Targeting Ignition

SUCCESSFUL experiments at the world's most energetic laser, the National Ignition Facility (NIF) at Lawrence Livermore, rely on great complexity in a tiny package—an exquisitely designed and meticulously assembled target. Since 2010, researchers at NIF have been conducting experiments as part of the National Ignition Campaign, a collaborative international effort to demonstrate fusion ignition with energy gain in a laboratory setting for the first time. Two recent target improvements, one operational and the other design-oriented, demonstrate the precision that ignition experiments demand and mark important progress toward achieving this grand challenge.

The target for an ignition experiment consists of two components: a hohlraum and a fuel capsule. The hohlraum is a metal object about the size and shape of a pencil eraser with holes at each end for laser beams to enter. Centered within this cylinder is a gas-filled, spherical fuel capsule only 2 millimeters in diameter. During experiments, the hohlraum serves as an oven, focusing laser energy in the form of x rays on the capsule. The x rays heat and compress deuterium–tritium fuel inside the capsule to extremely high pressures and temperatures—conditions matched only by those found in the interior of stars or exploding nuclear weapons.

A Crystallized Layering Process

Coating the ignition capsule's interior surface is a thin, frozen layer of hydrogen isotopes. For optimal fuel implosion during an experiment, the ice layer must have a uniform thickness, and its inner surface must be extremely smooth. These characteristics are best achieved if the layer is made from a single crystal. However, no seed can be isolated in the NIF fuel capsule to start the normal crystal growth process.

"In a perfect world, we would use a crystal seed of our own making," says Livermore physicist Evan Mapoles. "But we can't do that for these targets because the layering process begins at room temperature where no seed of solid hydrogen can exist." He adds that crystal seeds will form only when temperatures are cooled to about 20 kelvins (–253°C), close to the triple point of the hydrogen isotope mixture—the temperature at which a substance's solid, liquid, and gas phases can coexist in equilibrium.

The Livermore team has distilled a process that maximizes the probability of growing a layer from a single seed crystal. Before an experiment begins, a target is mounted on the end of the target positioner, which sits in a large vacuum vessel just outside the NIF target chamber. There, a sophisticated system fills the capsule with liquid hydrogen fuel, characterizes the cryogenic fuel layer, and maintains the layer quality. The entire target package is kept below 20 kelvins and is sheltered by shrouds while the layer is formed. The package is then positioned and aligned at the center of the target chamber, ready for the experiment to begin.

The layering process begins by preparing and cooling the target and then adding deuterium–tritium fuel through a slender fill tube attached to the capsule. (See the photo at right.) Technicians can precisely control the fuel volume by adjusting the relative temperature of the capsule and the fuel reservoir. Once the volume is satisfactory for the upcoming experiment, the liquid is rapidly frozen.

Mapoles describes the resulting ice as "a polycrystalline mess." This initial layer is completely melted, leaving only an ice plug in the fill line to maintain a constant fuel mass in the capsule. Then the capsule is cooled until ice grows out of the fill tube into the capsule. This process requires some supercooling of the liquid. When ice enters the capsule, it grows rapidly, typically leaving just a few ice crystals in the capsule. The capsule is heated again until only the smallest discernible fraction of ice remains. The capsule is cooled and melted again to reveal a crystal seed. It is then cooled slowly for several hours to grow the final ice layer, which is a mere 69 micrometers thick. Scientists use x-ray diagnostics to assess the layer quality and either accept or reject it. If the layer is rejected, the melting and cooling cycle begins again. The layer formation process takes a little less than a day, and achieving a good layer generally requires one to four attempts.

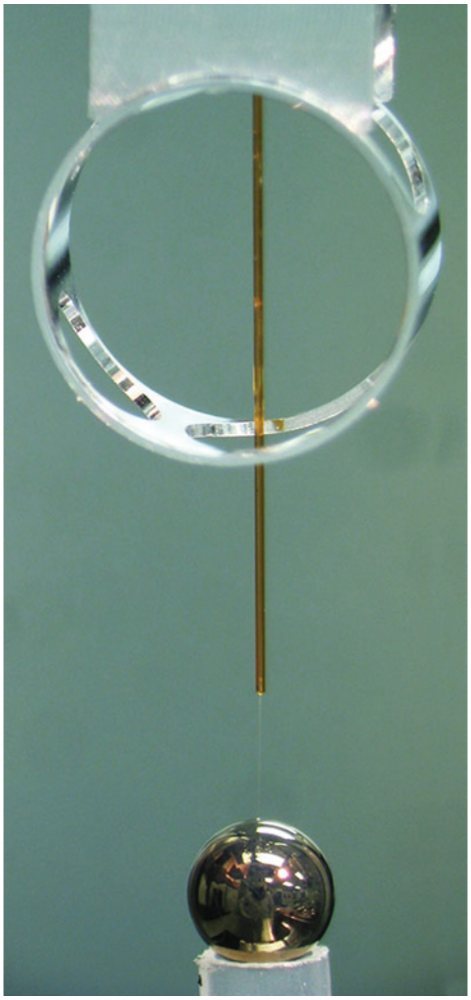
Playing It Smooth

A radiation hydrodynamics code called LASNEX models the full geometry of the hohlraum, capsule, and interacting laser light during an experiment. Simulations allow researchers to observe how factors such as perturbations on the surface of the ice and in the fill tube affect the fuel implosion. Model accuracy is continually enhanced by incorporating data from ignition experiments. Through modeling, Mapoles says, "We know that the ice's inner surface is a critical factor in target performance."

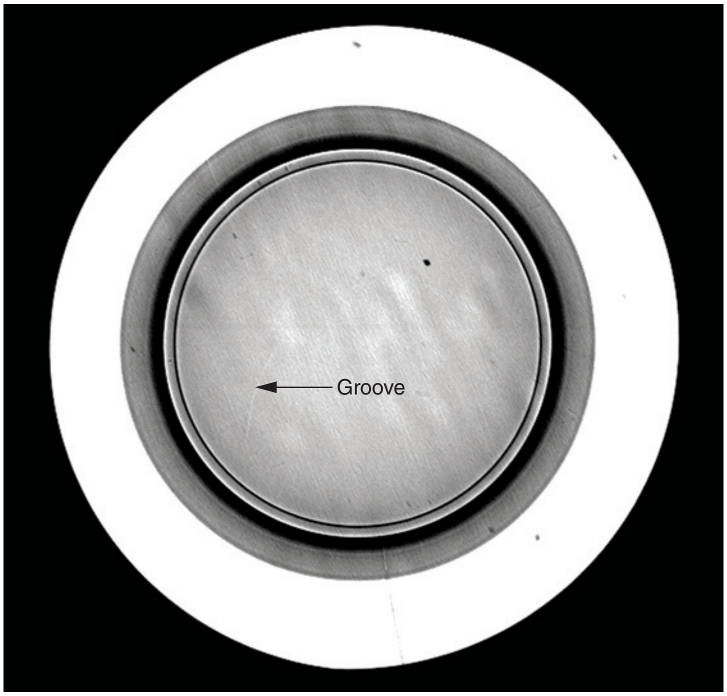
As a result, the NIF team has developed a set of target requirements that limit the size and quantity of grooves and the surface roughness allowed on the capsule for an acceptable ice layer. For each experiment, the layer is carefully characterized to locate imperfections in shape and smoothness and for isolated defects. Minor shape issues identified in the fully formed layer can often be corrected with a "shimming" process using small heaters in the target. According to Mapoles, the most common cause for layer failure is natural crystal defects, which tend to cluster and form grooves. Impurities introduced before or during the layering operation can produce occasional imperfections.

In the characterization process, x-ray cameras record the target through slits in the hohlraum walls and the laser entrance holes, producing hundreds of images for a single layering sequence. Within minutes, an automated workflow system processes, combines, and displays the images for analysis. Imaging at both high and low magnification ensures that each target is thoroughly reviewed. High-resolution images taken at three orthogonal views illuminate grooves that are no more than 1 or 2 micrometers deep and are effective at finding defects near the perimeter. Lower-magnification images taken through the hohlraum laser entrance holes offer better contrast, helping analysts identify short, deep grooves across the full ice layer.

Researchers also developed methods to control contamination during the layering process. Before a target is filled, sensitive equipment scans the fuel for pollutants. Improved gas-purging processes and hardware minimize opportunities for undesirable materials to enter the target capsule. Adding a cold trap in the fill tube and keeping this tube and the fuel reservoir below 25 kelvins help isolate the capsule interior from contaminants.



A glass tube smaller than a human hair transfers deuterium–tritium fuel to a 2-millimeter-diameter target capsule for an experiment at the National Ignition Facility (NIF). The design for the NIF fill tubes is the same as that for the tiny needle used to penetrate a single egg during in vitro fertilization.



An x-ray image of a NIF target captured through the hohlraum laser entrance holes allows researchers to evaluate the shape and smoothness of the ice layer and to determine whether a groove would enhance or impair experimental results.

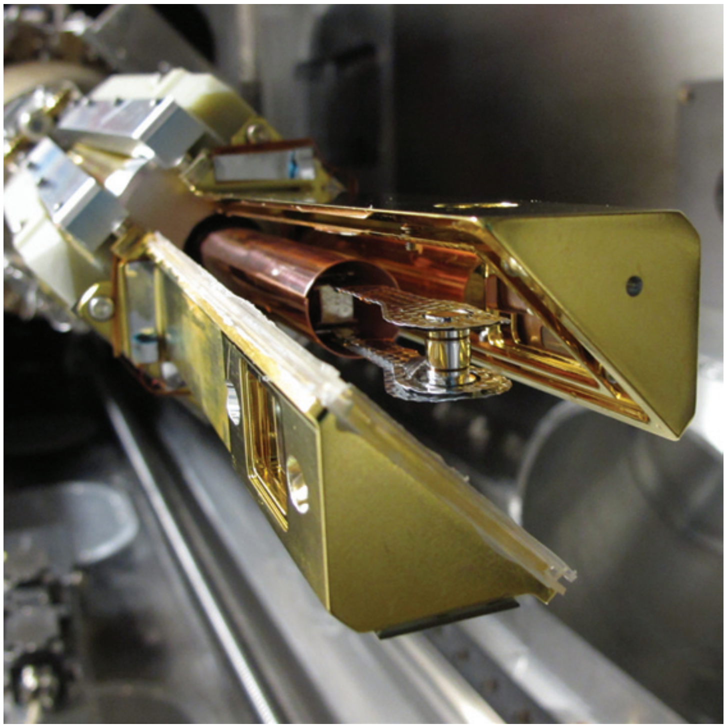
As a result of these improvements, the team is producing high-quality cryogenic layers consistently and efficiently. Researchers are now working to enhance the speed, automation, and reliability of the entire process to accommodate an increased pace of NIF experiments, and more engineers and physicists are being trained to make and characterize the layers.

A Window on Implosion

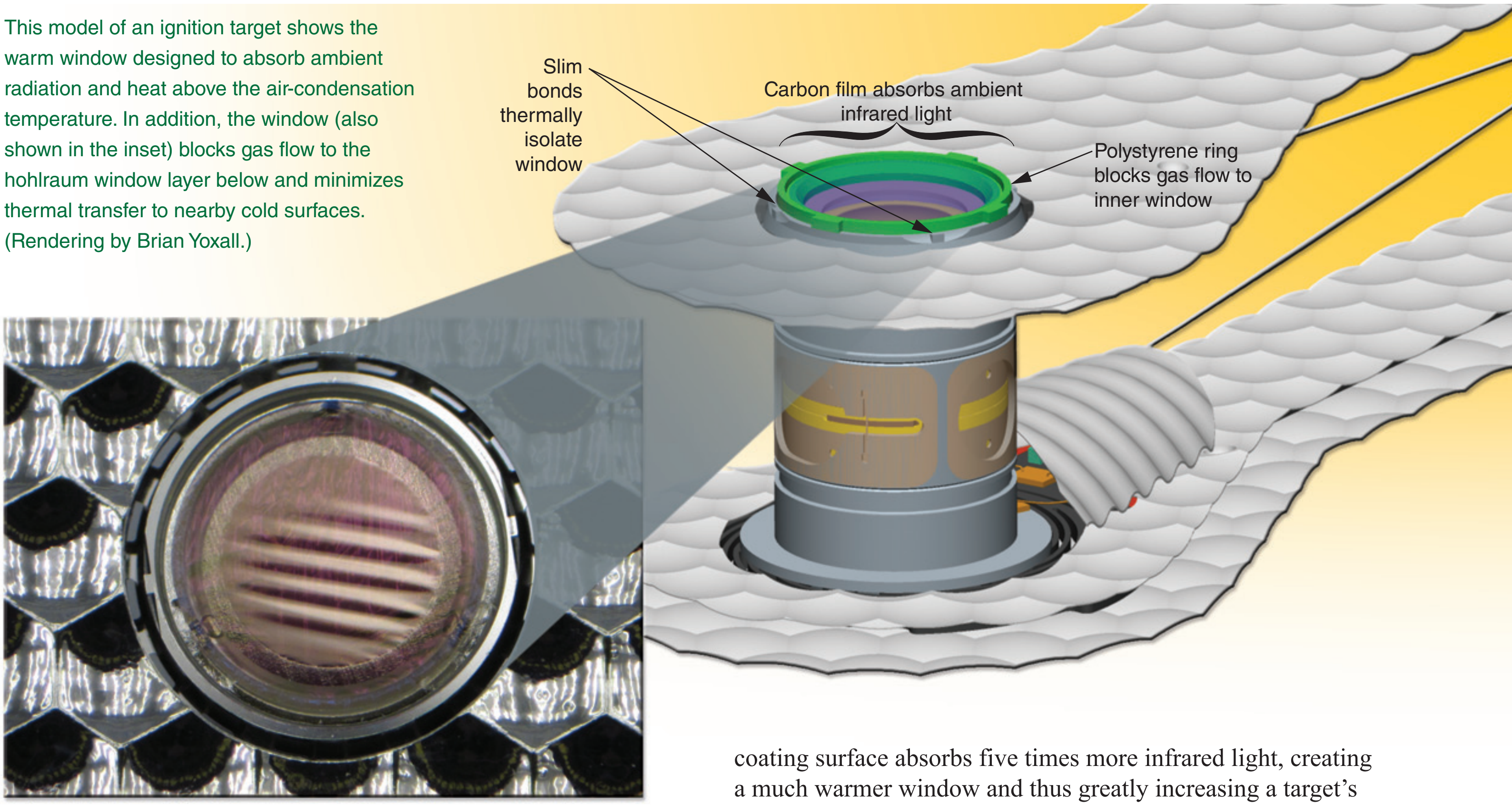
Producing extremely smooth ice layers was a known challenge for the National Ignition Campaign. More unexpected was finding that ice sometimes formed in the wrong places. In ignition experiments, the laser pulse must be precisely tailored in shape and time to produce four shock waves that compress the hydrogen fuel to the required temperature and density. Early experiments on shock timing produced results at odds with simulations and expectations. Using the VISAR (Velocity Interferometer System for Any Reflector) diagnostic, NIF scientists pinpointed the cause of this inconsistency: the arrival time of the first shock wave.

Physicist Harry Robey explains that the four shocks must coalesce inside the gas portion of the capsule. "If the first shock is very slow, the shocks merge early," he says. "As a result, they transfer too much energy to the ice layer, which severely limits how much we can compress the fuel." Ignition hohlraums have thin windows over the laser entrance holes. Although the surrounding shrouds have tight seals, gas would in some instances leak through, allowing a thin coating of frozen oxygen and nitrogen to accumulate on a window. Unfortunately, a condensation layer just 0.1 micrometers thick could delay the laser energy on its way to the target and disrupt the timing required to compress the fuel to the desired density.

Working with colleagues from General Atomics, the NIF researchers designed a second, warmer window to cover the top of each entrance hole, making targets impervious to frost formation. This second window absorbs enough infrared radiation to prevent gases from condensing on the warmed surface. Three tiny feet protruding from the window are attached by low-conductivity bonds to the cold hohlraum below and provide thermal isolation. Initially, gases can flow through the gap between the two windows, but once the system is brought to vacuum, they are blocked from reaching the entrance holes by the polystyrene ring surrounding the warm window.



This cryogenic layered target, shown mounted on the target positioning system, was used in an experiment at the National Ignition Facility in September 2010. The two triangular arms form a shroud around the cold target to protect it until seconds before a shot.



This model of an ignition target shows the warm window designed to absorb ambient radiation and heat above the air-condensation temperature. In addition, the window (also shown in the inset) blocks gas flow to the hohlraum window layer below and minimizes thermal transfer to nearby cold surfaces. (Rendering by Brian Yoxall.)

Warming to a Solution

The Livermore–General Atomics collaboration moved the warm window from idea to prototype in just 10 weeks. The design has a polyimide layer topped with a thinner amorphous carbon layer that together are only 150 nanometers thick. The carbon surface film efficiently uses the ambient thermal radiation from the chamber walls, yet does not interact with laser light so x rays cannot interfere to skew the experimental results. Windows are positioned 500 micrometers above each laser entrance hole. As the carbon film absorbs infrared radiation, it warms the window to above 25 kelvins, the point at which any residual air in the chamber condenses.

When the team tested the first prototype in February 2011, x-ray spectrometer measurements indicated no frost buildup, validating the design. Chemical engineer Jim Fair, who leads the warm window project, says, “Every target that is susceptible to frost is now fitted with a warm window. It is an integral part of the target design.”

Researchers continue to enhance the window’s performance. Instead of applying the carbon coating with a sputtering technique, the team has switched to electron-beam deposition. The new coating surface absorbs five times more infrared light, creating a much warmer window and thus greatly increasing a target’s operating margin before frost is produced. The team is also working on an adhesive-free method to attach the window to the hohlraum and further reduce thermal conductivity.

Mapoles notes that creating and fielding consistently high-quality cryogenic layered targets has been a team effort. “When we look at the integrated technologies going into these targets, we see that we’re pulling from a lot of areas of expertise at the Laboratory,” he says. “We have many success stories.” As they have so many times before, Livermore physicists, chemists, engineers, computer scientists, technicians, and operations specialists are working as part of a multidisciplinary team to create effective solutions in pursuit of a scientific grand challenge—the pioneering effort to achieve ignition.

—Rose Hansen

Key Words: cryogenic target, crystal growth, deuterium–tritium fuel, electron-beam deposition, hohlraum, ignition, laser entrance hole, LASNEX, National Ignition Facility (NIF), shock timing, warm window, x-ray characterization.

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