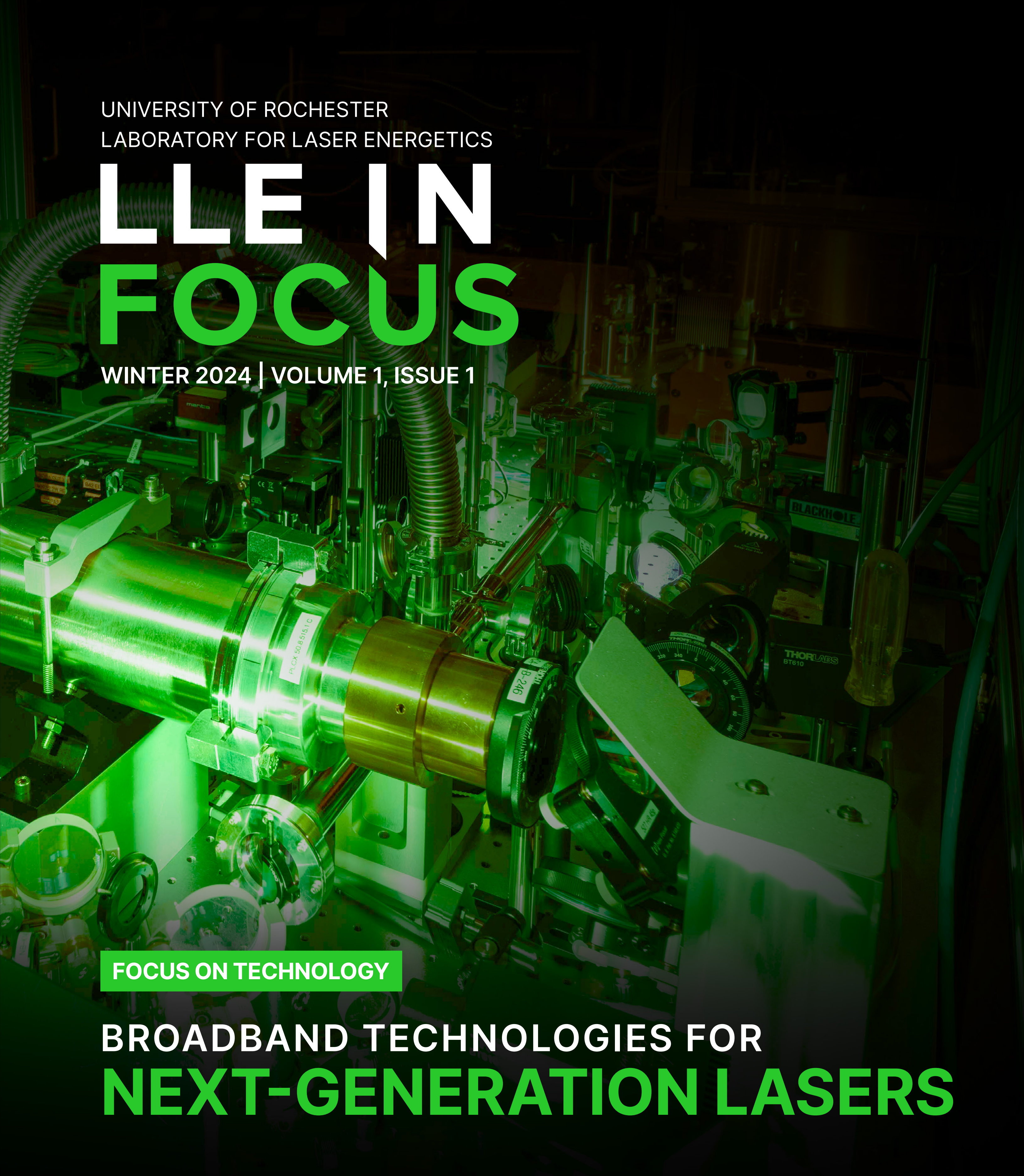

UNIVERSITY OF ROCHESTER
LABORATORY FOR LASER ENERGETICS

LLE IN FOCUS

WINTER 2024 | VOLUME 1, ISSUE 1

FOCUS ON TECHNOLOGY

BROADBAND TECHNOLOGIES FOR NEXT-GENERATION LASERS

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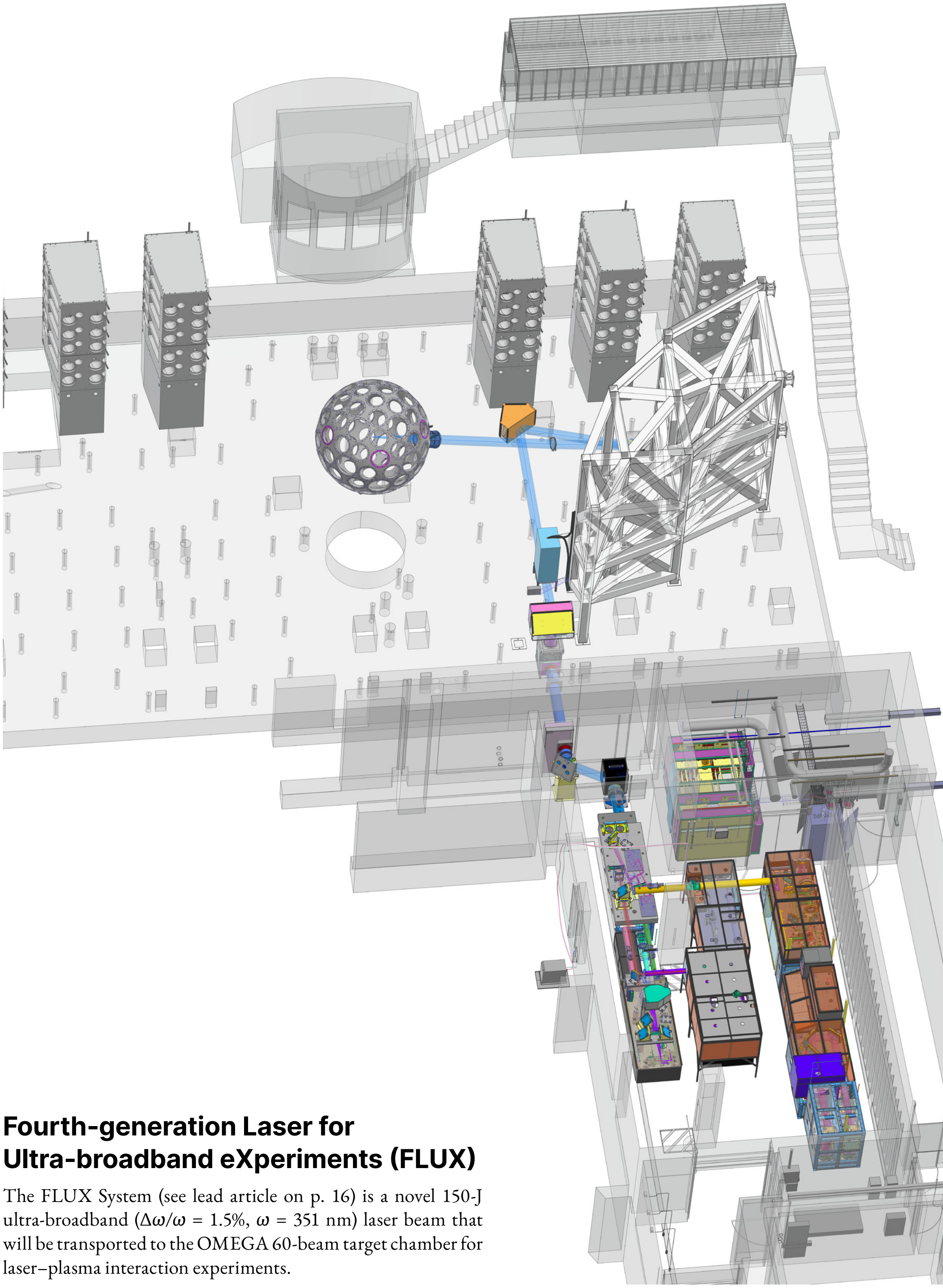
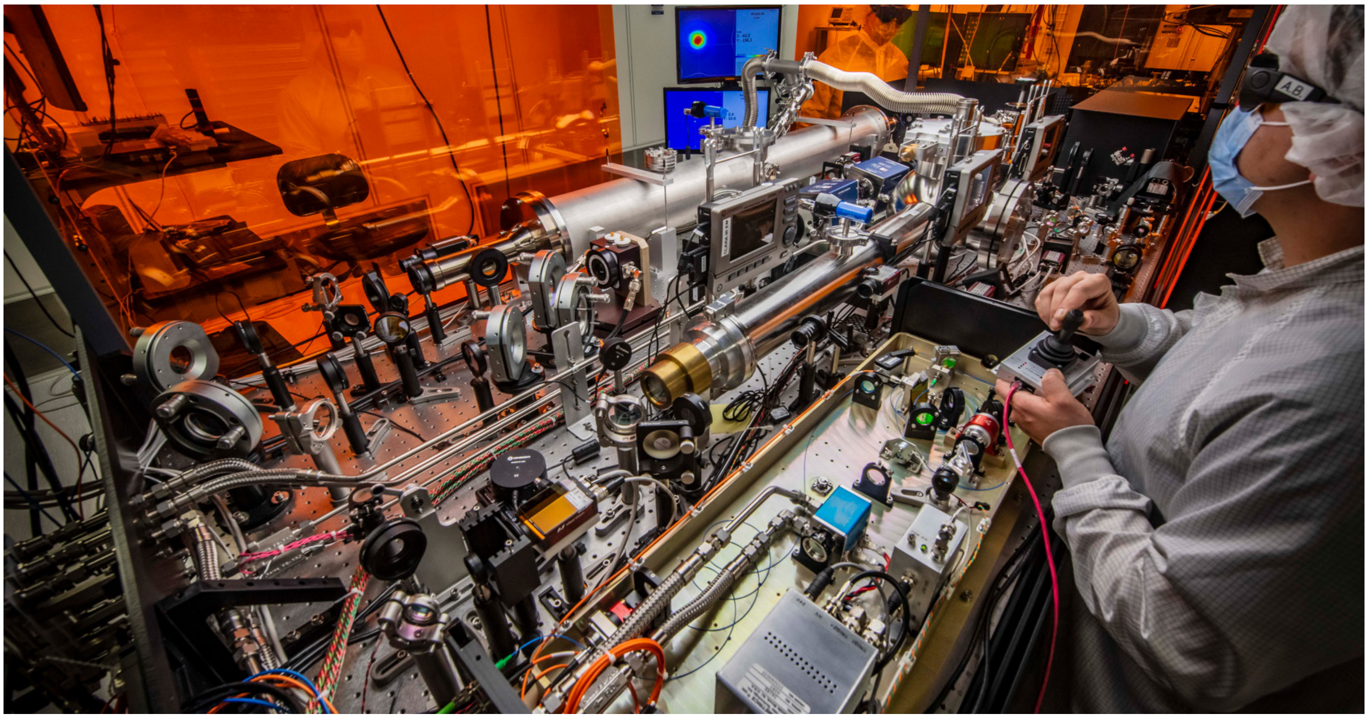


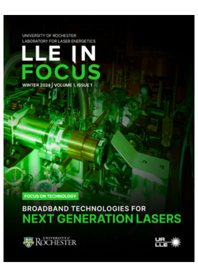
Fourth-generation Laser for Ultra-broadband eXperiments (FLUX)

The FLUX System (see lead article on p. 16) is a novel 150-J ultra-broadband ($\Delta\omega/\omega$ = 1.5%, ω = 351 nm) laser beam that will be transported to the OMEGA 60-beam target chamber for laser–plasma interaction experiments.

LLE IN FOCUS

Focus on Technology
Winter 2024
Volume 1, Issue 1





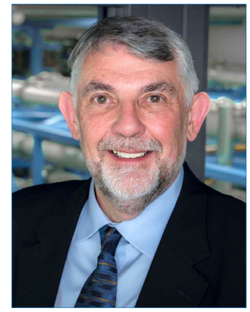
About the cover

An optical parametric amplifier in the FLUX System is shown being pumped by an energetic narrowband green laser to amplify a unique broadband laser pulse. The broadband long-duration pulse is temporally incoherent and spatially coherent such that the beam can be focused with all colors present at all times—a necessary condition to mitigate laser–plasma instabilities. FLUX was adapted from state-of-the-art laser technologies developed for ultrashort-pulse lasers (see MTW-OPAL on p. 28). FLUX will be commissioned in July of 2024.

LLE IN FOCUS

From the Director

DR. CHRISTOPHER DEENEY | DIRECTOR, LABORATORY FOR LASER ENERGETICS



First, quite simply: "Wow!" Thank you, Larry Kessler, for the challenge. Larry, a member of the distinguished University of Rochester Board of Trustees, challenged me with the size and usefulness of LLE's quarterly reports. I brought the challenge back to the extraordinary LLE team, who clearly exemplify the University motto of "Meliora," which means "ever better." This new *LLE In Focus* aims to embody a *Scientific American*-style publication showing the progress at LLE. The Publications and Design Group, technical editors, and content generators have produced a wonderful document, which is a delight to read with excellent visuals. Thank you for the hard work in creating the first issue of this new-concept quarterly report. It is clear that the bar is now set very high.

Praising the document is worthwhile, but it is more insightful to reflect on the volume and quality of the science, technology, and education that *LLE In Focus* contains, especially regarding next-generation lasers. The new physics regimes that an NSF-OPAL Laser Facility would enable is an exciting new frontier. The potential mitigation of laser–plasma instabilities, which should create new paths to fusion through the use of higher-bandwidth lasers, is also discussed in this edition. The FLUX System will soon be allowing experiments on the 60-beam OMEGA laser to explore the physics of broadband lasers interacting with plasmas.

Our scientific team continues to receive major awards, and one of LLE's secret weapons, David VanWey, received the University of Rochester's prestigious Witmer Award for his service to the institution. David has been LLE's human resources guru for many years, and he is the consummate team player who exemplifies a commitment to everyone at LLE. Thank you, David! Furthermore, LLE is proud to have graduated 11 PhD students in 2023, and we have highlighted some of these students in this report.

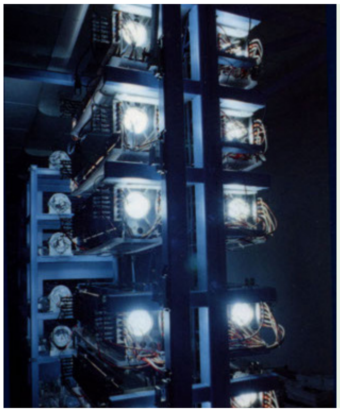
Finally, I thank our sponsors. In particular, the National Nuclear Security Administration. NNSA just awarded a new five-year Cooperative Agreement without which LLE could not maintain its scientific output. In addition, the National Science Foundation awarded the RI-1 design phase for NSF-OPAL, which is discussed on p. 24. This exciting facility will open the doors to new scientific research and a wealth of other opportunities. This laser alone will be over 1000 times more powerful than the original Nobel-Award-winning laboratory demonstration of chirped-pulse amplification by Donna Strickland and Gérard Mourou at LLE in 1985.

Please enjoy this new quarterly report and I hope your reading of it communicates why I am so proud of LLE.

Christopher Deeney
Director, Laboratory for Laser Energetics

First Focus

In LLE History



30 years ago

In January 1994, the 60-beam OMEGA control room began operations. Shown here is a cluster of 15-cm disk amplifiers undergoing test firing.

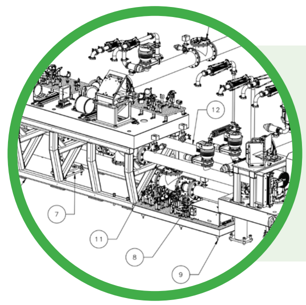
10 years ago

The Isotope Separation System was created to provide a flexible tritium fuel supply and ensure its purity.

Fast Facts

2466

unique custom component parts were manufactured by LLE's Mechanical Engineering Group in 2023.

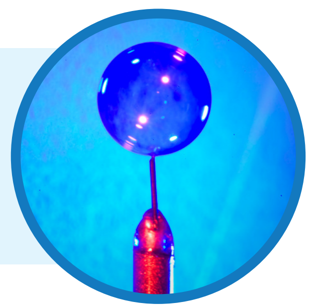


1864

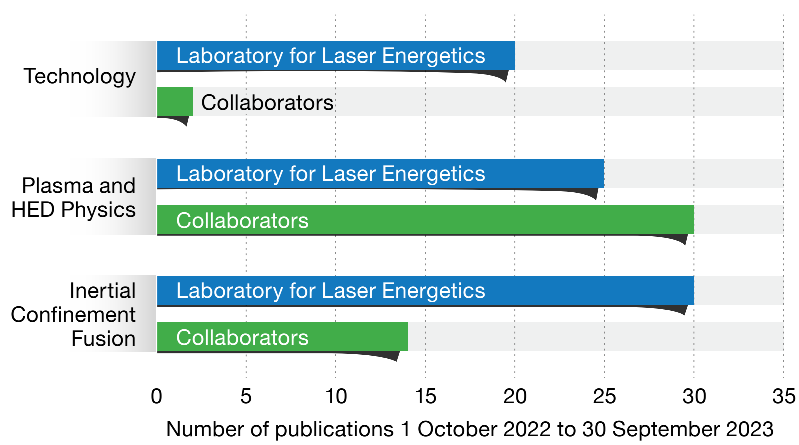
custom component drawings were released by LLE's Mechanical Engineering Design Office in 2023.

2640

targets were produced by LLE's Target Fabrication Group in 2023.



Publications

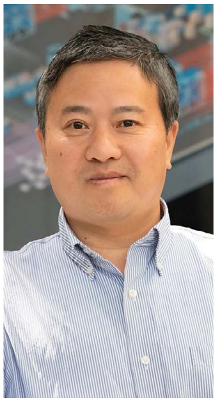


Research Highlights

The science and engineering research at LLE is captured through peer-reviewed publications, which include LLE lead-authored (blue bars) and LLE co-authored (green bars) papers. LLE averages more than 120 published articles annually across three broad areas: Technology, Plasma and High-Energy-Density (HED) Physics, and Inertial Confinement Fusion.

LLE EXCELS

Awards and Honors



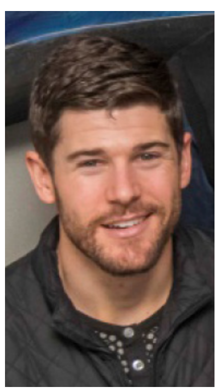
Professorships

Suxing Hu (left), Distinguished Scientist and Group Leader of the High-Energy-Density Physics Theory Group, was promoted to Professor of Physics (Research) in the Department of Physics and Astronomy. He also holds a joint appointment as Professor (Research) in the Department of Mechanical Engineering. Jessica Shaw (center), Scientist in the Relativistic Laser-Plasma Experiments Group, was appointed to the position of Assistant Professor in the Department of Physics and Astronomy. Katelynn Bauer (right), Laser System Scientist, was appointed to the position of Assistant Professor of Optics in the Institute of Optics.

David VanWey Awarded Witmer Award for Distinguished Service

David VanWey, HR/Benefits Representative and Lead Analyst/Programmer, was awarded the University of Rochester Witmer Award for Distinguished Service. The Witmer Award is presented to staff members whose careers have been characterized by outstanding and sustained contributions to the University. VanWey is well-respected among his peers and known for his compassion, empathy, and willingness to help employees navigate all aspects of the University's benefits and HR policies and procedures. He has served LLE for over 30 years and is a valued colleague and friend to many across the University.





CY21 Defense Programs Award of Excellence

Cliff Thomas (left), along with Hans Rinderknecht (center), and David Turnbull (right), were awarded a Defense Programs Award of Excellence by Marvin Adams, Deputy Administrator for Defense Program. Members of the team were recognized for "exceeding Lawson's criterion for ignition in an inertial fusion experiment."

Danae Polsin Receives SUNY Geneseo Outstanding Young Alum Award

Danae Polsin, Scientist in the High-Energy-Density Experimental Physics Group and Assistant Professor in the Department of Mechanical Engineering at the University of Rochester, received the 2023 Outstanding Young Alum Award from the State University of New York (SUNY) at Geneseo Alumni Association. This annual award recognizes SUNY Geneseo graduates who have achieved early distinction in a chosen profession.

Riccardo Betti Awarded the Blaise Pascal Medal

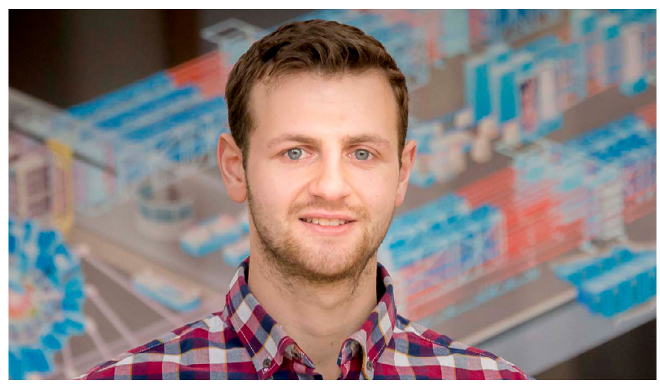
Riccardo Betti, Chief Scientist, Robert L. McCrory Professor, Professor of Mechanical Engineering, and Professor of Physics and Astronomy, was awarded the European Academy of Sciences' Blaise Pascal Medal. The award was given "in recognition for his outstanding contributions to high-temperature plasma physics with applications to nuclear fusion and for the development of the novel 'shock-ignition' approach to direct-drive inertial confinement fusion."

Four LLE Researchers Named Optica Senior Members

Four researchers in the Laser and Materials Technology Division (shown left to right), Chengyong Feng, Mark Meyers, Erik Power, and Ben Webb, were named Senior Members of Optica. This honor recognizes their experience and professional accomplishment in optics and photonics. To qualify for Optica Senior Membership, individuals must have at least ten years of significant professional experience in the field, five years of active Optica membership, and two endorsement statements from current Optica members.

David Turnbull Selected for the 2023 Edouard Fabre Prize

David Turnbull, Laser–Plasma Interactions Group Leader, was selected to receive the 2023 Edouard Fabre Prize for his pioneering contributions to inertial confinement fusion (ICF) through innovative laser–plasma instability studies. Turnbull has a passion for ICF that has guided his research and driven him to make significant contributions to the understanding of laser–plasma instabilities. Experiments looking at cross-beam energy transfer (CBET) that he conducted both as a postdoctoral scientist at Lawrence Livermore National Laboratory and later at LLE helped build the confidence to use CBET modeling quantitatively to enable indirect-drive fusion. Through his scientific leadership, he has developed into a significant national player in both the indirect-drive and direct-drive ICF programs.



Avi Milder Selected to Receive the Chiyoe Yamanaka Award

Horton alumnus Avi Milder was selected to receive the Chiyoe Yamanaka Award at the 2023 Inertial Fusion Sciences and Applications Conference. The award was given for his research performed at the Omega Laser Facility that used angularly resolved Thomson scattering to demonstrate non-Maxwellian electron distribution functions in laser-produced plasmas and their effects on atomic physics and laser–plasma interactions—both effects only previously predicted by theory. This seminal technique has opened an avenue of fundamental plasma-physics exploration that will allow researchers to directly measure the velocity distribution functions across a variety of plasma phenomena, including nonlocal thermal transport. The Yamanaka award is given to early-career scientists in the spirit of Chiyoe Yamanaka, a pioneer of inertial fusion sciences and applications.

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) Program, National Laser Users' Facility (NLUF), and Laboratory Basic Science (LBS), in addition to other research and educational efforts (see Fig. 1). During FY23, the Omega Laser Facility conducted 1255 target shots on OMEGA and 806 target shots on OMEGA EP for a total of 2061 target shots. OMEGA averaged 9.7 target shots per operating day, averaging 93% availability and 93% experimental effectiveness. OMEGA EP averaged 7.5 target shots per operating day, averaging 94% availability and 95% experimental effectiveness.

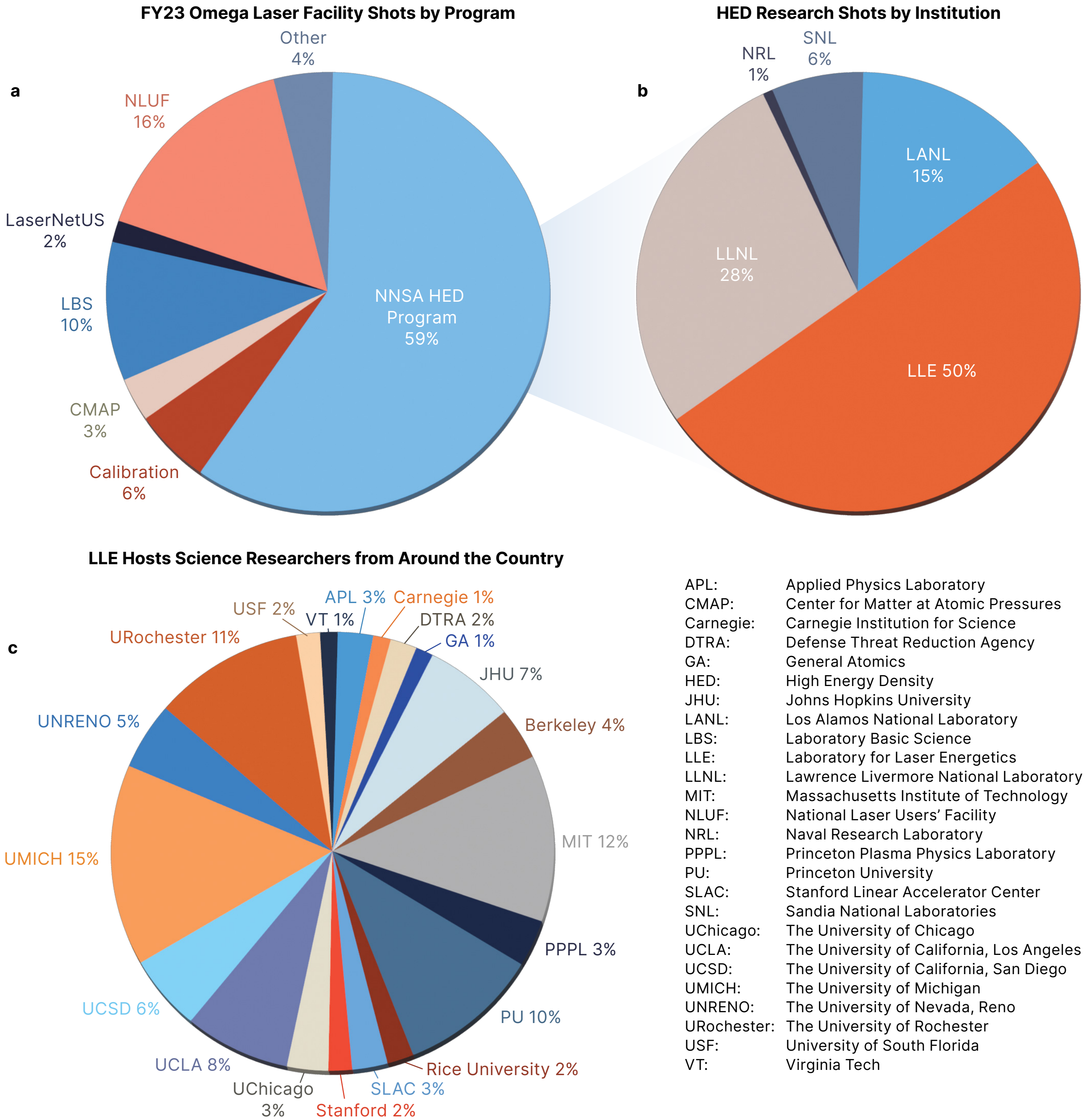


Figure 1. (a) The Omega Laser Facility delivered 2061 target shots for a variety of research programs. (b) The HED Program shots are led by researchers from both LLE and collaborators at national labs. (c) LLE is a user facility that hosts researchers from around the country. A total of 465 shots were completed for a variety of university researchers and research institutions.

Beam-Delay Extenders

A frequent request from users has been implemented on the OMEGA Laser System: beam-delay extenders (BDEs) to enable an additional 4 ns of delay on ten beams. This project involved the installation of added bay structures to hold two-state mirror pairs that divert the beam through an extended path length. In conjunction with the path-length adjustment system, these ten beams can now be timed over a 14-ns range.

The beam-delay extending capability increases the temporal diagnostic window available when conducting single-driver experiments on the 60-beam OMEGA laser and will be valuable to many users, including providing support for cylindrical implosion experiments. This is especially important because it allows for experiments that can directly scale between the Omega Laser Facility and the National Ignition Facility (NIF). Experiments that directly scale between the two facilities are rather unique, enabling this platform to benefit from the NIF's experimental size and energy and Omega's higher shot rate and experimental configuration flexibility. Cylindrical implosions have the advantage of providing direct observation of instability growth due to Rayleigh–Taylor and Richtmyer–Meshkov instabilities while retaining the effects of convergence. Control of hydrodynamic instabilities plays a central role for the success of inertial confinement fusion. Thus, these experiments enable an excellent path to validating codes with the goal of utilizing the NIF to achieve convergence ratios of 10 to 15, directly relevant for the inner shell of a double shell and for laser direct drive, as well as moving to more-relevant regimes for laser indirect drive.

The BDE structure provides a stable and safe support for the optics mounted on it. Each BDE beam path uses two OptoSigma mirror mounts and two LLE-designed fixed mirror mounts to achieve the 4-ns delay. The OptoSigma mirrors are mounted to a carriage on high-precision linear rails that can be manually moved from the storage position to the shot position. Thorough structure design and analysis predict acceptable overall pointing errors while demonstrating high factors in ensuring safety.

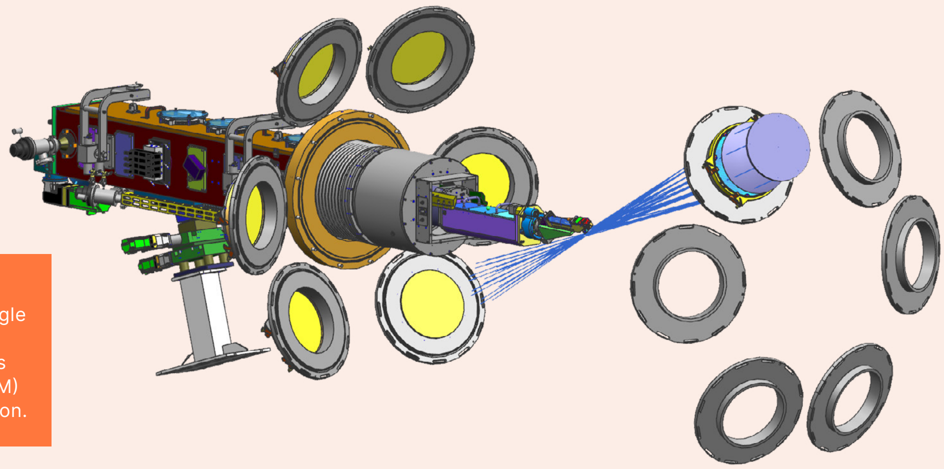
Shots utilizing the BDE structure began in August 2023. A high degree of planning, coordination, and expertise by adept individuals has been required to ensure the success of this structure.

Construction of the BDE (left); finished structure (right).

Members of the BDE team from left to right: (First row) Jeff Hart, Matt Heimbueger, Ryan Fairbanks, and Ray Huff. (Second row) Brian Lee, Dave Weiner, Joe Kwiatkowski, Troy Walker, John Szczepanski, Jeff Hettrick, and Rachel Mickel. (Third row) Mark Romanofsky, Matt Soffa, Greg Amos, Mark Sickles, Amy Rigatti, and Milt Shoup. (Fourth row) Matt Kamm, Tim Clark, Vince Guiliano, Karen Antonow, and Gary Mitchell.
Not pictured: Erik Bredesen, Thomas Buczek, Bill Byrne, Pete Charles, Albert Consentino, Tyler Coppenbarger, Hope D'Alessandro, Richard Dean, Russ Edwards, Steven Engels, Michael Hofer, Mike Hubbard, Mark Labuzeta, Nathan Landis, Annie Liu, Alexander Maltsev, Paul Melnik, Samuel Morse, Jason Puth, Louis Santiago, Michael Scipione, and Todd Smith.

FBIT Express

The full-beam-in-tank (FBIT) diagnostic characterizes the laser beam at the target plane during a full-energy OMEGA laser shot. This diagnostic makes direct measurements to help scientists diagnose the spatial profile and wavefront of the laser pulse after it travels through the entire laser chain. These measurements include the active effects of laser glass and all associated shot effects are characterized. Over the past year, the FBIT has been reconfigured by allowing the wedged sampling optic to be outside of the vacuum chamber so that it can be more quickly used on a beamline to allow for data acquisition without requiring fully dedicated multiday campaigns.



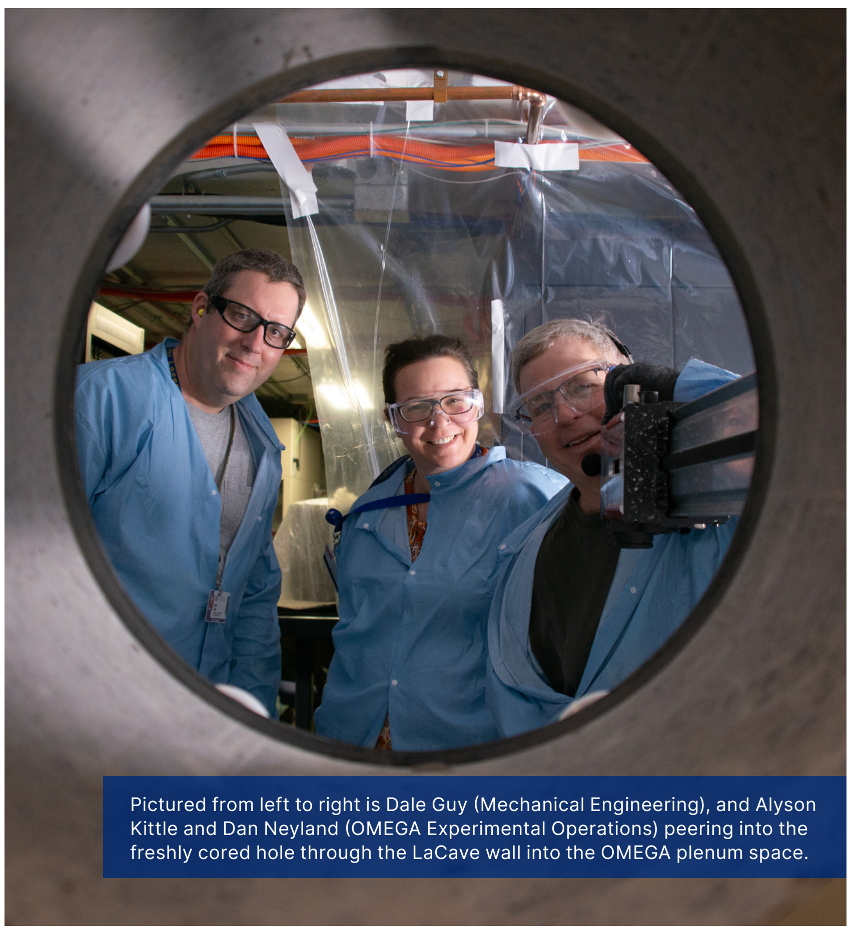
A CAD drawing of the FBIT diagnostic depicts making measurements in a single beam. The equipment is now easily reconfigured to measure the six beams opposite of a ten-inch manipulator (TIM) before moving to a different TIM location.

FLUX Preparations

As the Fourth-generation Laser for Ultra-Broadband eXperiments (FLUX) System is being built, work is being completed to transport the laser pulse to the OMEGA target chamber. Many subsystems in OMEGA have been relocated to provide the necessary space and in April, core drilling provided an open path from the FLUX laboratory space to the Omega Target Bay.

The FLUX Beam Transport Project provides a safe beam-transport path from the FLUX system in Room 5101 to the P9 port of the 60-beam OMEGA target chamber. This includes clearing the path and designing/installing the required beam-transport hardware components. Accomplishing this has involved extensive relocation of equipment and electrical services that resided along the established path. Clearing the path also involved coring 16-in.-diam holes through the concrete wall between the OMEGA plenum space and LaCave and through the concrete floor between LaCave and the 60-beam OMEGA target chamber.

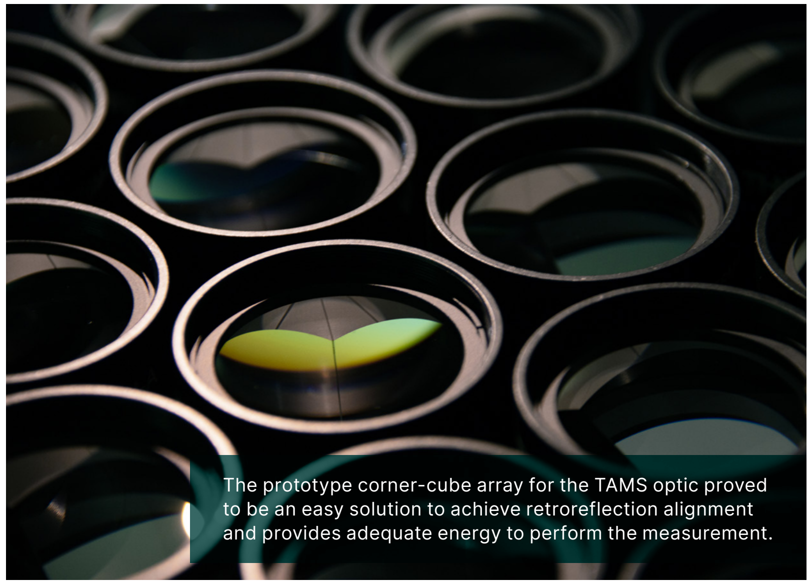
The coring operations were completed using the Mechanical Engineering team's coring equipment, which uses a closed-loop cooling water filtration system to significantly mitigate contamination in the clean-room areas. Coring through the 15-in.-thick wall took one day while the 30-in.-thick Target Bay floor took a day and a half.



Pictured from left to right is Dale Guy (Mechanical Engineering), and Alyson Kittle and Dan Neyland (OMEGA Experimental Operations) peering into the freshly cored hole through the LaCave wall into the OMEGA plenum space.

Target-Alignment Monitoring System (TAMS) Development

The current design of the OMEGA 60-beam system allows for a symmetric laser illumination of targets with high uniformity. The setup of the laser requires a time-consuming (3- to 4-hour) process for completion and target and/or laser-beam alignment drifts during the day reduce the achieved uniformity. A project has been started and prototyped to measure and characterize the system's alignment within a few minutes, enabling the diagnosis and correction of alignment drift. This novel system will illuminate a scattering sphere at target chamber center that is imaged by existing alignment sensor packages using 60 insertable corner-cube arrays at the shield wall.

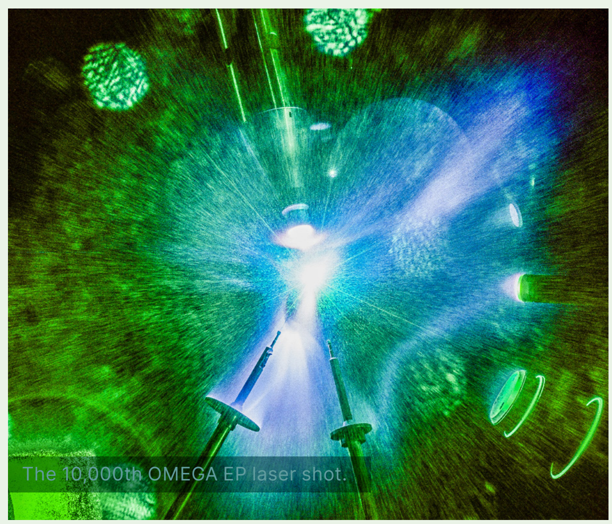


The prototype corner-cube array for the TAMS optic proved to be an easy solution to achieve retroreflection alignment and provides adequate energy to perform the measurement.

OMEGA EP: 10,000 Shots

The OMEGA EP Laser System achieved a notable milestone in December 2022 with the completion of its 10,000th laser shot. Shot Director Scott Householder made the following announcement as the shot was being fired to commemorate the milestone:

"Shot 38181 on this day, the 20th of December 2022, represents a significant event. It was the 10,000th target shot taken since the OMEGA EP system was commissioned in 2008. This achievement is indicative of the 14 years of prolific target shot production that has provided a rich database of scientific insights and advances in the science of short- and long-pulse, high-energy-density physics. Increased OMEGA EP capability over years of operation has extended the range of experiments possible, aided the recent ignition demonstration on the NIF, and enabled numerous scientific discoveries. Congratulations and thank you to all!"



The 10,000th OMEGA EP laser shot.

The Operations team:
(First row) Michelle Leone, David Canning, Patrick Wilson, Dustin Fess, William Donaldson, Scott Householder, and John Hoffmann.
(Second row) Matthew Barczys, Sam Morse, Brian Kruschwitz, Calvin Ryan, Jeremy Czirr, Adam Kalb, Scott Inscho, Mark Guardalben, and R. Jay Brown.

J. Puth, M. Labuzeta, D. Canning, R. Janezic, and R. Schwartz

Some of LLE's graduating students participated in University of Rochester's Commencement ceremony in May 2023. Pictured here (left to right) are Phil Franke, Dillon Ramsey, Maggie Huff, Luis Leal, and Somto Nwabunwanne.

LLE GRADUATE STUDENTS

The Future of Science

The University of Rochester's continued commitment to a strong educational mission is exemplified by the wealth of opportunities available to students at LLE. Students have participated in a number of educational opportunities, including integrated summer programs for high school students, internships for science and engineering undergraduates, and fully funded research opportunities and fellowships for graduate students. This unique collaborative effort has helped guide and empower over 500 students in the past five years, including 230 graduate students from the University of Rochester and many other academic institutions, among which 72 earned their PhD degrees. Many have gone on to lead flourishing careers at prestigious national laboratories, universities, and industrial research facilities across the country.

LLE is proud to recognize the achievements of five graduate students who recently earned their PhD degrees. The doctoral research of Xuchen Gong, Maggie Huff, Ruobin Jia, Somto Nwabunwanne, and Dillon Ramsey has contributed to advances across various areas of high-energy-density science. From important developments in laser-damage performance and detector fabrication technology to expanding our knowledge and understanding of astrophysics and planetary science, the combined accomplishments of these graduate students represent a culmination of years of dedication, innovation, excellence in research, and a true embodiment of this exceptional mission.

Dr. Xuchen Gong

Department: **Mechanical Engineering**
Advisor: **G. W. Collins**

The investigation of properties of matter at extreme pressures and not-so-extreme temperatures has become an exciting subfield in high-energy-density research since the advent of the ramp-compression technique, which involves increasing pressure gradually with time, yet slowly enough to keep the material relatively cold.

Xuchen Gong's graduate work at LLE focused on the application of x-ray and optical diagnostics to measure the properties of ramp-compressed materials. Xuchen co-designed a ramp laser pulse shape that successfully compressed sodium into an electride state, where electrons are forced into interstitial regions on nanosecond time scales, and later employed the same pulse to measure the structural phase transformations of silicon under ramp compression using an x-ray diffraction technique. Importantly, the disparity Xuchen found in theoretical predictions and experimental measurements revealed outstanding issues in our current way of thinking about phase transformations induced by nanosecond compressions.

During his work on various ramp-compression experiments, Xuchen was met with the challenge of obtaining useful information about such modest temperature samples using existing optical pyrometry techniques. The question remained: How does one detect something if it rarely exposes itself? Xuchen therefore proposed and developed a new model with the ability to interrogate information from pyrometry data for samples even at modest temperatures. This model, which has since broadened the way for temperature measurements in future ramp-compression experiments, corroborates other possible techniques. Xuchen is excited to continue tackling the many questions that remain unanswered in this field as a research postdoctoral associate at the Center of Matter at Atomic Pressures (CMAP) at the University of Rochester.

It has been a pleasure to work with the helpful staff of the world-class laser facilities at LLE. The HED group offers plentiful opportunities for internal and external collaborations and provides the perfect environment to pursue knowledge in this fast-developing and exciting field of science.

> LLE has been an incredible place to do research as a graduate student. I've been a part of many collaborations and learned how to plan an experiment from scratch. **The facilities and the team are amazing to work with and have set me up exceptionally well to continue my scientific career.**

Dr. Maggie Huff

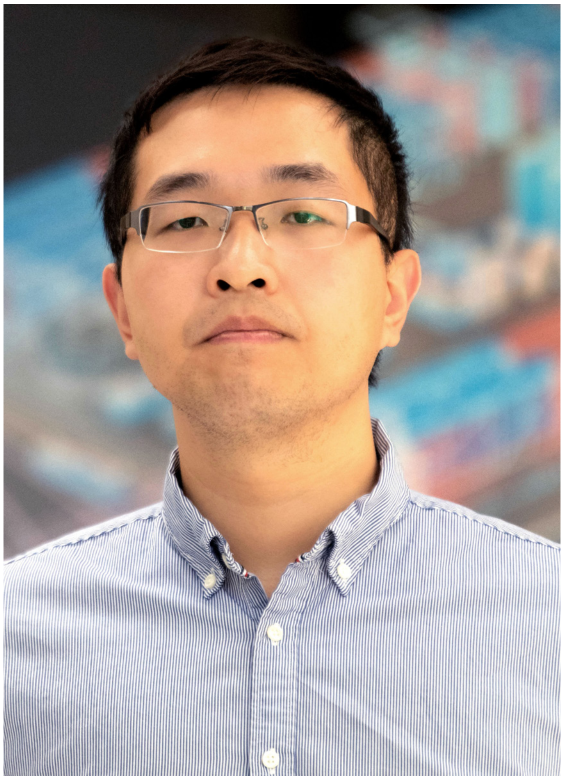
Department: **Physics and Astronomy**
Advisors: **G. W. Collins and J. R. Rygg**

To answer the question of what happens to matter far beneath the surface and deep within the innermost layers of our earth and other planets, Maggie Huff employed the world-class OMEGA EP Laser System to reach extremely high pressures and temperatures in iron and silicate planetary materials. While it is not possible to directly investigate the cores of planets at millions of atmospheres and hundreds of thousands of degrees, a target containing such planetary materials can be compressed for a few nanoseconds to match these conditions. In her graduate work, Maggie implemented velocity interferometry and optical pyrometry techniques to measure a shock wave as it traveled through a target, and used the data she collected to learn about the material's response to extreme conditions.

What can such an experiment tell us about the core conditions of a planet? Some of the most interesting findings of Maggie's research reveals new evidence in the relationship between the melt temperature and conductivity of a material and its potential for magnetic-field generation in super-Earth type planets. This work, which has wide-ranging applications in the warm-dense-matter field, is understandably of great importance for planetary scientists. After a challenging and fulfilling graduate career at LLE, Maggie plans to join the P-4 Thermonuclear Burn Plasma Physics Group at Los Alamos National Laboratory.

Dr. Ruobin Jia

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



Ruobin Jia's doctoral research focused on using monomolecular coatings to control the physical and chemical surface properties of optical and electronic devices. Because of their structured nature and great compositional variety, these monomolecular coatings offer (1) improved tunability of material interfaces, (2) enhanced stability due to strong covalent bonding to substrates, and (3) minimal interference with bulk substrate properties due to their ultrathin nature.

One key aspect of Ruobin's project was aimed at developing particle-contamination–resistant coatings to help improve the operational performance of optical components for high-power and/or high-peak-intensity laser systems. The long-term performance of high-power laser systems can be adversely affected by particle contamination during the installation and operation of the laser system. Particle contaminants that accumulate on optical components can absorb or concentrate laser energy, reduce the system's laser-induced–damage-threshold values, and cause secondary contaminations from the damage sites. This can rapidly degrade the laser-damage performance of the optical components and in turn significantly limit the laser-power output and operational lifetime of the optics.

The molecular film coatings that Ruobin developed alter the strength of the noncovalent van der Waals interactions between the contaminant particles and the optical substrates, significantly reducing the lateral gas-flow force needed to dislodge the particles from the interface. The results of the experiments, which used fused-silica optical substrates and model contamination particles of dielectric and metal materials, suggest that the developed coatings significantly improve the removal process of particle contaminants via gas cleaning. Results also show that these coatings do not adversely affect the damage threshold of the optical substrates and that they are stable for prolonged periods of time in both vacuum and ambient environments.

This innovative approach to particle contamination management may become a viable new method for increasing the lifetime and performance of optical components, and for reducing the operational costs of high-power laser systems.

"Working at one of the world's best research facilities has been an honorable and precious experience as an international student. **I will carry all the insightful thoughts I have encountered here at LLE into my future life within the field of science.**"

> “Professor William Donaldson and indeed the entire LLE family **gave me immense freedom to think, execute excellent research that addressed real-world physical and engineering problems,** publish results on global platforms, and rediscover my passion for the quest of knowledge.”

Dr. Somto Nwabunwanne

Department: **Electrical and Computer Engineering**
Advisor: **W. R. Donaldson**

Somto Nwabunwanne’s doctoral thesis research on improving the methods used to measure short ultraviolet (UV) pulses represents a significant break from the current technology, which is over 30 years old and relies primarily on vacuum tubes. These improvements offer a wealth of possibilities for picosecond optical diagnostics in the High-Energy-Density–Physics (HEDP) community by moving to semiconducting, solid-state detectors, which have been used for decades to measure picosecond optical pulses that fall within the visible and infrared (IR) ranges of the electromagnetic spectrum.

The telecommunications industry has been a primary driver for the development of fast IR detectors, and for good reason: the faster the detector, the greater the number of optical data pulses that can be squeezed into an optical fiber in a given time window. IR detectors, however, do not work very well in the UV range, which is necessary to illuminate targets and diagnose the plasmas that are subsequently created. HEDP scientists must measure UV signals on picosecond time scales. When UV photons are absorbed, they generate free electrons at the surface of the IR semiconductor detectors and are difficult to extract. IR photons, on the other hand, generate carriers deep within the bulk of the detector, where electrons flow freely.

In his work at the fabrication facilities at URnano, Somto developed new compound semiconductors based on AlGaN (aluminum gallium nitride), which absorb UV light within the bulk of the detector, and successfully increased the efficiency of these detectors by two orders of magnitude by improving their electrode configuration. He then shifted from using simple undoped materials to epitaxially structured materials to deterministically adjust the absorption spectra and hold-off voltage of the photodetectors.

As a result, Somto’s innovative work has laid the foundation for the fabrication of highly sensitive picosecond detectors for the UV range, where wavelength sensitivity can be adjusted to match to the physical system being studied. A Small Business Innovation Research contract with Sydor Technologies, and funded by the Department of Energy, is in place to turn this remarkable technology into a commercial product.

I am grateful to be surrounded by experts who are also dedicated mentors. It's hard to imagine a better graduate school experience. **Doing research at LLE is world class and I am proud to be a part of the greater Rochester community.**

Dr. Dillon Ramsey

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

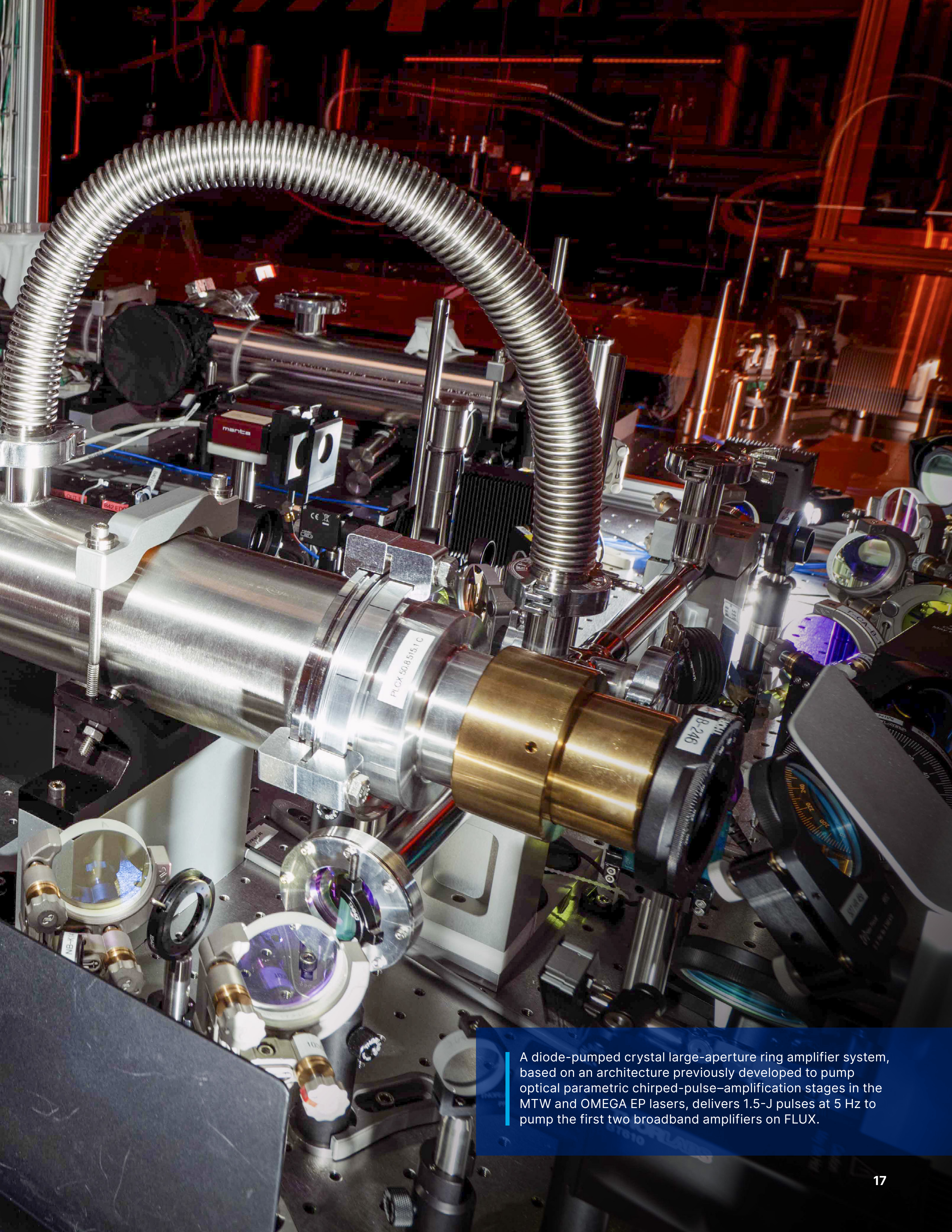
How do you control the intensity of a laser beam over a long distance? Dillon Ramsey's graduate work at LLE focused on this very topic: the investigation of electron acceleration and radiation generation driven by space–time-structured laser pulses. Such laser pulses and their applications are part of a rapidly growing area of research spurred on by recent experiments of laser pulses whose intensity peaks can travel long distances and at any velocity—even those faster than the speed of light. These aptly named "flying-focus" techniques were developed at LLE and control the time and location at which different temporal slices, annuli (rings), or frequencies within a laser pulse come to focus.

Dillon's work on deriving exact analytical solutions for the electromagnetic fields of flying-focus pulses revealed the full vector nature of such pulses and allowed for their generalization to arbitrary polarizations or orbital angular momenta. Dillon also discovered that a flying focus can accelerate charged particles in the backward direction—that is, opposite that of the pulse propagation. He used this property to successfully propose a novel scheme for nonlinear Thomson scattering, which increased the power radiated into x rays by orders of magnitude. After his impressive graduate career, Dillon is excited to continue his research developing advanced radiation sources and applications of space–time-structured laser pulses as an Assistant Scientist at LLE.

Next-generation laser technologies for laser–plasma instability mitigation

FLUX

The Fourth-generation Laser for Ultra-broadband eXperiments



A diode-pumped crystal large-aperture ring amplifier system, based on an architecture previously developed to pump optical parametric chirped-pulse–amplification stages in the MTW and OMEGA EP lasers, delivers 1.5-J pulses at 5 Hz to pump the first two broadband amplifiers on FLUX.

FOCUS ON TECHNOLOGY

FLUX

The Fourth-generation Laser for Ultra-broadband eXperiments

The need for bandwidth

High-energy lasers enable the exploration of laser–matter interactions in various scientific areas, such as laboratory astrophysics, high-energy-density physics, and inertial confinement fusion (ICF) [1]. In these experiments, a range of plasma instabilities occur during the interaction of the laser pulse with the target, which can lead to detrimental effects such as poor and nonuniform energy coupling. The typical laser–plasma instabilities (LPIs) relevant to ICF, particularly in the direct-drive configuration where the laser beams directly irradiate the target, include cross-beam energy transfer (CBET), two-plasmon decay, and stimulated Raman scattering. CBET is a resonant parametric process originating from the density perturbations that arise during the overlap of two or more narrowband beams in a plasma [Fig. 1(a)]. The generation of a periodic index modulation in the plasma essentially acts like a diffraction grating that deflects the incoming pulses, thereby reducing the energy fraction reaching the target.

Mostly based on modeling codes that have been benchmarked with relatively narrowband pulses, increasing the fractional bandwidth ($\Delta\omega/\omega_0$) of the pulses that interact with the target can mitigate LPIs. The required fractional bandwidth depends on the laser wavelength and the considered laser–plasma instability. Fractional bandwidths of the order of 1% and higher are expected to mitigate or even suppress LPIs in the near ultraviolet (UV) [2–6], as illustrated in Fig. 1(b) for CBET where laser absorption recovers to a value that one expects without CBET losses. Incoherent pulses with coherence time much shorter than their pulse duration prove beneficial because a large, instantaneous bandwidth is delivered at all times, as opposed to highly chirped optical pulses that are relatively narrowband at all times. The high-energy laser systems currently in operation do not have sufficient bandwidth for LPI mitigation. For example, Nd:glass systems typically operate with bandwidths less than 1 THz at 351 nm, while krypton fluoride excimer systems operate with similar bandwidths around 248 nm, resulting in $\Delta\omega/\omega_0 < 0.1\%$, unless techniques for spectral broadening are implemented [7]. Recent laser developments aim at generating high-energy pulses with significantly larger fractional bandwidths that would be suitable for LPI mitigation, including argon fluoride excimer systems [8,9] and broadband Nd:glass systems up-converted to their second harmonic [10].

A new generation of solid-state ICF/HED laser systems

Solid-state lasers developed to study high-energy laser–matter interactions with the aim of ultimately achieving fusion ignition have advanced significantly over the past six decades (Fig. 2) using Nd-doped laser glass in amplification modules with good optical quality, large transverse aperture, and relatively favorable laser performance. The first generation of high-energy Nd:glass laser systems performed experiments with pulses at the fundamental frequency (1ω, 1053 nm) [11]. The second generation of laser systems extended performance by frequency converting the laser output to the near ultraviolet (3ω, 351 nm) using a highly efficient frequency-tripling scheme [12] in order to take advantage of more-favorable interaction conditions at shorter wavelengths. Currently, the third generation employs smoothing by spectral dispersion with moderate 3ω fractional bandwidths ($\Delta\omega/\omega_0 < 0.1\%$) that provide improved single-beam, focal-spot uniformity [13–17]. Such bandwidth cannot mitigate laser–plasma instabilities, as

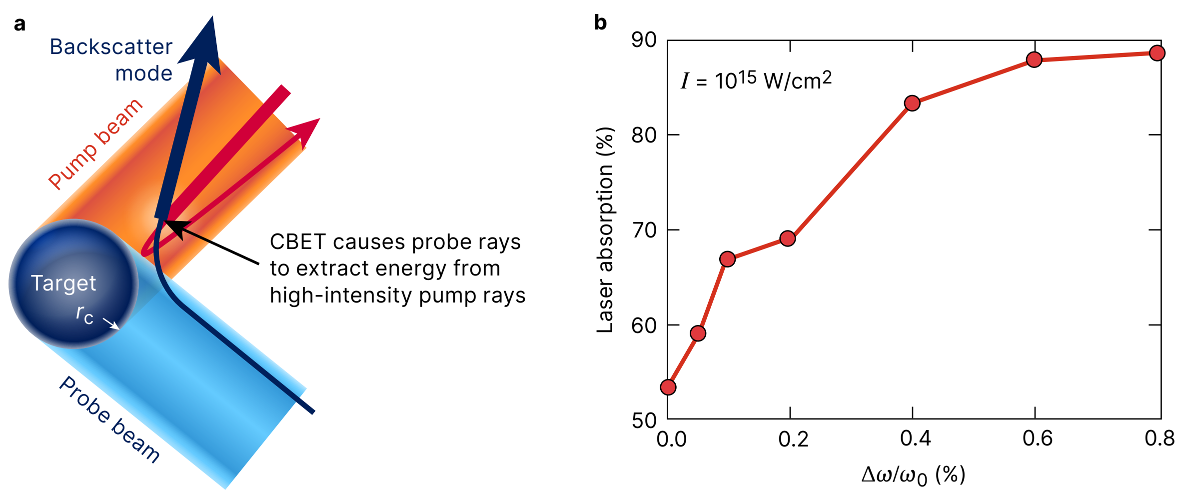


Figure 1. (a) Schematic representation of CBET and (b) laser absorption versus fractional bandwidth for a 16-beam planar configuration.

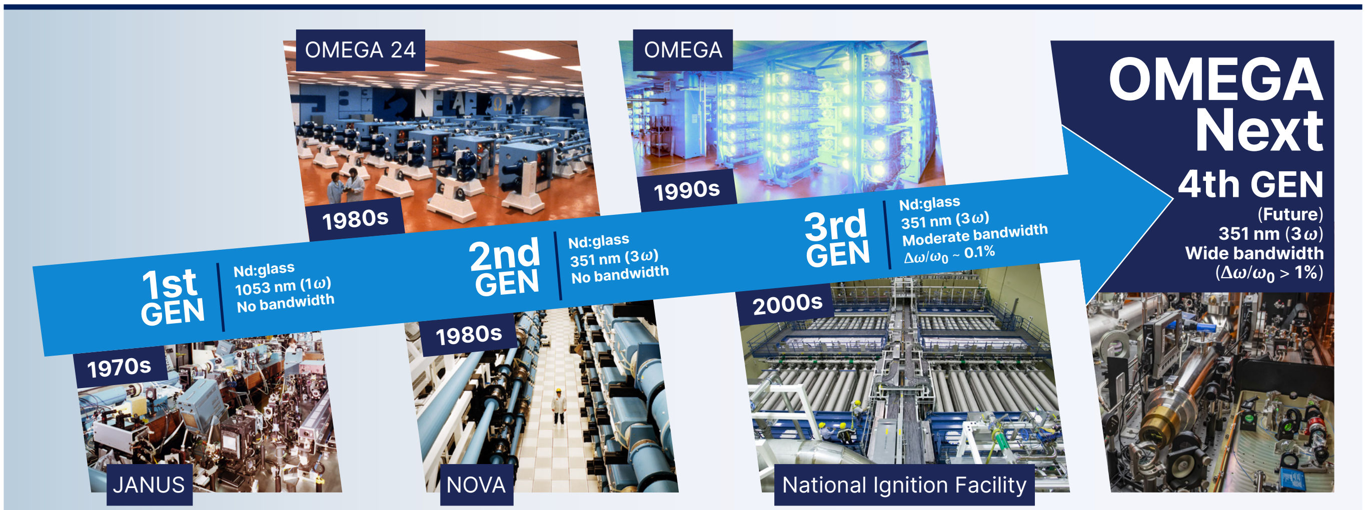


Figure 2. Illustration of the four generations of solid-state inertial confinement laser drivers.

previously discussed, which requires the development of a fourth generation of laser systems. The Laboratory for Laser Energetics started conceptualizing and designing a demonstration of a Fourth-generation Laser for Ultra-broadband eXperiments (FLUX) in 2018. Now under construction, the first OMEGA experiments are expected in 2024.

FLUX specifications

Table 1 lists the on-target laser performance required for the planned FLUX experimental demonstration with intensities up to 10^{15} W/cm^2 required to produce relevant laser–matter interaction conditions. A tunable fractional bandwidth that can reach up to 1.5% was requested to map out the influence of bandwidth on LPI mitigation. Existing OMEGA SG4 phase plates that produce 100-μm focal spots can reach the required intensities to study LPIs. Operating a broadband, incoherent laser at 3ω allows for comparison with the large number of experiments that have already been performed on solid-state laser facilities. It also has the practical advantage of reusing preexisting technical know-how and infrastructure, such as optical components and diagnostics. A flat-in-time pulse with a 1.5-ns duration will reproduce the conditions in which significant laser–plasma instabilities arise during the peak-power portion of a direct-drive ICF implosion. Transport to the existing P9 port of the OMEGA target chamber as a 61st beam synchronized with the 60 relatively narrowband 3ω OMEGA beams will enable experiments that test different LPI beam-interaction geometries.

Table 1. FLUX general requirements

Quantity	Value
Central wavelength	351 nm (3ω)
Fractional bandwidth	1.5%
Pulse duration/shape	1.5 ns/flat in time
Energy	150 J
On-target power	0.1 TW
Far-field size	Focusable to 100 μm (with distributed phase plates)
On-target intensity	10^{15} W/cm^2

For LPI mitigation, a given fractional bandwidth can be achieved either with a single, full-bandwidth beam or with multiple spatially overlapping beams at different central wavelengths using an approach similar to the StarDriver™ concept [18]. A single-beam architecture was chosen based on the relative complexity and cost of developing a multibeam system (e.g., ten ~10-J narrowband beams spread over a 1% frequency range) compared to a single-beam system (one ~100-J broadband beam with a 1% fractional bandwidth).

FLUX design

Spectral gain narrowing in solid-state laser-amplification materials and phase-matching conditions in nonlinear crystals limit the bandwidth of pulses generated by high-energy solid-state laser systems. FLUX can support large fractional bandwidths at 3ω by using optical parametric amplification at 1ω followed by a novel sum-frequency-generation (SFG) scheme as shown in Fig. 3.

In an optical parametric amplifier (OPA), shown schematically in Fig. 4, three-wave nonlinear mixing can efficiently transfer energy from a pump pulse (wave at the highest optical frequency ω_P) to the signal and idler (two waves at lower optical frequencies ω_S and ω_I), so long as energy and momentum are conserved ($\omega_P = \omega_S + \omega_I$ and $\mathbf{k}_P = \mathbf{k}_S + \mathbf{k}_I$), respectively (where $\mathbf{k}_P$, $\mathbf{k}_S$, and $\mathbf{k}_I$ are the corresponding wave vectors). The phase-matching condition can support broad bandwidths by angularly tuning the OPA crystal. In the FLUX front end, two noncollinear OPAs (NOPA1 and NOPA2) amplify the broadband seed pulses from a fiber front end from hundreds of nanojoules to hundreds of millijoules. The noncollinear configuration produces amplified signal and idler waves propagating in different directions (not shown in Fig. 4, which illustrates a collinear OPA). This allows for spatially removing idler waves during the early stages of amplification since the presence of these waves in subsequent amplifiers could degrade their performance.

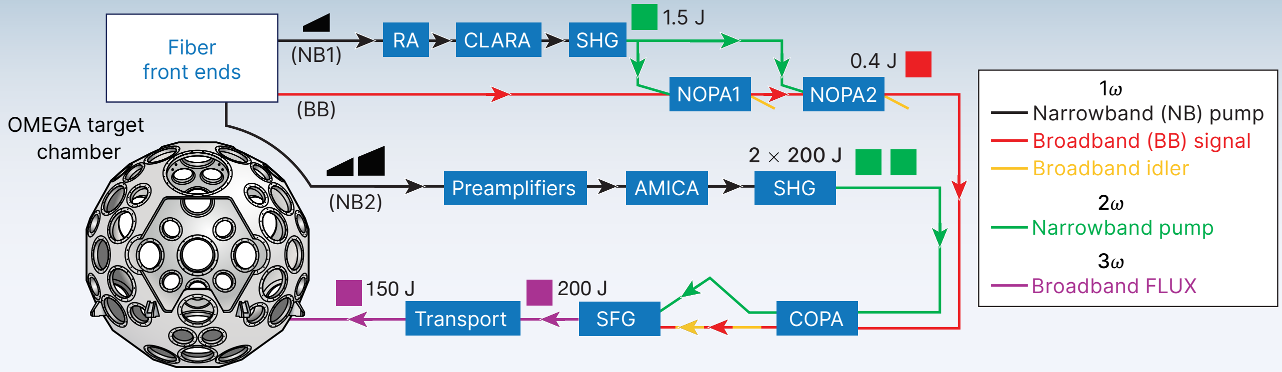


Figure 3. FLUX schematic. Narrowband fiber laser front-end systems provide seed pulses for the CLARA and AMICA pump lasers, plus broadband seed pulses for the NOPA and COPA stages before frequency up-conversion to the ultraviolet.

The final high-energy FLUX amplifier (see Fig. 3) employs a collinear OPA (COPA), which delivers an amplified signal and idler wave that spatially overlap and propagate in the same direction, essentially acting like a single beam at 1ω [Fig. 4(a)]. This configuration allows for approximately doubling the output energy that will be subsequently frequency-upconverted. In the spectrally nondegenerate configuration where the amplified signal and generated idler have different central wavelengths, the combined waves span a larger range of frequencies [Fig. 4(b)].

The parametric amplification of incoherent pulses has been modeled and experimentally studied [19–21]. The FLUX OPA's rely on two 2ω pump lasers seeded by two narrowband fiber front ends. A diode-pumped regenerative amplifier (RA) and crystal large-aperture ring amplifier (CLARA) system, based on an architecture previously developed to pump optical parametric chirped-pulse–amplification stages in the MTW and OMEGA EP lasers, deliver 1.5-J pulses at 5 Hz to pump NOPA1 and NOPA2. A high-energy flashlamp-pumped active multipass imaging cavity amplifier (AMICA) system has been developed to pump the COPA and SFG stages, as shown in Fig. 5. This amplifier is designed to deliver up to 600 J at 1ω and 400 J at 2ω after second harmonic generation (SHG) in two time-multiplexed pulses. The second narrowband 2ω pulse pumps the COPA stage, resulting in the combined broadband high-energy signal and idler waves. As part of this new laser development, a mid-scale plasma-electrode Pockels cell (mPEPC) was designed and qualified to facilitate multiple round trips through a 20-cm OMEGA disk amplifier (Fig. 6) before polarization switching the amplified pulse out of the self-imaging cavity.

In the near-ultraviolet solid-state lasers currently in operation, a fraction of the 1ω output is frequency converted to 2ω, then mixed with the remaining 1ω to generate the 3ω output [12]. This process, referred to as frequency tripling, does not have sufficient bandwidth for FLUX. Instead, the broadband 1ω COPA output is routed to an SFG stage where it is mixed with the first narrowband 2ω pulse from the AMICA. This frequency conversion can be efficient and broadband with the proper choice of the crystal angle, the noncollinear angle between the broadband 1ω and narrowband 2ω beam, and the angular dispersion induced on the 1ω beam by a diffraction grating (Fig. 7). This combination allows for adjusting the phase-matching conditions for a large range of frequencies, essentially leading to broadband efficient conversion from 1ω to 3ω [22]. After sum-frequency generation in the KDP crystal, a 3ω grating disperses the divergent broadband 3ω signal in the opposite direction to point the wavelength-dependent beams in the same direction. Alternately, a residual dispersion can be introduced to realize smoothing by spectral dispersion. Beam transport to the OMEGA target chamber and focusing to target include achromatic designs to preserve the desired focal spot.

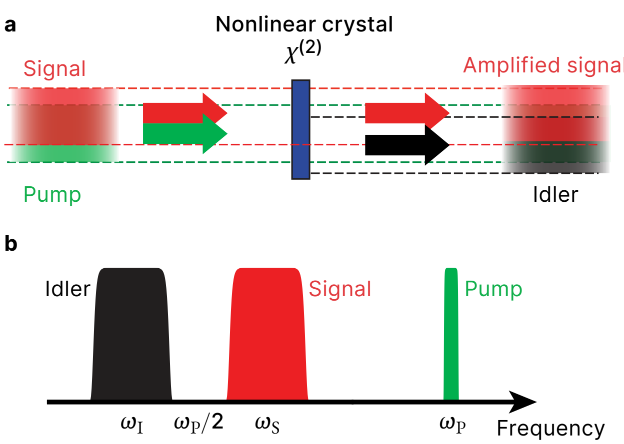


Figure 4. (a) Collinear OPA, producing collinear signal and idler waves, and (b) spectrally nondegenerate OPA, leading to larger spectral coverage from the signal and idler waves.

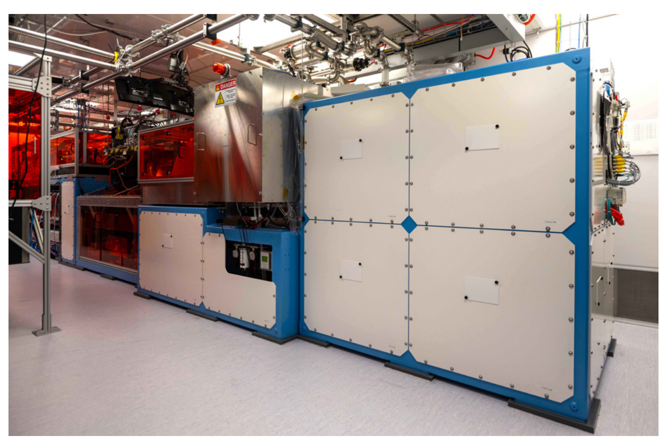


Figure 5. An AMICA laser delivering 400-J laser pulses at 2ω pumps the final COPA and SFG stages.

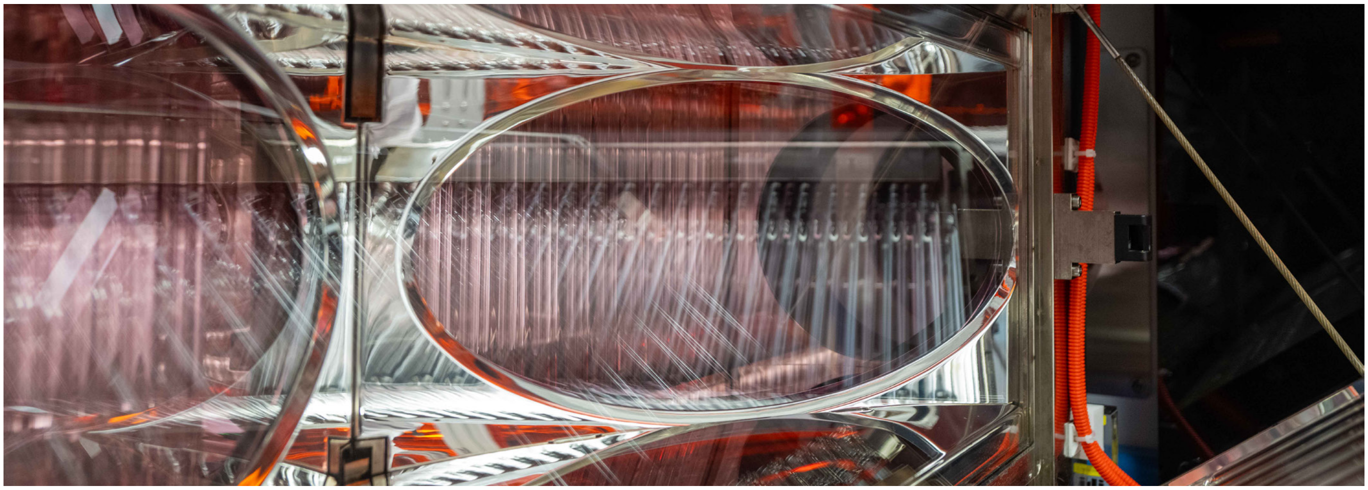


Figure 6. An inside view of the Nd:glass slab amplifier in AMICA. The AMICA laser employs a standard, flashlamp-pumped, 20-cm disk amplifier used in the 60-beam OMEGA Laser System. The flashlamps can be seen in reflections from the pink laser glass disks.

Current plans for completing the FLUX system and beam transport to the P9 port of OMEGA show that the overall FLUX system will be ready for initial experiments by the middle of 2024. A future issue of *LLE in Focus* will elaborate on details about these FLUX experiments.

C. Dorrer, E. M. Hill, and J. D. Zuegel

To learn more about the FLUX Laser System Team and their efforts to make FLUX possible, follow the link provided in the QR code.

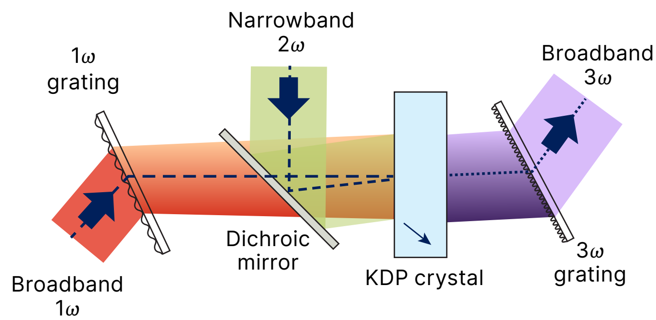


Figure 7. Broadband SFG scheme for FLUX.

Focus Points

- Laser–plasma instabilities, which degrade inertial confinement fusion experiments, can be mitigated by increasing the fractional bandwidth of high-energy laser pulses.
- Innovations to solid-state laser technology over the past 60 years have vastly improved and extended system performance. A fourth-generation laser driver, currently under construction, presents a potential path for experimental breakthroughs at unprecedented bandwidths.
- Optical parametric amplifiers, the foundation of the new FLUX system, are employed to maximize the output energy that will subsequently be frequency converted to produce ultra-broadband 3ω (~200-J) pulses.

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MP3 Workshop

The Multi-Petawatt Physics Prioritization (MP3) Workshop, a community-initiated, international workshop held April 20–22, 2022 at Sorbonne University in Paris, France, developed questions to guide research and future experiments in four areas of discovery science enabled by a new generation of ultra-intense lasers:

- high-field physics and quantum electrodynamics,
- laboratory astrophysics and planetary physics,
- laser-driven nuclear physics, and
- particle acceleration and advanced light sources.

A yearlong series of virtual working groups and all-hands meetings reviewed concepts and developed scientific themes and questions derived from 97 white papers solicited from 265 registered MP3 community members. The combined in-person and Zoom participation for the MP3 workshop totaled 154 people. The MP3 science questions were grouped into three themes and summarized in the MP3 workshop report.

Highest-energy phenomena in the universe

High-power laser facilities now enable unprecedented focused intensities and field strengths in the laboratory. Experiments using multipetawatt laser pulses promise access to extraordinary field strengths that exceed the threshold where quantum electrodynamic effects play an important role in the dynamics of the system. Two science questions resulted:

- How might multipetawatt lasers reveal the physical mechanisms that produce the most energetic particles and brightest events in the universe?
- How does light transform into a plasma fireball composed of matter, antimatter, and photons?

The origin and nature of space–time and matter in the universe

Current and future laser facilities can create matter and radiation at extreme conditions that can replicate a large variety of environments known to exist in the visible universe. Some experiments to date have not yet produced results predicted from first-principles calculations that demonstrate the importance of testing theoretical predictions. Multipetawatt lasers can generate these conditions of ultrahigh temperature, pressure, and acceleration, as well as new diagnostic probes to interrogate them. Three science questions emerged:

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

Nuclear astrophysics and the age and course of the universe

Nuclear physics using intense lasers can open new frontiers in scientific research. Laser-driven sources of energetic particles such as protons, neutrons, and energetic photons (i.e., x rays and gamma rays), can induce nuclear reactions, probe nuclear physics, and enable practical applications. Two questions arose:

- What can be learned about heavy-element formation using laser-driven nucleosynthesis in plasma conditions that are far from equilibrium?
- How can high-flux gamma sources generated from multipetawatt lasers be used to explore hadronic physics (low-energy quantum chromodynamics)?

High-energy particle and radiation sources based on multipetawatt lasers constitute a core area of underlying research that can provide unique capabilities for addressing the MP3 science questions, as well as enabling new applications based on these sources.

The MP3 Workshop addressed these science themes and questions using a common approach:

- Road mapping science goals and flagship experiments using and building on existing capabilities;
- Identifying any missing critical needs, such as diagnostics, theory, and computation; and
- Identifying any underlying research needed to produce high-energy particle and photon sources.

The MP3 workshop report summarizes collaborative frameworks and joint strategies to realize needs for meeting roadmap goals, and presents a vision for next-generation multipetawatt laser facility capabilities.

To read the full MP3 workshop report, follow the link provided in the QR code.

X-lites Network

In 2022, the National Science Foundation (NSF) awarded a two-year planning grant led by The Ohio State University to develop the Extreme Light in Intensity, Time, and Space (X-lites) network as part of the Accelerating Research through International Network-to-Network Collaborations (AccelNet) Program. The AccelNet Program aims to advance the process of scientific discovery and prepare the next generation of US researchers for multi team, international collaborations.

X-lites will develop a "network of networks" to address grand challenge questions defined at the frontiers of laser–matter coherent interactions at the shortest distances, highest intensities, and fastest times. The X-lites network includes ten networks as shown in Fig. 1:

- The Compact X-Ray Free Electron Laser (CXFEL) at Arizona State University;
- Zettawatt-Equivalent Ultrashort Pulse Laser System (ZEUS) at the University of Michigan;
- National eXtreme Ultrafast Science (NeXUS) at The Ohio State University;
- The Laboratory for Laser Energetics at the University of Rochester (UR/LLE);
- The Joint Centre for Extreme Photonics (JCEP), a joint undertaking between the National Research Council and the University of Ottawa, in Ottawa, Ontario, Canada;
- The European Union AttoChem network that focuses on using sculpted attosecond light pulses to control chemical reactions via precise tuning of molecular charge migrations;
- The Central Laser Facility at Rutherford Appleton Laboratory in the United Kingdom;
- The Laboratoire pour l'Utilisation des Lasers Intenses (LULI) outside Paris, France;
- ELI ERIC, the organizing body for three Extreme Light Infrastructure (ELI) facilities: ELI Beamlines (Czechia), ELI ALPS (Hungary), and ELI Nuclear Physics (Romania); and
- Laserlab Europe, a European-Union–funded project linking 35 leading institutions in laser-based interdisciplinary research from 18 countries.

X-lites will promote collaboration around the world to make use of new extreme light facilities. The network has brought together facility users and facility operators to support high-impact science and engineering using extreme light with three goals:

- Promote collaboration across the global community of laser facility users and operators.
- Broaden engagement across diverse scientific fields and with next-generation research leaders.
- Identify and address knowledge and technological gaps that require a collaborative approach to bridge.

X-lites applies the science of team science (SciTS) to build on existing networks of researchers developing and applying extreme light. Users are a diverse community of researchers taking advantage of infrastructure investments to explore questions in physics, chemistry, biology, materials, and other fields. X-lites will host workshops and short courses on effective team building, followed by meetings of the research community to strengthen connections, enable collaboration, gather feedback on the key technical challenges, and shape the future of the network. These activities will intentionally engage early-career researchers from a diverse community (demographics, scientific specialties, and geographic locations). These researchers, who embody the future of these fields, will be essential in driving X-lites and extreme light science, technologies, and other applications forward.

To learn more about the X-lites Network, follow the link provided in the QR code.

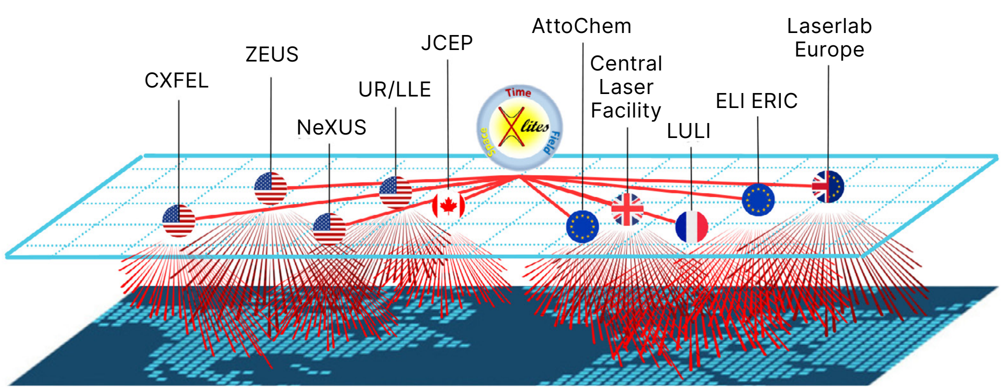


Figure 1. Map showing the X-lites network locations.

FOCUS ON TECHNOLOGY

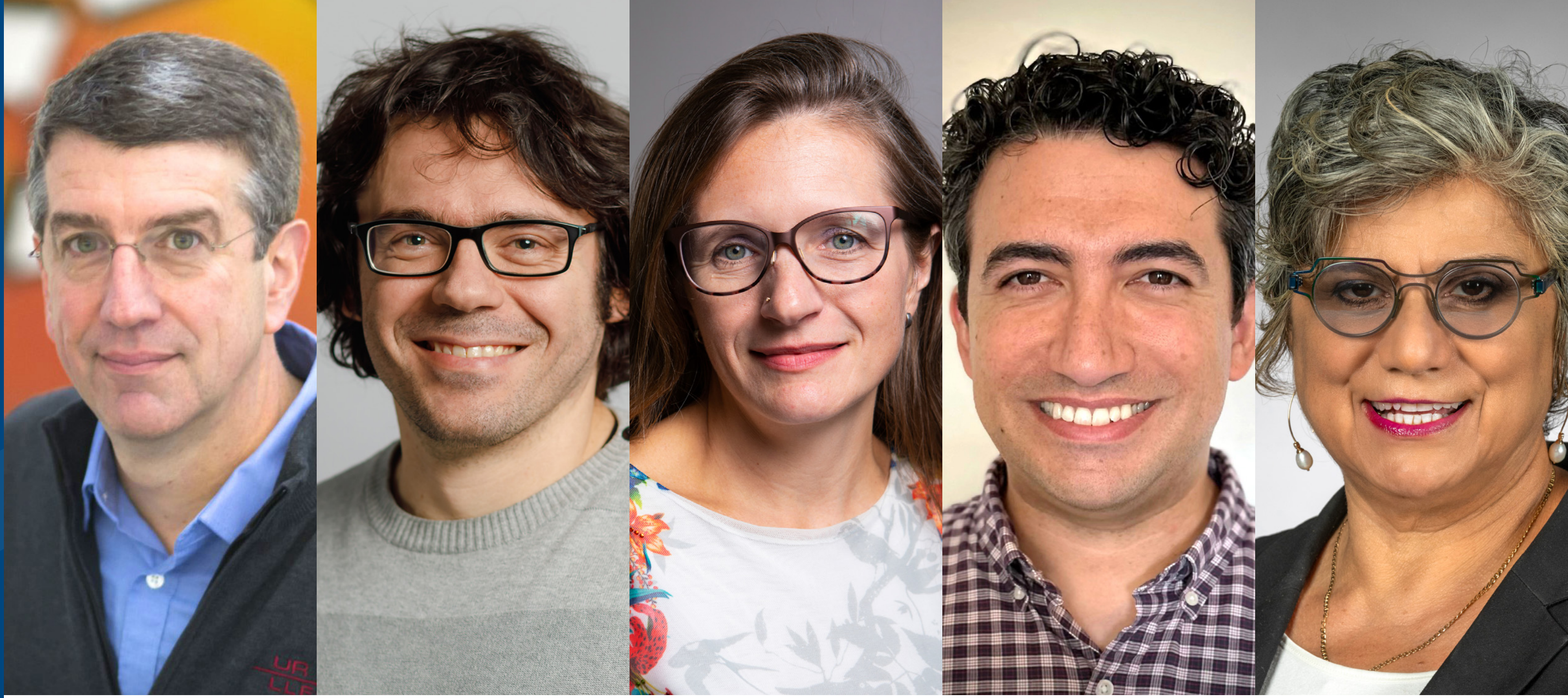
A next-generation NSF research infrastructure for studying ultrahigh-intensity laser–matter interactions

OPAL

Optical Parametric Amplifier Lines

National Science Foundation

UNIVERSITY of ROCHESTER



The project's principal investigators include (left to right) Jonathan Zuegel and Antonino Di Piazza from the University of Rochester; Eva Zurek from the University at Buffalo; Franklin Dollar from the University of California, Irvine; and Ani Aprahamian from the University of Notre Dame.

FOCUS ON TECHNOLOGY

NSF-OPAL

The National Science Foundation (NSF) has awarded the University of Rochester a mid-scale research infrastructure (RI-1) design project for an optical parametric amplifier line (OPAL) facility that envisions two new powerful lasers to be located at the Laboratory for Laser Energetics. NSF-OPAL will employ chirped-pulse amplification—a technique developed at the University of Rochester/LLE for the generation of very powerful, ultrashort laser pulses and recognized by the 2018 Nobel Prize in Physics awarded to Gérard Mourou and Donna Strickland.

> ***It's thrilling to see chirped-pulse amplification come full circle with Rochester once again leading the charge to develop and implement the most-powerful lasers in the world.***
>
> *Nobel laureate Donna Strickland*

NSF-OPAL aims to push beyond current state-of-the-art capabilities in peak laser power to achieve and study extreme physical conditions, such as ultrahigh electromagnetic fields, temperatures, and pressures that represent the frontier of science in studying matter in the universe. A successful NSF-OPAL design would lead to the creation of the highest-power laser system in the world, with two 25-petawatt lasers using optical parametric chirped-pulse amplification (OPCPA), shown schematically in Fig. 1. The two combined laser beams would deliver nearly the same total power as incident on the Earth's surface from the Sun, but focused into an area smaller than the cross section of a human hair. The University of Rochester would construct a new building to house the facility next to the new Office and Lab Extension, shown conceptually in Fig. 2.

The NSF-OPAL facility design will address the most-pressing scientific questions that can be answered using such a laser system in four areas of frontier research: particle acceleration and advanced light sources; high-field physics and quantum electrodynamics; laboratory astrophysics and planetary physics; and laser-driven nuclear physics. Co-principal investigators in each of these four areas at the University of Rochester; the University at Buffalo; the University of California, Irvine; and the University of Notre Dame will work with University of Rochester/LLE senior personnel to define the requirements and guide the facility design efforts. This RI-1 award will also support individuals at the University of Maryland, College Park; The Ohio State University; the University of Michigan; and Plymouth Grating Laboratory to develop laser and experimental technologies and assist in the NSF-OPAL facility design. The facility is envisioned to serve as a learning environment and a hub for diverse scientific networks, offering opportunities for fundamental research, innovation, and societal benefit.

> ***With a clear vision for better engaging groups underrepresented in science and engineering, this project embodies our institutional commitment to making the world ever better.***
>
> *University of Rochester President, Sarah Mangelsdorf*

The NSF-OPAL design effort will include: (1) preparing the NSF-OPAL user facility design with laser, experimental, and diagnostic systems for potential future construction; (2) prototyping high-energy lasers that operate at shot rates greater than ten times that of existing systems, leading to increased and faster scientific breakthroughs; (3) working with US industry to develop critical laser optics, including diffraction gratings more than twice as large as those available today, that will enable NSF-OPAL and future state-of-the-art facilities; and (4) providing hands-on training to a new generation of laser-facility designers and builders.

Housed at a university and openly accessible to a broad user base, an experimental facility like NSF-OPAL could open the doors to a new era of high-impact research. The facility would be capable of creating the extreme conditions in a laboratory that are now found only in the most exotic parts of the universe and there is no doubt that the facility will be a unique research tool of the highest value to the US research community.

The potential benefits of NSF-OPAL extend even beyond the current scientific community. Cutting-edge laser systems and facilities are vital to the ongoing quest of tackling societal grand challenges in other fields, including energy, national security, manufacturing, and life sciences. Mid-scale research infrastructures specifically can have significant implications for the economy, security, and competitiveness of the United States.

J. D. Zuegel

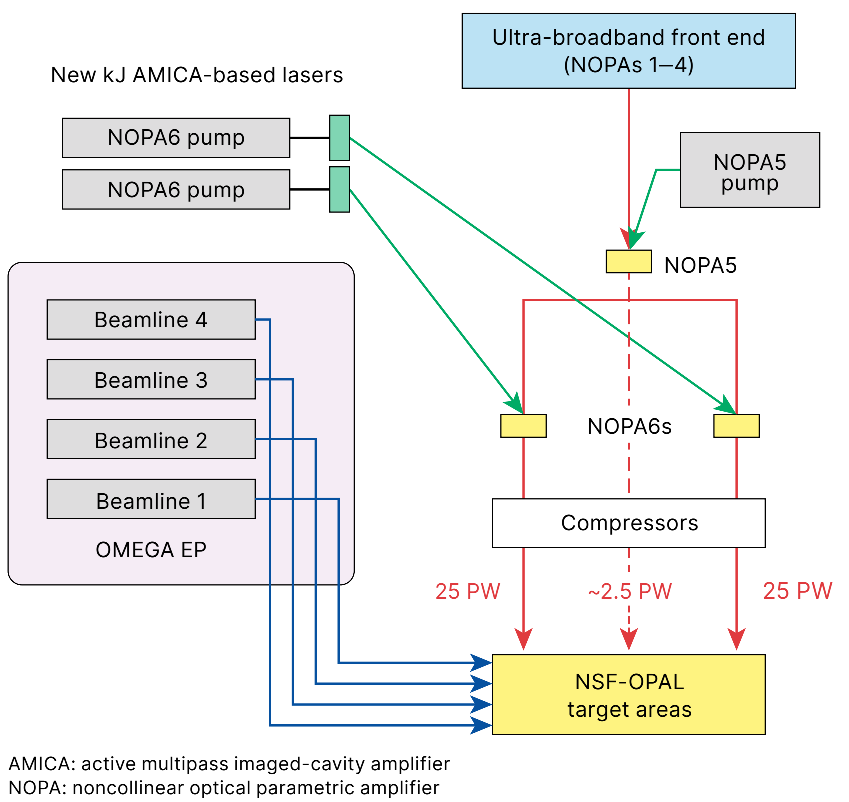


Figure 1. Conceptual NSF-OPAL design. The baseline design includes two 25-PW laser beams employing OPCPA and coupling OMEGA EP beamlines to new target areas.

Focus Points

- The NSF-funded NSF-OPAL design project, an extension of the OMEGA EP Laser System, would be a new facility dedicated to the study of ultrahigh-intensity laser–matter interactions.
- A successful NSF-OPAL design would enable the highest-power laser system in the world.
- Leveraging the expertise, resources, and talents of partner institutions nationwide, NSF-OPAL will advance current state-of-the-art capabilities in peak laser power and play a pivotal role in serving the global research community.

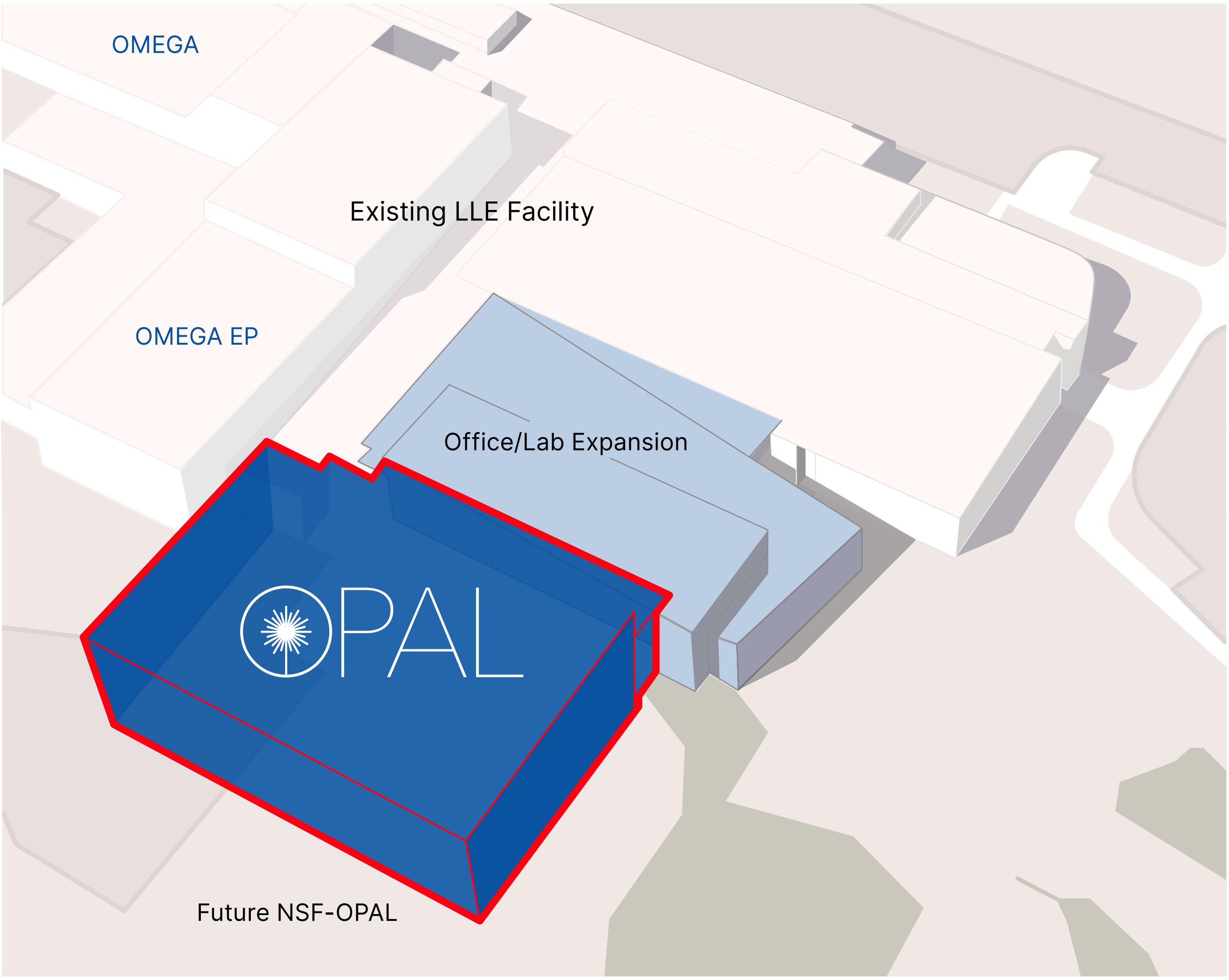


Figure 2. Conceptual NSF-OPAL design. A new building will house the NSF-OPAL facility.

UNIVERSITY of ROCHESTER

University at Buffalo

UNIVERSITY OF MARYLAND

UCI University of California, Irvine

UNIVERSITY OF NOTRE DAME

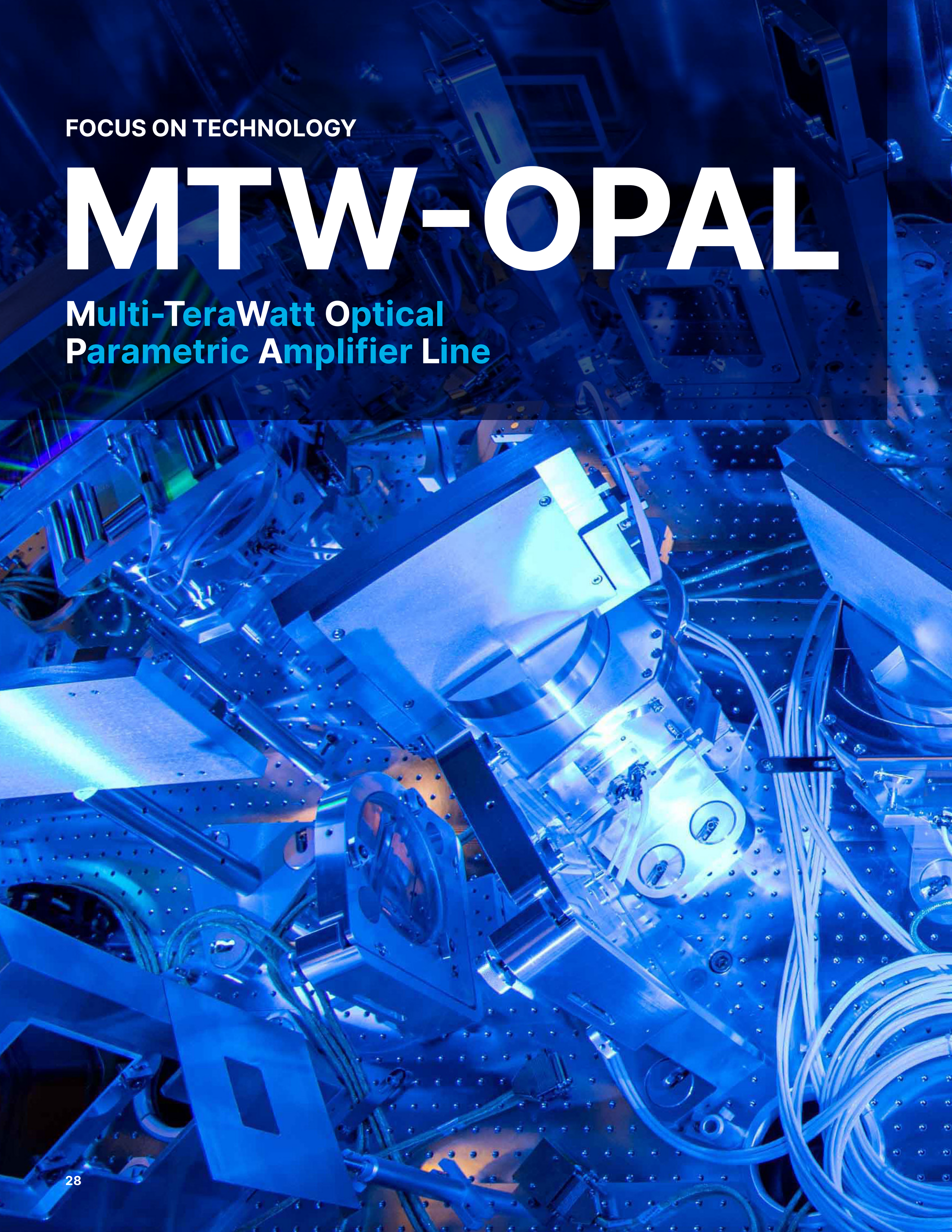
UNIVERSITY OF MICHIGAN

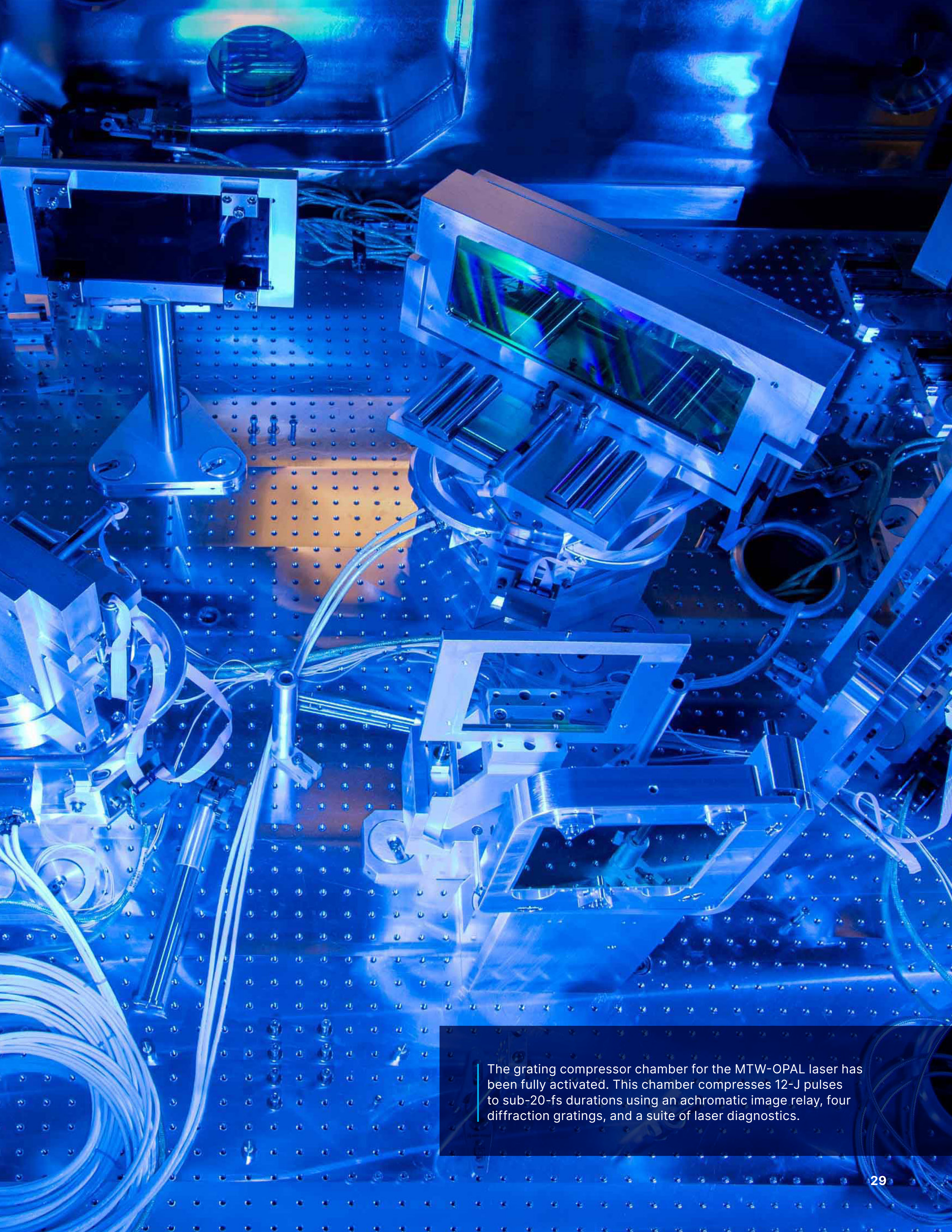
THE OHIO STATE UNIVERSITY

FOCUS ON TECHNOLOGY

MTW-OPAL

Multi-TeraWatt Optical Parametric Amplifier Line





The grating compressor chamber for the MTW-OPAL laser has been fully activated. This chamber compresses 12-J pulses to sub-20-fs durations using an achromatic image relay, four diffraction gratings, and a suite of laser diagnostics.

FOCUS ON TECHNOLOGY

MTW-OPAL
Design and Performance

Introduction

Petawatt lasers prove indispensable tools for high-field science and for generating advanced secondary sources of particles and radiation [1,2]. Ultraintense laser systems being developed by several institutions use deuterated potassium dihydrogen phosphate (DKDP) for high-energy optical parametric chirped-pulse amplification (OPCPA) [3–7]. Noncollinear optical parametric amplifiers (NOPAs) based on large DKDP crystals can produce ultrabroadband gain for supporting kilojoule-class pulses compressible to sub-20-fs durations. Although OPCPA finds routine applications in small-scale laser systems and in front ends for larger systems, scaling OPCPA to >100 J remains an active area of research and development. The Laboratory for Laser Energetics has activated a new optical parametric amplifier line (OPAL) pumped by the Multi-Terawatt (MTW) laser. The mid-scale MTW-OPAL laser serves as a subscale prototype for multi-10-PW systems, such as the OPAL (NSF-OPAL) design project recently awarded by the National Science Foundation for a full-scale 2 × 25-PW system described earlier in this issue. MTW-OPAL will also serve as a mid-scale scientific user facility.

MTW-OPAL is the latest and largest addition to the MTW Laser Facility, which began over 20 years ago with the MTW laser—a prototype front end for OMEGA EP [8,9]. The MTW Facility time line spanning the past, present, and near future is shown in Fig. 1. Shortly after the OPCPA front end and Nd:glass laser amplifier were activated, a compressor and the first target chamber were added [10]. The MTW Facility, which has benefitted from more than 20 years of laser development, taken over 15,000 shots, and supported over 500 science campaigns, continues to develop [11]. In addition to providing broadband, picosecond pulses for a variety of target experiments, the MTW laser is capable of providing the narrowband, nanosecond pulses required to pump the final DKDP NOPA of MTW-OPAL.

MTW-OPAL achieved "first light" in 2020 at the 0.35-PW level. This required a number of novel developments ranging from components (e.g., optical coatings) to system-wide technologies (e.g., ultra-broadband transport) at a mid-scale level that provides a critical stepping stone toward full-scale multi-10-PW facilities. Since first light, the team has continued to make improvements and upgrades. Plans are currently underway for "back-end" upgrades align with a proposed new shielded target area (see Fig. 1). This review highlights the novel aspects of the MTW-OPAL system design, its current performance, and plans for the future.

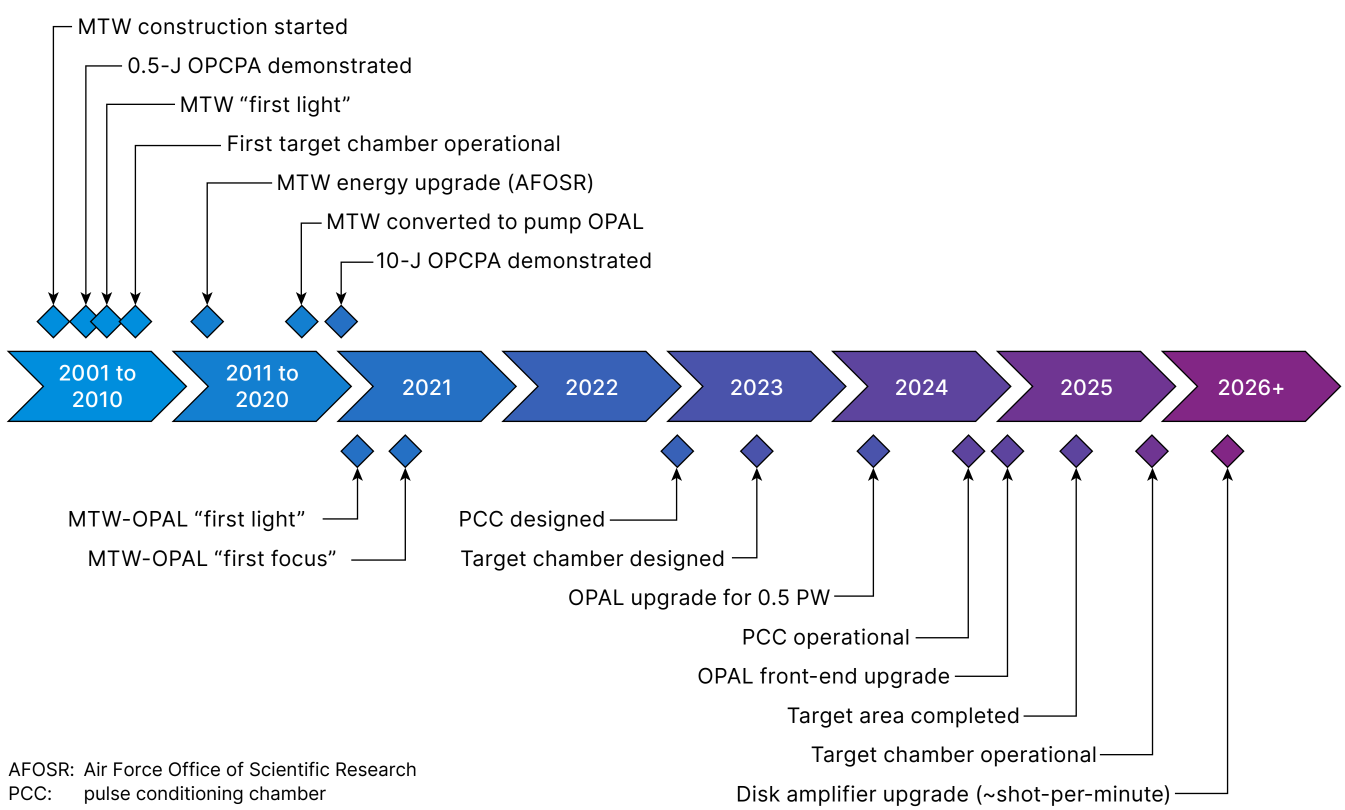


Figure 1. MTW Facility time line showing major milestones in the past, present, and near future.

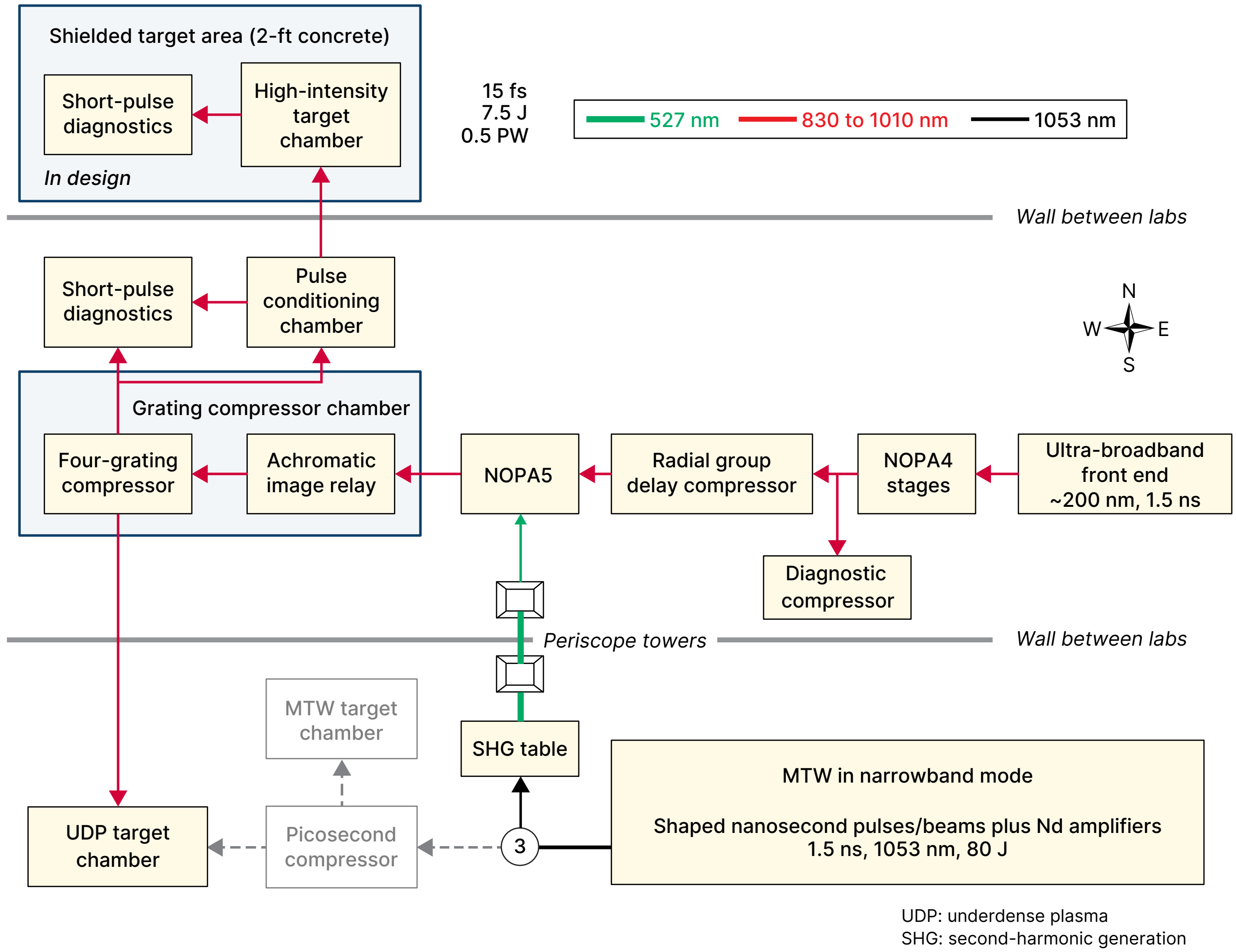


Figure 2. Schematic of the MTW-OPAL laser system.

MTW-OPAL system overview

Fundamentally, the MTW-OPAL system architecture follows a straightforward concept: ultrashort pulses are created, stretched, amplified, compressed, and focused tightly to produce high intensities exceeding 10^{21} W/cm^2. Achieving sub-20-fs pulses requires an optical bandwidth of more than 150 nm when centered at 920 nm, the optimum wavelength range for ultra-broadband OPCPA using DKDP. Achieving multijoule energies requires beam dimensions of several centimeters to keep fluences below 0.1 J/cm^2, an acceptable level for this pulse width. Most of the design choices follow from these fundamental architecture, bandwidth, and beam-size requirements.

The laser system is shown schematically in Fig. 2. What follows here is an overview; more details are given in two review papers [12,13]. An ultra-broadband front end (UFE) produces pulses compressible to less than 12 fs using a 250-fs fiber laser system to generate white-light continuum (not shown in Fig. 2) [14]. The fiber system also provides enough power to pump the first NOPA stage that provides ~25 dB of broadband gain in a subpicosecond temporal window. White-light-continuum generation followed by a series of NOPAs is now widely used to produce millijoule-scale, few-femtosecond pulses in the visible, near-infrared, and mid-infrared for a variety of applications. This approach provides more bandwidth than required for MTW-OPAL in a coherent pulse with excellent focusability. Furthermore, measurements show a high prepulse temporal contrast greater than 10^{12} [15], measured as the power before the main pulse relative to the peak, which results in a fast rising edge that is critical for many experiments—particularly those requiring solid targets.

Additional picosecond-pumped stages (NOPA2 and NOPA3, not shown in Fig. 2) amplify the pulse to millijoule levels before it is stretched to 1.5 ns for further amplification to more than 10 J. A crystal large-aperture ring amplifier, capable of providing joule-class pump pulses at 5 Hz [16] and initially developed on MTW for OMEGA EP, pumps NOPA4. Although DKDP crystals could be used, other nonlinear crystals at this small (subcentimeter) beam size, such as beta barium borate (BBO), prove a better choice for all but the final stage, NOPA5. The MTW laser operating in a narrowband mode pumps NOPA5 with 33-J, 527-nm pulses 1.5 ns in duration, and demonstrates efficient energy transfer as high as 41% from the pump to the broadband signal pulse [17]. This record performance results in large part from the high spatiotemporal quality of the MTW laser pump pulses; optimized flattop temporal and spatial

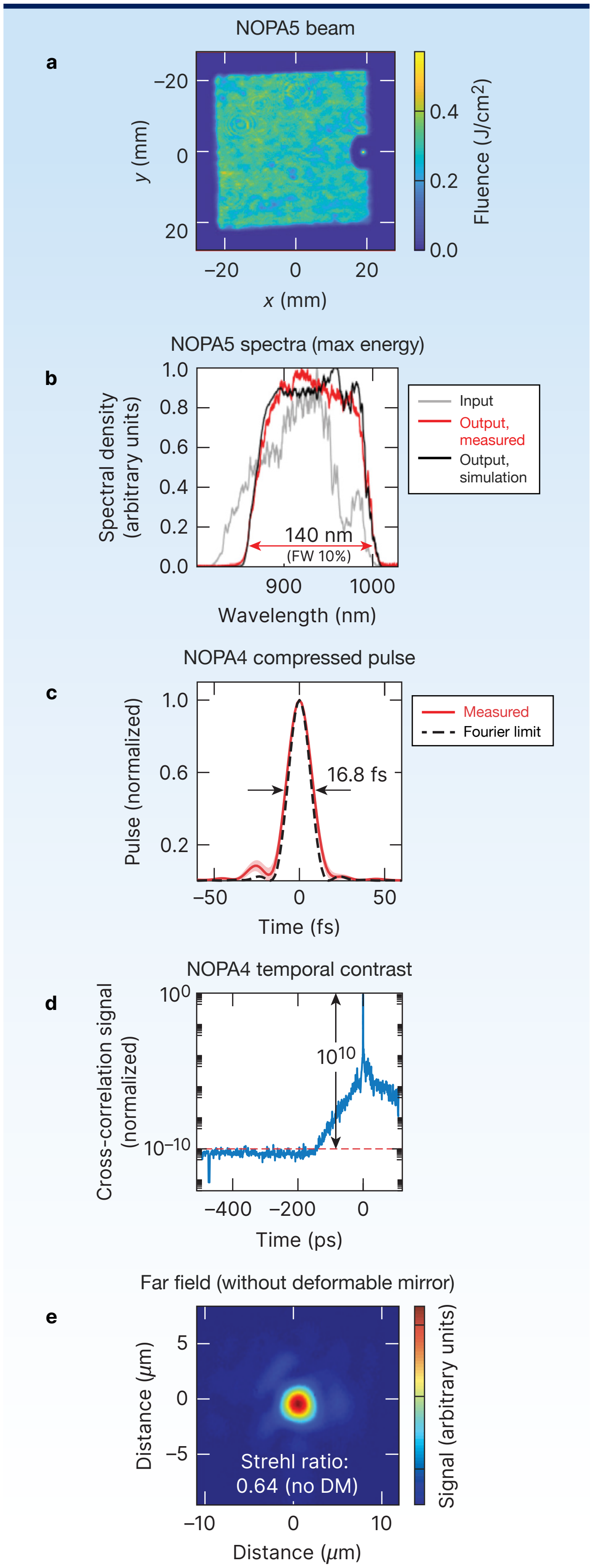


Figure 3. Primary performance metrics of the MTW-OPAL system.

profiles using arbitrary waveform generators and programmable spatial light modulators, respectively, ensure optimum efficiency in space and time.

High-fidelity pulse stretching and recompression depend on careful design and alignment [18]. MTW-OPAL employs a novel stretcher using cylindrical mirrors, called the cylindrical Offner stretcher [19]. This system can support significantly higher pulse energies than the conventional spherical Offner stretcher since no line foci exist on any optical surfaces. This enables more amplification in the picosecond-pumped NOPA stages before the pulse must be stretched, which reduces temporal contrast degradation from parametric fluorescence that can exist nanoseconds before the main pulse [20]. Furthermore, simulations show an increased tolerance to stretcher-mirror surface roughness, another source of temporal contrast degradation [21,22]. A large vacuum grating compression chamber (GCC) houses a standard four-grating vacuum compressor with gold-coated gratings that recompresses pulses to 15 fs. The gratings have the lowest damage threshold in the system, so the 90 × 90 mm^2 beam size at the gratings results in a maximum beam-normal fluence <100 mJ/cm^2, which is comfortably below the typical damage threshold of 200 to 300 mJ/cm^2 for gold-coated gratings. To date, no major issues have been found, but this continues to serve as an important testing ground as we learn more about gratings and back-end optics over prolonged use.

Propagating the broadband pulses between stages also required techniques not typically used for nanosecond or even picosecond laser systems. "Ultra-broadband transport" refers not to a specific subsystem but rather to the components and strategies required to propagate pulses from the start of the UFE system through amplifier stages by means of image relay optics into the vacuum compressor chamber and on to the focal spot at the target location. Chromatic aberrations in lens-based image relays were compensated using a radial group delay compensator positioned in the middle of the OPAL system [23]. The final image relay after NOPA5 into the grating compressor chamber employs a novel all-reflective, achromatic image relay using four spherical mirrors [24].

The ultra-broadband beam transport system required developing ultrashort-pulse optical coatings. Before the pulse reaches the grating compressor, broadband dielectric mirrors transport *s*-polarized, 1.5-ns chirped pulses propagating in air and vacuum with fluences up to ~1 J/cm^2. After the compressor, transporting 20-fs pulses in vacuum with nominal fluences of 100 mJ/cm^2 requires mirrors for both *s* and *p* polarizations [25].

MTW-OPAL performance

A suite of laser diagnostics enables analyzing and optimizing system performance shown in Fig. 3 and Table 1. The higher-than-expected efficiency of NOPA5 and transmission through the GCC enabled the use of lower-than-intended pump energies for NOPA5 while still exceeding the design goal of >7 J at the output of the GCC. Full-energy pulse compression to 20 fs has been demonstrated. The bandwidth of the UFE and NOPA4 stages was close to the design point. The 70%

Table 1. Latest performance of MTW-OPAL, design goals, and plans for upgrades.

Energetics			Temporal and spectral properties			Spatial and angular properties		
Metric	First light	Design goal	Metric	First light	Design goal	Metric	First light	Design goal
NOPA5 pump energy (max, rms)	41.7 J (1.4%)	50 J	NOPA4 bandwidth	175 nm (FW10%)	>180 nm (FW10%)	NOPA5 signal beam modulation	1.4:1 (peak-to-mean)	<1.8:1 (peak-to-mean)
NOPA5 transfer efficiency	30%	25%	NOPA5 bandwidth	140 nm (FW10%)	>175 nm (FW10%)	GCC output pointing stability (rms)	3 μrad (horizontal) 10 μrad (vertical)	<25 μrad (rms)
NOPA5 signal energy (max, rms)	11.2 J (4%)	12.5 J	Compressed pulse width	17 fs (NOPA4) 20 fs (NOPA5) (FWHM)	15 fs (FWHM)	Wavefront (rms)	0.108 λ no correction 0.040 λ calc. with correction	<0.075 λ
GCC output energy	7.3 J	7 J	Prepulse contrast at diagnostic compressor	$>10^{10}$ (−150 ps)	$>10^{10}$ assumes adding plasma mirror(s)	Strehl ratio	~0.64 no correction >0.90 calc. with correction	>0.80 assumes wavefront correction
Sufficient NOPA5 energy with better efficiency than expected; ramped the GCC to 7.3 J, 85% of available energy			Good compression of available bandwidth and 95% DKDP received for more; adding plasma mirrors			Meets beam-quality and pointing; deformable mirror is being tested		

deuteration level of the NOPA5 DKDP crystal—the highest commercially available deuteration level at the required size—limited the gain bandwidth of NOPA5. A recent delivery of specially grown 95% deuterated crystals should support 15-fs pulses for 0.5-PW peak powers. Preliminary measurements of the focusability using an *f*/2 off-axis parabola show good performance. The temporal contrast of the system currently has a pedestal that ramps up from ~150 ps before the main pulse. Recent experiments identified a mechanism that appears to convert postpulse features into prepulses that will require more work to identify the underlying cause [26].

Future plans for upgrades and expansion

A pulse conditioning chamber (PCC) that will be activated in 2024 will include subsystems that optimize the spatial and temporal properties of compressed pulses before they propagate to the target chamber. The PCC will include a deformable mirror that provides wavefront correction for an optimized focal spot, plasma mirrors for enhanced temporal contrast, and an innovative all-reflective four-mirror system for manipulating the laser-beam polarization state. These capabilities will employ approaches scalable to NSF-OPAL.

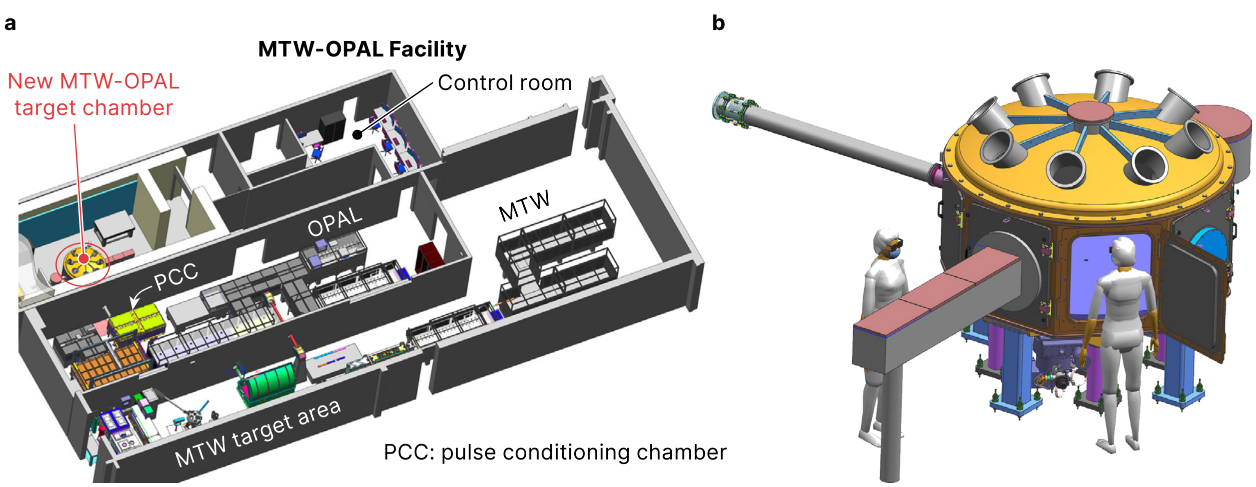
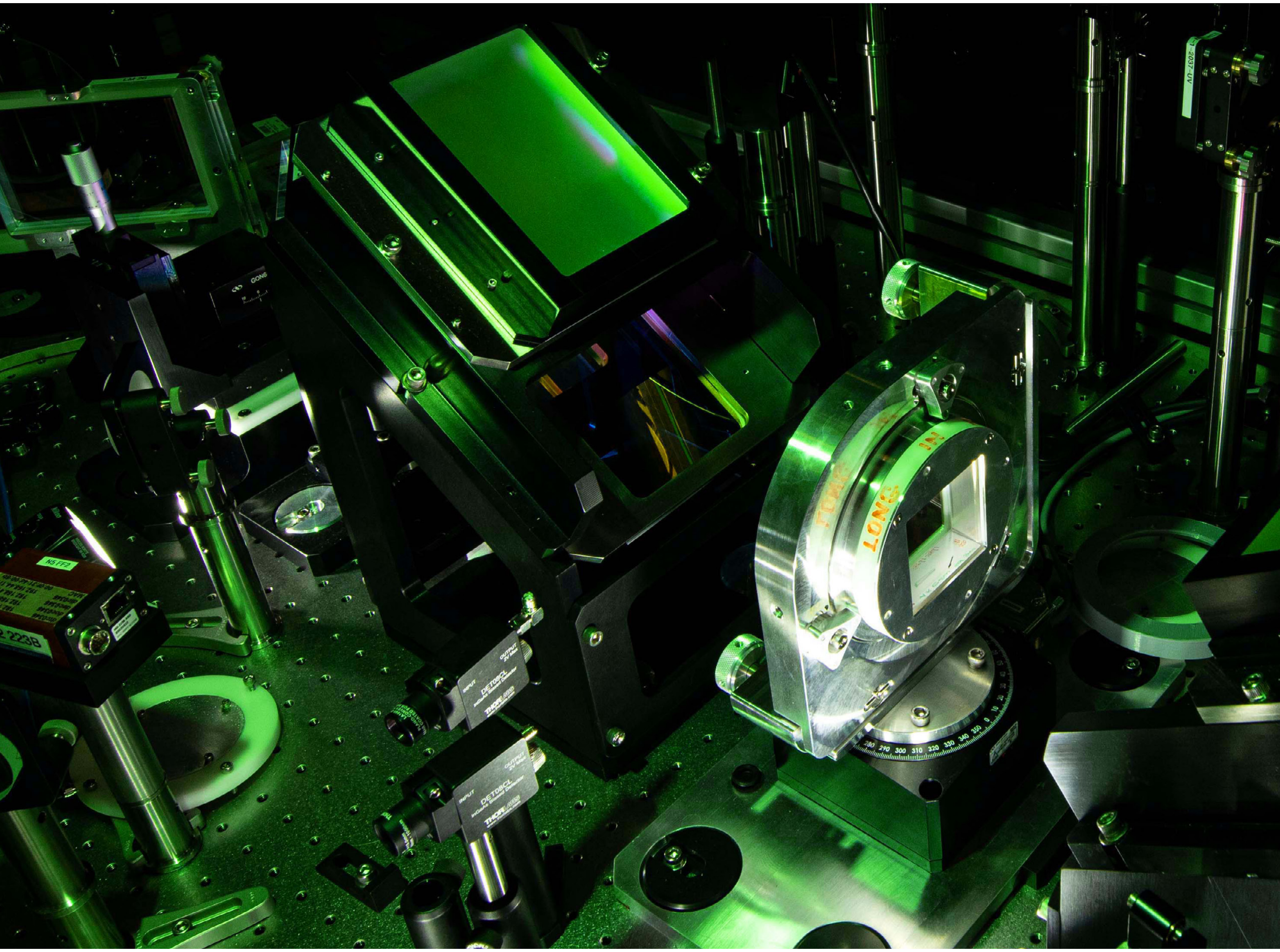


Figure 4. (a) Schematic showing the full MTW Facility including the new MTW-OPAL target chamber. (b) View of the target chamber with the MTW-OPAL beam entering from the left side.

Full-intensity experiments that take advantage of the 0.5-PW pulses require a new target area with radiation shielding and more space. Figure 4(a) shows the design and relative location of the new target area and a new MTW-OPAL control room. The target area has been designed with clean room air handling, reduced vibration, and radiation shielding sufficient to support solid–target experiments. The target chamber will provide an environment for investigators to advance novel science across multiple disciplines including high-power lasers, laser–matter interactions, THz science, and high-energy-density physics. The new MTW-OPAL target chamber will be procured in late 2023 and funded by the Air Force Research Laboratory (AFOSR-DURIP Award no. FA9550-23-1-0475).

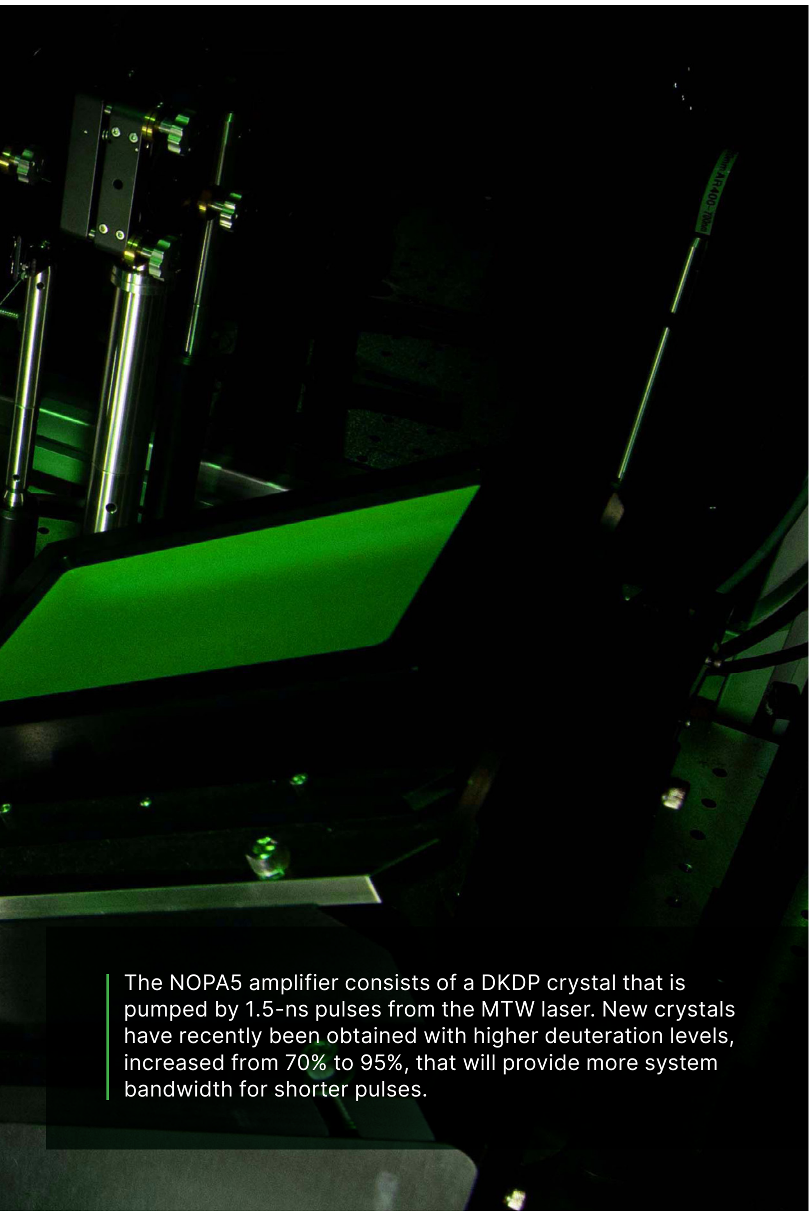
The development time line (Fig. 1) includes a long-term goal of upgrading the disk amplifier in the MTW pump laser with active cooling to improve the shot rate for higher scientific productivity and improved system optimization. The full-energy shot cycle time will be reduced by approximately an order of magnitude by replacing the 15-cm uncooled Nd:glass disk amplifier with liquid cooling, similar to that used on the L4 Aton laser at ELI Beamlines [27–29] and in a similar approach independently developed by Commissariat à l'énergie atomique (CEA) [30]. This amplifier technology proves critical for a number of LLE interests including NSF-OPAL, for which the MTW Facility will serve as an important test site.

J. Bromage, S.-W. Bahk, M. Bedzyk, I. A. Begishev, S. Bucht, C. Dorrer, C. Feng, C. Jeon, C. Mileham, R.G. Roides, K. Shaughnessy, M. J. Shoup III, M. Spilatro, B. Webb, D. Weiner, and J. D. Zuegel



Focus Points

- The MTW-OPAL laser serves as a subscale prototype for multi-10-PW systems, such as the NSF-OPAL design project recently awarded by the National Science Foundation for a full-scale 2 × 25-PW system.
- MTW-OPAL "first-light" measurements have met or exceeded design performance goals.
- Planned upgrades, now underway, include a new pulse-conditioning chamber and a new target area with radiation shielding and more space.



The NOPA5 amplifier consists of a DKDP crystal that is pumped by 1.5-ns pulses from the MTW laser. New crystals have recently been obtained with higher deuteration levels, increased from 70% to 95%, that will provide more system bandwidth for shorter pulses.

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Scientist Erik Power and Research Engineer Sara Bucht work to align a flow-cell grating substrate prior to testing under high-average-power load.

FOCUS ON TECHNOLOGY

Actively Cooled "Flow-Cell" Optical Substrates for High-Average-Power Laser Applications

Scaling high-peak-power laser systems suitable for inertial fusion energy, laser-plasma acceleration, high-energy-density plasma physics, and laboratory astrophysics experiments at ever-higher repetition rates presents many challenges. Thermally managing components in laser generation and transport systems proves important because the absorption of laser light leads to heating and induced deformation of the optics. Optics physically bulge due to thermal expansion and the optical index of refraction for transmissive optics varies spatially, which leads to wavefront aberrations that must be corrected to preserve beam quality.

> *The flow-cell design dramatically exceeds the average power handling of back- and side-cooling schemes by ~10× and passive cooling by ~50×.*

Chirped-pulse amplification (CPA), a technique used to achieve the highest peak powers, often employs diffraction gratings to temporally stretch and compress pulses. This is critical because the reduced peak power of stretched pulses allows for amplification without causing damage. Existing multiterawatt and petawatt CPA lasers [1] operate at relatively low repetition rates no greater than about 1 Hz and low average powers, so thermal effects experienced by compressor gratings located in vacuum chambers are negligible. Thermal deformation of gratings under high-average-power conditions can cause focusing and stretching/compression errors that lead to unacceptable spatial and temporal degradation of the focused laser spot and compressed pulse, respectively [2]. Large diffraction gratings are expensive, so system designers strive to minimize grating size and operate close to but safely below their limits, which include thermally induced degradation and the laser-induced–damage threshold. Presently, thermally induced degradation limits operating at high average powers.

Two approaches exist for operating compressor gratings at high average powers. Broadband multilayer dielectric (MLD) coatings minimize absorption and heat deposition, but they limit the bandwidth of pulse-compression gratings and resulting pulse widths to ≥30 fs [3]. Metal-coated (gold and silver) gratings, on the other hand, can support the bandwidth for ultrashort pulses (<30 fs), but gold and silver absorb ~5% and ~2% of the incident power, respectively, at the near-infrared wavelengths most often used for high-power laser systems. Thus, the underlying grating substrate must be able to tolerate the associated heating. This article reports on published design and prototype results of a novel active cooling scheme [4].

A thermal-loading test stand was constructed to evaluate the deformation of optical substrates under high-average-power conditions. As shown in Fig. 1, the test stand uses a heater laser to deform a sample and evaluates the results using interferometry (to measure surface shape), a thermal imaging camera, and temperature sensors. Figure 2 illustrates the "flow-cell" integrated active-cooling design, which provides integrated cooling in an ultralow-expansion (ULE) cordierite ceramic substrate. Figure 2(a) shows the flow-cell design, which employs hexagonal unit cells similar to the lightweighted optics used in aerospace applications. The substrate here, however, has a closed back surface and integrated input/output channels to direct liquid coolant close to the front surface where the laser beam deposits heat. Coolant flows into the cells by means of columns connected to an inlet plenum on the top edge and exits by means of similar columns connected to an outlet plenum on the bottom edge. Figure 2(b) depicts a simulation where the flow cell efficiently removes heat in a direction normal to the optical surface, which

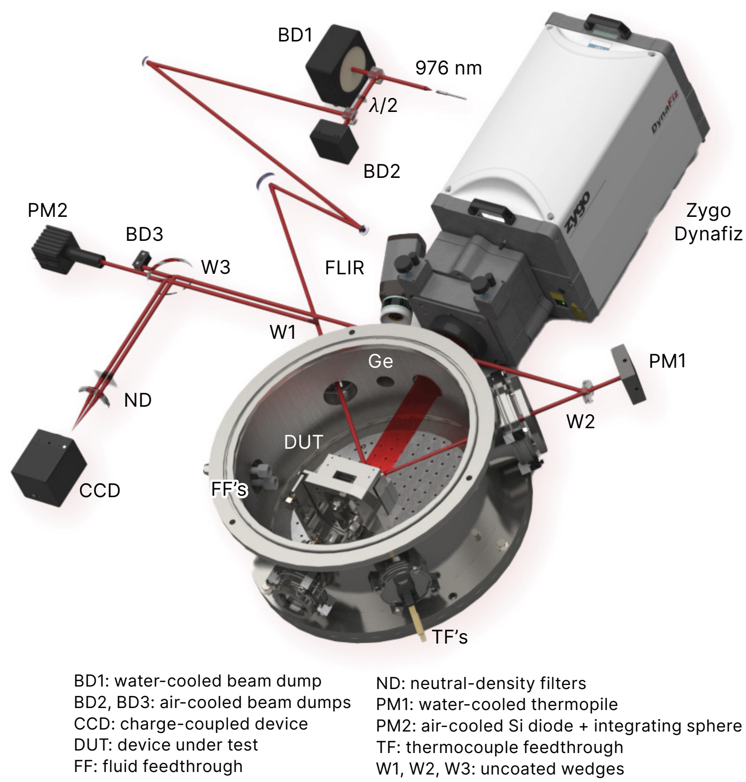

Figure 1. Thermal loading test stand layout using the 976-nm heater source. Ge window for the FLIR thermal imaging camera shown—all other windows are V-coated for the appropriate wavelength (976-nm heater or 632.8-nm Fizeau).

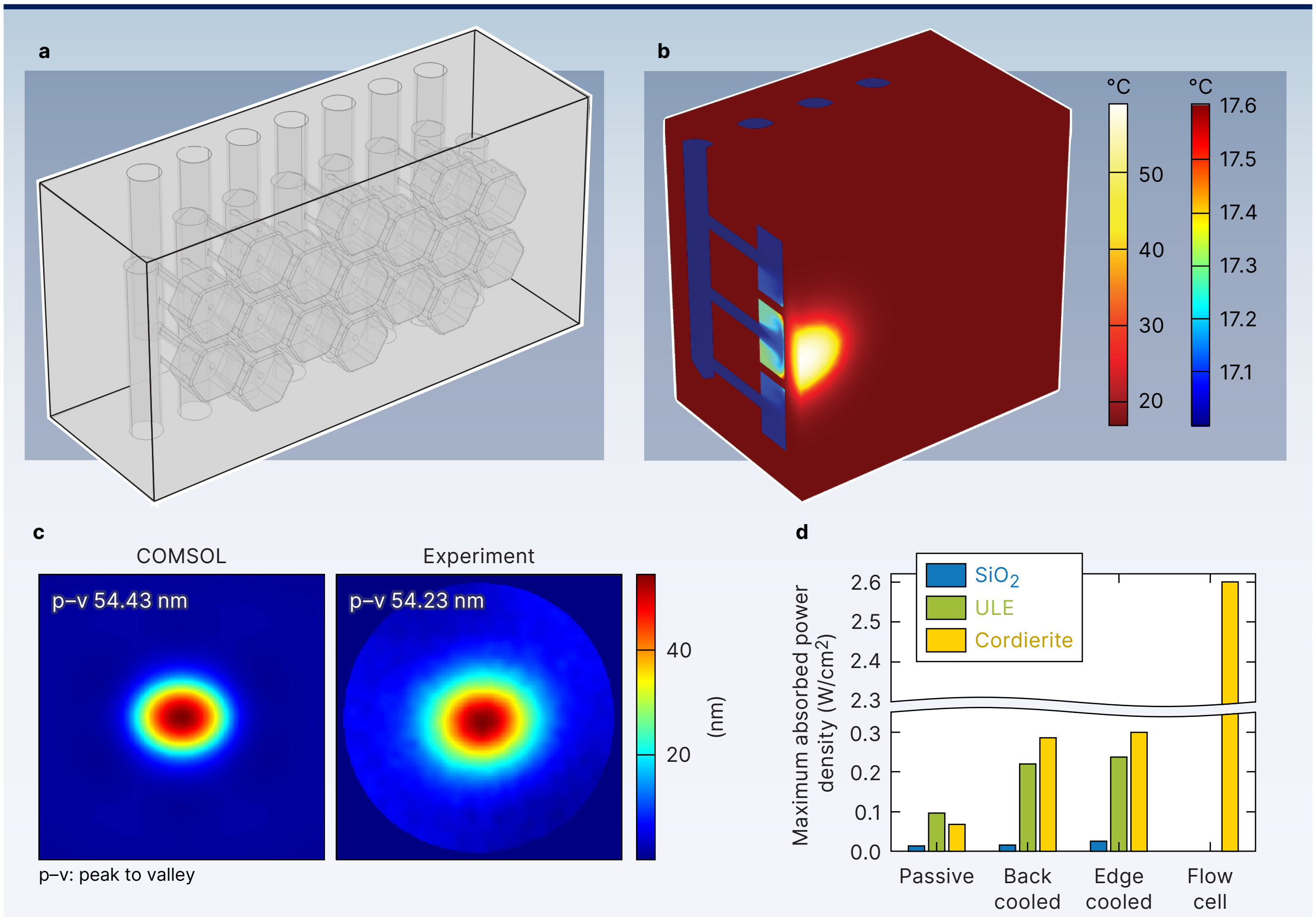

Figure 2. (a) Transparent rendering of the flow-cell prototype. (b) Predicted steady-state thermal distribution for the prototype test conditions. (c) Predicted steady-state surface deformation (left) and measured steady-state surface deformation (right). (d) Comparison of the maximum tolerable absorbed power density for SiO_2, ULE, and cordierite using four possible cooling schemes.

minimizes transverse thermal variations that degrade laser performance. Simulations compare favorably with an experimental measurement of an aluminum-coated (7.5% absorption) prototype with a 4-in. × 2-in. clear aperture and illuminated with a 100-W continuous-wave laser, as seen in Fig. 2(c). The patented flow-cell design [4-5] dramatically exceeds the average power handling of back- and side-cooling schemes by ~10× and passive cooling by ~50×, as illustrated in Fig. 2(d). Implementing the flow-cell substrate design with MLD-based gratings and mirrors will allow operation at even higher average powers with significantly reduced component size.

E. P. Power, S. Bucht, J. Bromage, and J. D. Zuegel

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Focus Points

- The absorption of laser light in high-average-power laser systems can lead to thermally induced deformation of system optics.
- To mitigate thermal expansion, integrated active-cooling designs have been developed in which coolant "flow-cells" efficiently remove heat generated by the laser beam.
- Used in conjunction with multilayer dielectric or metal-coated diffraction gratings employed in chirped-pulse amplification, these "flow-cell" optical substrates will allow for more-compact and cost-effective compressor designs limited only by the laser-damage threshold of the gratings.

FOCUS ON TECHNOLOGY

Nonlinear Regenerative Amplification with Tunable Nonlinearity

Thin-disk laser technology has revolutionized high-average-power ultrafast lasers in the last decade [1]. Most notably, Yb:YAG thin-disk regenerative amplifiers can deliver joule-class pulses with kilowatt average power using chirped-pulse amplification (CPA). Due to their limited gain bandwidth, these amplifiers can only produce pulses 500 fs or longer. Nonlinear post-compression in multipass cells [2,3] can produce shorter pulses, but this increases size and cost. This article reports on nonlinear regenerative amplification, which directly amplifies ultrashort pulses and broadens the spectrum by means of self-phase modulation during pulse amplification. The amplified and spectrally broadened pulse can then be compressed to shorter pulses.

The positive Kerr effect ($n_2 > 0$) from intracavity components, such as a Pockels cell (PC), spectrally broadens a pulse during regenerative amplification [4], but self-focusing limits the achievable pulse energy and spectral broadening. Cascaded quadratic nonlinearity (CQN) [5] provides a means of tuning the nonlinearity in both magnitude and sign ($n_2 > 0$ or $n_2 < 0$) [6]. Self-phase modulation with CQN with $n_2 < 0$ precludes catastrophic self-focusing and makes it suitable for amplifying intense pulses [7]. The spatial nonuniformity of the nonlinear phase shift imposed on Gaussian and other non-plane wave beams limits its usefulness in single-pass applications [8] but applying self-phase modulation using CQN in a resonant cavity that spatially homogenizes the nonlinear phase shift [9,10] overcomes this limitation.

This article reports on a nonlinear regenerative amplifier with tunable nonlinearity for direct amplification (without CPA) of ultrashort pulses. Figure 1(a) shows the schematic diagram of an Yb:YAG thin-disk regenerative amplifier using a ring resonator. The regenerative amplifier was seeded with transform-limited 1.2-ps pulses at a repetition rate of 1 kHz. A phase-mismatched second-harmonic–generation (SHG) beta barium borate (BBO) crystal mounted on a motorized, precision-rotation stage provides flexible tuning of the net nonlinearity using CQN. Tuning of the phase matching resulted in three different regimes of net nonlinearity shown in Fig. 1(b). Regimes I and II, corresponding to enhanced-positive and negative net nonlinearity, respectively, were extensively investigated for spectral broadening. Following amplification, dispersive mirrors were used to compress the spectrally broadened pulses.

Spectral broadening and pulse compression were observed when operating in both regimes I and II, with results presented in the top and bottom rows of Fig. 2, respectively. In both cases, the 10-μJ seed pulses

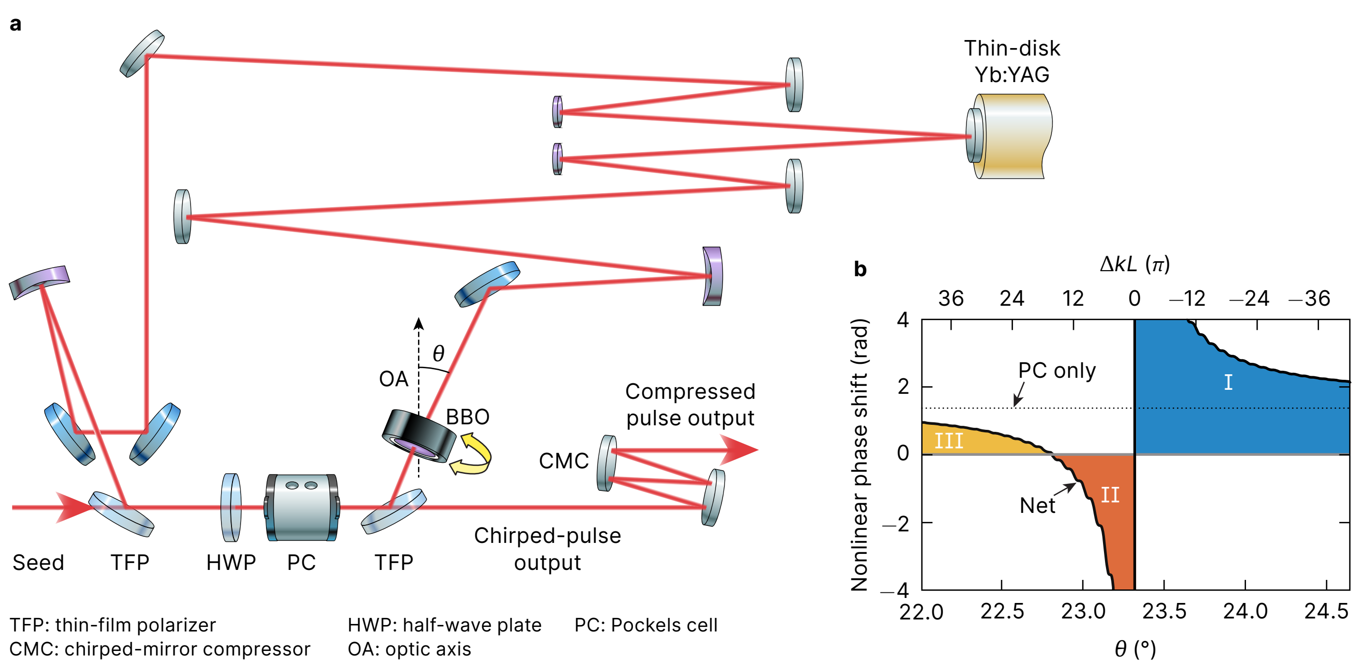

Figure 1. (a) Schematic of the regenerative amplifier with ring resonator. A 5-mm-long BBO crystal provides an intracavity cascaded quadratic nonlinearity. (b) Calculated single-pass nonlinear phase shift accumulated by a 0.5-mJ, 1.2-ps pulse from the PC only (dotted line) or PC plus the BBO crystal (net, solid line), where the net-nonlinear phase shift depends on the propagation angle θ relative to the BBO optic axis (bottom scale) or the phase mismatch ΔkL (top scale). The nonlinearity from the thin-disk Yb:YAG, half-wave plate, and air is negligible and therefore not included. Three different regimes for the net-nonlinear phase shift exist: regime I (enhanced net-positive nonlinearity), regime II (net-negative nonlinearity), and regime III (reduced net-positive nonlinearity).

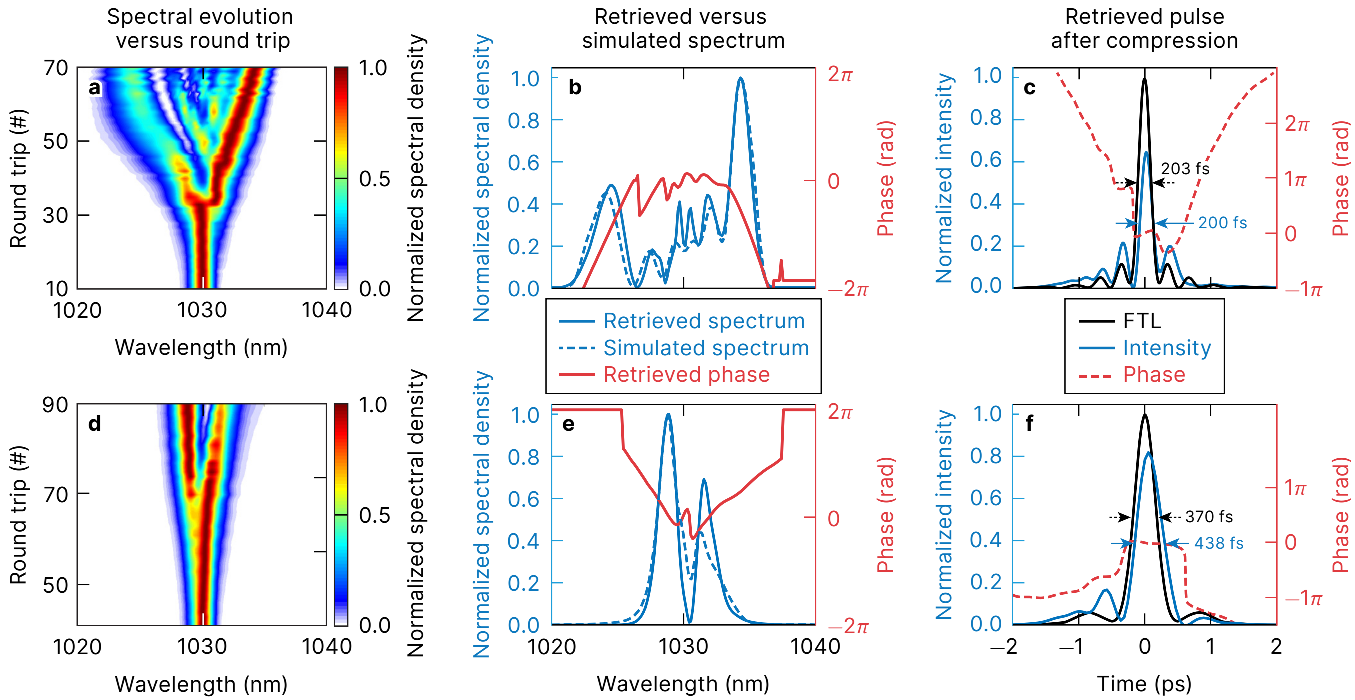

Figure 2. Results obtained in regimes I (top row) and II (bottom row). [(a),(d)] spectral evolution versus round trip; [(b),(e)] FROG-retrieved spectrum and spectral phase plus the simulated spectrum from the last round trip; and [(c),(f)] FROG-retrieved compressed pulse and temporal phase, plus the Fourier transform-limited pulse. The full width at half maximum (FWHM) of the pulses is labeled.

were amplified to approximately 0.5 mJ. Unlike in CPA, where pulses experience spectral gain narrowing during amplification, the spectrum broadens once amplification produces intensity high enough to create self-phase modulation [Figs. 2(a) and 2(d)]. The different signs of net nonlinearity in regimes I and II lead to distinct spectral features with the amplified pulses exhibiting positive and negative chirp, respectively. Figures 2(b) and 2(e) show good agreement between simulated and output spectra retrieved by SHG frequency-resolved optical gating (FROG) measurements.

After spectral broadening in the cases of regimes I and II, dispersive mirrors with a total $-80{,}000\text{-fs}^2$ and $+70{,}000\text{-fs}^2$ group-delay dispersion were used, respectively, to compress the pulses to as short as 200 fs and 438 fs [Figs. 2(c) and 2(f)]. The reduced peak intensity compared to the Fourier transform limit (FTL) in both cases can be attributed to uncompensated high-order dispersion. In both regimes, the laser output exhibited excellent beam quality with $M^2 < 1.5$ and no signs of self-focusing. The outputs showed excellent spatiospectral homogeneity and good output power stability <0.8% rms over an hour.

The current design is capable of supporting output pulse energies well over 1 mJ at repetition rates >100 kHz, producing average powers in excess of 100 W. Optimizing operating conditions, such as the round-trip gain and the amount of net-negative nonlinearity when operating in regime II ($n_2 < 0$), has the potential to enhance the spectral broadening and produce even shorter pulses.

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Focus Points

- Cascaded quadratic nonlinearity enables nonlinearity-tunable regenerative amplification to produce pulses shorter than those attainable from chirped-pulse amplification.
- Nonlinearity-tunable regenerative amplification is capable of generating femtosecond pulses with average powers in excess of 100 W, with wide applications in both science and industry.

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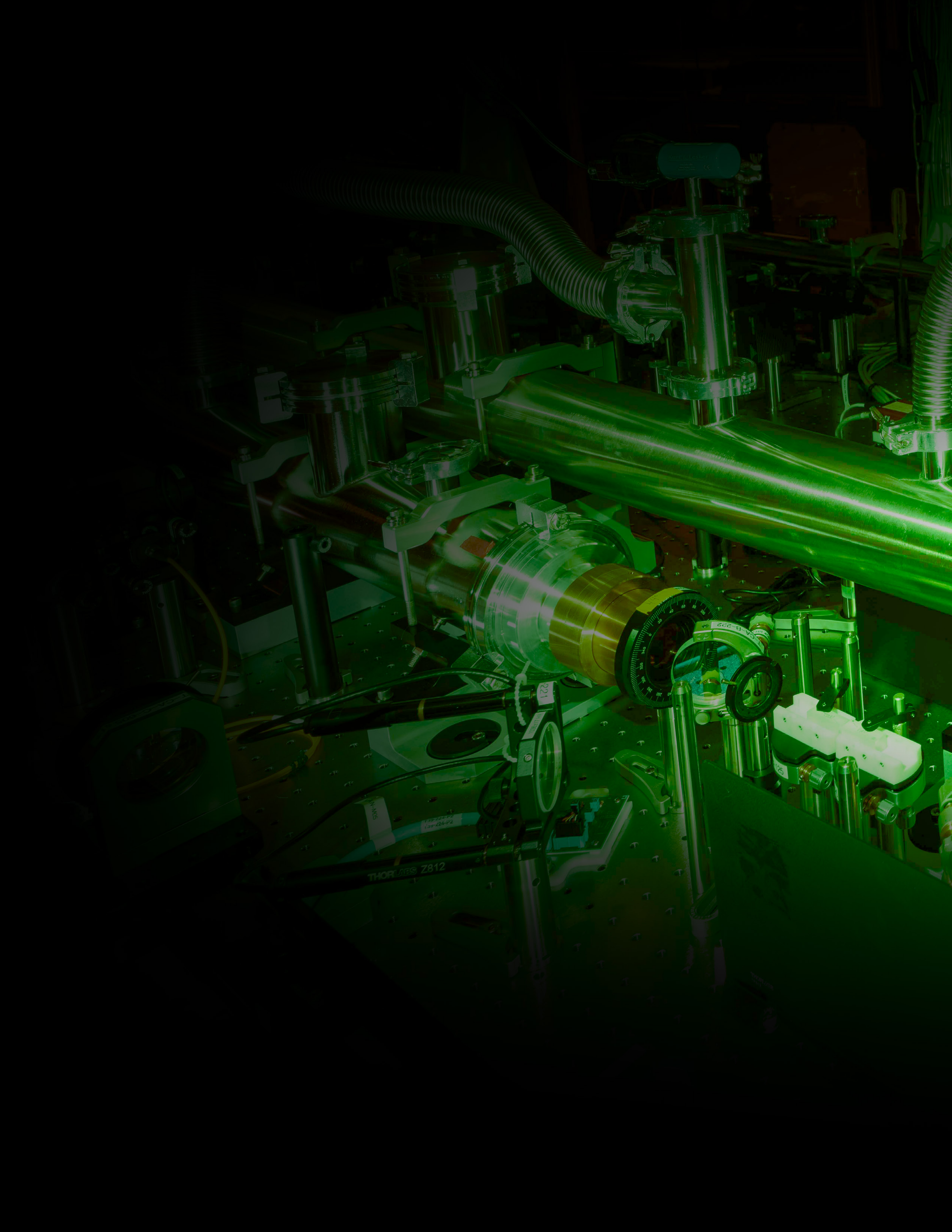
This material is based upon work supported by award numbers Department of Energy (DOE) National Nuclear Security Administration DE-NA0003856; DOE ARPA-E DE-AR0001272-062197-002 and DE-AR0001269-062274-002; DOE DE-SC0024415, DE-SC0021032-062471-002, DE-SC0021057-062426-002, DE-SC0020431-061817-002, DE-SC0022979, DE-SC0023331, DE-SC0021057, DE-SC0023246, and DE-SC0023239; New York State Energy Research and Development Authority 568-FFES-FUC-83; Department of Defense; Commissariat à l'énergie atomique 3957; National Science Foundation 2329970, 2205521; Lawrence Livermore National Laboratory B647588, Subcontracts B637954 and B647770; Air Force Office of Scientific Research FA9550-23-1-0475; Stanford University Subcontract 217663; Sandia National Laboratories PO 2300100, PO 2378255, and PO 2332811; SLAC 228271; Johns Hopkins University Subawards 2004758202 and 181839; Seurat Technologies; United Kingdom Atomic Energy Authority COL054-2022 and COL055-2022; Duke University 323-000028; Verus Research Subcontract No. 1175-00083; Sydor Instruments LLC; Mission Support and Test Services LLC 286264; Los Alamos National Laboratory Subcontract 20345; and University of California at San Diego Subaward 705841.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