

A Significant Achievement on the

A new shape for the laser pulse used in ignition experiments at the National Ignition Facility is taming long-standing instabilities and increasing the amount of alpha heating and neutron yield.

TEAMWORK among scientists in different disciplines has been a hallmark of research conducted at Lawrence Livermore. Ernest O. Lawrence, the Laboratory's cofounder, was noted for eschewing job titles and assembling cohesive teams of researchers with a variety of expertise. Once again, this enduring strategy has paid off. Scientists from two Livermore principal directorates—National Ignition Facility (NIF) and Photon Science, and Weapons and Complex Integration—are collaborating on a series of NIF experiments in which fusion reactions have generated substantially more energy than the laser-driven implosion had deposited into the fusion fuel.

The experimental results are remarkably close to supercomputer simulations. They also provide an important benchmark for the models used to predict the behavior of

matter under extreme conditions, such as those generated during a nuclear explosion. These results, which were reported in leading physics journals in early 2014, have also energized scientists worldwide who have been working for more than four decades to understand and control fusion, the power source of the Sun and stars.

The experiments use a new shape to NIF's laser pulse. Called a high foot, this pulse shape is more forgiving of imperfections in the fusion fuel capsule and of instabilities that can grow quickly and dampen fusion reactions. The goal of these experiments is to "gain control and learn more about what Mother Nature is doing," says Livermore scientist Omar Hurricane, who led the high-foot campaign. He adds that the campaign builds on advances in laser operations, experimental platforms and diagnostics, cryogenics,

target fabrication, and physics results, which were developed under the National Ignition Campaign (NIC). NIF itself grew out of decades of research at laser facilities worldwide, including those at the University of Rochester's Laboratory for Laser Energetics.

Since the summer of 2013, high-foot shots have produced record yields of fusion neutrons through a process called alpha heating—a result that is consistent with predictions made in computer simulations. In alpha heating, helium nuclei (alpha particles) generated by the fusion of deuterium and tritium (DT) atoms deposit enough energy to increase the fuel's temperature above that produced as the fuel capsule is compressed by the x-ray energy from NIF's laser light. The alpha particles further heat the fuel, increasing the rate



Path to Ignition

of fusion reactions and thereby producing additional alpha particles. This feedback process is the mechanism that is needed to achieve ignition on NIF. “We see a steadily increasing contribution to the yield coming from alpha-particle self-heating as we push the implosion a little harder with every experiment,” says Hurricane.

Since September 2013, the fusion yield in high-foot experiments has systematically increased by more than a factor of 10 over previous approaches, largely because the implosion is better controlled. An experiment on September 27, 2013, resulted in about 5 quadrillion (5×10^{15}) neutrons and about 14.4 kilojoules of energy, almost 75 percent more than NIF’s previous record. In addition, for the first time, the amount of energy released through fusion reactions exceeded the

amount of energy deposited in the fusion fuel (11 kilojoules). The contribution from alpha heating was also substantial, exceeding any previous shot.

A subsequent high-foot experiment on November 19 produced an even higher neutron yield of 6.1×10^{15} for 17.3 kilojoules of energy. On January 20, 2014, an experiment delivered 9.3×10^{15} neutrons or 26 kilojoules of energy, and a March 4 experiment essentially duplicated these results, yielding 9.6×10^{15} neutrons or 27 kilojoules.

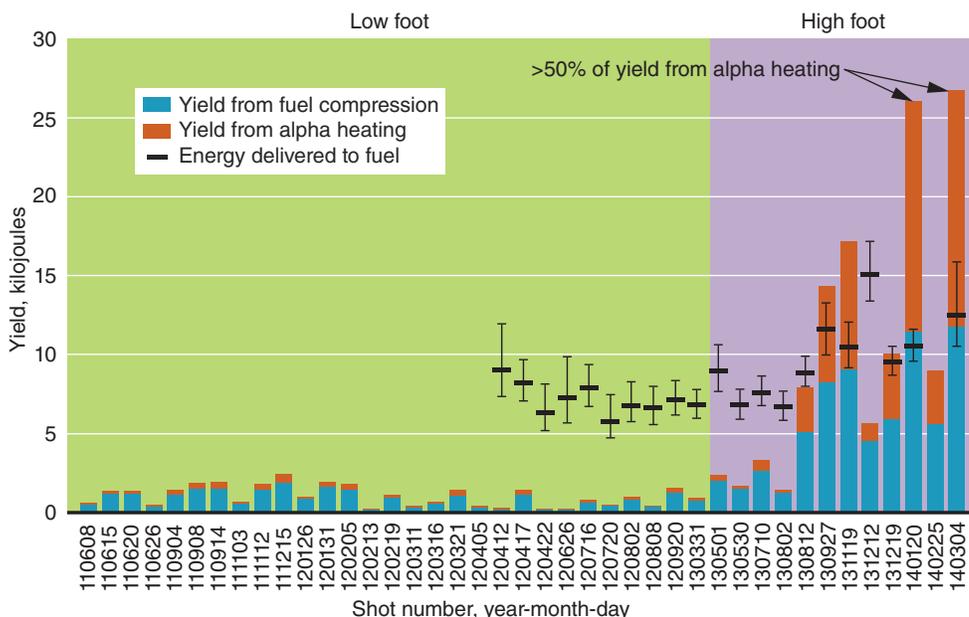
In the January 20 and March 4 shots, the fusion yield from alpha-particle self-heating was 1.25 times the yield from fuel compression, another historic accomplishment. The number of neutrons produced during each shot was just shy of 10^{16} , a target for neutron yield set by the National Nuclear Security Administration

(NNSA) in 2009 as a clear demonstration of alpha-particle self-heating.

Quest for Ignition

The 192-beam NIF, the world’s largest and most energetic laser, is designed to demonstrate thermonuclear burn and energy gain in a laboratory setting. NIF’s primary mission is to provide experimental insight and data for NNSA’s science-based Stockpile Stewardship Program. After NIF construction was completed in March 2009, researchers embarked on NIC, a three-year experimental effort to achieve ignition.

NIC experiments (and the later high-foot shots) used indirect drive, in which a fuel capsule containing DT fuel is placed inside a 1-centimeter-long gold cylinder, or hohlraum. Laser energy focused onto the interior walls of the hohlraum is converted



This graph shows the yield of fusion neutrons that result from fuel compression (blue) and alpha heating (orange) in low- and high-foot experiments at the National Ignition Facility (NIF). The shot number is the date of the experiment in year-month-day format (for example, 110608 is June 8, 2011). Two shots in 2014 achieved a performance milestone for ignition experiments when the amount of fusion energy yield from alpha heating exceeded that from fuel compression.

into x rays, which bathe the plastic shell of the capsule, ablate the shell’s surface, and drive the capsule inward like a rocket blast. The implosion heats and compresses a layer of frozen DT positioned just inside the outer plastic layer, creating a hotspot within a high-pressure region about 60 micrometers in diameter, where temperatures exceed 50 million kelvins. Each fusion reaction within the hotspot produces a helium nucleus and a neutron. Measuring the number of neutrons generated is one way to characterize the extent of fusion in an experiment.

Simulations and theoretical calculations show that, under ignition conditions, a self-sustaining burn wave starts in the hotspot when the fuel capsule is at peak compression and propagates into the surrounding main fuel. Because the energy that NIF delivers does not provide a large performance margin for achieving

ignition, the implosion of DT fuel must be nearly perfect in terms of compression, with implosion velocities greater than 300 kilometers per second, a uniformly spherical hotspot, and minimal mixing of the ablator shell with the core fuel. (See *S&TR*, March 2013, pp. 10–17.) The design of the laser pulse is critical to reaching these conditions. The pulse must be shaped to send a precisely timed series of shocks that propagate through the capsule ablator and overtake each other near the DT–gas interface.

Under NIC, researchers adopted a low-foot laser pulse to obtain maximum compression by keeping the capsule relatively cool until near the end of the pulse. With this pulse shape, they could meet a large fraction of the conditions required to achieve ignition in key areas independently, but not all at the same time. The highest neutron yield obtained was

7.5×10^{14} , about 10 times below both the simulated values and the regime in which alpha heating begins to dominate. Increasingly, scientists suspected that the low-foot pulse made the implosion susceptible to instabilities that grew significantly during compression and decreased neutron yield.

Improved Understanding

The high-foot campaign, along with experiments on hydrodynamic growth radiography, carbon–deuterium mix, and Viewfactor measurements, has focused on improving scientific understanding of implosion physics and validating computer simulations. The high-foot experiments are part of the Path Forward effort, sponsored by NNSA, to study how defects grow on the capsule’s outside surface, penetrate the hotspot, and affect performance. Results show that with the high-foot pulse shape, the ablator is more resistant to breakup during the high-velocity implosion, and hydrodynamic instabilities are thus less likely to cause ablator material to mix with the DT fuel.

The high-foot pulse lasts 15 nanoseconds (instead of the 20 nanoseconds used in low-foot shots) and features three main shocks instead of four. It also uses a higher power initial pulse, called the “picket,” and a lower peak power. Turning up the power during the picket increases the radiation drive temperature, which generates a stronger first shock in the foot, or trough period, of the pulse (hence the name high-foot pulse).

Boosting the x-ray drive early in the implosion and eliminating one of the four low-foot shocks help control ablator instability by increasing the density gradient scale length (essentially the in-flight thickness of the ablator). These changes also smooth out the ablator’s roughness early on. Because the high-foot picket heats up the hohlraum more than the first low-foot shock, the overall pulse is shortened by 5 nanoseconds. With the higher heating, helium gas in the

hohlraum must be increased from 0.96 to 1.6 milligrams per cubic centimeter to hold back gold ions vaporized from the inner hohlraum wall, which can interfere with the propagation of NIF’s inner laser beams. The three high-foot shocks passing through the DT ice also yield simpler wave structures of transmitted shocks than the four shocks used with previous experiments.

The higher adiabat (a measure of entropy) improves performance but with a trade-off: it reduces the compression of the fuel capsule. Low-foot experiments were designed to optimize compression to obtain ignition. The high-foot design is better at controlling instabilities and brings experimental performance in line with simulations. Although compression

is reduced, the absolute implosion performance remains relatively high.

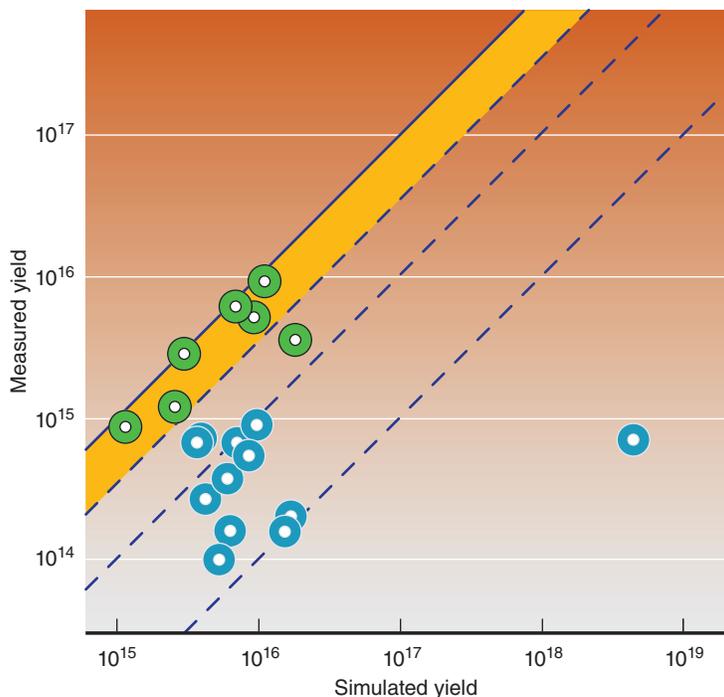
Sharing Ideas for Progress

The high-foot campaign was conceived in 2012 after scientists explored possible methods to address hydrodynamic instabilities observed in low-foot experiments, including the ablator shell breakup and hotspot mix. A May 2012 workshop organized by Laboratory Director Bill Goldstein (at the time, deputy director for Science and Technology) brought together experts from throughout the world to share ideas for advancing ignition experiments and countering instabilities.

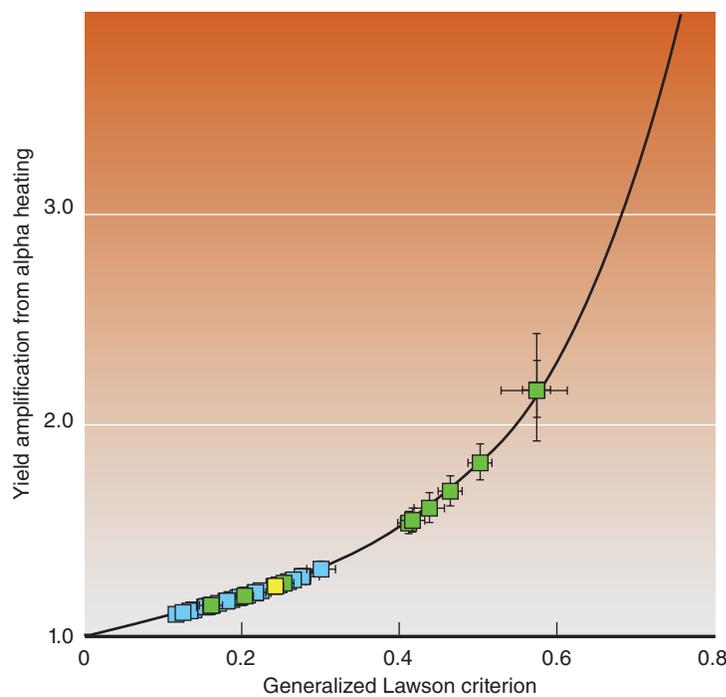
Many promising ideas resulted from the workshop. “Given time and money

constraints, we wanted to test a concept that would not require a lot of research and development, such as a new ablator material, but that could make a difference in performance,” says Hurricane. “We wanted to make a simple change and test it. That way, if the change didn’t work, we would ‘fail fast’ and could move on to another idea. We chose the high foot because simulations showed that changing the pulse characteristics could pay off.” He adds that the ensuing experiments “were born out of the fierce competition of ideas but then coming together as a team to move the best ideas forward.”

The first high-foot experiment using frozen DT fuel, performed on May 1, 2013, yielded 7.6×10^{14} neutrons and matched the best NIC shot. The experimental results



This graph compares the alpha-heating yield predicted by two-dimensional simulations (dashed lines) with yield produced in low-foot (blue circles) and high-foot (green circles) experiments on NIF. The high-foot pulse shape produces results that agree with simulations at close to 100 percent (solid blue line). Experimental data also show that yields from high-foot experiments have mostly increased with each successive shot.



A high-foot experiment conducted in March 2014 (upper right square) more than doubled the fusion yield from alpha heating compared with low-foot shots (blue squares). Green squares denote data from high-foot shots. The yellow square indicates an experiment using a high-density carbon ablator shell instead of plastic. Generalized Lawson criterion defines the conditions needed to reach ignition, which is 1.0.

also demonstrated much better consistency with simulations. A July 10 experiment using higher laser power and energy than the original May 1 shot resulted in more than 1×10^{15} neutrons. However, instead of being round, the hotspot had a toroidal shape. Tests with a longer hohlraum flattened the toroidal shape, and the yield declined.

The team returned to lower power but increased the laser energy, reasoning

(correctly) that this combination would better control the hotspot shape and increase yield. On August 13, an imploded capsule released a neutron yield of nearly 2.8×10^{15} (or about 8 kilojoules of energy), almost three times NIF’s previous record for neutron yield in cryogenic implosions. Shots since September 2013 have continued to produce increased neutron yields and greater contributions from alpha heating.

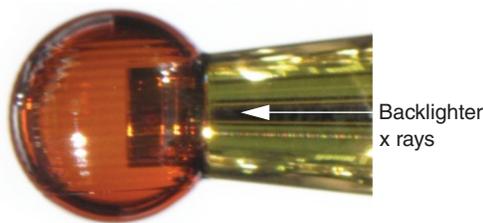
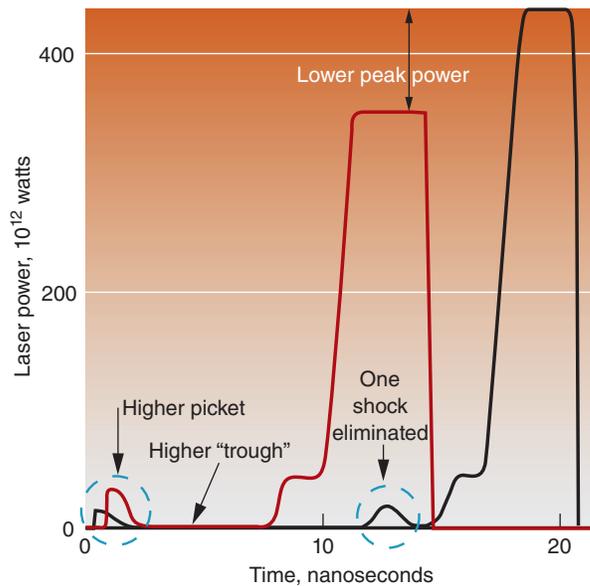
Examining Implosion Physics

The high-foot experiments are only one of several efforts to examine the physics of ignition experiments in detail. For example, although General Atomics manufactures the surface of the plastic ablator to an unprecedented degree of smoothness, it still contains microscopic bumps and dips. Once the capsule begins to implode, these tiny surface variations can cause fast-growing Rayleigh–Taylor instabilities, which can lead to the damaging mix of plastic and fuel.

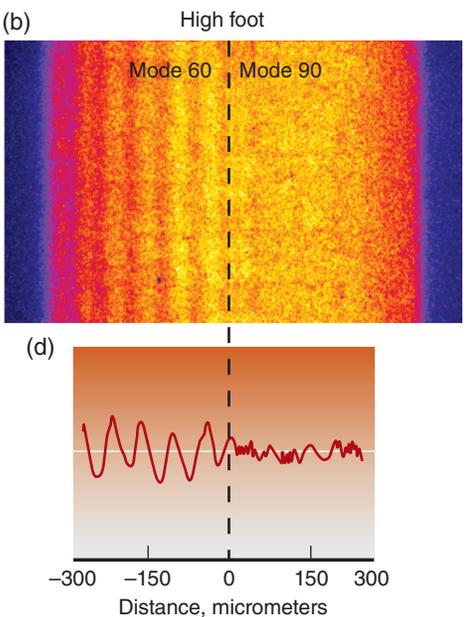
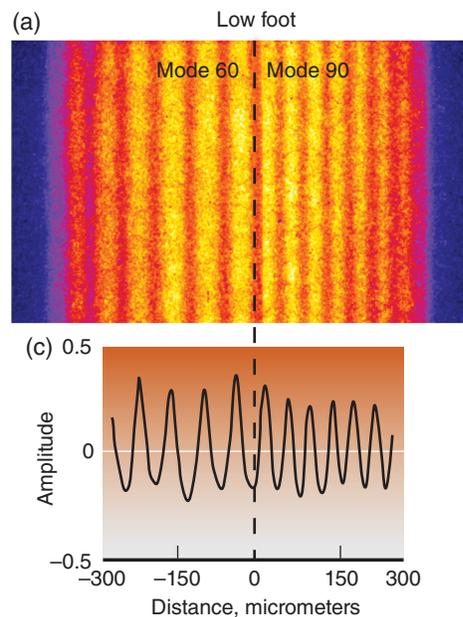
High-fidelity radiographic images of the ablation front have verified the accuracy of instability models. Hydrodynamic growth rate experiments, currently led by physicist Vladimir Smalyuk, confirmed that high-foot pulses damp down surface instabilities. For these experiments, modulations, or “ripples,” of different sizes were inscribed on the ablator’s surface to seed instabilities during the implosion. X rays entering the hohlraum through a gold cone in each capsule backlight the capsule. The cone works like a periscope, allowing researchers to observe the growth of perturbations as the capsule implodes.

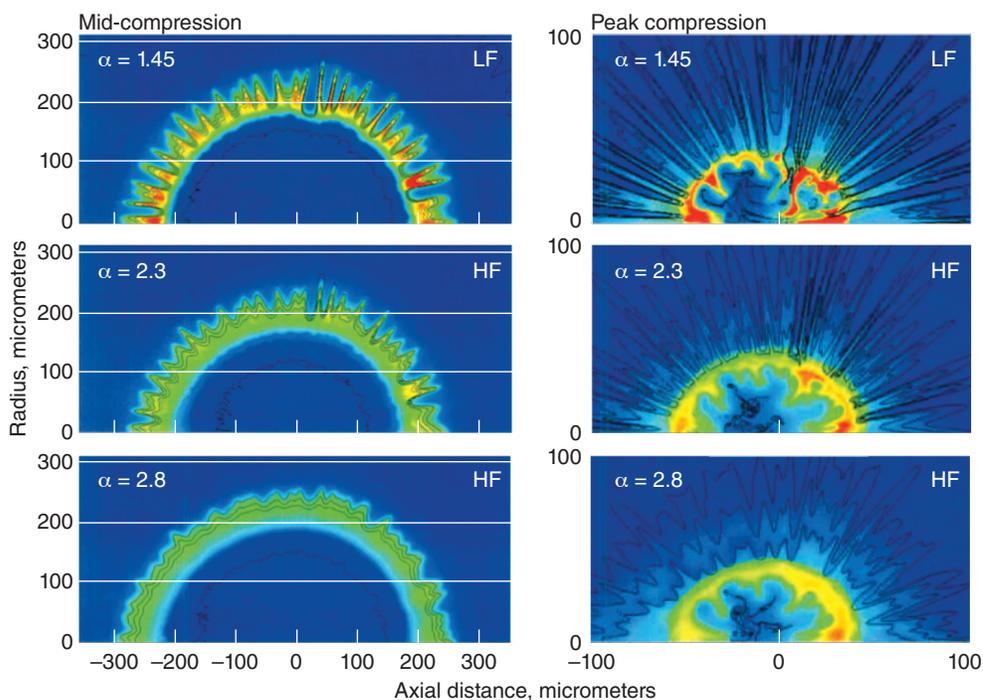
The modulations are inscribed as perfectly as possible so they are easier

The high-foot pulse (red curve) for ignition experiments lasts 15 nanoseconds, instead of the 20 nanoseconds used in low-foot (black curve) shots. High-foot experiments also feature three main shocks instead of four, a higher-power initial pulse called a “picket,” and lower peak power.



Hydrodynamic growth rate experiments measure the growth of different-size “ripples,” which are inscribed on the outside surface of a plastic ablator (above) to seed instabilities during an implosion. X rays enter the hohlraum through a gold cone inserted into each capsule. The resulting radiographs track the growth of instabilities in (a) low- and (b) high-foot experiments. The ripple amplitude is more pronounced in (c) low-foot shots than in (d) high-foot shots, indicating that the high-foot pulse substantially reduces implosion instabilities.





Computer simulations show how a plastic fuel capsule filled with deuterium–tritium fuel responds to compression in low-foot (LF) and high-foot (HF) experiments. The capsule’s plastic shell has been “roughened” to better illustrate the effect of instabilities. At mid-compression (left column), the LF pulse (top row) produces an adiabat (α , a measure of entropy) of 1.45, whereas the HF pulse results in adiabats of (middle row) 2.3 and (bottom row) 2.8. At peak compression (right column), the low-foot capsule suffers extensive mixing.

to model. Time-resolved radiographs taken with a framing camera through 20-micrometer-wide slits track the growth of instabilities in the ablator during both high- and low-foot experiments. The images clearly show that the high-foot pulse substantially reduces implosion instabilities. Ablator surface imperfections are one potential seed for instability. Other sources include glint from the laser beams hitting the hohlraum wall, surface imperfections in the DT ice layer, and the plastic tent holding the fuel capsule in place inside the hohlraum. Scientists suspected that features looking like rips in the fuel capsule originated in the tent, not the ablator. However, high-foot implosions showed no evidence of the tent ripping the capsule because of the improved stability from the experimental design.

A Laboratory team led by physicist Steve MacLaren is using a Viewfactor diagnostic to measure the hohlraum x-ray drive during low- and high-foot pulses. For these experiments, one end is cut off an ignition-scale hohlraum, exposing the hohlraum interior and the far laser entrance hole to x-ray diagnostics. The traditional

fuel capsule is replaced by a thin plastic shell to reproduce the plasma environment of an ignition experiment while keeping the capsule transparent for x-ray diagnostics and permitting a more complete view of the hohlraum interior than is possible with a fully enclosed hohlraum. The experiments are for the first time allowing researchers to measure x-ray emission across the entire region where the laser deposits its energy at peak power.

Viewfactor experiments demonstrated that the magnitude of x-ray drive had been overestimated by up to 20 percent. Those results explain why computational scientists had to “dial down” the simulated strength of the implosion x-ray drive for model predictions to match experimental data. The work showed that the hohlraum model, not the ablator model, was the source of the discrepancy in the slower-than-expected capsule implosion velocity. Viewfactor images revealed three-dimensional gold “bubbles” appearing in the hohlraum wall, much like a growing blister. These bubbles may absorb some of the laser light and reduce the efficiency of converting laser energy into x rays.

One possible solution is to manufacture the hohlraum from depleted uranium (DU) to improve the efficiency of the hohlraum walls. DU would also improve the symmetry of the capsule irradiation by allowing inner-cone laser beams to penetrate more deeply. High-foot shots using a DU hohlraum have attained promising results.

Other experiments have focused on measuring the mix of ablator shell fragments into the gas core, which dampens the fusion energy yield. An experimental series using carbon and deuterium identified the ablator shell regions that contribute most to hydrodynamic mix. In those shots, a noncryogenic capsule with pure tritium gas in the center was surrounded by an ablator with a 4-micrometer-thick layer of carbon–deuterium placed at a different depth in each experiment. The resulting DT yield provided a direct measure of how much the carbon–deuterium layer penetrated the pure tritium hotspot and where in the ablator the debris originated.

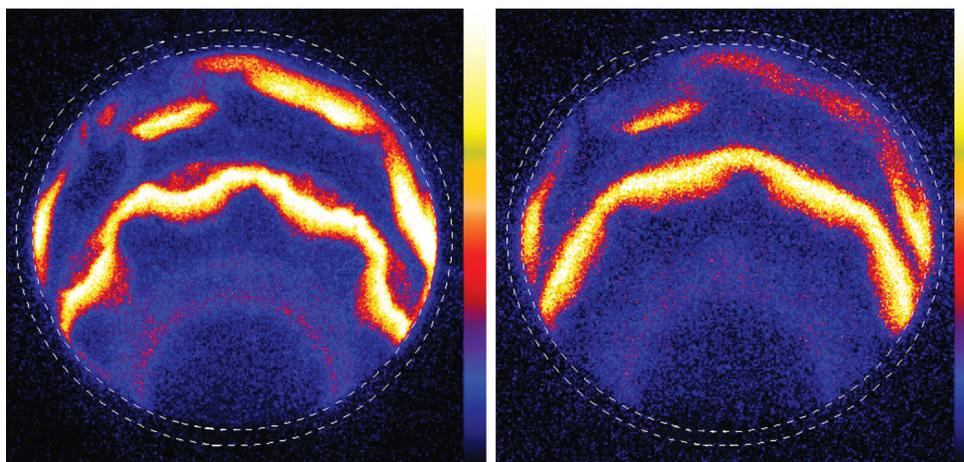
Results indicate that the ablator region closest to the inner-shell boundary

is responsible for most of the mix. In addition, the reduced yield with pure tritium is consistent with instability growth at the outer-shell surface, underscoring the importance of ablator surface smoothness.

High Foot Still Evolving

Hurricane notes that the high-foot strategy represents a wide spectrum of possible pulse shapes. “For example, we can change the degree of ‘highness’ to control how much we suppress instability and increase compression,” he says. “We know we need to increase pressure, and we know what levers affect pressure. Our results from the high-foot campaign provide a new understanding that we can build on.”

Laboratory researchers are exploring modest changes to NIF’s pulse shape to increase implosion speeds and obtain greater peak pressures. In addition, they want the hotspot shape to be rounder, an effort that may involve modifying the cylindrical hohlraum into different shapes, such as one resembling a rugby ball. Scientists at Los Alamos are exploring ablators made of beryllium to determine whether this design would



Results from Viewfactor experiments show the hohlraum x-ray drive occurring in the fuel capsule during (left) low- and (right) high-foot experiments. Colors indicate the intensity of soft x-ray emission, which ranges from high (white) to low (black). For these experiments, one end of the hohlraum is cut off, exposing the interior and the far laser entrance hole to x-ray diagnostics. The cutaway also permits diagnostics for the first time to measure x-ray emissions where the laser deposits its energy. The high-foot shot design produced a more uniform x-ray emission pattern.

lead to higher pressures. A separate effort involving Lawrence Livermore and General Atomics is testing ablators composed of high-density carbon (also called diamond).

Ignition—a long-sought goal for generations of laser scientists—has proven to be fiendishly difficult to achieve. By working together, across disciplines and organizational boundaries, Laboratory researchers on the high-foot campaign and related experiments have advanced scientific understanding of indirect-drive implosion physics

and taken a key step along the path to ignition.

—Arnie Heller

Key Words: alpha heating, alpha particle, carbon–deuterium mix, depleted uranium (DU), deuterium–tritium (DT) fuel, high-foot pulse shape, hohlraum, hydrodynamic growth rate, ignition, low-foot pulse shape, National Ignition Campaign (NIC), National Ignition Facility (NIF), pure tritium gas, Viewfactor experiment.

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