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Lightweight Target Generates Bright, Energetic X-Rays

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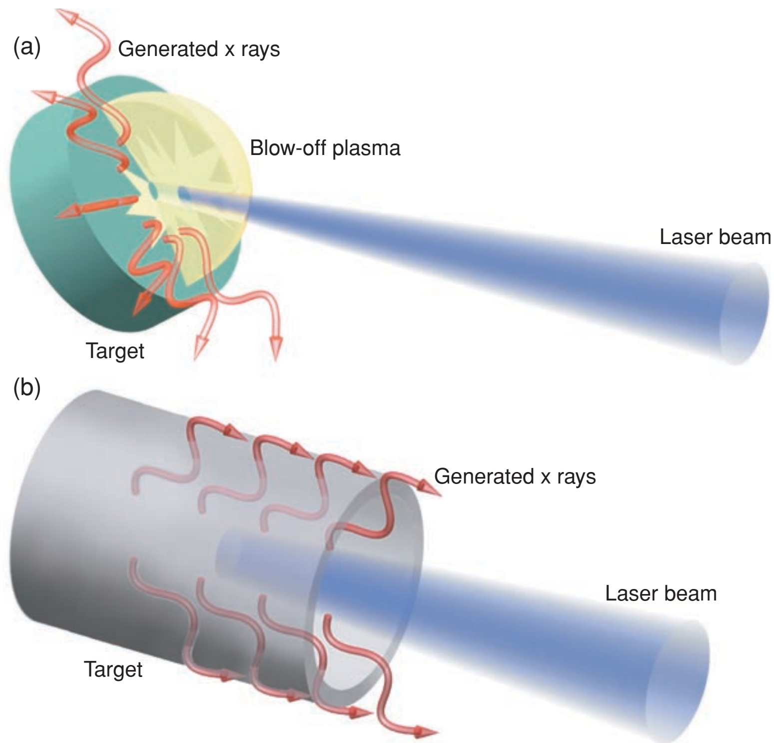

(a) In solid targets, the laser energy is deposited far from the emitting region of the target and in the plasma that is blown off. (b) In underdense targets, the laser beam deposits its energy volumetrically (as a whole), and x-ray emitting atoms are ionized supersonically by a laser bleaching wave.

RADIOGRAPHY with x rays is a long-established method to see inside objects, from human limbs to weapon parts. Livermore scientists have a continuing need for powerful x rays for such applications as backlighting, or illuminating, inertial confinement fusion (ICF) experiments and imaging still or exploding materials for the nation's Stockpile Stewardship Program.

X-radiography is one of the prime diagnostics for ICF experiments because it captures the fine detail needed to determine what happens to nearly microscopic targets when they are compressed by laser light. For example, Livermore scientists participating in the National Ignition Facility's (NIF's) 18-month-long Early Light experimental campaign, which ended in 2004, used x rays to examine hydrodynamic instabilities in jets of plasma. In these experiments, one laser beam irradiated a solid target of titanium, causing it to form a high-temperature plasma that generated x rays of about 4.65 kiloelectronvolts (keV). These x rays backlit a jet of plasma formed when two other laser beams hit a plastic ablator and sent a shock to an aluminum washer.

Livermore physicist Kevin Fournier of the Physics and Advanced Technologies Directorate leads a team that is working to increase the efficiency of converting laser energy into x rays so the resulting images provide more information about the object being illuminated. The main characteristics of x-ray sources are energy and brightness. "As experimental targets get larger and as compression of the targets increases, the backlighter sources must be brighter and more energetic," says Fournier. The more energetic the x rays, the further they penetrate an object. The brighter the source—that is, the more photons it has—the clearer the image.

Historically, researchers have used solid targets such as thin metal foils to generate x rays. However, when photon energies are greater than a few kiloelectronvolts, the conversion efficiency of solid targets is only a fraction of 1 percent. Solid targets have low efficiencies because much of the laser energy is deposited far from the target's x-ray emitting region, and the energy is carried by the relatively slow process of thermal conduction.

"The laser beam ablates material from the massive target, and that material moves away from the target's surface," says Fournier. "With a nanosecond pulse or longer, the laser interacts with the blow-off plasma rather than the remaining bulk sample. As a result, much of the laser's energy goes into the kinetic energy of the blow-off material, not into heating the bulk of the foil.

Heating Supersonically

Fournier worked with colleagues in Livermore's ICF Program, which is part of the NIF Programs Directorate, and in the Nonproliferation, Arms Control, and International Security (NAI) Directorate to test gas-filled, thin plastic bags as an alternative to the metal-foil targets. A gas bag is attractive because a laser beam can heat the gas molecules all at once, a process called volumetric heating. X rays are then produced by a so-called laser bleaching wave, in which the laser wave front passes through the gas supersonically.

Materials that interact supersonically with a laser are said to be underdense. "Underdense targets allow the laser to propagate as

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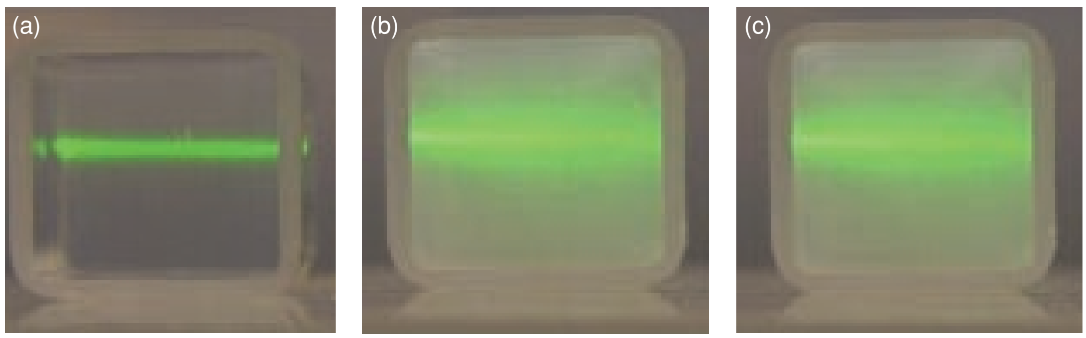
fast as possible to ionize all the gas molecules," says Fournier, "so they generate x rays more efficiently than solid targets can at comparable energies."

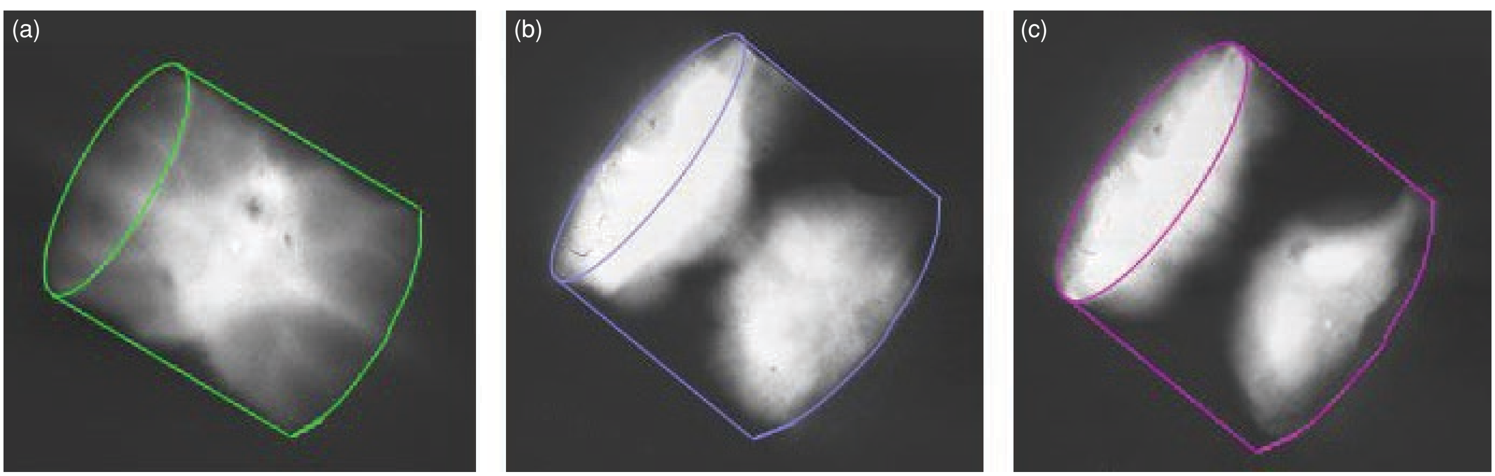
To examine the underdense targets, ICF physicists Christina Back and Carmen Constantin led experiments at the OMEGA laser facility at the University of Rochester's Laboratory for Laser Energetics. The team analyzed x rays produced by gas-filled bags struck simultaneously with 40 of OMEGA's 60 beams. When the bags were filled with krypton, the x rays generated ranged from 1 to 3 keV; with xenon, they ranged from 4 to 7 keV. Although the experiments were successful, gaseous targets have significant disadvantages. For example, gas can leak from the bag; bags can pop if filled too much; and only noble gases such as argon, krypton, and xenon can be used.

As an alternative, Fournier's team began testing aerogels—materials that, unlike gas-filled bags, are solid at room temperature and can be less dense than air. In addition, aerogels are robust materials and have a long shelf life. To develop aerogel targets, the team took advantage of the Laboratory's expertise in solgel chemistry, in which nanometer-sized particles form and then connect with one another to create a three-dimensional solid network in the aerogel. (See *S&TR*, May 2005, pp. 24–26.)

Fournier's team used the HELEN laser at the Atomic Weapons Establishment (AWE) in the United Kingdom to test aerogel targets of silicon dioxide (SiO_2) with a density of 1 milligram per cubic centimeter, about one-third the density of air. The team also used OMEGA to test aerogels with a density of 3.1 milligrams per cubic centimeter, about the same density of air. "Because the aerogel



Livermore scientists are developing lightweight aerogels to use as x-ray sources. Shown here in a 1-centimeter cube of Pyrex and illuminated by a laser pointer are (a) an aerogel doped with 20-percent germanium atoms, (b) an aerogel doped with 3-percent titanium atoms, and (c) a pure germanium dioxide aerogel, which contains 33-percent germanium atoms.



In experiments with the aerogel targets, the Livermore team placed samples in beryllium cylinders and heated them with laser beams. The aerogel samples had densities of (a) 3.1, (b) 4.8, and (c) 6.5 milligrams per cubic centimeter. The lowest density aerogel (a) is heated volumetrically and more uniformly than the other two (b, c).

density is so low, the laser sees the aerogel as a gas, not a solid, so it travels through the material at supersonic speeds," says Fournier.

By themselves, SiO_2 aerogels are poor x-ray radiators. In 2003 and 2004, Fournier worked with scientists from ICF, NAI, and the Chemistry and Materials Science Directorate to introduce a heavy element in a low-density aerogel. The researchers developed a technique to suspend titanium or zinc homogeneously in a SiO_2 aerogel. The titanium-doped SiO_2 aerogel generated 4.7-keV x rays, and the zinc-doped aerogel generated 9-keV x rays. "With this approach, we can theoretically tune the aerogel to produce the x-ray energy we need by substituting one dopant for another," says Fournier.

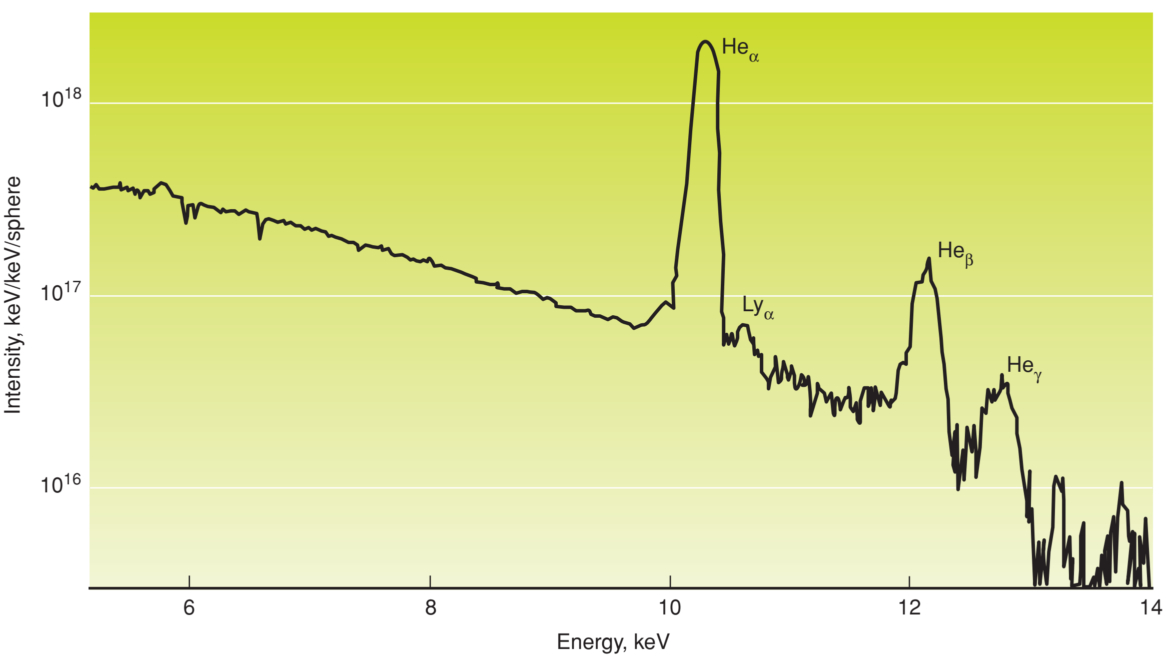
However, dopants affect how an aerogel forms. "If we make the dopant concentration too high, the aerogel can't support it, and the structure collapses," Fournier says. The team successfully introduced 3-percent titanium atoms into a SiO_2 aerogel with a density of about 3 milligrams per cubic centimeter. The titanium remained suspended after the aerogel solvent was removed and stayed uniformly dispersed. The doped aerogel was cast in cylindrical beryllium tubes that had walls 80 micrometers thick and were 2.2 millimeters long, with a 2-millimeter inner diameter.

For tests of the titanium-doped aerogels, the researchers used 40 OMEGA beams with 7 to 14 terawatts of power to illuminate the target's two cylindrical faces. The titanium within the aerogel target converted the blue laser light into 4.7-keV x rays with a conversion efficiency between 1 and 2 percent, performing three to four times better than a titanium foil target and with minimum scattering. The walls allowed 90 to 95 percent of the x rays to pass through, and researchers observed strongly supersonic propagation of the laser bleaching wave.

After the titanium-doped aerogel experiments, the team developed aerogels doped with germanium, which produces x rays at 10.3 keV. Germanium is a better dopant than titanium or zinc because it is chemically similar to silicon. Therefore, germanium atoms can be incorporated directly into the aerogel matrix, resulting in much higher concentrations. In March 2005, the team used OMEGA to successfully shoot germanium silicon dioxide ($[GeSi]O_2$) targets that contained 20-percent germanium atoms at densities of 4.8 and 6.5 milligrams per cubic centimeter. Again, the lower density doped-aerogel targets output significantly more 10.3-keV x rays than similarly irradiated germanium foils. By replacing the silicon atoms with germanium, the Livermore team also made a germanium dioxide (GeO_2) aerogel containing 33-percent germanium. Tests on the GeO_2 targets will be conducted in the near future.

Testing for X-Ray Effects

Another important application for doped aerogels is in radiation-effects testing. Military experts are interested in such testing to determine how x rays may affect different components of a ballistic



This x-ray spectrum shows results from radiation-effects tests using a germanium silicon dioxide target (keV = kiloelectronvolts). The three heliumlike lines (He_α, He_β, and He_γ) were generated by germanium ions with all but two electrons stripped by the laser energy. The Lyman-series (Ly) lines were produced by germanium ions with all but one electron stripped.

missile defense system. For example, an intercept of a nuclear-tipped missile might inadvertently trigger a high-altitude detonation. Such a detonation would generate x rays that might damage space- and Earth-based structures, optics, and electronics. "The radiation threats to a ballistic missile defense system create stringent hardness requirements because the systems must operate in especially stressful environments," says Fournier. "We need adequate simulators to validate the systems under these different scenarios.

Typically, scientists conduct radiation-effects tests using pulsed-power facilities such as the Z-pinch accelerator at Sandia National Laboratories in Albuquerque, New Mexico. Pulsed-power machines generate substantial debris, which increases costs. "Our radiation-effects testing with a laser produced fewer x rays than the Z-pinch but with no debris," says Fournier. "It's a complementary technology to pulsed-power testing."

To determine the effectiveness of $(GeSi)O_2$ aerogel targets in radiation-effects tests, Fournier and his collaborators from Sandia, AWE, and Ktech Corporation used 40 OMEGA beams with nearly 20 terawatts of laser power. As part of the experiments, they placed different objects close to the doped aerogel and measured each object's response to the generated x rays. They obtained an average spectral energy of 7 keV and a 1- to 1.5-percent conversion efficiency, much better than in tests with solid targets that generate x rays in this energy range. The x rays produced thermomechanical shocks in aluminum plates and induced electrical currents in some test objects.

Much work remains to optimize the low-density, doped aerogels as efficient x-ray sources. In particular, the team looks forward to testing GeO_2 targets and wants to adjust the SiO_2 aerogel formation process to increase the percentage of titanium atoms. More experiments are planned in the quest to make x rays as bright and energetic as possible.

—Arnie Heller

Key Words: aerogels, doped aerogels, HELEN laser, inertial confinement fusion (ICF), National Ignition Facility (NIF), OMEGA laser, radiation-effects tests, x rays, Z-pinch accelerator.

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