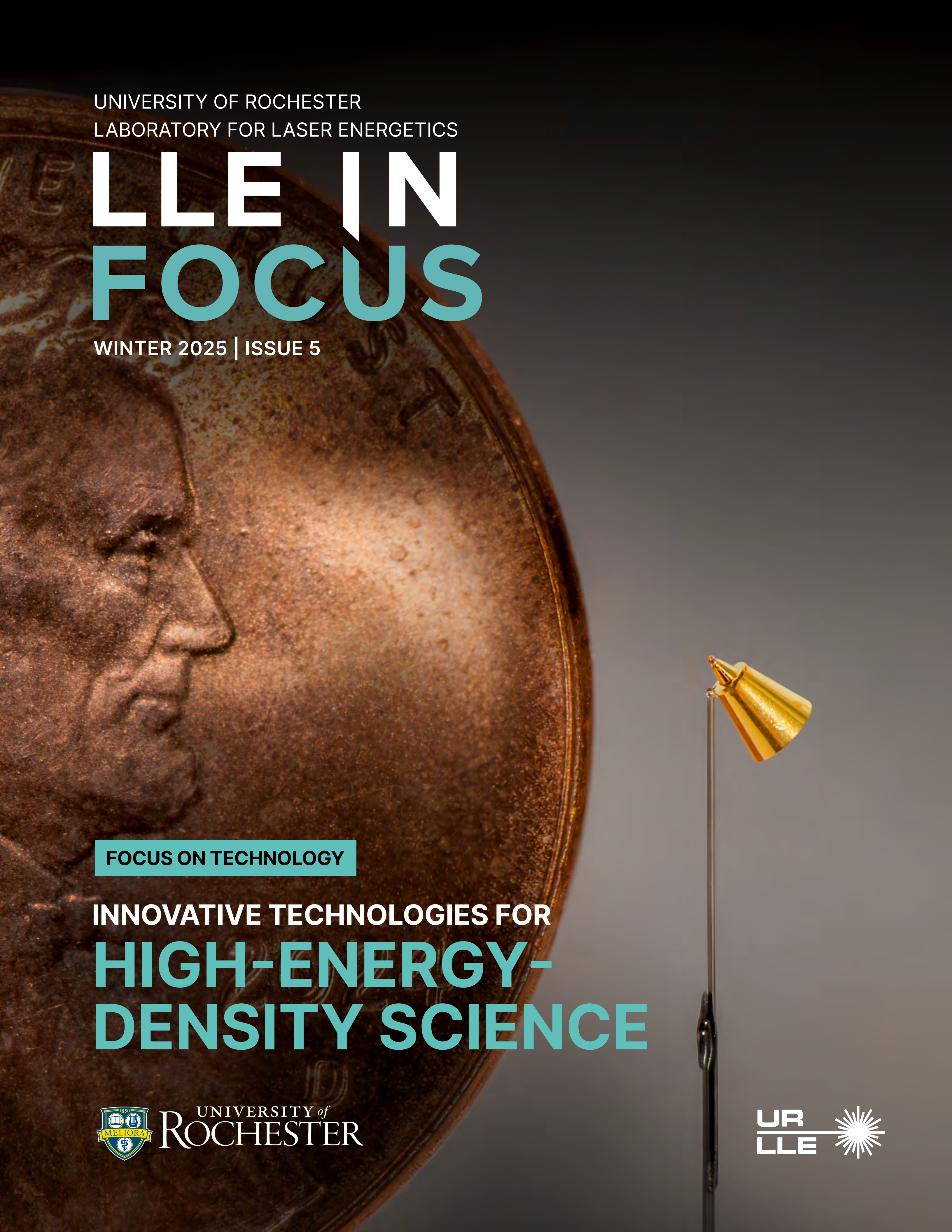
UNIVERSITY OF ROCHESTER
LABORATORY FOR LASER ENERGETICS

LLE IN FOCUS

WINTER 2025 | ISSUE 5



FOCUS ON TECHNOLOGY

INNOVATIVE TECHNOLOGIES FOR HIGH-ENERGY-DENSITY SCIENCE

UNIVERSITY *of* ROCHESTER

UR LLE

LLE IN FOCUS

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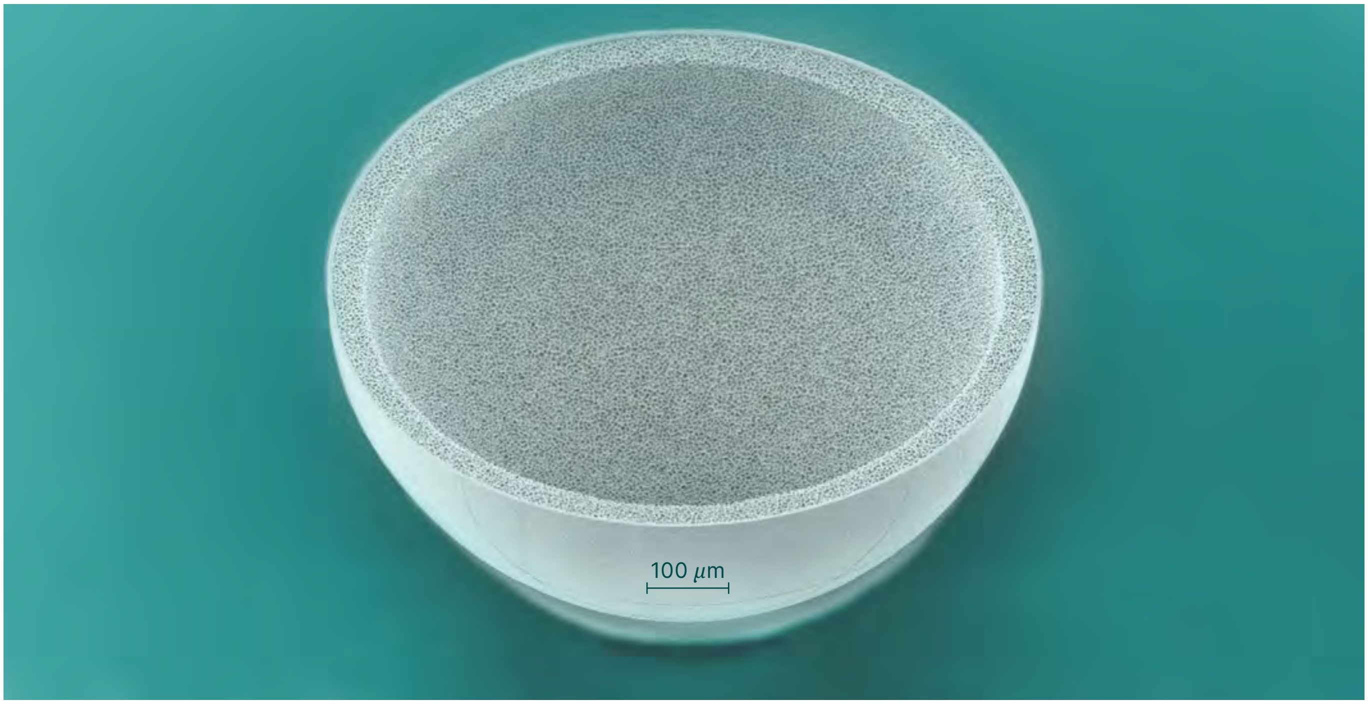
READ LLE IN FOCUS ONLINE

A magnetized liner inertial fusion (MagLIF) target created for Sandia National Laboratories at LLE. The target includes components from General Atomics (GA), Luxel Corp, and Protolabs, and was assembled by Julie Fooks, a GA employee stationed at LLE.

LLE IN FOCUS

Focus on: Technology

Winter 2025 | Issue 5



Shown above is an electron microscope image of a target that is in development for experiments on OMEGA. The inner cellular (foam) structure of this hemishell is visible: 0.9 mm in diameter, it has a solid 5-μm-thick outer wall, and a 45-μm-thick inner foam wall. What distinguishes this target and development effort from other targets is that the entire structure was printed using the latest additive manufacturing tools.

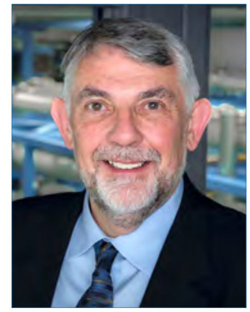
COLUMNS

FEATURED ARTICLES

About the cover

The cover shows a fast-ignition target displayed next to a penny, illustrating its incredibly small size and precision. The target was created by Katharine Gerbsch, a General Atomics (GA) employee stationed at LLE, using components supplied by GA. Read more about the LLE–GA collaboration on page 24.

LLE IN FOCUS



From the Director

DR. CHRISTOPHER DEENEY | DIRECTOR, LABORATORY FOR LASER ENERGETICS

This winter, I'm proud to reflect on the significant strides we've made at the Laboratory for Laser Energetics (LLE) in advancing our core mission of conducting impactful world-class research. To borrow from the real estate community, inertial confinement fusion and high-energy-density physics have three important factors: precision, precision, precision. Consequently, a key focus has been ensuring micron-level precision in everything we do, from the design and fabrication of experimental targets to the precision manufacturing that supports our work. In addition, we have a culture of, "if we can make it, we must also be able to measure it." Our **Target Fabrication Group** has continued to innovate, developing specialized target manufacturing and metrology for high-energy-density–physics experiments that are critical for advancing fusion research and laser science.

Also vital to our success is the **Machine Shop and Quality Control Department**, whose expertise in building custom components and maintaining exacting standards ensures the accuracy and reliability of every part used in our experiments. The department's craftsmanship plays an integral role in enabling the high level of precision required for our research in next-generation technologies and diagnostics. The collaboration between our fabrication teams and the broader research community remains a cornerstone of LLE's continued ability to push the boundaries of scientific discovery. In fact, on a visit in 2022 to LLE, the head of the Physics Division at the National Science Foundation, Dr. Denise Caldwell, specifically highlighted our ability to make precision instrumentation and systems.

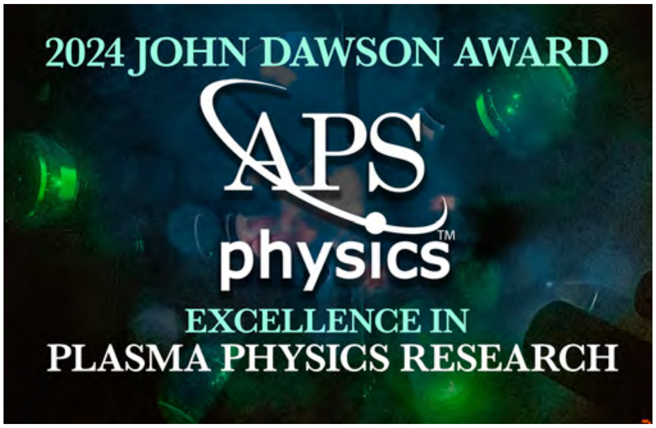
We are also excited about the significant progress we've made in achieving **ultrahigh contrast levels on our Multi-Terawatt (MTW) Laser System**. These advancements will maximize the power and precision of multipetawatt short-pulse lasers, enabling cleaner, more-controlled experiments with unprecedented accuracy.

All our great work is achieved through the individuals and teams who comprise LLE and the collaborators we value. **General Atomics** has been a key partner in advancing our target fabrication, as well as the **University of Nebraska–Lincoln**. This has also been an important quarter for acknowledging our efforts. Our operational and safety teams were given awards to recognize their important roles at LLE. In addition, a team from LLE was given the Dawson Award from the American Physical Society—one of the most prestigious awards in plasma physics.

As we continue to make groundbreaking strides, we are equally proud of the achievements of our faculty, staff, and students, whose work has earned recognition in the scientific community. The commitment to quality, precision, and collaboration that defines LLE is truly at the heart of everything we do, and I'm excited for the discoveries that lie ahead as we continue to build on these strong foundations.

Christopher Deeney
Director, Laboratory for Laser Energetics

Awards and Honors



LLE Team Receives Prestigious APS Award

The American Physical Society (APS) awarded a research team from LLE with the 2024 John Dawson Award, recognizing their pioneering work in developing statistical models to predict, design, and analyze implosion experiments on the 30-kJ OMEGA laser. Key contributors included Riccardo Betti, Mike Campbell, Duc Cao, Chad Forrest, James Knauer, Aarne Lees, Varchas Gopalaswamy, Sean Regan, Rahul Shah, Cliff Thomas, and Connor Williams. The team's work is expected to guide future implosion experiments and accelerate progress in high-yield inertial confinement fusion and inertial fusion energy.

LLE Undergraduate Kaan Aytekin Awarded Best Poster by APS-DPP

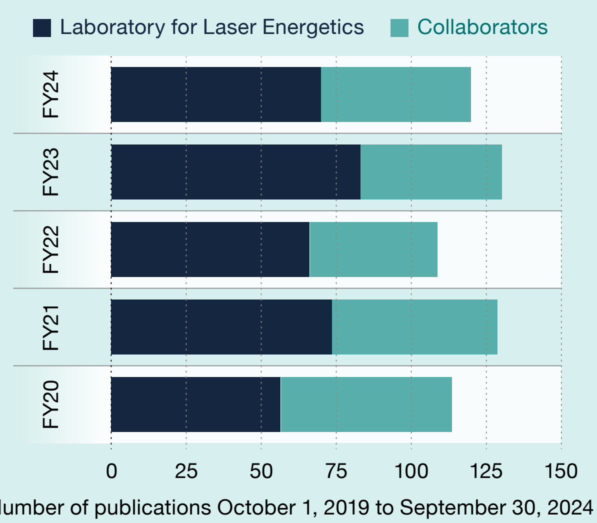
Kaan Aytekin, a junior at the University of Rochester's Hajim School of Engineering & Applied Sciences and a member of LLE's Undergraduate Education Program in the High-Energy-Density Theory Group, won an Outstanding Poster Award at the 2024 APS Division of Plasma Physics conference. His presentation, titled "Fast Free-Free Absorption Coefficient Calculations Including Plasma Screening," was selected from over 150 other student posters and was one of only five presentations to receive this award.

2024 Operations Awards

The LLE Operations Awards honor individuals who have demonstrated exceptional dedication to the safe and effective operation of the OMEGA, OMEGA EP, and Cryogenic and Tritium Facilities. The 2024 awards were presented at the third annual ceremony this past fall. Shown here from left to right are awardees Melody Scott, Steven Verbridge, Eric Schwartz, Jeremy Czirr, and Elliot Carter, each recognized for their exemplary contributions to advancing LLE's mission and maintaining high standards in safe operation.

Publications

The multidisciplinary science and engineering research at LLE is captured through peer-reviewed publications. LLE averages more than 100 publications annually across three broad areas: high-energy-density physics, inertial confinement fusion, and technology.



FOCUS ON

Artificial Intelligence and Machine Learning

Fusion research generates vast amounts of data, posing challenges for extracting meaningful insights through traditional methods. In inertial confinement fusion, the complexity of the problem restricts analysis to a limited number of target shots, even with the most-advanced supercomputers. This limitation prevents current scaling methods from handling the extensive datasets generated on OMEGA. To address this, we can utilize reduced-order models for experiments and allow the datasets to reveal their insights. Artificial intelligence (AI), particularly machine learning (ML), excels at analyzing large datasets and detecting subtle patterns beyond human capability. By applying AI/ML to fusion experiments and high-energy-density–physics research, LLE is able to unlock new avenues for understanding and optimizing these complex processes.

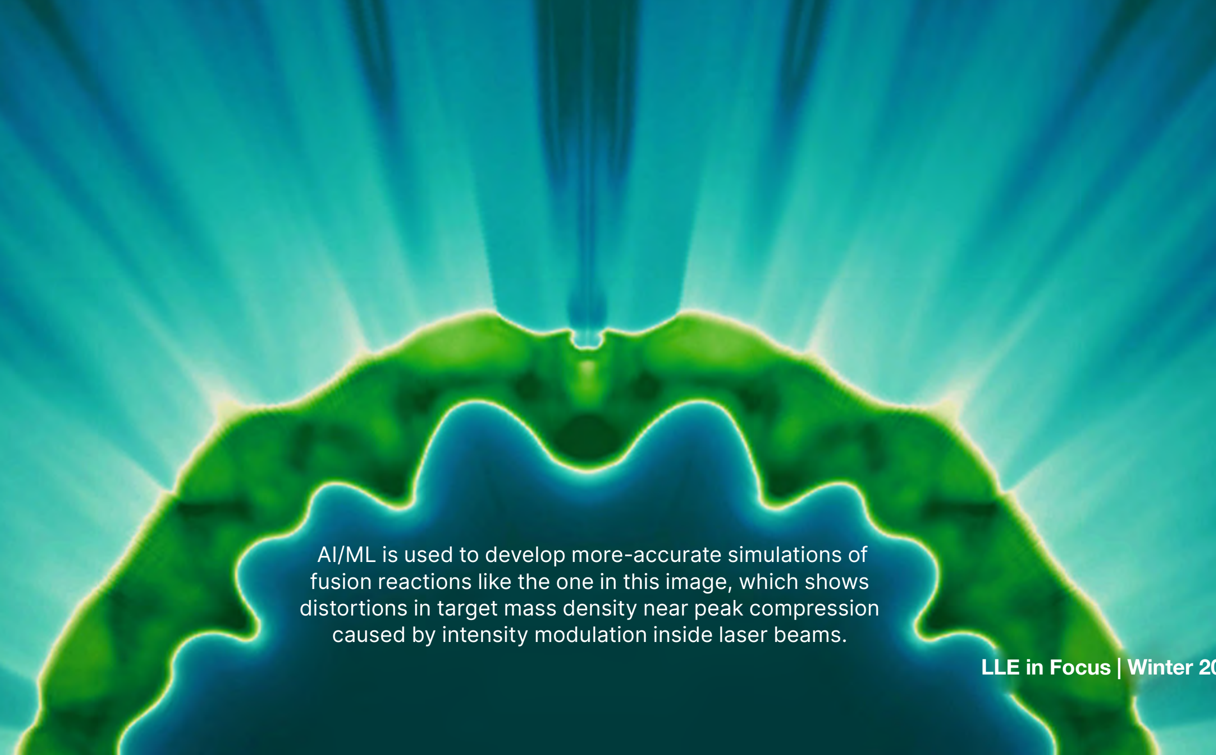
One of the most-promising applications of AI at LLE is in data analysis. AI models are able to analyze experimental data, identifying trends, anomalies, and correlations that can provide valuable clues about the underlying physics of fusion. For example, AI can help researchers spot unexpected fluctuations in plasma behavior or identify optimal experimental conditions for achieving specific fusion reactions.

Beyond data analysis, AI/ML is also being used to develop more-accurate simulations of fusion reactions. By training ML models using massive amounts of experimental data, LLE researchers create sophisticated simulations that can predict the behavior of fusion plasmas under various conditions. These simulations help optimize experiments and accelerate discoveries.

While AI/ML offers significant potential, it is essential to approach its application with caution. The complexity of physics and fusion experiments means that machine-learning interpretations must be carefully analyzed to ensure they align with our understanding of underlying principles. Even with AI/ML, human expertise is essential to interpret results. For example, ML might incorrectly associate long pulse shapes with poor performance, when the true causal factor is the adiabat, which is influenced by the picket design. Understanding such nuances requires human insight to guide AI conclusions. To fully leverage the power of AI, a multidisciplinary approach is necessary. "We need AI experts to develop and train the machine-learning models," says scientist Varchas Gopalaswamy, "but to interpret whether our models are doing the right things for the right reasons, we need physicists. We also need engineers, technologists, and materials scientists—a whole ecosystem."

To learn more about how LLE scientists are harnessing AI to advance fusion research, be sure to read Melissa Pheterson's article "How Artificial Intelligence is Powering the Fusion Revolution" at the University of Rochester's News Center.

UNIVERSITY of ROCHESTER News Center



AI/ML is used to develop more-accurate simulations of fusion reactions like the one in this image, which shows distortions in target mass density near peak compression caused by intensity modulation inside laser beams.

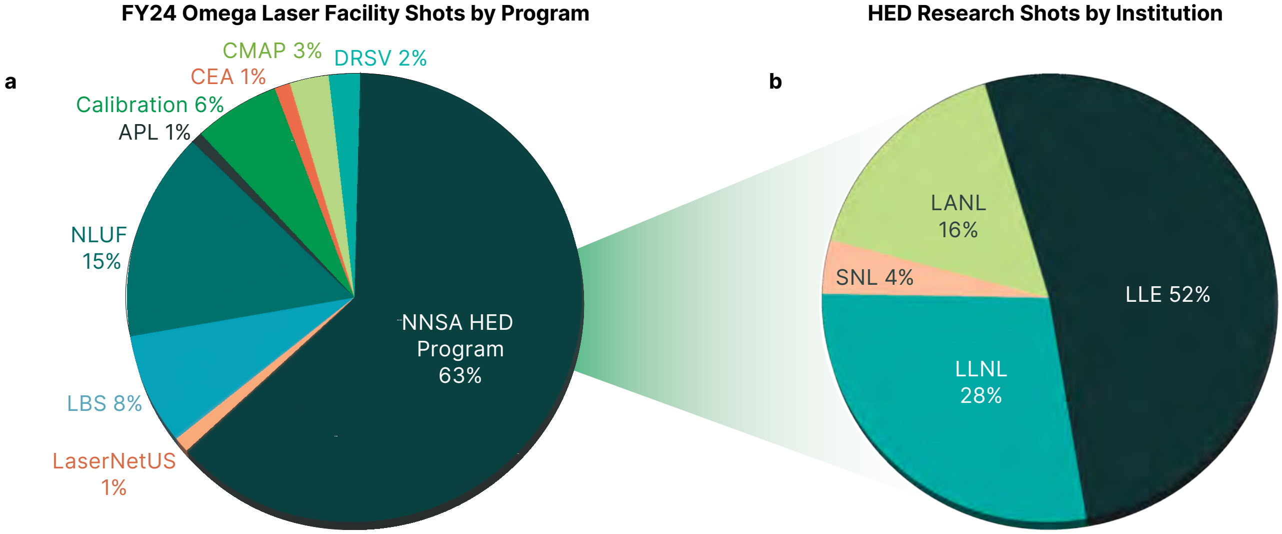
FOCUS ON THE FACILITY

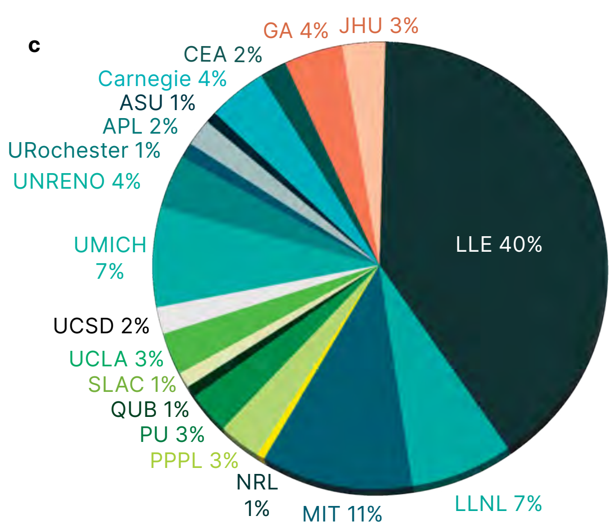
Laser Facility Report

The Omega Laser Facility conducts experiments for research and development in support of the NNSA High-Energy-Density (HED), National Laser Users' Facility (NLUF), and Laboratory Basic Science (LBS) Programs, in addition to other research and educational efforts. During FY24, the Omega Laser Facility conducted 1071 target shots on OMEGA and 704 on OMEGA EP with a total of 1775 target shots for 221 campaigns. Of these, 34 target shots were cryogenic targets. OMEGA averaged 93.5% availability and 91.5% experimental effectiveness while OMEGA EP averaged 92.3% availability and 94% experimental effectiveness. See Fig. 1(a) for a breakdown of target shots by program.

Approximately 60% of the experiments conducted at LLE supported the NNSA HED Physics Program, while the remaining experiments involved collaborations with other national laboratories, academic institutions, and researchers from the NLUF and LBS Programs.

In the HED Program, shots are performed by LLE and other national labs. During FY24, 1116 HED target shots were taken by LLE, LLNL, LANL, and SNL. See Fig. 1(b) for a breakdown of HED shots by laboratory. The remaining 659 target shots were taken by a variety of researchers, with over half taken by scientists from external institutions. See Fig. 1(c) for a breakdown of these shots by institution.





APL:	Applied Physics Laboratory
ASU:	Arizona State University
Carnegie:	Carnegie Institution for Science
CEA:	French Alternative Energies and Atomic Energy Commission
CMAP:	Center for Matter at Atomic Pressures
DRSV:	Director's Reserve
GA:	General Atomics
HED:	High Energy Density
JHU:	Johns Hopkins University
LANL:	Los Alamos National Laboratory
LBS:	Laboratory Basic Science
LLE:	Laboratory for Laser Energetics
LLNL:	Lawrence Livermore National Laboratory
MIT:	Massachusetts Institute of Technology
NLUF:	National Laser Users' Facility
NRL:	Naval Research Laboratory
PPPL:	Princeton Plasma Physics Laboratory
PU:	Princeton University
QUB:	The Queen's University of Belfast
SLAC:	Stanford Linear Accelerator Center
SNL:	Sandia National Laboratories
UCLA:	The University of California, Los Angeles
UCSD:	The University of California, San Diego
UMICH:	The University of Michigan
UNRENO:	The University of Nevada, Reno
URochester:	The University of Rochester

Figure 1. Distribution of shots performed at the Omega Laser Facility for FY24.

Front-End Laser Systems on OMEGA EP

Pulse shaping and timing the OMEGA EP beams are the responsibility of the Front-End Laser Systems Group, which manages the source lasers and the manipulation of the beam characteristics before the beams reach the large-aperture power amplifiers. Pulse shaping is the process of making tweaks to the electrical output of the arbitrary waveform generator (AWG) so that it precompensates for the distortion imparted as the laser pulse traverses each gain stage on its way to the target.

In Fig. 2, the same pulse is represented at three different stages. Working backward from (c) [the desired square pulse at the output of the crystal large-aperture ring amplifier (CLARA)], (b) the regen (regenerative amplifier) output must be a ramped pulse. To achieve a ramped pulse at the regen output, the AWG must output (a) a "rhino horn" pulse shape.

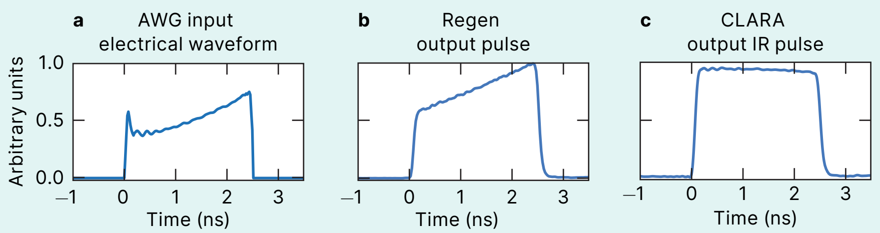


Figure 2. Pulse shapes are controlled to achieve the desired laser output. The shape of (a) is used to precompensate gain effects. At intermediary stages, the pulse shape (b) is observed to be ramped before entering the CLARA amplifier stage. The shape (c) is the result of controlling the electrical waveform.

Time-Multiplexed Pulse-Shaping Upgrade

Timing is critical to the success of experiments on OMEGA EP. Beams must be co-timed relative to each other, as well as to diagnostics and other equipment. Previously, the four OMEGA EP beams each had separate front ends that could drift independently, making co-timing the beams challenging. Now that the same AWG is able to generate all four sources on the same record, beams will drift together and stay co-timed to each other (Fig. 3).

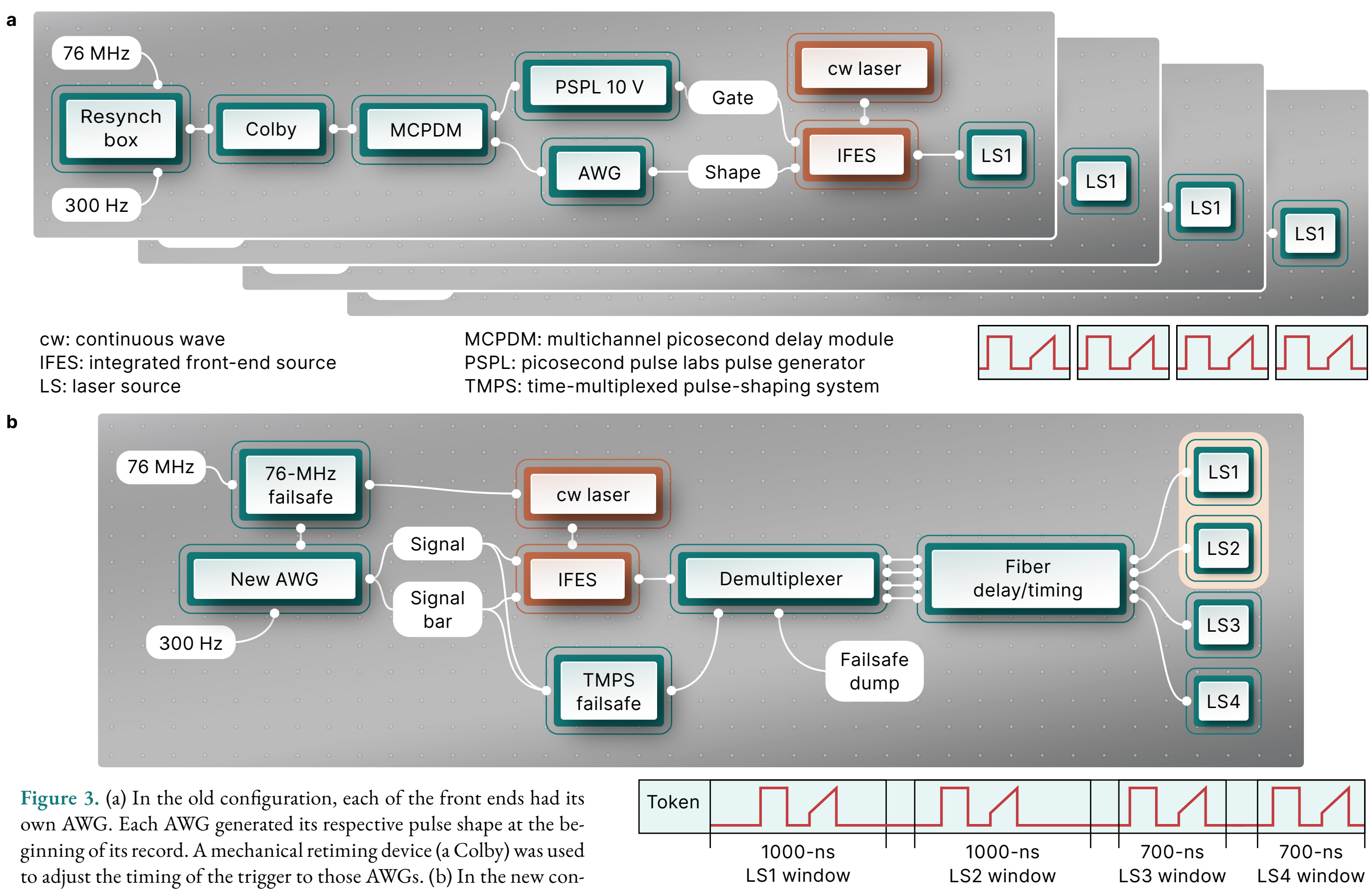


Figure 3. (a) In the old configuration, each of the front ends had its own AWG. Each AWG generated its respective pulse shape at the beginning of its record. A mechanical retiming device (a Colby) was used to adjust the timing of the trigger to those AWGs. (b) In the new configuration, a single AWG feeds all four sources, and timing is adjusted via the AWG itself, rather than via a mechanical delay.

GRADUATE STUDENTS

The Future of Science

Dr. David Bishel

Department: **Physics and Astronomy**
Advisors: **G. W. Collins and J. R. Rygg**
Technical Advisor: **P. M. Nilson**

Every so often, a student comes along with the ability to make transformational discoveries, deftly describe the impact of such discoveries to a general audience, teach and mentor students at all levels, engage and inspire underrepresented groups in science, or be a catalyst for collaboration. During his doctoral work at LLE, David Bishel proved to be gifted with all of these qualities. Receiving his undergraduate degree in physics with distinction from California State University, Stanislaus, David engaged in summer research at both Lawrence Livermore National Laboratory (LLNL) and SLAC National Accelerator Laboratory. We are thrilled to now congratulate Dr. Bishel on receiving his PhD in Physics and Astronomy from the University of Rochester.

David's research uncovers the nature of atoms and radiation at atomic pressures—conditions common to the deep interiors of stars and late stages of inertial confinement fusion implosions. In such dense plasmas, electrons typically considered free and unbound can penetrate the core orbitals of atoms, screening the nuclear charge and thus dramatically shifting the characteristic energy levels of atoms. Understanding such behavior is essential to determining high-pressure equations of state and the radiative properties that allow atoms to communicate with each other and their environment.

In his work at LLE, David was able to produce these extreme conditions through carefully tailored implosions, which both compressed the sample and produced a short burst of x rays for high-resolution spectroscopic mapping of atomic energy levels versus pressure. David's careful experiments, analysis, and intuitive theoretical modeling enabled him to see for the first time how unbound electrons get squeezed into core atomic orbitals at such extreme pressures—that is, how the atoms themselves change. Along the way, David helped launch several working groups to build a collaborative learning environment while teaching classes to students typically underrepresented in science. He also led several outreach activities including those at the Rochester Museum and Science Center. Currently a postdoc at the Center for Matter at Atomic Pressures, David looks forward to pursuing a further postdoc position at LLNL.

> "LLE has been a spectacular place to grow as a scientist, and I am grateful for the many opportunities. **Tackling hard problems has taught me to invent new solutions.** Lengthy discussions with scientists have taught me both fundamentals and nuances, and the community of students made it all the more enjoyable."

Dr. Russell Dent

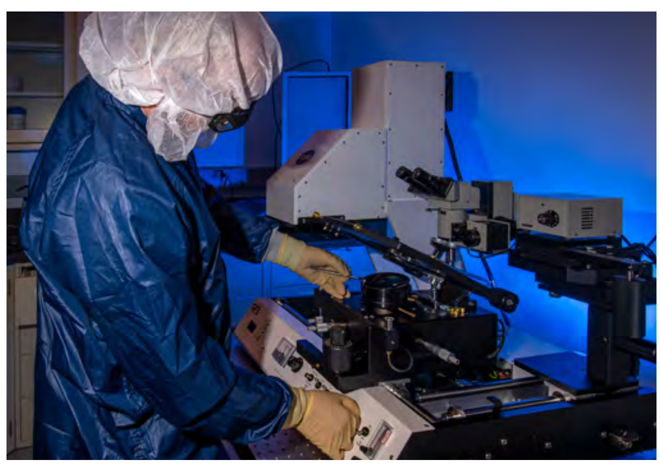
Department: **Chemical Engineering**
Advisors: **S. G. Demos and A. A. Shestopalov**

Pulse-compression gratings are the weak link in short-pulse laser systems because they limit the laser output due to a reduced laser-induced–damage threshold, which arises in large part from fabrication-related imperfections and process-induced contamination. To mitigate this problem, the aperture of the laser is increased; as a result, however, this causes grating fabrication to be extremely expensive. Advances in fabrication techniques will therefore support the development of more-compact/robust gratings that would significantly impact the field—a simple problem without a simple solution, but one that Russ Dent committed to confront in his thesis work.

During his doctoral studies in the University of Rochester's chemical engineering department and at LLE, Russ held a Horton Fellowship and explored various aspects of the grating-fabrication process using facilities at LLE, the Integrated Nanosystems Center at the University of Rochester, the Semiconductor Nanofabrication Lab at the Rochester Institute of Technology, and the Cornell Nanoscale Facility. By studying the role of various process steps in current-generation photolithography for grating fabrication in the performance of as-fabricated optics, Russ recognized the need to explore more-recent technologies including modern lithographic processes, such as deep-ultraviolet photolithography for the production of pulse-compression gratings. In the later part of his thesis research, Russ successfully fabricated gratings compatible with those used on OMEGA EP using this technology. These gratings met the diffraction-efficiency specifications and provided good laser-damage performance. Most importantly, Russ's work has paved the way for LLE to investigate and inform on the fabrication of next-generation gratings and help to understand parameters related to the optimization of the lifetime of the gratings, commonly referred to as damage growth.

Russ looks forward to continuing work on gratings after his graduation and believes there is a window for significant advancement in the field using a multifaceted approach to grating fabrication, where optical design is engineered to optimize optic lifetime.

"I'm very grateful to my colleagues at LLE for making my time in Rochester so enjoyable. The opportunity to do work that has a **tangible benefit to the research world and society as a whole** is the most-rewarding experience I could ask for."



Dr. Junchi Zhang

Department: **Optics**
Advisor: **W. R. Donaldson**

Junchi Zhang started at LLE in 2020 as a Research Assistant funded by a National Science Foundation (NSF) grant with William Donaldson and Govind Agrawal as co-principal investigators. The title of the NSF award was "Novel Photonic Devices Based on the Concept of Space–Time Duality." The research envisioned studying temporal boundaries both experimentally and theoretically. Because of the pandemic, however, 2020 was a difficult year to begin experiments and to have a mentor in the laboratory, so Junchi started his research developing theoretical models of temporal boundaries.

When light propagates through space, it can encounter boundaries where material properties—like the index of refraction—change. This interaction can split the wave into reflected and transmitted components, leading to phenomena such as total internal reflection. Similarly, in optical fibers, intense pulses can cause transient changes in the index of refraction via the nonlinear Kerr effect, allowing other waves to interact with this excitation. These interactions, analogous to spatial boundaries, can produce both reflected and transmitted waves. To observe these small effects in the lab, interacting waves must propagate at nearly the same velocity over long distances, which is achievable in optical fibers.

Junchi was able to make a number of conclusions: he determined which frequencies can interact in a given medium; what happens when boundaries are not infinitely sharp but have a finite spatial and temporal limit; how to craft an intense pump pulse that propagates over long distances and still maintains a consistent index change; and finally, what happens when multiple pump pulses are injected into an optical fiber. These simulations resulted in five first-author journal publications.

When COVID restrictions lessened, Junchi was able to return to LLE and learn the skills that would enable him to test the models he had developed. The models were sophisticated and incorporated many of the real-world limitations that typically prevent idealized models from matching the nuanced experimental results. His hands-on experience with the experimental setup further enhanced his understanding of these limitations. This resulted in an additional two first-author journal publications on the experimental results.

These results lay the groundwork for novel optical devices. For example, we consider an experiment in which two femtosecond optical pulses with different frequencies are injected into an optical fiber with arbitrary time delay. If the first pulse is configured to form a temporal boundary that produces the analog of total internal reflection of the second pulse, the latter will never override the first pulse, even if the second pulse initially travels at a higher velocity. Such a device would automatically synchronize two lasers with femtosecond precision.

Junchi looks forward to continuing his research on optical fibers at Lumentum in San Jose, CA, where he will be working on high-power fiber lasers.

"During my time at LLE, I've had the privilege to **engage with cutting-edge research** and collaborate with some of the brightest minds in the field. The support and mentorship I received here have been instrumental in shaping my scientific journey."

FOCUS ON TECHNOLOGY

Record Contrast Achieved on the MTW Laser System

Innovations in Short-Pulse Laser Technology

LLE's Multi-Terawatt (MTW) Laser System has been a source of innovation for over two decades, and this past summer, scientists celebrated the 20th anniversary of the first shot of the laser system (Fig. 1), which took place on July 26, 2004. The MTW Laser System, which was originally built as a prototype of the OMEGA EP front end, is used to perform experiments supporting laser and laser diagnostic development, target diagnostic development, ultrafast plasma physics, and nonlinear optics. This article reports on a recent record achievement on the MTW laser: the demonstration of a temporal contrast exceeding 10^{19}.

In recent years, one of the cutting-edge advancements in laser technology has been the generation of multipetawatt pulses—brief, yet extraordinarily powerful bursts of light. To harness the full potential of these pulses, however, scientists must overcome a challenge: the presence of "prepulses," or flashes that precede the main pulse. These prepulses can interfere with experiments by illuminating the target with energy well before the main pulse arrives; if the prepulse is energetic enough, the target will be damaged or destroyed well before the high intensity arrives. At the very least, the prepulse has the potential to form a coronal plasma on the target surface, which would affect the coupling of the high-intensity laser beam to the target. Therefore, it is essential to suppress prepulses as much as possible. As the short-pulse community pushes the boundaries of laser intensities, and as LLE strives to build NSF OPAL (optical parametric amplifier lines)—the highest-power laser in the world—achieving contrast between the peak intensity and these prepulses becomes increasingly challenging.

Figure 1. View of the MTW Laser Facility from the target chamber area. Scientist Ildar Begishev, who has worked on the MTW laser since its construction, is pictured to the left.

Various methods have been developed to tackle this issue, and some of the most-effective results—achieving contrasts of 10^{12} to 10^{17}—have been attained by using a plasma mirror. This method effectively minimizes prepulses by using the main pulse to create a reflective plasma on the surface of a transitive optic: the lower-intensity prepulses transmit through the optic, and the high-intensity main pulse is reflected with high efficiency.

Another powerful approach to improving contrast is through second-harmonic generation, a nonlinear optical process that converts the laser light into a different frequency or "color." A remarkable aspect of second-harmonic

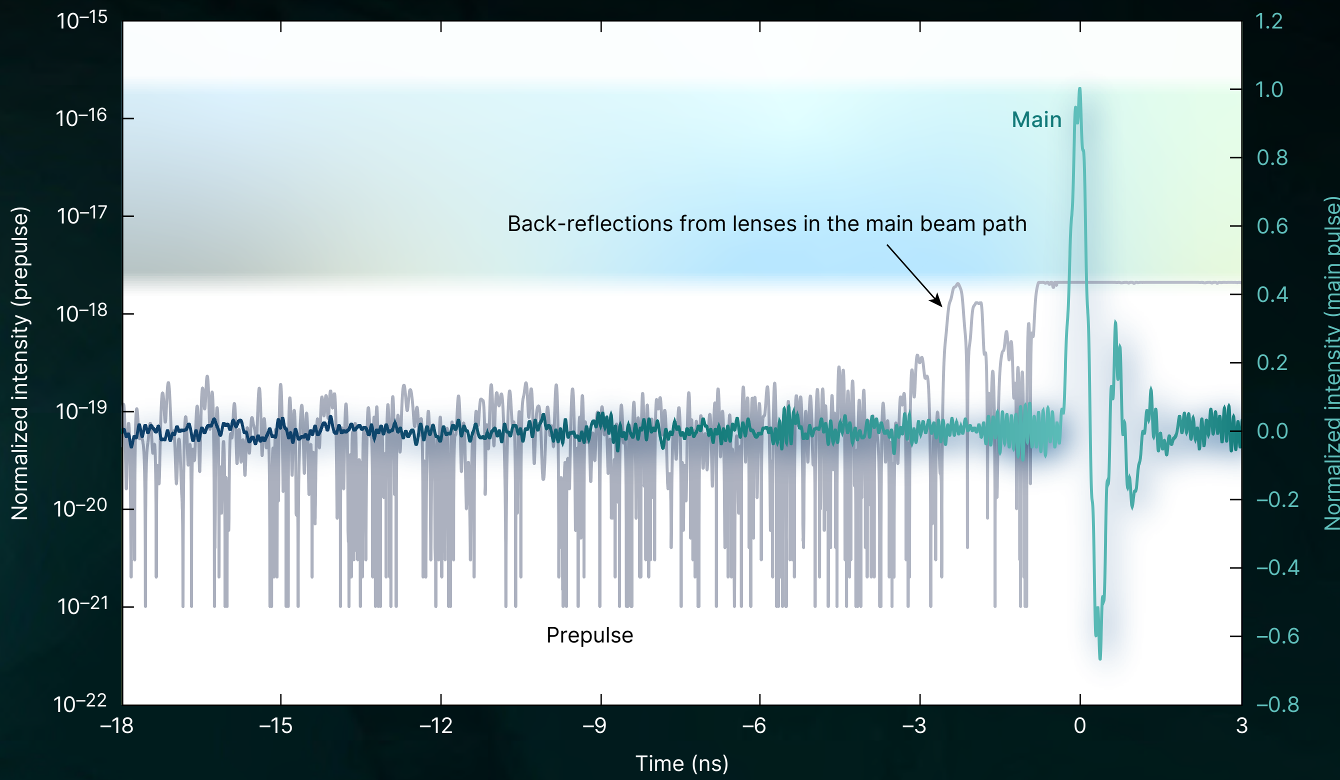


Figure 2. The main pulse and prepulse recorded on separate shots and normalized on the intensity of the main pulse. Back-reflections from lenses in the main beam path provide intensity and timing references.

generation is that it suppresses prepulses quadratically, which means that the process is not just linearly dependent on the intensity but dramatically stronger—only the high intensities are frequency-converted.

In our recent work at LLE, we explored these concepts with unprecedented results (Fig. 2). By using second-harmonic generation, a contrast level of 10^{19} was achieved—an astonishing accomplishment. This means that the peak intensity of the main pulse was ten quintillion times stronger than any prepulses, allowing for incredibly clean and precise laser applications. We also identified the specific sources of these prepulses, which provide insights into how to refine this technology.

Our experiment utilized the MTW laser, a high-power laser system used to develop innovative laser science technologies built on optical parametric chirped-pulse amplification. To achieve these record contrasts, a thin crystal of potassium dihydrogen phosphate was inserted into the laser's optical path, converting the laser light to its second harmonic with an efficiency of 80%.

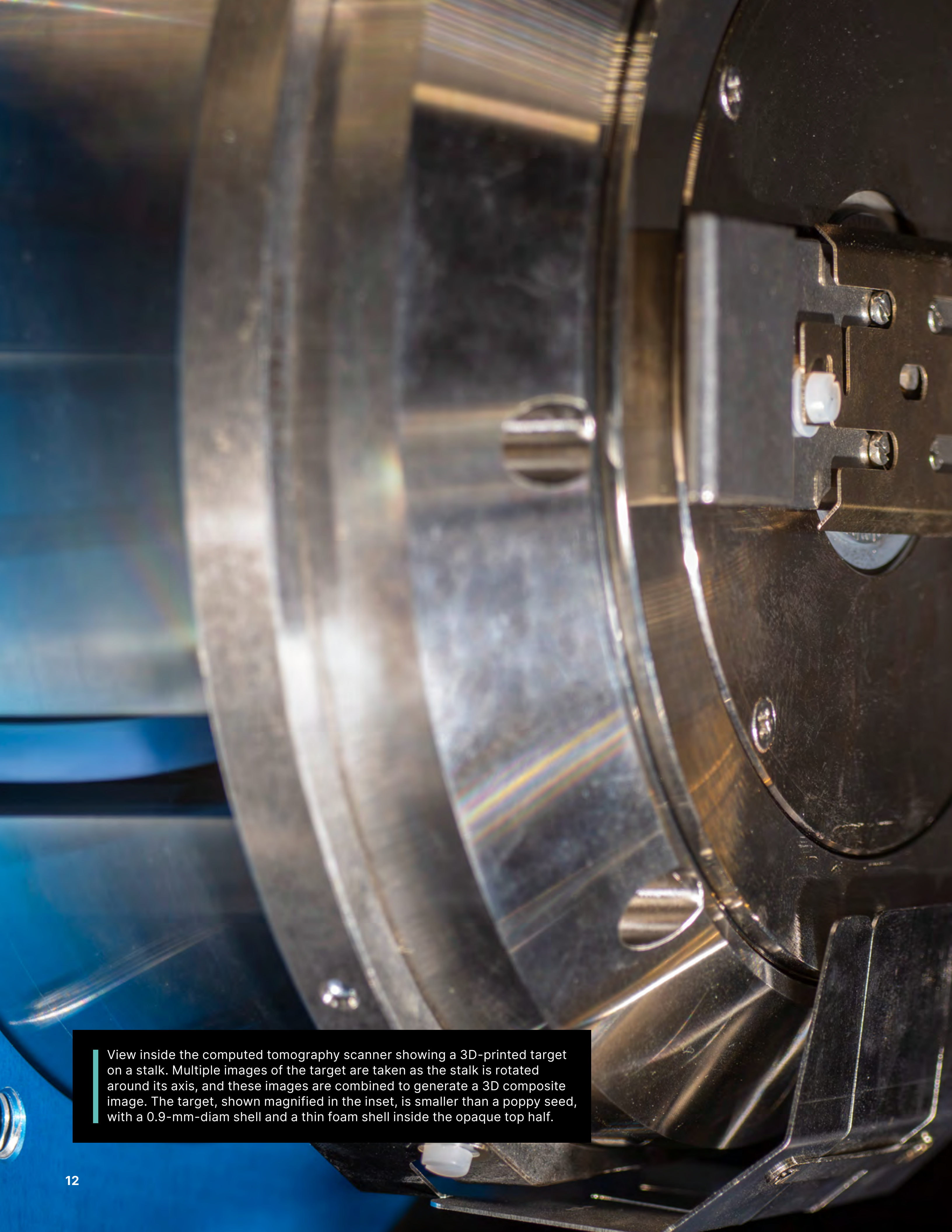
The contrast was diagnosed by measuring the main pulse and prepulses on separate shots. By splitting the laser beam and using filters and mirrors, the pulses could be analyzed at both the original and second-harmonic frequencies. The results confirmed our expectations: the prepulses at the second-harmonic frequency were significantly weaker, which is in line with the quadratic suppression effect of second-harmonic generation.

This work opens up exciting possibilities for future laser experiments and applications. By extending the limits of contrast, we can push the boundaries of laser systems without disrupting experiments by illuminating the targets before the high intensities arrive. While there are still challenges to overcome, such as the limitations imposed by the damage threshold of our laser components, our results mark a significant step forward in the quest for more-precise laser pulses.

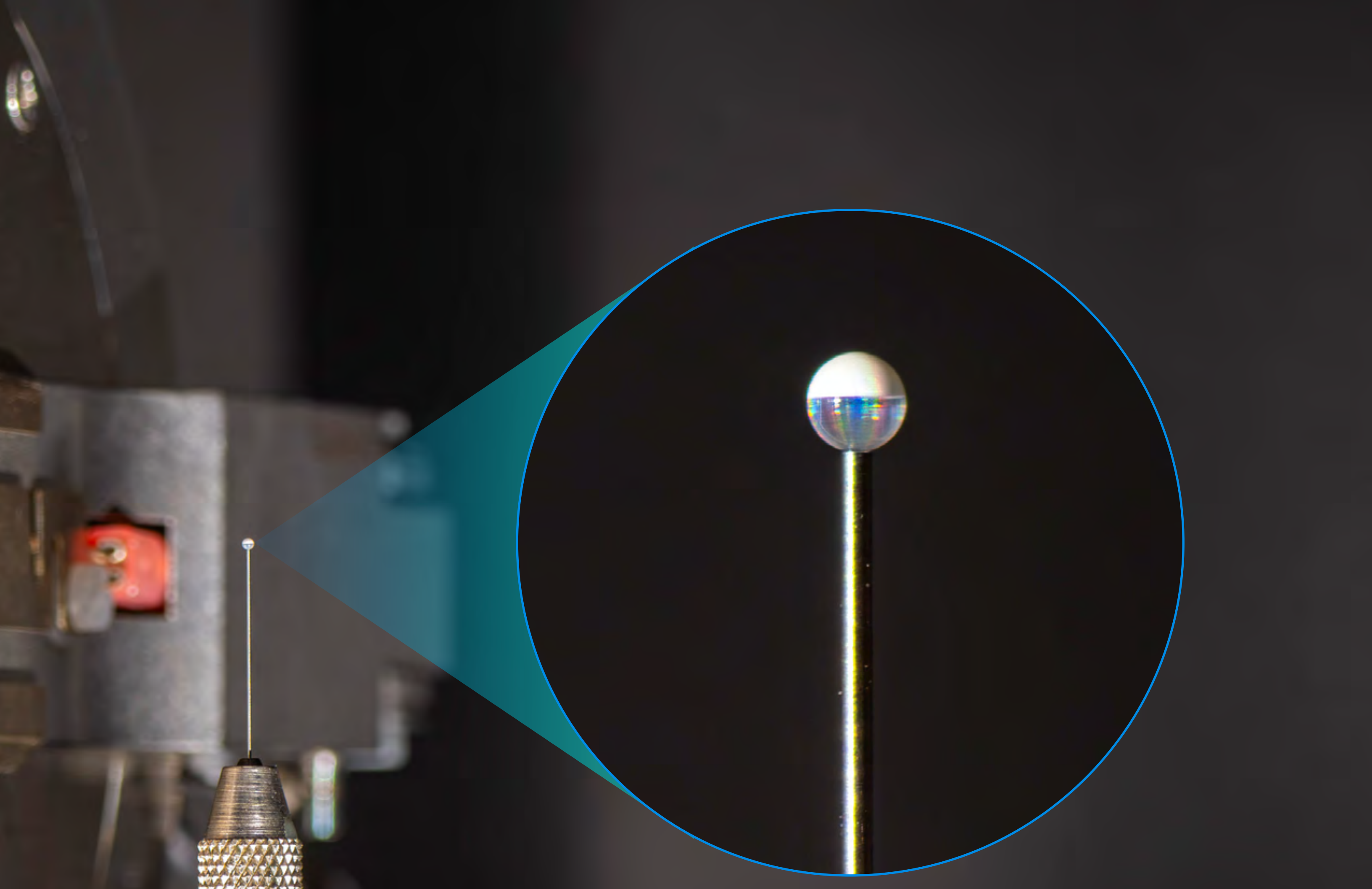
Corresponding author: Ildar Begishev (ibeg@lle.rochester.edu)

Focus Points

- Incorporating second-harmonic generation has enabled ultrahigh contrast levels of 10^{19} by suppressing unwanted prepulses.
- This enhancement enables cleaner, more-precise laser experiments, opening new possibilities in high-power laser applications.



View inside the computed tomography scanner showing a 3D-printed target on a stalk. Multiple images of the target are taken as the stalk is rotated around its axis, and these images are combined to generate a 3D composite image. The target, shown magnified in the inset, is smaller than a poppy seed, with a 0.9-mm-diam shell and a thin foam shell inside the opaque top half.



PRECISION AT THE MICRON LEVEL

STATE-OF-THE-ART TARGET FABRICATION

Learn more about the nanoscopic to macroscopic world being created every day at the Laboratory for Laser Energetics

FOCUS ON TECHNOLOGY

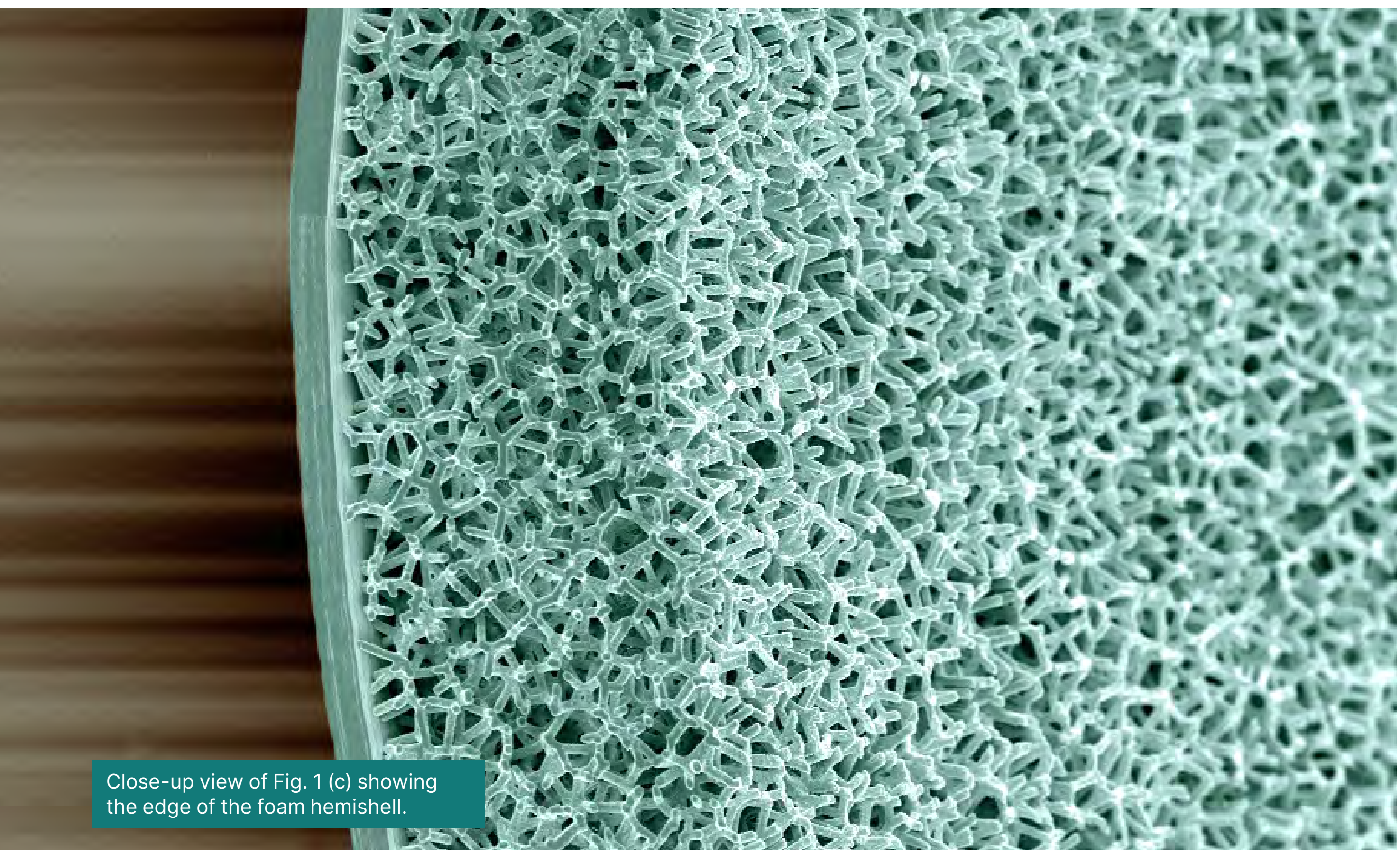
Miniature Marvels: Target Research and Development

In the heart of the Laboratory for Laser Energetics a team of 12 individuals, including four on-site contractors from General Atomics, are fabricating objects on a scale spanning the nanoscopic to the macroscopic range. These targets, designed and fabricated to the required accuracy and precision tolerances, are an integral part of the experiments conducted at LLE's Omega Laser Facility.

As principal investigators (PIs) envision groundbreaking experiments on OMEGA, they turn to the Target Fabrication Group to push the boundaries of target design, fabrication, and metrology to realize their research goals. Today, the team's research and development projects delve into the intricate geometries of foam structures and the delicate layers of cryogenic fuels, with the ultimate goal of mass producing targets for experiments.

Additive Manufacturing of Foam Targets for Liquid-Layer DT Implosions and Imprint Mitigation

For decades, the creation of spherical shell ablator targets for fusion experiments has been a cornerstone of LLE's research. While traditional methods have served us well, the LLE Target Fabrication Group has elevated these targets to new heights. By incorporating high-*Z* dopants such as silicon or germanium and fine-tuning their physical dimensions and surface characteristics, the General Atomics team (featured in the accompanying article) has fabricated targets that meet the target requirements set by the PIs.



Close-up view of Fig. 1 (c) showing the edge of the foam hemishell.

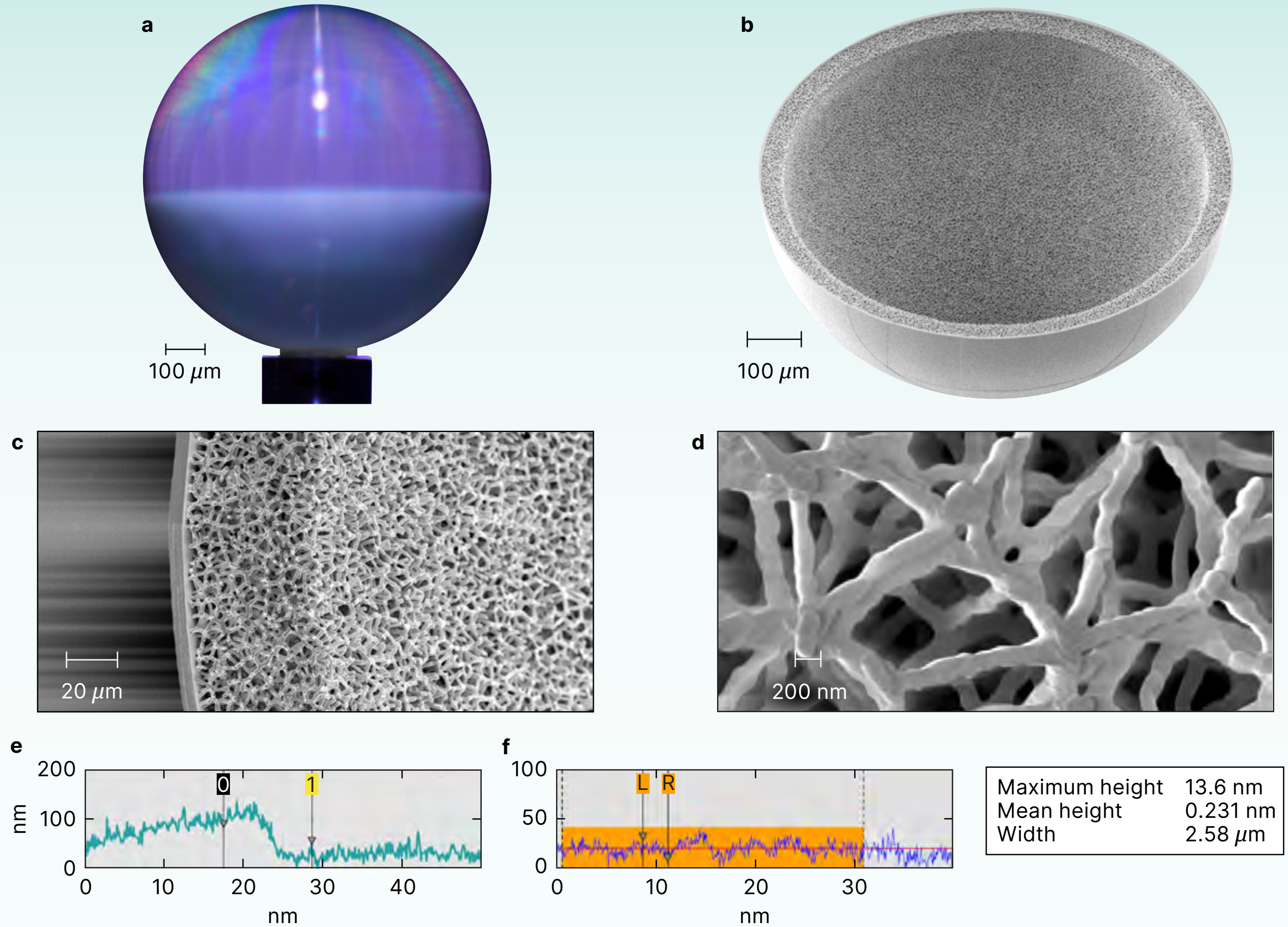


Figure 1. (a) Optical image of a printed shell (860-μm diam) with of an inner foam layer (40-μm thick; 40.5 g/cm^3) in the bottom half. (b) Electron microscope image of a hemishell with a stochastic foam and a 5-μm-thick outer ablator; filament sizes are ~1 μm. (c) Magnified view of the edge of the foam hemishell showing the foam/ablator interface. (d) Images of the thinnest filaments produced to date. One-dimensional profile (e) of the surface of a printed target showing the step height between successive print blocks (an artifact of the printing process) and (f) the smaller-scale rms roughness within each print block.

Two-photon polymerization, an additive manufacturing technique, is revolutionizing the fabrication of plastic shells. By precisely controlling the laser printing process, researchers can now tailor the radial density profile of the target to meet specific experimental requirements [1]. This versatility has opened up new possibilities for target design, enabling the creation of shells with intricate foam structures, either embedded within the solid-density, plastic ablator as shown in Fig. 1 or surrounding it.

In the clean room, the Nanoscribe two-photon printer uses a stereolithographic file as a blueprint from which the printer meticulously constructs these microscopic structures with unprecedented precision [2]. Nanoscribe allows for the creation of shells with remarkably smooth surfaces (rms roughness values of 20 to 30 nm) and stochastic foam structures featuring randomly oriented filaments as small as 150 to 200 nm.

To achieve these exact levels of precision, the printing process demands a high-numerical-aperture lens (NA = 1.4) and a meticulously detailed structural mesh. This precision, however, comes at a cost: the field of view is limited to a cube measuring 300 × 300 × 300 μm^3. While structures within this small volume can be printed at lightning speed (tens of millimeters per second), larger targets require a more-intricate process. By "stitching" together multiple print fields, the printer can create larger structures, although this introduces potential discontinuities between the seams.

Although two-photon polymerization offers remarkable precision, it is not without limitations. The software that translates the 3D design file into machine code imposes a significant constraint: the mesh defining the structure cannot exceed 1.5 GB in size. This limitation becomes particularly challenging when creating foams with extremely fine filaments since these require denser meshes that quickly exceed the memory threshold.

The Target Fabrication Group continues to find new ways to overcome these challenges. Their efforts focus on printing foams with micron-scale filaments with densities as low as 30 mg/cm^3, while simultaneously striving to demonstrate the feasibility of producing structures with filaments as thin as 200 nm. Future research aims to push these boundaries even further, reducing filament diameters to below 150 nm and pore sizes to 500 nm.

Three-Dimensional Characterization of Targets with Submicrometer Resolution

While traditional imaging techniques have provided valuable insights into the macroscopic features of implosion targets, the quest for understanding their microscopic intricacies remains a critical challenge. To accurately simulate the performance of these targets in high-energy-density–physics (HEDP) experiments, researchers must delve into the depths of their internal structure, examining features as small as half a micrometer. This knowledge is essential for unraveling the complexities of glue layers, identifying hidden voids within solid and foam, and ultimately optimizing target design.

To fully characterize these targets, the Target Fabrication Group takes a two-pronged approach. On one front, they use coherent anti-Stokes Raman spectroscopy (CARS), a cutting-edge optical technique that can reveal the intricacies of transparent targets. In collaboration with researchers at the University of Nebraska–Lincoln (UNL), the team is using CARS to probe the molecular structure of these materials with unprecedented precision.

CARS works by interacting with the molecules within the target, exciting them to higher-energy states, and then detecting the emitted light [3]. This process provides not only detailed spatial information but also valuable insights into the chemical composition of the target.

The intensity of the CARS signal is directly linked to the polarizability of the molecules within the target. For plastic shells, with their strong C–H vibration mode, and for cryogenic deuterium–tritium (D–T) mixtures, the signal is particularly intense. By scanning a focused femtosecond laser across the target, researchers can create a 3D map of Raman-active molecules. This process, while meticulous, can take up to 12 hours for a target with a diameter of 1 mm. The resulting data provide not only spatial information on the structure of the target, but also valuable insights into the chemical composition of the target.

To ensure efficient energy transfer and to maximize the signal, the CARS technique requires a precisely aligned pair of laser beams with carefully selected wavelengths and intensities. The emitted anti-Stokes signal, distinct from the background noise, is then captured and analyzed. This sophisticated process allows researchers to identify the presence of the various atomic and molecular configurations of hydrogen isotopes (i.e., hydrogen, deuterium, and tritium), and various hydrocarbons.

Characterization of Plastic Targets Using CARS

Fully characterizing the plastic shells with CARS began with a collaborative effort between Schafer Corporation and Yongfeng Lu, Professor of Electrical and Computer Engineering, at UNL. This partnership laid the groundwork for further exploration, leading to a collaboration between the University of Rochester and Professor Lu 's group at UNL to characterize polystyrene and glow-discharge polymer targets.

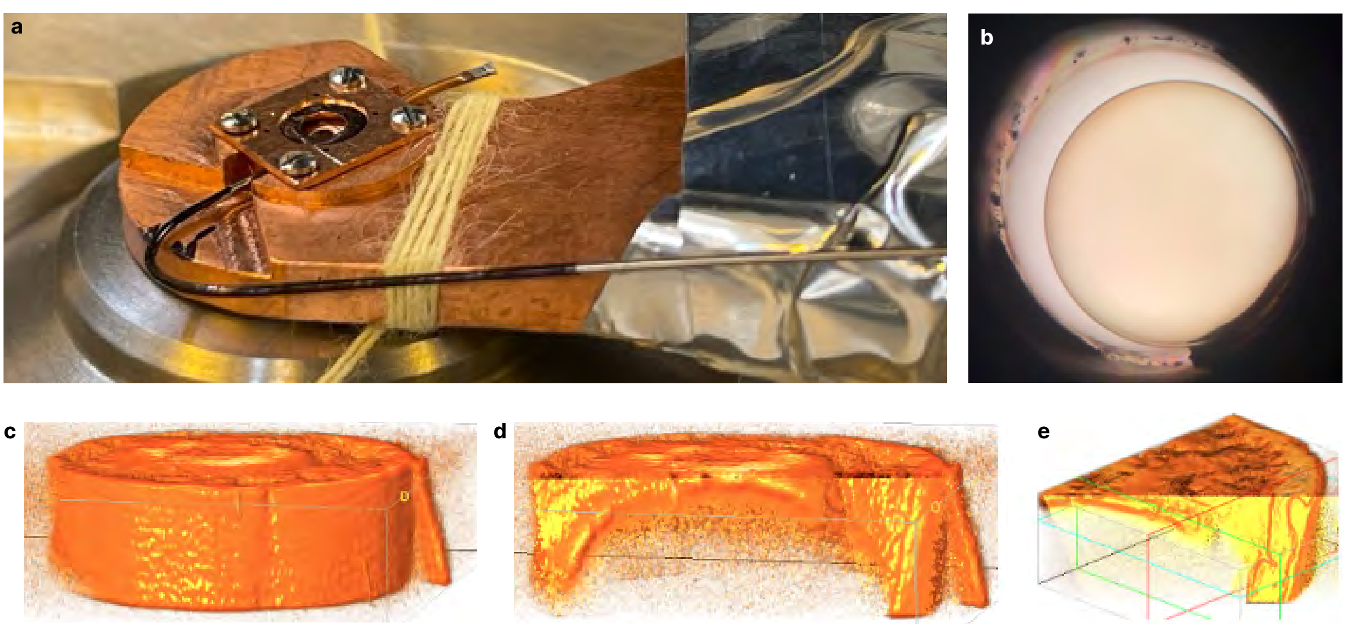
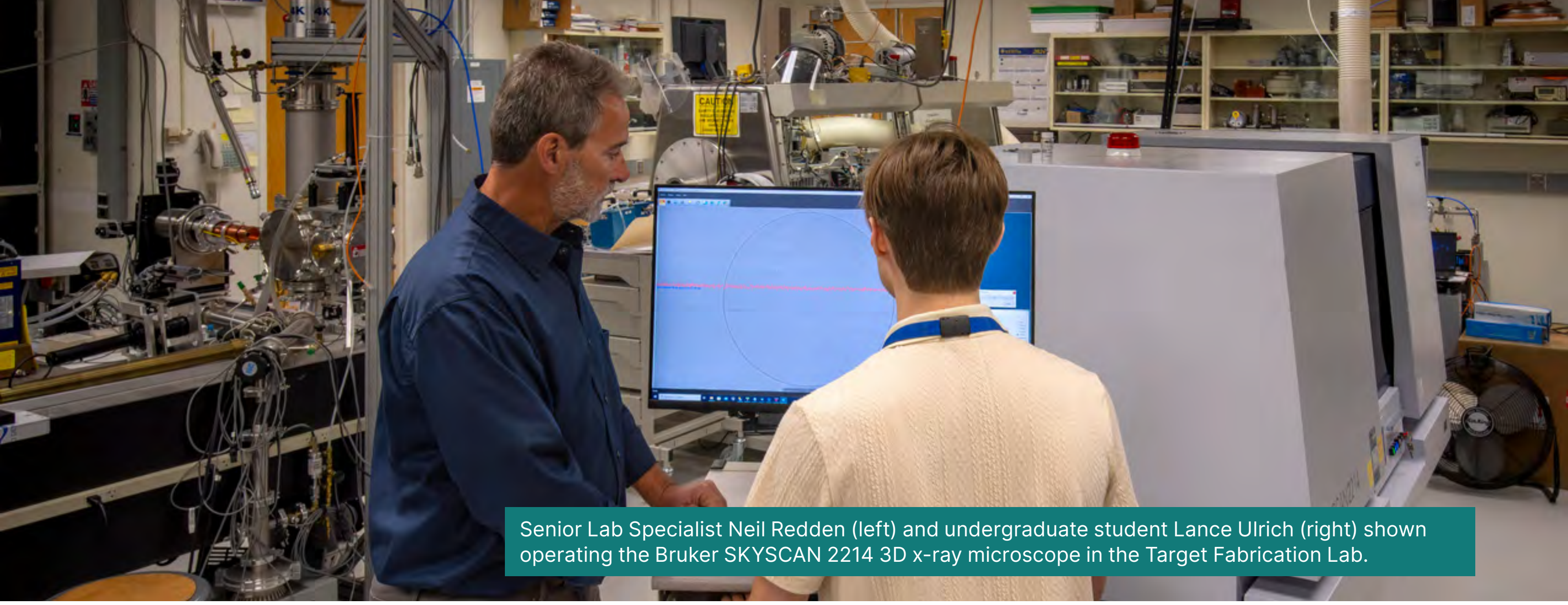


Figure 2. (a) The copper structure attached to the cryocooler is positioned close to the reentrant steel retaining ring for the window. Gas enters the cylindrical bore of the copper cell from a reservoir (not shown) through a tube. (b) View down the bore of the cylinder showing a target at room temperature. (c) Three-dimensional reconstruction of the ice layer. (d) A vertical slice through the full ice layer condensed around the shell showing the internal shape of the ice hugging the curvature of the shell. (e) same as (d) but the vertical slice is taken in an orthogonal direction.



Senior Lab Specialist Neil Redden (left) and undergraduate student Lance Ulrich (right) shown operating the Bruker SKYSCAN 2214 3D x-ray microscope in the Target Fabrication Lab.

Through meticulous experimentation, the researchers captured a series of detailed images of a polystyrene target. By carefully adjusting the laser's focal position, they were able to characterize 80% of the target in transmission. The remaining 20%, a narrow band near the equator, required a different approach due to internal reflections. By employing a reflection technique, however, the researchers were able to visualize this hidden region.

Characterization of Deuterium Ice Using CARS

Characterizing hydrogen isotopes at cryogenic temperatures using CARS involves overcoming unique challenges. For instance, achieving the desired spatial resolution of less than 1 μm requires a high-NA lens, which is incompatible with cryogenic systems. Moreover, the quantum selection rules governing hydrogen isotopes at these temperatures can complicate analysis. However, cryogenic conditions also offer an advantage: they enhance signal strength, aiding in precise measurements.

The Target Fabrication Group and their collaborators at UNL are working on a proof-of-principle CARS experiment using a cryostat target designed for hydrogen and deuterium (see Fig. 2). Once the technique is demonstrated at UNL, the CARS metrology station will be transferred to LLE, where it will be used to study cryogenic targets containing hydrogen, deuterium, and tritium. The ultimate goal is to characterize the distribution of hydrogen isotopes in the target, identify voids in the bulk, and measure the density and composition of the gas trapped in the center of the layered target.

The prototype cryostat features a cylindrical chamber where the deuterium ice can condense, surrounded by a copper structure that helps regulate the temperature. As the target is cooled, the CARS technique is used to monitor the transition from liquid to solid states. The data collected reveal the formation of crystal boundaries and fractures within the ice, providing valuable insights into the target's internal structure.

To assess the feasibility of this complex experiment, the team initially focused on using deuterium and hydrogen mixtures, a less costly and less-hazardous approach. At cryogenic temperatures, deuterium exists primarily in two low-energy states, known as para and ortho. This unique configuration, combined with the high density of deuterium ice, creates favorable conditions for CARS analysis. When irradiated with a focused laser, the deuterium molecules absorb energy and transition to higher energy states. These excited molecules emit light to relax to a higher rotational state in the ground vibration level and that state is re-excited by the second laser beam. It is the emission from the second excitation that is the CARS signal.

Characterizing deuterium ice using CARS, however, presents certain challenges. The intense laser power required to generate a strong signal can damage the cryogenic target. To overcome this limitation, the team is exploring the use of a new femtosecond laser with a narrower spectral bandwidth, which can deliver just the right amount of spectral energy for the CARS measurement without overheating the deuterium ice.

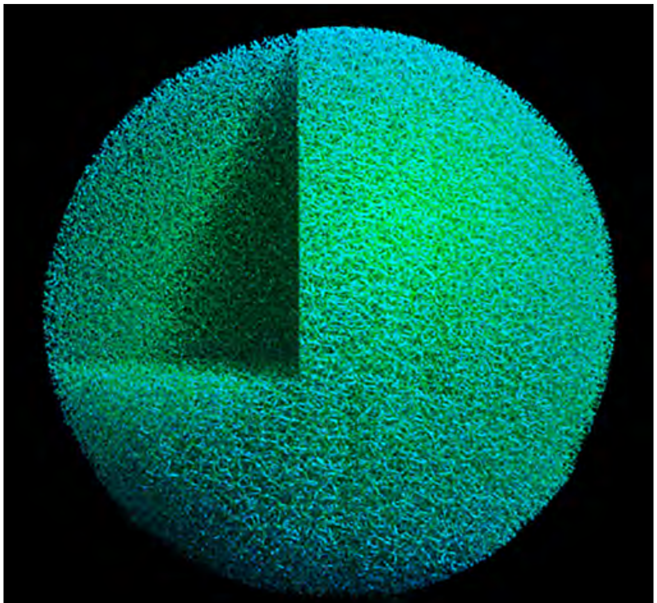


Figure 3. A 3D x-ray microscope image of a printed foam sphere (680-μm diam; 160 mg/cm^3) with 2- to 3-μm-diam filaments. The triangular void was removed in software to show the internal structure.

Characterization of Targets Using X-Ray Tomography

To delve deeper into the intricate structure of opaque targets, LLE has recently acquired a Bruker SKYSCAN 2214 3D x-ray microscope. This powerful tool allows researchers to nondestructively examine a wide range of targets, from multifoil assemblies to foam structures. By analyzing the x-ray images, scientists can assess the flatness of foils, the quality of interfaces, and the uniformity of glue layers. The microscope can also measure the dimensions of shell walls with unprecedented precision, even when they contain embedded dopant layers.

The SKYSCAN 2214, with its exceptional resolution of 0.4 to 0.5 μm and a minimum pixel size of 70 nm, is a powerful tool for unraveling the intricate details of opaque targets. While data acquisition can take several days, the resulting 3D images provide invaluable insights into the internal structure of these complex objects.

Characterizing high-energy-density–physics targets, including direct-drive ICF targets, presents unique challenges due to their composition. These targets often consist of multiple layers of materials with varying densities and absorption properties. An example of a 3D x-ray microscope measurement of a printed foam sphere, which illustrates such complexity, is shown in Fig. 3. To penetrate these materials, the x-ray microscope requires high-energy radiation, which can be challenging for low-density materials. Additionally, foams and thin-walled shells, especially those with low-Z elements, use phase-retrieval methods to ensure accurate characterization.

Despite these challenges, the x-ray microscope has demonstrated its capabilities in various applications. For example, it has been used to analyze foam targets, revealing the presence of voids and other defects that could impact their performance. By studying these imperfections, researchers can gain valuable insights into the manufacturing process and identify areas for improvement.

Researchers showcase the capabilities of the x-ray microscope by

- studying the interaction between a laser-driven ablator and a foam material. By analyzing the x-ray images, researchers were able to precisely measure the deformation of the foam and identify potential defects that could impact the propagation of shock waves.
- investigating a printed foam sphere designed for the "dynamic-shell" concept [4]. The high-resolution images revealed the intricate details of the sphere's internal structure, including the size and distribution of its filaments.
- characterizing a low-density foam target, with low x-ray absorption. By utilizing phase-contrast techniques,

Undergraduate student Lance Ulrich working inside the microCT scanner in the Target Fabrication Group Laboratory.

researchers were able to successfully reconstruct the 3D image of this target, providing valuable insights into its structure and properties.

The Target Fabrication Group remains at forefront of target fabrication technology. Through state-of-the-art research in additive manufacturing, metrology techniques, and x-ray tomography, the team working with its collaborators has made significant strides in understanding and controlling the intricate structures of these essential components for fusion and HEDP experiments.

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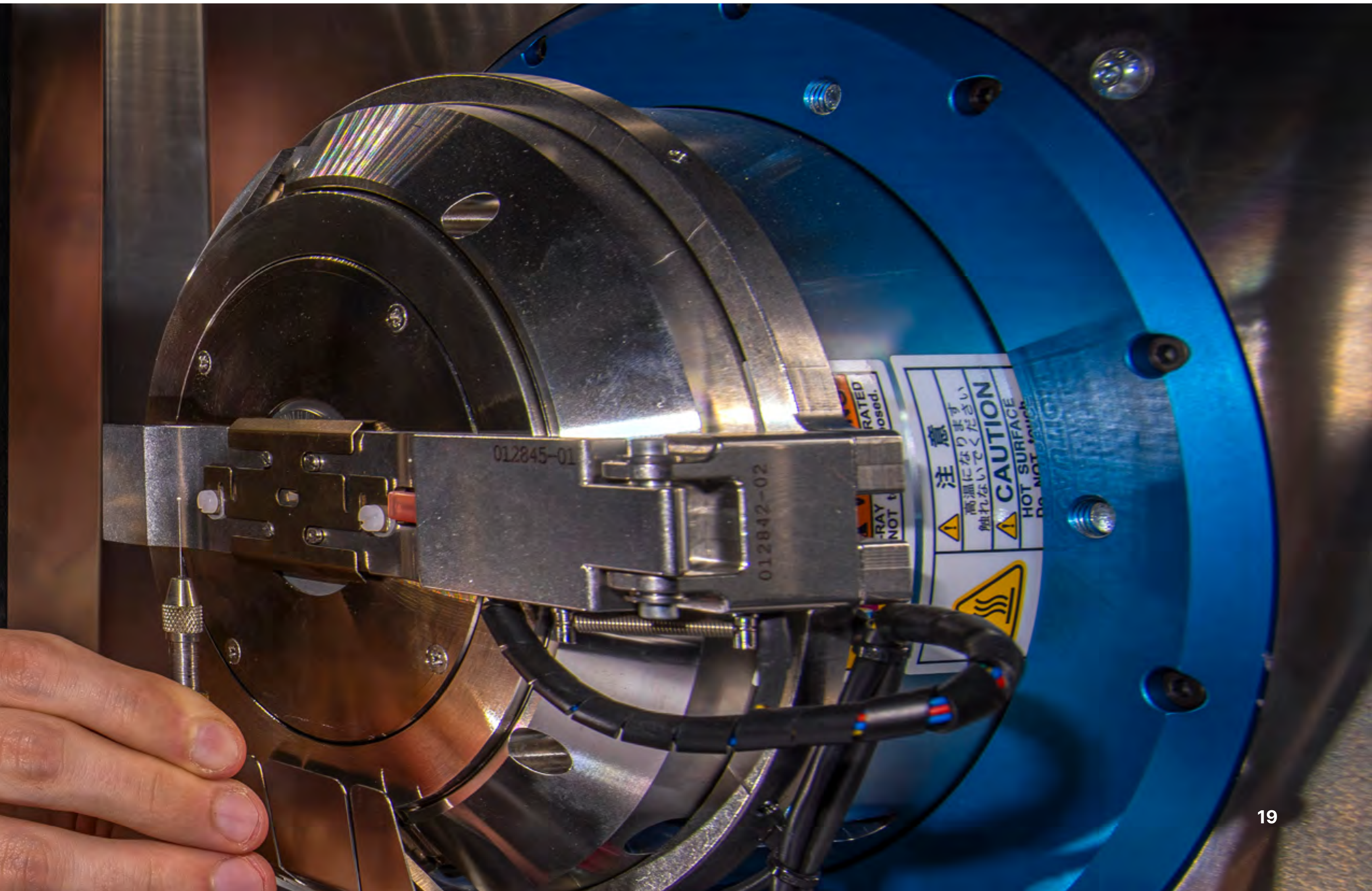
Focus Points

- The LLE Target Fabrication Group, including four on-site contractors from General Atomics, produces approximately 2500 targets each year for the Omega Laser Facility, including those for high-energy-density–physics (HEDP) experiments conducted by principal investigators (PIs) from LLE, the National Laser Users' Facility, and national laboratories.
- With the development of two-photon polymerization, a specialized version of additive manufacturing, a different method of making plastic spherical shell targets at LLE is now possible where the radial density profile of the shell can be tailored for a particular implosion design.
- Three-dimensional characterization of targets with submicrometer resolution is being developed at LLE for transparent targets using coherent anti-Stokes Raman spectroscopy (CARS) and for opaque targets using x-ray tomography.



FOCUS ON TECHNOLOGY

Mastering the Micro

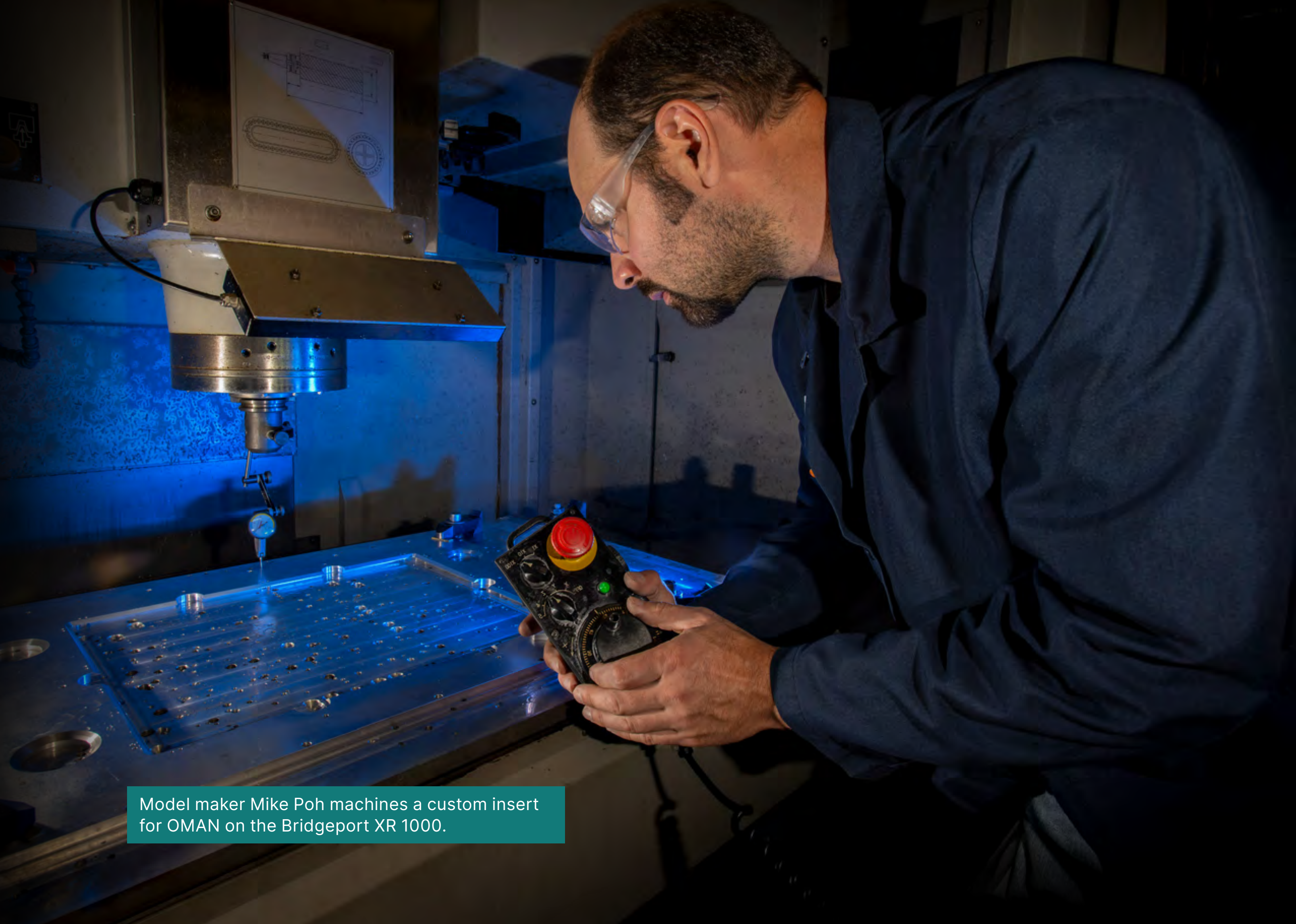
Inside LLE's Machine Shop and Quality Control Department

Realizing scientific ideas in the laboratory relies on the ability of LLE staff to engineer and fabricate scientific equipment that meet the experimental requirements of the Omega Laser Facility and a wide variety of other labs throughout LLE. From manufacturing the smallest components to mastering the most-advanced machining techniques, each of the six members of LLE's Machine Shop and Quality Control Department plays a crucial role in advancing the laboratory's cutting-edge projects. This past year alone (October 2023 to September 2024), the shop produced nearly 600 unique fabricated components with a total of over 2000 parts all together. In addition, external vendors provided nearly 1000 unique fabricated components with more than 13,000 parts in total—which means that a staggering combined number of over 15,000 parts was required to pass through LLE's Quality Control Department. In this article, we highlight the dedication and talent of Scott Gross, Pat Kalish, Cliff Matthews, Bob McAllister, Mike Payne, and Mike Poh—all of whom are true masters of the micro.

Precision Metrology for Advanced Research

Experiments on LLE's Multi-Terawatt (MTW) and OMEGA Laser Systems generate THz sources of radiation for high-energy-density–physics experiments. The success of these

Model maker Mike Payne uses a dial indicator to check the edge of a THz mirror on the Haas VM-2, ensuring precise alignment.



Model maker Mike Poh machines a custom insert for OMAN on the Bridgeport XR 1000.

experiments depends on model maker Mike Payne to perform metrology on the edge of a THz mirror on the VM-2 using a dial indicator as shown on p. 20. The VM-2, a high-performance vertical milling center known for its accuracy and used in mold making and tool and die work, is vital for producing components that support LLE's cutting-edge research in THz technology. Mike's meticulous attention to detail ensures that every component is machined to the highest standards.

Custom Fixtures for Large Optics

LLE's Optical Manufacturing (OMAN) Group is a world leader in fabricating and coating optics for inertial confinement fusion lasers such as the Omega Laser Facility, the National Ignition Facility at Lawrence Livermore National Laboratory, and the Laser Mégajoule in France. OMAN relies on the LLE Machine Shop and the Quality Control Department to fabricate mechanical fixtures to support and handle large optics, which are manipulated in sputtering chambers that are used to apply specialized optical coatings. Model maker Mike Poh demonstrates his precision and

Coolant is shown spraying during the cutting process of machining a custom part.

skill operating the high-performance vertical machining center Bridgeport XR 1000. In his work, he machines a custom insert for OMAN that aids in holding large optics during coating processes, with coolant spraying as the machine expertly cuts through material. The XR 1000's 12,000-rpm spindle speed and precise capabilities make it an invaluable tool for these complex operations and allows it to expertly cut through material such as steel and iron.

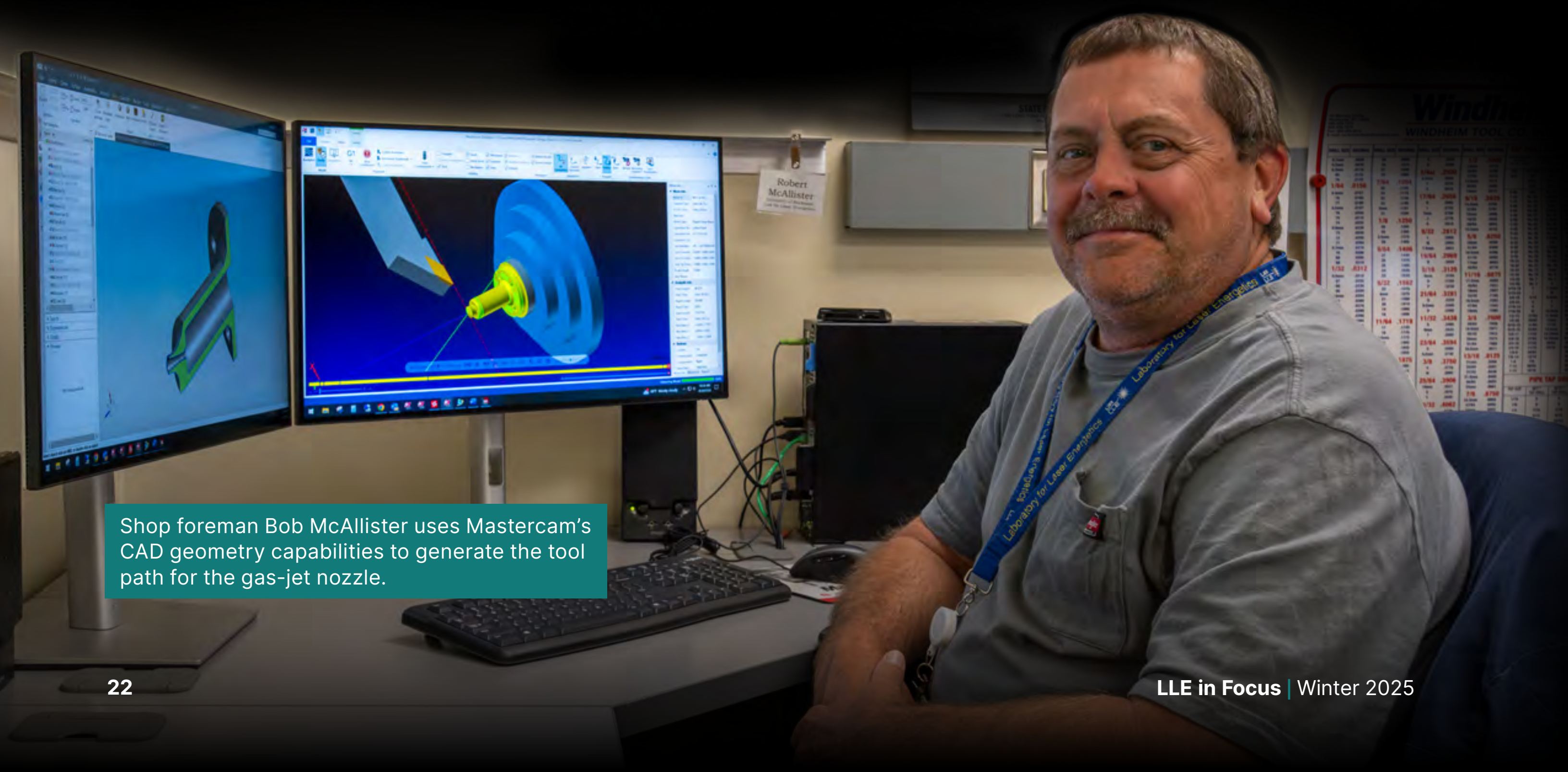
Crafting the Gas-Jet Nozzle

Gas jets are deployed on OMEGA as a target for laser–plasma interaction and laboratory astrophysics experiments. The short burst of gas injected into the target chamber requires custom gas-jet nozzles, which are fabricated in LLE's Machine Shop. Each nozzle is designed to achieve the required conditions in the gas plume (i.e., Mach number and gas density) for the experiment. A gas-jet nozzle (shown to the right) with an outlet diameter as small as 250 μm, or roughly the size of a grain of sand, is a prime example of the high-precision work performed in the Shop.

The process of fabricating a gas-jet nozzle starts with shop foreman Bob McAllister, who uses advanced CAD (computer-aided design) and CAM (computer-aided manufacturing) software to design and program tool paths. McAllister leverages his expertise by accessing and refining the digital geometry of parts, adjusting dimensions and features to meet exact specifications using CAD. He then uses CAM software to program the machining process and generate tool paths that dictate how and where each precise cut will be made. This integration between CAD and CAM ensures that even the most-intricate designs are translated accurately.

Model maker Scott Gross then crafts the custom gas-jet nozzles by machining an angled version of the nozzle on the office mill, which can run at a staggering 30,000 rpm and remove as little as 0.0005 inches of material at a time.

Close up of a custom gas-jet nozzle with an outlet diameter roughly the size of a grain of sand.



Shop foreman Bob McAllister uses Mastercam's CAD geometry capabilities to generate the tool path for the gas-jet nozzle.

Quality control inspector Cliff Matthews inspects a cross section of a gas-jet nozzle on the Hawk Vision Scope.

Model maker Scott Gross machines an angled version of the gas-jet nozzle on the office mill.

He uses custom fixtures to hold the nozzle at the precise angle required for the vertical milling operation. The fabrication of parts relies on the care and expertise of model maker Pat Kalish in tool preparation. Pat works on the surface grinder, as shown in the image below. Whether machining an angled version on the office mill or using custom fixtures to hold the nozzle at the exact angle for vertical milling, Pat must maintain a high level of accuracy and versatility in his work.

Meeting Exacting Standards

In LLE's Quality Control Department, Cliff Matthews inspects the gas-jet nozzles before they are released for assembly and used in experiments. This final step in the process ensures that every part meets the exacting standards required for LLE's high-performance projects.

Cliff performs similar quality controls for all fabricated parts from the Machine Shop, using tools to detect flaws down to micron-level tolerances and visually inspecting components for dimensional accuracy, surface quality, and functional characteristics defined by design engineers. Any deviation from these parameters results in adjustments or rework to maintain the lab's commitment to quality and reliability.

The LLE Machine Shop and Quality Control Department combine precision, innovation, and teamwork to support the groundbreaking work done at LLE. From the initial design to the final inspection, every step in the process is carefully executed to ensure the highest quality in every component produced. Simply put, the cutting-edge science that LLE is known for could not happen without this integral department.

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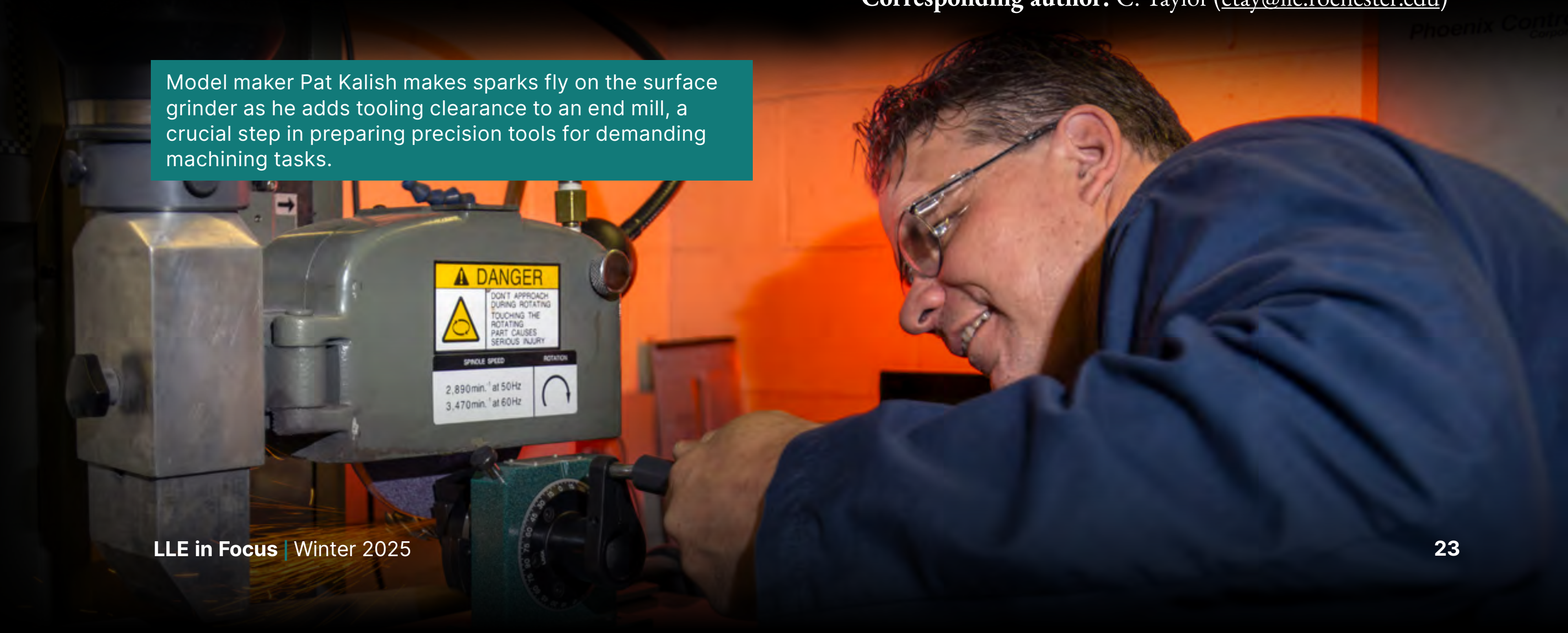

Model maker Pat Kalish makes sparks fly on the surface grinder as he adds tooling clearance to an end mill, a crucial step in preparing precision tools for demanding machining tasks.

FOCUS ON TECHNOLOGY

Thirty Years of Mutual Collaboration

General Atomics and LLE Advance Target Fabrication to Meet Complexity Demands

The University of Rochester's Laboratory for Laser Energetics has served as a center for the investigation of the interaction between matter and intense laser radiation since its founding in 1970. In its near 55-year history, the laboratory has celebrated many notable successes and achievements, including an array of scientific and technological breakthroughs that continue to advance the frontiers of physics research and lay the groundwork for the next generation of scientists. Many of these achievements would be impossible, however, without the dedicated efforts of LLE's collaborative partners. In this article, we describe LLE's longstanding relationship with San Diego-based defense and diversified technologies company General Atomics (GA) and highlight some of LLE–GA's most important accomplishments in recent years.

LLE's development of a series of high-power, neodymium-glass laser systems (DELTA, ZETA, and the 24-beam OMEGA laser) over the years eventually led to the 60-beam OMEGA Laser System. Operational since 1995 for the Department of Energy's (DOE's) National Nuclear Security Administration, the 60-beam OMEGA laser is one of the primary research tools for inertial confinement fusion (ICF) and high-energy-density–physics research in the US. The laser can focus up to 30,000 joules of 351-nm laser energy onto a target that measures less than 1 millimeter in diameter in approximately one billionth of a second. In addition to the 60-beam OMEGA laser, the four-beam high-energy and high-intensity OMEGA EP Laser System has also been a main research tool for the community since 2008 [1].

Since 1991, nearly all LLE target capsules, which hold the material that is compressed by the laser pulses, have been manufactured by GA [2]. The three-decade LLE–GA collaboration began in the early 1990s when DOE awarded GA the contract to fabricate targets for the national ICF Program, which supports much of the research at LLE, and has led to many key advances in target design, fabrication, and metrology [3].

Mutual Collaboration Drives Continuous Improvement at LLE

The four-person team that GA has permanently stationed at LLE supports experimental campaigns on both the 60-beam OMEGA laser and OMEGA EP, working closely with the members of the LLE Target Fabrication Group. The team's primary responsibilities are to provide target-specific shot support for the national labs (Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratories), as well as the National Laser Users' Facility (NLUF) Program, which accounts for almost half of the experimental campaigns that occur annually at these facilities.

Figure 1. Shown are three of the four members of the GA–LLE team: Julie Fooks (left), Keith Manning (middle), and Katharine Gerbsch (right) in the capsule fabrication clean room at the GA San Diego campus (Dayna Wasilewski not pictured).

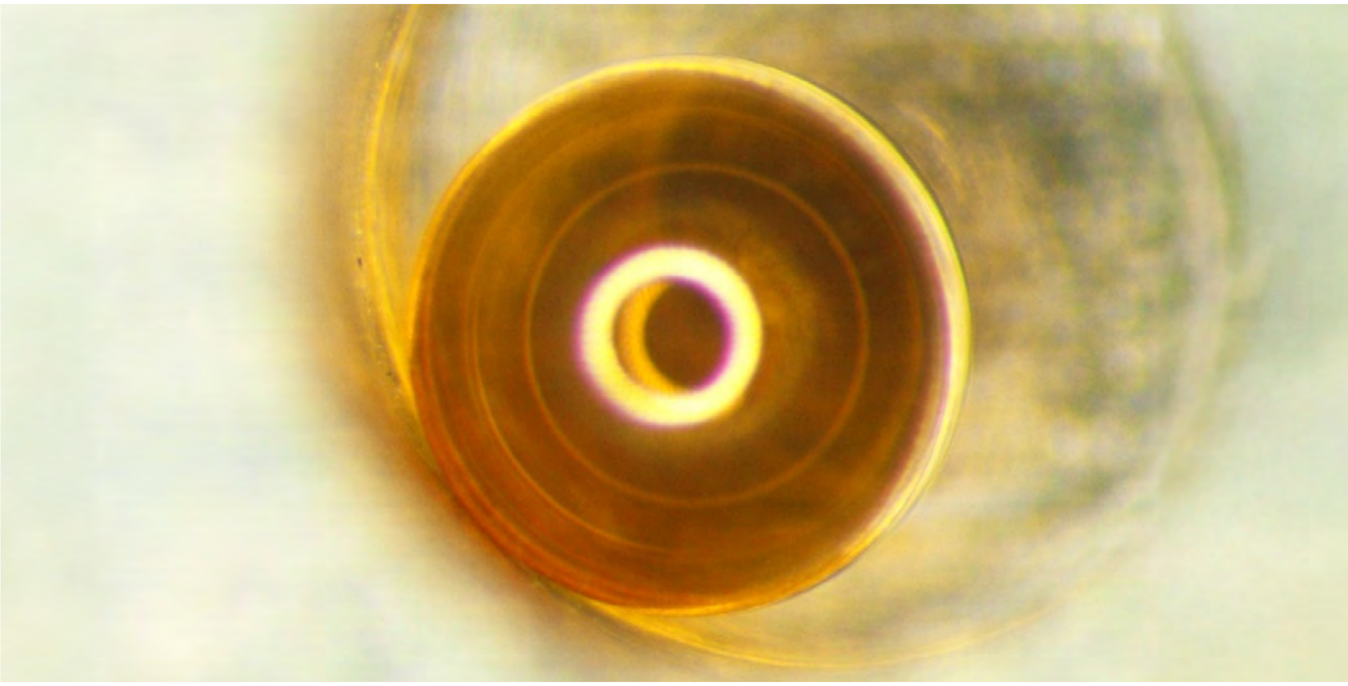

Figure 2. A 1-mm-diam Si-doped polymer (plastic) capsule (orange) in a capsule eggcrate pocket (the bright white ring in the center is a reflection of microscope's camera ring light).

These GA staff members work closely with the LLE Target Fabrication Group and the principal investigators (PIs) to understand the physics and goals of the experiments and are often involved as early as the design phase to provide expertise on the assembly compatibility of target designs, component dimensions, and materials. The details are transcribed into specs and dimensions for the Target Fabrication team. The team performs the assembly and metrology of a wide variety of targets, in addition to as-needed repairs, rebuilds, reinforcements, and modifications of targets requested by PIs.

GA staff also ensure that targets are delivered to the appropriate facility, providing on-demand support and working both shifts of a shot day for experiments as required. The team contributes to general improvements by championing projects such as the Powell scope metrology station upgrade, the redesign of target component storage and organizational systems, the design of new lab space, and a complete revamp of the capsule database, updated from a Microsoft Access database to a multi-user web-based database.

The LLE Target Fabrication team and GA staff members have regular meetings and share knowledge to ensure that both teams stay aligned on the goals of an experiment. LLE-stationed staff (Fig. 1) regularly travel to GA's San Diego campus, and these meetings help drive the improvement of target fabrication processes. In August 2023, LLE Chief Scientist Riccardo Betti visited GA to give a lecture on the physics, purpose, and recent results of LLE cryogenic ICF implosion campaigns involving some of the most-precise capsules produced for the Omega Laser Facility.

GA's production manager for OMEGA leads the setup, organization, and performance of the Target Request Form website, which is hosted by LLE's IT Group. Together, the joint LLE–GA team maintains a system to provide all data and drawings to researchers as soon as they become available. The data are preserved for future reference, and the system is used for planning and scheduling experimental campaigns at the Omega Laser Facility.

NLUF and Academic Support

Approximately 15% of the NNSA-supported experiments conducted at the Omega Laser Facility are for the NLUF Program, which provides beam-time access for basic science research led by scientists in both academia and private industry. DOE/NNSA funds the operation of NLUF, making it possible for researchers, including students, to conduct experiments without a direct facility charge.

GA plays a key role in NLUF Program and academic research projects by supplying targets for these experiments. GA recently established a new, more organized process to support the coordination of target fabrication and assembly for all NLUF campaigns. The four-gate process, which started in FY23, improves engagement and communication with the NLUF PIs at the Omega Laser Facility.

Target Production

Before ICF experiments are conducted, the direct-drive fusion targets on OMEGA are filled with fusion fuel, a mixture of the hydrogen isotopes deuterium and tritium (DT). To increase the amount of fuel each target can hold, and to start with the highest density, the DT fuel is frozen at cryogenic

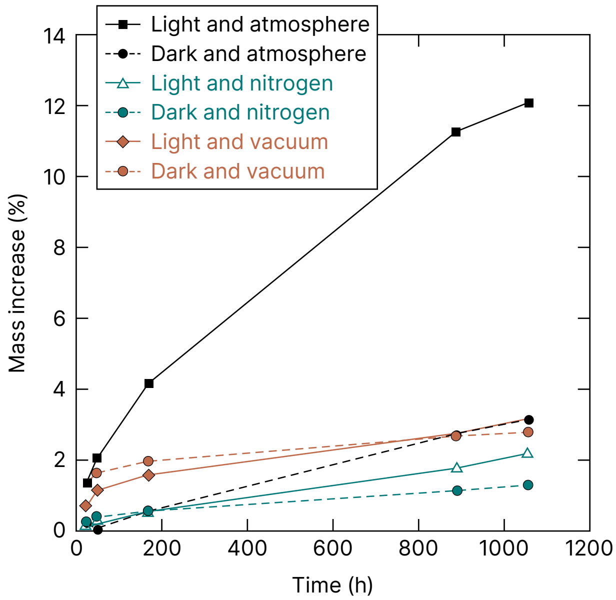

Figure 3. The oxygen concentration for air and nitrogen atmospheres for Si-doped GDP and undoped GDP.

temperatures. These tiny cryogenic capsules are then placed into the target chamber in preparation for the shot.

The design of these capsules has continually grown in complexity over the past two decades, evolving from a single layer of glow-discharge polymer (GDP) material to two layers, and most recently, to as many as three. Researchers have also experimented with the level of dopant in the GDP material to improve performance.

Since 2021, GA has fabricated cryogenic Si-doped GDP capsules of varying diameters, thicknesses, and dopant levels with multilayer designs (Fig. 2)—an initiative driven by experiments showing increased yield (up to 50%) from Si-doped GDP capsules [4]. LLE researchers requested new varieties of Si-doped capsules, with increased atomic percentage levels of silicon in the GDP layer.

Starting in 2023, GA chemists and materials scientists have investigated ways of incorporating higher levels of atomic silicon with the GDP matrix, eventually achieving dopant levels as high as 9% in both single- and multilayer capsules (Fig. 3). The first shot using a capsule with a high atomic level of silicon, ImprintModel-25A, is scheduled for February 2025.

One characteristic of GDP is that it can absorb oxygen over time since oxygen bonds to the hydrogen in the polymer. This oxygen uptake, which can affect experimental results, has been studied by GA for these new Si-doped designs so that LLE PIs can use this information in their simulations. The work has also developed ways to minimize the total oxygen uptake between capsule production and processing at LLE. Results show that, consistent with past studies of undoped GDP capsules, keeping the capsules in a light-free environment has a dramatic effect in minimizing total uptake, even if the capsules have been exposed to air (Fig. 3).

High-Temperature Conversion Oven

Glass shells used in OMEGA experiments were historically fabricated using a device known as a drop tower, a 30-ft-tall oven in which capsules form as they travel through a heated column under gravity [5]. This equipment was eventually decommissioned in 2024 after an agreement was made between the national laboratories that were the primary users of this type of capsule.

The replacement system developed by GA is a much more cost-effective approach in which Si-doped GDP capsules are fabricated and heated past their transition temperature in a high-temperature conversion oven (Fig. 4). This process allows for the fabrication of capsules that have a much broader range of diameters and wall thicknesses. In addition, wall thickness uniformity—a critical parameter for successful experiments—can be held to much tighter tolerances. This technique can also be used to manufacture glass shells with precise amounts of mid- to high-atomic-number dopants that

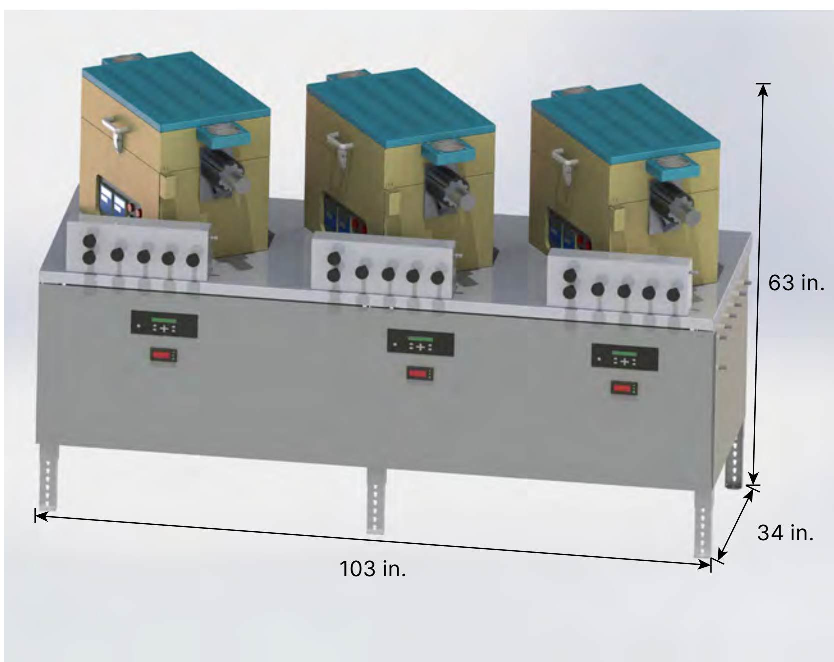

Figure 4. The new capsule conversion ovens operated by a programmable logic controller allow for data control and better user-friendliness.

can be filled with precise pressures of noble gas if required by the experiment.

The upgraded system accommodates the increased fabrication demand for this type of glass capsule as well as the potentially useful Noir glass capsule (see Planned Developments, p. 28). The new system has a much smaller footprint, higher temperature limit (1100°C versus 900°C), and better pyrolysis atmosphere control, which allows the outcome of the process (e.g., shell size, composition, and wall thickness) to be controlled more deterministically.

Capsule Fill Station Upgrade

Gas-filled, room-temperature target capsules are the focus of many OMEGA experiments, and the equipment used for injecting the fuel gas is a critical element in the delivery of these targets. The system used to fill capsules for shots on OMEGA was originally developed two decades ago, and although maintenance and periodic upgrades kept it operational, it had started to show signs of age.

Figure 5. The new fill station with two heated ovens allows for double the throughput for capsules that require heated fills. The station is operated by a programmable logic controller to improve data control and user-friendliness, with two independent control screens to allow for simultaneous operation by two different operators.

Challenges included control software that was no longer compatible with current PCs and hardware that needed replacement, requiring parts that were no longer available. In addition, due to the incremental nature of the system's development, its documentation was incomplete, making troubleshooting, maintenance, and repair work extremely difficult.

Operational requirements from the original gas fill station were developed to drive the design of a new system. Both systems were documented, and the documents were released on GA's product life-cycle management system.

The upgrades include new programmable logic controlled software, as well as manual and fully automated valve control options over the full operational parameter space needed to support experiments on OMEGA. The newly assembled system has been used on production since October 2024 (Fig. 5).

Metrology

Automated White-Light Interferometer

Over the past decade, ICF target production volume has continually increased, while nonuniformity requirements have simultaneously become ever more stringent. Currently, wall thickness nonuniformity of 0.1 μm is frequently requested for OMEGA cryo-quality targets with wall thicknesses of less than 8 μm.

White-light interferometric (WLI) microscopy is a primary metrology technique for the characterization of transparent plastic capsules to ensure capsule adherence to specifications [6]. In this method, the operator (usually a highly skilled scientist) precisely measures the inside and outside diameters and wall thickness in a single θ–ϕ orientation. While effective, this approach has inherent operator biases.

To address this problem, GA engineers are currently developing an automated station to remove measurement bias and decrease measurement error. The automated WLI system will facilitate significantly higher sampling size per capsule and per batch, thus tightening the reported confidence interval. This automated system is slated to transition to routine capsule metrology in early FY25.

Dark-Field Defect Detection

In addition to surface defects, implosion capsules can have small vacuole defects (voids, crystals, and other inclusions) in their walls, which pose challenges to metrology. These defects are volumetrically distributed, so typical diagnostic tools that are designed for the semiconductor industry have trouble dealing with the 3D distribution. Further, the defect size of concern for direct-drive ICF goes to a deep submicron scale, which can be several times smaller than the diffraction limit of the microscopes used for imaging.

To solve this problem, GA developed a dark-field scanning method that can quantify vacuole sizes below 0.1 μm by using light-scattering intensity, a method previously used in the semiconductor industry, but adapted for 3D scanning through the full capsule wall thickness. GA plans to develop a similar tool for GDP ablator capsules using infrared light to enable dark field defect quantification.

Planned Developments

GA and LLE continue to work together on improving capsule production efficiency and capsule performance. One of the most-effective National Ignition Facility capsule production systems developed in the past few years was the Automated Batch Assessment System (ABAS) (Fig. 6), which can handle shells, acquire data, analyze measurement data, and determine capsule quality in a fully autonomous fashion. ABAS has been integral in hands-off standardized optical GDP and poly-alpha-methylstyrene (PAMS) capsule inspection [7]. GA is developing this application for OMEGA capsules, where it is currently at the proof-of-concept stage. Further development work is necessary before full deployment. GA is also exploring additive manufacturing for capsule fabrication.

To improve on glass capsules derived from Si-doped GDP, GA is developing improved backlighter capsules with the goal of reducing production time (nominally four weeks) while improving quality. One potential capsule under development consists of 20% to 25% silicon, ~60% carbon, and the remainder oxygen. This first-ever black capsule has been termed "Noir glass."

Although the lack of transparency may present challenges, Noir glass has significant potential benefits in addition to a much shorter production time. These include a higher strength (~3×) than glass, average lower Z, no residual gases, and the ability to fill with hydrogen, helium, and noble gases. In addition, early results indicate that these capsules can be prepared with a 1- to 4-μm pure-carbon inner layer, or an inner M-doped carbon diagnostic layer, thereby potentially making them useful for more than just backlighters.

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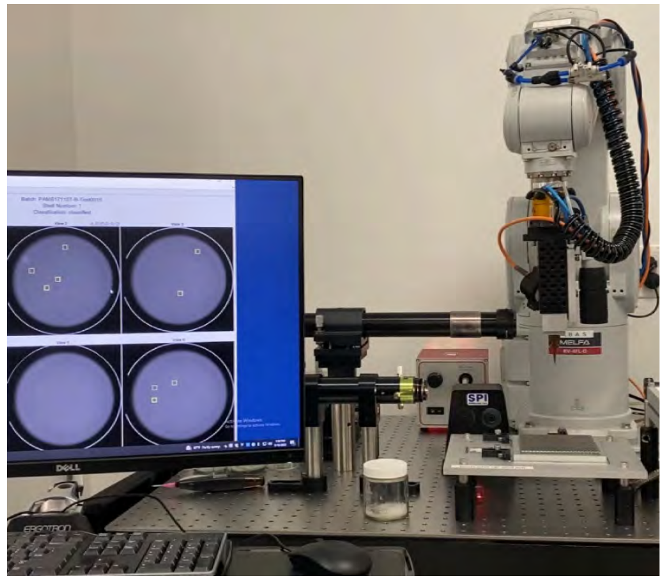

Figure 6. The ABAS system uses a vacuum wand and vision system to pick up individual capsules from a random pile one at a time, where they are inspected in front of a high-magnification camera system at two orthogonal angles per shell. The shell images are then analyzed by a machine-learning algorithm, labeled, and classified as pass or fail.

Focus Points

- Successful ICF experiments on the Omega Laser Facility require a high degree of collaboration between PIs, LLE staff, and General Atomics, which fabricates nearly all ICF targets.
- LLE staff work with experts at GA to develop the next generation of ICF targets and keep the fabrication pipeline on the cutting edge.
- ICF target production volume has continuously increased over the past decade while quality requirements have become much stricter. GA has responded to this need by LLE PIs by developing innovative, highly automated characterization and selection instruments to ensure target quality.

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