Sparking Fusion

A step toward laser-initiated nuclear fusion reactions

By IVARS PETERSON

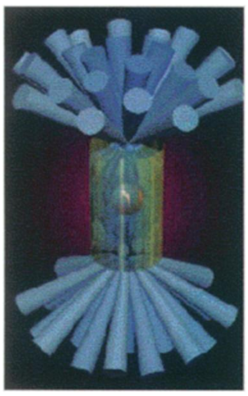
The fusion furnace at the sun's core burns hydrogen to make helium.

Each time two hydrogen nuclei, or protons, merge to create a deuterium nucleus, the process releases energy. A chain of additional energy-producing nuclear reactions then converts deuterium into helium.

Because protons, with their like electric charges, naturally repel each other, high temperatures and tremendous pressures are needed to force them together closely enough to initiate and sustain the reactions. These mergers cost energy initially, but the return on that investment proves prodigious.

On Earth, such an energy payoff has been achieved only in the uncontrolled fury of a detonated hydrogen bomb. The vision of harnessing and controlling nuclear fusion as a terrestrial energy source has yet to be fulfilled.

The proposed National Ignition Facility (NIF) represents an ambitious effort to use powerful lasers to deposit sufficient energy in a small capsule of nuclear fuel to trigger fusion (SN: 11/5/94, p. 303). These ignition experiments could yield about 10 times the energy that the lasers put in, says William J. Hogan, NIF deputy project manager at the Lawrence Livermore (Calif.) National Laboratory, where NIF is most likely to be built.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An array of laser beams enters a metal cylinder to heat up a tiny fuel capsule containing a mixture of deuterium and tritium gas.

Such a gain would be less than that required for a practical power plant, Hogan notes, but sufficient for a variety of tests and studies to determine whether this approach to fusion power is worth pursuing.

The main justification for the NIF project, however, is to ensure that a core group of physicists and engineers maintains its expertise in the physics of nuclear weapons. Such knowledge would secure the future safety and reliability of the U.S. stockpile in the anticipated absence of nuclear tests, according to the Department of Energy.

Congress has already allocated $61 million for planning, construction, and operating expenses of NIF this year, with increased funding slated for next year. DOE has just completed an environmental impact assessment, setting the stage for the final phase of the site selection process. The project's total cost is estimated at $1.1 billion.

For many researchers, NIF represents a powerful and versatile tool for probing matter under conditions not previously accessible in the laboratory, potentially providing new insights into high-temperature, high-pressure processes such as the reactions that power the sun.

"This presents unique opportunities in astrophysics, in plasma physics, and in materials science," says Richard D. Petrasso of the Plasma Fusion Center at the Massachusetts Institute of Technology.

Getting a fusion reaction started is a bit like trying to ignite wet charcoal. Even after ignition, energy is needed to confine the heated nuclear material and so keep the process going.

For the last few decades, researchers worldwide have been exploring several different methods of heating and compressing nuclear fuel to create the necessary conditions for fusion. Up to now, most attention has focused on the effort to use magnetically confined plasmas of charged particles in large, doughnut-shaped reactors called tokamaks (SN: 6/11/94, p. 381).

Now, national security concerns have sparked new interest in an alternative method. Called inertial confinement fusion, this approach involves shooting lasers or beams of particles at a pea-sized spherical target. The target typically consists of a vapor of heavy hydrogen isotopes (tritium and deuterium) encased in plastic.

At Livermore, researchers have used short, powerful pulses of ultraviolet light from the Nova laser to initiate fusion in small capsules (SN: 11/5/94, p. 303). The beams rapidly heat the surface of a fuel capsule to form an envelope of plasma. As this heated material explosively vaporizes and blows outward, it drives the rest of the fuel inward, where it reaches a density 20 times that of lead and a temperature of about 100 million kelvins at its core. Deuterium and tritium nuclei fuse, releasing energy, which heats and compresses more fuel. The reaction quickly propagates outward into the cooler regions of the imploded capsule.

The biggest challenge is to reach ignition—the point at which the heat generated by the fuel exceeds the energy supplied by laser beams or some other external source.

The goal of the NIF project is to achieve ignition and significant energy gain for the first time in inertial confinement fusion. Current plans call for a laser system of 192 beams housed in a building the size of a football stadium. In the target area, the set of ultraviolet light pulses, each lasting about 3 billionths of second, would jolt fuel capsules with a total of 1.8 megajoules of energy. That's about how much energy it takes to brew a few cups of coffee, but it's delivered in such a short time that the power momentarily reaches 500 trillion watts—about 1,000 times the total electric generating capacity of the United States.

If NIF is completed in 2002, as scheduled, experiments could lead to ignition by 2005, Hogan says.

The facility is a key element of DOE's Stockpile Stewardship and Management Program. This program takes on new importance with the recent adoption of the Comprehensive Test Ban Treaty by the members of the United Nations General Assembly (SN: 9/21/96, p. 183).

In keeping with the treaty, "nuclear explosive testing will no longer be a permissible method of scientific inquiry," John D. Holum, director of the U.S. Arms Control and Disarmament Agency, remarked earlier this year at an American Physical Society meeting in Indianapolis. It will limit the ability to further refine knowledge about how nuclear weapons work, he said.

The stewardship program represents a focused, multifaceted effort to understand, evaluate, and maintain the stockpile of nuclear weapons without further explosive testing.

"The full stockpile program is expensive, but it is a necessary and prudent use of our fiscal and intellectual resources," Holum argued. "So long as the United States relies on its nuclear deterrent, the safety and reliability of our stockpile cannot be compromised."

Data from NIF experiments on the behavior of materials and plasmas under the conditions typical of a nuclear explosion would provide information necessary for improving large computer simulations devoted to modeling the performance and effectiveness of nuclear weapons. Such refinements would enable scientists and engineers to identify potential problems in aging nuclear weapons and to aid interpretation of data from past underground tests. Over the years, the United States has conducted more than 1,000 such tests.

The NIF "would give us practical experience in an otherwise unreachable regime of temperature, pressure, and confinement, giving us, in principle, confidence in the computer simulations," says MIT's Henry W. Kendall, who heads the Union of Concerned Scientists board of directors.

Some critics charge that the stewardship program and facilities such as NIF would serve as a training ground for weapons scientists and might represent a covert way of designing new nuclear weapons. Officials of the Western States Legal Foundation in Oakland, Calif., argue that the science-based stockpile stewardship program, as now formulated, would have serious repercussions for nuclear nonproliferation and could lead nations like Russia and China to resist progress toward disarmament.

Late last year, DOE's Office of Arms Control and Nonproliferation released a study that describes ways in which DOE can manage NIF so that it doesn't contribute to nuclear proliferation. A major suggestion was that it operate the facility in the most open manner possible.

A large proportion—perhaps 80 percent—of the research conducted at NIF is to be unclassified, opening up opportunities for a wide range of scientific investigations. Groups of physicists and other researchers are already developing plans for exploiting the high temperatures and pressures potentially achievable at NIF.

"You could, for example, get densities six times greater than the density at the sun's core," Petrasso notes. "These are conditions we've never been able to generate before."

Because it's difficult to measure what's happening inside stars, for instance, astrophysicists are looking forward to generating in the laboratory the conditions necessary to study the formation of elements, the fluid instabilities that occur when a star explodes as a supernova, and the physics of solar flares, when huge masses of hot plasma erupt from the sun.

Such studies would provide details of how the density and temperature of stellar material are related to its pressure and energy. They would also reveal the rates of the various nuclear reactions that power the sun and other stars.

Furthermore, researchers intend to use NIF to explore the motion of fluids under the extreme conditions possible during star formation and other processes that create huge shock waves in the gases and other material permeating galaxies.

The planning and construction of NIF are also expected to fuel a variety of scientific advances, such as the development of advanced, high-energy lasers and means of converting this laser energy into X rays and other forms of radiation.

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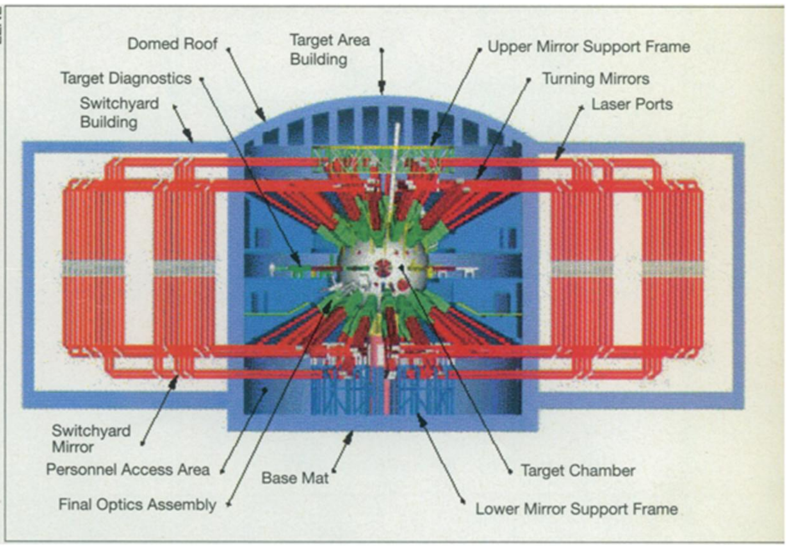

A cutaway view of the target area at the proposed National Ignition Facility. Laser beams focus energy on a fuel capsule located at the chamber's center.

Researchers are already using laser facilities to demonstrate techniques potentially applicable to NIF and to make measurements useful for checking computer simulations of plasma and astrophysical phenomena.

In the Sept. 23 PHYSICAL REVIEW LETTERS, Petrasso and his coworkers propose a new diagnostic method to measure the density and distribution of hot matter during a capsule implosion that triggers ignition. Their technique hinges on detecting high-energy protons generated in a process that starts with the fusion of deuterium and tritium nuclei to create helium nuclei (alpha particles) and neutrons. The resulting neutrons occasionally collide with deuterium nuclei to boost their energy, and these nuclei, in turn, can combine with helium-3 nuclei to spawn alpha particles and high-energy protons.

"These protons are sufficiently energetic that they blast right through the compressed material," Petrasso says.

By measuring the numbers, energies, and directions of escaping protons, researchers can deduce the density and distribution of matter at the core of an imploding fuel capsule, he contends. Such a proton detection technique could be used for probing experiments at Omega, the world's most powerful ultraviolet laser, which recently went into operation at the University of Rochester (N.Y.) Laboratory for Laser Energetics (SN: 6/24/95, p. 394).

Although many scientists eagerly anticipate NIF, a few have questioned the coupling of a defense weapons program with open research. Others have wondered whether the investment in inertial confinement fusion is worthwhile in the general scheme of developing alternative energy sources.

At the same time, not all weapons experts and military personnel are convinced that computer simulations can adequately represent what happens during something as complex as the explosion of a nuclear warhead.

Both NIF's defense-related components and its research aspects, however, intrigue scientists in "a whole group of different communities," Kendall says. "The pure physics aspects are quite tantalizing."

In a May letter to Rep. Ronald V. Dellums (D–Calif.), Kendall, Hans A. Bethe of Cornell University, and Herbert F. York of the University California, San Diego argued that NIF is important not only to the stewardship program but also to fusion energy and basic science. They wrote, "Such opportunities will help attract and maintain the scientific and technical talent that the nation will need in the future as we continue all aspects of the program to reduce the worldwide nuclear threat." □