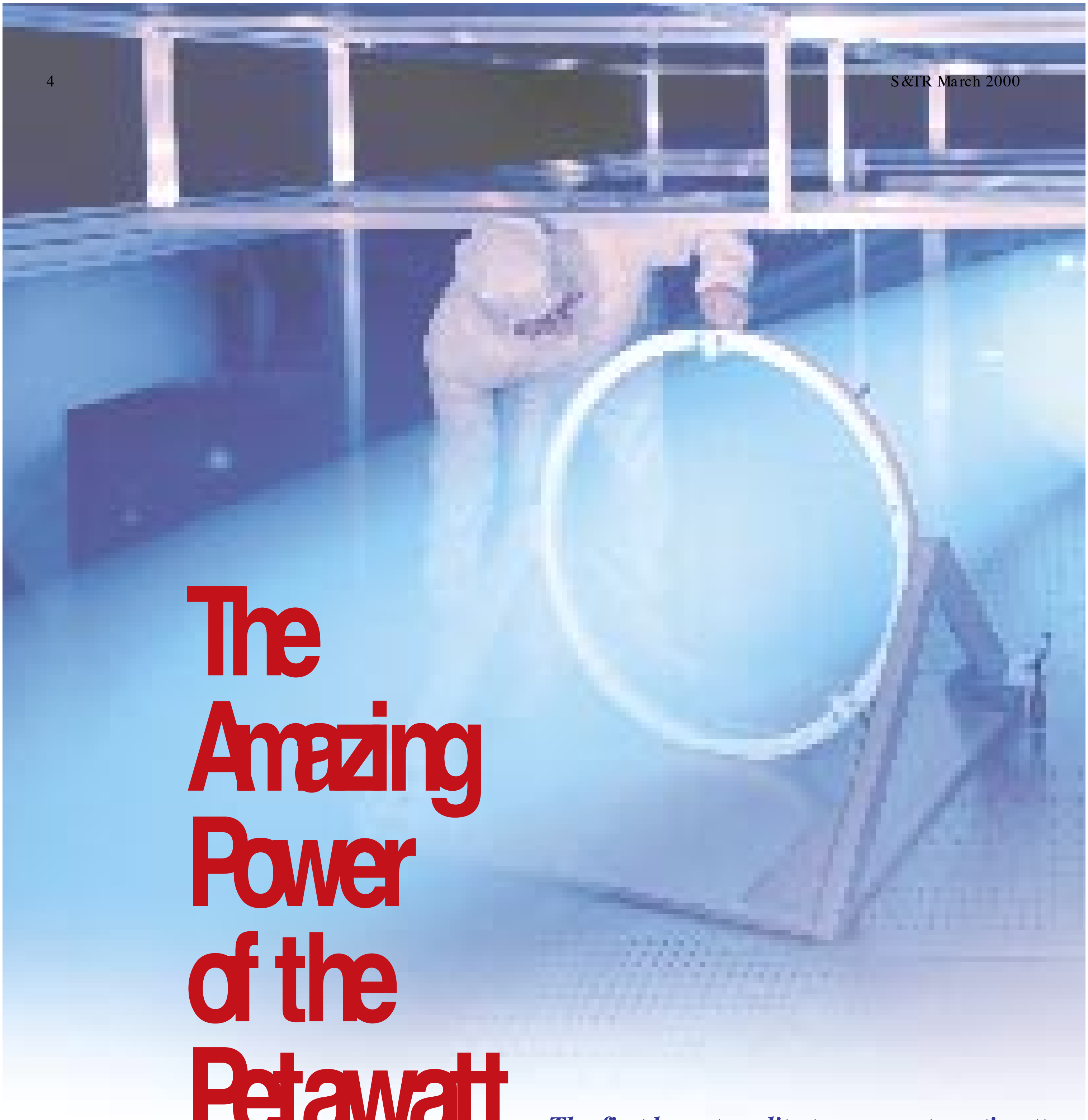


The Amazing Power of the Petawatt

The first laser to split atoms, create antimatter,

THE intense beam of Livermore's Petawatt laser was powerful enough to break up atoms by causing reactions in their nuclei. Accelerated by the laser, electrons traveling at nearly the speed of light collided with nuclei in a gold foil target, producing gamma rays that knocked out some of the neutrons from other gold nuclei and caused the gold to decay into elements such as platinum. Gamma rays also zoomed in on a layer of uranium sitting behind the gold and split uranium nuclei into lighter elements. Before the Petawatt, all of these effects had been solely in the domain of particle accelerators or nuclear reactors.

Accelerated to energies exceeding 100 megaelectronvolts, the electrons in the gold targets produced high-energy x rays. These in turn decayed into pairs of electrons and their antimatter counterparts, positrons, in such large numbers as to possibly generate an electron–positron plasma, never before created in the laboratory. An intense beam of protons also turned up. Not only was the Petawatt the most powerful laser in the world, but, unexpectedly, it also was a powerful ion accelerator.

Livermore's Petawatt laser operated for three years, until its last shot was fired on May 27, 1999. At full energy of about 680 joules, the shots delivered more than a quadrillion watts (or petawatt, which equals 10^{15} watts) of power, exceeding the entire electrical generating capacity of the U.S. by more than 1,200 times. But the Petawatt's shots lasted for just a fleeting moment—less than a trillionth of a second, or 440 femtoseconds to be precise.

and generate an intense, well-focused proton beam—such was the power of the Petawatt.

The Petawatt laser was developed originally to test the fast ignition path to inertial confinement fusion in the ongoing attempt to ignite a pellet of hydrogen fuel and harness the energy that powers the sun. The power of the Petawatt also opened up entirely new physical regimes to study. Now scientists can use lasers, not just particle accelerators, to study high-energy-density physics and the fundamental properties of matter. They may also be able to recreate in the laboratory the energized plasmas around black holes and neutron stars for astrophysical research.

The Petawatt was developed by a team of physicists, engineers, and technicians under the leadership of physicist Michael Perry. Going into the project, the team knew that the ultrashort pulses and extremely high irradiance (power per unit area) of the Petawatt would push electrons almost to light speed with power densities never before seen in the laboratory. The researchers hoped to bring the fast ignitor concept for laser fusion closer to reality and planned to study the Petawatt as an x-ray source for flash x-radiography. But the Petawatt also brought several surprises and unusual spinoffs. Surprises are common enough in physics research, but the Petawatt created more than its fair share.

Just the Latest Record-Breaker

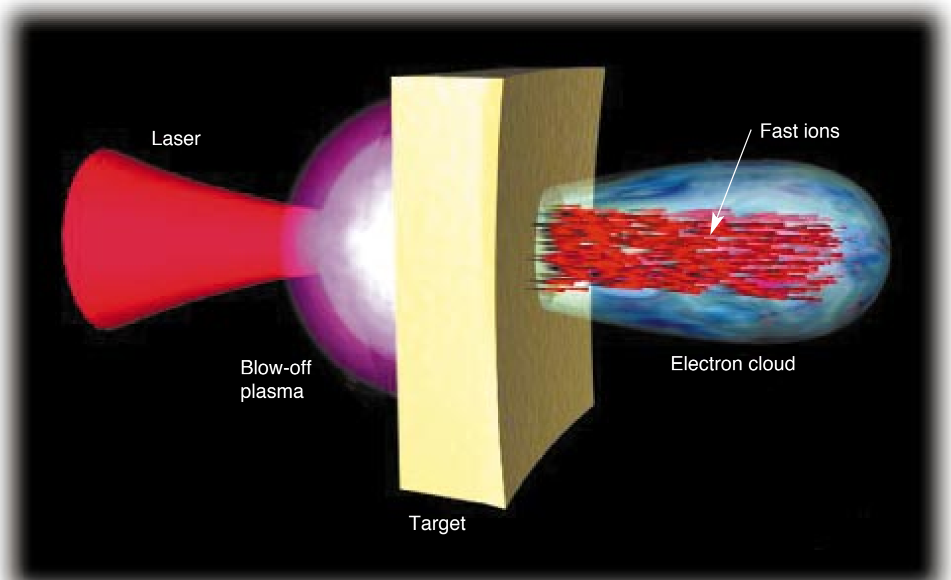
After four years of development, the laser achieved petawatt peak power on May 23, 1996, and became the latest in Livermore's long line of record-breaking lasers, each with greater peak power than its predecessor. Recognized in 1966 as one of the most significant advances in laser technology, the Petawatt operated on one arm of Livermore's 10-beam Nova laser until Nova was dismantled in 1999 to make way for the National Ignition Facility. The Petawatt laser combined the short pulses available from titanium-doped sapphire (Ti:sapphire) lasers and chirped-pulse amplification in the Nova glass laser to create high-powered, extremely short pulses with a peak power more than an order of magnitude greater than Livermore's previous record of 100 terawatts, set in 1995. (See *S&TR*, December 1996, pp. 4–11.)

Without chirped-pulse amplification, laser pulses of extremely high power density (gigawatts per square centimeter) can rapidly self-focus and severely damage such optical components as amplifiers, lenses, and mirrors. The technique of chirped-pulse amplification stretches a low-energy laser pulse by more than 25,000 times in duration prior to amplification and afterward recompresses it to near its original duration. Because the pulse passes through the laser optics when it is long, there is no damage to expensive optics. Pulse recompression takes place in a vacuum because by this time, the laser is too intense to pass through any material (including air) without causing damage.

Crossing the Relativistic Barrier

The Petawatt laser achieved a focused power density approaching 10^{21} W/cm^2 (almost a sextillion watts of energy concentrated on a square centimeter) and an energy density of 30 billion joules in a cubic centimeter—far exceeding the energy density inside stars. The associated electric fields are so strong—approximately a thousand times stronger than those that bind electrons to atomic nuclei—that they strip electrons off atoms and accelerate them to relativistic velocity (that is, comparable to the speed of light). The acceleration happens within a microscopic scale, compared to that in conventional particle accelerators. The enormous electric fields impart huge "quiver" energy to the free electrons in the plasma, which flings some of the electrons out of their oscillation. This then causes laser energy to convert to electron thermal energy, which in turn heats the ions and forms dense, high-temperature plasmas.

When particles are moving at almost the speed of light, strange things happen. In this relativistic regime, the electron's energy exceeds its "rest mass" (that is,



In laboratory experiments, the Petawatt laser's tremendous power produced intense beams of protons, proving the laser to be a powerful ion accelerator.

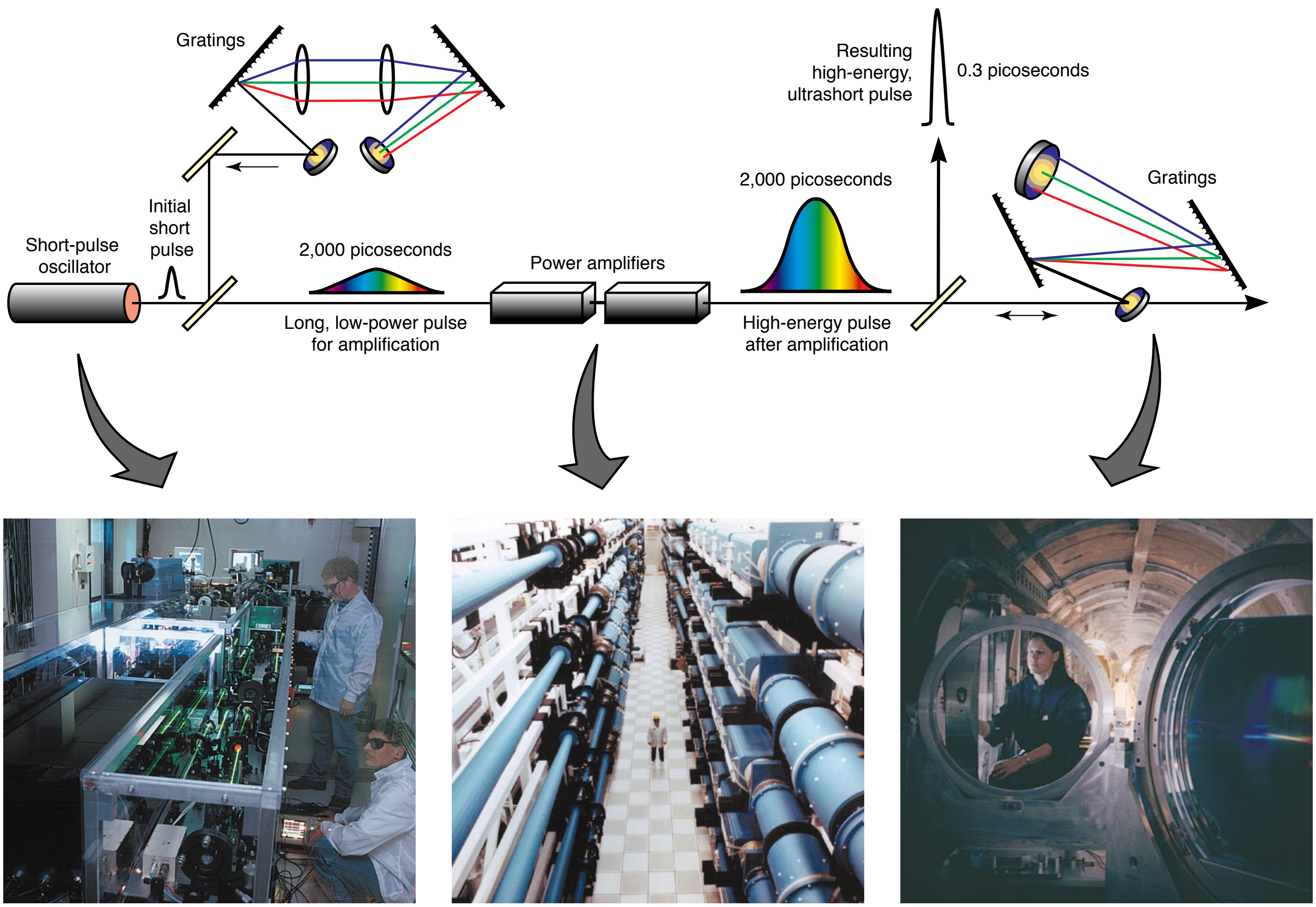
the energy that would be released if it were turned into pure energy, $e = mc^2$). Its mass also increases with increasing speed.

Another feature of the high energy density is the correspondingly high pressure. The light pressure of the Petawatt beam is approximately 30 petapascals, or about 300 billion times greater than Earth's atmospheric pressure at sea level. This huge pressure works like a snow plow, effectively shoving the plasma forward. As a result, the light can penetrate to a density much greater than is possible with normal lasers. The effects of using the light pressure to confine and even shape near-solid-density plasmas may have applications in inertial confinement fusion.

Unexpected Discoveries

Early experiments showed that when the Petawatt's intense beam hit a high-atomic-number target such as gold, very energetic electrons were produced. The energies were as high as 100 megaelectronvolts, with average energies ranging from 1 to 10 megaelectronvolts. Petawatt research first examined the characteristics of these relativistic electrons, which had never before been seen in such huge numbers in laser experiments.

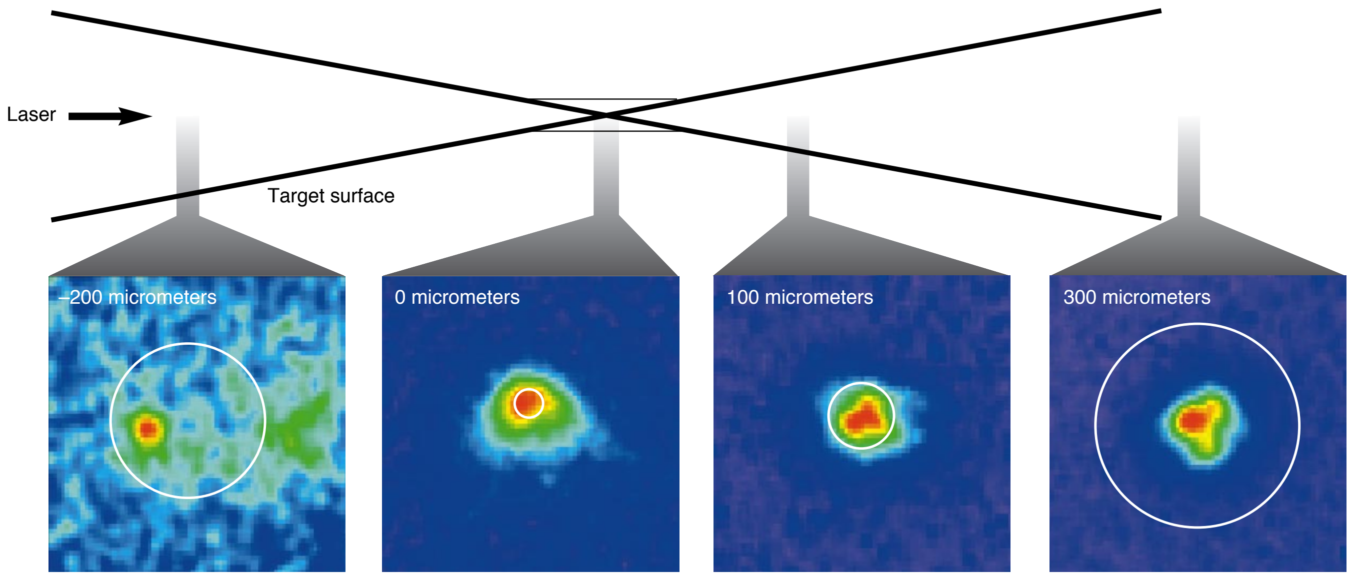
To determine the electron energies, two electron spectrometers were mounted at angles to the target. Each one used magnets to separate electrons



The chirped-pulse amplification technique makes it possible for the Petawatt laser's high-power pulses to pass through laser optics without damaging them. Before amplification, low-energy laser pulses are passed through diffraction gratings to stretch their duration by as much as 25,000 times. After amplification, the pulses are recompressed back to near their original duration. Because the pulses pass through the laser optics when they are long, they cause no damage.

and positrons. Each also incorporated a pair of nuclear emulsion track detectors to record the tracks of each charged particle. The particle tracks were counted by a group at the NASA Marshall Space Flight Center in Huntsville, Alabama, which routinely monitors high-energy radiation from space.

Electron energies greater than about 2 megaelectronvolts produce gamma rays that can be transformed into pairs of electrons and positrons (pair production). But using some very thin gold targets, physicist Tom Cowan and others found more positrons than expected, which may indicate that they had created an electron–positron plasma. In these extraordinarily high-



The Petawatt beam undergoes relativistic self-focusing, seen here in x-ray images of the target in which a heated region is made smaller than the optical focal spot (white circles) when the target is 300 micrometers beyond the focal spot.

The Laser Cutting Revolution

A primary spinoff from the Petawatt laser has been the development of ultrashort-pulse lasers for high-precision laser cutting and machining. Brent Stuart and others first observed the laser's cutting capabilities during early research on the laser damage threshold for a variety of optical materials. Using laser pulses ranging from 0.1 to 1,000 picoseconds, they observed a fundamental change in the damage mechanism when the pulse length is less than about 20 picoseconds. The ultrashort pulses are too brief to transfer heat or shock to the material being cut, so cutting, drilling, and machining can occur with virtually no damage to surrounding material.

This discovery was put into practical use in developing the first femtosecond laser cutter for use as a precision cutting tool in dismantling weapons at DOE's Y-12 Plant. For Livermore's High Explosives Application Facility, Stuart and his team developed a second-generation system that can cut high explosives without deflagration or detonation. Third-generation ultrashort-pulse machine tools are now being developed at Livermore for a variety of high-precision machining and medical applications.

The laser can also be used to produce high-quality thin films by using the laser to ablate (blow off) material. The high-energy plasma generated during ablation enables the deposition of smooth films containing no particulates.

When the laser is attached to a spectrometer, the operator can identify what material is being cut by watching the changing spectra. A surgeon could thus carefully differentiate between bone and muscle, which have very different spectra. This differentiation could also be useful in paleontology excavations for cutting away rock without damaging bones embedded in them.

energy plasmas, which are believed to exist near black holes and neutron stars, positrons are continually being created as particles collide with one another. Next-generation petawatt-class lasers producing even higher irradiance than the Petawatt should be able to create these antimatter plasmas in the laboratory, providing a new tool for astrophysical research.

To study the angular pattern of the beam of electrons, one researcher installed a conical assembly behind the target. Tantalum of varying thicknesses was layered together with radiochromic film, which recorded the angular pattern of relativistic electrons escaping a variety of targets. The figure below shows the results of a typical experiment using a 125-micrometer-thick gold target.

Researchers were puzzled by the dark spot that is visible in the figure. They first took it to be a particularly well-focused part of the electron beam. At the same time, a radiation physicist began observing a large number of defects in a type of plastic (Cr-39) used to detect particles, which could only have been induced by high-energy protons. At this point, experimental team leader Mike Key reanalyzed the radiochromic pictures and showed that the beam could be explained as a proton beam. Several specific tests were devised to confirm this hypothesis.

Conclusive evidence that this beam was composed of protons was obtained from a series of nuclear chemistry experiments. The experimental team used a multilayer detector of titanium and beryllium and radiochromic film to observe the nuclear reactions induced in both the titanium and the beryllium, which could only be produced by protons with energies greater than 40 megaelectronvolts. Combined with several other diagnostics, these measurements showed that the proton beam must contain more than 30 trillion protons or over 40 joules of energy (integrated over the proton spectrum).

Further evidence for the proton beam was provided by a proton-sensitive nuclear emulsion strip added to the magnetic spectrometer shown in the figure in the middle of p. 10. Because protons have about 1,800 times the mass of electrons and are deflected less as they travel through the magnetic field in the spectrometer, a proton-sensitive strip was attached at the far end of the spectrometer. The emulsion was turned black by the extraordinary number of protons, giving evidence of proton energies greater than 55 megaelectronvolts.

Delivered in the short duration of the Petawatt's laser pulse, the proton beam current is over 10 million amperes, making the Petawatt one of the world's most powerful ion accelerators.

Experiments with wedge-shaped targets showed that most of the proton beam was emitted perpendicular to the rear surface of the target, independent of how the target was aligned to the laser beam. This finding is important for understanding how the beam is generated. More work is needed to characterize the beam, but such a powerful proton beam will surely find many uses. It might replace the front end of large accelerators or be used itself as an ignitor in fast ignition.

Advances in Fast Ignition

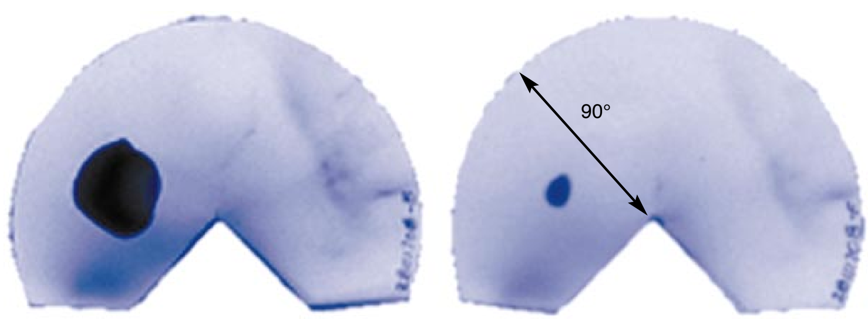
In both fast-ignitor and conventional inertial confinement fusion (ICF), laser or x-ray pulses rapidly heat the surface of a fusion target capsule, enveloping it in plasma. The fuel inside the target is compressed by a rocketlike blowoff of the surface material. In conventional ICF, the plasma must remain highly symmetrical and spherical during implosion if the fuel is to reach 20 times the density of lead and ignite at 100 million degrees. This level of symmetry requires enormous energy and precision from the laser.

In comparison, in fast-ignitor ICF, at the moment of maximum compression, a laser pulse plows through the plasma to make a path for another very short, high-intensity pulse to reach and ignite the compressed fuel. Neither spherical geometry nor the formation of a central hot spot is required in this approach. In theory, fast ignition reduces both the laser energy and precision requirements for achieving ignition.

But fast ignition faces its own challenges. The spot to be heated must be large enough to ignite all the fuel, but not so large as to waste energy. Electrons must be driven far enough to penetrate the plasma and heat the ions

(a) 200-micrometer-thick tantalum layer

(b) 600-micrometer-thick tantalum layer



Radiochromic film images show a highly collimated beam of protons penetrating different layer thicknesses of tantalum. The beam cone angle narrows for protons of higher energy that penetrate greater thicknesses of tantalum. In (a), protons with greater than 17-megaelectronvolt energy penetrate a 200-micrometer-thick tantalum layer, and in (b), protons with greater than 30-megaelectronvolt energy penetrate a 600-micrometer-thick tantalum layer.

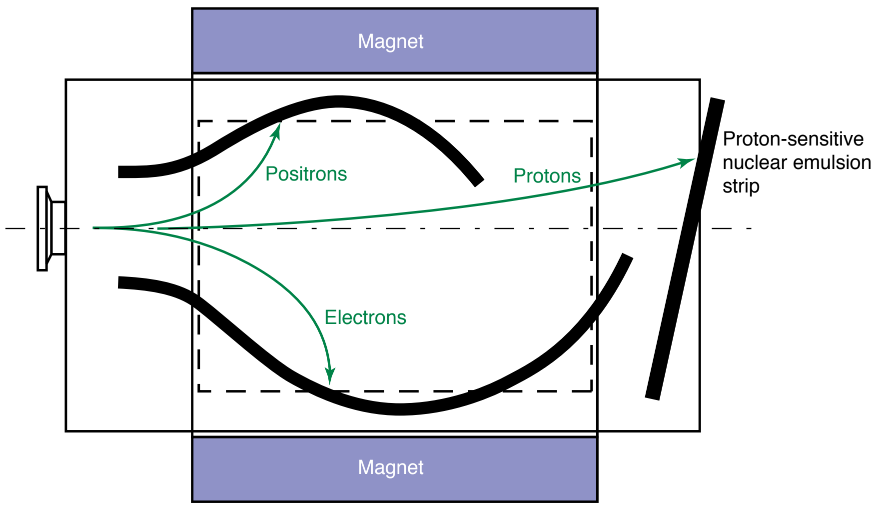
on the surface of the dense cores, but not any farther.

The short, high-intensity pulses of the Petawatt were created specifically to study the delivery of electrons to the right spot. But the Petawatt's designers knew that its kilojoule of energy was not enough for ignition. A much more powerful laser will eventually be needed.

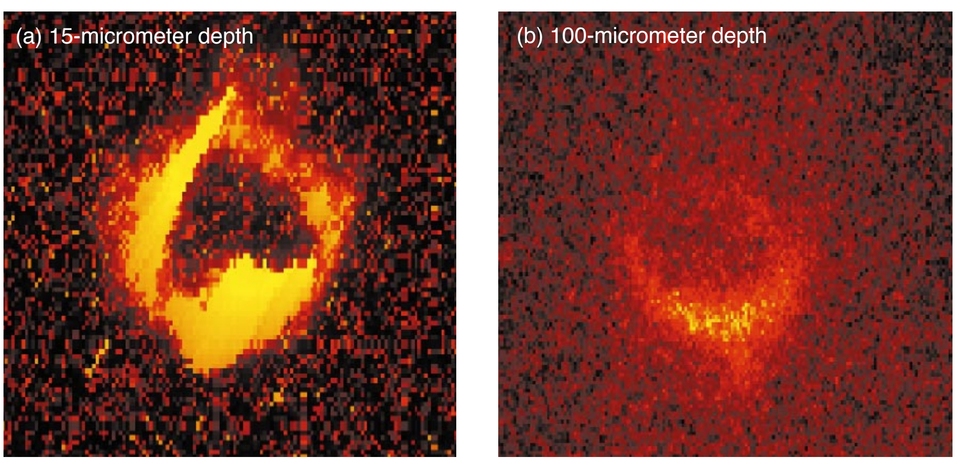
Experimenters examined the efficiency of energy transfer from a short-pulse ignitor beam to the ignition spark via the surrounding plasma. Specifically, they sought evidence for the heating of electrons in solid targets. One experiment used a sophisticated neutron detector that recorded neutrons produced by deuteron–deuteron thermonuclear fusion, indicating heating of the ions to temperatures in the 0.5- to 1-kiloelectronvolt range. These temperatures are not enough for ignition but are higher than temperatures previously seen.

Another experiment looked at aluminum foil sensors buried in polystyrene targets. When heated to about 300 electronvolts, the buried foil emitted x rays. Of particular interest were pinhole camera images of the x rays from the aluminum, which showed an annular (circular) pattern of heating with an 80-micrometer diameter. Images from the rear surface showed a similar annulus up to 100 micrometers deep inside the solid target, and some emission was also observed at a 200-micrometer depth. These data strongly suggest heating in a well-focused pattern, as predicted by theoretical modeling.

The existence of the proton beam, which was discovered only during the final weeks of Petawatt experiments, may change the fast-ignitor picture. Unlike electrons, whose energy diminishes with distance, protons deliver most of their energy where the beam stops. Because of their greater mass, protons are less easily deflected as they pass through the intervening plasma and may therefore be transported to the thermonuclear fuel much better than electrons.



To verify that the beam measured in the previous figure was composed of protons, a spectrometer was used to separate electrons, positrons, and protons. The more massive protons were deflected less by the magnets and passed through to a proton-sensitive nuclear emulsion strip. There were so many protons that the strip was turned black.



Results of an experiment to examine energy transport in dense materials (efficient energy transport is crucial to fast ignition). Shown are pinhole camera images of x rays emitted by heated aluminum sensors buried in polystyrene targets. The heating showed an annular (circular) pattern at a 15-micrometer depth, similar to the annulus seen at 100 micrometers inside the solid target. This suggests the heating had a well-focused pattern, as predicted by theoretical modeling.

Laser-Driven Radiography

The use of petawatt-class lasers for the production of high-energy x rays had been proposed a number of years before the Petawatt was built. The intense, ultrashort pulse of the Petawatt was expected to yield large doses of high-energy x rays, possibly enough to compete with the electron beam accelerators that are now used for x-radiography of explosively driven devices such as Livermore's Flash X Ray (FXR) facility at Site 300 and the Dual-Axis Radiographic Hydrotest Facility (DARHT) currently under construction at Los Alamos National Laboratory.

A laser-driven source would have several advantages over an accelerator. It would be simpler in design and less expensive for taking radiographs of a single experiment from several views. It would also achieve higher spatial and temporal resolution than accelerators can provide.

During experiments to examine the Petawatt's x-ray spectrum, photonuclear reactions (nuclear breakdown induced by hard x rays) were first seen. As described previously, the focused light of the Petawatt was so intense that it caused electrons in a gold target to generate many hard x rays. These x rays produced photonuclear reactions in almost all materials associated with the target assembly and vacuum chamber.

The photonuclear data showed that the Petawatt's x-ray spectrum ranged as high as 60 megaelectronvolts. Monte Carlo modeling estimated that from 40 to

The Largest Diffraction Gratings

In the 1990s, when chirped-pulse amplification required pulse compression gratings of sufficient size, optical quality, and ability to withstand the enormous power of the Petawatt laser pulse, Livermore developed them. No facilities were capable of producing the necessary optics, and different fabrication techniques and grating designs were needed. The bold, high-risk approach taken by program leader Mike Perry, physicist Bruce Shore, laser engineer Bob Boyd, and chemical engineer Jerry Britten has resulted in a grating design and fabrication capability that is unique. It produces the largest single-element gratings in the world, up to a meter across.

Different types of diffractive optics, which have wavelength-scale surface structures, are used to manipulate light delivery and distribution. They can be either reflective like a mirror or transmissive like a lens; they can produce multiple beams or shape the beam. Diffraction gratings can stretch or compress a broadband laser pulse, sample a beam of light, or steer it. Fresnel (diffraction) lenses help to focus light beams, and phase plates shape beams and homogenize them. Diffractive optics can be made on thin, lightweight substrates and yet can have very high efficiency.

In the Livermore fabrication process, the substrate is first polished and made very flat. A layer of photoresist is then applied. The thickness of the photoresist layer may be less than a micrometer or as much as 30 micrometers, depending on the use for the optic. For gratings, interference lithography or a mask is used to expose a layer of photoresist and create a groove pattern. The finer the groove pattern—up to 3,000 lines per millimeter—the more light will be dispersed by the optic. By carefully controlling the photoresist type and the exposure and development steps, a variety of groove profiles can be produced. A "curved" optical component can even be made out of flat glass by curving the grooves or varying the spacing of the grooves.

Following production of the grating pattern in the photoresist, the component is either gold-coated for metal gratings or ion-beam etched for multilayer or transmissive optics.

Livermore's Diffractive Optics Group produced about 50 gratings last year. Currently, they are fabricating optics for laser facilities in the U.S. and several other countries, including the diffractive optics for petawatt-class lasers under construction in Germany, Japan, and England. They are also developing diffractive optics for the National Ignition Facility and lightweight optics to be used in various space applications.

In this booth, interference lithography exposes a layer of photoresist in a groove pattern.

50 percent of laser energy might be converted to electrons, which could yield an x-ray dose comparable to that achieved with the FXR.

Radiographs of objects with a density greater than 150 grams per square centimeter exceeded the resolution achievable with accelerator sources. Although the achievable dose was comparable to some accelerator-based x-ray sources, it was less than that achievable with advanced, large-scale induction accelerators such as DARHT.

Petawatts around the World

Other researchers around the world have not been blind to the new regime of physics that the Petawatt laser has produced. Scientists in Germany, England, France, and Japan are developing petawatt-class lasers of their own. Livermore will provide the diffraction gratings used to stretch and compress the pulse for many of these lasers. At the same time, Livermore scientists are planning collaborative research projects so they can continue to perform experiments on these powerful lasers.

—Katie Walter

Key Words: chirped-pulse amplification, diffractive optics, fast ignition, laser cutting, Nova, Petawatt, proton beam.

For Further Reading

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For further information contact Michael Perry (925) 423-4915 (perry10@llnl.gov).

About the Scientist

MICHAEL PERRY joined Lawrence Livermore National Laboratory as a physicist in October 1987. He is a graduate of the University of California at Berkeley with a B.S. in both nuclear engineering and chemical engineering, an M.S. in nuclear engineering, and a Ph.D. in nuclear engineering–physics. He is currently associate program leader for Short-Pulse Lasers, Applications and Technology in the Laser Programs Directorate. He has authored more than 100 professional publications on the development and use of high-power lasers and diffractive optics.