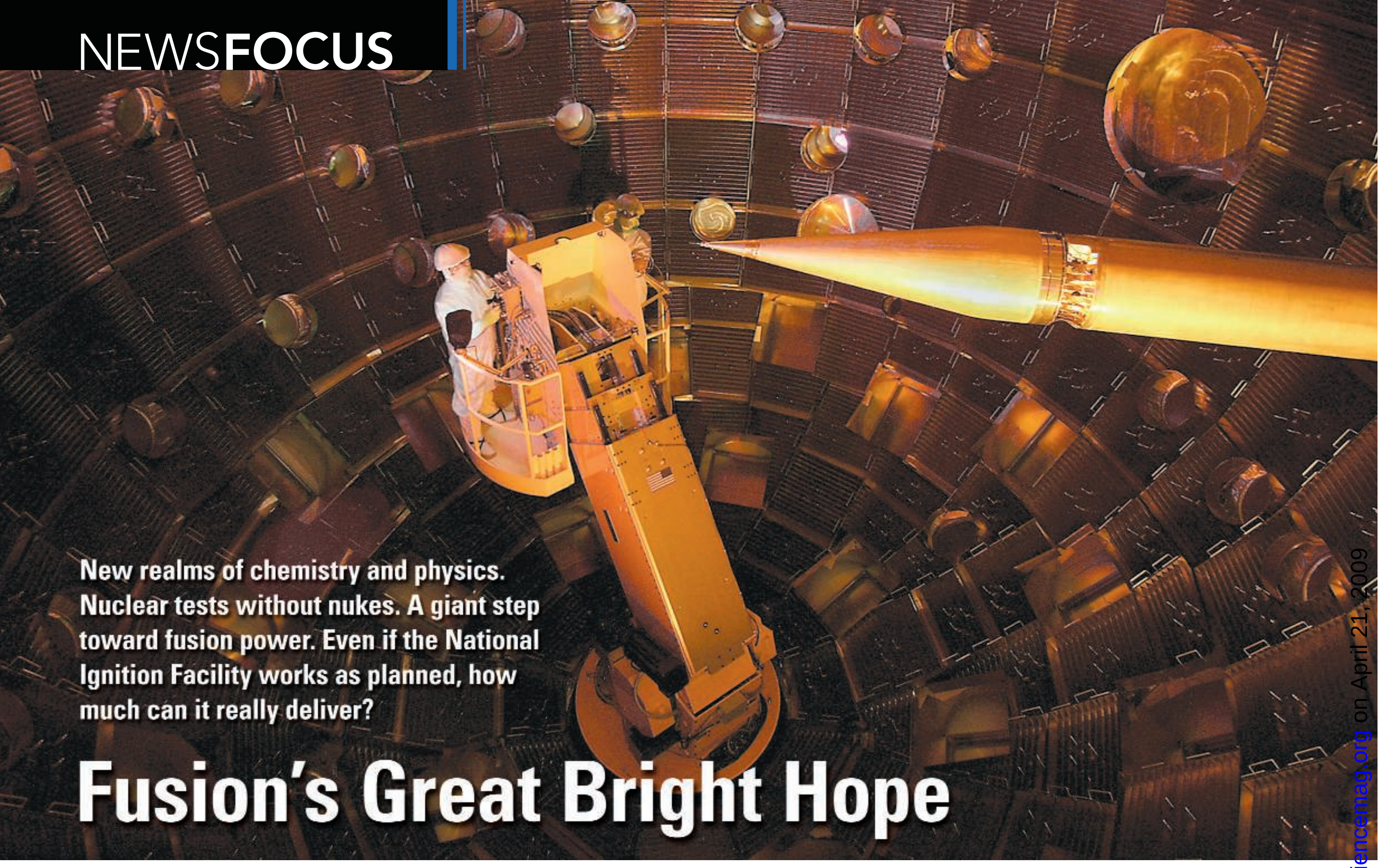


New realms of chemistry and physics. Nuclear tests without nukes. A giant step toward fusion power. Even if the National Ignition Facility works as planned, how much can it really deliver?

Fusion's Great Bright Hope

IN NOVEMBER 1957, GORDON GOULD, A grad student at Columbia University, jotted down in a notebook some ideas on how to make a laser, a term that he coined. Possible uses for such a device, he noted, included spectrometry, interferometry, radar, and nuclear fusion—all 3 years before a laser was actually demonstrated. Gould's innovations were disputed: He was not included in the 1981 Nobel Prize for the laser, and for 3 decades he fought in the patent courts to assert his inventions. He was eventually successful, and many of the applications he dreamed up, such as heating and evaporating materials, measuring distance, communications, and television, have come true—apart, that is, from nuclear fusion.

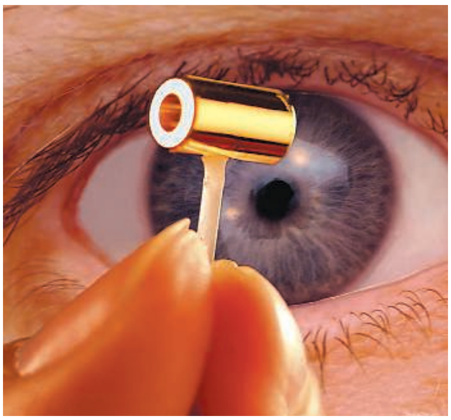
Next year, researchers at the Lawrence Livermore National Laboratory (LLNL) in California hope to tick that box off Gould's list. Despite his foresight, Gould could not have imagined the lengths to which scientists and engineers would have to go to bring his prediction to reality. LLNL's National Ignition Facility (NIF), which was officially completed last month, is a laser on a truly epic scale. The building housing it is 10 stories high and covers an area the size of three football fields; for a very brief instant, its beams deliver a power of 500 terawatts, more than the power-generating capacity of the entire United States.

Online
sciencemag.org
Podcast interview with author Daniel Clery.

If all goes according to plan, some time in 2010 the power of those beams will be directed at a small beryllium sphere filled with hydrogen isotopes. The resulting implosion will crush the hydrogen to a temperature and pressure higher than in the core of the sun. If NIF's scientists get everything right, the hydrogen isotopes will do what they do in the sun: fuse together into helium nuclei and release a huge store of energy. NIF's principal aim is to reach "ignition": a self-sustaining fusion burn that gives off more energy than was put in to make it happen—something that so far has occurred only in nuclear explosions and stars.

"People have been waiting for this moment for a long time," says NIF Principal Associate Director Edward Moses. The achievement could have profound implications for our future energy supply. If the fusion gain—the ratio of energy out over energy in—is high enough and a laser could be developed to spark such ignitions at a steady rate, laser fusion could provide almost limitless energy with little radioactive waste. "This will ignite a change in the political debate," says Mike Dunne, head of the Central Laser Facility of the Rutherford Appleton Laboratory near Oxford, U.K.

Energy production is not NIF's raison d'être, however. Its funding comes not from energy or science budgets but from the coffers of the National Nuclear Security Administration (NNSA), the agency tasked with the maintenance and security of nuclear weapons and naval reactors. NIF's overarching role is to provide hard data that can confirm computer simulations of nuclear explosions. In the absence of nuclear testing, NIF is the best way weapons



Pin point. All 192 beams must shine into the ends of this gold cylinder, which encloses the target.

CREDITS: LAWRENCE LIVERMORE NATIONAL LABORATORY

Published by AAAS

Focal point. Engineers prepare the target assembly at the center of NIF's cavernous target chamber.

designers can know what happens when one of their bombs goes off. But basic science should be a big beneficiary: Researchers plan to use NIF to simulate the interiors of supernovas, stars, and giant planets, as well as to shed light on how materials behave under such previously unattainable conditions. "Really, it's a very, very exciting period for all of plasma physics," says Jacques Ebrardt of France's Atomic Energy Commission and one of the leaders of a rival fusion project, Laser Megajoule.

After a dozen years of construction, researchers are keen to see these dreams realized soon. NIF staff members think they won't have long to wait. "We're feeling pretty confident," says Moses. But some other researchers say such temperatures and pressures are uncharted territory, and controlling them may not be as straightforward as NIF's proponents think. "It's just very, very complicated. Shots even close to this power have never been done before," says Steven Cowley, director of the Culham Science Centre, the U.K. fusion research lab near Oxford. Some think NIF is bound to fail: that the leap in laser technology is too great or that we don't yet understand enough about how plasmas and other materials will behave under these conditions.

Practical questions have also dogged NIF. Technical and managerial problems early on stretched out construction by 7 years and drove up costs; at \$3.5 billion, the price tag is several times the original estimate. Some say that money should have paid for several smaller, less risky facilities.

NIF is perhaps one of the most scrutinized scientific projects in recent history, the subject of countless reviews, panels, and investigations. But the time for predicting its future has passed. That future will soon be decided by a brilliant flash of light and whether it does what researchers hope it will do. Either it will usher in a new era of fusion research, or some hard questions will have to be answered. If NIF works, "we're going to have a gold rush of people being interested. It'll grab the attention of the world," says Robert McCrory, director of the Laboratory for Laser Energetics at the University of Rochester in New York state.

"Every scale of problem"

The route to fusion that has won the most attention and funding is magnetic confinement fusion, which uses huge electromagnets to confine a hot but low-density plasma inside

A LONG, WINDING ROAD TO IGNITION

The National Ignition Facility (NIF) beam starts life in one of two ytterbium-doped optical fiber lasers known as the master oscillators. These produce an infrared flash (1053 nanometers in wavelength) that has an energy in nanojoules. This flash is split into 48 beams and passed through 48 preamplifier modules, slabs of neodymium glass pumped with bright light just before the beams arrive. Four passes through the preamplifiers boost the total energy 10 billion times to about 6 joules. Each of the 48 beams is then split further into four beamlets.

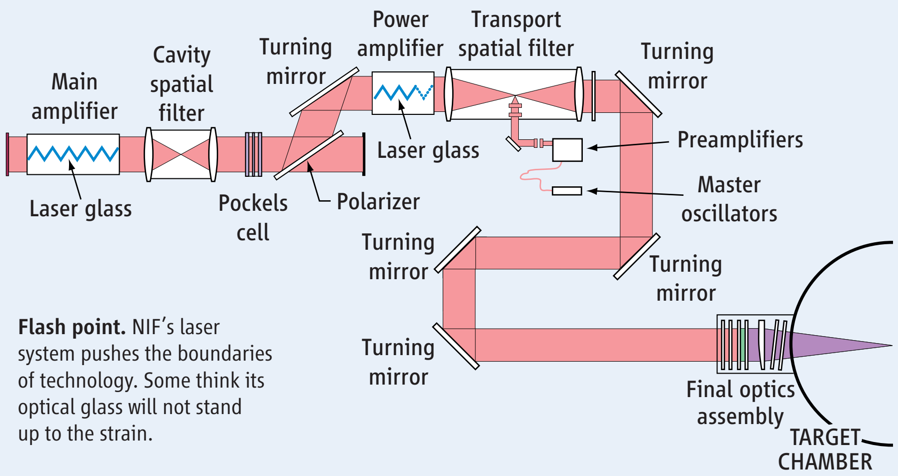
The 192 beamlets pass through the power amplifier into the main beamline, which includes the 48 main amplifiers, each made of 11 1-meter-long slabs of neodymium-doped phosphate glass. Just before the beam is first generated, the amplifiers are pumped full of light by 7680 xenon flash lamps, storing 400 megajoules (MJ) of electrical energy. As the beams pass through, the amplifiers dump that energy into the beam. An optical switch called a Pockels cell traps the light between two mirrors so that the beams pass back and forth through the amplifiers four times before they are switched back up through the power amplifier and on toward the switchyards. The beams now have a total energy of 6 MJ.

The 10-story-high switchyards use mirrors to route the beams into the 10-meter-wide target chamber from all directions around the sphere. Just before entering the chamber, the beams pass through the final optics assemblies, which condition the beams and step down their wavelengths. Frequency converters made from thin sheets cut from single crystals of potassium dihydrogen phosphate convert the infrared beams first to green (527 nanometers) and then to ultraviolet (351 nanometers), which is much more effective at heating the target. Losses bring the total energy down to 1.8 MJ. But because the flash is only 20 nanoseconds long, its power is 500 terawatts, more than the generating capacity of the entire United States. All told, the beam travels 305 meters from master oscillator to target, a journey that takes 25 nanoseconds.

The target is a tiny, hollow sphere made of beryllium about the size of a peppercorn. Inside is 150 micrograms of deuterium and tritium, two isotopes of hydrogen, chilled to 18 kelvin so that they form a uniform layer of ice on the inside of the sphere. The target capsule sits at the center of a tiny gold cylinder about the size of a pencil eraser, called a hohlraum. The beams shine into the ends of the hohlraum, heating its inside surface to such an extreme temperature that it emits a pulse of x-rays. The x-rays cause the beryllium capsule to explode, and the outward blast drives the deuterium-tritium ice inward toward the center of the capsule.

If the implosion is completely spherically symmetric, it will compress the fuel to a density 100 times that of lead. But the fuel still needs a spark to ignite fusion. A shock wave from the original beryllium explosion arrives in the center and heats the core of the fuel to 100 million kelvin. As nuclei fuse in the core, they release enough heat to trigger more fusion in the surrounding fuel in a chain reaction. If all goes according to plan, the reactions will generate enough heat to make the fusion burn self-sustaining and will generate more energy than the laser pumped into the hohlraum, a result known as "ignition"—one of the ultimate goals of NIF.

–D.C.



Flash point. NIF's laser system pushes the boundaries of technology. Some think its optical glass will not stand up to the strain.

a vessel known as a tokamak. The premier magnetic fusion device, which aims to show large energy gain for extended periods, is ITER, currently being constructed by a worldwide collaboration in southern France. Meanwhile, a smaller community has attempted to achieve fusion by imploding small capsules of fuel using light or particle beams—a technique known as inertial confinement fusion (ICF) because inward inertia of the implosion holds the fuel in place.

The first experiments with ICF were carried out in the 1960s using ruby lasers soon after they were invented. But a key paper by LLNL physicist John Nuckolls in 1972 predicted that ignition would need laser pulses of 1 kilojoule and that high gain would require 1 megajoule (MJ). There followed a series of attempts at fusion: During the 1970s, LLNL built increasingly powerful lasers—Janus, Cyclops, Argus, and finally Shiva, a 20-beam, 10-kilojoule laser with amplifiers made from neodymium-doped silica glass. With every attempt, however, researchers encountered new difficulties with power-draining interactions between the beam and the plasma and achieving a smoothly symmetric implosion of the fuel capsule.

In 1980, researchers at Rochester developed crystals that could triple the frequency of high-intensity laser light, converting it from infrared to ultraviolet, which interacts with plasma less and causes a better implosion. Rochester soon put the crystals into practice with its 24-beam Omega laser, and LLNL followed suit with Nova in 1984. Funding for fusion stagnated during the 1980s, but Nova and Omega advanced the science enough that by the late 1980s and early 1990s, several labs were developing designs for a next-generation machine.

> ***"There needs to be more than one miracle for everything to work in time."***
>
> **—DAVID HAMMER, CORNELL UNIVERSITY**

In 1992, the United States stopped testing nuclear weapons, and new methods were needed to ensure that existing weapons would still work when needed and that new weapons could be developed without testing. In discussions between the national weapons laboratories, officials decided that an ICF device was needed to validate computer simulations of nuclear explosions. In 1994, a design for NIF emerged that would produce a 1.8-MJ ultraviolet beam at a cost of just over $1 billion with completion penciled in for 2002.

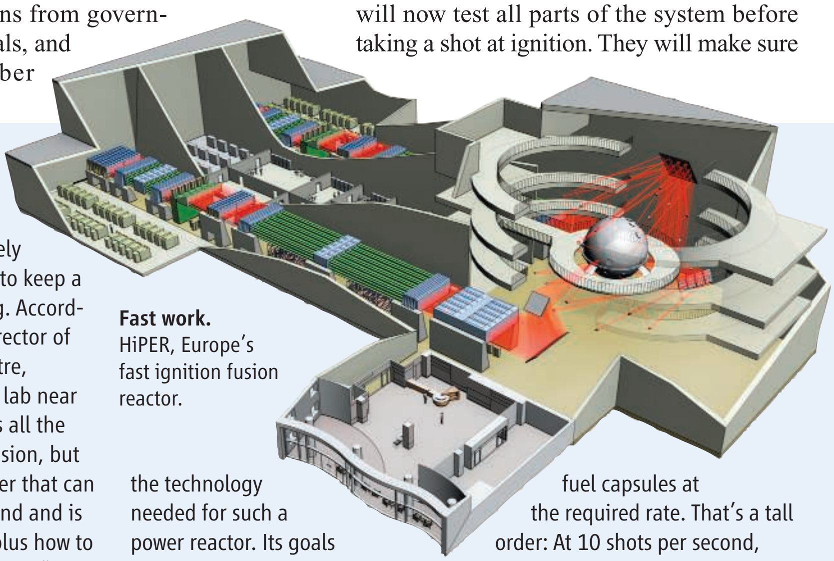
Problems emerged with the design soon after construction began in 1997. Capacitors failed in the pulse power modules that supply current to the flash lamps that pump the laser amplifiers, and there were persistent problems with dust on optical surfaces: Powerful beams would heat up the dust specks and damage the surfaces. NIF staff members hid delays and cost overruns from government officials, and in September 1999, NIF Associate Director E. Michael Campbell stepped down after anonymous tips revealed he had not finished a claimed doctorate from Princeton University.

Those revelations caused the Department of Energy (DOE) to carry out a thorough reevaluation of the project, and Congress ordered an independent review by the Government Accountability Office. GAO's damning report prompted DOE to rebaseline the project with a new cost estimate of about $4 billion and completion slated for 2008.

Moses took over the troubled project in 1999 and found "every scale of problem," he says. He worked to develop a "partnership" with vendors and a cultural shift among the staff so that they would speak up if there were a problem. He tackled the dust issue by building a huge clean room where optical elements are enclosed in sealed units that could easily be slotted into and out of the beamline. He also began commissioning the beamlines one at a time, beginning in 2001, rather than all of them in parallel, so that any bugs in the first completed beamlines could be corrected in later ones. "That had a huge impact," says Mark Newton, leader of NIF's engineering division.

Under the new management, NIF has pretty much kept to the revised schedule and budget, culminating in last month's official completion and, according to Moses, a test shot with an energy of 1.1 MJ. Researchers will now test all parts of the system before taking a shot at ignition. They will make sure

WHAT'S NEXT FOR ICF?



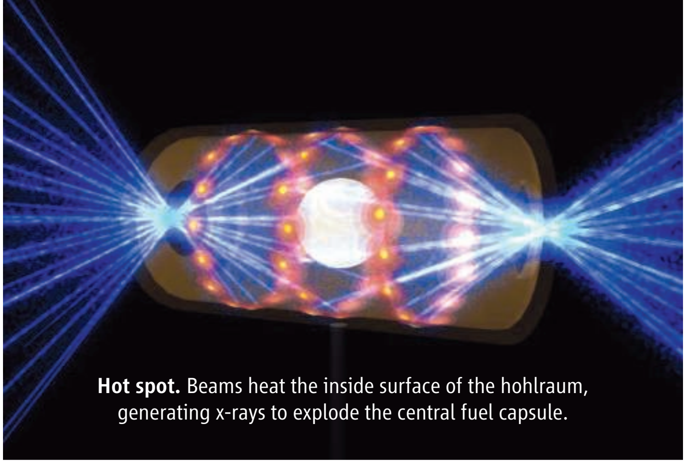
Fast work. HiPER, Europe's fast ignition fusion reactor.

If the National Ignition Facility (NIF) reaches its goal of ignition—a self-sustaining fusion burn that produces more energy than was put in to create it—researchers will celebrate a triumph of plasma science. But they will still be far from showing that inertial confinement fusion (ICF) is a viable energy source for the future.

One key stumbling block for an ICF energy reactor is laser technology. NIF managers hope to perform about two shots a day because of the time needed to let optical elements cool down, check for damage, replace any damaged parts, and install a new fuel capsule. At that rate, with each shot producing fusion burns of 20 megajoules—its initial target—NIF will barely generate enough power to keep a single light bulb glowing. According to Steven Cowley, director of the Culham Science Centre, Britain's fusion research lab near Oxford, "laser fusion has all the problems of magnetic fusion, but ICF also has to find a laser that can fire many times per second and is 20% to 30% efficient, plus how to make fuel pellets at low cost."

The National Nuclear Security Administration, which funds NIF, has also been backing the High Average Power Laser (HAPL) program, bringing together researchers at national labs, universities, and industry to develop the technology needed for such a power reactor. Its goals include a laser that can fire as many as 10 shots a second, optics that can withstand that much power for long periods, a target chamber that can absorb the neutrons produced by fusion and convert their energy into heat, and a target factory that can churn out fuel capsules at the required rate. That's a tall order: At 10 shots per second, more than 850,000 fuel capsules would be needed every day.

The favored laser design is a krypton fluoride gas laser pumped with electron beams that is being developed at the Naval Research Laboratory (NRL) in Washington, D.C. NRL's Electra laser has recently


Hot spot. Beams heat the inside surface of the hohlraum, generating x-rays to explode the central fuel capsule.

that all 192 beamlets can be focused, smoothed, and targeted accurately; that they can direct them into the ends of the hohlraum, the gold cylinder that houses the fuel capsule; and that they can get a capsule to implode symmetrically. "By the end of the campaigns, we'll have a pretty good idea of what to expect," says Gilbert Collins, leader of NIF's shock physics group. Moses is similarly confident: "Ignition is a grand challenge. Our aim is to do it in 2010," he says.

Other researchers have heaped praise on LLNL's achievements. "The laser is really quite tremendous and truly awe-inspiring," says particle physicist Roy Schwitters of the University of Texas, Austin, who chairs the JASON Defense Advisory Group, an organization of scientists that assesses defense-related projects, such as NIF, for government clients. Cowley is similarly effusive: "NIF is a triumph of laser construction." But few agree with Moses that NIF will be able to move rapidly to ignition by next year. "The schedule looks almost unattainable," says Cowley. And according to nuclear engineer David Hammer of Cornell University, "There needs to be more than one miracle for everything to work in time for the first ignition experiment."

Wrestling instabilities

Most researchers cite two areas where nature may throw NIF a curve ball: laser-plasma interactions (LPI), which affect the beams as they enter the hohlraum; and hydrodynamic instabilities (HDI), which can cause the fuel capsule not to implode symmetrically. Both effects plagued earlier ICF experiments, and NIF researchers have spent years simulating and testing ways to control them. But NIF's huge energies may still spring surprises. "Until they put a beam into the hohlraum, we won't know what nature will do," says Hammer.

LPI happens when the beams enter the hohlraum and hit its inside wall, kicking up enough gold atoms to create a plasma inside the cylinder. The interaction of the beams with this plasma can reduce the power deposited into the beryllium capsule and can preheat the fuel, making it harder to compress. The plasma can even reflect some of the beam out through the hole again, reducing efficiency. "We have a woeful ability to predict" LPI, says Dunne. Mordy Rosen of LLNL's Weapons and Complex Integration Directorate agrees. "We're going to a place we've never been before. It's going to be a new game," he says. Nevertheless, he adds, "I think we've got what it takes to respond to those issues that come up."

Steven Bodner, retired head of laser fusion at the Naval Research Laboratory in Washington, D.C., says NIF has even bigger problems: He believes the quality of its beams is not up to specification. The design describes a maximum beam spot size that will fit into the hohlraum without touching the entrance hole or the fuel capsule, as well as a bandwidth the beams must be detuned to in order to combat LPI. Bodner says that in results released so far, beams have achieved both of these criteria, but not at the same time while operating at full power. "If they can't focus the beam into the hohlraum, they can't get ignition," he says. Bodner thinks NIF's chance of reaching ignition "is worse than a snowball's chance in hell." NIF counters by citing the conclusion in February this year of the National Ignition Campaign Review Committee, which stated that "each and every one of the laser performance completion criteria has been met or exceeded."

Compressing the fuel capsule is also fraught with difficulties, collectively known as HDI. If you imagine trying to squeeze a balloon with your two hands, you'll see what the exploding capsule is trying to do: compress the contents uniformly without bits of it bulging out again. Many things can cause HDI: The bath of x-rays coming from the heated hohlraum may not be uniform or there

demonstrated continuous operation for 10 hours firing 2.5 shots per second at ultraviolet wavelengths. Researchers still have to ensure that a working laser can keep that up for years and boost its power to the levels needed for ICF.

The Lawrence Livermore National Laboratory in California, home of NIF, is working on a high-repetition-rate version of the neodymium-doped glass lasers used on NIF. Livermore's Mercury laser dispenses with the inefficient and slow flash lamps used to pump NIF's laser amplifiers and replaces them with solid-state laser diodes. Mercury has shown a repetition rate of 10 hertz firing at infrared wavelengths.

The HAPL project is currently stalled, however, because it received no funding in the 2009 omnibus funding bill. "Hopefully, through some combination of actions by the new Administration and Congress, the challenge of funding HAPL and other such inertial fusion energy research in the U.S. will be resolved soon," says Steven Obenschain, head of NRL's laser plasma branch.

"Laser fusion has all the problems of magnetic fusion," and more.

—STEVEN COWLEY, CULHAM SCIENCE CENTRE

In Europe, researchers are plotting a slightly different route to laser fusion energy. In traditional ICF, a single laser pulse plays two roles: compressing the fuel and sparking fusion at its center. An alternative, known as fast ignition fusion, uses one laser to compress the fuel and a second pulse, with extremely high power (10^{15} watts) but short duration, to set off the fusion burn. The advantage is a significant reduction in the energy requirement of the lasers. "If it works, it could lower the energy necessary to get high gain, making the economics more tantalizing," says NIF Principal Associate Director Edward Moses.

The idea of fast ignition was conceived 15 years ago, and early experiments with the Gekko laser at Osaka University in Japan suggested it might work. Researchers at the University of Rochester in New York state are hoping to put it to some sterner tests with their newly upgraded Omega EP laser. But a design study funded by the European Union is planning something bigger: a dedicated fast-ignition facility with high repetition rates, dubbed HiPER. "We're putting together all the building blocks so that politicians can make a decision," says HiPER Director Mike Dunne of the Rutherford Appleton Laboratory's Central Laser Facility near Oxford, U.K. He's hoping construction could start in 2015. Some caution, however, that fast ignition should learn to walk before it tries running. Says nuclear engineer David Hammer of Cornell University, "Fast ignition is one of those attractive ideas that haven't been tested yet." **–D.C.**

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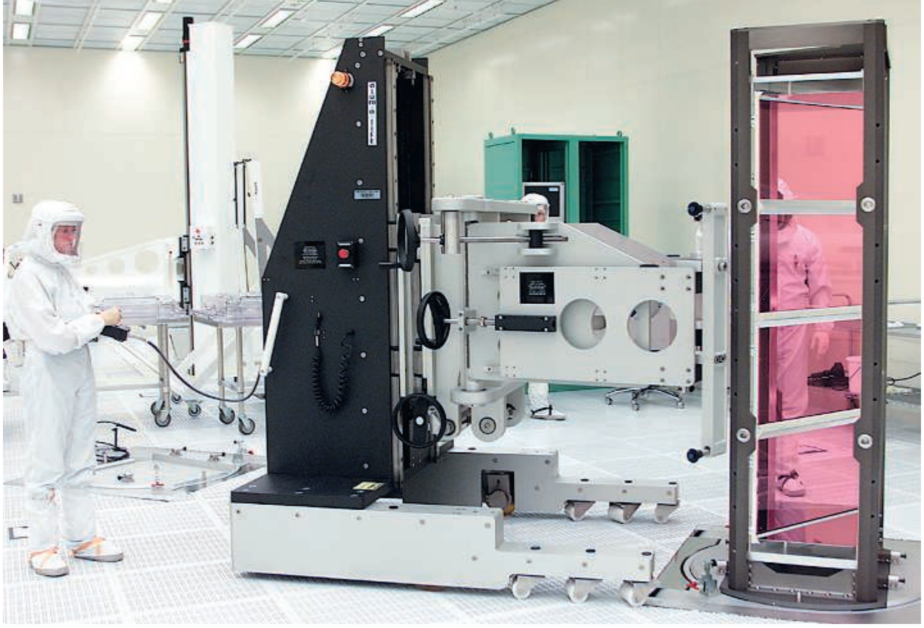

Clean machines. In conditions worthy of a semiconductor plant, technicians prepare a laser glass slab (*right*) for insertion into the beamline.

may be some flaw in the capsule or fuel layer. Even under ideal conditions, instabilities are inevitable, researchers say. The key to beating them is speed: "We need to do it fast enough so instabilities don't get big. It's extremely hot and high pressure. It wants to blow itself apart," Rosen says.

Breaking glass

Apart from LPI and HDI, other issues could prove a headache for NIF's managers. According to some outside LLNL, the risk of damage to the laser optics has not gone away. The energy contained in each laser pulse is not huge, but because it is pumped through in only a few nanoseconds, the power is enormous. Hammer says NIF can cope with a certain amount of damage to glass, "but if 192 beams destroy several optical elements, a lot of optics is involved." The "triplers," which convert the final beam into ultraviolet, are particularly tricky, he says, and because they are very close to the target chamber, they could do substantial damage if they explode. Moses says scientists have done a huge amount of research on damage mechanisms and removing defects from surfaces. "We've shown we can get surfaces to work at full performance. … That was our biggest challenge."

Some experts also worry that NIF's choice of beryllium for the capsule material, which requires more energy to explode than alternatives such as plastic, leaves little margin for error in reaching ignition. In 2005, a JASON panel investigated NIF's chances of achieving ignition. Noting plans to start out at energies of about 1 MJ, it concluded "that success in the early attempts at ignition in 2010, while possible, is unlikely." The panel was invited back to view progress in January of this year, but its report has yet to be released by NNSA. Hammer, who co-chaired the panel, says that in his own opinion there's still not enough power available. He thinks that a couple of years after the first attempts at ignition, they will have a 50:50 chance of success. "They will throw everything at it to get there," says Cowley. "By 2010, they might, but if they operate it for a long time they'll learn how to do it."

Illuminating the stars

Some researchers are less concerned about the trials of reaching ignition than what they can do once it's achieved. These are the plasma physicists, planetary scientists, and astrophysicists who want to use NIF to do basic research. Twenty percent of time at NIF is earmarked for basic research, and several groups are gearing up to take advantage of it. Planetary scientist Raymond Jeanloz of the University of California, Berkeley, is preparing experiments for NIF that will replicate pressures at the cores of giant planets. "NIF will give us 100 times the energy we can currently deposit into samples," he says. "We will begin to turn the page on a new kind of chemistry that wasn't accessible before." Cowley, who has worked in astrophysics as well as plasma physics, says ignition at NIF will produce "an unbelievable neutron flux if you get really close"—conditions akin to extreme astrophysical events such as supernovas. This will open up new opportunities in the burgeoning field of experimental astrophysics. "There are wonderful things you can do with NIF," Cowley says.

Also hoping to do wonderful things, although with less visible results, are the weapons scientists involved in stockpile stewardship. Ever since the idea of NIF was first mooted, it has faced controversy over how useful it really will be to weapons research, including sniping from other national laboratories that benefited less from NNSA's largess. "I've never viewed it as relevant to weapon design. The parameters are very different, it's orders of magnitude wrong," says Bodner. A 2007 report on stockpile stewardship from the Federation of American Scientists concluded that the nation's nuclear weapons were being kept safe and reliable through careful monitoring and the judicious replacement of parts. "The NIF could be ended without reducing the confidence in the existing nuclear stockpile," it said.

NIF's relevance to weapons "has been reviewed for 20 years by blue-ribbon panels, everyone under the sun," says Moses. "The community has spoken, the NNSA continues to fund us, that's pretty much put to bed." What's more, France is spending billions constructing Laser Megajoule, a similar machine that will carry out its first experiments by the end of 2012, also aiming for ignition and weapons verification. "The architecture is basically the same," says Ebrardt, and some components, such as the amplifier glass, were developed jointly by the two teams.

Nevertheless, just as NIF reaches the stage at which it can prove itself, the tide of politics is flowing away from its original mission. President Barack Obama has spoken much more about nuclear disarmament than about maintaining a credible deterrent, and his appointments and funding decisions show a keen interest in developing new sources of energy. It's perhaps no coincidence that most news coverage of NIF's completion last month focused on its significance for energy, not weapons. LLNL researchers have also been busy developing designs and technology for fusion-energy projects that would come after NIF (see sidebar, p. 328). "[NIF] is not a power-production machine," Collins acknowledges, but it "will unveil the science needed to get there."

"We're going to a place we've never been before. It's going to be a new game."

—MORDY ROSEN, LAWRENCE LIVERMORE NATIONAL LABORATORY

For NIF researchers, waiting to see if a dozen or more years of work will pay off, there is now some respite from the constant probing and questioning of NIF's abilities and rationale. "Some of our most serious critics are waiting and seeing. The rhetoric has really dropped down," says Collins. Rosen, for one, is ready. "It's up to us now," he says. "Mother Nature is waiting."

–DANIEL CLERY

With reporting by Robert F. Service.

CREDIT: LAWRENCE LIVERMORE NATIONAL LABORATORY