UNIVERSITY OF ROCHESTER
LABORATORY FOR LASER ENERGETICS

LLE IN FOCUS

SPRING 2024 | VOLUME 1, ISSUE 2

FOCUS ON INERTIAL CONFINEMENT FUSION

LASER-DRIVEN ICF

THE PATH TO ROBUST IGNITION PLATFORMS

UNIVERSITY of ROCHESTER

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250 E. River Rd.
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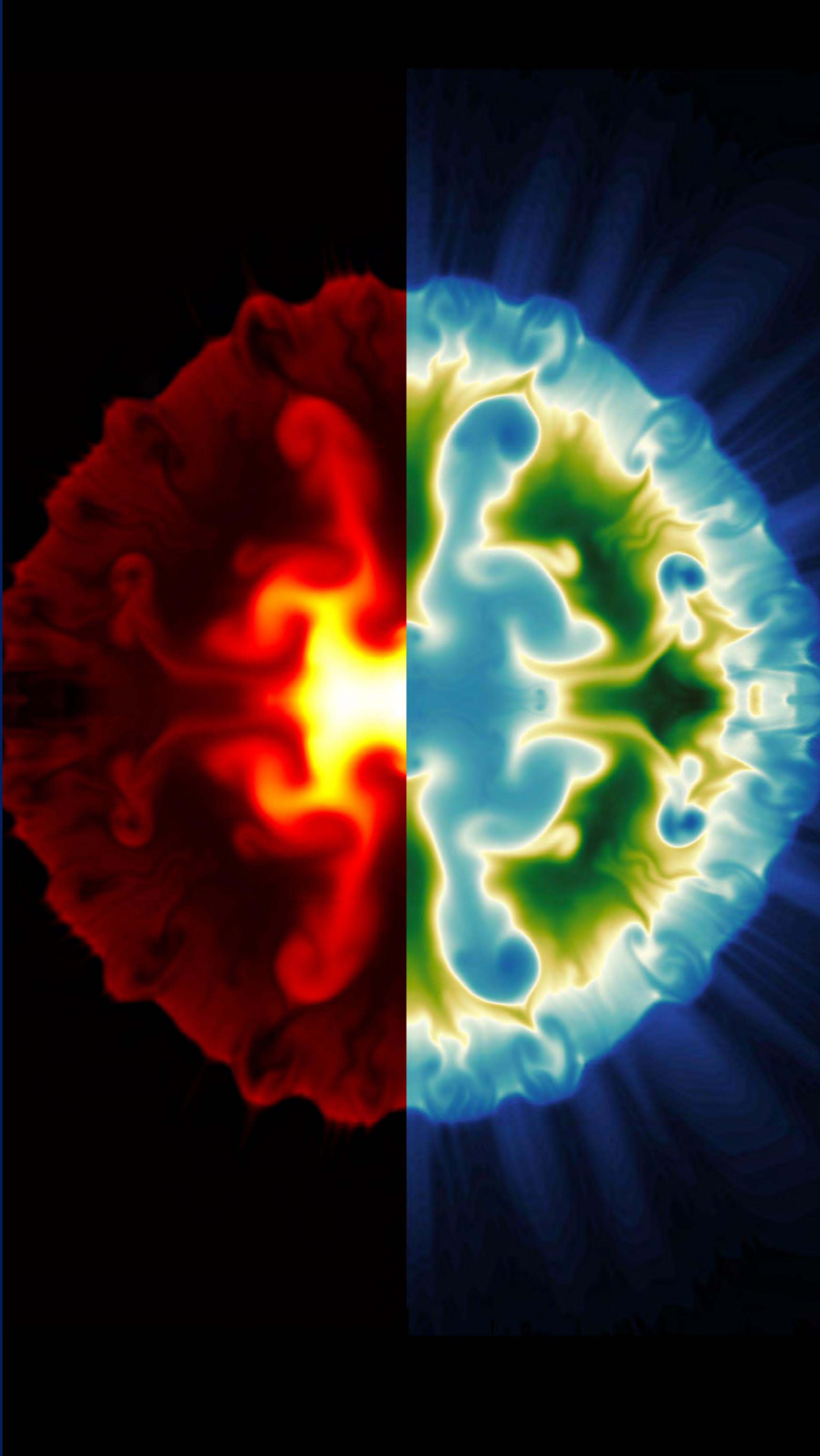
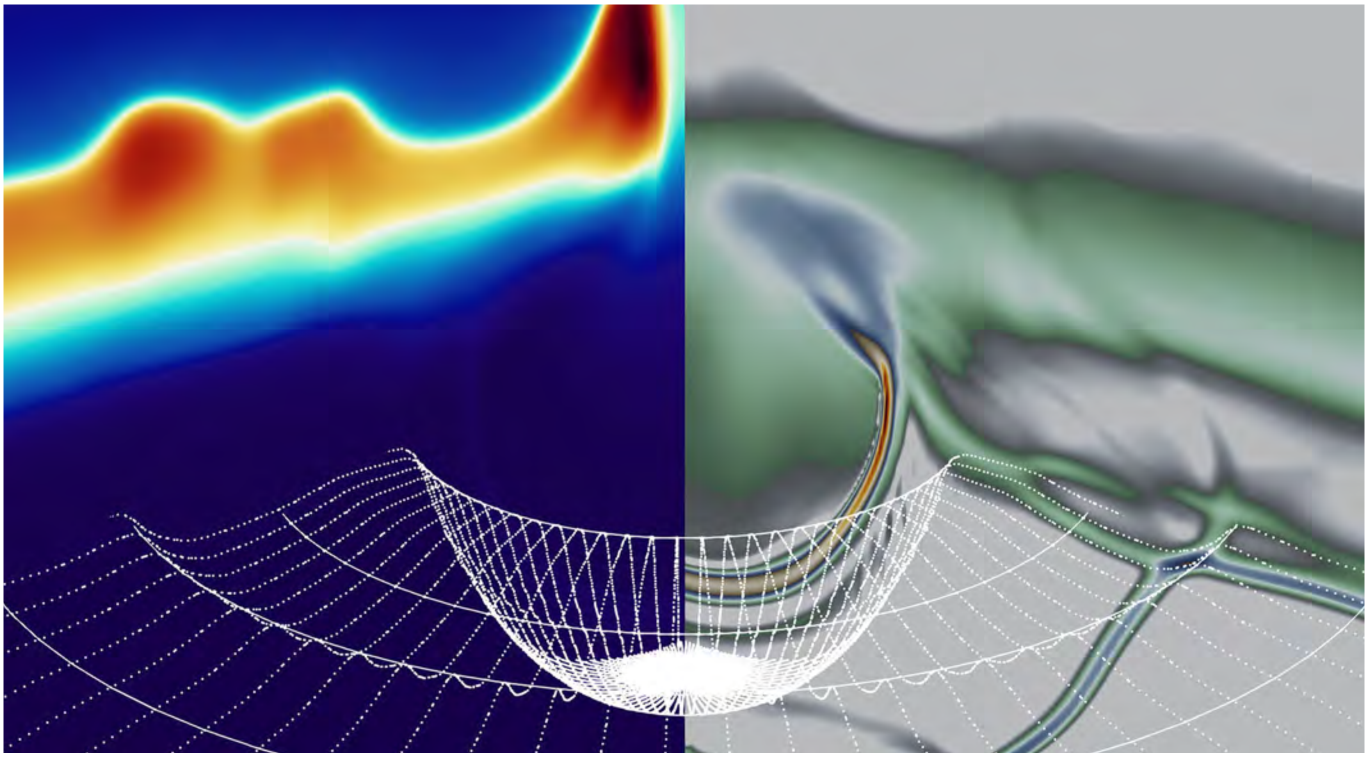


LLE IN FOCUS

Focus on: ICF

Spring 2024
Volume 1, Issue 2



Complex details of the evolution of target defects in inertial confinement fusion are modeled using the low-numerical-dissipation, high-order spatial accuracy hydrodynamic code, CYGNUS, developed at LLE. Displayed are mass density (left), inverse pressure scale length (right), and a low-density isosurface (white lines) showing the bubble of material injected into the hot spot by hydrodynamic instability growth.

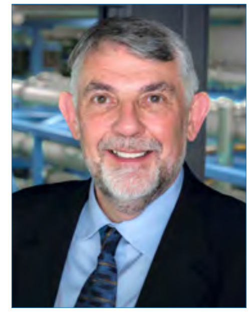
About the cover

The complex evolution of deuterium–tritium fuel in inertial confinement fusion implosions at LLE is modeled using the multiphysics hydrodynamic code DRACO. Shown are mass density (front cover) and ion temperature (back cover) maps of OMEGA shot 82717 near peak fuel compression.

LLE IN FOCUS

From the Director

DR. CHRISTOPHER DEENEY | DIRECTOR, LABORATORY FOR LASER ENERGETICS



In February 2024, I attended the National Nuclear Security Administration (NNSA) Academic Programs meeting in Washington, DC. Many of the talks focused on experiments conducted on OMEGA or OMEGA EP by researchers, ranging from graduate students to senior professors. Additionally, the pervasive impact of our facilities was acknowledged by several NNSA managers. Running these facilities is a great service which we provide the community, in both supporting our own mission-driven program as well as the community's research agendas. More than 50% of the experiments at our facilities go to external users. Much of the research involves training graduate students and this quarterly report introduces some awesome new students who have completed their PhDs here at the University of Rochester.

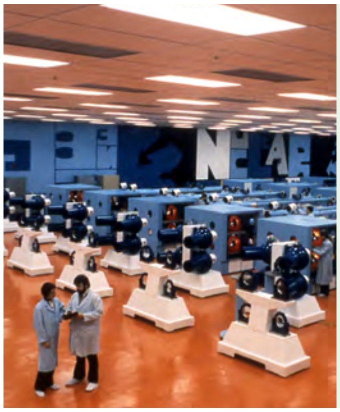
This issue has a technical focus on fusion. Laser-direct-drive fusion is a key scientific challenge for which LLE is the technical lead for NNSA. Back in the early '90s, as the National Ignition Facility (NIF) was in its planning stages, direct drive was an option, but indirect drive (i.e., using a hohlraum) was the primary plan. Polar-direct-drive experiments have been used on the NIF, but ignition was ultimately achieved using indirect drive. It has been a complex, challenging journey to ignition, and great credit goes to the amazing teams and leaders at Lawrence Livermore National Laboratory (LLNL)—including Mike Campbell, Ed Moses, and Mark Herrmann—for the vision of building the NIF, for the construction of an excellent laser, and for the ten-year-plus scientific journey post-construction (2009) to the demonstration of iginition in 2022. LLNL involved the community and led a successful set of experiments, collectively demonstrating gain >1. In this issue, we describe LLE's contributions to this journey to ignition. As a real demonstration of the educational value of our Omega facilities, both the lead experimenter and designer for the ignition shot, Alex Zylstra and Annie Kritcher, respectively, conducted their PhD research at Omega.

Well, what about direct-drive fusion? Does ignition with laser indirect drive limit the future? The answer is "No." First, at the scale of Omega, direct drive is the only method to train future students on the complex physics of inertial confinement fusion. Second, LLE has advanced community knowledge since the early 1990s when the NIF was first envisioned. New laser technologies, discussed in Issue 1 of *LLE in Focus*, will enable a new path to direct fusion, which is discussed in "Laser-Driven Inertial Confinement Fusion: The Path to Robust Ignition Platforms," p. 20. These paths open up avenues for ignition at a much lower laser energy than the NIF (note: still bigger than presently available on Omega) and a route to coupling megajoules of energy to a capsule which could enable high-yield fusion. An exciting future indeed!

Christopher Deeney
Director, Laboratory for Laser Energetics

First Focus

In LLE History



40
years ago

The original OMEGA 24-beam Laser System fired its 10,000th shot.

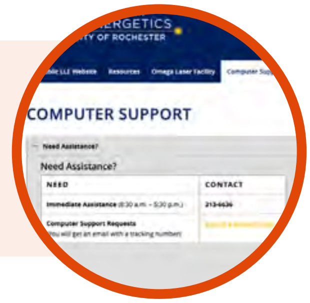
20
years ago

The OMEGA EP building construction was completed in December 2004.

Fast Facts

5113

LLE computer support requests were processed in 2023.



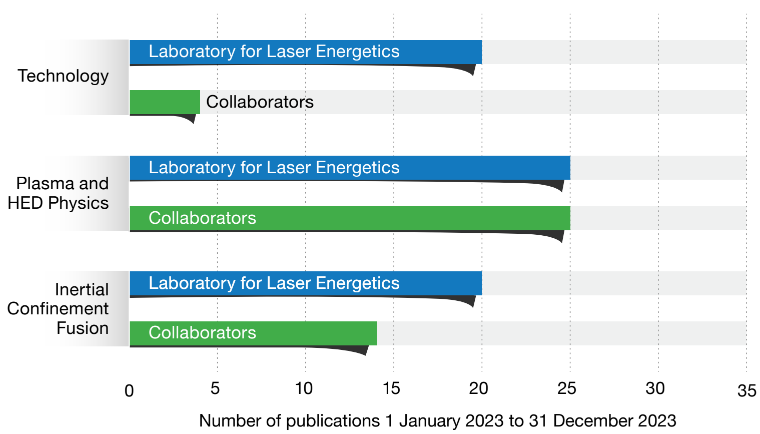
224,000

work hours were put into the LLE Office and Lab expansion.

>1.2M

lines of code have been written for over 200 custom programs produced by LLE's Software Development Group.

Publications



Research Highlights

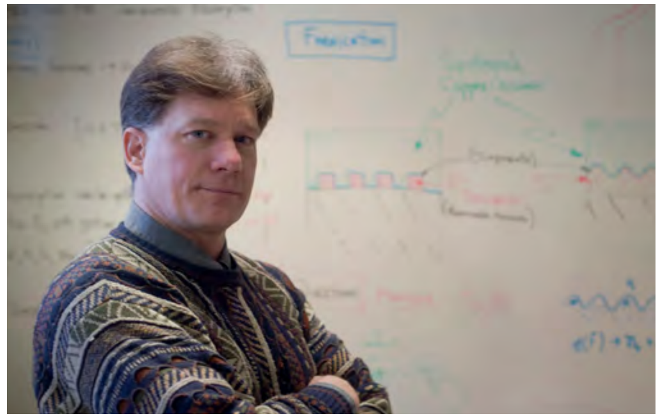
The science and engineering research at LLE is captured through peer-reviewed publications, which include LLE lead-authored (blue bars) and LLE co-authored papers (green bars). LLE averages more than 100 published articles annually across three broad areas: Technology, Plasma and High-Energy-Density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

LLE EXCELS

Awards and Honors

David Turnbull Receives Thomas H. Stix Award

David Turnbull received the 2023 Thomas H. Stix Award for his outstanding contributions in pioneering experiments on plasma photonics and laser–plasma instability. Demonstrating exceptional scientific leadership, Turnbull has developed into a significant national player in both indirect-drive and direct-drive inertial confinement fusion programs. Turnbull's prolific publication record of over 50 articles includes one in *Nature Physics* and eight in *Physical Review Letters*. His work as a graduate student at Princeton University, as a postdoctoral fellow at Lawrence Livermore National Laboratory, and currently as a scientist at LLE has been of the highest caliber.



Terrance Kessler Elected Optica Fellow

Terrence Kessler, Senior Research Engineer and Diversity Manager, was elected a Fellow by the Board of Directors of Optica. This award recognizes distinguished scientific achievements in the optics and photonics community. He was recognized "for pioneering innovations in the technology and applications of large-aperture optics used for fusion and chirped-pulse–amplification lasers." Terry's pioneering work on phase plates and laser beam smoothing has had a major impact on OMEGA, OMEGA EP, and the National Ignition Facility. Terry has also made significant contributions to the development of diffractive optics, including gratings for beam smoothing, the OMEGA EP grating tiling system and diffractive color corrector, and flying focus.

Lavonne Mack Receives HEDP Scholarship

Lavonne Mack, a first-year graduate student in the University of Rochester's Physics and Astronomy Department received the 2023 High-Energy-Density–Physics (HEDP) Scholarship. Mack is advised by John Palastro, a Senior Scientist in the Laser–Plasma Physics Group. She will be exploring the application of structured light and structured plasmas to advance laser-driven accelerators.

2023 Capt. Loucks Awards

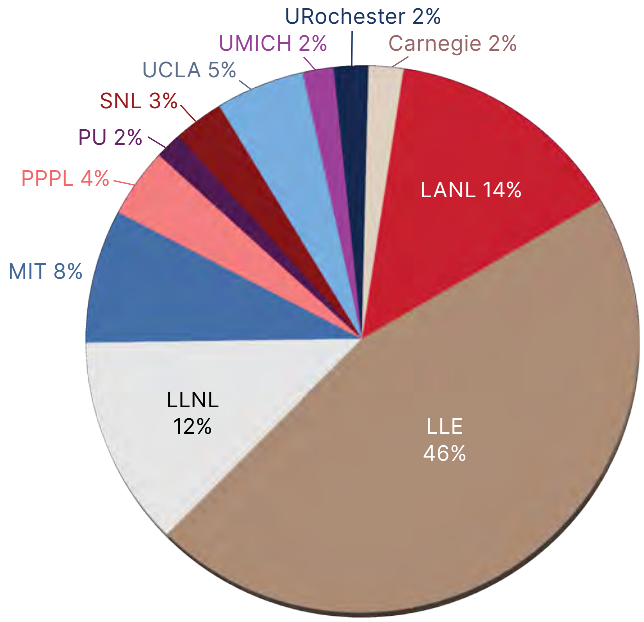
The Capt. Loucks Award recognizes individuals who have made exceptional contributions that exemplify a commitment to operations and safety in any area of the Omega Laser Facility. The recipients, Mason Schleigh, Richard Dean, Jeffery Konzel, Benjamin Stanley, and Heath Ferry (left to right) are shown here holding plaques detailing their recognition. They are flanked by Capt. Steven Loucks (top left) for whom the award is named, LLE Director Chris Deeney (top right) and Omega Facility Division Director, Sam Morse (far right).

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 Program, National Laser Users' Facility, and Laboratory Basic Science, in addition to other research and educational efforts (see Fig. 1). During the first quarter of FY24, the Omega Laser Facility conducted 251 target shots on OMEGA and 192 target shots on OMEGA EP for a total of 443 target shots. OMEGA averaged 92% availability and 90% experimental effectiveness. OMEGA EP averaged 94% availability and 93% experimental effectiveness.

FY24TD Omega Laser Facility Site Summary

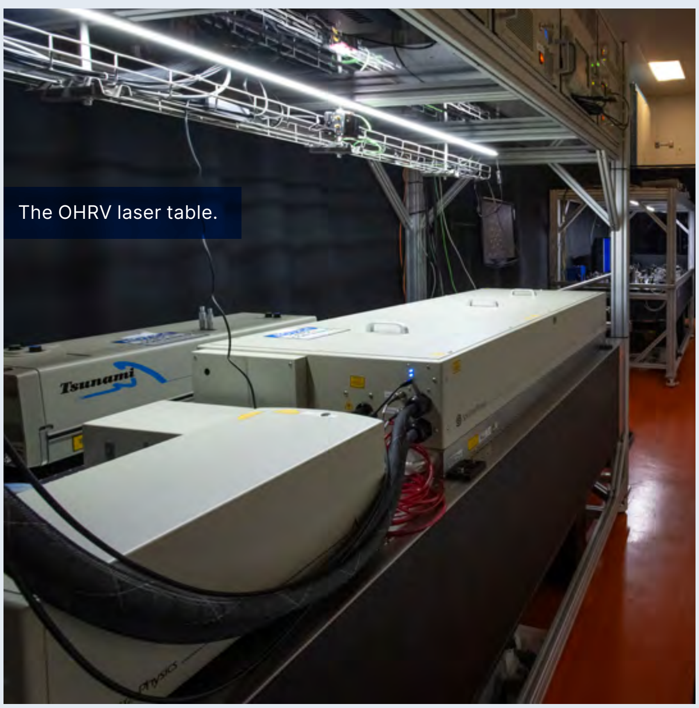


Carnegie:	Carnegie Institution for Science
LANL:	Los Alamos National Laboratory
LLE:	Laboratory for Laser Energetics
LLNL:	Lawrence Livermore National Laboratory
MIT:	Massachusetts Institute of Technology
PPPL:	Princeton Plasma Physics Laboratory
PU:	Princeton University
SNL:	Sandia National Laboratories
UCLA:	The University of California, Los Angeles
UMICH:	The University of Michigan
URochester:	The University of Rochester

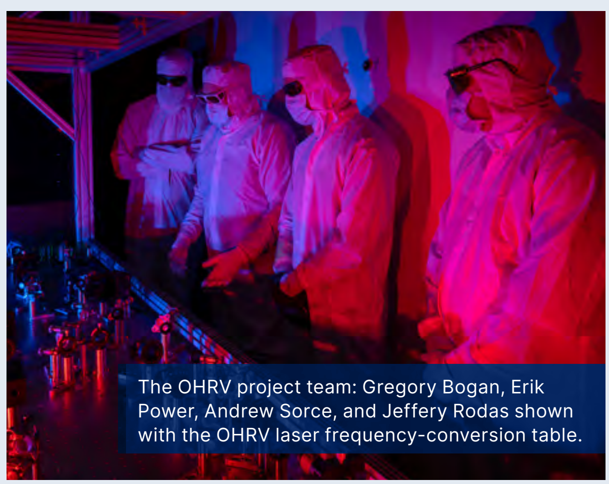
Figure 1. LLE provides a large portion of experimental opportunities to researchers from around the country.

OMEGA High-Resolution Velocimeter (OHRV) Laser

The OMEGA Laser System hosts a broad user base, which contributes to the experimental platform at LLE. One diagnostic platform, the OMEGA high-resolution velocimeter, is the result of a long-standing collaboration with scientists from Lawrence Livermore National Laboratory. After a decade of use, the source laser for this diagnostic has been upgraded. The laser was relocated to improve system access for operations and maintenance.



The OHRV laser table.

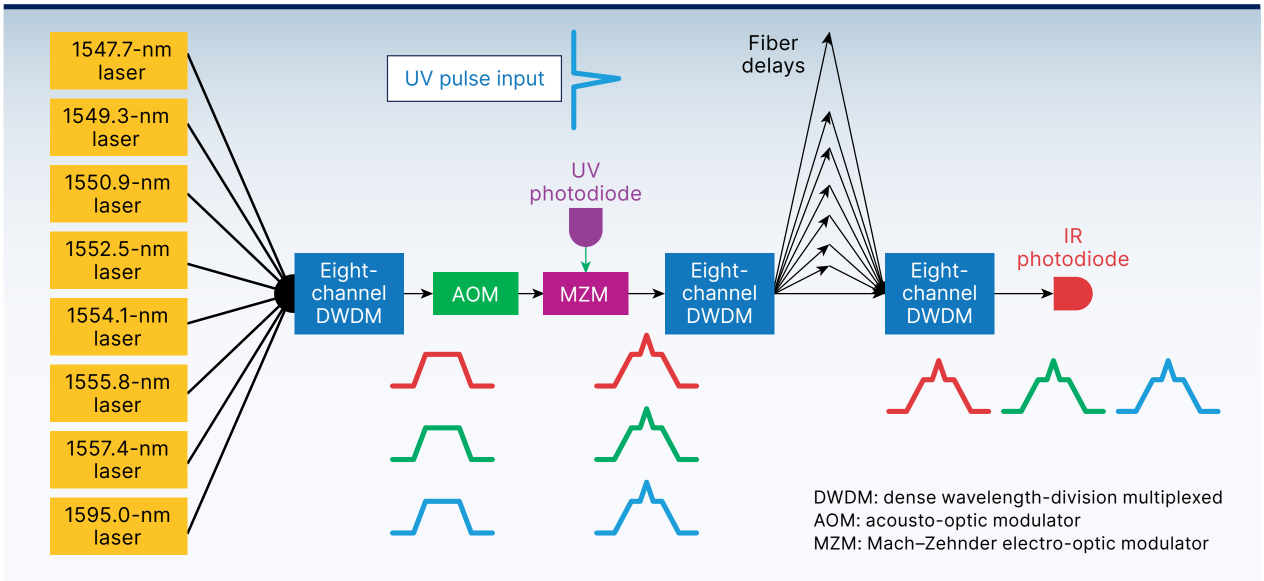


The OHRV project team: Gregory Bogan, Erik Power, Andrew Sorce, and Jeffery Rodas shown with the OHRV laser frequency-conversion table.

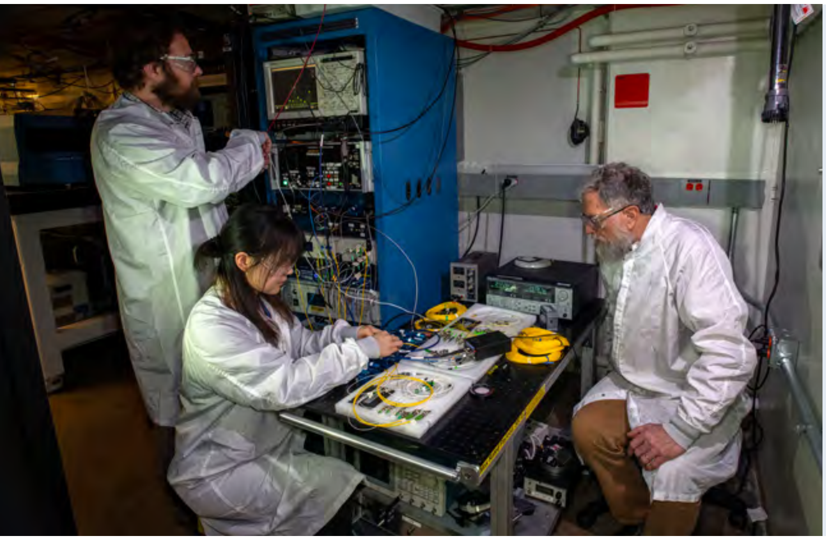
New UV Pulse-Shaping Diagnostic Development

LLE scientists pride themselves on the high quality of experimental data collected during routine operations at the Omega Laser Facility. One specific characteristic that is accurately measured is the ultraviolet pulse shape. The pulse-shape measurements enable researchers to understand the laser pulse incident on the target and to use this information to decipher important target physics. For many years, the university has depended on streak cameras to make these high-fidelity pulse-shape measurements on the 60-beam OMEGA Laser System. As the target system ages, LLE is investing in a new generation of diagnostics based upon the latest innovations in technology. A fiber-optic measurement approach to pulse shape measurements is currently being prototyped in the facility with OMEGA laser pulses.

Ultraviolet pulse shapes can be difficult to measure due to both the limited options for photodiodes and the inability to transmit laser pulses over long distances of fiber. To overcome these challenges, the new LLE design will use an ultraviolet photodiode developed in-house to encode the pulse shape into multiple infrared signals. These signals will be separated by wavelength and transmitted over variable fiber delays to make a train of pulses, which can then be averaged to improve the signal-to-noise ratio of the measurement.



Readily available telecom laser sources are dense wavelength-division multiplexed to a single fiber where an acousto-optic modulator is utilized to make flat optical pulses. The ultraviolet (UV) signal on a fast photodiode provides the voltage to a Mach–Zehnder electro-optic modulator to write the pulse shape onto the infrared (IR) pulses simultaneously. The signal is replicated into variable fiber lengths to temporally separate the pulses into a pulse train that can be analyzed for high-fidelity pulse-shape measurements.



One of the core tenets of LLE's mission is to train the next generation of scientists. We do this by including students in cutting edge research. Senior Scientist William Donaldson (right) currently leads a team including graduate student Yihan Liu (center) and Research Engineer Matthew Heimbueger (left) on the design of this system.

Focus on Omega Amplifiers

OMEGA and OMEGA EP are powered by amplifiers that energize our laser pulses. Each amplifier contains neodymium-doped phosphate glass, which is pumped by flashlamps immediately prior to light traveling through them. Between OMEGA and OMEGA EP, there are more than 9200 flashlamps that populate the 292 amplifier heads. There are four different amplifier designs and each contains a unique flashlamp size. A flashlamp is energized using a pulse of up to 13 kV of electricity at the time of shot and then water-cooled to extract heat. These flashlamps regularly require maintenance, with 1250 annual flashlamp service exchanges. Regular inspections identify flashlamp issues, but lamp failures can be serviced during the shot cycle of the laser system. Thanks to the excellent team of amplifier technicians, the Omega Laser Facility achieves a high availability of experimental time each year.

Lab Specialist Josh Reindl inspecting amplifiers on OMEGA EP.

Corresponding author: J. Puth (jput@lle.rochester.edu)

LLE graduate student Alex Chin aligning a beam splitter.

LLE GRADUATE STUDENTS

The Future of Science

One of the most enduring aspects of LLE and its unique position as part of the University of Rochester is its strong educational mission. The laboratory's dedication to providing high school, undergraduate, and graduate students with integrated hands-on research opportunities, from summer programs and internships to fully funded fellowships, has made a significant impact on the lives and careers of over 500 students in the past five years. The laser systems at LLE—the largest in any academic setting and the foremost user facility in the world for high-energy-density (HED) physics—offer students a world-class research experience in addition to vital workforce and career-building opportunities.

In 2023, LLE celebrated the achievements of 19 graduate students—five of whom earned their PhD degrees within the last quarter and are highlighted here. The doctoral work of Shihui Cao, Alex Chin, Dhrumir Patel, Grigoriy Tabak, and Connor Williams pushes the frontiers of HED science and inertial confinement fusion (ICF) research. Some of the many contributions made by these talented and innovative young scientists include improving the predictive capabilities for laser–plasma instabilities, optimizing cryogenic target implosions in direct-drive ICF, and expanding our knowledge and understanding of the behaviors of matter at extreme pressures and temperatures found within the cores of planets and stars. The scientists and staff at LLE offer their congratulations to Shihui, Alex, Dhrumir, Grigoriy, and Connor as they embark on the next chapter of their careers.

Dr. Shihui Cao

Department: **Mechanical Engineering**
Advisor: **C. Ren**

Following the recent ignition breakthrough at the National Ignition Facility (NIF) in December 2022, direct-drive ICF has become an attractive candidate for a fusion energy source due to its high laser–target coupling efficiency. The Laboratory for Laser Energetics is currently leading a vigorous program to show that when Omega experimental results are hydrodynamically scaled to NIF laser energy levels, direct-drive ICF can achieve ignition. A critical unknown, however, is how laser–plasma instabilities (LPIs) will scale with laser energy and target sizes. Will the NIF laser be able to couple to the target with the same efficiency and uniformity? Can LPI-generated hot electrons be controlled at a level that would avoid preheating the fuel, thereby preventing ignition?

Shihui's Cao's doctoral thesis has mapped out a path with a predictive capability for LPI, particularly in terms of hot-electron generation. During his research, Shihui developed a methodology for combining 2D and 3D particle-in-cell (PIC) and hydrodynamic simulations to predict, the generation of hot electrons during an implosion. With further input from experimental data, this method has not only been shown to be capable of predicting hot-electron generation in Omega warm implosions within experimental uncertainty, but can also potentially be applied to NIF-scale experiments. Shihui's work has demonstrated promise for PIC simulations to be used as a first-principles–based predictive tool for LPI in direct-drive ICF. After graduation, Shihui will be working as a postdoctoral researcher at the University of Rochester to develop high-performance plasma simulation codes for a novel optoelectrical chip.

> “For me, scientific research represents an expedition into the realm of the unknown, and **I deeply appreciate the assistance provided by everyone at LLE on this journey.**”

“Working at LLE has been an amazing opportunity, allowing me to perform cutting-edge research and learn from some of the great scientists in the field. **This experience has given me the tools to succeed in my next steps moving forward.**”

Dr. Alex Chin

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

With the discovery of thousands of new exoplanets, novel experimental techniques are required to understand the behavior of matter at the atom-crushing pressures found within planetary cores. Alex Chin's graduate research focused on using x-ray absorption fine-structure spectroscopy to analyze the impact of these extreme conditions on the wave functions of iron oxides. To accomplish this, many experimental improvements were required. First, Alex identified new emission phases of the implosion x-ray sources and optimized the x-ray source design by increasing the x-ray output. Second, he designed and built a new x-ray spectrometer for absorption spectroscopy measurements.

The new spectral resolution—a key enhancement of this x-ray spectrometer—enabled the first near-edge absorption measurements at these conditions, as well as the characterization of the behavior of iron valence electrons and their interaction with neighboring oxygen atoms. Alex then used these improvements to measure the x-ray absorption spectra of Fe_2O_3 when compressed to core conditions of super-Earth exoplanets. The near-edge absorption measurements he found indicated how neighboring oxygen atoms perturbed the iron wave functions as the oxygen atoms were compressed toward the central iron atom. Alex's research opens new avenues for understanding how atomic wave functions are changed at the extreme conditions found at planetary cores. Alex will continue working at LLE in the High-Energy-Density Experimental Group and on Department of Defense contracts.

> My time at LLE has been an incredibly rewarding journey. The stimulating environment, talented colleagues, and impactful research opportunities have not only fueled my curiosity but also enhanced my skills and knowledge. **It was an invaluable experience and will certainly remain an important chapter in my life.**

Dr. Dhrumir Patel

Department: **Mechanical Engineering**
Advisor: **R. Betti**

Dhrumir Patel earned a bachelor's and master's degree in aeronautical engineering at Gujarat University, India, and Imperial College London, UK, respectively, before joining the University of Rochester for his PhD studies. He was awarded a Horton Fellowship by LLE in 2016 to carry out research in ICF at the Omega Laser Facility under the supervision of Professor Riccardo Betti.

"Dhrumir is a very creative scientist and an original thinker," says Betti. Dhrumir's thesis focused on the analysis of cryogenic implosion experiments at the Omega Laser Facility. In studying the effects of laser bandwidth on the growth of hydrodynamic instabilities in laser-fusion implosions, Dhrumir found that laser bandwidth greatly improves performance when implosions are designed near hydrodynamic stability limits. "This is a very important finding that resulted from a large collaboration within LLE led by Dhrumir and Dr. James Knauer," says Betti. These results were recently published in *Physical Review Letters*.

In addition, Dhrumir discovered a way to improve temperature measurements in laser-fusion implosions. His analysis of the signal used in these measurements was hailed by both reviewers of his paper in *Physics of Plasmas* as "an important contribution to the understanding in the field" and "an excellent piece of work and [...] a very enjoyable read." Dhrumir is currently employed as a postdoctoral researcher by the University of Rochester's Mechanical Engineering department. In this role, he focuses on experimental diagnostics related to ICF experiments and utilizing machine-learning techniques to enhance cryogenic implosions on the OMEGA laser.

Dr. Grigoriy Tabak

Department: **Physics and Astronomy**
Advisor: **G. W. Collins**

At extreme pressures and temperatures, such as those deep within the cores of planets, stars, or in an ICF capsule, the properties of materials can be dramatically different from those at ambient conditions. While LLE has done pioneering work in studying high-pressure materials with dynamic, laser-driven compression, a complementary methodology exists for static compression, where small samples are essentially squeezed between two diamonds.

Greg Tabak's graduate work focused on combining static and dynamic compression methods by precompressing materials with diamond anvil cells (DACs) to several GPa and then using laser-driven shocks to compress them further to several hundred GPa. The precompression, which varies the initial density of a material, makes it possible to span a wider range of pressure–temperature conditions. Greg applied this technique to study methane (CH_4) and neon, measuring their equations of state and optical reflectivity.

Greg's work also connects to the ongoing ICF effort and other dynamic experiments that use hydrocarbon plastic ablators with different stoichiometries (CH and CH_2). Methane is one of the "ices" predicted to exist in giant planets such as Neptune. In his experiments, Greg was able to document the insulator-to-conductor transition in methane for the first time, where the compound transforms from an insulator to a highly reflective and conductive state, suggesting that this transition is in fact driven by the dissociation of methane itself. Equation-of-state measurements of shocked hydrocarbons like methane will help to calibrate planetary interior models and improve future experimental designs that use plastic ablator layers.

Neon, on the other hand, is predicted to have unusual electronic properties at extreme conditions. The precompression with DACs therefore makes it possible for neon to span a "grid" of pressure and temperature conditions, and decouple the effects of each, showing that reflectivity decreases with pressure in neon. This is an unusual behavior since most materials, including hydrogen and helium, demonstrate the opposite trend.

> **"Planning and executing experiments at LLE has been a unique and enjoyable learning experience that gave me a strong foundation for my scientific career.** The team here is fantastic and I am deeply grateful to my colleagues and mentors for their invaluable support."

Dr. Connor Williams

Department: **Physics and Astronomy**
Advisor: **R. Betti**

Connor Williams graduated with a bachelor's degree in physics and minor degrees in mathematics and Spanish from Villanova University in 2019. He then joined the University of Rochester's Physics and Astronomy department to pursue a PhD under the supervision of Professor Riccardo Betti.

Connor's doctoral research focused on improving the fusion output of current laser-driven implosions on the OMEGA laser. For his thesis, Connor designed a new class of targets and laser pulses with the goal of achieving the highest fusion yields on the OMEGA laser. He studied the stability of these targets and developed a laser pulse that maintains stability while attaining the highest implosion velocities. His designs and analyses were published in *Physics of Plasmas* in 2021.

The remaining task was to carry out an experiment to determine whether his designs could break the previous yield record of 200 trillion fusion reactions on OMEGA. These designs were tested in 2022 and a new yield record was established. "Connor has achieved what we thought was impossible until a few years ago: an output of 300 trillion fusion reactions from a single implosion," says Betti. While analyzing the experimental results, Connor discovered that a subset of OMEGA implosions, including those using his designs, produced more fusion energy than the energy stored within the fusing plasma itself. This finding, defined as "fuel gain above unity," is a milestone for laser fusion, and Connor's exemplary paper was recently accepted for publication in *Nature Physics*.

Connor is currently a staff scientist at Sandia National Laboratories, where he brings his deep knowledge of implosion physics to enhance the performance and understanding of pulsed-power–driven implosions on the Z machine.

"I will forever be grateful for my LLE experience. **LLE taught me how to be a scientist and continually placed me in positions to grow as a scientific communicator.** I am proud to be an alumnus of LLE and look forward to returning home for experiments in the future."

On December 5, 2022, researchers at Lawrence Livermore National Laboratory's (LLNL) National Ignition Facility (NIF) made the historic breakthrough of carrying out the first-ever nuclear fusion reaction to successfully achieve ignition—meaning the amount of energy released by the reaction was greater than the amount of laser energy used to drive it. The ability to harness nuclear fusion, a process that occurs naturally in the Sun and other stars, could have major implications for providing a clean and abundant supply of energy on Earth.

Although the realization of true fusion power is still a long way off, this accomplishment is a vital step forward and the result of extraordinary efforts by scientists, engineers, and researchers on the NIF and facilities across the country, including LLE. In fact, this milestone event validates the laser-driven implosion techniques that scientists at LLNL and LLE have closely collaborated on for decades. LLE's contributions to the pursuit of ignition are vast and include advances in laser technologies, diagnostics, simulation capabilities, physics understanding, and more. As the largest university-based US Department of Energy program in the nation, LLE is perfectly poised as a unique national resource for education in science and technology. Many of the students who trained at LLE's Omega Laser Facility have been recruited by national laboratories, and several were directly involved in this experiment, with LLE scientists participating in the review of the ignition results.

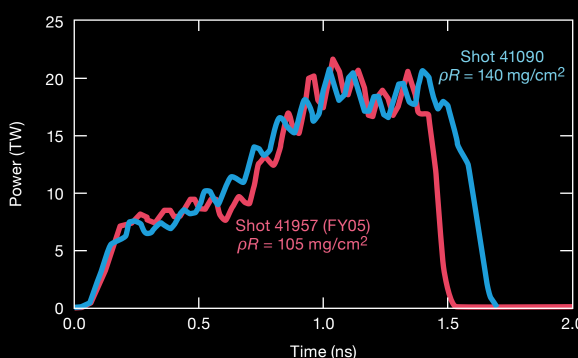
LLE'S CONTRIBUTIONS TO IGNITION

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Lawrence Livermore National Laboratory

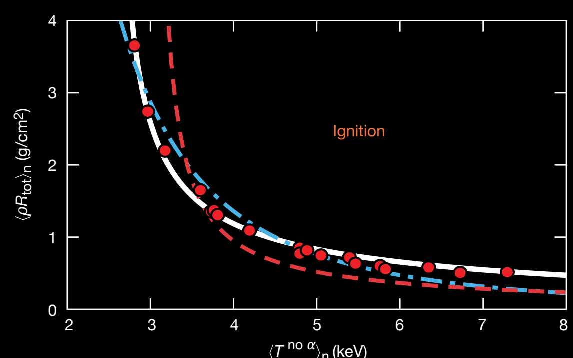
SHELL COAST



LLE was the first to investigate the effect of shell coast (time between the end of laser pulse and start of shell deceleration) on target performance. Minimizing the coast time was the key to achieving ignition on the NIF.

P. B. Radha *et al.*, Phys. Plasmas **18**, 012705 (2011).

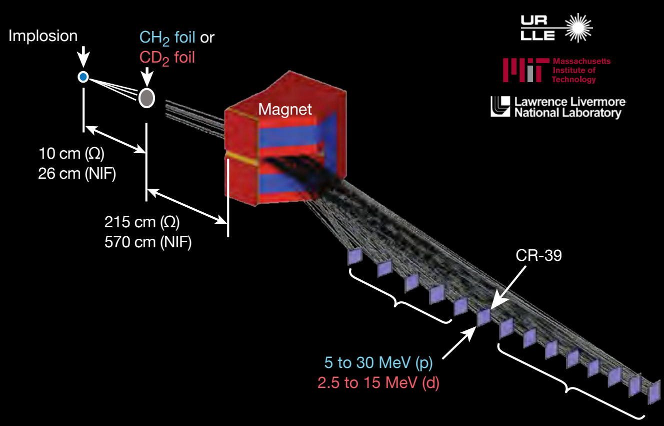
MEASURABLE LAWSON CRITERION FOR ICF



The first Lawson criterion for inertial confinement fusion (ICF) using measurable parameters was developed at LLE.

C. D. Zhou and R. Betti, Phys. Plasmas **15**, 102707 (2008); **16**, 079905(E) (2009).

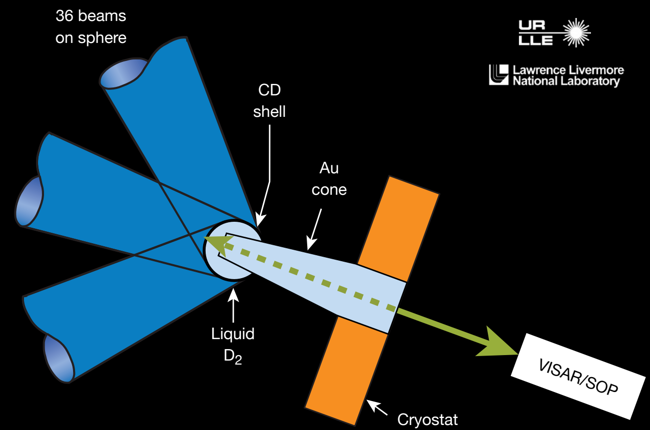
MAGNETIC RECOIL SPECTROMETER



The magnetic recoil spectrometer (MRS) at the Omega Laser Facility made the first measurement of compressed DT areal density. It was the basis for LLE and MIT designing, building, calibrating, and operating an MRS on the NIF to measure the neutron spectrum and the first compressed DT areal-density measurement on the NIF. The MRS measures absolute DT yield, which is used with LLNL activation measurements to give high-confidence yields of record.

J. A. Frenje *et al.*, Rev. Sci. Instrum. **79**, 10E502 (2008); T. C. Sangster *et al.*, Phys. Rev. Lett. **100**, 185006 (2008); D. T. Casey *et al.*, Rev. Sci. Instrum. **84**, 043506 (2013); A. J. Mackinnon *et al.*, Phys. Rev. Lett. **108**, 215005 (2012).

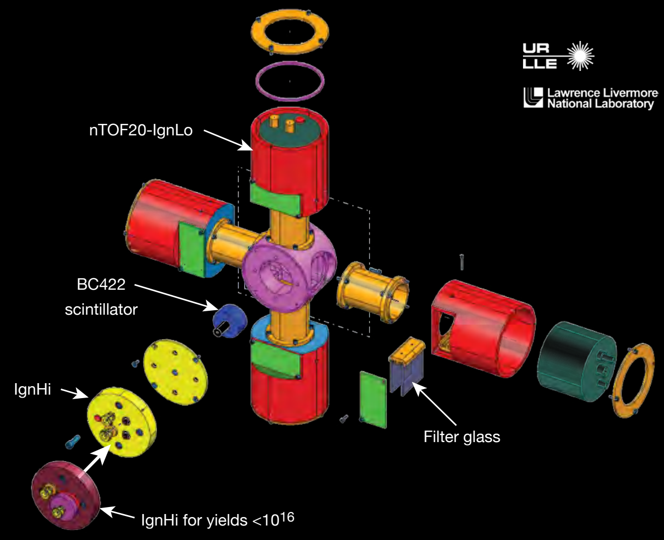
SHOCK-TIMING TECHNIQUE



Ignition experiments on the NIF use a line velocity interferometer system for any reflector (VISAR) shock-timing technique developed by an LLE–LLNL team and validated by experiments at the Omega Laser Facility. The team also developed and used a 2D shock breakout VISAR on OMEGA to infer ablator melt in the foot of NIF laser pulses.

T. R. Boehly *et al.*, Phys. Plasmas **16**, 056302 (2009); T. R. Boehly *et al.*, Phys. Rev. Lett. **106**, 195005 (2011); H. F. Robey *et al.*, Phys. Plasmas **19**, 042706 (2012); H. F. Robey *et al.*, Phys. Rev. Lett. **108**, 215004 (2012); S. J. Ali *et al.* Phys. Plasmas **25**, 092708 (2018).

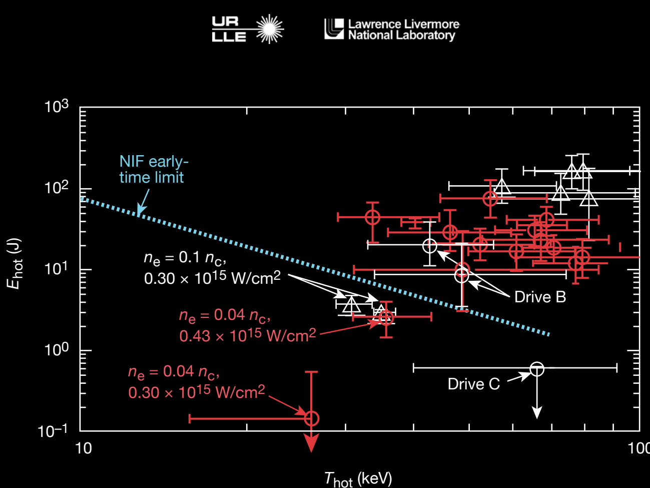
NEUTRON TIME-OF-FLIGHT SYSTEM



A first-generation set of neutron time-of-flight (nTOF) systems was built and calibrated on OMEGA and used for several years on NIF DT implosions. OMEGA was also used for testing later versions of NIF nTOF systems.

V. Yu. Glebov *et al.*, Rev. Sci. Instrum. **75**, 3559 (2004); V. Yu. Glebov *et al.*, Rev. Sci. Instrum. **77**, 10E715 (2006); V. Yu. Glebov *et al.*, Rev. Sci. Instrum. **81**, 10D325 (2010); V. Yu. Glebov *et al.*, Rev. Sci. Instrum. **83**, 10D309 (2012).

SUPRATHERMAL ELECTRON GENERATION



The observation of a burst of suprathermal electrons from the exploding laser entrance hole window of gas-filled hohlraums on OMEGA was used to mitigate preheat by window hot electrons in ignition hohlraums on the NIF.

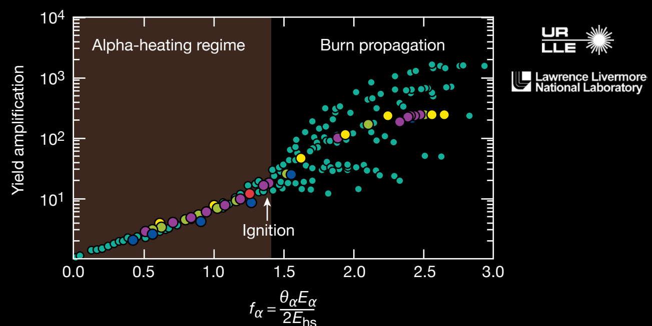
S. P. Regan *et al.*, Phys. Plasmas **17**, 020703 (2010).

EDUCATION

Alex Zylstra (PhD, MIT, 2015), left, and Annie Kritcher (PhD, UC Berkeley, 2009), right, who led the team on the ignition shot, developed novel diagnostics and conducted many ICF and high-energy-density physics experiments (nearly 1000 target shots combined) at the Omega Laser Facility. Examples include Alex's thesis research using fusion-product spectroscopy to study charged-particle stopping power and astrophysical nucleosynthesis, and Annie's thesis work on the first x-ray Thomson-scattering measurements of temperature and density of ICF implosion targets.

A. B. Zylstra *et al.*, Phys. Rev. Lett. **114**, 215002 (2015); A. B. Zylstra *et al.*, Phys. Rev. Lett. **117**, 035002 (2016); A. L. Kritcher *et al.*, Phys. Rev. Lett. **107**, 015002 (2011); A. L. Kritcher *et al.*, High Energy Density Phys. **7**, 271 (2011).

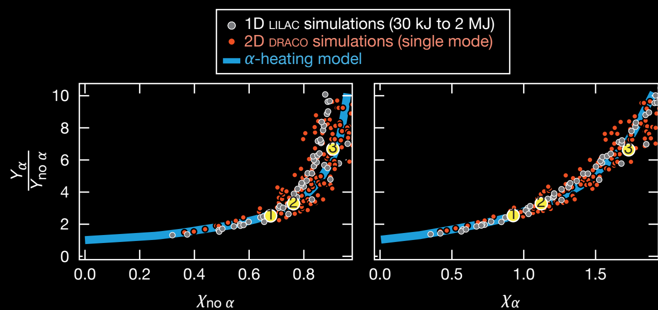
CRITERION FOR BURN PROPAGATION



A measurable criterion for the onset of burn propagation was developed at LLE and LLNL. This metric was used in the NIF ignition shot of August 2021.

A. R. Christopherson, R. Betti, and J. D. Lindl, Phys. Rev. E **99**, 021201(R) (2019).

CRITERION FOR BURNING PLASMAS



The first criterion for the onset of burning plasmas in inertial confinement fusion was developed at LLE and used in the first NIF shots that achieved burning plasmas.

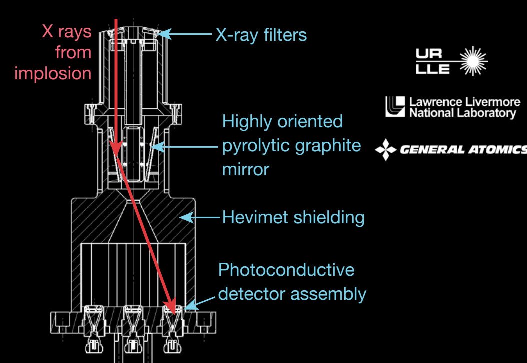
R. Betti *et al.*, Phys. Rev. Lett. **114**, 255003 (2015).

OPTICAL MANUFACTURING

The Optical Manufacturing Group (OMAN) at LLE has collaborated with LLNL since 1995 on optical coatings for the NIF to improve source stability, process monitoring, damage threshold, and stress control. The NIF facilitated new equipment at LLE to clean optics before coating, measure performance with photometry and 1ω interferometry, and laser condition coated optics. Modifications to the coating chamber improved deposition control and coating uniformity. OMAN supported production of all 192 deformable mirrors and coated more than half the remaining large mirrors and polarizers in the NIF beamlines (over 1000 optics to date). OMAN manufactures spare mirrors for the NIF and develops methods for improved coating performance.

C. J. Stolz *et al.*, Proc. SPIE **5193**, 50 (2004).

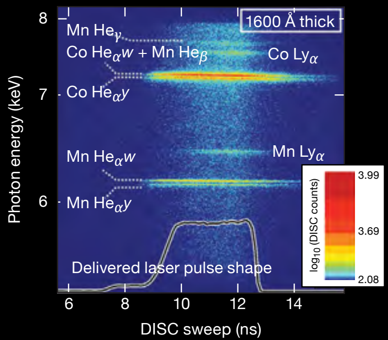
SOUTH POLE BANG-TIME DIAGNOSTIC



The south pole bang-time (SPBT) diagnostic views NIF implosions through the lower-hohlraum laser entrance hole to measure the time of peak x-ray emission (peak compression) in indirect-drive implosions. Five diamond photoconductive detectors with different filtrations and sensitivities record the time-varying x rays emitted by the target. The SPBT was one of the primary x-ray diagnostics used to study the onset of hydrodynamic mix.

D. H. Edgell *et al.*, Rev. Sci. Instrum. **83**, 10E119 (2012); T. Ma *et al.*, Phys. Rev. Lett. **111**, 085004 (2013).

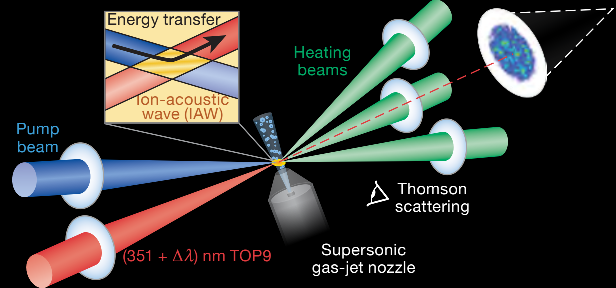
NIF HOHLRAUM MEASUREMENTS



The first measurement of the electron temperature inside a NIF hohlraum was obtained using temporally resolved K-shell x-ray spectroscopy of a mid-Z tracer dot measured with the NIF x-ray spectrometer that was designed and fabricated at LLE and calibrated on OMEGA.

M. A. Barrios *et al.*, Phys. Plasmas **23**, 056307 (2016).

CROSS-BEAM ENERGY TRANSFER



The use of wavelength detuning to leverage cross-beam energy transfer (CBET) was instrumental in the success of ignition. Confidence in the ability to reliably control CBET has increased in recent years, thanks to focused gas-jet experiments that have demonstrated quantitative understanding of the mechanism, including those using the tunable OMEGA P9 (TOP9) beam at LLE.

A. Hansen *et al.*, Phys. Rev. Lett. **126**, 075002 (2021); D. Turnbull *et al.*, Nat. Phys. **16**, 181 (2020).

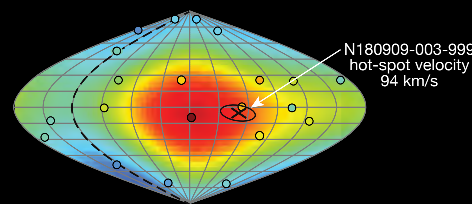
FIRST IGNITION CRITERION VALID IN 3D

$$\rho R^{\text{no }\alpha}_{\text{tot(n)}} \left[Y^{\text{ex}}_{16(\text{no }\alpha)} / M^{\text{mg}}_{\text{sh}} \right]^{0.58} \approx 1$$

The first ignition criterion valid in 3D using yields, areal densities, and DT mass was developed at LLE and LLNL. It later became widely used to assess progress toward ignition.

P. Y. Chang *et al.*, Phys. Rev. Lett. **104**, 135002 (2010).

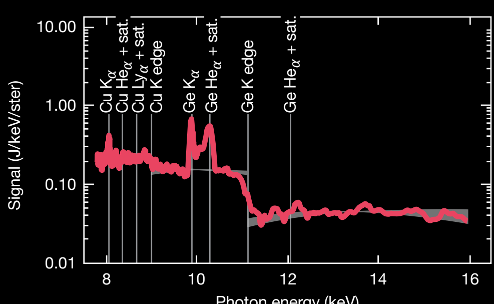
NTOF DETECTORS



The neutron time-of-flight (nTOF) detectors developed, tested, and calibrated on OMEGA were used to measure residual hot-spot flow velocity in NIF ICF implosions. Residual velocity and a correlated asymmetry in areal density were caused by mode-1 asymmetries in the hohlraum drive, capsule, and ice layer that impeded ignition.

H. G. Rinderknecht *et al.*, Phys. Rev. Lett. **124**, 145002 (2020).

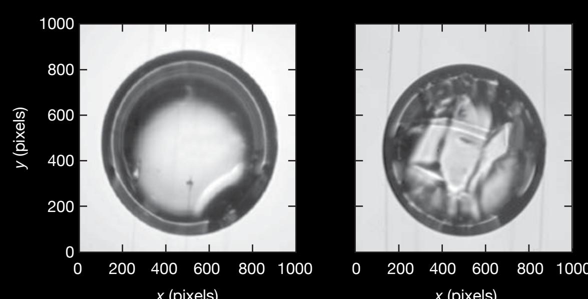
HOT-SPOT MIX IN IGNITION-SCALE ICF TARGETS



Mixing of plastic ablator material doped with Cu and Ge dopants deep into the hot spot of ignition-scale ICF implosions by hydrodynamic instabilities was diagnosed with LLE-built and calibrated x-ray spectrometers on the NIF by a joint LLNL–LLE team. The amount of hot-spot mix mass was determined from the absolute brightness of the emergent Cu and Ge K-shell emission. The Cu and Ge dopants placed at different radial locations in the plastic ablator show that the ablation-front hydrodynamic instability is primarily responsible for hot-spot mix.

B. A. Hammel *et al.*, High Energy Density Phys. **6**, 171 (2010); S. P. Regan *et al.*, Phys. Plasmas **19**, 056307 (2012); S. P. Regan *et al.*, Phys. Rev. Lett. **111**, 045001 (2013).

DEUTERIUM–TRITIUM CRYOGENIC LAYERS



The process of reliably forming layers for laser direct drive at LLE provided key insights for the layering-capable cryogenic target positioning system on the NIF. The thin-walled plastic direct-drive capsules are filled with DT via diffusion and placed inside a spherical cavity where a solid layer is formed to smooth the fuel layer. Layering is performed in multiple moving cryostats and the target is inserted into the OMEGA target chamber when a suitable layer is ready.

D. Harding *et al.*, Phys. Plasmas **13**, 056316 (2006); T. C. Sangster *et al.*, Phys. Plasmas **14**, 058101 (2007); T. Parham *et al.*, Fusion Sci. Technol. **69**, 407 (2016).

Pictured from left to right are Valeri Goncharov, Distinguished Scientist and Theory Division Director; Varchas Gopalaswamy, Assistant Scientist; and Duc Cao, Scientist, discussing simulation results of cryogenic implosions on OMEGA at the University of Rochester's VISTA Collaboratory.

LASER-DRIVEN INERTIAL CONFINEMENT FUSION

The Path to Robust Ignition Platforms

LASER-DRIVEN INERTIAL CONFINEMENT FUSION

The Path to Robust Ignition Platforms

Fundamentals of high-yield target design

In this article, we review the basic principles of high-yield target design using a laser-driven inertial confinement fusion (ICF) approach. We will show that drive (ablation) pressure plays a key role in determining the laser-energy requirement for robust ignition platforms in a laboratory setting. By mitigating the deleterious effects of laser–plasma interactions, new broadband laser technology provides an attractive option for significantly enhancing the drive pressures in laser-direct-drive experiments.

ICF 101: Fusion fuel, spherical compression, and ignition conditions

Fusion fuel

The goal of an ICF experiment is to create the necessary conditions for nuclear fusion to occur. Fusion is the process of merging two lighter atomic nuclei to form a heavier nucleus and releasing energy, which is typically carried by a lighter particle. The most-common fusion fuel in a laboratory consists of a mixture of two hydrogen isotopes—deuterium and tritium. When deuterium and tritium fuse, a heavier helium nucleus, called an alpha particle, is formed and most of the energy released is carried by the neutron. Because the release of energy due to fusion resembles the release of energy that occurs when burning fossil fuels, such as gasoline in a combustion engine, fusing significant fractions of deuterium and tritium atoms in an ICF target is referred to as "fuel burn," or ignition. In the conventional "hot-spot" approach to ICF implosions, the deuterium–tritium (DT) fuel is ignited using a "spark" that is formed at the low-density central region of the target.

Achieving robust ignition in a laboratory requires two main components: (1) the formation of a hot spot (spark) and (2) burning a significant fraction (>20%) of the "fuel." To form a hot spot, a small fraction of the fuel in an ICF target is spherically compressed to a high temperature of several hundred million degrees and to a high pressure of several hundred billion atmospheres. A target in a conventional ICF design [shown in Fig. 1(a) Initial target] consists of a higher-density DT layer of ice and a lower-density central vapor region. An outermost layer, typically made of plastic, absorbs the laser energy and rapidly expands or "ablates" during the experiment.

Spherical compression

In a laser-direct-drive ICF experiment, the target is compressed by ablation pressure, which is the result of mass ablating from the surface of the target. Similar to creating thrust in a rocket from the exhaust flow of burnt rocket fuel, the blow-off flow of the ablated material creates the push that drives the target inward.

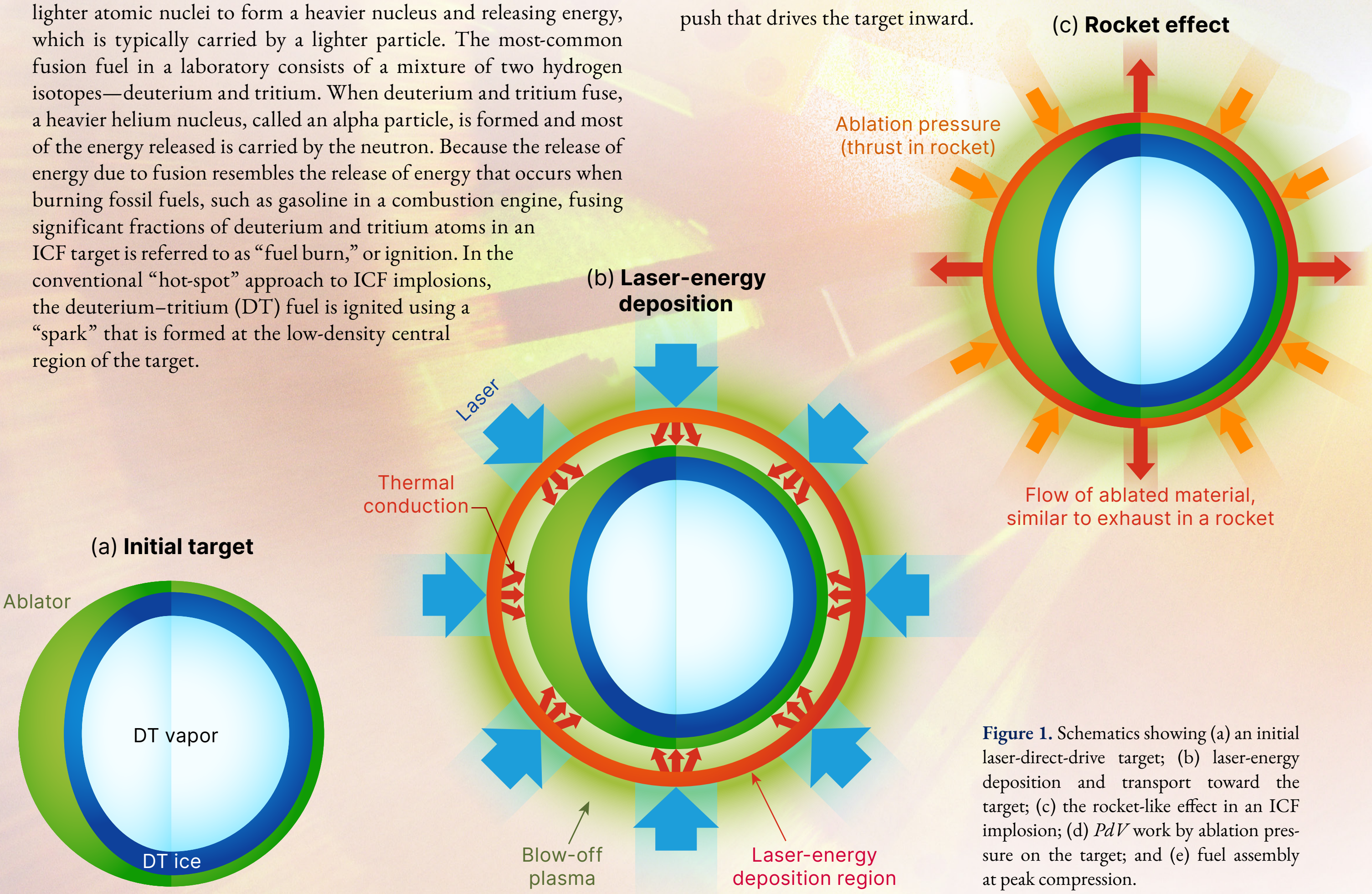
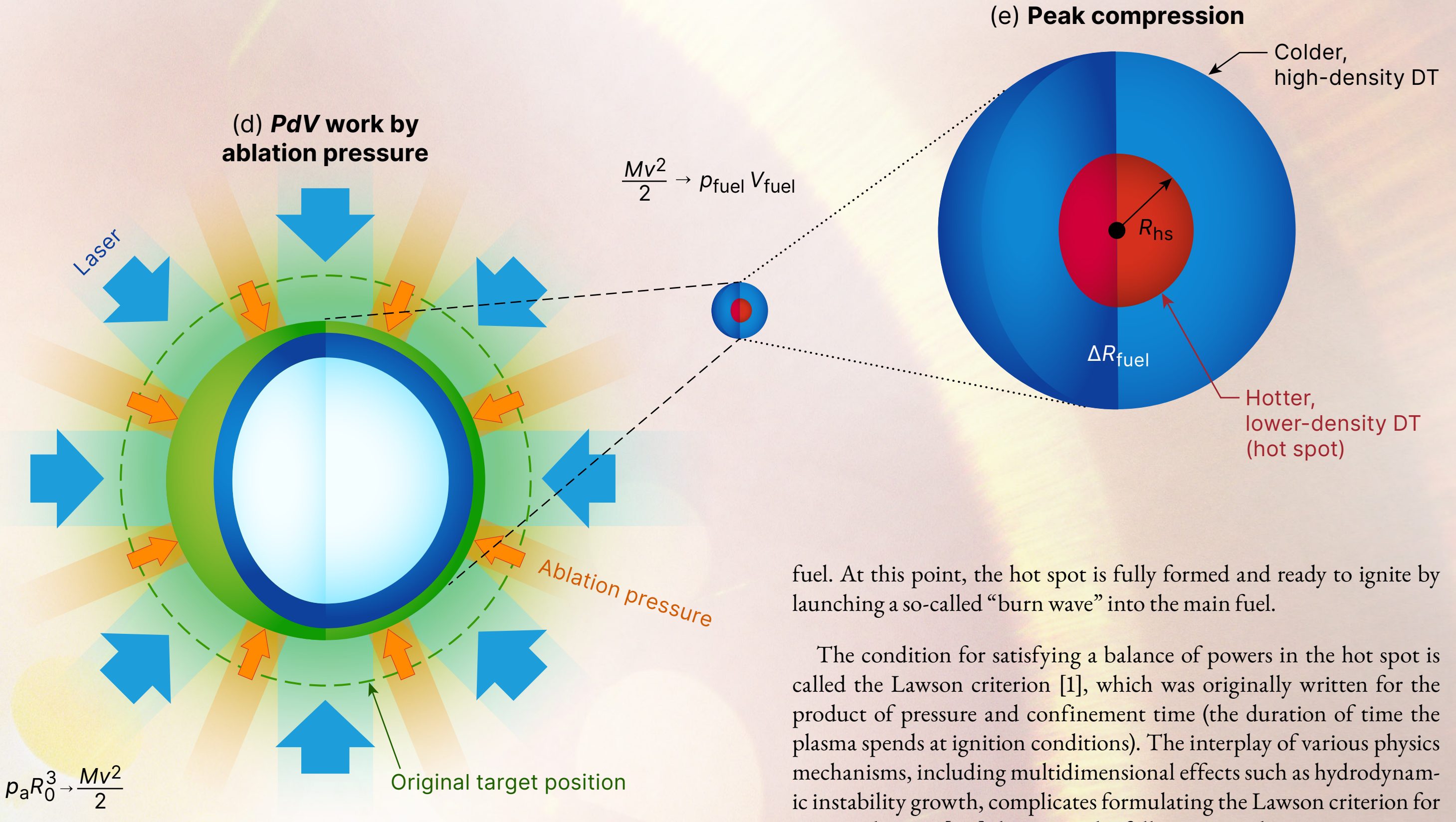


Figure 1. Schematics showing (a) an initial laser-direct-drive target; (b) laser-energy deposition and transport toward the target; (c) the rocket-like effect in an ICF implosion; (d) *PdV* work by ablation pressure on the target; and (e) fuel assembly at peak compression.



The ablation process in laser-direct-drive ICF is driven mainly by electron thermal conduction, which transports the laser energy absorbed in the blow-off plasma into the target [see Fig. 1(b) Laser-energy deposition]. This energy ablates a thin outer layer of the target, which produces the rocket-like effect of pushing the target inward [Fig. 1(c) Rocket effect]. As the target implodes, the high-density shell of DT fuel gains kinetic energy from the work done by the ablation pressure [Fig. 1(d) *PdV* work by ablation pressure]. As the target converges, the pressure inside its central vapor region builds up and at some point starts pushing back on the high-density shell. In the final stage of the implosion, the pressure inside the vapor region stops the incoming shell, converting its kinetic energy into internal energy of the fuel. The fuel assembly at this stage of maximum compression has a lower-density, hotter central region surrounded by a higher-density, colder fuel, as shown in Fig. 1(e) Peak compression. In an igniting design, the central region forms a hot spot or "spark" that ignites and burns the surrounding colder, high-density fuel.

Ignition conditions

Alpha particles produced by fusion reactions play a key role in hot-spot creation. When conditions are right, most of the alpha particles deposit their energy inside the low-density central region. The central region enters a self-heating regime when the alpha-particle energy deposition rate (power) exceeds the combined power of all loss mechanisms (including cooling due to hydrodynamic expansion, as well as radiation and thermal conduction). In this regime, the temperature of the hot spot continues to rise, producing more fusion reactions and, consequently, more alpha particles. When the hot-spot temperature exceeds ~30 keV, it enters into a thermal "runaway" regime, producing enough alpha particles to heat not only itself but also a thin adjacent layer of higher-density fuel. At this point, the hot spot is fully formed and ready to ignite by launching a so-called "burn wave" into the main fuel.

The condition for satisfying a balance of powers in the hot spot is called the Lawson criterion [1], which was originally written for the product of pressure and confinement time (the duration of time the plasma spends at ignition conditions). The interplay of various physics mechanisms, including multidimensional effects such as hydrodynamic instability growth, complicates formulating the Lawson criterion for ICF implosions [1,2], however, the following conditions approximate the onset of hot-spot self-heating, or "ignition" [3,4]:

$$p_{hs} R_{hs} > 1 \text{ Gbar cm, and } T > T_{ign}, \tag{1}$$

where p_{hs} is hot-spot pressure and R_{hs} is the hot-spot radius (see Fig. 1, Peak compression). This relationship shows that the required hot-spot pressure decreases and energy ($\sim p_{hs} R_{hs}^3$) increases as the hot spot grows. Larger hot spots require less hot-spot pressure, making ignition easier to achieve, but this generally requires more laser energy. For example, a pressure of 500 Gbar (500 billion atmospheres) is necessary to ignite a 20-μm-sized hot spot (OMEGA scale), while a pressure of only 100 Gbar is sufficient to ignite a 100-μm hot spot (NIF scale).

In addition to the pressure threshold, the hot spot must be hot enough to enter the self-heating regime. If the temperature is lower than the so-called "ignition temperature," T_{ign}, radiation losses from the hot spot will dominate alpha-particle heating, and a positive power balance inside the hot spot will not be achieved. For pure DT fuel, $T_{ign} \simeq 4.5$ keV, but the ignition temperature increases rapidly with ion charge, which sets a strict limit on the amount of ablator material that penetrates into the hot spot (due to hydrodynamic mixing, for example) before ignition fails.

Even though smaller hot spots require greater pressure to ignite, they contain less energy according to Eq. (1). Igniting a 20-μm hot spot requires only 2.5 kJ, while a 100-μm hot spot requires more than 60 kJ. This emphasizes the importance of the hot-spot size in determining laser energy for ignition experiments. As explained earlier, hot-spot energy is provided by the kinetic energy of the shell and, in a typical laser-direct-drive design, ~30% of the kinetic energy is coupled to the hot spot; therefore, greater than 200 kJ of kinetic energy is required to ignite a design with a 100-μm hot spot, while ~10 kJ is sufficient to ignite a 20-μm hot-spot design.

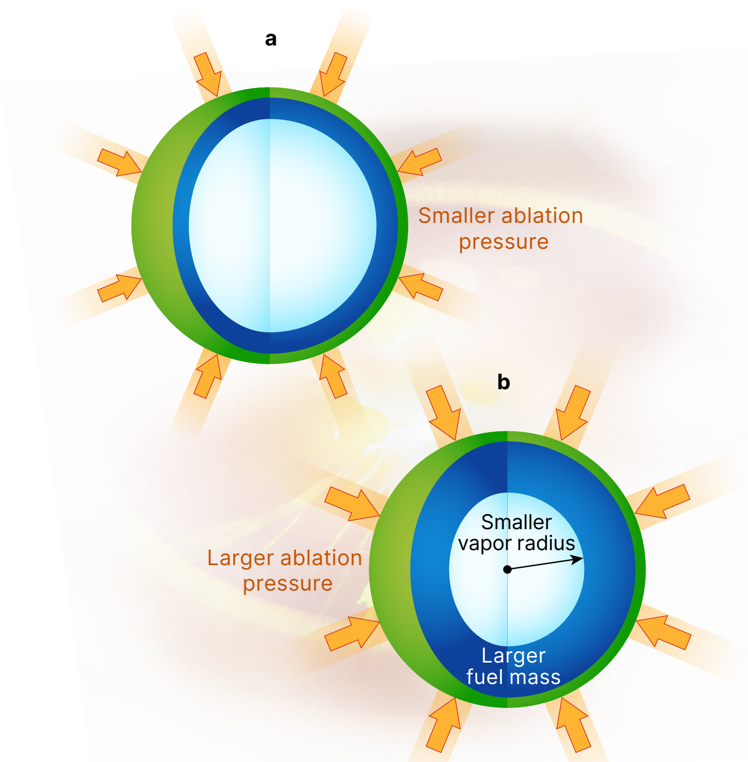


Figure 2. Larger ablation pressures lead to an increase in fuel mass and a reduction in size of the vapor region.

Benefits of larger ablation pressure: A quick overview

Although designs with smaller hot spots require less laser energy, the deleterious multidimensional hydrodynamic effects—in particular, shell nonuniformity growth—can severely limit their performance. Smaller hot spots are typically the result of higher shell convergence, which leads to increased amplification of shell nonuniformities. So, according to common wisdom, there should be a trade-off between between laser energy and target uniformity requirements. As shown later in this article, improving laser coupling, which leads to increased ablation pressure, is the key element in reducing the hot-spot size without increasing shell convergence (the ratio of the initial size of the vapor region to the hot-spot size). In addition, a larger ablation pressure significantly improves shell stability during acceleration. The main mechanisms that lead to these effects are illustrated in Fig. 2.

First, a larger ablation pressure allows *PdV* work to accelerate the shell to the required kinetic energy over a smaller acceleration distance (the initial vapor size can be reduced) [Fig. 2(b)]. This enables a smaller hot-spot size without an increase in shell convergence.

> ***Larger ablation pressure enables a smaller hot-spot size without an increase in shell convergence.***

Second, because smaller hot spots need less energy to ignite [see Eq. (1)], the shell velocity can be reduced and the fuel mass increased [as illustrated in Fig. 2(b)]. Increased shell mass leads to the following effects that improve stability:

(1) At the early stages of the implosion, the maximum pressure is equal to the ablation pressure. At later stages, as convergence effects become stronger, the volume of the shell starts to decrease, squeezing the mass inside of the shell and increasing the internal pressure beyond the ablation pressure. At this point, there is a reversal in the pressure gradient at the outer surface of the shell, which becomes stable to Rayleigh–Taylor (RT) growth (for RT to occur, the pressure and density gradients need to have opposite directions). After this, the target mass continues to gain velocity and kinetic energy but without further hydrodynamic nonuniformity growth. Because convergence effects start earlier in the implosion with a more-massive target and smaller initial vapor region, these implosions are more robust to RT nonuniformity growth.

(2) Increased shell thickness also increases the distance that shell perturbations must penetrate to degrade implosion performance. Thus, thicker shells relax the requirement on target quality for the ignition design. This is illustrated in Fig. 3, where 2D simulations using the hydrodynamic code DRACO [5] are shown for two designs: one with a thinner shell [Fig. 3(a)] and one with a thicker shell [Fig. 3(b)]. The shell in the thicker design remains integral during the entire implosion process, while the thinner shell is broken at the end of acceleration, leading to severe performance degradation at peak fuel compression.

Requirement on shell confinement

Creating an ignition hot spot is not the only condition necessary for achieving high yields (>100 MJ) in ICF implosions. The shell must also provide sufficient confinement time to support the launch of the burn wave and its propagation through the main fuel. Shell confinement time is limited by the time of the outgoing shock-wave propagation through the shell during the final stage of fuel compression (Fig. 4). The outgoing shock is launched into the incoming shell when the pressure in the central region of the target, built up due to convergence, starts to exceed the pressure in the shell [Fig. 4(a)]. The hot spot is confined and its energy loss due to expansion is limited while the shock remains within the shell [Fig. 4(b)]. If the shock breaks out of the shell [Fig. 4(c)] prior to the hot spot entering into the runaway regime, the expansion of the shell and hot spot accelerates, exacerbating *PdV* losses and preventing ignition. For robust burn propagation, it is important that at the time when the hot-spot ignition condition shown in Eq. (1) is satisfied, the outgoing shock stays well within the shell [Fig 4. (b)].

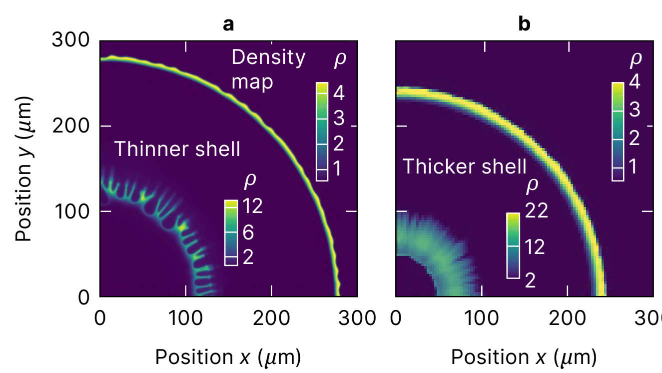


Figure 3. Two-dimensional DRACO simulations of target implosions for (a) thinner-shell and (b) thicker-shell designs. The larger shell corresponds to an earlier time in the implosion (beginning of acceleration) and the smaller shell corresponds to the end of acceleration. Minor shell distortions observed at an earlier time are amplified due to Rayleigh–Taylor instability, leading to shell breakup in the thinner-shell design.

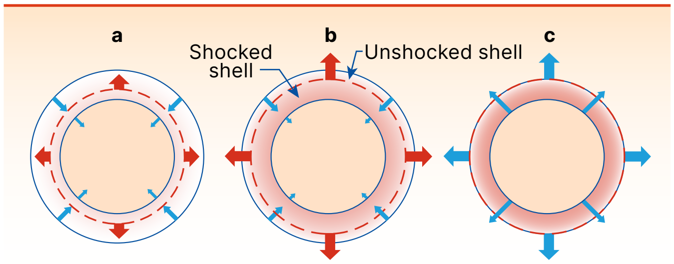


Figure 4. Schematics of shell (blue circles) and shock (red dashed circles) position, as well as velocity direction (blue arrows for the shell and red for the shock) and velocity magnitude (arrow length).

An additional constraint on the shock location at the onset of ignition is imposed by hydrodynamic instability growth. As the shell is accelerated inward, shell nonuniformities are amplified at the outer surface due to RT instability growth, as shown in Fig. 3. This growth is seeded by shell defects accumulated during target production as well as nonuniformity in laser drive caused by high-intensity speckles that are generated by the interference of laser beams at the target surface. The RT instability leads to the formation of bubbles of the low-density ablated material penetrating the shell. This causes the decompression of the exterior of the shell and a significant reduction in its ability to provide hot-spot confinement [see Fig. 3(a)]. Therefore, in addition to Eq. (1), the fuel assembly for robust ignition must satisfy the requirement on shocked-shell fraction:

$$f_M \equiv M_{\mathrm{sh}}/M_{\mathrm{DT}} < f_{M,\mathrm{lim}} \quad (2)$$

where M_{DT} is the total fuel mass and M_{sh} is the fuel mass overtaken by the shock (shocked mass) at the time of ignition. The limit on the shocked-shell fraction ($f_{M,\mathrm{lim}}$) depends on details of the target design [shell in-flight aspect ratio (IFAR), shell entropy, etc.] and nonuniformity seeds (laser power imbalance, target imperfections, and laser imprint), but a reasonable guide is $f_{M,\mathrm{lim}} < 1/2$. **Maintaining the return shock within the inner half of the shell imposes a maximum velocity that creates a robust design space for direct-drive implosions when combined with the minimum velocity for ignition.**

High-yield parameter space and gain curves

The ignition requirements shown in Eqs. (1) and (2) depend on hydrodynamic conditions near peak compression. We can relate these conditions to design parameters in order to set the required laser energy and pulse shape, as well as the initial dimensions of an ignition target. These design parameters are defined as:

- ***Implosion velocity*** $\mathbf{v}_{imp}$ is the maximum, mass-averaged shell velocity during target acceleration.
- ***Shell adiabat*** $\boldsymbol{\alpha}$ quantifies the extent to which the target compression deviates from an ideal compression when the fuel has the maximum possible density at a given applied pressure. Since plasma pressure p cannot be lower than Fermi pressure p_{Fermi}, adiabat is defined as $\alpha = p/p_{\mathrm{Fermi}}$. For direct-drive implosion designs, the adiabat is determined primarily by the shocks that are launched into the fuel at the beginning of the drive, causing fuel heating.
- ***Ablation pressure*** $\mathbf{p}_a$ in laser-direct-drive implosions is determined by the incident laser intensity I (defined as laser power divided by initial outer-shell surface area), laser wavelength, and target material properties. Ablation pressure is also affected by the physics that controls laser coupling, including inverse bremsstrahlung absorption, and laser–plasma interactions such as cross-beam energy transfer (CBET), two-plasmon decay, and stimulated Raman scattering. Because of the geometric amplification of the ablation pressure during an implosion, as a design parameter in this article, we report p_{a} when a target's outer surface converges by factor of 3.
- ***Fuel mass*** **M** in laser-direct-drive implosions is equal to the mass of the shell. In an optimized design, the ablator material is fully ablated by the end of the acceleration. The fuel mass, together with the fuel areal density at peak compression, determines the neutron yield in an ignition target.

When substituting scaling laws for hot-spot pressure and size into the ignition condition Eq. (1), the latter defines the minimum implosion velocity required to create an ignition hot spot. This "ignition velocity" is a function of several design parameters such as ablation pressure, laser intensity and energy, and fuel adiabat.

> ***It is misleading, however, to use only the ignition velocity to define the design parameters for robust ignition.***

Figure 5 shows that the ignition velocity (shown with solid lines) increases with shell adiabat (i.e., more energy is required to ignite a design with higher α). This is caused by a larger hot spot, and, according to Eq. (1), greater hot-spot energy required to reach ignition conditions. On the other hand, the ignition velocity decreases with ablation pressure. This is a result of a smaller hot spot and, consequently, reduced hot-spot energy. Lower hot-spot energy requires a smaller shell kinetic energy and implosion velocity.

It is misleading, however, to use only the ignition velocity to define the design parameters for robust ignition. In addition, the return shock must remain within the shell at the onset of ignition [see Eq. (2)]. Substituting scaling laws for the shocked and total fuel mass into Eq. (2) sets the upper limit on the implosion velocity. This "maximum robust velocity" is shown with dashed lines in Fig. 5 and, along with the ignition velocity, define the parameter space for robust ignition (shaded area in Fig. 5). The region of robust ignition becomes smaller as laser energy decreases or when there is a decrease in laser coupling and ablation pressure.

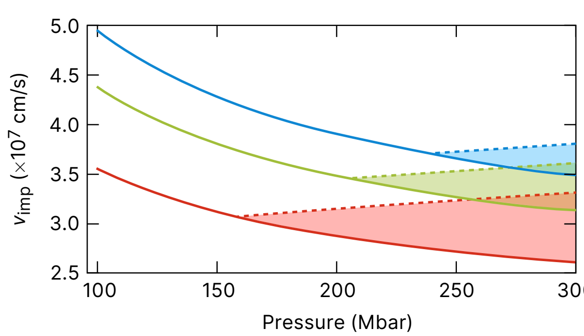


Figure 5. The shaded area defines the region for robust ignition and is bounded by the minimum ignition velocity (solid lines) and the maximum robust velocity (dashed lines) for a design with a laser energy of $E_{\mathrm{L}} = 1.5$ MJ and drive intensity $I = 10^{15}$ W/cm^2. The design for $\alpha = 1$ is shown in red, $\alpha = 2$ in green, and $\alpha = 3$ in blue.

Next, we plot the target yield for the robust ignition designs as a function of incident laser energy [6]. We assume that the laser coupling and ablation pressure are maximized by mitigating the deleterious effects of laser–plasma interactions. Calculations show that this leads to an ablation pressure that scales with laser intensity as $p_a \simeq 230\ I_{15}^{0.8}$ Mbar. Additionally, if a reduction in the focal spot of the laser beam is implemented during shell acceleration (beam zooming), ablation pressure can be further increased to $p_a \simeq 340\ I_{15}^{0.8}$ Mbar. Here, I_{15} is the incident laser intensity in units of 10^{15} W/cm^2. There is a trade-off between target yield, drive intensity (limited by laser–plasma interactions), and hydrodynamic stability.

Neutron yields in 1D hydrodynamic simulations increase with a reduction in intensity—the result of a larger initial target radius (and, therefore, fuel mass) since a lower drive pressure requires longer acceleration distances. A larger initial shell radius, however, leads to a higher in-flight aspect ratio and, consequently, a reduced robustness to instability growth during shell acceleration.

Conclusions: A laser-direct-drive path for high-gain robust designs

Figure 6 shows target yield as a function of incident laser energy for robust ignition designs where both the minimum velocity for ignition is achieved [Eq. (1)] and the maximum robust velocity is not exceeded (shaded regions in Fig. 5).

Using existing laser technologies to drive laser-direct-drive implosions leads to the excitation of laser–plasma instabilities, which reduce laser coupling and ablation pressure (due to CBET) and produce energetic electrons (with energies >100 keV) that preheat the fuel, significantly raising fuel adiabat. Experiments conducted on narrowband lasers (i.e., OMEGA and the NIF) have shown that when driven at an incident intensity limited by the hot-electron threshold (~10^{15} W/cm^2), ablation pressure reaches $p_a \simeq$ 130 to 150 Mbar on OMEGA and $p_a \simeq$ 80 to 100 Mbar on the NIF depending on the choice of ablator material. Figure 5 shows that these ablation pressures are not sufficient for robust ignition target designs at laser energies below 2 MJ. Increasing the laser energy to above E_L = 4.5 MJ will therefore be required, although this is significantly greater than what current capabilities allow on the NIF. Furthermore, since the density scale length in the plasma corona increases with laser energy and target size, a significant increase in coupling losses due to laser–plasma instabilities is expected, reducing the ablation pressure to well below 100 Mbar. Such low ablation pressures will require an even greater laser energy, which, in turn, will lead to further enhancement in coupling losses. **Therefore, in this scenario, where narrowband lasers drive CBET, there is no laser energy that will satisfy the requirements for robust ignition.**

The ablation pressure must be increased by mitigating coupling losses due to laser–plasma instabilities to create the conditions for robust ignition. Recent simulations and initial experimental data demonstrate that introducing laser bandwidth ($\Delta\omega_L/\omega_L \sim$ 1.5% to 3%) significantly reduces such losses and increases the incident laser intensity threshold for generating hot electrons to above $I = 10^{15}$ W/cm^2. Simulations suggest that full CBET mitigation increases ablation pressure to $p_a \simeq$ 230 Mbar at an intensity of $I = 10^{15}$ W/cm^2. A further increase in ablation pressure is possible by implementing beam zooming. This is predicted to raise the ablation pressure to 340 Mbar, providing a significant margin for high-yield designs. The target yield of Y_n = 200 MJ at such pressure can be achieved with an E_L = 1.7-MJ laser driver, which provides an attractive path for inertial fusion energy and stockpile stewardship science. This design is very hydrodynamically stable (IFAR $\simeq$ 8) and has a low shocked-mass fraction of $f_M \simeq 0.33$ but requires a low adiabat, $\alpha \simeq 1.5$, which may lead to a reduced ablative stabilization of RT instability during target acceleration. Experiments must be conducted to verify that the designs with low adiabat and, at the same time, low IFAR and f_M are stable to both laser imprint and target defects. If a higher adiabat is required to achieve the desirable stability, this can be accomplished using an $\alpha = 4$, E_L = 2.5-MJ design, which is still extremely attractive for a future high-yield ICF facility.

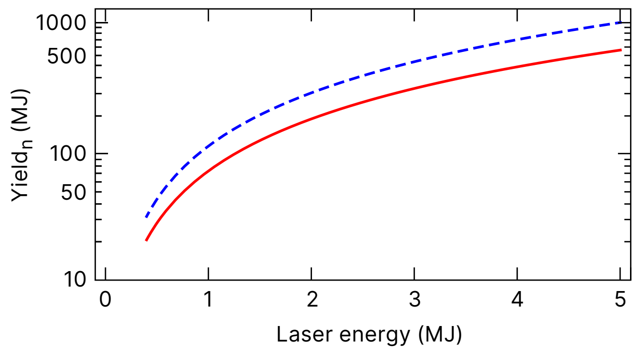


Figure 6. Neutron yield in target designs (α = 1.5) with p_a = 230 Mbar (red), and p_a = 340 Mbar (dashed blue). The lines start at the energies where f_M = 0.5. As laser energy increases, f_M decreases. Target yield scales with laser energy as $Y \sim E_L^{1.4}$.

Corresponding author:
V. N. Goncharov (vgon@lle.rochester.edu)

Focus Points

- A target for a robust ignition platform must achieve an igniting hot spot and support the burn of a significant fraction of the main fuel.
- Ablation pressure plays a key role in determining the laser-energy requirement for robust ignition platforms in a laboratory setting.
- Demonstrating the mitigation of deleterious effects of laser–plasma interactions using novel broadband laser technologies will pave a very attractive path to a future high-yield ignition facility.

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