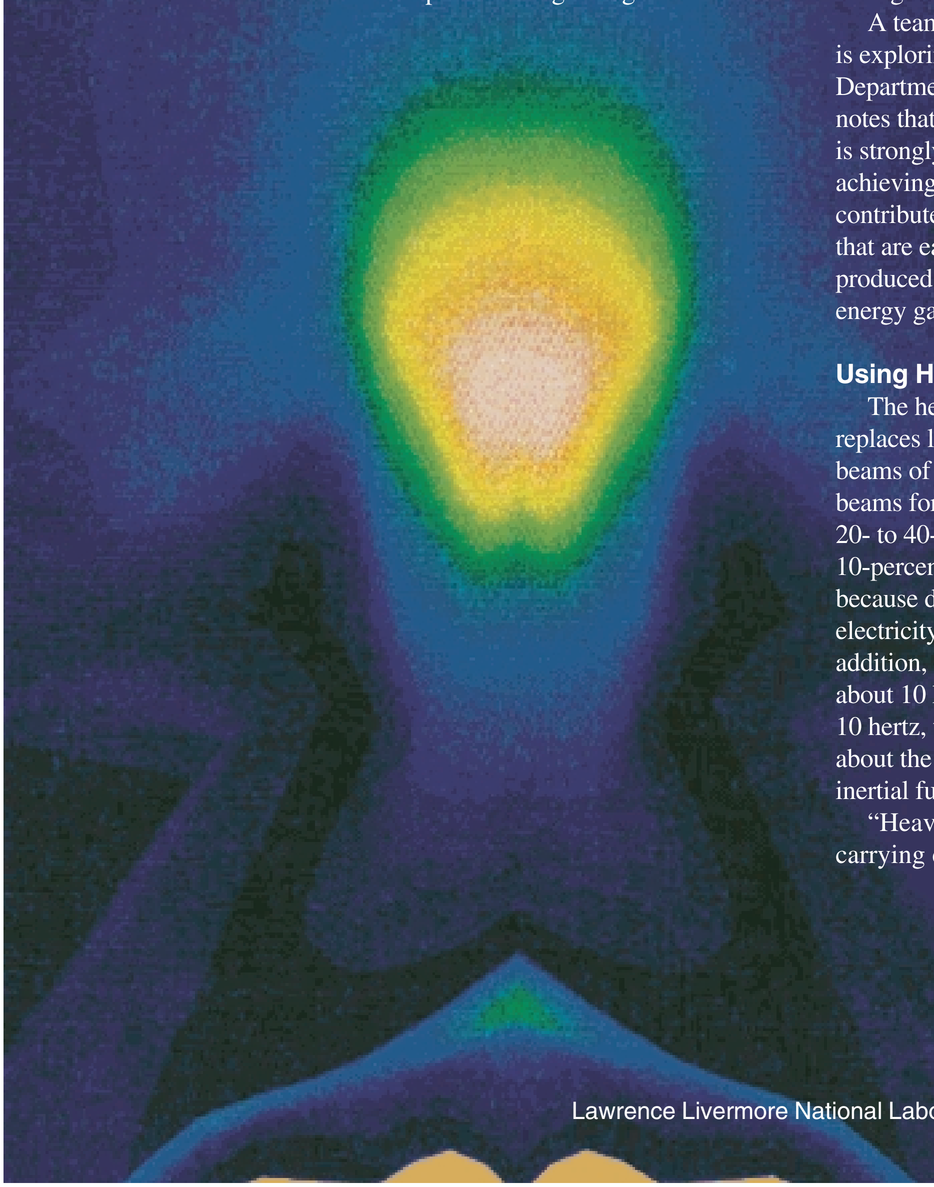
New Targets for Inertial Fusion

A central goal of fusion energy research is to develop the technology and firm scientific understanding to warrant construction of an electric power plant. One route to commercial fusion energy is inertial fusion, and a leading means of creating inertial fusion is with high-energy lasers. In this technique, laser pulses either directly compress a BB-sized capsule, or target, of fusion fuel (deuterium and tritium ions), causing the fuel to ignite; or the pulses are converted first into x rays inside a metal case, called a hohlraum, that contains the fuel capsule, and the x rays compress the capsule, leading to ignition of the fuel. The first method is called direct drive, and the second is termed indirect drive. In both methods, the goal is to have the fuel maintain compression long enough for its deuterium and tritium nuclei to fuse and liberate more energy than is required to drive the reaction. The ratio of energy in to energy out is called gain. The energy produced will be used to boil water to drive the electric turbines of a commercial power plant.



In practice, however, achieving inertial fusion requires enormous energy delivered uniformly to the capsule. For years, scientists have explored ways to achieve inertial fusion that reduced the cost and are compatible with a power plant. Two concepts—heavy-ion fusion and fast ignition—are being explored by Lawrence Livermore physicists and collaborators as attractive candidates for producing commercial electricity through fusion.

A team of Lawrence Livermore physicists led by Max Tabak is exploring target designs for both concepts as part of the Department of Energy's Inertial Fusion Energy Program. Tabak notes that the feasibility of an inertial fusion energy power plant is strongly affected by the requirements of the target for achieving ignition and high gain. "We want targets that will contribute to lower system costs," he says. That means targets that are easy to fabricate, that minimize environmental hazards produced during the fusion reaction, and that permit higher energy gains.

Using Heavy Ions Instead of Photons

The heavy-ion-fusion concept, first discussed in 1975, replaces lasers with induction accelerators that produce intense beams of heavy ions such as lead. Accelerators that produce ion beams for high-energy physics research have demonstrated 20- to 40-percent operating efficiency, as opposed to the 5- to 10-percent efficiency of lasers. The difference is important because driver efficiency determines how much of the electricity produced must be fed back to power the driver. In addition, scientists have ample experience using accelerators at about 10 hertz (repetitions per second). Scientists believe that 10 hertz, the approximate firing rate of a car engine at idle, is about the rate at which an accelerator would need to fire at an inertial fusion power plant.

"Heavy-ion beams are potentially a better means of carrying energy and power to a target than are the photons of a laser," Tabak says. Heavy ions are preferable to light ions because their current would be tens of kiloamperes lower. Lower beam currents make focusing the beam, done with magnetic fields, easier. In contrast, beams of protons, the lightest ions, would generate enormous currents that would be more difficult to focus.

However, scientists are unsure whether powerful ion beams could be focused easily onto targets. The problem is that unlike photons, which are electrically neutral, ions "feel" their electrical charge and, as a result, tend to move away from each other. This self-repulsion could make precise focusing difficult. "Heavy-ion beams present major scientific challenges," says Tabak, "but many experts believe they are surmountable."

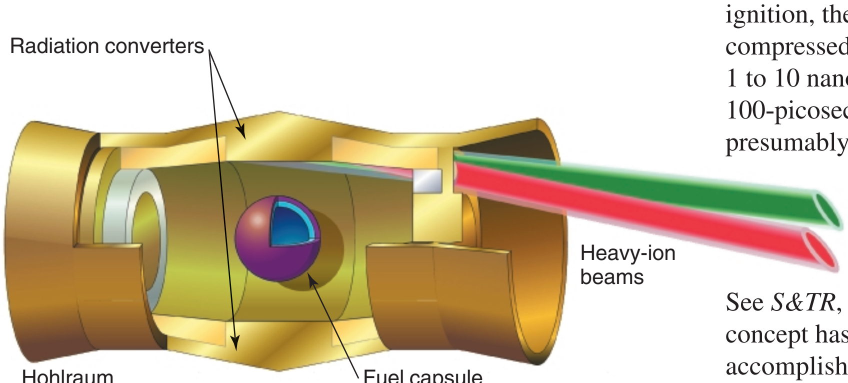
The team is working on a broad range of target designs to satisfy both accelerator builders, who want designs that best couple the ion energy to the fusion fuel, and target builders, who desire designs that are cost-effective and easy to mass-produce. "We're giving both groups a lot of options," says Tabak.

And the Leading Candidates Are . . .

The leading target candidates are so-called distributed radiator targets in which a metal hohlraum contains carefully located radiation converters to stop the ion beam and symmetrically convert its energy into x rays that compress and ignite a plastic fuel-filled capsule. One variant is a close-coupled target, designed by Lawrence Livermore physicist Debra Callahan-Miller, that features a smaller hohlraum. This design permits halving the heavy-ion beam energy required to obtain fusion. However, the close-coupled target also requires a smaller beam focal spot than conventional distributed radiator targets. Simulations using Livermore's LASNEX code show gains of 130 (energy liberated by the fusion reaction divided by energy put into the target) at 3.3 megajoules of ion beam energy and 90 at 1.75 megajoules of ion beam energy.

Another option is a hybrid design by Callahan-Miller that features a thick metal shield to block the path of the heavy-ion beam. The energy deposited behind the shield radiates through the hohlraum to the capsule. Because this design alone does not produce adequate symmetry of the fuel capsule, iron radiation shims are used to remove the last 1 to 2 percent of asymmetry.

The team's heavy-ion target designs are part of a wider effort of the Lawrence Livermore Heavy Ion Fusion group that is working to understand better the physics of intense ion beams and their interactions with fusion targets. The group is a part of a national inertial fusion effort that includes fusion researchers at Lawrence Berkeley and Sandia national laboratories, Princeton Plasma Physics Laboratory, General Atomics, Massachusetts Institute of Technology, and other centers.



The leading target design for heavy-ion-beam fusion are so-called distributed radiator targets in which a metal hohlraum contains radiation converters to stop the ion beam and symmetrically convert its energy into x rays that compress and ignite a plastic capsule containing fusion fuel.

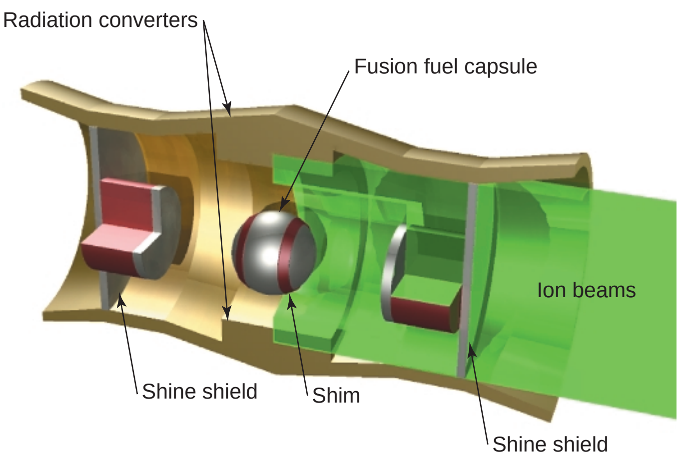
Fast Ignition Adds Second Driver

Fast ignition was conceived by Tabak and other researchers in 1990. Since publication of the first paper in 1994, research on the concept has spread from Livermore to other national laboratories and to research centers in Europe, Japan, and Russia.

Fast ignition can be used with laser-driven direct or indirect drive, greatly relaxing the efficiency requirement on the driver and providing an attractive pathway to fusion energy. In fast ignition, the capsule's deuterium–tritium fuel is first compressed to high density by a standard laser pulse lasting 1 to 10 nanoseconds. Then, an extremely short, 10- to 100-picosecond, high-intensity pulse from a second laser, presumably a petawatt laser, ignites the fuel's dense plasma core with enormous currents (1 billion amperes) of super-hot electrons. (The first petawatt laser was developed by Lawrence Livermore researchers in the mid-1990s to test the fast ignition concept. See *S&TR*, March 2000, pp. 4–12.) A hybrid fast-ignition concept has been explored in which target compression is accomplished with an ion beam and ignition is achieved with a petawatt laser.

Fast ignition offers the prospect of significantly reduced driver energy and the compression symmetry needed to achieve ignition. For example, various models show that the required energy of the compression beams could be reduced from 3 to 5 megajoules to less than 1 megajoule. Even with the added cost of the ignition laser, such relaxed driver requirements might provide capital cost savings of 30 to 40 percent for a fusion power plant. Tabak says that fast ignition should also allow lower target-fabrication-finish requirements.

The Livermore team has also explored several different target geometries for fast ignition. Tabak notes that fast ignition may not need a hohlraum. The overriding design requirement is to ensure that the energy from the petawatt laser couples efficiently to the ignition region of the compressed fuel.



A hybrid design for heavy-ion beam fusion features a thick metal shield that blocks the path of the heavy-ion beam. The energy deposited behind the shield radiates through the hohlraum to compress the capsule of fusion fuel. Iron radiation shims are used to enhance symmetry of the fuel's compression.

One novel design features a gold cone attached to the spherical shell enclosing the deuterium–tritium fuel. The cone penetrates almost to the center of the capsule. In this way, the petawatt pulse has direct access to the ignition region. "The cone provides a clear path for the petawatt laser so that its energy can be deposited within about 100 micrometers or less of the high-density core," explains Tabak. The design team is exploring variations in cone designs to reduce the distance between the capsule's ignition region and the apex of the cone.

Fast-ignition simulations, combined with recent experiments in Japan and on the Omega laser at the University of Rochester, continue to show considerable promise for the concept. The experiments on Omega use prototype capsules designed by Lawrence Livermore physicist Steve Hatchett and manufactured by General Atomics. One series of experiments is showing scientists how the presence of a cone on the target affects the compression of fusion fuel.

Livermore target designs continue to evolve as the design team gains insight from experiments, simulations, and advances in the theoretical underpinnings of fast ignition and heavy-ion beams. The team is motivated by the steady progress its work is making toward eventual deployment of a fusion power plant. Whatever inertial fusion method is ultimately selected for commercial development, it will be using minuscule targets that are precisely designed.

—Arnie Heller

Key Words: fast ignition, heavy-ion fusion, hohlraum, inertial fusion energy, laser fusion, Omega laser, petawatt laser.

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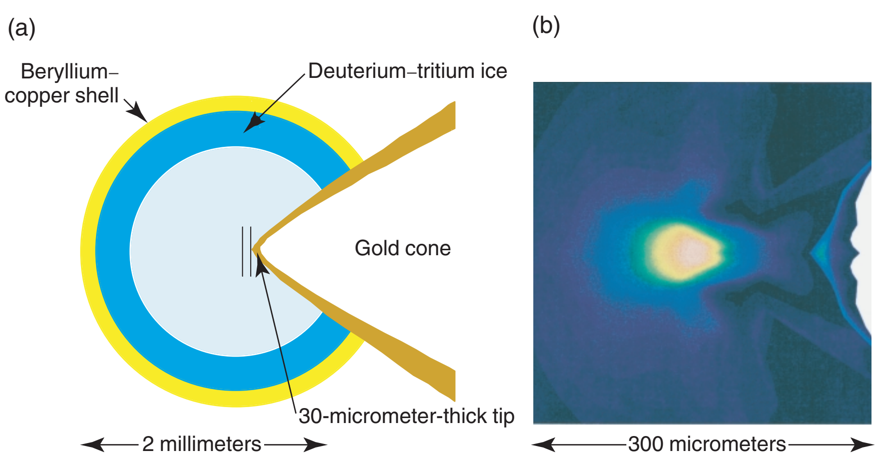

(a) In this design for a fast-ignition target, a gold cone is attached to the beryllium–copper spherical shell enclosing deuterium–tritium fusion fuel. The cone penetrates almost to the center of the capsule to allow a petawatt laser to directly deposit its energy to the compressed fuel. (b) A computer simulation of the target fuel being ignited by a petawatt laser. The fuel has a hollow core and is located about 100 micrometers from the tip of the cone.