. However, in order to work in single photon counting mode, this diagnostic will need to accumulate over several tens of shots. CdZnTe detectors with 400×400 pixels are currently available, and the high pixel count will enable us to collect more photons per shot. In order to reduce the photon flux to acceptable levels, the diagnostic will have to be setup in a Compton scattering geometry as used by Cipiccia et al. [11] (see figure 1b).

The pixelated detector or the scintillator stacks, are able to measure spectrum only up to about $1 - 2$ MeV photon energy. However, a forward Compton scattering spectrometer can provide high resolution spectrum of photons in the energy range $4 - 20$ MeV. The results from testing the spectrometer with bremsstrahlung generated from a linear accelerator are shown in figure 1c. The current version of the spectrometer utilizes imaging plate detectors, and future upgrade to active detection is planned. We tested the spectrometer on petawatt class laser systems for bremsstrahlung measurement, but no signal was measured because of the low efficiency of the diagnostic. However, we were able to demonstrate the robustness of the shielding of the spectrometer, as we measured just a handful of stray X-rays on the image plate detector.



(a) **(b)** **(c)**

Figure 1: (a) Example of a filtered scintillator stack and raw data collected by it from bremsstrahlung generated by a PW class laser[6]. (b) A possible geometry of scattered gamma ray measurement using pixelated CdZnTe detector. (c) Experimental data from testing the forward Compton scattering spectrometer on a linear accelerator[9].

Tools required: Our collaboration has performed extensive particle-in-cell simulations to estimate the relative contributions of bremsstrahlung and inverse Compton scattering[12]. For focused intensities exceeding 10^{22} W/cm^2, we expect that the photons generated by inverse Compton scattering will have an angular distribution peaking at about 30° from the laser axis, and have a temperature of a few MeV. These should be measurable with the diagnostics described earlier, but may need to accumulate data over several hundred shots for the pixelated detector and the forward Compton spectrometer. It is desirable to have a fast solid target delivery system (for e.g., a tape target) which can provide kapton targets of thickness as low as 2 μm. A space of $\sim$ 1.5 m between the laser focus to the chamber wall is desired to place the forward Compton spectrometer.

Our collaboration will continue to develop similar diagnostics and test them on upcoming multi-petawatt facilities across the world (Apollon, ELI facilities, etc.), to be useful for future operation of facilities like ZEUS and OPAL.

Scientific impact(s): High energy photon generation by the effect of radiation reaction has not been observed so far in solid target experiments. Such measurements will be able to confirm the focused intensity on target ($> 10^{22}$ W/cm^2). Such measurement will also improve our understanding of laser coupling at ultra high intensities. It should be noted that the measurement of electron spectrum in such experiments may be corrupted by the presence of sheath fields around the target, and so measured photon spectrum provides direct information of high energy electron dynamics.

Broader impacts: An increased efficiency of multi MeV gamma ray generation will lead to development of a photon source covering the giant dipole resonance for many nuclei. Consequently, it will have immense benefits in nuclear physics research and homeland security applications. The high energy photon diagnostics being developed for such experiments are motivated by detector development in the field of high energy physics. Thus, these experiments also foster fruitful cross-discipline collaborations.

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Quantum vacuum signatures in laser pulse collisions

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Nonlinear self-interactions of light are a direct manifestation of the intricate properties of the quantum vacuum. They represent a demarcation from Maxwell's classical theory of the electromagnetic field, violating the superposition principle as a fundamental property of the classical vacuum.

We propose to investigate quantum vacuum nonlinearities using collisions of high-intensity laser pulses. For such discovery experiments, several challenges have to be met: a high-degree of laser pulse control as well as spacetime-resolved signal photon detection on the experimental side, and a quantitative treatment of virtual quantum processes in realistic laser pulses and the induced signatures dynamically in space and time on the theoretical and modeling side.

Achieving the goal of a first discovery would represent an unprecedented step into uncharted territory of quantum vacuum physics at the high-intensity frontier.

I. SCIENTIFIC GOAL

In addition to the manifold applications of high-intensity lasers in basic and applied science, these new facilities open up unprecedented opportunities in fundamental physics. In comparison with many decades of research at the high-energy frontier in order to explore the elementary properties of matter and their interactions, the high-intensity frontier is coming within reach just now. Fundamental properties of matter and – most paradigmatically – the ground state of nature, i.e. the *quantum vacuum* may become testable with the aid of petawatt class lasers. Specifically the long-standing prediction of quantum fluctuation mediated nonlinear interactions of electromagnetic fields in the vacuum as described by the Heisenberg-Euler effective action [1–3]

$$\Gamma_{\rm int} = \frac{1}{360\pi^2}\frac{e^4}{m_e^4}\int (\mathbf{E}^2-\mathbf{B}^2)^2 + 7(\mathbf{E}\cdot\mathbf{B})^2 + \ldots \quad (1)$$

can become directly verifiable for the first time. This cornerstone of quantum field theory and quantum electrodynamics (QED) as the fundamental theory of light-matter interactions still awaits its fully controlled experimental discovery.

We propose a concerted development of theoretical and experimental tools with the goal to perform a designated experimental discovery campaign at future petawatt class laser facilities.

In fact, the last two decades have witnessed a substantial set of theoretical studies and proposals [4–26] suggesting to use various forms of laser pulse collisions in order to measure the vacuum nonlinearities of Eq. (1). In recent years, theoretical investigations have managed to describe these phenomena for realistic laser pulses for the first time [27–34]. Especially the vacuum-emission picture [35, 36] has become a versatile tool to predict quantum vacuum signatures from first principles. However, this theoretical advance has also revealed the relevance of the classical background to be distinguished from the desired quantum vacuum signatures. Modern theoretical studies now focus on *discernible* photons [31, 34, 37], i.e. photonic quantum signals that can be separated from the classical background by suitable filtering and detection techniques. An example for the discernible-photon concept for a specific laser pulse collision is shown in Fig.1 (taken from [31]).

These developments pave the way for a systematic exploration of optimized configurations of laser pulse collisions towards the goal of a discovery experiment of inherent nonlinear properties of the quantum vacuum.

II. TOOLS REQUIRED

For such a challenging project, all facets on the experimental as well as theoretical side have to go hand in hand. While a maximum of available laser power is certainly desirable, the decisive steps towards a discovery ultimately need to be made by high-precision detector development satisfying the needs as predicted in terms of discernible signal photons.

Recent theoretical proposals which produce a finite discernible photon number of $\gtrsim \mathcal{O}(1)$ per shot above an idealized background [28, 31, 34] typically consider a multi petawatt class laser; e.g., a 10 PW laser delivering 250 J with pulse duration 25 fs which can be focused close to the diffraction limit would be desirable.

The discernible-photon concept suggests to aim at a maximum separation between signal and background

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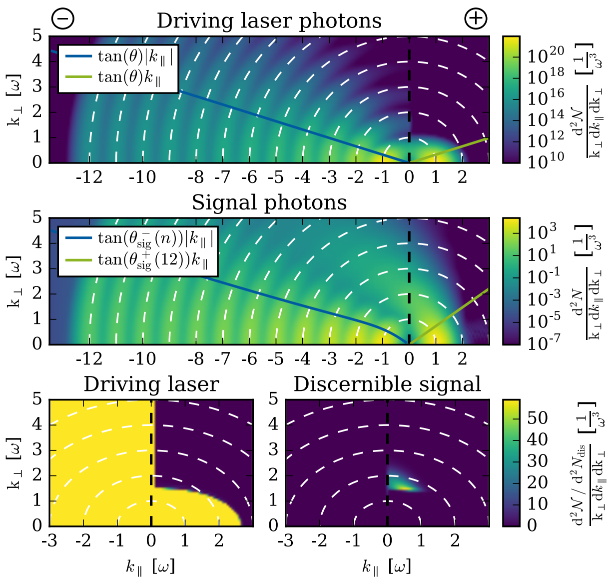

FIG. 1: Differential photon number in Fourier space after a pulse collision of two pulses, one having undergone coherent harmonic focusing. The top panel depicts the classical background, the middle panel the signal photons produced by quantum vacuum nonlinearities. The bottom right panel shows the spectrum of discernible photons where the spectrum of signal photons is larger than the classical background. In this example, the integrated spectrum yields $N_{\rm dis} \approx 26.06$ discernible signal photons per shot; example taken from [31].

photons in all accessible parameters. One such important parameter is the photon frequency. For this reason, it appears useful to split the original beam in two or more sub-beams, some of which may undergo frequency doubling; through sum and difference frequency generation, signal photons can occur in inelastic frequency channels which renders them more discernible. While frequency doubling preserving the pulse duration at an energy loss of only 50% is realistic [38], further R&D at petawatt class systems may be needed.

A key ingredient for distinguishing signal photons from background are photon detection mechanisms at the single photon level with a sufficient resolution in space and time. The challenge is to achieve spatial/angular resolution and temporal/frequency resolution at the transform limit for each pair of parameters and matching these to the source of vacuum-emitted photons defined by the drive laser. This can be achieved using non-linear gating techniques and high resolution imaging systems, thereby restricting the detected photon phase-space to the volume where the vacuum emission photons are the dominant photon source.

Finally, the vacuum in the interaction region has to be controlled to a high degree in order to avoid contamination of a possible signal channel through classical scattering processes. This can be achieved by a combination of techniques resulting in a sufficiently low vacuum pressure and/or ensuring the efficient detection of the presence of contaminating particles using high sensitivity particle detection techniques familiar from atomic physics experiments. Flexible introduction of prepulses capable of ionising background gas at long time-scales (>10ns) prior to peak of the pulse allows ionisation and subsequent dynamic 'cleaning' of interaction volume using electrostatic extraction of particles. In combination, these techniques allow precise control of the interaction volume required for high-fidelity experiments.

On the side of theory and simulation-tool development, the vacuum emission picture offers already a highly efficient and elegant computational framework for quantum vacuum signatures in rather general fields from first principles. In can be used for analytical studies of tailored beams [39], and can straightforwardly be implemented numerically. Several codes have already been developed and used for complex pulse-collision geometries [27, 30, 33]. First developments for a general-purpose code platform [30] need to be continued and intensified.

A necessary further step is the theoretical modeling of the realistic classical background in a concrete experimental set-up. For this, the vacuum emission codes have to be merged with classical Maxwell solvers [40] and potentially with conventional PIC simulations. Strategies along this line have already been suggested [30] but need to be implemented within a concrete software platform.

Finally, the various sources for deviations from ideal settings which cannot fully be controlled have to be modeled and statistically accounted for. A prominent example is spacetime jitter of the high-intensity pulses; strategies for such a modeling in the context of quantum vacuum phenomena have already been developed and used [41], but need to be adapted for a concrete setting.

To summarize: while many steps towards the goal of a first discovery of vacuum nonlinearities still remain challenging, current concerted experimental and theoretical efforts are highly promising, such that this goal appears to be within reach at upcoming petawatt class laser systems.

III. SCIENTIFIC IMPACT

The impact of achieving this scientific goal cannot be overestimated. Since the goal is a discovery of fundamental phenomena of nature the predictions of which date back to the first half of the past century, reaching this goal may be comparable to first-detection experiments in other branches of fundamental physics. From a conceptual perspective, this goal would verify and quantify our picture of the quantum vacuum as a "substance" that features inherent properties similar to that of a nonlinear medium. Virtual zero-point fluctuations of all elementary degrees of freedom in nature leave their imprint in the ground state and thus contribute to the quantitative properties of the quantum vacuum.

Achieving this goal would thus constitute a first step into this uncharted territory of nonlinear quantum vacuum response at the high-intensity frontier. It is obvious that forseeable ever-increasing intensities of future laser facilities will have the opportunity to explore this landscape in much more detail.

IV. BROADER IMPACTS

The investigation of fundamental physics at the high-intensity frontier offers a new route to elementary particle physics: since each elementary degree of freedom contributes indirectly to the properties of the quantum vacuum, studies of the induced nonlinearities can be viewed as a microscope illuminating the subatomic world, with largest sensitivity to light particles coupling to electromagnetism. In addition to electrons, the contributions of further leptons or light mesons could eventually be discovered. High-intensity lasers also have the potential to search for new hypothetical particles [42–44] that may couple feebly to electromagnetism via suppressed interactions (e.g., so-called higher dimensional operators); paradigmatic examples are axion-like particles (ALP) which also represent a candidate for dark matter.

It is obvious that quantum vacuum nonlinearities also offer the potential of future applications: in the same manner that the properties of media or plasmas are used to create optical devices, the properties of the quantum vacuum may eventually be used to measure, steer and control electromagnetic fields and propagating waves at highest intensities. Since there is no way to screen intense fields from quantum vacuum properties, future high-intensity laser systems will always have to constructively deal with the rich set of phenomena offered by the ground state of nature.

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Relativistic Electron Isochoric Heating with Petawatt Femtosecond Lasers for Creation of Warm Dense Matter

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Abstract:
This white paper describes current challenges of relativistic electron isochoric heating research and experimental needs to create well-characterized warm dense matter by using petawatt class repetitive femtosecond lasers. In the interaction of a high intensity, short-pulse laser with a solid, the short duration of the laser pulse enables rapid target ionization and heating before it hydrodynamically expands, known as isochoric heating. The generation of laser-driven electrons with relativistic energies is broadly understood. However, experimental verification of the plasma condition of the electron-impacted target and its temporal evolution is scarce because of lack of ultrafast diagnostics and experimental opportunities to develop such diagnostics. A recent research reveals that an isochorically heated solid target is in a non-equilibrium state of strongly coupled/Fermi degenerate matter, which is in different temperature-density regimes from equilibrium shockwave-driven plasmas. This unique heating scheme creating solid density, highly charged matter could provide currently inaccessible datasets of the warm dense matter for testing models in atomic physics and other numerical codes. Pump-probe experiments using multiple petawatt femtosecond laser beamlines with high beam energies and repetition rates could accelerate an understanding of the isochoric plasma creation processes for studies of materials science, degenerate matter and fusion energy.

Scientific goal:
The goals of this research are to develop a diagnostic capability for characterizing the condition of isochorically heated solid density matter and to establish a measurement-based scaling of the target heating as a function of laser parameters. In fast electron isochoric heating of a solid, three heating mechanisms coexist: resistive heating, drag heating and diffusive heating.[1] When a high intensity, short pulse laser irradiates on a solid foil, a low intensity pedestal prior to the main pulse of the laser generates preplasma near the foil surface. Fast electrons generated in the interaction of the main high intensity pulse with the preplasma propagate in the forward direction into the solid target and draw the return current of cold electrons that resistively heat the bulk electrons. Heating by direct collision (drag heating) is negligible at the solid density and becomes important in extremely high-density plasmas (> $\sim 10^{25}$ 1/cm^3). Diffusive heating occurs at the interface between the hot preplasma and cold solid target. Understanding of the resistive and diffusive heating with various laser energies and pulse durations is essential for achieving significant heating of a solid density target to keV electron temperatures. [2]

To probe rapidly evolving high density plasma conditions, ultrafast time-resolved measurements are required. Time-integrated x-ray spectroscopy has been used in numerous single-beam high intensity laser experiments, but inferred electron temperatures from measurements of spectral shapes and intensities vary in a wide range from tens of eV to several keV because the spectral analysis heavily relies on atomic physics calculations and how the contribution of nonthermal electrons is treated in the calculations [3]. In addition, x-ray emissions from a preplasma and a solid bulk are indistinguishable even with spatially resolved measurements due to a thin layer of preplasma. To overcome these challenges with spectrometers, an effort to directly probe dense matter with an external x-ray beam has been made.[4] Although ultrafast time-resolved measurements with an x-ray free electron laser (XFEL) have been pursued, development of an ultrafast plasma diagnostic capability at high energy petawatt femtosecond laser facilities is important because of high laser beam energies (>100 J) only available at the laser facilities and limited beamtime allocations at XFEL facilities. Measurement techniques developed could be transferrable to other laser and/or x-ray laser facilities.

Tools required:

This research requires a repetitive relativistic intensity laser system delivering at least two beams. A standard configuration is a pump-probe experimental geometry where one laser beam irradiates a main target and a second laser beam produces an ultrashort x-ray pulse to probe the interior of the matter. The relativistic laser intensity defined as $I\,[W/cm^2] \geq 1.37 \times 10^{18}/\lambda^2[\mu m^2]$ is a minimum intensity required. Experimental variables are laser beam energies, pulse durations and delay timing of the probe beam. Since experimental characterization of preplasma is extremely challenging, the laser-target interaction will be monitored by measuring escaping electrons with an electron spectrometer. The slope of the electrons representing the mean energy of the electron distribution is sensitive to the on-target peak laser intensity in preplasma. The direct electron measurement is critical to characterize the input source because the electron spectrum could drastically vary from one laser system to another due to different laser-target interaction (preplasma, spot size, laser polarization, incident angle, laser contrast, etc.) even at a same peak intensity quoted.

The primary diagnostic technique is x-ray absorption spectroscopy. Several experiments based on short-pulse laser-produced x-rays have been reported.[5-8] In near edge x-ray absorption spectroscopy, smearing of a K- or L-edge profile can be used to infer the electron temperature (T_e) of ionized matter, while a measurement of 1s-2p absorption lines can provide the information on T_e of high density warm plasma. To measure x-ray absorption features, a target material, backlighter x-ray spectrum and a spectrometer range must be carefully selected and need to be developed (for instance, Al K-edge at 1.56 keV, Cu L-edge ~0.94 keV, Cu K-edge 8.98 keV). Interpretation of the measured absorption spectrum requires density functional theory calculations for edge measurements or atomic physics calculations for absorption lines. For hot dense matter in which ions are fully ionized (no absorption lines), x-ray Thomson scattering could be an alternative technique to deduce the plasma temperature.

Scientific impacts:

Isochoric heating with laser-driven relativistic electrons creates non-equilibrium warm dense matter. This heating method is a complementary to shock waves launched by long pulse lasers or pulsed power generators, and direct laser absorption in a skin depth by non-relativistic femtosecond lasers. The ionization states and electron temperatures of a relativistic laser-irradiated target will encompass conditions that cannot be accessed by the latter two methods.

Particularly, the electron isochoric heating could produce highly ionized high-Z matter that is difficult to create by compression. Time-resolved experimental data of a material transitioning from the solid density to warm dense matter will help understand applicability of various numerical codes such as for molecular dynamics, density functional theory, plasma atomic physics and particle-in-cell calculations.

The measurement techniques developed in this research could be applied to other isochoric heating experiments using energetic protons or an x-ray free electron laser. A better understanding of how high-density plasma is isochorically heated and cooled could lead to development of an alternative ignition concept for inertial fusion energy.

Broader impacts:
The short-pulse-laser-solid interaction can produce various energies of nonthermal electrons. Well-characterized electron-impacted targets can be used to study the electron-matter interaction physics relevant to fusion research. In magnetic confinement fusion, the interaction of MeV runaway electrons with in-vessel components is a serious issue causing damage of the chamber wall, while preheat of a dense fuel shell by tens of keV nonthermal electrons is a critical issue in inertial confinement fusion. Furthermore, finding efficient energy deposition of nonthermal electrons in dense plasma could potentially aid to realizing a high-gain inertial fusion energy concept. Relativistic electron isochoric heating with petawatt class femtosecond lasers could be a novel pumping scheme to ionize and modify the electronic structure of a material via electron impact ionization, which could be a complementary means to photoionization with ultrafast x-ray free electron lasers for atomic, molecular and optical physics and chemical physics.

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MP3 White Paper 2021

The Role of High Repetition Rate Experiments in Advancing HEDP Science

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Abstract
High repetition-rate (HRR) experiments ($\geq$ 1 shot per minute) can permit active feedback control, collect large datasets for statistics and machine learning, systematically vary parameters, and employ novel diagnostics to perform high quality science. Until recently, these techniques have been out of reach for high energy density physics (HEDP) experiments (which are typically restricted to repetition rates of a few per day). Recent advancements in laser technology, target fabrication, and diagnostics are starting to change this fact, opening an exciting new frontier of high repetition rate HEDP experiments. Next-generation high intensity laser facilities should take advantage of this new frontier.

Scientific Goals

HRR experiments could produce large datasets and enable new experimental techniques that would have far-reaching impacts for multi-Petawatt laser physics [1]. Datasets with high spatial and temporal resolution over a wide range of parameters can be constructed by varying timing or diagnostic positioning across many shots. These datasets provide a comprehensive, multi-dimensional view of phenomena that is well suited to the validation of numerical simulations or the application of sophisticated theoretical techniques. Varying parameters with fixed diagnostics allows large parameters spaces to be probed with high resolution, which is ideal for studying nonlinear processes (e.g. laser-plasma interactions) or phenomena that span multiple regimes (e.g. magnetic reconnection). Low-signal events otherwise lost in noise can be observed in the mean of many identical shots, such as all-optical tests of vacuum birefringence [2] or searches for beyond-standard-model physics [3]. Rigorous statistical analysis of stochastic processes such as turbulence or quantum-dominated radiation [4] requires large sample sizes, which are pragmatically only obtainable with a HRR experiment. Large datasets are also useful for the potential application of machine learning techniques [5, 6], either as part of a real-time feedback loop during an experiment (e.g. optimizing a parameter) or during post-analysis.

Tools required

Significant progress has already been made towards achieving technological readiness for HRR HEDP experiments [7]. Several mid-scale laser facilities have already demonstrated the operation of intense lasers at HRR [8]. Advanced HRR targets [9] and optical diagnostics are being implemented. Particle and field diagnostics (eg. neutronics, charged particle radiography) require more substantial development, but are a subject of ongoing research [10].

Operation of experiments at HRR also presents challenges to data acquisition, storage, access, and analysis. Even with conservative estimates of data size and repetition rate (100 MB/shot, 1 shot/minute), it is clear that HRR experiments will produce on the order of hundreds of gigabytes of data per day. The technology to process, analyze, and store this data flow has already been developed [11] and utilized in large-scale physics experiments such as the Large Hadron Collider [12]. Addressing this computational challenge should be a high priority for a next-generation laser facility.

Scientific Impacts

Several recent NAS reports [13, 14] and FESAC reports [15, 16] have recognized the necessity of HRR to realize the potential of high intensity/high average power short-pulse lasers. For example, laser-accelerated proton beams must be operated at HRR in order to provide the luminosity required for particle physics experiments or cancer therapy [17]. Experiments on a short-pulse HRR facility could include measurements of spatial structures and parametric dependencies of laser wakefield acceleration, target-normal sheath acceleration, nonlinear interactions of particle beams, and other high-intensity laser phenomena. Large datasets could be used in combination with machine learning techniques to optimize accelerated beam profiles.

A HRR multi-Petawatt facility will also significantly advance fundamental science. Ultra-relativistic laser-particle interactions, in which the electric field is boosted above the Schwinger critical field strength in the reference frame of a counter-propagating particle, will access previously-untested quantum-dominated regimes for radiation and field-particle interactions. These experiments will depend on repeatable interaction of ultrafast laser and particle probes. HRR will enable active control of the beam paths on the relevant temporal and spatial orders ($\tau \sim 10$ fs, $c\tau \sim 3$ μm) and improve statistical sampling for rare events. For intensities below 5×10^{23} W/cm^2, many strong-field QED processes such as Breit-Wheeler (BW) pair production [18] remain in the perturbative regime, where HRR will improve the statistics for comparatively small effects. Measurement of vacuum birefringence and, ultimately, the Unruh radiation that is analogous to Hawking radiation in GR [19], will test field theories deeply and require sensitive discrimination of low signals in a high background.

Laboratory astrophysics experiments on shocks, magnetic reconnection, jets, and dynamos would all benefit from high temporal and spatial resolution datasets that complement the limitations of remote sensing observations. For scientific topics in the heliosphere, HRR experiments directly address the shortcomings of current spacecraft missions, which are inherently limited to at most a few spatial data points transverse to their trajectory, cannot definitively discriminate between spatial and temporal variations, and don't allow repeated observations under identical conditions. Multi-petawatt laser-driven neutron spallation sources may create unprecedented neutron brightness, enabling studies relevant to r-process nucleosynthesis that would benefit from the high statistics of HRR experiments.

Experiments probing turbulent and/or non-linear plasma processes (one of the central challenges in modern plasma physics) would also substantially benefit from HRR, since rigorously studying these phenomena inherently requires the observation of many events over a range of parameters due to their stochastic and strongly parametric nature. HEDP experiments are uniquely capable of accessing regimes (e.g. high density) of interest to this field, but must be performed at HRR to be transformative.

Broader Impacts

Many potential applications for ultra-intense lasers, such as proton acceleration for cancer therapy [17] or industrial applications would necessitate operation at HRR. In addition to enhancing fundamental research in these areas, the technological development required to build and operate a HRR ultra-intese laser facility would translate directly to these applications.

Several multi-Petawatt high repetition rate lasers have been constructed or are under construction outside of the US [8]. Several of these are included in the European Cluster of Advanced Laser

Light Sources (EUCALL) consortium [20], including ELI's HAPLS system (constructed by LLNL). These projects have spurred the creation of an HEDP ecosystem including conferences [21] and private-sector investment [22] in HRR target fabrication. The fact that none of these facilities or their associated infrastructure reside in or are operated by the US represents a loss of leadership in this field. The construction and operation of such a facility would restore US preeminence in this area.

HRR facilities are ideal platforms for training students based on their relatively low cost-per-shot. University-scale HRR HEDP experiments will produce scientists with the necessary skills for a large-scale HRR facility.

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MP3 White Paper 2021
Title: Laser wakefield acceleration with MultiPetawatt lasers

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Abstract: Laser wakefield accelerators using Petawatt laser systems may be able to miniaturize particle accelerators having energies up to 20-30 GeV for physics applications and also enable new sources of ultrafast, extreme brightness and precise x-rays for applications from the life-sciences to industry. In laser wakefield acceleration (LWFA), an electron bunch "surfs" on the electron plasma wave (the "wakefield") generated by the ponderomotive force of an intense laser. The plasma wave has a strong longitudinal electric field that stays in phase with the relativistic driver so that relativistic particles may remain in phase with the accelerating field over long distances and gain ultra-relativistic energies. The accelerating electric field strength that the plasma wave can support can be many orders of magnitude higher than that of conventional accelerators, which makes laser wakefield acceleration an exciting prospect as an advanced accelerator concept.

Scientific goal:

Multi-Petawatt laser facilities can be used to investigate laser wakefield acceleration in ultra-high power laser plasma interactions and will be able to demonstrate how such systems can scale for future electron positron colliders at high energy. Dual beam experimental configurations will enable flexibility for many frontier experiments, in particular two beam injection experiments, and positron generation/ acceleration experiments.

This type of research is relevant to the **Z**ettawatt-**E**quivalent **U**ltrashort pulse laser **S**ystem (**ZEUS**) project which is presently under construction at the Center for Ultrafast Optical Science (CUOS) at the University of Michigan as funded by the US National Science Foundation. ZEUS will consist of two beamlines that are designed to operate simultaneously and in perfect synchronization. It will also be able to operate in a single beam 3 PetaWatt (PW) mode or in a 500 TW beamline at higher rep rate.

Scaling of the Laser Wakefield Acceleration mechanism to Multi-PW powers is one of the main goals of our proposed research project. To produce high-energy electron beams of narrow energy spread and high charge is important to future High Energy Physics applications. Particularly important topics to investigate are injection mechanisms such as shock injection and two beam ionization injection, which can be used to control and improve the properties of the accelerated electron beams (with respect to energy spread, emittance, divergence, stability etc.)

Another exciting prospect for laser generated electron beam sources is that the high current density relativistic beams can be used to generate other particles, such as positrons, pions and muons etc. through bremsstrahlung production and subsequent gamma interactions in high-Z material. Although conventional particle accelerators are routinely able to produce such particles, the laser-generated electron source has an unusually high particle density (small source size), ultrashort duration and is synchronized with the laser pulse. In particular, the generation and acceleration of positron beams will be critical for applications of any future laser-driven accelerator for high energy physics experiments. The positrons are produced primarily by a two-step process, with conversion into gamma rays being followed by the gamma ray interacting with a nucleus to generate an electron-positron pair. Important future experiments will involve characterization of the positron beam properties such as the emittance, divergence and energy spread.

An important next step is to show that these positron beams can subsequently be accelerated using plasma waves. Since standard laser generated plasma waves are not necessarily an ideal structure for positron acceleration due to the de-focusing fields it is possible to control the focus of the laser pulse to generate an azimuthally symmetric "donut–shaped" wakefield which enables further acceleration of the positron beam. After passing through this wakefield the properties of the accelerated positron beam can also be characterized with respect to energy increase and beam emittance.

The key aims of such research programs are therefore:

- assessment and control of factors affecting the emittance, stability, and energy spread of LWFA electron beams at multi-PW powers using dual laser beams in particular with regard to control of electron injection
- determination of how the emittance and divergence of the positron beams generated scale with electron beam properties and the generation and characterization of "donut–shaped" wakefields and acceleration of positrons

Tools required: In addition to the high power laser system the require tools involve standard diagnostic systems such as electron spectrometers, optical spectrometers, charged particle spectrometers probe beams etc. – all of which are available for this work.

Scientific impact: This will lead to advances in compact particle sources for scientific, medical and and industrial applications.

Broader impacts: The impacts of this research involve applications in science, medicine and homeland security. Students and postdocs will also be trained as a result of such research projects.

MP3 White Paper 2021
Title: The quest for precision measurements of strong-field QED effects

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Abstract: Strong-field QED effects such as copious emission of energetic photons and high-energy photon conversion into electron-positron pairs are expected to play a crucial role in the presence of the ultrahigh fields enabled by next-generation multi-petawatt laser systems as well as around compact astrophysical objects such as pulsars. Yet, to date, theoretical models of strong-field QED effects have not been validated experimentally, neither in the classical nor in the quantum regime. Recent pioneering experiments could only provide evidence of radiation reaction effects [1], and of their quantum nature [2]. Most of the current prediction and numerical simulations heavily rely on the so-called locally-constant-field approximation (LCFA). However, recent theoretical work has shown that the LCFA is applicable to only part of the photon spectrum [3], and novel advanced models have been to proposed to describe photon emission beyond the LCFA [3-6]. Here we propose to fill this gap by performing ad-hoc experiments aiming at validating theoretical models for radiation reaction effects from the classical to the quantum regime.

Scientific goal: In the classical regime, validate the predictions for radiation reaction effects of the so-called Landau-Lifshitz (LL) equation [7] in terms of electron beam energy losses [8-9], nonlinear effects allowing to control the electron dynamics via radiation reaction with two-frequency laser pulses [10], and the expected contraction of the electron beam phase-space volume [11]. In the intermediate classical to quantum regime, check the validity of semiclassical models of the radiation reaction force [2, 9] and the competition between “classical” effects driving electron beam phase-space contraction and stochasticity effects leading to electron beam phase-space expansion [12, 13]. In the quantum regime, validate advanced theoretical models [3-6] of photon emission in electron beam-laser pulse collision with laser normalized amplitudes a_0 ranging from unity to values much larger than unity. Test recent predictions that quantum radiation reaction effects can be used for the on-shot diagnostic of electron beam-laser pulse interaction [14]. The above program can be carried by coupling a well-controlled electron beam generated by a LINAC to a high-power laser system. All-optical solutions involving electron beam generation via laser-wakefield acceleration are also possible, provided a high degree of stability is attained.

Tools required: stable and tunable high-power laser system and adaptive optics capable of delivering optical laser pulses with normalized laser amplitude ranging from 1 to approximately 20 with a laser pulse waist radius ranging from approximately 4 to 10 micrometers. Large BBO crystal for frequency doubling in the experiment with a two-frequency laser pulse. Stable highly-collimated and energy tunable electron beam. Accurate electron beam and photon beam diagnostic for on-shot measurement of the electron and photon beam spectrum and angular distribution.

Scientific impact: Test and determine the limits of validity of equations and theoretical models widely employed for analytical and numerical predictions of the electron dynamics in the presence of superstrong background electromagnetic fields. This has implications in strong-field QED, where an uncharted regime can be probed for the first time, and in astrophysics and cosmology, where prediction of energy losses and of the dynamics around compact objects as well as the limitations on the attainable energy of cosmic rays are inferred by applying these theoretical models to observations.

Broader impacts: The generation of hard X- and gamma rays enabled by electron beam-laser collision at high intensity has also potential impact in nuclear physics and nuclear astrophysics, where it enables the study of photofission and nuclear transitions, with precision measurements of the energy levels of elements of astrophysical interest. For instance, this is a key goal of Extreme Light Infrastructure Nuclear Physics (ELI-NP) facility

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Abstract: The interaction of a multi-petawatt laser pulse with an ultrarelativistic electron beam could be utilized to produce polarized positron-beam source or conduct confirmatory experiments on QED theory, as investigated in Refs. [1, 2]. Through polarization transfer from the polarized seed electrons by the medium of high-energy photons, the created positrons during nonlinear Breit-Wheeler process could be polarized longitudinally, which are much desirable for applications in high-energy physics and material science. This scheme requires a laser pulse of 10^{22} W/cm^2. Our second scheme is proposed to detect quantum stochasticity. Contrary to common perception that the angular distribution of the electron beam scattered would keep symmetrically in transverse directions even under the ponderomotive force of the laser pulse, an asymmetric angular distribution of the electron beam could arise due to the quantum stochasticity effect. The asymmetry is robust against a variety of laser and electron parameters, providing an experimentally detectable signature for the nature of quantum stochasticity of photon emission with laser (>2 × 10^{20} W/cm^2) and electron beams (>100 MeV) currently available.

Scientific goal: Investigation the fundamental QED issues including the polarization effects during nonlinear Compton scattering and Breit-Wheeler pair-production process and the quantum stochasticity effect during nonlinear Compton scattering, experimentally, to validate the theoretical methods recently established.

Tools required:

1) For generation of the polarized positron source, a laser pulse with the power near 5 PW, or the peak intensity up to 10^{22} W/cm^2 is needed. The seed electron beam should be polarized initially by means of laser-wakefield acceleration of prepolarized electrons [3] or extracting polarized electrons directly from polarized photocathodes [4]. Polarimetry based on Møller scattering [5] or Compton scattering [6], is required to determinate the polarization degrees of electrons and positrons.
2) For observation of the quantum stochasticity effect, the intensity of the laser pulse is required to be more than 2 × 10^{20} W/cm^2 (a_0>12). The initial average energy of the counterpropagating electron beam the should be more than 100 MeV. The initial angular divergence of the electron beam is required to be ~ 1 mrad.

Scientific impact(s): Polarization effect and the quantum stochasticity effect during nonlinear Compton scattering and Breit-Wheeler pair-production process are fundamental QED issues investigated extensively in recent years as the research interests much stimulated from the development of ultrashort ultraintense laser techniques. However, almost all these investigations are limited to the theoretical researches which are urgently to be tested.

Broader impacts: Spin-polarized positron beams working as a powerful probe are playing irreplaceable roles in fundamental physical studies and applications, such as improving the sensitivity of the two photon effect experiments, unambiguous determination of the nucleon structure, and testing the standard model or searching for new physics beyond it. Moreover, the positron beam generated in this way has an ultrashort duration (Le ≃ 20 fs), which is favorable for applications in probing the surface and bulk magnetism of materials along with a potential for ultrafast diagnosis. The quantum stochasticity effect capable of modifying the electrons distribution (in plasma) is associated with the new physics in the next generation of ultra-high intensity laser-matter experiments and the resulting applications such as novel particle or photon sources.

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MP3 white paper Multi-Petawatt Physics Prioritization Workshop

Relativistic astrophysical jets from accreting massive black holes in galactic centers

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Working Group: laboratory astrophysics (LAP)

Abstract:

Fast, axially collimated outflows, or "jets," are ubiquitous in astrophysics. They flow from most classes of compact objects that spin and/or accrete matter from their surroundings, which range from young stellar objects (YSOs), neutron stars, and stellar mass black holes (BH), to supermassive black holes (SMBH) at the centers of galaxies. The famous M87 [Snios 2019] and Cygnus-A [Snios 2020] relativistic jets are examples of jets launched from the center of accreting supermassive black holes. There are a multitude of open questions about astrophysical jets. How are they launched, what are their properties, how do they remain stable over such enormous distances, what is the energy input that maintains the jet, and what can they tell us about the conditions near a supermassive black hole? We propose to explore launching dynamics of relativistic jets in the laboratory using the next generation ultraintense lasers.

Scientific goal

We propose research to improve the understanding of astrophysical relativistic jets, typically associated with accreting compact objects and supermassive black holes (SMBH) at galactic centers. Fast, axially collimated outflows, or "jets," are ubiquitous in astrophysics. [WOPA 2010] They flow from most classes of compact objects that spin and/or accrete matter from their surroundings. Examples include jets emanating from young stellar objects (YSOs) such as Herig-Haro jets like HH-30, HH-34, HH-47, and HH-111, [Heathcote 1996] and relativistic jets from accreting super massive black holes (SMBH) in galactic centers, such as the jets emerging from M87 [Snios 2019] and Cygnus-A [Bartel 1995; Snios 2020] as shown in Fig. 1a and 1b, resp. Compactness leads to high gravitational potential. Rapid spin provides a second free energy source. The axial symmetry of spin allows energy, momentum, and angular momentum to concentrate and be transported away along the symmetry axis, typically in oppositely directed jet pairs. Some jets are probably matter dominated (highly ionized plasmas), and the most relativistic jets from SMBH likely involve electron-positron pairs. The jet speed can range from a few tens of kilometers per second for Herbig-Haro objects to close to the speed of light for pair plasma jets from SMBHs. The total jet energy can be a significant fraction of the gravitational energy released during the formation of the host objects.

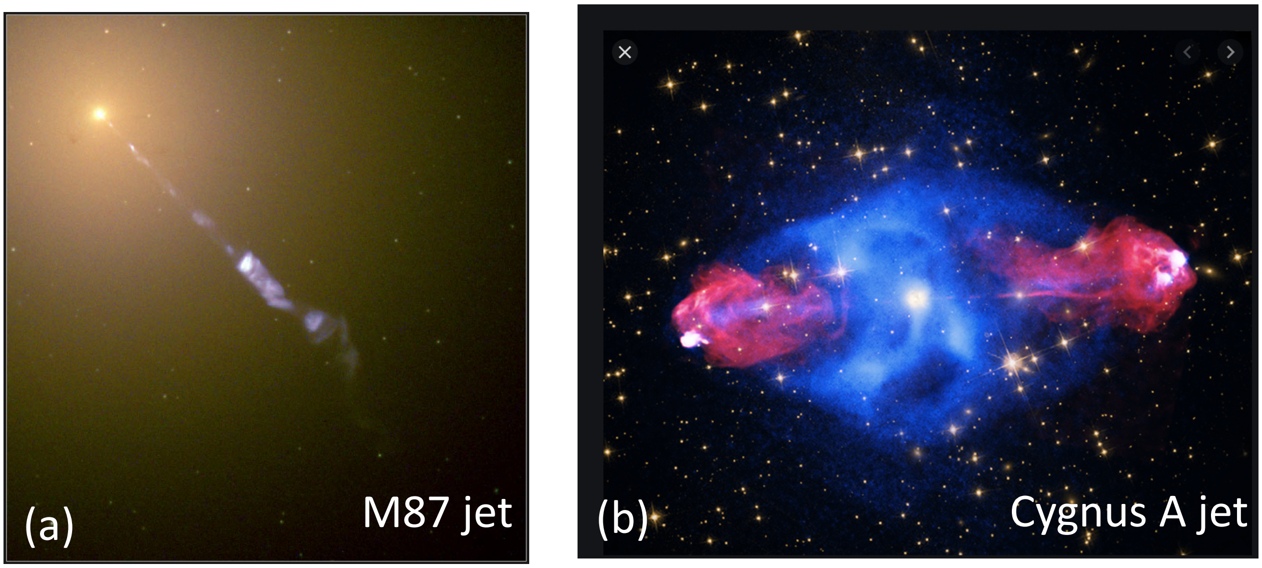

Fig. 1. (a) The image on the left (M87 jet) [Snios 2019] is a Hubble image of the 4.9 kLY long relativistic jet emanating from the M87 giant elliptical galaxy which is located 50 MLY away. (b) The composite image on the right shows the Cygnus A massive elliptical galaxy at a distance of 600 MLY away. The two oppositely directed jets are each about 300 kLY in length. The colors correspond to x-rays (blue), radio waves (red), and opitical light (yellow). The two web addresses correspond to:
< https://imgsrc.hubblesite.org/hvi/uploads/image_file/image_attachment/6274/pdf.pdf> for M87, and
<https://astronomy.com/news/2019/02/this-supermassive-black-hole-sends-jets-ricocheting-through-its-galaxy> for Cygnus A.

We also now realize that jets play an important feedback role in the evolution of their host systems. Jets from protostars energize the parent, star-forming molecular cloud, possibly regulating the rate and efficiency of star formation. There is ample evidence that jets from SMBHs in galactic nuclei both energize the nearby interstellar plasma and, for those in galaxy clusters, have an impact on the intracluster medium (ICM) and the inter-galactic medium (IGM). This contributes to the extragalactic magnetic fields and cosmic rays, including ultra-high-energy cosmic rays (UHECRs), neutrinos, and gamma rays. Jets and lobes serve as a useful calorimeter of the non- thermal energy component in the overall cosmic energy flow. Many fundamental challenges remain for the understanding of jets and outflows, such as the following.

1. The plasma conditions of jets are not well known. What are jets made of? More and better measurements are needed around the jet “engine” (source) of the jets, and at the jet termination.

2. The range of scales is vast. As an example, the jet originates from a SMBH at approximately 1 astronomical unit (10^{13} centimeters) scale but extends to megaparsecs (10^{24} centimeters). There are even smaller scales associated with the collisionless nature of jet plasmas. This vast scale separation makes it extremely challenging to build a coherent theory from engine to termination.

3. There is a lack of plasma physics understanding. Plasma physics processes govern the energy transfer among gravitational, kinetic, thermal, and magnetic-electric components, and particles. How are jets accelerated and collimated? How do magnetic fields behave? Why are jets stable? How does large-scale

fluid motion “communicate” with small-scale kinetic processes? Will relativistic effects change the physics drastically? What are the dissipation processes to produce 10 TeV electrons and 10^{20} eV cosmic rays?

Jets and outflows therefore present a suite of important laboratories to test our understanding of plasma physics. Such knowledge conversely provides part of the necessary physics underpinning for understanding the dynamics and evolution of the universe. Thus, astrophysical jets and outflows offer a natural laboratory for a concerted study by the astrophysics and plasma communities. Substantial progress can only be made when these two communities work together; when observation, laboratory experiments, theory, and simulation communities have built strong ties; and when the infrastructure (for research collaboration and funding) is conducive for such efforts. There have been a number of scaled laboratory astrophysics experiments to study high velocity, nonrelativistic hydrodynamic jets on high energy density (HED) facilities such as high energy, pulsed lasers [Blue 2005, Foster 2002, Farley 1999, Li 2016, Santala 2000, Shigemori 2000, Stone 2000] and high power Z-pinches. [Lebedev 2002, Lebedev 2004, Sinars 2004], relevant to the Herbig-Haro (nonrelativistic) astrophysical jets emanating from YSO in the star formation process.

Tools required: We propose to use current and next generation ultraintense laser facilities to study the properties of relativistic jets launched by petawatt laser irradiation of various types of targets. A wide variety of diagnostics will be utilized to image and characterize the properties of the jets inflight. Examples include x-ray emission imaging, optical imaging, x-ray and/or optical Thomson scattering, interferometry, nuclear particle detectors, and magnetic field characterization via proton deflectometry or Faraday rotation.

Scientific impacts

The HED experiments to date on jet generation and transport have been on high power magnetic pinch facilities and high energy lasers. The newest class of lasers that are being used widely for target physics experiments are ultaintense, short pulse laser, where the intensities can exceed 10^{19} W/cm^2, but the pulse durations are at the level of 10s of psec or shorter. Under these conditions, the target physics sample can reach ~MeV level temperatures, and flow velocities for the electrons and positrons can approach the speed of light. In these new relativistic regimes, it is worth considering whether experiments relevant to accreting SMBHs may become possible.

Broader impacts

One of the most challenging aspects of understanding jets is why they are stable over long distances (the extent of the jets can be greater than 10^{10} times the size of the engine). Since stability is closely tied with global jet dynamics, this is one parameter space that observations (having enough resolution), experiments, and theory and simulations can jointly address. The challenges include better constraints on the jet composition on large scales and well-developed theory incorporating more detailed measurements and observations. We believe that through a close collaboration among observation, experiment, and theory and simulation, significant progress can be made in this area, including modeling the jet energetics, stability, and morphologies in well-characterized background environments (e.g., radio jets and lobes in galaxy clusters).

The study of astrophysical jets is an active research area in astronomy and astrophysics, and it is ripe for progress with significant inputs from plasma physics. Nearly all current major observatories (e.g., Fermi, Chandra, Spitzer, Pierre Auger, HST, VLT, EVLA, VLBA/VLBI) contribute strongly to understanding the nature of jets. It has been well established that jets play an important role in determining the physical condition of the interstellar medium, the intra-cluster medium, and the inter-galactic medium. Furthermore, jets could be closely related to the origin of ultra-high energy cosmic rays. The last decade also saw major advances on two fronts: the use of laboratory experiments to study jets, and sophisticated multi-dimensional general relativistic MHD simulations of jets. Yet we do not have an intellectual grasp on these systems. We urgently need an understanding from the plasma physics point of view of jets. A couple of preliminary scoping studies suggest that such laser experiments are both possible and will be illuminating. [Chen 2010, Chen 2014, and Kim 2020] Presently, jet research is fragmented, with relatively little collaboration among observers, experimentalists, theoreticians, and people doing simulations. Different funding agencies, while supporting jet research in certain ways, have different priorities and constraints.

The study of jets naturally brings together a number of topics. For example, the existence and critical role of magnetic fields in disks around stars and black holes — and in facilitating jet launching — are closely related to the dynamo and angular momentum transport processes. Particle acceleration processes such as collisionless shocks and reconnection determine the production of high-energy particles (perhaps UHECRs) and photons (observed up to 10 TeV). The relativistic speeds observed in jets, and the inferred high magnetization, call for studies of relativistic plasmas in extreme parameters. The accretion into SMBHs that sometimes leads to jet formation can also produce some of the most prodigiously luminous radiators in the universe where radiation hydrodynamics play an essential role. Accretion disks, and jets and lobes, are believed to be inherently turbulent. Turbulence could strongly influence the accretion process and energy conversion from magnetic fields to particles. On large scales, jet propagation and stability requires a better understanding of shear instabilities. [WOPA 2010]

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MP3 white paper Multi-Petawatt Physics Prioritization Workshop

Laser produced relativistic pair plasmas in the laboratory

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Abstract

Unlike electrons and ions in conventional plasmas, the electrons and positrons in a pair plasma have equal masses, so many standard plasma approximations break down. Instabilities and shocks in pair plasmas have been theorized as key mechanisms in particle acceleration to extraordinarily high energies as well as magnetic field generation, amplification, and dissipation. The possibility to produce and study a relativistic pair plasma in the laboratory is compelling as it would enable a detailed understanding of the collective processes associated with these extreme astrophysical conditions and provide a new route to benchmark numerical and theoretical models. Making relativistic electron-positron (antimatter) plasmas in the laboratory has proved challenging. Key difficulties include producing pair plasmas with high enough number of particles and maintaining charge neutrality to study collective plasma processes given the short lifetime of positrons. As a result, no reliable experimental platforms are available yet that can simulate the relativistic pair plasma processes relevant to astrophysical conditions. In the last decade, however, it has become clear that multi-patawatt lasers can play a very important role in this endeavor.

Scientific goal

Copious numbers of electron-positron pairs are now being generated using ultra-intense lasers through predominately the Bethe-Heitler (BH) process (Heitler 1954). In the BH process, the laser-produced hot electrons make high-energy bremsstrahlung photons that produce electron-positron pairs upon interacting with the nuclei. This is in contrast to the direct Breit-Wheeler process of pair creation by high-energy photons interacting with an ultraintense laser. While existing laser intensities are still orders of magnitude below the Schwinger limit, Breit-Wheeler pair production could be realized by combining an intense laser with multi-GeV electron beam, as in the seminal E-144 experiment (Burke 1997). This is because in the frame of the electron or high-energy photon, the laser field is Lorentz boosted and can exceed the Schwinger critical field, giving rise to prolific pair production.

In the past decade, significant progress has been made towards lasers producing large numbers of relativistic pairs via the BH process. For example, electron-positron jets at relativistic temperatures have been made using intense lasers either by direct laser irradiation of a target (ex. Cowan 1999, Chen 2008, 2015, Liang 2017), , or by irradiating the target using electrons accelerated by laser wake field acceleration method (ex. Gahn, 2002, Sarri 2013, 2018). Interestingly, it was found that laser generated relativistic pairs have a few key characteristics that are particularly useful. First, intense lasers can make a very large number of positrons (10^{10} to 10^{12} per shot) in a short time (10 – 100 ps). This feature, together with the small volume (~mm^3)

these positrons occupy, leads to a high density of positrons. Experimental data reveals a quadratic scaling of positron yield with laser energy: yield ~ E_L^2 (Chen 2015). The second characteristic is that the target sheath field can accelerate these positrons to 10s of MeV, enabling positrons to be created and accelerated to relativistic regimes in one integrated process. The third characteristic is that the laser-target interaction produces overlapping jets of MeV electrons and positrons behind the target, allowing much higher pair densities than would be possible if the pairs were distributed isotropically (Chen2010). Theoretically, extremely high density (>10^{19} cm^{-3}) of relativistic pairs can be produced from ultra-high intensity (>10^{24} W/cm^2) lasers (ex. Ridgers 2012, Del Sorbo 2018). Once realized, this would open up new parameter regimes for this relativistic laboratory astrophysics.

Tools required

To perform experiments testing astrophysical processes using laser-produced pairs will need further development to achieve. Higher pair density, volume and life-time are critical. For example, to use colliding laboratory pair jets to study the development of streaming instabilities (e.g. Weibel instability) and the magnetic field and particle acceleration dynamics associated with relativistic collisionless shocks, as shown in Fig. 2. A possible experiment would require the duration of the pair jets to be much greater than the typical time for instability growth, which is about 1 ps for pair density >10^{15} /cm^3, and longer for lower pair density. Moreover, the transverse scale of the plasma needs to be much larger than the typical spatial scale of the instability and the plasma skin depth. These requirements may be achieved in a laser that has multi-kJ energy at ultra-relativistic laser intensity, similar to the EP-OPAL laser that has been planned at the Omega facility, the NIF-ARC laser at LLNL, or facilities with similar parameters available elsewhere.

Scientific impacts

The importance of understanding the basic plasma physics processes behind some of the most energetic phenomena in the universe such GRBs (illustrated in Fig. 1) has long been recognized, as for example in the review “Frontiers in High Energy Density Physics” conducted by National Research Council (2003) [Frontier2003]. More recently, extraordinary astrophysical discoveries associated with compact objects together with the unique opportunities emergeies in the laboratory by advances in laser technology are further highlighting the need and timeliness of research on the basic physics of relativistic pair plasmas. This has been highlighted in multiple recent assessments (NSA Report [NSA2018], 2019 Brightest Light Initiative [BLI2019] and Basic Research Needs Workshop report [BRN2019], Plasma 2017 [Adamovich], [Plasma science, 2021]) as high impact research in the near future.

In the past decade, extraordinary discoveries associated with extreme astrophysical plasmas have excited scientists and the public alike — from the first image of plasma orbiting a black hole [EHT] to the high-energy cosmic rays and radiation produced by relativistic jets from active galactic nuclei (AGN) [IceCub]. It has long been recognized that the plasmas at the core of these extreme environments are relativistic and often electron-positron (e^-e^+) pair dominated and that these plasmas have unique properties. The interactions of gamma-ray photons with each other and with strong magnetic fields in the environments of compact objects, such as black holes or neutron stars, lead to prolific e^-e^+ pair creation and to the ejection of the resulting pair plasma into the universe via relativistic winds or jets. Important examples are pulsar magnetospheres, AGN jets, and gamma-ray bursts (GRBs). Pair-driven plasma processes shape the dynamics and energy partition in these extreme environments.

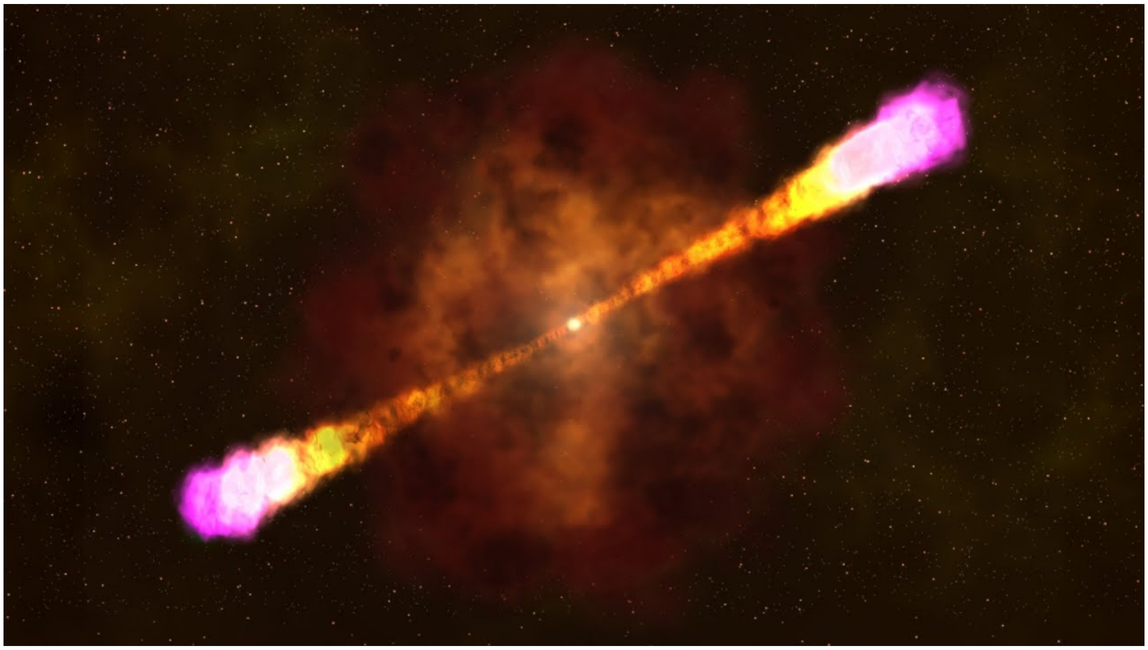

Fig. 1: Gamma-ray bursts (GRBs) are the most luminous explosions in the cosmos. Astronomers think most GRBs occur when the core of a massive star runs out of nuclear fuel, collapses under its own weight, and forms a black hole. The black hole then drives jets of particles that drill all the way through the collapsing star at nearly the speed of light. The image is an artist's rendering. Credit: NASA's Goddard Space Flight Center.

Fig. 2 shows the achieved pair density and temperature from various laser experiments to-date (yellow region); the black ellips represents potential pair parameters achievable with future lasers.

Eventually, a colliding relativistic pair jet experiment simulating the physics of a GRB can be envisioned, as illustrated in Fig. 3. Adding magnetic collimation of the pair jets may further benefit the experiments by extending the interaction length without sacrificing the pair density (Chen 2014). By observing the shock formation and particle acceleration, one would be able to put important constrains on the particle acceleration and magnetic field amplification associated with the GRB fireball model.

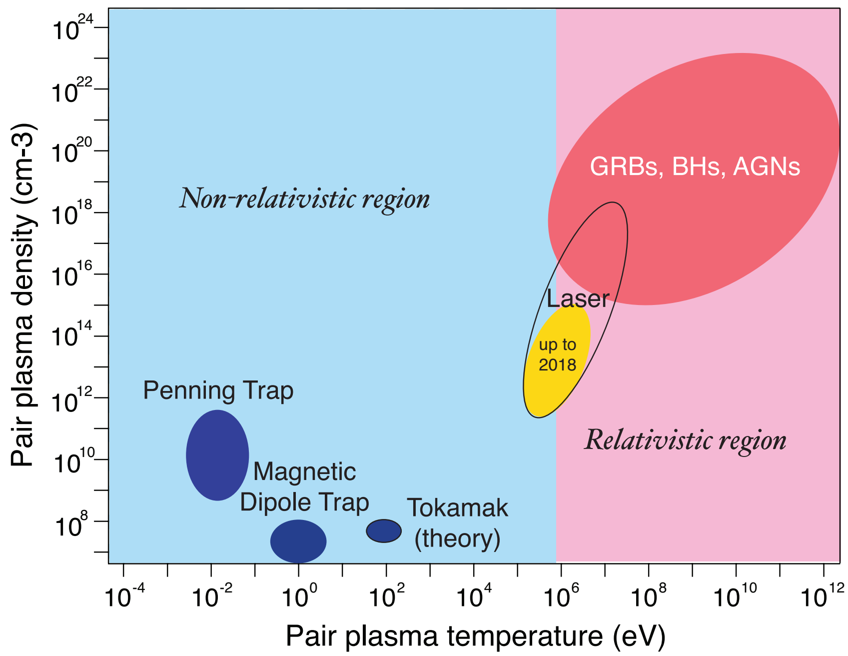

Fig. 2: The densities and temperatures from laboratory antimatter (electron-positron) plasmas and some astrophysical objects. The temperature in the relativistic case refers to the bulk Lorentz factor of the plasma.

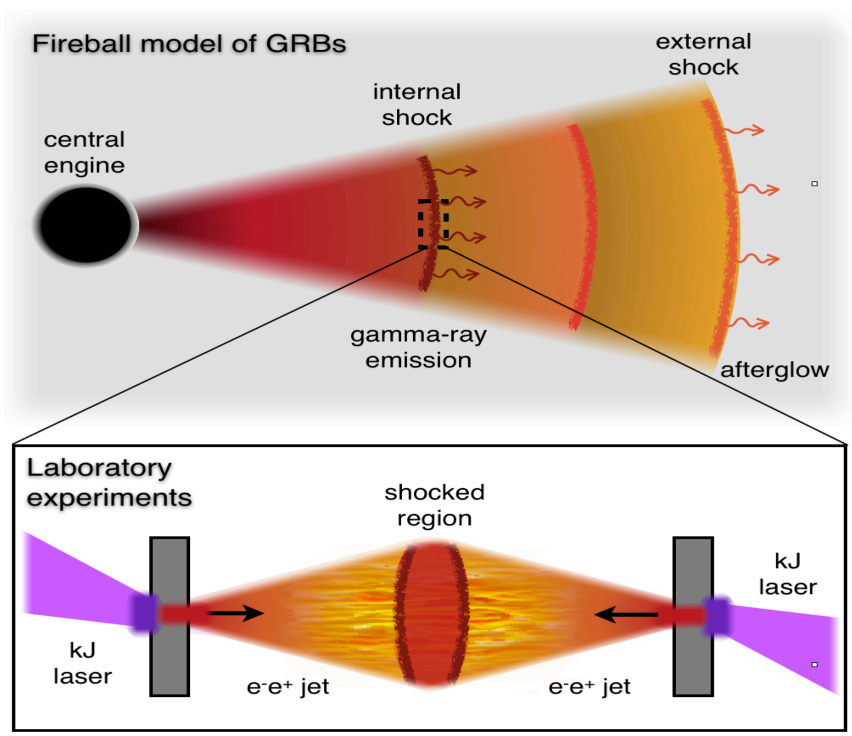

Fig. 3: Internal shocks from pair plasmas have been hypothesized as the engine to drive particle acceleration and gamma radiation. The relativistic plasma dynamics and flows used in the model might be studied in the laboratory using two colliding relativistic jets of dense pairs.

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MP3 Opportunities for Benchmark-quality Lab-Astro Experiments

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Working Group: Laboratory Astrophysics

Abstract: The developing capabilities enabled by bright, multi-petawatt lasers open new paths for benchmark-quality measurements of atomic-scale properties in matter at extreme conditions. In this white paper, we advocate for a research program that emphasizes extensive, high-precision diagnostics that characterize both the plasma conditions and astrophysically relevant properties of uniform samples in the warm dense matter (WDM) and non-equilibrium plasma regimes. In particular, ionization balances, line shapes, opacities, and validation of x-ray diagnostics such as scattering, emission, and fluorescence spectra enabled by bright broad- and narrow-band backlighter sources, coupled to well-designed targets that reach uniform 10 eV – 1 keV temperatures at or near solid densities would make enduring contributions to HEDP and astrophysical science.

Scientific goal: Our understanding of astrophysical objects – and our ability to diagnose and control terrestrial plasma sources – relies on adequate modeling and simulations, which in turn require a robust, well-tested understanding of material properties of matter in extreme conditions. The transience, gradients, and structural complexity of terrestrial plasma sources make the kind of careful, quantitative measurements that advance most other areas of science especially challenging, particularly when coupled to the difficulty of developing diagnostics that may need to include active probes of sufficient energy and intensity to overwhelm plasma emission and the circular difficulty of interpreting any such diagnostics in the absence of benchmarked methods and models. The goal of this white paper is to encourage high-precision, benchmark quality measurements, suggest directions for platform development in regimes that would have high impact on HEDP and laboratory astrophysics, and help guide requirements for diagnostics and platform characterization. In particular, we encourage investigation of benchmark-quality plasmas that are 1) far from local thermodynamic equilibrium (LTE), with temperatures approaching 1 keV and atmospheric-scale densities, 2) in the warm dense matter regime, with temperatures near 10 eV and near-solid densities and 3) extensive diagnostics that constrain both the plasma conditions and a material quantity of interest, such as conductivity, electron-ion equilibration times, spectroscopic line shapes, opacity, or emissivity.

Tools required: The primary needs are in experimental platform development and diagnostic deployment. Creating laser-plasma platforms with minimal spatial and temporal gradients is a challenge, since energy is typically deposited via either shock or direct absorption, both of which are highly non-uniform. Yet the energy requirements for non-LTE and WDM are relatively modest and can be achieved at university scales: while ~MJ-class facilities like NIF or Z are required to produce useful high-temperature-density samples in LTE, only ~10-100 J are required to heat ~0.5mm volumes of atmospheric-density gas to ~ 1 keV temperatures for a useful non-LTE experiment, or ~0.1mm solid volumes to ~10 eV for a WDM experiment. These two regimes pose particular modeling challenges and are most in need of benchmarking data. Within these general plasma categories, researchers can identify opportunities to create at-parameter laboratory plasmas that match conditions of astrophysical objects or key HED systems.

Quiescent plasmas are a pipe dream, since energy loss rates tend to be much larger than equilibration rates, however advances in multi-petawatt lasers open new opportunities for diagnostic snapshots that can track plasma evolution and equilibration in non-LTE and WDM plasmas. In particular, short-pulse lasers that produce active probes for absorption, fluorescence, or scattering measurements can track material response in WDM, and fast energy deposition in a non-LTE plasma could provide signatures that complement time-integrated self-emission and the advancing capabilities of time-gating (e.g. UXI).

We do not here prescribe particular experiments or diagnostics, since recent advances in atomic-scale material models have poised the HEDP community to exploit almost any benchmark-quality data the MP3 community generates. When models ensure consistency among predicted quantities, such as, for example, line shapes and collisions, or equilibration times and stopping powers, the details of the particular plasma or even the quantities measured are less important than the quality of the platform and precision of diagnostics: every single piece of high-quality benchmark data is precious to the modeling community and will be highly cited: the three examples in Refs 1-3 below have more than 800 citations combined.

Scientific impact(s): Reliable, benchmarked material models could be transformative in helping us understand large-scale simulations of astrophysical objects such as accretion disks, stellar atmospheres, and stellar evolution. They would also help inform our predictive simulations of terrestrial source plasmas for radiation effects and fusion research. In both cases, reducing the significant uncertainties now associated with materials properties like equations of state, conductivities, and radiative properties would increase our confidence in our understanding and, for terrestrial plasmas, predictive control.

Broader impacts: Platform development of non-LTE and WDM plasmas at university scales could open gateways for new partnerships, broadening the field of contributors to laboratory astrophysics and HEDP science.

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What are the time-scales of particle formation in the Schwinger effect?

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Theoretical Developments

Muti-petawatt lasers might allow for the first time a verification of electron-positron pair production by ultra-strong fields via the Schwinger effect. Recent theoretical investigations have elucidated many aspects of this essentially non-perturbative effect. However, there is, at least, one fundamental question which has remained elusive: What is the formation time of the electron (or, equivalently, of the positron) in this process? We will discuss whether and how this question can be formulated as a well-posed problem. Furthermore, we will analyze the numerical results obtained in Dirac-Heisenberg-Wigner formalism for time-dependent and inhomogeneous electric fields in 1+1-dimensional QED to extract time-scales which are relevant for particle formation. Hereby, the time evolution of late-time-observable quantities such as the charge density and the particle number density are studied with respect to the influence of spatial and temporal field variations. An outlook for a corresponding investigation in 3+1-dimensional QED will be given.

I. INTRODUCTION

The vacuum of quantum electrodynamics (QED) is unstable against the formation of particle-antiparticle pairs in the presence of an external electric field. With the electron being the lightest electrically charged particle this effect is expected to manifest itself as the creation of electron-positron pairs [1]. This has been a long-standing but still unobserved prediction as the generation of the required field strengths $E_{cr} \sim 10^{18}\,\mathrm{V/m}$ has not been feasible so far. However, due to the advent of a new generation of high-intensity laser systems an experimental verification might be in reach, especially in the version of the so-called dynamically assisted Schwinger effect [2, 3].

An experimental verification of the Schwinger effect is not only wanted for confirming the present understanding of strong-field QED but also in view of the fact that it will provide a firmer basis to theoretically similar physical phenomena like, *e.g.*, particle production in the expanding universe, Hawking radiation, and the Unruh effect.

Based on the Dirac sea picture one can relate the Schwinger effect to a tunneling problem. This analogy proved very helpful, and quite a number of concepts show strong similarities when applied to a tunneling-based effect like atomic ionization or the Schwinger effect. Therefore, one might expect strong hints about the time-scales important for the Schwinger effect from the analogous tunneling time problem in atomic ionization which is accessible via ultra-fast laser pulses on the attosecond time-scale, see, *e.g.*, the review [4]. Leaving aside for the moment that the Schwinger effect is a genuinely relativistic problem, and that therefore eigen-times might differ solely on the basis of the particles' velocities with respect to the laboratory, one might hope that an analysis of the time-scales in time-dependent tunneling[1] will elucidate the question whether a particle formation time can be a well-defined concept for the Schwinger effect, and if so, how one would derive or calculate the respective time-scale. However, it turned out that the Büttiker-Landauer, Eisenbud-Wigner or Pollack-Miller time scales are by far too large to account for the experimental results [4]: The 'attoclock' measurements of the electron tunneling delay time are more than a factor of two below the theoretical expectations over the entire intensity range probed by the experiment.

Leaving aside that this situation is still requiring a better understanding of the time-scales in atomic ionization the expected guidance for a corresponding investigation of the time-scales in the Schwinger effect is therefore not well-founded.

In this context it is important to note that in a time-dependent background field it is impossible, at least in principle, to extract a well-defined particle number as long as there are substantial time variations in the background field. Only if the field has become to large degree time-independent one can identify the calculated particle number with the observable one. The reason for this is quite straightforward: On the one hand, the time in-

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[1] For a brief review of the definition of the Büttiker-Landauer time, the Eisenbud-Wigner time, and the Pollack-Miller time we refer the reader to the review [4].

terval for extracting the particle number should be short enough to restrict the variation of the background field to a negligible amount. On the other hand, Heisenberg's uncertainty principle leads for short time intervals to a large spread in energy, and thus to the possibility of a large number of virtual pairs, and a correspondingly undetermined particle number.

In the following section we will briefly review how the time evolution of the charge and particle number densities is calculated within the Dirac-Heisenberg-Wigner (DHW) formalism. In Sect. III we will analyse and discuss the time-scales extracted from this calculations. In the last section we will provide an outlook on the corresponding research project.

II. CHARGE AND PARTICLE NUMBER DENSITIES FROM THE DHW FORMALISM

This brief review of the time evolution of the charge and particle number densities is based on the method introduced in [5] and further developed in [6, 7], see, *e.g.*, the PhD theses [8, 9] for more details.

At its core the DHW formalism describes the time-evolution of the density operator within relativistic quantum plasmas thus, as all kinetic theories, granting access to the particles entire phase-space. The gauge-invariant density operator is defined as

$$\hat{\mathcal{C}}_{\alpha\beta}(r,s) = \mathcal{U}(A,r,s)\ \left[\bar{\Psi}_\beta(r-s/2), \Psi_\alpha(r+s/2)\right], \tag{1}$$

with the center-of-mass coordinate r and the relative coordinate s. Gauge-invariance is ensured by the Wilson line factor

$$\mathcal{U}(A,r,s) = \exp\left(\mathrm{i}e\int \mathrm{d}\xi\ A(r+\xi s)\ s\right). \tag{2}$$

As the vector potential A_μ is treated as a c-number instead of as an operator no path ordering is required. To determine the spinors Ψ one starts from QED, *i.e.*, from

$$\mathcal{L}\left(\Psi,\bar{\Psi},A\right) = \frac{1}{2}\left(\mathrm{i}\bar{\Psi}\gamma^\mu\mathcal{D}_\mu\Psi - \mathrm{i}\bar{\Psi}\mathcal{D}_\mu^\dagger\gamma^\mu\Psi\right) - m\bar{\Psi}\Psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \tag{3}$$

with the covariant derivatives $\mathcal{D}_\mu = \partial_\mu + \mathrm{i}eA_\mu$, $\mathcal{D}_\mu^\dagger = \overleftarrow{\partial}_\mu - \mathrm{i}eA_\mu$ and the Dirac matrices γ^μ. In order to obtain a kinetic formalism in familiar momentum- and position variables, one performs a Fourier transform in s, thus obtaining the covariant Wigner operator

$$\hat{\mathcal{W}}_{\alpha\beta}(r,p) = \frac{1}{2}\int \mathrm{d}^4s\ \mathrm{e}^{\mathrm{i}ps}\ \hat{\mathcal{C}}_{\alpha\beta}(r,s). \tag{4}$$

Evolution equations for $\hat{\mathcal{W}}_{\alpha\beta}(r,p)$ are then obtained based on eq. (1) and the (adjoint) Dirac equation:

$$\left(\frac{1}{2}\hat{D}_\mu - \mathrm{i}\hat{P}_\mu\right)\gamma^\mu\hat{\mathcal{W}}(r,p) = -\mathrm{i}m\hat{\mathcal{W}}(r,p), \tag{5}$$

$$\left(\frac{1}{2}\hat{D}_\mu + \mathrm{i}\hat{P}_\mu\right)\hat{\mathcal{W}}(r,p)\gamma^\mu = \mathrm{i}m\hat{\mathcal{W}}(r,p). \tag{6}$$

In this regard, the covariant derivatives $\mathcal{D}_\mu$ are replaced by nonlocal, pseudodifferential operators

$$\hat{D}_\mu = \partial_\mu^r - e\int_{-1/2}^{1/2}\mathrm{d}\xi\quad F_{\mu\nu}\left(r - \mathrm{i}\xi\partial^p\right)\partial_p^\nu, \tag{7}$$

$$\hat{P}_\mu = p_\mu - \mathrm{i}e\int_{-1/2}^{1/2}\mathrm{d}\xi\ \xi\ F_{\mu\nu}\left(r - \mathrm{i}\xi\partial^p\right)\partial_p^\nu, \tag{8}$$

making use of the electromagnetic field strength tensor $F_{\mu\nu}$ instead of A_μ. The integration path in eqs. (7,8) are determined by identifying p as the kinetic momentum.

An equation of motion for the Wigner function $\mathcal{W}$, the vacuum expectation value (VEV) of the Wigner operator,

$$\mathcal{W}(r,p) = \langle\Phi|\hat{\mathcal{W}}(r,p)|\Phi\rangle. \tag{9}$$

is obtained by taking the VEV of eqs. (5,6),

To simplify the notation we proceed by converting the matrix-valued time-evolution of $\mathcal{W}$ into a set of differential equations for the components $\mathbb{S}$ (scalar), $\mathbb{P}$ (pseudoscalar), $\mathbb{V}$ (vector), $\mathbb{A}$ (axialvector) and $\mathbb{T}$ (tensor),

$$\mathcal{W}(r,p) = \frac{1}{4}\left(\mathbb{1}\mathbb{S} + \mathrm{i}\gamma_5\mathbb{P} + \gamma^\mu\mathbb{V}_\mu + \gamma^\mu\gamma_5\mathbb{A}_\mu + \sigma^{\mu\nu}\mathbb{T}_{\mu\nu}\right). \tag{10}$$

Furthermore, at this point we give up covariance through projection on equal times, *i.e.*, by applying $\int \mathrm{d}p_0/(2\pi)$ on all covariant Wigner components $\mathbb{W}$ resulting in equal-time Wigner components $\mathbb{w}(t,\boldsymbol{x},\boldsymbol{p}) = \int \mathrm{d}p_0/(2\pi)\ \ \mathbb{W}(r,p)$. Thereby, we reformulate the approach as an initial value problem with a clear, intuitive way to interpret the results.

Eventually, we obtain a time-evolution equation for each equal-time Wigner component

$$\begin{aligned}
&D_t\mathbb{s} && -2\boldsymbol{\Pi}\cdot\mathbb{t}_1 &&= 0,\\
&D_t\mathbb{p} && +2\boldsymbol{\Pi}\cdot\mathbb{t}_2 &&= -2m\mathbb{a}_0,\\
&D_t\mathbb{v}_0 + \boldsymbol{D}\cdot\mathbb{v} && &&= 0,\\
&D_t\mathbb{a}_0 + \boldsymbol{D}\cdot\mathbb{a} && &&= 2m\mathbb{p},\\
&D_t\mathbb{v}\ + \boldsymbol{D}\ \mathbb{v}_0 && +2\boldsymbol{\Pi}\times\mathbb{a} &&= -2m\mathbb{t}_1,\\
&D_t\mathbb{a}\ + \boldsymbol{D}\ \mathbb{a}_0 && +2\boldsymbol{\Pi}\times\mathbb{v} &&= 0,\\
&D_t\mathbb{t}_1 + \boldsymbol{D}\times\mathbb{t}_2 && +2\boldsymbol{\Pi}\ \mathbb{s} &&= 2m\mathbb{v},\\
&D_t\mathbb{t}_2 - \boldsymbol{D}\times\mathbb{t}_1 && -2\boldsymbol{\Pi}\ \mathbb{p} &&= 0.
\end{aligned} \tag{11}$$

with $\mathbb{t}_1 = 2\mathbb{t}^{i0}\boldsymbol{e}_i$ and $\mathbb{t}_2 = \epsilon_{ijk}\mathbb{t}^{jk}\boldsymbol{e}_i$. The pseudodifferential operators D_t, $\boldsymbol{D}$ and $\boldsymbol{\Pi}$ are given by

$$D_t = \partial_t\ \ + e\int \mathrm{d}\xi\ \ \boldsymbol{E}\left(\boldsymbol{x} + \mathrm{i}\xi\boldsymbol{\nabla}_p, t\right)\ \cdot\boldsymbol{\nabla}_p, \tag{12}$$

$$\boldsymbol{D} = \boldsymbol{\nabla}_x + e\int \mathrm{d}\xi\ \ \boldsymbol{B}\left(\boldsymbol{x} + \mathrm{i}\xi\boldsymbol{\nabla}_p, t\right)\times\boldsymbol{\nabla}_p, \tag{13}$$

$$\boldsymbol{\Pi} = \boldsymbol{p}\ \ - \mathrm{i}e\int \mathrm{d}\xi\xi\boldsymbol{B}\left(\boldsymbol{x} + \mathrm{i}\xi\boldsymbol{\nabla}_p, t\right)\times\boldsymbol{\nabla}_p. \tag{14}$$

As initial condition a vacuum state is considered:

$$\mathbb{s}_{\mathrm{vac}}(\boldsymbol{p}) = -\frac{m}{\sqrt{m^2+\boldsymbol{p}^2}},\ \ \mathbb{v}_{\mathrm{vac}}(\boldsymbol{p}) = -\frac{\boldsymbol{p}}{\sqrt{m^2+\boldsymbol{p}^2}}, \tag{15}$$

with all other Wigner components vanishing.

Charge and particle number densities are derived applying Noether's theorem linking Wigner components with observable quantities. In this way, we obtain the charge density

$$q(t, \boldsymbol{x}, \boldsymbol{p}) = e\ \mathbb{v}_0, \tag{16}$$

and, through normalizing the energy density by the one-particle energy, the particle number density

$$n(\boldsymbol{x}, \boldsymbol{p}) = \frac{m(\mathbb{s} - \mathbb{s}_{\text{vac}}) + \boldsymbol{p} \cdot (\mathbb{v} - \mathbb{v}_{\text{vac}})}{2\sqrt{m^2 + \boldsymbol{p}^2}}. \tag{17}$$

Corresponding spectral distributions are given by integration with respect to $\int \mathrm{d}^3x/(2\pi)^3$. Total yields are extracted by further integrating over $\int \mathrm{d}^3p$.

Numerical results for a number of different field configurations can be found, *e.g.*, in refs. [8, 9].

III. EXTRACTING TIME SCALES

In an ongoing exploratory investigation employing the DHW formalism for 1+1-dimensional QED we try to identify several time-scales for the Schwinger effect from the numerical results and analyze their origin by comparing the propagation of the created wave-packets to a semi-classical picture.

To this end we note that one time-scale is given by the electron mass, namely the Compton time $t_c = \hbar/m_e = 1.3 \cdot 10^{-21}$s=1.3 zs. Additional time-scales are given by the model for the electric, resp., electromagnetic field, more precisely by
(i) the inverse of the frequency $1/\omega$,
(ii) the pulse duration, *i.e.*, the time interval characterising the envelope of the field, τ, and
(iii) the spatial extent of the electric field λ, resp., λ/c.
(NB: As magnetic fields do not work they contribute only indirectly to pair creation, see, *e.g.*, the discussion in ref. [10]. And as the electromagnetic field anyhow needs to fulfil the homogeneous Maxwell equations the time-dependencies of the electric and magnetic fields are linked.) Further time-scales as they might be present by chirping the field, a non-vanishing carrier phase, etc., are not taken into account.

First of all, typical peak field strengths used in our investigation are of the order of 10% of E_{cr}, the critical Schwinger field strength. As we want to investigate the Schwinger effect this puts already constraints on the frequency ω. (NB: Technically this amounts to requiring a small Keldysh parameter, $\gamma \ll 1$ and thus $\omega \ll eE_{cr}/m_e$.) Correspondingly, the chosen time-scale $1/\omega$ is of the order of attoseconds, *i.e.*, $\mathcal{O}(1000\, t_c)$ which is not far from the corresponding XFEL parameter. Furthermore, we require $\omega\tau \approx 10$ to describe an oscillating field, and $\lambda/c \approx \tau$ for simplicity.

In a first step, we try to identify for the different model fields the time-scale on which the electron field has acquired enough energy from the background field to match the rest mass of the pair, *i.e.*, $2m_e$. This relates roughly in the tunneling analogy to the time the wave-packet is mostly localized in the classically forbidden region.

In a second step, based on the observation that both, the number and the charge density, undergo strong fluctuations due to ongoing constructive and destructive interferences within the electron (positron) field we want to quantify for each model field the time-scale on which those fluctuations become in a well-defined sense sufficiently faint and the electron (positron) wave-packet becomes correspondingly sufficiently smooth. Note that at these time-scales the charge and the number densities still cannot be identified with the observable ones. The extracted second time-scale also marks the onset of the validity of a semiclassical description and thus identifies the mean trajectory of the wave-packet which eventually becomes the emitted particle. A back-extrapolation of this trajectory and an analysis of the behaviour of the electron field amplitude along this trajectory then eventually allows the identification of a particle formation time.

IV. OUTLOOK

Within this exploratory study we have adapted existing and developed new code for the DHW numerical calculation and subsequent analysis for the 1+1-dimensional case. The already obtained results have to be checked for correctness and consistency, but nevertheless at the time of the workshop we will be very likely able to report at least results for the lower-dimensional case.

The main reason for studying the lower dimensional case is, however, to gain intuition which type of model fields can and should be used in the 3+1-dimensional investigation. To this end we note that, to the best of our knowledge, a DHW simulation of a very general 3+1-dimensional electric field has not yet been done, mostly because such a computation is very CPU expensive. Being able to investigate the related time-scales in cases of electric fields which display certain symmetries will, however, make such computations not only feasible but reduce the CPU cost so much that they can be performed on relatively small compute clusters or even a high-end desktop computer.

This project opens up the fascinating possibility to understand particle creation and formation including the related time-scales in great detail. The theorist's phrase "*Apply a particle creation operator ...*" might become a much deeper meaning when understanding all those related aspects of "real" particle creation.

As within this project for every case along the extraction of the particle's formation time the electron (positron) spectrum will be calculated, a comparison of the resulting spectra with upcoming experimental results can then be interpreted as a verification (or falsification) of the particles' formation time.

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MP3 White Paper 2021
Title: Soft X-ray emission spectroscopy to search for Unruh radiation

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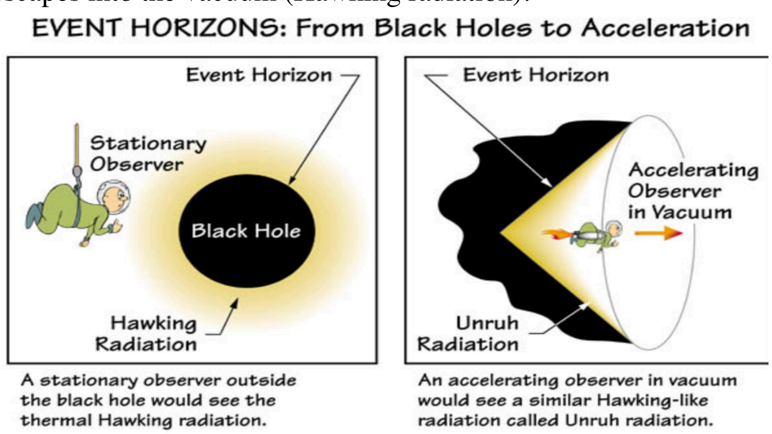
Abstract: The goal of this proposal is to design a high intensity, short pulsed laser-based experiment to test two fundamental physics principles: First, the generation of a non-bremsstrahlung, thermal bath (called Unruh radiation) from a mass under extreme acceleration. Although never detected, quantum field theory suggest Unruh must exist for an accelerating mass. The concept uses extremely high-intensity laser-matter interactions to accelerated ions with bound states and measure the effect of the UR on the bound states. As with static ions in a radiation field, the addition thermal background should shift the ionization balance of the ions.

Scientific goal: The current understanding of gravity is based on the acceleration of mass due to the distortion of space-time. Einstein's Equivalence Principle[1] suggests the equivalence between acceleration resulting from the distortion of space-time (gravitational) and objects accelerated by other means (inertial). In the case of highly dense, massive objects, space-time can be distorted to such extreme levels that nothing that travels within a calculated distance can escape (called the event horizon). The uncertainty principal allows for the existence of virtual particle pairs in the vacuum short durations, which are constantly being created and destroyed[2] However, the pairs can manifest radiation near a black hole when one particle is trapped in heavily distorted space-time while the other escapes into the vacuum (Hawking radiation).



An equivalent process occurs with an accelerating mass, As mass accelerates, it generates a boarder, which represent a boundary where information can no longer reach the accelerating mass (called a Rindler horizon). As with the generation of Hawking radiation at the extreme gravitational distortion of space-time, an analogous radiation is generated at the Rindler horizon, called Unruh Radiation.

Measuring UR is challenging. The detection of the UR requires measuring the effects in the accelerated frame (i.e, the detector needs to move with the accelerating mass). A potential solution to this problem is to measure physical effects of Unruh radiation on an ion with a bound state. Previously, a group of scientists suggested using x-ray Thompson scattering off accelerated electrons to measure Unruh radiation[3]. The experiment is based on the UR radiation producing spectral broadening of the x-ray Thompson beam. While we believe this is an exciting idea and has significant positives, the measurement requires access to an XFEL which could potentially limit the servicing of the experiment. Another interesting conceptual idea for measuring Unruh radiation was proposed by Thirolf[4], et al, using laser accelerated electrons and a counter propagating laser beam to act as an optical modulator.

We propose an alternative approach. Rather than observing scattered XFEL radiation or radiation generated by modulated electrons, we suggest accelerating an ion with bound states and measuring the effects of the UR on the bound electrons by emission spectrum to determine the ionization balance. The accelerated ions would act as a natural detector in the accelerated frame. As excited ionic states decay, the emission would reflect the effects of a radiation field with a temperature characteristic of the UR. The emission spectrum will be used to infer the ionization balance during acceleration. The accelerated emission spectrum will be compared to a static plasma at the same plasma conditions and systematic changes in the acceleration by changing the focused laser intensity. The relative difference will provide an estimate of the Unruh radiation temperature as a function of acceleration.

Tools required: Several developments are required to successfully perform the experiment. Because the proposed experiment requires accelerating ions, the focused laser intensity is much larger than the intensity required for the equivalent experiment using electrons. Additionally, the experiment will require isolating the effects of the internal plasma radiation on the ionization balance. Based on the calculations from reference 4, we have estimated approximately a laser intensity between 10^{25} and 10^{27} W/cm^2 produce as much as an 80 eV Unruh temperature for carbon ions. While ambitious, we believe achieving these high intensities would be in line with the goals of the multi-petawatt effort.

Additional measurements will be needed to confirm the plasma temperature and measure the ionization balance. A time-resolved and a time-integrated variable line-spaced spectrometer would be used to determine the ionization balance (with the time-integrated spectrometer will used to reference the post-shot integrated, time-resolved measurements). Since the effect of the Unruh radiation is expected to only exist during the acceleration period, the time resolution will help minimize background radiation for from non-Unruh plasma emission.

Finally, detailed simulations (along with estimates of sensitivities to the various mitigating effects) are needed to design an experiment that could be fielded.

Scientific impact(s): Recognizing the goal is indeed ambitious, the successful execution of this (or any of the other concepts) could provide insight and understanding to the effects of vacuum fluctuations on accelerated masses.

Broader impacts: A potential application of these results could extend to the observation to understanding the effect on bound states of spectroscopic emission of atoms (or ions) in strong gravitational fields.

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MP3 White Paper 2021

Direct Measure of Quantum Vacuum Properties

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Abstract
We suggest a photon-photon experiment (both IR) to measure fundamental QED parameters. This will allow various possible QED models to be distinguished while providing additional information that could help to determine whether or not axion-like particles exist in this specific energy range as well as other proposed particles not included in the standard model.

Scientific goal:
It is commonly believed that a tightly-focused laser to beyond the critical intensity (about 10^{29} W/cm^2) pair creation is possible. The mechanism needs a convergent wave, not a pure travelling wave, and the result is predicted to be a cascade of electron positron pairs. This is considered to be the threshold of unstable vacuum and many new effects are expected to be found there. However, reaching this critical intensity in the lab frame will require substantial improvements in extreme-laser technology and could still take several decades to achieve.

Pair production may not be the best way to obtain deep knowledge of the quantum vacuum. Before the expected onset of pair creation there are a number of effects that can be experimentally analyzed. Among them is the direct observation of the quantum vacuum Lagrangian. We may consider two extreme lasers propagating head on. One of them tightly focused to get the max available fluence and the other a bit less tightly focused to be used as a probe. The more intense laser can polarize the vacuum and the second laser can experience an induced phase change. The weakness of the photon-photon scattering also requires a very intense probe beam (near petawatt at least).

The photon-photon cross section measurement for counter-propagating intense lasers is one way to see the key parameters of the QED Lagrangian directly [Tommasini2008, Tommasini2010]. What is relevant in those papers is the relationship between the nonlinear QED coefficients and the phase shift of the probe beam. Such an experiment would allow, for the first time, a direct measurement of the QED Lagrangian coupling parameters.

The direct measurement of the nonlinear Lagrangian coupling parameters can be a major breakthrough in QED because it makes no a priori assumptions about the coupling. The advantage of this method is that we can measure directly the QED coupling coefficients and distinguish, also for the first time, between the Heisenberg-Euler QED and Born-Infeld Lagrangian (the latter predicting no birefringence of the vacuum), as well as others [Tommasini2014].

For head-on collisions, it has been calculated that the probe beam experiences a phase shift that is directly given by the non-linear Lagrangian coefficients, one for parallel polarizations (pump-probe) and a different one for crossed polarizations. This would be a unique way to get experimental measurement of the QED Lagrangian and observe possible effects due to the existence of the axions or mini-charged particles. Those objects, if they exist, would influence the QED coupling coefficients in a measurable way [Tommasini2014]. Also, the information will be complementary to the information obtained in high magnetic-field experiments such as PVLAS [Ejlli2020] and other polarimetry-base experiments. Most importantly, the photon-collision experiment will give quantitative information in the unlikely case that the quantum vacuum is not birefringent.

Scientific impact: The advantage of measuring directly the photon-photon cross section is that it is going to give quantitative information about the core of the QED Lagrangian and their coefficients. Therefore, there is no need to make a priori assumptions on the couplings. The experiment would give direct information and thus bring new insight into the basic mechanisms governing the quantum vacuum. In case of the existence of axions, mini-charged particles, or any other form of dark matter candidate particles (and their antiparticles) such an experiment might provide a way to explore them directly. Even the birefringence of vacuum, that is predicted by the Heisenberg-Euler QED interpretation can be checked experimentally before arriving to the creation of real electron-positron pairs expected at the critical field.

Risk: Not clear if we are going to reach the region where the QED coefficients are expected. But, in any case we could investigate regions of the parameter space not explored by PVLAS [Tommasini2014] and related techniques with ultrahigh magnetic fields. Just a reduction of the multiple QED possibilities can eliminate some models and give credence to others.

There are ongoing experiments looking for the birefringence of vacuum, which is also an indication of the fundamental couplings on the vacuum. The most advanced ones, among them, the Paulus group using the European XFEL and the HIBEF station, are looking for the polarization rotation of an X-ray very precisely aligned beam against a petawatt-scale laser.

Laser technology is required to allow Multi-Petawatt beams to counter propagate head on.

Laser required: Our underlying assumption is that planned Multi-Petawatt laser pulses will have good optical quality, and can be focused beyond 10^{24} W/cm^2. We further assume that the pulse duration is a few tens of fs, so in the focus the beam specs will be in the 25 PW = 1 KJ / 40fs neighborhood and linearly polarized.

This project will require one Multi Petawatt Laser plus a second **close-to-Petawatt laser**. Multiple shots are going to be required to gather enough statistics. So, this can be a long-term experiment.

Other configurations are possible. In the case of the availability of twin Multi-Petawatt lasers, the number of photons available for the probe can be optimized. This would improve the signal-to-noise ratio, which is the main bottleneck of this experiment. At the same time, the range of parameters that could be explored would be wider than with a single Multi-Petawatt laser. In the case of twin Multi-Petawatt lasers it would also be possible to consider three-laser configurations, provided the availability of a near-petawatt third beam as a probe beam. In this case the twin Multi-Petawatt lasers can be used to generate a standing wave pattern that could be probed at different angles. This will require precise synchronization of the three femtosecond pulses and thus much harder to implement.

Vacuum required: There is no target, it is a vacuum experiment. Therefore, it is necessary to prepare at least one region of the chamber with a record high vacuum level. This requires technological developments, some of which can be related to sweeping out the electrons and protons by a combination of a diode electric field between capacitor plates and a strong laser pre-pulse (ponderomotive forces).

Diagnostics requirements: Need of single photon detection and sub nanosecond time gated detection.

Modeling difficulty: Not difficult, and already done.

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MP3 White Paper 2021

Radiation from the electron-positron virtual pairs accompanying laser driven electrons.

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Working Group: HFP/QED

Abstract
A driven electron in the focus of a Multi-Petawatt laser will experience a very violent acceleration. This acceleration can be high enough to affect the cloud of virtual pairs that surrounds the charge. We propose to investigate the virtual-cloud dynamics.

Scientific goal:
This proposal is a high-risk, high-reward idea but may provide very valuable scientific information. We always consider the electron a point-like particle. However, in the scope of QED dressed potentials it is possible to consider the electron not as a single point particle (a point-like particle has disturbing infinities – an infinite potential well and an infinitely high potential energy). A number of models have been developed based on the electron being surrounded by a cloud of virtual particle pairs (electron-positron). While many models have been developed, all of them static. What is going to happen when the electron is driven by a huge laser field? An electron driven by a linearly polarized laser field experiences the well-known figure-8 motion (in the average drift frame). In the lab frame this trajectory shows a cusp corresponding to the point of max acceleration. At this point the electric field is maximum and so this gives the maximum possibility to stress this gedanken structure of the electron. The surrounding virtual electron cloud is going to be pushed to one side while the virtual positron cloud will move oppositely. The restoring force, whatever this may be, will be reflected in an internal vibration showing for the first time an "internal structure" of the "dressed" electron.

The frequency of this vibration is going to be direct evidence of the driven dressed electron and the way to polarize this dressing will also be a fundamental piece of information for QED. The intensity of the Multi-Petawatt laser pulse must be below the critical QED intensity, i.e., below the breakdown intensity of the vacuum.

This proposal is the preliminary part of a very relevant experiment, the SLAC-144 [Burke1997]. In that experiment the goal was to produce pairs and to detect the positrons produced, without observing what happened before the onset of positron production. The idea of getting matter from light was the raison d'être of that experiment and the only concern was the detection of electron and positron produced. To our knowledge, the dressed electron was not considered; Multi-Petawatt lasers, however can be exploited for the study being proposed here.

The driven electron trajectory is very well known and in the case of a linearly polarized wave there is a very nice analytical solution [Sarachik1970]. In the lab frame the motion is a very peculiar Doppler shifted oscillation with clear cusps, something very strange in physics. The cusps (of the form $x^3=y^2$) correspond precisely to the point of maximal electric field. Therefore, at those points the electron has its smallest velocity but highest acceleration. At the same time, the cusps are the points where the virtual pairs dressing the electron experience the highest stress, and where they will start vibrating.

It is not clear which are going to be the oscillation forces related to the electron, versus the positron restoring forces, but it can be assumed that the energies involved have to be smaller than twice the electron mass otherwise real electron-positron pairs would be created. The observation of this unknown X-ray radiation can be separated from the background because it is going to be pulsed radiation with a periodicity equal to half of the Doppler shifted laser period.

The driven electron cusps have certain similarities with the Zitterbewegung oscillations. It has been shown that the driven Dirac electron follows quite well the classical trajectory except precisely at those cusps [SanRoman 2003].

Scientific impact:
The impact of finding this radiation would represent for the first time ever a radiation pattern coming from the "internal structure" of the electron. It may give relevant information on the roots of QED and might be used to gain a better understanding of the vacuum speed of light, its connection to the bath density of virtual electron-positron pairs and perhaps how to change it [Urban2013].

Additionally, a second part of this experiment can be done by injecting muons instead of electrons. Laser driven muons have not been deeply studied so far, probably because of their large mass. However, internal properties of the muon represent, even now, a big challenge. For example, very recently the Muon g-2 Collaboration reported a discrepancy in the muon magnetic anomaly of more than four standard deviations between theory and experiment [Abi2021].

Laser requirement: One Multi Petawatt Laser required. Our underlying assumption is that planned Multi-Petawatt laser pulses will have good optical quality, and can be focused beyond 10^{24} W/cm^2. We further assume that the pulse duration is a few tens of fs, so in the focus the beam specs will be in the 25 PW = 1 KJ / 40fs neighborhood and linearly polarized.

Vacuum requirements: Just a residual gas to avoid collisions.

Diagnostics requirements: X-ray spectrometer coupled to a picosecond x-ray streak camera.

Modeling requirements: Not very demanding a priori.

Feasibility:
There is a high risk because there is no a priori information of the resonant frequencies and thus of the X-ray radiation expected (other than a fundamental limit). However, the spectrum from the relativistically driven point like electron is well known, variations of this spectrum will give an important information.

Difficulty added:
The reaction radiation from the same electron. Fortunately, the point of max acceleration corresponds to the point of zero speed.

An alternate case:
Additionally, it seems possible to consider a second case of pre-accelerated electrons. These can be accelerated electrons obtained with the probe laser. With a PW-class probe laser multi-hundred MeV electron energies are possible and the Lorentz boost in the electron's frame will result in a relativisitcally boosted interaction field from the main laser close to the Schwinger critical field. The existence of the two lasers and accelerated electrons results in a more complex experiment but the hypothetical radiation coming from the internal degrees of freedom is going to be Lorentz down boosted so becoming easier to detect. In this case it would be worth working just below the onset of real electron-positron pair creation.

In this second case the tools required will be the Multi Petawatt Laser required plus a close-Petawatt laser.

Feasibility:
Risk not much larger than the single multi-PW laser experiment because electron LWFA mechanisms are very well controlled now.

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MP3 White Paper 2021

In situ intensity gauge adapted for extremely-high intensities

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Working Group: HFP/QED, PAALS, LDNP

Abstract
We suggest a method to measure in situ, the intensity of Multi-Petawatt lasers employing protons. The method is an extension of relativistic Thomson scattering of electrons in the laser focus in the regime where electron motion begins to be relativistic; protons become relativistic at intensities about six orders of magnitude higher.

Scientific goal:
All that follows considers ultra-low-density targets (well below a millibar), always working in a collisionless regime. Therefore, we can assume that the mean free path of each of the particles, in absence of the laser is the vacuum chamber width. With denser targets it is possible to get a large number of interesting effects, using the laser-plasma possibilities, but that is beyond what we present here.

We first point out that the difficulty of measuring the intensity of a Multi-Petawatt laser will be more severe than it is today. The key idea is to consider that at the focus of a super intense laser there are going to be just ions and electrons. Neutral atoms will be ionized at the turning-on of the main pulse or they can be ionized with a convenient pre-pulse.

Electrons are going to move relativistically at "moderate" intensities (moderate in this context means about 10^{18} W/cm^2 for a near IR laser). Protons will attain relativistic speeds beyond 10^{24} W/cm^2 for such a near IR laser, at which point electrons will be strongly relativistic and, according to simulations, will be ejected from the focus well before 10^{24} W/cm^2.

We propose using protons from hydrogen (which is always present in vacuum chambers) at very low pressures, because hydrogen will be quickly ionized, and the electrons expelled from the focus. So, if we have only protons in the laser focal spot, then it is possible to get a direct measure of the proton Thomson scattering. This is probably the best direct, in situ way to measure the intensity at the 10^{24} W/cm^2 frontier.

This technique has been shown for electrons recently using a sub-petawatt laser [He2019]. In that paper it was discussed that electrons undergoing relativistic Thomson scattering produce a rich spectrum of intensity-dependent, Doppler-shifted laser wavelengths and their harmonics. The benefit of using Thomson scattering for measuring high intensity radiation is threefold:

- it can be generated from low-density, background gas in the experimental chamber;
- it can be captured with off-the-shelf optics near, but outside, the focal volume; and
- the Doppler shifts are straightforward to calculate,

This technique for in situ intensity measurement at the 10^{24} W/cm^2 frontier is based on the same relativistic Thomson scattering mechanism but using protons instead of electrons. Moreover, electrons in such super-intense fields will be too relativistic to be useful; furthermore, their radiation reaction would have to be taken into account, complicating the measurement process. For protons, however, their radiation reaction is negligibly small.

Tools required:
Laser: One Multi Petawatt Laser is required. Our underlying assumption is that planned Multi-Petawatt laser pulses will have good optical quality, and can be focused beyond 10^{24} W/cm^2. We further assume that the pulse duration is a few tens of fs, so in the focus the beam specs will be in the 25 PW = 1 KJ / 40fs neighborhood and linearly polarized.

Target: Very low-density hydrogen gas (~10^{-6} mbar or less).

Diagnostics: Spectrometer- streak camera system collecting light at different angles.

Modeling: Relativistic particle tracker and radiation emission calculations – already developed for electrons.

Scientific impact:
The development of a robust and accurate technique to characterize the peak intensity would be highly useful at all Multi-PW laser systems around the world.

Broader impacts:
Accurate measurements of focal spot intensity are a prerequisite for the proper interpretation of most HFP/QED experiments. The study of proton Thomson scattering would also be interesting and fundamental.

Feasibility:
Straightforward, based on our experience with electrons. The model works very well at the onset of the relativistic motion, between 10^{18} and 10^{19} W/cm^2 for electrons and should work well between 10^{24} and 10^{25} W/cm^2 for protons.

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MP3 White Paper 2021

Title: Controlled γ-ray secondary source

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Working Group: PAALS

Abstract:

The generation of high-energy γ-photons using Compton scattering is a promising tool for a secondary source with a very broad range of applications. Even though the underlying physical process is rather well established and understood, the actual exploitation of this process in a controlled laser-plasma experiment is non-trivial. Depending on the details oft he geometrical setup and the interaction parameters sources can be created which differ considerably as far as maximum energy, spectrum, mono-energeticity, directionality, opening angle and pulse length is concerned. The present paper proposes the interaction of a high-intensity laser pulse with near-critical plasmas to generate photons up to GeV range with high directionality. The source term can be tuned in a controlled way by adjusting the two main parameters: the background plasma density and the peak laser intensity.

Scientific goal:

The goal is to realize experimentally what has been shown up to now only in multi-dimensional kinetic simulations in the radiation-dominated regime. The available predictive simulations need to be verified by actual laser-plasma experiments on ultra-high intensity laser installations. A corresponding experimental setup would allow to systematically optimize the source for a wide range of applications. The subsequent step would be to prove the feasibility of a repetition-rate source based on high repetition-rate laser systems in the ~Hz range. Depending on the laser intensity and the required energy range of the photons the interaction configuration can either been based on classical wakefield or, in the case of very high intensity, would exploit the ponderomotive force in the longitudinal direction of the propagating laser pulse.

Tools required:

Ultra-high intensity laser pulses in the range 10^{21} – 10^{23} W/cm^2 are required. Ideally the pulse length could be varied in the 10s of femtosecond range. Near critical homogeneous plasmas are necessary which potentially could originate from either high-density gas jets or foam targets. The tools for more detailed predictive simulations are readily available in the community. Diagnostics are necessary to determine the energy spectrum and the directionality/opening angle of the generated gamma-ray beams.

Scientific impact:

A well-controlled high-energy γ-ray source is of great interest to nuclear science (see e.g. ELI-NP project) to study fundamental excitation mechanisms, nuclear resonance fluorescence and can also be used to study certain nuclear astrophysical phenomena in the laboratory. Potentially two such sources could be used in a counter-propagating geometry to realize a gamma-gamma collider to study fundamental phenomena of quantum electrodynamics.

Broader impact:

The impact of such a well-defined and robust γ-ray secondary source can hardly be overestimated. The number of industrial applications in such areas as material science, nuclear waste imaging, nuclear fuel assay, security, high-resolution deep-penetration radiography etc. is well established. However, due to fluence issues the feasibility of a high-repetition rate source would be mandatory.

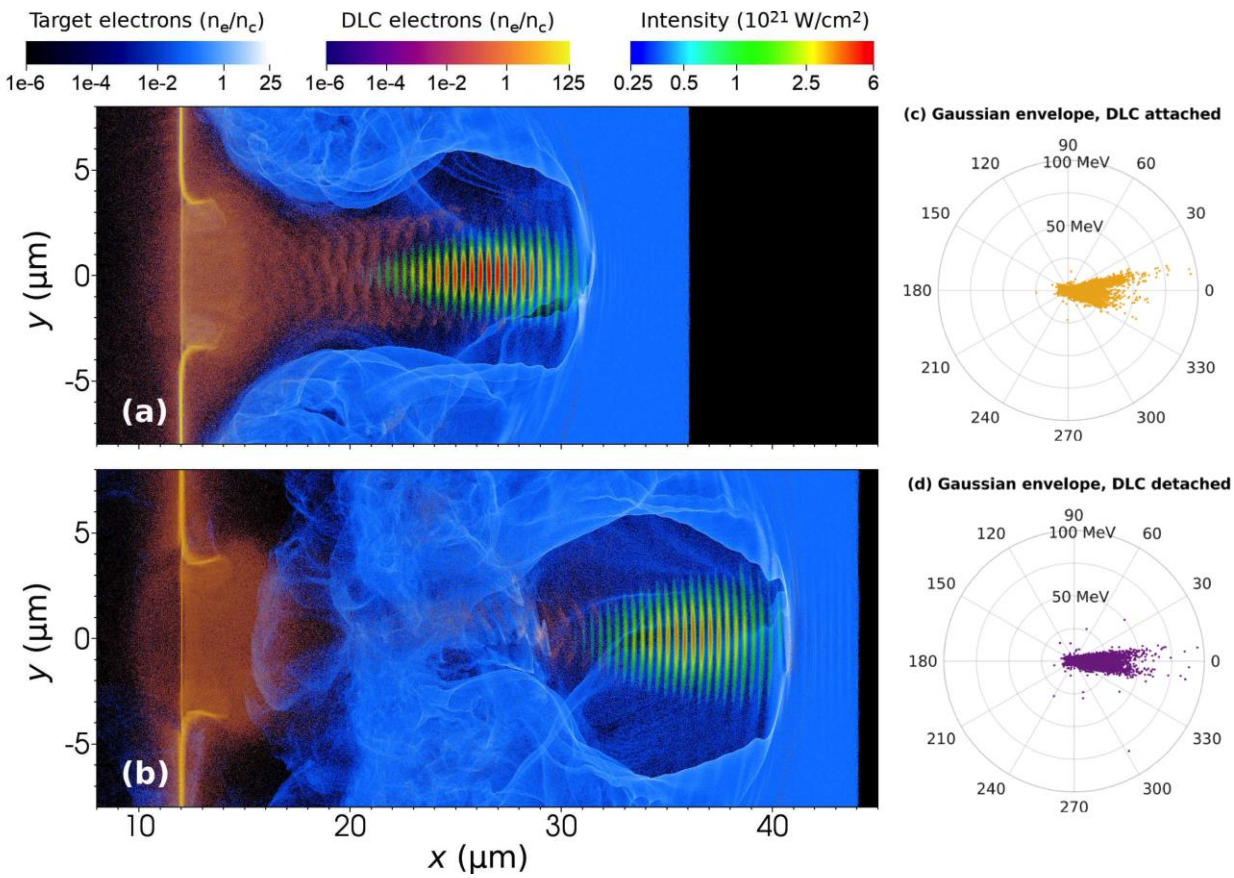

Figure 1: The density of electrons (originating from plasma shutter - orange and the target - blue) and the laser intensity in simulation where a plasma shutter is attached to the underdense plasma to enhance electron acceleration and gamma photon emission. The plasma shutter (DLC foil) is either attached (a) or detached (b) from the under-dense plasma and the resulting angular-energy distribution of gamma photons is shown in (c) and (d), respectively (from [5]).

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MP3 White Paper 2021

Title: Atomic high-field diagnostic using multiple sequential ionization

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Working Group: HFP/QED

Abstract:

We present a method for direct and unambiguous measurement of ultrahigh laser intensities exceeding 10^{20} W/cm^2. The approach is based on the multiple sequential tunneling ionization process of heavy atoms with sufficiently high ionization potentials. We demonstrate that, due to a highly nonlinear dependence of tunneling ionization rates on the electromagnetic field strength, an offset in the charge distribution of ions appears sufficiently sensitive to the peak value of the laser intensity at the laser focus. We present a simple analytic theory able to correctly estimate the maximal charge state produced at a given intensity via the tunnel-ionization mechanism. The theory also allows for calculating qualitatively a distribution in charge states generated in different parts of the laser focus. Furthermore, the geometrical properties of the laser beam can be straightforwardly incorporated in the model. Our qualitative predictions are supported by rigorous numerical simulations of the tunneling cascades developed in the interaction of a short intense laser pulse with a low-density target. Over the basis of the experimental conditions, noble gases are used as targets, including argon, krypton, and xenon, but, in principle, any other species in gas-phase could be employed. Results of these simulations show that, using this technique, intensities in the range 10^{20}–10^{24} W/cm^2 can be measured with sufficient reliability. For 2-electron ions, we have validated the tunneling ionization formula with more elaborated approaches.

Scientific goal:

The continuous development of high-power laser sources in the past few decades, most of them operating at optical and infrared wavelengths, has made possible to see a considerable growth in the intensities of electromagnetic radiation available in laboratories worldwide. Presently, intensities on the onset of 10^{20} W/cm^2 are being routinely used in many laser facilities. Additionally, several lasers of petawatt (PW) powers, delivering pulses of intensities up to 10^{21} W/cm^2, are already commissioned or being in the agenda to be operative soon. Singular reports of even higher intensities, on the order of 10^{22} W/cm^2, still lack of an independent and unambiguous confirmation. However, the forthcoming commissioning of several 10 PW-class laser facilities opens a way to a considerable step forward, both from the theoretical and experimental viewpoints.
For a laser power of 3 PW, expected to be reached at the ELI-Beamlines facility within the next 1–2 years, the peak intensity in a, for instance, 3λ focal spot of an 800 nm laser pulse will exceed 5×10^{22} W/cm^2. If we increase the power to 10 PW, laser pulses focused down to the diffraction limit, promises intensities on the order of 10^{24} W/cm^2 or even higher. These ultrahigh intensities are expected to make new regimes of laser-matter interactions accessible for experimental research, including the radiation-dominated regime, where radiation friction forces play a major role in plasma dynamics, observation of relativistic tunneling, generation of QED cascades of elementary particles developed from seed particles in a laser focus, and many other effects inaccessible at the laser intensities presently available.

Tools required:

Experimental verification and subsequent optimization of the measurement process requires multi-PW laser systems, which operate in a very stable way on a shot-to-shot basis. Ion diagnostics are well-established for this purpose and not a demanding tool. For comparison with experimental data simple simulation tools are available to compare with theoretical prediction. Other, more complicated, approaches for determining the laser intensity might be considered for initial benchmarking of the proposed approach.

Scientific impact:

The problem of precise and unambiguous determination of the electromagnetic field intensity in a laser focus becomes of exceptional importance. From a theoretical viewpoint it is clear that, a precise value of the laser electric field is mandatory, if reliable predictions of the different observables are required. The simplest process, laser-ionization, has a strongly non-linear character. This means that a small change in the electric field peak amplitude has an enormous influence in, for instance, the ionization rate values.
Correct and successful interpretation of any experiment in the field of laser-plasma interaction requires precise knowledge of the in-situ laser intensity and should not be based on extrapolation of low-power measurements.

Broader impact:

The method could be extremely useful and of high demand in view of the expected commissioning of several new laser facilities worldwide capable of delivering ultrapowerful light pulses in this domain of intensities.

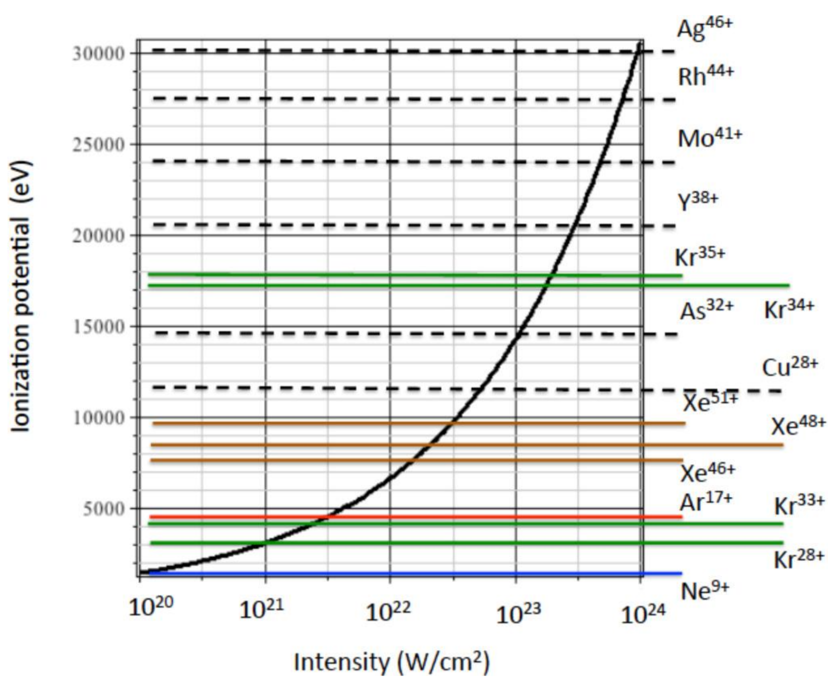

Figure 1: Ionization offset shown by a thick black line as a function of laser intensity. Ionization potentials of several highly charged ions are shown by horizontal lines, including neon (blue), argon (red), krypton (green), and xenon (brown) (from [1]).

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MP3 White Paper 2021

Title: Plasma Amplification for High-Power Lasers

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Working Group: HFP/QED

Abstract:

The upcoming multi-PW laser installations worldwide show a clear interest of the community to push for ever higher laser intensities. This trend is likely to continue for many more years, in particular in the light of near-future important scientific results in completely new laser-matter interaction regimes at ultra-high electromagnetic field strengths. However, this trend requires either continuously increasing sizes of optical components (difficult to manufacture and extremely expensive) or on coherent beam combining (extremely challenging from the technology point of view and not flexible for operation). In this context the use of plasmas for manipulating coherent light has gained considerable interest over the last two decades. It is proposed to invest in more detailed understanding of how to use plasmas in an efficient way for the generation and focusing (re-imaging) of short, ultra-intense light pulses. This will open up the way for laser powers in the multi-hundreds PW regime.

Scientific goal:

Plasma amplification as well as EPM-focusing have been proven experimentally. However, what is missing are proof-of-principle experiments in the high-energy scenario. It needs to be shown that kilo-Joule. Ps-scale pump pulses can be compressed to the 10s of fs-scale and subsequently re-focused with EPMs. If this were shown to be feasible, one could seriously consider the next generation of ultra-high intensity lasers systems to be based on the use of plasma optics in order to approach the exa-watt level in the next decade. A closely related activity is the generation of relatively long lived dynamic plasma gratings in a controlled to change the properties of light pulses, e.g. changing spectral properties, polarization, splitting etc.

Tools required:

An extremely promising scheme for the plasma amplification process and the generation of dynamic gratings is the strong-coupling Brillouin regime, where a pump and seed laser pulse at the same wavelength are required. The seed beam should have the flexibility of variable pulse length from a few cycles to ~100 fs but requires only a low energy level of maximum ~Joule-level. More demanding is the pump beam which is in the range of a few ps up to a few 10s of ps with energies in the kilo-Joule range. The necessary diagnostic tools are standard in the laser-plasma community and well-established. Supporting kinetic and fluid simulations are also necessary but the corresponding codes are available already in the community. As far as the re-focusing with ellipsoidal plasma mirrors is concerned there is a necessity to find a way for mass-production.

Scientific impact:

The scientific impact would be considerable as laser intensities above 10^{24} W/cm^2 could be achieved, going far beyond the expectations of present multi-PW laser systems in the commissioning phase worldwide.

Broader impact:

Such a project would provide considerable incentive to invest more in the growing field of plasma optics for manipulating coherent light. Many experiments have been performed on the "academic level" and need to be expanded in order to show full control of the optical element. This will allow to transfer the scheme to the next level and also push for potential industrial applications.

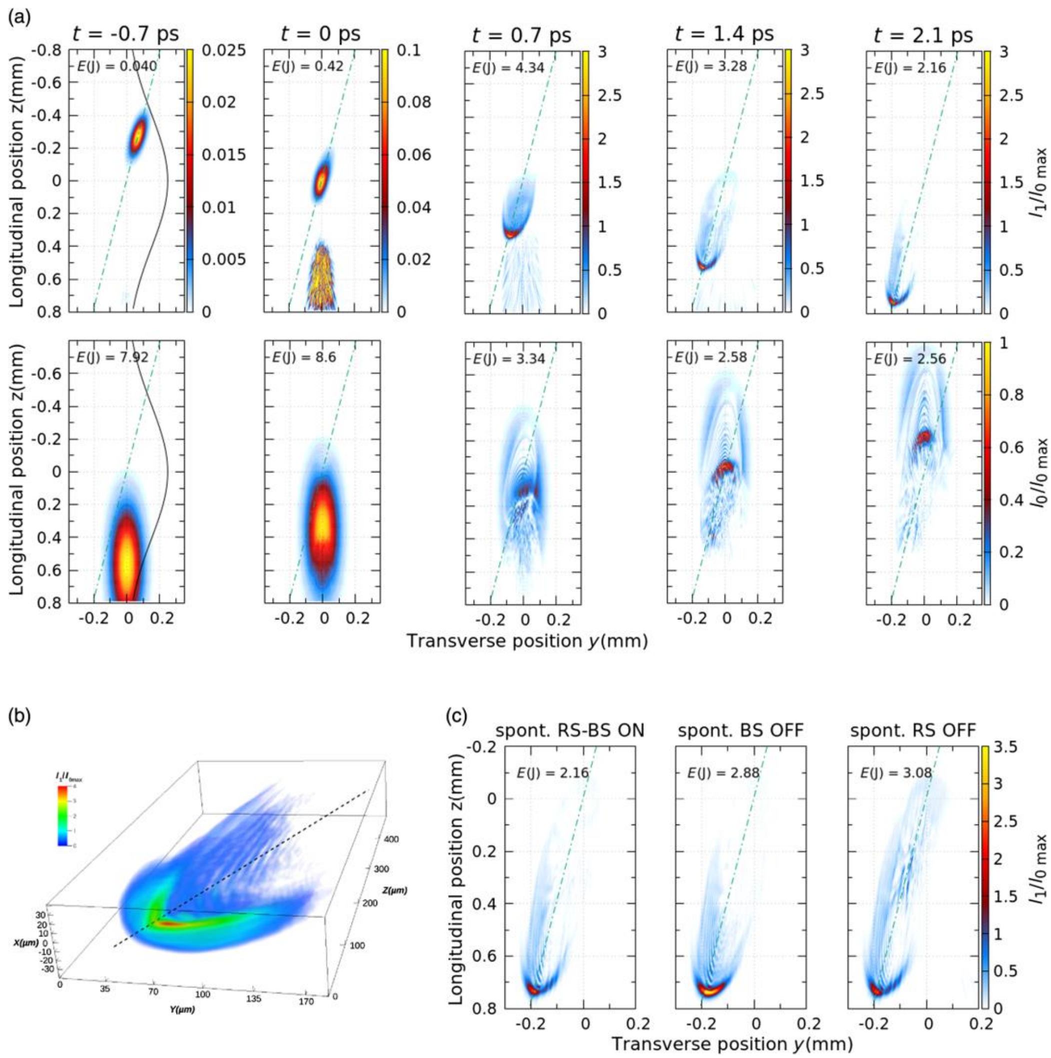

Figure 1: Three-dimensional pump-seed interaction, PF3D simulations. (a) Intensity profiles in the interaction plane (y-z) of the seed [(a) upper images] and pump [(a) bottom images] pulses at different times (increasing from left to right). The green dashed line indicates the seed propagation axis (165° from the pump). The black line in the left images indicates the plasma density profile along the z axis. The pump arrives at the plasma center 1 ps after the seed ($t_0 - t_1$ =1 ps). Intensities are normalized to the incident pump maximum intensity ($I_{0\,max}$ = 4 x 10^{16} W/cm^2). The laser-plasma parameters are the experimental ones; see the experimental setup section. (b) Three-dimensional intensity profile of the amplified seed that reveals the 3D asymmetry [the same laser-plasma parameters as in (a), at time t = 1.7 ps (exit of the plasma)]. The internal spatiotemporal structure of the pulse is visualized through the y-z and x-z plane cuts. (c) Intensity profile in the y-z plane of the seed pulse at the plasma exit (t = 2.1 ps), with [(c) left] or without spontaneous Brillouin [(c) center] and Raman [(c) right] instabilities. The central figure [(c) center] is without ion-acoustic fluctuations, SBS always on. The other parameters are the same as in (a) (from [1]).

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MP3 White Paper 2021
Title: Stochastic laser-plasma interaction with kJ-class petawatt laser light

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Working Group(s): [PAALS]

Abstract: Brief description, maximum of 250 words.

Relativistic intensity lasers with large focal spots and long pulse durations enable us to study laser-plasma interactions as open systems in non-thermal equilibrium states. Under over-pico-second intense laser irradiation, plasma particle distributions in energy and spatial spaces can be quasi-stationary by the balance between laser heating and energy transfer among electrons, ions, and self-generated fields [1, 2]. In the picosecond-scale interactions, electrons exhibit stochastic behaviors through multiple interactions with laser and self-generated fields, which can produce non-thermal energy distributions.

In nature, non-thermal distributions are seen ubiquitously, many of which are generated through stochastic processes in open systems. In universe, the plasma particle distribution evolve to a stationary state when acceleration, friction, and particle flow are balanced, as seen in the cosmic ray energy distribution. Understanding plasma energy distributions is important also for laboratory applications.

In laser-foil interactions, the recirculating electrons are scattered by fluctuating surface fields. The electrons show a random walk laterally in the spot, and the electrons' average energy keeps increasing via stochastic accelerations, which can generate a power law energy spectrum. Such a stochastic electron heating is a key to understand the energetic ion accelerations by multi-ps intense lasers [3, 4]. We can further investigate the evolution of electron distributions in the stochastic interactions including the collisional effects, by using kJ-class petawatt lasers that have relativistic intensities, 10 ps order pulse durations, and spot sizes much wider than the wavelength. For higher intensities, we can study the distribution formations including the energy dissipation by radiations.

Scientific goal: Description of the goal and the methods that would be used.

Understand the plasma structure formation in the open system, e.g., quasi-stationary state of the laser-plasma interface, particle energy distribution, and particle spatial distribution, and construct theoretical models. To verify the models, we use PIC simulations and experimental data.

Tools required: Parameters required for the experiment, or technical requirements/abilities of modeling tools, or theory development. Identify any facility/diagnostic/code developments that need to be made to achieve the goal.

- Current laser systems: Relativistic laser light with a multi-picosecond duration and a few tens of micron large focal spot, e.g., NIF-ARC and LFEX.
- Future laser systems: Petawatt, kJ laser light with higher intensities ~ 10^{20} W/cm^2, 10 ps order duration, and a few tens of micron or larger focal spot.
- Diagnostics: Diagnostics to observe electron/ion particle distributions in a wide energy range, e.g., keV – several tens of MeV electrons. Plasma density and energy density diagnostics to observe plasma expansion and heating. X-ray and gamma-ray diagnostics to observe radiations from high energy electrons.
- PICLS code: Multi-dimensional PIC with collisions, ionizations, and radiations. Advanced modeling is required to simulate the long time (mesoscale) interactions.

Scientific impact(s): What will the impact of achieving this scientific goal be?

The basic theoretical models establish here are important for the applications such as plasma particle acceleration, intense x-/gamma-ray and neutron sources, and controlled fusion.

Broader impacts: Highlight other areas / fields or benefits to broader society where this research could make an impact.

Understanding the physics of the distribution formation in open system is a common interest in a wide range of plasma physics such as magnetically-confined fusion plasmas and astrophysical plasmas.

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Experimental Access to Laser-Driven Gamma Flare

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Working Group(s): HFP/QED: High-Field Physics and Quantum Electrodynamics & LDNP: Laser-Driven Nuclear Physics

Abstract:

Petawatt lasers induce highly nonlinear collective dynamics of matter producing secondary radiation. Photon, lepton, meson and barion beams are generated with unique properties (inherited from femtosecond and micrometer scales and ultra-high irradiance of the laser field): short duration, high density, collimation (low transverse emittance) and femtosecond-scale jitter. Theory predicts a Gamma Flare, where the laser energy is efficiently converted at a tailored plasma into high-power femtosecond beamed gamma radiation. Petawatt lasers can reveal a subthreshold onset of this regime, thus paving the way towards the Gamma Flare realization.

Scientific goal:

In the concept of the Gamma Flare [1-3], a multi-petawatt laser beam effectively penetrates into, slows down in, and strongly couples with a plasma having a gradually increasing density causing the collective regular motion of fast electrons which emit gamma rays, Fig. 1. Under optimal conditions, the interaction occurs in the radiation reaction dominant regime [4,5], and even half of the laser energy can be converted into a gamma ray beam with photon energies in the 10’s of MeV range [3]. The radiation reaction dominates at laser irradiance of the order of or greater than 10^{23} W/cm^2 [4-6], which is achieved in a tight micrometer-scale focus of the multi-petawatt laser, therefore, the resulting gamma ray is shorter than the laser pulse and has a source size less than the laser focus, which makes it high-power and ultra-bright. In addition, the excellent femtosecond time synchronization of the laser system firmly limits the Gamma Flare jitter.

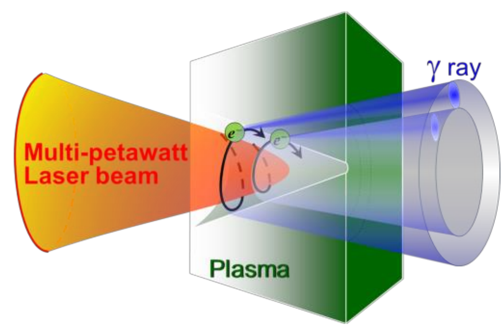

Figure 1 Gamma flare.

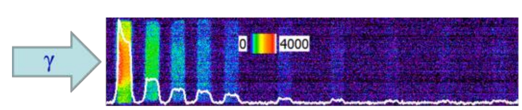

Figure 2 Raw data from a linear scintillator array hard x-ray spectrometer [13,14] (0.1 to 2 MeV) obtained in a single shot [15] of the petawatt class J-KAREN-P laser [16-18].

Multi-petawatt lasers focusable to produce irradiance from 10^{23} to 10^{24} W/cm^2 will be soon available [7-12]. In principle, under optimal conditions and sophisticated diagnostics [13,14] a subthreshold onset of the Gamma Flare regime can be seen [15] with lasers of petawatt class [16-18], Fig. 2. In this case the indication of the Gamma Flare is the presence of sufficiently high-energy, both in terms of photon energy and total energy, gamma rays whose properties make it well distinguishable from bremsstrahlung and other possible channels. In particular, the gamma rays should be shorter than or of the same duration as the laser pulse and should have a characteristic angular distribution and polarization.

According to theory and simulations [1-6], the necessary optimal conditions are mainly related to the target density profile and the laser focusability, both determined by the laser pulse quality, in terms of the Strehl ratio and the contrast ratio (between ASE with prepulses and the main pulse). Although an optimal target profile can be formed through an ablation due to ASE, a more controllable method makes use of target pre-shot modifications, e.g., with a separate auxiliary laser. For diagnostics, new detectors and methods must be developed, especially femtosecond time resolved detectors for the gamma rays, preferably capable of single-shot operation.

Tools required:

Subthreshold experiments on the Gamma Flash require (1) high-stability (low shot-to-shot fluctuations of all the laser parameters) high-quality laser capable of producing irradiation of 10^{22} W/cm^2 or higher on target; (2) new methods for producing optimal targets, e.g, target pre-shot modifications by a separate auxiliary laser or by other mechanisms; (3) femtosecond-scale time resolved gamma ray diagnostics; (4) extensive simulations of the laser-plasma interaction, of targetry modifications and of novel diagnostics.

Scientific impact(s):

The fundamental goal is the experimental access to collective effects in lepton-photon plasma in the Gamma Flare regime itself and in the separate processes where the Gamma Flare beams are used for pumping or probing. In particular, subthreshold experiments with petawatt lasers will be used for validation of theoretical models and the development of gamma ray diagnostics.

Broader impacts:

Femtosecond petawatt gamma ray beams will be a revolutionary tool for time-resolved measurements in fundamental nuclear physics, laboratory astrophysics and nuclear technology, including security applications. New gamma ray diagnostics and detectors will be important in various fields of physics and technology. Last but not least, experimental demonstration of the Gamma Flare will provide validation of a high on-target laser irradiance.

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Muon production for the detection of high-energy photons from laser-electron collisions

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The interaction of fundamental particles (predominantly electrons and photons) with laser fields approaching the critical Schwinger electric field ($E_S = 1.32 \times 10^{18}$ V/m) is one of the emerging topics of research in ultra-intense laser-plasma physics. As such, in the coming years, quantum electrodynamical effects will be explored experimentally at multi-PW laser (CoReLS, ELI-NP, Apollon, ZEUS, OPAL-EP, etc.) [1,2,3,4] and accelerator (LUXE@DESY, FACET-II@ SLAC) [4,5] facilities. Of particular interest will be the investigation of laser-electron collisions, opening a gateway to explore nonlinear Compton scattering (NCS), to examine models of radiation reaction, to produce e-e+ pairs, and to generate bright photon beams.

It is expected that the photon spectra produced in laser-electron collisions will be of central importance to understand the physical mechanisms under study. The spectra will exhibit complex structures spanning in the energy range of 1 MeV - 20 GeV and particle numbers ranging over several orders of magnitude. Features such as cutoffs, harmonics, plateaus, and slope structures will carry the signatures of physical models [6] and will therefore require precise and complementary detection methods.

In this work, we investigate alternative methods for the high energy gamma photon detection ($E\gamma > 200$ MeV), in particular the feasibility of using the dimuon production process ($\gamma + Z \rightarrow Z + \mu^+ + \mu^-$) for detecting specific features of the photon beam spectra. Muon production has been proposed for laser-based experiments, but rather from the bremsstrahlung production ($e + Z \rightarrow e' + \gamma + Z$; $\gamma + Z \rightarrow Z + \mu^+ + \mu^-$) and electron-nuclei interaction ($e + Z \rightarrow e' + Z + \mu^+ + \mu^-$) using LWFA-accelerated electron beams [7,8,9,10,11]. However, the cross section of the photon induced pair production (0.5 mb at 1 GeV) [9] can render direct muon photo-production as a more efficient mechanism than the electron-muon production.

As the muon has a mass m_μ=105.7 MeV/c^2 , the pair production process requires a photon energy threshold $E_\gamma > E_{\mu+} + E_{\mu-} > 211$ MeV. Significant production is expected to be triggered by the interaction of 0.3-10 GeV photon beams with dense high-Z targets. Such photons can be produced, for example, during nonlinear Compton scattering by colliding an LWFA accelerated electron beam (up to 10 GeV) with a high-intensity laser pulse of $I > 10^{20}$W/cm^2 ; this source is cleaner than a bremsstrahlung source from an electron-target interaction, as it does not generate significant background particles besides photons, electrons and positrons. We discuss the expected properties of muons produced from NCS photons, their spectral and angular distribution, various setups, and dependence on the photon spectral shape. The muons carry with them the signatures of the photon spectra and their properties will be crucial for developing future detection setups [10].

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High-energy and high-quality positron beams from a laser wake-field accelerator

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White paper submission for working group PAALS

Abstract
While plasma-based acceleration of electrons is now sufficiently mature for applied studies, plasma-based positron acceleration is still at its infancy, due to intrinsic difficulties in efficient accelerating them in a plasma structure. With only limited options for test facilities worldwide, it is now pressing to provide high-quality GeV-scale positron beams to the community. Following recent numerical work and preliminary experimental validations, we propose here to use multi-PW laser systems to generate fs-scale ultra-relativistic positron beams with high spatial and spectral quality. This would represent an ideal tool to experimentally study wakefield acceleration of positron beams, a stepping stone towards the possibility of building plasma-based colliders.

Scientific goal

The goal of this proposal is to demonstrate, for the first time, laser-driven generation of positron beams with high charge per bunch (of the order of 1 pC in a 5% energy slice), ultra-short duration (few fs), high-energy (tuneable from 0.5 to 10 Gev), and good normalised emittance (of the order of 100 μm at 10 GeV) directly from a laser-driven wakefield accelerator. Numerical simulations [1] and preliminary experimental work at the 100-MeV level [2] and at the GeV level [3] confirm the full feasibility of the experiment. By measuring the positron spectrum, total charge, and energy-dependent emittance of both the positrons and electrons, we aim at fully characterising the system and demonstrate generation of high-quality multi-GeV positrons directly from a laser-wakefield accelerators.

In a nutshell, we aim at using a long focal length parabola (F/40 or more) to focus the multi-PW beam onto a high-pressure gas-jet of variable length (from a few mm up to a few cm) and gas composition (mainly either pure helium or helium doped with a variable percentage of nitrogen, to favour ionisation injection) to generate a heavily-loaded wakefield accelerator that will provide multi-GeV electron beams with a total charge of the order, if not exceeding, 100 pC. The electron beam will then be directed onto a relatively thick high-Z converter target (e.g., 0.5 – 1 cm of lead) to generate the positron beams, alongside gamma-ray radiation and scattered electrons. It is important to note here that the requirements on the primary electron beam are significantly relaxed, without any real constraint on the spectral shape of the beam. The only requirements are a high peak energy and a high overall charge, both elements that contribute towards maximising the number of positrons per bunch. An already tested magnetic dog-leg can then be used to separate the positrons from the rest of the products of the electromagnetic cascade in the converter target. It can also be used to provide energy selection capability in the system. An already designed emittance mask can then be inserted to measure the energy-dependent geometrical emittance of both the positron beam and the scattered electrons, as already tested at the 100-MeV level [2] and at the GeV level [3].

Main tools required

- Long-focussing off-axis parabola (F/40 or, if possible, more)
- High-pressure gas-jet of variable length (from a few mm up to a few cm)
- Different gases, mainly pure helium and helium doped with a variable percentage of nitrogen (from 0.5 to 5%)
- Two static magnetic dipoles
- Scintillator screens and imaging plates
- Emittance mask (to be provided by QUB)
- Shielding
- For numerical modelling, mainly Monte-Carlo scattering codes such as FLUKA or GEANT4, and Particle-In-Cell codes such as EPOCH for the electron beam generation. All numerical modelling tools are already available at QUB.

Scientific impact

The generation of high-quality and ultra-short ultra-relativistic positron beams would represent a pivotal tool for several branches of fundamental physics. First of all, it will provide a unique test facility to study plasma-based acceleration of positrons, a fervent area of research at the minute, as demonstrated, for example, by the interest of several international communities and committees [4-6]. As an example, Gev-scale positron beams is one of the main user areas proposed for the plasma-based European accelerator EuPRAXIA [4].

It is envisaged that further optimisation could even lead to demonstrating laser-driven systems as suitable and compact GeV-level injectors for positron accelerators and, in a future, lepton colliders.

It will also provide a unique facility to study the dynamics of neutral electron-positron beams (obtainable by increasing the target thickness to about 4-5 radiation lengths) in the relativistic regime [7,8]. Exotic, and yet central in astrophysics, phenomena such as Weibel-like generation of magnetic fields, collision-less field dissipation, and reconnection could all be studied in a controlled and monitored environment, providing unique data in the emerging field of laboratory astrophysics.

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High-field quantum electrodynamics in the field of an intense laser

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White paper submission for working group HFP/QED

Abstract: multi-PW laser systems will allow to reach unprecedented focussed field intensities of the order of, if not exceeding, 10^{23} Wcm^{-2}. The propagation of an ultra-relativistic electron beam or a high-energy photon beam through a field of such intensity is expected to trigger exotic phenomena, including quantum radiation reaction, highly non-linear Compton scattering, and Breit-Wheeler pair production, where quantum effects in the electron or photon dynamics will play a dominant role. Such an experimental configuration will represent a unique platform to test quantum electrodynamics in a non-perturbative regime, allowing for the first experimental studies of this novel branch of fundamental physics, with ample repercussions in several areas of physics, including astrophysics, particle physics, and plasma physics.

Scientific goal: the goal of this proposal is to perform a series of experimental campaigns devoted to experimentally studying, with high-statistics and high-precision, several key features of non-perturbative quantum electrodynamics. Several iconic phenomena can be created and methodically characterised, including the quantum nature of radiation reaction, highly non-linear (i.e., multi-photon) Compton scattering and linear (i.e., above threshold) and non-linear (i.e. below threshold) Breit-Wheeler pair production. This will inaugurate a novel branch of experimental physics and provide unique and precious data to advance our understanding of non-perturbative quantum electrodynamics, with far-reaching and profound implications for several branches of physics, including astrophysics, particle physics, and plasma physics.

In a first configuration, multi-GeV and high-quality (i.e., low divergence and narrow bandwidth) electron beams from a laser-driven wakefield accelerator will be made to interact, either head on or at a small angle, with the tight focus of a high-intensity laser beam. Multi-PW laser systems are expected to achieve focussed intensities of the order of, if not exceeding, 10^{23} Wcm^{-2}, resulting in a laser dimensionless amplitude $a_0 \sim 100$. For the sake of discussion, we can assume a 2 GeV primary electron beam, easily achievable nowadays even with sub-PW laser systems. In their own rest frame, the electrons will then experience a field of the order of 1 to 2 times the critical field of quantum electrodynamics. In this regime, a classical description of radiation reaction, as described by the Landau-Lifshitz formula, will be inaccurate and quantum effects such as a hard cut-off in the frequency of the emitted radiation and the stochastic nature of photon emission must be taken into full account. Correspondingly, highly non-linear Compton scattering (i.e. multi-photon) will be a dominant mechanism. Our group has performed preliminary experiments at the sub-PW level using the Astra-Gemini laser hosted by the Central Laser Facility in the UK, providing the first experimental indications of the quantum nature of radiation reaction [1,2].

We aim at fully characterising these phenomena by measuring the spectrum of the scattered electrons and the spectrum and spatial profile of the Compton-scattered photon beam, implementing a gamma-ray spectrometer design that we have recently proposed [3]. In this regime it is also expected that a non-negligible number of electron-positron pairs will be generated, mainly following the interaction of the Compton-scattered photon beam with the remainder of the laser photons. As an example, a 2 GeV electron beam interacting with a focussed laser intensity with a dimensionless intensity of $a_0 \sim 100$ is expected to generate up to 10^{-3} pairs per incoming primary electron. As an example, even if only 0.1 pC of electrons interact with the high intensity part of the laser focus, this would still result in ~ 600 pairs per event. By measuring the spectrum and yield of positrons per shot we can thus provide the first full characterisation of non-linear Breit-Wheeler pair production, parametrising it with electron energy (thus providing the dependence of the production rate with the field experienced in the electron rest frame) and with the laser intensity (thus providing the dependence of the production rate with the non-linearity of the interaction, i.e., with the number of photons absorbed per formation length).

By inserting a thin converter target in the path of the primary electron beam we can also perform studies of direct photon-photon interactions, either below threshold (bremsstrahlung photons interacting directly with the laser field) or above threshold (bremsstrahlung photons interacting with an x-ray bath produced by a laser-driven exploding foil). This will represent the first experimental demonstration of direct conversion of energy into matter, in a pure photon-photon collision. It must be noted that even if pair production is a well-established process, this will be the first time this phenomenon will be observed in a clean environment, i.e., without the complications associated with nuclear and particle physics phenomena brought in by the presence of atomic nuclei or massive particle beams in the interaction area.

In all configurations, even though two laser beams would be desirable, it must be noted that the experiments can still be performed with a single laser beam, provided that adequate splitting is performed for the lasers driving the wakefield and providing the scattering field.

In a nutshell, we then envisage a staged approach leading to a series of experimental campaigns. In a first stage, the electron beam will be made to directly interact with a tightly focussed laser. A magnetic spectrometer will then allow for the measurement of the phase space of the scattered electrons, whereas a suite of gamma-ray diagnostics including a gamma-ray profiler and a gamma-ray spectrometer [3] will be used to measure the spatial and spectral properties of the Compton-scattered photons. Calorimetry and single-particle detectors in a highly shielded environment can then be used to measure the yield and spectrum of the positrons generated via Breit-Wheeler pair production.

We then propose to insert a thin converter target into the path of the primary electron beam, to provide a high-energy and high-flux photon beam following bremsstrahlung of the electrons in the converter. After sweeping away the scattered electrons, the bremsstrahlung radiation can then be made to interact either with the focus of a high-intensity laser or with x-ray radiation produced by a laser-driven exploding foil. We will then measure the yield and spectrum of both the electrons and positrons generated via linear (in the interaction with x-ray radiation) or non-linear (in the interaction with the laser focus) Breit-Wheeler pair production.

This work is in collaboration with several research groups, including, but not limited to, Imperial College London, University of Michigan, Helmholtz Institute Jena, Max Planck Institute for Nuclear Physics in Heidelberg and University of York.

Main tools required

- Laser wakefield accelerator

- Long-focussing off-axis parabola (F/40 or, if possible, more)
- Gas-cell of variable length (from a few mm up to a few cm) or gas-jet of variable length with a motorised razor blade to perform shock-injection.
- Different gases, mainly pure helium and helium doped with a variable percentage of nitrogen (from 0.5 to 5%)
- Static magnetic dipole and scintillator screens
- For numerical modelling Particle-In-Cell codes such as EPOCH for the electron beam generation. Capability available at QUB

- Scattering laser

- Short focus off-axis parabola (e.g. F/2)
- Spectral interferometry [4] for fine synchronisation at the interaction point.
- Apodised laser splitting system (if only one laser beam available).

- Photon production and detectors

- Thin converter target (sub-mm) for bremsstrahlung generation and ultra-thin (tens of nm) solid target for x-ray generation.
- Extra dipole magnet to sweep scattered electrons from the interaction point.

- Calorimetry and single particle detectors for the detection of electron-positron pairs (available at QUB and from collaborators)
- Gamma-ray profiler and gamma-ray spectrometer (available at QUB).
- For the modelling part, Monte-Carlo simulations for the detector response and the bremsstrahlung generation (available at QUB). For the QED phenomena both single particle and multi-particle codes available from our collaborators at Max Planck Institute for Nuclear Physics in Heidelberg and University of York.

Scientific impact: the field of laser-based HIQED is rapidly progressing worldwide, with our group and collaborators being the first, and thus far only, scientists to provide experimental evidence of quantum effects in the dynamics of an electron beam in a intense laser field in an all-optical setup [1,2]. QED phenomena will be of interest for Multi-PW facilities that are now coming up online worldwide: South Korea has an operating multi-PW laser system, CoReLS; China is constructing a 100 PW laser system, the Station of Extreme Light (SEL); the US are evaluating a proposal to fund a 75 PW laser system EP-OPAL as part of LaserNetUS; and in Europe, the multi-PW Extreme Light Infrastructure (ELI) pillars in the Czech Republic, Romania, and Hungary are currently being commissioned, alongside the multi-PW French laser system, Apollon. This international interest in high-field QED (HIQED) experiments is further demonstrated by their inclusion as major areas of future research by international research bodies and entities, such as the Plasma Wakefield Accelerator Steering Committee in the UK [5], the EU-funded EuPRAXIA [6], and the US Department of Energy [7].

Studying HIQED is not only of fundamental interest, but is also a necessary stepping stone towards the optimisation of laser-driven particle and photon sources. Multi-PW laser systems are expected to generate particle beams of sufficient quality for a variety of applications. For instance, proton beams of hundreds of MeV will allow for laser-based hadron-therapy; extreme multi-MeV up to GeV gamma-ray beams will allow for unprecedented nuclear studies and inspection of strategically important materials through thick high-Z containers; softer x-ray sources will allow for phase-contrast imaging at unprecedented resolution and with negligible dose delivery to the tissue. HIQED effects will play a pivotal role in the generation of these beams, which can thus only be optimised with a thorough understanding of this branch of physics.

At sufficiently high electromagnetic field intensities, plasma dynamics is dominated by quantum processes. Several numerical codes have been developed worldwide, including CAIN, GUINEA-PIG, OSIRIS, and the UK-developed code EPOCH, which include HIQED processes and their interplay with particle dynamics. However, the majority of such codes use approximations that a) have never been tested experimentally and b) only have intensity-specific ranges of validity. Testing and improving these approximations is urgent to ensure accurate experimental design and interpretation. HIQED effects are also invoked to explain the dynamics and radiative properties of astrophysical plasmas in the proximity of ultra-massive objects and understanding them will aid the design of next-generation particle colliders (CLIC and ILC will reach the critical field at the interaction point).

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High Power Gamma Flashes Generated in Multi-Petawatt Laser-Matter Interaction for Fundamental Science and Applications

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Working Groups: HFP/QED: High-Field Physics and Quantum Electrodynamics & LDNP: Laser-Driven Nuclear Physics

Abstract:
Multi-petawatt lasers interacting with solid density targets produce copious number of high energy charged particles and photons. By optimizing the laser-target parameters we can enter the regimes of extremely high efficiency of the laser energy conversion to the energy of high power collimated gamma ray beams. This process is accompanied by production of the electron-positron pairs and by the electron and ion acceleration. We believe that these gamma ray sources will find a wide range of application in applied and fundamental sciences in particular in such areas as material science and nuclear physics.

Scientific goal:
Petawatt class lasers are already routinely operating at facilities all over the world [1]. Ten-PW lasers are coming into operation at ELI-BL and ELI-NP [2, 3]. There are projects of developing hundred PW lasers [4, 5]. Multi-PW lasers are expected to be available producing intensities ranging from 10^{23} to 10^{25} W/cm^2. At the high intensity end, irradiation of plasma targets by a multi-PW laser will lead to the manifestation of nonlinear Thomson and Compton scattering processes, causing emission of gamma-photons with energies up to the GeV-scale. Generation of high power gamma-flares is considered to be one of the primary goals for high power laser facilities [5, 6]. A laser-based gamma-ray source may be applicable in radiation chemistry and materials sciences, in medicine, in nuclear physics, where gamma-rays will help to excite isotopes for further use, as well as for laboratory astrophysics research, testing theories on astrophysical gamma-ray burst generation and behavior of a quantum electrodynamics (QED) plasma in pulsar magnetospheres.

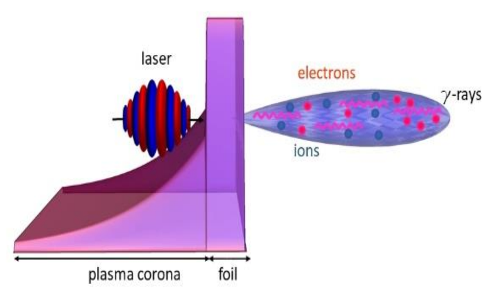

Fig. 1. The concept of high power gamma-ray flash generation in the laser-matter interaction.

Tools required:

As theoretically foreseen, an irradiation of plasma targets by multi-petawatt laser radiation can result in high efficiency of the laser energy conversion to the energy of gamma-ray flash [7-9] with the conversion efficiency approaching 50% observed from multi-parametric scans performed with PIC simulations using computer codes with the QED process description implemented. Concrete regimes of the gamma-flash generation depend on whether the high power laser pulse is of long or ultra-short duration.

In the case of a relatively long (a few tens of fs) laser pulse the plasma corona preceding the high density slab target (see Fig. 1) plays a crucial role. The plasma corona formation by the laser ASE pedestal or by additional long laser pulse requires detailed study and extensive hydrodynamics simulations using high-performance computers [10, 11].

For ultra-short pulse lasers the choice of the laser pulse polarization plays a key role. As shown in Ref. [12] a 75 PW single cycle laser pulse with TM polarization irradiating an optimal thickness high Z target allows extremely high (up to 50%) energy conversion to a collimated gamma beam (Figs. 2 and 3). The electromagnetic field used there can be considered as the realization of the multi-pulse concept formulated in [13] with the 3D TM mode configuration proposed in [14] (see also papers [15-17]).

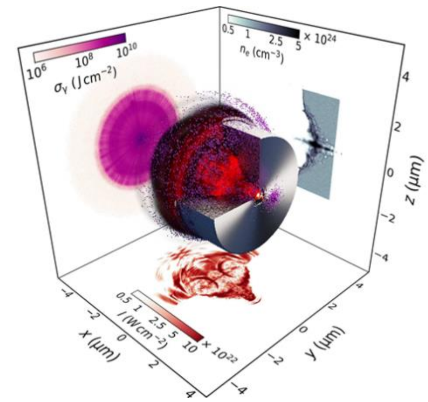

Fig. 2. The laser intensity and electron density (red and gray colors); the purple dots are the gamma-photons. The (x,y)-plane and (x,z)-plane at z = 0 show the cross-sections of the intensity and electron density. The gamma-photons surface energy density is shown in the (y,z)-plane [12].

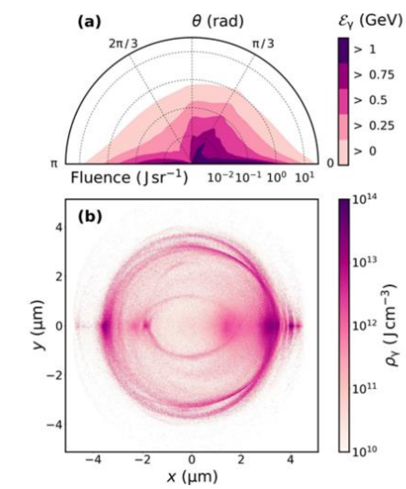

Fig. 3. (a) The angular distribution of the gamma-photon fluence. (b) The gamma photon energy density in the (x,y)-plane [12].

Scientific impact(s):

The development of the scientific program described above will allow the researches to obtain a gamma ray source with unprecedented parameters in that it concerns the laser energy conversion efficiency into the gamma photons and fast particles providing a versatile tool for fundamental science (e.g. for nuclear physics) and for various applications.

Broader impacts:

The studying of the processes resulting in the gamma-flash generation will undoubtedly enrich our knowledge on the properties of the emerging state of matter governed by the electrodynamics of radiation dominated continuous media in the ultra-relativistic limit characterized by collective processes which include electron-positron pair creation, gamma ray generation and acceleration of ions and electrons [18-21].

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Measurements of Transport Properties in Warm Dense Matter with Multi-Petawatt Lasers

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Working Group: LAP: Laboratory Astrophysics

Abstract: Measurements of transport properties such as diffusion, thermal conductivity, and viscosity present a significant challenge in the study of high-energy-density matter (HED), current experiments are hindered by the inability to generate uniformly heated macroscopic samples[1]. In shock compression experiments, probing multiple temporally evolving states complicates the analysis, with measurements of dynamic processes showing particular sensitivity to thermodynamic gradients[2]. Samples heated isochorically with intense X-ray or particle beams display more uniformity[3]. However, the experiment's duration is often limited by the small sample size, which at pressures above ∼10 megabar is restricted by inertial confinement. Current experiments disassemble on a sub-tens-of-nanoseconds timescale. This presents a problem when studying long-lived phenomena directly—for example, transport processes.

A new generation of ultra-intense and powerful lasers will lead to an increase in the energy and fluence of secondary radiation sources such as protons, electrons, or X-rays. With the higher energies comes an increased penetration depth and the ability to uniformly and isochorically heat multi-millimeter-scale samples to temperatures of tens to hundreds of electronvolts. At these conditions, such samples would last for hundreds of nanoseconds before disassembly, paving the way for new high fidelity measurements of thermal conductivity and particle diffusion. Both of which play a vital role in several areas of contemporary HED research, including astrophysical and inertial confinement fusion (ICF) systems.

Scientific goal: Measurements of transport properties in warm dense matter samples are difficult and few and far between. One reason, highlighted for particle and heat diffusion in table 1, is that they are slow. In experiments limited to a few nanoseconds, heat transport effects may be observed in materials with high thermal conductivity. However, on nanosecond timescales, a direct measurement of diffusion is challenging, and for heavier elements, it is currently unfeasible.

Quantity	Typical Value	Scale length (nm)			
		1 ns	10 ns	100 ns	1000 ns
Diffusion (Deuterium, 1 eV)	1×10^{-2} cm^2/s	60	200	450	2000
Diffusion (Deuterium, 100 eV)	1 cm^2/s	600	2000	4500	20000
Diffusion (Iron 10 eV)	2×10^{-3} cm^2/s	30	100	300	1000
Thermal Conductivity (CH, 1 eV)	10 W/m/K	150	500	1500	5000
Thermal Conductivity (W, 1 g/cc, 1 eV)	30 W/m/K	1000	3500	10000	35000

Table 1: Scale length of diffusion and thermal conductivity in warm dense matter samples with increasing time.

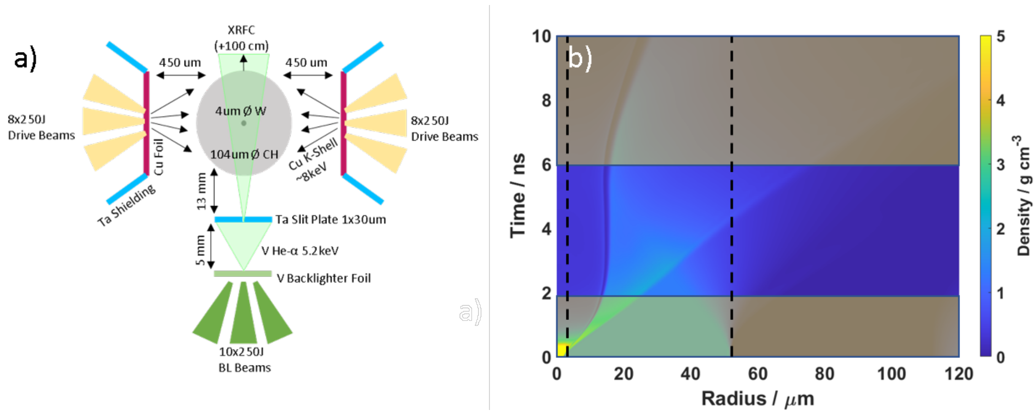

Figure 1: Experimental setup and hydrodynamic simulations showing target evolution. The two shaded regions denote areas where short-pulse multi-Petawatt lasers can improve such experiments. At early time the rapid expansion of the target requires an temporally short probe such as that provided by K_α emission. At late times, the disassembly of the target can be delayed by creating increasingly macroscopic samples. The black-dashed lines denote the initial radius of the buried wire and outer cylinder.

Figure 1 presents a schematic for our isochoric heating platform developed initially for the OMEGA laser facility. It couples X-ray heated cylindrical samples with micron-wide slits for diffraction-enhanced imaging of the interface with ultra-high (sub-micron) resolution. Using this platform, we have successfully measured the evolution of the scale length at the interface between the two materials, which, between 2 and 6 ns, is driven predominantly by thermal conduction. Our goal is to extend such experiments by utilizing the secondary radiation sources produced in multi-petawatt laser-solid target interactions to instantly and uniformly heat much larger samples to extreme conditions.

At high intensities, the lower conversion efficiency of K_α emission when compared to conventional He-α or M-L band emission makes X-ray heating of large samples challenging. With that said, textured or nano-wire tagets have demonstrated high conversion efficiencies in the sub-picosecond regime[4]. Nonetheless, the short duration and narrower line profile of K_α emission make an excellent probe suitable for capturing fast phenomena such as the initial expansion of the driven target.

An alternative secondary source for isochoric heating is fast electrons. At high intensity and linear polarisation, both j×B and vacuum heating convert tens of percent of laser energy into a suprathermal population of fast electrons. In turn, these electrons volumetrically heat the target through thermal diffusion, resistive heating by a cold return current, or through direct collisions[5]. For the highest intensity lasers, fast electrons with tens of MeV of energy are injected into the target[6]. These electrons have a multi-millimeter range in even the densest materials. For electrons above 10 MeV, the stopping power and range increase in most materials, allowing for hotter, larger, and more uniform samples. However, creating a sufficient number of hot electrons to heat the entirety of a large target uniformly requires multi-petawatt class systems delivering hundreds of Joules of energy. Additionally, the electrons' increased range allows the target to be situated further from the intense laser interaction, reducing problematic hard X-ray noise and interference.

A third option is laser–ion acceleration through target-normal-sheath-acceleration or, at the highest intensities ($> 10^{22}$ W/cm^2), radiation pressure acceleration. Such schemes can generate GeV ions with centimeter ranges, however, the broad spectrum leads to large temporal dispersion that make them less suitable than electrons for isochoric heating of macroscopic samples[3].

Tools required: The pump-probe experiments described necessarily require at least two high-intensity laser beams. Particle acceleration typically requires high-contrast ($> 10^8$) with sub-picosecond pulse lengths. Assuming a conversion efficiency into secondary radiation of tens of percent and requiring uniform volumetric heating of multi-millimeter samples to electronvolt temperatures requires hundreds of Joules of energy in the optical. Efficient X-ray generation with structured targets requires exceptionally high contrast ($\sim 10^{12}$) to prevent target damage by the prepulse. Additionally, the colocation of a multi-petawatt laser with other unique laser systems opens the door to novel experiments. A long-pulse driver coupled to an isochoric heating platform could explore off-Hugoniot parts of phase space, while an XFEL would provide exceptional diagnostic capabilities.

Scientific impact: Our current understanding of many astrophysical objects relies on the complex modeling of many competing effects such as particle diffusion, thermal conduction, hydrodynamics, chemistry, equation of state, and gravity. In white dwarf and neutron stars, diffusion is key to atmospheric purification[7]. In models of Jovian planets' interiors, an understanding of the transport properties is necessary to determine both flow dynamics and magnetic field generation [8]. At the same time, understanding the peculiar magnetic fields of Uranus and Neptune relies on calculated values of the thermal conductivity[9]. A dearth of experimental measurements has led to a considerable body of theoretical and computational work[10]. Specifically, a measurement of the diffusion coefficient in iron, relevant to the interiors of Uranus and Neptune[11], could validate state-of-the-art quantum mechanical simulations[12].

Broader impacts: Warm dense matter also has practical applications for understanding controlled thermonuclear fusion and in material processing. The design of ICF implosions depends on the thermal conductivity and diffusivity of both the ablator materials and the fuel mixture[13]. Diffusion is a mechanism for fuel degradation and a corresponding reduction in efficiency, affecting the growth of instabilities at the interface between ablator and fuel within the fusion capsule[14]. The Rayleigh-Taylor instability in particular is sensitive to the mutual diffusion coefficient[15], while inside the fusion capsule itself mutual diffusion between Deuterium and Tritium plays a key role.

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MP3 White Paper 2021
Energy deposition in magnetized dense plasma by laser-driven relativistic electrons

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Abstract:

A power laser can inject plenty of energy into matter in a small volume within a short time duration. The matter becomes a high-energy-density state that is applicable to various areas of scientific research. Especially, the fast isochoric laser heating of a compressed dense plasma core is one of the schemes to create an extremely high-energy-density state, which is equivalent to the state for inertial confinement fusion (ICF) science.

High gain ICF scenarios may be enabled by the beneficial heating from relativistic electron beam produced with an intense laser. Improving the electron confinement along the propagation axis would significantly raise the electron energy flux deep into a target. Several challenges remain for the realization elated to the accurate description of the magneto-hydrodynamics of the implosion, such as the magnetization of the dense core, and the optimization of the electron energy deposition into the core.

Scientific goal:

In the context of ICF, the fast isochoric heating also known as fast ignition had been proposed as an alternative approach to the ICF ignition [1]. This approach separates compression and heating processes using a stable compression followed by an external energy injection by laser-driven relativistic electrons. It has been estimated that the electron beam with kinetic energies of 1–2MeV needs to deposit ≈ 20 kJ into a 20μm radius lateral hot spot in the compressed core to trigger ignition [2]. However, the generation and transport of the electron beam from its generation point to the dense core is complex and raised several issues, mainly due to the beam divergence. A major challenge is therefore to ensure a guided electron beam propagation within the FI integrated target before it reaches the fuel core.

The method employs a magnetic field that is applied to the transport region from the relativistic electron beam generation zone to the core which results in guiding the relativistic electron beam along the magnetic field lines to the core had been proposed. This scheme may provide more efficient energy coupling compared to the conventional Inertial Confinement Fusion scheme. For example, the gyroradius of a 1 MeV electron under the influence of a 1 kT magnetic field is 5 μm, which is smaller than a typical core radius (20 μm); therefore, a kilo-Tesla-level magnetic field is sufficient to guide the electron beam to the core. The guidance of the electron beam by an external magnetic field has already been demonstrated experimentally in an uncompressed planar geometry at LULI2000 facility [3]. We need to demonstrate this scheme in compressed geometry.

Tools required:

We performed a cylindrical implosion experiment [4] using an initial magnetic field of 18T at OMEGA laser facility to investigate the energy deposition in magnetized dense plasma. Our PIC-Hybrid simulations unraveled the magnetic field guiding in this geometry primarily depends on the initial strength of the external magnetic field [5]. In the case of the initial magnetic field = 10 T, the conversion efficiencies near the maximum compression time, significantly increase 0.2% to 1.8% as the compressed magnetic field becomes larger than the self-generated magnetic field near the front surface of the cylinder target. For a stronger external magnetic field, the efficiencies keep increasing with the magnetic field strength. The Magnetic Field Generation Device (MIFEDS) in OMEGA delivered 18 T around the cylinder target, which is enough to see the effect of electron beam guiding. If the MIFEDS can generate stronger magnetic field, it may more helps the electrons to deposit their energy.

The implosion history was obtained with an X-ray framing camera compared with 2D FLASH simulation [6]. Predicted maximum compression time using FLASH code agrees well with the experimental results of XRFC. The implosion histories without and with the magnetic field were similar in the experiment, except for the absolute amount of emission. The FLASH only includes the magnetic field pressure as magnetohydrodynamics (MHD) effect, so it is difficult to predict the difference of the absolute amount of emission. An extended MHD-code such as Gorgon [7] is suitable for further understanding of the data.

The Electron energy deposition was measured via time-integrated K-shell spectroscopy of tracer foils located on each end of the cylinder. We successfully measured time-integrated K-shell spectroscopy of tracer foils even in the strong background signal of the implosion which will allow us to discuss the energy deposition in magnetized dense plasma. But for further investigation, time-resolved K-shell spectroscopy such as Streaked X-ray Spectrometer (SXS) is required. We had the Streaked X-ray Spectrometer (SXS) using the SSC-A streak camera in our last shot day. However, the SXS spectra is so different with time-integrated spectrometer that we cannot identify lines. We need to confirm that the diagnostics are working properly.

Scientific impact(s):

Understanding the role of the magnetic field is important for advanced fusion schemes such as Fast Ignition Inertial Confinement Fusion [1] and Magnetized Liner Inertial Fusion [8]. High gain ICF scenarios may be enabled by the beneficial heating from relativistic electron beam produced with an intense laser. Improving the electron confinement along the propagation axis would significantly raise the electron energy flux deep into a target. And applying a magnetic field is a method of reducing thermal conduction losses from the compressed hotspot. It was predicted that the application of a strong magnetic field to fusion targets relaxes the ignition requirements in two-dimensional magnetohydrodynamics simulations due to the reduction of hot-spot cooling through the application of external magnetic fields [9].

Broader impacts:

The Efficient way to create the high-energy-density state that is an interesting and unique test bed for various areas of scientific research such as laboratory astrophysics [10] and several kinds of radiation sources: x rays, charged particles, and neutrons [11,12]. It can also contribute to the clarification of the physics of the heating mechanism that has already been done by using a short pulse laser [13] and x-ray free electron laser [14].

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MP3 White Paper 2021
Title: Next-generation Lightsources and Applications

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Working Group: PAALS

Abstract: Compact, laser-driven next-generation lightsources have the potential to provide unique tools for cutting-edge research and can complement large-scale facilities, such as X-ray free-electron lasers (XFELs). These electron-beam-based lightsources are capable of generating pulses with femtosecond duration and photon energies spanning a broad spectral range. The intrinsic temporal synchronization to the driver laser and their compact dimensions enable novel research modalities that are not even possible at large-scale facilities. Despite tremendous progress over the last two decades, the routine application of these sources still requires significant further developments. While some parameters of the laser-driven sources are comparable or even go beyond the current state-of the art, many other parameters still require significant improvement. This includes the source brilliance, shot-to-shot reproducibility, conversion efficiency and repetition rate. The improvement of these parameters requires further fundamental understanding of the laser-plasma interaction and the impact on the radiation generation. The detailed understanding of the dynamics can only be obtained through combined experimental and theoretical/simulation efforts. It will require driver lasers with parameters that are currently unavailable and novel diagnostics that will allow to observe all relevant aspects of the process with exquisite resolution. Further source improvements will also require novel methods to specifically manipulate the laser-plasma interaction and the generated electron beam at (sub-) femtosecond temporal and (sub-) micron spatial resolution.

Scientific goal: Description of the goal and the methods that would be used.

Tools required: Parameters required for the experiment, or technical requirements/abilities of modeling tools, or theory development. Identify any facility/diagnostic/code developments that need to be made to achieve the goal.

Scientific impact(s): What will the impact of achieving this scientific goal be?

Broader impacts: Highlight other areas / fields or benefits to broader society where this research could make an impact.

References:
Include doi if available.

Instructions: White papers should be 2-3 pages in length (not counting references), using a minimum font size of 11pt on letter paper. Include the following sections in your white paper. Deadline for white paper submissions is April 9th 2021.

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MP3 White Paper 2021
Title: Enhancing hot electron generation via magnetized laser absorption

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Working Group: *PAALS*

Abstract:
Laser generated hot electrons can drive compact x-ray sources, whose spectrum is controlled by the electron energy and brightness is determined by the electron flux. Using particle-in-cell simulations, we show that both the energy and the flux can be significantly increased by magnetizing the plasma in which hot electrons are generated. Apart from well-known confinement effects, which occur on longer transport time scales, we show that a strong oblique magnetic field plays a direct role on picosecond time scales by enhancing collisionless laser energy absorption. The enhanced absorption is mediated by parametric decays of the laser into multiple magnetized plasma waves, whose collisionless damping synergistically pushes the bulk of the electron distribution function towards its high energy tail. Compared with the unmagnetized case, the resultant temperature and density of hot electrons are increased by orders of magnitude. For this magnetized absorption mechanism to occur, the requisite magnetic field is large wherein the electron gyro frequency is comparable to the plasma frequency, which means ~10 kT fields for ~10^{20} cc density. Such large magnetic fields are nevertheless feasible via the Biermann battery effect by focusing an intense short-pulse laser onto a planar target. Then, passing another laser with only moderate intensity through the strongly magnetized plasma to generate hot electrons, which subsequently drive x rays in secondary targets, more accessible table-top x-ray sources with better performance may be developed for security and medical applications.

Scientific goal and methods:
The goal of the proposed experiment is to demonstrate improvements to x-ray sources via magnetization. The experiment will be accompanied by modeling and theory efforts, which are needed to identify favorable parameters as well as to consolidate the scientific understanding of the underlying mechanisms.

Using particle-in-cell simulations, we have recently demonstrated enhancement of hot electron generation when the plasma becomes strongly magnetized [1]. A comparison between the magnetized and unmagnetized cases is shown in **Figure 1**. In the unmagnetized case, the laser pumps the growth of Langmuir waves, whose collisionless damping creates plateaus in the distribution function at velocities that are resonant with the Langmuir waves. At an intensity of ~10^{16} W/cm^2, the dominant Langmuir waves are due to primary and secondary backscattering of the laser. These Langmuir waves have nearly opposite phase velocities, so the plateaus caused by these waves are disconnected. In contrast, in the strongly magnetized case, in addition to decaying to upper-hybrid-like (P) waves, which are the magnetized analog of Langmuir waves, the laser can also decay to electron-cyclotron-like (F) waves. Moreover, when the electron gyro

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frequency is comparable to the plasma frequency, both the P and F waves have comparable couplings as well as comparable phase velocities. In this case, the plateaus due to P and F waves merge, which jointly develops into a hotter electron tail that is substantially denser.

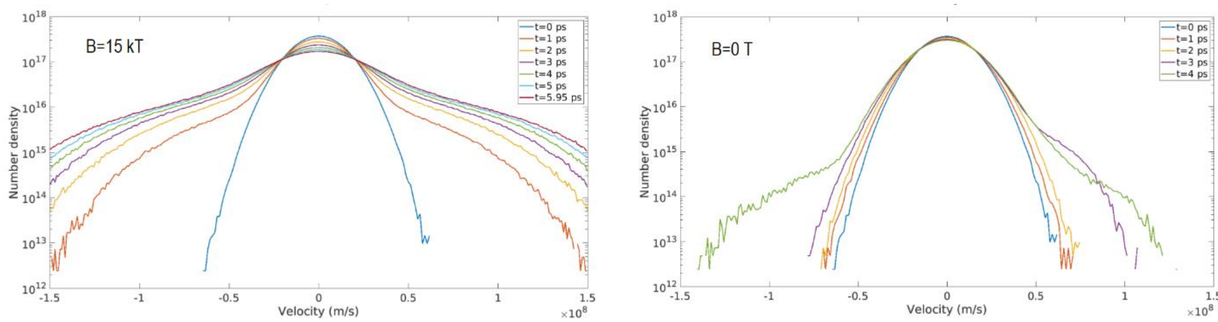

Figure 1. *Perpendicular electron distribution functions when a laser propagates through a plasma with B=15 kT (left) and B=0 T (right). The 0.351-μm laser has an intensity of 10^{16} W/cm^2, and the plasma has an initial density of 10^{21} cc and a temperature of 1 keV. In the magnetized case, both the temperature and the density of hot electrons are substantially increased.*

The experimental demonstration that the magnetized absorption mechanism can lead to better table-top x-ray sources is comprised of three stages. (1) We will *demonstrate and characterize the ~10 kT fields* needed for the absorption mechanism to occur, by building upon a literature of laser-driven Biermann battery fields, e.g. [2]. This requires a planar target and a drive laser at an intensity of ~10^{18} W/cm^2 for the magnetized case, and a much lower intensity for the unmagnetized comparison. (2) We will *investigate magnetization effects on the generation of hot electrons by measuring the electron energy spectrum*. The hot electrons may be generated using a separate pump laser at a much lower intensity of ~10^{16} W/cm^2, which propagates through the magnetized plasma volume that is created by the drive laser. To measure the hot electrons that escape the plasma, an electron energy spectrometer sensitive in the ~keV to ~MeV range will be employed. (3) We will *convert the enhanced hot electron tail to x rays using secondary targets*. For example, using a high-Z foil surrounding the primary target, x rays may be generated from the isotropic component of the hot electrons via bremsstrahlung. Additionally, the beam component of the hot electrons, which co-propagates with the pump laser, may further drive x rays via inverse Compton scattering when interacting with the reflected pump laser from a plasma mirror [3]. Stages (1) and (2) have previously been demonstrated experimentally, and the primary goal of this experiment is to demonstrate stage (2), which will be accompanied by detailed theoretical and numerical analyses.

Tools required:

For experiments, the required drive laser intensity is ~10^{18} W/cm^2, which is used to generates a strongly magnetized plasma volume via the Biermann battery effect. Additionally, a separate pump laser with an intensity of ~10^{16} W/cm^2 is required to generate hot electrons. Having separate beam paths for the drive and the pump lasers is desirable. To fully diagnose the plasma and the magnetic fields using interferometry and polarimetry, an equivalent of a 4-ω side lighter system is required. Finally, to measure the hot electron distribution, at least one electron energy spectrometer is needed. The energy range of interest is ~keV to ~MeV, and the spectrometer should be able to deploy at various locations with respect to the primary target.

Scientific impacts:
First, enhanced collisionless laser energy absorption in strongly magnetized plasmas is an unexplored phenomenon. Investigating the underlying processes will elucidate novel aspects of laser-plasma interactions in magnetized environments, where the additional degrees of freedom due to the magnetic fields may have profound effects. Second, since the Biermann battery fields are omnipresent in laser-plasma experiments, understanding the full scope of their secondary effects, for example on hot electron generation, may be necessary for better interpreting existing results and predicting outcomes of future experiments.

Broader impacts:
The enhanced hot electron generation in strongly magnetized plasmas may lead to novel compact x-ray sources for medical and security applications. At a given laser intensity, magnetization substantially increases both the flux and the energy of the x rays, leading to better sources with improved radiographical capabilities. Moreover, with a significantly higher conversion efficiently, a given application now require a much lower drive laser energy, making the table-top sources smaller, cheaper, and more accessible.

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MP3 White Paper 2021

Title: Efficient laser-driven ion acceleration using teamporally shaped high-intensity pulses

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Abstract

Laser-driven ion beams have been significantly improved in recent years and maximizing yield and energy of ions for a given laser configuration would be beneficial for nearly all applications. However, there are still barriers to enhancing ion beams that are due to technical challenges such as limited laser energy, intensity, and pulse duration resulting in limitation of maximum proton energies to 100 MeV [Higginson18].

Recent experimental and numerical studies [Kim18] using double pulses (quasi-shaped pulses) with multi-picosecond duration have shown very promising results, suggesting a new approach to ion acceleration. Experimentally demonstrated proton energies of 50 MeV with the double pulses are significantly higher than the maximum energy predicted by the well-established TNSA model scalings and experimental results for the same laser intensity with sub-ps pulses (~35 MeV). Additionally, recent computational studies show a new scheme of laser-driven ion acceleration is feasible that utilizes the synergetic effects of laser-induced target transparency and continuous field acceleration. By employing precisely shaped or double laser pulses at high (>10^{20}) , the onset of target transparency and driving of a continuous electric field at the accelerating front can be efficiently achieved compared to using a single pulse. This results in an increase of maximum ion energy by a factor of 2.5-3 compared to a typical TNSA for the given laser intensity. The creative and precise delivery of temporally shaped pulses will provide a robust and advanced laser-driven ion source for numerous HED experimental applications.

Scientific Goal

Demonstration of a significant step forward in enhancing ion beam yield (10+% conversion efficiency) and maximum ion energy (>100 MeV), is our scientific goal.

Our previous studies [Kim18, Mariscal19] indicate that fast-rising hot electron temperature is beneficial to increase maximum proton energies. However, if the electron source supports higher temperatures [Robinson13, Kemp20] even later in time, the proton energy can still increase. With this idea, we focus on applying pulse shaping that combines a fast-rising “picket” pulse with a long “pump” pulse to have a synergetic effect of quick acceleration and sustained fields for sustained boosting of ion energies.

Tools Required

Multiple laser pulses with accurate time control.

OMEGA EP case:

100s-to-kilojoule energy, multi-picosecond laser with 50-100 μm focal spot is preferred. Quasi-shaped pulse could be achieved with multiple beams, e.g. with inter-beam timing (picosecond precision)
CSU or BELLA:
The need for developing a single beam short pulse shaping capability: implementing a single beam pulse-shaping capability on an existing mid-scale laser facility with 10's of Joule laser energy. In order to implement a system for generating two gaussian-like laser pulses with different energies and inter-beam timings, relatively simple and low-cost optical elements can be used.

Scientific Impacts

The ideal facility would be capable of delivering 10's of kJ laser energy with precision temporal pulse shape control in order to demonstrate a new regime of short-pulse laser ion acceleration by maximizing the synergetic effects of continuous field acceleration and shaped/double pulses.
Based on experimental data, further study will help to understand new physics that includes particle-fields dynamics, interaction of laser and expanding plasma for multi-ps duration, and the transition between the various ion acceleration mechanisms (TNSA, RPA, BOA, etc.) [Albright07, Bulanov10, Yin07] while developing scalings in these newer advanced ion acceleration regimes .

Broader Impacts

Advanced ion beams will be a significant contribution to the field of high energy density plasma and potential applications such as high-energy and high-fluence proton radiography, exotic isotope creation, proton isochoric heating for warm dense matter study [patel03], medical tumor therapy, ion fast ignition inertial fusion concept, or high yield directional neutron sources [Higginson10].

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Multi-Petawatt Physics Prioritization (MP3) Workshop White Paper:

Laser wakefield acceleration using multi-PW lasers

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April 12, 2021

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Working Group: Particle Acceleration and Advanced Light Sources (PAALS)

Abstract: Laser wakefield accelerators using multi-PW, short pulse (sub-100 fs) lasers are able to compactly generate >10 GeV electron beams in underdense plasmas. As well as advancing the understanding of laser-plasma acceleration for future high-energy physics colliders, by interacting the beams with high intensity laser pulses, these compact sources of high-energy beams could be employed in studies of high-field physics and nonlinear quantum electrodynamics (QED). During the acceleration process, the electrons undergo betatron oscillations in the multi-PW-laser-driven plasma wave, emitting energetic (>MeV) photons. Such ultrafast radiation sources, with intrinsic femtosecond synchronization to the drive laser and secondary sources of photons and particles, may be applied in a broad range of biological, material, nuclear, and high-energy density science applications.

Scientific goal: Laser wakefield accelerators [1, 2] have the ability to generate accelerating gradients of 1-100 GV/m, several orders of magnitude larger than conventional metallic RF accelerators, enabling compact acceleration of electron beams. Laser wakefield accelerators rely on intense ($> 10^{18}$ W/cm^2), short-pulse (sub-100 fs) lasers to ponderomotively excite large amplitude electron plasma waves, or wakefields, in an underdense plasma. This resonant laser-plasma interaction requires the laser pulse duration to be of the order of the plasma period. A fraction of the background plasma electrons interacting with the wakefields can be trapped, accelerated to near the speed of light, resonantly gaining energy from the laser-driven plasma wave.

There has been tremendous experimental progress in the field of laser-driven plasma-based accelerators in the last two decades. Much of the progress has been the result of laser technology advances and a more complete understanding of the laser-plasma interaction physics. An important experimental milestone was achieved in 2004 when three laboratories reported [3, 4, 5] the acceleration of background plasma electrons to produce quasi-mono-energetic electron beams at energies of approximately 100 MeV using 10-TW-class laser pulses. In 2006, 1 GeV electron beams were produced using 100-TW-class laser pulses in a few-cm-long plasma channel [6]. Today, many laboratories around the world are able to achieve laser-plasma-accelerated electron beams with energies ranging from 100 MeV to 1 GeV. Most recently, electrons were accelerated up to 8 GeV over 20 cm using an 850 TW laser pulse propagating in a plasma channel [7]. Recent research has focused on improved electron beam quality (e.g., reducing energy spread) and reproducibility using triggered injection techniques.

Operation of a laser wakefield accelerator using multi-PW lasers would enable the generation of >10 GeV electron beams in less than a meter. For operation in the nonlinear bubble regime, and relying on laser self-guiding, the electron energy gain scales as $\gamma \propto P^{1/3}$, where P is the peak laser power, and the accelerated charge in the bunch scales as $N_b \propto P^{1/2}$. Note that other regimes of laser-plasma acceleration may be explored. For example, one may operate at lower plasma densities using plasma-channel guiding in the quasi-linear laser wakefield accelerator regime, where one expects a linear laser power scaling. One may also consider a "flying focus" geometry to operate the laser-plasma accelerator at higher plasma densities without the limitation of dephasing [8].

Laser wakefield accelerator experiments using multi-PW pulses will advance our understanding of laser-plasma acceleration, verifying the scalings toward higher beam energy, relevant for possible future high-energy physics machines. This would compliment R&D on current facilities and on high-average power laser wakefield accelerators using future 100 TW peak-power kHz laser systems. With a compact source of multi-GeV electron beams, high-field physics and nonlinear QED studies may be performed by interacting the multi-GeV beams with ultra-intense lasers. (See, for example, the white papers submitted to the MP3 HFP/QED working group.)

Such electron beams may be also employed as compact radiation sources for various applications. For example, as the beam is accelerated in the plasma wakefield, the electrons undergo intrinsic betatron oscillations and radiate broadband x-rays [9, 10]. This photon source is ultrashort (of the order the beam duration, ∼10 fs) and has a broad spectrum characterized by the critical photon energy, $\hbar\omega_{\rm cr}[\text{keV}] \approx 10^{-5}\gamma^2 n[10^{18}\text{cm}^{-3}]r_\beta[\mu\text{m}]$, where n is the plasma ion density and r_β is the amplitude of the betatron oscillations of the beam electrons in the wakefield. As the laser power increases one expects harder photons to be emitted with the scaling $\hbar\omega_{\rm cr} \propto P^{5/6}$, as well as increased number of photons per pulse, $N_{\rm ph} \propto P^{5/6}$. Using a multi-PW laser would produce an ultrashort pulse of hard (>MeV) photons. The hard photons allow for investigation of thicker (multi-cm) samples such as overcritical plasma and high-Z materials, but also samples embedded in other environments (such as a nuclear-active samples behind shielding, or a tumor inside a patient). While the intense photon emission enables single-shot data acquisition, the micron-size source enables excellent spatial resolution in phase-contrast imaging [11], and excellent spectral resolution in transmission spectroscopy [12].

Tools required: The laser wakefield accelerator requires laser parameters for efficient plasma wave excitation and laser guiding. To resonantly excite the nonlinear plasma waves, the laser system bandwidth should support sub-100 fs pulse durations, such that the laser duration satisfies $\tau_L < \omega_p^{-1}$, where $\omega_p = 2\pi c/\lambda_p$ is the plasma frequency, and $\lambda_p[\mu\text{m}] \simeq 3.3 \times 10^{10}/(n[\text{cm}^{-3}])^{1/2}$. Focusing optics (off-axis parabolic mirrors) should provide focused laser spot sizes that satisfy, approximately, $w_L \approx 2\sqrt{a}c/\omega_p$, where the normalized laser intensity is $a^2 \simeq 7.3\times10^{-19}(\lambda[\mu\text{m}])^2 I[\text{W/cm}^2]$, and $a^2 \gg 1$ is assumed. This condition will provide self-guiding of the laser in the plasma with normalized power $P/P_c = (\omega_p w_L a/c)^2/32 = a^3/8$.

The laser interacts with an underdense neutral plasma with typical plasma densities of $n \sim 10^{17}$–10^{19} cm^{-3}. The length of the plasma should be approximately the dephasing length, $L \sim (\lambda_p/2)(\omega/\omega_p)^2$, where ω is the frequency of the laser, and the plasma length is $L < 1$ m for typical densities and a 1 μm laser wavelength. Such a plasma may be generated by photo-ionizing a gas jet or gas cell.

In addition to the required laser-plasma parameters, beam and x-ray diagnostics will be required to diagnose the electron beam and betatron emission.

Scientific and broader impacts: Compact sources of energetic electron beams are actively being researched for high-energy physics and light source applications. In addition to laser-plasma-based accelerator development, the availability of a compact source of multi-GeV electrons, synchronized to an intense laser, opens up a wide range of studies in high-field physics and nonlinear QED.

The development of radiation sources based on laser wakefield accelerated electron beams offers compactness, high-temporal resolution (few-fs radiation pulse lengths), strong fluxes, and intrinsic femtosecond synchronization to a host of hyper-spectral beams of photons and charged particles that may be driven by the same laser system. These sources have applications in biological, material, nuclear, and high-energy density sciences. Betatron emission from laser wakefield accelerated beams has already been applied to x-ray phase contrast imaging and time-resolved x-ray absorption spectroscopy. In addition to discovery science, these sources may have medical, security, and industrial applications (see Ref. [11] for a discussion of the broad range of applications).

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X-ray light sources from laser plasma acceleration and their applications
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Abstract: This white paper discusses the opportunities related to the development of novel x-ray light sources based on laser-plasma acceleration on multi-petawatt laser systems. This approach is based on laser plasma acceleration (LPA) to drive betatron, compton scattering, x-ray free electron laser and bremsstrahlung sources to produce keV-MeV photons with unprecedented spatial, temporal and spectral properties. Such sources are poised to become standard tools for probing high energy density science experiments and conditions using various techniques (imaging, absorption spectroscopy or diffraction).

Scientific goal

Our goal is to develop novel x-ray light sources based on laser-plasma acceleration so that at large scale facilities such as NIF, LCLS, and OMEGA and multi-petawatt systems such as the proposed EP-OPAL facility, they become standard tools for probing high energy density science experiments and conditions using various techniques (imaging, absorption spectroscopy or diffraction). This means coupling such facilities with multi-petawatt (PW), short pulse laser systems.

The advent of chirped-pulse amplification (CPA) laser technology in 1985 [1], for which Donna Strickland and Gérard Mourou were awarded the 2018 Nobel prize in Physics [2], has enabled many revolutionary applications. Uses of lasers based on CPA include corrective eye surgery, and dedicated PW-class installations for fundamental science, such as the Extreme Light Infrastructure (ELI) in Europe (1-10 PW) [3], the newly established LaserNetUS network in the U.S. (up to 1 PW) [4], and projected 100 PW-class systems in Asia [5]. One application of CPA lasers, proposed in 1979 by Tajima and Dawson [6], is laser-plasma acceleration (LPA) [7]. When a CPA laser pulse with an intensity superior to 10^{18} W/cm^2 is focused onto a gas target or an underdense plasma (corresponding to electron densities of about 10^{19} cm^{-3}), its ponderomotive force (light pressure) displaces the plasma electrons such that a wake with a longitudinal electric field is produced. Plasma electrons trapped in this structure can subsequently be accelerated to relativistic energies. LPA experiments now routinely demonstrate electron acceleration up to GeV-class energies at many high-intensity laser facilities around the U.S. and the world [8,9]. One of the most promising applications of LPA, with major potential impact for science, society, and high energy density physics (HEDP) is the development of novel, compact light sources with photon energies spanning almost the entire range of the electromagnetic spectrum [10,11]. Relativistic electron beams generated by LPA can be harnessed to produce compact, bright sources of radiation with unique properties targeted for novel applications. Hard X-rays of energies ranging from 100 eV to MeV may be produced by betatron oscillations of the relativistic electrons in the transverse fields of the plasma wakefield generated behind the laser pulse, inverse Compton scattering from a counter-propagating laser field, or oscillations in a conventional magnetic undulator. LPA can also bremsstrahlung radiation. LPA-driven light sources have various degrees of maturity, and they offer the promise of laboratory-scale, cost-effective complementary sources to linac-based light sources (such as synchrotrons and free electron lasers), with attractive parameters (such as sub-picosecond to femtosecond pulse duration).

This white paper discusses the some of the progress made by our community on each of the LPA-driven light sources over the past decade, as well as the prospect of using them for applications, including HEDP, in the near future. The source development, intimately tied with the mechanisms of laser-plasma acceleration, and the applications enabled will both continue to give opportunities for new rich physics. It is important to note that the development of these light sources will be further enhanced by novel laser technology (in particular high repetition rate), plasma diagnostics, targets, machine learning, and the need for improved parameters motivated by revolutionary applications. The community working on the physics, development and applications of LPA-driven light sources is broad, global, and pursuing synergistic efforts toward making such sources a practical reality.

For plasma science, the importance of LPA-driven light sources is twofold. First, measuring their temporal, spatial and spectral properties serves as a diagnostic and unique insight into the physics of LPA. Then, these sources are powerful drivers and probes for the study of plasma physics and materials under extreme conditions of temperature and pressure, important for plasma and fusion sciences [12,13].

Tools required

Our required tools and approach are articulated around two main thrusts: (i) proof of principle experiments at small scale facilities (for example, through LaserNetUs) to demonstrate that x-ray sources driven by LPA can tackle physics problems specific to HEDP. Examples include the measurement of Rayleigh-Taylor instabilities with a 1 μm resolution, or the measurement of electron/ion equilibration in warm dense matter with an ultrafast x-ray source; (ii) deployment of these sources so that they become standard backlighters and diagnostic configurations for HEDP experiments at large scale facilities (NIF, OMEGA-EP, LCLS and future EP-OPAL Facilities). For this, we need to couple PW-class lasers to these facilities. One current limit of LPA-driven light sources (compared to conventional accelerator technology) is their lower average flux, and their lack of reproducibility from shot to shot. These achievements, along with overcoming technological difficulties, are needed. This should be possible thanks to developments in high repetition rate laser, diagnostic and target technology, to the emergence of new, petawatt-class short pulse laser facilities around the world.

This global effort will require expertise in both source development (laser plasma acceleration), applications (warm dense matter, material science, fusion sciences, planetary sciences, hydrodynamics), diagnostic development (time-resolved x-ray imaging and spectroscopy from keV to MeV photon energies), and computation (particle in cell, hydro, atomic physics).

The paragraphs below describe the different x-ray sources, their advantages over other approaches, and some of their applications in HEDP experiments. For proof-of-principle experiments short pulse lasers (<100 fs) with modest energy (0.1 – 1 PW level) can be used to demonstrate some of the applications, however higher energy systems (1-10 PW and beyond) will be necessary to provide the community with x-ray sources that produce sufficient flux for backlighting. Most proof-of-principle experiments can be done at the university scale level, however the overall effort will require expertise in both source development (laser plasma acceleration), applications (warm dense matter, material science, fusion sciences, planetary sciences, hydrodynamics), diagnostic development (time-resolved x-ray imaging and spectroscopy), and computation (particle in cell, hydro, atomic physics).

Betatron x-ray radiation is the most mature and well known of light sources driven by LPA [14], both in terms of development and applications. It was first observed in a beam-driven LPA [15] and then in a laser-driven LPA in 2004 [16]. Such radiation is emitted due to the betatron oscillations of relativistic electrons in the laser-driven electron plasma wave and arises naturally in laser wakefield acceleration experiments. Its properties resemble those of radiation produced in large synchrotron facilities (a well-collimated beam of x-rays in the 1-100 keV range), but with a 1000-fold shorter pulse duration, which makes it attractive for ultrafast science studies. The source is routinely produced at several high intensity laser facilities in the world, and much work has been dedicated to improving its flux, photon energy, and stability [17-19], and methods to improve this source, such as structured plasma channels, are continuously proposed [20,21]. Several applications have already been tackled with betatron radiation in proof-of-principle experiments, however the source needs to be enhanced further with improved flux, stability, and robustness to convince other scientific communities that the source is a viable complement to synchrotrons. Notable applications include x-ray phase contrast imaging (XPCI) [22-24], which benefits from the µm-scale source size of betatron radiation. Betatron x-rays have been used to produce high quality XPCI images (sensitive to small density variations) of insects or tissue in 3D using tomographic techniques, making the source an attractive tool for medicine (diagnostic radiology), biology, but also for studying the propagation of laser-driven shocks in materials. In this case, the potential high repetition rate of the source will be an advantage over conventional sources used for micro CT. Because of its short pulse duration (< 100 fs), the source has enormous potential for dynamic pump-probe experiments, using either radiography or spectroscopy techniques. Condensed matter physicists aim to learn how atoms rearrange during phase transitions between different states (amorphous, liquid or crystalline). For most processes governed by atomic motion, the timescale of interest corresponds to one vibrational period—about 100 fs, a duration that conventional synchrotrons cannot match. The future of the source on this topic is promising, as a couple of experiments have successfully looked at the equilibration of warm dense matter (with ~ solid densities and ~ eV temperatures) by using x-ray absorption spectroscopy [25], enabled by the broadband spectrum of betatron radiation. If coupled to large scale laser or x-ray free electron lasers, this source will also be a powerful diagnostic probe of hydrodynamic instabilities and matter driven to extreme conditions of temperature and pressure, as found in fusion plasmas and laboratory astrophysics experiments.

Inverse Compton scattering occurs when a laser photon scatters from a relativistic electron beam and, due to energy-momentum conservation, is upshifted in energy by a factor of $4\gamma^2$, where γ is the electron relativistic factor. LPA-driven Compton scattering was first demonstrated in the few keV range in a two-beam collision setup [26]. In 2012, another scheme, where a plasma mirror was used to reflect the intense laser back onto the accelerated electrons, generated more photons at higher, 100's keV energies [27-29]. This was soon followed by a demonstration using two separate laser pulses to drive the electrons and scattering photons with more control and tunability [30, 31]. The source is not yet as widespread as betatron radiation, but its development continues. It can be easily tuned (with the electron energy) and allows for higher photon energies than betatron radiation with the same electron beam energy.

The LPA-driven Compton scattering source is also collimated, with a µm-scale source size, and can be broadband. Thus, applications listed for betatron radiation also apply here, although similar photon energies can be reached with a more modest laser system. However, since it produces higher photon energies (several 100 keV to MeV) more easily than betatron radiation, and can be potentially more narrowband, different applications can be targeted, in particular for national security, with high energy, precision radiography or by triggering nuclear processes. These applications will be enabled by high repetition rate laser technology and precision laser beam and spatio-temporal shaping. Recently, the Compton scattering scheme has also become a solid base for the investigation of nonlinear quantum electrodynamics (QED) such as radiation reaction and pair creation in the nonlinear QED regime [32, 33]. This field will rapidly make new discoveries with the establishment of 10-100 PW-class laser facilities, where intensities beyond 10^{24} W/cm^2 and electron beam energies of several 10s of GeV should be possible.

An LPA-driven X-FEL would work along the same basic principles as a linac-based X-FEL, using a magnetic undulator to produce coherent x-rays [34]. Due to the difficulty of producing LPA electrons with qualities similar to a RF linac (in particular, electron beam energy spread, as well as a low enough divergence to permit beam transport) [35], this scheme has not yet been demonstrated. However, there is wide consensus among our community that FEL lasing is achievable through appropriate transport and phase-space manipulation (for example, by de-compressing the ultra-short beam), which would be a game changer for many scientific disciplines [36, 37]. Several large projects in the United States, Europe and Asia, typically at the national-lab or multi-lab/university scale, are now actively working on this topic. This should be actively pursued and requires close collaboration between plasma physics and conventional accelerator communities.

Bremsstrahlung: LPA electrons can be bombarded onto solid, high-Z targets to produce copious amounts of highly directional bremsstrahlung radiation up to several GeVs in a narrow, $1/\gamma$ radiation cone, depending on the electron beam energy spectrum and choice of target parameters. Few experiments have been performed on this topic over the past decade, however promising applications, in particular in non-destructive imaging for industry and defense, are beginning. Within this context, high-resolution gamma-ray radiography (at MeV photon energies) enables better than 30 µm resolution [38-40], which is interesting for probing dense objects with large areal densities.

Application techniques that use external sources of particles and photons to probe HEDP environments are advantageous because scientists can directly measure the effects that their interaction with an HED plasma creates. Unlike visible light, x-ray photons can pass through dense plasmas, and absorption of the x-rays can be directly measured, via spectroscopy or imaging. In this context, x-rays are one of the most versatile tools physicists can use to probe HED plasmas. Because of their remarkable spectral, spatial and temporal properties, the LPA-driven light sources described above will have a tremendous potential for application in HEDP. Most of these applications require a driver (ns, high energy laser with shaping capability, x-rays from an XFEL, or intense particle beams) to bring samples to HEDP conditions, coupled with a short pulse laser (0.1 PW up to several PW, <100 fs) to generate the probe beam. Techniques include x-ray phase contrast imaging or imaging with micron resolution (to investigate laser-driven shocks or hydrodynamic instabilities), x-ray absorption spectroscopy (to measure electron-ion equilibration in warm dense matter and opacities in HEDP conditions with fs resolution), or x-ray diffraction (to measure lattice structure dynamics with fs resolution).

Impact: This research effort directly expands the fundamental understanding of matter at very high temperatures and densities and allows us the study of plasma and how it interacts with its surroundings. It creates opportunities for new light sources with potential impact in fundamental science (probing experiments with unprecedented spatial, temporal and spectral resolution), industry (nondestructive imaging, additive manufacturing), and medicine (diagnostic and imaging capabilities).

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MP3 White Paper WP-49

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Abstract: We propose development of a new laser-based platform capable of measuring nuclear reaction rates in hot plasmas that have up to now only been measured using accelerated beams hitting cold material; an essential part of this platform is the efficient acceleration of large quantities of electrons to MeV energies in nano-wire foam targets. The scope of our work includes simulation, experimental design, proof-of-principle experiments, and the measurement of a rare reactivity in a hot plasma, such as that of $^{12}C(p,\gamma)^{13}C$. The technical approach taken is to use detailed fully relativistic, explicit collisional particle-in-cell simulations to understand how to create (by using high rep-rate, energetic short pulse laser pulses at relativistic intensities around 10^{19}W/cm^2 interacting with dense foams) previously unreachable temperature-density regions of phase space. The impact of our proposed work on the field of nuclear physics would be transformational, in that reactivities for a large number of nuclear processes that are currently only measured in cold solids would finally be measured in hot plasmas, where electron screening is important.

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https://doi.org/10.1038/s41467-019-12076-x |

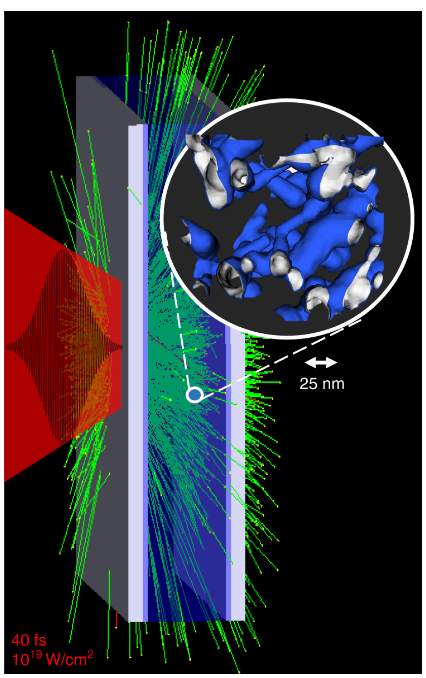

Figure - Schematic setup of encapsulated nanofoam target. A laser pulse (40 fs long, 10^19 W/cm2, indicated in red) generates relativistic electrons that flood the target, causing quasi-static electric fields that expand the unstructured foam (foam structure is shown in inset; the typical scale of the foam is 25 nm).

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- PAALS: Particle Acceleration and Advanced Light Source

Multi-petawatt electron acceleration and strong magnetic field generation

Electrons within a plasma channel can gain considerable energy under the action of laser and channel fields. At ultrahigh intensities, strong quasi-static azimuthal magnetic fields [Stark et al., *PRL* 18. 185003] can play a considerable role in electron acceleration [Gong et al., *Phys. Rev. E*, 013206, 2020, Hussein et al., *New. J. Phys.* 23, 2 2021]. Further, using ultra-intense beams from multi-petawatt laser systems, the radiation reaction can play an important role in the electron acceleration process for efficient acceleration of copious GeV electrons [Vranic et al., *PPCF*, 60, 034002, Jirka et al., *New J. Phys.* 083059, 2020].

Strong quasi-static magnetic fields are particularly compelling for electron acceleration experiments with multi-petawatt laser systems because magnetic fields are robust to ion motion, whereas electric channel fields have been shown to undergo field reversal following ion acceleration [Kar et al., *New. J. Phys.* 9, 402 2007]. The persistence of these strong magnetic fields invites the development and implementation of novel diagnostics.

Demonstration of high energy, high charge electron beams using multi-petawatt laser systems could enable new applications such as positron production through the interaction of energetic electrons with a high-intensity laser pulse [Chen et al, *PRL*, 102, 105001 2009] experimental verification of the two-photon Breit-Wheeler process [Pike et al., *Nat. Photonics* 8, 6 2014] and the generation of brillant gamma-ray pulses [Chang et al., *Sci. Rep.* 7, 45031, 2017]

Abstract: Brief description, maximum of 250 words.

Scientific goal: Description of the goal and the methods that would be used.

Tools required: Parameters required for the experiment, or technical requirements/abilities of modeling tools, or theory development. Identify any facility/diagnostic/code developments that need to be made to achieve the goal

Scientific impact(s): What will the impact of achieving this scientific goal be?

Broader impacts: Highlight other areas / fields or benefits to broader society where this research could make an impact.

References: Include doi if available.

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MP3 white paper: Multi-Petawatt Physics Prioritization Workshop GOING BEYOND THE STANDARD MODEL WITH HIGH POWER LASERS

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It is well known that particle-production phenomena can occur in a curved or dynamic spacetime [1]. For example, thermal radiation can arise from particle production near the event horizon of a black hole, an effect commonly known as the Hawking radiation [2, 3]. The expansion of the universe also occurs in curved spacetime described by the Friedmann-Lemaître-Robertson-Walker (FLRW) metric. Due to the varying gravitational field, particle production occurs [4–7]. Of particular interest is the inflationary period, from 10^{-36} s until 10^{-32} s after the big bang. During this time, it is thought that the universe expanded exponentially, and spacetime was highly curved and dynamic. Understanding particle production [8–10] during inflation [11, 12] will help to address fundamental questions in cosmology and may also be relevant for (non-thermal) production of supermassive dark matter in the early universe. Alternatively dark matter may correspond to the energy density of coherent oscillations of an ultralight field such as the axion.

The axion is a pseudo Nambu-Goldstone boson which arises from the spontaneous breaking of the Peccei-Quinn symmetry symmetry which was invoked to explain the absence of CP-violation by the strong interaction [13]. Both astrophysical bounds from stars and galaxies [14, 15] as well as laboratory searches [16, 17] have provided limits for the mass and coupling constants of these hypothetical particles. Axions may also be responsible for generating a primordial magnetic field at the epoch of the QCD cross-over in the early universe [18]. While experimental searches so far have not yet identified an axion candidate, the parameter space left to explore is still large and there is a need of more sensitive probes before the axion existence can be confidently ruled out.

Recent advancements in ultra-high intensity lasers [19] have stirred interest in the possibility of detecting both the Schwinger effect and testing non-perturbative QED effects [20–23]. Projects such as the European Extreme Light Infrastructure [24], which will provide radiation beams of intensities exceeding 10^{23} W/cm^2. An electron placed at the focus of such beams should then experience an acceleration comparable to what it would feel if placed near the event horizon of a 6×10^{18} kg ($= 3\times10^{-12}\ M_{\rm sun}$) black hole. Indeed for such low mass black holes the surface gravity is strong enough that pairs of entangled photons can be produced from the vacuum, with one of the pair escaping to infinity. The black hole can then radiate, and the spectrum of such radiation is a blackbody at the Hawking temperature.

While the scientific community generally believes that the derivation of Hawking radiation is sound, this is nevertheless made possible by several approximations that have not been tested; it raises a wider range of fundamental questions such as whether it implies a loss of information or an arbitrarily fine resolution of spacetime.

Given the insurmountable difficulties in directly observing Hawking radiation, Unruh proposed, by virtue of the equivalence principle (of gravitational and inertial accelerations), that a similar effect could be measured by an accelerated observer [25]. While this can, in principle, be realised in the laboratory, the required accelerations have remained very difficult to achieve. For this reason, Unruh and others have instead adopted an alternative approach to exploit the mathematical analogy between trans-sonic flowing water [26], Bose-Einstein condensates [27] and other analogue systems [28] and the behaviour of quantum fields in the vicinity of a black hole horizon. While these experiments have successfully demonstrated the mathematical soundness of Hawking's solution, they may have fallen short in proving that the radiation is actually emitted by non-inertial bodies and that the underlying theory is indeed physically correct [29].

The same mechanism that gives rise to the production of Unruh photons is also responsible for the production of other particles such as light pseudoscalars (ie, axions) [30–32], dark photons and/or millicharged particles.

Moreover, the process described here is not restricted to accelerated charged observers, and it can be also applied to any accelerated frame. For example, neutral particles could be accelerated using radiation pressure from a laser beam [33].

In summary, with the development of high intensity lasers we can envision groundbreaking precision tests of observables that are manifest only at very high-energies. This allows probes of quantum gravity and tests for deviations from the Standard Model of particle physics while being far below the Planck scale of 10^{19} GeV that is beyond the direct reach of any particle accelerator.

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Using inverse Compton scattering from a short pulse laser to measure the properties of warm dense matter produced by pulsed-power drivers

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Abstract:

Warm dense matter can be found at the center of giant planets, from Jupiter to super-earths. Since astrophysical observations can yield a relatively precise mass and size of a planet, its density can be defined. If the equation of state of materials under core conditions was known, the composition of the planet could be determined from its density. But, measuring the mass density and pressure of warm dense matter in the laboratory requires a bright x-ray source. Measuring temperature using Thomson scattering requires a source that is even brighter. Typically, these extremely bright x-ray sources are produced by x-ray free electron lasers, where an electron bunch is accelerated to GeV energies using a linac. Rather than using a mile-long device, this paper proposes to use a multi-petawatt laser coupled to a meter-long x-band linac to generate 20keV x-rays from inverse Compton scattering to measure the equation of state of warm dense matter using pulsed-power. The source is inherently tunable: the x-ray energy is directly related to the electron energy and can reach several hundreds of keV; compact: the device is an order of magnitude smaller than GeV linacs and more cost effective to maintain; coherently driven: multiple x-ray pulses can be generated simultaneously with one single laser but multiple electron bunches. The x-ray pulses are coherent and the phase between them can be controlled by timing the electron bunches adequately. With coherence, x-ray interferometry can be used to measure the electron density in warm dense matter, also giving a direct measurement of ionization by comparing the electron density with the mass (ion) density, measured from x-ray backlighting. By controlling the timing between multiple bunches, exquisite time resolution would allow to measure the equation of state of matter in hydrostatic equilibrium, leading to a deeper understanding of dense quantum materials in thermal equilibrium.

Key words: warm dense matter, pulsed-power, inverse Compton scattering, x-ray interferometer, linac, quantum mechanics

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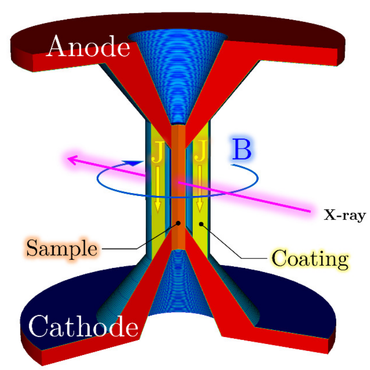

Figure 1: Schematic of the magnetic anvil cell experiment. The current flows between the anode and cathode. The magnetic field compresses the sample on the order of hundreds of nanoseconds. The coating prevents the formation of late 3D instabilities.

Warm dense matter (WDM) is a state of matter where strong Coulomb coupling and electron degeneracy co-exist. Such state is characterized by particle densities, between 0.1 to 10 times solid, and electron temperatures between 0.1 to 100 eV. The core of giant planets in our solar system such as Jupiter, Saturn or Uranus[1,2] are in this state. Without experimental data on the basic properties of matter under such pressures, understanding their formation and predicting their evolution strongly will remain uncertain. More recently, the discovery of Mega-Earths[3] also raised important questions on how the properties of a WDM planetary core impact the habitability of a planet. Can a giant, rocky planet sustain magnetic fields large enough to protect its atmosphere from stellar winds? Is plate tectonics enhanced or inhibited by a WDM core? Can planets with WDM core have stable climate patterns? Since very little is known about the physical properties of WDM, these questions simply have no answers. In this regime, quantum and thermal effects coexist constructively. *So, how can we reconcile the probabilistic nature of quantum mechanics in a system where randomness, caused by thermal motion, cannot be ignored?*

The level of complexity this union entails has baffled modern physics so far. Experiments investigating the property of matter at high densities are needed more than ever to verify new, emerging theories in quantum mechanics. While physics was initially successful in keeping quantum and statistical mechanics separate, it has yet to devise a theory where quantum and statistical effects are on equal footings. Yet, from inertial fusion to planetary science[4,5], new discoveries demand an understanding of quantum mechanics in a very different framework[6] than the one used today. We now need to address long-range, statistically averaged, strongly coupled interactions. The very nature of these interactions rules the compression of deuterium in ignition capsules[7] or prevents core collapse in Jupiter or giant exo-planets[8]. It might open up the road to materials more resilient to neutron loads found in fusion reactors[9].

But any significant scientific progress requires dedicated facilities able to generate hundreds of gigawatts of raw power to form such matter in the laboratory and, more importantly, terawatts of x-ray power to diagnose it. Traditionally, WDM is generated by isochoric heating from intense lasers[10,11,12] or heavy ion beams[13], where $pV\lambda_T^2$ is a constant. p is the kinetic pressure, V the volume and λ_T the de Broglie wavelength. The drive pulse should be short (<1ns) since the high-pressure material is kept together only by inertial confinement. Unfortunately, short pulses also hinder our ability to observe compressed matter in a macroscopic (~1mm) equilibrium[14], which is key to understand the equation of state of warm dense matter in planetary cores. While electrons equilibrate in tens of picoseconds[15] under these conditions, the ion-ion equilibration time is typically $(m_i/m_e)^{1/2}$ larger, on the order of several nanoseconds, resulting in non-equilibrium (e.g. shock) conditions for short experiments. To study large amount of matter compressed to a hydrostatic equilibrium relevant to study planetary interiors, it was proposed to produce warm dense matter[16] by using a pulsed power driver[17] via isentropic compression (e.g. Ref. 18). Under these conditions, $p^{1-\frac{1}{\gamma}}\lambda_T^2$ is constant and the deBroglie wavelength decreases more slowly compared to isochoric heating as the pressure increases. An example of experimental setup to generate warm dense matter using pulsed-power drivers is shown on Figure 1. The sample is 10mm high.

While short-pulse lasers can create focused x-ray source from K-shell spectroscopic lines (e.g. Ref. 19), we propose to use inverse Compton scattering to diagnose warm dense matter. This approach offer greater flexibility, better source control, and multiple, coherent x-ray sources. In this case, we would couple a multi-mega-ampere pulsed power driver to an x-band multi-MeV linac[20] or synchrotron[21] *and* a short-pulse laser. This approach brings devices together, each able to perform a specialized task extremely well, to reach the overarching physics goal of understanding quantum effects under extreme conditions. Inverse Compton scattering has been used successfully by combing a high-power laser with x-band linac to generate x-ray pulses. In inverse Compton scattering (ICS) experiments, an electron bunch travels at great energies (>1MeV) toward an incoming laser pulse. The electromagnetic field of the laser acts as a undulator, in which both electric and magnetic fields slosh the electron bunch in the transverse direction. In the rest frame of the electrons, part of the laser light is scattered by the bunch. In the laboratory frame, the scattered laser with initial frequency f_L has been upshifted to a frequency

$$f_s = \gamma^2(1+\beta^2)f_L, \quad (1)$$

where γ is the Lorentz factor of the electron bunch and β is the ratio of the bunch speed to the speed of light. Since the laser acts as an undulator which wiggles the bunch using both the electric and the magnetic fields, the number of photons N_{ph} per electron can be computed as[22]

$$N_{ph} = \frac{4\pi}{3}\alpha N K_u^2, \quad (2)$$

where α is the fine structure constant, N is the number of undulator periods and K_u is the undulator parameter defined by

$$K_u = \frac{e}{2\pi m_e}\frac{B_L}{f_L}. \quad (3)$$

Here $B_L = \sqrt{\mu_0 I/c}$ corresponds to the magnetic field of a laser pulse of intensity I. Both linac and laser size can be relatively modest for steady-state applications[20].

However, studying warm dense matter requires ICS x-ray pulses with copious amounts of photons (>10^{10} for density measurement and >10^{12} for x-ray Thomson scattering). As Eq. (2) shows, the laser power and/or the number of electrons inside a bunch must be increased substantially. Increasing the number of electrons per bunch would also require increasing the bunch energy, or the bunch would quickly disassemble. In turn, this would increase the x-ray energy, which is problematic. X-ray produced above 50 keV cannot be detected easily.

Typically, x-ray CCD[23] using Si (E<20 keV) or CdTe (E<50keV) are transparent above these energies. At this point, it makes sense to use a free electron laser than ICS.

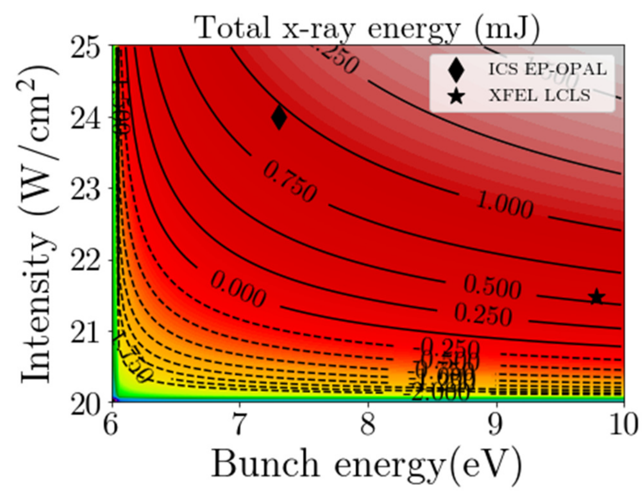

Figure 2: Total ICS x-ray energy radiated at 20 keV as a function of the bunch energy and laser intensity. All scales are log₁₀. LCLS-II monochromatic 20 keV energy is also indicated. There is no laser intensity correspondence for LCLS. Note that the ICS spectrum is usually boarder than an XFEL.

The ICS route becomes more interesting when the laser intensity can be increased substantially. This has many advantages over a linac driven free electron laser. First, the requirement on the electron bunch are relatively easy to satisfy with x-band accelerators which can accelerate electrons up to 100 MeV in a couple of meters[20]. All the hard work is done by the laser instead. Second, laser amplification is much easier than particle acceleration at high energies. The laser intensity limitation is set by the energy density that the grating can sustain rather than the asymptotic limitation coming from the Lorentz factor. Third, the system functions well at room temperature. GeV linacs require cryogenic temperatures to function. Finally, reaching large intensities requires a focusing of the laser beam to micron size, which perfectly matches the size of a pC electron bunch. *As an example, a 5-m long linac with parameters given in Table 1 can generate 10^{12} photons at 20 keV (quasi-monochromatic) using a laser wavelength of 527 nm with a laser intensity of 10^{24} W/cm^2.* Figure 2 shows how the total x-ray energy varies as a function of the bunch energy and the laser intensity. As an example, the EP-OPAL short pulse laser is indicated, next to LCLS-II, for comparison. While this number is relatively large it is important to realize that we used Gaussian distributions, for both the laser and bunches, leading to an x-ray beam that is not mono-chromatic, since the magnetic field is not constant across the "laser undulator".

Parameters	Values
Charge	5pC
Energy	20 MeV
Length	20 fs
Radius	10 m

Table 1. Example of e-bunch parameters

ICS moves the technical difficulties faced by linacs to the ones faced by short pulse lasers. However, the technology is close to its limits when it comes to linacs (using NbSn cavities[24] might soften these limits) and the only option left would be adding more length to the device. This has been discussed in length by the linac community and it will be a very difficult challenge (e.g. Ref. 25). While laser wakefield accelerators[26] and inverse free-electron laser (IFEL)[27] could become contenders to linacs, they have not yet demonstrated the level of control found with linacs. There is a very different story for lasers. Present day technology is still far from the nonlinear interaction between light and vacuum, giving ICS ample room to grow.

Further, short-pulse laser technology advances, using plasma mirrors, flying focii[28] and segmented gratings, clearly points to a bright future for ICS, if the x-ray source quality can be tightly controlled on the laser side.

However, ICS is more than a bright x-ray source. First, it is possible to illuminate many electron bunches with the same laser beam, resulting in multiple, delayed x-ray pulses (1 to 10 of ns) for dynamics study. Yet it still requires one single laser pulse. Even more interesting is the ability to form tight bunch pairs by masking parts the photocathode of the RF photogun with a mesh. The laser beam scattering from the bunch pair would generate two coherent x-ray sources, allowing to measure the electron density inside a warm dense matter sample using x-ray interferometry. X-ray attenuation would also give a direct measure of the mass density of the sample of dense matter. Combining the two would give the average ionization of the sample under dense conditions. Besides the proposed experiments, the hardware can also be used to study non-linear effects in ICS[29], produce ICS gamma rays if larger bunch energies are used, develop GeV inverse free electron lasers[25] or characterize the short-pulse laser beam quality at maximum focus by measuring the x-ray source characteristics. The groundwork behind this proposal could be validated using the high repetition rate accelerator CBETA[30] to understand the connection between bunch and laser spot geometries using detailed measurements of the ICS spectrum[31].

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MP3 White Paper WP-53

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At the GSI Helmholtz-Center for Heavy-Ion Research the department of Plasma Physics operates since over 10 years the high-energy short-pulse laser system PHELIX as a user facility hosting on average up to 10 external beamtimes per year. Besides this service, the laser team continuously works on improving laser performance, e.g. novel stretcher and front-end designs to provide ultra-high temporal contrast pulses, high-dynamic range temporal pulse characterization, or adaptive optics for improved focusability. One of the core scientific areas pursued by the in-house plasma physics group is in the field of ultra-intense laser-matter interactions (e.g. [Bagnoud]). Exploiting the high-fidelity laser pulses, the use of advanced targetry allows to explore novel approaches. For example, sub-micron foils, nano-structured surfaces, reduced mass targets, and near-critical foams [Wagner, Khaghani, Hilz, Rosmej] have been used successfully to increase energy, particle numbers, energy density, and high-energy electron and gamma emission.

As part of a multidisciplinary collaboration, the group is pioneering the coupling of laser-accelerated protons with conventional accelerator structures, and has demonstrated efficient collection, bandwidth control, temporal recompression and sub-mm focusing of laser-accelerated proton pulses [Busold]. In the mid-term these will be used to achieve higher precision in ion stopping power measurements in plasma [Cayzac], and for isochoric heating of samples to warm-dense matter conditions [White]. In the longer term this development bears the intriguing prospect of directly injecting laser-generated particles into the heavy-ion synchrotron, circumventing 100m of conventional linear accelerator.

As a major extension to the existing heavy-ion accelerator at GSI, the ~2B$ Facility for Antiproton and Ion Research, FAIR, is currently under construction. Within the rich scientific scope pursued at this international facility, reaching from hot nuclear matter, neutron-rich nuclei and antiproton research to atomic, bio-physics and materials research, the international HED@FAIR-collaboration is preparing a science program in the field of high-energy density physics. Pulses of relativistic heavy ions, focused to unprecedented peak fluences, will allow volumetric heating of mm-sized samples, providing a novel path to generate matter at extreme conditions. To complement this unique capability with state-of-the-art diagnostic probing techniques used in HED science experiments, a new high-energy short-pulse laser is currently under consideration, foreseen to be a kJ/sub-ps system. Addressing already first technological bottlenecks expected in the design/conception of such a system, the laser development group at GSI is already testing first prototypes of liquid-cooled large aperture glass amplifier modules for significantly increased repetition rates.

Besides enabling many well-established and robust schemes for generation of secondary sources of highly penetrating radiation, such a laser system will also reach the still largely unexplored multi-PW regime. This holds the potential for more directed emission and significantly enhanced conversion of laser energy expected in novel schemes such radiation pressure acceleration or involving relativistic induced transparency for high-energy protons pulses, or high charge electron bunches and low-divergence betatron x-ray yield from self-modulated wakefield acceleration [Albert].

Consequently, we have a strong interest in the study of multi-PW physics to gain improved understanding in this both experimentally and theoretically very challenging regime. This will help not only with successfully scaling traditional schemes for generation of secondary radiation to unprecedented laser intensities and energies, but also to possibly exploring entirely new schemes with much enhanced diagnostic application potential.

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MP3 White Paper 2021
Radiation reaction experiment with 60 PW laser pulse and 10 GeV electron bunch

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Abstract:
Nonlinear quantum electrodynamics (QED) was tested experimentally in several high-power laser facilities [Bamber1990, Bula1996]. The nonlinearity in QED refers to the number of laser photons absorbed is more than one in the interaction with a single electron and is only possible with high-intensity laser. The laser intensity plays a significant role in switching the radiation reaction (RR) from classical to quantum regime supported by nonlinear QED. To date, electron beam optics is not sufficient to provide perfect spot size matching with the tightly-focused laser pulse. This results in small interaction probability and the quantum nature of RR is difficult to be observed. To maintain the laser intensity while having larger focusing spot size, a higher laser power is required. We propose to investigate the effect of RR in the quantum regime by using GeV-electron bunch with 60 PW laser. Our numerical results suggest that the energy of electron required to produce 2 GeV photon would be around 10 GeV. Such a high energy photon would facilitate the secondary process such as electron-positron pair production by the nonlinear Briet-Wheeler process.

Scientific goal:
The goal of this proposal is to investigate the effects of RR with 60 PW laser. The experiment of RR was proposed [Zhidkov2002] and has been carried out with laser intensity $10^{21\text{-}22}$ W/cm^2 [Cole2018, Poder2018]. The regime of RR is visualized by the quantumness parameter $\chi \propto (\text{electron energy}, E) \times \sqrt{(\text{laser intensity}, I)}$ and the nonlinearity parameter $N \propto \mathrm{I}/E \times \xi/(1-\xi)$ for electron energy E, laser intensity I, and $\xi = (\text{emitted photon energy})/E$. Figure 1 shows the regime of performed/planned RR experiments by the plots [Seto2021], we hereby propose the RR experiment by the laser pulse of 10^{22} W/cm^2 at peak intensity and 10 GeV electron marked by the star symbol. It is a new plot in nonlinear QED. The power spectrum $\hbar\omega \times dN/\mathrm{d}(\hbar\omega)$ of emitted photon has its peak at about 100 MeV ideally. However, these experiments suffer from the following drawback: laser-electron bunch size mismatch.

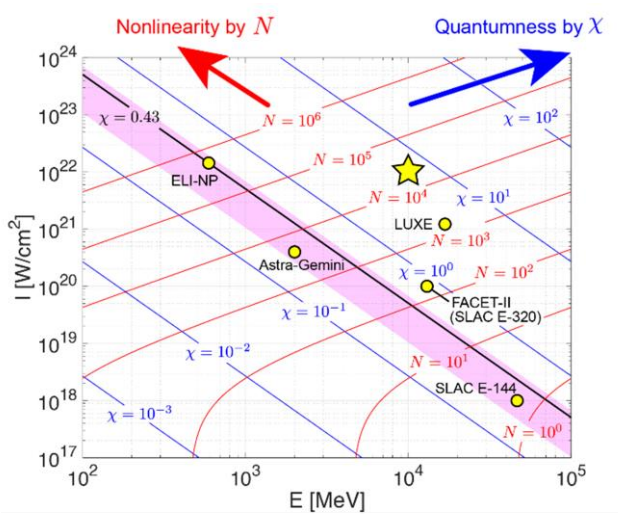

Fig. 1 The physical regime diagram of RR. The present proposal locates at the star symbol.

Typically, the expected diameter of an electron bunch is around 30 micron, which is larger than the laser spot size of 2-3 micron order. Namely, only a few percent of electrons in the bunch can interact with the laser peak intensity in a single shot. A 60 PW laser pulse focusing into 15-20 micron spot size (FWHM) could provide laser with intensity 10^{22} W/cm^2. This laser spot size can make the experiment much more feasible and realistic to be achieved and the problem of laser beam diffraction at the focusing spot is suppressed.

Tools required:

Figure 2 shows the result of our numerical calculation of the head-on collision between an electron bunch of 10 GeV and a laser pulse of 10^{22} W/cm^2 at peak intensity. We gave the transverse electron profile as $\propto \exp(-r^2/2\sigma^2)$ and the laser profile as $\propto \exp(-2r^2/w_0^2)$ in its intensity. The left panel shows the case $w_0 > \sigma$ and the right figure is $w_0 < \sigma$. We expect to see the finer structure of RR (the slope of the energy decay) to discriminate a model by the setup in the left panel case of about a 60 PW laser pulse.

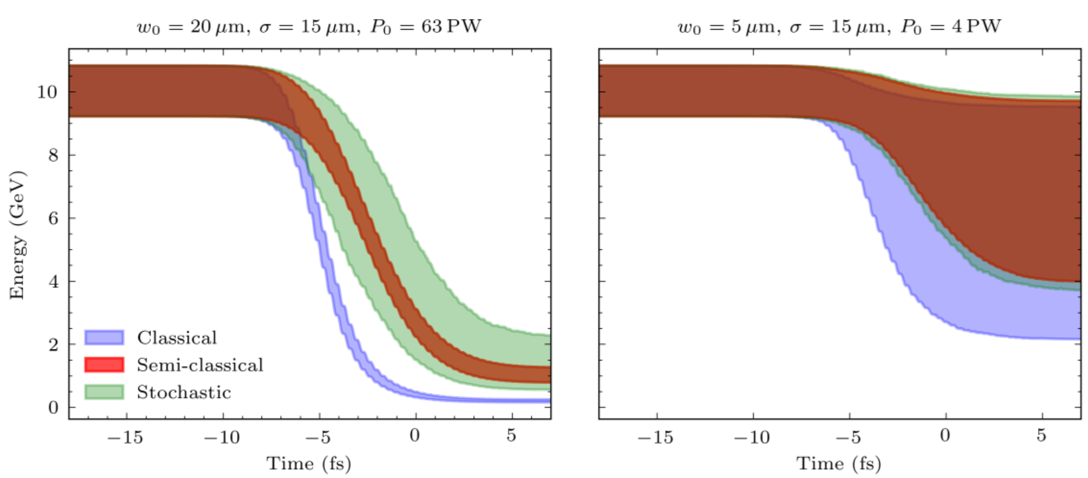

Figure 2 The time evolution of average electron energy with standard deviation as energy spread for classical, semi-classical, and stochastic model.

Collision geometry

A head-on collision between a laser pulse and an electron beam.

Laser

The maximum laser power of 60 PW is considered following the discussion above. The good beam profile is required at the focusing point. The laser wavelength around 1 micron order is expected. Its focusing spot size, w_0, need to satisfy $w_0 > \sigma$ for the electron bunch size, σ at the focusing point.

Electron beam

The electron beam with energy in the order of 10 GeV is expected. This beam can either provided by the linear accelerator or from laser wakefield acceleration (LWFA). For the latter case, two laser arms are required: one for LWFA and another for RR. In any method of electron source, we also hope to install an electron focusing magnet (quadrupole magnets, etc.). The electron bunch size, σ, need to satisfy $w_0 > \sigma$ for the laser spot size, w_0.

Radiation diagnostic

We consider to use the gamma calorie polarimetry meter in this experiment for photon detection. A long interaction-to-detector distance (10-20 m) will be required. In this way, one can collimate the desired signal in the forward direction of incoming electrons. The radiation distribution will be one of the key characteristics.

We plan spectroscopy for the scattered electrons up to 10 GeV of the initial energy.

We consider the uses of the theoretical model by [King2020] in the design of the signal collimation of emitted photons.

Scientific impact(s):

Our goal is to control RR by selecting parameters. This links to **Broader impacts**.

RR can be found in a photon-electron collider. A conventional collider has provided a jet of many particles by a binary collision of two heavy particles. RR is a collision between an electron and a significant number of laser photons at the eV range. This different collider geometry from the previous particle colliders is interesting to see the difference from hadron physics.

Broader impacts:

RR gives various photon energy depending on the energy of the incoming electron. The emission yield will be proportional to a number of electrons ideally. When we can control RR perfectly, it becomes a new synchrotron radiation source. Especially, we can introduce the LWFA for an electron bunch. Then, RR can be performed all-optical setup. Namely, the large laser facility has the potential to become a synchrotron facility, too. Then, we can use this synchrotron radiation for material science, bioscience, industrial uses, etc.

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MP3 white paper Multi-Petawatt Physics Prioritization Workshop

High power laser experiments probing plasma nuclear science

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Working Groups: LAP Laboratory astrophysics, and LDNP Laser-driven nuclear physics

Abstract

Intense lasers are now being used to recreate aspects of astrophysical phenomena in the laboratory, allowing the creation of experimental test beds where observations and models can be quantitatively compared with laboratory data in relevant astrophysical conditions. Recent experiments on high energy, long pulse lasers have demonstrated the ability to measure astrophysical nuclear reaction rates at temperatures ranging from 2 – 20 keV, relevant to a wide range of stellar core conditions, ranging from hot blue supergiants to near solar conditions. [Johnson 2017, Johnson 2018, Casey 2017] The next generations of ultraintense, short pulse, high rep-rate lasers will open a new frontier in plasma astrophysics, with characteristic temperatures in the ~1-10 MeV range or higher. For reference, these temperatures are in the range of supernova shock waves, which trigger copious amounts of nucleosynthesis; and are a factor of 1000 higher than the keV level temperatures of stellar cores, which are driving nuclear burning. [Casey 2017, Johnson 2017, Roth 2013] Hence, experiments under these conditions should enable the study of nuclear science at the ultrahigh temperature conditions relevant to the explosion phase of core-collapse supernovae, thermonuclear supernovae, and gamma-ray bursts; and the exploration of plasma effects on nuclear reaction rates at these high density-temperature conditions. [Ledingham 2000, Boller 2020, Zamfir 2014].

Scientific goal

Nuclear physics has traditionally been studied in the laboratory at accelerator facilities. While extremely productive over the last several decades, such techniques miss aspects important to astrophysics, where most nuclear reactions occur in a plasma environments. In addition, some nuclear processes such as in supernovae or neutron-star mergers occur at particle fluxes orders of magnitude higher than can be achieved by traditional techniques. The density-temperature regimes relevant to stellar interiors as a function of stellar mass are plotted in Figs. 1a, and the corresponding nuclear reactivities $\langle\sigma v\rangle$ are shown in Fig. 1b. [Casey 2017]

Indirect drive capsule implosion experiments on NIF, illustrated in Fig. 2a, generate nuclear reactions in conditions relevant to stellar interiors for stars of various masses and ages, as shown in Fig. 2b. On smaller, short pulse lasers such as the Phelix laser in Darmstadt, Germany, [Bagnoud 2009] TNSA protons in the energy range of 10-90 MeV have been generated and used to trigger fission reactions, which were diagnosed by the post-shot radioactivity of the reaction products, as shown in Fig. 3a and Fig. 3b. [Boller 2020]. And finally, the bremsstrahlung x-ray radiation from 50 TW laser irradiation of planar Ta targets at the Vulcan laser have been used to study (γ,n) reactions in Cu and other activation targets at plasma temperatures of ~1 – 2 MeV. At these plasma temperatures, copious nuclear reactions should be activated. [Ledingham 2000]. And activation foils, shown in Fig. 4a and Fig. 4b, are often used as detectors. They are irradiated, then analyzed after exposure to infer the dose of x-rays received. Combined data analysis and simulations allow the activity ratio of $^{11}C/^{62}Cu$ to be plotted vs plasma temperature in Fig. 4. In addition, various particle, x-ray, and γ-ray detectors will measure spectra as a function of energy and angle, allowing the emission angular distribution to be measured.

The goal of this white paper is to describe new regimes of nuclear science and nuclear astrophysics enabled by the next generation of high intensity, short pulse, high repetition rate lasers. A coordinated investigation using high energy, long pulse lasers to study keV plasmas relevant to solar-mass stars, and MeV plasmas using high intensity, short pulse lasers relevant to hot supergiant stars, accreting compact objects such as black holes, and colliding neutron stars should generate new advances in our understanding of plasma nuclear science of particular interest to nuclear astrophysics.

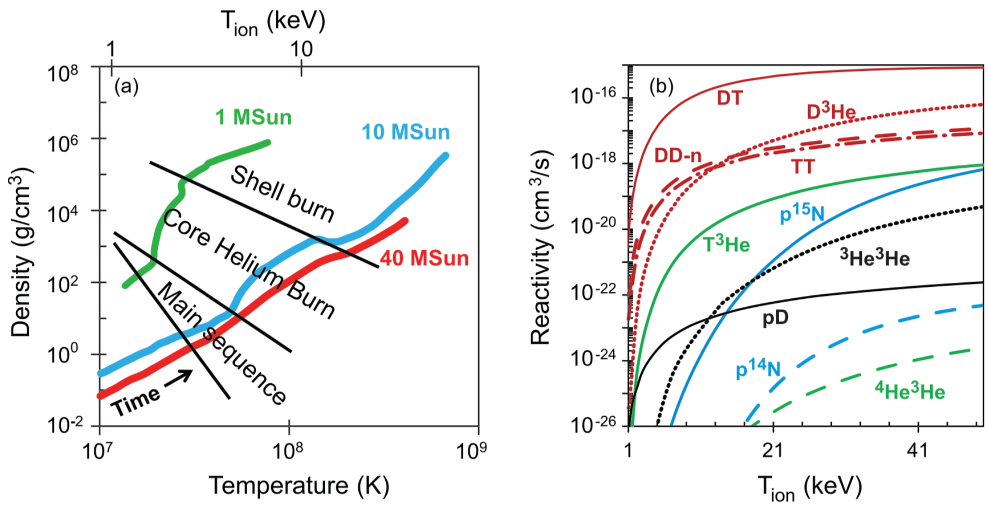

Figure 1. (a) Density vs temperature for star populations. (b) Predicted nuclear reactivities , <σv>, vs ion temperature, in stellar interior conditions. [Johnson 2017]

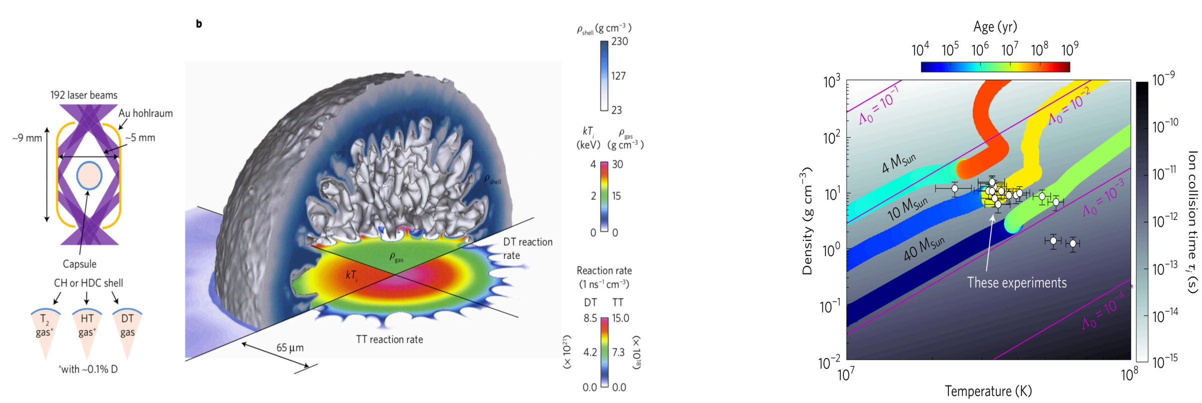

Figure 2. (a) Simulation of a NIF capsule implosion, showing the regimes that can be reached. (b) Density-temperature plot of stellar interiors vs their age, compared with NIF implosion experiments. [Casey 2017]

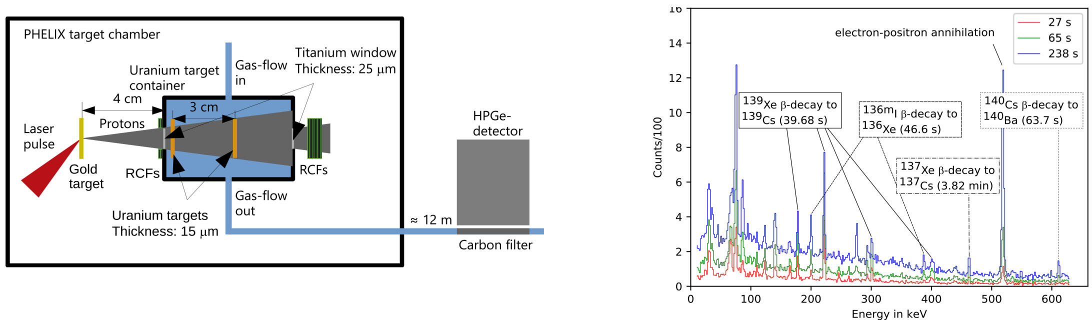

Figure 3. (a) Experimental setup for laser driven fission experiment. The short pulse Phelix laser drives a beam of TNSA protons from an Au foil, which then impact a uranium foil, (b) triggering fission reactions. [Boller 2020]

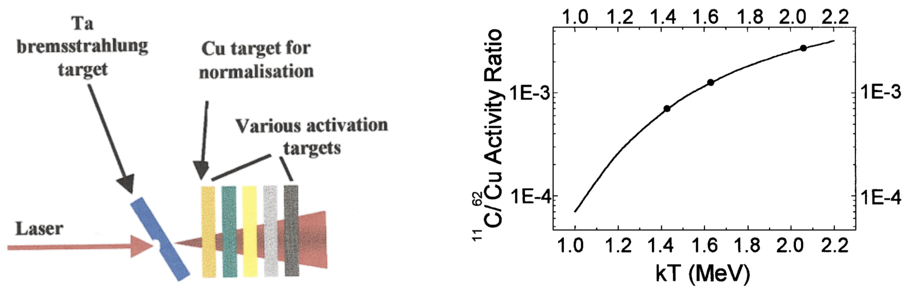

Figure 4. (a) Experimental configuration for a high intensity laser activation experiment. The laser irradiates a Ta foil to generate a forward directed flux of high energy bremsstrahlung x-rays that irradiate an array of diamond and Cu activation foils. (b) These foils are analyzed for radioactivity vs plasma temperature. [Ledingham, 2000]

Requirements:

For the nuclear studies of interest to this initiative, new nuclear diagnostic capabilities at the next generation ultraintense laser facilities would be required. These include γ-ray spectroscopy, which is often lacking at HEDP facilities, improved particle detectors for burst mode neutrons and charged particles, and radiochemistry collection and analysis of activation samples. These experiments are proposed to take place on new high intensity, high rep rate facilities. The Phelix laser experiments are used as an example in this white paper.

Scientific impact(s):

The intersection of plasma and nuclear physics is a fundamental area that should be explored by both communities. In particular, the nuclear science capabilities enabled by ultrahigh intensity, short pulsed lasers should be explored. While some work in this area is emerging, a more concerted effort by the community would accelerate progress. Possible issues to look at include MeV temperate high energy astrophysics phenomena and the effects of dense plasma on nuclear reaction rates. New regimes that should become experimentally accessible are numerous, such as nuclear reactions in hot blue giant stars, accretion disks around compact objects and black holes, neutron star mergers, and supernova and gamma ray burst explosions.

Broader impacts:

Pursuing research in plasma nuclear science will maintain US leadership in HEDP, and attract new talent to the field. While the US currently enjoys an advantage in high-energy long-pulse laser facilities such as NIF, Omega, and EP, similar capabilities are under construction internationally, and specialized facilities for plasma nuclear studies, notably ELI-NP, are also being planned or under construction. And there is an increased level of activity in relativistic plasma nuclear science enabled by high intensity, short pulse laser facilities in Europe and Asia.

Conclusion

There is a good scientific case for exploring the possibility of using state-of-the-art high intensity laser plasma physics facilities to conduct unique nuclear astrophysics. Developments in the last decade suggest that short pulse, high intensity lasers could be used to study plasma nuclear physics relevant to energetic astrophysical settings. In particular, experiments where the nuclear rates are affected by the presence of high density plasma and experiments at conditions relevant to supergiant stellar cores, accreting compact objects, gamma ray bursts, and supernova explosions seem possible. We note that there is obvious nuclear burning at solar core conditions of ~1.3 keV temperatures. Hence, petawatt laser driven plasmas at ~MeV temperatures should enable a multitude of nuclear reactions to be studied. This potential for unique and beneficial nuclear astrophysics on short pulse, high intensity lasers should be explored.

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MP3 White Paper 2021
Machine Learning for 3D Reconstruction of High Density Laser-Plasma

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Working Group(s): [PAALS]

Abstract (250 words).

Proton and ion acceleration to few hundred MeV's and further to GeV range using the next generation lasers producing peak optical power approaching 100 PW is probably one of the major goals in high energy density physics. While the power of lasers has increased steadily in the last decades reaching recently 10 PW, a paradigm shift has been seen also in the target morphology, from micrometer flat targets to micro- and nanostructured targets. Targets consisting in alternating micro- and nano layers made of different materials, nanotubes, nanowires, foams, gratings, are now under consideration for the current experiments. It is crucial to understand at the microscopic level the intricate coupling between the laser light, the target and the high density plasma produced at the target. We propose to develop machine learning (ML) algorithms to reconstruct the 3D plasma plume from different lines of sight using high speed x-ray imaging. The goal is to get insight into the plasma formation and its temporal evolution and be able to quantify the different phases of the acceleration mechanism and any hydrodynamic instabilities that can hinder this process.

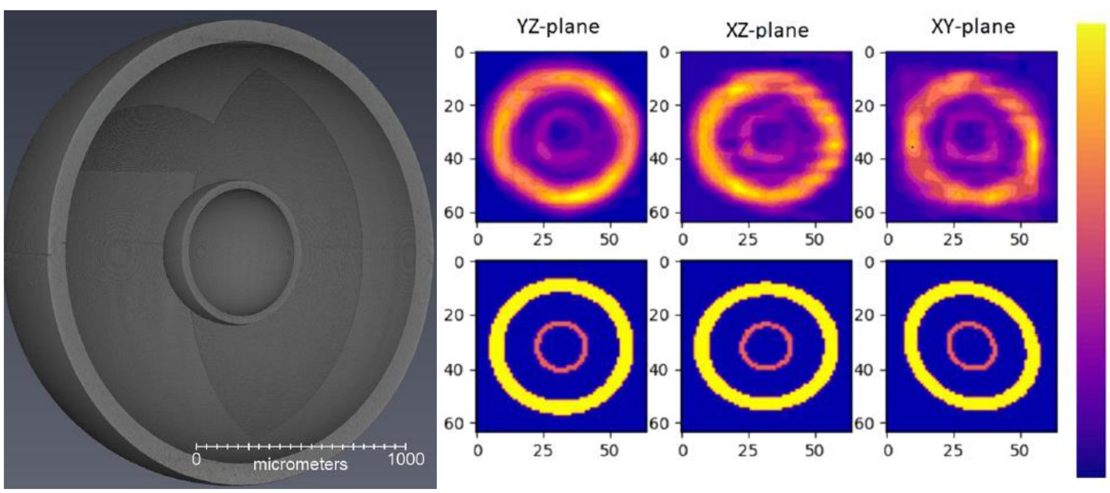
Scientific goal (Description of the goal and the methods that would be used.)

Acceleration of protons to hundred MeV's and ions to several GeV is one of the long sought goals of high power laser facilities [1]. The lasers have increased steadily in power in the last decades reaching recently 10 PW [2]. The next generation lasers will go even higher by an order of magnitude up to 100 PW. It appears that at this power level new acceleration mechanisms come into play, besides TNSA, such as the "light sailing" or radiation pressure acceleration (RPA) [3,4]. On the other hand a paradigm shift has been seen also in the target morphology, from micrometer flat targets to micro- and nanostructured targets. Targets consisting in alternating micro- and nano layers made of different materials, nanotubes, nanowire, foams, micro-gratings, are now in view for the current experiments [3-7]. This move has been linked with the more efficient laser absorption of laser power and heating of the electrons in order to reach higher accelerating fields. Given the complexity of the target structure, femtosecond laser wavefront and short interaction time it has become increasingly difficult to make an experimental characterization of the processes involved. It is crucial to understand at the microscopic level the intricate coupling between the laser light and the high density produced plasma. X-ray imaging is a powerful diagnostic tool which overcomes the opacity of the plasma at the critical density.
With the increase in cost of each experimental shot it is not possible for acquiring large data sets. The integrity of optics imposes limitations on the number of delivered shots at peak powers. Also the manufacturing process of the structured targets is more elaborate and the delivery of large batches is not always possible. At best one has to deal with a little number of shots and valid experimental results which can be a drastic drawback when looking for the most efficient parameters sets or when interpolating to different operating regimes.

We propose to develop and demonstrate machine learning (ML) algorithms as a valuable tool to reconstruct the 3D plasma plume from different lines of sight using a high speed x-ray imaging. The formation and time evolution of X-ray emission from the plasma formed when the laser pulse hits the target will be diagnosed. The 2D radiographs will be converted to 3D models. This will enable to identify the corresponding ion and proton acceleration phases based on plasma dynamics.

Tools required: Parameters required for the experiment, or technical requirements/abilities of modeling tools, or theory development. Identify any facility/diagnostic/code developments that need to be made to achieve the goal.

We will employ a gated x-ray framing camera and dedicated computing hardware and existing software. A convolutional neural network (CNN) will be trained to analyze the 2D radiographs. Preliminary results employing this type of network have been obtained on millimeter size ICF shells, where their 3D structure has been revealed from 2D radiographs [7]. An example is shown in Fig. 1. The plan is to implement the same technique for real-time plasma plume diagnostics. The resolution obtained so far is 50 μm per voxel (3D pixel) but the plan is to improve it by a factor of 10.



a) b)

Fig. 1. a) Image of ICF shell from x-ray CT image. B) Reconstructed 3D spherical shells (top row) from synthetic data obtained with the trained network and true images obtained by the x-ray CT, from [7].

Scientific impact(s): What will the impact of achieving this scientific goal be?

It will demonstrate the role of ML in optimizing the output of ion and proton laser-plasma acceleration. It will pave the way for more intensive research in this direction and will possibly lead to a more diverse approach allowing comparison between different algorithms. ML has been already implemented in fusion experiments leading to optimization of alpha particle output in the field-reversed configuration (FRC) proposed by TAE Technologies. Also ML is nowadays applied successfully to tokamak operation (DIIID, JET) for predicting and avoiding instabilities.

Broader impacts: Highlight other areas / fields or benefits to broader society where this research could make an impact.

Achieving GeV energies for laser plasma accelerated protons and ions will open up new avenues in many societal applications, just to mention a few: fusion, medicine, radiography.

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MP3 White Paper 2021
Title: Unruh Radiation Detection

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Working Group(s): HFP/QED

Abstract:
Unruh radiation plays an important role in understanding the entanglement structure of the vacuum and arises in various cosmological and high energy physics contexts [1], [2], [3]. Its experimental detection is currently beyond the capabilities of the available lasers mainly due to the high acceleration required for the detectors perceive the thermal photons. Several experiments are being considered [4], [5] in which high intensity lasers play an important role. The main idea would be to produce an electron beam and to intersect it with a high intensity laser, resulting in the acceleration of the electrons so that detectable Unruh radiation results. Larmor radiation will also result. The distinction between the two arises due to the fact that the Larmor radiation will be monochromatic while the Unruh radiation will be produced in pairs of entangled photons covering a broader range of frequencies.

Scientific goal:
Detection of the Unruh radiation by means of high intensity lasers as well as establishing the entanglement structure of the outgoing radiation. Such entanglement will occur in polarisation and evidence of it could be practically detectable. The idea behind the Unruh radiation is that the vacuum appears to be excited from the perspective of an accelerated observer. Therefore an accelerated electron would interact with quanta of this pseudo-vacuum, for example via Thomson scattering, resulting in entangled photon pairs that can be detected. Similarly, an accelerated detector considered to have two internal states, is expected to be excited from the lower to the upper state by quanta of the Unruh radiation. Such a two state detector (which could in principle be an electron, an atom, etc. [10]) initially in its ground state in a weak coupling limit has a transition probability towards its first excited state of

$$\rho^R_{1,1}|_{\gamma\eta\to 0} \xrightarrow{\eta>>a^{-1}} \frac{\lambda_0^2}{4\pi m_0}[\frac{\eta}{e^{2\pi\Omega_r/a}-1}] \qquad \eta = \tau - \tau_0$$

Where "a" is the proper acceleration. The Minkowski observer detects no field quanta. In the same context with a two state detector coupled to a massless field the transition probability in the first perturbative approximation is

$$P_{0\to n} = \frac{1}{\hbar^2}\sum_{n_k} |\langle E_n, n_k| \int_{-\infty}^{+\infty} d\tau H_I(\tau) e^{i(E_n-E_0)\tau/\hbar} |E_0, 0_M\rangle|^2 =$$

$$= \frac{\lambda_0^2}{\hbar^2} |\langle E_n| Q(0) |E_0\rangle|^2 \mathcal{R}(\frac{E_n-E_0}{\hbar})$$

$$\mathcal{R}(k) = \int_{-\infty}^{\infty} d\tau d\tau' e^{-ik(\tau-\tau')} \langle 0_M| \Phi(z(\tau))\Phi(z(\tau')) |0_M\rangle =$$

$$= \frac{\hbar}{2\pi}\frac{k\eta}{e^{2\pi k/a}-1}$$

$$D^{+(a)}_{UA}(\tau,\tau') = \langle 0_M| \Phi(z(\tau))\Phi(z(\tau')) |0_M\rangle =$$

$$= -\frac{\hbar}{(2\pi)^2}\frac{a^2}{4sinh^2(\frac{a}{2}(\Delta - i\epsilon))}$$

$$\eta = \int_{-\infty}^{\infty} d\tau$$

$$\Delta = \tau - \tau'$$

After tracing the modes beyond the Rindler Horizon we obtain

$$|0_M\rangle = \prod_k \frac{1}{cosh(r_k)} \sum_{n_k}^{\infty} tanh^n(r_k)\, |n_k\rangle_{\mathcal{L}}\, |n_k\rangle_{\mathcal{R}}$$

$$\rho_{\mathcal{R}} = Tr_{\mathcal{L}}\, |0_M\rangle \langle 0_M| = \mathcal{N} \prod_k \sum_{n_k=0}^{\infty} e^{-2\pi n\omega/a}\, |n_k\rangle_{\mathcal{R}\mathcal{R}} \langle n_k|$$

$$\omega = |k|$$

$$cosh(r_k) = (1 - e^{-2\pi\omega/a})^{-1/2}$$

The accelerated electron will perceive the scattering of a photon out of the thermal bath by the electron. The resulting temperature will be

$$T_U = \frac{\hbar}{2\pi k_B c} a$$

In the inertial laboratory frame this corresponds to the emission of a pair of real photons. Therefore accelerated electrons convert virtual quantum fluctuations into real particle pairs. This is a signature of the Unruh radiation. The experimental idea is to shoot ultra-relativistic electrons into a strong periodic electromagnetic field (as that from an intense laser beam). In the frame of the electrons the transversal field strength is boosted and the acceleration felt by the electrons is amplified. During each acceleration cycle the electrons generate a probability amplitude associated to photon pair creation. These amplitudes can be summed up constructively.

Tools required:

We need an external electromagnetic field described by E and B. The electron will feel a classical quivering motion [5] in the rest frame

$$r_{cl}(t) = e_z \frac{qE}{m\omega^2} cos(\omega t)$$

The classical and quantum effects of the electromagnetic field are governed by

$$L(\dot{r}_e, r_e) = \frac{m}{2}\dot{r}_e^2 - q\dot{r}_e \cdot A(r_e)$$

A being the vector potential in the temporal gauge. The small quantum fluctuations in the e.m. field appear as perturbations. This leads to two types of electron motions combining in its trajectory, namely the classical quivering motion plus small quantum fluctuations due to the coupling to the quantised electromagnetic field. Using the Euler Lagrange equations

$$\frac{d}{dt}\left[m\dot{\boldsymbol{r}}_e - q\boldsymbol{A}(\boldsymbol{r}_e)\right] = -q\frac{\partial}{\partial \boldsymbol{r}_e}\left[\dot{\boldsymbol{r}}_e \cdot \boldsymbol{A}(\boldsymbol{r}_e)\right]$$

we see that the canonical momentum is conserved to first order in the quantum momentum if the right hand side vanishes. This is the condition for planar Thomson scattering, satisfied if the polarisations are orthogonal

$$\boldsymbol{A}_{\mathrm{qu}} \perp \boldsymbol{A}_{\mathrm{cl}} \parallel \boldsymbol{r}_{\mathrm{cl}} \perp \boldsymbol{r}_{\mathrm{qu}} \vee \boldsymbol{k}_{\mathrm{qu}} \perp \boldsymbol{r}_{\mathrm{qu}} \parallel \boldsymbol{A}_{\mathrm{qu}} \perp \boldsymbol{k}_{\mathrm{cl}}$$

We therefore obtain $\dot{\boldsymbol{r}}_{\mathrm{qu}} = \frac{q}{m}\boldsymbol{A}_{\mathrm{qu}}$

Now consider the equations of the electromagnetic field depending on the full trajectory of the electron

$$\ddot{\boldsymbol{A}} - \boldsymbol{\nabla} \times (\boldsymbol{\nabla} \times \boldsymbol{A}) = -q\dot{\boldsymbol{r}}_e \delta^3(\boldsymbol{r}_e - \boldsymbol{r})$$

Inserting the split $\boldsymbol{r}_e = \boldsymbol{r}_{\mathrm{cl}} + \boldsymbol{r}_{\mathrm{qu}}$ into the source term we obtain the classical Larmor radiation

plus quantum corrections. Since the first contribution vanishes for parallel photons and does not generate polarisation correlations we will focus on the quantum current only

Combining the quantum current with the full equations for the electromagnetic field we obtain

$$\hat{H}_{eff}(t) = \frac{q^2}{2m}\hat{A}^2[t, r_{cl}(t)]$$

This is the effective interaction Hamiltonian for planar Thomson scattering. This effective Hamiltonian is justified by the fact that the produced Unruh photons are expected to be of low energy.

The process of non-inertial scattering generates the photon pairs out of the vacuum with the two-photon amplitude

$$U_{k,\lambda,k',\lambda'} = \frac{q^2}{4m}\frac{e_{k,\lambda} \cdot e_{k',\lambda'}}{V\sqrt{kk'}}\mathcal{F}_{k,k'}$$

The time integral is

$$\mathcal{F}_{k,k'} = i\int dtexp\{i(k+k')t - i(k+k') \cdot r_{cl}(t)\}$$

Which after a series expansion for small oscillation amplitudes leads to

$$\mathcal{F}_{k,k'} = \int dtexp\{i(k+k')\} \cdot r_{cl}(t)$$

Giving at the resonance condition $k + k' = \omega$

the amplitude is

$$U_{k,\lambda,k',\lambda} = \frac{q^3 E}{8m^2} \frac{e_{k,\lambda} \cdot e_{k',\lambda'}}{\omega^3 V} \frac{k_z + k'_z}{\sqrt{kk'}} \omega T$$

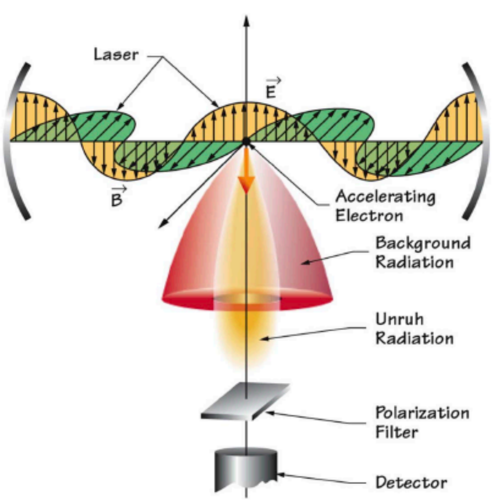
where the number of laser cycles is represented by the last two factors. The probability of the photon emission in the resonance band is

$$P_{Unruh} > \frac{\alpha_{QED}^2}{(4\pi)^2} \cdot (\frac{E}{E_S})^2 \times \mathcal{O}(\frac{\omega T}{30})$$

Where the Schwinger limit is given by $E_S = m^2/q$

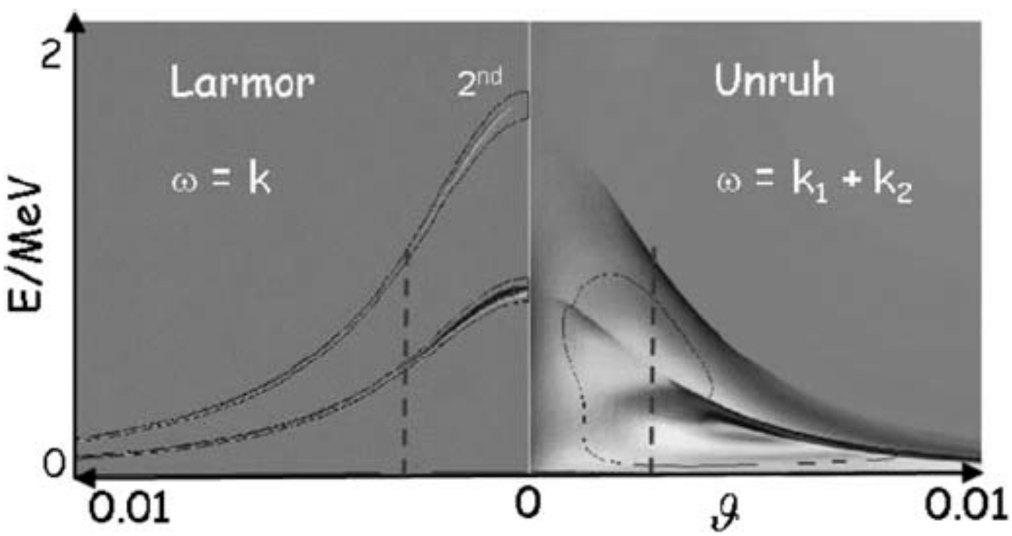
The classical Larmor probability of emission is much larger than the Unruh probability but the classical resonance condition for Larmor photons forces them to be monochromatic. The Unruh photons however are not and are correlated in energy and polarisation-entangled.
At a photon energy of 2.5 eV in the lab frame and a boost of 300 the photon energy in the rest frame of the electrons will reach 1.5 keV. A laser intensity of 10^18 W/cm^2 in the lab frame produces an electric field of a factor 1000 below the Schwinger limit in the rest frame of the electrons. After 100 laser cycles the two photon probability will be around 10^-11 from one electron. The sum of the energies of the created photons in the lab frame will be around 500 keV.
Aside of this example, the parameters encoding the intensity, the electric field, the energy of the photon, the resulting acceleration, and the Unruh temperature are provided in the following table

Method	I [W/cm^2]	E [V/m]	$\hbar\omega$ [eV]	a [g]	kT_{Unruh} [keV]	Horizon distance d
Laser focus	10^{23}	10^{15}	1	2×10^{25}	8×10^{-2}	0.5 nm
Coherent harmonic focusing	5×10^{29}	1.3×10^{18}	1	2×10^{28}	80	0.5 pm
Lorentz boost ($\gamma = 10^3$)	2×10^{36}	3×10^{21}	1	4×10^{31}	1.6×10^5	0.3 fm



Schematic Diagram for Detecting Unruh Radiation

[4], [5]. The laser focus method combined with ultrarelativistic electrons is what this proposal entails.
Indeed short pulse, high intensity lasers would allow accelerations of electrons that would bring the resulting temperature of the Unruh heat bath to rise up to detectable values. Electrons accelerated to relativistic energies of the order of GeV in a distance domain of a few millimeters are combined with the technique of coherent harmonic focusing of an optical laser serving as undulator. These will probe the vacuum fluctuations by the creation of Unruh photon pairs at the level of keV.
The competing Larmor radiation occurs with a probability of 10^-2 but this will be monochromatic and can be filtered out. The scattering properties of the medium are changed with the given frequency leading to the generation of quantum vacuum fluctuations of the QED being converted into pairs of entangled photons. The result is a set of entangled photons with high energies. If we have many electron systems we have both classical and quantum radiation which can be in coherent or incoherent superposition. A pulse of 10^9 independent electrons sent into a laser beam would produce one Unruh event in a hundred shots. The amplitudes generated by many electrons coherently leads to a non-perturbative regime. Quantum radiation will correspond to a multi-mode squeezed state where for small amplitudes the number of photons scales quadratically with the number of electrons, but after a certain amplitude the threshold is reached and the growth becomes exponential.



Scientific impact(s):

This experiment would have two major scientific implications. First it would experimentally prove the existence of Unruh radiation, a task that was beyond the capabilities of most laser facilities to date. Second, it would potentially allow us to understand the procedure of entanglement extraction from vacuum [3]. As mentioned before, the emerging photons should be polarisation entangled and this could become detectable by using simple photon-detectors and polarisation filters. The result would be important as it would shed new light on the entanglement structure of the vacuum and hence would show in what way a similar phenomenon, namely that of Hawking radiation would result in entangled particles. It is noteworthy to mention that entanglement is considered to play an essential role in understanding the Black Hole information paradox and hence a potential experimental verification, even if only in the case of Unruh radiation would bring us more details about how the information paradox could be solved. Unruh radiation produced by a system of many accelerated electrons could also reveal details about non-local phenomena that would have their origin in the holographic bulk [4]. Correlations in the electrons after their interaction with the thermal bath would possibly give us insight into how the holographic bulk (described by a manageable gravitational problem) would affect the quantum field theories in the boundary.

Broader impacts:

The Unruh effect has certain non-trivial theoretical implications. As we know from ref. [7], [8], [9] the Unruh heat bath detected by non-local observables (in our case a many electron system) can encode bulk information and hence become a portal towards understanding the holographic duality better. The spectral energy density in the Unruh heat bath can be altered by quantum gravity effects coupling to matter. Indeed, the semiclassical expression

$$\langle \mathrm{M} | \, \omega \, a^{\dagger}_{\omega} a_{\omega} \, | \mathrm{M} \rangle$$

is corrected by Schwarzian contributions. A Black Hole, is a fast scrambler and hence it is a chaotic quantum system. Such systems are characterised by the exponential dependence on changing initial conditions. In quantum theory this means that operators grow exponentially in time. This effect can be computed by calculating out-of-time-order correlators (OTOC). The gravity dual of such a phenomenon is the exponential redshift close to gravitational horizons resulting in gravitational shockwaves. Another hallmark of chaotic quantum systems is the evolution of the level statistics. Quantum chaotic systems present level repulsion. That means that the local spectral statistics of any quantum chaotic system can be described using random matrix statistics. Deviations of the Unruh radiation suggesting chaotic behaviour could signal nontrivial quantum gravitational behaviour in the bulk.

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MP3 White Paper 2021

Nuclear physics research in laser induced plasma with a multi-petawatt laser system: production and decay studies of cosmogenic ^{26}Al

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Working Group(s): HFP/QED, PAALS, LDNP

Abstract: High power laser systems (HPLS) exhibiting 10's of PW have the potential to be a disruptive technology, as they can provide Earth-bound astrophysical entropy conditions, allowing the study of nuclear processes as they unfold in hot stellar plasma. Cosmogenic ^{26}Al is of outstanding importance in this regard since its presence in the Galaxy provides an *unambigous* direct evidence for ongoing nucleosynthesis. Interpretation of astrophysical data of ^{26}Al is hampered because of its complex nuclear structure. In cold conditions, its first excited state at 228 keV ($^{26m}Al_{228}$) β^+ decays with $t_{1/2} = 6.35$ s directly into the ground state $^{26}Mg_0$ in neighboring magnesium and not into its very own long-lived ground-state $^{26}Al_0$ ($t_{1/2} = 0.72$ My). Theory states, however, that an intricate coupling between $^{26}Al_0$ and $^{26m}Al_{228}$ *via* higher-lying excitations will lead to a dramatic enhancement of the effective decay constant, λ_{eff} by a staggering 10^{25} orders of magnitude for hot temperatures in the GK region. This monumentally influences astrophysical models regarding the age of the Universe, which rely on the Galactic abundance of ^{26}Al. As instigated by our group, due to the high proton fluxes of an HPLS, temporary high yields of $^{26m}Al_{228}$ *and* ultrashort higher-lying excited states can be provided *in-situ* for fleeting durations. As a result, for ps-long production time-scales, astrophysical entropies are mimicked that can be probed by hard X-ray flashes to evaluate λ_{eff}. These experimental opportunities are only granted by coinciding ultraintense ion- and X-ray-pulses available exclusively from HPLS.

Scientific goal: Since its discovery in the Galaxy in 1984 [1] cosmogenic ^{26}Al is seen to be of outstanding astrophysical significance [2], as theory states that the isotope derives from explosive burning cycles, supernovae explosions, and supermassive stars [3, 4]. The excesses of its daughter product ^{26}Mg informs about the formation time of primitive meteorites, and its estimated high Galatic abundance of$\sim$ 3 $M_\odot$ is not accounted for by theory [5, 6, 7]. A study of the effective decay constant λ_{eff} of ^{26}Al as it unfolds in stellar plasma is henceforth necessary to benchmark astrophysical theory. Fig. 1 displays the complex decay pattern of ^{26}Al. Most importantly, a direct decay from $^{26m}Al_{228}$ to $^{26}Al_0$ is prohibited due to the high spin difference, $\Delta J= 5$, therefore excluding the onset of thermal equilibrium in cold environments. Earth-bound, RF- and DC-accelerator systems can only provide low entropy conditions in which ^{26}Al β^+ decays from two different states. Firstly *via* a 2nd order forbidden β^+ decay from its $J = 5^+$ ground state, $^{26}Al_0$ with $t_{1/2} = 0.72$ My and secondly *via* from its 0^+ first excited state $^{26m}Al_{228}$ ($t_{1/2} = 6.35$ s) which is a superallowed β^+-decay.

Theory predicts however, that a thermal equilibrium between those two states will occur at high temperatures (T $>$ 10^6 K) *via* a manifold of interlinking transitions to short-lived (fs - ns), high-energy levels, resulting in a 10^{25} higher value for λ_{eff} [9, 10, 11]. Fig. 2 depicts this dramatic change of λ_{eff} if GK ($\equiv$ T_9) temperatures are reached. Obviously, even a multi-PW HPLS cannot directly supply the entropy conditions of MeV plasma. However, as theoretically and experimentally evaluated by Spohr *et al.* [12], the shortness of the reaction driven proton pulse, will result in population yield distributions that mimick the entropy scenarios at very hot environments. Therein, the first three states $^{26}\text{Al}_0$, $^{26m}\text{Al}_{228}$, and $^{26}\text{Al}_{417}$ with $t_{1/2}$ = 1.6 ns at 417 keV represent the core levels that govern the interplay of the internal equilibrium. As shown in [13], the yield ratios between any two states can be mapped to a corresponding Maxwell-Boltzmann distribution describing a thermal equilibrium of temperature T, *via*,

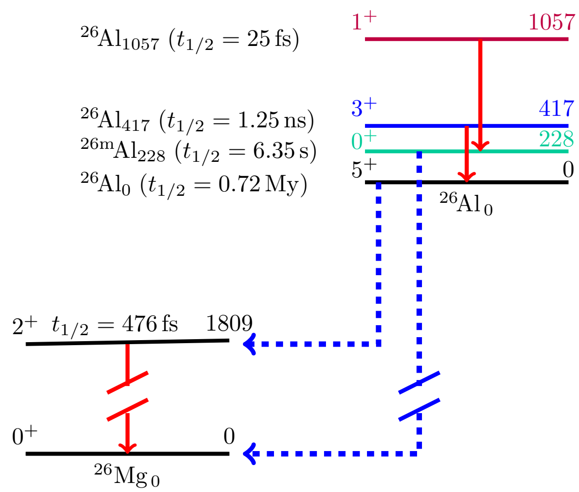

Figure 1: Simplified decay pattern of ^{26}Al. The two β^+ decay branches are depicted with the blue dotted lines. Red arrows: γ-transitions [8].

$$\frac{Y_2(t)}{Y_1(t)} = \frac{(2 \cdot J_2 + 1)}{(2 \cdot J_1 + 1)} \cdot \exp - \left(\frac{E_2 - E_1}{k_B T} \right), \tag{1}$$

in which Y_1 and Y_2 are the yields of any two states at a given time, J_1 and J_2 their spins values, and E_1 and E_2 their energy values ($E_2 > E_1$).

Fig. 3 shows the simulated T_9 equivalents of the yield distributions following Eq. 1 as function of time, assuming a 200 ps long impact by reaction driving protons and the very precisely measured cross-sections for $^{26}\text{Al}_0$ $^{26m}\text{Al}_{228}$, and $^{26m}\text{Al}_{417}$ from [14]. Fig, 3 illustrates further that after the initial laser-proton ^{26}Al production shot, a second, hard X-ray beam can be applied to probe the change of λ_{eff} by interlinking the excited states. Any change of the yield in ^{26m}Al will allow to benchmark the onset of thermalization between $^{26}\text{Al}_0$ and $^{26}\text{Al}_{228}$ as suggested in [11]. Due to its short 6.35 s long lifetime, a LaBr_3 detector should be placed inside the target chamber for the activation measurement of $^{26m}\text{Al}_{228}$ following [12]. The reaction of choice, $^{26}\text{Mg}(\text{p},\text{n})^{26}\text{Al}$ has a low threshold at E_p = 4.99 MeV. The associated cross-sections in [14] will

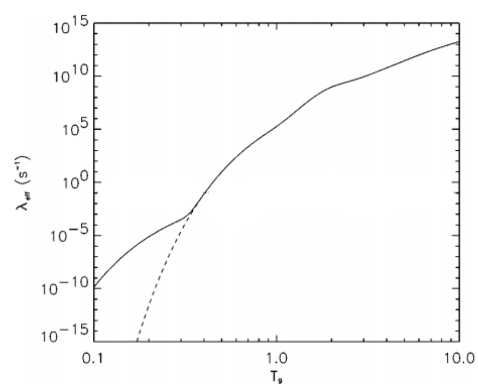

Figure 2: Theoretical $\lambda_{\text{eff}}(^{26}\text{Al})$ as function of T_9. Solid line: full calculation. Dashed line: transitions between $^{26m}\text{Al}_{228}$, and $^{26}\text{Al}_{417}$ disabled [11].

allow a precise analysis of data based on Eq. 1.

Tools required: The multi-petawatt laser pulses need to provide a focal intensity of I_0 to reach a maximum yield for MeV protons from the primary target. The secondary ^{26}Mg reaction target should be in cm-close vicinity. Around 30% of the laser energy should be directed to a 4 mm Ta-converter to provide a coincident high-intensity MeV X-ray flux to probe the interlinking of states. Selection and diagnostics of $E_p \sim 10$ MeV protons is essential. After the shot, $LaBr_3$ detectors placed inside the vacuum chamber should be used to measure the activity of $^{26m}Al_{228}$ with $t_{1/2} = 6.35$ s.

Scientific impact(s): The experiment will be the first to study the production and decay of cosmogenic ^{26}Al under mimicked entropy conditions that correspond to hot environments of stellar scenarios. As such, it would establish HPLS as a useful tool for experimental, laboratory-based astrophysics. Current accelerator technology cannot provide the coincident dual-beam burst of ions to produce the excited states and hard X-rays probing their interplay. Besides that, it would be the first time that nuclear measurements would be made on excited nuclear states, allowing to replace very uncertain theoretical calculations based on Hauser-Feshbach approximations which is currently the only way to estimate cross-sections of excited states [15]. A very interesting tool to progress this project will be the VEGA source for hard, monochromatic X-ray production at ELI-NP, to be operational in 2023. With VEGA the interlinking of states could be measured with highest precision, assuming some 10^{17} of the very rare ^{26}Al isotopes can be sourced from collaborators.

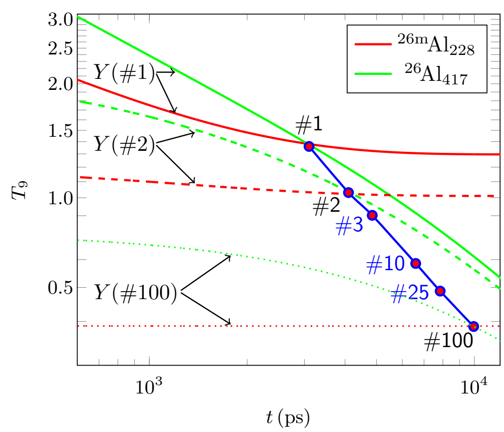

Figure 3: Calculated T_9 equivalents for Y_{228}/Y_0 (red) and Y_{417}/Y_0 (green) acc. to Eq. 1 from [12] with integral cross-sections from [14]. Consecutive shots #1 (solid), #2 (dashed), and #100 (dotted) are considered to irradiate the same volume in the secondary target, hence Y_0 builds up leading to lower T_9 equivalents. The times t_{equi} at which the two yield ratios converge to mimic a single value for T_9, are indicated by the blue/red circles connected by a blue line to guide the eye. For shot numbers depicted in blue the Y functions are omitted.

Broader impacts: To study the production and decay of the prominent ^{26}Al will allow astrophysicist to benchmark their theories regarding the age of the Universe. This has wider implications for related fields such as *e.g.*, the Standard Model and Dark Matter research. Besides undoubtedly opening up a new era in Earth-bound astrophysics, a series of related experiments could be instigated that focus on production and released decay of nuclear isotopes of pronounced applied interest.

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MP3 White Paper 2021

Laser-driven population and release of the 2.4 MeV isomer in ^{93}Mo, towards a 'Nuclear Battery'

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Abstract: Nuclear physics research will benefit from multi-PW lasers' ability to provide intense beams of accelerated protons simultaneously with hard X-rays. Facilitating this unique feature allows a study of the production and triggered release of the long-lived ($t_{1/2}$ = 6.85 hr) nuclear isomer ^{93m}Mo. The isomer resides at the high energy of 2.425 MeV, and an intermediate short-lived ($t_{1/2}$ = 3.52 ns) state situated only 4.85 keV above can act as a gateway to trigger the immediate release of its energy, resulting in a 500-fold energy amplification. A laser-driven control of this process will henceforth enable the harvesting of energy densities in the nuclear regime ('Nuclear Battery'). The principle of unsolicited ^{93m}Mo release *via* the intermediate state has already been observed by Chiara *et al.* [1], who assigned it to the Nuclear Excitation by Electron Capture NEEC process. However, this NEEC interpretation is challenged by the world-renowned theory group of the MPIK[1] [2]. To achieve complete control of the decay of ^{93m}Mo and solve the theoretical conundrum, we plan to use laser-induced MeV protons to produce the isotope *via* ^{93}Nb$(\mathrm{p,n})^{93m}$Mo. After production, ^{93m}Mo will be exposed to hr-long high fluxes of MeV X-rays, electrons, or directly to the multi-PW laser light to study a possible triggered release. The research will support the theory of nuclear processes in plasma and instigate further research into a 'Nuclear Battery' concept.

Scientific goal: The controlled production and triggered release of a nuclear isomer will allow harvesting the highest human-made energy density ratio in the region of 1 GJ/kg, comparable only to nuclear fission ('Nuclear Battery'). Our project will test High Power Laser Plasma Systems (HPLS) 's ability to provide the high level of mastery needed to manipulate isomers accordingly. The isomeric state ^{93m}Mo is the prime candidate for this endeavour as it lies at a staggering 2.425 MeV above the ground-state and has a rather long half-life of $t_{1/2}$ = 6.85 hr. The triggered freeing of the isomer's energy can proceed *via* an intermediate, short-lived ($t_{1/2}$ = 3.52 ns) state situated only 4.85 keV directly above ^{93m}Mo at 2.430 MeV, see Fig. 1. A steered depopulation of the isomer will, therefore, result in a 500-fold energy amplification. In 2018 Chiara *et al.* confirmed this pathway for triggered depopulation of

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^{93m}Mo using a conventional accelerator system, albeit coinciding with the production reaction, hence unsolicited. They claimed the hitherto unobserved Nuclear Excitation by Electron Capture (NEEC) caused by the stopping process of ^{93m}Mo in the production target as triggering mechanism and derived a very high excitation probability of $P_{\text{NEEC}} = 0.010(4)$. NEEC is the reverse of internal conversion. The process sets in when the absorbed electron's kinetic energy plus its atomic binding energy matches the energy difference between two nuclear states [4]. However, the very high value of P_{NEEC} is not supported by the world-renowned theoreticians at the MPIK, who have published widely on that process [5, 6, 7, 8, 9] and derived a value for P_{NEEC} that is a staggering nine orders of magnitude lower [2] than cited in [1]. They strongly suggest that another novel and hitherto unobserved process triggers this remarkable effect. Since the experimental evidence is not in question, (only) an investigation at a multi-PW system can clarify the current conundrum between observation and theoretical explanation. At an HPLS one can produce the isomer in question with MeV protons *via* $^{93}\text{Nb}(\text{p},\text{n})^{93\text{m}}\text{Mo}$, (Fig. 2, Part a)). A substantial yield can be guaranteed as the irradiation time can be in the order of several hours as $t_{1/2}(^{93\text{m}}\text{Mo}) = 6.85\,\text{hr}$. If a depopulation of ^{93m}Mo is achieved with high fluxes of X-rays (Fig. 2, Part b)), it is more likely that photoabsorption is responsible for the results in [1]. If, however, a keV electron plasma (Fig. 2, Part c)) will lead to depopulation of ^{93m}Mo, independent verification of NEEC is confirmed. Theory suggests that such a keV-plasma is already achieved for $I \gtrsim 10^{17}\,\text{Wcm}^{-2}$ in a ^{93}Nb target, which will allow a large surface to be irradiated by a multi-PW laser system [10]. The intensities will be derived from the experimental yields $Y(^{93\text{m}}\text{Mo})$ as retrieved in off-line activity measurements with a High Purity Ge-detector (HPGe). In any case, our experiment will shed light on the underlying nature of the interaction between the isomer ^{93m}Mo in a flux of keV X-rays and laser-plasma. It would also be exciting to test the isomer's response in Warm Dense Matter (WDM) if the reaction protons can be bundled with specifically designed targets to induce this peculiar state of matter. The proof of controlled production and decay, resulting in a 500-fold energy amplification, will significantly impact further research into the 'Nuclear Battery' concept.

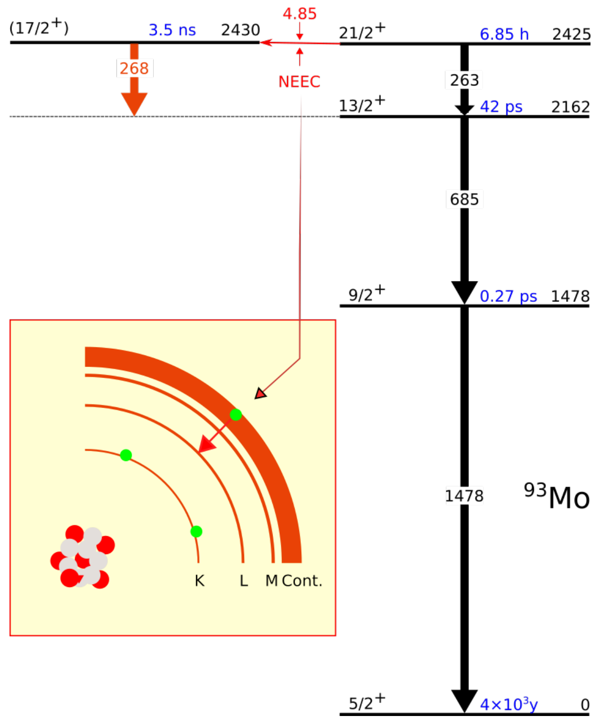

Figure 1: NEEC schematics (yellow inset) and partial ^{93}Mo level scheme from [3].

Tools required: The multi-petawatt laser pulses need to provide a focal intensity of I_0 to reach a maximum yield for MeV protons from the primary target. The secondary sandwiched ^{93}Nb reaction target should be in cm-close vicinity for the production experiments (Fig. 2, Part a)). To expose the isotope to keV X-ray radiation the laser pulse should be directed to a 4 mm Ta-converter to provide the highest possible X-ray flux (Fig. 2, Part b)). For direct laser irradiation to induce keV laser-plasma in the secondary target (Fig. 2, Part c)), the ^{93}Nb sandwich target should be shifted towards the laser propagation direction out of the laser's focal spot, to obtain maximum area coverage of $I \gtrsim 10^{17}\,\mathrm{Wcm}^{-2}$. Selection and diagnostics of $3\,\mathrm{MeV} \lesssim E_\mathrm{p} \lesssim 15\,\mathrm{MeV}$ protons is essential, as well as diagnostic tools to evaluate the laser-plasma in the target (X-ray backlighter). After the hr-long production and induced decay shots, the activity should be measured by a HPGe detector offline.

Scientific impact(s): The experiment will be essential to study the production and decay of ^{93m}Mo in laser-induced plasma and will follow and enhance inaugural work performed at ELI-NP. Results may settle the prominent dispute between the NEEC interpretation in [1] (Nature) and [2] (PRL) that is currently unresolved. Any progress with respect to the controlled production and triggered decay of a nuclear isomer has to be seen as a potential landmark experiment, as it will spearhead further technological applications for nuclear isomers, esp. in respect of developing a form of 'Nuclear Battery'.

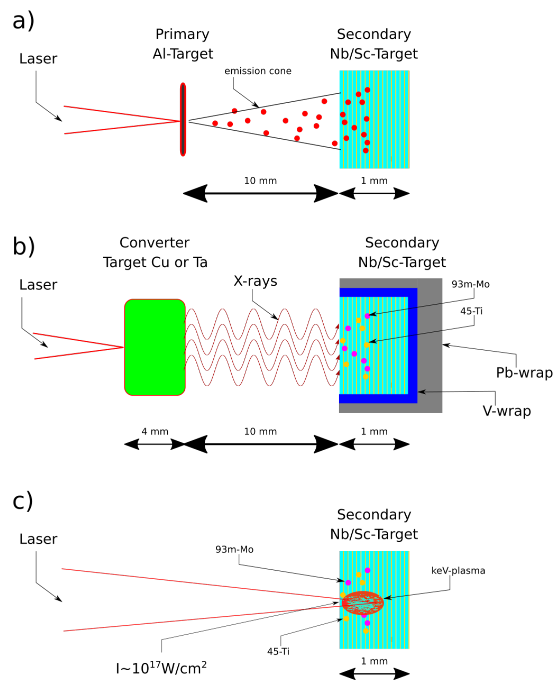

Figure 2: Part a) Setup for proton production shots, with the secondary ^{93}Nb target. Part b) Setup for the depopulation of by X-rays from a Ta- converter target. The wrapping in V- and Pb-sheets is to maximize the X-ray flux. Part c) Direct laser irradiation.

Broader impacts: The controlled release of a MeV isomer by a keV radiation will enable a gamut of potential applications. First on foremost, one can think of medical applications in which a big burst of radiation could be triggered by a relatively modest exposure to X-ray radiation. Moreover, the high probability as reported in [1] is very intriguing as it may indicate that there are further hitherto non-observed nor theoretically considered processes at the interface of laser-plasma, atomic, and nuclear physics. A multi-PW system is ideally placed to investigate such interactions that demand an overarching holistic strategy in experimental design.

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A Proposal for the Observation of Pair Production in Intense Field Regime

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Abstract

We discuss the scientific motivations for an experiment, the main goal of which is to study electron-positron production at the focal spot of a multi-petawatt intense laser. The set-up consists of two main stages, in which a high charge density electron beam undergoes collision against a counter-propagating secondary laser pulse, producing hard photons. These hard photons in the subsequent stage pass through the focal spot of the primary laser, producing pairs. We outline the scientific and broader implications for the field.

I Scientific Goal

In the theoretical framework, it has been long established that the QED vacuum can decay into electron-positron pairs under the influence of external electromagnetic fields[1]. In particular, when a laser pulse focused into a tiny spot, there is a small chance that low energy photons can create pairs via quantum tunneling. The pair creation rate is given by[2]:

$$W = \frac{(eE)^2}{4\pi^3\hbar^2 c}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-\pi n\frac{E_s}{E_0}\right] \tag{1}$$

where $E_s = m^2c^3/e\hbar$, is the critical field. This phenomenon, also known as the Schwinger effect, is exponentially suppressed for field strengths $E_0 \ll E_s$, Tailoring a pulse having field strength at the order of E_s remains to be out of reach with the currently available technology. Threshold for the decay however can be overcome when an energetic photon collides against a linearly polarized laser pulse and absorbs several low energy seed photons. The minimum number of absorbed quanta for the pair production to take place depends on two dimensionless parameters [3]

$$n_0 > \frac{2\eta}{\chi}\sqrt{1+\eta^2/2} \tag{2}$$

where η and χ are respectively called the intensity and quantum non-linearity parameters. In the particular case where a gamma photon undergoes a head-on collision against a constant-crossed field these parameters assume a simple form:

$$\eta = \frac{eE_0}{m\omega_0 c}, \quad \chi = \frac{2\hbar\omega_\gamma}{mc^2}\frac{E_0}{E_s} \tag{3}$$

Above scenario was in fact implemented during the SLAC-E144 experiment in a two stage process, in which an energetic electron beam was collided with a laser pulse, producing gamma photons, which subsequently underwent into collision with the laser photons [4]. The number of absorbed low energy photons was reported to be $n \sim 5$, with $\eta = 0.36$. In such regime ($\eta \ll 1$) the pair production rate obeys a simple power law[5]:

$$W \sim \eta^{2n_0} \tag{4}$$

Remarkably, the above scaling property was indeed verified by performing measurements at different intensities.

The planned 60 Petawatt laser facility in Rochester University will make it possible to reach unprecedented intensities around $\sim 10^{23} - 10^{24}\,\mathrm{W/cm^2}$. When compared to E-144 parameters, this amounts to an enhancement in the intensity by a 5-6 orders magnitude. This will open up the possibility to explore pair production phenomenon in a new regime, where the number of the absorbed of photons gets large i.e $\eta \gg 1$. In this regime the laser pulse, up to a good approximation, can be treated as constant crossed field[6, 7]. The corresponding pair production rate is approximately:

$$W \approx \frac{3}{16}\sqrt{\frac{3}{2}}\frac{\alpha m^2 c^4}{\hbar^2\omega_\gamma}\rho_\gamma\,\chi\,e^{-\frac{8}{3\chi}}, \quad \chi \ll 1 \tag{5}$$

Here, ρ_γ is the density of gamma photons. Above formula shows that χ plays the role of scaling parameter in the intense field regime and it shows exponential sensitivity to both gamma photon energy and the peak field strength. At the onset of nonlinear regime, where $\chi \gg 1$, the production rate is approximately:

$$W \approx 3^{2/3}\,\Gamma[2/3]^4\frac{15}{28\pi^2}\frac{\alpha m^2 c^4}{\hbar^2\omega_\gamma}\rho_\gamma\,\chi^{2/3}, \quad \chi \gg 1 \tag{6}$$

The study of the scaling behavior of W with respect to χ in both domains remains to be an uncharted area from the experimental point of view. In conjunction with this, we propose an experiment in which a high brilliance gamma beam collides against an intense short laser pulse. We propose to realize this in a two step process, in which $\sim$ GeV scale electron beam passes through the focal spot of counter-propagating, secondary $\sim 1-10$ PW laser, producing gamma photons, which subsequently pass through the focal spot of the primary ~ 60 PW laser. Here, the energy supplied by gamma photons would compensate the exponential suppression brought by the factor E_0/E_s that appear in the exponent in (5). For instance, assuming peak field strength of $10^{15}\,\mathrm{V/cm}$ for the primary laser, one has a factor of ~ 1000 in the exponent. This suppression can be compensated by gamma photons having energy ~ 0.5 GeV.

For the first stage, we may put a crude estimate on the number of hard photons produced via nonlinear Compton scattering. In this initial estimate we assume the idealized case of perfect overlap between the beams, and neglect the ponderomotive effects and any other damping factors introduced by the setup. We consider the following tentative values for the electron beam: bunch length 10^{-3}m, energy 800 MeV, radius 7×10^{-5} m and 5×10^9 electrons in the bunch, and for the secondary laser: 50 Joule energy, 25 femtosecond duration, wavelength of 820 nm, focal radius of

5×10^{-5} m. These values roughly translate into $\sim 10^7$ photons per shot, within a single cycle, with an angular spread $\approx 1/(2\gamma_e)$ [8, 9]. Here, γ_e is the Lorentz factor of the electron beam. This angular spread results in a dilution in the density of gamma photons that reach the high field focus of the primary pulse, making it a challenging task to achieve significant number collision events. For a 60 PW laser with focal radius $\sim 10^{-6}$ m, we estimate ~ 50 pairs are created per ~ 200 MeV gamma photon reaching the high field volume per unit time.

II Tools

A high charge density ($\sim 10^9$ electrons per bunch), GeV scale electron beam. With the advent of laser wakefield acceleration (LWFA) techniques, high energy electron beams can be produced in more compact setups, compared to linear accelerators. In one particular scenario, a 10 PW beam is split into two, one of the arms is used for electron acceleration where the other arm can be used for backscattering.

A 1-10 PW femto-second second pulse, with $\sim 10^{-5}$ m focal radius. The envisaged peak field strength is at the order of $10^{13} - 10^{14}$ V/m.

A 60 PW femto-second primary pulse, with $\sim 10^{-6}$ m focal radius. The envisaged peak field strength is at the order of 10^{15} V/m.

Electromagnetic calorimeters. Required for extracting information on the incoming flux and energy of charged particles and gamma photons.

Beam diagnostic tools. Required for precise intensity and energy measurement of the optical pulse.

Optical components. Required for the beam transport.

III Scientific Impact

The proposed experiment will test the QED in the non-perturbative regime. We believe this will not only set a milestone but will also pave the way for testing the theory in the forefront, the nonlinear-regime.

IV Broader Impacts

Overall, there are vast technical challenges involved in this project; the intensity measurement for the beam diagnostics, producing higher density electron beams to name a few, will push the field further into the innovation zone. Tailoring optical pulses at such intensities and producing high brilliance gamma beams will be tremendous technical achievements in their own right. A successful collision between the two beams requires extremely accurate and precise synchronization. Overcoming such an obstacle is a formidable task but once it is accomplished, a similar collision setup can be used for measuring the birefringent property of QED vacuum, which still remains to be verified in the laboratory.

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White Paper, MP3 Multi-Petawatt Physics Prioritization Workshop

Positron creation and acceleration with multi-petawatt lasers

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Abstract

Colliding intense lasers with relativistic particle beams opens many new research avenues, which become ever more exciting as the available laser intensity or particle energy increases. We can leverage this configuration to generate hard x-ray or gamma-ray beams, study the radiation reaction effects in the transition from the classical to the quantum-dominated regime of interaction, and create copious amount of electron-positron pairs. The pairs can appear as direct products of light-by-light scattering (multi-photon Breit-Wheeler process), or in solid targets where the strong electromagnetic background is ensured by the vicinity of an ion nucleus (Bethe-Heitler process). Both of these processes have already been demonstrated experimentally, but the potential practical applications rely on the possibility of producing dense matter-antimatter plasma in a controlled and reproducible way.
How should we set up experiments to obtain the maximum number of pairs with the available laser technology? What is the minimum required laser intensity to create a dense enough electron-positron plasma that would show collective effects? Can we accelerate positrons in plasmas after creating them, and what is the most robust configuration to achieve that? Can we deliver beams of high quality? Would it be possible to create and accelerate electron-positron-photon beams? These open questions, their intimate connection with our understanding of astrophysical plasmas in extreme environments, as well as opportunities for various applications and fundamental discoveries, entice researchers from different physics disciplines to join forces and pursue the answers together.

Scientific goal

The main goal is to generate and accelerate positrons or electron-positron beams to ultra-relativistic energies. This task is challenging in multiple ways. The creation of a large number of leptons requires extreme laser intensities and strategies how to maintain the produced particles close (traveling together as a beam or spatially confined within an optical trap). In addition, due to the positive charge, all the know-how we have acquired over the years to accelerate electrons in plasmas can prove to be prohibitively inadequate for positron acceleration. To an attentive reader, accelerating electrons and positrons at the same time may even sound impossible.
As this research direction is still in its infancy, analytical studies supported by first-principle simulations will be crucial to explore the viability of promising configurations, which could eventually suggest the directions for experimental exploration. In parallel, experiments with currently available laser technology can help refine our understanding of processes near the pair production threshold, and the practical challenges of collecting the produced particles and directing them towards an accelerating structure (e.g. inserting them into the right phase of a plasma wakefield). Electron-positron colliders were envisioned decades ago, and the debate regarding the final conception where both could be efficiently created and accelerated remains open. Due to the inherent nonlinearity of the laser-lepton interaction at extreme intensities, particle-in-cell codes are now commonly enriched with first-principle QED modules to include hard photon emission and pair production. They represent valuable numerical tools for pursuing the aforementioned challenges.

Tools required

Creation of positrons requires either high laser intensities or ultra-relativistic electron beams. Pairs created via the multi-photon Breit-Wheeler process [1] were first observed in the E-144 experiment at SLAC [2] colliding an accelerator beam (~ 50 GeV) with a moderate intensity laser ($I \sim 10^{18}$ W/cm^2). Here, the positron count was low but detectable. Future planned experiments will be able to produce more pairs per collision, using lower-energy electron beams and more intense lasers [3, 4]. Another approach for creating pairs is by irradiating an intense laser or an electron beam to a high-Z solid target resulting in the Bethe-Heitler pair production [5]. Several experiments have already achieved a typical yield of 10^{10} pairs / laser shot [6-9], but in this setup, a fraction of positrons can be lost while propagating within the target, and there is a concern about the debris from target expansion mixing with the generated leptons. Once created, in both of these configurations (head-on laser-electron collision or BH pair production) the pairs are not significantly further accelerated. A different scheme suggests we could accelerate the newly-created positrons directly, in the same interaction stage [10]. Here, we take advantage of the fact that the leptons are created at 90 degrees of incidence within the laser focal region, and sometimes the interaction lasts only a fraction of their oscillation cycle. This allows the pairs to retain the energy received from the laser and even be propelled in the same direction regardless of their charge, as they are both accelerated towards the direction of the light pressure (the local ExB direction). Using an angular aperture, it is possible to collect an electron-positron beam containing 50% of each species. The existence of such an acceleration setup allows us to conceive a possibility of a future electron-positron beam source, but we are still far from demonstrating it could be done in practice. Using a similar setup with two counter-propagating lasers within a plasma channel could provide two positron generation channels (linear and non-linear BW) and potentially favourable conditions for further acceleration [11].
Apart from creation, the acceleration of positrons in plasmas is a grand challenge by itself. Previous experience from electron acceleration schemes cannot be readily ported to positron acceleration. The reason is that a robust accelerating configuration provides both acceleration

and guiding [12, 13]. Transverse fields that focus electrons defocus positrons, so the opposite charge is a challenge for both, acceleration and guiding. In addition, it was shown that the beam quality degrades while positrons propagate through plasmas [14,15].
Despite all the obstacles, positron acceleration for several GeVs was recently demonstrated via the plasma wakefields [16], and other ideas to circumvent the challenges are emerging. For example, we could accelerate positrons in hollow channels [17-20], or use spatially tailored laser beams with orbital angular momentum that create inverted focusing fields suited for positron acceleration [20]. Direct laser acceleration in plasma channels is also a promising direction, as electrons above 10 GeV are expected with the next generation of lasers [22, 23]. The same scheme could be used for positrons, if one could reliably change the structure of the background plasma fields to be focusing for positrons (e.g. by beam loading). This is encouraging because > 100 nC of electrons were already accelerated in a near-critical plasma plume with a moderately intense laser ($I \sim 10^{19}$ W/cm2) [24].
To obtain energetic positrons, besides creation and acceleration, it is also necessary to solve the problem of injection inside the accelerating structure. All three challenges are intertwined and using high-fidelity modeling will be critical for assessing the viability of different setups. Several particle-in-cell codes (PIC) already incorporate the lowest-order QED processes [25-30] to be able to model both pair creation and subsequent nonlinear plasma interaction. However, the Monte-Carlo-based QED module is slower than the standard PIC loop, and full-scale 3D simulations may be impracticable for most scenarios. It is, therefore ,necessary to keep developing the reduced geometry solutions (e.g. Quasi-3D algorithm [31, 32]) applicable to some problems.

Scientific impacts

The research proposed is of fundamental interest, which has been recognized by the leading funding agencies and scientific journals [33, 34]. An important contribution would be studying the collective effects in electron-positron plasmas (provided that we are able to create a high enough density and size to contain several plasma skin depths). The lepton plasmas are expected to have unique properties due to their mass ratio of 1. Besides the fundamental interest, easy access to reliable sources of pair plasmas would provide tools for other branches of science. The most immediate impact would be for laboratory astrophysics - if we can generate relativistic electron-positron beams, we could set up a variety of experiments that mimic astrophysical conditions in the lab. For example, this would help understand the radiation emission and the electrodynamics of pulsars which are still open problems [35]. Another direction would be to pursue collisionless shock formation in counter-streaming pair plasmas and particle acceleration via beam-plasma instabilities [36, 37].

Broader impacts

The most exciting, but maybe furthest down the road, would be to use the positrons for electron-positron colliders. This requires not only to produce and accelerate enough positrons, but also an adequate control of positron beam quality. The beam quality represents a major challenge for plasma-based accelerators even for electron beams. However, some experiments have already shown that though difficult, this is not an impossible task [38]. There are no fundamental caveats for achieving this with positron beams [39], but further research will be required to get there. Meanwhile, there are near-term applications that deserve to be mentioned. Positrons can be used as a probe for radiography [40], for positron annihilation spectroscopy for material studies [41], or for defect imaging [42]. Many more applications are bound to emerge as the positron sources become available at scale and at a lower cost.

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MP3 all-optical vacuum birefringence experiment proposal

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Abstract. An all-optical vacuum birefringence experiment becomes closer to feasibility as multi-petawatt class lasers come into existence. With the unprecedented 75 PW peak power of the EP OPAL laser, electric fields in the order of $E_L \sim 10^{15}$ V/m can be expected in a focused spot size $\sim 3\,\mu$m. With these values and some readily available equipment we expect a measurable output signal. We discuss propose and detail two measurement schemes, namely a Mach-Zender and a Sagnac-type interferometer.

I. SCIENTIFIC GOAL

The goal of this proposal is to measure the vacuum birefringence of vacuum in the low energy limit ($\hbar\omega \ll m_e c^2$), subjected to a strong electro-magentic field. The most expected outcome would be the confirmation of this long-standing QED prediction, however, deviations from it would be even more interesting, since this discrepancy would imply New Physics.

Vacuum birefringence (VBir) [1–3] is one of the QED predictions yet to be tested in a lab environment. A consequence of the Heisenberg-Euler effective Lagrangian [4–6], to this day the only experimental evidence comes from astrophysical events [7], with some doubts [8] still existing.

On the terrestrial experimental side, one must mention the purely magnetic field VBir experiments [9–13]. The PVLAS collaboration reported more and more sensitive measurements [14–16] placing their experimental sensitivity at a factor of 50 above the QED limit, with no vacuum birefringence signal detected.

However, the advent of ultra-short peta-watt class lasers completely changed the paradigm [17], leading to the availability of unprecedented electric/magnetic field intensities. While 1 PW laser facilities are almost commonplace, multi-PW lasers have been already reported: GIST [18] (4.2 PW in 2017), ELI-NP [19, 20] (10 PW in 2020). Focused intensities of 2×10^{22} W/cm^2 [21] have been obtained already more than a decade ago while 5.5×10^{22} W/cm^2 was recently repoted [22]. The upcoming EP-OPAL [23] facility is expected to go beyond this values for a maximum pulse power of 75 PW.

The prospect of these high intensities as well as their configuration (perpendicular E and B fields, both perpendicular on the probe beam propagation) makes vacuum birefringence a compelling experimental proposal. Indeed, in this scenario one has a magneto-electric birefringence in the quantum vacuum, a discussed by Rikken and Rizzo [24, 25].

A Mach-Zehnder based interferometric proposal was introduced in reference [26] and its experimental feasibility estimated for classical light probe beams as well as for non-classical (squeezed light) probes. It was shown that under reasonably optimistic experimental assumptions, such a measurement is actually feasible.

Very recently, an experiment to test the "optically induced change of the vacuum index" was reported [27]. The authors used a Sagnac-based experimental setup.

In the following we detail two experimental proposals, one based on a Mach-Zehnder interferometer [26] and a second one based on a Sagnac-type interferometer.

In both cases we assume a (weak) probe beam propagating through a disturbed vacuum. We assume the vacuum is disturbed by a strong (multi PW-class) counter-propagating laser. Taking into account the magneto-electric effect [24], too, the probe beam parallel ($\|$) or perpendicular ($\perp$) to the PW laser polarization sees a refraction index [25, 26, 28]

$$\left\{ \begin{array}{c} n_{QED,\|} \\ n_{QED,\perp} \end{array} \right\} = 1 + 2\xi \times \left\{ \begin{array}{c} 4 \\ 7 \end{array} \right\} \times E_L^2 \qquad (1)$$

where $n_{\|}$ ($n_{\perp}$) is the vacuum refraction index when the probe beam's polarization is parallel

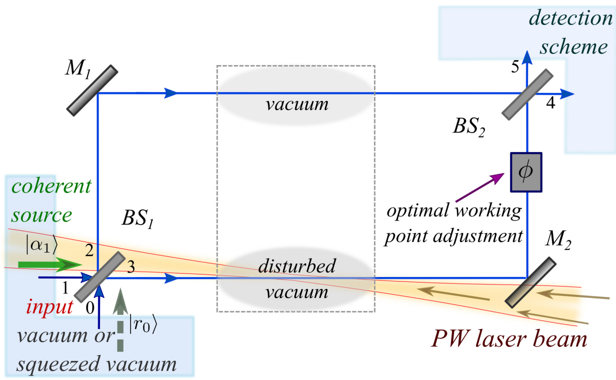

FIG. 1. Mach-Zender xxperimental setup of the proposed all-optical vacuum birefringence experiment.

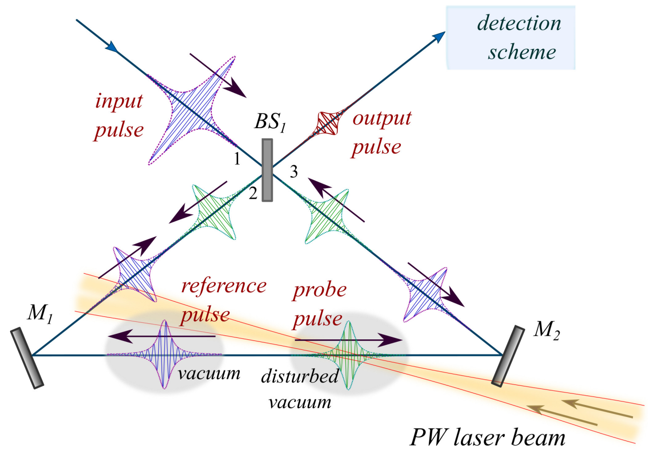

FIG. 2. Sagnac interferometer setup with an input pulsed laser.

(perpendicular) to the pump beam's polarization and we have the constant [26, 28]

$$\xi = \frac{\hbar e^4}{180\pi\epsilon_0 m_e^4 c^7} \approx 9.2039 \times 10^{-41} \quad \frac{\mathrm{m}^2}{\mathrm{V}^2}. \quad (2)$$

Consider the probe beam (of wavelength λ_p and frequency $\omega_p = 2\pi c/\lambda_p$) counter-propagating (see Fig. 1) over a length $b = 2z_R$ (depth of focus) with a pump laser that disturbed the vacuum where $z_R = \pi w_0^2/\lambda_L$ is the Rayleigh distance. Here λ_L is the pump laser wavelength and w_0 the Gaussian beam's waist. The phase shift of this beam in respect with the same beam propagated in an unperturbed vacuum is $\Delta\varphi_{QED,\parallel/\perp} = \omega_p b/c \left(n_{QED,\parallel/\perp} - 1\right)$ and plugging in the the values from Eq. (1) yields

$$\left\{ \begin{array}{c} \Delta\varphi_{QED,\parallel} \\ \Delta\varphi_{QED,\perp} \end{array} \right\} = \frac{8\pi^2 w_0^2 \xi}{\lambda_p \lambda_L} \times \left\{ \begin{array}{c} 4 \\ 7 \end{array} \right\} \times E_L^2 \quad (3)$$

It is experimentally interesting to have $\lambda_p \neq \lambda_L$. Throughout the depth of focus we assume a constant electrical field (equal to its maximum specified value, E_L). We assume $E_L \sim 10^{15}$ V/m. For $\lambda_p = 532$ nm, $\lambda_L = 820$ nm and a waist $w_0 \approx 3\mu$m, the QED-predicted phase shifts are

$$\left\{ \begin{array}{c} \Delta\varphi_{QED,\parallel} \\ \Delta\varphi_{QED,\perp} \end{array} \right\} \approx \left\{ \begin{array}{c} 6 \\ 10 \end{array} \right\} \times 10^{-7}. \quad (4)$$

The phase sensitivity of an interferometer using classical light (lasers in this case) is lower bounded by the standard quantum limit (SQL) [29]

$$\Delta\varphi_{SQL} \geq \frac{1}{\sqrt{\langle N \rangle}} \quad (5)$$

where $\langle N \rangle$ denotes the average number of photons. Considering a pulsed probe laser of pulse length $\tau_p \sim \tau_L \sim 25$ fs and requiring $\Delta\varphi_{SQL} \sim \Delta\varphi_{QED,\parallel} \sim \Delta\varphi_{QED,\perp} \sim 10^{-7}$ we find the needed peak power of the pulsed probe laser

$$P_p = \frac{\hbar\omega_p}{(\Delta\varphi_{SQL})^2 \tau_p} \sim 10 \text{ TW} \quad (6)$$

Such peak powers for femto-second class lasers are nowadays readily available.

Mach-Zehnder type interferometer setup. In the case of a Mach-Zehnder type interferometer (Fig. 1) the input port 1 is assumed to be fed with the coherent source (probe laser) while input port 0 is kept in the vacuum state (dark port). This implies the SQL translating into the phase sensitivity (5). The result can also be confirmed by computing the quantum Fisher information and using the quantum Cramér-Rao bound [29].

Sagnac-type interferometer setup. The Sagnac-type interferometer setup is depicted in Fig. 2. A pulsed laser is assumed as the input and the beam splitter BS_1 splits this laser into "probe pulse" and "reference pulse". The timing of the probe pulse is assumed to be calculated so that it overlaps with the focused, counter-propagating strong PW laser. The "reference pulse" is assumed not to intersect the strong PW laser. When recombining in BS_1, the difference between the two pulses will yield the signal to be detected.

II. TOOLS REQUIRED

Multi PW-class laser. A laser peak power of $60 - 75$ PW is assumed to translate into a focused maximum electric field $E_L \approx 10^{15}$ V/m.

It is also assumed that a suitable focusing mirror will be available. The focused spot size where an almost maximum electric field can be assumed is $\sim 3\ \mu$m.

High-precision interferometry. Both proposed experimental setups (Figs. 1-2) are relying on high-sensitivity interferometry. It is also assumed that they are in vacuum, at least until the detection part. It is assumed that the user can choose the probe laser's polarization, both $\parallel$ and $\perp$ wrt the pump laser.

Due to the smallness of the expected phase shift, seismic isolation and environmental vibration damping have to be considered, including suspended mirrors by double or multiple pendulums [30] and eventually employing active actuators [31].

In future evolutions, the phase sensitivity can be taken beyond the shot-noise limit (*i. e.* $\Delta\varphi \sim 1/\sqrt{\langle N \rangle}$). The theoretical Heisenberg scaling $\Delta\varphi \sim 1/\langle N \rangle$ [29] seems unrealistic for this experimental setup, however improvements $\Delta\varphi \approx 0.1/\sqrt{\langle N \rangle}$ can be expected by adding squeezed vacuum [26].

III. SCIENTIFIC IMPACT(S)

QED is indeed an accurate and well tested theory. One must mention here the $g-2$ for the electron 12 digit theory-experiment matching, the Lamb shift, Dellbrück scattering etc. However, one fundamental process (predicted way before the inception of QED as a theory), namely the 4-field interaction [4, 5] with only photons in both the input and the output states lacks experimental verification. To this day, to the best of our knowledge, there is no direct experimental evidence of this interaction.

This QED interaction (considered to only first order since laboratory fields obey $E \ll E_S$ and $B \ll B_S$) implies two effects: light by light scattering and vacuum birefringence (VBir). While the first effect is a microscopic one, VBir is a macroscopic effect that can be seen as a direct manifestation of the quantum vacuum. The only experiment to date supporting light-by-light scattering in vacuum is the ALTAS/CMB experiment involving $\gamma-\gamma$ pair emission during Pb-Pb peripheral collisions [32, 33]. However, this experiment was performed in the high energy domain ($\hbar\omega \gg m_e c^2$) and the involved photons were "quasi-real".

Thus, as we stand today, this purely quantum mechanical effect needs a direct laboratory verification in the low energy regime. Its confirmation would close one of the last QED predictions needing experimental validation. However, this low energy limit comes with additional benefits, since many beyond-SM particles are expected to lie in this regime.

IV. BROADER IMPACTS

Besides being a major milestone in the high field QED community, a precise result in the low energy vacuum birefringence measurement would probe for axion like particles [34], millicharged particles [35], chameleons/Dark Energy [36] as well as certain candidates for Dark Matter [37].

Indeed, deviation for the QED predictions are not ruled out and any such experimental result will immediately point to New Physics.

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Laser driven-acceleration of ion and energy scaling modification by competitive processes.

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Abstract: It is two decades since laser-driven acceleration of proton to energies of the order of 10s of MeV was first demonstrated [1]. From that time, laser-driven particle acceleration has received increasing interest in the scope of fundamental research and applications such as mainly biomedical applications (e.g. hadron therapy, radiobiology) and nuclear and particle physics, (e.g., ion fast ignition). Until recently, most experimental research has been understood in terms of the Target Normal Sheath Acceleration (TNSA) mechanism [2-4], which occurs when ions are accelerated by a space charge field generated at the rear surface of the target by highly energetic electrons directly accelerated by the laser. However, in some cases, not yet well investigated, a more complex acceleration dynamics can occur during the laser-plasma interaction, as more processes can coexist. Understanding, these processes is mandatory for controlling the parameters of secondary particle sources. In fact, different applications will require different ion beam characteristics, such as higher energies and flux than currently achieved (e.g., for hadron therapy and high rate nuclear reactions), as well as beam properties control (e.g., energy spectrum, beam duration, beam divergence). Therefore, the acceleration mechanisms studied so far (e.g., TNSA, RPA), will need to be further investigated at higher laser intensities and within different conditions of laser-target interaction. In particular, in the future, most of the research will need to focus on laser-driven acceleration involving ultra-thin foil (tens of nanometers) and high-power laser of the order of 10s of PW.

Scientific goal: Nowadays, high-power lasers can be focused to such intensities that an electron can directly be accelerated to relativistic speed. At such a speed very close to speed of light in vacuum the electrons are essentially collisionless and can easily cross a relative thick solid density material leaving the target bulk positively charged. The excess of positive charge creates an electric field at the surfaces of the target that can reach a strength of the order of TV/m [2,4,5]. This field allows for the acceleration of the positive ions (e.g., ionized hydrocarbure contaminants) located on the surface of the target to energies of 10s of MeV. This mechanism of acceleration is generally understood as TNSA (Target Normal Sheath Acceleration). The acceleration involves the molecules present at the surface of the target, while the bulk of the target just provides a support for those molecules. In this circumstance, TNSA can generated proton beams highly laminar, with very low emittance, and a broad energy spectrum, with the cut-off energy scaling with the square root of the laser intensity I_0 for a given laser wavelength in vacuum λ_0, that is $E_{max} \sim (I_0\lambda_0^2)^{1/2}$, or in terms of normalized vector potential $a_0 = 0.85\ (I_0[10^{18}\ Wcm^{-2}])^{1/2}\ \lambda_0[\mu m]$, as $E_{max} \sim a_0$ [2-4,6]. This is a robust acceleration mechanic but it has not a fast energy scaling and generates a relative low density proton beam at a practical distance (~ 10s cm) from the target.

In the last few years, other accelerating mechanisms have become evident experimentally due to advancements in acceleration schemes and the continuous trend towards pulsed laser of higher power and larger energy. Radiation Pressure Acceleration (RPA), is one of the novel acceleration mechanisms which is emerging and becoming increasingly prevalent [2,6]. Differently from the TNSA, the RPA allows for target bulk acceleration via different acceleration sub-mechanisms (e.g., Hole-Boring (HB), Light Sail (LS), Relativistic Induced Transparency (RIT), Coulomb Explosion (CE)) owing to a strong and ideally uniform ponderomotive light pressure which acts on the entire volume of the irradiated region [3,5-7]. In specific conditions, that is $\delta \sim a_0$, (where $\delta=\pi(n_e/n_c)(L/\lambda_0)$ is the normalized area density, with n_e the electron density of the bulk and n_c the critical electron density for λ_0, and L the thickness of the target), and generally for ultra-short laser pulse duration, when the light pressure acting on the electrons makes them to slightly separate from the bulk and allows for the ions of the bulk to stably follow the electron sheath, the process can be interpreted as Light Sail (LS) [8,9], which ideally accelerated the particles to high energies (~ 100s MeV/amu) and with a compactness of the beam near solid density [7]. This particular RPA acceleration mechanism, as above-mentioned, not only allows generating ultra-high dense beams from basically any solid material, but also the cut-off ion energy scale faster with the laser intensity, with comparison to the TNSA case. For ion energies up to 100 MeV/amu the energy scales as Emax ~ a_0^4 (i.e. with the second power of the laser intensity), while for relativistic energies ~ GeV/amu, it scales as a_0^2 (i.e., linearly with the laser intensity) [6, 9, 10]. These fast scalings allow for an efficient acceleration, and pave the way to compact laser accelerators. Therefore, investigating and understanding the physics underlaying this phenomenon is necessary for future applications. To achieve ion energies of the order GeV/amu, a multi-petawatt laser of the order of 10s PW is needed, as the laser intensities required should certainly be above 10^{23} Wcm^{-2} (see Fig. 1). However, at such level of intensity QED phenomena come into play and the laser energy is partitioned among different processes, making the acceleration of ion becoming harder and more complex. For instance, the laser

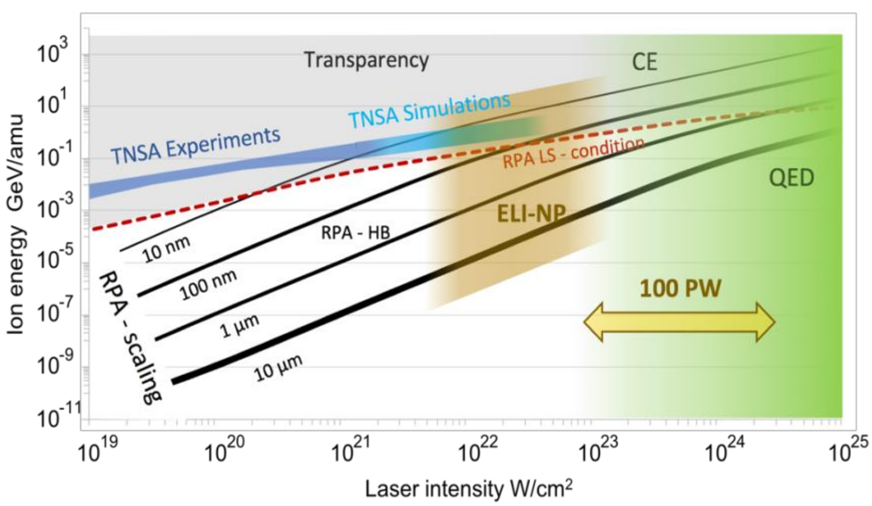

Figure 1: in the Figure is illustrated the energy scaling of TNSA and RPA acceleration schemes for an Aluminum target of optimized thickness for the TNSA and a range of thicknesses (from 10 nm to 10 µm) for the RPA (theoretical scaling). The TNSA scaling is slower than the RPA one, but at laser intensities lower than 10^{21} Wcm^{-2} TNSA can generate protons with energies greater than the one achievable in realistic conditions by any RPA scheme. The TNSA proton energies predicated by PIC simulations start becoming comparable to the predicted RPA ones for laser intensities up to sub-10^{22} Wcm^{-2}, then for even higher laser intensities the RPA ion energy per nucleon increases significantly. The latter is the region of investigation of the ELI-NP 10 PW laser. Above such intensities the QED effects starts becoming significant and this region will probably need a multi-ten PW laser for to become properly accessible.

interaction with near solid density targets may initiate a pair cascade resulting in an efficient generation of energetic gamma photons and the quenching of the ion acceleration [11-15]. Consequently, different scaling laws from those above-mentioned will arise from such high energy density interaction. Soon, experiments with a 10 PW laser will start at Extreme Light Infrastructure for Nuclear Physics (ELI-NP) in Romania, and novel physics will be investigated and better understood, extending the knowledge attained in the last 2 decades from experiments at a PW level [16,17]. Although, the high laser intensity that will be available at ELI-NP (sub-10^{23} Wcm^{-2}) will give access to new aspect of the laser matter interaction, yet most of the QED phenomena will need an even higher laser intensity to be properly explored [11-15].

Tools required: The described experiments require laser intensity sufficiently high for accessing the QED regime, that is a laser intensity of the order of at least 10^{24} Wcm^{-2} or even higher. Such laser intensity will require a ~100 PW laser system to be focused down to a spot size of the order of a few μm diameter. For instance, a Ti:Sapphire laser of 20 fs pulse duration and 810 nm wavelength and a full energy of 2 kJ focused down by a F/2 parabolic mirror will provide an intensity of about a few 10^{24} Wcm^{-2}.

Scientific impact(s): The understanding of laser-driven acceleration will open up the possibility of building a compact accelerator for ion energies up to few GeV/amu allowing numerous applications in valorous fields. Other relevant topics are the generation of very bright gamma-ray beams of multi-PW power and the QED physics related to this [11-15].

Broader impacts: One specific application of high-density and high-energy ion beams of great impact for the society is the hadrontherapy with ultra-high dose rate ion beams (e.g., proton, Carbon) [18-22]. As recently it has been proven, fast irradiation or FLASH has better effectiveness and lesser side effects than a conventional low rate exposure proton therapy [23].

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Title: High-Energy Astrophysics Experiments Based on Ultra-intense Lasers Irradiating Solid Targets

Abstract:

Ultra-intense laser provides a unique laboratory platform where some of the most exotic and energetic astrophysical phenomena can be studied in a controllable setting. Outstanding high-energy astrophysics (HEA) phenomena include gamma-ray bursts, pulsar winds, magnetar flares and AGN jets. The common features of these energetic astrophysical phenomena include relativistic outflows, preponderance of e+e- pair plasmas, copious emission of MeV to GeV gamma-rays, and super-strong electromagnetic fields. All of these can potentially be pursued in the laboratory using ultra-intense lasers.

Scientific goals:

The major goals in Laboratory High Energy Astrophysics (LHEA) experiments include:
1. Creation and characterization of relativistic jets.
2. Creation of high-density e+e- pair plasmas and investigating their observable manifestations.
3. Creation of ultra-intense gamma-ray sources and studying their interactions with ambient medium.
4. Creation and applications of super-strong electromagnetic (EM) fields.

Ultra-intense PW-class lasers focused to peak intensities > 10^{21}W.cm^{-2} irradiating *solid targets* can convert 10% - 50% of the laser energy into multi-MeV hot electron jets, which in turn create super-Alfvenic currents, super-strong electromagnetic fields and copious bremsstrahlung gamma-rays. Up to ≥10% of laser energy can be directly converted into multi-MeV gamma-rays. With high-Z targets, dense electron-positron pair plasmas with $n_{\pm} \geq 10^{15}$/cc can be created via the Bethe-Heitler (γZ=>Ze+e-) process.

Currently there is no other practical terrestrial platform that can produce similar physical conditions to study these exotic astrophysical phenomena, with comparable energy efficiency, through put and flexibility. This ultra-intense laser-solid-target platform is *complementary* to LWFA-driven laser-particle accelerators using gas targets. LWFA-based schemes can deliver higher electron energy and narrower beam with lower laser intensity, but producing much fewer hot electrons, pairs and gamma-rays per laser pulse.

Tools required:

For LHEA applications utilizing the laser-solid-target platform, high laser contrast and high rep-rate are not necessary. Instead, higher total laser energy, higher peak intensity (≥10^{21}W/cm^2), *larger* focal spot size, and shorter laser pulse are most desirable. Higher laser energy creates more total hot electrons, pairs and gamma-rays. Higher laser intensity creates more energetic gamma-rays and stronger in-situ EM fields. Larger spot size creates bigger, more uniform, plasmas for easier diagnostics and facilitates more particle-particle and particle-photon interactions. Finally, shorter laser pulse leads to higher density of hot electrons, gamma-rays and pairs, which in turn results in a more robust "pair plasma" whose size can become >> pair skin depth.

In addition, multiple PW lasers capable of hitting a solid target from different directions, or hitting multiple adjacent targets simultaneously, will facilitate more integrated LHEA experiments to be performed. Examples include trapping of pair plasmas by super-strong magnetic fields, or Compton fireballs from the collisions of hot electrons with dense x-gamma-rays.

Because ultra-intense lasers irradiating high-Z solid targets unavoidably create high radiation environments, the target chamber and the experimental area for such facilities must be heavily shielded. At the same time, the work areas adjacent to the target chamber must be sufficiently spacious to facilitate the installation and movement of heavy equipment, since most detectors must be heavily shielded. Inside the target chamber, remote-control debris shields must be installed to protect the optics and diagnostics from the solid target debris. The debris shield requirement is especially important if we choose a short focal length to increase laser intensity, and use large (≥ cm size) high-Z solid targets to maximize gamma-ray production. Easy access to the interior of the entire target chamber is also important, with as many removable doors and port holes as practically possible.

Diagnostic of LHEA experiments will be the most challenging. Such laser facilities must invest heavily in new diagnostics for charged particles and gamma-rays, in the spectral, spatial and temporal domains. High-resolution, high-fidelity, EM field measurements in both the space and time domains are also extremely desirable.

Scientific impacts:

Most HEA phenomena in the universe can only be studied remotely via their radiation, from electromagnetic and gravitational waves to neutrinos and cosmic rays. It is extremely difficult to directly investigate the microphysics underlying such phenomena. Laboratory experiments, on the other hand, allow us to directly probe the microphysics under controllable conditions, albeit on much smaller space and time scales. Hence LHEA experiments and astronomical observations are complementary to each other. Laboratory experiments are also needed in calibrating, validating and improving computer simulations of HEA phenomena.

In summary, short-pulse ultra-intense lasers irradiating solid targets can provide a new laboratory platform for studying HEA. Together with astronomical observations and computer simulations, it will complete the "triad" needed to study HEA phenomena.

Broader impacts:

High-density, short-pulse, multi-MeV electrons, positrons and gamma-ray beams have broad applications to many fields beyond HEA. These include, but are not limited to, medical therapy, homeland security, inertial fusion and nuclear waste transmutation. While accelerator-driven beams can in principle be used for some of the same applications, their beam properties are often different from laser-driven beams. Hence the optimal applications may also be different.

Magnetic field annihilation and charged particle acceleration in ultra-relativistic laser plasmas

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Working Groups: LAP: Laboratory Astrophysics

Abstract:
Magnetic reconnection driven by laser plasma interactions attracts great interests in the recent decades. Motivated by the rapid development of the laser technology, the ultra-strong magnetic field generated by the laser-plasma accelerated electrons provides unique environment to investigate the relativistic magnetic field annihilation and reconnection. It opens a new way for understanding relativistic regimes of fast magnetic field dissipation particularly in space plasmas, where the large scale magnetic field energy is converted to the energy of the non-thermal charged particles.

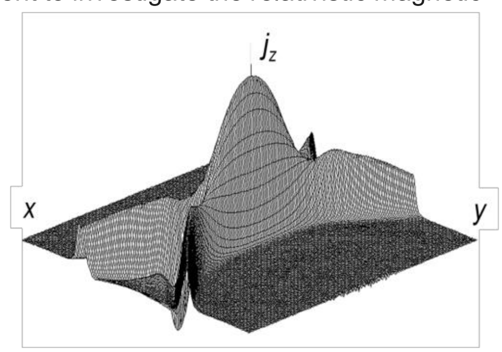

Fig. 1. Current sheet formed at the critical line of the magnetic field [5].

Scientific goal:
One of the central problems of contemporary plasma physics, which has been studied for 70 years, is the reconnection of magnetic field lines. The idea of magnetic field line reconnection stems from the works aimed at finding mechanisms of charged particle acceleration in space plasmas. Then it evolved into the paradigm embracing vast area of theories, experiments, and engineering problems related to fundamental sciences and applications of magnetized plasmas [1-3]. With the development of the high-power laser technology the magnetic reconnection in laser plasmas, foreseen a number of years ago [4], has recently attracted a great deal of attention from several groups conducting experiments and developing theory and computer simulations in this field [4]. The relativistic effects in magnetic reconnection important under the conditions of space and laser plasmas manifest themselves in the displacement current effects playing a role of 'dissipation' in the ultrarelativistic limit. They result in the strong electric field generation, which accelerates charged particles [6, 7].

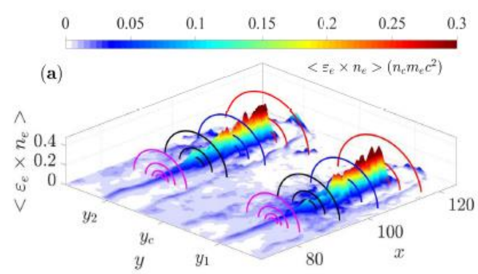

Fig. 2. The energy density distribution of electrons. The round circles represent the azimuthal magnetic fields [6].

Tools required:
Under the terrestrial laboratory conditions, the relativistic regimes can be realized only with the multi-petawatt power lasers. In the limit of extremely high laser power, one should take into account the effects of radiation friction and of effects predicted by quantum electrodynamics [7,8]. The radiation friction effects on the charged particle acceleration during the magnetic field line reconnection have recently been actively discussed since they are related to the interpretation of the high-energy gamma-ray flares in astrophysics [9].

Scientific impact(s):

During interaction of ultra-intense lasers with plasma targets strong static magnetic fields can be generated via the electric current produced by the energetic electron beams accelerated by the laser. In the relativistic laser plasma the generated magnetic field plays an active role leading to the magnetic interaction and coalescence of the self focusing channels, their bending, and accumulating of the magnetic energy [4]. The magnetic field left behind the ultrashort laser pulse as well as at the vacuum plasma interface has a pattern determined by the electron vortices, which can annihilate resulting in the electron and ion acceleration [10].

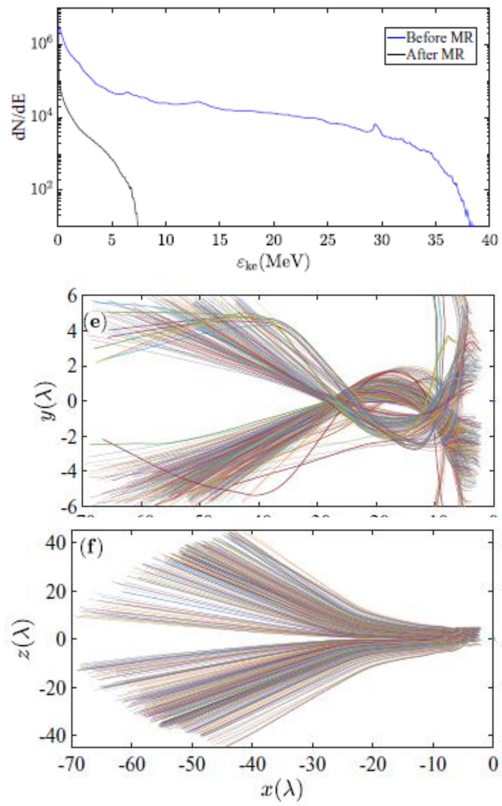

Fig. 3. The energy distributions of the electrons inside current sheet before and after magnetic field reconnection. The trajectories of charged particles given by the theory and by kinetic simulations [6].

Broader impacts:

The studying of the processes resulting relativistic regimes of the magnetic field line reconnection will undoubtedly enrich our knowledge on the properties of the emerging state of matter governed by the electrodynamics of radiation dominated continuous media in the ultra-relativistic limit. The development of super-intense lasers with parameters in the MP range will provide the necessary conditions for experimental physics where it will become possible to model the astrophysical particle accelerators. A fundamental property of the plasma to create nonlinear coherent structures, such as relativistic solitons and vortices, collisionless shock waves and high energy particle beams, and to provide the conditions for relativistic regimes of the magnetic field line reconnection, makes the area of relativistic laser plasmas attractive for modeling of processes of key importance for relativistic astrophysics.

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MP3 White Paper 2021
Enhanced laser-plasma experiments with helical laser beams

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Working Group(s): HFP/QED, PAALS, LDNP

Abstract: Light beams with helical phase profile have the unique property of carrying orbital angular momentum (OAM) and can be used to apply torque to matter, or to excite forbidden quantum transitions. In the past few years, the potential of high intensity helical beams started to be explored. Laguerre-Gaussian (LG) beams for the acceleration of electrons, positrons and ions in plasmas has been studied through Particle-in-Cell (PIC) simulations, showing that the laser OAM can be transferred to the accelerated particles. First experiments are underway around the world to demonstrate the effects of such peculiar laser beam at petawatt level. Here we propose to extend the use of helical PW beams to unprecedented intensities and OAM orders for enhanced effects in laser-matter interaction. The research has potential impact in plasma accelerators, fast ignition schemes and nuclear physics experiments.

Scientific goal: The proposed research consist in adding the OAM degree of freedom to extreme types of light and to measure specific effects of their interactions with matter. We make the fundamental hypothesis that the plasma rotation induced by the OAM carried by the helical beam leads to quenching of plasma instabilities and thus strongly improve laser-plasma acceleration of particles (electron and ions) and in-target nuclear reactions.
Recent works revealed that the energy scaling of the accelerated ions greatly improves with an helical laser beam [1]. Indeed, different articles predict that extremely rapid plasma rotation can be induced in dense targets by intense helical beams, with the efficiency of the OAM transferred to the plasma increasing with the laser intensity and helicity order [2]. As the focal spot size rapidly increases with the increase of the OAM orders, then reducing significantly the laser intensity, very high petawatt lasers (e.g., 10s PW) are needed to achieve laser intensities in excess of 10^{22} W/cm^2. Using a model for the estimation of plasma rotation induced by a helical beam together with the predicted instability growth rates for laser accelerated plasmas, one can infer the regime needed to effectively suppress instabilities. This happens when the rotational velocity shear Γ_S is comparable to the instability growth rate, Γ_I [2,3]. The predicted Rayleigh-Taylor instability growth rates for laser accelerated foils are in the range $\Gamma_I \approx 10^{13}$ s^{-1} [4]. Preliminary PIC simulations for high intensity light (I=10^{22} W/cm^2, a_0 =156, OAM order 3) show that rotations of $\omega \approx \Gamma_S \approx 10^{13}$ s^{-1} $\approx \Gamma_I$ can be obtained [5]. Figure 1a shows the proton density in the target, indicating the formation of a dense proton ring, together with a dense proton core. The plasma does not break up, even at this intensity. The hollow intensity profile of helical LG beams should also be beneficial for RPA ion acceleration, as it tends to produce a flat plasma instead of the "bowed" plasma achieved with

Gaussian beams [6]. As discussed by Dollar et al, the bowing of the plasma leads to direct heating of the electrons, which expands the plasma early, impeding the RPA mechanism. Figure 1b confirms that the total angular momentum of the particles increases rapidly with the helical beam intensity, scaling linearly with a_0. An interesting additional point is to evaluate the energies of rotating ions in the bulk of the target. Depending on the above parameters, the energy can be tuned to reach hundreds of keV – MeV energies, covering many nuclear reaction cross-sections [7]. Together with lower plasma instabilities effect it can lead to enhanced in-target nuclear reactions, compared to Gaussian laser TNSA reaction rates.

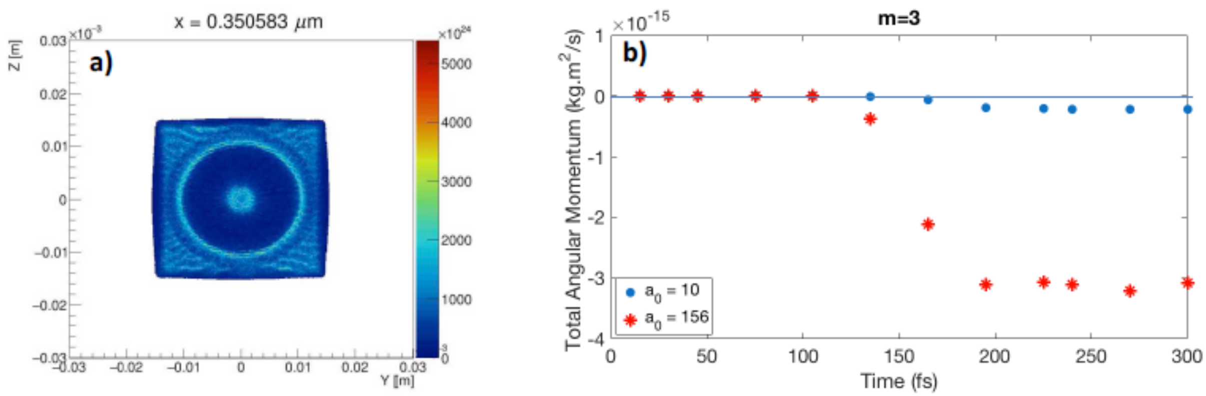

Figure 1: a) Proton density in the target for I=10^{22} W/cm^2, m=3, at t=225 fs. b) Total angular momentum as a function of time for a_0=10 and for a_0=156.

Our analytic calculations and recent PIC simulations, suggest that the electron energy, as well as the energy and intensity of the associated X-ray emission, could be considerably improved when using helical beams for LWFA in gas targets [5, 8]. In addition, we can build on studies that predict that the OAM of the helical laser light can be transferred by inverse Compton backscattering to electrons, which will emit photons with OAM [9, 10]. A helical gamma beam can thus be produced by introducing a helical mirror or phase plate in the laser beam before its collision the electron beam. The production of OAM gammas will be demonstrated by observing the hollow intensity pattern characteristic of OAM beams [11]. These helical gamma beams will have a strong impact on heavy nuclei nuclear photonics studies [12].

Tools required: Experiments of ion and electron acceleration with helical beams are proposed, consisting first in a direct comparison of particle energy spectra, with a helical laser beam, vs. conventional Gaussian beam. To generate the helical laser beams, one of the folding planar mirrors typically found in such setups can be replaced with a helical phase mirror with different topological charge [13]. Alternatively, for a high contrast laser beam, a helical sacrificial/plasma mirror with position dependent set of parameters and fabricated through a controlled corrosion process could be used in the vicinity of the target, as shown in Figure 2 [14]. Another possibility is to use smaller phase plates in the laser system and carefully monitoring the laser fluence on the optical elements, critical for large OAM orders. For this case, ramping to up intensities and OAM orders simultaneously requires power levels of the laser in the range of 10s of PW. For all-optical collision experiments, two high power, fs-synchronized laser beams are needed.

Theoretical support will be provided in the form of 3-D PIC calculations of the expected ion and electron spectra in connection with GEANT4 simulations. As targets, conventional gas jet / gas cell target with intensity matched parameters for LWFA experiments and foil targets for ion experiments will be employed. From diagnostic point of view, besides the general detectors associated with laser-plasma acceleration experiments and nuclear reactions diagnostics, dedicated setups to evaluate the helical order of the laser beams/ X - gamma beam are needed [5, 11, 13].

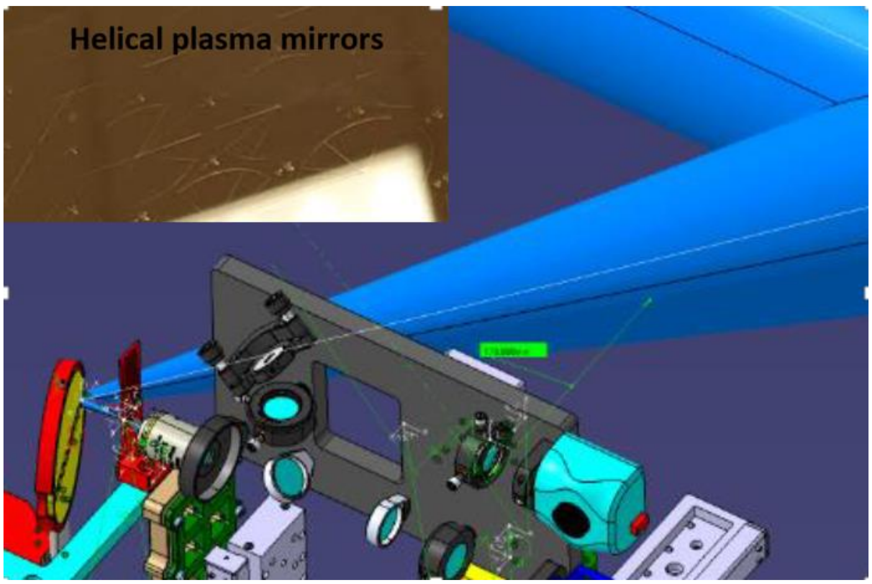

Figure 2. Example of the CAD design of the helical plasma mirror setup in preparation at ELI-NP. A folding helical plasma mirror will be used just before the target for ion acceleration experiments. The exact setup geometry was considered when designing the phase profile of the mirror [14,15].

Scientific impact(s): At the core of this future direction is the effect of the OAM in a strong laser-matter interaction and understanding the impact of plasma rotation on the acceleration of particles. The proposed research could open the way to steeper scaling power-laws of the accelerating particles and positively affect the generated particles beam parameters such as energy, energy bandwidth and divergence [1, 8, 16, 17].

Broader impacts: The research will impact the future laser-plasma colliders, understand the orbital angular momentum impact on extreme laser-mater interaction and its signature in QED experiments [18,19]. Additionally, the improved X-ray emission sources obtained could be used for nuclear photonics experiments and if properly mastered, helical laser beams will impact the study of nuclear reactions in plasma, major points of interest for both nuclear astrophysics and nuclear engineering.

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MP3 White Paper 2021 Title: "Electron-Positron Pair Production Interaction Chambers with Counter-propagating, Colliding multi-PW Laser Pulses"

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Working Group: High-Field Physics and Quantum Electrodynamics

Abstract:

It is proposed to design and implement interaction chambers for counter-propagating, synchronized, colliding 10PW laser pulses in order to study and optimize the multiphoton Breit–Wheeler (BW) process of pair production. A new generation of high power laser facilities will provide laser pulses with extremely high powers of 10 Petawatt (PW) and even 100 PW, capable of reaching intensities of 10^{22} - 10^{23} W/cm^2 in the laser focus. These ultra-high intensities are nevertheless lower than the Schwinger intensity I_S =2.3×10^{29} W/cm^2 at which the theory of High Field Quantum Electrodynamics (QED) predicts that a large part of the pure energy of the laser photons will be transformed into matter via electron-positron pair production: light is transformed into matter. The Schwinger intensity threshold can be lowered to the 10^{22} - 10^{23} W/cm^2 level through the multiphoton Breit–Wheeler (BW) process. First a relativistic electron, (e^-) , collides with the laser pulse photons, $(h\nu)_L$, thorough the Nonlinear, multiphoton, inverse Compton scattering, emitting a gamma-ray (GR): $e^- + m(h\nu)_L \rightarrow e^- + (h\nu)_{GR}$. Second, the electron–positron pair is produced from the gamma-ray absorbing laser photons by the multiphoton Breit–Wheeler (BW) in the presence of the high field of the focused laser: $(h\nu)_{GR} + m(h\nu)_L \rightarrow e^- + e^+$. The BW process experiments can be optimized by colliding two counter-propagating 10PW laser pulses. The first multi-PW laser pulse accelerates the electrons to relativistic energies, while the second, tightly focussed multi-PW pulse provides the ultra-high EM field for the multiphoton Breit–Wheeler (BW) process of pair production (Ref. 1 and 2. and references within). Indeed avalanches of electron-poitron pairs are predicted by theory resulting in high conversion efficiency of the laser pulse energy into pair production..

Scientific goal: Experimental demonstration of High Field QED effects predicted by theory: (a) nonlinear, multiphoton, inverse Compton scattering; (b) radiation reaction; (c) copious electron-positron pair production by the multiphoton Breit–Wheeler (BW) process . Comparison of the experimental results with the theoretical predictions. Improve our understanding or HF-QED by adding corrections to the theory to bring it in agreement with experiments.

Tools required: Implementation of interaction chambers designed for colliding, counter-propagating, synchronized multi-PW laser pulses. The multi-PW laser pulses need be synchronized. This could be accomplished in the future, for example, by splitting a 100PW pulse into a colliding10PW –for electron acceleration- and a 90PW pulse – providing the ultra- high field in its tight focus. Synchronization can also be obtained by seeding two parallel laser amplifiers from the same laser-oscillator pulse for example at the the Astra-Gemini PW laser at the Central Laser Facility in UK or ELI-NP 10PW laser in Romania. In this case further, femtosecond-level synchronization is required at the focal point of the colliding laser pulses[1,2] . Two configurations interaction chambers are required for colliding multi-PW laser-pulses in gas targets and solid targets respectively[1,2]. When the electron is accelerated by focusing the multi-PW laser on gas targets the accelerating laser pulse is focused with a long focal length lens, say F:100 and could generate multi-GeV electron pulses. The colliding, counter-propagating multi-PW pulse is tightly focused (F:3 or shorter) to intensities of > 10^{22} onto the relativistic electron-bunch to produce electron-positron pairs by the multiphoton Breit–Wheeler (BW) process. The electrons can also be accelerated in solid targets to lower energy but to higher flux. In this case both counter-propagating, colliding multi-PW laser pulses are tightly focused (F:3 or shorter) on either side of a thin solid foil target. Ref 1. (and references within) presents examples of interaction chambers designed for: gas targets in Fig. 4 (ELI-NP 10PW facility) and Fig. 6 (Astra-Gemini PW facility); as well as for solid target interaction chamber in Fig. 5 (ELI-NP 10PW facility).

Scientific impacts:

(i) Experimental demonstration of High Field QED effects, and especially transforming copious amounts of the photons of light <u>pure energy into mass</u> in the form of electron-positron pairs through the multiphoton Breit–Wheeler (BW) process.
(ii) Improve our understanding or High Field QED by adding corrections to the theory to bring it in agreement with experiments.
(iii) Discover new High Field QED effects, not yet predicted by theory.
(iv) Better understanding of our Universe as a result our improved QED understanding of QED which provides one of the key descriptions of the natural world.

Broader impacts:

(i) Generation of powerful positron sources
(ii) Generation of powerful Gamma-ray sources
(iii) Technology provides a steps towards a TeV electron-positron collider using multi-PW colliding laser pulses

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Investigating strong-field QED processes in laser-electron beam collisions at Apollon

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Abstract - A new class of high-power lasers is emerging that will soon allow for the realisation of pioneering experiments in the field of extreme light laser-matter interaction, where relativistic laser-plasma physics is strongly impacted by quantum electrodynamics (QED) effects. Experiments are being designed that will be performed at the Apollon research infrastructure (RI) [1-3], a multi-beam multi-PW facility on the *Plateau de Saclay*, 20 km south of Paris. Such a facility represents an exceptional environment for the scientific community to study the collision of a laser-driven multi-GeV electron beam with a multi-petawatt (up to 10 PW), ultra-intense ($\gtrsim 10^{23}$ W/cm^2), ultra-short (15 - 20 fs) light pulse. This experimental approach is indeed of utmost importance for the emerging field of extreme light physics. It provides the shortest, all-optical path to unlock a yet largely unexplored regime of laser-matter interaction, and will ultimately make it possible to develop novel ultra-bright sources of high-energy (from 10s of MeV up to several GeV) γ-photons and high-charge beams (from 100 pC to few nC) ultra-relativistic electron-positron pairs. Completing this experimental objective, however, will necessitate substantial developments in terms of particle and photon diagnostics and high-performance computing (HPC), together with advances in the understanding of the physical processes at play. Beyond the possibility to create new sources of light and particles, such work can also open new opportunities in terms of fundamental science [4].

Scientific goal

Studying the interaction of ultra-relativistic electron beams with multi-PW laser pulses opens one of the most promising avenues to the new regime of extreme light physics. As the Apollon RI offers multiple high-power (PW to multi-PW) laser beam capabilities, see Sec. *Required Tools* for details, it provides the scientific community with all the required tools to investigate strong-field QED processes in laser-electron beam collisions.

The flagship experiment envisioned in this project was investigated *in silico*, in a recent work by partners of this project [5]. This work presented the first fully integrated numerical simulation of what such an experiment would ultimately lead to, if performed on the Apollon facility. In this numerical experiment, the F2 (1PW) beam of the Apollon RI is used to drive an electron beam with nC charge and a few GeV energy (60% of the total beam charges have an energy in between 2.5 and 3.8 GeV). This beam is then collided with a 5PW, 15 fs light pulse focused to a peak intensity $I_0 \sim 10^{23}$ W/cm^2, as accessible with the main Apollon beam F1. This on-chip experiment led to two remarkable predictions. First, the electron-light collision produces an ultrafast (~10 fs) γ-photon burst, over a broad spectrum of energies: the average photon energy is typically of a few tens of MeV, and goes up to a maximum energy of a few GeV, slightly below the maximum incident electron energy. The reported brilliance of the photon source, of the order of 5×10^{23} photons/s/mm^2/mrad^2 0.1%BW, is particularly striking, as it is three orders of magnitude larger than the current experimental record in laser-based Compton sources [6]. Second, as this photon burst interacts back with the multi-PW laser pulse, it produces a high energy (average energy of a few 100's MeV and maximum energy of a few GeV), low divergence (<0.1 rad) electron-positron pair plasma jet with a total charge of a few 100s pC.

The realization of such an experiment at Apollon will require cross-field expertise and the tight collaboration between experts in various fields of research, from laser-plasma interaction to strong-field QED, from designing high-energy particle diagnostics to performing high-fidelity simulations on the latest HPC architectures. With this challenging framework, the achievement of this flagship experiment relies on the progressive fulfilment of three interdependent experimental milestones.

Developing a well-controlled multi-GeV laser wakefield electron source – A first challenge consists in the implementation of a multi-GeV laser wakefield electron source. Accelerating high-quality electron beams in a single stage is a key objective of the project that will require combining laser-guiding and controlled injection techniques for LWFA. Both techniques have never been made to work together on a multi-PW-class laser such as Apollon. Meeting this challenge is however possible by using an innovative technique for laser guiding that has been recently developed at the *Laboratoire d'Optique Appliquée* [7,8] and that is compatible with controlled injection techniques. Electron beams with energies of 8-10 GeV are expected.

Performing experiments on high-energy photon emission and radiation reaction, from the classical to quantum regimes – The dynamics of ultra-relativistic electrons in a relativistically intense ($I_0 \gg 10^{18}$ W/cm^2, for laser beams with wavelength $\lambda \sim 1\mu$m) light pulse is highly nonlinear. At very high intensities, electrons are also so strongly accelerated/decelerated that they start emitting very high-energy radiation in the form of γ-photons. Doing so, they lose part of their energy and momentum, and their dynamics is strongly modified, a process known as radiation reaction (RR).

In the classical regime, γ-photon emission by an ultra-relativistic electron can be modeled as incoherent synchrotron emission, also referred to as nonlinear Thomson scattering. In this regime, RR follows from the cumulative effect of many such emissions, each emitted photon carrying away a very small part of the emitting electron energy [4]. It can be modeled as a continuous force acting on the electron which turns out to be the classical RR force predicted by Landau and Lifshitz [9].

As either the laser field strength (corr. intensity) or electron energy increases, so does the characteristic energy of the emitted photons. The energy of a single photon eventually becomes of the order of the energy of the emitting electron. At this stage, the quantum nature of high-energy photon emission and its back-reaction can be only understood in a relativistic and quantum framework, that of QED, and strong-field QED in particular. The quantum nature of the photon emission manifests itself through three effects. (i) The strong electron recoil as it emits a photon carrying away a significant fraction of its energy leads to a cut-off in the radiation spectrum at large photon energies. (ii) A spin contribution to the radiation needs to be included. When both effects are important, one no longer refers to the emission process as nonlinear Thomson scattering, but as Inverse Compton Scattering (ICS). The associated modification in the photon spectrum will be among the experimental signatures searched for when investigating quantum RR in the forthcoming experiments. (iii) The third and most striking effect is the stochastic nature of the photon emission that has a lasting and measurable (broadening) impact on the electron energy distribution [10-13], in particular if the beam initially has an initially narrow energy spread.

There is a strong fundamental interest in performing such experiments. The full experimental characterization of RR in the relativistic regime still eludes us, despite strong efforts in this direction (in the UK using the high-power laser GEMINI [14,15], and at CERN using electron beams in aligned crystals [16], to mention only the most recent works). It should also be noted that, under the extreme conditions envisioned at Apollon, the RR force will be of the same order as the Lorentz force, and its impact on laser-plasma interaction becomes unavoidable. Last, on a more practical side, this kind of experiment is particularly interesting as it naturally gives rise to strong, collimated and ultrafast emissions of γ-photons, potentially leading to the brightest achievable laser-based photon sources.

Probing strong-field QED and electron-positron pair production – The most exotic process and striking demonstration of strong-field QED envisioned at Apollon is electron-positron pair production. This pure-QED process mainly follows from the interaction of a high-energy γ-photon with a strong electromagnetic field. When the interaction of the high-energy γ-photons (produced by ICS during the electron-laser collision) is directly with the strong laser field, the QED process is then referred to as the nonlinear Breit-Wheeler pair process. It was first observed in the seminal E-144 experiment [17], performed at SLAC in the mid-1990's. However, this experiment was performed in a marginally relativistic laser interaction regime and only a few (106±14) positrons were detected in over 20 000 electron-laser beam collisions. Abundant production of nonlinear Breit-Wheeler pairs on multi-PW-class laser facilities would be an important contribution to the field of extreme light physics, as well as a major experimental achievement with outstanding repercussions in terms of radiation and particle sources. As previously pointed out, the recent numerical experiments by Lobet *et al*. [5] suggests that billions of positrons would be produced together with the brightest γ-ray flash ever produced in a laser-plasma experiment.

Tools required

This experimental study will be performed at the multi-beam, multi-PW Apollon RI, over the next years, at its different development stages. Apollon will feature at full capability 4 independent beams, with a 1shot/min repetition rate. A main 10PW beam (F1) will deliver up to 150J on target, within 15fs (and up to few ps). A second 1PW beam (F2) will deliver 15J in 15 fs (and up to few ps). These two ultra-high intensity beams will be completed by a ns beam (F3) delivering up to 200J, and a probe beam (F4) delivering 0.2J within less than 20fs.

All beams will be delivered to either one of the two radio-protected experimental areas: the Short Focal Area (SFA) and Long Focal Area (LFA). The SFA has been designed for tight-focusing of both F1 and F2 beams, thus allowing for the highest intensities on target. Yet, this area can be ill suited for the study of electron-laser-beam collisions, as envisioned here. In contrast, the LFA, primarily designed for the study of laser-driven electron acceleration, is well adapted to performing experiments with GeV to multi-GeV electron beams, and can be tuned for studying the collision of such a particle beam with an intense light pulse. As of today, commissioning experiments are being performed with the F2 beam, at full energy on target, in both experimental rooms.

In order to fully exploit Apollon IR capabilities and experimentally investigate the physics at play, novel and dedicated particle and photon diagnostics will be developed and implemented to characterize the energy and angular distributions of the particles, leptons or photons, resulting from the electron-laser-beam collisions. Accuracy in the spectral features of both electrons/positrons and photons will be needed to distinguish the signatures of the different regimes of interaction and describe the transition from one to the other. The upgrade of currently available diagnostics and developments of novel ones will meet the strict requirements in terms of sensitivity and robustness in a very noisy environment and work at the high repetition rate of 1 shot/min.

Last, HPC-relevant simulation tools, such as the particle-in-cell codes CALDER [18,19] and SMILEI [20], will continue to be developed to support the design of and help interpreting future experiments.

Scientific impacts

The process leading to the realization of such experiments will require and foster important fundamental studies, the development of simulation codes with the capability to model QED plasmas on the latest supercomputer architectures, as well as the development of new diagnostics for high-energy particle detection and characterization. Important contributions will be made to fundamental science questions related to the study of high-energy photon production and its back-reaction on the electron dynamics, as well as electron-pair production in strong Coulomb or electromagnetic fields.

Beyond these fundamental aspects, the kind of experiments designed and performed at Apollon at the different steps of this experimental program will ultimately lead to the realization of novel, ultra-bright sources of high-energy (from 10's of MeV up to several GeV) γ-photons and highly-charged (from 100 pC to potentially few nC) ultra-relativistic electron-positron pair jets.

Broader impacts

The advent of multi-PW laser facilities will unlock the largely unexplored regime of extreme light laser-matter interaction. It will enable extreme plasma environments to be studied where collective relativistic effects and strong-field QED processes are intrinsically intertwined. It will allow theoretical models as well as new simulation tools to be tested in regimes never achieved before. Such extreme regimes are not only important for the new generation of multi-PW laser facilities, they are also relevant to astrophysical settings such as encountered during the lepton epoch or in the vicinity of the most extreme objects found in the Universe, such as pulsars' magnetospheres and nebulae or gamma-ray bursts.

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MP3 White Paper WP-69

Exploring cosmic-ray physics with high-energy, high-intensity lasers

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Abstract

Understanding the interplay between energetic-particle currents and self-excited magnetic fields is key to addressing open questions of cosmic-ray origins. Capturing the multi-scale physics involved presents a challenge to numerical simulations and a deeper understanding would benefit from experimental investigation. Preliminary studies to measure the onset of magnetic field amplification are ongoing using laser-driven currents and magnetised background plasma [9]. Higher laser power coupled with target and charged-particle diagnostic development would enable detailed study of magneto-collisional and related instabilities over long-timescales, addressing questions of cosmic-ray self-confinement and maximum energy.

1 Scientific goal

The Earth's upper atmosphere is continuously bombarded by cosmic rays (CRs), non-thermal energetic particles spanning more than 10 decades in energy. After a century of measurements, a detailed picture of the local particle spectrum, including its composition has emerged. Their relatively short mean free path in the turbulent interstellar magnetic fields prevents back-tracing these particles to potential nearby sources, although simple energetic arguments favour a supernova origin, at least for the majority of CRs produced in our own Galaxy. The diffusive shock acceleration process [3] provides a convincing acceleration mechanism that is remarkably consistent with observations of supernova remnants (SNRs). The enhanced magnetic fields revealed by high-resolution X-ray images of the outer shocks of several young SNR, have motivated studies of the plasma processes that drive amplification, and the possible implications for CR acceleration. While theory and simulations have pushed this field forward, gaps in the global picture remain that would benefit from experimental insights.

High-power laser experiments to study collisionless particle transport in magnetised plasmas have already provided useful analogues for the journey of these cosmic messengers, for example by mimicking the small-angle scattering regime of extra-galactic CRs [10]. Many questions remain, in particular the non-linear feedback of the CRs themselves. Key outstanding issues in this regard include: (a) CR self-confinement; (b) current driven magnetic field amplification, and (c) the maximum achievable energy. These 3 aspects are of course closely inter-connected, and provide inviting opportunities for laboratory astrophysics experiments. Advancing our understanding of any one of these issues will have important consequences for the others.

Theoretical models have tied these questions to the development of current-driven non-resonant instabilities [4, 17, 5]. These instabilities provide the required rapid amplification of initially weak magnetic field fluctuations which, although driven initially at small scales, grow to scales comparable to the Larmor radius of the energetic particles providing the current in the non-linear phase. This is generally necessary to effectively confine the same particles. Once self-confined, these energetic particles can be further accelerated through scattering within the background plasma/shock. How long they can be confined by this feedback loop and the resulting maximum achievable energy is an open question.

The challenge is therefore to generate an energetic particle current in the regime that can excite the instabilities relevant to scaled astrophysical conditions, and evidence of non-linear feedback indicative of self-confinement.

2 Tools required: Experimental parameters and technical requirements

Parameters for current-driven instability studies: Excitation of the CR driven non-resonant instability can be expected to occur whenever the Lorentz force of the CRs dominates over the magnetic tension on scales below the Larmor radius of the driving beam. For non-relativistic beams, this equates to a condition $v_{\text{beam}} \gg (n_{\text{beam}}/n_{\text{gas}})^{1/2} v_{\text{Alfven}}$, (where v_{beam}, v_{Alfven} are the beam and Alfvén velocities respectively) - a condition easily satisfied in the laboratory. For a given current density j, the maximum growth rate is $\gamma_{max} = \frac{1}{2} j \sqrt{\frac{\mu_0}{\rho_{\text{gas}}}}$, growing on a scale $\ell_{\max} = 2\pi v_{\text{Alfven}}/\gamma_{\max}$. At longer wavelengths, the growth is a factor of $\sqrt{\ell/\ell_{\max}}$ times slower, but cuts off rapidly on shorter length scales. For a reference current of $j_{\text{ref}} = 1$ kA mm^{-2}, gas number density of 10^{17} cm^{-3} and $B_{\text{ref}} = 0.1$ T, one finds a growth time $\gamma_{\max}^{-1} \approx 5$ ns, occurring at the scale $\ell_{\max} \approx 1$ mm. It is evident that non-linear growth requires a strong current, over an interaction volume greater than a few hundred microns and sustained for several nanoseconds. For substantial non-linear growth, we require a sufficient period of sustained driving ($\sim 5\gamma^{-1}$), and preferably while maintaining magnetised electrons in the gas ($\ell/r_{\text{g,e}} \gg 1$).

Technical requirements: High-intensity ($I > 10^{18}$ W/cm^2) laser-plasma interactions can produce charged particle beams with very high (kA) peak currents through plasma wakefield acceleration of electrons or laser-driven acceleration of protons from thin foils (target normal sheath acceleration (TNSA)). For plasma wakefields, the electron bunch duration is on the order of a few fs while for TNSA the acceleration time of protons is comparable to the laser pulse duration [13], typically several ps. In addition, the broad energy-bandwidth, and non-relativistic nature of TNSA protons leads to velocity dispersion that elongates the beam in time. Over cm distances the proton bunch may reach ns duration. Interestingly, this makes a TNSA proton beam driven by a multi-Petawatt, multi-picosecond laser a promising source of 'CR-analogue' to drive the instability in the laboratory.

The two Omega-EP CPA beams, with a combined maximum energy of 2.3 kJ, can in principle provide the intensity required for TNSA over 100 ps. While such long pulses are not ideal for proton acceleration to high energies, this setup has been demonstrated to produce a high flux; ≤ 4 MeV proton beam with a current density of 1.7 kA/mm^2 close to the source [9]. Preliminary experiments exploring the onset of the NRH instability will use this kA proton beam to initiate the NRH instability in a pre-magnetised plasma provided by the TDYNO target platform [24, 6].

The key experimental challenges to capturing long-term evolution of the instability are (i) the short duration of the drive current at its source relative to the growth timescale ($\sim$ nanoseconds) and (ii) the divergence of the proton beam from the source which necessitates a short distance between proton source and the background magnetised plasma (the target plasma) in which the instability is driven. These challenges will be addressed as outlined below:

a) Increasing current duration to drive the instability over multiple growth periods: While the proton current duration is linked to the laser pulse duration this has only been demonstrated for few ps drive lasers. Expansion of the target foil over 100 ps timescales is likely to inhibit the efficacy of longer laser-pulses to achieve longer drive currents. Alternatively, velocity dispersion of the protons during propagation can be used to increase the duration of the current by increasing the stand-off of the proton source foil from the target plasma. For example, 16 mm is sufficient to disperse a proton beam spanning 0.45-3 MeV over a 1 ns window.

A large stand-off between the proton source foil and any other plasmas or high-power laser interactions is also beneficial in protecting the proton source foil from damage by expanding coronal plasma or x-ray emission from neighbouring plasmas which reduces the efficiency of proton acceleration.

b) Maintaining high-current at the target plasma: Due to the strong divergence of the TNSA proton beam from the target ($\sim 20°$ [14]), increased distance between the proton source foil and target plasma necessitates a scheme for focusing the protons in order to maintain current density at the target plasma. Options for focusing include: hemisphere targets with large radius of curvature which can focus over 100s μm [21, 2, 18]; spiral guide structures that have demonstrated focusing over many mm [16, 1] and RF beam optics or plasma lenses (e.g. Gabor lens) which focus protons over metre scales [23, 7, 19]. Of these, the spiral focusing structures have favourable length scales, and energy bandwidth, for the environment and goal. However, there has been limited exploration of laser-driven proton acceleration with > 10 ps duration [8] and none which couples the accelerator to a focusing structure. Development studies would be required to optimise focusing for longer laser pulses.

In addition, although focusing can be used to constrain the protons beam laterally, due to the requirement to disperse the proton beam in time to provide a sustained kA current, it is important to ensure that the initial conversion from laser energy to proton current is maximised. A multi-Petawatt, multi-picosecond laser could sustain kA/mm^2 current densities over the required volumes.

c) Maximising conversion efficiency: The accelerated charge in the proton beam is strongly dependent on the laser energy; more energy typically leads to higher conversion efficiency into MeV protons. Increased laser power permits a larger focal volume and therefore greater coupling of laser energy into hot electrons, and consequently to proton current [12]. In addition, the shallower focusing required to produce a larger laser focus provides a greater depth of focus easing the tolerance on target positioning. Recent work has also demonstrated improved conversion efficiency into protons for kJ, multi-ps lasers when a preplasma is formed at the foil surface before the arrival of the high-intensity laser pulse, either by a prepulse or ASE pedestal [22]. Although more study is required to optimise the level and timing of this preplasma generation, temporal shaping of a multi-Petawatt laser combined with independently controllable 'prepulses' would likely facilitate the production of unprecedented proton beam charge, enabling these and other high-current experiments.

Facility target/diagnostic developments: The target plasma should be a low-density, weakly-collisional plasma embedded with a seed magnetic field. Preliminary studies use an ablation plasma in which the seed field is generated during the ablation through Biermann battery. However, a target with a magnetic field independent to the plasma conditions would provide greater control to address isolated challenges (field amplification, self-confinement). This could be provided by the use of an ablation foil or gas-based target [15] and externally imposed magnetic field, for example, a small ($\sim 0.01 - 0.1$ T) permanent magnet.

Measurements for these studies would utilise many existing diagnostics (e.g. PRAD, TSS (with polarimetry), high magnification imaging of x-ray self-emission). However, the development of charge calibrated diagnostics coupling spatially and energy resolving measurements of protons (e.g structured scintillator detector under development by LLNL (Ma, Mariscal) [11]) are required with the ability to be fielded with small stand-off ($<$ 10s cm) to capture a large solid angle of the proton beam. This would allow characterisation of the current and beam 'break-up' due to the instability. In addition, to demonstrate self-confinement, it is vital to characterise the proton beam *before and after* the target plasma. This requires the development of minimally destructive proton beam diagnostics (e.g. spectrally resolved imaging detectors for PIXE [20, 18]) for characterisation of the pre-target proton beam.

3 Scientific impact(s)

Understanding the non-linear interplay between accelerated particles and their self-generated magnetic fields at astrophysical shocks remains one of the major outstanding theoretical obstacles in the cosmic-ray origin story. The development of experimental platforms to study this phenomenon has the potential for cross-community impact.

4 Broader impacts

The interaction of energetic charged particles with weakly-collisional, magnetised background plasma is of fundamental importance to many plasma experimental endeavours, not just in laboratory astrophysics studies, but also for example inertial confinement fusion schemes, where uncontrolled preheating by hot electrons is detrimental while controlled energy deposition by a fast ignition species is advantageous. A deep understanding of charged particle transport and feedback between fields and currents is clearly desirable.

The diagnostic development and TNSA conversion efficiency optimisation will also impact more broadly on the other experiments at high-power facilities utilising MeV proton beams for time-resolved radiography and isochoric heating of matter respectively.

A multi-Petawatt facility providing access to the academic community would have transformative potential for studies such as those described in this white paper.

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Generation of polarized high-energy lepton and photon beams

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Abstract: Spin effects gain importance in multi-petawatt laser-matter interaction. Recently, we have investigated spin dynamics of relativistic particles in strong-field QED processes and proposed several near-term experimentally feasible schemes of producing highly polarized electron, positrons, and gamma-ray beams with strong laser fields [1-5]. Here, we propose proof-of-principle experiments of producing polarized particle beams employing the upcoming multi-petawatt laser facility in Rochester. It is possible to use a multi-petawatt laser pulse with specific polarizations or structures to produce polarized ultrarelativistic electrons and positrons. For example, up to 70% polarization of a GeV electron beam can be obtained during interaction with an elliptically polarized laser pulse [1]; high energy polarized positrons can be generated via the interaction of an ultrarelativistic electron beam with a counterpropagating two-color petawatt laser pulse [2] or with an elliptically polarized laser [3]. On the other hand, highly polarized multi-GeV gamma-rays and positrons can be obtained via helicity transfer of an initially spin-polarized electron beam scattering off a laser pulse. In particular, multi-GeV circularly polarized γ-rays with a polarization of up to about 95% can be generated by a longitudinally spin-polarized electron beam, with a photon flux meeting the requirements for the vacuum birefringence measurement in ultrastrong laser fields [4]; or with a seed electron beam of 10 GeV energy, with polarization degree 80%, a high-quality positron beam of 1.4 GeV energy can be generated with polarization degree 40% [5]. The inverse of these effects can be employed also for ultrarelativistic electron [6] and γ-photon [7] polarimetry.

Scientific goal: Conduct proof-of-principle experiments of producing polarized electron, positron, γ-ray beams employing the upcoming multi-petawatt lasers, paving the way towards the realization of laser-driven polarized particle sources for high-energy physics studies.

I. Generation of spin-polarized GeV electron beams

The goal is achieved using the interaction of an elliptically polarized strong laser beam (with a proper choice of a small value of ellipticity) with a counterpropagating unpolarized electron beam. The electron beam is polarized and split along the propagation direction into two parts with opposite transverse polarizations, which is due to spin-dependent radiation reaction [1]. With a proper angular coolimation of a mrad-scale, an electron beam with above 70% polarization can be generated in a single shot from the 10% of the incoming electron beam of a GeV energy.

II. Generation of spin-polarized GeV positron beams

Polarized positrons are generated in the interaction of an ultraintense laser pulse with a counterpropagating ultrarelativistic electron beam. Intermediately created γ-photons due to nonlinear Compton scattering produce electron-positron pairs via the multiphoton Breit-Wheeler process during further interaction with the laser pulse. Due to the large spin asymmetry of the pair production process, the produced positrons are highly polarized along the laser magnetic field.

a) **Using a two-color laser field**

Net polarization of the positrons created in different laser field phases is due to the asymmetry of the two-color laser field. Positron beams of GeV energy, with a polarization degree of 60%, can be produced in a single shot, with an angular divergence of 70 mrad, and a density $\sim 10^{14}$ cm^{-3} [2].

b) **Using an elliptically polarized laser field**

With a proper choice of ellipticity of the laser field, the created positrons are split into two beams with respect to the spin projection. The spin-dependent asymmetry of the pair production is dominating and brings about a 75% polarized positron beam with a particle number of about 10% of the incoming electron beam [3].

III. Polarization transfer from an electron beam to γ-photons and positrons

a) Generation of polarized multi-GeV γ-rays

Circularly polarized γ-rays are generated via nonlinear Compton scattering of a strong laser beam off the longitudinally spin-polarized electrons [4]. High-flux γ-photons with polarization beyond 95% are produced in a single-shot interaction. The total number of emitted γ photons is about 10^8 for energies larger than 1 MeV and about 10^7 for energies larger than 1 GeV. γ-rays of about 10, 8, and 6 GeV can be emitted with circular polarization of about 99%, 94%, and 81%, respectively, and with brilliances of about 6×10^{18}, 4×10^{20}, and 10^{21} photons/s/mm^2/ mrad^2/0.1% BW. The photon flux meets the requirements for the vacuum birefringence measurement in ultrastrong laser fields [8]. It is also possible to obtain linearly polarized γ-rays employing an elliptically-polarized laser pulse with a small ellipticity colliding with a transversely spin-polarized electron beam.

b) **Generation of polarized positrons**

The polarized positron beam is produced via nonlinear Breit-Wheeler processes during the interaction of an ultraintense circularly polarized laser pulse with a longitudinally spin-polarized ultrarelativistic electron beam. The produced positrons are longitudinally polarized through polarization transferred from the polarized electrons via intermediate high-energy γ-photons. A highly polarized (40%–65%), intense (10^5–10^6 e^+/bunch), collimated (5–70 mrad) positron beam can be obtained in a single shot.

IV. Demonstration of polarization dependence of nonlinear Breit-Wheeler processes

The nonlinear Breit-Wheeler (BW) pair production process depends significantly on the γ-photon polarization. We can demonstrate this in a two-stage setup, using laser fields of different linear polarizations (LP) and different intensities in these stages [7]. In the first stage LP γ-photons are produced via collision of an unpolarized ultrarelativistic electron beam with a strong LP laser pulse. In the second stage LP γ-photons create pairs during collision with an ultrastrong LP laser field. The dependence of the pair yield on the relative direction of LP in the first and second stages elucidate the polarization dependence of the BW process.

Tools required:

1) Transversely Polarized Electrons and linearly polarized γ-rays*:

   (a) *Multi-Petawatt Lasers*: Laser pulses with a_0=50 (Power of about 2-5 PW, peak intensity up to 10^{21} ~10^{22} W/cm^2, beam waist radius w_0 near 2~3μm), wavelength λ_0=1μm. The laser polarization either 1) elliptically polarized with a small ellipticity ϵ =0.05, or 2) a linearly polarized two-color laser pulse with a_{01}/ a_{02}=4, a_{01}= a_0, ω_1/ω_2=1/2.

   (b) *Multi-GeV Electron Beam*: Electron radius w_0=2~3μm, length L=5μm, energy spread $\Delta\varepsilon_0/\varepsilon_0$=0.06, angular divergence 0.2 mrad.

2) Longitudinally Polarized Positrons and Circularly Polarized γ-Rays:

   (a) *Multi-Petawatt Lasers*: Circularly polarized laser pulses with intensity a_0=70 (power 2-5 PW, peak intensity up to 10^{21} ~10^{22} W/cm^2, beam waist radius w_0 near 2-3μm), wavelength λ_0=1μm,

   (b) *Ultra-relativistic longitudinally polarized electron beam*: Electron radius w_0=2~3μm, length L=5μm, energy spread $\Delta\varepsilon_0/\varepsilon_0$=0.06, angular divergence 0.2mrad, kinetic energy 10 GeV. The seed electron beam should be longitudinally polarized, which can be obtained by laser-wakefield acceleration of pre-polarized electrons [9] or extracting polarized electrons directly from polarized photocathodes [10].

3) Polarimetry:

   Electron, Positron Polarimetry [6,11,12] and γ-ray Polarimetry [7,13,14] at the GeV scale is required to determinate the polarization degrees of electrons, positrons and γ-rays.

Scientific impact(s): The experimental realization of producing polarized electrons, positrons and γ-ray beams will provide experimental evidence of radiative polarization in laser-plasma and laser-electron beam interaction, verify the theoretical models for the spin-resolved strong-field QED, and improve our understanding of polarization effects in ultrastrong laser fields.

Broader impacts:

Spin-polarized ultrarelativistic electron and positron beams represent a powerful probe in studies of fundamental physics and high-energy applications. For instance, they are applied for improving the sensitivity of the two photon effect experiments, unambiguous determination of the nucleon structure, and testing the standard model or searching for new physics beyond it. Moreover, the positron beam generated in this way has an ultrashort duration (Le $\simeq$ 20 fs), which is favorable for applications in probing the surface and bulk magnetism of materials along with a potential for ultrafast diagnosis. Meanwhile, multi-GeV polarized gamma-rays can be used to detect vacuum birefringence, taking advantage of the fact that the QED vacuum nonlinearity is significantly enhanced for high-energy photons. In conclusion, polarized electron, positron and gamma-rays are beneficial for solid-state physics, nuclear physics, high energy physics and laboratory astrophysics studies.

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* Transversely polarized positrons can be obtained by the increasing laser intensity to $a_0\approx$90 (power P≈7 PW, peak intensity I up to 10^{22} W/cm^2, beam waist radius w_0 is near 2 λ_0) or increasing electron energy to 10 GeV.

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Nonlinear Electromagnetic Waves in Quantum Vacuum

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Abstract:
Extremely intense electromagnetic fields modify the Maxwell equations due to the photon-photon scattering that makes the vacuum refraction index to depend on the field amplitude. This makes the ultra-relativistic electron to emit high energy photons via the Synergic Cherenkov-Compton radiation mechanism. In the presence of electromagnetic waves the vacuum behaves as a dispersive medium resulting in wave steepening, subsequent generation of high order harmonics and shock wave formation with electron-positron pair generation at the shock front. The interplay between the vacuum dispersion and the nonlinear effects in the interaction of electromagnetic waves results in the formation of solitons that can propagate without changing their shape.

Scientific goal:
At the focus of 100 PW laser the field intensity can reach 10^{25} W/cm^2 which corresponds to the normalized field amplitude. At this e.m. field intensity the photon-photon scattering can change the electromagnetic wave behavior in vacuum (e.g. see [1-3]). It is well known that the nonlinear QED effects can result in the change of the phase of two head-on colliding electromagnetic pulses and the rotation of their polarization [4]. Counter-action of extremely high amplitude electromagnetic waves leads to the nonlinear wave steepening [5], generation of high order harmonics [6-9], formation of electromagnetic solitons [10, 11] and other nonlinear electromagnetic configurations [12-14]. Required highest radiation intensity implies sharp focusing or/and using multiple colliding e.m. pulse configuration [15-19].

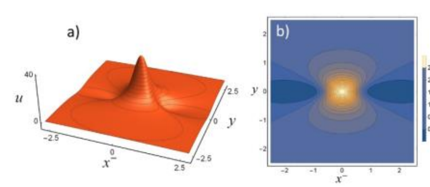

Fig. 1. KP-type lamp electromagnetic soliton [10].

The 100 PW class lasers will allow for the LWFA acceleration of ultrarelativistic electrons with the energy above 100 GeV whose collision with the focused light will provide the conditions for nonlinear QED vacuum texture probing [20]. As it has been foreseen in Ref. [21] ultra-relativistic electron to emit high energy photons via the Cherenkov radiation mechanism (see also [22, 23]). During the interaction with strong e.m. wave, the electron also radiates photons via Compton scattering. A synergic Cherenkov-Compton process [23] can be observed by colliding laser accelerated electrons with a high-intensity electromagnetic pulse. At extremely high photon energy end the vacuum refraction index tends to unity quenching the Cherenkov radiation. Experiments on studying these phenomena will reveal the properties of the vacuum predicted by nonlinear quantum electrodynamics. The ultra-relativistic electron interaction with extremely intense electromagnetic field requires careful consideration of the effects of the radiation friction in the quantum limit [24].

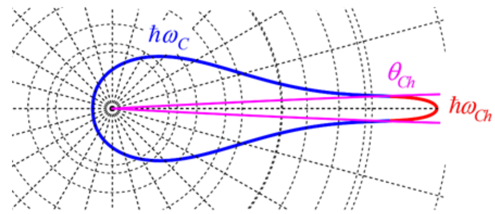

Fig. 2. Angle distribution of the energy for a photon radiated synergic Cherenkov-Compton process. [23].

Tools required:
Multiple-petawatt lasers interacting with the plasma targets can accelerate ultra-relativistic electrons to the energy above tens of GeV (with 1 PW laser the experimentally achieved LWFA accelerated electrons is of 7.8 GeV [25]). A scheme of the experiments on the laser accelerated electron interaction with focused e.m. wave aimed at studying such fundamental physics processes as the radiation friction effects, electron-positron pair creation, and vacuum polarization has been considered in [20, 26]. Its principle setup was realized in the experiments whose results are presented in [27].

Scientific impact:
The electron undergoing multi-photon Compton scattering also emits the Cherenkov radiation in the QED vacuum, where a strong electromagnetic field induces a refraction index larger than unity, thus entering the regime of Synergic Cherenkov-Compton Radiation-Scattering. In the range of the parameters where the Cherenkov and Compton modes can be distinguished the angle and energy distributions for the gamma photons emitted by these two mechanisms are different. With extreme high power lasers the synergic Cherenkov-Compton process can be observed by colliding laser accelerated electrons with a high-intensity electromagnetic pulse.

Broader impacts:
Observation of discussed above phenomena will shed light on the properties of nonlinear QED vacuum, allowing us to reveal the physical processes on a way towards the limit when αχ2/3, i.e., when the electromagnetic field interaction with charged particles develops according to non-perturbative regime scenario [28-31].

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MP3 White Paper 2021
Title: Laboratory gamma-electron-positron plasma – a new frontier in strong-field QED and relativistic laboratory astrophysics

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Abstract: Neutral electron-positron plasmas have long been theorized to have distinctly different properties than conventional electron-ion plasmas due to the mass symmetry of electrons and positrons [1, 2]. Due to their predicted unique properties, pair plasmas are systems of primary interest for fundamental plasma physics research. Moreover, electron-positron plasmas play an important role in astrophysics. For example, electron-positron pairs dominate the matter content of relativistic jets that stream from the nuclei of active galaxies [3]. Also, pairs fill the magnetosphere of magnetars and pulsars, where the nonstationary dynamics of electron-positron pair discharges is thought to result in bright non-thermal emission [4]. Electron-positron pair generation as well as the formation of gamma-electron-positron cascades in the presence of intense background electromagnetic fields is also central for probing strong-field QED in the nonperturbative regime [5]. Despite recent pioneering experiments [6, 7], the key impediment to creating a dense electron-positron pair plasma concerns the difficulty in accumulating sufficiently large numbers of positrons. The availability of multi-petawatt laser systems opens up the possibility of converting a large part of the laser energy into pairs, therefore allowing to generate dense neutral gamma-electron-positron plasmas extending over several skin depths in the laboratory [8-17]. This enables access, for the first time, to a new regime dominated by the interplay between strong-field QED effects and collective plasma dynamics. Such regime, in turn, is seminal to laboratory studies that can provide unique insights into extreme phenomena occurring in the atmospheres of compact astrophysical objects [18-20].

Scientific goals: (i) Conversion of a macroscopic amount of electromagnetic energy into a quasi-neutral dense gamma-electron-positron plasma with several plasma skin depths radius; (ii) Probe the collective dynamics of the generated gamma-electron-positron plasma by measuring its response to the excitation induced by a probe laser pulse; (iii) preparation of tailored gamma-electron-positron plasma beams interacting with strong magnetic fields and conventional electron-ion plasma flows to gain insights into fundamental processes of astrophysical interest such as energy and particle transport within a pulsar wind nebula and the production of nonthermal radiation from radio to gamma rays [19, 20].
Depending on the desired electron-plasma properties, there are two main routes to an electron positron plasma with lasers: (1) the collision of two or multiple high-power and tightly focused laser pulses with a gas or a solid target to generate a high-temperature dense electron-positron plasma with zero or modest average drift velocity [8-17]; (2) the generation of extremely dense photon beams with their subsequent conversion in dense collimated electron-positron beams [21]. High-energy photon conversion in pairs can occur via ultra-strong self-generated fields [21], or in the collision with an intense counter-propagating optical laser pulse, which could already provide

signatures of the collective electron-positron dynamics [22]. Attaining large plasma densities is of essential importance to trigger new phenomena of interest for strong-field QED and plasma physics such as amplified emission due to strong-self-generated fields [23] and efficient conversion of kinetic energy into energetic photons [25]. For astrophysically relevant applications, it is highly desirable that the pairs fill a volume that exceeds the collisionless skin-depth in all spatial dimensions.
The interaction of the generated gamma-electron-positron plasma with flows of conventional matter can be done by irradiating solid targets with energetic and powerful laser beams, i.e., following a similar methodology of previous laboratory astrophysics experiments [25].

Tools required: Multiple PW-class laser pulses to be focused on a spot with few micrometer radius in the case of zero or modest average drift velocity electron-positron pair plasma generation. High-pointing stability and good synchronization of the laser pulses are a key factor [15]. Further energetic laser pulses are required to generate matter flows that collide with the pair plasma or to directly probe the electron-positron plasma [23]. For the generation of collimated electron-positron jets, a high-current (250 kA) and high-energy (10 GeV) electron beam and thin aluminum foils are sufficient for the generation of dense collimated gamma-electron-positron beams [21]. Powerful drive laser pulses are required in this case only to probe the pair plasma dynamics, to further trigger photon conversion into pairs, and to generate hot matter flows. The availability of an external tesla-scale magnetic field, although not strictly necessary, enables the investigation of magnetized electron-positron plasmas and the influence of magnetic fields on streaming instabilities in pair-matter flow collision.

Scientific impact: Access to an unexplored regime of simultaneous primary interest for strong-field QED, plasma physics, and relativistic laboratory astrophysics. Demonstrate the conversion of macroscopic amounts of electromagnetic energy into matter-antimatter, probe the collective dynamics of matter-antimatter plasmas, reproduce on laboratory scale processes occurring in extreme astrophysical environments such as around pulsars and magnetars.
By radiatively cooling the electron-positron plasma, scientific research includes the creation of large samples of exotic species such as positronium atoms and molecules and the investigation of positron interaction with ordinary matter including atoms and molecules both for precision measurements and for fundamental physics tests. These investigations and tests include the study phases of the many-electron, many-positron system, and the gravitational attraction of antimatter to matter, or fundamental symmetries such as the predicted invariance of the relativistic quantum field theories under charge conjugation, parity and time reversal (CPT).

Broader impacts: The use of antimatter for scientific and technological purposes has become increasingly important in the last decades [26]. For instance, positrons are used to characterize materials and surfaces, and for positron emission tomography (PET), which is used in drug design, cancer diagnostics, and to study metabolic processes.

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Compact Hadron Collider with the Ion Accelerator Using the Laser Radiation Pressure

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Abstract:

When the laser pulse radiation pressure is dominant, the efficiency of the laser energy transformation into the energy of relativistic ions is very high. In the multi-ten-petawatt power laser limit the collision of the ultrarelativistic accelerated ion beams may open a way towards compact hadron collider.

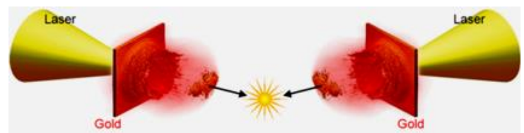

Fig. 1. Laser RPA hadron collider [7].

Scientific goal:

The laser accelerated ion beams [1,2] have been considered for a wide area of applications ranging from the hadron therapy in oncology [3], fast ignition of thermonuclear fusion targets [4], generation of high brightness hard electromagnetic radiation [5, 6] to development of compact hadron collider [7], Figs. 1, 2. The ions can be accelerated in laser plasmas via several mechanisms including the Coulomb Explosion (CE), Target Normal Sheath Acceleration (TNSA), Radiation Pressure Acceleration (RPA) mechanism and Magnetic Vortex Acceleration (MVA) (see Ref. 8 and Fig. 3). There are also several composite mechanisms, which are either the combinations of basic ones or somehow their enhancement. The RPA ion acceleration has been observed in the laser-matter interaction experiments [9,10]. Also, the use of composite targets was proposed in a number of papers to either inject the ions into accelerating fields, enhance the interaction of the laser pulse with the high-density part of the target, mitigate the effect of instabilities, or alter the accelerated ion spectra [11, 12]. The development of the Rayleigh–Taylor-like instability [13] in a controllable way may result in the transverse expansion of the irradiated thin-foil target, Fig. 2, or prolonged acceleration of the mass-limited target, Fig. 4, greatly enhancing the accelerator performance [14, 15]. The expansion decreases the number of accelerated ions in the irradiated region increasing the energy of the remaining ions, Fig. 2. The proposed in Ref. 7 compact hadron collider can be developed in the multi-ten-petawatt power laser limit, Fig. 1.

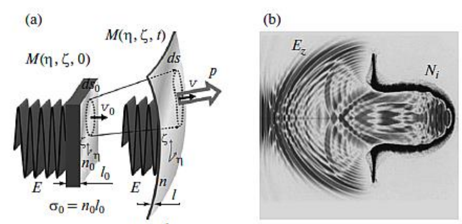

Fig. 2. a) Thin plasma shell pushed by the electromagnetic wave radiation pressure. b) The RPA ion acceleration by strong laser pulse [7].

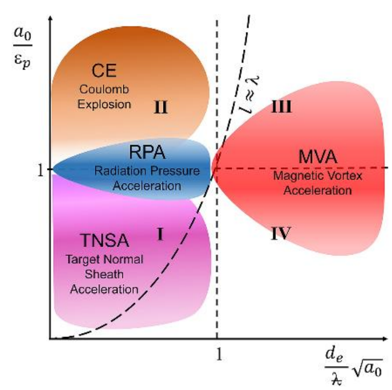

Fig. 3. The basic laser ion acceleration mechanisms in the plane of parameters, characterizing the laser pulse amplitude and the target transparency [8].

Tools required:

Under the laser-plasma-interaction conditions, the RPA ion acceleration regimes can be realized with the multi-petawatt power lasers of high contrast. Fabrication of structured thin foil targets is also required.

Scientific impacts:

Development of high efficiency laser ion accelerator is opening multiple ways towards various applications having great societal and technological impacts as well as having a potential for elaborating compact ion accelerators for fundamental sciences.

Broader impacts:

As in the case of the Laser Wake Field Acceleration of ultra-relativistic electrons and positrons where the multi-stage electron-positron collider will enable the development of the accelerator required in the elementary particle physics [16], the compact hadron collider [7] will make important impact in the fundamental science research.

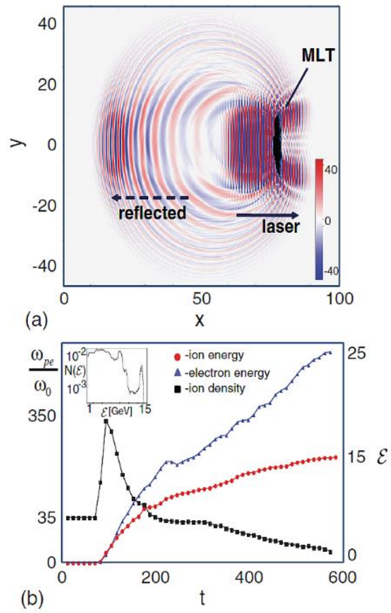

Fig. 4. Laser pulse, reflected radiation, and target shown as a superposition of the ion density and the electric field (b) Electron and ion energy and the normalized Langmuir frequency corresponding to the ion density versus time. Inset: Ion energy spectrum [14, 15].

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Towards investigating astrophysically relevant fast collisionless shocks

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Laboratory experiments on collisionless shocks using high-power lasers have been lately extremely fruitful, whether exploiting the expansion of a plasma "piston" within a pre-existing electromagnetic structure [1,2], in order to induce energy dissipation and shock formation, or by having two plasmas interact [3,4,5]. In the latter case, microscopic streaming instabilities give rise to an electromagnetic turbulence [6], which in turn mediates energy dissipation and shock formation. Current lasers can create plasma conditions similar to those found at the Earth's bow shock or in supernova remnants (SNR) [2], and we are now about to be able to study in the laboratory how particles picked up from the background can be energized, as well as the hierarchy of the subsequent acceleration mechanisms [2]. With the next generation of multi-PW lasers, which will deliver more energetic and powerful pulses than presently available, and which can be coupled to devices able to strongly magnetize background plasmas [2], progress can be envisioned in two directions: (1) Create piston flows much faster than previously achieved (>2000 km/s), by irradiating a thin foil and exploiting a mixed regime between target normal sheath acceleration and radiation pressure acceleration [7]. The high-Mach-number shocks induced by such flows expanding into magnetized background plasmas may be subject to rippling, leading to particle acceleration [8] and shock reformation. (2) Excite the Weibel-type instabilities that mediate initially unmagnetized shocks [6] in higher-energy regimes than presently accessible, in order to probe the shock physics of more extreme astrophysical environments (e.g. SuperNova Remnants, Gamma-Ray Bursts).

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MP3 White Paper 2021

Research Opportunities Enabled by Co-locating Multi-Petawatt Lasers with Dense Ultra-Relativistic Electron Beams

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Novel emergent phenomena are expected to occur under conditions exceeding the QED critical electric field, 1.3×10^{16} V/cm, where the vacuum becomes unstable to electron-positron pair production. The required intensity to reach this regime, $\gtrsim 10^{29}\,\mathrm{W/cm^2}$, cannot be achieved even with the most intense lasers now being planned/constructed without a sizeable Lorentz boost provided by interactions with ultrarelativistic particles. Seeded laser-laser collisions may access this strong-field QED regime at laser intensities as low as $\sim 10^{24}\,\mathrm{W/cm^2}$. Counterpropagating e-beam–laser interactions exceed the QED critical field at still lower intensities ($\sim 10^{20}\,\mathrm{W/cm^2}$ at $\sim 10\,\mathrm{GeV}$). Novel emergent phenomena are predicted to occur in the "QED plasma regime", where strong-field quantum and collective plasma effects play off one another. Here the electron beam density becomes a decisive factor. Thus, the challenge is not just to exceed the QED critical field, but to do so with high quality, approaching solid-density electron beams. Even though laser wakefield accelerators (LWFA) represent a very promising research field, conventional accelerators still provide orders of magnitude higher charge densities at energies $\gtrsim 10\,\mathrm{GeV}$. Co-location of extremely dense and highly energetic electron beams with a multi-petawatt laser system would therefore enable seminal research opportunities in high-field physics and laboratory astrophysics. This white paper elucidates the potential scientific impact of multi-beam capabilities that combine a multi-PW optical laser, high-energy/density electron beam, and high-intensity x rays and outlines how to achieve such capabilities by co-locating a 3–10 PW laser with a state-of-the-art linear accelerator.

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Scientific goals

The Schwinger critical electric field $E_{\rm cr} \approx 1.3 \times 10^{16}\,{\rm V/cm}$, where the quantum vacuum becomes unstable, can be reached by combining a ultra-intense optical and/or x-ray laser with a high-energy electron beam in a single facility [1]. This opens scientific opportunities to study fundamental questions in QED, novel plasma physics, and properties of extreme astrophysical environments.

In this white paper, we focus on the specific opportunities made available by co-locating a $3-10\,{\rm PW}$ laser with a $30\,{\rm GeV}$, $\sim 10^{21}\,{\rm cm}^{-3}$ density electron beam. The electron beam could be provided at SLAC, by combining the FACET accelerator test facility with the adjacent LCLS copper LINAC using new beam compression techniques being explored at FACET-II [2], and brought to an experimental hall where interaction with the beam of a multi-PW laser would be possible.

Such a facility, with an intense electron beam interacting with an intense laser beam, brings two important advantages to the program of studying QED in the critical field regime. First, such a facility would give the highest value available with current technology of the most important figure of merit for these experiments — the value of the laser field as experienced in the frame of the high-energy electrons. The parameters in the previous paragraph lead to field values an order of magnitude larger than the Schwinger criterion. Further, the density of the beam and thus the produced plasma is such that one enters the QED plasma regime, in which an electron initiates the production of a large number of electron-positron pairs that are not only produced coherently, but also display collective effects that can be rather easy to observe [3]. In this regime, collective plasma and strong-field QED effects co-exist [4], and new processes appear such as coherent recollision of electron-positron pairs [5].

The large Lorentz boost of the 30 GeV electron beam significantly softens the intensity requirements to the $10^{22}\,{\rm W/cm}^2$-scale, implying that the produced pair plasma has a much lower relativistic gamma factor. This reduces the density requirements to see collective effects and therefore solves the coupled production-observation problem. As a result, this facility would make it possible not only to test the basic QED processes in the high-field region but also to study a new and unique regime of plasma physics.

This QED plasma regime has its own importance, but it also plays a role in systems of great interest in nature. One of the most enigmatic objects studied in astrophysics, the magnetar, is a neutron stars with a surface magnetic field as high as $\sim 10^2 B_{\rm cr}$, where $B_{\rm cr} \approx 4 \times 10^9\,{\rm T}$ is the Schwinger critical magnetic field [6]. So far, magnetars represent the only class of active galaxies that are confirmed to be responsible for Fast Radio Bursts (FRBs) [7]. QED plasmas are also expected to be produced in the interaction regions of high energy particle colliders [8–10]. To understand these phenomena, we need codes that account quantitatively for the behavior of electron-positron plasmas as they pass from more familiar settings to the extreme-field regime. This requires control of the experimental conditions, and the ability to adjust the beam parameters continuously. This is the second advantage of co-locating a high-power laser with an electron beam from a LINAC. The electron beam is well-defined and is characterized by well-understood diagnostics. The transition from the low-field to the high-field regime is achieved by raising the electron beam energy systematically.

These advantages of co-location contrast with the situation for facilities with high-power optical lasers only. It is very difficult to probe the fully nonperturbative sector of QED [11] with optical lasers, since reaching this regime requires ~ 10 attoseconds pulse durations to mitigate radiative energy losses [12, 13]. Having intense x rays present in such a facility could therefore be highly advantageous for studying matter in extreme electromagnetic fields due to the high frequency (penetrating power and broad bandwidth) of the radiation.

Laser-laser collisions [14] depend crucially on the seeding process [15], which is rather difficult to control. The presence of a gas or solid target at the interaction point adds significant background to the light-by-light scattering reaction. One can create high-energy electron beams with high-power lasers using laser wakefield acceleration [16]. But today conventional RF LINACs provide considerably higher particle energies, lower energy spread, and higher charge density [1, 2], in addition to the advantages in terms of experimental control discussed above [17, 18].

The multi-beam facility that we are discussing will also enable a broad physics program in topics outside strong-field QED. These topics include advanced accelerator development, attosecond atomic and solid-state physics, and high energy density and inertial confinement physics. We will discuss these topics in a separate section toward the end of the white paper.

Tools required

The research opportunities presented above all make use of co-location of different combinations of three major tools: a $3-10$ PW laser, a $10-30$ GeV ultra-relativistic and high-density ($n \gtrsim 10^{21}\,\mathrm{cm}^{-3}$) electron beam, and multi-millijoule multi-kilovolt x-ray free-electron lasers.

Major pieces of the technology already exist or are planned at this moment, but co-location is a key feature that must be part of the planning, as well as focus on key critical machine parameters.

The required accelerator technology to produce dense electron beams at $\gtrsim$ 30 GeV is currently being developed actively at FACET-II at the 10 GeV-scale [2]. The goal of 30 GeV in electron energy can be achieved at SLAC with conventional RF acceleration if the FACET-II LINAC is connected to the current LCLS copper LINAC. Higher electron energies can also be achieved via beam- and laser-driven plasma acceleration.

Multiple 10 PW-scale laser systems have recently been commissioned, e.g., ELI-Beamlines and ELI-NP [19–21], and more are planned. Exceeding the 10 PW-scale requires coherent combination of multiple laser pulses and/or new technology, therefore this pathway is much more risky [22].

Today, the LCLS generates x-ray pulses with a peak power of 100 GW or more and a pulse duration of about $10-20$ fs. The x rays can be focused to a spot size of 50 nm rms radius, giving at the focus an intensity larger than $10^{21}\,\mathrm{W/cm^2}$ and an electric field of about $5 \times 10^{13}\,\mathrm{V/m}$. Several recent studies have shown that it is possible to increase the peak power by two to three times using the existing system. It has also been shown that using a new superconducting undulator the power level can be increased by one order of magnitude to several TW, pushing the power density and electric field at the focus to over $10^{23}\,\mathrm{W/cm^2}$ and $1.5 \times 10^{14}\,\mathrm{V/m}$ [23]. When backscattered on a 15 GeV electron beam the electric field E^* seen by the electrons is enhanced by the beam relativistic factor, γ, to $E^* \sim 5 \times 10^{19}\,\mathrm{V/m}$, well above the Schwinger critical electrical field, allowing the exploration of QED in a region with $E^* \gtrsim E_{\mathrm{cr}}$ and dimensionless vector potential of order one, a regime not accessible using petawatt optical laser.

Scientific impact in the area of Strong-Field QED

QED plasmas: The complex interplay between strong-field quantum and collective plasma effects in the “QED plasma regime” renders analytical *ab initio* calculation impossible. As a result, our insights rely almost exclusively on the QED-PIC methodology [24], which employs many approximations. Challenging existing predictions by comparing them to experimental data will be essential for improving our understanding of the QED plasma regime.

High-Energy Astrophysics: Co-location of a multi-petawatt laser with a high-energy, high-density electron beam would provide a *novel platform for laboratory astrophysics* that will provide important insights into the most extreme plasma conditions present in our universe [4], e.g., around magnetars [6], which are progenitors of fast radio bursts [7], neutron-star merging events [25], and potentially also black holes [26, 27]. Relativistic pair plasmas have unique properties which differ considerably from conventional plasmas. Reaching extreme pair-plasma densities and temperatures via beam-driven QED cascades enables a novel high energy-density physics (HEDP) research frontier, that is highly relevant for the emerging field of multi-messenger astronomy.

Linear Collider Physics: The experiments carried out at such a facility will provide important insights that could lead to a paradigm change in linear collider design: the limitations of linear lepton colliders are essentially determined by beamstrahlung [9, 10]. A change from long and flat to short and cylindrical bunches could drastically decrease the operational costs of the collider while ensuring scalability to the multi-10 TeV regime [8]. They are essential for developing the science case for a future "nonperturbative QED collider", which can access the fully nonperturbative regime of QED [11], e.g., by changing the final focus design of ILC.

Scientific impact in areas beyond Strong-Field QED

Laser Wakefield Accelerators: The proposed capabilities will likely have a disruptive impact on LWFA. LWFA represents a very promising technology, but does not yet deliver the combination of energy, beam density, repetition rate, and stability of the facility described here. Staging has been demonstrated with low capture efficiency [28] and seeding a LWFA stage with a high-quality, well controllable electron beam would facilitate systematic studies that could solve the challenging staging problem, essential for reaching TeV-scale energies [29, 30].

X-ray science: The availability of a high-quality ultra-dense high-energy electron beam would provide a setting for an x-ray free electron laser with higher x-ray and/or pulse energies than currently operating facilities. This will open a plethora of opportunities in materials science and nuclear physics, as well as attosecond and strong-field atomic and condensed-matter physics. In combination with the multi-PW optical laser this becomes a powerful facility for high-energy density science.

High energy density: This high-intensity XFEL would enable opportunities in high energy density and inertial confinement physics not possible anywhere else. The combination of the laser for compression of materials and the XFEL for diagnostics would be a major step forward in the study of high-pressure materials such as metallic hydrogen. Novel physics could become accessible by focusing extremely intense hard x rays on a deuterium target, which is predicted to enhance the d-d fusion cross section [31].

Broader impacts

Megaprojects like the 100 PW "Station of Extreme Light" (SEL) in Shanghai [32] are exciting the public about science and therefore play a crucial role in justifying basic research. Creating a flagship high-intensity laser facility will re-establish U.S. leadership in an area where it has fallen behind in recent years [33]. It will have a big impact on outreach programs, inspire students to pursue a scientific career and attract current and future scientific leaders.

In the light of substantial international investment into (multi-) petawatt laser infrastructure, it is very hard to stay internationally competitive with only all-optical facilities. Therefore, it is advisable to concentrate resources and benefit from existing infrastructure. The envisioned combination of PW lasers with high energy, high density electron and x-ray beams will create a unique environment that enables synergies, cross-fertilization, and novel frontiers at the intersections of these research fields. Co-location of a multi-petawatt laser system with an ultra-relativistic electron beam will provide seminal, world-wide unique research opportunities that will attract the best scientists in these research fields to the U.S.

Acknowledgments

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Electron acceleration beyond the single-stage laser wakefield acceleration

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One of the main research interest at CoReLS is to harness its state-of-the-art multi petawatt laser facility [1] and plasma-based-accelerator capabilities [2] to study and experimentally verify the theories of strong-field quantum electrodynamics (SF-QED) [3]. One of the experimental configurations of interest is the collision of multi GeV electron beam with an ultra-intense laser pulse. Such sophisticated experiments also require strong theoretical support, more specifically simulation support, not only at the designing stage of the experiment but also after the experiment to understand the results.

For such experiments, to produce multi-GeV electron beam, we are exploring various interesting concepts, such as, all optical-dual-staged laser wakefield acceleration [4], and transitional laser-plasma electron acceleration (Transition from laser to electron beam driven wakefield acceleration). We here discuss some of the possible ways to extend the acceleration of electron bunch beyond the single-stage LWFA, without compromising the beam quality.

We show the transition from LWFA to PWFA with full-scale 3D PIC OSIRIS [5] simulations, where the energies of the electrons bunch can be doubled. In such hybrid acceleration process the electron bunch first accelerated by a short and intense laser pulse, then drives its own wake after the depletion of the laser pulse. The coupling between the two processes strongly depend on the laser and plasma parameters, and we demonstrate that by controlling these parameters we can control the accelerated beam quality.

Then, we extend the discussion on acceleration beyond the single-stage LWFA by proposing an all-optical dual-stage LWFA [4], staged with co-propagating two-color laser pulses in a plasma medium. After the depletion of the leading fundamental laser pulse that initiates self-injection and sets up the first stage particle acceleration, the subsequent second-harmonic laser pulse takes over the acceleration process and accelerates the electron bunch in the second stage over a significantly longer distance than in the first stage.

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Opening the experimental investigation of heavy elements nucleosynthesis through extreme brightness neutron beams generated by multi-PetaWatt-class lasers

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With the next generation of multi-PetaWatt-class lasers, it will be possible to generate efficiently, through spallation driven by laser-accelerated protons [1], the short duration and the extremely high neutron flux needed for the nucleosynthesis s-process and r-process investigations [1]. Already present-day laser driven neutron production has unique advantages, compared to traditional sources, in terms of short duration [2,3] and is already on-par in terms of brightness [4]. We expect that with ion sources driven by upcoming multi-PetaWatt-class, which are only several orders of magnitude better than conventional sources in terms of current and duration (i.e. MAmp and picosecond at the source, in a single shot), but should also reach hundreds of MeV of peak energy, the extreme brightness required for investigating experimentally the nucleosynthesis of heavy elements will be reached. Furthermore, using lasers and not particle accelerator facilities to perform such investigations will offer unique opportunities to perform neutron capture in the plasma environment and in unstable nuclei, since (i) lasers allow to generate plasma states that can be suitable scaled to astrophysical environments, and (ii) the neutron bunch is shorter than the plasma hydrodynamic time scale and decay time respectively.

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MP3 White Paper WP-78

MP3 Whitepaper: Relativistic Plasma Physics in Supercritical Fields Working Group: HFP/QED

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(Dated: April 2021)

Combined with advances in our understanding of the kinetics of relativistic plasma, studies of laser-plasma interactions are entering a new regime where the physics of relativistic plasmas is strongly affected by strong-field quantum electrodynamics (QED) processes, including hard photon emission and electron-positron (e^+-e^-) pair production. This coupling of quantum emission processes and relativistic collective particle dynamics can result in dramatically new plasma physics phenomena, such as the generation of dense e^+-e^- pair plasma from near vacuum or laser energy absorption by QED processes. In addition to being of fundamental interest, it is crucial to study this new regime to understand the next generation of ultra-high intensity laser-matter experiments and their resulting applications.

I. SCIENTIFIC GOAL

While QED is probably one of the best verified theories so far on a single particle level[1,2], the new collective phenomena that arise when electrons, positrons, and photons are exposed to *strong* electromagnetic fields are not yet well understood. Strong electric fields are those that approach or exceed the *QED critical field strength*, $E_{cr} = m_e^2c^3/e\hbar$, in which interactions become highly nonlinear. In particular, the prolific production of electrons and positrons can cause complex plasma interactions with these fields, which are conditions that are only starting to be theoretically explored.

The highest laser intensities demonstrated to date are seven orders of magnitude lower than necessary to reach the critical field E_{cr}. However, since the electric field is not a Lorentz invariant, in the rest frame of an ultrarelativistic particle a subcritical field strength may be boosted to the critical field strength and beyond, as characterized by the parameter $\chi = c|F^{\mu\nu}p_\nu|/mE_{cr}$. Therefore, SF QED processes such as multiphoton Compton emission of photons and multiphoton Breit-Wheeler electron-positron pair production occur at significantly lower field strengths than E_{cr}. This allows studies of the *physics of plasmas in supercritical fields* with present day and near future technology. Particle accelerators or extremely powerful lasers are able to generate high-energy particles that can experience these boosted field strengths (e.g. return forces from ions in plasmas, or fields in standing waves).

Laser fields may provide both the strong electromagnetic field and generate the high-energy particles[4] and

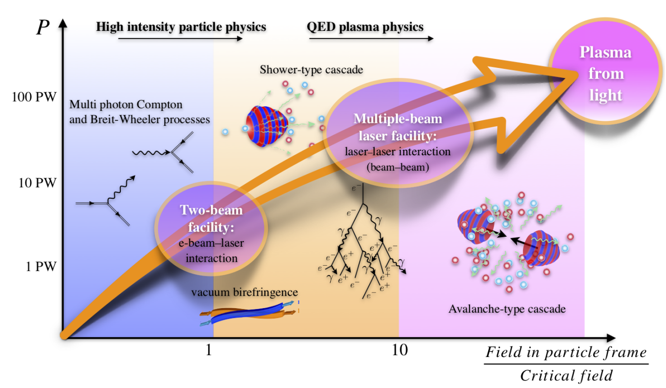

FIG. 1. Timeline of the QED-plasma studies envisioned as a three-stage process[3].

therefore represent a particularly interesting environment for studying plasma physics in supercritically strong fields[5–7]. Despite tremendous progress achieved in recent years , there are a lot of unanswered questions and unsolved problems that need to be addressed both theoretically and in experiments. As shown in Fig. 1, facilities to address these questions are likely to follow a three step approach, first developing a colliding beam facility, and subsequently a multi-beam capability at much higher pulse powers.

II. TOOLS REQUIRED

Experiments in this area depend highly on the availability facilities capable of reaching large values of χ, since it will not be feasible in the near term to achieve the critical field strength in the laboratory frame. We note that reaching large values of χ is an important problem by itself that needs to be addressed by future facility designs. It is due to the fact that electrons and positrons

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quite easily radiate their energy away when interacting with strong EM fields, so several approaches were proposed to counter this energy loss[8–10] to ensure that high energy particles reach the region of highest field intensity.

Critical fields in the zero momentum frame of a high energy particle (pair) can be achieved with two basic configurations: either an externally accelerated relativistic charged particle beam interacting with a perpendicular field or a particle orbiting in a rotating field configuration. In addition to that, the choice of laser wavelength plays an important role in what areas of the interaction parameter space can be accessed[11,12]. In Figure 2 we show how the wavelength of lasers used affects the ability to access strong field QED regimes (defined by reaching $\chi = 1$) and strongly radiation dominated regimes [defined by reaching $\alpha a_0 \chi g(\chi) = 1$, where $g(\chi) \leq 1$ describes the reduced radiated power in the quantum regime[13,14]], in either a multiple colliding laser configuration (lower panel) or laser colliding with a 5-50 GeV lepton beam (upper panel). It is clear from these charts that very short wavelength lasers are able to reach the $\chi = 1$ limit most easily and may therefore be the optimal experimental platforms to study nonlinear QED processes. The technology able to produce very short wavelength lasers with required power is not yet developed. Moreover, to study the physics of relativistic *plasmas* in supercritical fields, where the process rates are sufficient that the quantum processes affect the plasma dynamics, we also need to be in the radiation dominated regime. For the multiple laser pulse configuration, the crossing point where radiation dominated and quantum dominated regimes are simultaneously important is near 1 μm wavelength at 10's of PW laser power.

In Fig. 3 we sketch a principal design for SF QED/plasma accelerator facility that would provide an ultimate test to the advanced accelerator technologies as well as to supercritical field effects in high energy physics and plasma physics. Such facility would combine both Stage 1 and Stage 2 capabilities at higher energy and intensity levels.

III. SCIENTIFIC IMPACT

Collective plasma processes in the QED-Plasma regime are expected to be dramatically different from the well studied classical plasmas. There are several examples of such processes in the literature already, starting from radiation reaction effects, to electron-positron pair production in plasma by plane EM waves[15], which does not happen in vacuum, to the backreaction of pair production on the properties of the EM wave due to the created electron-positron plasma[16], to the laser absorption by created electron-positron plasma during the avalanche-type cascade[17,18], to the laser driven ion[19,20] and electron[21] acceleration, to the reversal of relativistic transparency in QED plasma[22], strong collective plasma fields[23] or energy enhancement by radiation reaction[24].

The new plasma state that is created in the presence of supercritical fields is similar to that thought to exist in extreme astrophysical environments. The physics of such plasmas in strong fields is relevant to early universe conditions[25], extreme astrophysical objects such as neutron star atmospheres[26] and black hole environments[27], and is critical to future high-intensity laser driven relativistic plasma physics.

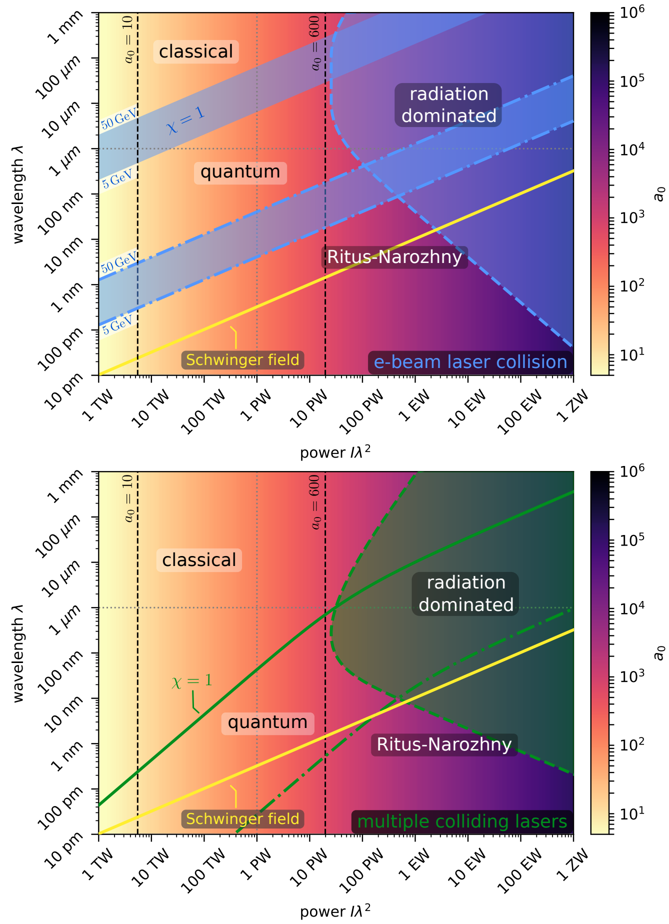

FIG. 2. The different regimes of SF QED plasma interactions can be reached with various laser power and wavelength for the e-beam laser collider (upper) and the multiple-laser beam interactions (lower). The blue diagonal band in the upper plot marks the transition from the classical for the quantum regime at $\chi = 1$ for colliding beams of various electron beam energy. The green solid curve in the lower plot is the same for the multiple laser interaction. Below the dash-dotted lines is the Ritus-Narozhny regime (Note that it is most easily accessed using short-wavelength radiation in the collider scenario). The shaded regions right of the dashed curves is the radiation dominated regime. The intersection point of the quantum-classical transition and the transition to radiation dominated dynamics occurs around 30 PW and 1 μm for the multiple laser beam interaction case. We assume focusing to a 2λ spot size for both plots[3].

In terrestrial laboratories, the sources of the highest intensity EM fields are lasers, with the exception of aligned crystals[28,29] and highly charged ion interactions, the latter are, unfortunately, dominated by quantum chromodynamics effects. The interaction of lasers with electrons, positrons, and photons, whether they act as single particles or plasma constituents, may lead to a number of SF QED effects including vacuum "breakdown" and polarization, light by light scattering, vacuum birefringence,

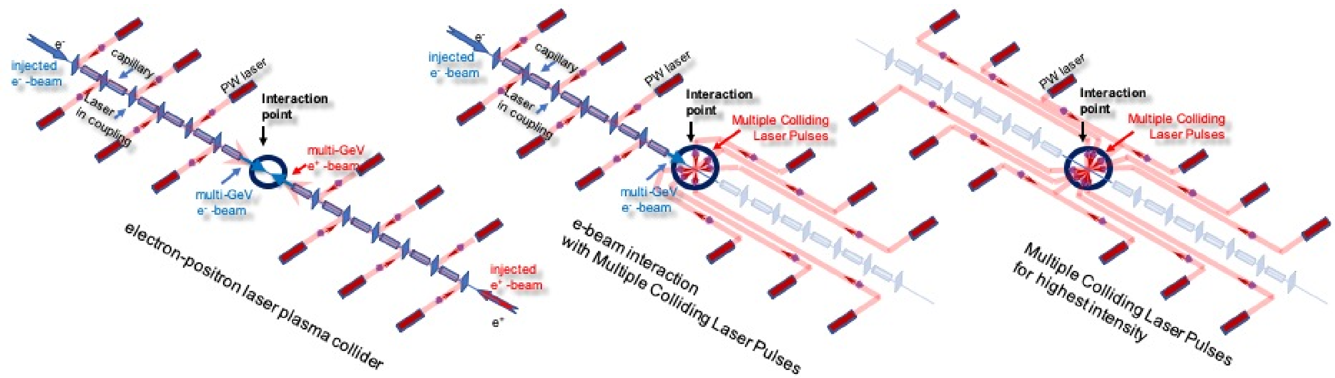

FIG. 3. The principle scheme of the ultimate SF QED facility, housing multiple PW-class lasers. Depending on the designed c.m. energy the number of stages can be increased correspondingly. The facility can operate in several modes, including (i) e^+e^- laser collider with all lasers utilized to drive the staged acceleration of electron and positron beams; (ii) electron beam interaction with high intensity EM field, where half of the lasers is driving the staged acceleration of the electron beam, and another half provides high intensity field through the multiple colliding pulses configuration; and (iii) all the laser pulses are brought to the interaction point to generate highest intensity possible through the multiple colliding pulses configuration.

4-wave mixing, high harmonics generation from vacuum, and EM cascades of different types. It was shown theoretically and in computer simulations that one can expect the generation of dense electron-positron plasma from near vacuum, complete laser absorption, or a stopping of an ultrarelativistic particle beam by a laser light.

All these phenomena are of fundamental interest for quantum field theory. Moreover, they should dominate the next generation of laser-matter interaction experiments, and may be important for future TeV-class lepton colliders.

IV. BROADER IMPACT

Applications resulting from high-intensity laser-matter interactions, including high energy ion, electron, positron, and photon sources for fundamental physics studies, medical radiotherapy and next generation radiography for homeland security and industry will benefit from advances in this area.

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Spin and Polarization in High-Intensity Laser-Matter Interactions

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There has been a recent surge in theoretical investigations of the behaviour of lepton spin and photon polarization in high-energy laser-matter interactions. These investigations are important not only for generating spin-polarized electron beams for proposed TeV scale plasma based colliders, but are also relevant in the regime of QED-plasma physics. In addition to ongoing theoretical efforts it will be essential to develop full scale simulation capabilities as well as experimental platforms for particle polarimetry compatible with high-power laser plasma experiments.

Keywords: HFP/QED

A. Scientific goal:

One of the driving forces in the development of petawatt class laser systems can be seen in novel laser-plasma based accelerator concepts. Laser wakefield acceleration experiments have already achieved nearly 10 GeV energy in a single stage and may enable future novel TeV electron-positron colliders for high-energy physics. Spin-polarized beams are crucial for high-energy collider applications, for instance in order to suppress the standard-model background in searches for new physics beyond the standard model. Investigating the dynamics of spin-polarized electron beams in a plasma wakefield is therefore an important subject [1, 2, 3, 4].

It is known that initially unpolarized lepton beams radiatively polarize slowly in storage rings due to asymmetries in the rates for synchrotron emission, the so-called Sokolov-Ternov effect. We previously demonstrated that a similar spin polarization can occur for electrons circulating at the magnetic nodes of two colliding intense laser pulses [5, 6], with polarization timescales of few femtoseconds for high laser intensities. However, the particle orbits in such a field configutation tend to be unstable in general. The development of polarized QED cascades has been investigated [7], where the production of macroscopic amounts of polarized matter might occur.

By first accelerating electrons to high energy and then colliding them with a laser pulse, it is possible to achieve $\chi \gtrsim 1$ with current PW class high-intensity lasers operating at intensities 10^{21} W/cm^{-2} and study radiative spin polarization in the strongly quantum regime. This laser-electron-beam collider setup was used in seminal SLAC E-144 experiments demonstrating nonlinear Compton scattering and electron-positron pair production and has recently been used to observe quantum radiation reaction. We found a polarization dependence of the radiation reaction force, related to the fact that spin-down electrons radiate more power than spin-up electrons [8].

It has been demonstrated that a high-energy lepton beam can be radiatively polarized in collisions with an ultrashort pulsed bichromatic laser field by the spin-dependent nonlinear Compton process [8, 9]. The essential feature is that the admixture of 2ω light breaks the up-down symmetry of the oscillating magnetic field and hence allows for the build-up of an asymptotic net polarization degree. In this geometry it was shown that on the order of 5–10 % polarization degree are achievable when colliding an 8 GeV electron beam with a 100s fs duration laser pulse with a power of 1 PW [8] at $a_0 = 10$. About 30 % of the total laser energy needs to be in the 2ω component. In a similar scenario one could achieve the production of polarized positrons with a high degree of polarization up to 60 % at $a_0 = 100$ [10] via the spin-dependence of nonlinear Breit-Wheeler pair production [11].

The aforementioned theoretical studies showed the principal opportunities of accessing spin-dependent interaction with present or near-future laser facilities. In these studies the principal coupling of radiation emission processes and radiation reaction constitutes an interesting subject by itself. Not only does the strong-field QED interaction lead to a polarization of the leptons, but also the rate of energy loss is different for up and down electrons, leading to spin-dependent radiation reaction, and spin-straggling effects. Moreover, the polarized leptons emit polarized photons which could become interesting as a polarized GeV photon source.

B. Tools required:

What needs to be done most urgently is to develop theoretical tools to perform full-scale simulations of the spin-dynamics in high-power laser-plasma and laser-beam interactions. That means one needs not only to take into account the spin precession in a strong field, but also include radiative spin-flips and the production of polarized particles by adding spin and polarization resolved strong-field QED processes into particle-in-cell (PIC) codes [4, 12, 13, 14].

For experiments, spin-flip processes are most important in QED strong fields, which can be accessed using colliding laser/lepton beam geometries or extremely intense lasers. One key challenge is to develop a platform for polarimetry diagnostics, for both leptons and photons, capable of dealing with high-power laser-plasma/beam experiments. This remains an unresolved issue.

C. Scientific impact(s):

The parameter space accessible through particle collisions may be considerably enhanced by adding spin and polarization degrees of freedom, hence by considering the scattering of spin-polarized particles. For instance, the polarized deep inelastic scattering of polarized leptons on polarized protons revealed intriguing details on the spin-structure of the constituents of the proton [15, 16], and polarized beams have been used in investigations of parity non-conservation effects [17, 18]. Moreover, polarized beams are required for upcoming high-energy lepton-lepton colliders to help suppress background [19]. Plasma accelerators have been put forward as a novel concept for accelerating leptons to high energies. A full understanding of spin dynamics in plasma, including classical spin dynamics and spin scattering interactions, especially during radiation emission, has not been achieved yet. That may be why in most studies of high-intensity laser-plasma interactions the electron polarization is not taken into account [20]. Recent studies have shown that the dynamics of a spin-polarized lepton in extremely strong field showed model-dependent discrepancies under certain conditions [21], scrutinizing models of spinning radiating particles. This could be important at the interaction point of polarized lepton colliders, and could possibly be tested with high-power lasers. It thus seems timely to model plasma-based particle acceleration for high energy physics applications including spin dynamics. Another area of interest is the polarized gamma rays that are emitted from such processes, which are also potentially useful as a source.

D. Broader impacts:

The scattering of spin-polarized particles is an important aspect of high-energy physics, not only for deep inelastic scattering [15, 16], parity non-conservation effects [17, 18], and to suppress standard-model background in searches for new physics beyond the standard model [19]. Spin forces have been suggested to be important in both astrophysical systems and high intensity laser-plasma interactions [22]. With increasing interest in high intensity laser-plasma interactions [23], it is important to develop tools capable of modeling spin correctly to improve the predictive capabilities of numerical simulations. As well as having an effect on the effective forces at high intensity, such as radiation reaction, because of the exponential nature of pair-creation probabilities, even small differences in the photon emission rates due to lepton spin polarization can have dramatic effects on electron-positron pair cascades [7, 24], for example.

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Understanding Transients: Needs from the Laboratory Astrophysics Community

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Abstract: A growing number of astrophysical transients are pushing astronomers to develop increasingly complex computational tools to model both radiation hydrodynamics and electron transport. Here we review the physics needs and simulation uncertainties associated with modeling these transients. Although this review will focus on theory and simulation aspects of this problem, we also review some experiments designed to study this physics.

Scientific Goals: Astrophysical transients are powered through both shock heating and energy deposition from electrons produced in the beta-decay of radioactive isotopes. Accurate modeling of these energy deposition mechanisms is critical to using observations of these transients to probe properties of these explosions, from understanding the true yields from the ejecta from neutron star merger events to studying the properties of supernova progenitors and the violent mass loss that precedes the supernova explosion. Astrophysicists are developing increasingly sophisticated physics modules to more accurately calculate this physics. Laboratory experiments are in a prime position to validate these new methods, ensuring the accuracy of these new methods.

Shock Heating: In the simplest supernova models, a spherically symmetric shock plows through a spherically symmetric star and surrounding wind profile. In this simplified picture, shock heating is limited to a forward shock and, because the shock decelerates, the subsequent reverse shock. Analytic solutions of this shock heating can be used to model a number of observed transient phenomena from shock breakout to superluminous supernovae. Unfortunately, the explosion is asymmetric and it plows through stellar/circumstellar media that harbor their own asymmetries. These asymmetries drive a complex series of shocks that cannot be solved by analytic solutions alone. Detailed radiation-hydrodynamics models are required to capture this evolution.

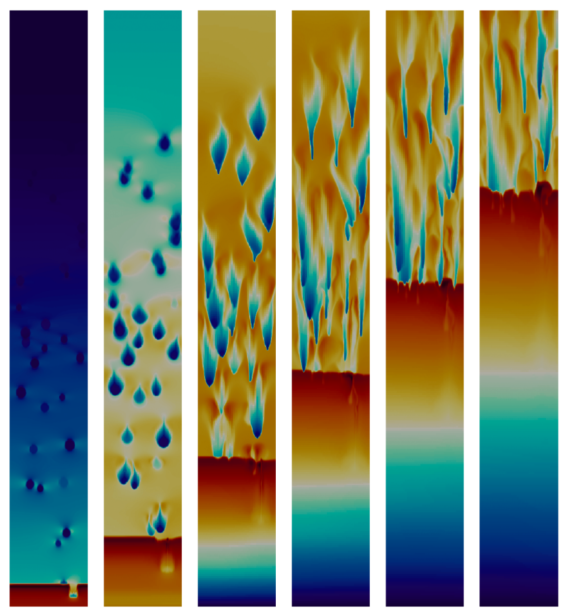

Figure 1: Time series of radiation-hydrodynamics simulation of a supernova shock interacting with turbulent wind medium. Shocks from these interactions reheat the supernova ejecta producing X-ray and UV emission seen in supernovae at early times. These calculations require detailed coupling of the radiation propagation with the hydrodynamic turbulence.

An example of this physics in an astrophysical transient is the early-time shock emergence in core-collapse supernovae. In most supernovae, the photon emission makes up only a fraction of the energy stored in the supernova blast wave. Turbulence in the massive stellar wind produces a clumpy wind medium. When the supernova blast wave drives through this clumpy wind medium, the resultant shocks from this interaction heat up the ejecta, converting the kinetic energy of the blast wave into bright X-ray and ultraviolet emission[1]. Figure 1 shows simulations using the LANL's radiation-hydrodynamics Cassio code[1-3]. Understanding how this shock and its radiation will interact with this clump (for example, does the radiation preheat the clump prior to a strong shock developing?) is critical in determining the exact strength of these shocks. Experiments that can validate the radiation-hydrodynamics coupling methods are critical to improving astrophysical calculations of this phenomena. This physics also plays a role in thermonuclear supernovae (interactions of the blast wave of the exploding star with its binary companion) and superluminous supernovae where extremely bright supernovae are produced when the energetic blastwave interacts with a shell of material from a mass-loss episode in stellar evolution (binary mass ejection, stellar pulsations).

At LANL, a suite of experiments has been developed to study this flow, developing and testing a temperature diagnostic to better measure the radiation flow across a boundary and through stochastic medium: COAX, Radishock, OuTi [4-6]. This temperature diagnostic has provided a strong constraint on the nature of the radiation flow, but much more work must be done to constrain the uncertainties in these experiments to probe the radiation-hydrodynamics methods developed at LANL.

Electron Heating: The other primary source of heating that drives the emission in astrophysical transients arises from the deposition of energy of energetic electrons produced in the beta decay of radioactive isotopes produced in the explosive engine behind these transients. Thermonuclear supernovae are powered by the decay of radioactive ^{56}Ni produced in the explosion. Energetic electrons produced in this decay deposit their energy as they scatter through the ejecta, ultimately heating the ejecta and powering the emission observed in these supernovae. This electron heating is important in a wide range of transient light-curves including the core-collapse explosion of Wolf-Rayet stars (type Ib/c supernovae) and the newly observed "kilonova" transient rising from the ejecta produced in the merger of neutron stars (in this latter case, the radioactive elements are heavy rapid neutron capture isotopes). Codes are being developed to improve the modeling of electron transport at higher fidelity. Even so, electron transport is modeled with simplified solutions using angle-integrated interaction cross-sections. In addition, electron transport will need to include the effects of the magnetic fields developed in the turbulent exploding medium.

Tools Required: Because this paper focuses on the validations needs for theory and not the design of upcoming experiments, we focus just on the theoretical tools in development to better model this physics. For shock heating, the key computational tools needed are improved radiation-hydrodynamics coupling models. Although higher-order transport schemes (e.g. implicit Monte Carlo and discrete ordinate methods such as S_N) are becoming increasingly common, the coupling of these schemes to hydrodynamics is still typically done through simplified operator-split methods and few methods incorporate transport schemes that leverage the sub-grid turbulence models in these hydrodynamics calculations. Methods to include this physics are currently under development and validation experiments are critical.

Transport methods for electrons range from fully-kinetic calculations (e.g. particle-in-cell) that include effects of these electrons on the magnetic fields to in-situ energy deposition, calculating only the energy deposited without even modeling the spatial disposition of this heating. Kinetic calculations are too computationally costly to model the full astrophysical event, but a number of new approaches are being proposed: reduced-order models, higher-order transport methods focusing on electron transport. For astrophysical transients, the most critical physics is probably the electron transport. Advances in electron transport require a better understanding of interaction cross-sections for the electrons. In addition to the cross-sections, the propagation through turbulent magnetic fields must also be included.

Scientific Impact: We have already discussed some of the astrophysical transients that require next-generation modeling. These phenomena have strong ties to upcoming NASA missions. For the early emission from supernovae, a number of satellites are being proposed that will observe the ultraviolet or X-ray emission from these early time outbursts. Our current understanding of this emission has been set by serendipitous observations from the Swift satellite. The UltraSAT mission has initial funding and will increase the number of observations of this emission (only in the ultraviolet)[]. The proposed SIBEX mission will increase the number of such observations by at least tenfold in both X-rays and ultraviolet (including spectra). Both ground- and space-based missions exist and are being developed to observed transients from neutron star mergers (counterparts to gravitational wave detections). Needless to say, time-domain and multi-messenger astronomy are one of the most active areas of research in astronomy and understanding the physics behind these transients is becoming increasingly critical.

Any experiments validating the physics behind these two important energy sources for astrophysical transients will also validate codes used in a number of other applications from inertial confinement fusion to space weather.

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MP3 Multi-Petawatt Physics Prioritization Workshop – White Paper

Electron-only radiation dominated magnetic reconnection

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Abstract

We propose the use of two extremely intense laser-pulses to create a laser-driven reconnection experiment. Through the use of short-pulse lasers with intensities >10^{23} W/cm^2 we aim to study the dynamics of magnetic reconnection in a regime where magnetization is so extreme that outflow velocities from the reconnection layer approach c, and radiation becomes important to the dynamics. This regime is relevant to extremely energetic astrophysical environments such as those near black holes or magnetars. By diagnosing reconnection rates, radiation and electron spectra, and the structure of the reconnection layer, the physics relevant to astrophysical theories can be examined.

Scientific Goal

Magnetic reconnection is a fundamental process that rapidly converts magnetic potential energy into particle kinetic energy [1]. It has been theorized to be the main driver of many high-energy phenomena in our solar system [2, 3] and in more extreme astrophysical environments [4]. Several experiments have been performed to study magnetic reconnection using large plasma devices and laser-plasma interactions.

Nilson *et al.* were first to demonstrate laser-driven reconnection [5]. This experiment used two moderate intensity ($\sim 10^{15}$ W/cm^2) laser pulses to generate rapidly expanding plasma plumes with azimuthal ~1 MG magnetic fields through the Biermann mechanism on the surface of metal foils [6]. The plumes expand and interact with antiparallel magnetic fields forming a geometry resembling the simple picture of Sweet-Parker reconnection [2]. This two-pulse geometry has been adopted as the standard laser-driven reconnection geometry with slight modifications to study the many intricacies of the reconnection process [7, 8].

Uzdensky studied the reconnection physics in the vicinity of extreme environments such as those near black holes or magnetars, focusing on relativistic effects, radiation effects, and pair creation [4]. In reconnecting plasmas with extreme magnetization where the magnetic energy density exceeds the particle rest mass energy and plasma pressure, relativistic outflow velocities from the reconnection region are expected to be achieved. This is parametrized by $\sigma_{hot} = B^2/4\pi w$ where w is the sum of the relativistic energy density and plasma pressure. This parameter is particle specific, therefore plasmas with relativistically magnetized electrons, but sub-relativistically magnetized ions can exist forming the semi-relativistic reconnection regime studied by Werner *et al.* [9]. This is the highest energy regime of reconnection that has been accessed experimentally [7, 10]. The work by Werner *et al.* showed that reconnection rates and particle spectra in the relativistic regime may be different from the non-relativistic regime, but these properties have not been measured experimentally. At even higher magnetizations, the production of radiation or pairs through quantum electrodynamic processes in the reconnection layer may occur that could greatly affect the reconnection dynamics [11]. For example, in an optically thin plasma the highest energy electrons may convert kinetic energy to radiation, cooling the reconnection layer thereby affecting the reconnection rates and resulting particle spectra. If the radiation is of a high enough energy, pairs may be produced, increasing the density of the reconnection layer, potentially to the point of being optically thick.

Here we propose that a multi-petawatt laser could be used to investigate electron-only laser-driven radiation dominated reconnection. This reconnection experiment will use either the standard reconnection geometry of Nilson *et al.* or potentially a novel setup that optimizes the field strengths, radiation, or pairs produced. In the standard experimental geometry extremely high intensity lasers interacting with solid foils will accelerate highly magnetized electrons along the surface of the target. The electrons heated by one laser will interact with those from the other laser. Each extreme intensity laser pulse (>10^{23} W/cm^2) will reflect from the target, constructively interfering, allowing for the interaction of strong fields with the accelerated electrons, thereby generating photons [12]. These photons will also enter the reconnection layer, potentially affecting the dynamics of the reconnection. Due to the extreme intensities necessary to accelerate protons to relativistic energies, the reconnection should be driven almost entirely by electrons. This “electron-only” reconnection was observed recently in the turbulent plasma of the earth’s magnetosheath and is theorized to be one of the main energy dissipation mechanisms in these turbulent systems [13].

Tools required

The highest energy reconnection experiments have only reached the threshold for semi-relativistic reconnection at intensities of 10^{19} W/cm^2 [7]. Reaching a regime where radiation becomes important in the standard geometry will likely require two multi-petawatt beams with intensities >10^{23} W/cm^2. Diagnosing this experiment will involve the measurement of particle and x-ray spectra along with imaging of fields on the target surface. Signatures of reconnection may be on the order of shot-to-shot fluctuations, therefore large datasets may be necessary to average over these fluctuations. A facility that can take a shot every few minutes would then be ideal. Previous reconnection experiments have imaged surface fields using proton radiography from target-normal sheath accelerated or capsule implosion generated protons [5, 14]. At the very large magnetic field strengths $\vartheta(0.1\ \mathrm{MT})$ expected, the $\vartheta(10\ \mathrm{MeV})$ protons will see large deflections creating caustics, thereby stopping us from using standard radiography analysis techniques [15]. Higher energy particles are required to prevent caustic formation. Producing these particle beams will require another high-intensity laser, for a total of three high-intensity beams used for this experiment. Additional diagnostics may include shadowgraphy to look at jet formation, or copper K-α imaging to look at energy deposition.

Scientific Impacts

Successful and rigorous characterization of a reconnection experiment in the radiative, or even in the relativistic regime will be very impactful to the field of Astrophysics. Current reconnection theory in these high-energy regimes is based on the observation of the radiation produced by extremely energetic astrophysical bodies. Having a source of data that can be diagnosed in greater detail may provide validation of these theories and the many simulations that have been used to support them. In particular, the measurement of particle and radiation spectra, reconnection rates, and the structure of the reconnection layer would be impactful.

Broader Impacts

This experiment could provide the basis for many other studies where large magnetic fields and photons are used e.g. relativistic turbulence, relativistic bow shock formation.

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MP3 White Paper 2021

Title: Enhanced laser coupling, matter heating, and particle acceleration by multiplexing PetaWatt-class lasers

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Abstract: The next generation of multi-PetaWatt-class lasers are, and will be, a combination of several beamlines, e.g., the XCELS project in Russia [1], the SULF project in China [2], or the iCAN project [3]. The overlapping of these spatially separated beamlines is inevitable and may affect the laser energy coupling [4-6]. We have been investigating, in a proof-of-principle experiment performed at the Target Area West (TAW) of the Rutherford Appleton Laboratory (RAL) Vulcan laser facility, that by overlapping two intense laser beams in a mirror-like configuration, i.e. having them irradiate symmetrically a solid target front surface, that the hot-electron beam (HEB) generation at the target front is well enhanced and that the ion acceleration at the rear side of the target is also improved (both in their maximum energy and collimation). The underlying mechanism is pinpointed with three-dimensional Particle-in-Cell simulations, which show that magnetic reconnection is induced at the target front (by the self-generated magnetic fields) when the two beams are close enough to each other and that this plays a major role in the HEB generation enhancement. Our simulations show that further enhancement of the laser energy coupling can be expected when overlapping more beamlines. Such a scheme would be highly beneficial to the multi-PW project proposed at LLE.

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Performance metrics for laser-electron colliders to aid design and discovery

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Abstract (<251 words)

We propose to develop and evaluate performance metrics that quantify facilities'/experiments' capability to generate signals of strong-field QED focusing on dependence on electron and laser beam characteristics. These performance metrics facilitate optimizing facility capability given fixed or maximum laser parameters. The optimum is often nontrivial: preliminary simulations have shown that for some facilities stronger focusing is not always better, but instead moderate or weak focusing yields more electrons with higher probability of generating QED events. Performance metrics will enable more consistent and unified planning and design of facilities and experiments as well as more efficient use of resources. Looking ahead, they provide a necessary, more quantitative basis for design search for rarer, more difficult to measure processes, such as photon-photon scattering or axion interactions, expected to be made more accessible with high-intensity lasers.

Total <3pgs (not counting references)

Scientific goal

Recent high-intensity laser facilities and facility upgrades have been undertaken with the goal of experimenting in the strong-field regime of quantum electrodynamics (QED), as characterized by the Lorentz invariant parameter $\chi = \left|p_{\mu} eF^{\mu\nu}\right| \hbar/m^{3}c > 1$chi=peF/m^3>1, which combines the electron 4-momentum p^{μ} with the electromagnetic field strength. Designs are based on maximizing χ, since the probabilities of QED processes increase with χ [1,2]. We support this community goal with more quantitative and refined measures of facility performance, that take into account electron and laser beam characteristics [3]. For example, a facility providing an electron beam with greater charge or at a higher repetition rate will deliver more nonlinear Compton photons and more electron-positron pairs than a facility with lower beam charge or repetition rate when run for the same amount of time. By introducing quantitative metrics for this capability to generate signals of strong-field QED, we can compare advantages and refine experimental designs to maximize the capability to discover and measure the uniquely strong-field phenomena.

The performance metric is defined from generic characteristics of a laser pulse-electron beam collision, and in general must be evaluated using numerical Monte Carlo simulation to account for the electron dynamics in the laser field. Any effort to systematically improve the design and performance of the laser facilities and experiments must be supported by accurate and thorough measurements of the laser pulse and electron beam.

Tools and Theory Development

The primary tools for evaluating the performance metrics are 1) rigorous theory of the QED event probabilities and 2) numerical Monte Carlo simulations implementing those event probabilities. The stochastic nature of the QED events combined with nontrivial electron dynamics in a focused laser field require that we compute numerically the expected number of events for a given set of initial electron and laser initial conditions. Since the electron beam is in practice described by a distribution, a Monte Carlo approach is suited to construct the distribution of expected events. The event probabilities in the Monte Carlo algorithm are necessarily approximated and must be founded on a rigorous relation of analytic theoretical calculations to practical separations of the classical trajectory and the quantized radiation event.

To appreciate the utility of such a tool, consider that some parameters of a facility have limited variability or have a maximum fixed by design, such as total pulse energy. To use the facility most effectively, we should then ask, given fixed pulse energy, do we deliver more QED events with stronger focusing to achieve a higher field in a smaller focal volume or with weaker focusing to have a larger focal volume to interact with more electrons?

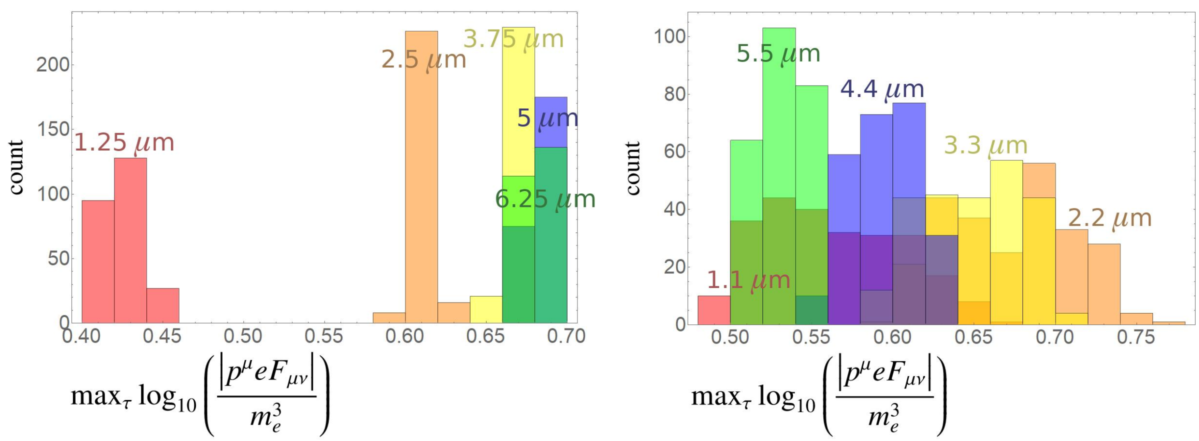

Figure 1. *Histograms of the number of electrons achieving a given maximum χ during their interaction with the laser field. The electrons all counter-propagating with energy 400 MeV and are uniformly distributed in a cylinder of radius 2 μm around the laser axis. The different colors present different laser spot sizes. At left, a laser modeled after the Texas Petawatt (TPW) [4[: 1 micron wavelength, pulse energy 150 J, pulse duration 150 fs and spot sizes ranging from approximately f/1.5 final focusing to f/7. At right, a laser modeled after Arcturus [5]: wavelength 800 nm, pulse energy 7 J, pulse duration, 30 fs.*

In Figure 1, we see that optimizing the use of the laser pulse energy at the TPW and Arcturus calls for moderate or weak focusing. At Arcturus, ~f/3 focusing results in the largest number of electrons achieving the highest χ, whereas at TPW, weak focusing (~f/7) achieves the same goal. This outcome might have been expected considering that the electron beam is larger than the smallest spot size, so that some electrons are not aligned with the region of peak intensity. More interestingly, the electron trajectories diverge from the axis enough--even in the 30-fs pulse--that strongest focusing does not yield the highest achieved χ. Other simulations show that these outcomes vary significantly from facility to facility; different combinations of pulse energy, duration and spot size reveal different optimums. For example we should also ask which is more advantageous for discovery: a broad distribution of electrons with only a few reaching higher χ, or a narrow distribution with all electrons achieving the same more moderate χ? Which will yield the greater number of QED events or the most easily distinguishable signal? We propose to develop metrics to help decide these questions.

Such performance metrics will only be usefully quantitative and accurate to the extent that the facility parameters entering the simulations are accurate and useful characterizations. Therefore, facilities must be able to measure the laser pulse and electron beam parameters accurately and consistently. Many measurements of laser pulse parameters present great technical challenges, which should anyway be addressed: for example, knowing the focal spot size is essential not only to accurate evaluation of the laser field strengths in the focal region but also achieving good laser pulse-electron beam overlap.

Scientific Impact

Creating performance metrics and evaluating the capabilities of a particular laser facility and experimental design enables more consistent and unified planning and more efficient use of resources. Computing the expected number of events and measuring experiments provides clearer more quantitative guidance for design processes and allows the search for rarer, more difficult to measure processes, such as photon-photon scattering or axion interactions, expected to be made more accessible with high-intensity lasers.

Broader Impact

This approach is similar to metrics such as luminosity used in high-energy particle physics to evaluate facilities and quantity the physics “reach” of the facility. We anticipate being able to measure progress towards specific physics goals by extending the metrics to estimate the amount of relevant data accumulated, especially towards rarer processes. In these ways, performance metrics will greatly enhance communication with both funding agencies and other physics communities (e.g. high-energy particle physics or astrophysics) that may have an interest in the lab-based discoveries possible with high-intensity lasers.

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Extra text

At present, best-available theory work suggests the local constant field approximation for evaluating the QED event probabilities is accurate in the high-intensity (a0=eE/m omega>>1) regime.

Recent theory work suggests that the local constant field approximation for evaluating the QED event probabilities is accurate in the high-intensity (a0=eE/m omega>>1) regime. The electron momentum and the local value of the electromagnetic field strength vary over a single laser cycle and of course over the electron's traversal of the laser field, requiring that the electron trajectory be solved in between QED events.

Photon-photon scattering in a plane-wave background

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1 Abstract:

Recently, two of the authors used the worldline formalism to derive a master formula for the one-loop N-photon amplitudes in a plane-wave background in quantum electrodynamics. We propose to use this result for a first calculation of the photon-photon scattering cross section in such a background to explore possible observable signals in upcoming laser experiments.

2 Scientific goal:

The goal of this project is to obtain a parameter-integral representation of the photon-photon scattering cross section in a general plane-wave field suitable for performing numerical studies of relevance for realistic laser experiments. Although the plane-wave field, defined by $eA_\mu(x) = a_\mu(n \cdot x)$ with a null-vector n^μ, is one of the few field configurations that allows for a non-perturbative treatment in strong-field QED (see, e.g., [1, 2]), beyond the simplest special cases such calculations tend to be extremely lengthy and tedious [3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. For example, the one-loop QED mass and polarisation operators [21] and vertex [22] in a plane-wave field have been calculated only very recently.

Building on previous work by A. Ilderton and G. Torgrimsson for the vacuum-polarisation case [23, 24], two of the authors recently derived a master formula for the one-loop N-photon amplitudes in a plane-wave background in quantum electrodynamics [25]. The formula is based on Feynman's worldline path-integral representation of these amplitudes [26, 27, 28, 29, 30, 31, 32], which in strong-field QED has already been extensively used for photonic processes in constant-field backgrounds [30, 33, 34, 35, 36, 37] and uses the peculiar kinematics of the plane-wave background in light-front gauge $n \cdot a = 0$ to reduce the path integration to a gaussian one. The characteristics of the plane-wave field then enter only through a few integral quantities involving the values of a^μ along the semi-classical trajectory.

For our present purposes, we must expand the master formulas for $N = 4$, which is a straightforward programming exercise. Since for this case the master formula is manifestly free of UV and IR singularities, we expect to obtain a parameter integral representation for the cross section suitable for numerical integration without any essential restrictions on the plane-wave background.

3 Tools required:

The project requires only standard hardware and MATHEMATICA programming.

4 Scientific impact:

Contrary to the impressive successes of perturbation theory in vacuum QED, in the strong-field QED community there has been a growing sentiment of the inadequacy of existing methods for performing loop-level calculations in the complicated types of electromagnetic fields involved in experiments at existing and future laser facilities. With the present calculation, we hope to draw the attention of this community to the potential of the worldline formalism, already recognised for its efficiency in vacuum and constant electromagnetic backgrounds, for improving on the more established Feynman-diagrammatic and operatorial formalisms beyond the well-studied constant-field case.

5 Broader impacts:

This project is part of a long-term effort to use methods originally developed in the context of string-theory to improve on the efficiency of the perturbative calculation of amplitudes and effective actions in gauge theory and gravitation.

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MP3 White Paper 2021
Title: Extreme THz Pulse Generation and Interaction with Matter

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Abstract: Even the THz radiation has been used as a condensed matter diagnostic and industrial tool for decades [1], but THz pulse energy and peak power has typically been extremely weak in comparison with other more common types of radiation, such as IR and visible light, restricting the utility of THz radiation for basic science [2]. Recent advances in ultrafast laser-driven THz generation have changed this paradigm [5,6,7,9]. Using lasers with intensity above 10^{18} W/cm^2 as drivers, laser to THz conversion efficiency exceeding 0.1% can be achieved with solid targets, [6, 7] and gaseous targets may reach an order of magnitude beyond that given the proper laser conditions [9]. Thus, Joule-class THz pulses can be generated using kJ class lasers. Focusing these joule level THz pulses onto solid, liquid and gas targets will open up a new regime of relativistic optics [2,3,4,6]. Due to the inverse scaling of the laser strength parameter a_0 with wavelength, a THz pulse only requires ~10^{14} W/cm^2 to enter the relativistic regime, compared to >10^{18} W/cm^2 that is needed for optical radiation. The long wavelength of THz radiation combined with the extremely fast (< 1 ps) drive laser also results in single or even half-cycle THz pulse from the target. This extreme region of relativistic optics has never been explored and has the potential to benefit charged particle manipulation [10,14,15], offer insight into phonon and carrier dynamics [8, 13], and generate never before seen relativistic optical phenomena such as THz induced transparency [2,3,4,6,16].

Scientific goal: Extreme THz-matter physics is a new field with few experiments having been performed and almost none in the relativistic regime [7]. The scientific goal of this project is to develop an experimental platform to drive relativistic THz-matter interactions and begin exploring this frontier area. Similar work with high-powered mid-infrared lasers already indicates that interesting relativistic optical phenomena should emerge with THz radiation at relativistic intensities [11]. Previous work with lower intensity THz pulses have already shown promising results for non-linear THz-matter interaction experiments [6], charged particle acceleration [10, 14,15], and THz pump/probe experiments [13].

Tools required: Recent laser-plasma THz generation experiments have shown generation efficiency on the order of 0.1% or greater [5,6,7,9], with THz generation efficiency scaling with the laser pulse. We require a multi-PW, kJ class, <500 fsec laser with the ability to reach intensities exceeding 10^{20} W/cm^2 on target. It is also preferable if this laser driver has both a high repetition rate to allow the use of sampling method and the ability to pick off a small portion of the beam to be used in an electro-optical THz detector. Electro-optical THz detection techniques are the premier method of coherent THz detection and require synchronized fs-scale laser beams to operate and provide spectral information [1]. The co-location of this beam with other state-of-the-art laser facility diagnostics will be required to provide x-ray, optical, and charged particle information during the experiments. Co-location with a ns-pulse drive laser may also prove useful for performing non-linear THz studies of matter in extreme conditions after the platform has been fully developed. In addition, co-location with an x-ray free electron laser would be valuable for the study of non-linear THz-matter interactions using x-ray diffraction as a probe. An even more ideal facility would provide two multi-PW, kJ class beams so that multi-beam generation techniques can be employed, or to provide an avenue for interacting THz pulses with short pulse laser generated charged particle beams.

Scientific impact(s): Relativistic THz-matter interactions would open up an entirely new field of relativistic optics to explore [2,3,4,6]. The longer time and length-scales of THz electric fields compared to optical lasers allow for single or even half-cycle relativistic laser interactions to be much more easily generated than with traditional optical pulses, adding to the scientific utility and uniqueness of high-intensity THz sources. Interacting intense THz pulses with matter transitions the typical linear THz dynamics that are commonly studied [12] into a non-linear regime. Non-linear THz-matter interaction experiments provide insight into both carrier dynamics and phonon dynamics [8,13], and have the potential to directly move nuclei and induce phase changes in materials. These extremely intense THz sources not only are useful for basic research, but can be used to control or generate beams of charged particles [10]. THz driven waveguides can be used to generate very intense, short and monochromatic pulses of electrons which are useful for performing ultrafast electron diffraction [14]. They also can be used to bunch or chirp [15] charged particle beams generated via other means, such as laser wakefield acceleration.

Broader impacts: Relativistic THz-matter interactions may prove to be a crucial probe to help understand carrier and phonon dynamics [8,12,13] in important materials such as high-temperature superconductors. Weak THz pulses are already used to study superconductors and adding more diagnostic capability will only improve results. Powerful THz pulses also have potential interest in biological applications [17] and as probes of magnetic fields in fusion reactors [18]. In addition, the use of THz radiation to accelerate and manipulate charged particles [10,14,15] has the potential to improve both current and future particle accelerators for scientific, medical and industrial use. Combining powerful THz pulses for bunch control with the short acceleration distances of laser wakefield acceleration may prove to be a powerful way to transition PW-laser-driven electron beams out of the lab and into active use.

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Astrophysical analogues of laser-plasma interaction

1. COHERENT EMISSION IN PULSARS AND FAST RADIO BURSTS

Relativistic astrophysical sources, primarily neutron stars, produce high brightness coherent emission. Pulsar emission mechanisms remain illusive for more than half a century (Goldreich & Keeley 1971; Ruderman & Sutherland 1975; Cheng & Ruderman 1977; Beskin et al. 1988; Melrose 1992; Melrose & Gedalin 1999; Melrose 2000; Lyutikov et al. 1999; Melrose 2017; Beskin 2018). Discoveries related to Fast Radio Bursts (Petroff et al. 2019; Cordes & Chatterjee 2019) renewed interest in production of coherent emission in compact objects.

Fast Radio Bursts (FRBs) are millisecond-long bursts of radio emission coming half way across the universe (Petroff et al. 2019; Cordes & Chatterjee 2019). Taken at face value (so that duration is indicative of the size), the corresponding laser nonlinearity parameter $a_0 \sim 10^6$ is in the millions (Luan & Goldreich 2014; Lyutikov et al. 2016). In this regime a number of new effects appear, *e.g.* non-linear Thomson scattering, large parallel ponderomotive force from a laser pulse, and large radiative losses. Both the transverse and parallel Lorentz factors become large in such waves $\sim a_0$.

Simultaneous observations of radio and X-ray bursts coming from a magnetar (highly magnetized neutron stars with magnetic fields of the order of critical quantum field CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020; Mereghetti et al. 2020) point to magnetospheric origin of FRBs *loci*. Observations of FRBs from magnetars are consistent with the concept that radio and X-ray bursts are generated during reconnection events, by accompanying relativistic jets, within the magnetospheres of magnetars.

Magnetic fields in magnetars exceed the quantum magnetic field (Thompson & Duncan 1995). Interaction of high intensity pulse with magnetospheric plasma of magnetars will proceed in an unusual regime of guide-field dominance, so that the frequency of electromagnetic waves is much smaller than the cyclotron frequency associated with the guide field, $\omega \ll \omega_B$. This is a new, mostly unexplored regime of laser-plasma interaction. In this regime the relevant parameter is the ratio of the fluctuating laser field B_w to the guide field B_0

$$a_H = \frac{B_w}{B_0} \leq 1 \tag{1}$$

Qualitatively, a charge in a wave is accelerated on time scales $\sim 1/\omega_B$ instead of $\sim 1/\omega$ (Lyutikov 2021).

2. LIGHT DARTS: PARTICLE INTERACTION WITH RELATIVISTIC ALFVEN WAVES

In addition to interaction with radiation escaping from astrophysical sources, laser-plasma experiments may shed light on interaction of relativistic Alfvén waves with particles. In plasmas of pulsars and magnetars the Alfvén velocity is relativistic, so Alfvén waves becomes a nearly vacuum wave, resembling laser pulses. For a mildly non-linear Alfvén wave with a wave length of the order of the neutron star radius in quantum magnetic field the laser intensity parameter becomes a staggering

$$a_A \sim \frac{R_{NS} m_e c}{2\pi\hbar} = 4 \times 10^{15} \tag{2}$$

(Lyutikov 2021).

Collision of such Alfvén waves may also lead to plasma break-down: formation of regions with electric field larger than magnetic field, and ensuing dissipation and particle acceleration (TenBarge et al. 2021)

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Ultrafast phase transformation studies in planetary materials to terapascal pressures using x-ray and electron diffraction

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White paper for the MP3 working group on laboratory astrophysics (LAP)

ABSTRACT

The structures that major planetary constituents (e.g., silicates, oxides, iron, hydrogen, and ices) adopt as they are compressed to the crushing pressures deep beneath the surface towards the core play a significant role in the planet's interior dynamics, heat flow, and evolution. Experimental measurements of phase transitions (solid-solid, freezing, and melting) in these materials to terapascal pressures (1 TPa = 10 Mbar) are vital to our understanding planetary interiors within and outside of our solar system. These experiments require state-of-the-art high-energy-density drivers (such as high power lasers or pulsed-power machines) to carefully tune the pressure-temperature path of the material upon compression to the relevant conditions and an *in situ* probe to elicit information about the transient ultra-dense high-pressure structure. Diffraction by up to ∼MeV electrons or ∼20-100 keV x-rays would provide information about the long-range order of these phases. This white paper describes using x rays or electrons generated using laser wakefield acceleration by a multi-PW short pulse laser to perform femtosecond diffraction of compressed astrophysical materials.

SCIENTIFIC GOAL

The scientific goal is to unambiguously determine the structures from measured diffraction of the complex highly-coordinated phases of planetary materials that are predicted to exist in exoplanet interiors [1, 2]. Complex solid or liquid structures having significant long range order are not easily detected using diffraction by current x-ray sources because of the limited Q range ($Q = 4\pi sin\theta/\lambda$) of the data, which is dictated by the radiation source energy and detector coverage. Many planetary materials, such as silicates and ices (e.g., water, ammonia, methane), have relatively low Z, making them poor scatterers and necessitating higher flux probes to obtain good quality diffraction data with acceptable signal-to-noise above the background and resolution of the diffraction peaks. Short-duration (femtosecond) high-energy electron (∼100 keV to MeV) or x-ray (∼100 keV) probes, such as those generated via laser wakefield acceleration (LFWA) by ultra-short high-intensity lasers [3], could be used to unravel the complex structure of liquids or the long-range coordinated solids at extreme compressions.

TOOLS REQUIRED

Recent advancements in generating these radiation sources using LWFA have led to the possibility of using them for diffraction [4, 5]. A major advantage of these LWFA-based sources is the high flux over short femtosecond time scales. We require an LWFA-driven electron or x-ray (from betatron or Compton scattering processes [3, 4]) probe beam coupled to a TW long-pulse (>30 ns) laser with precise pulse shaping capabilities to ramp, shock, or shock-ramp compress the materials. The colocation of the multi-PW short pulse laser with long pulse drive lasers is critical for using this technique to study planetary materials at the pressures, densities, and temperatures needed to make a meaningful impact on our understanding and modeling of terrestrial and gas giant planets. This LFWA-based configuration may be advantageous when PW short pulse lasers, but not x-ray free electron lasers (XFELs) or synchrotron sources having 10's of keV energy, are colocated with the required long-pulse lasers drivers.

The beam should be quasimonochromatic (δE/E $\approx$ 1) and have a duration of several femtoseconds [4]. Approximate requirements for the electron beam are energies of $\sim$100 keV to several MeV, a divergence of $<0.1^\circ$, and flux of $\sim$1 pC/pulse. Significant efforts towards target design and development will be necessary because the electron probe has a short penetration depth and interacts very strongly with the target. Collimation of the electron beam to obtain the desired energy and spot size may be required [6]. The x-ray beam should have energy of several 10's to 100 keV to investigate the long-range coordination and $>10^{11}$ photons/pulse to be competitive with XFELs.

SCIENTIFIC IMPACT

Diffraction using up to MeV electrons or 100 keV x rays would allow us to understand the level of complexity of long-range coordinated systems at high pressure. This capability is extremely important for planetary materials because their stable phases become increasingly complex with pressure and significantly affect the planet's interior dynamics, heat flow, and evolution [2]. These new techniques can help unravel the complex structures of ultradense solids and liquids under pressure that are currently unsettled because of insufficient signal or Q-range [7]. This capability will also provide insight to the amorphous structures of liquids under pressure, where a large Q-range of the measured diffraction data is needed in order to resolve its radial distribution function and extract quantitative information such as coordination number and density [8]. The properties of compressed gases at high pressure, such as hydrogen and helium that are critically important to understanding Jupiter, Saturn, and potentially other gas-giant exoplanets [9], can be probed using electron diffraction, which is not possible using x-ray diffraction [10].

Femtosecond electron diffraction of materials may change the way we think about phase transformations, including the nucleation and growth model, and dislocations and deformation mechanisms. Ultrafast electron diffraction can be used to probe structural dynamics of on the fundamental timescale of phonon vibrations ($\sim$100fs to 1 ps) [11], giving us insight into how atoms rearrange in real time.

BROADER IMPACTS

High-temperature superconducting materials (e.g., rare-Earth metal superhydrides [12] and carbonaceous sulfur hydrides [13]) have long range order that could be probed using these techniques to better understand their unusual behavior. Characterization of the local electronic structure and coordination of these hydrogen-rich materials at high pressure are very important but extremely challenging [13]. Recent studies have noted that they cannot currently rely on x-ray diffraction to determine the structure under pressure because the heavier nuclei dominate the diffraction signal for the rare-Earth metal superhydrides and the C-S-H systems are poor scatterers [12]. Higher flux x-ray probes or more sensitive electron diffraction probes could be beneficial in these areas.

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Multi-Petawatt Laser Systems to Interrogate Matter at Atomic Pressures

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Abstract: The interiors of planets and stars are dominated by conditions of pressure that are so strong they alter the nature of atoms. To understand the origin, nature, and evolution of these planets, the properties of high energy density matter must be known. Multi-Petawatt Laser systems will allow us to use direct or indirect drive techniques to access pressures higher than those currently available using shock, and ramp compression techniques, and employ advanced diagnostics including: femtosecond x-ray and electron diffraction, spectroscopy, and broadband reflectivity. This will enable the experimental study of matter under the unchartered extreme pressures at which most of the known mass in the universe resides.

Scientific goals: The quantum unit of pressure, 29.4 TPa, is the pressure required to disrupt the shell structure of atoms, engage core electrons in bonding, and unlock a new regime where correlations of electrons and ions can grow to the macroscale at high temperatures. Most of the recently discovered extrasolar planets and stars have internal pressures approaching or exceeding such conditions. First-principles based predictions have suggested remarkable behavior of matter at these conditions including transforming simple metals into transparent insulators, the generation of superionic phases such in water, hot superconductivity, unexplained bonding in dense plasmas and more. Herein, we describe how advances in multi-petawatt laser will allow researchers to explore the behavior of matter at such extreme pressures, and how this will make it possible for scientists to model and understand the behavior of our own planet as well as that of exoplanets. The pressure of planetary cores in our solar system are listed in Figure 1.

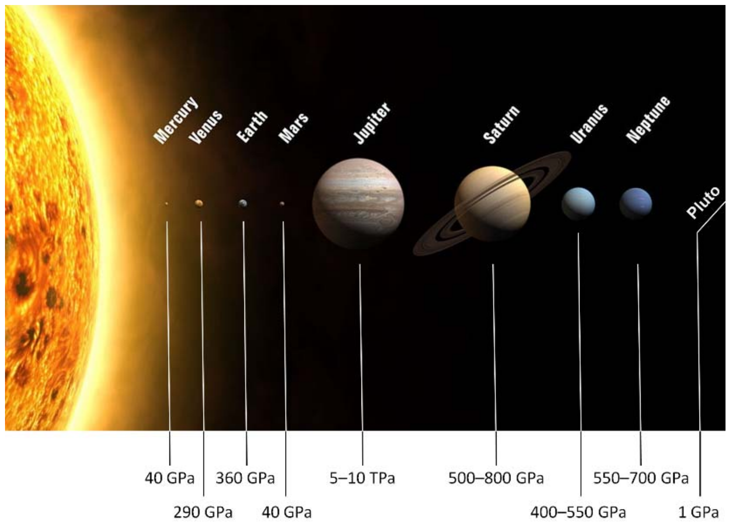

Figure 1: The pressures of the planetary cores in our solar system. In the universe pressure spans over an astounding sixty orders of magnitude, from the pressure in intergalactic space (10^{-32} atm) to the center of a neutron star (10^{32} atm).

Dense hydrogen, helium, and their miscibility: Hydrogen is the most abundant element in the universe, and the major constituent of giant planets and stars, yet its behavior at extreme densities is extremely challenging to study both theoretically and experimentally. Unsolved predictions for hydrogen include a high-temperature superconducting phase, a dense plasma ground state, and Wigner crystallization. Mixing/demixing regions of H-He mixtures, and the equation of states (EOS) of H-He is important for Jupiter and Saturn interior conditions and a central question in the evolution of giant planets. The high-temperature plasma state of hydrogen isotopes is of relevance not only to the large radii of extrasolar gas giants, but also in inertial confinement fusion. Because there is no systematic way to improve density functional theory calculations, a challenge for theory for the past decade is the accurate and reliable description of hydrogen. One way forward is to combine recent meta-GGA functionals with path-integral molecular dynamics quantum simulations for the ions. However, the only way to test the applicability of this method is to compare the calculated EOS with reliable experiments.

Atoms and molecules at atomic pressure: Both theory and experiments are revealing that molecules and their mixtures at extreme pressures exhibit entirely new and unprecedented behavior. They illustrate that the long-held belief that all matter, when sufficiently compressed, will assume a Thomas-Fermi-Dirac state where a sea of electrons surrounds ionic cores, and simple compact structures are assumed, is too simple. Elements that are metallic at 1 atm may become insulating with accumulation of charge in interstitial regions, which can be thought of as "quasi-atoms", the energy ordering of atomic orbitals is affected so that normally unoccupied orbitals become valence, and core or semi-core orbitals mix with the valence states. This allows core electrons to participate in bonding, and atoms may assume unprecedented oxidation states. We propose to carry out systematic experiments to uncover the potentially complex phases and electronic structures assumed by elements under pressure, determine bonding rules for compressed matter, and construct a catalog of potential compounds of planet interiors.

Because currently most first-principles based crystal structure prediction techniques map out the 0 K potential energy surface, they may not locate the most stable phases at high pressures and high temperatures. Therefore, comparison of theory and experiments will lead to theoretical developments that can be used to predict the structures assumed within the hot and dense planetary interiors. The study of dense plasmas and their mixtures will let us determine the constituents of ice-giant planets, determine this effect on planetary dynamos, and discover the chemistry between water and rocky planet materials at extreme conditions. Furthermore, we will interrogate the EOS of terrestrial constituents.

Transport at atomic scale pressure: Transport in extreme matter encompasses all forms of micro- and macrophysical changes related to the flow of charge, mass, energy, and momentum. Reflectivity measurements will be employed to map the transport and localization of electrons to atomic pressures. We will measure the thermal conductivity of dense iron, iron alloys, and select silicates at conditions relevant to understanding heat flow from the core, estimated age, and thermal evolution of Earth to super-Earths. The effects of extreme density on radiation transport in dense plasmas will be measured, and the results employed to benchmark theory. New methodologies for measuring opacities and viscosity will be developed.

Tools required: In order to achieve the highest possible pressures we will use a combination of long-pulse laser drives together with the highest-intensity laser drives. Long pulse beams will ramp-compress the sample up to ~100s Mbar. At relativistic laser intensities, the expected laser-drive ablation pressure is $P_L = 330\ \frac{I\,\lambda_{\mu m}^2}{10^{18}}$ Mbar. To minimize hot-electron pre-heating, the laser must be circularly polarized operating at the third harmonic. At $I > 10^{20}$ W/cm^2, we expect $P_L > 3$ Gbar (300 TPa) and at $I > 10^{23}$ W/cm^2, we expect $P_L > 3$ Tbar (300 PPa) – comparable to the pressure found in the interior of main-sequence stars. Advanced diagnostics will be developed to take advantage of the femtosecond x-ray and electron beams with simultaneous velocimetry, reflectivity, and spectroscopy.

Scientific impact(s): Achieving these scientific goals will allow us to produce state of the art next generation planetary models across all planetary types. It will allow us to study the formation, evolution, interior structure, and magnetic fields of planets within our own solar system, as well as that of the thousands of known exoplanets with their huge diversity in mass, radius, and orbital semi-major axes. Moreover, it will lead to the creation of revolutionary states of matter such as hot superconductors.

Broader impacts: The findings will have a fundamental impact in the field of chemistry, where it is traditionally assumed that only valence electrons are involved in chemical bonding. The stoichiometries, compositions and structures assumed under pressure are totally different than those that are found at 1 atmosphere. This research will lead to the development of periodic tables for specific pressure regimes. The research is also of great relevance to various materials-science and energy related research, for example some of the hydrogen-rich materials that are studied may exhibit superconductivity above room-temperature, and others could be topological insulators. The experimental observables will be used to benchmark theoretical developments in next-generation density functionals, methods that can be employed to treat anharmonic and quantum nuclear effects, and evolve crystal structure prediction techniques so they may be used at finite temperatures.

Moreover, the matter states to be explored is within the parameter range of the envelope of white dwarf stars. Whether these envelopes are in a glassy or crystalline state depends crucially on the details of the EOS at multi-TPa pressures. The existence of a glassy state in white dwarfs would affect their thermal conductivity and overall luminosity. A precise characterization of white dwarf crystallization has, on the other hand, important implication for cosmochronology, as the star luminosity is used to determine the age of the halo and disk in galaxies, and it is calibrated against other standard candles methods. In fact, the change of luminosity on old white dwarfs in the globular cluster NGC 6397 has been interpreted as the release of the latent heat of crystallization, but other effects such as phase separation of carbon and oxygen may also play an important role.

Discussion of XFELs & Laser-Driven FELs

Petawatt Laser Initiative

X-ray Free-Electron Lasers (XFELs) have become important research tools since the first operation of the Linac Coherent Light Source in 2009 [1]. Since that time, as shown in Table 1, XEL facilities have been built in Germany, Japan, Korea, Switzerland, Italy and China [2-10]. Many of these facilities are characterized by low repetition rates which limit the number of user experiments that can be performed in any given time window. Newer facilities characterized by high repetition rates are currently being built, or designed, which employ superconducting radio-frequency linear accelerators which require substantial cryogenic plants, but will greatly expand the number of experiments that will be supported. However, one feature that all of these facilities have in common is that the "buy in" cost is measured in the billions of dollars. As a result, these are nation-scale facilities and the number of XFELs based on these technologies cannot be expected to increase substantially from those shown in Table 1.

Facility	Country	Beam Energy (GeV)	Photon Energy (eV)	Rep Rate (Hz)
FLASH	Germany	0.35 – 1.25	14 – 620	$4 \times 10^3 - 10^6$
LCLS	USA	2.5 – 16.9	280 – 12800	120
SACLA	Japan	5.1 – 8.5	4000 – 20000	60
FERMI	Italy	1 – 1.5	20 – 310	50
PAL-XFEL	Korea	3.5 – 10	275 – 20000	60
SwissFEL	Swiss	2.1 – 5.8	250 – 1240	100
Euro XFEL	Germany	8.5 – 17.5	240 – 25000	2.7×10^4
SXFEL	China	1.0 – 1.6	124 – 1000	50
LCLS-II (HE)	USA	4 – 15	200 – 25000	$120/10^8$

Table 1: Summary of existing and planned XFELs worldwide.

The advantage conferred with XFELs over Synchrotron light sources is shown clearly in Fig. 1 [11]. It is clear from the figure that the brightness of the photon beams from XFELs is anywhere from 4 – 9 orders of magnitude higher than what is possible from Synchrotron light sources. As such, the use of XFELs opens up an entirely new range of experiments and will become increasingly in demand in a wide range of fields of study.

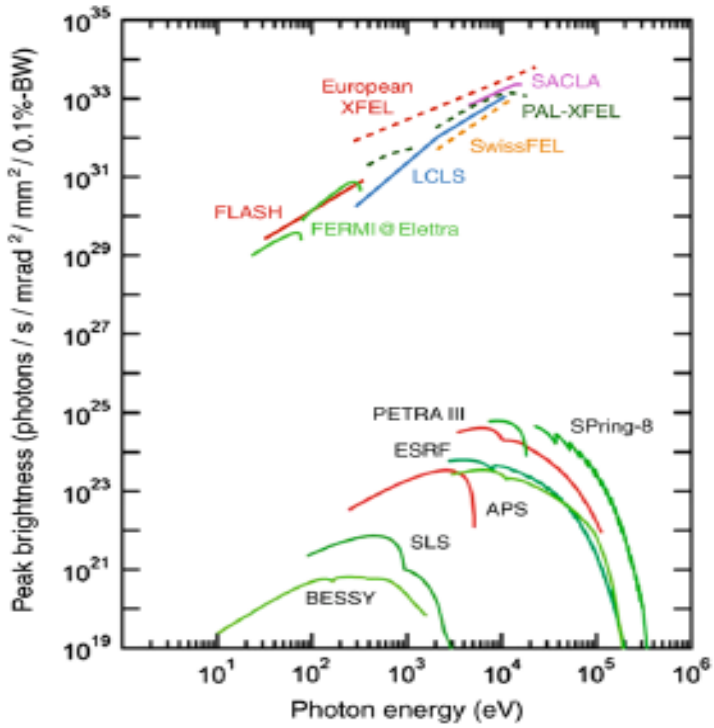

Fig. 1: Comparison of XFEL and Synchrotron light sources [11].

However, the high cost associated with the current generation of XFELs which rely on large radio-frequency linear accelerators introduces a bottleneck in the queue of researchers looking for time on these machines and lower cost alternative configurations would be a welcome addition to the mix of x-ray light sources. To that end research has been underway for many years on the development of laser-driven accelerators which could replace the radio-frequency linear accelerators in use today. The difficulty faced by developers of laser-based accelerators for use in FELs was the stringent requirements on the brightness of the electron beams required to drive short wavelength FELs. However, that limitation has been overcome in a recently published experiment where a laser wakefield accelerator has been used to drive a 27-nanometer wavelength FEL [12]. This experiment represents a breakthrough in the field, and we can be confident that, with consistent levels of support, that continued progress in laser wakefield accelerators will allow for their use in shorter and shorter wavelength FELs. While the lasers driving these accelerators are, typically, low repetition rate devices, the lower cost of these systems will permit the construction of a larger number of such XFEL facilities. As a result, this represents an important enabling technology which will allow us to address many of the fundamental physics questions posed byu the Petawatt Laser initiative.

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MP3 White Paper 2021

Title: "Colliding Relativistic Light-Sails accelerated by Multi-PW lasers"

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Abstract:

Two nano-foils are accelerated to near-relativistic energies towards one another by two counter-propagating Multi-PW lasers focused at ultrahigh intensity of ~ 10^{23} W/cm^2 on the two 'light-sails'. The laser Radiation Pressure will accelerate the 'light-sails' ions to energies of ~300MeV/nucleon. Such a collision could generate pressures of hundreds of TeraBar. Such high pressure collisions involving ions, electrons and photons could provide laboratory demonstration of Astrophysical Phenomena, Laser-Driven Nuclear Reactions and Quantum Electrodynamics.

Scientific goal: Experimental demonstration of matter behaviour at extreme pressures and temperatures for: Astrophysical Phenomena, Laser-Driven Nuclear Reactions and High Field Quantum Electrodynamics.

Tools required:

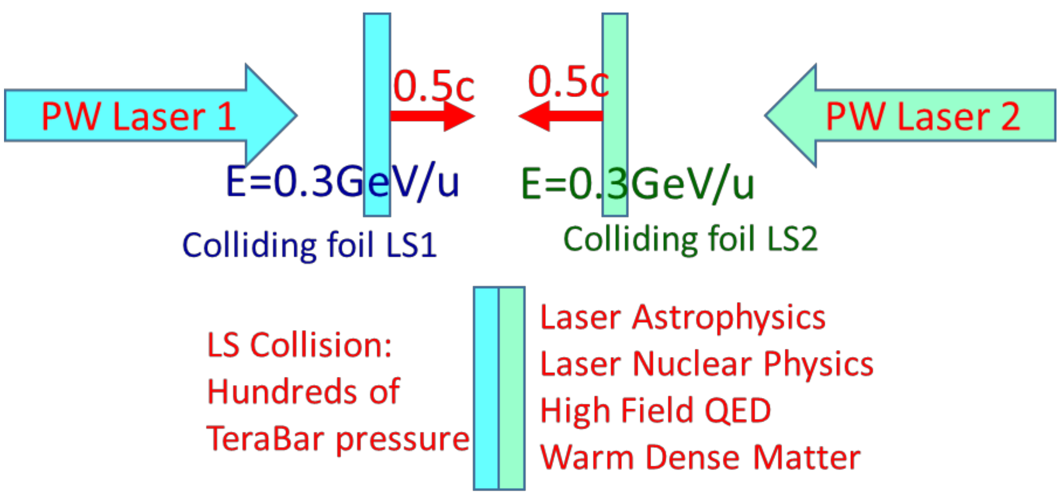

Fig. 1. High energy colliding foils, 'Light Sails=LS' driven by Multi-Petawatt lasers focused on nanometre-thick, micrometre-diameter solid foils at ultrahigh intensity.

The concept of colliding relativistic 'light sails' is described in Fig.1. The colliding light sails LS1 and LS2, are, for example, two nano-foils of thickness ~ t_{LS}~10nm, micrometre-diameter and solid density $\rho_{(LS)}$ ~ 1 g/cm^3. The light sails are accelerated to relativistic speeds by two colliding multi-Petawatt lasers L1 and L2 which are focused to ultra-high intensity $I_L=10^{23}$W/cm^2 on the light sails. It is predicted that a nano-foil irradiated with such ultra-high laser intensity will be accelerated to near-relativistic energies, as a whole, and the ions inside the nano-foil will reach energies of ~300MeV/nucleon, Ref.1. It is proposed to collide such relativistic 'light-sails' and the pressure developed is estimated at ~ several hundreds of TeraBar and possible collisional shocks could exceed ~1PetaBar = 10^{15} Bar. To note that the interaction will be quite complex involving colliding relativistic plasmas and high density of photons.

The laser pulses could be chosen such as to minimize the heating of the plasma in the Light-Sails and to maximize the Radiation-Pressure-Acceleration of the Light Sail: (a) circular polarization and (b) shorter wavelength, e.g. 400nm.

An example of a laser facility providing 10PW colliding pulses is the ELI-NP laser with two beams of 10PW which will be available in counter-propagating geometry. (Ref. 2 and 3)

Scientific impacts:

(i) Laboratory demonstration of Astrophysical Phenomena
(ii) Laboratory demonstration of nuclear reactions
(iii) Laboratory demonstration of High Field QED phenomena
(iv) Laboratory study of warm-dense matter

Broader impacts:

(i) Applications of laser produced nuclear reactions using proposed geometry
(ii) Applications of the intense radiation emitted by collisions between relativistic light-sails

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Petawatt Class Lasers for Realizing Optical Free-Electron Lasers with Traveling-Wave Thomson-Scattering

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Abstract

Traveling-Wave Thomson-Scattering (TWTS) is a scheme for the realization of optical free-electron lasers (OFELs) from the interaction of ultra-short, high-power laser pulses with relativistic electrons. The laser pulse thereby provides the undulator field which typically needs to include a few 100 to several 1000 undulator periods for OFEL operation. Such long optical undulators are realized in TWTS by the combination of a side-scattering geometry where electron and laser pulse propagation directions enclose the interaction angle ϕ and a laser pulse-front tilt $\alpha_{\mathrm{tilt}} = \phi/2$ of half the interaction angle. This combination of side-scattering and pulse-front tilt ensures continuous overlap of electrons and laser pulse during the passage of the electrons through the laser pulse. Interaction durations between laser pulse, electrons, and their emitted radiation can be long enough to initiate microbunching of the electron pulse and subsequent coherent amplification of radiation provided electron and laser pulse are of sufficient quality. Requirements on electron and laser pulse quality can be met for VUV TWTS OFELs with existing technology already today and higher power laser pulses enable TWTS OFELs at shorter wavelength, e. g. EUV TWTS OFELs.

1 Scientific Goal

Realization of a compact Free-Electron Laser by utilizing lasers as optical undulators.

2 Tools Required

The Traveling-Wave Thomson-Scattering geometry is depicted in Fig. 1.

Laser pulse diameters of a few centimeter in the interaction plane are required for OFEL operation and are available with multi-hundred terawatt and petawatt laser systems at laser intensities required for optical undulators.

Optimum spatial overlap of electrons and laser pulse is provided by focusing the laser pulse in the plane perpendicular to both propagation directions with a cylindrical mirror, the focal line of which is on the electron trajectory. Then all of the available laser photons interact with the electrons contrary to head-on Thomson scattering where laser defocusing reduces the overlap of laser and electrons ultimately limiting the available interaction distance [1]. Thus much longer interaction distances can be provided in TWTS setups increasing the photon output and reducing the radiation bandwidth leading to orders of magnitude higher brilliance of standard head-on Thomson sources [2].

Furthermore the variability of TWTS with respect to the interaction angle grants control over the scattered wavelength λ_{FEL} even if the electron energy $\gamma_0 m_e c^2$ is fixed by tuning the interaction angle and thereby changing the effective undulator period, see Fig. 2.

$$\lambda_{\mathrm{FEL}} \approx \lambda_{\mathrm{Laser}} \frac{(1 + a_0^2/2)}{2\gamma_0^2(1 - \cos\phi)} \,. \qquad (1)$$

A 1.5D analytical theory of the TWTS FEL shows that electron and radiation field dynamics in TWTS OFELs can be described equivalently to standard magnetic FELs. Consequently, microbunching and exponential gain is present in TWTS OFELs as in standard magnetic FELs [3].

A tilt of the laser pulse-front can be introduced by a grating. Yet, angular dispersion is introduced together with the tilt in the laser pulse which in turn distorts the pulse properties during propagation, i. e. while the laser pulse propagates to the interaction region and during the interaction. Since it is vital for TWTS OFEL operation that the field of the laser pulse resembles a monochromatic plane wave along the electron trajectory as close as possible, these pulse distortions need to be compensated. Pulse distortions can be compensated locally at the position of the electrons during interaction with an additional grating [4], see Fig. 3c.

Since electron and radiation field dynamics in TWTS OFELs can be described equivalently to standard FELs, results of standard FEL theory can be used to evaluate electron, laser and radiation beam requirements as well as expected performance of TWTS OFELs. Scaling laws for electron beam requirements in terms of energy spread, space charge parameter and normalized emittance as well as the requirement on the Rayleigh length of the radiation are applicable for TWTS OFELs [5]. These and more scaling laws regarding TWTS OFEL operation are summarized in tab. 1.

In the following examples the optical undulator is provided by a petawatt laser system operating at 1035 nm central wavelength and electrons are assumed to have an energy of 15 MeV(VUV) and 22 MeV(EUV) as well as a peak current of 0.8 kA(VUV) and 1.5 kA(EUV) for the VUV and EUV TWTS OFEL, respectively. The interaction angles are set to $\phi = 10.1°$(VUV) and $\phi = 12.1°$(EUV). Determining laser, electron and setup parameters of VUV and EUV TWTS OFELs requires to combine the scaling laws for the setup including focusing in the interaction plane given in Ref. [4] and the scaling laws for electron bunch and laser pulse requirements for TWTS OFELs given in Tab. 1. The final choice of electron and laser parameters is shown in Tab. 2

Table 3 lists the complete set of optical setup parameters and alignment tolerances for the VUV and EUV TWTS OFELs.

The presented example of a VUV TWTS OFEL utilized a laser system delivering pulses of one petawatt power. With higher power laser systems being available today, the VUV TWTS OFEL requirements on lab space as well as electron bunch and laser quality can be reduced or the radiation wavelength shortened.

A reduction of required lab space is achieved by allowing for a larger laser pulse oversize at the interaction point compared to the above example, i. e. increasing n_w from 1.12 to 2.24 if for example 2 PW laser pulses are available. Such an increase of a factor of two in available laser power translates to a reduction of effective focal distance by a factor of $\sqrt{2}$ due to the increase in input laser diameter becoming necessary to keep the areal energy density of the pulse constant.

This reduction in effective focal distance can be exploited to use setups at lower electron bunch peak current which have lower requirements on laser pulse quality. For instance, a lower optical undulator strength

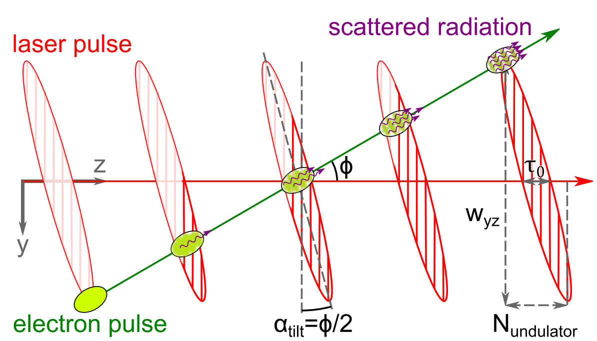


Figure 1: Depicts the Traveling-Wave Thomson-Scattering (TWTS) geometry where electron direction of motion and laser propagation direction enclose the interaction angle ϕ. The laser pulse-front tilt about the angle α_{tilt} ensures continuous overlap of electrons and laser pulse. The combination of side-scattering and laser pulse-front tilt in TWTS allows for the realization of optical undulators where the number of undulator periods $N_{\text{undulator}}$ is not limited by the laser pulse duration τ_0 but instead by the laser pulse width. With current petawatt class laser systems interaction distances long enough for microbunching of the electron pulse and thus coherent amplification of emitted radiation can be realized allowing for compact optical free-electron lasers (OFEL).

Table 1: Summary of the scaling laws used to estimate and tune the parameters of a TWTS OFEL setup. The columns from left to right name the parameter of interest and its scaling law. The table is subdivided into four parts corresponding from top to bottom to TWTS OFEL parameters, radiation parameters and requirements, electron bunch requirements, laser requirements and requirements on the optical setup, cf. Ref. [4].

Description	**Relation**
Optical undulator period	$\lambda_{\mathrm{und}} = \lambda_{\mathrm{Laser}}/(1-\beta_0\cos\phi)$
Radiated wavelength	$\lambda_{\mathrm{FEL}} = \frac{\lambda_{\mathrm{Laser}}(1+a_0^2/2+\gamma_0^2\phi_{\mathrm{sc}}^2)}{2\gamma_0^2(1-\beta_0\cos\phi)}$
Emission angle of coherent radiation for $\lambda_{\mathrm{FEL}} \ll \lambda_{\mathrm{Laser}}$	$\phi_{\mathrm{sc}} \approx \frac{\sin\phi}{2\gamma_0^2(1-\beta_0\cos\phi)}(1+a_0^2/2)$
Pierce parameter	$\rho = \left[\frac{1}{16\gamma_0^3}\frac{I_{\mathrm{p}}}{I_{\mathrm{A}}}\left(\frac{\lambda_{\mathrm{Laser}}a_0 f_{\mathrm{B}}}{2\pi\sigma_{\mathrm{b}}(1-\beta_0\cos\phi)}\right)^2\right]^{1/3}$
Gain length	$L_{\mathrm{G}} = \frac{\lambda_{\mathrm{Laser}}}{4\pi\sqrt{3}(1-\beta_0\cos\phi)\rho}$
Interaction distance	$L_{\mathrm{int}} \approx 16\cdot L_{\mathrm{g}}$
Radiated peak power	$P \approx \rho\gamma_0 mc^2 I_{\mathrm{p}}/e$
Radiation defocusing	$\frac{L_{\mathrm{G}}\lambda_{\mathrm{FEL}}}{4\pi\sigma_{\mathrm{b}}^2} < 1$
Walk-off	$\frac{L_{\mathrm{G}}\tan\phi_{\mathrm{sc}}}{2\sqrt{2}\sigma_{\mathrm{b}}} < 1$
Relative electron energy spread	$\frac{\Delta\gamma_0}{\gamma_0} \leq \rho$
Emittance limit from λ_{FEL} shift	$\epsilon_{\mathrm{N}} \leq \sigma_{\mathrm{b}}\sqrt{2\rho(1+a_0^2/2)}$
Emittance limit for overlap	$\epsilon_{\mathrm{N}} \leq 2\sigma_{\mathrm{b}}^2\gamma_0/L_{\mathrm{int}}$
Emittance limit for transverse coherence	$\frac{2\pi\epsilon_{\mathrm{N}}}{\gamma_0\lambda_{\mathrm{FEL}}} = 0.5\cdots 10$
Space charge parameter	$\sqrt{\frac{I_{\mathrm{p}}}{I_{\mathrm{A}}}\frac{2}{\sigma_{\mathrm{b}}^2\gamma_0^3}}L_{\mathrm{G}} < 1$
Laser width in interaction plane	$w_y = n_w L_{\mathrm{int}}\sin\phi$
Laser focal width for overlap	$w_x = \sqrt{2\pi}\sigma_{\mathrm{b}}$
Laser pulse duration for overlap	$\tau_0 \gtrsim \tau_{\mathrm{b}} + \frac{\sigma_{\mathrm{b}}}{c}\tan(\phi/2)$
Laser power	$P_{\mathrm{Laser}}\,[\mathrm{TW}] = 34.29e-3\cdot\sigma_{\mathrm{b}}\frac{a_0^2}{\lambda_{\mathrm{Laser}}^2}n_w L_{\mathrm{int}}\sin\phi$
Irradiance variation limit from wavelength shift	$\frac{\Delta I}{I} \leq 4\rho\frac{1+a_0^2/2}{a_0^2}$
Irradiance limit from ponderomotive deflection	$\frac{\Delta I}{I} \leq \frac{4}{a_0}\left(\frac{\pi\rho(1+a_0^2/2)\sigma_{\mathrm{b}}^2\gamma_0^2}{L_{\mathrm{int}}^2}\right)^{1/4}$
Focal distance of second cylindrical mirror	$f_x = D_{\mathrm{in,x}}\sqrt{2\pi}\sigma_{\mathrm{b}}/\lambda_{\mathrm{Laser}}$
Effective focal distance of off-axis cylindrical mirror	$f_{\mathrm{eff}} = \frac{D_{\mathrm{in}}\sin\phi}{2\pi n_w(1-\beta\cos\phi)\rho}$
Out-of-focus distance	$\lvert\Delta f\rvert \gtrsim \frac{L_{\mathrm{int}}\sin^2\phi}{2\rho(1-\beta\cos\phi)}$

Table 2: Parameters and requirements of electrons and laser pulse for TWTS OFELs radiating at 100 nm and 13.5 nm.

Electron and optical undulator parameters	**VUV TWTS OFEL w/ focusing**	**EUV TWTS OFEL w/ focusing**
Resonant wavelength λ_{FEL} [nm]	100	13.5
Interaction angle ϕ [°]	10.1	12.1
Undulator wavelength λ_{u} [µm]	65	46
Electron energy E_{el} [MeV]	15	22
Peak current I_{p} [kA]	0.8	1.5
Electron bunch charge [pC]	350	350
Electron bunch duration (rms) $\sigma_{\mathrm{t,b}}$ [fs]	175	93
Electron bunch rms radius σ_{b} [µm]	7	10
Norm. transv. emittance ϵ_{N} [mm mrad]	0.5	0.5
Rel. energy spread $\sigma_{\mathrm{E}}/E_{\mathrm{el}}$	0.8%	0.2%
Undulator parameter a	2	0.5
Minimum laser peak power for OFEL [TW]	890	283
Transv. intensity profile stability	2.5%	3.6%
Gain length [mm]	0.35	1
Interaction distance L_{int} [cm]	0.57	1.68
Peak radiation power [MW]	104	68
Number of Photons	2×10^{13}	1×10^{12}

Table 3: Optical components parameters for the 100 nm and 13.5 nm TWTS OFEL in the setup providing focusing in the interaction plane, c. f. Ref. [4]. The acceptable angle and distance variations originate solely from the variation of optical undulator amplitude due to loss of overlap, c. f. Tab. 1. The undulator frequency variation is negligible within this acceptance range.

Optical setup parameters	**VUV TWTS OFEL w/ focusing**	**EUV TWTS OFEL w/ focusing**
Laser wavelength λ_{Laser} [µm]	1.035	1.035
Laser pulse duration as FWHM of intensity $\tau_{\mathrm{FWHM,I}}$ [fs]	120	120
Laser peak power P_0 [TW]	997	1016
Laser oversize at interaction point n_w	1.12	3.6
Laser incident diameter D_{in} [mm]	175	175
1st grating line density n_1 [l/mm]	1000	960
1st grating incidence angle $\psi_{\mathrm{in,1}}$ [°]	40.56	26.36
1st grating incidence angle variation $\Delta\psi_{\mathrm{in,1}}$ [mrad]	14	2.8
Distance between gratings L_{grating} [mm]	3603	2828
Distance between gratings variation $\Delta L_{\mathrm{grating}}$ [mm]	290	75
2nd grating rotation angle ϵ [°]	-4.343	-6.076
2nd grating rotation angle variation $\Delta\epsilon$ [mrad]	14	3.7
2nd grating line density n_2 [l/mm]	1030	1040
Dist. between 2nd grating and off-axis cylindrical mirror L_{mirror} [mm]	2000	2000
Dist. between 2nd grating and off-axis cyl. mirr. variation $\Delta L_{\mathrm{mirror}}$ [m]	many	many
Off-axis cyl. mirror deflection angle ψ_{defl} [°]	15	15
Off-axis cyl. mirror effective focal dist. f_{eff} [mm]	32429	35854
Effective focal dist. variation Δf_{eff} [mm]	2400	1000
2nd cyl. mirror focusing dist. f_{el} [mm]	2967	4238
Out-of-focus distance Δf [mm]	-647	-8170
Propagation distance from off-axis cyl. mirror to interaction point z_{prop} [m]	31.8	27.7
Interaction angle variation $\Delta\phi$ [mrad]	14	4.6

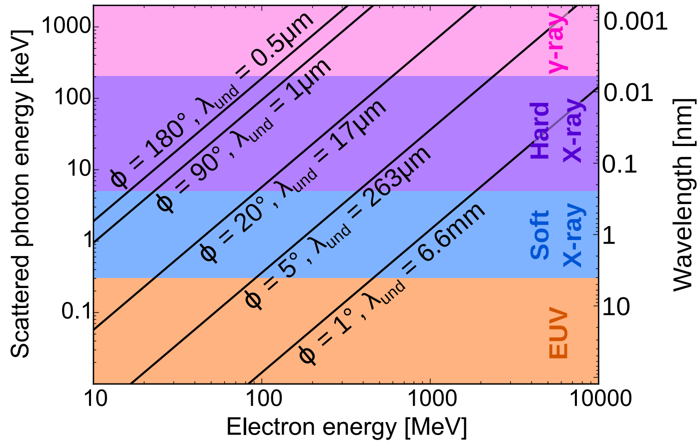
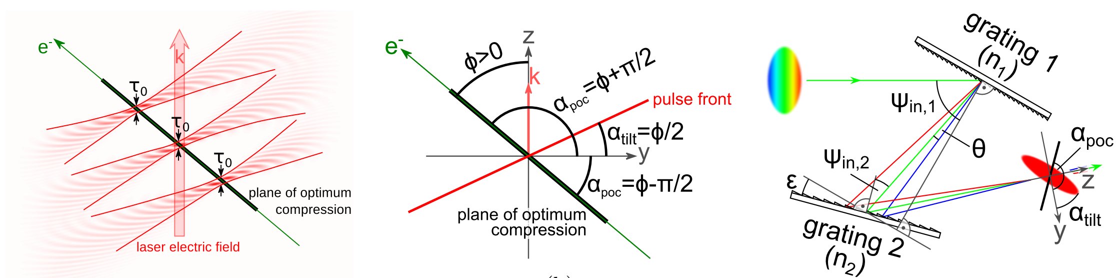


Figure 2: Scaling of scattered photon energy for optical undulators with laser wavelength $\lambda_{\text{Laser}} = 1\,\mu\text{m}$ in dependence of electron energy and interaction angle ϕ. The corresponding undulator period $\lambda_{\text{und}} \approx \lambda_{\text{Laser}}/(1-\cos\phi)$ is given for each interaction angle. With constant electron energy the scattered photon energy can be tuned from the extreme ultraviolet (EUV) to the hard X-ray range just by adjusting the interaction angle.



(a) (b) (c)

Figure 3: (a) Visualization of the plane of optimum compression. The electric field of a laser pulse traveling upwards is shown three times during Traveling-Wave Thomson-Scattering. Where the laser pulse overlaps with the electron trajectory, it is locally GDD-free manifesting in the shortest possible pulse-duration in this region. Away from the electron trajectory, the laser pulse has GDD which increases its duration. (b) Shows the angles important when searching for grating setups to form laser pulses for TWTS. As the plane of optimum compression only needs to be aligned with the electron trajectory, there are two possible angles α_{poc} for its orientation. (c) Grating pair arrangement for the generation and orientation of pulse-front tilt and plane of optimum compression in TWTS geometries. Parameters controlling pulse-front tilt and plane of optimum compression alignment are first and second grating line density, n_1 and n_2 respectively, laser pulse angle of incidence at the first grating $\psi_{\text{in},1}$ and the second grating rotation angle ϵ measuring its rotation out of parallel alignment to the first grating. The angle θ quantifies the angular deviation between the propagation directions of a frequency component relative to the central laser frequency (green).

of $a_0 = 0.8$ can be used. On the one hand, this allows for a larger variation of laser irradiance since these variations result in a smaller variation of radiation wavelength. On the other hand, the effective focal distance is larger compared to the above VUV TWTS OFEL, though this can be offset again by a larger laser oversize.

Furthermore, higher power laser pulses in combination with lower peak currents can be exploited to reduce the electron bunch quality requirements. For the chosen VUV TWTS OFEL parameters of $I_{\text{p}} = 0.8\,\text{kA}$, $a_0 = 2$ and $\sigma_{\text{b}} = 7\,\mu\text{m}$ the acceptable relative electron energy spread for TWTS OFEL operation is 0.83 %, which is given by the Pierce parameter, just coincides with the energy spread after electron bunch compression, which is determined by the conservation of longitudinal emittance. For equal a_0 and σ_{b} but at lower peak current of $I_{\text{p}} = 0.4\,\text{kA}$, however, the required electron bunch quality is lower because the relative electron energy spread after compression is 0.41 % while the acceptable energy spread is 0.67 %.

More laser power could also be utilized to reduce the radiation wavelength. If one electron source is used to produce radiation at different wavelengths, for example by tuning the interaction angle, the production of shorter wavelengths will require longer interaction distances and more laser power to achieve saturation. But the combination of longer interaction distances and larger laser pulse widths ultimately increases the lab space requirement due to the necessity of longer effective focal distances for sufficiently large pulse widths at the interaction point. Then again, this can be offset by a larger laser oversize allowing stronger focusing.

3 Scientific Impact

A vacuum ultraviolet (VUV) TWTS OFEL providing intense and ultrashort radiation pulses at 100 nm wavelength is realizable today. Besides serving as a demonstrator for TWTS OFEL operation, the presented TWTS OFEL setups have applications e. g. to the study of ionization dynamics in nonlinear high intensity laser interaction with matter [6], to observe reaction kinetics at surfaces [7,8], to study ablation from materials surfaces [9] on a laboratory scale, or to seed shorter wavelength FELs. EUV TWTS OFELs providing ultrashort coherent radiation pulses at an extreme ultraviolet (EUV) wavelength of 13.5 nm have applications for example in 3D structure determination of nanoscale objects [10] or in imaging ultra-fast transient, nanoscale dynamics [11]. High yield EUV sources are also applied in materials science [12,13] and are demanded by the semiconductor industry [14]. Compared to existing large scale conventional FEL facilities such as FLASH [15] or FERMI@Elletra [16] a TWTS OFEL is a potentially more compact source due to the lower electron energy and shorter interaction distance.

4 Broader Impact

Besides offerering a path towards the realization of optical FELs, TWTS generally allows for the realization of ultra-compact, inherently synchronized and highly brilliant light sources over a broad spectral range from eV to MeV photon energies with applications in various fields of research and industry. In the TWTS geometry all of the available laser photons interact with the electrons contrary to head-on Thomson scattering where laser defocusing reduces the overlap of laser and electrons, ultimately limiting the available interaction distance [1]. Thus much longer interaction distances can be provided in TWTS setups increasing the photon output and reducing the radiation bandwidth leading to orders of magnitude higher brilliance of standard head-on Thomson sources [2].

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Scaling Laser-Plasma Electron Accelerators to 100GeV-scale Energies using TWEAC and Multi-Petawatt Lasers

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Abstract:
The quest for advanced acceleration techniques for providing more compact accelerators is a grand challenge of particle accelerator physics. Addressing this challenge will allow to further scale up energies for high-energy physics, as well as enable accelerator technology to be more commonly available.

Despite tremendous advances in Laser-Plasma accelerators (LPAs) with respect to beam energy, quality, charge and stability, sustaining scalability of compact LPAs to even higher electron energies and more brilliant secondary radiation sources is one of the yet to be solved key challenges of the field.

These limitations can be overcome by TWEAC (Traveling-Wave Electron ACceleration), a novel laser-plasma interaction geometry relying on spatio-temporally shaped ultrashort, high-power laser pulses using existing laser technology. These laser pulses provide "flying" focal regions propagating at tuneable velocities close to the speed of light without the need for external guiding.

Multi-petawatt laser facilities together with TWEAC pave the way towards scalable LPAs on the 100GeV scale without the need for multiple laser-accelerator stages.

*[Disclaimer: This is still a draft and is based on the work of Debus et al., Circumventing the Dephasing and Depletion Limits of Laser-Wakefield Acceleration, Phys. Rev. X **9**, 031044 (2019)]*

Scientific goal: Description of the goal and the methods that would be used.

The goal is to build compact, laser plasma accelerators to reach electron energies beyond 10GeV towards the 100GeV energy scale.

Despite state-of-the-art ultrashort, petawatt-scale lasers easily exceeding intensity and pulse energy requirements of LWFA, there are three basic limitations (electron beam dephasing, laser-pump depletion and laser defocusing) that currently constrain LWFA peak energies to a range of hundreds of MeV to several GeV (with the current world record being 8 GeV).

In principle, these limitations can be overcome by using multiple LWFA stages to successively accelerate one electron beam to higher energies. However, in practice, this approach introduces severe (yet unsolved) challenges with regard to electron beam transport in between stages, which need to be spaced apart due to coupling in and coupling out of the laser beam, hence leading to charge loss and emittance growth.

The Traveling-Wave Electron ACceleration (TWEAC) geometry (see Ref. [1], Fig. 1) is an alternative non-collinear interaction geometry, which can simultaneously avert all these limits without the need for staging.

Figure 1 outlines the working principle of TWEAC: the wakefield driver is not provided by a single laser pulse, but instead by a region of overlap of two obliquely incident, ultrashort laser pulses with tilted pulse-fronts in the line foci of two cylindrical mirrors, aligned to coincide with the trajectory of subsequently accelerated electrons. Such a geometry of laterally coupling the laser into a plasma allows for the region of overlap to move with the vacuum speed of light, while its field is continuously being replenished by the successive parts of the laser pulse. The wakefield driver is not provided by a single laser pulse, but instead by a region of overlap of two obliquely incident, ultrashort laser pulses with tilted pulse-fronts in the line foci of two cylindrical mirrors, aligned to coincide with the trajectory of subsequently accelerated electrons. Such a geometry of laterally coupling the laser into a plasma allows for the region of overlap to move with the vacuum speed of light, while its field is continuously being replenished by the successive parts of the laser pulse.

Tools required: Parameters required for the experiment, or technical requirements/abilities of modeling tools, or theory development. Identify any facility/diagnostic/code developments that need to be made to achieve the goal

The main experimental challenge for realizing TWEAC is due to its non-standard geometry. Although all required techniques already exist using existing lasers, the challenge is to provide, diagnose and control the the non-collinear laser geometry in a multi-PW environment. The spatio-temporal properties of the two laser beams can be realized and controlled using two optical gratings in addition to the CPA compressor before the experiment. (see Ref. [2])

Initial applications can be done at 100TW to PW level. At multi-PW impact of the new technique is expected to become more pronounced.

Scientific impact(s): What will the impact of achieving this scientific goal be?

The TWEAC scheme simultaneously prevents all three basic LPA limitations: electron beam dephasing, laser pump depletion and laser beam defocusing.

1) Averting Dephasing: By tuning to the right combination of sideways incident angle phi and a laser pulse-front tilt phi/2 the interaction geometry enforces a crossing region of the two beams in plasma which moves through the gas target at the vacuum speed of light. Thus avoiding dephasing of the electron beam accelerated by the thus excited plasma wave.

2) Averting Depletion: In the sideways geometry of TWEAC one always has a "fresh" part of laser beam entering an unperturbed portion of the plasma, where it transfers a sizable fraction of its energy and exits at the other side before being fully degraded. The choice of incident angle phi, laser focal spot size and plasma density determines the balance of how much energy is being deposited. This mechanism of gradually, but continuously cycling through the laser beam through the plasma target avoids reaching pump depletion in the laser-plasma interaction region driving the accelerating plasma cavity.

3) Averting Defocusing: The line focus of the two cylindrically-focused defines the dimensions of the "flying focus" and extends over the entire interaction length. In particular, the interaction geometry does not rely on self-guiding or external guiding techniques and thus avoids laser defocusing along the laser plasma accelerator length.

TWEAC allows for scalability beyond 10GeV without the need for staging, see Fig. 2:

- In principle, TWEAC can be arbitrarily extended in length (and thus final energy), as long as laser energy of ultrahigh, high-intensity laser systems is available. The design provides quasi-stationary conditions of strong acceleration (GeV/cm-scale) in a laser-plasma accelerator.

- Beyond 10GeV, TWEAC eliminates the need for several tens of LWFA stages, with its challenges to transport the electron beam in between stages without charge loss or beam quality degradations, as well as repeated laser pulse insertion and extraction along the main accelerator axis.

- TWEAC combined with a multi-PW facility is ideally suited for scaling LPA accelerators to the 100GeV-scale and beyond.

Broader impacts:

On a longer-term horizon, these highly scalable plasma-based accelerators pave the way towards compact compact multi-TeV electron-positron colliders for answering fundamental questions in high-energy physics.

- The techniques used for synthesizing and controlling the pulse-front-tilted lasers of ultrashort laser pulses for TWEAC are very similar as for compact all-optical FELs based on Traveling-Wave Thomson-Scattering (see corresponding white paper).
- Beyond high electron energy applications using multi-PW laser facilities, TWEAC is also interesting for lower power (~10TW) high-repetition rate lasers for providing a compact GeV-scale electron accelerator at high-repetition rate, particularly for making light source applications more readily available for medicine, biology, engineering and industry.

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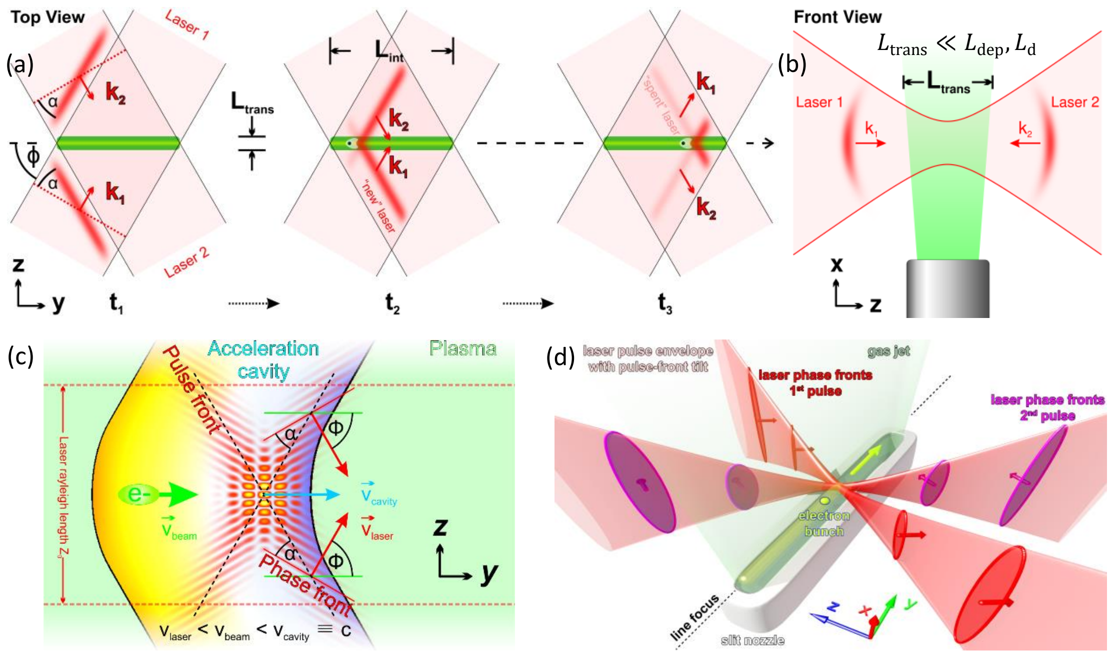

Fig. 1: Traveling-Wave Electron Acceleration (TWEAC) features a laser-plasma interaction region, which propagates with exactly the speed of light, thus remaining synchronized to the accelerated electron bunch arbitrarily far beyond the dephasing length – limited by the spatial extent of the laser pulse only. (a) illustrates the comoving laser overlap, as well as the laser field cycling through the laser-plasma interaction region. (b) depicts the cylindrical focusing geometry. (c) shows a zoomed-in schematic of the accelerating region. The two TWEAC lasers (red intensity contours) drive a copropagating V-shaped plasma cavity with $v_{\mathrm{laser}} < v_{\mathrm{beam}} < v_{\mathrm{cavity}} \equiv c$ that accelerates an electron bunch in its longitudinal cavity field (orange-white-purple). (d) illustrates in overview the combined geometry of two ultrashort, pulse-front tilted, obliquely incident laser beams in a line focus, driving a wakefield in a slit-nozzle generated gas jet for accelerating an electron bunch.

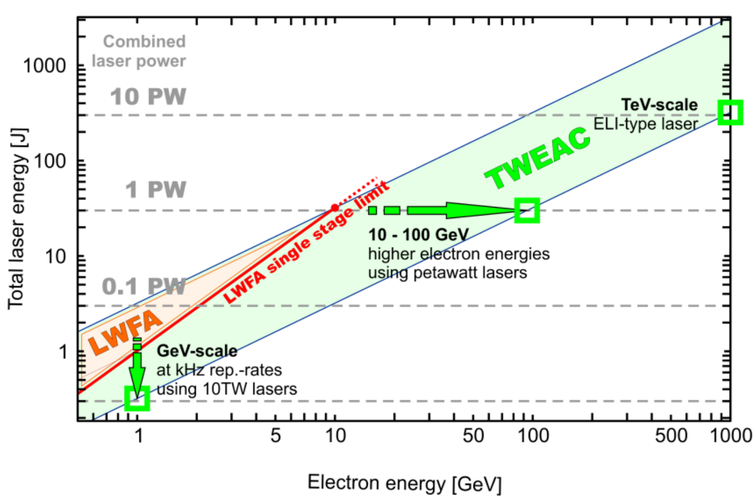

Fig. 2: Traveling-wave electron-acceleration (TWEAC) provides scalable laser-plasma acceleration, paving the way to high electron energies for multi-PW laser systems.

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