

# Using Proton Beams to Create and Probe Plasmas

*Proton beams generated by ultrashort-pulse lasers will help advance our understanding of plasmas.*

**P**ROTONS, the positively charged, subatomic particles discovered by Lord Rutherford nearly 100 years ago, are still surprising scientists. Lawrence Livermore researchers are discovering that proton beams created by powerful, ultrashort pulses of laser light can be used to create and even diagnose plasmas, the superhot state of matter that exists in the cores of stars and in detonating nuclear weapons. The proton-beam experiments promise new techniques for maintaining the nation's nuclear arsenal and for better understanding how stars function.

The proton beams used in the Laboratory's experiments are produced by pulses of laser light lasting only about 100 femtoseconds (a femtosecond is  $10^{-15}$  seconds, or one-quadrillionth of a second) and having a brightness, or irradiance, up to  $5 \times 10^{20}$  watts per square centimeter. When such fleeting pulses are focused onto thin foil targets, as many as 100 billion protons are emitted, with energies up to 25 megaelectronvolts. The protons come from a spot on the foil about 200 micrometers in diameter, and the beam's duration is a few times longer than the laser pulse. The highest-energy protons diverge 1 to 2 degrees from the perpendicular, while the lowest-energy protons form a cone about 20 degrees from perpendicular.

Funded by the Laboratory Directed Research and Development Program, the Livermore experiments are led by physicists Pravesh Patel and Andrew Mackinnon. Patel, who works in the Laboratory's Physics and Advanced

Technologies Directorate, is researching new ways to create and better understand plasmas. Mackinnon, from Livermore's National Ignition Facility (NIF) Programs Directorate, is developing new ways to measure the plasmas created in NIF experiments. Both physicists are collaborating with colleagues from Queen's University in Belfast, Northern Ireland; Heinrich-Heine-Universität in Düsseldorf, Germany; the LULI laser facility at l'Ecole Polytechnique in France; Rutherford Appleton Laboratory in the United Kingdom; and the University of California (UC) at Davis.

"Plasmas are often referred to as the fourth state of matter," says Patel. "They are abundant in the universe but relatively uncommon on Earth. Plasmas are extremely hot, highly transient objects and thus are difficult to control or to accurately probe."

The team wants to develop new methods for creating plasmas in the laboratory, so they can study them at temperatures ranging from a few electronvolts to hundreds of electronvolts and at the high energy densities (more than 100,000 joules

per gram) that exist in stars. The current generation of high-power lasers makes such studies possible because they can compress and heat matter to these extreme states.

Ideally, scientists want to measure plasmas in a uniform-density, single-temperature state. As a material is heated to several electronvolts, the pressure in it increases to more than a million times atmospheric pressure. This increased pressure causes the plasma to expand hydrodynamically, as in a violent explosion. Under these conditions, measuring plasma properties is extremely difficult.

One way to overcome these problems is to use what scientists call isochoric heating—heating at constant volume. With isochoric heating, plasmas don't expand during the time they are heated, and their energy can be relatively uniform. Established methods of isochoric heating, such as laser-driven shock heating, x-ray heating, and ion heating, are relatively fast ( $10^{-6}$  to  $10^{-9}$  seconds), but these timescales are still longer than those during which significant hydrodynamic expansion can occur ( $10^{-11}$  to  $10^{-12}$  seconds).

Another method, direct heating with intense subpicosecond ( $10^{-12}$  seconds) laser pulses, creates a highly nonuniform heating pattern. The laser energy is absorbed within less than 100 nanometers of material, and the heat localization creates a large temperature and density gradient.

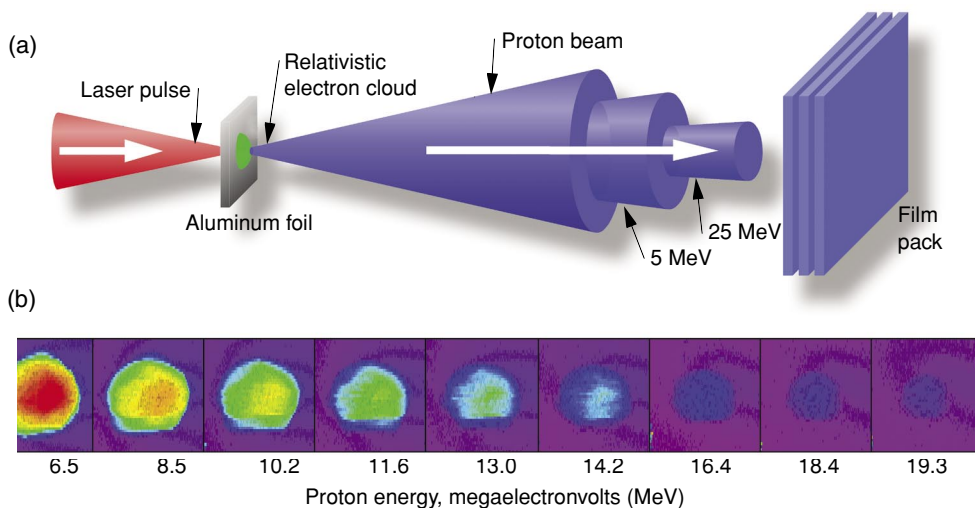
A novel approach to isochoric heating, discovered at Livermore, uses laser-produced proton beams to generate fleeting, dense plasma states at constant volume and density. The heating period is shorter than the time needed for significant hydrodynamic expansion to occur, so the material is heated to a plasma state in a few picoseconds. In effect, says Patel, the proton beam dumps a huge amount of energy almost instantaneously and suddenly increases a target's temperature to millions of degrees.

### JanUSP Makes It Possible

In their experiments, the researchers rely on Livermore's Janus ultrashort-pulse (JanUSP) laser, one of the brightest lasers in the world. (See *S&TR*, May 2000, pp. 25–27.) JanUSP produces a beam with an average intensity of  $5 \times 10^{20}$  watts per square centimeter that lasts about 100 femtoseconds. The laser operates at a wavelength of 800 nanometers and delivers 10 joules of energy.

In one set of experiments, the laser pulse produced a proton beam from a 10-micrometer-thick sheet of aluminum foil. The proton beam then heated a second 10-micrometer-thick aluminum foil that was placed 250 micrometers directly behind the first. Within a few picoseconds, the heating created a 4-electronvolt plasma almost 200 micrometers in diameter—too short for much hydrodynamic expansion to occur.

The discovery that intense, highly directional proton beams could be generated from an ultrashort laser pulse heating a solid target was made by Livermore researchers several years ago while conducting experiments with the Laboratory's Petawatt laser. The Petawatt laser operated on 1 of the 10 beam lines



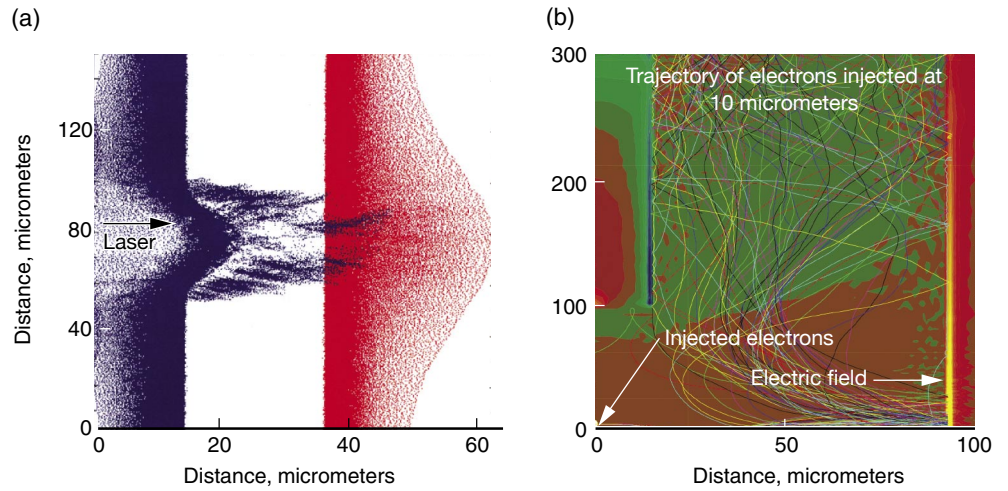
(a) Diagnostic setup for imaging proton beams produced by a 10-joule pulse of laser light that lasts only 100 femtoseconds. The pulse irradiates a thin aluminum foil. The generated protons are then "pulled" from the back side of the foil by electrons traveling close to the speed of light. Protons with the highest energy diverge the least from an angle perpendicular to the back foil surface. (b) Images from a multilayer film pack taken over a broad energy range show that the number of protons decreases with increasing energy.

of Livermore's Nova laser, which was decommissioned in 1999. (See *S&TR*, March 2000, pp. 4–12.) Experiments by Livermore physicist Richard Snavely and others to characterize the proton beams revealed a unique combination of properties, including peak proton energies of 55 megaelectronvolts and conversion efficiencies (of laser energy to proton energy) up to 7 percent.

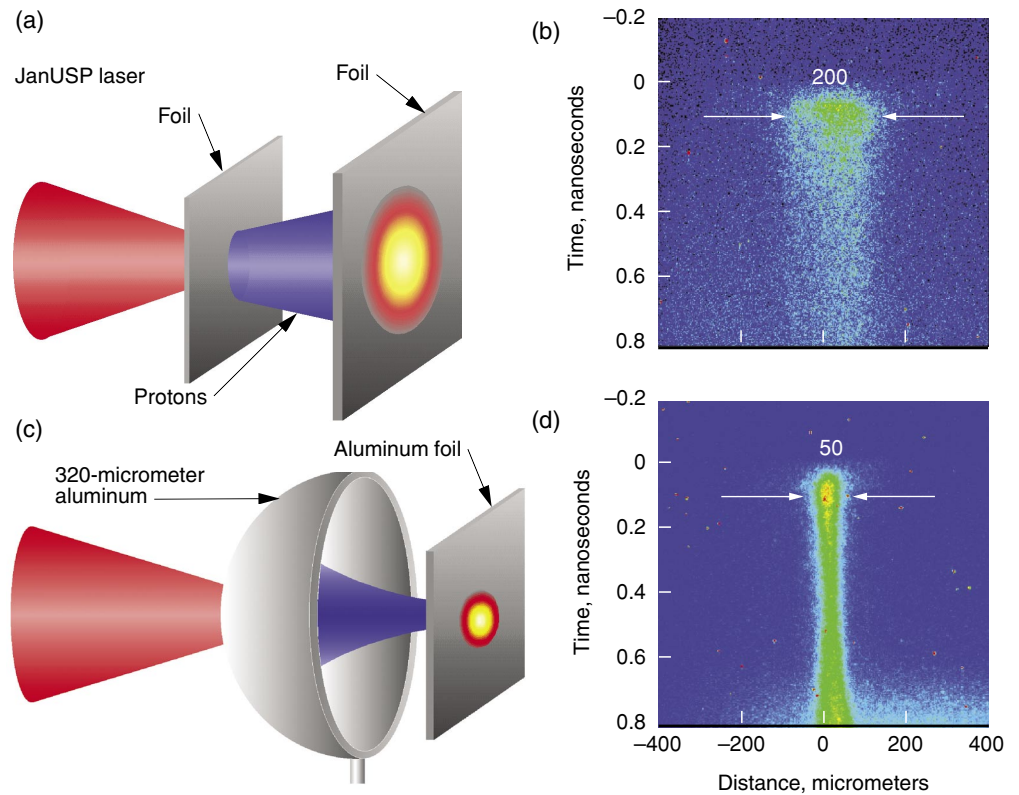
The scientists also discovered that the protons in the beam originated in hydrocarbons found in surface contamination on the foil's back surface. Livermore theoretical physicists, led by Steve Hatchett and Scott Wilks, used computer simulations to study this behavior. They found that the pulse from an ultrashort laser accelerates electrons from the interaction region at the front of the target with relativistic energies; that is, the electrons travel close to the speed of light. The electrons emerging at the foil's rear surface induce a large electrostatic charge field, which in turn accelerates protons from hydrocarbon contaminants on the rear surface. The protons accelerate from 0 to 20 megaelectronvolts at 20 percent the speed of light and travel in a well-defined, highly directional beam perpendicular to the target. X rays, in contrast, are emitted at random angles.

Simulations by Wilks showed that by curving the laser target's rear surface, the proton beam could be focused to a far higher state of energy density. To test this design, the team asked General Atomics in San Diego, California, to manufacture aluminum hemispheres that are 10 micrometers thick, 320 micrometers in diameter, and almost perfectly smooth on the inside to ensure a high-quality proton beam. With the shaped targets, the proton beam was almost 10 times more powerful than the beam produced from flat targets. The proton beam was focused on a 50-micrometer-diameter area of a foil placed behind the target, which was then heated to 23 electronvolts.

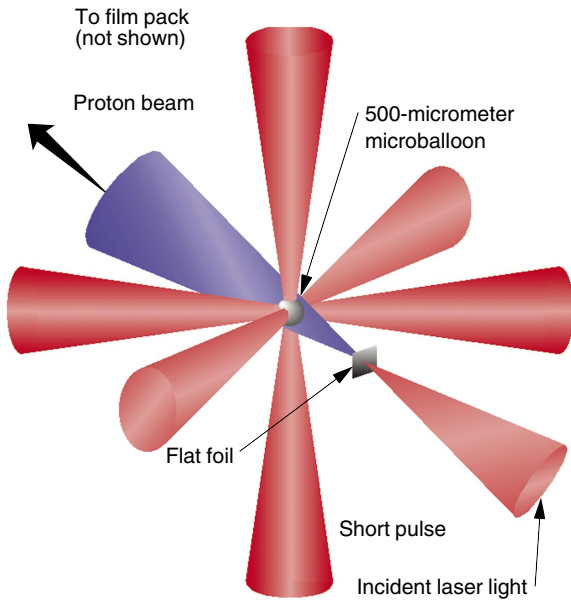
"For the first time, the experiments showed that we can focus proton beams," says Patel. He notes that when the



(a) Particle-in-cell code showing how a thin foil target expands after laser irradiation. (b) Hybrid code calculation of the transport of high-energy electrons through a solid density foil. The calculation shows the complex electron trajectories and large electric fields at the rear surface of the foil that create the protons.



(a) Layout for the proton-beam experiments using the Janus ultrashort-pulse (JanUSP) laser. When JanUSP irradiates an aluminum foil, it creates a proton beam that then heats a second foil. Both foils are 10 micrometers thick, and the second foil is placed 250 micrometers behind the first. (b) The plasma created in the second foil is almost 200 micrometers in diameter. (c) Layout for the experiments with a curved target. (d) When the target's rear surface is curved, the laser produces a focused proton beam that is 50 micrometers in diameter and almost 10 times more powerful than the beam produced with a flat target.



The first proton probing experiments of laser-driven implosions were conducted using the 100-terawatt Vulcan laser system at Rutherford Appleton Laboratory in the United Kingdom. The targets were plastic microballoons, 500 micrometers in diameter. Six beams from the Vulcan laser were focused onto a microballoon while an ultrashort-pulse laser beam was used to make either the diagnostic proton or x-ray beam.

techniques of proton heating and focusing can be applied with more powerful lasers, scientists may be able to isochorically heat plasmas to much higher temperatures and pressures. This advance would provide many opportunities in high-energy-density physics and fusion energy research.

**Using Protons for Radiography**

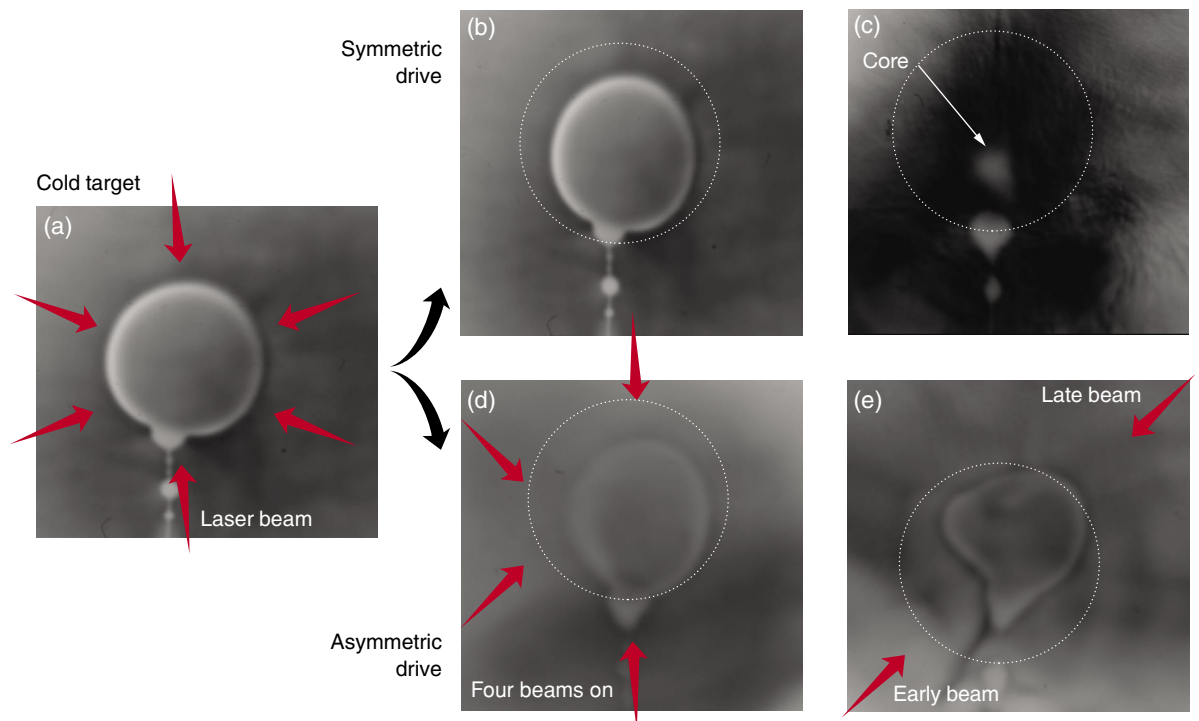
The team is also using proton beams for radiographic applications to diagnose plasma conditions generated by high-power lasers at picosecond timescales. The first proton probing experiments of a laser-driven implosion were conducted by Mackinnon in 2002 using the 100-terawatt Vulcan laser at Rutherford Appleton Laboratory. This experiment was conducted in collaboration with scientists at Queen’s University and UC Davis. “We wanted to investigate the suitability of proton radiographs to diagnose an implosion capsule in inertial confinement fusion experiments,” says Mackinnon.

Plastic microballoons, 500 micrometers in diameter—or about one-fourth the size of the targets planned for NIF—were used as

targets. Each of the Vulcan laser’s six long-pulse beams was fired for 1 nanosecond at a wavelength of 1 micrometer and an irradiance of 10 terawatts per centimeter. Each beam’s energy was 100 to 150 joules, so the maximum energy on the target was up to 900 joules. The six laser beams illuminating the target arrived from six orthogonal directions, a setup designed to provide the best symmetry for this number of beams.

In addition, an ultrashort laser beam was used to make either a diagnostic proton beam of about 7 megaelectronvolts or a diagnostic x-ray beam of about 4.5 kiloelectronvolts. The proton beam was obtained by focusing a 100-joule laser pulse with an irradiance of about  $5 \times 10^{19}$  watts per square centimeter for 1 picosecond onto a tungsten foil 25 micrometers thick. To image the implosion, the team used a multilayer pack of dosimetry film in which each piece of film was filtered by the preceding piece. In this way, the film pack gave a series of images from each shot with an energy ranging from 3 to 15 megaelectronvolts.

Proton radiographs showing the evolution of a laser-driven implosion of a 500-micrometer-diameter balloon: (a) prior to implosion and at (b) 2 nanoseconds and (c) 3 nanoseconds after the laser pulse. When the laser beams are slightly mistimed, the radiographs show asymmetries in the target: (d) Only four beams (shown by red arrows) strike the target, all at 4 nanoseconds after the laser pulse. (e) Beam arrival is staggered from 1 to 5 nanoseconds after the laser pulse.



The team took radiographs of microballoons both before and during implosion. One image, of a 500-micrometer-diameter microballoon with a 7-micrometer wall thickness, showed good contrast at a resolution of 5 to 10 micrometers. A series of radiographs (shown on p. 14), which were taken by varying the delay between the implosion beams and the beam used to produce the proton or x-ray beam, revealed how the implosion process evolved.

In one experiment, the beams were set to converge on the target asymmetrically—that is, the six beams arrived at the target at slightly different times. The laser beams on the left-hand side arrived 1 to 2 nanoseconds before the laser beams on the right-hand side. This asymmetry led to significant distortions. For example, the shell traveled much farther inward on the left-hand side than it did on the right.

Under more symmetric drive conditions, the target remained nearly spherical during the implosion. However, even when the beams arrived at the same time, the proton radiographs revealed some plasma asymmetries. For example, in one experiment, the upper part of the shell traveled almost twice the distance traveled by the lower part of the shell.

These proton radiographs were the first taken of a laser-driven implosion with

picosecond resolution. The team found that the temporal and spatial resolution remained high throughout all stages of the implosion.

“The images show the promise of proton radiography for diagnosing early time distortions in the implosion process with high resolution and very good image contrast,” says Mackinnon. “The x-radiographs also had good resolution, but the image contrast was high only when the density was high.”

According to Mackinnon, proton beams with energies from 50 to 100 megaelectronvolts, produced by an ultrashort-pulse laser, could one day be used to probe the cores of NIF targets as they are compressed by laser light. Lower-energy protons also could be useful, for example, to diagnose electric and magnetic fields inside hohlraums, the metal cases that enclose many NIF targets. More experimental and theoretical work is under way to fully investigate this promising technique.

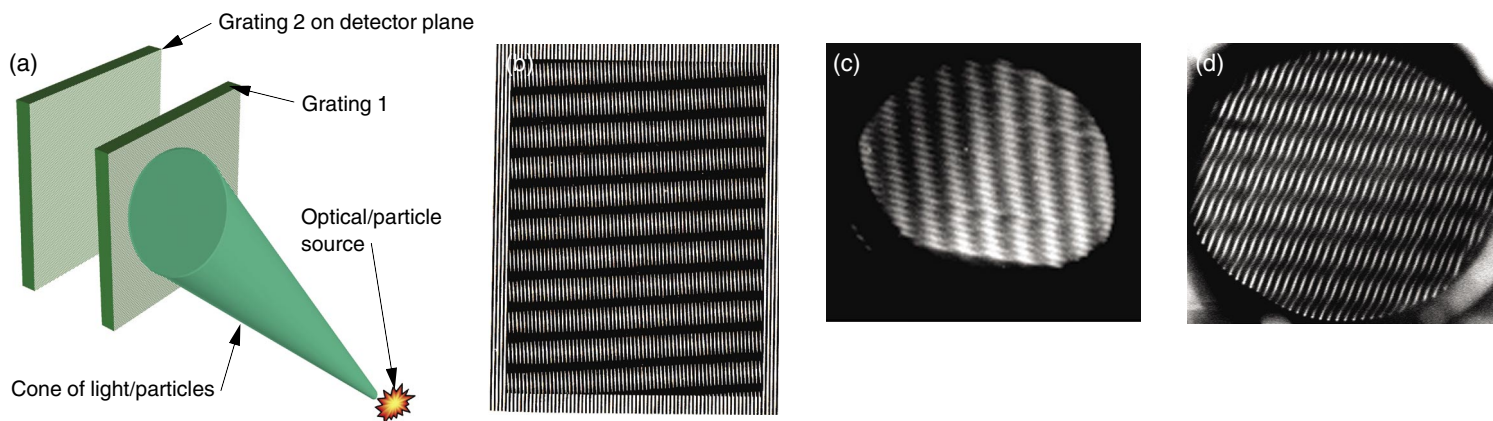
Mackinnon notes that another kind of proton radiography is being studied by researchers at Lawrence Livermore and Los Alamos national laboratories. But the protons created in those studies are much more energetic—about 800 megaelectronvolts. (See *S&TR*, November 2000, pp. 12–18.) That research centers on beams of

extremely high-energy protons focused with magnetic lenses and is designed to image deep inside larger exploding objects.

Livermore physicists Mike Key and Richard Town are also studying whether proton beams, instead of electron beams, can be used to drive fast ignition on NIF. (See *S&TR*, March 2000, p. 4–12.) In fast ignition, at the moment of maximum compression, a laser pulse plows through the plasma to make a path for another very short, high-intensity pulse (presumably, of electrons) to ignite the compressed fuel. In theory, fast ignition reduces both the laser energy and the precision requirements for achieving ignition.

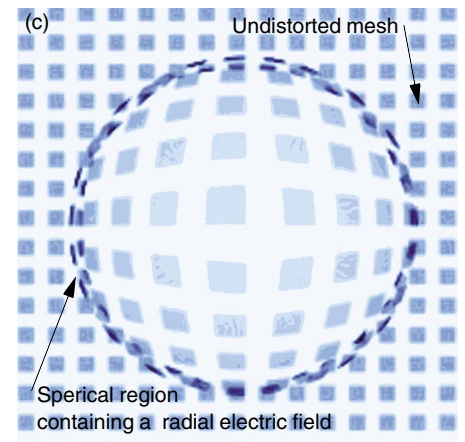
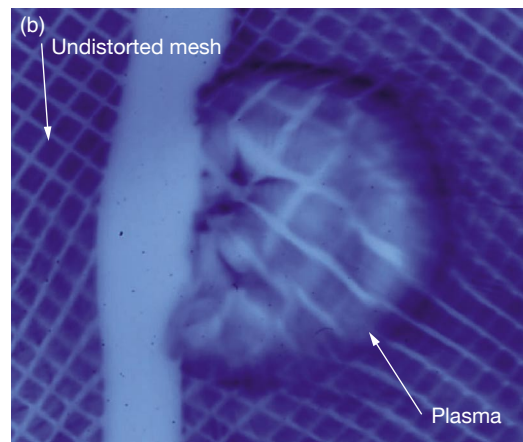
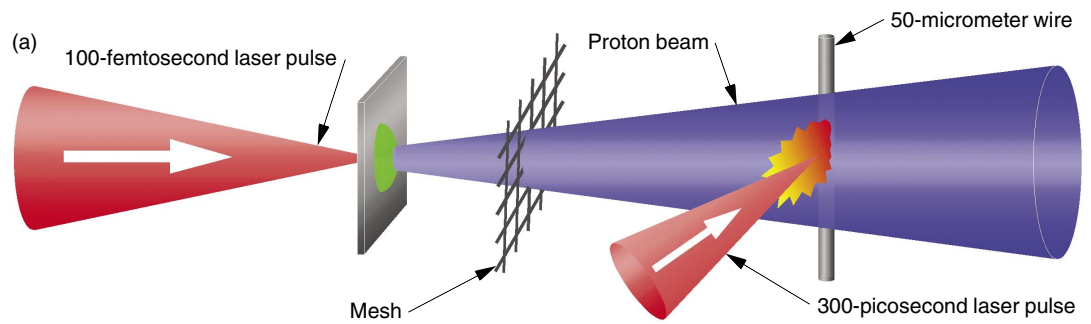
### Field Strength and Geometry

In collaboration with Marco Borghesi from Queen’s University and Oswald Willi and G. Pretzler from Heinrich-Heine-Universität, the Livermore team is investigating another aspect of proton radiography: diagnosing the transient electric and magnetic fields directly through particle-deflection measurements. Unlike x rays, protons are electrically charged, so they interact with electric and magnetic fields in plasmas. Proton probing would provide a new method to visualize and measure fields in laser plasma experiments, which are not well understood.



(a) In one particle-deflection technique for diagnosing the transient electric and magnetic fields, a proton beam passes through two identical gratings. The gratings are separated by a small distance, and their rulings are rotated at slight angles to each other. (b) The proton beam is imprinted with a grating pattern called proton moiré. A proton beam passing through the plasma causes a shift in the moiré pattern, which can be used to infer the strength of the electric and magnetic fields. (c) Proton moiré is similar to (d) the more common optical moiré.

(a) Another particle-deflection technique uses a single grid to subdivide protons into hundreds of small proton beamlets. (b) Proton radiograph of plasma created by a 300-picosecond laser pulse on a 125-micrometer-thick wire shows the plasma magnified and distorted because of the plasma's electric and magnetic fields. The pattern is similar to (c) a hybrid code simulation of protons propagating through a spherical region that contains a radial electric field, which reproduces the essential features of the experiment.



For these experiments, the researchers are using the JanUSP, Vulcan, and LULI lasers. Developing such proton radiography diagnostics supports the Laboratory's stockpile stewardship mission by helping scientists better understand hot, dense plasmas.

In one technique, the proton beam passes through two identical gratings. The gratings are separated by a small distance, and their rulings are rotated at slight angles to each other. In effect, the proton beam is imprinted with a pattern of the gratings, called proton moiré. When the beam passes through the plasma, the electric and magnetic fields

can cause shifts in the moiré pattern. The change in pattern can then be used to infer the strength of the electric and magnetic fields.

A related technique uses a single, two-dimensional grid to subdivide protons into hundreds of small proton beamlets. A hybrid code that simulated proton propagation through a plasma containing a radial electric field essentially reproduced the main features of the experimental observations.

The Livermore team expects protons to complement x rays as a diagnostics tool, not replace them. The team is confident that its pioneering use of

protons to create and diagnose plasmas will advance a host of research projects, both at Livermore and at plasma research centers worldwide.

—Arnie Heller

**Key Words:** Janus ultrashort-pulse (JanUSP) laser, National Ignition Facility (NIF), Petawatt laser, plasma, protons.

**For further information contact Pravesh Patel (925) 423-7450 (patel9@llnl.gov) or Andy Mackinnon (925) 424-2711 (mackinnon2@llnl.gov).**