Dead center. A positioner arm holds the target at the heart of NIF's chamber.

ENERGY

Step by Step, NIF Researchers Trek Toward the Light

Like wilderness explorers, physicists at the National Ignition Facility seek the most direct path to their goal: an implosion that releases more energy than it consumes

LIVERMORE, CALIFORNIA—Ever since the razzmatazz of its official opening 2 years ago, there hasn't been a lot of news coming out of the National Ignition Facility (NIF), the huge laser fusion machine here at Lawrence Livermore National Laboratory. That doesn't mean researchers at the $3.5 billion facility haven't been busy. Some have been simulating what goes on in a supernova explosion, and others gauging the equation of state of materials at the heart of a giant planet. Nuclear weapons researchers have also been using NIF's enormous lasers to verify their computer models of nuclear explosions. But that's not the news most people are waiting for. They're waiting for the one thing important enough to be encapsulated in its name: ignition.

Ignition is the moment when a pulse of light from NIF's 192 laser beams heats a target containing a tiny capsule of fusion fuel and causes it to implode, heating the fuel enough for a large fraction of its nuclei to fuse together and release a burst of energy larger than the energy of the light pulse that created it. Fusion researchers have been trying to achieve ignition with lasers for more than 40 years; if NIF can reach the goal, it will finally show that, in principle, fusion could produce copious amounts of electricity from easily obtainable fuels, with no carbon emissions and minimal radioactive waste (*Science*, 17 April 2009, p. 326).

As the delays in starting up the Large Hadron Collider at the CERN particle physics lab in Switzerland underscore, however, getting a big, complex machine up and running takes skill and patience. "We have to find the path through the thicket that's the easiest way through," says NIF director Edward Moses.

Easier said than done. Back in 2009 when NIF was completed, Moses predicted his team would achieve ignition in 2010. That time is long gone, and ignition still doesn't look imminent. Last month, at the Inertial Fusion Sciences and Applications conference in Bordeaux, France, the U.S. Department of Energy's Under Secretary for Science, Steven Koonin, acknowledged that "ignition is proving more elusive than hoped." He added, "Some science discovery may be required" to make it a reality. The NIF team, however, maintains it is making steady progress toward the goal. "The potential is there, but it's so much harder when no one has done it before," NIF's chief scientist, John Lindl, says.

One potential Achilles' heel—NIF's vast laser system—has proved less of a problem than some had expected. No other machine had ever produced such high-energy beams: 1.8 megajoules (MJ) per 20-nanosecond pulse. Some researchers thought the energy would cause the glass optics to crack or explode, that optical elements would need constant replacement or repair, and that it would be impossible to achieve the required beam quality.

Instead, NIF's lasers are widely hailed as triumphs of engineering. The building that houses the fiber lasers that produce the initial beams, the hundreds of slabs of neodymium-doped glass that amplify them, the thousands of flash lamps that pump the glass full of energy, and all their associated paraphernalia is the size of three football fields and 10 stories high. The place hums with a clean, quiet efficiency, like a cross between a semiconductor plant and the lair of a James Bond villain bent on world domination. NIF researchers have their sledgehammer; now they just have to figure out how to crack the nut.

The devil, as always, is in the details: the exact speed, shape, temperature, and composition of the fuel as it implodes. Long experience with earlier laser fusion experiments has taught researchers that brute force alone is not enough: Ignition requires finesse too. The target in such experiments is a tiny plastic sphere just a millimeter or two across. Inside this capsule is a 50-50 mixture of the hydrogen isotopes deuterium and tritium—the fusion fuel. Before a laser shot, the capsule is cooled to a chilly 18 kelvin so that the fuel condenses as a smooth ice layer on the inside of the sphere. The laser beams do not physically crush the capsule, but they heat the plastic material so fast and to such a high temperature that it explodes and, like a spherical rocket, drives the fusion fuel toward the center.

If all goes as planned, this implosion will compress the fuel into a spherical blob some 30 micrometers across in which the very center reaches high temperature while most of the surrounding fuel remains cool. When the central hot spot reaches more than 100 million kelvin, deuterium and tritium nuclei will start to fuse, producing high-energy alpha particles (helium nuclei) and neutrons. "The aim is to get the alpha particles to deposit their energy in the dense fuel shell," says NIF's plasma physics group leader, Siegfried Glenzer, raising the surrounding fuel to high temperatures

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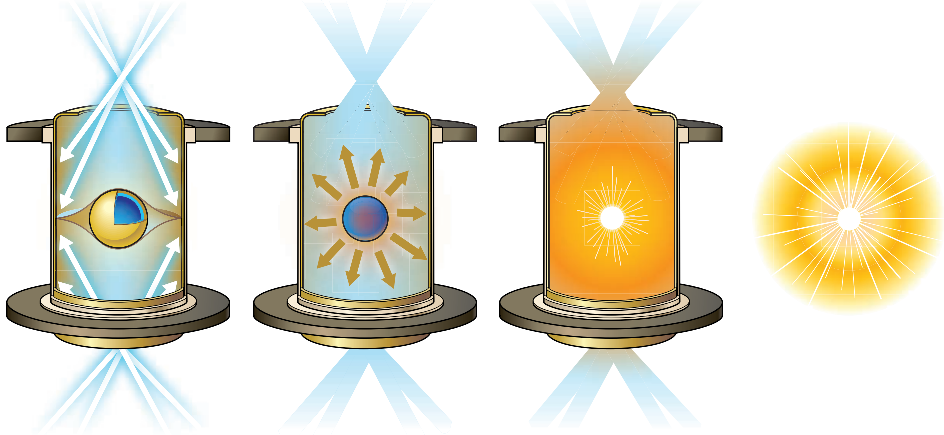
Canned heat. In NIF's "indirect drive" system, a cylindrical capsule (hohlraum) makes an x-ray oven to heat the tiny spherical fusion target.



1 Laser beams rapidly heat the inside surface of the hohlraum.

2 X-rays from the hohlraum create a rocketlike blowoff of capsule surface, compressing the fuel portion of the capsule.

3 During the final part of the implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000 K.

4 Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

so that the fusion burn propagates outward, rapidly consuming about a quarter of the fuel in an explosion of up to 18 MJ.

In earlier experiments, researchers found that it was almost impossible to get the lasers to heat the capsule evenly from all directions at once. The laser beams just weren't smooth enough, so compression wasn't symmetrical, and fuel escaped. They developed a different technique known as indirect drive: The capsule is placed in the center of a small gold cylinder called a hohlraum, about the size of a pencil eraser. The beams shine through the ends of the hohlraum and onto its inside walls. The walls get so hot they emit x-rays, and it is this bath of radiation that causes the capsule to explode, driving the fuel inward. "What indirect drive gives you is a good oven. It pushes uniformly," Moses says.

One potential problem is that the oven is dirty: When the beams hit the inside walls, they kick up debris that fills the hohlraum with a plasma that can scatter photons, reducing beam power and possibly causing uneven implosion. Fortunately, such laser-plasma interactions (LPI) have been less of a stumbling block than many feared. "Some aspects mystify us, but we can control it even though we don't understand the details," Moses says.

NIF researchers have even managed to turn LPI to their advantage (*Science*, 29 January 2010, p. 514). The pattern of laser beams coming into the hohlraum nudges the plasma into a regular pattern, which can be coaxed to act like a diffraction grating. The team has been able to manipulate that grating to steer the power of the incoming beams as needed to correct the shape of the implosion. "LPI has turned out to be a really controllable tool," Lindl says.

Such control is key. Scientists think four conditions must achieve critical values before fusion will happen: The imploding fuel must maintain its spherical shape; it must achieve a certain speed; the amount of mixing between the fuel and the capsule material must be kept low; and the entropy of the system must be kept down—in other words, the energy applied needs to be focused on compressing the fuel and not raising its temperature, which would impede compression.

To move toward ignition values, the NIF team has been focusing on a particular condition for a few months at a time, trying to improve its value without losing ground on the other three. They've identified 14 key parameters of the laser and three of the target: 17 knobs they can adjust to make fusion work. Earlier this year they focused on final density of the fuel just before ignition, which was far from its required value. By tweaking the shape of the laser pulses that spark implosion, they managed to double its value. "It's now 65% to 70% of where we're heading," Moses says.

Since early summer they've had velocity in their sights. The aim is to up the implosion speed from its current 300 kilometers per second to 370 km/s: the speed thought necessary for ignition. Here again, the shape of the laser pulse—actually a series of bursts, four short ones to put pressure on the capsule material followed by a big one to trigger the implosion—was key. At the beginning of the velocity campaign, the final shock was 50 times the energy of the initial ones, but the researchers planned to increase that figure to 300 times. "We're pushing the laser people a lot," Glenzer says.

Researchers also tweaked the design of the hohlraum, making it shorter and stubbier to help the incoming laser beams avoid interference from material blowing off the capsule surface from the early laser bursts. The new hohlraum "gives us more flexibility in shaping the implosion," Lindl says. And they've also replaced the germanium dopant in the capsule material with silicon, which explodes as well as germanium but doesn't heat the fuel as much, leading to better compression. Their efforts netted a velocity increase of 30 to 40 km/s. "We're still 30 kilometers per second low, but there is a straightforward path to get there," Lindl says. "The challenge is to get there while controlling the mixing [of capsule with fuel]."

"Playing around with mixing and velocity is the place you want to be," Moses says. "We're at the end of the beginning." Moses likens the group's efforts to the expedition of Lewis and Clark, the first explorers to cross North America. To find a way to the Pacific, he explains, they didn't explore every pass and tributary; they sought the path of least resistance. "This facility has everything you need to get there: the laser, the diagnostics, the targets," Moses says. "We don't have to understand all LPIs. We're staying away from complex environments, avoiding complexity at every choice."

Fusion researchers on the outside acknowledge the tough task NIF has ahead. "There's a good bit of work still to do," Glen Wurden of Los Alamos National Laboratory in New Mexico says. Robert McCrory, director of the Laboratory for Laser Energetics at the University of Rochester in New York state, agrees. "It's just hard, it really is hard," he says. "But once it's done, we can rewrite the script."

–DANIEL CLERY

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