A Stellar Performance

Recent experiments at the National Ignition Facility are demonstrating the laser's robust capabilities for bringing star power to Earth.

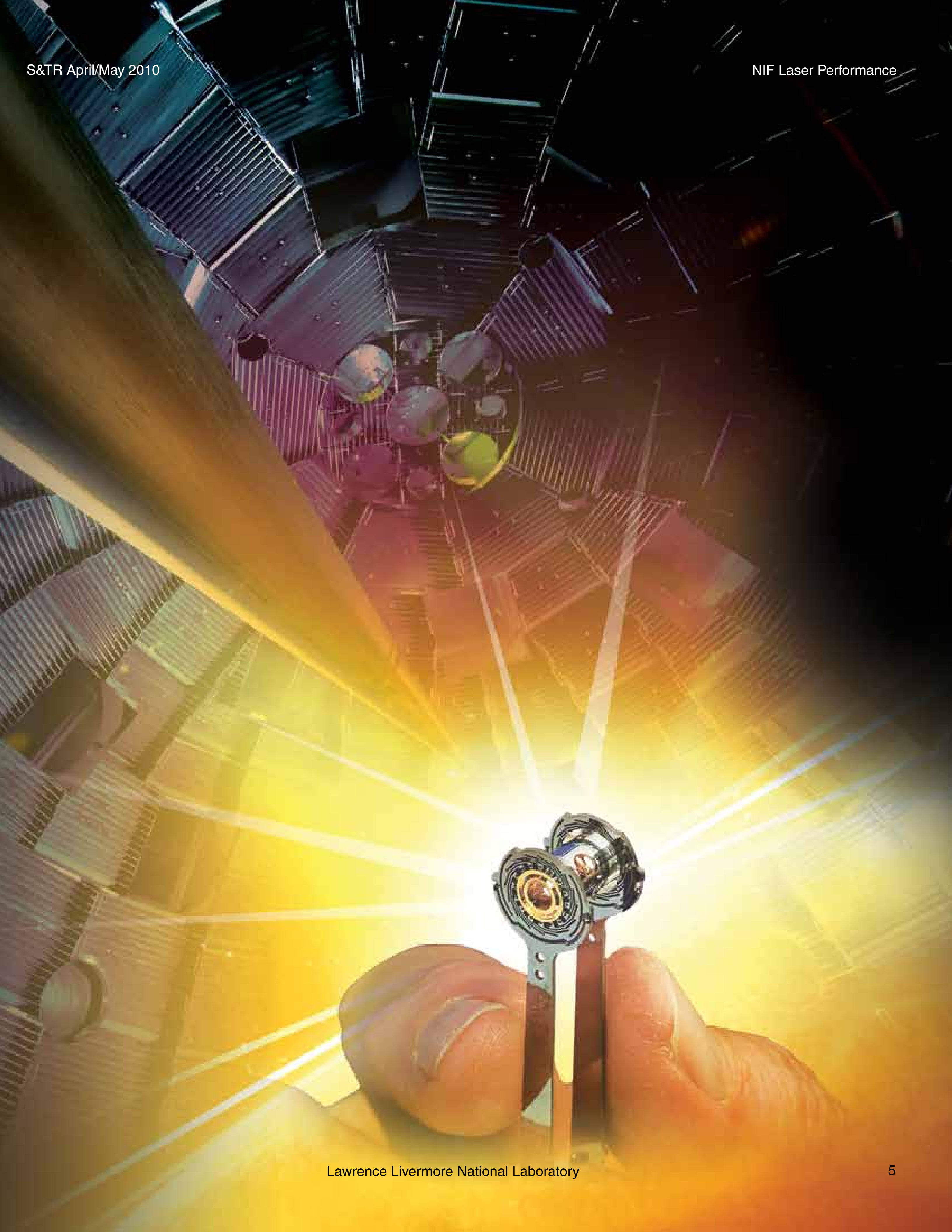
FIFTY years ago, Theodore Maiman first demonstrated a laser, the design of which was originally articulated by Nobel-prize-winning physicist Charles Townes. At that time, how the laser would evolve and its many applications were unknown. Almost simultaneously, Livermore's John Nuckolls and colleagues invented the idea of inertial confinement fusion (ICF), but they needed a powerful energy source to implode the fuel and create fusion. Scientists at Livermore began pursuing innovative research using lasers with ICF in mind. In 1972, the Laboratory officially formed a laser program to step up efforts to develop large lasers with the goal of achieving fusion in a laboratory setting. Recent experiments at the National Ignition Facility (NIF) move scientists even closer to achieving this goal.

Soon after the NIF dedication in May 2009, scientists ramped up an experimental campaign geared toward creating the necessary environment for ignition and overcoming any challenges associated with the task. Subsequent tests have shown how researchers can fine-tune the laser system to create the necessary conditions for ignition and have yielded valuable data on the timing, pulse shape, energy, and power requirements for ignition experiments.

The first step in obtaining ignition was commissioning the laser. To date, shot results have met or exceeded the laser performance criteria established by the Department of Energy's National Nuclear Security Administration (NNSA). The initial experimental results have not only shown a robust laser but also established the hohlraum design necessary for ignition experiments. "This accomplishment is a major milestone that demonstrates both the power and reliability of NIF's integrated laser system," says Ed Moses, principal associate director of NIF and Photon Science.

NIF is designed to produce well-controlled, precise, repeatable, and flexible shots that provide enhanced capabilities for a variety of applications. Since its completion, the laser system has been used in basic science research for studying the hydrodynamic processes in supernovae and for critical national security programs such as stockpile stewardship.

The National Ignition Facility (NIF) is a 192-beam laser system designed for high-energy-density science research. (opposite page) Inside the target chamber, scientists aim to create ignition and energy gain for the first time in a laboratory setting. A tiny metallic case called a hohlraum holds the fuel capsule for NIF experiments. The target positioner (top left) helps center the hohlraum.



In December 2009, NIF set a world record by firing more than 1 megajoule of ultraviolet energy at a target—more than 30 times the energy previously delivered to a target by any laser system. This shot combined with data from the experimental campaign suggest that NIF is on track to be the first facility in history to create self-sustaining nuclear burn in a laboratory setting, which is the initial step toward making ICF a feasible source of carbon-free, sustainable energy.

Infrared In, Ultraviolet Out

NIF's 192 individual beamlines are designed to simultaneously fire onto a 2-millimeter-diameter deuterium–tritium target capsule to create ignition and energy gain—where more energy is produced by the reaction than was put into it. (See the box below.) To achieve ignition, scientists calculate that the beams must simultaneously deliver about 1.3 megajoules of 351-nanometer (3-omega, ultraviolet) light with a peak power of about 400 terawatts (trillion watts) using the current target design.

Thousands of optics and diagnostics, as well as sophisticated mechanical and computer hardware, need to operate perfectly and in proper sequence to create the necessary conditions for ignition. It all begins at the NIF master oscillator, which generates an initial infrared laser pulse containing a few nanojoules of energy. This initial laser pulse is shaped specifically for each experiment and

The Art of Implosion

The National Ignition Facility (NIF) at Lawrence Livermore is leading the nation's effort to achieve ignition and energy gain for the first time inside a laboratory setting. This feat will require using the world's largest, most energetic laser to create extreme temperatures and pressures that for the time being occur only in the interiors of stars and in exploding nuclear weapons. Using NIF's 192 beamlines, scientists aim to deliver up to 1.8 megajoules of ultraviolet light, with a power of up to 500 trillion watts, onto a target about the size of a pea. The hot, intense conditions within the target capsule are expected to cause the fuel inside it to "ignite," producing more energy from the reaction than was used to initiate it. The target is a 2-millimeter-diameter capsule filled with a deuterium–tritium (DT) gas, which is surrounded by a few-nanometer-thick layer of DT ice.

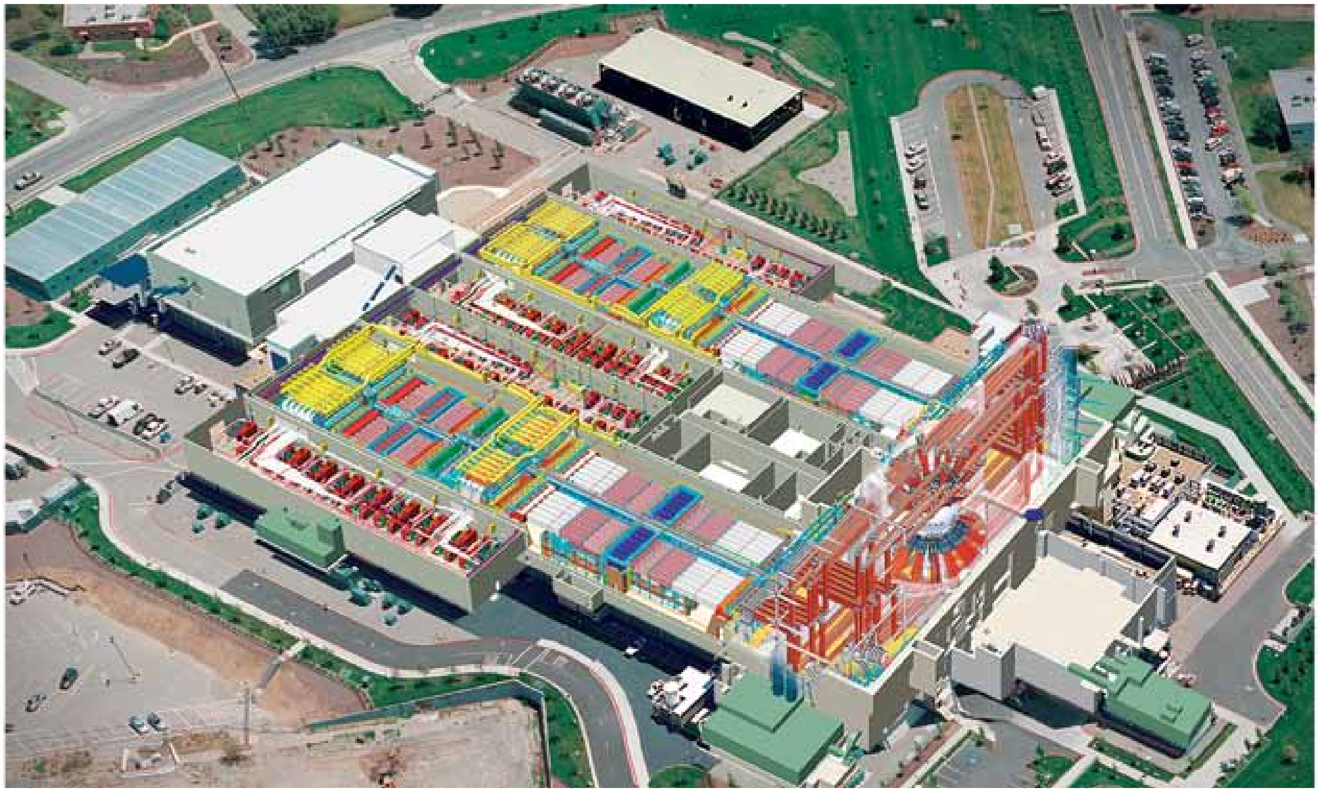
The entire capsule is housed in a cylindrical gold case called a hohlraum. Two openings, one on either side of the several-millimeter-long hohlraum body, are the entry points for the laser beams. A sophisticated target positioner and an automated alignment system place the target at the center of the 10-meter-diameter target chamber with an accuracy of less than the thickness of a human hair.

The 192 laser beams enter the target chamber from 48 points symmetrically positioned around the chamber's top and bottom sections and are directed into the entrance holes of the hohlraum. The lasers heat the hohlraum's inside walls, creating x rays that heat and vaporize the surface of the capsule. Based on Newton's third law of motion that states every force has an equal and opposite force, the vaporizing surface pushes on the central portion of the capsule, causing it to implode. As the fuel is compressed, it produces a shock wave that heats the fuel to its core. The heat is so intense—100 million degrees—that fusion reactions occur, creating thermonuclear burn and ultimately ignition. The entire process takes just 20-billionths of a second.

The ignition process requires that each of NIF's 192 beamlines be precisely positioned and timed to reach the target at exactly the same moment. The beams must also be spatially uniform and of equivalent energy so that the power (up to 500 terawatts) delivered to the target is balanced. From the moment the ignition pulse is generated at the master oscillator to when it reaches the target, the laser must perform flawlessly to produce the right conditions for ignition.

Decades of research have been devoted to creating fusion in the laboratory. With NIF operational and demonstrating its one-of-a-kind capabilities, the laser is on its way to helping scientists finally achieve their goal.

This polished capsule designed for inertial confinement fusion experiments is just 2 millimeters in diameter.



(above) The building housing the 192-beam laser and its target chamber is the size of three football fields. (below) Each of NIF's two identical laser bays has two clusters of 48 beamlines, one on either side of the utility spine running down the middle of the bay.

A technician assembles and aligns the components in a preamplifier module.

can vary in length and overall energy. The pulse is then split into 48 separate beams, which are directed into individual preamplifier modules that increase the beams' energies by billions of times—up to a few joules. The beams are then further split to create 192 beams.

Subsequently, each beam passes several times through its own series of glass amplifiers. By the time the beams are redirected to the switchyard, each one contains more than 4 megajoules of 1,053-nanometer-wavelength (1-omega, infrared) light. In the switchyard, mirrors merge the parallel array of beams into 48 groups of 4. Before entering the target chamber, these "quads" pass through 48 final optics assemblies that are symmetrically positioned around the top and bottom halves of the target chamber to precisely orient the beams onto the target.

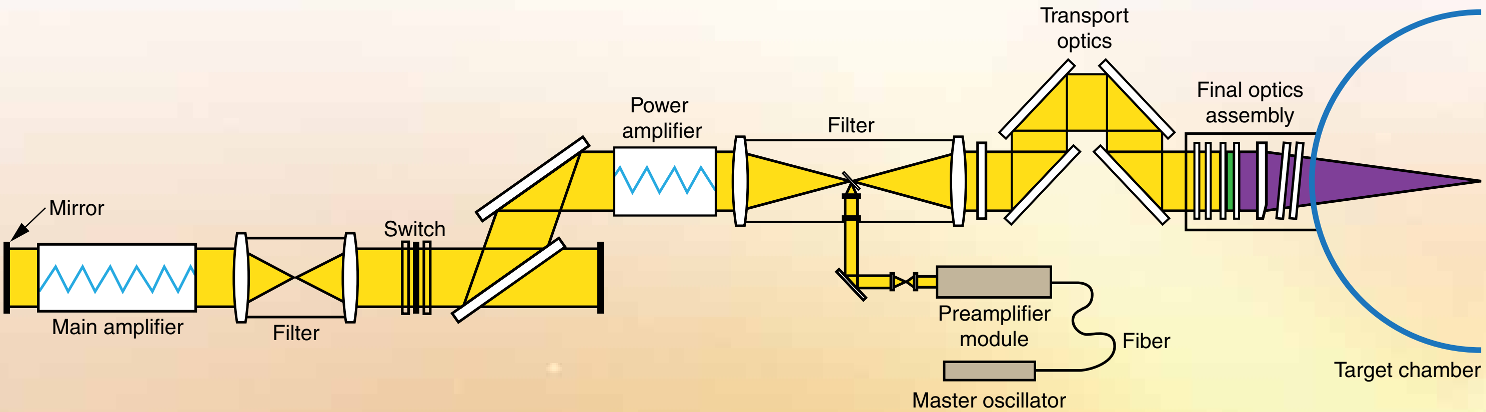
Inside the optics assemblies, potassium dihydrogen phosphate crystals convert the beams from 1-omega infrared light into the desired 3-omega ultraviolet light. This high-frequency, short-wavelength light improves the coupling of the energy into the target. Several other optics focus the light onto the target.

In total, a NIF laser beam travels approximately 1,500 meters within 5 millionths of a second from its birth at the master oscillator to when it reaches the target chamber. When the beams arrive at the target, they are aligned within 60 micrometers root mean square, less than the width of a human hair. Bruno Van Wonterghem, operations manager for NIF, says, "The precision NIF is designed to achieve is similar to throwing a dime from Livermore to San Francisco [a distance of about 64 kilometers] and landing it perfectly inside the coin slot of a parking meter."

Tuned to Perfection

One challenge of ignition is creating the perfect mix of physical conditions at a precise moment in time so that the target implodes uniformly. Recently, multiple test shots were fired to demonstrate how certain laser parameters can be manipulated to produce those conditions. "The laser is one of the main tools used to tune the ignition capsule," says Chris Haynam, manager of NIF's Laser Performance Integrated Experiment Team.

All shots are modeled, set up, and analyzed through a computational system called the Laser Performance Operation Model (LPOM). LPOM provides real-time information on the system requirements for meeting a specific set of laser energy, pulse length, and power goals. It defines the configuration for the master oscillator and preamplifier hardware, determines the



Every NIF beam starts at the master oscillator. The low-energy beam is amplified in the preamplifier module and then in the power amplifier, the main amplifier, and again in the power amplifier before the beam is run through the final optics assembly and into the target chamber.

diagnostic settings for a particular shot, and analyzes shot data. With LPOM, the team can compare predicted shot values with actual data and adjust the settings as necessary for later shots. The data are derived from the many instruments surrounding the target chamber—detectors, oscilloscopes, interferometers, streak cameras, and other diagnostics—that measure the system's performance and record experimental results.

More than a dozen laser parameters are "tuned" to control and optimize key physics parameters related to ignition capsule performance. For example, in ignition experiments, the master oscillator must produce a pulse consisting of four shocks that are timed to collapse the capsule in a precise sequence. Sudden amplitude (peak power) transitions in the pulse create these shocks, and the timing of them must be exact to create the ignition "hot spot"—which starts fusion burn—at the center of the compressed fuel. The amplitude, duration, timing, and energy of each shock can be manipulated by producing the desired pulse shape from the laser system.

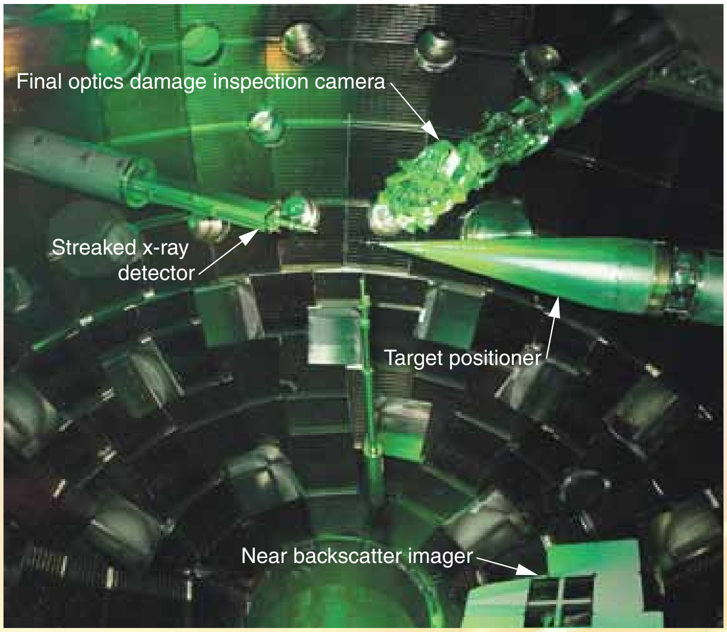
To show how the laser parameters could be adjusted to meet the shock-timing requirements needed for ignition, the team tested a single beamline in a separate unit known as the Precision Diagnostic System (PDS). The team fired 16 shots, then increased the amplitude of the pulse and delayed it by 100 picoseconds, before firing an additional 12 shots. "A comparison of the test data showed that the laser could make the precise changes in amplitude and timing required to tune the capsule to achieve ignition," says Haynam.

A Powerful, Shapely Spot

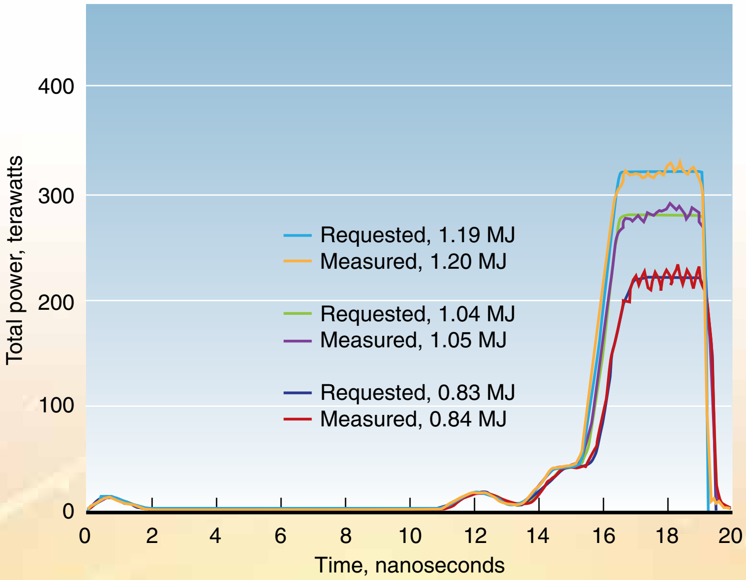
The amplitude and energy of the final shock produced by the laser pulse controls the velocity of capsule implosion and the ignition process. However, the uniformity of this velocity depends on the size and spatial uniformity of each focal spot inside the hohlraum. Haynam's team uses the sophisticated optics and lenses inside the final optics assembly to manipulate the focal spot size. For example, large-aperture diffractive optics, called continuous phase plates, adjust and fine-tune the laser beam to a prescribed size and shape, while maintaining the coherent properties of the laser light. (See *S&TR*, October 2007, pp. 12–13.) These continuous phase plates are combined with a wedged focusing lens to precisely control the focal spot size and uniformity of the beams as they enter the target chamber.

Focal spot size was also tested in PDS. Inside PDS, a beam's energy can be effectively attenuated while still providing accurate measurements. PDS includes an integrated optics module that converts 1-omega infrared light redirected from the switchyard into 3-omega ultraviolet light and then focuses the pulse in precisely the same way as NIF hardware.

Beam-smoothing techniques are used to reduce the intensity of the energy



Detectors, oscilloscopes, interferometers, streak cameras, and other diagnostics surround the target chamber to measure the laser system's performance and record experimental results.



The ability to reliably produce the desired laser pulses provides a stable experimental platform. This graph compares the requested and measured energy produced by three ignition pulses between 0.84 and 1.2 megajoules (MJ).

spikes, lower the contrast of the beam, and spatially shape the beam in a manner that meets target-size and irradiance requirements. A 17-gigahertz frequency modulator in the master oscillator first adjusts the beam's bandwidth. Then, a grating inside each preamplifier module creates a corresponding high-bandwidth pointing variation that promotes smoothing by spectral dispersion.

The team measured focal spot and beam-smoothing parameters for 1.1- and 1.8-megajoule shots inside PDS. "Both shots simultaneously met ignition requirements for beam conditioning, energy, temporal profile, and peak power," says Haynam. Using all the necessary smoothing techniques, the team then fired one NIF quad at 3 omega to the target chamber center. This shot demonstrated that the beam-smoothing and pulse-shaping requirements could be met on the main laser system at full energy and power (1.8 megajoules and 500 terawatts when scaled to 192 beams). In December 2009, the energetics shot series culminated in a shot where all of NIF's beams were fired simultaneously on an ignition-like target at 1.2 megajoules, meeting the beam-smoothing and pulse-shaping requirements for the entire laser.

The Balancing Act

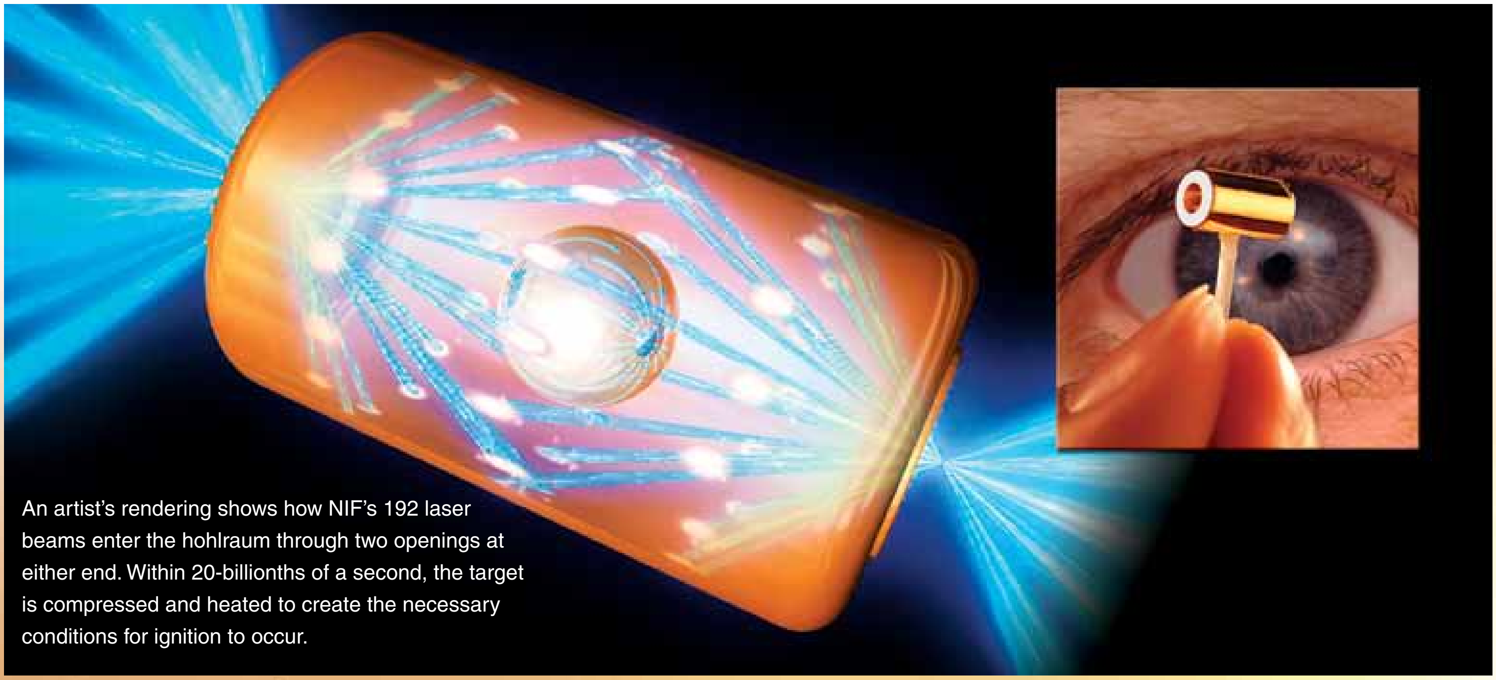
NIF's 192 beams are configured to form an inner and outer cone when they enter the hohlraum. (See the figure below.) The inner cone contains 16 quads (64 beams), and the outer cone contains 32 quads (128 beams). The wavelength separation of these beams affects the shape of the implosion. When beams at the entrance holes of the hohlraum interact with the hot plasma initiated from the x-ray bath occurring inside the hohlraum, energy can transfer between the beams as a result of laser–plasma interactions. In 2009, scientists effectively tuned the wavelength of beams in the outer cone to control this energy transfer, thus transforming a pancake-shaped implosion into a round one.

Power balance and synchronization of the beams are also key to achieving this optimal implosion shape. Balancing the power allows the x rays created inside the hohlraum to uniformly compress the target. "The process is analogous to pressing on a balloon," says Jeff Atherton, director of experiments for the National Ignition Campaign, currently under way. "Unless the balloon is pressed on evenly all the way around, it will bulge out in different directions. The same is true for compressing an ignition capsule. We analyzed the power balance at the start and the peak of the pulse, and it was well within the design requirements."

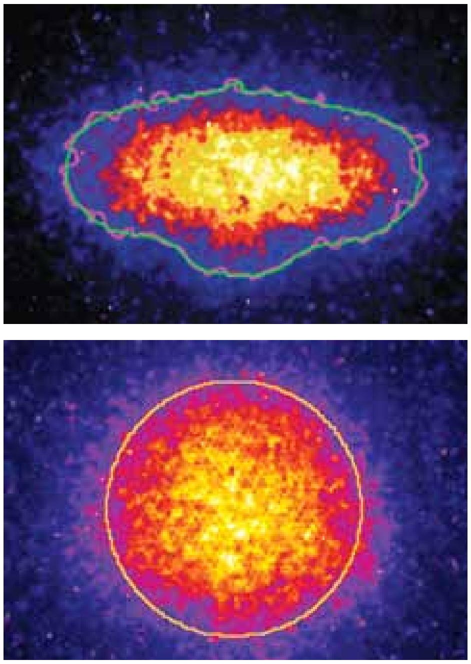
Haynam and his team's efforts are primarily geared toward demonstrating the laser's flexibility and how it can be tuned to create the conditions needed to occur inside the hohlraum for ignition. However, creating the perfect conditions for ignition also requires the right target. Another group of NIF scientists and engineers is studying target energetics and design requirements. Together, the laser and target experiments will provide the data needed so that operational processes and system components can be designed and engineered to meet optimal performance standards.

A Facility for the Ages

The National Ignition Campaign is dedicated to taking the necessary steps to achieve ignition and to developing a robust ignition platform. The campaign is



An artist's rendering shows how NIF's 192 laser beams enter the hohlraum through two openings at either end. Within 20-billionths of a second, the target is compressed and heated to create the necessary conditions for ignition to occur.



Using a new wavelength-tuning technique, scientists can control the direction and amount of energy transfer between laser beams, greatly improving the implosion symmetry of a target. Shown here is (top) an asymmetrical target implosion before tuning and (bottom) a spherical one after tuning.

More than 3,500 guests attended the formal dedication of NIF on May 29, 2009, 12 years to the day of the facility's groundbreaking ceremony.

a partnership of NNSA with members from Lawrence Livermore, Los Alamos, and Sandia national laboratories; the University of Rochester's Laboratory for Laser Energetics; General Atomics in San Diego, California; and numerous other national laboratories and universities including the Massachusetts Institute of Technology.

The first set of experiments demonstrated that NIF is a robust platform for the campaign. "The 173 target shots at 3 omega with 97-percent reliability provide high confidence of the laser and the ability to achieve ignition," says Van Wonterghem. "Over the next few years, we plan to continuously improve the laser to further increase performance, reliability, and shot rate." Ignition experiments will begin later this year, with the goal of creating a reproducible ignition platform by end of fiscal year 2012.

Scientists are also experimenting with NIF's capabilities for other high-energy-density research. For example, using a foil backlighter, they apply NIF's 1-omega light for x-ray radiography. These experiments allow researchers to see through and analyze materials in greater detail. Additionally, Haynam's team has demonstrated in PDS that NIF can operate using 527-nanometer-wavelength (2-omega, green) light equal to 3.4 megajoules of energy when scaled to the full NIF equivalent of 192 beams. "These results are exciting because 2-omega operation allows us to go up to higher energy while significantly extending the life of the optics," says Haynam.

The experimental work being performed at NIF is surpassing the expectations of many people. After a recent tour of the facility, Charles Townes said, "When I was inventing the laser and hoping to build the first one, I was hoping to get milliwatts of power with a small laboratory device. I just never imagined anything like this coming out of it." Fifty years later, advances in laser technology have brought us closer than ever before to achieving ignition and, with it, the potential to produce a secure, reliable source of limitless energy for future generations.

—*Caryn Meissner*

Key Words: energy gain, hohlraum, ignition, inertial confinement fusion (ICF), laser performance, pulse shape, National Ignition Campaign, National Ignition Facility (NIF), wavelength tuning.

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