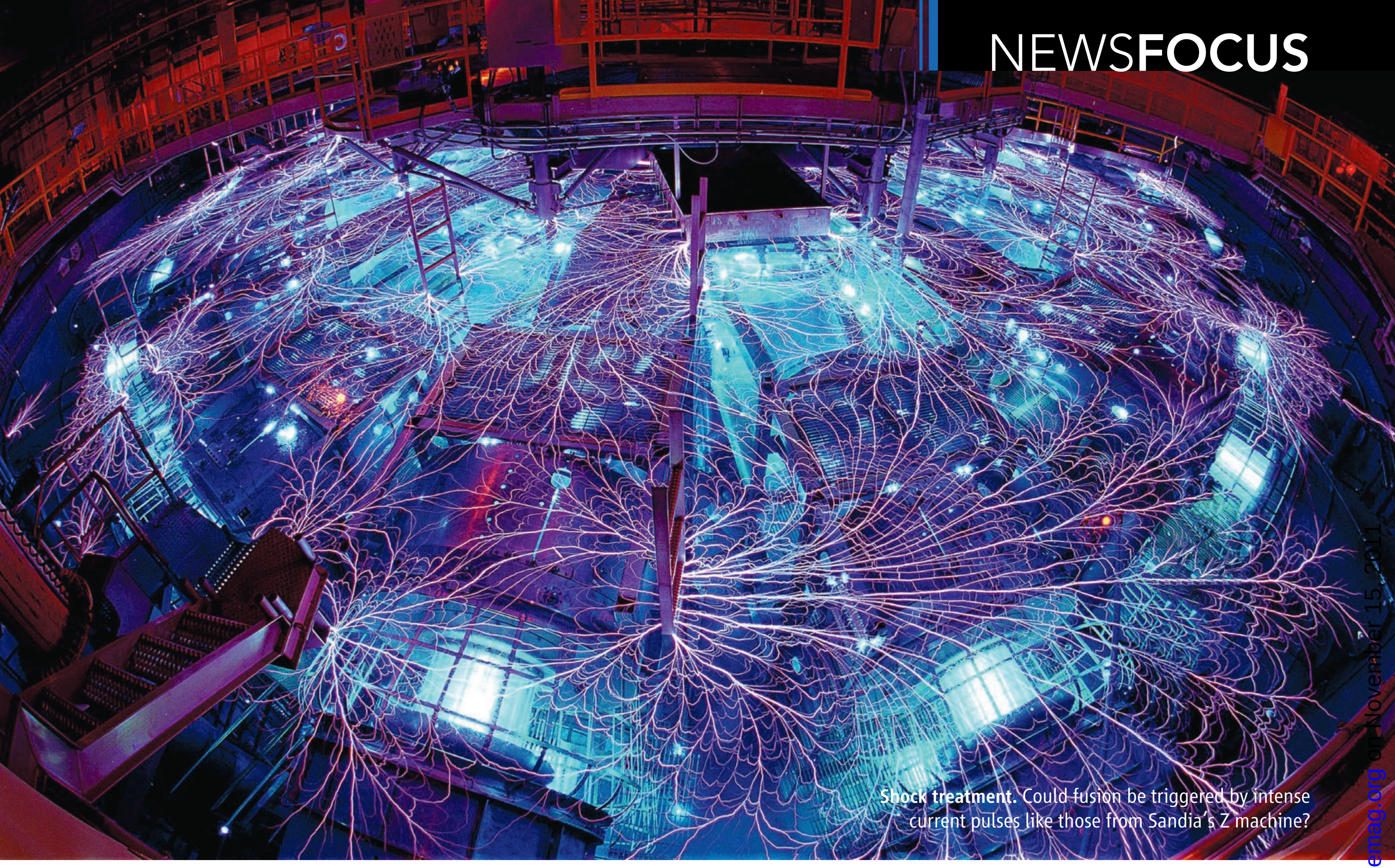


Shock treatment. Could fusion be triggered by intense current pulses like those from Sandia's Z machine?

CREDIT: COURTESY OF SANDIA NATIONAL LABORATORIES

Fusion Power's Road Not Yet Taken

Billed as a way of simulating tests of nuclear weapons, a dark-horse technique called inertial confinement fusion might outstrip mainstream fusion projects in producing commercial energy

IF NATURE SMILES ON THE RESEARCHERS AT Lawrence Livermore National Laboratory, sometime in the next year or two they will fire a high-energy laser pulse at a tiny target containing frozen hydrogen isotopes, and BANG! A small explosion will take place—not big enough to damage anything much, but big enough to prove that after more than 6 decades of trying, scientists can make fusion happen in a laboratory and create an excess of energy.

Fusion, the melding together of nuclei as opposed to the splitting apart that occurs in fission, sounds like the perfect energy source: Its fuel is cheap and plentiful (it comes from seawater), and it emits no carbon and minimal radioactive waste. What it does have is a credibility gap. Despite the enormous progress in understanding fusion and proving its viability, a genuine fusion power station always seems tantalizingly out of reach. Although researchers can cause fusion reactions in the lab, it takes more energy to make them happen than is produced. A major proof-of-principle step would be ignition: a self-sustaining fusion reaction that produces an excess of energy. As the name implies, Livermore's $3.5 billion laser center, the National Ignition Facility (NIF), has that goal in its sights (p. 449).

Online
sciencemag.org
Podcast interview with author Daniel Clery.

NIF's main goal is not energy production but stockpile stewardship: validating computer simulations of nuclear explosions. Nevertheless, fusion researchers are hoping that that small explosion will be a huge boost to their field. "A sea change could come after ignition at NIF," says Robert McCrory, director of the Laboratory for Laser Energetics (LLE) at the University of Rochester in New York state. Fusion energy research in the United States has been starved of funds over the past couple of decades, leading to the cancellation of many projects. And those involved in inertial confinement fusion (ICF), crushing pellets of fuel to cause small explosions, have been the poor relations compared with their colleagues in magnetic confinement fusion, who aim to confine much larger and less dense plasma using powerful magnets. Magnetic fusion researchers have pinned their hopes on ITER, a huge international reactor currently being built in France, which aims to prove the feasibility of magnetic fusion energy. The United States is committed to spend more than $1 billion on ITER, which is putting a severe strain on the Department of Energy's fusion budget (*Science*, 16 September, p. 1556).

In contrast, ICF hasn't been treated as energy research at all. It gets most of its funding through the National Nuclear Security Administration because of its ability to mimic nuclear weapons. But with the twin threats of climate change and declining oil stocks, interest in alternative sources of energy is growing. So ICF researchers across the country have been drawing up plans for research that would be needed to take their techniques out of the lab and into prototype power plants. They want to be ready in the event that ignition at NIF leads to a surge of interest in ICF and new money. "The whole field is on the brink of some amazing physics," says Michael Cuneo of Sandia National Laboratories in Albuquerque, New Mexico.

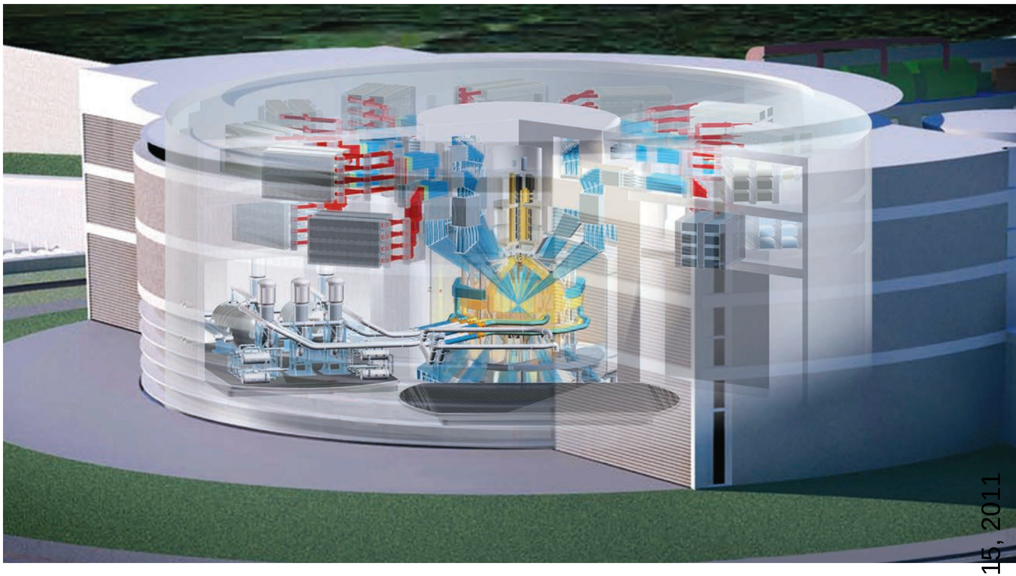
Politicians, too, are aware of the possibilities. Secretary of Energy Steven Chu and his Under Secretary for Science Steven Koonin have been following NIF's efforts and know the impact it may have. As a result, in 2010, Koonin asked the National Academy of Sciences (NAS) to carry out a study of ICF to explore—assuming that ignition is achieved—the prospects for an ICF power plant, identify the science and engineering challenges, and sketch out an R&D road map. Throughout this year, the NAS panel has been visiting labs and listening to dozens of presentations about ICF. Its interim report is expected to be published any time now. The question for ICF researchers is: What sort of research program will it recommend? No one is expecting a flood of money straightaway, but if nature does smile on NIF, could ICF become a genuine contender capable of putting electricity in the grid before ITER and its successors do?

Frantic pace

Even if NIF achieves its goals in full, there's still a very long way to go before ICF can produce power commercially, and a future power station may look nothing like NIF. Likening ignition to the first flight by the Wright brothers, Glen Wurden of Los Alamos National Laboratory in New Mexico says: "We're still at the wood, cloth, and wire stage, and it looks nothing like a 747."

Certain elements are common to all ICF approaches. First, you need a target. This is a small container filled with deuterium and tritium, two isotopes of hydrogen that will fuse if you heat them to more than 100 million kelvin. That temperature is reached by squeezing the target very rapidly. So the next thing you need is a driver, some impulsive force to crush the target. The most common driver is an array of lasers. NIF's vast laser bays produce the most energetic laser pulse in the world, at 1.8 million joules (MJ). But other ICF researchers use different drivers, including particle beams and intense electrical pulses.

An ICF power plant will also need a reaction chamber, sealed to contain the radioactive tritium and strong enough to withstand repeated explosions. Its walls have to absorb the intense neutron bombardment that carries most of the energy from the fusion and whisk that energy away as heat to boil water, make steam, drive a turbine, and generate electricity. The chamber walls have another role, too: breeding more fuel. Tritium doesn't exist naturally on Earth, but it can be made by bombarding lithium (from seawater) with neutrons. All fusion power schemes include plans to have lithium embedded in the walls in some fashion so that some of the neutrons from fusion can breed more tritium.



Coming soon? Researchers at NIF say their fusion reactor design, dubbed LIFE (for Laser Inertial Fusion Energy), could be built in 12 years by using replaceable off-the-shelf components and avoiding advanced materials.

CREDIT: LAWRENCE LIVERMORE NATIONAL LABORATORY

Perhaps the biggest challenge facing all ICF fusion schemes is repetition rate. Current research facilities do their shots in no particular hurry. They want hours, days, or even weeks to analyze their results. But because the energy from each shot is not high, a power station would need to do lots of them, anywhere from one every 10 seconds to 16 times per second—nearly 1.4 million shots a day. A high repetition rate is hard to achieve because the driver has to power up and produce a high-energy pulse very fast; the chamber has to be cleared of debris after each shot so it doesn't interfere with the next one; and targets must be manufactured at a high rate and placed precisely in the chamber.

Nothing fancy

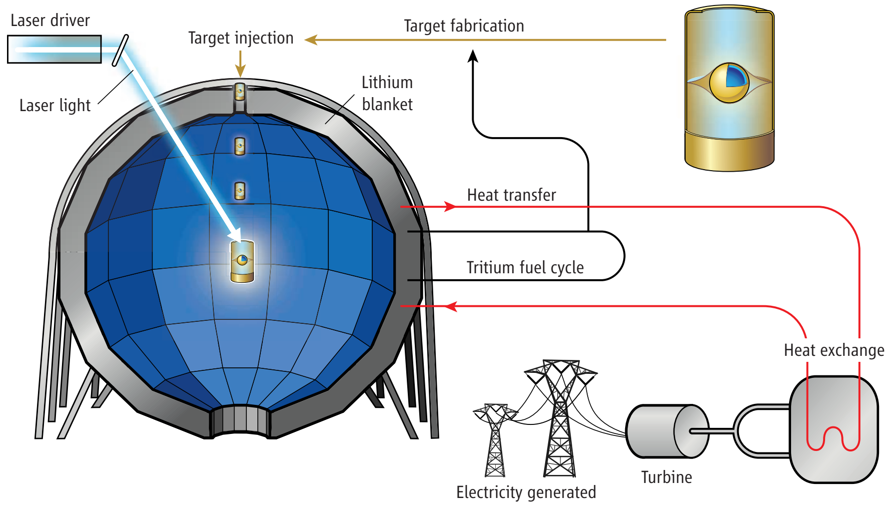
The most ambitious plans for an ICF power plant come from NIF itself. Researchers there set out to find the quickest route to generating power. They talked to electrical utilities about what sort of plant they would want and then designed one that filled their needs using the lowest risk approach. "It was a mindset change for us. What do end users want?" says Mike Dunne, director of NIF's laser fusion energy program. "We decided to make use of existing technology as much as possible. No advanced materials; only use what comes out of NIF. That's good enough." As a result, Dunne estimates that with ignition as a starting gun they could have a pilot plant—dubbed LIFE, for Laser Inertial Fusion Energy—running in 12 years.

Others are skeptical about the pace. McCrory says he won't believe that's possible "until they make a prototype beamline and do many shots." Nevertheless, they admire Livermore's ambition. "Livermore is in the vanguard of getting industry involved," McCrory says. "They're way ahead, the leading candidate."

NIF's current laser system is entirely unsuitable for a high-repetition driver. Its neodymium-doped glass laser amplifiers are pumped with energy by xenon flash lamps that are big, expensive, and take a long time to power up. For LIFE, solid-state diodes would take the place of the flash lamps. Suitable diodes exist today; they're very expensive, but like most semiconductors, their cost is expected to drop. Instead of NIF's single giant laser split into 192 beamlets, LIFE would have twice as many beamlets, each produced by a replaceable 8-kilojoule (kJ) laser unit. The laser units, each housed in a box big enough to accommodate a torpedo or two, would be built in a factory and delivered to the plant ready to use. If one or two of them failed, they could be replaced without stopping the power plant.

LIFE's reaction chamber would use liquid lithium as its coolant, filling the dual

KEY ELEMENTS OF AN INERTIAL CONFINEMENT FUSION POWER PLANT



Rapid fire. Any inertial fusion plant will need a driver, such as lasers; a large chamber to absorb the heat from neutrons with a lithium blanket to breed tritium fuel; and a way to make targets and drop them into place. Each component poses technical challenges.

role of extracting heat for power generation and breeding tritium. In line with LIFE's "no advanced materials" approach, the chamber would be built from steel. The problem with steel is that the constant bombardment by neutrons slowly weakens it and makes it radioactive. Dunne says the solution is to make the chamber a replaceable item. After 2 years, LIFE's chamber would be disconnected from the lithium circuit (its only connection) and wheeled out on rails to an adjacent building to "cool off," and a fresh chamber would be wheeled in. After a few months the level of activation would drop enough for the chamber to be dismantled and disposed of by shallow burial.

Dunne estimates that an initial 400-megawatt plant would produce electricity at 12 cents per kilowatt-hour. That's on the expensive side, but, Dunne says, "it's not about the ultimate cost performance. We need to show availability and reliability."

Shooting for simplicity

McCrory faults LIFE engineers' decision to use NIF's indirect drive technique. With indirect drive, the laser beams don't hit the target directly. Instead, the target sits inside a small gold cylinder called a hohlraum. The beams shine in through the ends of the hohlraum and heat the inside of its walls so intensely that they emit x-rays; the x-rays cause the capsule coating to explode, forcing the fuel inward. The hohlraum helps smooth out unevenness in the laser beams, which could make a target implode asymmetrically, causing the core of the fuel to break up without igniting fusion (see diagram, p. 450). Such an indirect approach, however, inevitably leads to a loss of efficiency. The peak energy of NIF's beams is 1.8 MJ, but the hohlraum is only 25% efficient at converting the ultraviolet beams into x-rays, so at most 450 kJ reaches the target capsule.

Since NIF's experiments were designed, researchers have developed ways to overcome the unevenness in laser beams. McCrory believes that direct drive is a better bet for a power plant because the target is simpler—there is no need for a hohlraum, and without it there is a huge gain in efficiency. The team at the LLE in Rochester has been working on a direct drive scheme that could be used at NIF if the indirect drive fails to achieve ignition. "Having a robust alternative approach is fiscally prudent," he says.

Researchers at the Naval Research Laboratory (NRL) in Washington, D.C., also favor direct drive, and they've been developing a different laser system to do it: the krypton-fluoride gas laser. KrF lasers have one big advantage over the neodymium glass lasers of NIF and LLE: They naturally produce ultraviolet beams. Early ICF researchers found that compression works better the higher the frequency of the laser beam; UV interacts with plasma less and causes a better implosion of the target. In 1980, LLE researchers found crystals that could boost the frequency of glass lasers' infrared output first to green light and then to UV. NIF uses such crystals, but they, too, have an efficiency penalty. The peak energy of NIF's laser system is actually 6 MJ, but passing the beams through crystals before they enter the chamber knocks that down to 1.8 MJ.

If a fusion power plant could do without frequency converters, it wouldn't need such a high-energy laser. NRL researchers have been working for years to demonstrate that KrF lasers—which are pumped with electron beams—are suitable for fusion. They've built ones that can operate for hundreds of millions of shots but have low power, and single-shot ones with higher power. The challenge now is to combine those techniques into a single, fusion-ready laser. They've also been grappling with the problem of unevenness in the beam. "We tried to make perfect beams, but it turned out to be very difficult," says NRL's John Sethian. One problem common to all beam wavefronts is a speckled pattern of high- and low-intensity regions. The researchers developed a way to make the pattern change more quickly than the target can react to it, causing the target to "see" a kind of average intensity.

Researchers at Sandia believe they can improve efficiency further still by dispensing with laser beams altogether. Their technique relies on a phenomenon called the pinch effect. If you pass a strong current through a conductor, it produces a magnetic field looping around itself. That magnetic field then interacts with the current to produce a force that pushes the current in toward the center of the conductor. If the conductor is a metal cylinder and the current is strong enough, the force will crush the cylinder. To use this as a fusion device, simply fill the cylinder with deuterium and tritium.

The key technology here is the pulsed current source. Sandia has a huge device called the Z machine, which stores up enormous amounts of electrical energy and then produces intense current pulses. Researchers use these pulses—up to 27 mega-amps (MA) for 100 nanoseconds—to produce x-rays and for other experiments. Although the Z machine can be used to test the feasibility of doing fusion with such pulsed power, Sandia's Cuneo says a new machine able to generate 60 MA will be needed to really put the theory to the test.

As with other drivers, the key challenge is repetition rate. Researchers at Sandia are testing a new technology called linear transformer drivers (LTDs). They have a couple of LTD modules rigged up, and each is producing 1-MA pulses at a rate of 1 every 10 seconds.

Sandia's plan calls for a circular array of LTDs feeding current via a central transmission line into a reaction chamber where the target is. Because of its slow repetition rate, a pulsed power fusion plant would need to have larger explosions. This would mean

CREDIT: ADAPTED FROM NIF

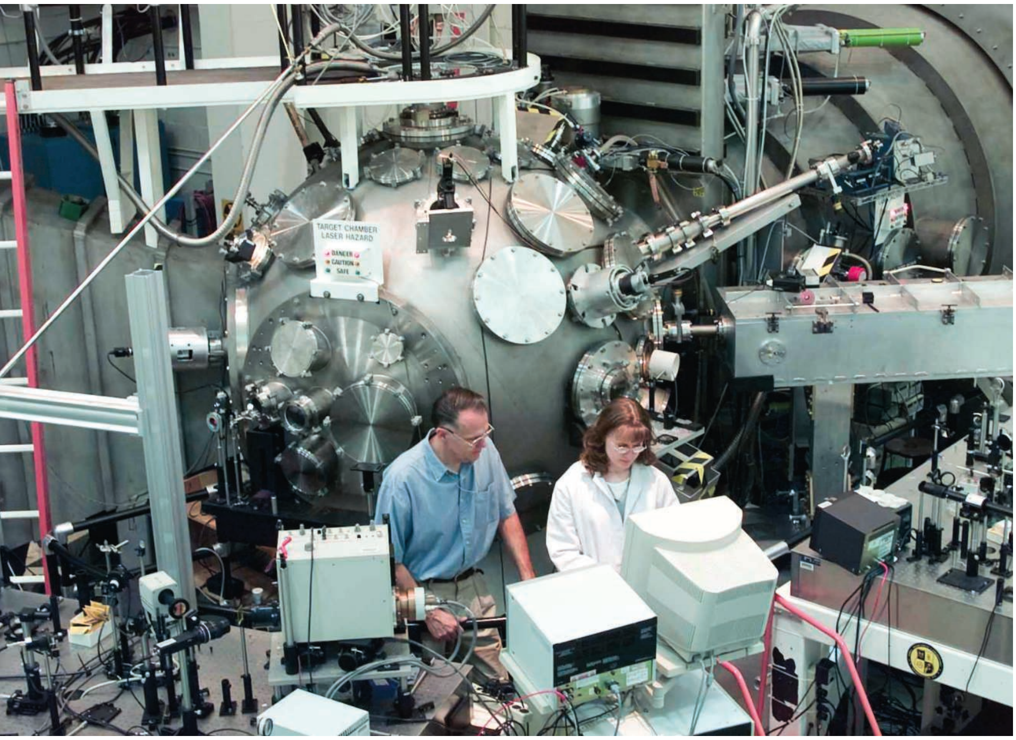
that the reaction chamber and other equipment would need to be stronger to withstand the blasts, and the cone-shaped transmission line as well as the cylindrical target would be destroyed in each shot. But the engineering of replacing a target every 10 seconds is a lot easier than that for 10 times a second.

Cuneo thinks the Sandia scheme's simple current pulses and low repetition rate give it a big advantage in simplicity. "A fusion power plant has to be as simple as you can imagine," he says. "After all, it's competing with plants that rely on shoveling coal into a boiler."

Another driver that claims the advantage of simplicity and efficiency is ion beams. Most particle accelerators concentrate on boosting a small number of particles to very high energy. These wouldn't work as fusion drivers because the particles would just shoot straight through the target without depositing any energy. Heating a target, which would be similar to those on NIF, requires heavy particles with moderate energy and lots of them. Researchers at Lawrence Berkeley National Laboratory (LBNL) are putting the finishing touches on a linear accelerator that will produce just that sort of beam. The LBNL team put together the Neutralized Drift Compression Experiment II (NDCX-II) with just $11 million of stimulus money by recycling parts from an earlier accelerator at Livermore. NDCX-II will spend some of its time studying warm dense matter—the stuff in the core of giant planets—and will also aim to make the sort of high-current, short-duration pulses that fusion needs and test its effects on target materials.

LBNL's Joe Kwan says ion beams offer an advantage: There is no need to place delicate optical elements close to a nuclear explosion. "Focusing is not done with lenses but with magnetic fields, so there are no lenses prone to damage," he says. "And ion acceleration is efficient, and there is no repetition rate problem."

Another way to make ICF easier, says Los Alamos's Wurden, is to poach some ideas from magnetic fusion. His team has been experimenting with a technique called magneto-inertial fusion (MIF, sometimes known as magnetized target fusion), which uses a magnetic field to help contain the plasma of deuterium and tritium in the target and stop heat from escaping. As a result, the driver does not need to be as strong or as fast. "You can use drivers that are 20 to 30 years old, on the $50-[million]-to-100-million scale," Wurden says.



Bull's-eye. The target station of NRL's Nike laser; krypton-fluoride lasers like those under development at NRL hold the promise of high repetition rate and ultraviolet output.

CREDIT: U.S. NAVAL RESEARCH LABORATORY, PLASMA PHYSICS DIVISION

In experiments at Los Alamos, researchers make a target from a metal can (roughly the size of a tall beer can) filled with plasma and apply a magnetic field of about 2 to 3 tesla to hold the plasma in the middle of the can. They use an explosive to compress the can to around 1 centimeter across in less than 20 microseconds. This is a pretty sedate compression by ICF standards, but the magnetic field inside the can gets boosted 100 times, to as much as 300 tesla—a field strength "so huge that it is not known in this corner of the galaxy," Wurden says. At the moment, the Los Alamos team is refining the compression technique, but its explosive driver is not practical for energy production.

The beauty of MIF, Wurden says, is that you can use almost any sort of driver. Sandia researchers have done experiments with magnetized targets on the Z machine, and LLE researchers have done the same with their OMEGA laser. A private company, General Fusion in Vancouver, Canada, is designing a fusion energy demonstrator using pneumatic pistons to crush an MIF target with an acoustic shock wave.

Which way to go?

No one is expecting the NAS panel to recommend, or the government to approve, lavish funding for ICF research. But if a convincing demonstration of ignition at NIF does raise the field's profile, the panel, confronted with this smorgasbord of different approaches, faces a dilemma: Should it pick the most promising candidate and fund it handsomely, or spread the bounty and hope the best one rises to the top? "The question facing the NAS panel is how to ensure the community remains healthy while still moving forward," NIF's Dunne says.

LIFE will be a tantalizing prospect for the panel, as the most ambitious and advanced design from the biggest ICF lab. But other researchers say a crash program to develop LIFE, to the exclusion of all else, is not the best way to go. They don't want to see ICF research starved in the way magnetic fusion is suffering at the hands of ITER's ever-increasing costs. "We should not go with one pony. We need lots of ponies in the field, and I hope the academy report will reflect that," Wurden says.

NRL's Steve Obenschain agrees. "We advocate competition: See which approach works better and choose in 5 to 10 years," he says. "You've got to have that competition. You don't want to end up doing the wrong thing extremely well."

All told, fusion researchers are cautiously optimistic that ICF's moment may be about to arrive; too bad it had to come in such a time of austerity. "People won't get all the money they need," McCrory says. "But if there's enough enthusiasm, we could go faster than people think."

–DANIEL CLERY