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DRIVING DISCOVERY THROUGH INNOVATION



University
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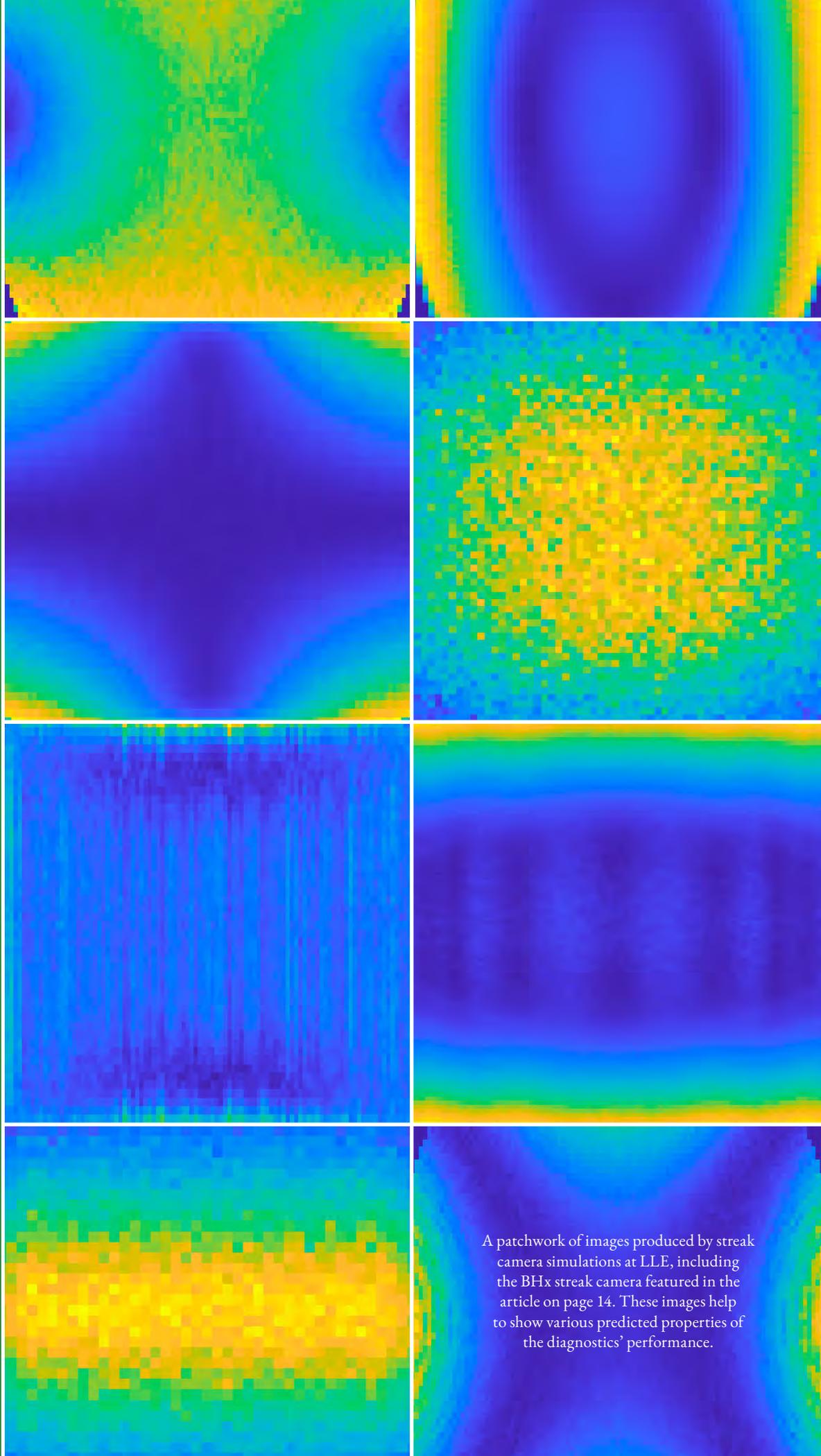
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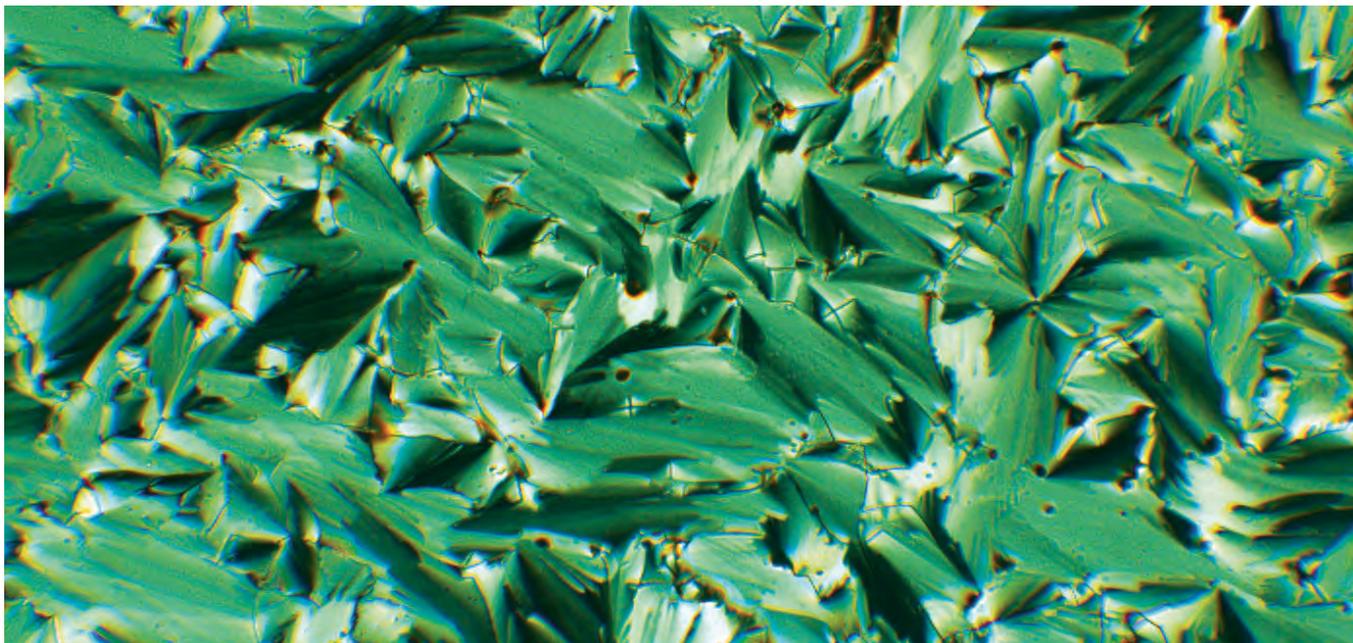
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A patchwork of images produced by streak camera simulations at LLE, including the BHx streak camera featured in the article on page 14. These images help to show various predicted properties of the diagnostics' performance.



A polarized optical microscopy image (10 \times) of a new liquid crystal mixture under development at LLE for enhancing pulse contrast of the NSF OPAL laser. The image was captured by LLE undergraduate student Jenny Zhao and shows the characteristic fan texture of the Smectic A liquid crystal phase. This phase is necessary for the formation of freestanding films that function as renewable plasma mirrors. Read more about how liquid crystals will play an important role for the NSF OPAL project in the article on [page 25](#).

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About the cover

Shown left to right, Shawn McPoyle, Anthony Raymond, Jeremy Hassett, and Nick Pelepchan install the BHx streak tube into its vacuum-chamber housing in the Diagnostics Evaluation Laboratory. The surrounding enclosure contains the laser optics used to evaluate the device's performance.

From the Director

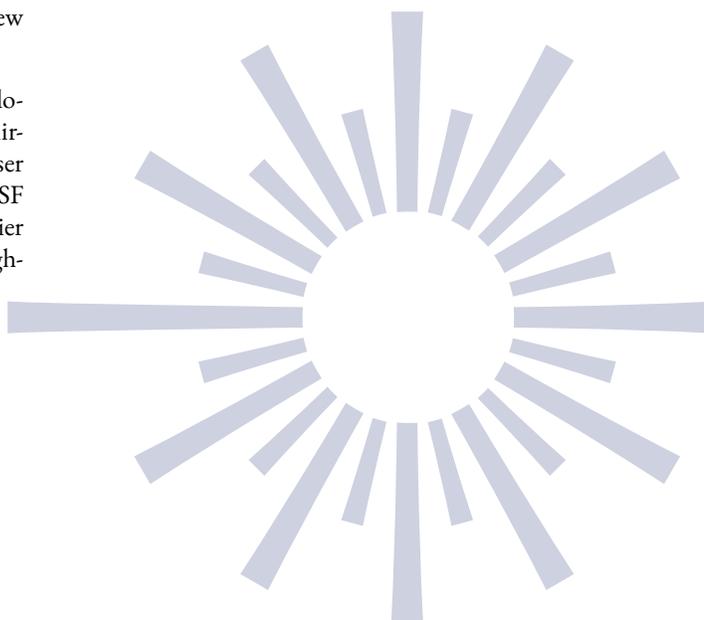
DR. CHRISTOPHER DEENEY | DIRECTOR
LABORATORY FOR LASER ENERGETICS

This issue of *LLE In Focus* zeroes in on the technology at the heart of our experiments and some of the people who make that work possible. The stories collected here reflect a laboratory that is moving quickly but always with precision, dedication, and a strong sense of shared mission.

As always, I'm extremely proud of the awardees in this issue. They highlight early-career scientists pushing into new physics regimes, senior staff whose expertise keeps complex systems performing day after day, and colleagues who invest deeply in mentoring and collaboration. Each of them is advancing LLE's mission in a different way, and together they show the depth of talent of this team. Hopefully, these awardees inspire the recent cadre of graduating students. Having seen the amazing research in their graduate work, I anticipate they will be highlighted in future *LLE In Focus* publications.

Large-scale science for the NNSA, DOE, and NSF missions are enabled by advanced technology. On the technology development front, this issue features systems that are redefining what is possible on OMEGA and OMEGA EP, with the BHx streak camera as a standout example. Designed to capture x-ray emission on picosecond timescales, BHx will give researchers a much clearer view of where laser energy goes in our most demanding experiments and help guide the next generation of target designs. The best of targets can be prevented from delivering the needed results due to laser prepulses. LLE is working on a new way to produce clean laser pulses, ideal for isochoric heating.

We've been making significant progress on other key technologies like high-performance mirrors, liquid crystal plasma mirrors, and methods for characterizing ultrahigh-intensity laser focus. These developments help build the foundations for NSF OPAL, a multipetawatt-class facility that can support frontier experiments in high-intensity laser-matter interaction and high-energy-density physics.



A handwritten signature in black ink, appearing to read 'C. Deeney'.

Christopher Deeney
Director, Laboratory for Laser Energetics

Awards and Honors



LLE Scientist David Turnbull Receives APS Fellowship

LLE Staff Scientist David Turnbull was recently selected by the Council of Representatives of the American Physical Society (APS) to become an APS Fellow. This prestigious honor recognizes Turnbull's outstanding work—in particular, his pioneering experiments and analysis revealing fundamental understanding of laser-plasma interactions that have helped to advance the fields of inertial confinement fusion (ICF) and plasma photonics.

A scientist of the highest caliber and one with a prolific publication record (more than 90 articles including over 20 first-authored), Turnbull is a significant national player in both the indirect-drive and direct-drive National ICF Programs, and his keen focus on ICF contributed to the achievement of ignition in 2022. With his unique ability to ask unassuming questions that reach the core of an issue, Turnbull excels at building collaborations, aiming for scientific understanding, and effectively communicating with diverse audiences to rapidly reach solid scientific conclusions.



LLE Scientist Danae Polsin Receives 2026 Neil Ashcroft Early Career Award

LLE Staff Scientist and University of Rochester Assistant Professor of Mechanical Engineering Danae Polsin has received the American Physical Society's 2026 Neil Ashcroft Early Career Award for Studies of Matter at Extreme High-Pressure Conditions. The award cites Polsin's work "for pioneering experiments mapping the evolution of electronic and ionic structural complexity of alkali metals to terapascal conditions."

Polsin is an outstanding scientist whose work pushes the boundaries of several new high-energy-density science directions, including extreme quantum matter, laboratory astrophysics and planetary physics, high strain-rate response of materials, optical properties of extreme matter, and the structure of matter at atomic pressures. She has over 11 invited talks and 30 publications in prestigious scientific journals. In addition, she has been awarded resources for multiple proposals, either as the principal investigator or co-principal investigator, at the National Ignition Facility, the Linac Coherent Light Source at SLAC, and the European X-Ray Free Electron Laser Facility.



2025 Operations and Safety Awards

The LLE Operations Awards honor individuals who have demonstrated exceptional dedication to the safe and effective operations at LLE. Shown in the photo, left to right, are this year's recipients: Daphne Lee, recognized for outstanding early career achievements in training, operations, and project support; Ryan McEvoy, honored for exceptional efforts in experimental operations preparation and attention to detail in shot execution; Ray Huff, awarded the Capt. Loucks Lifetime Achievement Award for over 30 years of leadership, project management, and operational excellence; Joshua Kendrick, recognized for proactive engagement in fostering a strong safety culture; and Christopher Czuhanych, honored for his tenacity in debugging electrical systems and contributions to projects. Congratulations to all awardees for their remarkable contributions to LLE's mission.



Alex Chin Receives 2026 APS Student and Dissertation Award

Congratulations to LLE Assistant Scientist David Alex Chin, who was recently selected by the APS as the winner of the 2026 GCCM (Topical Group on Compression of Condensed Matter) Student and Dissertation Research Award. For his dissertation, Chin developed an EXAFS (extended x-ray absorption fine structure) flat-crystal spectrometer capable of measuring high-resolution x-ray spectra. He designed and built the spectrometer from the ground up and successfully deployed it to probe the electronic structure of iron(III) oxide at pressures up to 800 GPa.

The committee received a total of eight nominations—five from the dynamic compression field and three from the static compression field—making for a highly competitive pool of candidates. The award was chaired by Sakun Duwal (Sandia National Laboratories), and committee members included Eric Brown (Los Alamos National Laboratory), Daniel Eakins (University of Oxford), Rebecca Lindsey (University of Michigan), and Anirban Mandal (Lawrence Livermore National Laboratory).

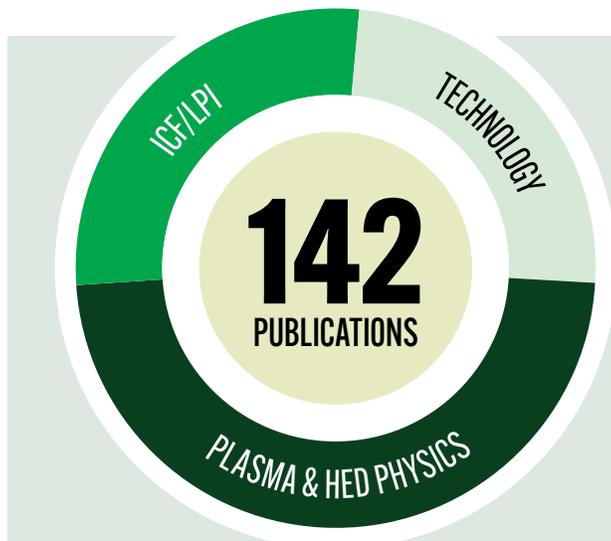


Antonino Di Piazza and International Team Win Prestigious ERC Synergy Grant for Quantum Research

Antonino Di Piazza, Professor of Physics at the University of Rochester and Distinguished Scientist at LLE, is part of an international collaboration that was recently awarded a prestigious €14M European Research Council (ERC) Synergy Grant. The multi-institutional team will use powerful lasers and plasma accelerators to test nonperturbative quantum electrodynamics (NP-QED) under intense electromagnetic fields, reaching regimes where the interaction between light and matter is expected to reveal entirely new physics.

Di Piazza plays a key theoretical role as a co-principal investigator on the proposed NSF OPAL facility, which aims to deliver two 25-PW laser beams and advance research at the frontiers of high-intensity laser science.

Above, the NP-QED team is shown (from left): Andreas Maier and Jenny List from Deutsches Elektronen-Synchrotron (DESY), Henri Vincenti from Commissariat à l'énergie atomique et aux énergies alternatives (CEA), and Antonino Di Piazza from the University of Rochester. *Photo courtesy of Antonino Di Piazza and Andreas Maier.*

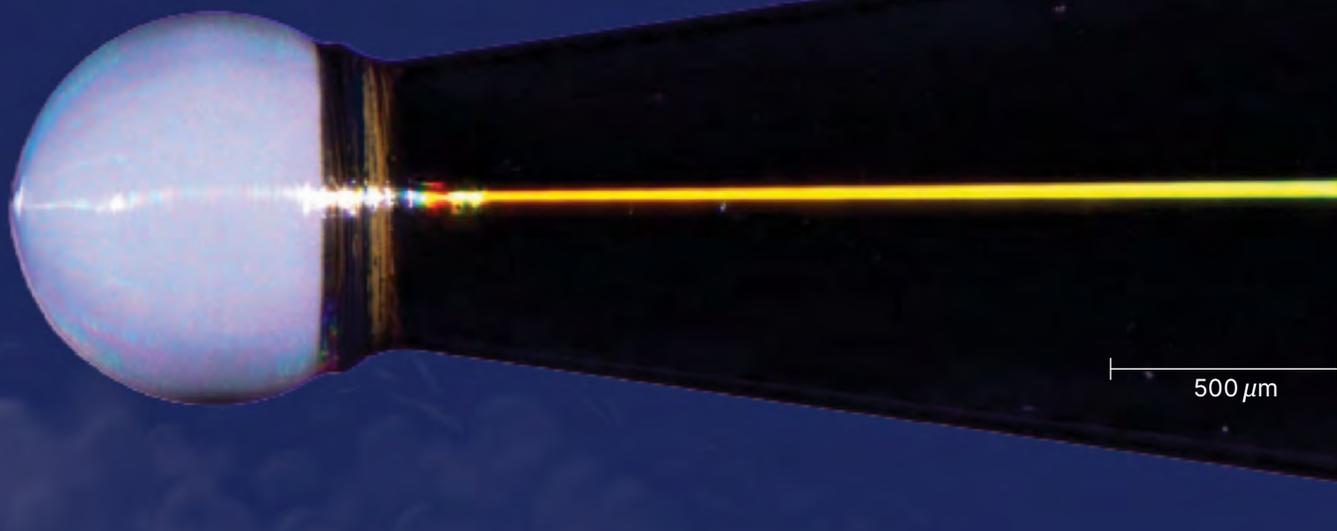


Publications

Research Highlights

LLE's science and engineering research is captured through peer-reviewed publications, which include LLE lead-authored and LLE coauthored papers. These publications reflect not only the laboratory's technical leadership but also its strong commitment to collaboration with external laboratories and academic partners. LLE averages more than 100 published articles annually across three broad areas: Technology, Plasma and High-Energy-Density (HED) Physics, and Inertial Confinement Fusion/Laser-Plasma Interactions (ICF/LPI). The graphic shows the distribution across topics for publications during the period October 1 2024 through September 30, 2025.

A Gentle Puff with a Big Impact: A New System Advances Cryogenic Target Technology



A new gas puffer system (GPS) is transforming how fusion scientists fill cryogenic targets, turning precise whiffs of deuterium gas into liquid fuel and opening the door to next-generation “wetted-foam” target experiments on the OMEGA Laser System.

Cryogenic implosions are fundamental to fusion research at LLE. In these experiments, tiny fuel-filled targets are cooled to extremely low temperatures and compressed by OMEGA to produce fusion reactions. Typical cryo implosions use solid layers of fuel, but some of today’s most advanced target designs include a wetted-foam layer—an ultrafine, 3D-printed internal structure into which cryogenically cooled liquid fuel wicks. Fuel in liquid form offers scientists greater flexibility when designing cryogenic implosions.

A New Way to Fuel Targets

The new Planar Cryo Gas Puffer System uses carefully timed, millisecond-scale bursts of deuterium gas to fill these delicate targets more reliably and with far greater control than ever before. Figure 1 shows one example of these targets, which appears milky white from the foam structure.

Traditional fill methods are slow and finicky. Any setback can cause long delays, and even when successful, these methods tend to fill the entire capsule and its fill cone with liquid fuel, more than many experiments require. For wetted-foam designs, researchers ideally want to wet only the foam layer with a thin, precisely placed film of liquid.

The GPS, currently mounted on planar cryogenic target carts used in OMEGA, was created to make selective filling possible. Inside the chilled capsule, held between 20 to 25 K (about -400°F), each “puff” of gas condenses into liquid as it enters the target and fills the foam layer. The long-term goal is to confine the liquid entirely to that foam structure rather than flood the whole capsule.

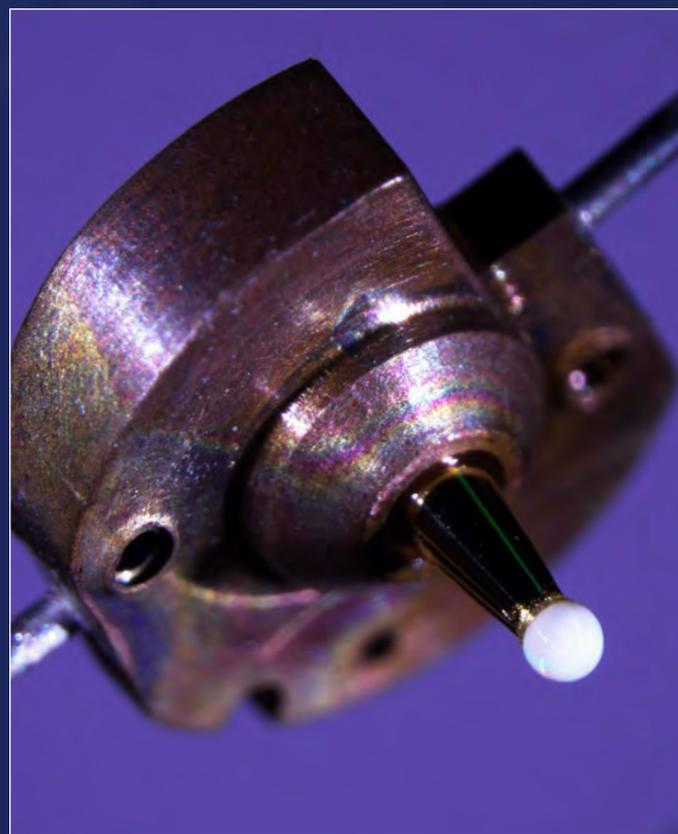


Figure 1. Cryogenic cone-in-shell targets used in early wetted-foam experiments on OMEGA. In the lower image, the tube coming from the top right connects to a new gas puffer system, which delivers successive millisecond-scale gas pulses that condense into liquid, wetting the internal foam layer.

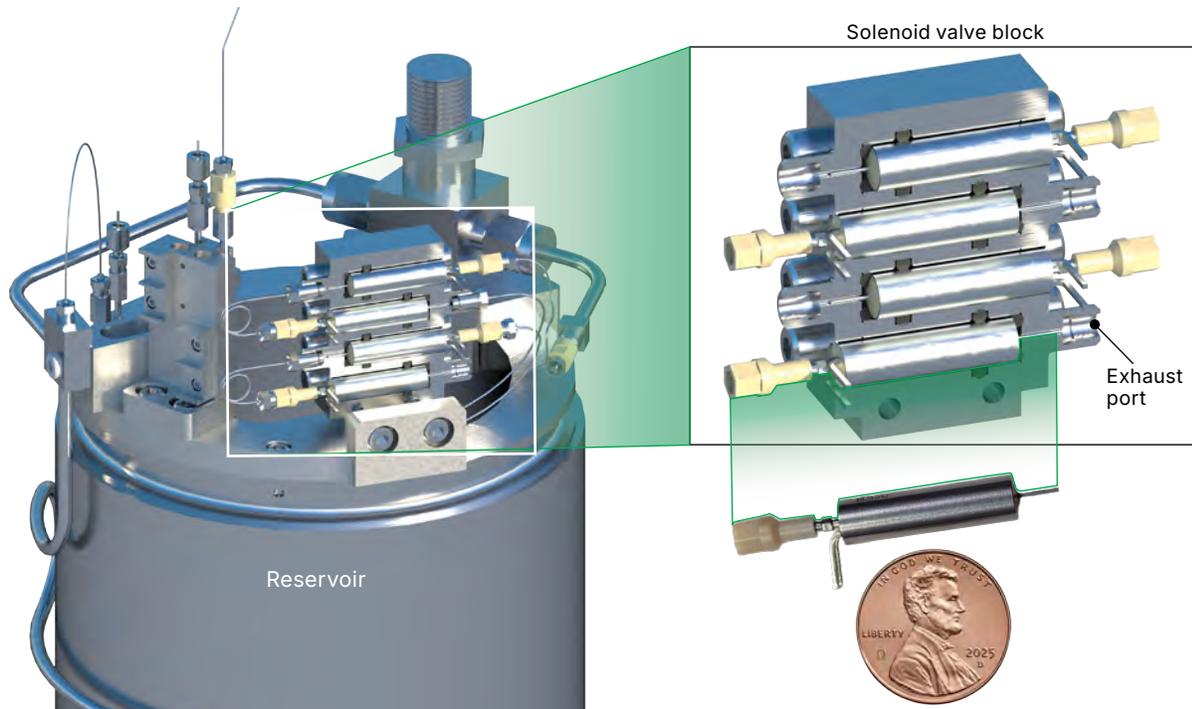


Figure 2. Rendering of the GPS showing the integrated solenoid valve block, reservoir volume, and vacuum exhaust assembly. This compact module mounts directly on a planar cryogenic cart to deliver precise deuterium gas pulses to the target. On the right, a cutaway view of the solenoid valve block featuring the fast-acting commercial inkjet-style valves used in the GPS design. A photograph of one of the valves next to a penny is shown for scale.

Inside the Technology

At the core of the GPS is an unexpected piece of hardware: the same type of miniature solenoid valves found in commercial inkjet printers (see Fig. 2). These fast-acting valves, paired with precision microfilters, are set up in a “trapped volume between two valves” configuration that has been used successfully for gas delivery in other applications at LLE. The valves open and close in milliseconds to deliver highly reproducible gas pulses.

The GPS integrates its valves, reservoir, thermal controls, and vacuum exhaust into a compact assembly that mounts cleanly on a planar cryogenic cart (moving cryostat). Operators monitor the fill progression in real time and stop at the desired point, enabling consistent wetting patterns and repeatable cryogenic conditions. Carts can switch between standard tank fills and GPS mode in one to two hours with no realignment.

Advanced 3D Printed Foams

Many of these next-generation targets use two-photon polymerization (2PP), a cutting-edge 3D-printing technique that builds microscopic foams and internal layers with extraordinary precision (see Fig 3.). These advances in target fabrication are a major reason the wetted-foam concept is gaining momentum today. For more information on 2PP, see [LLE In Focus Issue 5, Winter 2025, page 14.](#)

Why It Matters

The GPS system enables scientists to exploit several key advantages that liquid fuel has over solid-layered fuel in cryogenic targets: greater implosion stability, faster ablation, and tunable vapor pressure, while giving researchers control over how fuel is positioned inside the target. With its gentle, low-stress fill process,

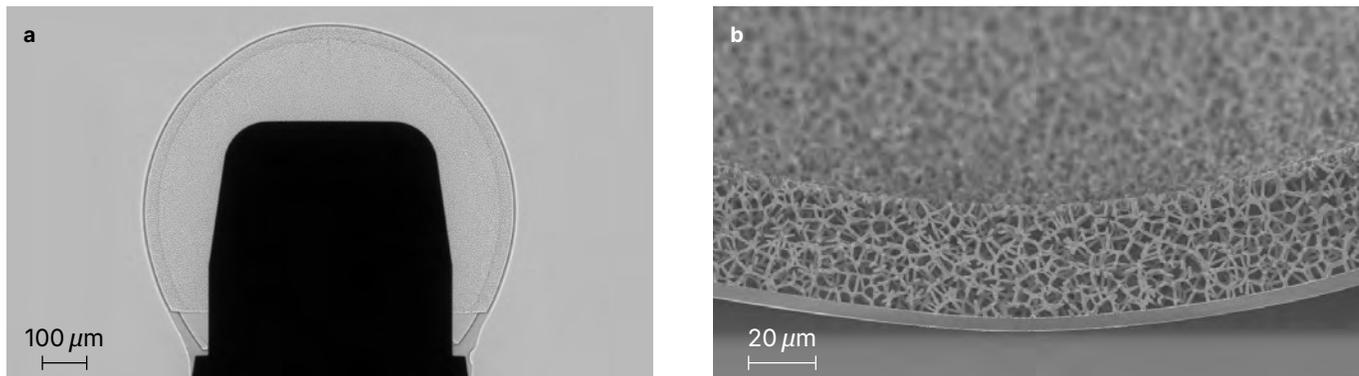


Figure 3. (a) X-ray radiograph and (b) scanning electron microscope image used in the prototyping of the cryogenic wetted-foam target design.

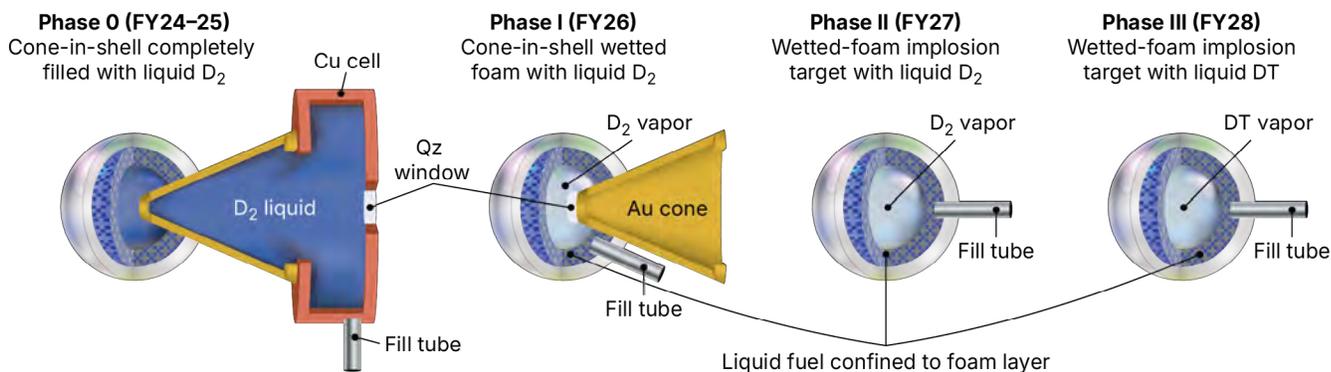


Figure 4. A staged implementation of the GPS began in FY24 (Phase 0). Planar cone-in-shell geometry was chosen as the starting platform due to a more straightforward design path. As the technology evolves, GPS is expected to eventually support fully spherical wetted-foam experiments on OMEGA.

the GPS also has the potential to benefit many other campaign platforms that have delicate targets. The GPS will support experiments studying ablation physics, shock timing, and laser–target interactions using these novel wetted-foam targets.

Wetted-foam targets are also important for the long-term vision of inertial fusion energy. For future power-plant concepts, these 2PP-printed, foam-based targets are easier and more cost-effective to mass-produce than traditional solid-layer capsules. The planar cryo GPS is the first step at LLE toward routinely fielding these designs on OMEGA.

From Concept to Reality

Development of the puffer approach began nearly a decade ago and accelerated in FY24–25. Over the past year, the team

- redesigned the valve block to improve assembly and maintenance ease,
- improved thermal-control systems,
- integrated the design onto a planar cryo cart, and
- field-tested the system in campaign operations.

Early tests necessarily filled the entire capsule and cone. The first generation of 2PP targets did not yet include the specialized interface required for GPS to connect directly to the foam layer. Updated targets, arriving in 2026, will enable the foam-only filling for which the GPS was designed.

During the recent Cryo-WetFoam-25A campaign, the first installed GPS successfully completed two operational fills, demonstrating reliable performance under real experimental conditions.

With two successful campaign fills already completed, the system has moved from concept to proven operational capability and the first step of a staged implementation is underway (Fig. 4). A second GPS unit is now being installed to support higher shot cadence and campaign flexibility.

What's Next

Successful deployment of the gas puffer system on a planar cryo platform is just the first step. Ultimately, the system will be adapted for use on spherical cryo campaigns. Once fully

deployed, multiple GPS-filled cryogenic targets will get fielded each day, supporting wetted-foam studies across both planar and spherical cryo platforms.

Upcoming work includes

- installing the second GPS on a second planar cryogenic cart,
- refining valve-timing “recipes” to confine liquid precisely to the foam layer,
- studying liquid distribution in advanced 2PP-fabricated shells and foams, and
- exploring *in situ* x-ray imaging to visualize wetting inside the target.

These efforts lay the groundwork for future symmetric, fully spherical (4π) direct-drive cryogenic implosions using wetted-foam capsules, an important milestone for advanced cryogenic target development and inertial fusion energy concepts. Together with recent advances in 3D-printed target fabrication, these efforts place LLE at the cutting edge of wetted-foam experimental development.

Corresponding author: B. Ehrich

Quarterly Shot Report

The Omega Laser Facility conducts experiments for research and development in support of the NNSA High-Energy-Density Program, National Laser Users’ Facility, and Laboratory Basic Science, in addition to other research and educational efforts. During FY25, the Omega Laser Facility conducted 986 target shots on OMEGA and 716 on OMEGA EP, totaling 1702 target shots for 224 campaigns. OMEGA averaged 91% availability and 91% experimental effectiveness, while OMEGA EP averaged 92% availability and 96% experimental effectiveness. There were 52 spherical cryogenic implosions and 80 planar cryogenic target shots conducted in FY25.

The Future of Science



Dr. Christopher Danly

Department: **Physics & Astronomy**

Advisor: **R. Betti**

Chris Danly earned a bachelor's degree in physics from Lehigh University and a master's degree in nuclear engineering from the University of New Mexico before enrolling in the University of Rochester's PhD program.

Chris has been involved in the development of nuclear diagnostics for inertial confinement fusion (ICF) since 2010, when he started at Los Alamos National Laboratory (LANL) as a post-bachelor student. He led LANL's nuclear diagnostics and neutron-imaging development efforts on the OMEGA laser for several years, and more recently, has also spearheaded the development of a new imaging technique, the first tests of reaction-in-flight neutron imaging for the National Ignition Facility (NIF). His other work includes the exploration of quantitative shape metrics, funded by a US Department of Energy grant from Laboratory Directed Research and Development, and supporting a pilot project to develop machine-learning tools for heterogeneous radiation flow modeling.

Chris's doctoral research focused on the development of a new diagnostic to measure the spatially resolved ion-temperature profile in inertial fusion implosions on the OMEGA laser. At the University of Rochester, Chris was advised by Professor Riccardo Betti, but most of his work was carried out at LANL in close collaboration with scientist Verena Geppert-Kleinrath and the LANL Nuclear Diagnostic Group.

"Chris developed a unique diagnostic that combines the principles of neutron imaging to the measurements of neutron spectra via the time-of-flight technique. This resulted in a very complex measurement requiring an enormous effort to resolve all the intricacies of combining two difficult diagnostic techniques. His hard work paid off and resulted in the first-ever measurement of the ion-temperature spatial profile in laser-driven implosions," says Betti.

Chris has published six first-author papers and coauthored over 40. For the groundbreaking results discussed in his PhD thesis, Chris was selected as an invited speaker at the November 2025 meeting of the American Physical Society's Division of Plasma Physics. After testing on the OMEGA laser, Chris's diagnostic can be modified for measurements on the NIF and used on ignition shots where the spatial distribution of the ion temperature is strongly affected by the thermonuclear burn. Ongoing work to extend this technique to a 2D or 3D measurement at high yields has already resulted in technological advances for optically multiplexed diagnostics, which have several other applications in ICF.

Prior to graduation, Chris was awarded a Directors's Post-doctoral Fellowship by LANL to investigate the climate, economic, and global security impacts of nascent fusion energy. He hopes to continue productive collaborations with LLE in this new role.

“LLE is the only place this work could have been done. The shot rate, facility flexibility, and expertise of the staff make LLE ideal for developing and proving out new concepts.”

Dr. Nesli Erez

Department: **Physics & Astronomy**

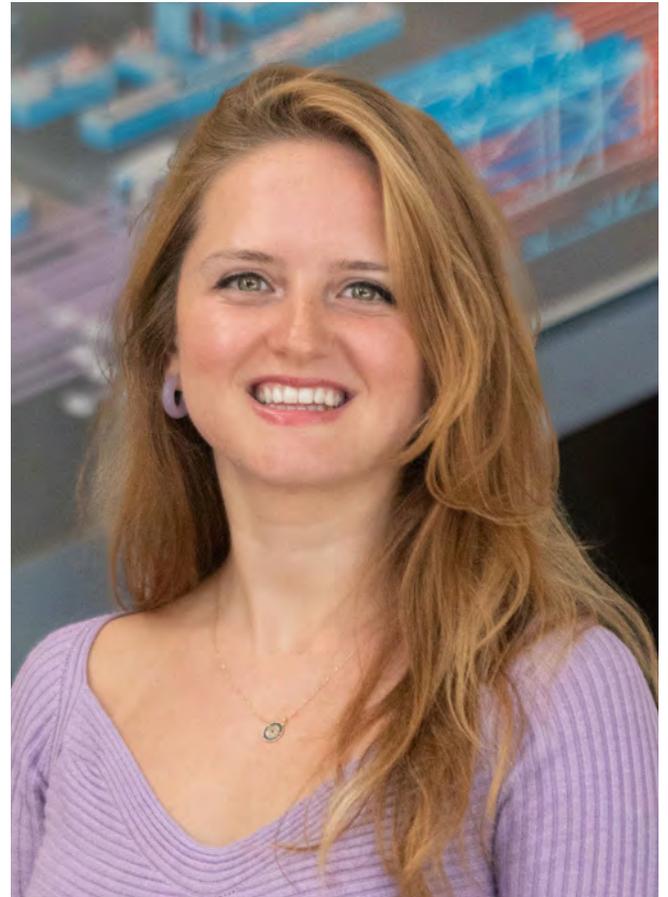
Advisor: **J. R. Davies and P. A. Gourdain**

Irem Nesli Erez proposed a new experimental platform for studying magnetized warm dense matter (WDM), an extreme state of matter relevant to both astrophysics and fusion research. Magnetized WDM is expected to exist in environments such as white dwarf stars and magnetized fusion experiments. Despite its importance, no dedicated experimental platform has yet been developed to create and study magnetized WDM in the laboratory, primarily because of the difficulty of maintaining laser access in regions of a strong magnetic field. Nesli's research directly addresses this gap and provides a versatile platform applicable to any experiment requiring laser access to strongly magnetized regions.

Her work builds on demonstrations of laser-driven magnetic flux compression, where high-power lasers ablate cylindrical targets to generate plasma flows that amplify magnetic fields to kilotesla strengths. Traditionally, such experiments have relied on irradiating the outer surface of a cylindrical shell to create a high-density plasma plume. Nesli's work introduced an alternative approach: by reorienting the laser beams to ablate the inner surface of the target, the resulting plasma expanding inward is at lower density and higher temperature. This plasma drives a cylindrical convergence that compresses the seed magnetic field. The resulting "halfraum" concept—distinct in geometry from conventional halfraums with instead a cut along its axial plane—not only enables the generation of strong magnetic fields in an open geometry, but also allows the field-generating coil to be placed closer to the target, strengthening the initial seed field before compression.

Extended magnetohydrodynamic simulations with the perseus code confirmed that this geometry can amplify magnetic fields to values exceeding 1 kT, the minimum required to magnetize WDM. The simulations further showed that the converging plasma remains at subcritical density, preserving laser access for creating and diagnosing the WDM sample. Complementary 1D studies demonstrated that magnetic-field gradients drive ohmic heating that raises the plasma into the WDM regime, though not simultaneously with peak field strength—reinforcing the need for laser access and validating the halfraum design. The halfraum-based scheme is broadly applicable to other magnetized plasma studies—including magnetized shocks, ion acceleration, and magnetized Rayleigh–Taylor instabilities—and can be adapted to different geometries, such as a full cylinder, for specific applications.

Nesli's work has laid the foundation for the first controlled laboratory studies of magnetized WDM, which will enable researchers to investigate how strong magnetic fields influence the properties and phase transitions of WDM, along with a wide range of applications to any magnetized studies. Her results demonstrate the feasibility of the halfraum approach and will guide future experimental campaigns to directly characterize compressed magnetic fields. Nesli's research represents a first step toward a new experimental frontier for the study of magnetized warm dense matter. She is currently a postdoctoral researcher at the University of Colorado Boulder, where she continues to advance experimental studies of magnetized plasmas and warm dense matter.



“As I graduate, I am proud to have contributed to the cutting-edge research at LLE. I am looking forward to traveling back for the Omega shot days I will be involved in as a postdoctoral researcher.”



Dr. Mary Kate Ginnane

Department: **Mechanical Engineering**

Advisors: **J. R. Rygg and G. W. Collins**

Mary Kate Ginnane's PhD research involved the development, refinement, and measurement of several techniques and reference materials for high-pressure research. This included the deployment of a combined precompression and x-ray diffraction platform for laser experiments, the calibration of an optical pyrometer temperature diagnostic on OMEGA EP, and the measurement of the compression and structural properties of platinum at high pressures.

Platinum is used extensively as a reference material for high-pressure research, and scientists rely on the accurate characterization of platinum's pressure dependence of compression and structure to draw conclusions about their own samples of interest. Yet despite platinum's status as a high-pressure reference material, various theoretical predictions and experimental extrapolations for the melt pressure of shocked platinum span nearly a factor of 6: from 2.5 to 14 million atmospheres. The melt transition, perhaps the most fundamental structural transformation of any material, is intimately related to its interatomic bonding and electronic structure and is an important benchmark for theoretical models to match to ascertain their accuracy.

Through a series of experiments on the OMEGA EP Laser System, Mary Kate measured the pressure, density, temperature, and structure of shocked platinum across the solid-liquid melt boundary. X-ray diffraction was used as a direct probe of the solid-to-liquid transition since these phases have distinct signatures in the x-ray scattering intensity. These experiments allowed Mary Kate to place new experimental constraints on the shock melt pressure, with melt starting on shock compression above 4.5 million atmospheres and completing by 6 million atmospheres. Tightening the melt-pressure interval from a factor of 5.6 to a factor of 1.3 provides a new benchmark for theoretical models and allows improvements to the accuracy of this important pressure reference material.

“ I feel so lucky for my time at LLE and the unique opportunities I was afforded here. **Everyone is willing to share their knowledge**, and that collaborative environment made my experience both rewarding and enjoyable. ”



Dr. Michael Lavell

Department: **Mechanical Engineering**

Advisor: **A. B. Sefkow**

Michael Lavell's doctoral research improved how we simulate collisional plasmas, or hot and radiative ionized gases found in stars and fusion reactors. The main goal was to improve how charged particles evolve, interact, scatter, and radiate within the extreme environments found in energetic plasma experiments.

Mike developed and tested new features for a computer program called TRIFORCE, which uses a special technique called "particle-in-cell with Monte Carlo collisions." The code can simulate and track many particles and their interactions with each other and electromagnetic fields. After passing numerous rigorous tests of the underlying algorithms and their ability to accurately model and reproduce previously published physics results, Mike used the code to study both magnetically confined and inertially confined plasma systems. Accurate "digital twins" of such experiments are valuable to researchers looking to understand what is happening inside them, and their development is crucial for designing future fusion power plants. Mike's detailed simulations allow for a very precise simulation of the plasma's behavior, balancing the need for microscopic detail with the ability to see the bigger picture of the plasma's overall dynamics. The enhanced TRIFORCE code was then put to the test on two cutting-edge types of fusion research.

In the area of magnetic confinement fusion, Mike's research focused on a device called a field-reversed configuration (FRC), which uses unique rotating magnetic fields with closed field lines to trap the plasma. The simulations showed that FRCs possess unusual and favorable characteristics for heating a plasma to high-temperature fusion conditions in a stable manner, suggesting that FRCs could be a promising pathway toward a practical fusion reactor.

In inertial confinement fusion, a tiny pellet of fuel is compressed to extreme densities and temperatures using powerful lasers, causing it to ignite and fuse. Mike's research modeled how "burn waves" propagate through these superdense plasmas. The simulations accurately captured how hot spots within the fuel expand and how ignition spreads energy through standard fuels like deuterium-tritium (DT). Crucially, the work highlighted that the individual motions of particles are vital for an improved understanding of fusion ignition. Furthermore, the research explored a more advanced, "cleaner" fusion fuel called proton-boron (p-B) fuel. The findings indicated that p-B fuel requires significantly higher densities and temperatures to sustain a fusion burn compared to DT. This is because p-B reacts at a lower rate and loses more energy through radiation, making it a tougher challenge but still a long-term goal for fusion.

Mike's research provides scientists with an additional powerful and accurate virtual tool to simulate the intricate dance of particles and energy within fusion plasmas, pushing us closer to a future powered by clean, abundant fusion energy.



“ It has been a privilege to learn from LLE's world-leading experts in laser fusion and computational physics. I have appreciated the freedom and encouragement to explore interesting problems and collaborate across disciplines. ”



Dr. Kassie Moczulski

Department: **Mechanical Engineering**

Advisor: **P. Tzeferacos**

The origin of cosmic magnetic fields will puzzle astronomers for many years to come. These fields are key players that shape and govern numerous fundamental astrophysical processes, mediating collisionless shocks and magnetohydrodynamic instabilities, accelerating the energetic particles of the cosmic ray spectrum, and governing their transport through the cosmos.

The advent of high-power lasers such as at LLE's Omega Laser Facility has opened a new field of magnetized plasma research where, using simple scaling relations, astrophysical environments can be reproduced in the laboratory, opening a new window to understanding the fundamental physics processes behind astrophysical phenomenology. These advances are spearheaded by the TDYNO (turbulent dynamo) collaboration, a partnership between the University of Rochester and the University of Oxford that leads a concerted effort to study magnetized turbulence and the astrophysical processes it mediates through laser-driven experiments at premier facilities around the world and high-performance computing simulations with the FLASH code.

Kassie Moczulski's thesis research in the context of the TDYNO effort focused on the modeling and design of experiments at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany to demonstrate for the first time in the laboratory the acceleration of charged ions in stochastic magnetic fields. Kassie led the simulation effort that predicted the plasma properties the platform would generate and showed that the experiments would reveal particle energization via the lower-hybrid drift instability. Her seminal article was published in *Physics of Plasmas* (**31**, 122105, 2024), selected as an Editor's Pick, and was highlighted on the cover of the journal.

In addition, Kassie also led the simulation effort to design new variants of the TDYNO platform, which have been used for the past seven years to experimentally study fluctuation dynamo and heat conduction suppression in magnetized turbulence, with experiments on the OMEGA laser and the NIF at Lawrence Livermore National Laboratory (LLNL). Her work in the development of physics capabilities of FLASH, her contributions to the astrophysical collisionless shock experiments with lasers (ACSEL) project led by Hye-Sook Park at LLNL, and her work as a peer advisor and mentor for CRANE, the NSF-funded Computational Research Access Network that trains underserved groups in computational physics, form an important part of her graduate experience. With her significant contributions, which span code development, laser-driven shock experiments, and computational training, Kassie is well-equipped to be a future leader in the fields of laboratory astrophysics and high-energy-density physics. After her PhD, Kassie will continue her career as a postdoctoral scholar at the Laboratoire pour l'utilisation des lasers intenses in Paris, France.

“ My time LLE has been instrumental in shaping my academic and professional journey. I've had the privilege of collaborating with international partners to design and conduct experiments at the cutting edge of plasma-physics research. ”

Dr. Jing Cheng

Department: **Materials Science Graduate Program**

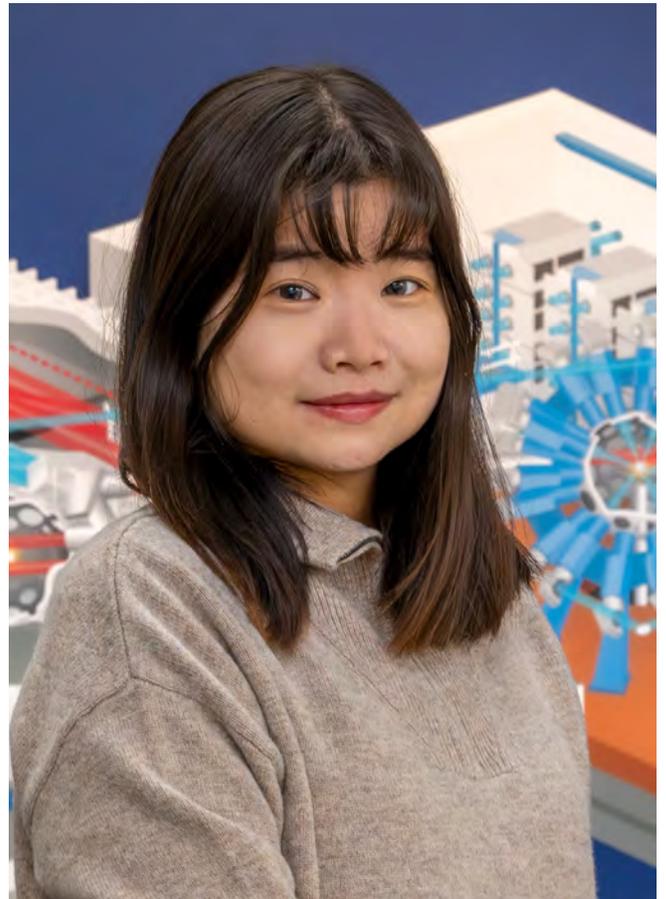
Advisors: **R. Sobolewski**

Jing Cheng completed her doctoral research on novel materials for ultrafast optoelectronic and spintronic devices and systems. In this work, her dissertation examined two complementary and central materials science research areas. The first of these involved semiconductor-based photodetectors for picosecond time-resolved detection of optical-to-x-ray electromagnetic radiation transients. The second involved novel spintronic nanoscale heterostructures for efficient-emission terahertz transients (i.e., bursts of electromagnetic radiation with subpicosecond time durations, or, equivalently, a spectral content extending well into the terahertz frequency range).

A ternary compound $\text{Cd}^x\text{Mg}^{1-x}\text{Te}$ (CMT) semiconductor was selected for the picosecond photodetector development. As demonstrated by Jing's research, which focused on complex charge-transport dynamics, direct-bandgap tunability, and photoresponsivity measurements, CMT exhibits not only an excellent crystalline structure, extremely high intrinsic resistivity, and a single-picosecond carrier lifetime, but is also characterized by a very large stopping power that enables the efficient detection of even hard x-ray photons. The CMT material studies and the photodetector development have been funded by Brimrose Technology at the request of the US Department of Energy to design and fabricate a picosecond optical-to-x-ray detector for coarse beam timing exclusively for the Stanford National Accelerator Laboratory. In addition to this targeted application, the CMT detectors also have the high potential to be used as a diagnostic tool in Omega experiments.

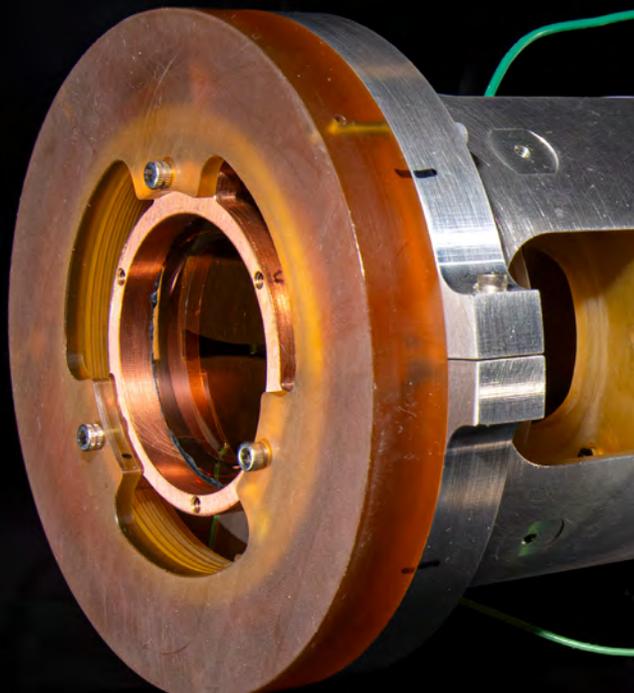
In the spintronic material thrust of the thesis, Jing worked on novel nanostructured emitters of terahertz transients based on few-nanometer-thick bilayers of a ferromagnet and a heavy metal (FM/HM). She successfully demonstrated that in all her tested samples in which the FM layer varied from a soft (e.g., permalloy) to a hard (FeCo) material, the physics behind the terahertz emission was the so-called inverse spin Hall effect. She also demonstrated that when a graphene layer was substituted for HM in a spintronic emitter, one could observe large emitted terahertz transients—this time, because of the inverse Rashba–Edelstein effect. This is the first direct observation of the strong spin-orbit coupling in graphene. As part of this broader line of investigation, the research on FM/HM spintronic emitters was conducted in a direct collaboration with the group of Dr. Roman Adam from the Juelich Research Centre in Juelich, Germany, where Jing spent two months performing experiments.

Jing has since joined KLA Laboratories as a product development engineer. In her current position, her work focuses on developing inspection technologies that enable the detection of yield-critical defects in advanced semiconductor manufacturing.



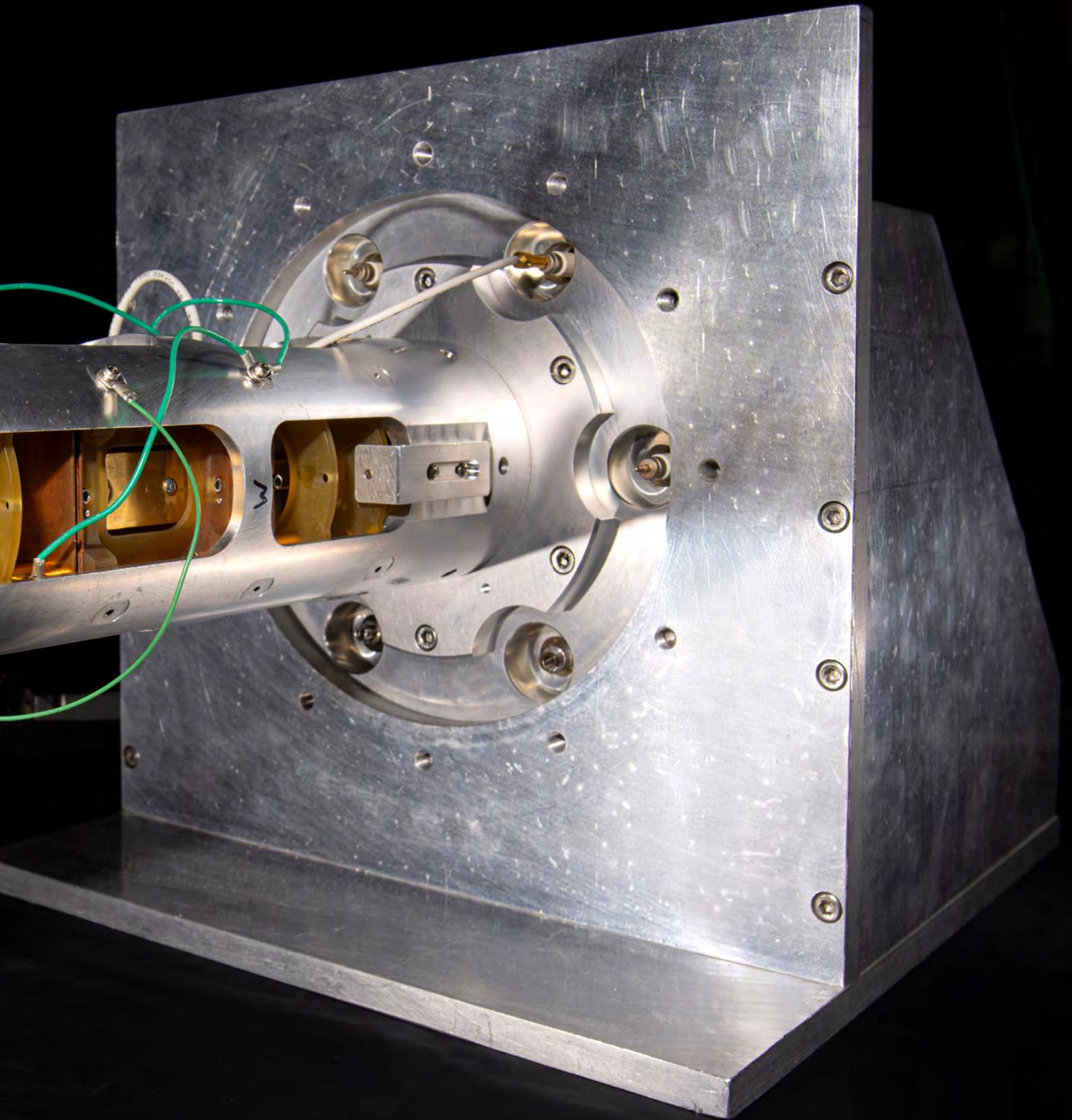
“ It has been a pleasure to work with the **dedicated staff at LLE’s world-class laser facilities**. Conducting research in such a collaborative and advanced environment has been truly rewarding, and the experience will continue to inspire my future in science. ”

BHX STREAK TUBE



BUILDING THE FASTEST CAMERA AT LLE

The BHX is designed to be the highest performing streak tube ever built. It acts like a slow-motion camera for x rays, capturing changes in light on a picosecond timescale so researchers can see exactly where laser energy goes, sharpen their models, and drive new advances in fusion and high-energy-density science.



The BHx Streak Tube

Enabling the Next Generation of Streak Cameras

Over the last several years, scientists and engineers at LLE have been developing the BHx streak tube, a cutting-edge instrument designed to capture changes in light on a trillionth-of-a-second timescale. LLE and the high-energy-density (HED) community generally rely on streak tubes for a variety of measurements, the most demanding of which is ultrafast x-ray spectroscopy. Streak-camera technology has struggled to keep up with experimental demands, and innovation has slowed significantly, causing concerns over facility sustainment and the ability to validate atomic physics models that fusion scientists rely on to design and interpret experiments.

The BHx aims to deliver higher signal levels over larger detection areas with finer resolution using an innovative electron-optical design pioneered at LLE. This work will not only improve the quality of the data for today's experiments—it will lay the foundation for the next generation of streak cameras, and sustain critical competencies at LLE in ultrafast diagnostics for decades to come.

Streak Tubes and Their Applications

Many laser-matter interactions evolve on picosecond (10^{-12} s) timescales. For example, the heating of electrons by an intense laser pulse, the onset of relativistic self-focusing, and the growth of plasma instabilities can all occur within a few picoseconds. In HED experiments, these dynamics govern energy deposition, hot-spot formation, and the evolution of shock fronts, making picosecond-resolved diagnostics essential for understanding and optimizing inertial confinement fusion implosions.

In these interactions and over these timescales, valuable information is carried by photons that escape from the plasma. As liberated electrons interact and recombine with ions, x rays are released. The energy spectra of these x rays feature peaks and continua that are affected by the local density, temperature, composition, and charge state of the plasma. In this way, time-resolved emission spectroscopy offers insight into the complex landscape of HED-relevant plasma conditions.

These x rays can be collected and dispersed by their wavelength via diffraction from a crystal lattice. Registering the temporal dynamics of this spectrum over trillionths of a second proves challenging since suitably fast x-ray charge-coupled devices (CCDs) or framing cameras do not exist. X-ray diodes can exhibit picosecond-scale resolution, but stacking them with sufficient density to capture the spatial variations of interest within a spectrum proves infeasible.

First developed in the 1950s by adapting technologies from photomultiplier tubes, electron microscopy, and high-voltage pulsed electronics, streak tubes address the challenge of detecting ultrafast temporal changes in a spatially resolved signal by

converting time variation into variation over space that can be recorded. While photons can be manipulated with conventional optics, it is difficult to measure their subpicosecond variations directly. The first step in a streak tube is to convert photons to electrons—negatively charged particles that can be precisely deflected and controlled with electromagnetic fields. Relying on the photoelectric effect, a photocathode converts spatial and temporal variations in the light signal into equivalent spatial and temporal variations in emitted electrons.

Under vacuum, a streak tube accelerates photocathode electrons to kilovolt energies and manipulates them using a series of electrodes to form a reproduction of the original image on a final detector with high resolution. The temporal resolution of the streak tube arises from deflecting the electrons with time-varying voltages applied across two deflection plates. This produces a 2D image on the detector: one dimension captures the spatial variation of the original light intensity; the other dimension represents its temporal variation. With carefully designed electrodes, such a system can capture detailed spatial information and its variation on picosecond or subpicosecond timescales.

This technology uniquely enables ultrafast x-ray spectroscopy, but it is also useful in many other contexts. Indeed, streak tubes are relied upon at LLE for time-resolved Thomson scattering and absorption measurements, as well as for measuring laser beam power over time. In each case, the signal of interest is a 1D distribution over space: either a spectrum, a slice of an image formed by a pinhole camera, or a series of linearly spaced laser beams.

Limitations in Streak-Tube Technology

The earliest streak tubes were developed with a combination of intuition, trial and error, and practical engineering compromises, without the benefit of rigorous modeling or predictive design tools. Modern computing power was not available to their designers, making it all the more impressive that they were able to build and refine these into instruments that met many of their original needs and continue to be used successfully today in certain applications. The needs of plasma physicists have outpaced the rate at which streak-tube technology has advanced, leaving insufficient resolution, signal level, and photocathode size to validate modern atomic physics models.

Today, computers enable the sophisticated and rapid modeling of electrode-generated fields and the propagation of charged particles by applying finite-element methods. In traditional optics, increased computing power allowed the design of photolithographic lens systems with dozens of elements, maximizing the numerical aperture while minimizing aberrations—ushering in the modern

semiconductor era. A similar transformation is now possible in electron-optical design, as demonstrated by the BHx streak tube.

Because the streak-tube user base is relatively small, limited commercial incentive exists for innovation. Successful research and development efforts can lead to industry partners manufacturing and servicing the instruments, as seen with the Rochester Optical Streak System (ROSS) line of streak cameras. This makes partnerships between research laboratories, academia, and industry essential.

The BHx Design: What's Different?

To address limitations found with existing instruments, the BHx streak tube, shown schematically in Fig. 1, was designed to provide subpicosecond temporal resolution with a 25-mm photocathode, a 70% maximum internal photoelectron throughput, and 2000 spatial-resolution elements.

Compared to the PJX3 streak camera, which is frequently used for ultrafast x-ray spectroscopy at LLE, the BHx is expected to exhibit a signal level and photocathode size that is several times higher and several times larger, respectively, while operating with higher temporal resolution.

The BHx was designed to accomplish this by implementing a sophisticated electron-optics layout refined over many years using modern electron-tracing software tools. It does this all in a smaller package than the PJX3 streak camera, ensuring compatibility with the ten-inch manipulator (TIM) platform use on the Omega Laser Facility. Additionally, the BHx tube uses two new

features: a bow-tie profile slot anode, and an aberration-compensating final focusing electrode enabled with the inclusion of an in-line conductive grid.

Bow-Tie Anode

The acceleration stage of a streak tube is responsible for light-to-electron conversion, the acceleration of the electrons to full energy, and for directing these electrons into the subsequent electron optics. The acceleration potential is formed in conjunction with the photocathode by either an extraction mesh or with a slot anode (a metal plate with a rectangular opening). In both scenarios, the electrons exit the acceleration stage either collimated or weakly divergent—large photocathode areas would require prohibitively large downstream electrodes to accept all of the electrons. The PJX3 tube solves this by using a large concave photocathode that naturally steers the electrons inward into the quadrupole assembly while keeping its form factor minimal. As is often the case in electron optics, solving this problem creates a new one: the curved photocathode introduces challenges in imaging at the detector plane, necessitating a curved final detector and resulting in significant imaging distortions.

The BHx enables a large photocathode without the need for either making it concave or for a large subsequent electrode by using a variant on the traditional rectangular slot-anode extractor. By making this aperture bow-tie shaped instead of rectangular, the electric-field structure set up within the extractor steers the electrons inward. This simple innovation enables the use of a flat, 25-mm photocathode without the drawbacks or

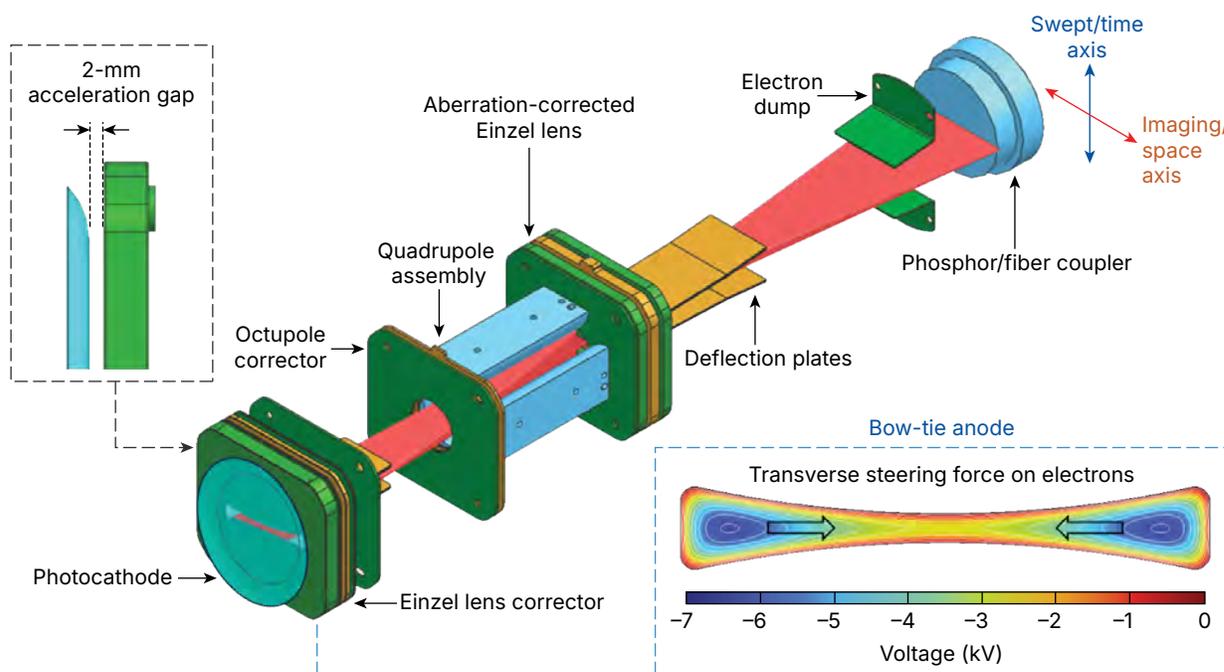


Figure 1. CAD rendering of the BHx streak tube. A bow-tie anode slot after the photocathode accelerates electrons emitted from the photocathode and shapes the electric field to steer the electrons transversely, which enables using a large, flat photocathode. An aberration-corrected final electron lens improves electron throughput while maintaining high resolution. Deflection plates sweep the electrons in the time-dependent dimension of the BHx streak tube, and a phosphor converts the electron image to an optical signal collected by a fiber array that couples to a CCD detector.

compromises associated with other streak-tube designs. It also enables a flat detector surface, leaving open the possibility of direct electron writing to a CCD rather than using a phosphor, which could further improve resolution.

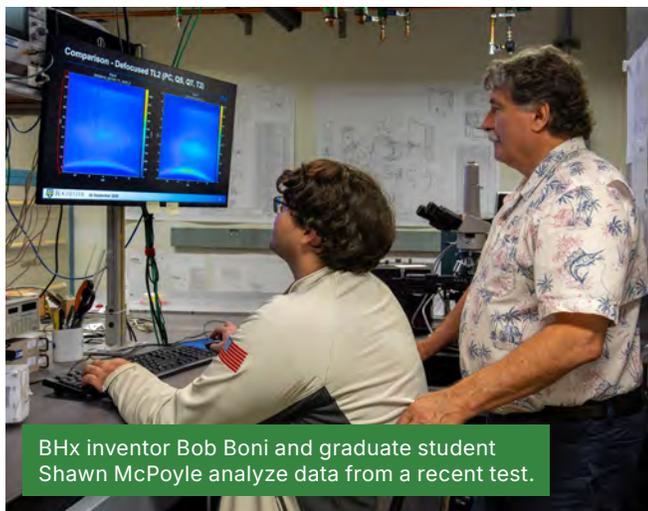
Aberration-Compensating Electron Lens

In many streak-tube designs, aberrations accumulate from multiple electron lenses in the system that heavily degrade focusing at the detector plane, limiting both spatial and temporal resolution. To improve the resolution to acceptable levels, a common approach is to strongly aperture the electron beam at the exit of the final focusing lens. Eliminating off-axis electron trajectories improves focusing at the expense of signal levels—similar to squinting one’s eyes to better read a chalkboard. The final focusing lens in the BHx streak tube employs an in-line conductive grid that modifies the field structure to reduce spherical aberrations accumulated in the system, allowing for larger throughput with high resolution.

Progress and Results

The BHx concept is the result of decades of cumulative experience involving various streak-tube designs, combining proven elements with new concepts tested through extensive computer modeling. A mechanical design derived from the computer model has come to life in a prototype streak tube. Over the last three years, the BHx team has been working to assess the real performance of this device against model predictions. In the process, they have made several improvements to both the mechanical and electron-optics designs.

While the ultimate application of the instrument is for use with x rays, early testing used an UV laser source due to its high repetition rate and the ease of assessing focusing performance of the tube. The UV laser illuminated a standard resolution target that could be optically relayed onto the photocathode surface. In this way, challenging optical patterns were presented to the photocathode and the BHx tube was evaluated by how well it could reproduce the image with electrons at the final detector.



BHx inventor Bob Boni and graduate student Shawn McPoyle analyze data from a recent test.

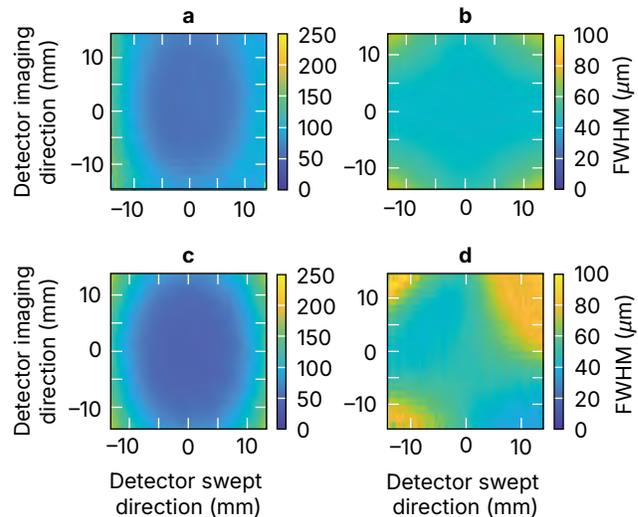


Figure 2. Comparison of the simulated and measured resolution of the prototype BHx streak tube. (a) Simulated point-spread function (PSF) full width at half maximum (FWHM) in the swept (time) direction (μm) with instrument convolution. (b) Simulated PSF in the spatial (imaging) dimension. (c) Measured FWHM in the swept (time) direction (μm). (d) Measured PSF in the spatial (imaging) dimension.

Assessing tube performance statically, rather than dynamically, also simplified testing. This involved applying a series of static voltages to the plates and recording data at each step, rather than a time-varying voltage to the deflection plates to sweep the electrons across the detector. Simulations were run to mimic these conditions (a UV light source and static deflection), and the tube voltages were optimized via lengthy, automated scans to identify the best focused performance.

Figure 2 shows results comparing the simulated and measured resolution in both space and swept directions, where bluer colors reflect better resolution. The results show good agreement, considering imperfections in the prototype’s mechanical assembly and after calibrating the resolution loss imparted by the final CCD detector itself. This provides confidence to continue to the next development stage: assessing time-resolved performance with swept deflection plates and a femtosecond-class UV laser source.

Ongoing Simulation Efforts

Simulations play a pivotal role in the BHx development effort, extending well beyond the initial design phase. Beyond supporting the development of complex electron-optical systems, they guide data interpretation, predict performance across varying experimental conditions, anticipate issues before they arise in the laboratory, and inform hardware revisions. These predictive capabilities prove essential for reducing experimental uncertainty and accelerating development.

The current simulation toolkit combines the particle-tracing code SIMION with complementary data from COMSOL Multiphysics modeling. This integrated approach enables the team to analyze challenges that occur at fast sweep speeds and evaluate potential mitigation strategies. Figure 3 shows the results of a COMSOL simulation of electrons deflected during

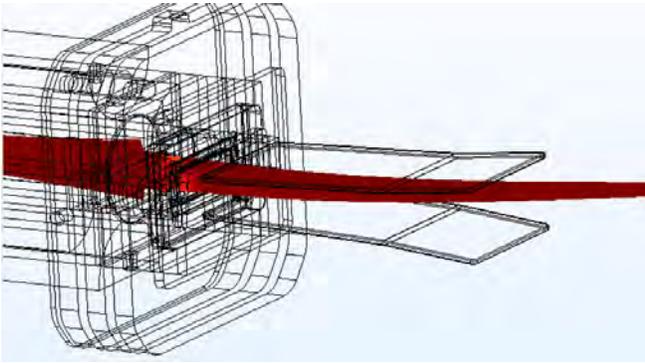


Figure 3. A screenshot from a COMSOL simulation of electrons undergoing deflection during a BHx streak-tube sweep.

a sweep. Simulations also support detailed tolerance studies, providing quantitative insight into how fabrication and alignment tolerances affect overall system performance.

Building and Sustaining Expertise

The BHx project has drawn on expertise from a wide range of disciplines, including mechanical and electrical engineering, electron optics, traditional optics, laboratory automation, and materials physics. A long history of developing, upgrading, and maintaining complex diagnostic instruments coupled with the concentration of relevant expertise at LLE provides a strong foundation for advancing streak-tube technology. The BHx team benefits from regular consultation with experienced diagnostic engineers and specialists in these specific fields. Complete ownership of the design and development of the instrument also strengthens the ability at LLE to spin off and field variant instruments for specific use cases.

In addition to advancing the technical design, the project has served as an important vehicle for knowledge transfer, ensuring

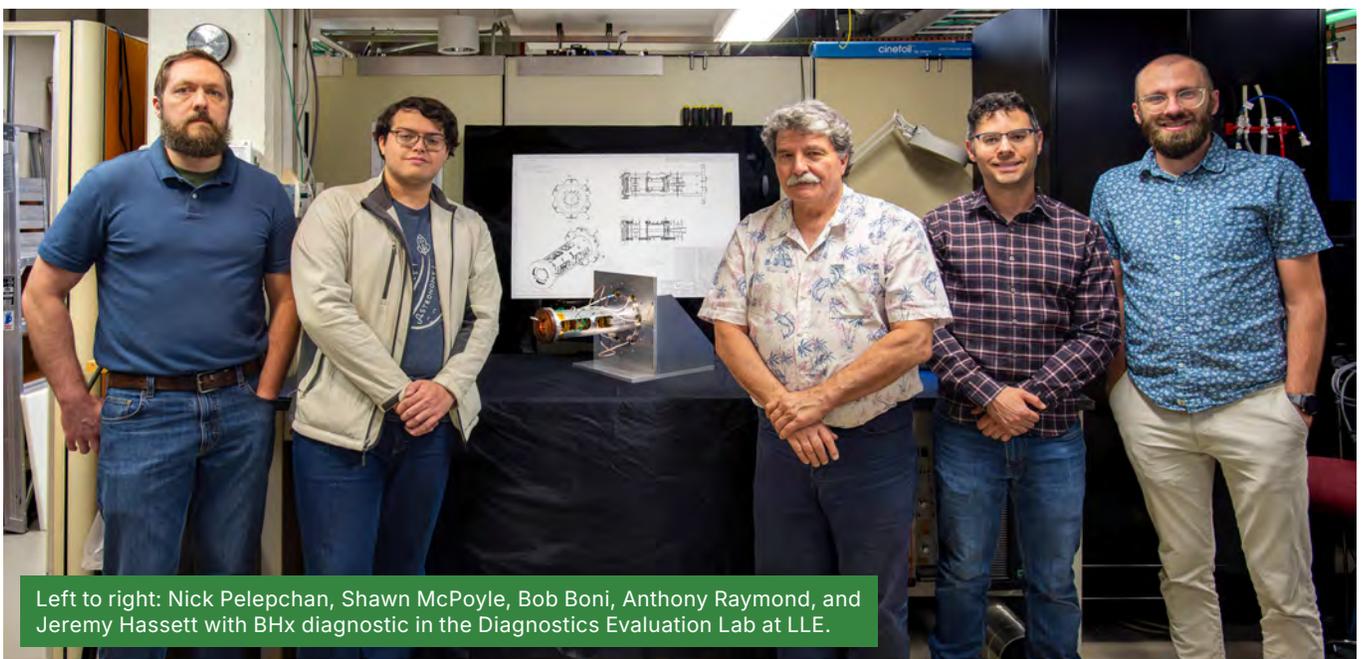
that expertise in streak-tube development, characterization, and operation is preserved and expanded within LLE.

Buried-layer experiments on the MTW-OPAL Laser System in FY27–28 mark the first planned use for a BHx-based streak camera. The combination of high photoelectron throughput, subpicosecond resolution, and a large, active photocathode area will provide high-fidelity measurements from materials heated to high-energy-density states, allowing for the detailed interrogation of atomic physics models relied upon for inertial confinement fusion efforts.

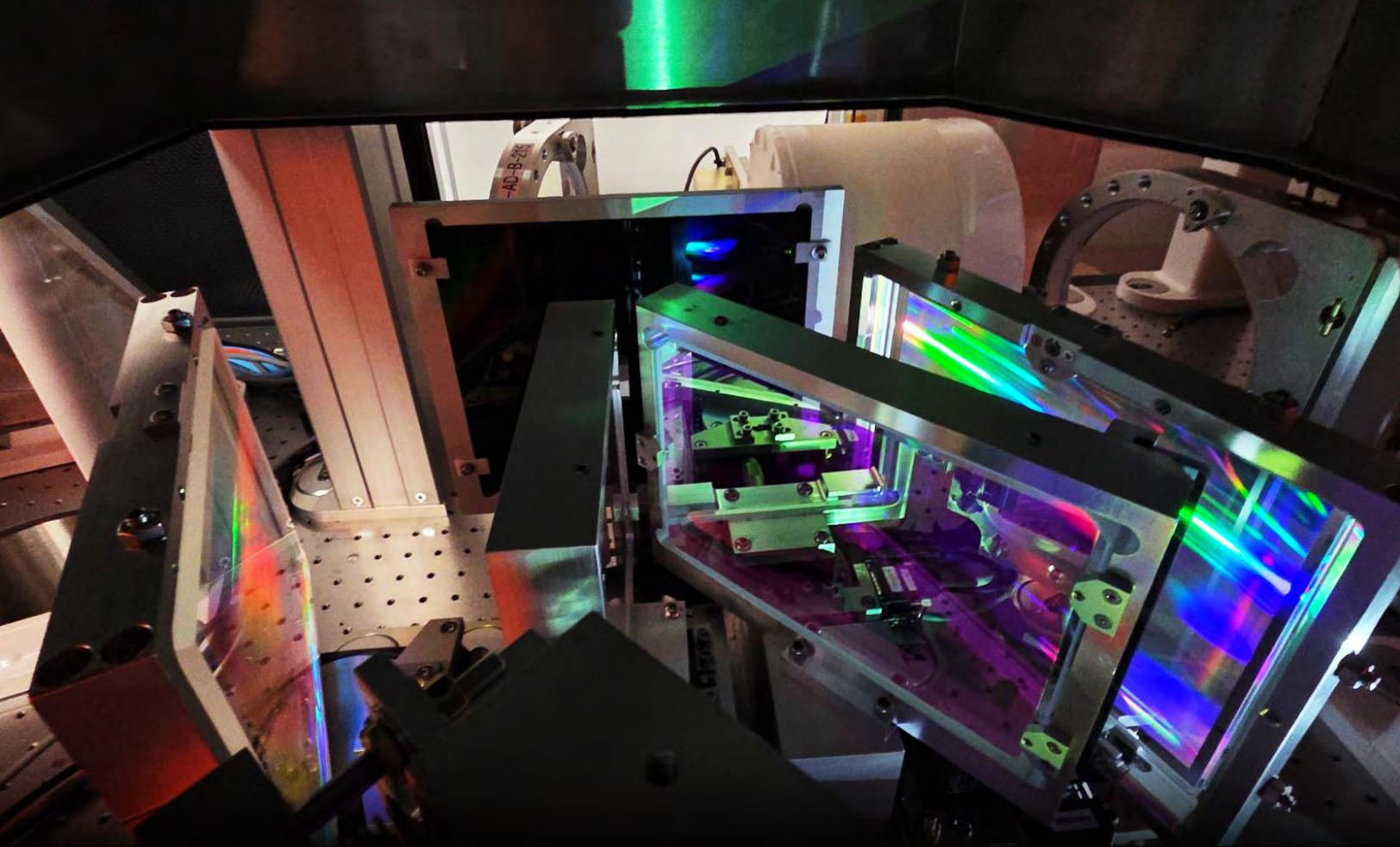
Corresponding author: A. E. Raymond

Focus Points

- The high-energy-density community relies on streak tubes for critical measurements, most demanding: ultrafast x-ray spectroscopy, but the signal level and resolution of these instruments is limiting.
- LLE has developed a brand new streak-tube design that implements novel electron optical techniques in order to address these concerns and to serve as the basis for the next generation of such instruments.
- The BHx team has made significant progress in characterizing and improving the design, de-risking the novel features, and motivating further development.



Left to right: Nick Pelepchan, Shawn McPoyle, Bob Boni, Anthony Raymond, and Jeremy Hassett with BHx diagnostic in the Diagnostics Evaluation Lab at LLE.



FLUX

A Next-Generation Broadband Laser for Direct- Drive Fusion Experiments

A NEW LASER CONCEPT TO MITIGATE LASER-PLASMA INSTABILITIES

Achieving fusion in the laboratory has proven a grand challenge of science. At its heart, fusion requires incredibly high pressures and temperatures, conditions rarely seen outside stellar cores. In December 2022, the National Ignition Facility (NIF) achieved a milestone in an indirect-drive inertial confinement fusion experiment that produced more energy from ignition than the laser energy delivered to the target chamber. Direct-drive ICF promises a more efficient approach since it does not involve converting laser energy to x rays that drive NIF implosions. Obstacles that remain, however, are laser-plasma instabilities (LPIs) can disrupt the laser energy delivered to the target.

Laser-Plasma Instabilities: A Barrier to Progress

When a high-power laser beam strikes a fusion target—a small capsule filled with deuterium and tritium fuel—the surface of the capsule ablates, forming a plasma: a hot, charged “soup” of ions and electrons. Ideally, the laser energy transferred to this

plasma drives the underlying fuel inward with the resultant implosion achieving the pressure and temperature needed for ignition. In reality, the laser interacting with the plasma creates a breeding ground for LPIs that significantly degrade direct-drive ICF implosions. Significant LPIs include:

- Stimulated Brillouin scattering (SBS): The laser wave couples with plasma sound waves, redirecting the laser energy. Multiple laser beams can interact in the plasma via SBS to exchange energy and degrade the required direct-drive spherical symmetry.
- Stimulated Raman scattering (SRS): The laser excites electron plasma waves, causing energy to scatter backward, which reduces the laser energy driving the fuel and can generate unwanted “hot” electrons that preheat the target and spoil the implosion.
- Two-plasmon decay: Another LPI mechanism that can ruin carefully designed compression experiments by generating “hot” electrons from laser-driven plasma waves.

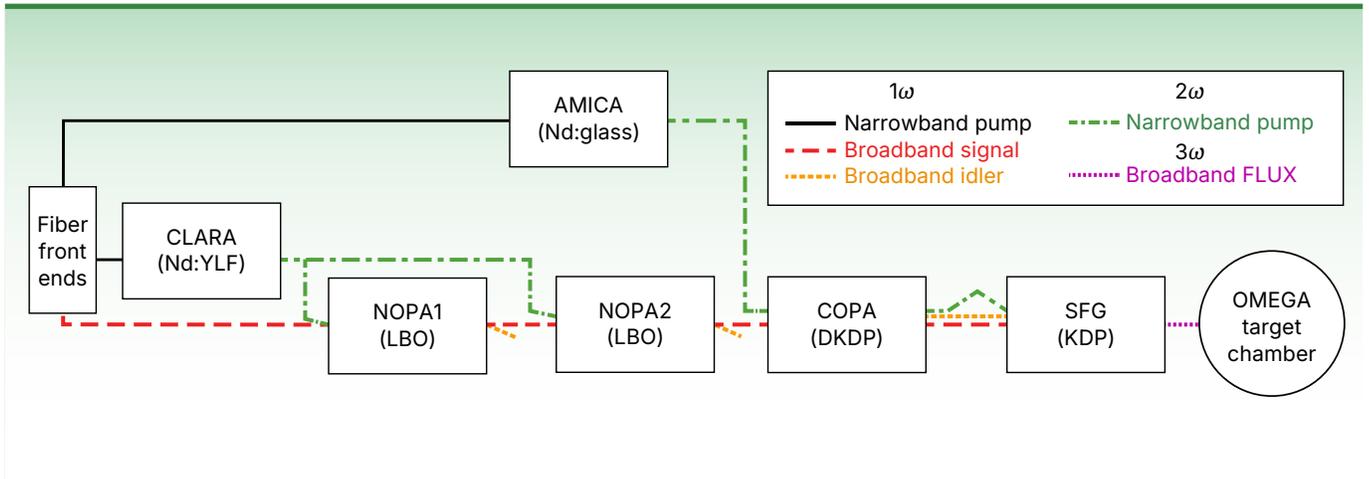


Figure 1. Block diagram of the FLUX noncollinear and collinear optical parametric amplification (NOPA and COPA) and sum-frequency generation (SFG) stages used to deliver broadband ultraviolet (3ω) laser pulses for experiments in the OMEGA target chamber.

Why Laser Bandwidth Matters

Solid-state ICF lasers historically use narrowband (nearly single color) lasers. Narrow bandwidth aggravates LPIs since the ICF laser beams on target can operate at intensities above the threshold for each LPI and resonantly drive the associated plasma waves. Powerful solid-state ICF lasers, like NIF and OMEGA, deliver near-ultraviolet (UV) laser pulses at 351 nm, a preferred wavelength regime for fusion experiments, with “fractional bandwidths” less than 0.15% ($\Delta\lambda/\lambda_0$, where $\Delta\lambda$ is the bandwidth and λ_0 is the center wavelength) [1].

Experiments and modeling suggest that using laser pulses with a broader range of wavelengths can disrupt these regular patterns and scramble the conditions needed for unwanted LPIs to thrive [2]. LPIs depend on precise “resonance” conditions between the laser frequency, plasma frequency, and various plasma waves. Broadband laser pulses can reduce or even eliminate these conditions, therefore increasing LPI thresholds and enabling a more uniform, symmetric drive essential for successful direct-drive ICF implosions.

Engineering a Solution: The FLUX System

The Fourth-generation Laser for Ultra-broadband eXperiments (FLUX) has been built at LLE to meet the challenge of mitigating or even suppressing LPIs. The FLUX system is designed from the ground up to generate, amplify, and convert broadband laser pulses to the UV with a much wider bandwidth—reaching up to 1.5%, an order of magnitude improvement over previous systems [3–5].

Figure 1 illustrates the FLUX architecture. It begins by producing a low-energy broadband pulse in the infrared in a fiber front end. A fiber-laser system shapes the spectrum and temporal shape of this broadband seed pulse, as well as two sets of narrowband seed pulses amplified by separate pump lasers. The resulting pump pulses, after laser amplification and frequency doubling from the infrared (1053 nm) to the

green (526.5 nm), amplify the broadband seed via optical parametric amplification (OPA), then frequency convert the broadband infrared pulse to the ultraviolet via sum-frequency generation (SFG).

OPAs amplify the broadband seed in nonlinear optical crystals by splitting higher-energy “pump” photons into pairs of lower-energy “signal” and “idler” photons [Fig. 2(a)]. By design of the FLUX system, the pump wavelength is 526.5 nm, and the signal is at wavelengths shorter than 1053 nm, resulting in idler wavelengths longer than 1053 nm. OPAs can operate with the input seed and pump propagating in slightly different directions (noncollinear OPA, NOPA), as pictured in Fig. 2(a), or with ideally copropagating seed and pump, which results in copropagating signal and idler beams, as is the case for the high-energy FLUX OPA (collinear OPA, COPA). SFG combines the amplified infrared signal and idler photons from the COPA with pump photons at 526.5 nm into higher-energy ultraviolet photons at wavelengths near 351 nm [Fig. 2(b)].

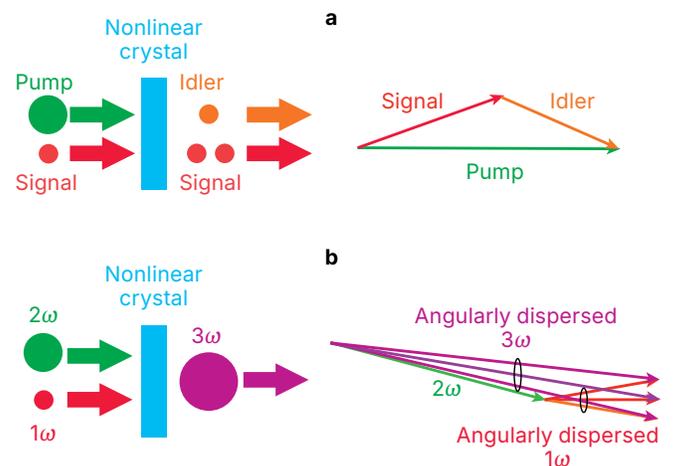


Figure 2. (a) OPA and (b) SFG nonlinear optical processes used in the FLUX system. COPA delivers signal and idler beams propagating in the same direction.

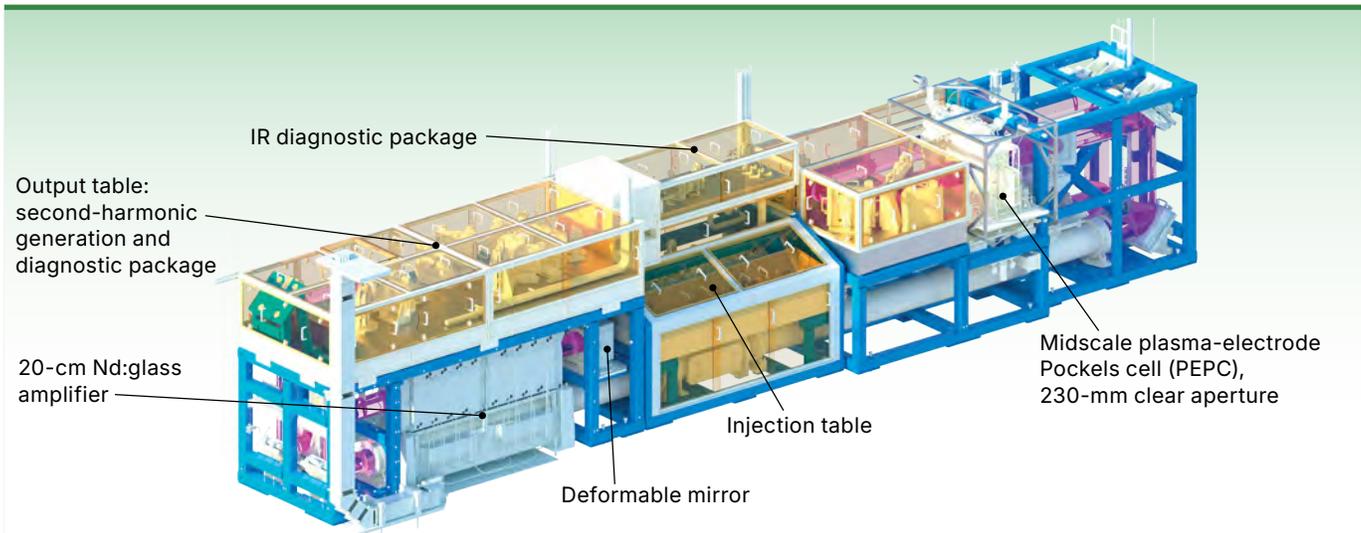


Figure 3. A CAD rendering of the active multipass imaged cavity amplifier (AMICA).

The pump pulse for the NOPA1 and NOPA2 stages originates from a diode-pumped Nd:YLF laser system (crystal large-aperture ring amplifier, CLARA), which is similar to the pump lasers used in the front ends of the Multi-Terawatt (MTW) laser, the short-pulse beamlines of the OMEGA EP beamlines, and the MTW-OPAL system. A newly developed flashlamp-pumped Nd:glass AMICA (active multipass imaged cavity amplifier) laser system delivers a total of 400 J in two time-multiplexed narrowband pump pulses for the COPA and SFG stages (Fig. 3). This pump laser uses laser amplification from an OMEGA 20-cm disk amplifier, polarization switching in and out of its cavity using a newly developed midscale plasma-electrode Pockels cell (a smaller-aperture version of the one used on OMEGA EP), and wavefront correction using a deformable mirror as an end-cavity mirror.

A time delay between the COPA and SFG stages overlaps in time each pump pulse with the broadband input pulse.

On FLUX, two NOPA stages and one high-energy COPA stage amplify broadband incoherent seed pulses. The idler output gets removed after each of the NOPA stages, while both the signal and idler from the COPA stage propagate in the same direction to essentially double the output energy and bandwidth in the infrared, as shown in Fig. 4(a). Producing high-energy ultraviolet pulses requires broadband SFG, which combines nonlinear optics with angular dispersion from two diffraction gratings [4], shown schematically in Fig. 5. The first grating disperses the broadband infrared beam relative to the pump beam. This angular dispersion, in combination with noncollinearly coupling the infrared beam and pump beam and tuning the SFG crystal, angularly sets the different

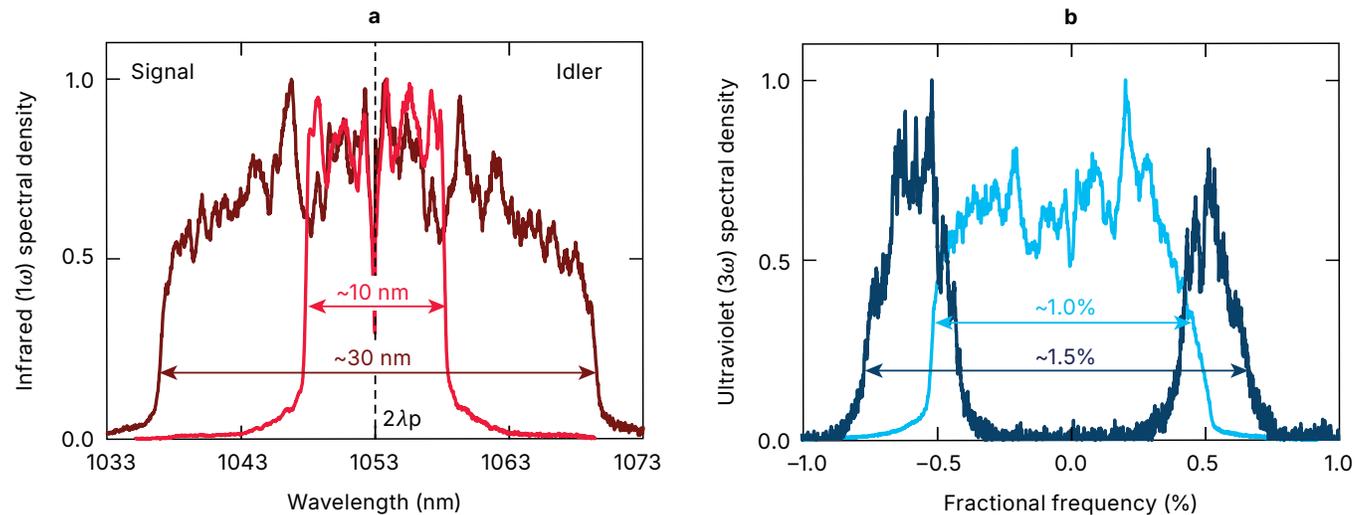


Figure 4. (a) Measured broadband COPA output spectra with $\Delta\lambda = 10$ nm ($\Delta\lambda/\lambda_0 \sim 1\%$, light red) and $\Delta\lambda = 30$ nm ($\Delta\lambda/\lambda_0 \sim 3\%$, dark red). (b) Measured SFG output spectra with $\Delta\lambda/\lambda_0 > 1\%$ in a continuous (light blue) or two-lobed spectrum (dark blue).

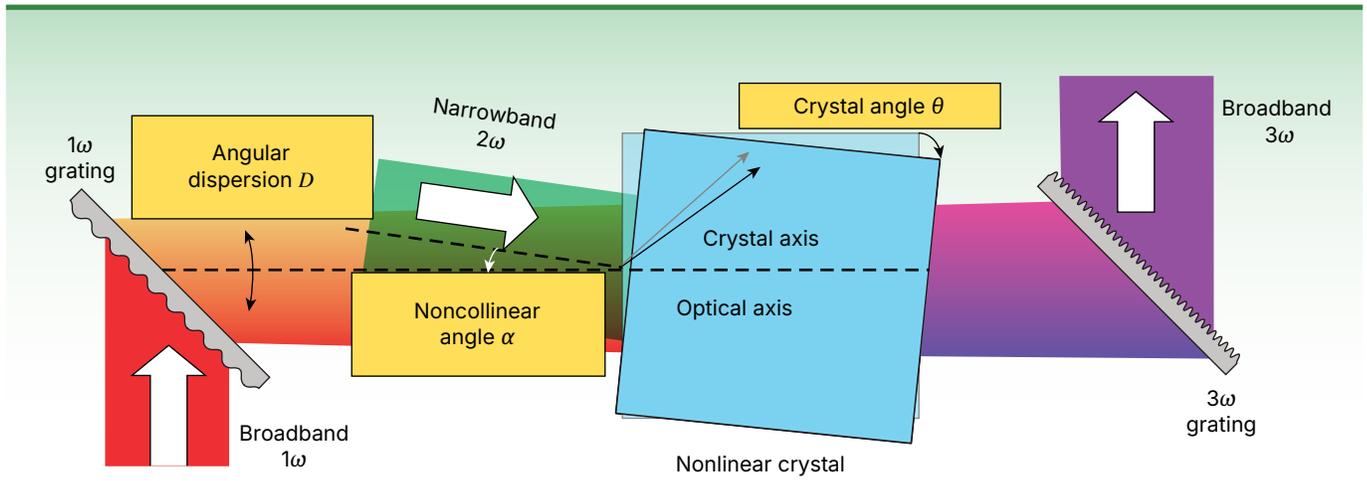


Figure 5. An illustration of the FLUX SFG stage. An infrared 1ω diffraction grating disperses the broadband infrared output (signal + idler) from the collinear optical parametric amplification (COPA) stage to optimize phase matching with the pump beam (green) in the SFG crystal. The pump beam reflects off a dichroic mirror to overlap it with the dispersed COPA output. A 3ω diffraction grating recollimates the broadband ultraviolet output before transport to the OMEGA target chamber.

spectral components of the broadband input to optimize the conditions for efficient SFG. A second diffraction grating located after the SFG crystal removes the angular dispersion of the broadband ultraviolet output so that spectral components propagate in the same direction. Residual dispersion of the bandwidth can provide beam smoothing by spectral dispersion on target to maximize laser drive uniformity [6].

FLUX aims to deliver laser pulses with UV bandwidth up to 1.5%, as shown in Fig. 4(b), which is approximately ten times more than previous high-energy solid-state laser systems. FLUX supported energies up to 20 J for initial target experiments in April 2025, and a campaign currently underway will ramp FLUX energy to deliver more than 100 J for experiments in early 2026.

How FLUX Enables Advances

FLUX is a powerful new tool to experimentally test the mitigation of LPIs in direct-drive experiments. Its unprecedented bandwidth and flexibility enable experiments to

- study LPI mitigation and possibly even suppression as a function of bandwidth,
- test new diagnostic tools for tracking plasma waves and backscattered light, and
- validate next-generation simulation codes and theoretical models for laser-plasma interaction.

Results from FLUX target experiments will guide the design of next-generation inertial confinement fusion facilities. Laser-plasma instabilities have stood as one of the most persistent barriers in the decades-long pursuit of inertial confinement fusion. FLUX marks a major stride forward by strategically targeting the root causes of these phenomena with an innovative broadband laser system. With experiments supported by FLUX and OMEGA, understanding LPIs and ways to control them will accelerate with the goal of unlocking the potential of fusion.

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Focus Points

- The FLUX system provides a tool for testing the efficacy of broadband lasers to mitigate laser-plasma instabilities.
- Nonlinear optics enables broadband infrared amplification and frequency conversion to the ultraviolet.
- A compact, kilojoule-class AMICA laser pumps the FLUX optical parametric amplification (OPA) and sum-frequency generation (SFG) stages.

Enabling Ultraclean Pulses from Kilojoule-Class Lasers

NSF OPAL is a proposed future user facility at LLE that is intended to enable scientists to create and study matter under extreme conditions. [1] To study these conditions, NSF OPAL laser pulses must be incredibly clean. When a laser fires, sometimes a small amount of energy leaks out before the main pulse. These early flashes—called prepulses—can damage or change the target before the main shot even arrives, which can ruin the experiment. To avoid this, NSF OPAL must have an extremely high temporal contrast, which means that any prepulse needs to be vastly less powerful than the main pulse. The contrast must be greater than one part in one hundred billion (i.e., 10^{11}). To get a sense of scale, imagine comparing one meter to the distance between Earth and Mars—an enormous difference that shows just how precisely NSF OPAL laser pulses must be controlled.

Several methods can “clean” laser pulses to achieve higher temporal pulse contrast. Plasma mirrors, described on [page 25](#) of this issue (“Liquid Crystal-Plasma Mirrors”), can improve temporal contrast by approximately $100\times$ per mirror by highly reflecting only the parts of the pulses that are above breakdown intensity. By design, plasma mirrors must be replaced or refreshed after every laser shot.

Second-harmonic generation (SHG) is a nonlinear optical process that doubles the laser frequency (1ω to 2ω , or halves the wavelength λ to $\lambda/2$). SHG provides another powerful pulse-cleaning approach since high efficiency can be achieved, and its small-signal conversion efficiency varies according to the square of the laser intensity ($I_{\text{SHG}} \propto I_{\text{Laser}}^2$). Separating the 2ω output from the unconverted (1ω) laser pulse can be accomplished using dichroic mirrors that preferentially reflect 2ω pulses, as shown in Fig. 1(a). Theoretically, the temporal contrast of NSF OPAL laser pulses with 10^{10} temporal contrast could be improved up to 10^{20} .

Frequency doubling intense laser pulses requires thin nonlinear crystals. SHG pulse cleaning on the Orion laser at the Atomic Weapons Establishment has demonstrated great utility using a 3-mm-thick, free-standing, 300-mm-diam KDP crystal to produce SHG pulse energies up to 100 J at 500 fs [2]. Similar performance was achieved using an 800- μm -thick LBO crystal with a 185-mm-diam titanium sapphire laser beam to produce 8-J, 30-fs pulses [3]. Larger-aperture crystals for these thicknesses proved impractical to fabricate, which limited the maximum SHG energy from both laser systems. NSF OPAL would require even thinner KDP crystals ($\sim 200\ \mu\text{m}$) to frequency convert 20-fs, 620-mm square beams. The L4 ATON laser at ELI Beamlines [4] faces a similar SHG challenge to frequency double its 1.5-kJ, 150-fs pulses with the same beam size as NSF OPAL.

Figure 1(b) conceptually illustrates a solution suitable for high-energy lasers: SHG mirrors. An SHG crystal with suitable antireflection and high-reflection coatings is mounted on a thick substrate to provide the mechanical stability required for ultrathin crystals. SHG mirror designs can optimize SHG phase matching for either incident 1ω pulses and reflect the 2ω output, or reflected 1ω pulses. Conventional optical manufacturing processes, like single-point

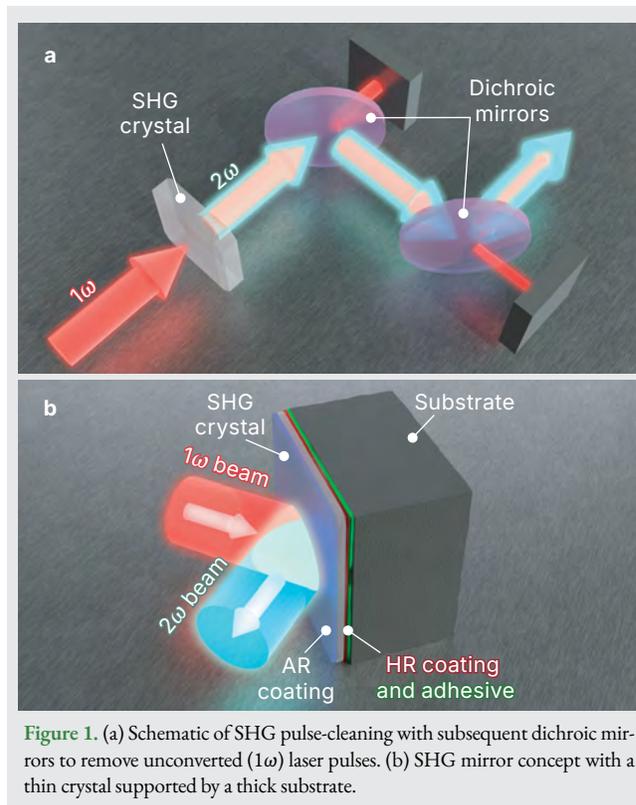


Figure 1. (a) Schematic of SHG pulse-cleaning with subsequent dichroic mirrors to remove unconverted (1ω) laser pulses. (b) SHG mirror concept with a thin crystal supported by a thick substrate.

diamond turning, would reduce the SHG crystal thickness in the assembly before applying the front-surface antireflective coating. LLE has started collaborations to develop SHG mirror technology that will be discussed in a future issue of *LLE In Focus*.

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Focus Points

- To create and study matter under extreme conditions, NSF OPAL laser pulses must be incredibly clean with essentially no prepulses.
- Second-harmonic generation mirrors promise a path to realize kilojoule-class pulse cleaning.

Liquid Crystal Plasma Mirrors

A Breakthrough for NSF OPAL

Researchers at LLE and The Ohio State University (OSU) have teamed together to develop renewable, liquid crystal plasma mirrors (LCPMs) to enhance the temporal contrast of the 25-PW pulses planned for NSF OPAL. High-peak-power lasers often deliver unwanted energy, known as a “prepulse,” that precedes the desired ultrashort pulses. Given the extremely high peak powers of the main pulse, these prepulses can disrupt experiments even when they are much smaller than the main pulses.

Pairs of plasma mirrors can improve temporal contrast by as much as 1000×, effectively mitigating the undesirable effects of the prepulse. They have low reflectivity until the pulse reaches an intensity that breaks down its front surface, forming a highly reflective plasma that then reflects only the parts of the pulse above the breakdown intensity. Plasma mirrors are inherently destroyed in every shot, but they protect the experimental target from the same fate.

Liquid crystals (LCs) are an innovative way to create renewable plasma mirror films. This approach was first demonstrated at OSU [1], where an LC compound was wiped across an open aperture to create ultrathin (<30-nm), freestanding films similar to a soap bubble (Fig. 1). These LC films demonstrated 80% reflectance at $2 \times 10^{16} \text{ W/cm}^2$ [2], which is comparable to conventional plasma mirrors. Repeatably wiping a new LC film proves to be a highly cost-effective (<\$0.01 per shot) and straightforward approach.

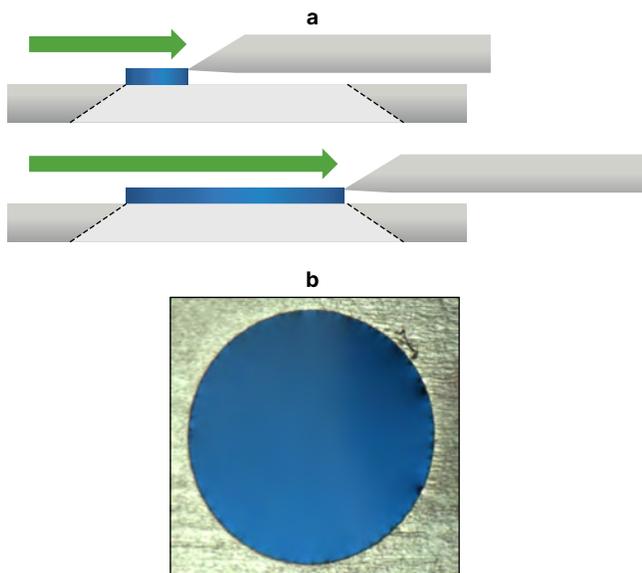
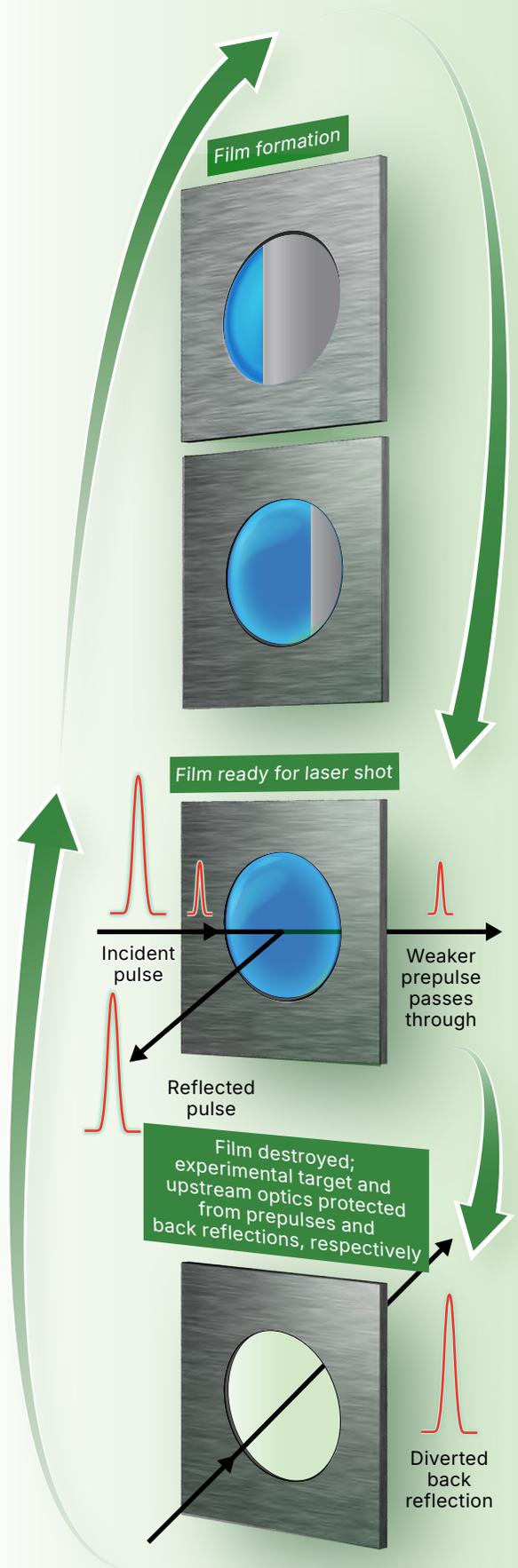


Figure 1. (a) The basic wiping concept for generating freestanding LCPMs. (b) Image of a freestanding LC film.



NSF OPAL will require large LC film diameters (~15-mm) that are optically flat ($\lambda/10$ or better) to maintain good focusing quality. Inherently, nonuniformities occur where the LC fluid meets the edge of the physical aperture, which reduces the usable portion of the film (Fig. 2). A prototype device with 24-mm-diam films of 8CB (the LC material used in early LCPMs) shows promise for supporting up to 4-PW beams, so a proposed experiment at the 3-PW NSF ZEUS Laser Facility aims to test the device. However, the 24-mm LCPM does not satisfy NSF OPAL film uniformity requirements, so the OSU-LLE team has built on the >40 years of LLE experience with LC materials for laser applications to explore new approaches.

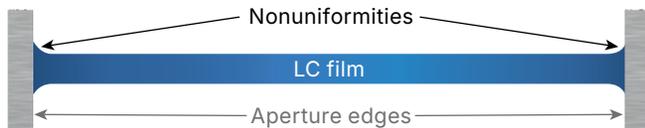


Figure 2. Nonuniformities in the LC film occur at the interface with the physical aperture and reduce the usable portion of the film.

Mixtures of LC molecules can enable the fine-tuning of material properties, much as metal alloys can improve upon pure metals. Over the past year, the LLE Optical Materials Group, including several student researchers, studied the physical properties of a wide variety of LC mixtures along with their temperature dependencies. Polarized optical microscopy imaging (Fig. 3) enabled LLE researchers to understand the crystalline nature of the mixtures and the temperatures required for forming high-quality films. One formulation using a cyanobicyclohexyl compound, known as CCH-2, performed exceptionally well in combination with 8CB. This mixture repeatedly demonstrated a 75% improvement in uniformity as compared to 8CB films of

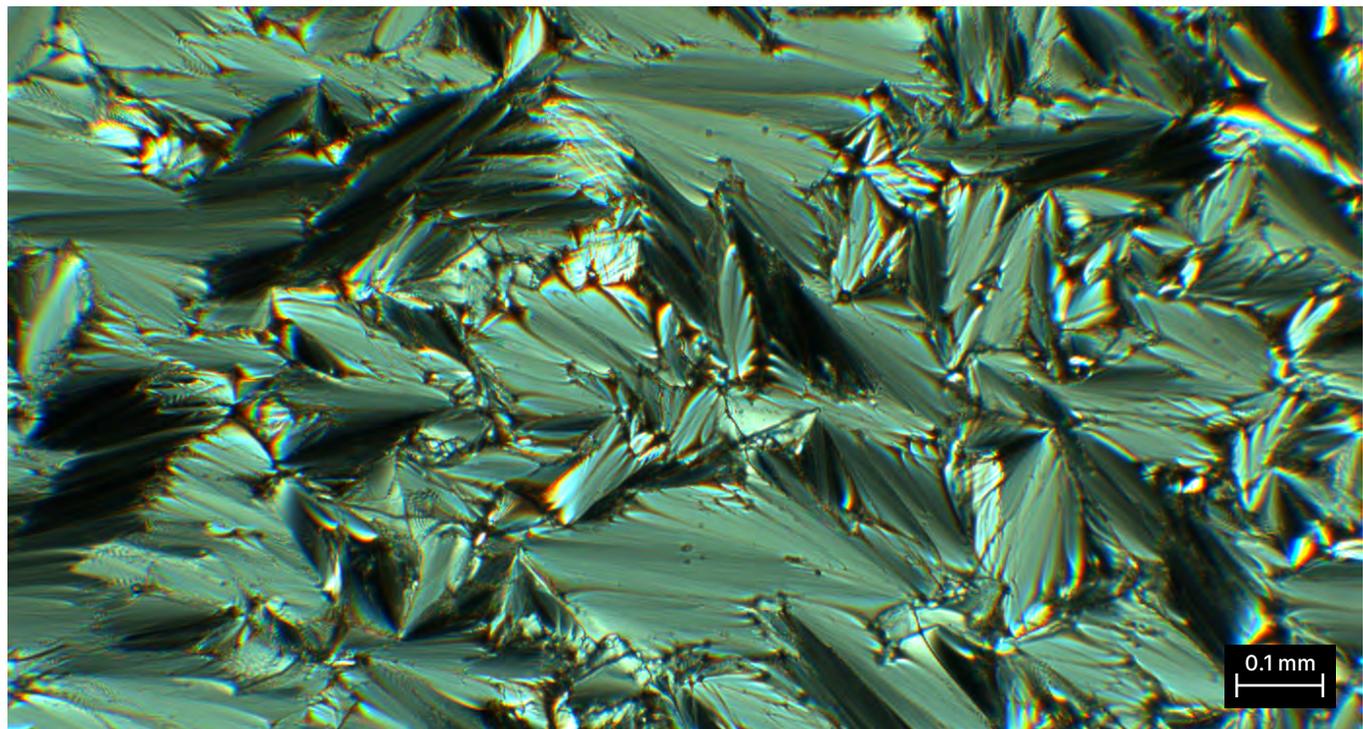


Figure 3. Polarized optical microscope image of a new LC mixture developed at LLE.

the same aperture size. This breakthrough is expected to provide the uniformity needed for NSF OPAL and other multipetawatt laser systems.

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Focus Points

- New multipetawatt laser systems, such as NSF OPAL, will require large-aperture, high-quality plasma mirrors to enhance temporal contrast.
- Liquid crystals provide a means to produce quickly renewable, low-cost plasma mirrors.
- LLE expertise in liquid crystal materials combined with pioneering technology developed at OSU has led to a breakthrough performance in the uniformity of liquid crystal plasma mirror films that will enable them to support 25-PW laser pulses.

New Mirror Technology for NSF OPAL

A future NSF OPAL laser user facility will require extremely large all-reflective optics estimated to weigh up to 1000 pounds using traditional solid substrates. Large beams are required to prevent laser-induced damage while delivering 25-PW peak-power pulses. Such massive substrates prove impractically expensive, however, given the need for up to 75 flat mirrors and up to 20 large off-axis parabolic mirrors, plus associated optomechanics required to achieve few-micron focusing and pointing stability.

Conventional methods to produce lightweight mirrors mechanically remove up to 90% of a solid substrate and then bond a faceplate to this “core” that can be finished to provide the required reflective surface. This approach adds cost, increases production time, and generates a significant amount of waste material. Therefore, developing methods to produce low-cost, lightweight mirrors would significantly reduce overall NSF OPAL facility costs.

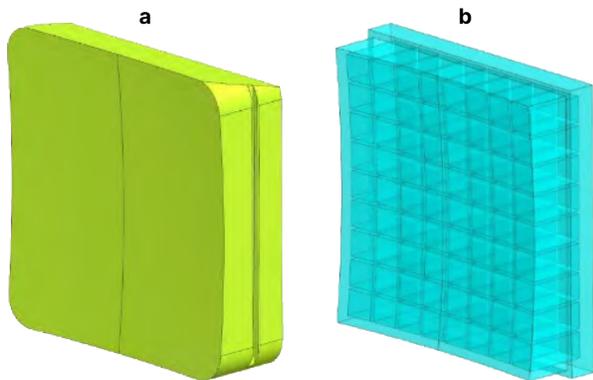


Figure 1. Examples of an OMEGA EP off-axis parabolic mirror fabricated using (a) a solid substrate and (b) a lightweight structure with a “constructed core” using a front faceplate for the reflective surface and a back grid for supporting and mounting the mirror.

Figures 1(a) and 1(b) illustrate examples of OMEGA EP off-axis parabolic mirrors using solid and lightweight substrates, respectively. The solid substrate shown in Fig. 1(a) has a reflective surface and other features, like side grooves for mirror mounts. These features are machined from optical materials like fused silica, which prove very expensive at the required size.

Figure 1(b) exemplifies new concepts that have emerged for constructing lightweight mirror cores. The supporting frame is constructed as a grid, with rectangular or hexagonal cells. The ribs are fabricated to define the reflecting surface. For focusing reflectors, the rough shape of the front reflector can be formed by “slumping” a flat glass faceplate onto the constructed core, which results in a shape within a few tens of microns of the prescribed surface that can be figured using conventional methods.

The lightweight structure can be formed using laser welding, glass-frit bonding (glass soldering), or low outgassing optical adhesives to construct the core and attach the faceplate to the core. Additive manufacturing (3D printing) provides an alternate method to fabricate metal or glass constructed cores. The face plate can be polished and coated using the same processes used to provide highly reflective surfaces for solid mirrors. The faceplate thickness determines how much of the core pattern “prints through” to the front surface. Testing demonstrates that glass faceplates with thicknesses in the range of 6 to 10 mm do not exhibit print through, which is referred to as “quilting.”

Lightweight mirror substrates must survive production steps, such as the polishing and deposition of reflective optical coatings that can involve temperatures up to 150 °C and vacuum cycles. Vents are required in the lightweight mirrors to prevent air from being trapped when operated in vacuum. Fortunately, strong interest exists in industry to produce lightweight mirrors needed for astronomical telescopes, especially for space-based and airborne applications where minimizing weight proves essential and reducing cost is highly desirable [1,2]. This broad commercial demand and capacity will be essential for realizing required optical performance and reducing costs.

The NSF OPAL design team has presented its needs to numerous companies and initiated a three-phase program that will start by testing promising methods by prototyping subscale mirrors. A request for proposals yielded cost estimates as much as five times lower than comparable solid substrates.

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Focus Points

- Conventional mirror technology would significantly increase construction costs for a future NSF OPAL facility, while emerging lightweight mirror substrates offer a promising path to cost savings.

Three-dimensional architectural rendering of the proposed NSF OPAL Facility, courtesy of SWBR.



NSF OPAL



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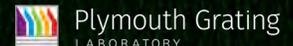


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