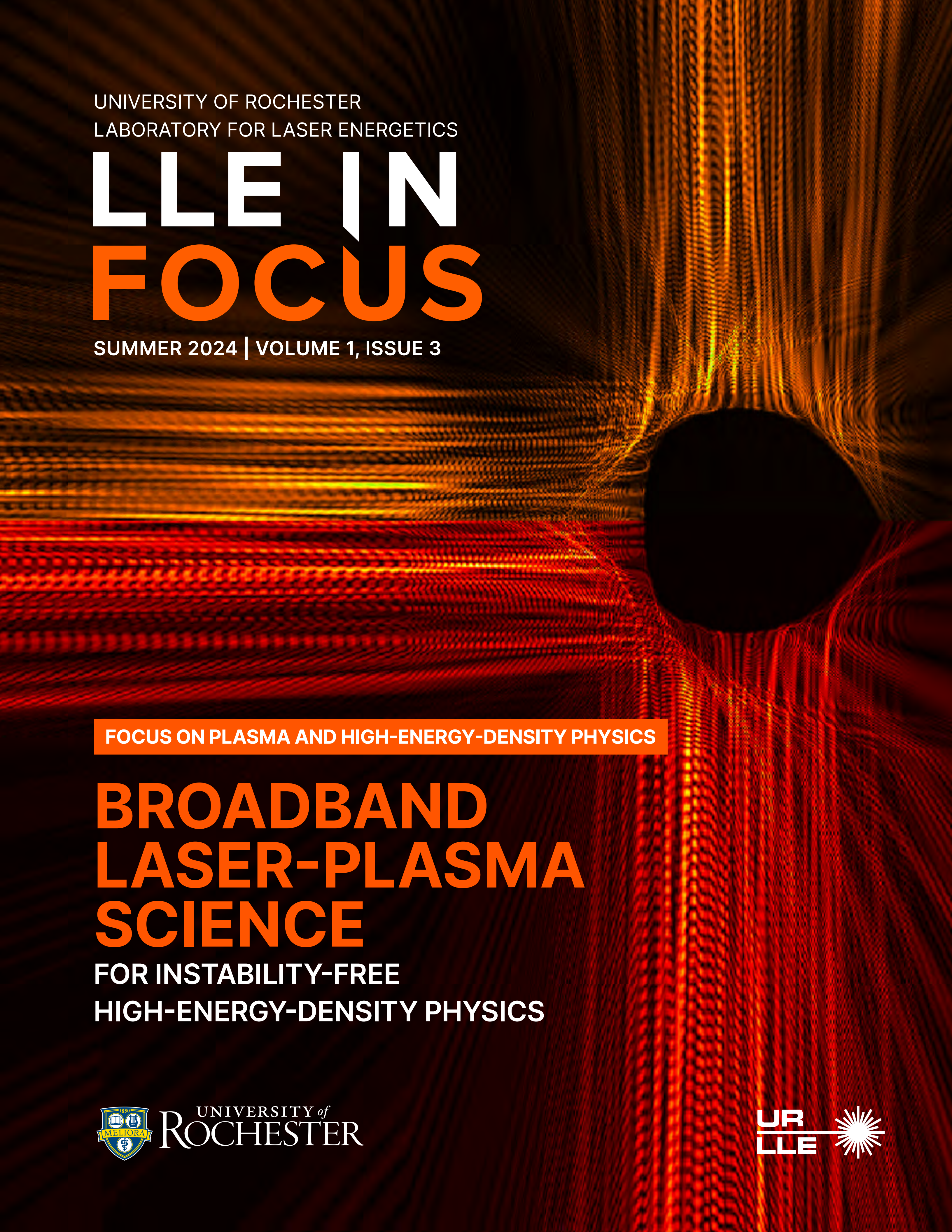

UNIVERSITY OF ROCHESTER
LABORATORY FOR LASER ENERGETICS

LLE IN FOCUS

SUMMER 2024 | VOLUME 1, ISSUE 3

FOCUS ON PLASMA AND HIGH-ENERGY-DENSITY PHYSICS

BROADBAND LASER-PLASMA SCIENCE

FOR INSTABILITY-FREE HIGH-ENERGY-DENSITY PHYSICS

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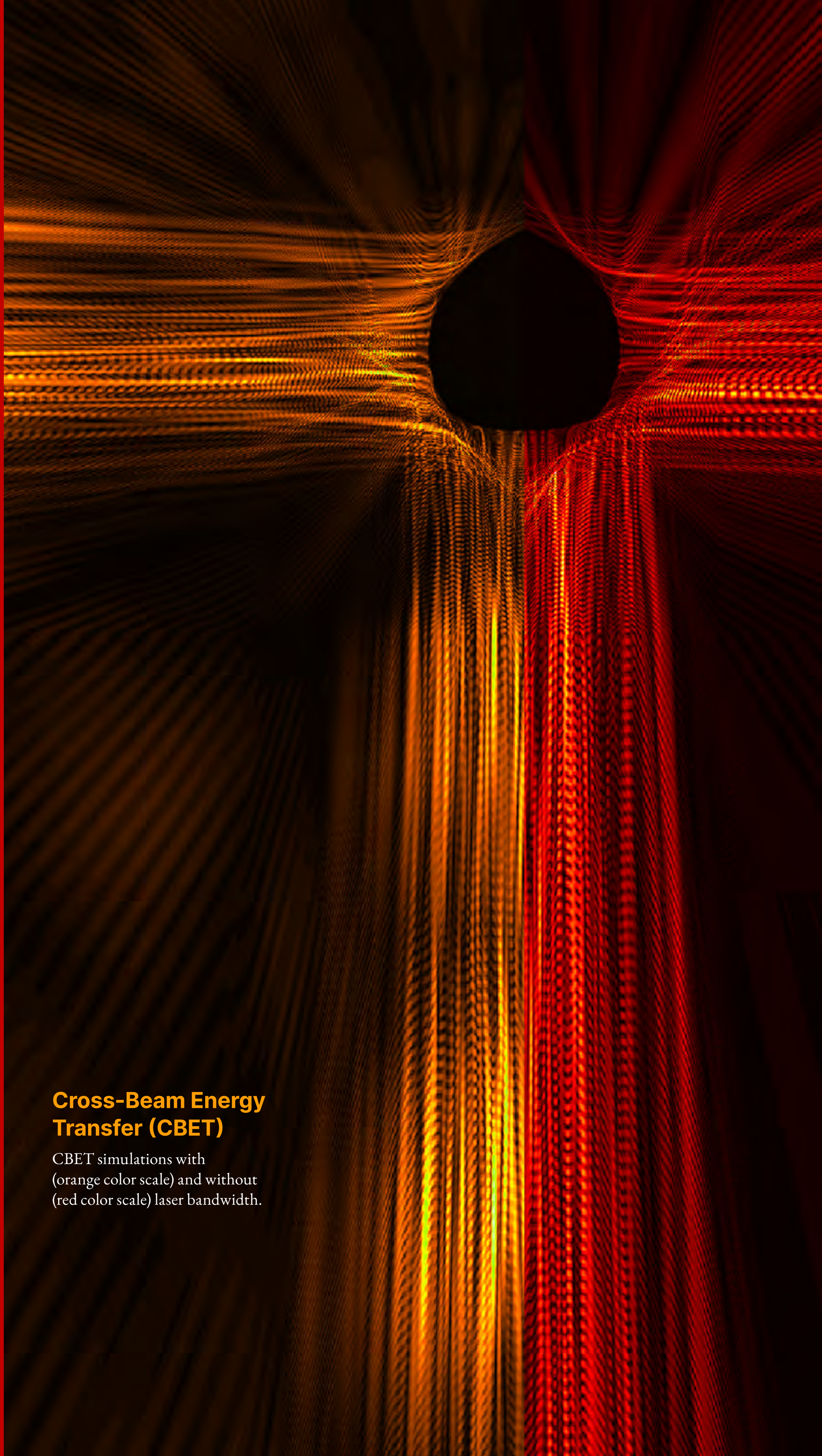


Cross-Beam Energy Transfer (CBET)

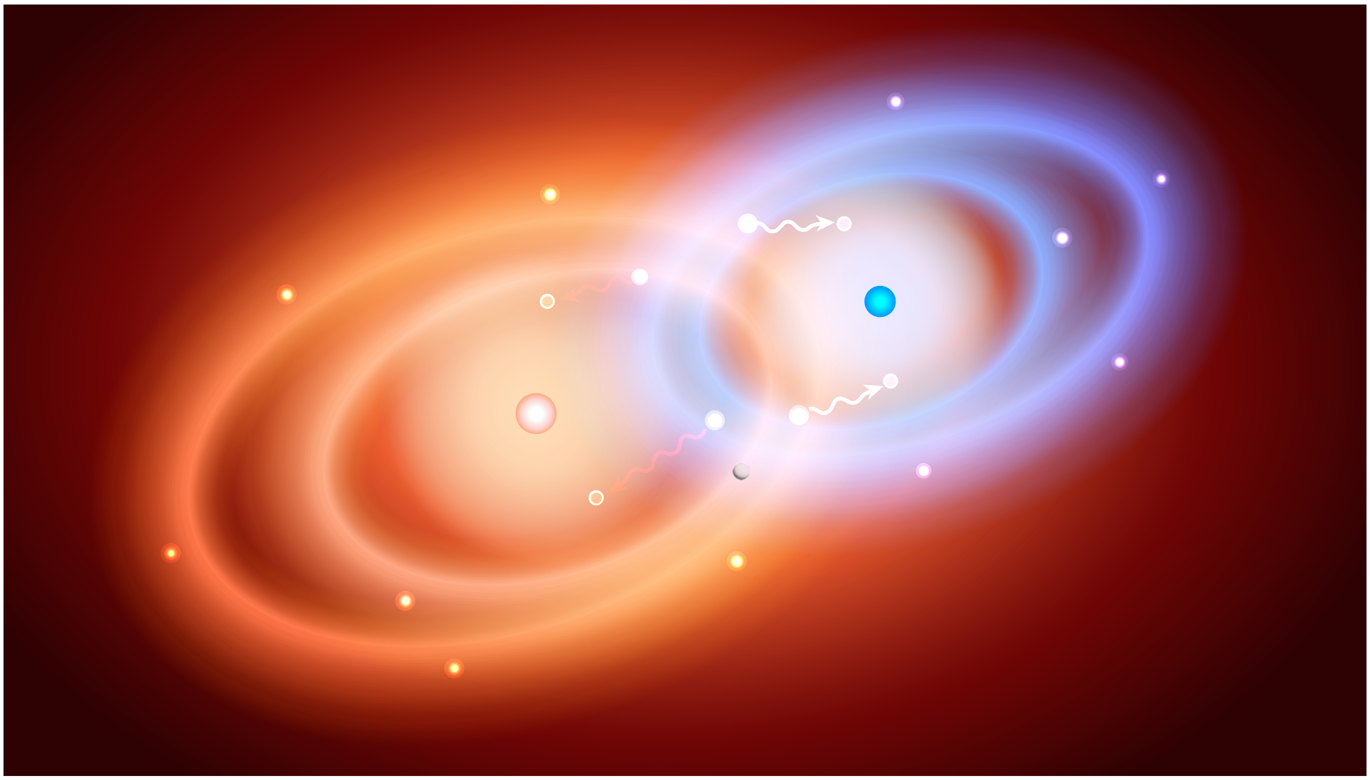
CBET simulations with (orange color scale) and without (red color scale) laser bandwidth.

LLE IN FOCUS

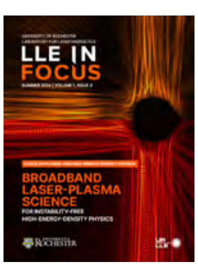
Focus on: Plasma and High-Energy-Density Physics

Summer 2024

Volume 1, Issue 3



An artistic depiction of quantum orbitals overlapping among atoms in superdense matter, encountered in stars and laser fusion targets.

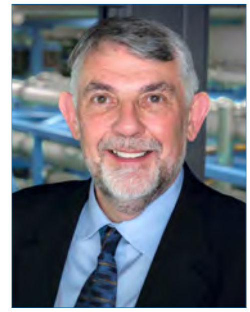


About the cover

The cover presents cross-beam energy transfer simulations of four laser beams incident on a direct-drive coronal plasma. The two narrowband laser beams, shown with a red intensity color bar, produce significantly more scattered light due to cross-beam energy transfer than the two broadband laser beams, shown with an orange intensity color bar.

LLE IN FOCUS

From the Director



DR. CHRISTOPHER DEENEY | DIRECTOR, LABORATORY FOR LASER ENERGETICS

Reading this third *LLE In Focus,* one word resonated with me—partnership. LLE is all about partnership, as evidenced in the technical collaborations in the publications listed on p. 3, through the target fabrication partnership with General Atomics, to the large team who came together to build our new building. Our Omega Facilities are a national resource for the National Nuclear Security Administration and the Department of Energy, with more than 50% of experiments being executed by institutions in partnership with us. The graduate students highlighted in this issue received and delivered on great scientific opportunities; in addition, they have seen the real value of partnership across organizations and skill sets.

If "partnership" could be embodied in an individual, it would be Mike Campbell, LLE's fourth director. On a beautiful spring day at the May 2024 commencement ceremony, we celebrated as Mike's contributions to LLE and the high-energy-density science community were acknowledged with an honorary Doctor of Science degree by the University of Rochester.

Our present partnerships are also paving the way for an amazing future. The possibilities presented in "A Future of Inertial Confinement Fusion Without Laser–Plasma Instabilities" on p. 22 are exciting. Reducing the size of an ignition-scale laser by about a factor of ten and/or creating high-yield capabilities with a laser twice the size of the National Ignition Facility would be major advances for the National Nuclear Security Administration and other sponsors. The next year will be exciting as the FLUX laser (see *LLE in Focus*, Fall 2024, p. 16) confirms the path to laser–plasma instability mitigation through bandwidth. The path to improved fundamental understanding of plasmas through machine-learning–based analysis and advanced spectroscopy will also inspire future research possibilities.

Christopher Deeney
Director, Laboratory for Laser Energetics

First Focus

In LLE History

45 YEARS AGO

The National Laser Users' Facility (NLUF) was established in 1979 to provide access to LLE's high-power laser facilities for basic research in high-energy-density science. Projects are selected through a peer-reviewed proposal process every two years. Since its inception, a total of 273 NLUF projects have conducted close to 6000 target shots at the Omega Laser Facility, with users from approximately 90 universities, government laboratories, and private companies around the globe. Over 300 graduate students and postdoctoral researchers have participated in NLUF experiments.

Fast Facts

106,574

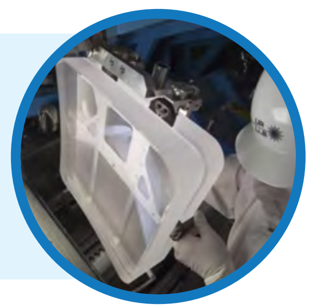
cryogenic targets could fit inside of a golf ball.

1600

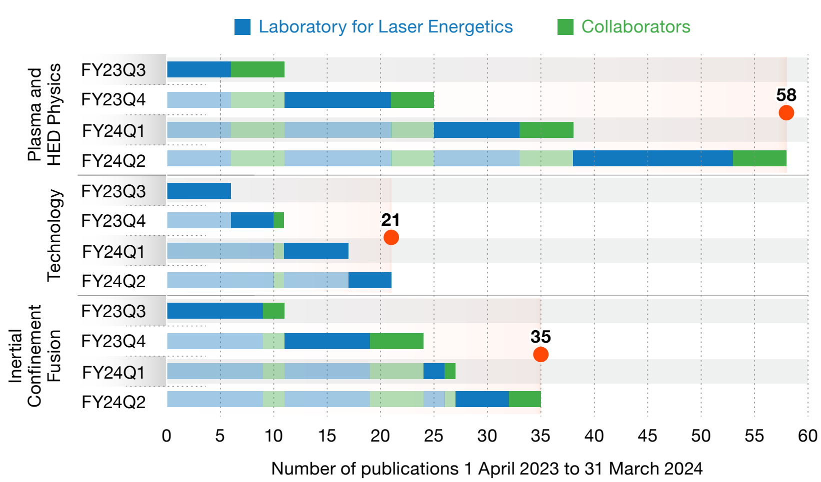
Windows operating systems are supported by the LLE Computer Support Group.

1300

OMEGA debris shields are sol-gel coated annually by LLE's Optical Manufacturing Group to support target shots.



Publications



Research Highlights

The science and engineering research at the Laboratory for Laser Energetics is captured through peer-reviewed publications, which include LLE-lead-authored (blue bars) and LLE co-authored papers (green bars). LLE averages more than 100 published articles annually across three broad areas: Technology, Plasma and High-Energy-Density (HED) Physics, and Inertial Confinement Fusion.

LLE EXCELS

Awards and Honors

Jeremy Pigeon Awarded Young Investigator Research Program Grant

Jeremy Pigeon, a Scientist in the Plasma & Ultrafast Laser Science & Engineering Division, was awarded a 2024 Young Investigator Research Program grant, with funding of $450,000 for research over the next three years. Individuals must have received their PhD degree in the last seven years and show exceptional ability and promise for conducting basic research for the Department of the Air Force. This award will fund the development of a TW-class mid-IR laser system built using chirped-pulse amplification. The primary application of this new laser will be for laser-plasma experiments at the wavelength frontier in support of the High-Energy Radiation-Matter Systems Program at the Air Force Office of Scientific Research.

Rip Collins Named American Association for the Advancement of Science Fellow

LLE Distinguished Scientist Gilbert (Rip) Collins was elected to the American Association for the Advancement of Science, the world's largest multidisciplinary scientific society and prestigious publisher of cutting-edge scientific research. Collins, who joined the University in 2016, is the Tracy Hyde Harris Professor of Mechanical Engineering, a professor of physics and astronomy, and the associate director of science, technology, and academics at LLE. He leads both the Center for Matter at Atomic Pressures and the Institute for Matter at Extreme Energy Density and is being recognized for his "distinguished contributions to Condensed Matter Physics, particularly for his seminal groundbreaking work in high-energy-density science of matter at extreme pressures."

Varchas Gopalaswamy Received the 2024 EPS–PPCF Sylvie Jacquemot Early Career Prize

Assistant Scientist Varchas Gopalaswamy has been awarded the 2024 European Physics Society–Plasma Physics and Controlled Fusion Sylvie Jacquemot Early Career Prize. This prize, which honors exceptional plasma physicists in the early stages of their careers, recognizes Gopalaswamy's impressive contributions to the development of statistical modeling to achieve accurate predictions of laser fusion experiments, thereby improving implosions and achieving record Lawson products for direct drive on OMEGA. In addition to a monetary award and certificate, Gopalaswamy has been invited to give a plenary talk at the EPS Plasma Physics Conference in Salamanca, Spain.

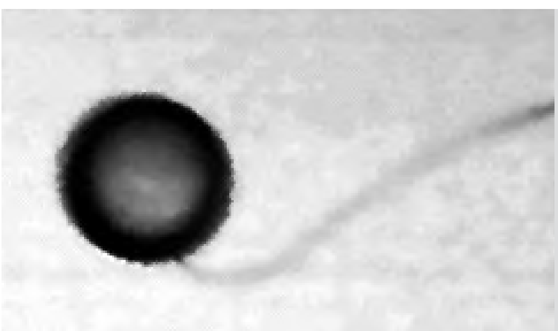
Hunter Markland Awarded 2024 Susumu Okubo Prize

University of Rochester graduate student and LLE Horton Fellow Hunter Markland received the prestigious Susumu Okubo Prize at the 2024 Department of Physics & Astronomy commencement ceremony on Saturday, May 18 in Hoyt Hall. This prize, given in honor of UR professor emeritus of physics Susumu Okubo, is awarded annually to two students for the most-outstanding performance on the graduate physics preliminary assessment. Hunter started his UR graduate work in the Department of Physics & Astronomy under advisor Jeremy Pigeon. Hunter's research, which is supported by the Air Force Office of Scientific Research, focuses on developing an intense THz probe using the flying-focus technique.

FOCUS ON TARGET FABRICATION

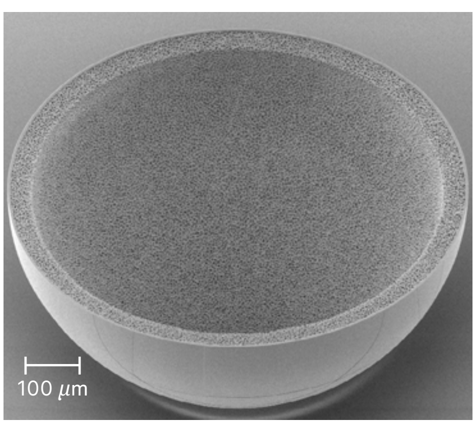
Target Fabrication

To meet the demands of our broad user base, LLE's Target Fabrication Facility manufactures over 2500 precision targets per year, while continuing to develop new target-production methods and conducting routine metrology of targets at micron resolution. The facility is home to various types of microscopy (scanning electron, atomic force, confocal, stereo, compound, and 3D x-ray tomography), a world-leading two-photon polymerization 3D printer, and multiple assembly stations.

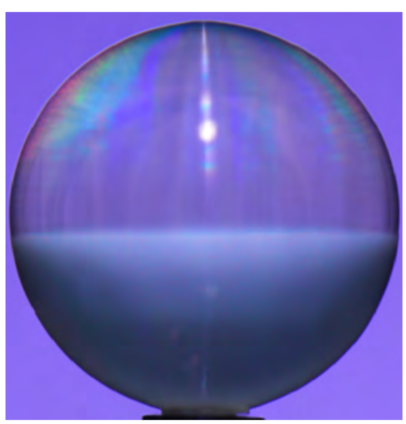


Snapshot

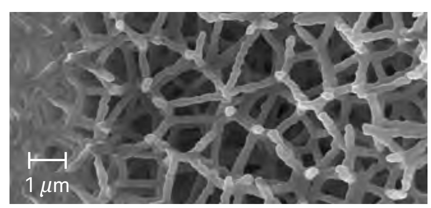
Shown to the left is a high-speed camera image of a 0.9-mm-diam plastic target mounted on a glass tube that was subjected to a high-g impulse to identify failure modes that cryogenic targets sometimes experience when they are moved from one location to another. Immediately after this image was taken, the glass tube shattered. The plastic shell, glass tube assembly, and the vibration experiment that produced the image were all created by General Atomics—the major production and R&D company in the Inertial Confinement Fusion Program. General Atomics provides LLE with all the plastic capsules and precision targets for NLUF and other users.

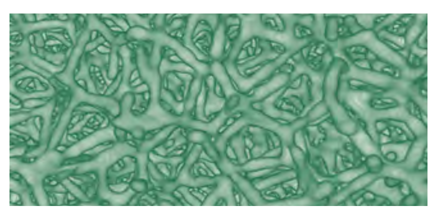


A 0.9-mm-diam hemishell with an 8-μm solid outer wall and a 45-μm foam wall consisting of 1-μm fibers and a density of 40 mg/cm^3.



Printed target (0.9-mm diam) with the bottom half containing a foam wall.





Top: Electron microscope image of a foam with 200-nm-diam fibers. Bottom: X-ray image of a foam with 2-μm-diam fibers.

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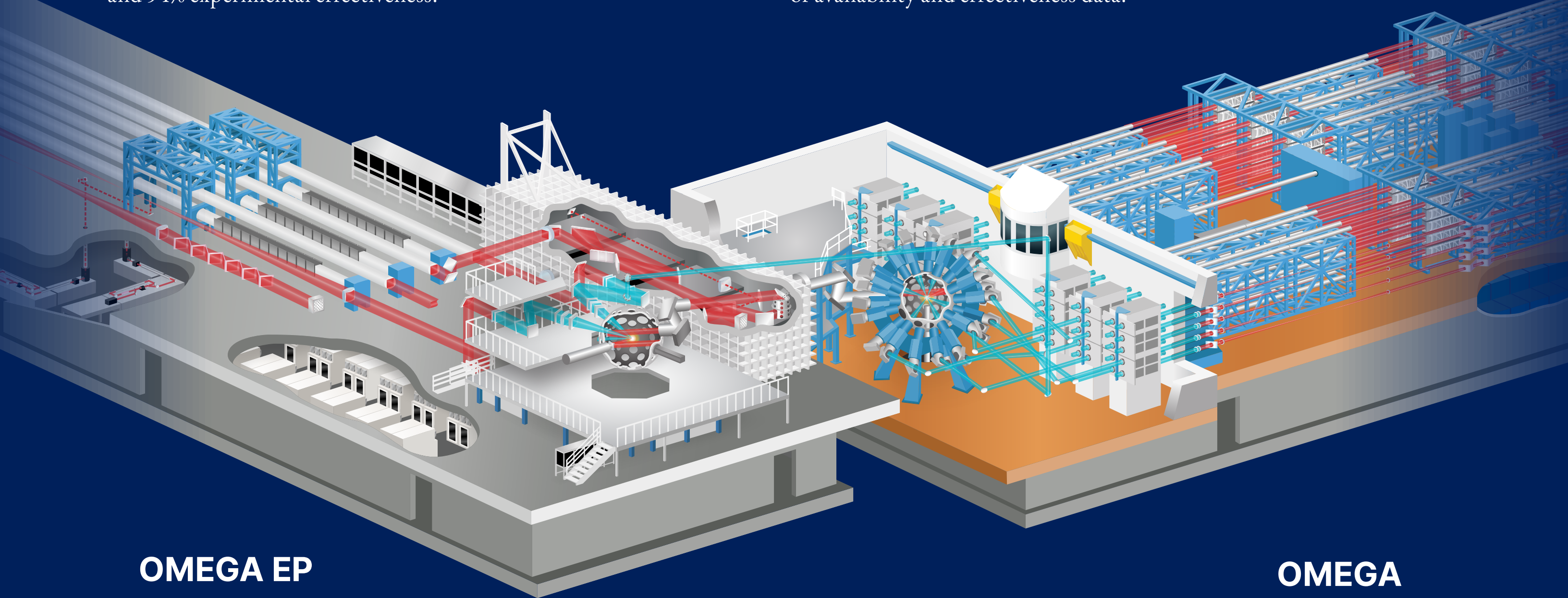
FOCUS ON THE FACILITY

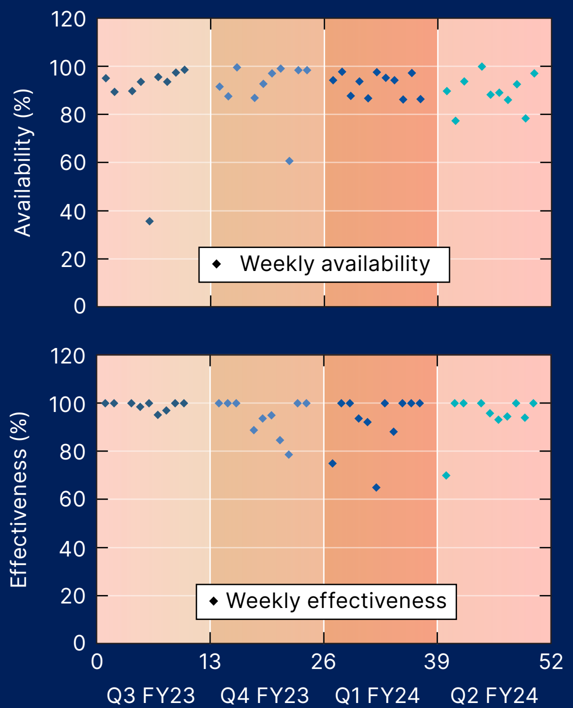
Laser Facility Report

The Omega Laser Facility conducts experiments for research and development in support of the National Nuclear Security Administration's High-Energy-Density Program, the National Laser Users' Facility, and the Laboratory Basic Science Program, in addition to other research and educational efforts. During Q2 of FY24, the Omega Laser Facility conducted 250 target shots on OMEGA and 183 on OMEGA EP for 433 total target shots for 51 unique campaigns. In Q2, OMEGA averaged 93% availability and 89% experimental effectiveness, while OMEGA EP averaged 91% availability and 94% experimental effectiveness.

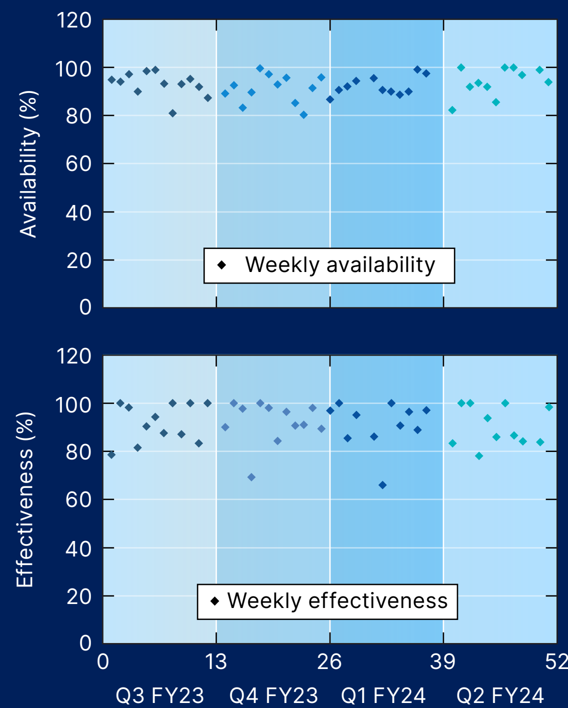
Availability is the fraction of time that the Omega Laser Facility is available based on the individual shot cycle (60 minutes on OMEGA or 105 minutes on OMEGA EP). Analyzing this data and the reason for delay allows the facility to address important improvement needs. Effectiveness tracks the Principal Investigator's initial assessment of the performance of the laser, target, and primary diagnostics, ensuring immediate response to their concerns. Over the last year of shots, OMEGA and OMEGA EP have maintained high average availability and effectiveness in the 90–95% range. See below for one year's worth of availability and effectiveness data.

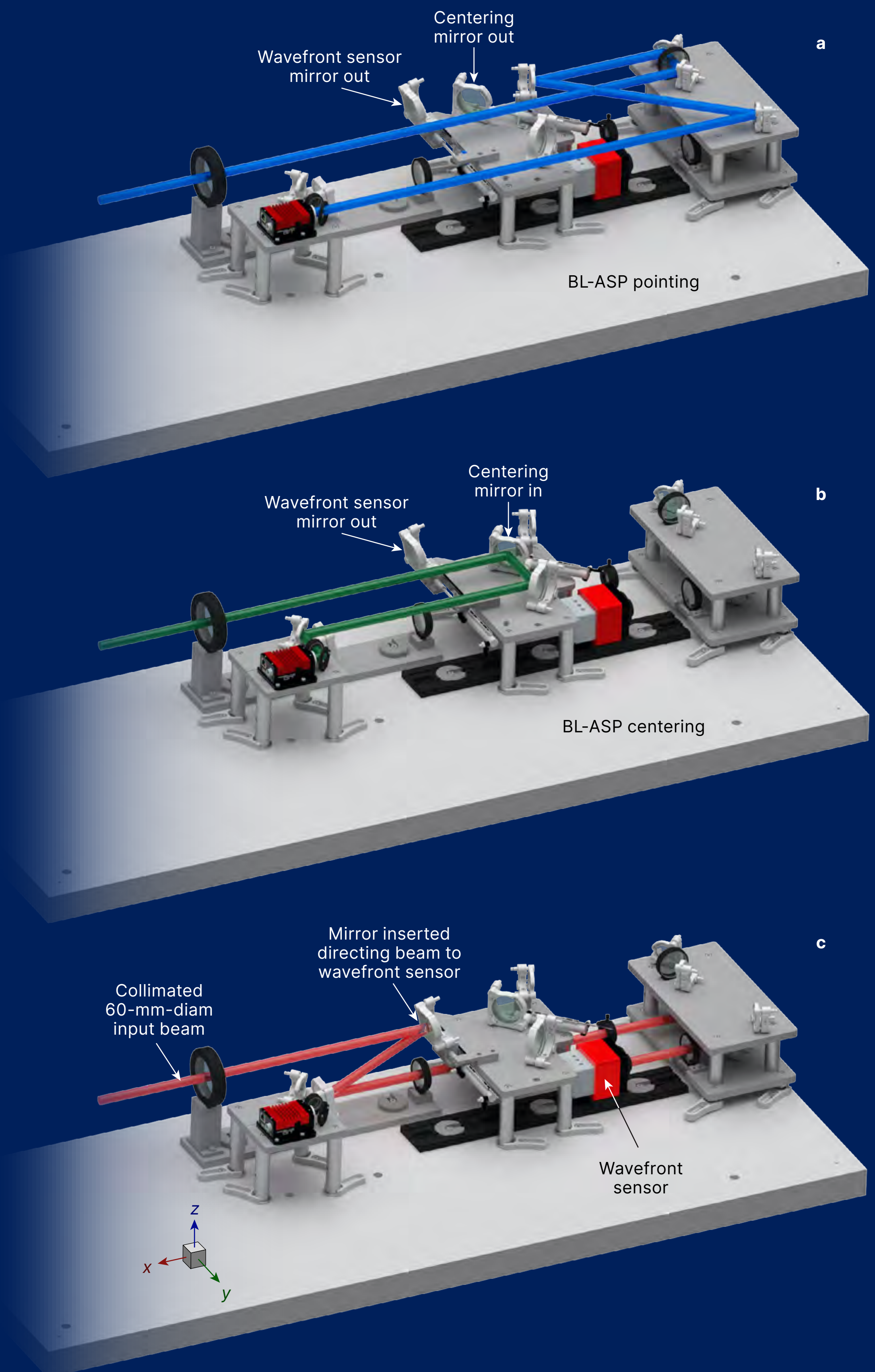


OMEGA EP



OMEGA





Backlighter Alignment Sensor Package and Wavefront Sensor Upgrade

The backlighter driver on OMEGA allows Principal Investigators to use two different pulse shapes on the same shot. The backlighter driver beam is injected into one of the three OMEGA legs, feeding 20 beams, while the SSD (smoothing by spectral dispersion) driver feeds the remaining 40 beams. The backlighter alignment sensor package and wavefront sensor (BL-ASP/WFS) upgrade consists of a new alignment sensor package that simplifies alignment of the backlighter driver and adds the capability of a wavefront sensor.

The newly designed BL-ASP now resides in the A split, allowing backlighter alignment checks to be performed between each shot without having to propagate to alignment sensors further down the beamline.

The mechanical design utilizes insertable mirrors to select one of three modes: BL-ASP pointing, BL-ASP centering, or the WFS. In BL-ASP pointing mode (a), both insertable mirrors are moved out of the beam path; the pointing alignment of the backlighter driver can then be checked pre-shot and the wavefront sensor is inactive. BL-ASP centering mode (b) is activated by inserting the centering mirror into the beam path; the centering alignment of the backlighter driver is checked and the wavefront sensor remains inactive. In WFS mode (c), the insertable mirror blocks the beam from entering the BL-ASP pointing and centering cameras, protecting them from being damaged on-shot. The new WFS mode replaces film-based shear images for diagnosing collimation and wavefront issues on the driver beam and allows wavefront data to be collected on each shot. Previously, "shear shots" were taken, requiring a dedicated shot on OMEGA. The new WFS is a multiwave lateral-shearing interferometer, utilizing a modified Prosilica GT4400 camera as the detector.

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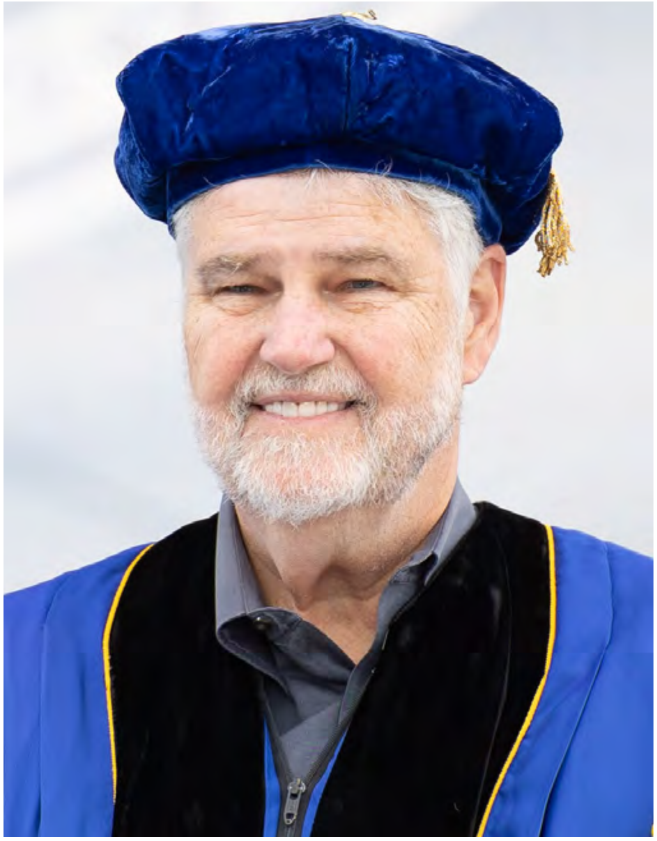
LLE GRADUATE STUDENTS

The Future of Science

Some of LLE's graduating students participated in the University of Rochester's Commencement ceremony in May 2024. Pictured here (left to right) are Tanner Simpson, Grigoriy Tabak, Maitrayee Ghosh, Linh Khan Nguyen, and Ming Wang.



"I am extremely honored to receive this honorary degree from the University. **I have worked at many world-class institutions but there is no question that LLE is unique and is a special place to me.** It was a great honor and pleasure for me to work with such outstanding staff at both LLE and the [University of Rochester] campus and be surrounded by such wonderful students who will make a better future for all of us."

Dr. E. Michael Campbell

Honorary Degree Recipient

LLE Director emeritus, Dr. E. Michael Campbell, received an honorary degree from the University of Rochester at the 2024 Commencement Ceremony this past May.

Campbell is an internationally known expert in inertial fusion, high-energy-density physics, and high-power lasers and their applications, including Generation-IV nuclear fission reactors and biofuels. He has won numerous awards including the Department of Energy's E. O. Lawrence Award, the American Nuclear Society's Edward Teller Award, the American Physical Society's John Dawson Award, the Department of Energy's Excellence in Weapons Research Award, and Fusion Power Associates' Leadership Award. A Fellow of the American Physical Society and Optica, Campbell has published over 250 articles in scientific journals and holds five patents, which include the design of the first laboratory x-ray laser. He has given numerous invited and plenary talks at both national and international conferences and is the originator of the Inertial Fusion Sciences and Applications Conference.

Campbell has been a member of numerous committees, providing advice and strategy to the National Academy of Sciences, Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, the University of Texas, the National Research Council of Canada, Lawrence Livermore National Laboratory, the University of Rochester, Lockheed Martin Corporation, and the Missile Defense Agency. He served on the board of Evans & Sutherland Corporation and has worked in various scientific and leadership positions at federal laboratories, universities, and the private sector, including Lawrence Livermore National Laboratory, where he was Associate Director for Lasers. Campbell was the originator of the National Ignition Facility and was Senior Vice President for Energy at General Atomics. He also worked at Logos Technologies, Sandia National Laboratories, and the University of Rochester. Campbell initiated an SMR (small modular reactor) program while at Logos Technologies for deployment in forward-operating bases and remote, off-grid sites. On this basis, the US Senate Committee on Armed Services instructed the US Department of Defense to explore the applications and need for SMRs—the beginning of the Pele Program, now underway.

Campbell retired in April 2022 from the University of Rochester, where he was the Director of the Laboratory for Laser Energetics. For his contributions to LLE, Rochester, and fusion research, he received an honorary doctorate from the University in 2024. Campbell now consults with a focus on fission energy, fusion, and high-power lasers and their applications. He has received degrees from the University of Pennsylvania, Princeton University, and the University of Western Sydney.

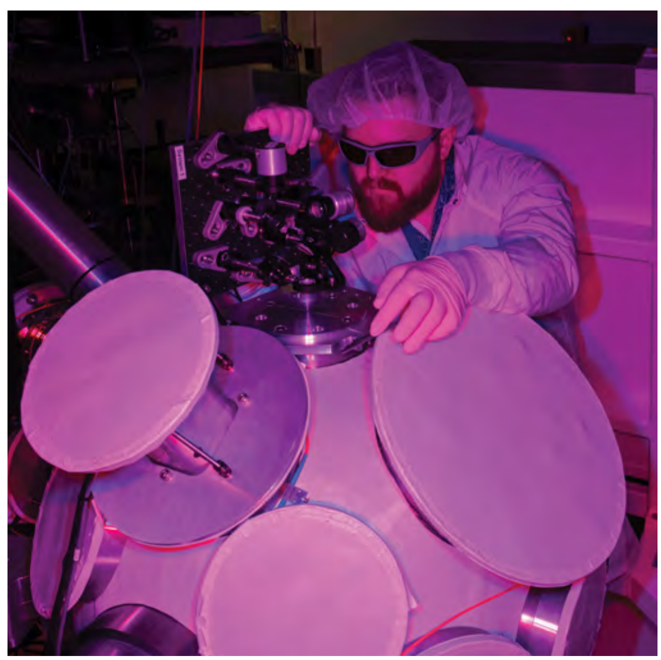
Dr. Gerrit Bruhaug

Department: **Mechanical Engineering**
Advisors: **G. W. Collins, J. R. Rygg, H. G. Rinderknect, and M. S. Wei**

Gerrit Bruhaug is an innovator. Soon after passing his PhD exam, Gerrit received multiple offers from a national laboratory, a fusion startup, and an acclaimed university. During his doctoral studies in the Department of Mechanical Engineering and at LLE, Gerrit held a Horton Fellowship and pioneered several new directions in high-energy-density (HED) science. While working on the MTW, OMEGA EP, and 60-beam OMEGA lasers, he developed several new techniques for producing terahertz (THz) radiation and holds the world record for producing the brightest THz source on the planet. These high-power, high-energy THz sources can be used as direct probes of conductivity and chemical structure in HED materials, and perhaps as a new driver for high-intensity-radiation matter experiments.

Gerrit also developed a laser-plasma accelerator-based electron radiography platform, which uses highly relativistic electrons for imaging thick (~8-g/cm^2) samples to high resolution. This source is currently being used to map the intense electric and magnetic fields in laser-produced plasmas. He also pushed for and helped develop key concepts for a next-generation x-ray source with >10-KeV photon energy and picosecond resolution. Each of these efforts could easily have led to an outstanding thesis, but for Gerrit to initiate and develop all of these capabilities during his doctoral studies is an inspiration. Congratulations to Gerrit and to all at LLE and UR who helped him along the way. After his remarkable graduate career, Gerrit looks forward to continuing his many research endeavors at Los Alamos National Laboratory.

> “**There is no better place to be a graduate student than at LLE.** I was given incredible opportunities and worked with a wide variety of amazing people. Plus, I did my research using enormous lasers. What could be cooler than that!?”



Dr. Josh Hinz

Department: **Physics and Astronomy**
Advisor: **V. V. Karasiev**

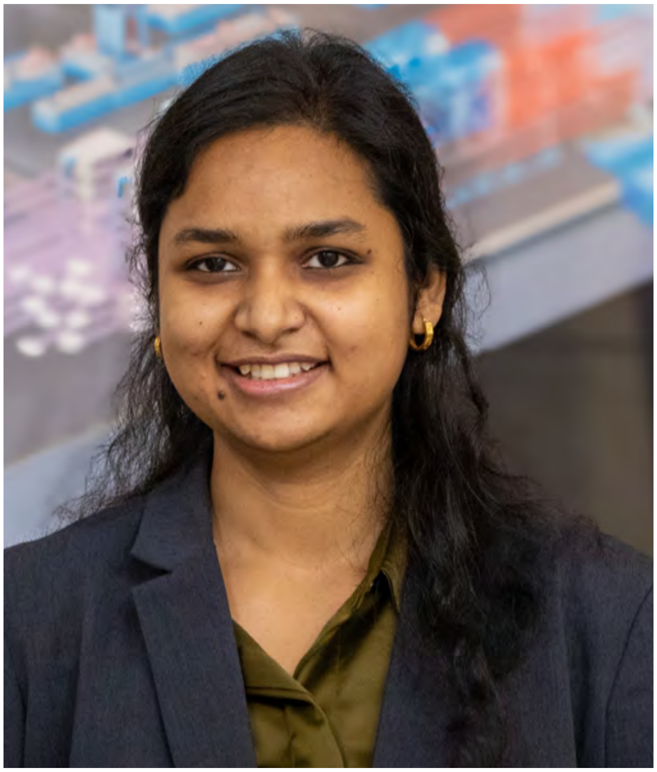
Josh Hinz's doctoral research focused on improving the accuracy–cost trade-off of first-principles–based simulations used to study warm-dense-matter systems. Josh's primary focus centered around warm dense hydrogen, whose properties play a crucial role in our understanding of dynamical processes in inertial confinement fusion implosions and within large gas giant planets such as Jupiter and Saturn. Josh utilized state-of-the-art methods within density functional theory (DFT) to re-examine the insulator-to-metal transition in warm dense hydrogen. This work, which resulted in tighter, more-accurate theoretical bounds on the insulator-to-metal-transition, was a precursor to the enhanced equation of state for hydrogen used today.

To tackle the exorbitant cost that can arise in first-principles simulations driven by Kohn–Sham (KS) DFT at elevated temperatures, Josh leveraged machine learning (ML) in his research. Here, he developed a ML force field that corrected the computationally feasible but less-accurate orbital-free (OF) DFT ionic forces to produce those comparable in accuracy to the computationally demanding KS ionic forces needed to drive reliable molecular-dynamics simulations. This work extended the temperature range for which OF-DFT is applicable ($T > 100{,}000$ K to $T > 10{,}000$ K), allowing for molecular-dynamics simulations with KS-level accuracy at a cost reduced by a factor of 10 or more. In addition, this work has enabled the simulation of larger systems over longer timescales, both of which are typically not possible with the standard KS-DFT approach.

Josh also pioneered the development of a physics-informed ML interpolation scheme that was used in conjunction with the resulting material properties from first-principles simulations to provide a fully thermodynamically consistent equation of state for warm dense polystyrene. This work has opened a path toward constructing fundamental equations of state that contain all contributions from the ions, including those from ionic entropy—which, at present, has been unavailable directly from first-principles simulations and plays a crucial role in many demixing situations often found in planetary interiors.

ML and its applications in the physical sciences is a rapidly evolving field, and Josh is excited to continue his research as a postdoctoral scholar at Southern University, where he will work in collaboration with the CMAP team here at the University of Rochester and beyond to leverage ML to provide further insights into warm dense matter from a first-principles viewpoint.

> "Studying here at LLE has been a great experience and one that has given me many tools to start my career off on the right track. **I am very thankful for my time in the High-Energy-Density Physics Theory Group,** where everyone created an amazing environment that fostered insightful conversations and cultivated scientific curiosity."



"LLE introduced me to the fascinating world of high-pressure chemistry—a cutting-edge research arena that changed and propelled my career in a new direction. **I am extremely thankful to my advisors and other scientists at LLE** for giving me this world-class research experience in graduate school."

Dr. Maitrayee Ghosh

Department: **Chemistry**
Advisors: **S. Zhang and S. X. Hu**

Maitrayee Ghosh's doctoral research focused on exploring the chemistry and physics of high-energy-density (HED) materials by using *ab initio* computer simulations. The materials she studied, including iron, alumina, and hydrocarbons, are the building blocks of planets and also widely used in HED and inertial confinement fusion (ICF) experiments. Understanding the behavior of these materials at extreme conditions relevant to planetary interiors and HED/ICF experiments is extremely useful for improving planetary models and experimental design and interpretation.

Maitrayee's work exemplifies the fact that materials under HED conditions behave differently from those at standard temperature and pressure, demonstrating new properties that could enhance what we know about the dynamics of planetary interiors and HED/ICF targets. Her work on iron at pressures found at the core of the Earth and super-Earths has confirmed the mechanism of a collective motion called "cooperative diffusion," which is exhibited by groups of atoms at temperatures of only a few thousand degrees Kelvin below the melting point. This was found to be associated with low-energy barriers along the direction of diffusion, large elastic anisotropy, as well as the mechanical and dynamic stability of the body-centered-cubic phase of iron—all of which offer possible explanations to seismic observations of the Earth's inner core.

Her calculations of alumina demonstrated an insulator-to-metal transition upon melting, which adds evidence to the dynamo theory and generation of magnetic fields within the magma oceans of early Earth and exoplanets. Finally, Maitrayee's simulations of carbon–hydrogen mixtures revealed the conditions necessary for diamond formation or disintegration within the interiors of ice giants. These results provide a wealth of knowledge that can be compared with previous experiments and calculations to help improve our understanding of the complex phase behaviors of plastic ablators widely used in ICF experiments.

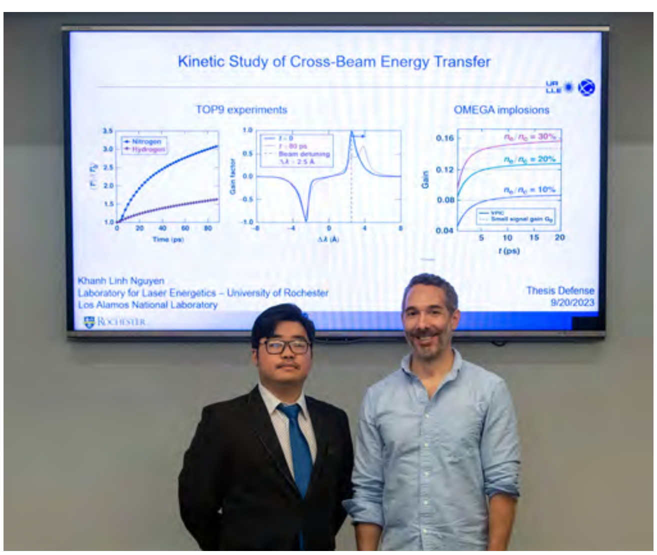
Many intriguing questions remain about materials under various HED conditions, and Maitrayee is excited to continue delving deeper into this field as a postdoctoral scholar at SLAC National Accelerator Laboratory at Stanford University.

Dr. Linh Nguyen

Department: **Physics and Astronomy**
Advisor: **J. P. Palastro**

Controlled fusion could deliver an almost endless supply of power with relatively low environmental impact and a nearly inexhaustible reserve of fuel. The laser-driven inertial confinement fusion approach employs an ensemble of laser pulses to compress a target of deuterium–tritium fuel encased in a thin outer ablator layer. Ablation of the target surface, however, forms a low-density plasma apt for the growth of instabilities. Of these instabilities, cross-beam energy transfer (CBET)—that is, the resonant exchange of energy between laser pulses mediated by ion-acoustic waves (IAWs)—has been identified as the leading cause of decreased energy coupling in direct-drive implosions on OMEGA.

Linh Nguyen's thesis focused on providing a deeper understanding of CBET by modeling the instability at the microscale level where electron and ion kinetics prevail. To do this, Linh harnessed some of the largest supercomputers in the world. Linh's work uncovered a novel mechanism that can prevent the unfettered growth of CBET. Specifically, he found that ions trapped in IAWs can modify the velocity distribution function of ions, thereby detuning the CBET resonance. Linh's predictions were then confirmed by experiments that used the TOP9 laser–plasma interaction (LPI) platform on the OMEGA laser. He also showed that this saturation mechanism for CBET is unlikely in hot-spot–ignition designs, but could play a role, along with stimulated Raman scattering and pump depletion, in shock-ignition designs. As a part of this research, Linh led a multi-laboratory collaboration between LLE and Los Alamos National Laboratory. After his impressive graduate career as a Horton Fellow at LLE, Linh will work as an LPI modeler for Focused Energy Inc., a German American laser-based fusion startup dedicated to developing fusion as a means of generating safe and clean energy.



"Working at LLE, I found not just knowledge but a reflection of my potential, and each moment there became a footprint on my PhD journey. **The stimulating academic environment provided by the laboratory has been unique and crucial to my scientific career.**"

Dr. Tanner Simpson

Department: **Physics and Astronomy**
Advisor: **J. P. Palastro**

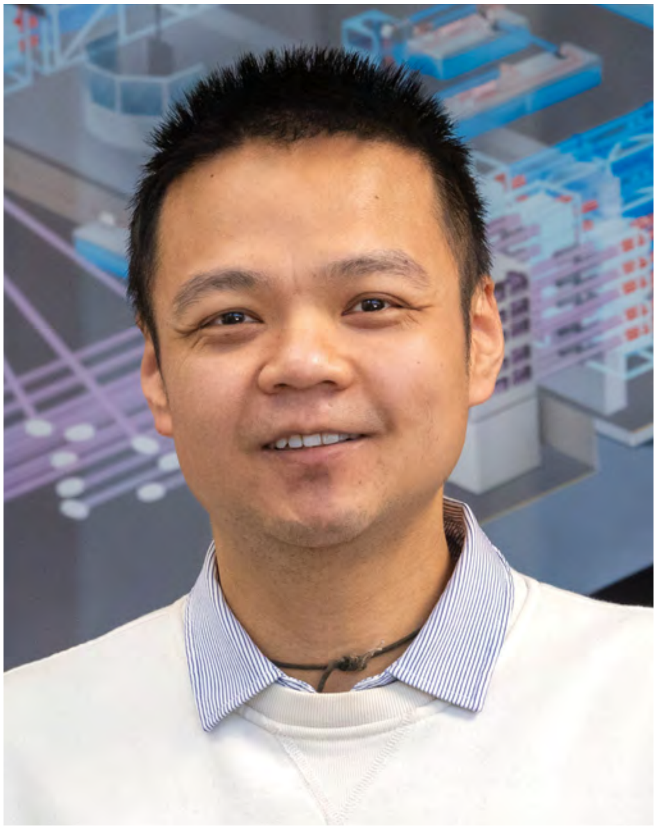
Sculptors mold raw materials into forms that evoke a sense of awe from their observers. Tanner Simpson is a sculptor of photons. Tanner's graduate work at LLE focused on shaping laser pulses into novel structures to enable and enhance a wide range of laser-plasma applications. A chisel, of course, does not work with photons, so instead, he used chromatic optical elements, which focus different colors to different locations, and nonlinear optical elements—special lenses that respond sensitively to the strength of a laser pulse. Using these elements, Tanner showed that the space–time structure of a laser pulse could be arranged to produce intensity peaks that can travel faster than the speed of light and feature electromagnetic vortices, or swimming pool-like eddies made of photons.

While the value of a sculpture may be purely aesthetic, the value of structured light is also keenly utilitarian. In this regard, Tanner applied his novel structured pulses to the spatiotemporal control of photoionization and THz generation. He wrote and used advanced simulations to show that a structured laser pulse can create much longer and more-contiguous plasma channels (a critical component of advanced particle and photon accelerators) than a conventional laser pulse. Tanner then demonstrated that the programmable velocity intensity peak of a structured laser pulse can be used to control the emission angle, focal spot, and spectrum of THz radiation—and increase the overall yield. The highly focusable, single-cycle THz pulses created by a structured pulse are ideal for probing picosecond dynamics of high-energy-density materials or pumping new states of matter. After his impressive graduate career, Tanner will continue to sculpt the future as a research scientist at Johns Hopkins University Applied Physics Laboratory.

> "The Laboratory for Laser Energetics is like a science factory. **The access to brilliant and engaging mentors is incredible.** I can't envision a better place for graduate research."

Dr. Ming Wang

Department: **Chemical Engineering**
Advisor: **D. R. Harding**



Ming Wang successfully defended his doctoral thesis, "Mechanical Properties of Additively-Manufactured Foam Structures Comprised of Micrometer-Size Cells" earlier this spring. His project was to develop a concept to improve the survivability of inertial confinement fusion (ICF) targets mounted on glass fill tubes. This project was initiated in 2018 to support the Cryogenic Fill-Tube Development portion of the 100-Gbar Project.

One of the biggest challenges in ICF target fabrication is minimizing the size of the structure used to support a target (in order to maximize its implosion performance), while ensuring that the target survives the high-vibration impulses it experiences as it is moved within the Omega Laser Facility. Targets weighing 50 μg are supported on a glass tube only 10 μm thick at the point of contact. The vibrations, which induce whiplash, bend the glass and can lead to it fracturing. To help dampen these vibrations, Ming developed a submillimeter-diameter foam "collar" to surround the glass tube away from the target (outside of the laser beams) and at the position where it experiences the highest flexure. This structure was additively manufactured with dimensions that were optimized to provide strength in high-stress regions while allowing the structure maximum flexure to dissipate energy.

"Professor Harding and the team have created a welcoming environment that is friendly, professional, and respectful. **Studying at LLE has been the most fortunate and invaluable experience in my life.** I will carry these precious memories into my future career in science."

New Foundations

LLE Unveils New Office and Laboratory Expansion

Focus on Plasma & HED Physics: New Foundations

After four years of extensive planning, design, and construction, the Laboratory for Laser Energetics is brimming with excitement after doors opened earlier this spring to the new Office and Laboratory Expansion—the first major addition to the facility in nearly 20 years. Since its founding in the fall of 1970, LLE has grown from its humble beginnings as an interdisciplinary entity within the University of Rochester's College of Engineering and Applied Science to a vibrant, innovative, and internationally renowned center for education and scientific research.

Located along the south side of the LLE building complex, the new 66,600-square-ft, three-floor building cuts a strikingly modern figure against the east end of the facility and will provide office and advanced laboratory space for over 100 scientists, students, and staff. Floor-to-ceiling tinted-glass windows illuminate nearly the entire width of the building, which looks out onto a neatly landscaped nature and picnic area, with sidewalks running along the lawn and around the facility to the nearby parking lots. Inside, a spacious atrium forms the architectural focus of the new building. Centered within the atrium, the main staircase is surrounded by common areas on two levels and flooded with natural light, and the warmth of the interior brick façade, which previously formed the exterior of the East building, creates a welcoming atmosphere for staff and students to meet, mingle, and share ideas.

The Office and Laboratory Expansion marks a particularly exciting new chapter in LLE history, with its timely opening following the finalization of a new cooperative agreement for a record $503 million between LLE and the US Department of Energy's National Nuclear Security Administration. The funding will enable LLE to continue operating the Omega Laser Facility; collaborate with the greater scientific community to develop novel diagnostics, experimental platforms, and laser technologies; expand LLE's role in high-energy-density–physics research, training, and education; and much more.

"LLE's work in high-energy-density science continues to grow with each new year, and now their physical footprint is catching up," said Sarah Mangelsdorf, University of Rochester President. "The addition of these state-of-the-art facilities helps strengthen LLE's designation as one of the leading laser laboratories in the world and will provide space to support its expanding research agenda."

LeChase Construction Service managed the build in collaboration with Cannon Design, Passero Associates, M/E Engineering, and 30 other primary contractors to complete the $46.1 million project. Highlights of the facility expansion, outlined in this article, include laboratory space for the new AMICA (active multipass imaging cavity amplifier) Laser System, a thin-film coating laboratory, a class-100 target fabrication laboratory, a new laser computing facility, and several other optics and general-purpose laboratories.

The scientific breakthroughs and technological advances made by scientists, students, engineers, and visiting scholars over the past 50 years since LLE's founding have been tremendous and no doubt made possible in part by the laboratory's world-class facilities and unique academic setting as part of the greater University of Rochester campus. We look forward to the next 50 years of innovation as we transition into this new cutting-edge facility.

AMICA

The largest laboratory space in the new facility will house the further development of the AMICA system—a state-of-the-art, high-energy, amplifier designed to be a modular component to future high-power laser systems. As a building block to generating high-power lasers, the AMICA system will be integral to all future laser systems built by LLE in support of the growing national need to use lasers to push the boundaries of science.

AMICA is the powerhouse for the Fourth-generation Laser for Ultra-broadband eXperiments (FLUX)—a recently developed system to demonstrate novel broadband laser technologies developed at LLE as part of the 60-beam OMEGA Laser System. To read about FLUX in detail, please see *LLE in Focus*, Winter 2024, p. 16. Scientists will use FLUX to pioneer research experiments on high bandwidth in long-pulse ultraviolet lasers—namely, to mitigate laser–plasma instabilities and create new paths to high-yield inertial confinement fusion.

From the archives: Construction of the original LLE facility and Laser Bay, 1976. Image courtesy of the Department of Rare Books & Special Collections, University of Rochester Libraries.

CONSTRUCTION BY THE NUMBERS

- **66,600** square feet
- **2587** cubic yards of concrete
- **3900** cubic yards of exported soils
- **1496** metal panels
- **224,000** total work hours
- **91** maximum crew size
- **154** door openings
- **420** tons of debris removed, >75% recycled
- **445** tons of steel

OMAN

The building expansion has been eagerly anticipated by staff in LLE's Optical Manufacturing Group (OMAN), an internationally renowned group that provides comprehensive optics support for large laser facilities around the world, including LLE's own Omega Laser Facility. OMAN produces some of the highest laser-damage–resistant coatings in the world and has supported several other major laser systems, including MTW-OPAL at LLE, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, and Laser Mégajoule at CEA (Commissariat à l'énergie atomique et aux énergies alternatives) in France.

OMAN's new lab space will greatly enhance the shop's coating capacity with the addition of a 96-in. vacuum coating chamber and an optical cleaning facility. In 2022, LLNL transferred this coating equipment to LLE to preserve the capacity of manufacturing high-laser-damage-threshold transport mirrors for the NIF and to be a secondary source for ion-assisted deposition for Advanced Radiographic Capability (ARC) gratings. One of LLE's many long-term goals is to utilize this equipment on future projects by taking advantage of OMAN's technical expertise in the area of large-optics coatings for high-peak-power laser systems.

Target Fabrication

For anyone who has seen the pinhead-sized sample targets used in Omega Laser Facility experiments, it is immediately apparent that these targets are nothing short of an engineering marvel—and a testimony to the dedication and skill of the staff in LLE's Target Fabrication Group. The group, which provides component design and fabrication at the Laboratory, as well as assembly, metrology, and delivery on shot days, will have a new and expanded facility that will be home for various types of microscopy (x-ray tomography, scanning electron, atomic force, confocal, stereo, and compound), which is used to clear the submillimeter-printed parts for quality assurance.

The new fabrication lab is a class-100 clean room, which will be vital for minimizing dust contamination on parts used in experiments on OMEGA. Most of LLE's clean room labs are class-1000—meaning there are up to a maximum of 1000 particles 0.5 μm in size in the sampled air volume of 1 cubic foot per unit of time—while this new space will be an order of magnitude better with less than 100 particles within the same volume of air. Therefore, to keep contamination levels below the laboratory's limit, the building was constructed with special considerations to create and maintain cleanliness, including special air handling and personnel interlocks for staff to ensure they do not introduce contamination when they enter the lab space.

Office Spaces

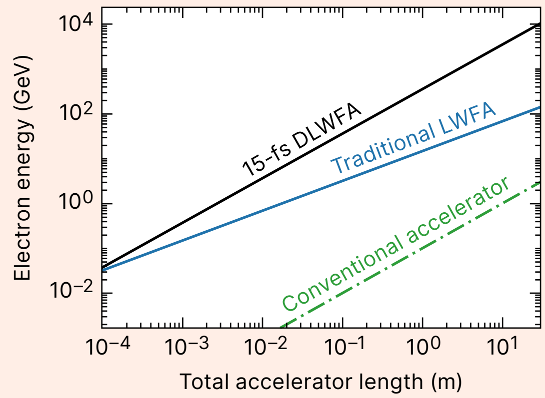
In recent years, as the Laboratory's research agenda and thriving educational opportunities have grown, space at LLE has been at a premium. The new facility, which features over 100 brightly lit new offices and cubicle spaces—in addition to several common areas along the building's expansive eastern windows—promises to be an inviting, comfortable, and productive environment for students and scientists alike.

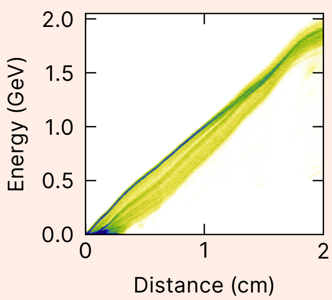
At the Energy Frontier

Novel concept presents path to a single-stage TeV electron accelerator

A novel laser-wakefield accelerator (LWFA) concept based on the LLE-invented "flying focus" [D. H. Froula *et al.*, Nat. Photonics **12**, 262 (2018)] offers a new paradigm in laser–plasma acceleration that could advance the dream of a TeV linear accelerator [J. P. Palastro *et al.*, Phys. Rev. Lett. **124**, 134802 (2020)].

This dephasingless laser wakefield accelerator (DLWFA) decouples the plasma conditions from the acceleration length and removes the need for a guiding structure, which presents a path to achieve electron energies beyond what conventional accelerators can achieve (right figure).





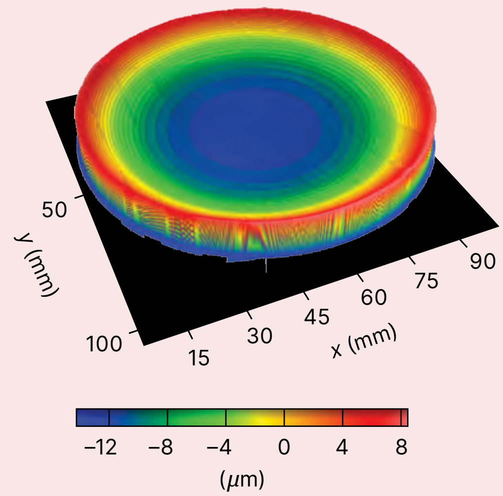
Simulations have demonstrated that focusing an ultrashort flying focus into a plasma creates an ion bubble that can propagate with a trajectory that matches the velocity of accelerating electrons (left figure) [K. G. Miller *et al.*, Sci. Rep. **13**, 21306 (2023)].

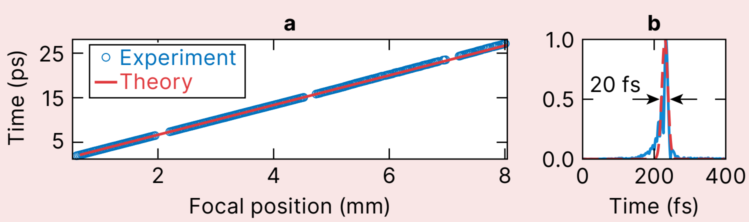
This accelerating structure was driven into a condition where increasing the laser energy directly allows the acceperator length to be extended, suggesting that a single sub-meter-long accelerator driven by the proposed NSF OPAL system [see *LLE in Focus*, Winter 2024, p. 24] would produce electrons beyond 100 GeV—an electron energy that would take 5 miles in a conventional accelerator.

Innovative optics designed, manufactured, and demonstrated at LLE

To enable a flying focus that produces ultrashort-pulse durations, a novel radial echelon optic was invented and coupled to a parabolic focusing optic with an engineered spherical aberration (axiparabola). The axiparabola focuses each radius to a different focal location, creating an extended longitudinal focus, while the radial echelon is a mirror that uses half-wavelength steps to control the time at which the light from a particular radius reaches the focus. Together, these optics control the trajectory of an intensity peak over an extended distance.

To fabricate the optics, LLE's Optical Manufacturing Group invented a coating technique that uses electron-beam evaporation to deposit silicon dioxide monolayers through a discontinuous (stepped) mask profile that creates a series of annular regions. White-light interferometry characterized the steps, which are 100× smaller than the diameter of a human hair (right figure).





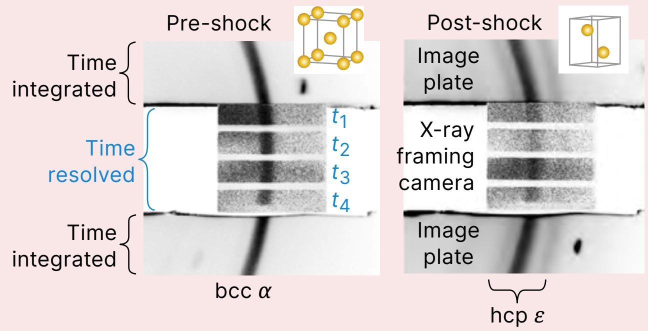
Experiments using the axiparabola-echelon pair demonstrated a small-diameter, ultrashort-duration laser pulse propagating at a controlled velocity over nearly a centimeter (left figures) [J. J. Pigeon *et al.*, Opt. Express **32**, 576 (2024)]. The team is now working to make a combined axi-echelon optic that will be used on MTW-OPAL experiments to demonstrate a DLWFA.

At Extreme Energy Densities

Timing phase changes under high pressure

We know that carbon atoms in graphite transform into diamond hundreds of kilometers below the Earth's surface, where conditions are ideal for atoms to lock into the strong crystal structure of a diamond. But what if these carbon atoms were subjected to extreme pressures and temperatures for one billionth of a second? Would that be long enough for the atoms to rearrange? This is the question we are trying to understand.

Using laser-driven shock waves, we impulsively pressurize materials in a few billionths of a second and use x-ray diffraction to measure the lattice-level arrangement of the atoms.

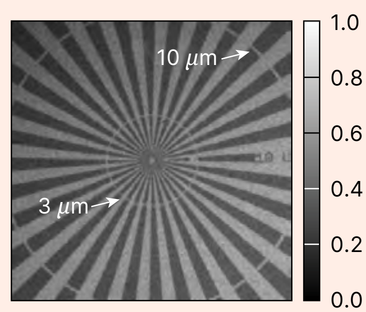


The first time-resolved x-ray diffraction measurements on OMEGA EP are shown in the figure above where a four-frame "movie" of the x-ray diffraction pattern of hot, dense iron was measured on an x-ray framing camera—each with a temporal resolution of 400 ps—and surrounded by time-integrating image plates. The ambient alpha phase was observed as the shock enters the iron (left-hand panel) and the high-pressure epsilon phase is observed at shock breakout (right-hand panel).

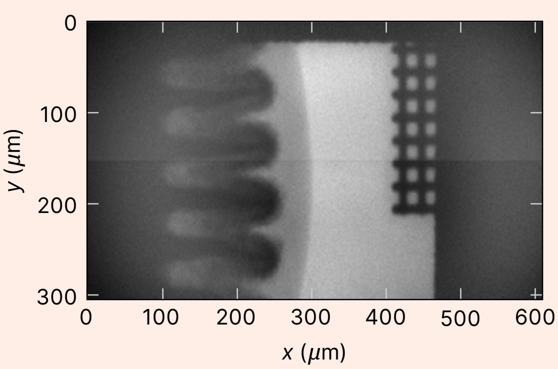
These measurements represent a significant milestone in the development of an experimental platform to collect time-resolved x-ray diffraction measurements on a single laser shot. In future experiments, this transformative diagnostic will be used to understand the role of kinetics on phase transformations under dynamic compression.

Visualizing high-pressure flows at the micron scale

Flow visualization is often beneficial for enhancing the design of both basic and practical high-energy-density systems. Yet despite substantial advancements in high-energy-density science in recent years, measuring complex hydrodynamic flows at fine phenomenological scales, especially beyond 1 Mbar, remains a challenge. Progress in this area has not been limited by the ability to create the necessary high-pressure conditions, but rather by the limitations in spatial and temporal resolutions of contemporary x-ray imaging techniques.



To address these limitations, LLE is forging new developments in high-resolution (micron-scale) flow visualization to evaluate the physics models used in multidimensional radiation-hydrodynamic simulations. In particular, LLE is developing a series of experimental flow-visualization platforms for studying nonlinear hydrodynamic instability and mix under high-pressure conditions. This includes acceleration, shock, and shear-driven flows that give rise to complex emergent phenomena, such as microjetting events and turbulence.



For this research, laser-driven x-ray radiography was implemented at the Omega Laser Facility using a Fresnel zone plate. A static spatial resolution test using a 100-ps-duration, laser-driven x-ray backlighter at 4.75 keV shows micron-level static spatial resolution. The circular regions shown in the figure above highlight where the bar width is 3 μm and 10 μm. This demonstration offers significant possibilities for an improved visualization of fine-scale features in a wide variety of complex flows that are relevant to high-energy-density science, inertial fusion energy research, and laboratory astrophysics.

In a recent instance, high-resolution x-ray radiography, left figure, was used to assess the growth of hydrodynamic instabilities at a modulated interface driven by a blast wave between a plastic pusher propelled by laser ablation and a foam of low density. By utilizing the Fresnel zone-plate imaging system and achieving dynamic resolution at the scale of a few microns, the results reveal evident growth of bubbles and spikes, as well as the impact of vorticity and asymmetric shear on the morphology of the spike tips.

A Future of Inertial Confinement Fusion Without Laser–Plasma Instabilities

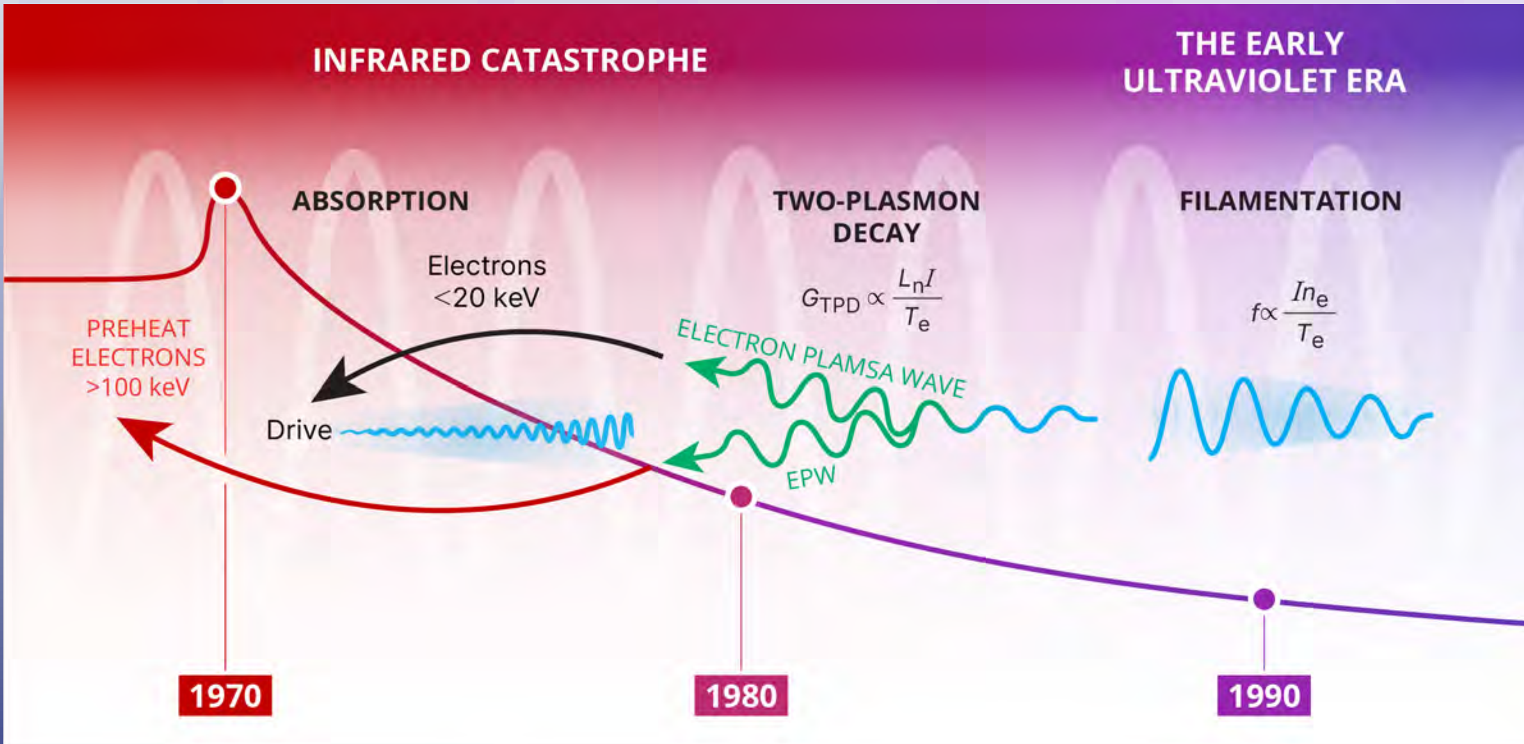
The history of LPIs in ICF

In December 2022, the National Ignition Facility (NIF) delivered 2.2 MJ of ultraviolet (351-nm) laser light into a hohlraum, generating an x-ray bath that coupled ~200 kJ of energy to the capsule, and resulted in a neutron yield well above the laser energy used [1]. This demonstration of ignition confirmed the fundamentals of laser-driven inertial confinement fusion (ICF) that were laid out over 50 years ago [2], illuminating the path to both inertial fusion energy (IFE) and high-yield (>200-MJ) stockpile stewardship science. Much of this path over the next decade is shared before it branches into two distinct sets of requirements that can roughly be divided into high-repetition-rate, moderate-yield implosions for IFE and single-shot, extremely high-yield implosions for stockpile stewardship science.

The process of converting the laser's energy into x rays is inherently inefficient, requiring megajoule lasers for ignition. In principle, this is in contrast to the direct-drive approach [3], in which laser beams directly illuminate the fusion capsule. In this approach, high coupling efficiency has the potential to allow for smaller laser systems to achieve robust ignition.

Nearly immediately after the laser was demonstrated, John Nuckolls recognized that high-energy lasers could enable efficient thermonuclear burn in the laboratory [2]. Within a decade, large Nd:glass and CO_2 gas laser systems were built on the promise of fusion. This included a significant effort at the University of Rochester led by the vision of LLE's first director, Moshe Lubin [4].

Early experiments, and virtually all subsequent experiments, demonstrated the fact that lasers do not like to propagate in plasmas. The collective nature of a plasma—and the fact that moving a single electron in one part of the system moves electrons across the whole system, coupled to the coherent electromagnetic field of the laser beam that oscillates electrons as it propagates into the plasma—leads to a zoo of laser–plasma instabilities (LPIs). It is this zoo of instabilities (Fig. 1) that the ICF community has sought to understand and ultimately tame in order to realize fusion in the laboratory.



The infrared catastrophe

In the 1970s, high-energy lasers were designed around efficient gain media to generate laser beams with wavelengths in the infrared (>1 μm). When these high-power lasers were used to drive targets that created significant surrounding plasmas, LPIs emerged and the challenge to control them began.

It was quickly realized that the maximum momentum a laser imparts on an electron scales with the laser's electric field and wavelength—often referred to as $I\lambda^2$, where I is the laser's intensity and λ is its wavelength. The laser's intensity determines how hard the electron is being pushed, while the wavelength determines how long the push happens—the longer the wavelength, the longer the electric field pushes on the electron and the more energy the electron gains.

> ***Long-wavelength lasers lead to lower-intensity thresholds for LPIs.***

It is the collective nature of the plasma that translates the electron's movement into LPIs: the collective motion of the electrons typically feeds back and intensifies the electric field of the laser, which ultimately prevents it from propagating effectively. It is this feedback that drives a process of exponential growth that is characteristic of nearly all LPIs.

This process was on full display when the large ICF CO_2 laser, Antares, was completed at the Los Alamos National Laboratory. Researchers demonstrated in only two campaigns that long-wavelength lasers generate copious amounts of "hot electrons" that preheat the target, raise the temperature of the fuel prematurely, and effectively prevent fusion. In its brief two years of operation, it was concluded that Antares' long-wavelength laser technologies were poor candidates for achieving fusion [5].

During this pinnacle of long-wavelength experiments that capped the first decade of inertial fusion research, scientists and engineers redesigned the nation's first full fusion machine, Nova, which was already under construction at Lawrence Livermore National Laboratory. At the beginning of construction, the Nova Laser System was envisioned to achieve fusion with 240 kJ of 1-μm light, but ultimately, Nova was scaled down to deliver ~30 kJ of ultraviolet (0.3-μm) laser energy.

The early ultraviolet era

The ability to efficiently frequency triple solid-state lasers to the ultraviolet was crucial for overcoming initial LPI challenges; as a result, the second generation of ICF facilities was born. The Nova mission was updated to develop the physics case for a future 10-MJ high-gain fusion facility and further experiments uncovered the next wave of LPI challenges. The Nova Technical Contract was presented to the community as a guide to justifying a fusion laser facility, which among other details required the community to demonstrate mitigation of filamentation, a key LPI for controlling laser propagation in a plasma.

One of the challenges faced by scientists in early ultraviolet laser experiments was the ability to deposit the laser's energy precisely where they intended. The high-power beams were "digging holes" in the plasma, which caused the laser beams to self-focus and filament. With the invention of phase plates in the late 1980s, the focal spots of the laser beams were broken into small "speckles," making them more robust against filamentation and the laser beams propagated to where they were pointed. The successful completion of the Nova Technical Contract led to the Department of Energy's recommendation to Congress for the construction of the NIF—even at the modest output

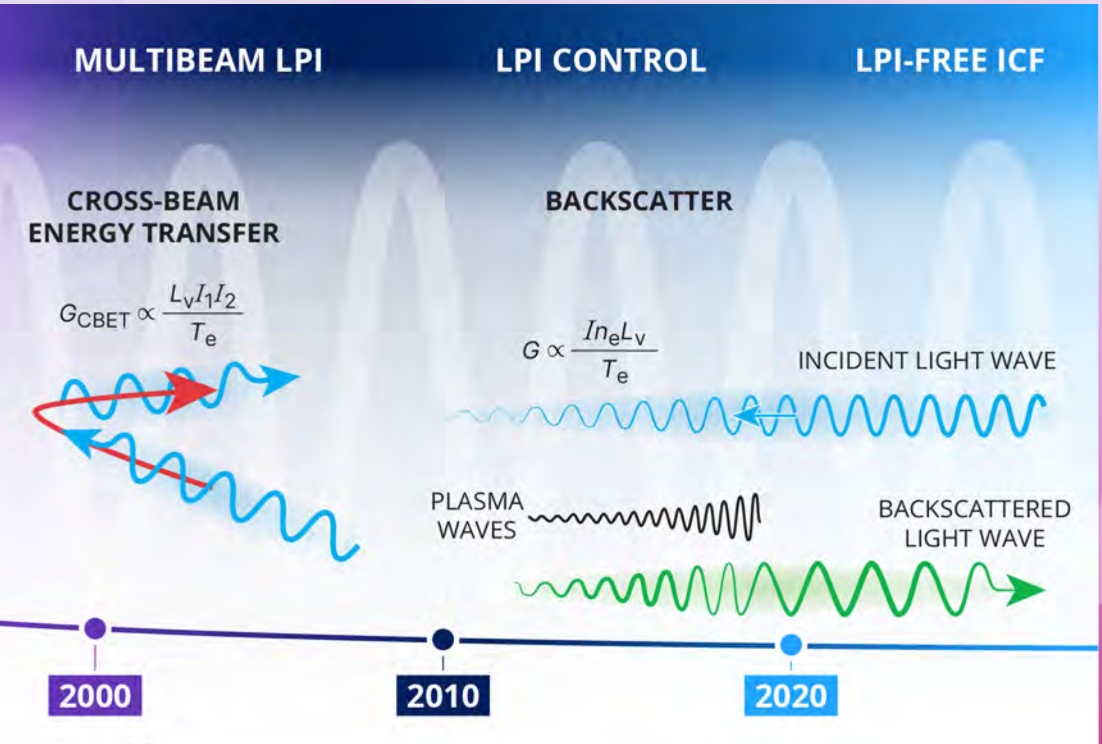


Figure 1. Schematic of a typical laser-produced density profile increasing from right to left. As laser beams propagate up the density gradient to the critical surface where laser light is efficiently absorbed, they are susceptible to several LPIs that can divert their energy, thereby reducing their energy coupling or directing the energy to regions that were not intended. During the "infrared catastrophe," long-wavelength lasers excited LPIs, which resulted in copious amounts of "hot electrons" preheating the target fuel. By reducing the wavelength of the laser beams, experiments during the "early ultraviolet era" uncovered the need to control filamentation. Large multibeam laser facilities provided the platform to investigate multibeam LPIs like cross-beam energy transfer. Learning to control multibeam instabilities and remaining below the thresholds for stimulated Brillouin and Raman scattering instabilities resulted in the first demonstration of ignition in the laboratory. Future ICF facilities will likely use laser bandwidth to operate LPI free.

energy of 1.8 MJ, the laser system was 60× more powerful than the next-largest laser facility in existence, even to this day.

Near the end of the 1990s, laser technologies matured to allow for the investigation of the effects of bandwidth on laser–plasma instabilities, but at the time, the available laser technologies limited the effects on instabilities to essentially mitigating filamentation.

Multibeam laser–plasma instabilities

In 1995, during the design and construction of the NIF, the OMEGA Laser System was completed at LLE. This laser system, the largest in any academic institution, uses 60 ultraviolet laser beams to deliver 30-kJ total energy directly to cryogenic capsules to study direct-drive fusion. OMEGA provided one of the first systems to experimentally study multibeam LPIs.

> ***Controlling multibeam LPIs was one of the final frontiers for demonstrating fusion.***

Mitigation of multibeam LPIs

From nearly the beginning of LPI research, it was known that adding bandwidth to the laser beam can mitigate instabilities, but the coherent nature of a laser creates an inherently narrow bandwidth—that is, laser beams have a single color and therefore efficiently drive LPIs. In the three decades after the construction of the OMEGA laser and the design of the NIF laser, broad-bandwidth (many-color) technologies required for producing short-laser pulses have thrived.

In 2018, LLE gathered a team of laser scientists, plasma physicists, and target designers to investigate a new laser system that could mitigate LPIs using this revolution in laser bandwidth technologies. The team was tasked with creating a system that could (1) achieve a direct-drive ablation pressure necessary for robust fusion (>200 Mbar), while (2) simultaneously mitigating instabilities that generate hot electrons. Because broadband amplifiers had been developed for short-pulse infrared lasers, and due to the technical challenges of frequency converting broadband laser light, studies were initially performed with 1-μm wavelength laser beams. They showed that even pushing the laser intensity beyond reasonable levels did not achieve the required ablation pressure for robust ignition. This process was then repeated for a 0.5-μm laser. It was shown that a relatively high laser intensity could achieve the required ablation pressure, but a fractional laser bandwidth greater than 8% would be required to mitigate hot-electron generation—a bandwidth more than 100× larger than any previously built ICF facility. Simulations using 0.35-μm lasers demonstrated promising results, requiring moderate laser intensities and fractional bandwidths of a few percent.

During this process, the laser science team at LLE invented two novel advancements that enabled broadband ultraviolet laser pulses for ICF: (1) high-energy parametric amplification of spectrally incoherent broadband pulses [6] and (2) a novel sum-frequency generation scheme to efficiently convert broadband infrared light into broadband ultraviolet light [7]. These advancements have been implemented in the Fourth generation Laser for broadband eXperiments (FLUX), which will be operational for LPI experiments at the Omega facility this year.

E. Michael Campbell

A Pioneer in Inertial Confinement Fusion

To many in the field, Mike Campbell is known as a legend and a pioneer who fostered the ICF program in its early days and rallied the community as fusion became inevitable. Mike began his career at Lawrence Livermore National Laboratory in the 1980s working as an experimentalist to understand the anomalously large x-ray signals generated in early ICF experiments. It was during this time that he coined the term "Infrared Catastrophe" in response to the large number of hot electrons generated by long-wavelength (infrared) lasers. Mike's genuine passion for science, combined with his compassion for people, laid the foundation for him to champion the case for the National Ignition Facility. This case was largely built through the Nova Technical Contract, which he authored and used to build community consensus and achieve the necessary Department of Energy and congressional support.

Mike moved to General Atomics in the late 1990s to focus on the challenges of target fabrication before spending time at Sandia National Laboratories to work on pulsed power. Returning to the ICF field in 2017 as the Director of LLE, Mike worked tirelessly to bring the often fractured ICF community together. He focused on greater collaboration among all of the major national players in order to find a common, coherent voice. Mike never lost sight of the community's goal to achieve fusion in the laboratory, and his retirement from LLE in 2021 coincided with what he dedicated so much of his life to: the generation of the world's first burning plasma on the laser system he had worked so hard to make happen, and with the community he helped build.

Mike Campbell holding his son with Vic Reis (father of the Stockpile Stewardship Program) at the proposed NIF site in 1998.

The ICF design space

In all approaches to laser-driven fusion, LPIs limit the available hydrodynamic parameter space. This basic edict arises from the fact that each approach to fusion benefits in some way from higher laser intensities, while LPIs limit the maximum intensity that can be used.

> ***Without LPIs, ICF would likely have been realized decades ago.***

Indirect-drive ICF

For the indirect-drive approach, the minimum size of the hohlraum's laser entrance holes are defined by the intensity threshold for LPIs. Smaller laser entrance holes are desirable for preventing radiation losses, providing greater symmetry control, and enabling higher radiation temperatures—all of which lead to greater fusion performance—but they also require smaller laser-beam diameters and, therefore, increased laser intensities, which exacerbate LPIs.

After the initial National Ignition Campaign, it was determined that LPI mitigation required a reduction in plasma density inside of the hohlraum. This reduced density restricts the hydrodynamic design space by limiting the total implosion time, and therefore requires the system to use challenging capsule materials. Although this path was ultimately successful in demonstrating ignition, LPIs have limited the ablation pressure (~175 Mbar) available to drive the capsule, therefore reducing the robustness of the implosions. As the laser energies are increased with narrowband laser systems like the NIF, the indirect-drive designers will continue to skirt the intensity thresholds of LPIs and walk a fine line of hydrodynamic trade-offs to maximize implosion performance.

Direct-drive ICF

For the direct-drive approach, larger laser intensities lead directly to higher ablation pressures and more hydrodynamically robust capsule designs, but the laser's intensity is limited by multibeam LPIs—typically, hot electrons generated by two-plasmon decay or stimulated Raman scattering. As the laser intensity is increased, the intensity threshold for hot-electron generation is exceeded, and hot electrons preheat the capsule, which prevents efficient compression and, therefore, ignition.

Although the ablation pressure available for a given laser energy has the potential to be significantly larger for direct drive than indirect drive, current narrow-bandwidth lasers produce a limited direct-drive ablation pressure in ignition implosions (<100 Mbar) due to losses driven from the cross-beam energy transfer (CBET) instability (Fig. 2). CBET results when narrowband laser beams cross in a plasma flowing at a velocity near its sound speed. In the direct-drive configuration, CBET scatters energy from the central region of the incident laser beams into the laser light that has refracted through the coronal plasma and is propagating away from the target. This process of transferring incident laser light into the outgoing laser light reduces the absorption of laser energy by a factor of ~1.5. The impact on the implosion, however, is magnified by the fact that the loss in energy comes from the central parts of the laser beams that would normally be more effective at driving the target, and the ablation pressure is reduced by a factor of ~2.

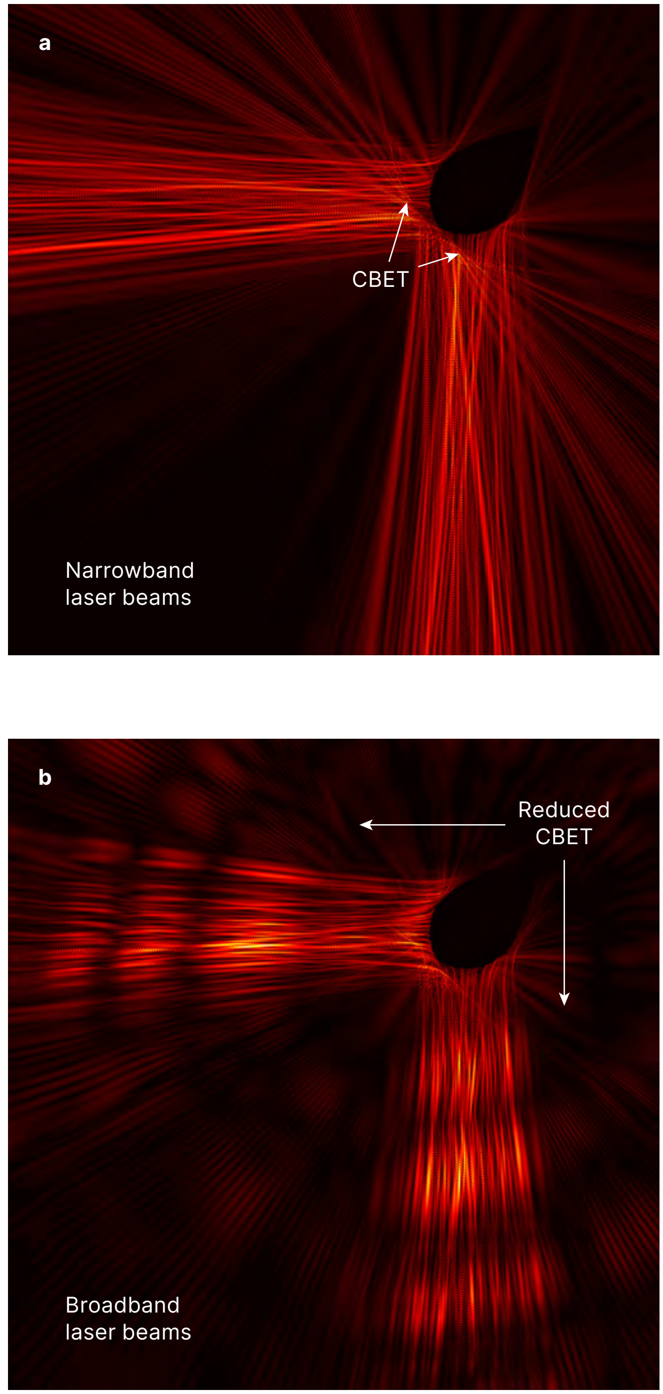


Figure 2. (a) Simulation of two laser beams incident on a spherical plasma from the left and bottom edges interact at the CBET resonant surface, which transfers energy from the central parts of the incident beams away from the target. CBET primarily increases the scattered light in the top left and bottom right quadrants. (b) Simulation of the same configuration but with broadband laser beams. The spectral incoherence generates rapid (~100-fs) temporal modulations in the incident beam intensities. A reduction of scattered light, compared with the narrowband simulation results, is observable in the top left and bottom right quadrants.

Broadband lasers for IFE

For direct-drive designs, the mitigation of LPIs opens the hydrodynamic parameter space by providing ablation pressures that exceed those achieved in current indirect-drive experiments. The laser–plasma simulation environment (LPSE) computer code was developed at LLE to accurately model LPIs at direct-drive fusion plasma conditions. In lieu of a high-power broadband ICF laser driver to conduct experimental validation, LPSE is the most-complete tool for quantifying the effects of laser bandwidth on LPIs and developing reduced models that can be efficiently implemented in advanced hydrodynamic codes.

> ***The creation of long-pulse ultraviolet laser beams with significant color present at all times is the transformative technology that will enable the fourth generation of ICF drivers.***

A laser ray-trace model that includes the effects of laser bandwidth on CBET was benchmarked against LPSE simulations and implemented in the hydrodynamic code LILAC to demonstrate the effects of laser bandwidth on integrated direct-drive implosions [Fig. 3(a)]. As the fractional laser bandwidth exceeds about 0.75%, CBET is mitigated and the ablation pressure approaches the maximum achievable for a given intensity.

As CBET is reduced, the intensity at the quarter-critical density location where hot electrons are generated increases [Fig. 3(b)], which, if not mitigated, would require the laser intensity to be reduced. This reduction in intensity would reduce the gains in ablation pressure shown in Fig. 3(a). While the quarter-critical intensity remains above the hot-electron threshold intensity (0 to 0.7%), even small increases in intensity will lead to large increases in hot electrons. Once the hot-electron threshold intensity exceeds the quarter-critical intensity, hot electrons will be mitigated. Increasing the laser's fractional bandwidth beyond ~0.7% will create an LPI-free zone where the laser intensity can be increased [Fig. 3(b)] and the hydrodynamic design space is expanded toward even more-robust implosions.

These modern state-of-the-art design tools predict an LPI-free design space where broadband lasers enable the significant benefits of direct-drive energy coupling to ablation pressure. This opens the possibility of robust ignition with moderate-scale lasers (Fig. 4). A broadband 30-kJ OMEGA laser with fractional bandwidths greater than a few percent would enable the demonstration of the mitigation of multibeam LPIs and drive cryogenic implosions with ablation pressures that are increased from ~130 Mbar to well above 200 Mbar, opening the design space to include massive hydrodynamically stable implosions.

It would be possible to hydrodynamically scale these LPI-free implosions to future broadband laser systems without neglecting the effects of LPIs—a significant limitation in current narrowband direct-drive implosion experiments that are routinely hydrodynamically scaled to megajoule laser energies. Furthermore, advanced hydrodynamic direct-drive simulations suggest that a broadband 300-kJ facility would achieve a burning plasma, which would enable the physics of robust fusion designs to be tested [see *LLE in Focus*, Spring 2024, p. 18]. These experiments would provide near-certain confidence in a future robust direct-drive fusion facility.

Over the next few years, LLE will work with the broader community to develop the mission need for an "OMEGA Next"—a university scale facility that is large enough to execute science relevant to the Stockpile Stewardship Program while facilitating science and technologies for IFE.

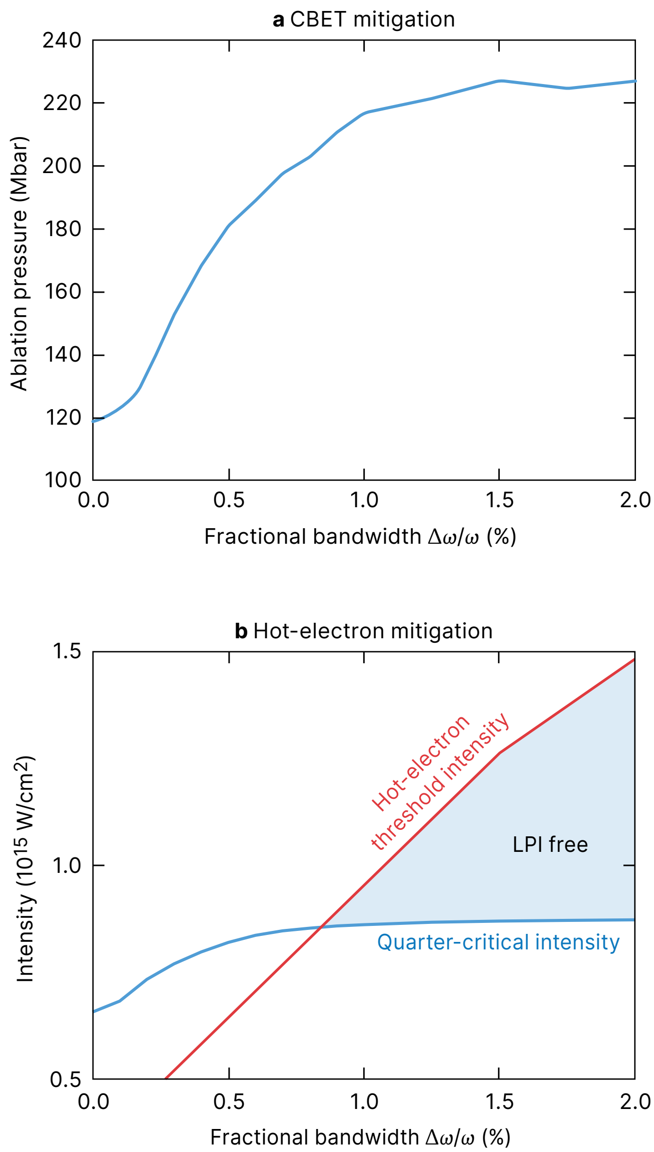


Figure 3. (a) The ablation pressure in hydrodynamic simulations increases as laser bandwidth mitigates CBET for a direct-drive design with a peak vacuum overlapped intensity of 10^{15} W/cm^2. (b) The mitigation of CBET increases the laser intensity at the critical surface where hot-electron instabilities are prominent (blue curve). As the laser bandwidth is increased, the threshold intensity for hot electrons (red curve) increases and exceeds the quarter-critical intensity. Further increasing the bandwidth provides a margin to increase the laser intensity and consequentially the ablation pressure (blue shaded region).

Pushing to high yields for the Stockpile Stewardship Program

Beyond narrowband laser drivers

When the United States stopped underground nuclear testing in 1992, the National Nuclear Security Administration (NNSA) initiated a science-based Stockpile Stewardship Program aimed at reliably testing and maintaining the nuclear stockpile. One of the consequences of this policy has been the need for a high-fusion yield (~500-MJ) ignition platform, which would enable stockpile stewardship science and applications at relevant conditions while providing radiation and neutron sources that meet the needs of the nation. A facility capable of meeting the Stockpile Stewardship Program's goals likely requires significant time between high-yield shots and a laser system capable of delivering >4 MJ of laser energy.

The current stockpile stewardship mission focuses on single-shot, high-yield indirect-drive fusion, which uses narrowband laser drivers that require the use of LPIs (specifically, CBET) to control the symmetry of the capsule while mitigating other LPIs through the use of low-density plasmas. This approach has enabled marginal ignition in the laboratory with moderate neutron gains (~2). The yields will likely continue to increase as the laser energy is increased, but it is yet to be determined if the current narrowband laser approach will continue to skirt the detrimental effects of LPIs as the program works to meet long-term, high-yield goals.

As the community's focus shifts from demonstrating ignition to achieving more-robust, high-yield implosions, the requirements placed on the ICF design space fundamentally change. Current marginal-ignition designs focus on limiting the target mass to drive high fuel velocities and maximize the energy coupled to the fuel to initiate self-heating. High-yield designs require robust confinement to enable efficient burning in the main fuel assembly and set a minimum ablation pressure requirement for robust performance (>200 Mbar). Achieving these conditions with indirect drive requires increasing the energy of the laser without exceeding LPI thresholds, whereas direct drive requires mitigating laser-coupling losses (such as CBET and stimulated Raman scattering) while eliminating hot-electron preheat sources.

One of LLE's principle strategies is to provide leadership in the community through technical solutions, design options, and advocacy for a robust, high-yield fusion platform for stockpile stewardship in the 2040s. Defining the path to robust high-yield implosions with direct drive will require advancing inertial fusion and ignition physics, developing ultraviolet broadband laser technologies, and demonstrating that fourth-generation drivers can mitigate LPIs at conditions relevant to ignition. Using next-generation broadband laser technologies to couple direct-drive ablation pressures at more than a factor of 2 higher than current narrowband laser systems will be a major focus of this work. Successfully demonstrating these scientific and technological requirements will drastically change the landscape for fusion research, making laser direct drive a compelling approach to delivering the high yields required to support the Stockpile Stewardship Program.

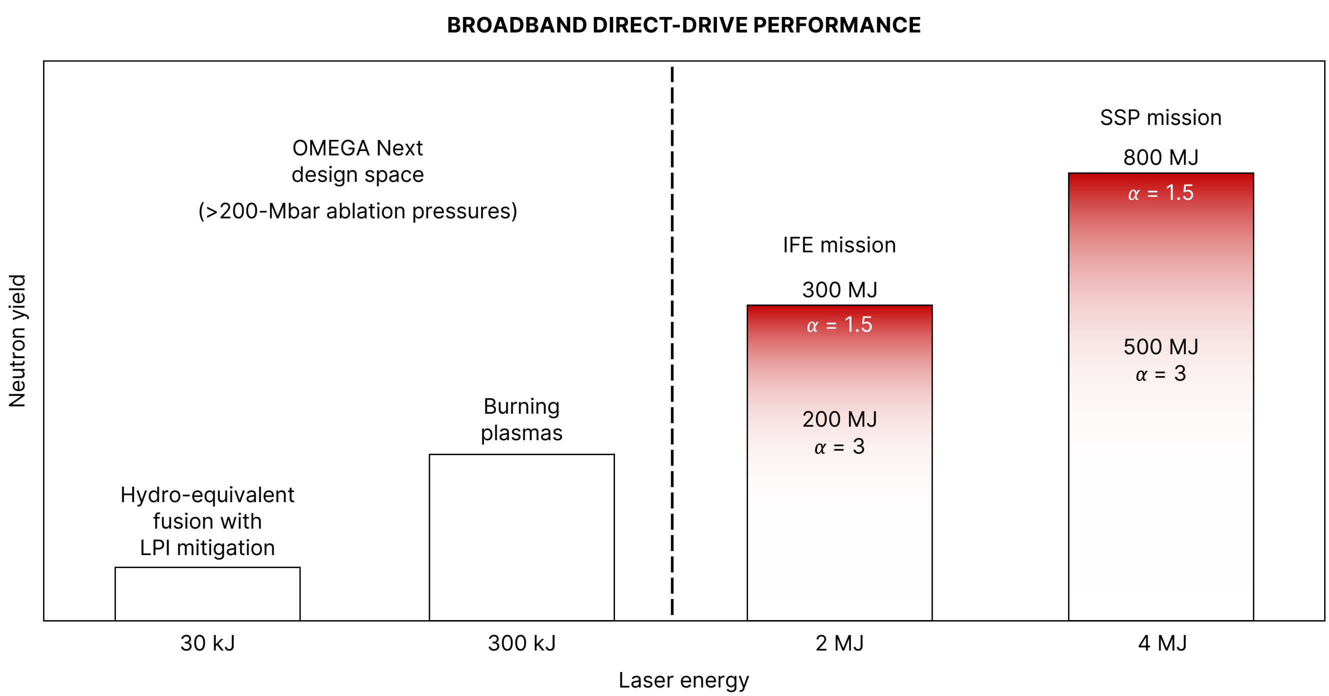


Figure 4. The community is currently defining the parameter space for OMEGA Next, which is envisioned to be a high-bandwidth facility. At 30 kJ, the facility would demonstrate LPI-free implosions with >200 Mbar of ablation pressure, which would scale hydrodynamically to robust ignition at megajoule laser energies. At 300 kJ, OMEGA Next would produce a burning plasma and would be the most-extensive demonstration of a robust direct-drive implosion. Megajoule (<2-MJ) broadband facilities would likely be the optimal energy for IFE by providing significant neutron gains that will ultimately depend on the achievable adiabat (α). Pushing the laser energies to the next level (4 MJ) opens the potential for direct-drive implosions to meet the ultimate goals of the Stockpile Stewardship Program (SSP).

LPI mitigation for IFE

High-bandwidth lasers are a step change for fusion energy

The recent demonstration of ignition in the laboratory has revitalized the pursuit of IFE. In 2023, LLE was awarded $10 million from the Department of Energy's Office of Fusion Energy Science as part of the nation's growing investment in IFE. The University of Rochester will lead the IFE-Consortium on LPI Research (IFE-COLoR) to advance research on IFE science and technology. The Hub brings together a lineup of experts from universities around the country and the private sector to directly address the most-significant science issues that currently pose challenges to the development of an IFE facility. At the outset, this research will present a path to IFE through experimentally tested models implemented in 3D hydrodynamic codes that demonstrate robust high-gain ignition with moderate laser energies.

When mitigating LPIs, direct-drive fusion is the most-efficient approach for coupling energy from the laser into the fusion yield while also providing the most-straightforward concept for IFE with its relatively simple target designs and open geometry. The high-bandwidth (>10-THz), solid-state ultraviolet FLUX system developed at LLE will be used to quantitatively test the physics of bandwidth on the LPIs that limit all IFE designs, which will further illuminate a clear direction to a future fusion energy facility.

> ***The science of bandwidth on LPIs must be quantitatively demonstrated to realize all laser-driven paths to IFE.***

Although much of the support structure for this effort exists, the mission of the Stockpile Stewardship Program that built this infrastructure is synergistic yet distinct from the IFE mission, and without a focused effort like IFE-COLoR, the path to the latter would be significantly longer. Two key attributes that differentiate an IFE facility from one that addresses high-yield stockpile stewardship science are the repetition rate and the total energy of the laser. An IFE facility will likely use the minimum energy possible to generate robust ignition (<2 MJ) at a repetition rate of greater than 10 Hz.

A path to end LPIs in ICF

Current direction

The current path to robust fusion is clear: increase ablation pressure above 200 Mbar to enable the implosion to be driven fast enough to meet the Lawson criterion but slow enough to ensure that the return shock does not break out of the fuel [see *LLE in Focus*, Spring 2024, p. 18]. For the indirect-drive approach, this will likely require increasing the laser energy into the hohlraum without exciting the deleterious effects of LPIs; for direct drive, it will require mitigating CBET and hot-electron instabilities. For both approaches, a high-bandwidth laser could provide the step change required.

Although there is still physics to understand in the hydrodynamic implosions, successfully demonstrating ignition proves that the fundamental principles of laser-based ICF are sound, demonstrating that (1) high-bandwidth lasers mitigate LPIs and (2) that this results in the predicted increase in ablation pressure remain the critical outstanding questions for direct-drive ignition.

FLUX campaigns

The FLUX system was developed to demonstrate the effects of laser bandwidth on LPIs in a well-controlled plasma environment. First-day FLUX experiments will target mature platforms on the OMEGA laser that were developed using narrowband ultraviolet beams and well-characterized gas-jet plasmas that allow the isolation of each of the initial LPIs of interest. One platform will use standard spherical targets illuminated by the 60 narrowband OMEGA beams and the FLUX beam to study the effects of bandwidth on CBET. By varying the FLUX bandwidth and measuring the energy in the transmitted narrowband beams, mitigation of CBET at conditions relevant to direct drive can be demonstrated.

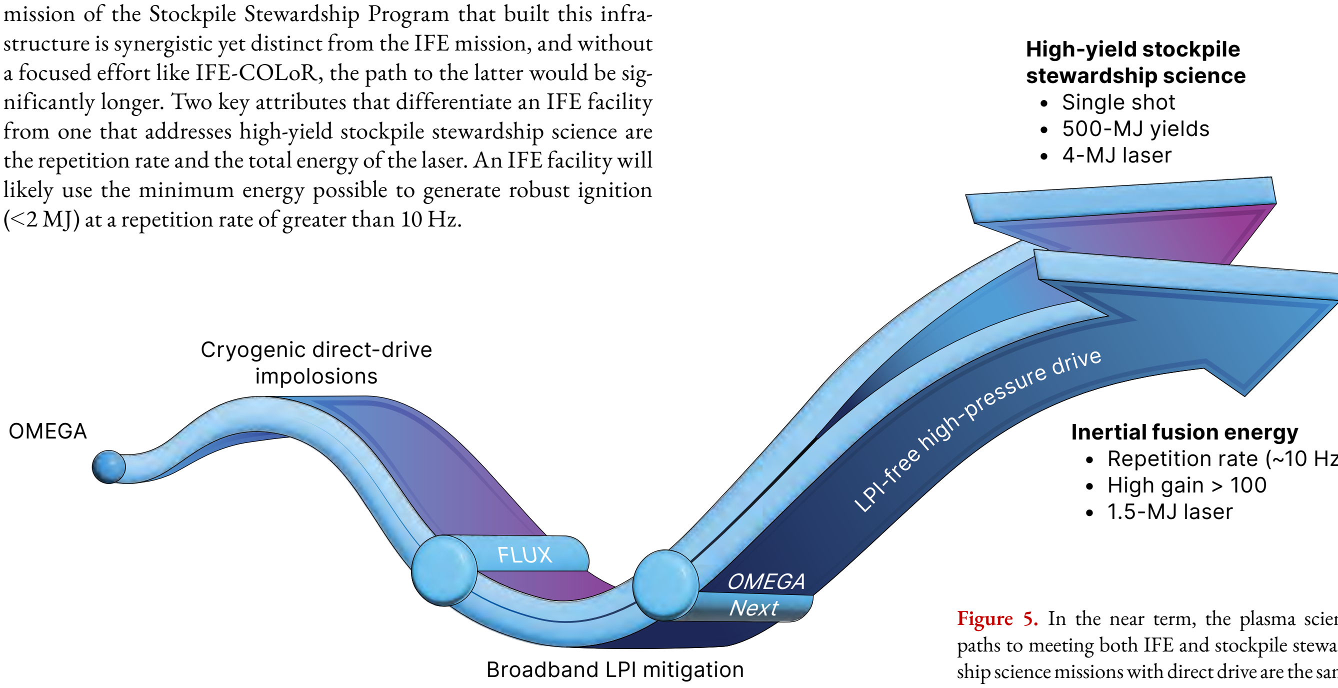


Figure 5. In the near term, the plasma science paths to meeting both IFE and stockpile stewardship science missions with direct drive are the same.

To isolate the hot-electron instabilities that are currently most concerning, a novel *f*/1 focusing configuration has been designed for FLUX. Theory shows that this change in the focusing geometry will raise the intensity threshold for filamentation and enable the hot-electron instabilities to be studied in isolation. Furthermore, the *f*/1 FLUX beam will effectively mimic the electromagnetic field generated by multiple overlapping beams but retain the ability to have laser bandwidth.

> ***The f/1 FLUX focusing configuration will isolate multibeam hot-electron instabilities.***

The FLUX experiments on OMEGA will demonstrate the effects of bandwidth on LPIs and provide a quantified assessment for a future LPI-free laser facility.

OMEGA Next

As OMEGA nears its third decade of operations in support of the Stockpile Stewardship Program, LLE has engaged the community in defining the next-generation facility. "OMEGA Next" is envisaged to be a facility that is large enough to execute science relevant to NNSA's mission needs as well as facilitating science and technology development for IFE while importantly maintaining its ability to train students and young scientists. OMEGA Next would be a next-generation, university-scale laser facility for advancing inertial fusion and high-energy-density science through data-driven discovery, transformational diagnostic methods, advanced computing, machine learning, and fourth-generation drivers.

By accelerating and enriching the discovery cycle at relevant scales, OMEGA Next would support the Stockpile Stewardship Program and, to the extent that the research is synergistic with NNSA's missions, support future IFE needs. This would be derived from a physics-based and data-driven approach to understanding compression and high-energy-density sciences, revealing the unknown physics in uncharted regimes. The current guiding principles for OMEGA Next are:

- Demonstrate at-scale technologies for broadband, multibeam laser facilities.
- Operate at an energy with controlled and/or mitigated LPIs and imprint suitable for testing high-yield direct- and indirect-drive physics concepts and scaling.
- Demonstrate the ablation drive pressure required for robust ignition designs (>200 Mbar).
- Provide the physics community involved in national defense with high-drive-pressure platforms for studying fundamental material properties.
- Allow for a transformational improvement in the target-physics data acquisition rate (e.g., from 5 to 10 shots/day to 50 to 100 shots/day).
- Demonstrate a high degree of operational automation based on machine learning and artificial intelligence algorithms to ensure near 100% experimental effectiveness and facility availability.

OMEGA Next would aggregate diagnostic and target innovations from the other facilities to become a platform on which the requirements for a future high-yield facility could be developed and tested. OMEGA Next would be a generational shift in scientific capabilities for the Stockpile Stewardship Program and culminate in a practical high-yield facility design. As such, OMEGA Next would concurrently push the boundaries of high-energy-density science and serve the user community into the 2040s.

Direct-drive paths split

Research on OMEGA Next would provide the foundation for a direct-drive, high-bandwidth ignition facility. At this point, the path to a future ignition facility diverges depending on the specific mission that is required (Fig. 5). The high-yield stockpile stewardship science mission likely considers a next-generation NIF with configurations to support both robust direct-drive and indirect-drive implosions—and potentially two target chambers to allow for the significant time to prepare and recover from high-yield (>200-MJ) experiments. The IFE community, on the other hand, likely considers a prototype high-bandwidth, high-repetition-rate (>10-Hz), moderate-energy (<2-MJ) facility that can demonstrate the technologies necessary to produce robust high-gain (>10) implosions.

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Focus Points

- It is the zoo of LPIs that the ICF community has sought to understand and ultimately tame in order to realize fusion in the laboratory.
- CBET significantly limits the efficiency of direct-drive implosions driven by narrowband laser beams and ultimately prevents robust ignition.
- FLUX experiments will quantitatively demonstrate mitigation of LPIs with laser bandwidth.
- OMEGA Next would enable hydrodynamic scaling of LPI-free implosions to future broadband laser systems without the need to neglect the effects of LPI.

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Machine Learning

A New Era for Thomson Scattering

Thomson scattering is a powerful technique for determining plasma conditions and over the last two decades has become a turnkey diagnostic on OMEGA. Measuring the light scattered from a laser beam propagating through a plasma is now routinely used to determine electron temperature and density. In 2023, the OMEGA Thomson-scattering diagnostic was used on nearly 40% of the shot days.

Over the past decade, a number of diagnostic improvements have opened new uses for Thomson scattering. These include improvements to the collection system that allow better transmission with less aberrations [1], a new spectrometer that uses polarization to remove the background signal generated by the hot plasma [2], an ultrafast version of the Thomson-scattering diagnostic capable of measuring plasma conditions with picosecond resolution [3], and an entirely new diagnostic—angularly resolved Thomson scattering—that measures electron distribution functions [4].

As scientists collect more Thomson-scattering data for more diverse projects, the ability to analyze the data in a timely manner has become critical. Thomson scattering is analyzed by matching a first-principles physical model to the measured spectrum. This matching has traditionally been done by the scientist modifying the plasma conditions and quantifying the resulting spectrum to see if it is in better agreement with the data. Automation of this multivariable fitting has been elusive, typically using a gradient descent algorithm that requires hours to adequately match a dataset, therefore limiting its usefulness in extracting all of the information.

A team at LLE has introduced machine learning to the Thomson-scattering analysis, which has reduced the analysis time by more than a factor of 100 [5]. By adapting the automatic-differentiation technique developed by the artificial intelligence community, the computer breaks the math into simple operations that are carried out rapidly at the hardware level. These computational improvements were complemented by automating the complete analysis and removing human intervention.

This improved analysis maintains the physical model developed for diagnostic analysis, allowing for a full understanding of the process, including detailed instrumental corrections, assumptions in the model, and error analysis. Moreover, this improved efficiency allows three changes to the current paradigm of Thomson-scattering analysis: (1) faster and higher-resolution analysis, which allows for a better understanding of the evolution of the plasma conditions in an experiment; (2) real-time data analysis, which provides an initial accurate picture of the plasma conditions within a few minutes, allowing the information to be used to educate the experimental team within an OMEGA shot cycle; and (3) the ability to employ more-complicated models such as the ability to determine the entire velocity distribution function.

Figure 1 shows the qualitative agreement achieved by this new algorithm when applied to time-resolved Thomson-scattering spectra obtained on OMEGA. Two spectral peaks associated with the blue-shifted and red-shifted electron plasma waves were observed as a function of time. Figure 1(b) shows the calculated synthetic spectrum, which reproduces the measured spectrum and includes the two features, their widths, and the light observed between them.

This synthetic spectrum represents 360 spectra at a resolution of 1 pixel per spectrum along the temporal direction, which was completed in 11.2 minutes. Previous analysis of this dataset using finite differencing required 90 minutes to analyze 20 spectra. This shows an 8× speedup and 18× resolution improvement, and an acceleration of the required time per spectrum of 144×. This is a generous comparison because the post-processing, refitting, and plotting times are included for the auto-differentiation calculation but not in the finite-differencing calculation. This highlights the effectiveness of applying auto-differentiation to accelerate analysis as a whole.

Figure 2 shows the level of detail in plasma conditions that can be extracted from a dataset and some options for an uncertainty analysis of these conditions. Plasma conditions were extracted from every pixel in the dataset, showing statistical variation in the extracted conditions as well as the long-term trend due to the plasma evolution. Here, the electron temperature and density rise early in time due to the laser heating and ionization of the plasma. This is followed by a period where the conditions are quasi-stationary as the laser heating is balanced by thermal conduction losses. Once the laser beam turns off at 1000 ps (~200 pixels), the temperature and density drop as the plasma cools and expands. By defining the electron-velocity distribution function as a super-Gaussian $\{\exp[-(x/x_0)^m]\}$, evolution is observed as the laser heating flattens the electron distribution function

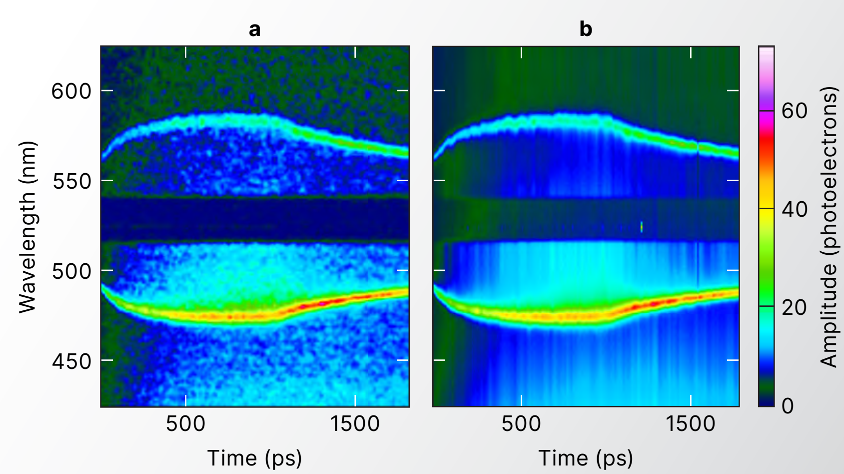

Figure 1. (a) Ray Thomson-scattering spectrum compared with (b) the calculated synthetic spectrum.

to the super-Gaussian order of 3.2, followed by cooling back to a super-Gaussian order of 2 once the heating laser turns off.

The statistical variations in the calculations were analyzed in two ways using the Hessian and a moving window. The Hessian-based technique was used to determine the 3σ contour. Auto-differentiation was used to efficiently calculate these second derivatives. A new option enabled by the resolution of this analysis was used to determine the variance within a diagnostic resolution unit. The diagnostic used for these data had a temporal resolution of 25 ps, corresponding to 5 pixels. A standard deviation was calculated for the 5-pixel moving window to determine the 3σ contour. These two techniques used to determine the statistical uncertainty are in good agreement.

Auto-differentiation combined with GPUs allows a dramatic improvement in the efficiency of model-based diagnostic analysis. For Thomson scattering, the analysis of a spectrum to extract plasma conditions was >140× more efficient. This improved analysis maintains the physical model developed for diagnostic analysis and allows a full understanding of the analysis, including detailed instrumental corrections, assumptions in the model, and error analysis. Moreover, this improved efficiency allows three changes to the current paradigm of Thomson-scattering analysis: (1) faster and higher-resolution analysis, which allows a better understanding of the evolution of the plasma conditions in an experiment; (2) near-real-time data analysis—by performing analysis at a lower resolution, an accurate picture of plasma conditions can be obtained in one to two minutes and then used to educate the next experiment during an OMEGA campaign; and (3) the ability to employ more-complicated models such as the entire distribution function or additional models for missing physics; this enables the field to tackle new and interesting problems. The necessary streamlining of an efficient algorithm has the side benefit of lowering the barrier to performing Thomson-scattering analysis. Finally, this differentiable programming approach has been applied to Thomson scattering as a proof of principle in its application to cutting-edge diagnostic analysis and stands as a blueprint for the application of these principles to other diagnostics.

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Focus Points

- Auto-differentiation combined with GPUs provides a significant improvement in the analysis efficiency—the analysis of a spectrum to extract plasma conditions was 140× more efficient.
- Decreased analysis time has enabled novel insight into the Thomson-scattering diagnostic and models used in the calculations, including quantitative error analysis.
- Thomson-scattering analysis can be done in near-real-time (one to two minutes), allowing information from one shot to be used in planning the next shot.

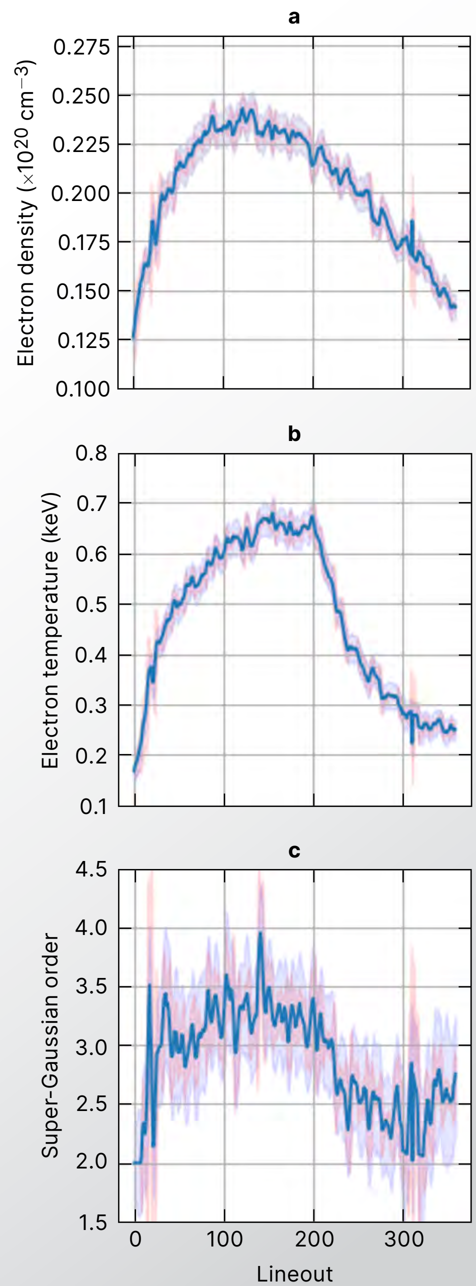

Figure 2. Plasma conditions including (a) electron density, (b) electron temperature, and (c) super-Gaussian order determined from the best-calculated synthetic Thomson-scattering spectrum. Plasma conditions (blue curve) are shown with a 3σ uncertainty calculated from the Hessian (blue shaded region) and from a 5-pixel moving standard deviation (red shaded region).

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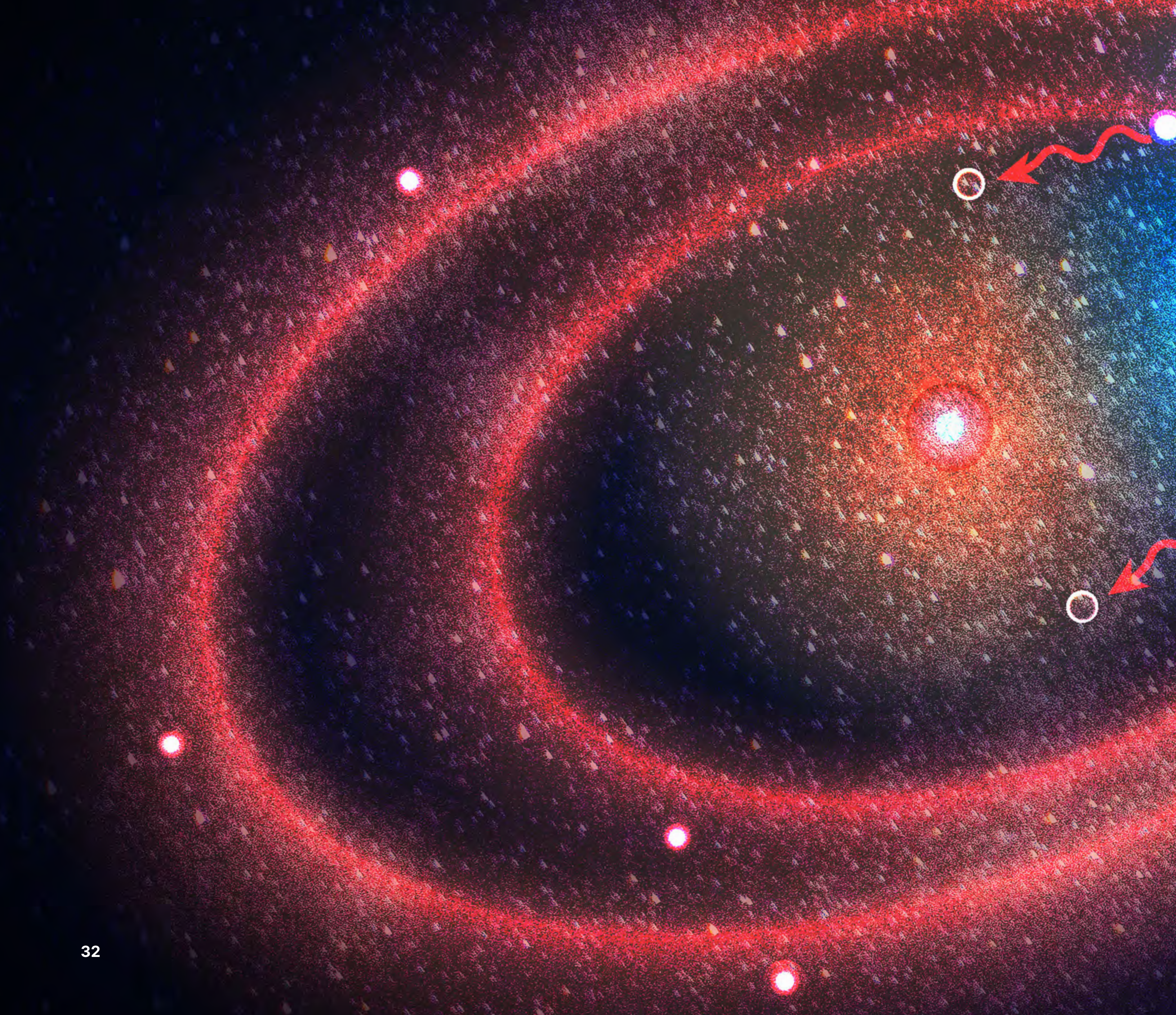
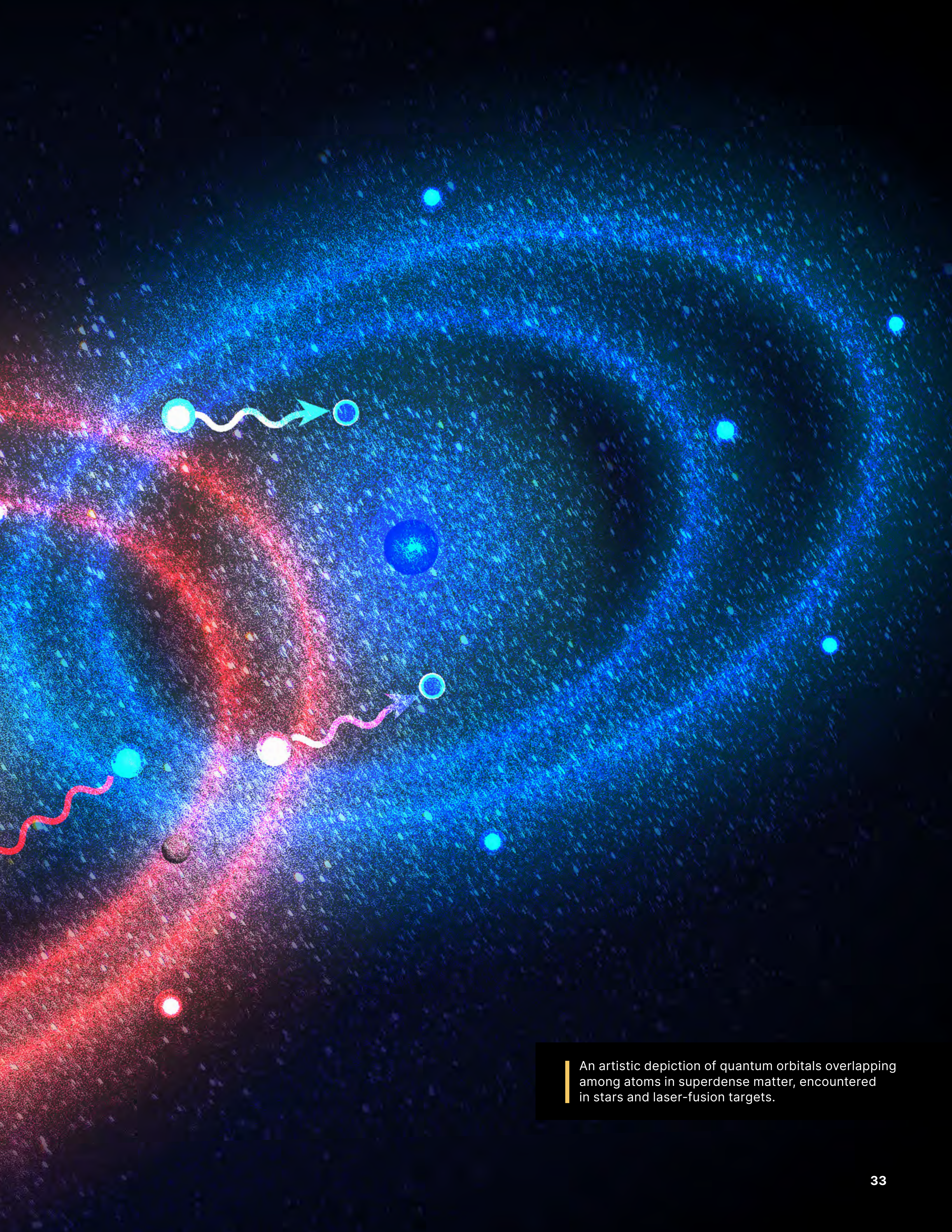
Probing Matter at Extreme Energy Densities

Fundamental and Applied Plasma Spectroscopy





An artistic depiction of quantum orbitals overlapping among atoms in superdense matter, encountered in stars and laser-fusion targets.

Exploring atomic physics through x-ray spectroscopy

Richard Feynman, the 1965 Nobel laureate in physics, famously stated, "Everything is made of atoms." Atoms, in turn, which are composed of electrons that orbit around a positively charged ion, follow the laws of quantum physics with respect to their structure and arrangement. When matter in the form of atoms (and molecules) is exposed to high-pressure and temperature conditions, it transforms into plasma. During this transformation, some or all of the atomic electrons are released and become mobile and are able to move significant distances from their parent ions. In these conditions, x rays are emitted by electrons moving through one of three processes: bremsstrahlung (free–free emission), bound–free emission, and bound–bound transitions.

In 1895, Wilhelm Röntgen discovered x rays, which subsequently laid the groundwork for various scientific disciplines, including quantum physics, quantum chemistry, crystallography, structural biology, and medical imaging. The emission and absorption of x rays in atoms can be considered the distinct "fingerprints" of these systems, with photon emission and absorption features corresponding directly to the movement of electrons within atoms. Consequently, the analysis of an x-ray spectrum provides valuable information about the atoms and the density and temperature of their plasma environments. This area of research is known as plasma spectroscopy.

X rays, unlike electromagnetic waves in the low-frequency range, can penetrate dense matter. In high-energy-density (HED) conditions, where pressures range from millions to trillions of times the atmospheric pressure on Earth, x-ray spectroscopy [1] becomes an imperative tool (sometimes the only means) to understand the physics and chemistry of HED systems. This is because many "unsolved" mysteries in HED science are rooted in the fundamental behavior of atoms in a highly correlated environment. X-ray spectroscopic techniques not only provide a unique diagnostic for electron density and temperature conditions of HED systems, but also serve as a means to explore new physics phenomena that emerge in extreme environments.

In experiments, two types of x-ray spectroscopy measurements are commonly used: x-ray emission spectroscopy and x-ray absorption spectroscopy. The latter includes specific types of spectroscopy such as x-ray absorption near-edge structure [2] and extended x-ray absorption fine structure [3]. These precise x-ray spectroscopy measurements are essential for validating the theoretical physics models of HED matter.

X-ray spectroscopy at LLE

The use of x-ray spectroscopy to diagnose plasmas in inertial confinement fusion implosions has been an important part of LLE history since its early days. In 1976, the late Barukh Yaakobi—who worked as a scientist at LLE for over 40 years—and his colleagues pioneered measurements of spatially resolved x-ray lines from laser-irradiated spherical targets [4]. The following year, Yaakobi's team used x-ray spectroscopy to determine the compression of a laser-driven implosion [5]. They inferred the density and size of the "hot spot" by analyzing Stark broadening, opacity broadening, and the spatial profiles of x-ray emission lines. These early works in x-ray spectroscopy established its continuous use as a diagnostic tool for measuring the density and temperature conditions of laser-produced plasmas.

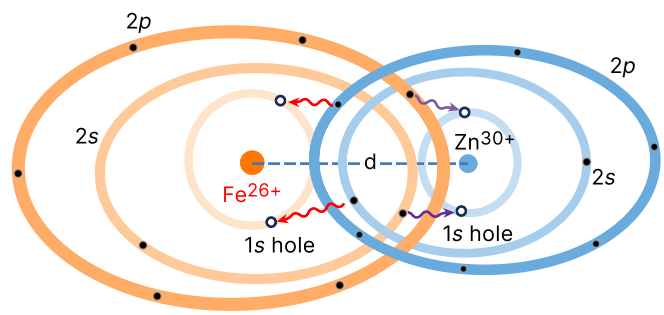


Figure 1. Schematic diagram of interspecies radiative transition in superdense iron (Fe) and zinc (Zn) plasma.

The interpretation of x-ray spectroscopic measurements relies on atomic physics calculations and typically requires *ad hoc* plasma effects to be included to reproduce the observed spectrum (e.g., utilizing plasma-physics models for continuum lowering and line broadening). While these traditional approaches have proven adequate in the classical plasma regime, they are now being questioned in the new HED regimes. This need to acquire new knowledge about quantum HED matter is currently driving both theoretical progress and experimental improvements in the spatial, temporal, and spectral resolutions of x-ray spectroscopy.

Discovering new physics phenomena at high energy densities

The exploration of the physics and chemistry of matter at high energy densities has implications for various scientific investigations and technological uses. This endeavor is essential for elucidating phenomena like crystallization in white dwarf stars, comprehending the long-term growth of the Earth's inner core, and designing targets for inertial confinement fusion.

Under high-density conditions, the behavior of atoms and molecules can drastically differ from what is observed in normal conditions. When subjected to extreme environments, the properties of atomic wave functions can be influenced by neighboring ions, leading to changes in radiation generation and transport in dense plasmas. In dense plasmas, the dipole-selection rule that applies to isolated atoms may no longer hold in certain circumstances. Furthermore, if a plasma mixture is compressed to densities above 1000 g/cm^3, the wave functions of deeply bound electrons from different atomic species may start to overlap.

Figure 1 shows a diagram that illustrates a highly condensed plasma scenario where iron and zinc ions interact. The close proximity between these two species can cause the outer electrons to undergo pressure ionization, resulting in significant distortion of their 2*s* and 2*p* states. This distortion leads to an overlap of the n = 2 states that could potentially give rise to a novel physics phenomenon known as interspecies radiative transition [6]. In this scenario, the creation of 1*s* holes in both iron and zinc ions enables the 2*s* and 2*p* electrons of one species to transition radiatively to the 1*s* hole of the other species, thereby generating interspecies K_α emission.

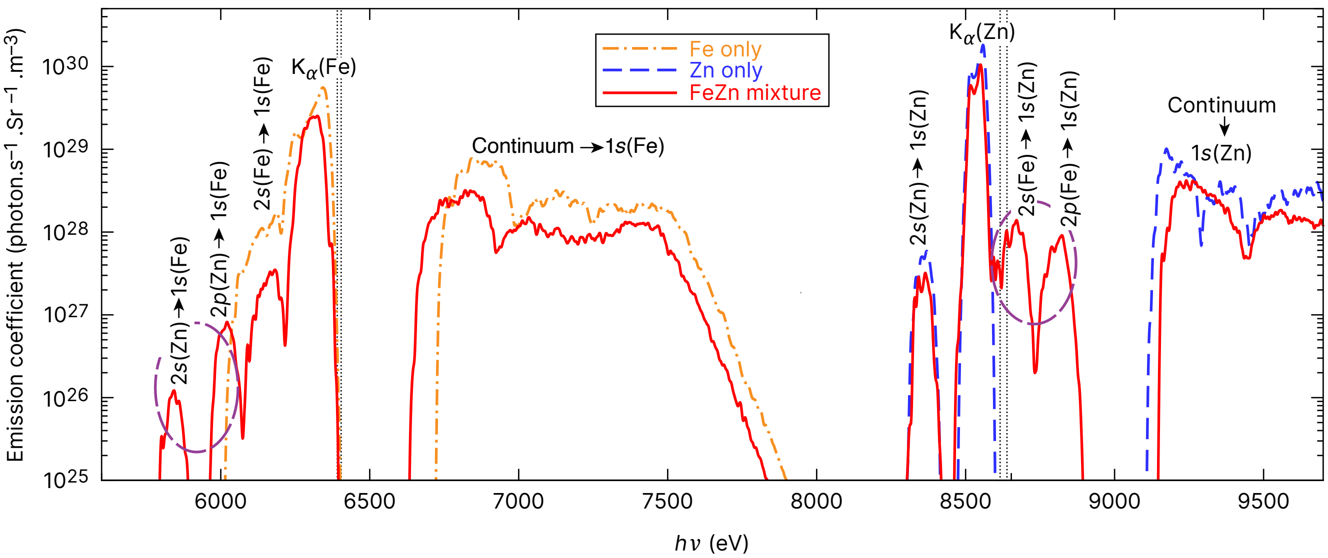


Figure 2. Emission spectra of superdense plasmas. Three cases are calculated for Fe only, Zn-only, and Fe–Zn mixture having 1*s* vacancy at densities of 1000 g/cm^3 and temperatures of 10^7 K using density functional theory.

Interspecies radiative transitions were examined recently by a team of LLE scientists using first-principles calculations with density functional theory [6]. Figure 2 shows four spectral peaks corresponding to transitions from the 2*s* and 2*p* states of the iron ion to the 1*s* hole of the zinc ion (and vice versa) calculated for conditions similar to those found in brown dwarf cores. The vertical dotted black lines mark the normal intra-atomic K_α locations for ambient iron and zinc, respectively. The shift of the intra-atomic $K\alpha$ line to lower energy is caused by the increased electron screening resulting from the dense plasma environment [7]. The intra-atomic $2s \rightarrow 1s$ transitions for each species, although being about three orders of magnitude weaker than the normal intra-atomic K_α lines, also appear as a consequence of the breaking down of the dipole selection rule due to the density-induced distortion of 2*s* states. Accurate x-ray spectroscopy measurements are necessary to experimentally observe these recently discovered physics phenomena that occur specifically under extreme energy densities.

Probing atomic physics at extreme energy densities

Laser-driven implosions combined with x-ray spectroscopy measurements provide a unique approach for interrogating dense and superplasmas. Spherical convergence effects along with the compression associated with shocks launched by the stagnating core squeeze matter to very high densities (up to 1000 g/cm^3) and temperatures ($T = 10^7$ K). Developing reliable atomic physics models at these conditions, guided by high-precision spectroscopic data, is vital for an improved understanding of radiation transport in both astrophysical objects and inertial fusion targets. Detailed spectroscopic measurements at these conditions are scarce, however, and traditional collisional-radiative equilibrium models, based on isolated atom calculations and *ad hoc* continuum-lowering models, have proven questionable, especially beyond solid density.

A groundbreaking study was recently performed by a team at LLE (Fig. 3) that obtained x-ray spectroscopic data and developed state-of-the-art simulation tools to expand the boundaries of this uncharted territory. The experiment involved using spherical laser-driven implosions on OMEGA to investigate how copper atoms respond to the changing density and temperature conditions in an imploding shell. In order to examine the compressed copper, a small amount of argon was added to the deuterium gas in the middle of the target to create a bright x-ray source at the center of the implosion. The high-quality spectroscopic data obtained from both time-integrated and time-resolved (Fig. 4) measurements enabled a quantitative interrogation of continuum-lowering models for dense plasmas.

The study facilitated the development of a self-consistent code, VERITAS, for interpreting x-ray spectroscopy of dense plasmas [8]. VERITAS is a density-functional-theory–based multiband radiative kinetic modeling code designed to accurately treat radiation generation and transport in warm and dense (or superdense) plasma environments. Figure 5 demonstrates that the VERITAS simulations reproduce the essential spectral features observed under these extreme conditions without invoking an *ad hoc* continuum-lowering model. In contrast, conventional plasma spectroscopy approaches are influenced by the choice of atomic physics and continuum-lowering models employed.

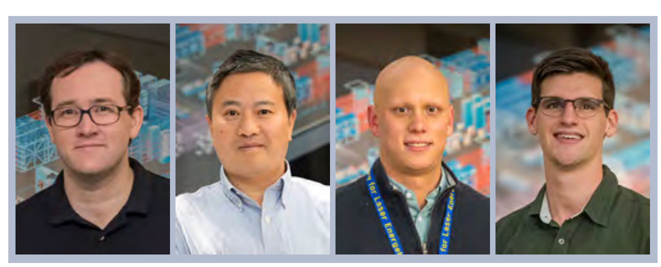


Figure 3. A key aspect of the success of this study was the close collaboration between leading experimentalist Philip Nilson, theorist Suxing Hu, and graduate students David Alex Chin and David Bishel (left to right).

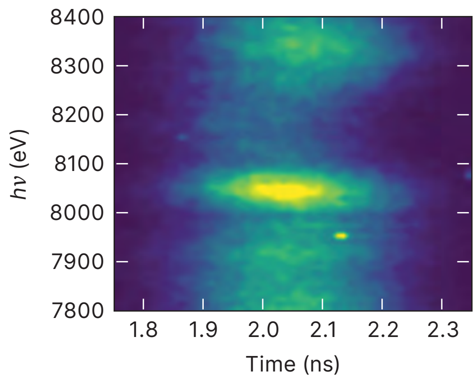


Figure 4. The novel experiments obtained high-quality x-ray spectra that were used to advance our understanding of atomic physics at these extreme conditions. The innovative target concept that embedded a small fraction of copper atoms in a layer between a conventional polystyrene directly driven shell enabled these pioneering results.

At early times [Fig. 5(a)], the standard model overpredicts the emission peak and resolves the K_{α_1} and K_{α_2} spectral lines (due to less broadening). As the heat wave reaches the copper-doped layer (t = 2.05 ns), a 1s to 2p absorption "dip" is observed [Fig. 5(b)] and the standard model exhibits stronger absorption at lower photon energy compared to the measurements, while the VERITAS calculations show the same level of 1s to 2p absorption. This work underscores the necessity for a self-consistent treatment of dense plasma effects on altering atomic energy levels/bands and their populations at high pressure.

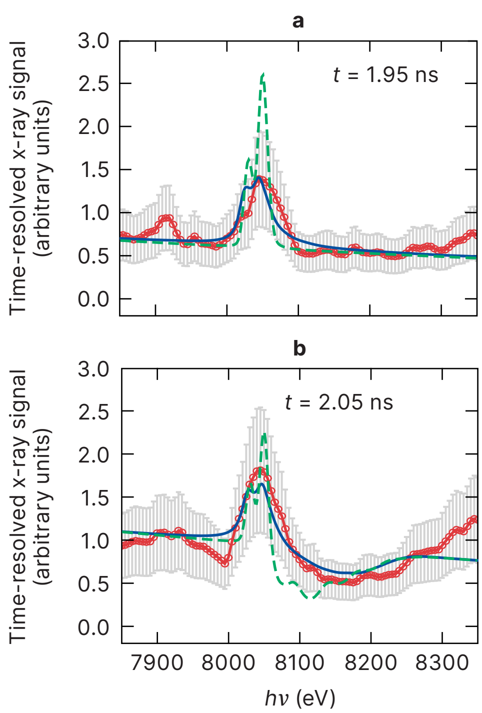


Figure 5. Comparison of measured (red curves) x-ray spectra and those calculated with the state-of-the-art VERITAS model (blue curves), and the standard model (green dashed curves) at two times: (a) t = 1.95 ns and (b) t = 2.05 ns.

The future of x-ray spectroscopy at LLE

The development of x-ray spectroscopy is crucial for advancements in high-energy-density science. This progress encompasses theory, computation, instrumentation, and experimentation. On the theoretical side, significant focus has been put into developing an in-house radiation physics code that incorporates dense plasma effects from density functional theory into detailed atomic configuration calculations using the flexible atomic code. Additionally, the line-shape code MERL is scheduled for an update to handle dense plasmas even more effectively. These efforts will result in a radiation physics code that enables accurate interpretation of high-quality x-ray spectroscopic data.

LLE's strategic plan involves the development of x-ray spectrometers with higher spectral resolution (<5 eV), finer spatial resolution (~10 μm), and shorter temporal resolution (~10 ps). These improved capabilities will open up new possibilities in high-precision x-ray spectroscopy and allow for the exploration of new physics and chemistry in matter under extreme energy densities.

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Focus Points

- Plasma spectroscopy, the analysis of x-ray spectra, is an invaluable diagnostic technique for investigating the behaviors of atoms at extreme conditions.
- A recent groundbreaking study performed on OMEGA obtained highly precise x-ray spectroscopic data, which were used to develop of state-of-the-art simulation tools to expand the boundaries of this uncharted territory.
- Further development of x-ray spectroscopy, currently a primary focus of LLE's overall strategic plan, is crucial for advancement in HED science.

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