UNIVERSITY OF ROCHESTER
LABORATORY FOR LASER ENERGETICS

LLE IN FOCUS

SUMMER 2026 | ISSUE 10

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A MILESTONE COMMEMORATIVE ISSUE

HONORING OUR PAST, BUILDING THE FUTURE

LABORATORY FOR LASER ENERGETICS | MELIORA University of Rochester

LLE IN FOCUS

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250 E. River Rd., Rochester, NY 14623
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Dedication

To the scientists, engineers, staff, and students of the Laboratory for Laser Energetics, past and present—whose curiosity, skill, and dedication have made this laboratory what it is.

To our sponsors—the National Nuclear Security Administration, our federal agency partners, New York State through Empire State Development, and our academic and industry partners, whose sustained commitment has ensured that consequential science can happen here.

To the University of Rochester—our home, our partner, and our foundation, whose facilities, resources, and commitment to education have shaped every facet of LLE's mission for 50 years, and whose collaboration in research and education remains central to all that we do.

With gratitude, on the occasion of LLE's 50th anniversary, the 40th anniversary of the invention of chirped-pulse amplification, and the 30th anniversary of the OMEGA Laser System.

LLE IN FOCUS

A Milestone Commemorative Issue

Summer 2026 | Issue 10

Moshe Lubin, Founding Director of the Laboratory for Laser Energetics, stands at the placement of the building's cornerstone in 1976. At far left is Robert Sproull, then-President of the University of Rochester, whose support was instrumental in the laboratory's founding. *Photo courtesy of the Department of Rare Books and Special Collections, University of Rochester Libraries © 2002 the University of Rochester. All rights reserved.*

IN THIS ISSUE

This issue marks three important milestones: 30 years of the OMEGA Laser System, 40 years of chirped-pulse amplification, and 50 years of the Laboratory for Laser Energetics, with reflections on the contributions of those who made them possible.

A Record of Innovation and Achievement

Sarah C. Mangelsdorf

President, University of Rochester

G. Robert Witmer, Jr. University Professor

In the trajectory of scientific discovery over the past 50 years, research endeavors with a sustained record of innovation and technological achievement turn bold ideas into action.

They create communities of curious, collegial researchers who work together, across departments and institutions and among private and public partners, to help one another advance science and serve a greater good.

That was the founding premise of the University of Rochester's Laboratory for Laser Energetics when it was established over 50 years ago. Now an internationally recognized leader in the study of the interactions of light and matter, LLE has an unparalleled, decades-long track record of leadership. In addition to its groundbreaking work in inertial confinement fusion, high-energy-density physics, and laser-based science and technology, LLE was the site for Nobel-winning research by Donna Strickland and Gérard Mourou—work that paved the way for innovations in medicine, computer science, and communications. Along the way, LLE has played a role in training generations of leading scientists, engineers, and technicians around the world.

LLE's success is possible because of the people who have contributed to its mission. Thank you to the staff, students, and research collaborators —both at Rochester and beyond—and to our local, state, and federal partners who have been part of LLE's story. I am confident that the next 50 years will be shaped by your dedication, curiosity, and commitment to Meliora.

Sarah C. Mangelsdorf

LLE at 50: From Foundation to Future

Christopher Deeney
*Director,
Laboratory for Laser Energetics*

Take a look at the picture on page one of this issue and you see Moshe Lubin, LLE's founding director, standing at the site of the building's cornerstone in 1976—a good 50 years ago. We have been an integral part of the University of Rochester since those early days, with Robert Sproull, president of the university and one of the laboratory's very ardent supporters, at our launch.

It's difficult not to get sentimental about the significance of this photo and the enthusiastic potential that launched the laboratory. The arc of technological innovation traced since then has seen LLE scientists and researchers produce remarkable inventions that have pushed the state of the art to higher levels. Team LLE embodies the University of Rochester's guiding value of Meliora, or "ever better."

The 50th anniversary of LLE is a good time to take stock of the early days and reflect on how far the laboratory has come over the past five decades. Anchored in the University of Rochester, LLE has nurtured a reputation for supporting critical imperatives for the nation while prioritizing scientific excellence, national security, and innovation.

LLE's groundbreaking innovations could not have been possible without robust funding from the National Nuclear Security Administration, the Fusion Energy Science program at the Office of Science, the National Science Foundation, the Department of Defense, the Air Force Office of Scientific Research, and the State of New York.

It goes without saying that no matter how much LLE grows, it is our people who make LLE what it is. Some have made their entire careers here, while promising students who walk in through our doors are beginning to get a peek at the many ways they too can realize their immense potential.

In 1978, LLE scientists developed Nd:phosphate laser glass, which makes high-energy laser amplification possible and is used worldwide in major fusion laser systems, including OMEGA and the National Ignition Facility. In 2008, the OMEGA EP Laser System was commissioned, which expanded LLE's experimental capabilities through the addition of four high-energy beams, two of which delivered ultrahigh-intensity laser pulses with the highest energy in the world at the time.

A revolution in Thomson scattering broke new ground in 2022 by measuring the details of plasma waves: it provided direct measurements of electron temperature, density, and plasma waves on OMEGA, and advanced our understanding of laser–plasma interactions critical to inertial confinement fusion. Fast-forward all the way to the present: in 2026, LLE scientists designed FLUX, a next-generation broadband laser system, to reduce laser–plasma instabilities and improve energy coupling in direct-drive fusion experiments. This transformative technology will likely make high yield (i.e., gigajoule-level yield) possible for national security and anchor an expanded fusion energy industry. Future laser systems currently under development at LLE such as NSF OPAL and OMEGA Next, both of which are discussed further in this issue, will play a vital role in this effort.

The 50th anniversary of LLE also marks 30 years of the OMEGA Laser System (see article on p. 8), a highly complex and capable laser system that has helped hundreds of researchers explore a wide range of scientific studies. International scientists have used the advanced facilities through the National Laser Users' Facility program, which has ensured equitable access to vetted scientists through established protocols. OMEGA has garnered some impressive achievements along the way, boosting the careers of more than 320 graduate students and postdoctoral researchers, and fundamental to research featured in thousands of publications.

In a special trifecta, this year also marks the 40th anniversary of a Nobel Prize-winning invention from LLE: chirped-pulse amplification, or CPA (see p. 18). In a small lab on the main floor of the LLE building, then-doctoral candidate Donna Strickland and her advisor, Gérard Mourou developed a way of circumventing the limitations of conventional laser pulses. The workaround was to produce an extremely short (chirped) pulse that could be stretched and amplified to a greater energy. This would then be recompressed to deliver a final output with a much higher intensity. Like many groundbreaking inventions, the thesis for CPA is elegant in its simplicity and has since pushed the capabilities of laser science into new realms.

Beyond these great examples, it is difficult to detail every groundbreaking innovation that LLE scientists have achieved over the years, but this commemorative issue includes an innovation timeline spread (p. 12) with some notable highlights.

As with OMEGA, CPA, and LLE's many other superb technical capabilities, it is the people who make these technologies work. Their generosity in sharing their ideas and enthusiasm with the next generation of scientists is what makes LLE such a phenomenal place to nurture careers in advanced science. Students keep us challenged and vibrant. Partnerships around the nation and the world keep us inspired and engaged. Our staff dedicate themselves to ensuring that our amazing facilities deliver high-quality data to our hundreds of users.

The impact of technological innovations developed by LLE scientists has been felt far and wide and is manifested in the high demand for use of our advanced facilities to conduct cutting-edge research. Equally important has been LLE's immense economic impact on the greater Rochester area, both in terms of jobs and in nurturing future generations of scientists.

As we set our sights on the next 50 years, we recognize that LLE's many technological advances have been born of the vision, passion, and hard work of legions of dedicated scientists. Such brilliance shapes what LLE is today and how we evolve tomorrow.

Thank you for being part of LLE's 50-year journey.

Christopher Deeney
Director, Laboratory for Laser Energetics

Fifty Years of Achievement

Over five decades, LLE has been recognized by leading scientific organizations for its contributions to laser science, plasma physics, and fusion research. Its researchers and collaborators have earned honors spanning the Nobel Prize in Physics, distinctions from the US Department of Energy and the American Physical Society, as well as early-career fellowships and industry awards. These recognitions span individual achievements, team-based efforts, and sustained programmatic contributions. Together, they reflect technical leadership, consistent collaboration with partners, and the broad impact of LLE's work across disciplines and institutions.

Nobel Prize in Physics

LLE's contributions to laser science are reflected in Nobel Prize-winning research. In 2018, Donna Strickland and Gérard Mourou were awarded the Nobel Prize in Physics for their groundbreaking work on laser chirped-pulse amplification (CPA), developed here at LLE in the 1980s. CPA technology has revolutionized laser science and enabled innovations ranging from laser eye surgery to advanced manufacturing. Read more on p. 18.

John Dawson Award for Excellence in Plasma Physics

The American Physical Society John Dawson Award for outstanding achievements in plasma physics has twice recognized research at LLE. In 2019, collaborative work at the OMEGA Laser Facility with the University of Chicago and the University of Oxford was honored for experiments demonstrating turbulent dynamo in the laboratory, establishing a path for studying magnetized plasmas and related astrophysical processes. In 2024, an LLE research team was recognized for statistical modeling that predicts and analyzes implosion experiments on OMEGA, achieving hot-spot energy gains above unity and record Lawson triple products for direct-drive fusion.

E. O. Lawrence Award

Two LLE scientists have received the Department of Energy's prestigious E. O. Lawrence Award for advancing laser-plasma science and fusion energy. Riccardo Betti earned the award in 2012 for seminal contributions to fusion theory and plasma physics, while Dustin Froula was recognized in 2021 for groundbreaking work in laser–matter interactions and diagnostic innovation.

Recognizing LLE Fellows

Across its history, LLE has been home to a distinguished group of researchers recognized as Fellows of leading professional societies, including the American Physical Society, IEEE, SPIE, and Optica. These honors span individuals who contributed to the laboratory at different points in its history, including past and present members whose work has shaped the field. Together, these fellowships reflect sustained technical achievement, leadership within the broader scientific community, and the continued influence of LLE's research across institutions.

American Physical Society Fellows


R. Bahukutumbi
2017


R. Betti
2001


E. M. Campbell
1980


G. W. Collins
2006


R. S. Craxton
2000


C. Deeney
1999


S. G. Demos
2015


D. H. Froula
2017


V. Yu. Glebov
2016

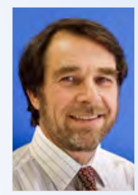

V. N. Goncharov
2007


S. X. Hu
2013


R. L. McCrory
1985


S. P. Regan
2015


T. C. Sangster
2011


W. Seka
1990


A. Simon
1956


S. Skupsky
1993


J. M. Soures
1992


C. Stoeckl
2017


W. Theobald
2018


D. Turnbull
2025


M. S. Wei
2018


B. Yaakobi
1985

IEEE Fellows


C. Deeney
2006

SPIE Fellows


S. D. Jacobs
2003

Optica Fellows


J. Bromage
2020


E. M. Campbell
2020


S. G. Demos
2017


C. Dorrer
2015

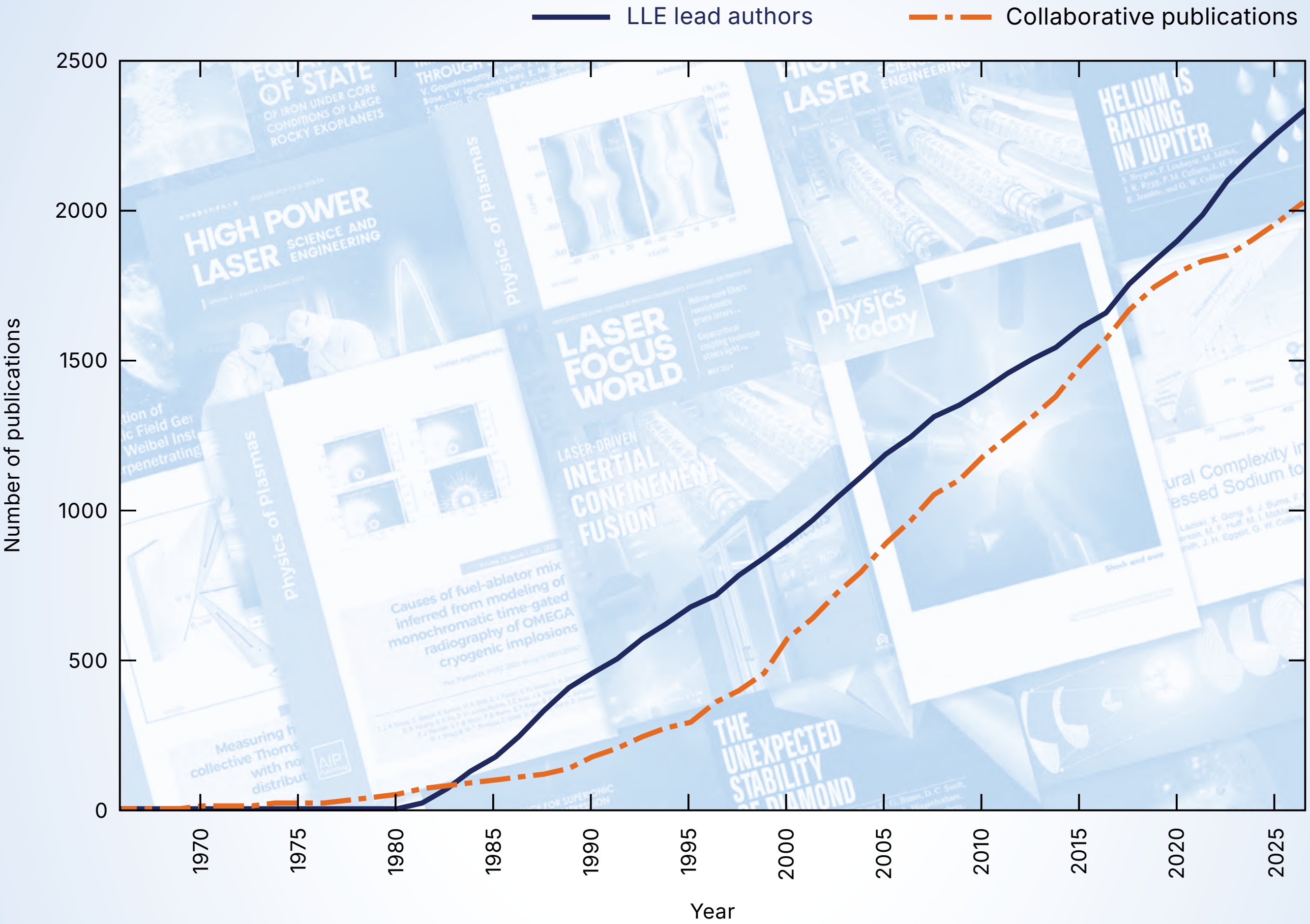

S. D. Jacobs
2006


T. J. Kessler
2023


J. D. Zuegel
2014

Fifty Years of Publications

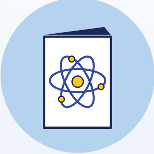
LLE's science and engineering research is documented through peer-reviewed publications, including both lead-authored and coauthored papers. Together, these works reflect the laboratory's technical leadership and sustained collaboration with external laboratories and academic partners. Over five decades, LLE has produced more than 4000 publications across over 350 journals, including publications in *Nature* journals, *Science, Physical Review Letters, Optica*, *Proceedings of the National Academy of Sciences*, and other leading journals in physics, optics, astronomy, and high-energy-density science.



LLE Publications by the Numbers

4000+
Publications

More than 4000 peer reviewed publications produced over the past five decades

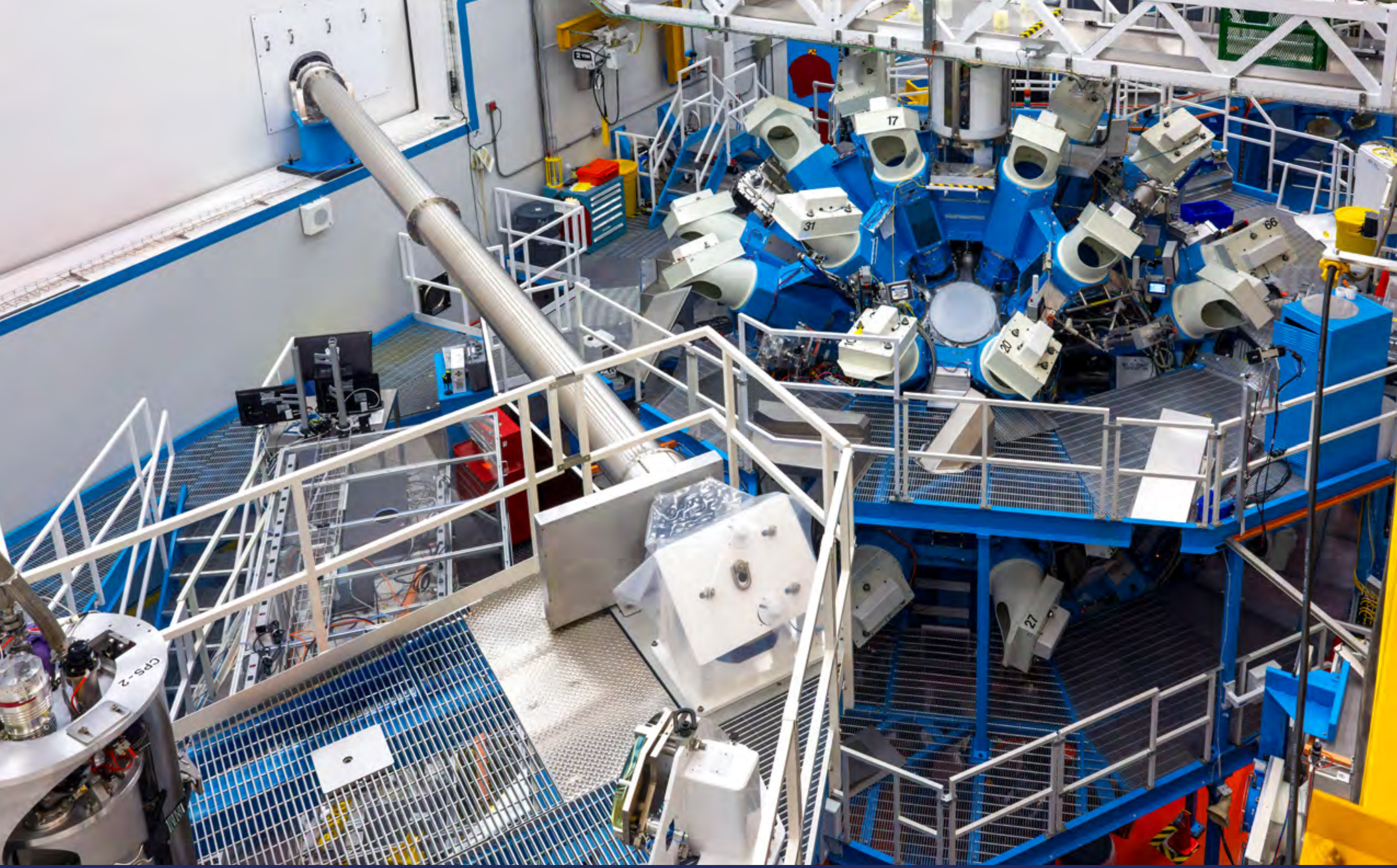


350+
Journals

Published in over 350 journals, including prestigious and leading field journals

100+
Average publications/year since 1983

Sustained productivity of more than 100 publications each year since 1983

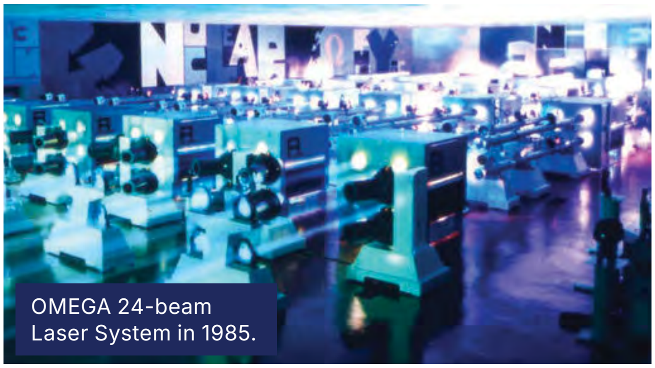


Celebrating 30 Years of OMEGA

An Enduring Legacy of Leadership and Innovation

LLE's Omega Laser Facility, the largest laser facility at any academic institution in the world and a premier high-energy-density science research center, is made up of two major laser systems, OMEGA-60 (also simply called OMEGA), and OMEGA EP (Extended Performance). This year, OMEGA-60 celebrates 30 years of operation. The facility has been invaluable to hundreds of scientists and students from LLE and across the nation, who have conducted more than 50,600 shots on the laser systems over the past three decades. Their findings have been crucial and have led to major breakthroughs at LLE and other labs, including the achievement of ignition at Lawrence Livermore National Laboratory's (LLNL's) National Ignition Facility (NIF) in 2022.

LLE receives substantial funding from the US Department of Energy's (DOE's) National Nuclear Security Administration (NNSA). OMEGA-60 and OMEGA EP play a direct role in supporting NNSA's mission-critical research activities relating to national security, stockpile stewardship, and scientific discovery. With approximately 2000 target shots conducted annually on the laser systems for experiments focusing on the exploration of fusion, astrophysics, plasma science, laser–matter interactions, and more, OMEGA-60 and OMEGA EP have accelerated our collective understanding of high-energy-density science, helped achieve inertial fusion in the laboratory, and transformed the landscape of laser science research. The facility also provides immense value to the greater Rochester region, offering an abundance of economic, educational, employment, and research opportunities to the community. It is a feat made possible by the dedication, creativity, and expertise of every department at LLE and by generous financial support from the University of Rochester, New York State, and the DOE.

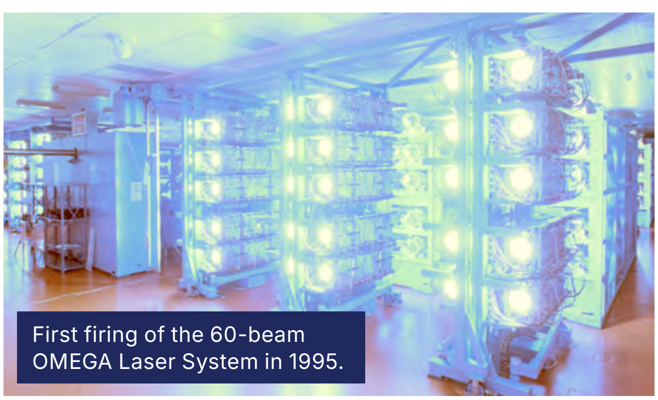


OMEGA 24-beam Laser System in 1985.

A Brief History

OMEGA-60's history is deeply intertwined with that of LLE itself, so a reflection on the origins of the laboratory is useful in understanding how and why the laser system came to be. After being inspired by the initial laser demonstrations of the early 1960s, Moshe Lubin and other scientists from the University of Rochester realized the potential of using lasers to develop a future renewable energy source. Their initial campus-based laser experiments evolved into larger endeavors, and within a few short years, backed by energetic support from then-University of Rochester president Robert Sproull and companies such as Eastman Kodak, LLE was founded in the fall of 1970, with Lubin as director. Established as a multidisciplinary teaching and research center within the College of Engineering and Applied Sciences, LLE was the first of its kind at any US university.

As the team's research objectives expanded, so too did LLE, and by 1975, the newly constructed four-beam DELTA laser system—the original precursor to OMEGA-60—was in operation. Within a year, construction began on the current facility site, with the original building opening in 1977. By 1980, after building on early successes such as the development of glass laser amplifiers, LLE had overseen the development and initial operation of the one-beam glass development laser (GDL), the six-beam ZETA laser, and the 24-beam OMEGA laser, all infrared lasers. LLE established the National Laser Users' Facility (NLUF) in 1979. In 1980, LLE used GDL to demonstrate how to efficiently convert infrared lasers to the ultraviolet. By 1985, all 24 OMEGA beams were converted. By the late 1980s, plans were in place to upgrade the 24-beam OMEGA laser to its current 60-beam configuration. This initiative was executed as a DOE major project with a cost of $62 million and led by then-LLE Director Robert McCrory. The development of LLE's laser systems was a monumental undertaking that required the commitment of hundreds of staff members.



First firing of the 60-beam OMEGA Laser System in 1995.

"It takes all of LLE to operate OMEGA-60," says former Omega Operations Division Director Sam Morse, who retired this past spring after a storied career of over 40 years at LLE. Morse witnessed the design, development, and evolution of the laser system from the very beginning: "The completion of OMEGA-60 in 1995 marked an inflection point in LLE's history," he says. "While the lab had previously conducted cryogenic deuterium–tritium (D–T) implosions, the new system's higher energy and precision enabled experiments at 'near-ignition' conditions. Almost immediately, experiments in 1995 demonstrated regimes that supported the development of ignition-relevant diagnostics, improved understanding of plasma conditions, and then led to many contributions to the national effort to achieve ignition on the NIF."

For over a decade, OMEGA-60 was the world's most powerful fusion laser, setting the standard for inertial confinement fusion (ICF) research. In 2008, the OMEGA EP Laser System was added, expanding the capabilities of the Omega Facility to include four NIF-scale beams, two of which can deliver ultrahigh-intensity laser pulses. Together, the two systems serve as the nation's workhorse for ICF research, providing 80% of the nation's high-energy-density physics experiments to the community.

Omega Excellence

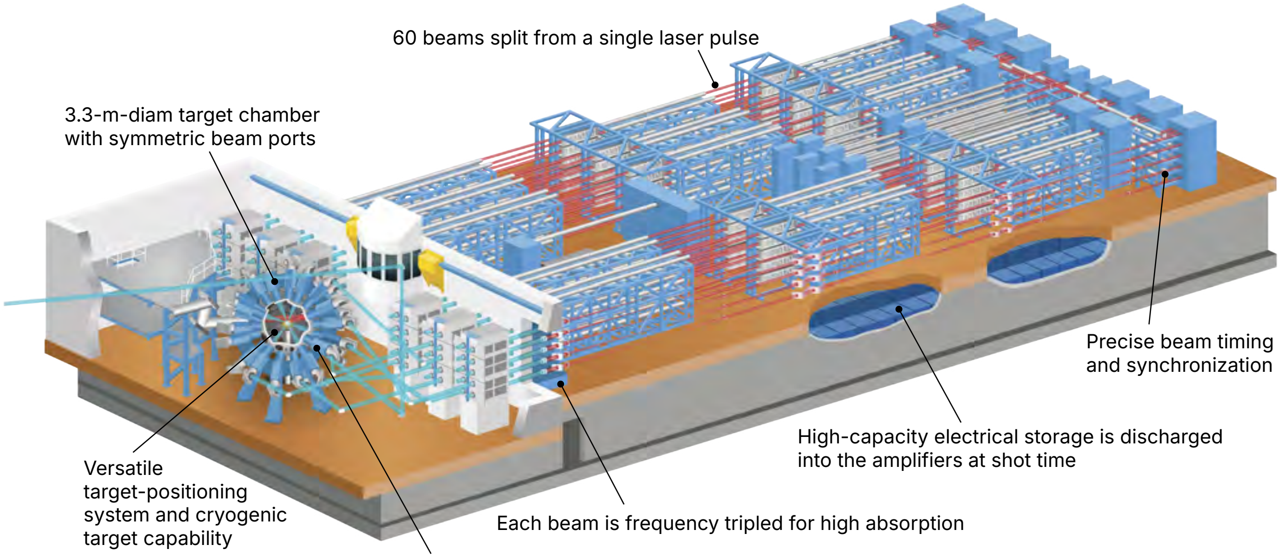
What makes the Omega facility so unique and important? First, in terms of scale, it is situated at a magic middle place: neither too large nor too small, the size of the facility is "just right." Practically speaking, this means that the laser systems can allow for greater productivity, flexibility, and a wider variety of experiments that are capable of pushing the boundaries of science with fewer costs, less-complex logistics, and a smaller workforce than are required to run a significantly larger laser system like the NIF. On the other hand, because OMEGA-60 and OMEGA EP are the largest of all university-based lasers, they can support experiments that are simply not possible on smaller systems. For the high-energy-density community, the facility's ideal size means that scientists can generate reproducible plasma conditions in experiments that can be executed and refined before being scaled up to larger facilities like the NIF.

I could never have asked for a more rewarding career. With the steady flow of new ideas, new challenges, new laser capabilities, and new experimental opportunities, the excitement of discovery has never changed since I came to LLE in 1976.

Stephen Craxton

Distinguished Scientist, Theoretical Division

OMEGA-60 at a Glance



Second, the vast capabilities of the OMEGA-60 laser system are key. Roughly the size of a football field, OMEGA-60 is an extremely powerful and versatile laser that can deliver up to 30 kJ of ultraviolet energy at 30 TW (that is, 30 trillion watts) onto a target using 60 beams that are arranged in a spherically symmetric pattern. All 60 beams are precisely synchronized and aligned in such a way that when the laser fires, the beams hit the surface of the target within picoseconds (trillionths of a second) of one another—at the right place and at the right time for a uniform implosion. Targets can be spherical, planar, cylindrical, or hohlraum in shape, or any combination thereof. The OMEGA-60 laser can be configured to bring to life highly complex experiments, which help develop some of the most sophisticated physics models in the world. A summary of OMEGA-60's many important features is listed below:

- Symmetric drive energy from 60 laser beams
- Infrared laser with an Nd:glass laser medium (1053 nm)
- Each beam is frequency tripled for high absorption (351 nm)
- A 3.3-m-diam target chamber
- Precise beam synchronization and alignment
- Flexible pulse shaping with custom shapes ranging from 100 ps to 4 ns in duration
- Advanced diagnostics suite
- Versatile target-positioning system
- Cryogenic target-handling capabilities

Third, the facility relies on a highly sophisticated and interconnected support system available at LLE—a system that has set the standard for operating high-power laser user facilities at scale. From the numerous scientists and engineers to the countless diagnosticians, facility operators, safety officers, and others, everyone at the lab plays a vital role in maintaining this infrastructure. as highlighted in the following sections.

Target fabrication department and Cryogenic and Tritium Facility

LLE is home to a robust target fabrication department and a cryogenic and tritium facility. Since 1991, LLE has been supported by its longtime partnership with San Diego-based energy and defense corporation General Atomics (GA), the DOE-designated target fabrication contractor for the US ICF program. GA maintains a dedicated onsite team within the target fabrication department, who together manufacture over 2500 targets each year, including over 100 DT cryogenic targets, that are used in experiments at the Omega Laser Facility. Engineering marvels mere millimeters in size, the cryogenic targets are plastic shells filled with a precise mixture of deuterium and tritium, two heavy isotopes of hydrogen, at pressures up to 1000 atm. The department provides additional support with target assembly, metrology, and delivery on shot days, as well as exemplary troubleshooting support for any target-related issues that may arise.

The experimental capabilities on OMEGA-60 are remarkably varied and deeply mature, which means we as researchers can pursue frontier science questions with a level of rigor, shot access, and configurability that simply isn't available elsewhere. This scientific richness is what makes the lab so compelling to work at.

Matthew Cufari
Graduate Student, MIT

The Cryogenic and Tritium Facility is one of the only cryogenic target production programs in the nation. Tritium, which is both rare and radioactive, requires extremely strict safety and handling regulations. The shells are cooled to cryogenic temperatures of –255°C (18 K) and undergo advanced ice-layering techniques to achieve the submicron-level smoothness and uniformity necessary for symmetric implosions before being transferred and delivered to the target chamber.

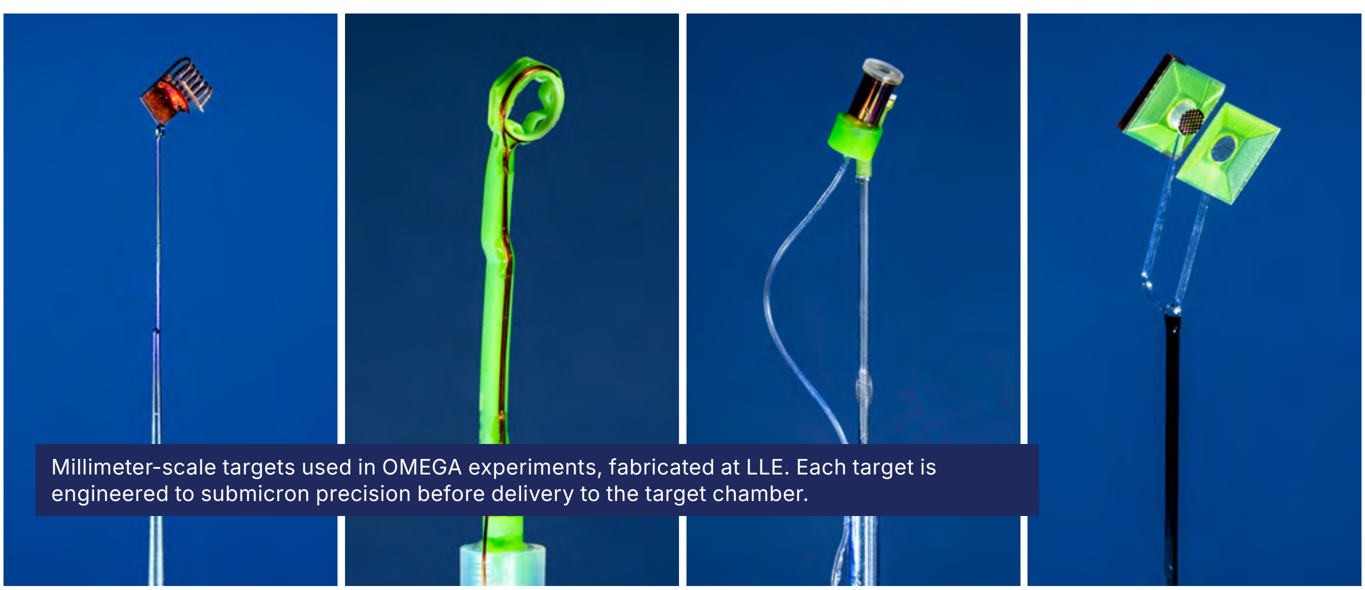
As LLE looks to the future, advances in target technology will lay the groundwork for new experimental concepts and next-generation laser facilities. One such advancement made by LLE engineers is the Cryo Gas Puffer System (GPS), a new and integrated system used to fill cryogenic targets with DT gas. Described in detail in *LLE In Focus*, Issue 8, the GPS vastly improves both the reliability and efficiency of the filling process, allowing scientists far greater control over target production capabilities than ever before. A second development that goes hand in hand with the GPS is a highly advanced 3D printing technique called two-photon polymerization, which essentially uses light and resin to create extraordinarily precise foam microstructures—filaments, some of which are as thin as 0.3 μm—that make up the delicate cryogenic wetted-foam target shells used in experiments on OMEGA-60 and OMEGA EP.

> *I enjoy working with the engineers, technicians, and laser facility managers at LLE. I truly appreciate their work because without their expertise and dedication, I wouldn't have had successful shot days! They create an environment where science can happen and principal investigators can thrive.*
>
> **Jaela Whitfield**
> *Graduate Student, University of Michigan*

Diagnostics and cutting-edge diagnostic development

The diagnostics required by OMEGA-60 and OMEGA EP measure and analyze both the laser beams and the experimental event that occurs when the beams strike a target. Many of the measurements require resolution on the micron scale (for reference, a strand of human hair is generally ~50 to 100 μm in diameter) and the picosecond scale (i.e., the time it takes light to travel 300 μm), so highly sophisticated instrumentation is paramount for effective experiments. LLE supports over 200 diagnostics on the laser systems, including an extensive suite of state-of-the-art optical, x-ray, particle, and magnetic-field measurement tools. Researchers can select the specific diagnostics and instrumentation they wish to use, which LLE's team of engineers and technicians then align and configure with extreme precision into the target chamber using advanced robotic diagnostic shuttles known as ten-inch manipulators. Even more importantly, researchers can rely on diagnostic experts to support measurements and help interpret the data these diagnostics produce.

As experimental needs evolve, so too must diagnostic capabilities. Each year, new diagnostics are developed and improved to maintain LLE's cutting-edge laser technologies. These diagnostics are vital to advancing capabilities at other national laboratories including the NIF and the Z Pulsed Power Facility. During her doctoral research, for example, Michelle Marshall, now High-Energy-Density-Physics Experiments Group Leader at LLE, calibrated the streaked optical pyrometer, one of OMEGA-60's workhorse diagnostics, which enabled temperature measurements of high-energy-density matter for dozens of users. Her close collaboration with LLNL on these projects not only advanced key research efforts, but also paved the way for her own postdoctoral work there. *Continued on* p.14



Millimeter-scale targets used in OMEGA experiments, fabricated at LLE. Each target is engineered to submicron precision before delivery to the target chamber.

LLE Innovation Timeline

Showcasing the breakthroughs that continue to drive discovery at LLE

1978

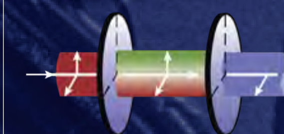
Nd:Phosphate Laser Glass

Developed at LLE, Nd:phosphate laser glass made high-energy laser amplification possible and is used worldwide in major fusion laser systems, including OMEGA and the National Ignition Facility (NIF).

1980

High-Efficiency Frequency Tripling

This technique, developed at LLE, converts laser light to ultraviolet with very high efficiency, delivering more energy to fusion experiments and enabling modern high-power laser systems.



1980

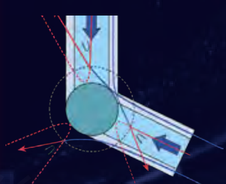
24-Beam OMEGA Laser System

LLE's first full-scale laser facility, OMEGA-24, provided uniform irradiation and exceeded performance goals. It established the lab as a leader in high-energy laser and fusion research.

2009

Cross-Beam Energy Transfer (CBET) Identified in Direct Drive

It was discovered that laser beams exchange energy during direct-drive experiments, reducing laser absorption and affecting how evenly fusion targets are compressed.



2008

OMEGA EP Commissioned

The OMEGA EP Laser System expanded LLE's experimental capabilities with the addition of four high-energy beams, two of which delivered ultrahigh-intensity laser pulses with the highest energy in the world at the time.

2007

Magnetic Recoil Spectrometer

Developed by MIT and LLE, the magnetic recoil spectrometer (MRS) on OMEGA, a forerunner of the NIF MRS, uses accurate measurements of neutron spectra to determine fuel areal density and implosion performance.

2007

Direct-Drive Implosions at 200 mg/cm^2

These results proved that hydrogen can be compressed to ignition-relevant levels using laser-driven capsules on OMEGA containing highly uniform layers of DT ice.

2005

Diffraction from Shock-Compressed Matter

Diffraction from shock-compressed matter was demonstrated, revealing phase transitions under extreme conditions and leading to routine use in high-energy-density experiments.

2012

High-Resolution Neutron Spectroscopy

Neutron time-of-flight diagnostics, developed at LLE to provide high-resolution measurements of neutron spectra on OMEGA, were also installed on the NIF to support DT implosion experiments.

2015

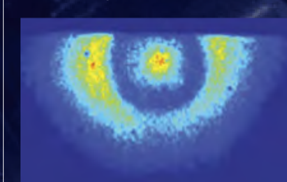
Implosions Exceeding 50-Gbar Hot-Spot Pressure

Based on laser, target, and diagnostic improvements, these results support efforts to achieve hydrodynamic equivalence on OMEGA to a direct-drive ignition capsule on the NIF.

2016

Radiography of Cryogenic Implosions

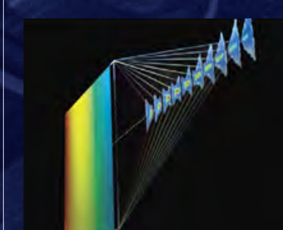
X-ray radiography, using a short-pulse OMEGA EP beam, is used to diagnose the compressed shell of DT cryogenic implosions at stagnation on OMEGA, demonstrating effective fuel compression.



2017

Flying Focus

The "flying-focus" concept uses chromatic focusing and a broadband laser pulse to create a high-intensity focal spot that moves with controllable velocity over distances much longer than a conventional focus.



2018

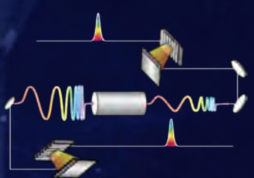
Nobel Prize in Physics

Donna Strickland and Gérard Mourou received the 2018 Nobel Prize in Physics for inventing chirped-pulse amplification at LLE, enabling the generation of ultrahigh-intensity laser pulses used across science, medicine, and industry.

1985

Chirped-Pulse Amplification

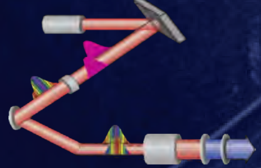
A landmark paper by Donna Strickland and Gérard Mourou at LLE introduced chirped-pulse amplification, allowing ultrashort laser pulses to reach petawatt power. This breakthrough underpins modern ultrahigh-power laser systems.



1989

Smoothing by Spectral Dispersion (SSD)

Pioneered at LLE, SSD produces uniform laser beams, permitting more-stable implosions and becoming the standard beam-smoothing method on major fusion laser facilities worldwide.



1995

60-Beam OMEGA Laser System

OMEGA-60 expanded LLE's capabilities with higher energy and improved uniformity, enabling precision direct-drive experiments at near-ignition conditions, and remains a core experimental platform today.

1997

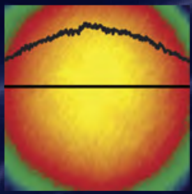
Magnetorheological Finishing

The commercialization of magnetorheological finishing, through the spin-off of QED Technologies, enabled ultraprecise polishing of advanced optical components including key NIF optics.

2000

Smoother Laser Beams

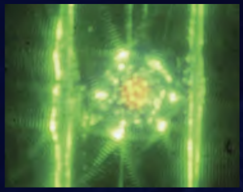
Advanced beam smoothing, including enhanced-bandwidth 2D SSD and polarization smoothing, was implemented on OMEGA. This improved irradiation uniformity supported higher-performance direct-drive implosions.



2000

First 60-Beam OMEGA Cryogenic Target Implosions

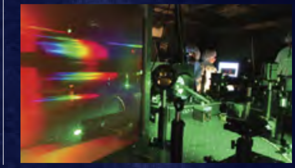
Cryogenic implosions of deuterium-filled targets were demonstrated, advancing direct-drive experiments toward ignition-relevant conditions.



2002

Optical Parametric Chirped-Pulse Amplification

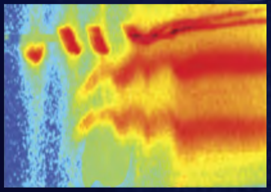
Building on chirped-pulse amplification, this technique which provides efficient amplification of ultrashort, high-intensity laser pulses, was included in the OMEGA EP design.



2002

UV Thomson Scattering

Thomson scattering provides direct measurements of electron temperature, density, and plasma waves on OMEGA, advancing understanding of laser–plasma interactions critical to inertial confinement fusion.



2004

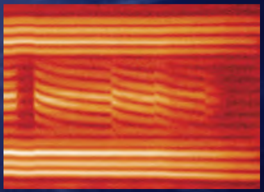
Rochester Optical Streak System

This system made ultrafast, high-precision experimental measurements possible and was commercialized through the launch of Sydor Technologies to bring the system to research facilities worldwide.

2004

VISAR Velocity Interferometer

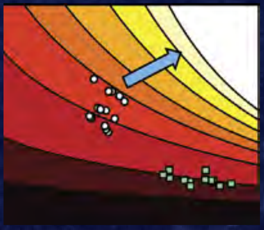
Used to measure shock velocities and reflectivity at extreme pressures, VISAR has led to improved equation-of-state and transport models and provided timing-shock sequences to set the implosion adiabat.



2019

Statistical Modeling Triples Yield

Statistical modeling was used to optimize direct-drive cryogenic implosions, tripling the fusion yield to the highest level achieved for OMEGA experiments.



2019

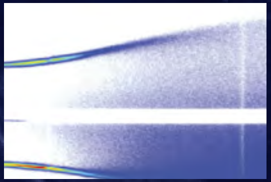
Tunable OMEGA Port 9 (TOP9)

The wavelength-tunable TOP9 platform was developed to study CBET in well-characterized plasmas, improving predictive modeling and demonstrating CBET mitigation through wavelength tuning.

2019

Effects of Non-Maxwellian Electrons on CBET

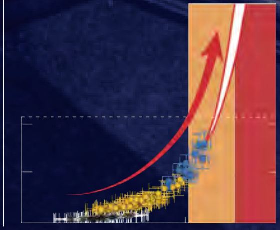
Employing the TOP9 platform, non-Maxwellian electron-velocity distributions were measured in laser plasmas using angularly resolved Thomson scattering. Reduced CBET was demonstrated.



2024

Hydrodynamically Equivalent Burning Plasma

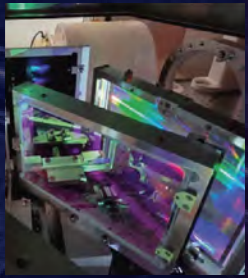
OMEGA direct-drive implosions scaled to 2.2-MJ laser-driver energy show burning-plasma conditions that exceed the threshold needed for ignition.



2026

FLUX

FLUX, a next-generation broadband laser system, was designed to reduce laser–plasma instabilities and improve energy coupling in direct-drive fusion experiments.



> *Stay curious—if you have a question, pursue it. There is a wealth of knowledge within this organization, and someone here likely has the expertise to help you find the answer.*
>
> **Tyler Burgett**
> *Experimental Operations Group Leader*

Advances in engineering

OMEGA-60 is a highly complex, versatile, and custom-designed laser system. Its capabilities have been supported over the past 30 years by continuous and integrated advances in engineering efforts that span across LLE's information technology, mechanical engineering, chemistry, and electrical and controls engineering groups. These advances, which improve both efficiency and precision, include software development and computer system support, the highly complex and delicate cryogenic systems that support LLE's target fabrication department, electromechanical assemblies used on the laser system, grating compressor chambers, the MIFEDS (or magneto-inertial fusion electrical discharge system) used to create magnetic fields for experiments, and more, and are vital to successful operations at the Omega Laser Facility.

Laser operations

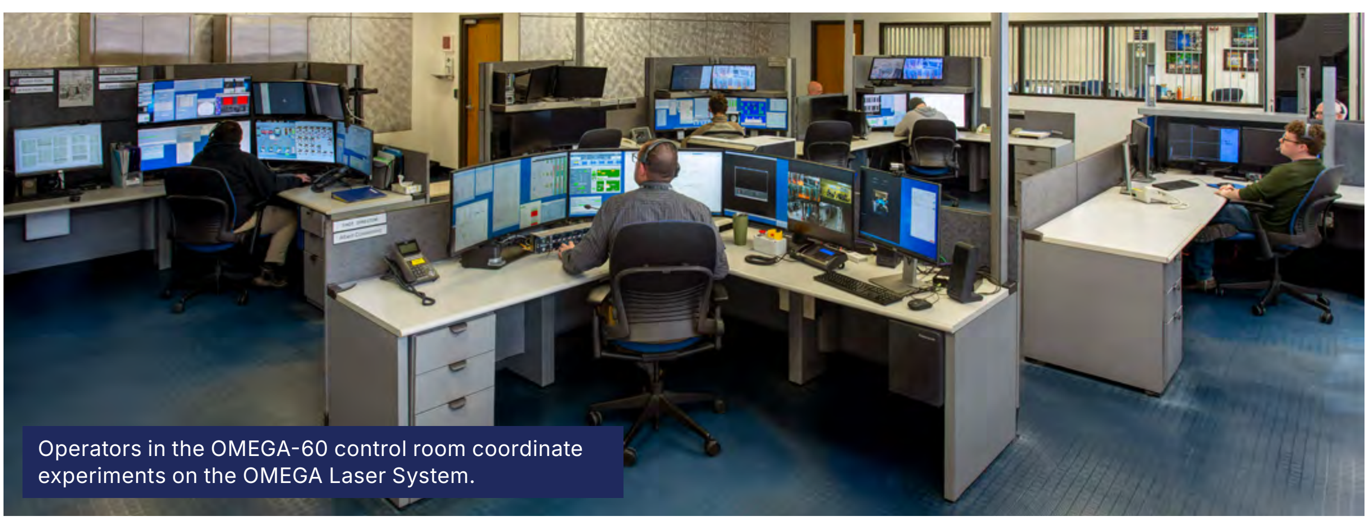
The unprecedented productivity, reliability, and effectiveness of OMEGA-60 have long been supported by a shift to formal and disciplined operations introduced by former US Navy submarine captain Steven J. Loucks. Loucks adapted the operational model developed by the US Navy to safely and efficiently operate highly complex nuclear power plants in the dynamic environments where submarines are required. This operational philosophy enables OMEGA-60 to mitigate the risk of human error while rapidly shifting from one experimental platform to another. Additionally, this philosophy enables the disciplined preventative maintenance that has kept OMEGA-60 firing for 30 years.

OMEGA-60's productivity is remarkable. While individual experimental campaigns are awarded single days and executed within them, it would be a misconception to believe that all effort required is completed on that specific day. OMEGA-60 operates similarly to an assembly line factory in which cars are completed at a rapid tempo, but the full production time of each unit is much longer. Every day, LLE is conceiving experiments for the future, planning for those in the midterm, finalizing the details of those approaching, executing today's experiments, and recovering from those past. One stark contrast between LLE's process and that of a typical assembly line is the total customization of each shot day: no two shot days are the same, and OMEGA-60 is able to support significant reconfiguration not only overnight, but also midday.

Tyler Burgett, who started at LLE as a student in 2013 and is now Experimental Operations Group Leader, has experienced this efficiency and productivity firsthand over the course of his career journey: "One thing that stands out from my early days is how much progress has been made over time," he says. "When I first started, we were typically limited to two or three cryogenic shots at most. Now, reaching five shots in a day is much more routine. That kind of improvement reflects not only advancements in capability, but also the importance of teamwork in achieving that success. For students and early-career scientists, my advice would be to keep learning beyond your formal education. Stay curious—if you have a question, pursue it. There is a wealth of knowledge within this organization, and someone here likely has the expertise to help you find the answer."

Laser and materials technology

LLE's Laser and Materials Technology (LMT) Division is a center for innovation at the lab and oversees the design, development, fabrication, and troubleshooting of the high-damage-threshold optics used in experiments at the Omega Laser Facility. This includes laser oscillators, amplifiers, pulse-shaping capabilities, and a significant number of laser diagnostics that are critical for successful operations.



Operators in the OMEGA-60 control room coordinate experiments on the OMEGA Laser System.

NLUF and LBS Users of the Omega Laser Facility by the Numbers

6500+
NLUF shots since 1995

350+
Graduate students and postdocs since 1979

300
Unique NLUF projects since 1979

4000+
LBS shots since 2008

1142
Publications since 2001

319
Unique LBS projects since 2008

LMT's Optical Manufacturing (OMAN) Group is a state-of-the-art facility that provides in-house expertise to ensure that every optical component meets exacting quality and performance standards for every shot conducted on the laser system. OMAN has the primary responsibility of manufacturing high-damage-threshold coatings for the optical components that form the architecture of the laser system design. These optics range in size from 25 mm in diameter to near-meter-diagonal rectangular optics. The thin-film coatings are used to control the direction and properties of the laser beams in terms of reflection or transmission at specific use angles and wavelengths and to control the beams' polarization. The work encompasses areas of thin-film design, material characterization, process development, photometric and interferometric measurement, mechanical tooling design and fabrication, mounting optics, and observations of *in situ* damage on laser optics over their use lifetime. The team maintains a "cradle to grave" approach in the careful handling of these expensive components from initial receipt through processing to installation and use until replacement is required. "Above all, we are passionate about our work in delivering the highest-quality, large-aperture laser optics in the world," says Amy Rigatti, OMAN Group Leader. "The OMAN Group consistently meets the challenges presented by each new laser project, pushing the accuracy and capability of the coating process to deliver components that meet ever more stringent technical requirements."

LMT also invests in ongoing efforts to develop new materials and processes that will support next-generation laser systems for future high-energy-density research. The Fourth-generation Laser for Ultra-broadband experiments (FLUX) laser system, developed by LMT's Laser Development Projects Group, is one such system that was built to meet the challenges faced by scientists in current ICF research—particularly, the laser–plasma instabilities that arise and undermine laser–matter interactions when using laser systems with narrowband beams. In a nutshell, FLUX provides a path to increased bandwidth (i.e., laser beams that emit light over a broad range of wavelengths) by using optical parametric amplification and sum-frequency generation, two nonlinear optical processes, to generate a high-energy, ultrabroadband beam that is then delivered to the OMEGA-60 Target Chamber. Results from FLUX experiments, now currently underway, are essential to ongoing research on laser–plasma interactions and will guide the development of next-generation laser systems at LLE and beyond.

Omega and the Broader Community

NLUF, LBS, and OLUG

With its premier technical capabilities, the Omega Laser Facility serves as a major hub for national and international researchers who are part of LLE's vibrant and engaging open-access programs, including the National Laser Users' Facility (NLUF) and the Laboratory Basic Science (LBS) Program. These two programs account for approximately 25% of shot time on OMEGA-60, and OMEGA EP.

NLUF, a grant program established in 1979 with the DOE, welcomes researchers year-round from universities, government laboratories, and private companies, providing them with access to LLE's laser facilities without direct charge. For nearly 50 years, scientists have flourished under NLUF, making important discoveries and advances in high-energy-density science, materials under extreme conditions, warm dense matter, nonlinear optics, laser–plasma interactions, laboratory astrophysics, atomic physics, nuclear physics, instrumentation development, and more. Since its inception, the program has importantly championed graduate education and training, supporting hundreds of students each year, many of whom have gone on to join DOE national laboratories.

The LBS Program, established in 2008, provides scientists from US ICF laboratories (LLNL, Sandia National Laboratories, Los Alamos National Laboratory, and LLE) as well as scientists from DOE Office of Science Laboratories (Princeton Plasma Physics Laboratory, SLAC National Accelerator Laboratory, and Lawrence Berkeley National Laboratory) with shot time at the Omega Laser Facility. LBS (and NLUF) projects are selected each year through a call for proposals and undergo a rigorous review

Above all, we are passionate about our work in delivering the highest-quality, large-aperture laser optics in the world.

Amy Rigatti
Optical Manufacturing Group Leader

Student and postdoc attendees at the seventeenth Omega Laser Facility Users Group (OLUG) Workshop located at LLE in April 2026.

process administered by LLE. Since inception, the program has granted over 300 awards for projects, of which over 50% have been led by postdoctoral researchers and early career scientists.

The Omega Laser Facility Users Group (OLUG) is another important resource for the high-energy-density physics community. Also established in 2008, OLUG is led by a ten-member executive committee and currently has more than 800 members from more than 70 institutions across 14 different countries. One of the most unique aspects of OLUG is the fact that OMEGA-60 and OMEGA EP users themselves have a direct say in how the facility is optimized. Each spring, the group holds a workshop at LLE to promote research and collaboration opportunities, identify and discuss ways to improve the capabilities of the Omega Laser Facility, and provide researchers—especially students—with a supportive and informal environment in which they can connect with others and showcase their work.

"OLUG is a welcoming community of brilliant and passionate researchers. What more could one ask for! It was not long ago that I became a member, and I cannot think of a moment when I did not feel supported, both technically and otherwise," says Perry Samimy, a UCSD graduate student who presented his research at the OLUG poster session this past April. "This has imbued my OLUG and LLE experience with a sense of being part of something greater than myself—a sentiment I've heard echoed by others, as well—and so deep fulfilment comes along with the interesting science. Suffice it to say that I always leave the annual OLUG workshops feeling inspired and having learned something new!"

Don't be afraid to reach out, ask questions, and get yourself into the lab. Opportunities like OLUG exist precisely for students like us. You just have to take that first step.

Damien Batayeh
Graduate student,
University of Nevada, Reno

With over 50% of Omega facility shots carried out by external users (non-LLE employees) each year, the impact of the laser facility on scientific study across the nation cannot be overemphasized. These programs are vital for keeping LLE—and, more broadly, the US—at the forefront of international research, continuously spurring on the development of scientific and technological innovations that support experiments and operations. The programs also highlight LLE's rich educational atmosphere and directly support NNSA's larger mission of building a next-generation workforce by creating a steady pipeline of trained experts who will lead the way in government, industry, and academia. "For students, there's really no other place to go get experience in big lasers," says Patrick Poole, a staff scientist at LLNL. "The great thing about OMEGA-60 and OMEGA EP is that you can have students come and try their ideas and take them to another laser down the line."

Crosscutting Initiatives with the University of Rochester

As part of a larger academic institution, LLE's Omega Laser Facility has been central to a wide range of research efforts led by undergraduates, graduate students, and faculty across various departments and groups at the University of Rochester. These include the Departments of Chemistry, Physics and Astronomy, Mechanical Engineering, Electrical and Computer Engineering, and the Institute of Optics, which has been a pioneer in optical technology and engineering for nearly a century since its founding in 1929. A shared mission of working toward a better and sustainable future, together with active collaboration between researchers at LLE and the Institute of Optics, in particular, has led to countless strides in the fields of lasers, optical materials, nonlinear optics, optoelectronics, ultrafast optics, and high-field sciences—all of which, in turn, have been vital to experiments conducted at the facility. "LLE has supported Institute of Optics graduate students for many years to work on fundamental science and engineering problems that are important to the next generation of lasers and laser-based systems," says Tom Brown, Director of the Institute of Optics.

By bringing together talent and expertise from multiple fields, such collaborations are a testament to the University of Rochester's commitment to innovation and discovery, and on a broader level, help fuel the Rochester region's unparalleled optics and photonics scene. This is evidenced by the burgeoning STELLAR (Science, Technology, and Engineering of Lasers and Laser Applications Research) ecosystem, a network of academic, industrial, government, and nonprofit organizations dedicated to restoring and advancing US leadership in laser science research, manufacturing, health, energy, and national security applications. Brown and Jon Zuegel, LLE Distinguished Scientist and Professor of Optics, have spearheaded this important effort, ensuring that both the Institute and LLE remain at the forefront of the charge. "I've personally been very grateful for a partnership with Jon Zuegel in working together to establish the STELLAR regional innovation engine—a program that will provide great momentum toward the next generation of extreme laser systems for energy and defense," says Brown.

Another example of an important interdisciplinary and intercollegiate initiative at the University of Rochester is the Center for Matter at Atomic Pressures (CMAP), a National Science Foundation Physics Frontier Center dedicated to the exploration of laboratory astrophysics. CMAP brings together researchers from the University of Rochester, MIT, Princeton University, UC Berkeley, UC Davis, the University at Buffalo, and LLNL, whose combined backgrounds of condensed matter and plasma physics, astronomy, materials science, planetary science, and more will help advance understanding of cosmic phenomena. On OMEGA, researchers can recreate the extreme temperature and pressure conditions found only in the core regions of stars—conditions that for years were inaccessible and only understandable from a theoretical perspective. "Today, if you want to study an astrophysical event like a supernova remnant, for example," says Dave Canning, OMEGA EP Laser Facility Manager, "we can create those conditions in the target chamber using our lasers."

Future Frontiers

As LLE looks to the next 30 years, what lies ahead for the Omega Laser Facility? First and most importantly is facility's sustainment. Experiments are conducted year-round at the facility, and over time, instruments and systems age and need to be upgraded or replaced. For laser systems as massive, complex, and powerful as OMEGA-60 and OMEGA EP, this is essential for enhancing performance, lowering operating costs, and continuing to drive world-class research and innovation while ensuring the safety of every member of the lab. Current sustainment projects at LLE focus on OMEGA-60, especially the optimization of beamlines, experimental operations, amplifier technology, power conditioning, and laser sources.

> *LLE is the go-to institution for high-energy-density science—developing next-generation capabilities like FLUX will enable fusion energy and underpin the nation's stockpile stewardship for decades to come.*
>
> **Dustin Froula**
> *LLE Distinguished Scientist and PULSE Division Director*

With this in mind, LLE is currently developing plans for a possible next-generation upgrade to OMEGA-60, which would serve LLE and the larger high-energy-density and inertial fusion energy communities well into the 2040s. The facility, OMEGA Next, is envisioned to complement the laser capabilities at LLNL with a laser system large enough to handle higher energy levels and repetition rates than those available at LLE today. Precision diagnostics, advanced computing systems, artificial intelligence and machine-learning techniques, and fourth-generation drivers will be key to realizing this effort. This facility will enable both direct-drive and indirect-drive ICF approaches to be studied—each of which is limited by laser–plasma instabilities. Therefore, continued research on mitigating these instabilities is crucial and lies at the heart of current experiments on LLE's FLUX laser system, which will define the requirements that will be needed for this next-generation facility. In addition to contributing to NNSA's missions of stockpile stewardship, education, and workforce development, OMEGA Next will have a significant educational, economic, and scientific impact on the Rochester region, New York State, and the nation at large by creating further employment opportunities for hundreds of individuals while driving technological growth and progress for future generations.

From the visionary scientists who conceptualized and laid the initial foundations of LLE to today's technicians, scientists, students, and staff who on a daily basis run, manage, and conduct experiments on OMEGA-60, this year's 30th anniversary goes beyond a celebration of the laser system itself and the countless individuals who have made its achievement possible. Ultimately, this anniversary is also a celebration of curiosity and wonder, and what it means to be human—to ask questions, to explore, and to strive to better understand and change the world around us. In short, this year's anniversary epitomizes the University of Rochester's Meliora values, to which LLE continues to be committed as it trains and nurtures the next generation of future leaders.

Corresponding author: R. Shojaie

Chirped-Pulse Amplification at 40

LLE's Nobel-Winning Innovation that Revolutionized Laser Science

Introduction

Forty years ago, when then-LLE graduate student Donna Strickland was racing to submit her very first scientific research paper outlining a new technique that she and her advisor Gérard Mourou had developed, she was confident that they were about to forever transform the entire landscape of laser science. Chirped-pulse amplification (CPA), Strickland and Mourou's revolutionary innovation, was a brilliant solution to a simple question: how can scientists safely achieve extremely high levels of laser power without damaging the laser system itself? The technique, now used today in a wide range of applications including high-energy-density physics, industrial machining, medicine, and beyond, earned Strickland and Mourou the 2018 Nobel Prize in Physics and remains a defining moment in LLE's legacy of innovation.

The story of CPA continues to resonate with those beyond the high-energy-density–physics world for a multitude of reasons—perhaps the most salient of which is that, at its core, CPA is a powerful reminder that a single student and mentor have the potential to make a big difference and have a lasting impact on their own field of study and on society at large. As CPA continues to shape the scientific world, it serves as a guiding light for LLE, which looks ahead with excitement, renewed vigor, and dedication to its mission of training the next generation of scientists who will lead the way into the future.

History

In order to appreciate the true power of CPA, it is useful to understand why and how the technique was developed. What was the technological landscape of laser systems prior to its invention, and what were some of the challenges that researchers were facing at the time?

In the two decades following physicist Theodore Maiman's first demonstration of the laser in 1960, dramatic leaps and bounds were made in the development of laser technology, with numerous advances in quantum optics, semiconductor manufacturing, spectroscopy, and more. Soon, scientists were venturing further into unexplored frontiers of laser science like nonlinear optics, the study of the interaction between intense

Gérard Mourou, left, photographed in Rochester in 1987, and Donna Strickland, right, aligning an optical fiber in her lab at LLE in 1985. The pair shared half of the 2018 Nobel Prize in Physics "for their method of generating high-intensity, ultrashort optical pulses."

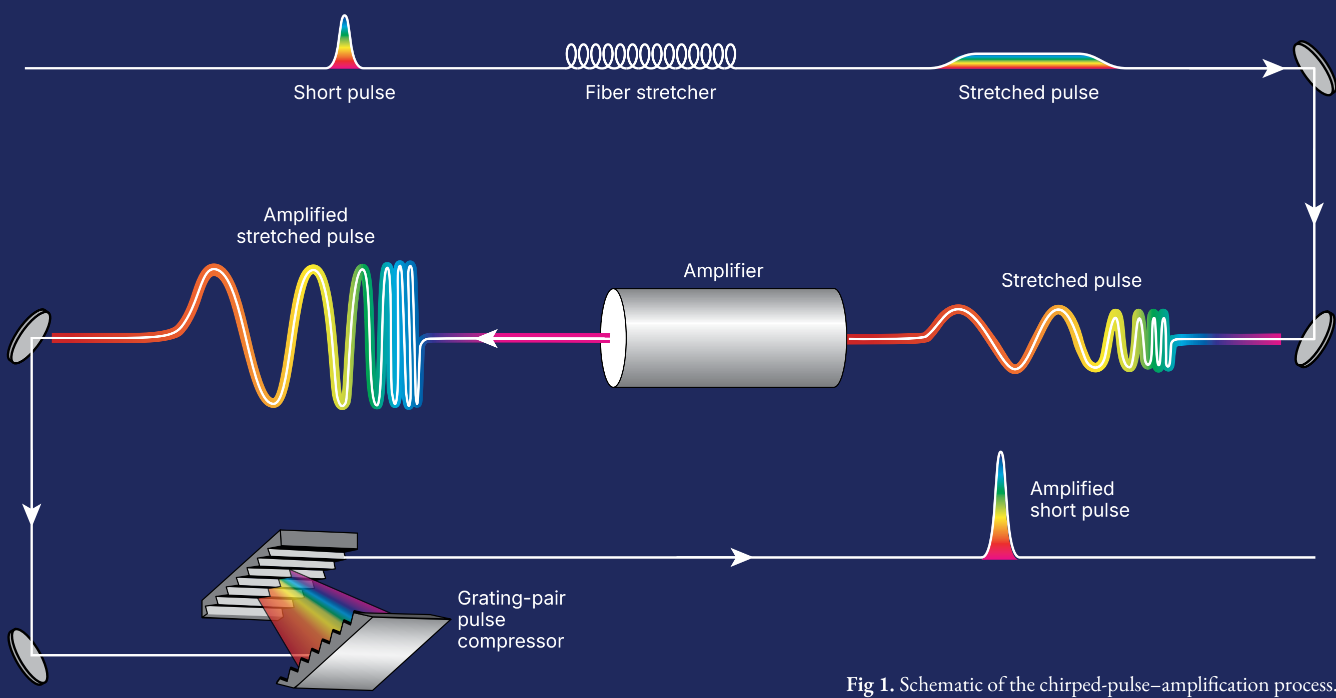


Fig 1. Schematic of the chirped-pulse–amplification process.

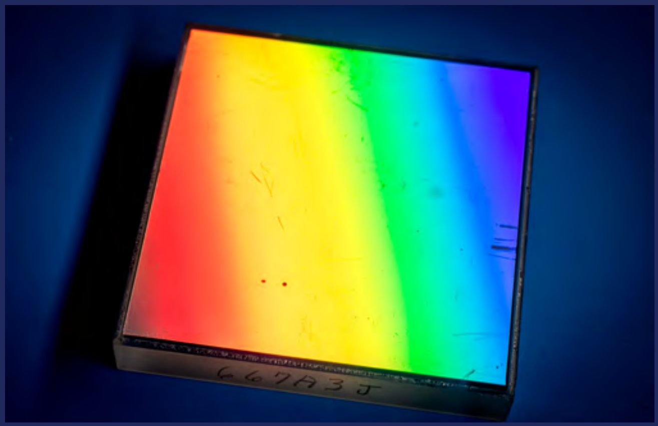
light and matter. As they pushed the boundaries of laser peak power, however, scientists soon realized that they had come to a literal breaking point in terms of the levels of intensity their optics could handle. They found that once power surpassed a certain threshold, the nonlinear effects of the laser system optics would cause the beams to self-focus, resulting in catastrophic and irreparable damage. Essentially, peak power was limited due to these self-focusing effects.

How, then, did scientists propose to circumvent this problem and reach higher levels of power? On the table were two options: the first, to build a physically larger laser system, was monumentally cost prohibitive due to the sheer scale of the components required. It was also slow and inefficient for a variety of reasons, including the time needed for the system's optical amplifiers to cool down after each shot. The second option, on the other hand, took a different approach entirely by proposing a unique alternative: to somehow manipulate the laser beams themselves in a way that would overcome these damaging nonlinear effects.

This was precisely the hypothesis that one scientist, Gérard Mourou, was mulling over in his lab at LLE in the early 1980s. He estimated that if the initial laser pulses could be spaced out, amplified, and then brought back together, the result would produce laser pulses of a much higher intensity [1]. In a nutshell, it was this combination of stretching, amplifying, and compressing the laser pulse—essentially, packing more energy into a short amount of time—that proved to be key. Donna Strickland, a young graduate student at the University of Rochester who had come on board at LLE after expressing interest in laser research, was tasked with making Mourou's hypothesis a reality. "It is the one time in my life that I worked very, very hard!" says Strickland, who was one of only three women in her class pursuing a PhD in physics at the time [1]. Inspired by the "chirp" technique that helped overcome limitations in radar technology, Strickland sought to apply a similar concept here [2].

Experiment and Breakthrough

Their experiment was simple and elegant in its execution: first, Strickland used a mode-locked, neodymium-doped yttrium aluminum garnet (Nd:YAG) dye laser to produce a short, 150-ps pulse, which would be chirped and "stretched" as it passed through a 1.4-km length of optical fiber, reducing its peak power [3]. This allowed the pulse to then be safely amplified to a greater energy level by way of an Nd:glass regenerative amplifier, as shown in Fig. 1. Finally, Strickland used a setup of two parallel diffraction gratings, which acted like prisms, to recompress the pulse back to its original duration—but now with a dramatically higher intensity and without any damage to the laser system or optics. "It is truly an amazing feeling when you know that you have built something that no one else ever has—and it actually works," says Strickland [1].



One of the gratings used by Donna Strickland in her original CPA research at LLE. Two damage spots, caused by trying to compress too much energy into the compressed pulse, can be seen in the lower left of the grating.

Strickland and Mourou's paper on this work, a mere three pages in length, was titled "Compression of Amplified Chirped Optical Pulses" and published in *Optics Communications* in December 1985, well before Strickland graduated with her PhD in optics in 1989. As further advances were made in laser technology, particularly in the form of the 1990 Ti:sapphire laser, which had several important advantages such as broad bandwidth, high damage threshold, and excellent thermal conductivity, CPA was able to fully take off and be implemented on laser systems small and large, at facilities across the nation and around the world.

Following CPA and LLE, Strickland went on to work at several important institutions across Canada and the United States, including the Canadian National Research Council, Lawrence Livermore National Laboratory, Princeton University, and the University of Waterloo, where she is currently a professor in the physics and astronomy department. After leaving LLE, Mourou brought CPA to the University of Michigan in 1988, where he went on to become a founding director of the Center for Ultrafast Optical Science, a multidisciplinary research center dedicated to the study of ultrafast laser science and its applications and home to NSF ZEUS, the most powerful laser system in the United States. Mourou later returned to France in the early 2000s, where he held several leadership positions in academia and beyond, including a directorship at the Laboratory for Applied Optics at the École Polytechnique. Most notably, Mourou proposed the establishment of a pan-European laser facility, which is today known as ELI (Extreme Light Infrastructure) Beamlines—one of the world's most important research centers for high-intensity laser science.

It is truly an amazing feeling when you know that you have built something that no one else has–and it actually works.

Donna Strickland

Out of the Lab and Into Everyday Life

As with many major inventions that seamlessly become part of the fabric of everyday life, it can be easy to forget just how transformative the invention of CPA was—and indeed how versatile and ubiquitous its modern applications are. Here are just a few of the ways in which CPA is being used today to touch the lives of ordinary people and further shape our scientific understanding [4]:

Corrective Eye Surgery

Laser-assisted *in situ* keratomileusis, or LASIK, is perhaps the most well-known example of corrective eye surgery performed today. In LASIK surgery, surgeons use femtosecond laser pulses in lieu of a scalpel to make a precise incision in the cornea of the eye, which is then reshaped to correct the patient's vision.

Radiotherapy and Oncology

In proton therapy, a noninvasive form of radiation therapy used by physicians to treat cancer, high-powered lasers are used to accelerate protons, which can be precisely targeted to destroy tumors—particularly deep-tissue tumors such as those that form in the brain.

Ultrafast Imaging

CPA techniques have helped advance ultrafast medical imaging such as MRI, enhancing our understanding of biological processes in real time. In fusion energy research, CPA is essential for ultrafast photography of fusion implosions and other split-second processes.

Industrial Machining

Did you know that the cover glass on your smartphone was made possible by CPA? With its high-precision capabilities, femtosecond laser technology is used in the machining of brittle materials like cover glass, the micromachining of circuit boards for semiconductor manufacturing, and more.

Laboratory Astrophysics

The high-intensity pulses generated by CPA are crucial for the study of astrophysical phenomena because they allow scientists to replicate within a laboratory setting the extreme temperature and pressure conditions found only in stellar cores and black holes.

CPA in Laser Research Today

In the four decades since its achievement, CPA has been a catalyst for advancing global progress in laser research, continuously spurring on new developments in optics, high-energy-density science, astrophysics, plasma physics, and beyond. An invention born of a simple idea and limited resources, CPA now underpins experiments at all major ultrahigh-power laser facilities around the world, including the Extreme Light Infrastructure facilities in Europe, the Central Laser Facility at Rutherford Appleton Laboratory in the United Kingdom, LaserNetUS and LaserLab Europe facilities, NSF ZEUS at the University of Michigan, and the OMEGA EP (Extended Performance) Laser System at LLE, which is one of the two laser systems (the other being the OMEGA Laser System) that make up the Omega Laser Facility.

The MTW-OPAL Group at LLE.

In addition, it is thanks to the achievement of CPA that LLE scientists and engineers were able to develop two of the laboratory's midscale lasers: the Multi-Terawatt (MTW) laser and the MTW-OPAL (optical parametric amplifier line) Laser System—each of which have been pivotal for further advances in laser technology at the lab and are described in detail in *LLE In Focus*, Issue 1. In operation since 2005, the MTW laser was the first high-power laser at LLE after the tabletop terawatt (T-cubed) laser on which Mourou and Strickland first demonstrated CPA. Built as the prototype front end for the OMEGA EP Laser System, MTW has a shot count of over 178,000 for a wide range of experiments that have focused on laser diagnostic development, ultrafast plasma physics, nonlinear optics, and more. MTW employs a nonlinear optical process called optical parametric amplification (OPA) to boost the energy of an initial broadband "seed" pulse by transferring energy from a high-energy laser pulse to it.

OPA is the basis of the MTW-OPAL Laser System, an all-OPCPA (optical parametric chirped-pulse–amplification) system and the second of LLE's midscale lasers. The system has proven to be a fertile and hands-on environment at the lab for training scientists, laser operators, and engineers, and serves as the prototype for one of the most exciting initiatives happening at LLE today: NSF OPAL, LLE's next big laser system. Funded by the National Science Foundation, this proposed new ultra-intense laser user facility will push beyond current peak-power limits and will be dedicated to exploring ultrahigh-intensity laser–matter interactions. "CPA is a state-of-the-art technique that's still being used to push lasers to higher and higher intensities," says Jonathan Zuegel, LLE Distinguished Scientist and Professor of Optics at the University of Rochester, who is at the head of the NSF OPAL effort [4]. NSF OPAL will feature two 25-PW lasers (that is, 25 thousand trillion watts of power) and have the capability of delivering 500-J, 20-fs pulses—500,000 times the power of the original Nd:YAG laser used by Strickland and Mourou. Set to become the world's most powerful laser, NSF OPAL will be a remarkable achievement made all the more special by the fact that the new laser system will be housed near the very site of the old lab in which CPA was invented 40 years ago.

Looking Ahead

In the brief four decades since the invention of CPA, tremendous strides have been made in ultrafast laser science, paving the way for countless innovative technologies that have impacted the lives of millions while shaping our collective understanding of the universe as we know it. Today, scientists are pushing peak power to the extremes—with laser pulses reaching ever higher intensities and ever shorter durations, even into the attosecond realm where pulses are as short as one quintillionth of a second—and expanding the horizons of a wide range of fields that explore the behavior of matter and molecular interaction. In addition, these same scientists are training and guiding the next generation of students who will one day take on the mantle of pushing these frontiers even further.

CPA holds a unique place at LLE and the University of Rochester, not only as a remarkable and impactful scientific achievement, but also because it represents the very best that is possible when curiosity is championed, students are supported, and collaboration is encouraged at every level of expertise. The invention of CPA did more than overcome a technological limitation: it fundamentally changed the trajectory of laser science and opened the doors to entirely new realms of discovery. Today, that same spirit continues to drive advances in ultrahigh-intensity laser–matter interactions, attosecond science, fusion energy research, and next-generation facilities such as NSF OPAL. At this year's anniversary celebration, we honor Donna Strickland, Gérard Mourou, and their collaborators, and celebrate the spirit of innovation that gave birth to CPA—a legacy that continues to inspire the next generation of scientists and will help define the laboratory's future for the next 40 years and beyond.

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Corresponding author: R. Shojaie

Ever Better: Stories of Learning and Collaboration at LLE

During his doctoral studies at LLE, David Bishel remembers asking a senior scientist about a problem he was struggling with. Without hesitation, the scientist invited David over to his office and promptly handed him an original print of an article he had published on the exact same subject more than 30 years ago. "It is this immediate access to such a high level of expertise in plasma physics, high-energy-density physics, diagnostics and detectors, laser systems, and more, that's one of the most beneficial aspects of being a student at LLE," says Bishel, who graduated from the the University of Rochester's Department of Physics and Astronomy in the fall of 2024. "My experience is one of countless examples of the ongoing legacy of expertise cultivated at LLE," Bishel says.

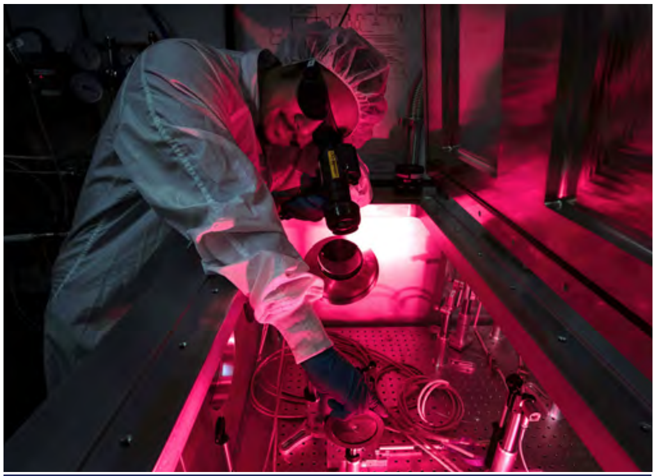
Bishel's experience does not surprise Dustin Froula, LLE Distinguished Scientist and PULSE Division Director. "The laboratory's deep commitment to research and innovation changes the professor–student dynamic," Froula says, adding that "the presence of more than 150 professionals with advanced degrees in the facility makes it easier to teach students about the latest developments in various fields." In that sense, LLE functions as both a working laboratory and an unparalleled learning environment.

Feeding a Talent Pipeline

Growing demand for skilled professionals in STEM fields has made the development of a robust, well-trained workforce more important than ever. LLE is committed to strengthening and expanding the workforce pipeline, which is key to sustaining momentum and accelerating progress in critical areas while supporting the larger mission of the National Nuclear Security Administration (NNSA) and National Security Complex. "We do this by providing students with the opportunity to develop the practical skills required to contribute to large and complex scientific efforts while also exposing them to environments far beyond their typical experiences," Froula says. The rewards are readily apparent—particularly in the job offers new graduates receive. Manfred Virgil Ambat, for example, defended his doctoral thesis this past spring and had an offer from Los Alamos National Laboratory before he even completed his studies.

Internships, scholarships, and awards such as the Horton Fellowship Program, for example, which was established in 1993 to honor the legacy of the late Congressman Frank J. Horton—a dedicated supporter of LLE's mission—go a long way in supporting graduate students during their time at LLE. The fellowship covers tuition costs, grants stipends to doctoral

LLE doctoral students and advisors at the 2026 commencement ceremony at the University of Rochester. From left to right: William Donaldson, Jessica Shaw, Atma Anand, Nitish Acharya, Kelin Kurzer-Ogul, Abigail Armstrong, Manfred Virgil Ambat, Christopher Danly, Katarina Nichols, Zachary Manning, Kristen Churnetski, Chris Deeney, Wayne Knox, and Petros Tzeferacos.



Graduate student Manfred Virgil Ambat working in the MTW-OPAL Laser Facility. LLE provides students with hands-on research experience in state-of-the-art laser laboratories during their education.

students, and has benefited over 260 fellows over the years. "The Horton Fellowship has helped bring full circle my dreams of becoming a scientist, and sharing that passion with [younger] students has been immensely rewarding," says Ambat.

Outreach Starts Early

In keeping with the spirit of feeding the talent pipeline, "It's important to start the process early," says Diane Boni, Director of the Undergraduate Research Program at LLE. The institution's outreach programs for Rochester-area high schools are part of this effort. "We want to reach students earlier in their high school career, before they've really mapped down a program of study, so they have an improved awareness about post-high school opportunities in STEM fields, and so that they can plan their courses for their junior and senior years," Boni says.

The eight-week Summer High School Research Program offers incoming seniors a peek into LLE's advanced facilities. Accepted students are assigned to a research project and supervised by a staff scientist or engineer. In addition, LLE's six-week summer Broad Exposure to Science and Technology (BEST) program, held at East High School in the Rochester City School District, exposes underrepresented students and their teachers to STEM-related research activities.

For undergraduates, the laboratory also offers mentored research experiences throughout the year, welcoming new students to the programs in both the fall and spring semesters. Through its Summer Undergraduate Education Program, launched in 2023, LLE hosts undergraduate researchers from the University of Rochester, Rochester Institute of Technology (RIT), and other colleges and universities around the country. Weekly seminar sessions highlight career development and different parts of the research experience. Students attending institutions in the Rochester area have the option to continue working on projects with their mentors even after the summer term has ended, and in some cases, a remote collaboration option is also available to students from outside the area.

One of the highlights of the undergraduate program is the unique opportunity for students to participate in an LLE-organized trip to visit and tour national laboratories, including Lawrence Livermore National Laboratory, Los Alamos National Laboratory, the Nevada National Security Site, and other facilities. The trip, which was launched in 2024, has been eye-opening for many, including Matthew Harmon-Prendas, a current electrical and computer engineering major. "I had always assumed that the national lab environment was mostly centered around the work of physicists, but I learned that engineers play a vital role in daily operations, even representing a majority of the technical staff," says Harmon-Prendas. "This trip has inspired me to learn more about the science of fusion, which will eventually benefit all humanity."

Inspiration fuels the rest of the summer research experience, and every day, students from high school all the way to the graduate school level have the chance to meet and interact with their peers, share their research, and take part in informal mentoring opportunities. Boni has witnessed graduate students helping undergraduate researchers prepare their research posters and share advice about life as a science researcher—a testament to the encouraging and supportive atmosphere LLE strives to create through its educational programs.

Collaborative Use of LLE Facilities

In addition to training the next generation of scientists, LLE also opens the doors of its facilities to researchers from other institutions. During scheduled collaborative shot days, external researchers work together with various teams at LLE to conduct experiments on the facility's high-power laser systems. Krish Bhutwala, a scientist from Princeton Plasma Physics Laboratory, remembers his shot day during his graduate studies at the University of California, San Diego. "In a single day, scientists from around the world come together to peek at nature's inner clockwork for a few select moments—an experience like no other," he says.

To facilitate further collaboration and the judicious use of the Omega Laser Facility, LLE launched the National Laser Users' Facility (NLUF) program in 1979, and for nearly 50 years, the program has enabled researchers to make leaps and bounds in the fields of high-energy-density physics, inertial confinement fusion, and beyond. NNSA funds the NLUF experiments through its Office of Experimental Sciences, allowing users to conduct basic science experiments without incurring direct facility charges. Limited target support for NLUF experiments is also provided by General Atomics and funded by NNSA. An open call for NLUF experiments goes out every two years, and applications are merit-reviewed by an independent committee. Projects are weighed based on their scientific and technical merit, feasibility, and impact. Mingsheng Wei, LLE Senior Scientist and manager of the NLUF and Laboratory Basic Science user programs, says the biggest challenge with the program is that demand always exceeds availability. Wei encourages researchers from multiple institutions to form collaborative teams with members working on different aspects of a project.

Researchers gather at the 2026 Omega Laser Users Group workshop to share results, foster collaboration, and engage with the facility and the federal sponsoring agencies.

This same spirit also lies at the heart of the Omega Laser Facility Users Group (OLUG) community, which is comprised of over 800 users from more than 70 institutions. Since 2008, LLE has hosted an OLUG workshop every April to facilitate communication, collaboration, and networking.

Kickstarting Lifelong Careers

LLE's comprehensive education initiatives have paid rich dividends, and students of every level regularly comment on the value of the cutting-edge research they have been able to perform, the mentorship they have received, and the career opportunities that have been made possible to them.

"My supervisor and the scientists with whom I work treat me, a student, as their equal and take the learning process incredibly seriously," says Pericles Farmakis, a mechanical engineering graduate student at URochester. "They not only encourage students to take up real responsibilities as theory or experimental principal investigators on projects worth hundreds of thousands of dollars but also offer classes no other university offers and leave their doors open for you, should you need anything. What students are encouraged to do at LLE is a unique endeavor in the US and the world. You come to realize the importance of collaboration, perseverance and resolve to extend human knowledge to new heights with your personal input."

While education and collaboration have expanded the talent pipeline for national laboratories and government agencies, private industry has also benefited from these relationships. Alison Christopherson, Head of Target Design at Xcimer Energy, did her graduate research at LLE and went on to become a staff scientist at Lawrence Livermore National Laboratory before joining Xcimer, a laser-fusion startup working to commercialize inertial fusion energy. The Xcimer team recently conducted and experiment on OMEGA as part of an NLUF campaign with the goal of generating experimental data to directly inform Xcimer's hohlraum design work, providing validation required for system-level confidence.

> *What students are encouraged to do at LLE is a unique endeavor in the US and the world.*
>
> **Pericles Farmakis**
>
> *Graduate Student, University of Rochester, LLE*

Margaret Huff, who received her PhD from the University of Rochester in 2023 and now works at Sydor Technologies, a manufacturer of imaging diagnostic systems, is grateful for LLE's role in shaping her career. "The skills I built at LLE have allowed me to contribute to the field of fusion both during my time as a postdoc at Los Alamos National Laboratory and now as a Solutions Scientist at Sydor Technologies," Huff says. "By enabling access to world-class scientists and staff, as well as facilities, LLE has provided me with a foundational knowledge of high-energy-density physics and diagnostic technology. The support provided to me as a graduate student made a huge difference in the way I interact with the field as an early-career professional now."

Looking Ahead

Over five decades, LLE's community of researchers, engineers, students, and collaborators has made countless strides across scientific discovery, technological development, and applied innovation—deepening our understanding of the physical world and producing capabilities that exist nowhere else. These achievements have largely been made possible by the laboratory's longstanding investments in educational and collaborative research opportunities for students and scientists of all levels. As new facilities, infrastructure, and outreach programs are being developed and refined, LLE looks ahead with renewed commitment to inspiring, nurturing, and empowering younger generations who will tackle tomorrow's challenges and carry the legacy forward.

This material is based upon work supported by award numbers Department of Energy (DOE) National Nuclear Security Administration DE-NA0004144; DOE DE-SC0024863, DE-SC0025573, DE-SC0024415, DE-SC0025517, DE-SC0021057, and DE-SC0022979; U.S. National Science Foundation 2329970 and 2205521; Department of Defense; Air Force Office of Scientific Research FA9550-23-1-0475 and FA9550-24-1-0160; Empire State Development Corporation C230113; Lawrence Livermore National Laboratory B629597 and B668277; Sandia National Laboratories PO 2663743, PO 2300100, and PO 2646399; Savannah River National Laboratory Subaward 800006058; Lawrence Berkeley National Laboratory Subcontract 7742075; Commissariat à l'énergie atomique 3957; Johns Hopkins University Subawards 2004758202 and 181839; European Research Executive Agency Project 101095207; Princeton University SUB0000841; Sydor Technologies; Seurat Technologies; Focused Energy DE-SC0025517; and Xcimer Energy. Sponsor information is subject to ongoing changes and reflects details available as of the publication date.