ON THE PATH TO IGNITION

National Ignition Facility experiments produce new states of matter as scientists close in on creating the conditions required to ignite fusion fuel.

AMONG the most challenging scientific quests over the past 50 years has been the international effort to create, in a laboratory setting, a miniature "star on Earth." The goal of this endeavor is to surpass the extreme mix of temperature, density, and pressure at the center of the Sun and generate conditions in which hydrogen fusion reactions can start and sustain themselves, thus creating a fusion fire in the laboratory. The ongoing fusion reaction in the Sun's center provides all the energy needed for life on Earth. Replicating this sustained reaction in a laboratory requires conditions that are even more extreme: temperatures in the tens of millions of degrees, pressures hundreds of billions of times Earth's atmosphere, and a density of burning matter that is more than 100 times the density of lead.

In their quest to bring "star power" to Earth, researchers at the National Ignition Facility (NIF) have worked over the past 18 months to produce states of matter never before achieved in a laboratory setting. Using all 192 beams of the giant laser, experimenters are generating temperatures and densities inside an imploding, peppercorn-size capsule of frozen hydrogen isotopes (deuterium and tritium, or D–T) that when compressed to the diameter of a human hair will sustain fusion burn.

Edward Moses, principal associate director for NIF and Photon Science and leader of the fusion program effort, says, "The ultimate goal of these experiments is to ignite a self-sustaining burn wave of fusion fuel, producing more energy than is delivered to the target—an event called ignition." NIF researchers are moving ever closer to achieving ignition and fulfilling the vision of early fusion pioneers such as former Laboratory Director John Nuckolls. Shortly after the laser's invention in 1960, Nuckolls conceived of using the x rays generated by a powerful laser pulse to fuse hydrogen isotopes, convert matter into energy (as in Einstein's famous equation, $E = mc^2$), and thereby liberate more energy than is delivered by the laser pulse.

"NIF was designed to be the world's largest laser," says NIF chief scientist John Lindl. "In fact, it now operates as such. We have known from the outset that the energy it delivers does not give us a large margin of performance to achieve ignition. Everything that occurs during the implosion of hydrogen fuel must be nearly perfect."

Lindl notes that significant progress has been made since precision experiments began in May 2011, as part of the National Ignition Campaign (NIC). (See the box on p. 12.) He attributes that success to the heroic efforts of the entire NIF staff. "In all areas of the organization—lasers, diagnostics, cryogenics, and operations—people have worked incredibly hard and with incredible skill. As a result, we have made huge advances in technology, materials, and scientific understanding. We have come a long way and routinely achieve environments that are extreme by any measure."

Indirect Drive Heats the Fuel

To achieve the extreme conditions required for fusion, NIF's 192 laser beams are focused into laser entrance holes at each end of a 1-centimeter-long cylindrical target, called a hohlraum. The laser beams irradiate the interior surface of the hohlraum, raising the interior temperature to more than 3 million degrees Celsius. At these temperatures, the hohlraum works much like an oven, radiating x rays into its own interior. The x rays in turn irradiate the plastic shell of the fuel capsule mounted in the hohlraum's center, ablating the surface and causing the capsule to implode through a rocketlike reaction.

X-ray and neutron emission images from ignition experiments show that the interior volume of the capsule collapses by almost a factor of 100,000, heating and compressing the frozen D–T ice layer, the fuel for ignition, lying just inside the outer plastic layer. In experiments to date, the resulting hot center, called the hot spot, reaches temperatures of nearly 40 million degrees Celsius with densities of 50 to 100 grams per cubic centimeter (5 to 10 times the density of lead) and pressures 150 to 200 billion times Earth's atmosphere. These conditions are hotter and nearly as dense as those in the center of the Sun.

The hot spot is surrounded by a region containing about 90 percent of the fusion fuel, which has a density of 600 to 800 grams per cubic centimeter at a temperature of 1 to 2 million degrees Celsius. The fuel's density is about 3,000 times the initial density of the frozen D–T layer—well in excess of that in the Sun's center and by far the highest

The National Ignition Campaign

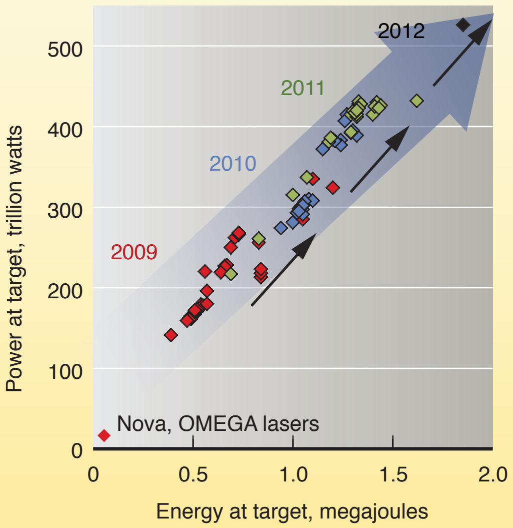
Ignition experiments on the National Ignition Facility (NIF) began as part of the National Nuclear Security Administration's (NNSA's) National Ignition Campaign (NIC). This campaign, which began in 2006 and ended September 30, 2012, had two principal goals: transition NIF to routine operations as the world's preeminent high-energy-density user facility for the nuclear weapons programs, fundamental science, nonproliferation, and other national security purposes and develop the capability to study and achieve ignition on NIF. The campaign involved the participation of Sandia and Los Alamos national laboratories, General Atomics, and the Laboratory for Laser Energetics at the University of Rochester. Other key contributors included the Massachusetts Institute of Technology, Lawrence Berkeley National Laboratory, Atomic Weapons Establishment in England, and the French Commissariat à l'Énergie Atomique.

Following completion of NIF construction in March 2009, researchers focused on installing, qualifying, and integrating the facility's many systems as well as developing the experimental platforms necessary to study and control, with adequate precision, the key processes necessary for achieving ignition. (See *S&TR*, September 2012, pp. 14–21.) Precision implosion-optimization experiments using these platforms steadily increased the pressure in the frozen hydrogen fuel from about 1,000 terapascals (or nearly 10 billion times atmospheric pressure) in the early implosions to currently about 15,000 terapascals, achieving densities in excess of 600 grams per cubic centimeter or about 60 times the density of lead. Although the pressures achieved are approaching those in the center of the Sun and are by far the highest ever achieved in the laboratory, they remain a factor of two to three below those needed for ignition.

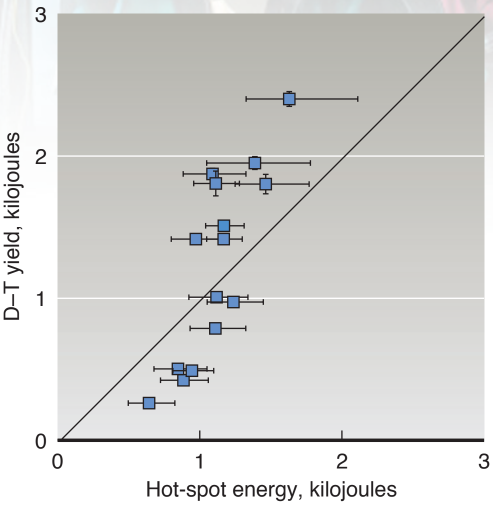
Over the course of NIC, a large body of scientific knowledge and major new experimental, diagnostic, and target manufacturing capabilities were developed and validated. NIF scientists and engineers steadily increased the laser's energy and power, culminating on July 5, 2012, when the system's 192 beams delivered more than 1.8 megajoules of ultraviolet light (in excess of 50 times more energy than any laser has demonstrated) and more than 500 trillion watts of power to the center of the target chamber. (See *S&TR*, September 2012, p. 2.) The combination of energy and power, along with the precision of laser beam pointing and power balance of all the beams, met the NIC specifications. International review committees have agreed that the laser has proven exceptionally reliable, durable, precise, and flexible in accommodating the unusually diverse needs of various research groups.

An NNSA report to Congress in December 2012 stated that "The NIF laser performed reliably and with great precision and executed thirty-seven cryogenic implosion experiments. Power and energy have exceeded initial design specifications. Target quality is superb, and diagnostics have been developed that are returning experimental data of unprecedented quality."

The report added, "The pursuit of ignition and high fusion yields in the laboratory is a major objective of the SSP [Stockpile Stewardship Program] and ICF [Inertial Confinement Fusion] Program and is a grand challenge scientific problem that tests our codes, our people, our facilities, and our integrated capabilities."



Scientists have steadily raised the power and energy levels at the National Ignition Facility (NIF) since it was completed in September 2009. On July 5, 2012, the laser system's 192 beams delivered more than 1.8 megajoules of ultraviolet (3-omega) light and more than 500 trillion watts of power to a target. This unprecedented combination of energy and power met NIF's original design specifications.



NIF researchers are continuing to work on elevating the hot-spot temperature and density through increased alpha heating to improve deuterium–tritium (D–T) yield. The yield attained in current experiments is about 50 times greater than that achieved on the first cryo-layered experiment in 2010 and is within a factor of 5 to 10 of the yield needed to initiate ignition.

density ever achieved in laboratory experiments.

The goal of current experiments is to increase the hot-spot density by another factor of three at about the same temperature already being achieved. Under these conditions, the fusion reaction rate would be sufficient to generate ignition, or burn conditions. The precursor step to ignition is attaining measurable alpha heating, in which the helium nuclei (alpha particles) produced by the fusing of deuterium and tritium nuclei deposit enough kinetic energy to increase the fuel's temperature well above that produced by the laser-generated implosion alone. "Alpha-particle heating is required for sustained fusion burn and the release of more energy than was necessary to initiate the reaction," explains Lindl.

Alpha heating can only happen when the hot-spot fuel is dense enough and has a sufficient radius to capture the alpha particles and absorb their energy. For the first time in any laboratory, NIF experiments are routinely producing fuel conditions sufficient to stop fusion-produced alpha particles, a critical requirement for self-heating of fusion fuel. In the better-performing implosions to date, more thermonuclear energy is produced from the hot spot than is delivered by compression heating from the laser energy alone. About one-fifth of this hot-spot energy is in the form of alpha particles. Calculations indicate that the alpha-particle yield must be about a factor of 10 higher to initiate ignition and a self-sustaining burn wave that starts in the hot spot and propagates into the surrounding main fuel, a process Lindl compares to lighting a fire with a match.

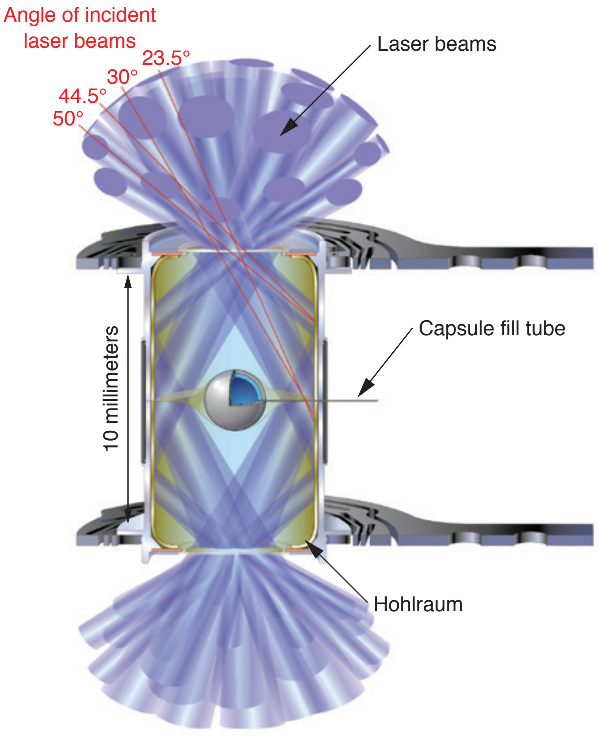
Perfecting Symmetry

Implosion velocities greater than 300 kilometers per second (or nearly 700,000 miles per hour) and a uniformly spherical implosion are essential for producing the fuel conditions needed for ignition. The hohlraum must be heated to 3 million degrees Celsius, and the flux of x rays streaming onto the fuel capsule must have a uniformity of better than 1 percent. Laser light thus needs to be absorbed by the gold hohlraum in a precise and prescribed manner. Achieving the required precision is challenging because of instabilities that inevitably occur when intense laser light interacts with the hot plasma, filling the hohlraum.

This complex, interactive laser propagation phenomenon is particularly difficult to model because the laser itself produces the hot plasma in the hohlraum. Codes developed to simulate laser–plasma interactions are at the edge of the Laboratory's current calculational capabilities. They have a voracious appetite for the computing capacity available on Livermore's high-performance machines.

Models describing hohlraum physics must accurately simulate a host of intricate processes. For example, laser light passes through the laser entrance holes and interacts with the ions and electrons that make up the plasma. Plasma energy heated by the laser is conducted away from the absorption regions. Absorbed light is subsequently converted into x rays that flow within the hohlraum and are absorbed into the fuel capsule's ablator layer. Codes must also model the physics during capsule implosion and the thermonuclear burn of the D–T fuel.

When NIC began, models of hohlraum physics had been developed and tested using the OMEGA laser at the University

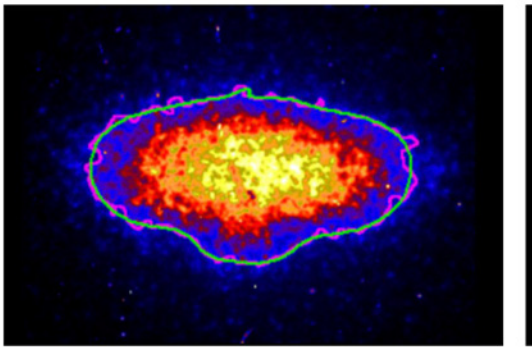


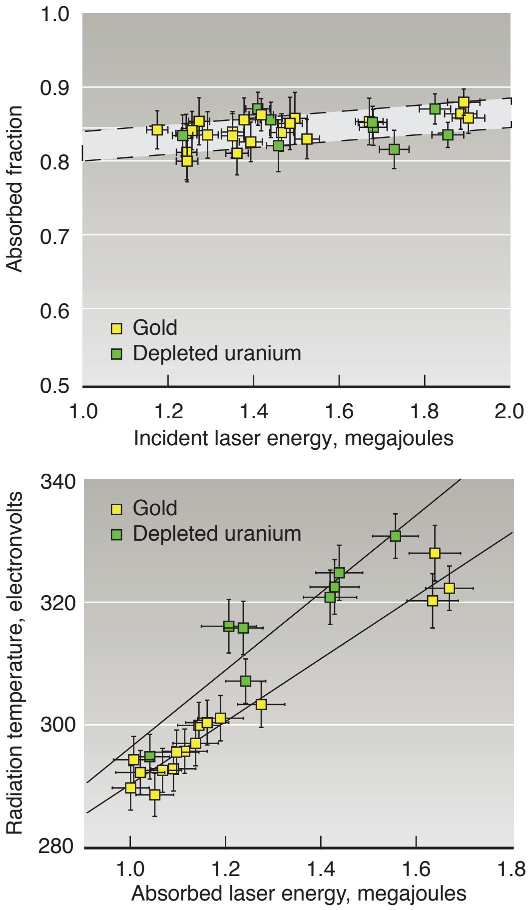
NIF laser light enters the two laser entrance holes to form an inner cone that illuminates the hohlraum wall near the equator of the capsule. An outer cone is also formed that illuminates an area of the wall closer to each laser entrance hole. The outer cone is composed of two subcones, one at 50 degrees and one at 44.5 degrees. The two inner subcones enter at 30 and 23.5 degrees.

of Rochester and, before that, Livermore's 10-beam Nova laser. Those experiments were performed on much smaller targets, using 50 to 100 times less laser energy than NIF routinely produces. Some researchers were concerned that these experiments and, consequently, the models would not be applicable when scaled to NIF. To address this concern, the NIF team tested and improved the models as NIC experiments gathered data at higher energy and on larger targets.

During an ignition experiment, laser light enters each laser entrance hole in the form of two cones. An inner cone containing one-third of the energy travels at a low angle into the hohlraum and illuminates the wall near the equator. An outer cone containing two-thirds of the energy enters at a high angle and illuminates an area of the hohlraum wall closer to each laser entrance hole. Each inner and outer cone is composed of two subcones. Beams forming the outer cone enter the top and bottom laser entrance holes at angles of 50 and 44.5 degrees with respect to the hohlraum's vertical axis. The inner beam energy is split equally between 30 and 23.5 degrees. This illumination pattern ensures that the x-ray drive on the target remains uniform in space and controllable in time.

Experiments show hohlraums absorbing about 85 percent of the laser energy. Losses are caused by instabilities that occur when laser light interacts with plasma ions and electrons emanating from the gold hohlraum, with the outer plastic layer of the fuel capsule, and with helium ions inside the hohlraum. Most interactions are unwelcome because they scatter laser light, thereby interfering with the uniform x-ray field needed to evenly compress the capsule. Interactions can also accelerate plasma electrons to energies high enough to preheat the capsule and make compression more difficult. The main type of laser–plasma interaction is stimulated Raman scattering on the inner beams, which produces energetic, superhot electrons.





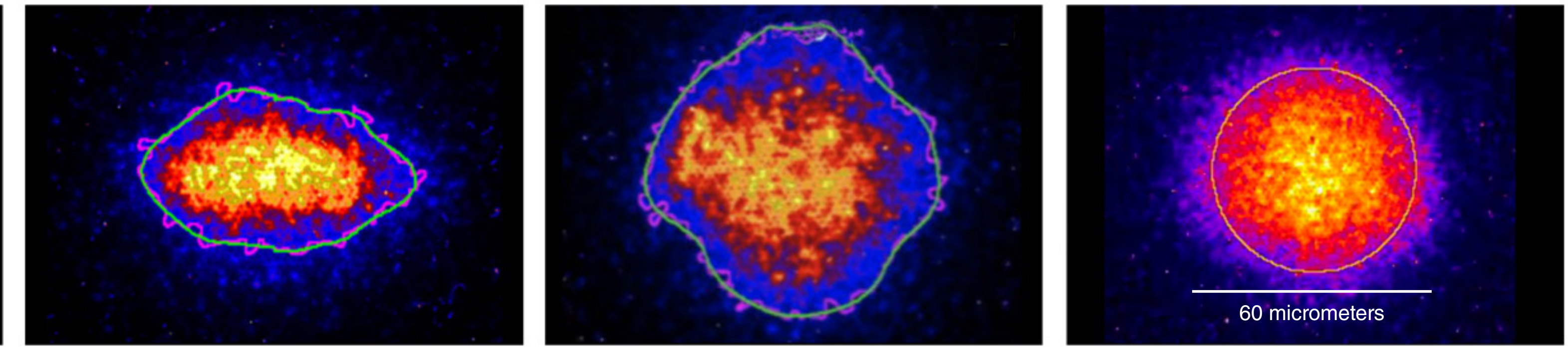
(top) Hohlraums, whether manufactured from gold or depleted uranium, absorb about 85 percent of the laser energy, a percentage that is nearly independent of laser energy. The shaded band shows the best fit to the data with ±1 standard deviation. (bottom) In contrast, hohlraum radiation temperatures rise with increased laser energy, as expected, and higher temperatures are achieved with depleted uranium compared with gold.

Taming Laser–Plasma Instabilities

The first NIF hohlraum energetics shots fielded from 2009 to 2010 yielded critical data for efforts to control laser–plasma instabilities. Some of the earliest results were not consistent with predictions from the standard model experimenters had been using with the less-energetic lasers. The NIF shots experienced more stimulated Raman scattering and much cooler plasma temperatures than predicted as well as a tendency toward pancake-shaped implosions (instead of the desired round shape). In addition, the x-ray drive on the fuel capsule differed from predictions.

The standard model was originally developed in the 1970s—an era when computer resources were much less capable than the current generation of supercomputers at Livermore. "Laser–plasma interactions such as stimulated Raman scattering are difficult to model, and to predict them accurately requires a correct notion of the plasma conditions," explains physicist Mordy Rosen. "Although we knew the standard model had shortcomings, its results were considered conservative."

In 2010, Rosen and colleagues developed the high flux model (HFM), which contains two important advances. It more realistically accounts for the



A series of micrographs shows the dramatic improvements (from left to right) made in implosion symmetry on the first four ignition experiments conducted September 2–5, 2009. The pancake-shaped implosions were inconsistent with predictions from the guiding standard model. Scientists used crossbeam energy transfer to make small adjustments in wavelengths and redirect energy from outer to inner cone beams. The technique, together with other adjustments, results in much more spherical implosions.

complex atomic physics occurring in the hot, partially ionized gold atoms from the hohlraum wall. It also incorporates a modified model for the flow of heat carried by the plasma electrons. The new model accurately predicted a much cooler hohlraum plasma (25 million degrees Celsius compared with the 40 million predicted by the standard model). This cooler plasma helped plasma physicists Denise Hinkel and Ed Williams explain the spectrum and level of the Raman light found in the data. HFM also predicted a higher flux of x-ray emission, as was indeed observed flowing from the hohlraums through the laser entrance holes.

In addition, HFM accurately predicted the unexpected pancaking of the fuel capsule that occurs because the outer beams convert laser light to x rays more efficiently than the inner beams. These x rays shone more brightly on the poles of the capsule, driving it toward a pancake shape instead of a uniformly round sphere. The cooler and denser plasma absorbed more light from the inner beams, preventing those beams from penetrating into the hohlraum's midplane. As a result, the inner beams could not provide enough drive on the central region of the hohlraum to counter the outer beams' drive on the pole regions. A pancake-shaped implosion thus ensued.

The NIC team took the unusual step of using laser–plasma interactions to overcome the uneven distribution of laser light on the hohlraum walls. The researchers used a technique called crossbeam energy transfer that can occur in plasma when two or more high-power lasers traveling in different directions overlap. This phenomenon permits redirecting energy between the outer and inner cone beams where they overlap at each laser entrance hole. Controlling the shift in the energy balance of the two cones requires adjusting the color, or wavelength, of beams forming the outer cone by 0.6 to 0.9 nanometers to provide 25 percent more power to the inner cone. "We had always assumed we would have to minimize crossbeam transfer," says physicist Debbie Callahan. "Then we realized it could be a tool to improve implosion symmetry."

Says Lindl, "Until recently, there was never a time when plasma phenomena could help us; it usually made life more difficult. We could try turning up the energy on the inner beams, but that approach would drive the laser harder. NIF works more efficiently when all beams have the same power. Instead, we shifted energy from the outer to the inner cones. NIF was built with the capability to adjust the wavelength of internal and external beams to minimize crossbeam transfer. Adjusting the wavelength separation to control symmetry wasn't part of the original NIF plan, but it works beautifully." With these insights, researchers are working to further reduce laser–plasma interactions.

Successful experiments in 2009 prompted scientists to add another refinement. They adjusted the relative wavelengths on the 23.5- and 30-degree inner beams by 0.1 nanometers to more precisely control the asymmetry as seen from the poles of the capsule in the hohlraum (when viewed up or down the hohlraum's axis).

The final arrangement involves first transferring energy from the 44.5- and 50-degree beams into the 23.5- and 30-degree beams. Energy is then transferred from the 30-degree beam to the 23.5-degree beam deeper into the hohlraum plasma, where only these beams continue to overlap. Together, the energy-transfer measures produce a much brighter beam that propagates more deeply into the hohlraum's center. For this pioneering work, a team of NIF researchers earned the American Physical Society's 2012 John Dawson Award for Excellence in Plasma Physics Research.

Adjusting the power levels among the subcones controlled only one aspect of implosion symmetry. Another aspect was achieved by more precisely pointing beams at spots on the hohlraum walls. Additionally, the team made small design changes to the hohlraum geometry. A somewhat shorter and wider hohlraum allows the inner beams better access to the waist region. Together, the more-precise beam pointing, crossbeam energy transfer, and modified hohlraum dimensions are key steps for meeting the stringent uniformity requirements of 99-percent capsule radiation flux to achieve ignition. Because HFM predictions have been consistent with various experimental observations, the model allows researchers to better understand hohlraum performance and the role of laser–plasma interactions.

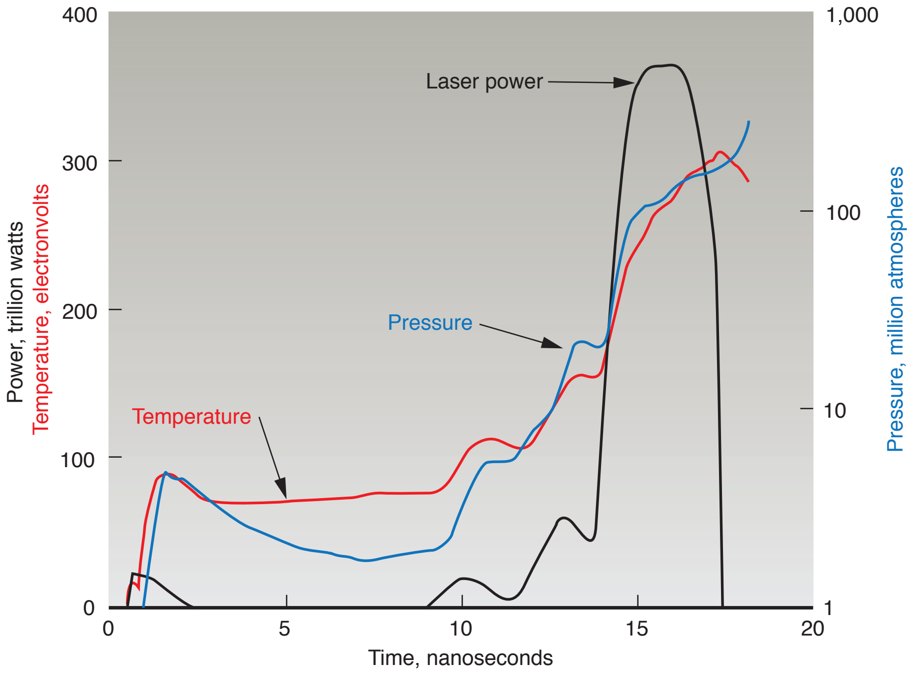
Lindl cautions that optimizing implosion symmetry is not yet complete. For example, the D–T fuel layer surrounding the hot spot can have a different shape than the hot spot. The NIF team is currently developing techniques such as Compton radiography (an x-ray shadowing technique) to provide data on the D–T layer's shape at peak compression. Early results show that the position of the outer beams on the hohlraum wall is not yet optimal for ensuring a symmetric implosion. Upcoming experiments will focus on improving the D–T layer's shape.

Pulse Shape of Four Precise Shocks

A nearly perfect x-ray drive on the outer plastic shell is only one essential element of ensuring ignition. In addition, the laser pulse must be carefully shaped to send a precisely timed series of shocks through the frozen D–T layer. The timing is such that the shocks overtake each other soon after they travel into the D–T gas comprising the very center of the fuel capsule.

"If we merely hit the capsule with the power required to generate the 10-terapascal pressure needed to achieve the desired implosion velocity, the shock from that pressure would generate too much internal heat and decompress the frozen D–T layer," says Lindl. "To obtain high velocity without significant shock heating, we must gradually increase the pressure. The NIF ignition pulse achieves the desired pressure of 10 terapascals in a sequence of four weaker shocks."

The goal of ignition shock-timing experiments has been to precisely set the power levels for each of the four shocks, which together create an overall pulse lasting about 20 nanoseconds. The pulse consists of an initial small shock (called a picket), followed by a relatively low-energy but important 9-nanosecond-long trough to maintain a constant first-shock velocity in the capsule. Second, third, and fourth shocks at increasing power are followed by a 3-nanosecond peak power pulse, which provides most of the drive for final acceleration of the shell. The symmetry of the imploded core (hot spot) is affected by the symmetry of each shock, but it is most sensitive to the initial picket and the x-ray drive produced by the final peak power pulse.



Achieving ignition requires a 20-nanosecond-long laser pulse that sends a carefully timed series of shocks to efficiently compress the fuel capsule. As each shock passes through the capsule, the fuel is further compressed. The 3-nanosecond peak power pulse that follows this sequence provides most of the drive for final acceleration of the capsule.

Physicist Harry Robey notes that each shock wave propagates through the capsule ablator and compresses the fuel layer. The first three shocks are adjusted to merge just after passing through the D–T layer. "We want these three shocks to merge at one time in a single radial location inside the capsule," says Robey. If they are not spaced correctly (and at ±50 picoseconds, or 50-trillionths of a second), the D–T fuel layer will not reach the required density at the end of the implosion. A correctly timed fourth shock, designed to overtake the first three shocks after they coalesce, is critical for keeping the fuel at maximum compression.

Experiments to measure the strength (velocity) and timing of these shocks are conducted in a keyhole target platform. Keyholes have a cone inserted through the side of the hohlraum wall and into a capsule filled with cooled liquid deuterium—an excellent substitute to the D–T ice layer. These experiments use the velocity interferometer system for any reflector (VISAR), where the shock in the plastic shell or the surrogate fuel reflects the

A NIF technician holds a keyhole target attached to equipment that is part of the cryogenic cooling system. Keyhole experiments measure the strength (velocity) and timing of the four shock waves from the laser pulse as they transit the capsule. For these experiments, a cone is inserted through the side of the hohlraum wall and into a capsule filled with cooled liquid deuterium. The inset shows the keyhole cone and capsule without a hohlraum around them.

VISAR laser. The instrument then precisely records the timing of all four shocks.

Ignition Ahead

Lindl notes that scientists have already achieved the required x-ray drive temperature, hot-spot shape, and shock timing, and they have nearly attained the needed implosion velocity. However, challenges remain. Densities in the D–T layer must reach 1,000 grams per cubic centimeter, somewhat higher than the 600 to 800 grams per cubic centimeter achieved in current experiments. Likewise, hot-spot pressures are a factor of two to three lower than those required for ignition. Looked at another way, because the measured hot-spot temperatures are close to those needed to reach ignition, the hot-spot density is a factor of two to three lower than required.

Recent experimental evidence also indicates that the achieved pressure is insufficient because the imploding D–T fuel layer surrounding the hot spot is not as spherical as required. “We believe that understanding and controlling three-dimensional departures from spherical implosions is a critical milestone on the path to ignition,” says physicist John Edwards, associate program leader for Inertial Confinement Fusion in the NIF and Photon Science Principal Directorate. Radiography of the D–T fuel at peak compression will better record the hot-spot shape and distinguish among different mechanisms that can affect the degree and uniformity of compression. When NIF’s Advanced Radiographic Capability goes online, it will generate a much brighter source of x rays for Compton radiography than can be obtained with the standard NIF beams. (See *S&TR*, December 2011, pp. 12–15.)

“NIF continues to make outstanding progress toward the goal of ignition,” says Lindl. “The laser, diagnostic systems, target design and fabrication, and round-the-clock operations are producing data of unprecedented quality.”

“Discovery science is the exploration of the unknown,” continues Lindl. “Ignition remains a grand scientific challenge that requires unprecedented precision from the laser, diagnostics, targets, and experiments. We can’t say exactly when we will achieve ignition, but we have made tremendous progress and have developed an exciting experimental plan to take us the rest of the way.”

—Arnie Heller

Key Words: Advanced Radiographic Capability, alpha heating, crossbeam transfer, high flux model (HFM), hohlraum, ignition, National Ignition Campaign (NIC), National Ignition Facility (NIF), stimulated Raman scattering, velocity interferometer system for any reflector (VISAR), wavelength tuning.

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