Laser Fusion Catches Fire

The National Ignition Facility, a half-billion-dollar bid to ignite a fusion "burn," is drawing a surprising following, aided by favorable reviews of the existing laser fusion program

Laser fusion has always had the flavor of a technological boondoggle. Consider just the bare essentials of what's required to pull it off: Start with some 200 lasers, each nearly as powerful as any laser now in existence and all firing in near-perfect synchrony, bombarding a hydrogen target a few millimeters across. The energy from the lasers has to make the target implode so smoothly and symmetrically that its inward collapse proceeds without the slightest instabilities—ripples—that could grow with nonlinear viciousness and destroy the whole process quicker than the blink of an eye. The pellet ultimately reaches one-thirtieth its starting radius and a density—for hydrogen, remember—10 to 100 times that of lead. "Not neutron star densities," as one nuclear physicist puts it, "but for lab physics pretty impressive, nonetheless."

The big squeeze. An artist's conception of the National Ignition Facility, which would focus 190 or more laser beams on tiny pellets of hydrogen to fuse them into helium.

Finally, if all has gone well, the hydrogen fuses into helium at the core of the pellet, initiating a burnwave, an outward rolling swell of fusion that consumes the pellet. This process—a thermonuclear explosion in miniature—emits energy in the form of heat and radiation. Therein lies the final challenge: harnessing this energy for less money than it cost to generate it.

Over the years, even officials in the Department of Energy's (DOE) weapons program, which has provided the funds for laser fusion, have had their doubts about the technology. Unlike DOE's magnetic fusion program, an effort to achieve fusion in a magnetically confined plasma, laser fusion has never been supported primarily as a future energy source, but rather for its defense applications. And those—studying the physics of hydrogen bombs—have seemed indirect at best. "Most of the real weaponeers didn't believe it had anything to do with weapons," says Princeton University physicist Will Happer, formerly head of DOE's Office of Energy Research, "and who needed it anyway because you could always test in Nevada." For years the program has been a line item in the DOE defense budget, protected by supporters in Congress.

But a surprising following for the technology, which is known as inertial confinement fusion (ICF), is emerging in both the defense and basic science quarters. With it has come a groundswell of support for the next step in developing ICF: a giant laser complex costing at least $500 million that would, for the first time, pump enough energy into a hydrogen capsule to achieve break-even. Now that a moratorium has halted weapons testing, DOE has taken to vigorously promoting the laser, known as the National Ignition Facility (NIF). "When they look to the future," says a staff member of the Energy and Water Development Appropriations subcommittee in the House of Representatives, "it's about the only major project they see in the defense area."

At the same time, the physicists on DOE's Inertial Confinement Fusion Advisory Committee (ICFAC) believe the existing laser fusion programs, at Lawrence Livermore National Laboratory, the University of Rochester, and elsewhere, have laid a solid scientific groundwork for NIF. The committee isn't expected to present its recommendation about the facility until next summer. But ICFAC chairman Venkatesh Narayanamurti, dean of the college of engineering at the University of California, Santa Barbara, thinks the program has made "enormous progress." Concludes Narayanamurti, "I'm convinced ultimately we will have to build NIF. If you want to continue with fusion, that's what it's all about."

NIF, as currently conceived, is an outgrowth of the classified laser fusion program at Livermore, which centers on a giant glass laser known as Nova and a strategy called indirect drive. In indirect drive the laser beams are directed into a small cylindrical cavity known as a hohlraum that surrounds the hydrogen pellet. The hohlraum is made of a heavy metal, such as gold, and when it is irradiated by the laser beams, it evaporates into a plasma, emitting x-rays. The x-rays bounce around the hohlraum and symmetrically bombard the pellet, compressing it.

That symmetry seemed to give the technique a key advantage over direct drive, which has been the province of an unclassified program at Rochester. In direct drive, the lasers shine directly on the fuel pellet to be imploded. The drawback of that seemingly straightforward strategy is the difficulty of getting the laser beams to strike the capsule with equal strength from all directions, which is an absolute necessity for successfully imploding the capsule. (Rochester is now engaged in a $60 million upgrade to its Omega laser facility, which should determine the ultimate feasibility of direct drive.) But until recently few physicists outside Livermore believed indirect drive could possibly be efficient enough—with its extra step of converting laser energy to x-rays—to induce a fuel pellet to ignite.

Taking the indirect route

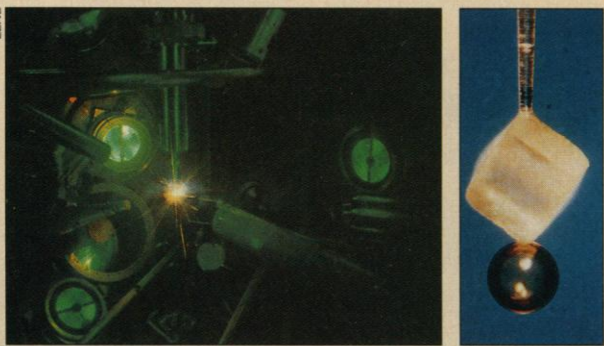
During the 1980s, however, a classified program known as Halite/Centurion demonstrated the feasibility of the concept using underground nuclear explosions. "It was very, very successful," says Mike Campbell, head of the Nova program, "and I can't tell you anything about it." Having done its job, Halite/Centurion was discontinued in 1990 on the advice of a National Academy of Sciences review committee headed by California Institute of Technology nuclear physicist Steven Koonin. The NAS committee also established the next priority for the nation's laser fusion program: an indirect drive laser, 25 to 50 times as powerful as Nova. The goal of the facility would be, as Campbell puts it, "to show that we can have these little fusion pellets ignite, which means the energy produced by fusion is equal to the energy the laser supplies to the pellet."

The panel's endorsement of NIF was conditional, however. The Nova program still had to surmount three hurdles facing the indirect drive concept (see sidebar): a better understanding of pellet compression, the ability to control laser aim and hohlraum

Getting a Fusion Target to Behave Under Pressure

Three years ago, Caltech physicist Steven Koonin and his colleagues on a National Academy of Sciences review panel set up a series of hurdles for the laser fusion program. If it surmounted the hurdles, said the panel, the program would be ready to move to the next step: the proposed National Ignition Facility (see main text). Now a new panel set up by the Department of Energy is reviewing the progress, and although panelists aren't delivering an official verdict yet, unofficially they say, as panelist Marshall Rosenbluth of the University of California, San Diego, puts it: "They have done what they said they were going to do." The remaining questions "aren't going to be resolved now until they actually do the experiment [with NIF]."

To prove ignition was feasible, Koonin's panel said, fusion researchers at Lawrence Livermore National Laboratory's Nova program had to prove they could control some of the thorniest aspects of indirect drive, the most popular scheme for laser fusion. In indirect drive, the lasers are trained on a hohlraum, or metal capsule, that encloses a hydrogen pellet. The lasers vaporize the hohlraum and generate a plasma that bathes the pellet in x-rays, imploding it and triggering fusion.



LLNL

To build a fire. A laser fusion pellet—a salt-grain-sized sphere of plastic and glass filled with isotopes of hydrogen *(right)*—is set aglow by the 10 beams of the Nova laser.

The most tractable aspect of that scenario has turned out to be the implosion itself. Koonin's committee required that the Livermore researchers learn to control instabilities so that the pellet would implode before they got out of hand. That, in turn, required developing ways to map the progress of the implosions by detecting and analyzing x-rays emitted from different points in the target. Once the researchers could trace what went right or wrong in an implosion, they could fine-tune the next one. As Nova physicist John Lindl explains, the experiments have shown that changes in the hohlraum material, the intensity of the laser, and the shape of the pulses can all help limit instabilities.

A smooth implosion also requires that the lasers bombard the hohlraum evenly. As Lindl explains, "[Even though] the hohlraum does a lot of smoothing for you, you still need to have a certain level of pointing accuracy and power balance." The committee wanted assurance that the x-rays generated by the hohlraum would vary in intensity by less than 1% across the pellet's surface—a challenge the physicists met by controlling the aim of the lasers and the geometry of the hohlraum.

The toughest problem now is proving that such precise control will still be possible as the hohlraums are scaled up in size. Hohlraums at NIF will be four times larger than those at Nova, and each laser pulse will be longer, with the result that each shot will generate a larger plasma. Laser beams can scatter in a plasma, throwing off their symmetry or generating high energy electrons—which are useless for fusion—rather than x-rays. And those concerns are helping to set Nova's agenda for the next few years: Figuring out how to produce still more uniform beams and simulate NIF's larger plasmas. Says Lindl, "We've shown that for the hohlraum size we have on Nova, things are well behaved. We have to make sure they remain well-behaved for larger plasmas."

–G.T.

shape to light up the fuel pellets evenly, and—hardest of all—making sure that all this would scale up to the larger hohlraums required for NIF.

Now, 3 years later, progress has been remarkable, say the ICFAC physicists. Koonin, who now serves on the ICFAC panel, says that time and again his response to learning of another Livermore experiment is, "Gee, you can really do that? That's pretty impressive." Last January, at the prompting of the ICFAC panel, DOE initiated what's called in the lingo key decision zero for NIF. This, says Campbell, "establishes a mission need for the project and allows us to do a conceptual design so we can estimate cost."

The conceptual design, on which physicists from the national laboratories and the University of Rochester are collaborating, will be finished by next spring, at which point the construction cost will be set somewhere between \$500 million and \$800 million. Nobody wants to be more specific yet. "People will always remember the lowest number you quote," explains Robert McCrory, director of Rochester's ICF program.

As it is now shaping up, NIF would likely be built at Livermore and would incorporate between 190 and 240 neodymium glass lasers. Each would generate 10 kilojoules of blue light—a quarter of Nova's total output—in a beam 35 centimeters in diameter that would then be tightly focused onto the target. All told, NIF would generate 1.8 megajoules, enough, researchers hope, to go well beyond ignition to fusion yields of 10 to 20 megajoules.

The designers of NIF are betting that it can be built for only three to four times the original cost of Nova. As Campbell points out, NIF represents late-1980s technology, while Nova was based on 1970s technology. "There have been lots of technological advances over the past 15 years," he says, "and NIF will take that into account." In particular, improvements in lens coatings and increases in crystal purity have raised the damage thresholds of the laser optics so that they can withstand much more intense light. In addition, while Nova's amplifiers and optical switches allowed each pulse to make just a single pass, NIF's optics would allow multiple passes. Both advances make it possible to wring more power from a laser of a given size. Livermore is now incorporating these features into a full-scale prototype of one arm of NIF, known as the beamlet, which should be finished by next summer to serve as a testbed for the NIF optics.

Although the outlook for big physics programs seems grim these days, the fusion physicists say they have reasons for optimism about NIF's prospects. "I think we will persist and it will happen," says Campbell. For starters, all the laser fusion labs are collaborating on NIF, so funding the program doesn't require a huge jump in the laser fusion budget—about \$220 million in fiscal year 1993—only a consolidation. During the construction of Nova, in contrast, the Livermore project competed for funds with another ICF project at Los Alamos and a third at Sandia National Laboratory. "There were three machines being built simultaneously," says Campbell, "all in the \$100 to \$200 million class. NIF will be done jointly, which reflects the reality that there's not going to be one for everybody."

In a step that should make the program

still more palatable, DOE seems to be on the verge of declassifying the Livermore program—a move Koonin's review committee urged 3 years ago. Now, says John Lindl, deputy program leader for the Livermore project, the National Security Council, the State Department, DOE, and the Defense Department have agreed to the recommendation; all that's lacking is approval by Energy Secretary Hazel O'Leary. "We're expecting she'll sign off on it," says Lindl, "but we don't have it yet." Besides widening the scientific constituency for the program, declassification should open the way to collaborations with, for instance, the Japanese, French, and Germans, all of whom have ongoing laser fusion programs.

Only a test

Still, physicists familiar with the program caution that it should not be oversold. For one thing, if and when NIF gets built—which could happen by 2001—laser fusion will still have a long way to go to become a practical energy source. The best NIF can offer, says Marshall Rosenbluth, a University of California, San Diego, physicist and a member of the ICFAC panel, is "a proof of principle test of inertial fusion either for defense applications, or in the longer run for energy applications."

That's because NIF, like Nova, would be what the physicists call a one-shot target experiment. "The laser could fire perhaps once an hour," says Lindl, because "a lot of waste heat comes off, and you have to allow the optics to cool." A fusion power plant would have to achieve the same implosion feats as NIF—but at the rate of at least five to ten times a second. The best bet for drivers that could achieve such repetition rates are heavy ion accelerators, says Campbell, and Livermore is working in collaboration with the Lawrence Berkeley Laboratory to develop them. Like lasers, the ion beams would bombard a hohlraum, which would emit x-rays and compress the pellet. But because they focus their beams using magnetic fields, accelerators are more resistant to neutrons and heat, and they're also far more efficient than glass lasers.

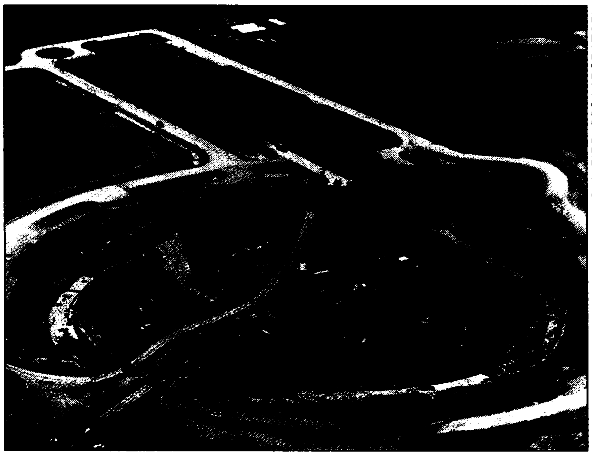
Such devices are at least a few decades in the future, however. For now, says Lindl, lasers are the best tool for studying ICF: "A lot of what we learn about hohlraums and pellets [at laser facilities] carries over to ion beams." And, for now, lasers also provide the best shot for achieving ignition. "When laser fusion started up," says Massachusetts Institute of Technology physicist Arthur Kerman, an ICFAC panelist, the technology "was eight orders of magnitude, 100 million times away, from a sensible version of what was needed. They have come a very long way in 30 years. They may have come far enough."

–**Gary Taubes**

SUPERCONDUCTING SUPER COLLIDER

Fight Heats Up Over SSC's Remains

Ever since Congress killed the Superconducting Super Collider (SSC) in October, physicists and Texas state officials have been hoping to salvage something from the $2 billion already spent on what was to be an $11 billion project. Like transplant surgeons examining a cadaver, they have identified several vital organs that could give new life to other projects. These include a central laboratory building, a $27 million liquid helium cryogenics facility considered among the best in the world, a magnet development and test facility, and a partially completed linear accelerator (linac) that would cost $60 million to finish. It's unclear, however, just who will get these former SSC body parts, and who will pay to operate them once the SSC lab is closed.



JOHN BIRD, SSC LABORATORY

Lining up. The partially completed linac building, top, was to be joined by low-energy and medium-energy boosters.

Part of the uncertainty comes from the ambiguous language in the legislation that brought the 7-year project to a halt. Department of Energy (DOE) Secretary Hazel O'Leary was told to carry out an "orderly termination" of the project, reflecting the desire of opponents to have the project done away with quickly and efficiently. But she was also told to submit a plan by July 1994 that would "maximize the value of the investment" and "minimize the loss to the United States and involved states and persons"—a process that could take a very long time. "On the one hand," says Fred Gilman, associate director of the SSC lab, "people point to the word 'termination' and think of leaving nothing behind. But other words talk about the possible use of assets, which would point the other way."

First in line for those assets appears to be the state of Texas. A memorandum of understanding between the DOE and Texas—which former SSC director Roy Schwitters calls "this famous agreement"—states that in the event of termination of the project, Texas has a legal claim to any facilities to which it contributed greater than half the value. Texas has already spent more than $400 million and, according to a DOE spokesman, its money has indeed paid for more than half of all the major scientific facilities built to date as well as the central laboratory building and computing resources.

Texas has already identified several possible uses for these facilities. In a recent meeting in Washington with O'Leary, Texas Governor Ann Richards proposed that the SSC lab become home to one or more of four possible projects: a national test beam facility, a cold magnet research and development facility, a central laboratory to facilitate future international physics collaborations, and a cancer treatment laboratory. Texas researchers have a fifth suggestion—convert the lab into a consortium for research on large superconducting devices. "The general impression was that it would be an embarrassment or a waste or sinful to say that, after $2 billion, you get nothing, zip, zero for it," says Vigdor Teplitz, head of the physics department at Southern Methodist University in Dallas, who organized a meeting last month of representatives from 10 research universities in the state.

But Texas is not the only relative with an interest in the deceased. The U.S. high-energy physics community as a whole is worried that money may be diverted from DOE's already tight high-energy physics budget into projects outside the field, or into operating a physics laboratory not on the frontiers of science. "The high-energy physics base program has been slowly eroded to help SSC," says Nick Samios, director of Brookhaven National Laboratory in New York. "We did that knowingly. Now we need restoration of the base program. If you have another mouth to feed, it will make it very difficult."

O'Leary has asked the department's High Energy Physics Advisory Panel (HEPAP) to form a subpanel to discuss how termination of the SSC can contribute to the long-term vitality of high-energy physics, and physicists across the country have already begun floating ideas to use SSC facilities to boost the base program. Robert Adair, a Yale physicist and HEPAP member, calls the proposals that have come up so far the equivalent of "corridor talk." The cryogenics facility, for instance, would be a useful addition to