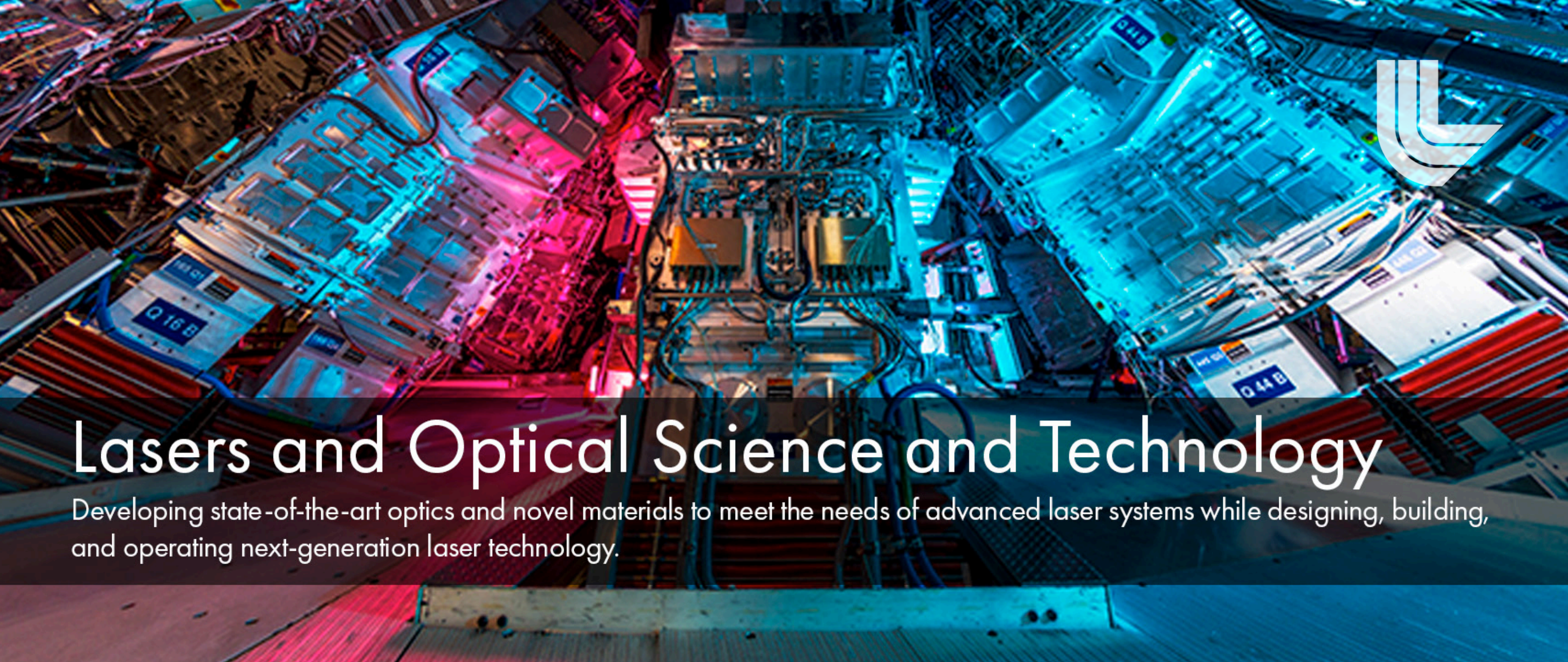


Lasers and Optical Science and Technology

Developing state-of-the-art optics and novel materials to meet the needs of advanced laser systems while designing, building, and operating next-generation laser technology.

Introduction

Lawrence Livermore National Laboratory (LLNL) designs, builds, and operates a series of large and complex laser facilities for basic and applied science driven by national security needs. These lasers have set world records in laser energy, power, and brightness. This singular capability enables world-beating science, including the first-ever achievement of fusion ignition in a laboratory on December 5, 2022.

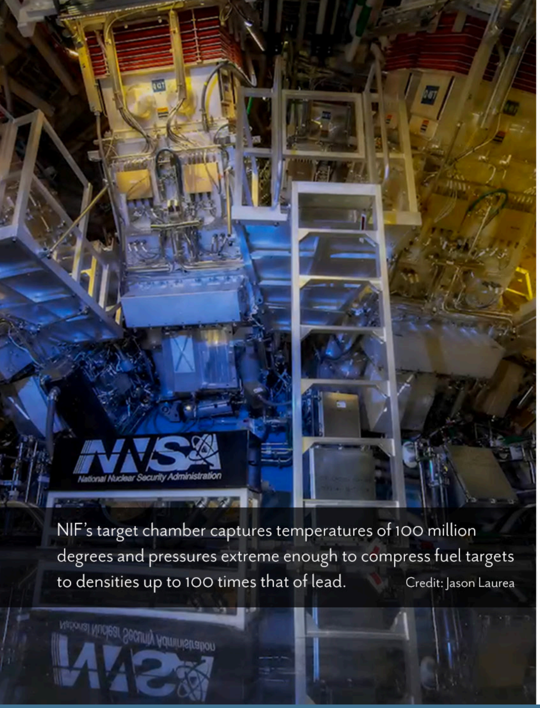
The National Ignition Facility (NIF) – home to fusion ignition – is an invaluable tool in pursuing the lab's core mission of safeguarding America's nuclear weapon stockpile as well as exploring high energy density (HED) regimes that cannot be replicated at other facilities. NIF provides key insights and data for simulation codes used in weapon-performance assessments and certification. It is also an important resource for weapons effects studies and nuclear forensics analysis.

The Laboratory's achievement of fusion ignition has the potential to accelerate the development of next-generation laser systems and optics science and technology. Such advances can help bring about a high-yield fusion facility for stockpile stewardship and lay the groundwork for inertial fusion energy (IFE).

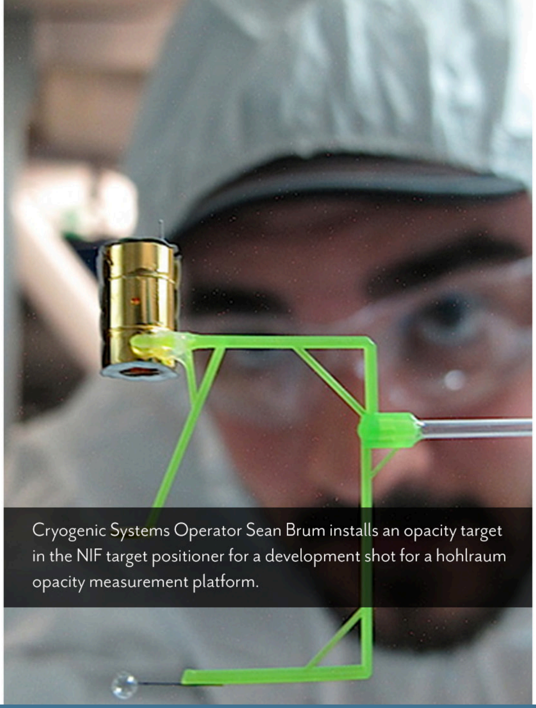
Applications

The Laboratory's leadership in lasers and optical science and technology reflects longstanding expertise in systems engineering, laser construction and operation, and collaboration with commercial partners. This is complemented by leadership in photonics, HED science, optical materials, the physics of laser–material interaction, and laser system modeling and simulations. The following areas of expertise exemplify LLNL's leadership:

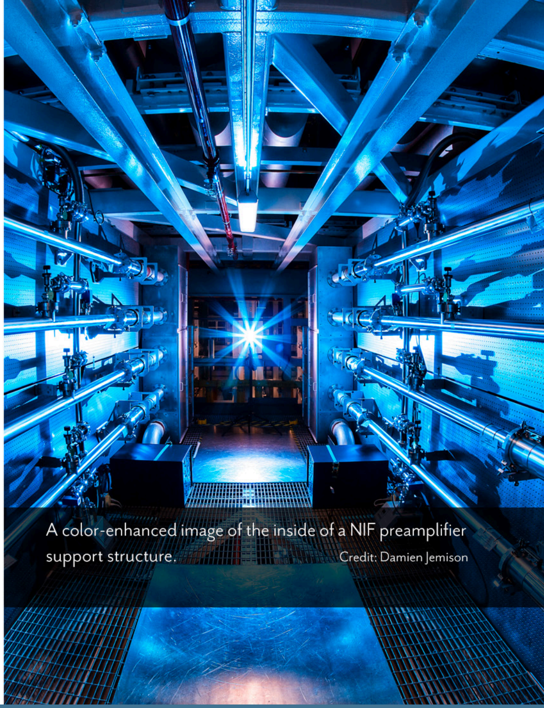
- **Advanced Laser Architectures and Technologies:** The Laboratory is on the leading edge of high energy, high peak power, and high average power laser technology. Extending its current capability will improve metrics like pulse energy, wavelength, repetition rate, peak power, efficiency, beam quality, laser precision, and cost-per-delivered-energy in scalable high energy laser systems.
- **Laser System Engineering and Performance Modeling Codes:** LLNL science is leveraging physics models-based systems design, optimization, and the use of high-performance computers. These tools enable innovative architectures with a shorter development cycle, reduced risks and costs, and safe operations.
- **Laser–Material Interaction Science:** The Laboratory's expertise in matter–light interactions extends well beyond laser conditions typically associated with HED science. It also includes optical material damage, laser effects in directed energy weaponry, and the fundamental science of laser-based material processing.
- **Optical Diagnostics and Photonics Technologies:** This area of expertise is supporting LLNL experimental science platforms, delivering data to the Stockpile Stewardship Program, measuring inertial confinement fusion (ICF) target performance, and certifying precision laser pulse shaping on the NIF.
- **Optics and Optics Manufacturing Technologies:** LLNL researchers are developing novel designs and processes, including coatings, materials, and recycling methods.
- **Pumping Technologies: Diodes, Pulsed Power, and Energy Storage:** LLNL is advancing pump diode technologies to enable efficient laser architecture. This is driving the need for energy storage and delivery technologies to power high-efficiency pump diodes, including new pulsed power technologies.
- **Beam and Pulse Shaping Technologies:** The Laboratory is advancing mission-critical technologies for the precision adjustment of laser beam profiles, wavefronts, waveforms, and spectra. These ensure reliable operation of experimental laser facilities, optimization of laser–target interactions, and high beam quality directed energy.



NIF's target chamber captures temperatures of 100 million degrees and pressures extreme enough to compress fuel targets to densities up to 100 times that of lead. Credit: Jason Laurea



Cryogenic Systems Operator Sean Brum installs an opacity target in the NIF target positioner for a development shot for a hohlraum opacity measurement platform.



A color-enhanced image of the inside of a NIF preamplifier support structure. Credit: Damien Jemison

Accomplishments

Over the last decades, LLNL has been a world-renowned center of excellence in the field of lasers and optical science and technology. The Laser Program has delivered major breakthroughs in ICF and other capabilities that support Department of Energy (DOE) and Department of Defense (DOD) missions. Recent accomplishments include:

- On December 5, 2022, the NIF laser precisely delivered 2.05 megajoules (MJ) of energy and 440 TW of peak power to the target enabling the first demonstration of fusion ignition in a laboratory setting. This achievement, which generated 3.15 MJ of fusion energy, has since been repeated at even higher levels.
- Optical component resilience to laser damage has been increased by 4 orders of magnitude since 1997, enabling higher energy densities in laser architectures, including NIF, and more sustained and economically viable operations.
- Recent debris-induced laser damage mitigations on optics have enabled NIF to operate at 2.2 MJ (>20% above initial facility requirements) and 440 TW in FY24.
- Dramatic enhancements of multi-physics laser modeling capabilities on high performance computing platforms with an increase in fidelity of 2-5× and spatial resolution by 3 orders of magnitude.
- Modernizing NIF pulse-shaping technology has improved the precision for power balance and accuracy on target by 2-5× while future STILETTO technology demonstrated shaping with sub-picosecond resolution over nanosecond record length.
- Designing, constructing, and operating state-of-the-art high energy and/or short pulse laser systems for the National Nuclear Security Administration, DOE, DOD, and scientific user facilities.
- Collaborating with the University of California in pioneering adaptive optics to compensate atmospheric turbulence for ground-based observatories and directed-energy applications.
- Understanding failure modes of, and innovating new thermal management schemes for laser diode stacks and arrays while deploying this technology for compact and efficient pumping for high power and high energy laser systems.
- Photonic analog-to-digital and digital-to-analog conversion systems operating at GHz bandwidths have demonstrated improved dynamic range over conventional electronic counterparts by over an order of magnitude.

The Future

The next generation of laser systems will continue to expand the envelope of capability in energy, pulse width, and repetition rate.

Optics mitigations will continue to increase functionality, lifetime, and yield to enable improved performance of high energy/power lasers; there will be special focus on even higher energy and power on NIF after facility sustainment efforts are completed.

Improving precision and control over all laser properties, including time-dependent waveforms and spectra, beam intensity and wavefront profiles, while tailoring polarization states will enable novel modalities for optimizing laser interactions with matter and mitigating instabilities.

The Laboratory will continue to advance the design, development, construction, and optimization of high energy laser systems for IFE and high-yield stockpile stewardship applications. LLNL is also building the next generation of ultrashort-pulse lasers, designed for DOE-relevant HED science applications as well as strategic DOD needs.

The achievement of fusion ignition is not just a historic milestone, but a stepping stone to new possibilities in laser and optical scientific innovation.

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