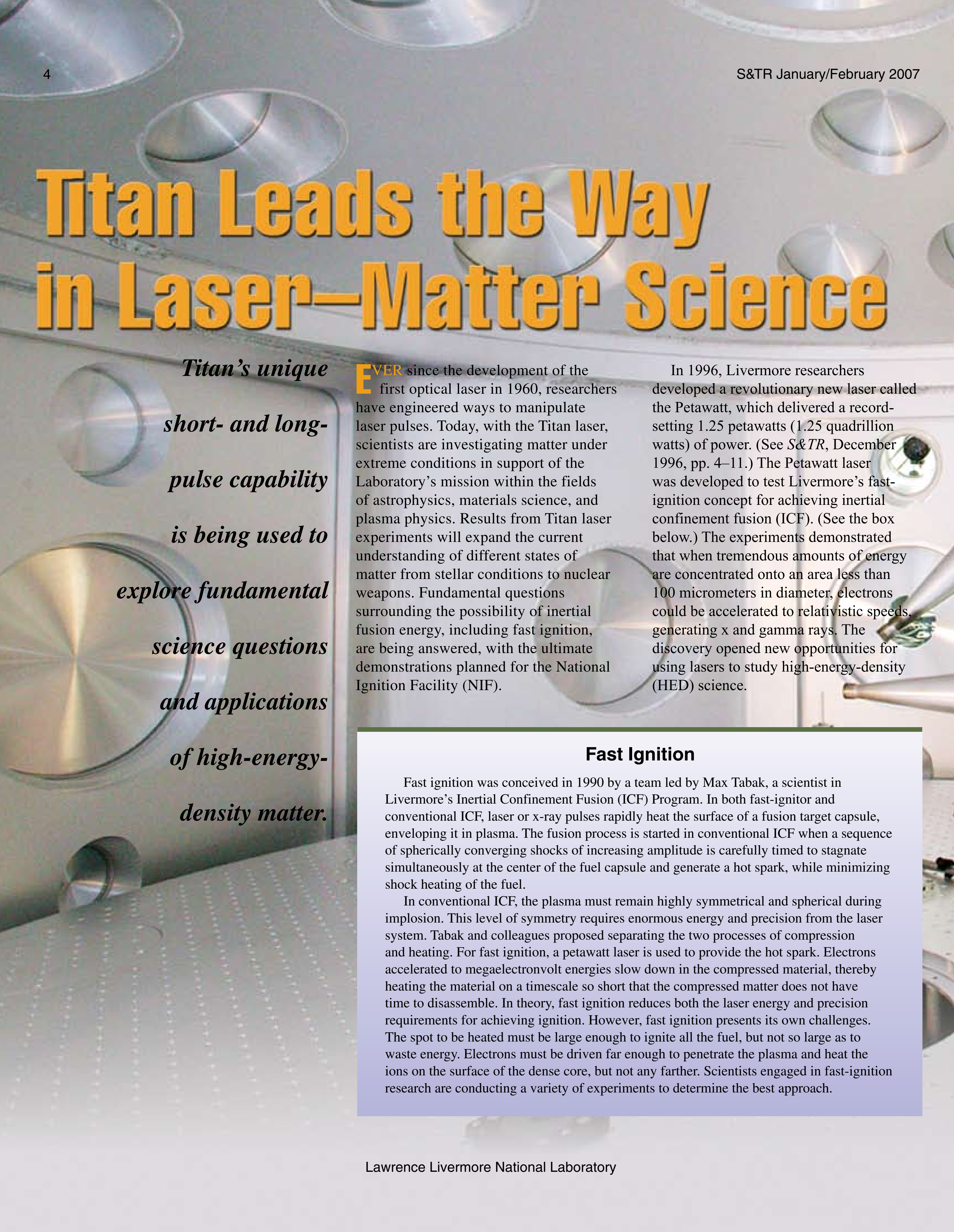


Titan Leads the Way in Laser–Matter Science

Titan's unique short- and long-pulse capability is being used to explore fundamental science questions and applications of high-energy-density matter.

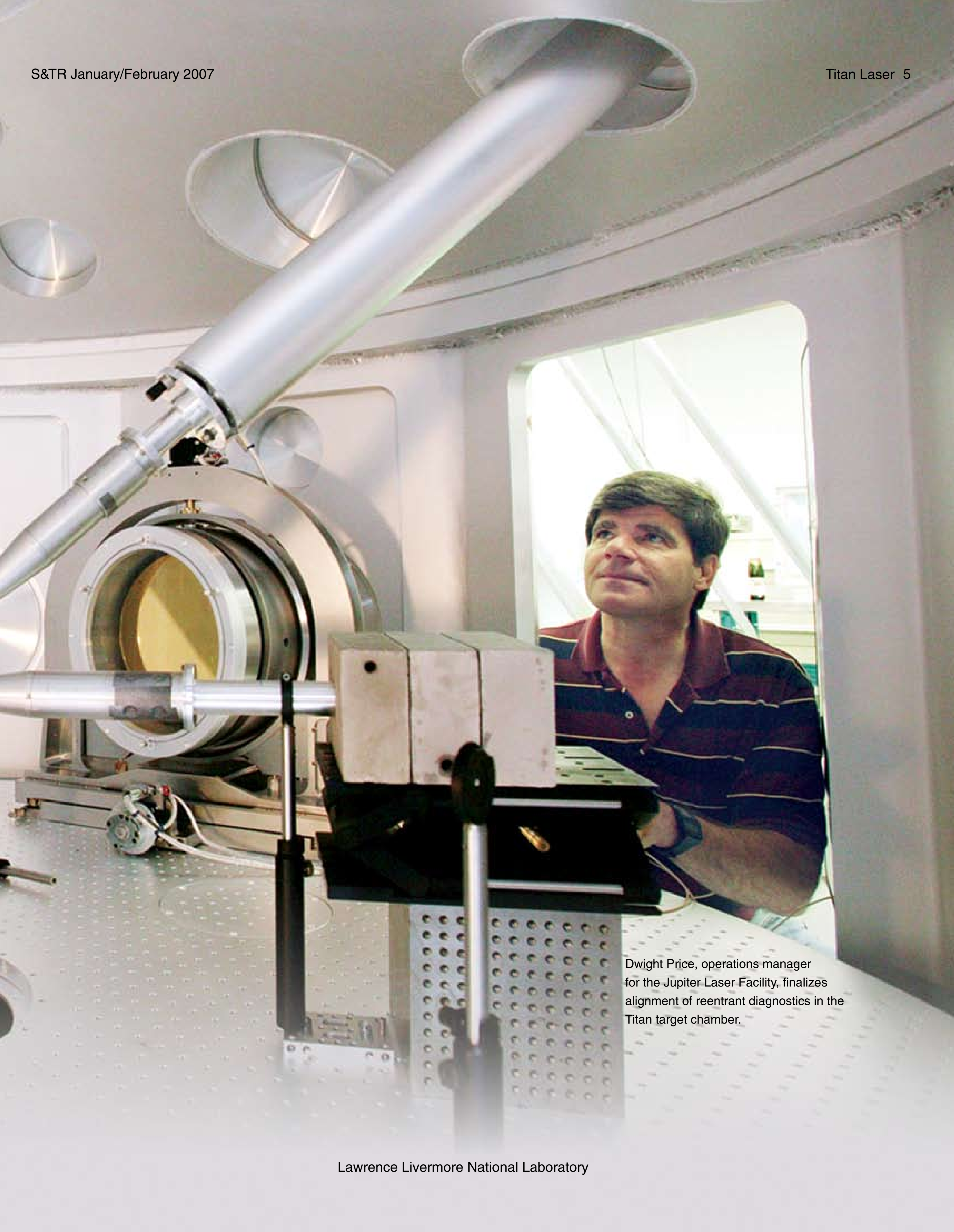
EVER since the development of the first optical laser in 1960, researchers have engineered ways to manipulate laser pulses. Today, with the Titan laser, scientists are investigating matter under extreme conditions in support of the Laboratory's mission within the fields of astrophysics, materials science, and plasma physics. Results from Titan laser experiments will expand the current understanding of different states of matter from stellar conditions to nuclear weapons. Fundamental questions surrounding the possibility of inertial fusion energy, including fast ignition, are being answered, with the ultimate demonstrations planned for the National Ignition Facility (NIF).

In 1996, Livermore researchers developed a revolutionary new laser called the Petawatt, which delivered a record-setting 1.25 petawatts (1.25 quadrillion watts) of power. (See *S&TR*, December 1996, pp. 4–11.) The Petawatt laser was developed to test Livermore's fast-ignition concept for achieving inertial confinement fusion (ICF). (See the box below.) The experiments demonstrated that when tremendous amounts of energy are concentrated onto an area less than 100 micrometers in diameter, electrons could be accelerated to relativistic speeds, generating x and gamma rays. The discovery opened new opportunities for using lasers to study high-energy-density (HED) science.

Fast Ignition

Fast ignition was conceived in 1990 by a team led by Max Tabak, a scientist in Livermore's Inertial Confinement Fusion (ICF) Program. In both fast-ignitor and conventional ICF, laser or x-ray pulses rapidly heat the surface of a fusion target capsule, enveloping it in plasma. The fusion process is started in conventional ICF when a sequence of spherically converging shocks of increasing amplitude is carefully timed to stagnate simultaneously at the center of the fuel capsule and generate a hot spark, while minimizing shock heating of the fuel.

In conventional ICF, the plasma must remain highly symmetrical and spherical during implosion. This level of symmetry requires enormous energy and precision from the laser system. Tabak and colleagues proposed separating the two processes of compression and heating. For fast ignition, a petawatt laser is used to provide the hot spark. Electrons accelerated to megaelectronvolt energies slow down in the compressed material, thereby heating the material on a timescale so short that the compressed matter does not have time to disassemble. In theory, fast ignition reduces both the laser energy and precision requirements for achieving ignition. However, fast ignition presents 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 on the surface of the dense core, but not any farther. Scientists engaged in fast-ignition research are conducting a variety of experiments to determine the best approach.



Dwight Price, operations manager for the Jupiter Laser Facility, finalizes alignment of reentrant diagnostics in the Titan target chamber.

However, generating tremendous amounts of laser energy is only part of what is necessary to conduct HED research. Once researchers generate the laser pulse, they must be able to observe the dynamic changes that occur over a time frame of billionths of a second after a laser beam strikes its target. A key scientific focus is to advance understanding of the temperature–pressure relationship, or equation of state (EOS), for material subjected to these extreme conditions.

One method researchers use to experimentally determine a material's EOS is shock compression. Gas guns are useful for creating high-pressure shock waves of about 500 gigapascals (5 million atmospheres of pressure). However, for some of the research to be performed at NIF, scientists need EOS data for materials subjected to pressures of 10 terapascals (100 million atmospheres) or more. High-performance lasers are the only instruments available to researchers that have the potential to obtain EOS data for materials at those pressures. NIF and Titan will be used in complementary experiments to obtain the required EOS data.

Lasers are designed to deliver a specific range of pulse energy and duration. This range dictates the phenomena that can be studied. For example, long pulses lasting nanoseconds are effective at compressing a material, whereas short pulses lasting pico- or femtoseconds are better for probing a material. In the past, high-energy lasers have been built to deliver either long or short pulses into an experimental area, but not both.

Two Beams Pack a Punch

In 2003, the Laboratory Science and Technology Office funded a collaboration between the Physics and Advanced Technologies (PAT), NIF Programs, Engineering, and Chemistry, Materials, and Life Sciences (CMLS) directorates to build Titan, the only laser in the world that couples a high-energy, petawatt short-pulse (subpicosecond) beam with a kilojoule long-pulse (nanosecond) beam. This unique capability is being used to explore a range of phenomena, including the acceleration of charged particles, hydrodynamics, and radiation emission and absorption in hot dense plasmas, all of which are fundamental to understanding HED materials. The research also helps to determine the physics requirements for experiments at NIF.

Titan joins the Janus, COMET, Europa, and Callisto lasers in PAT's Jupiter Laser Facility, which supports Laboratory research and collaborations with other institutions and universities. Andrew Ng of PAT, the facility's scientific director, says, "Every laser laboratory in the world would like to have a high-energy laser with long- and

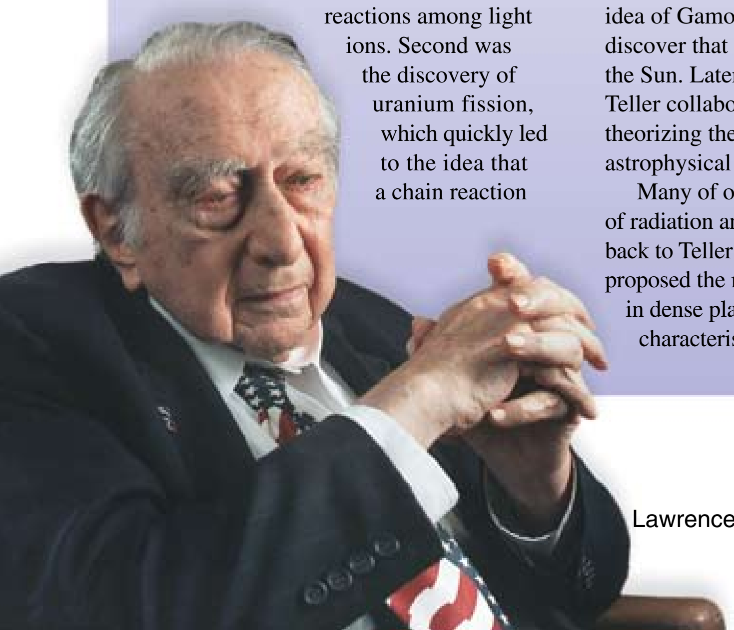
Edward Teller and High-Energy-Density Physics

After beginning his career by brilliantly applying the new quantum mechanics to the physics of atoms and molecules, Edward Teller began to show keen interest in high-energy-density (HED) physics—the science of matter and energy above 1 million atmospheres in pressure. Two major HED physics discoveries in the late 1930s engaged his imagination. First, his friend and colleague Hans Bethe proposed the basic explanation that stars are powered by thermonuclear reactions among light ions. Second was the discovery of uranium fission, which quickly led to the idea that a chain reaction could liberate nuclear energy. Thermonuclear reactions could be studied and exploited, and fission could be developed to make explosives and power reactors.

After emigrating to the U.S., Teller worked at George Washington University with George Gamow and others on a variety of physics topics, including HED. With Gamow, Teller wrote one of the earliest papers estimating the rates of key thermonuclear reactions and applying them to red giant stars. Bethe and a student of Teller's, Charles Critchfield, applied the new idea of Gamow–Teller nuclear beta decays to discover that the fusion of two protons powers the Sun. Later at the University of Chicago, Teller collaborated with Maria Mayer in papers theorizing the synthesis of heavy elements in astrophysical explosions.

Many of our key ideas describing the flow of radiation and energy in the HED regime date back to Teller's papers. With collaborators, he proposed the main ideas for the behaviors of ions in dense plasmas and their spectral radiation characteristics, and he worked out the rules for shock waves in magnetized plasmas. In his efforts to understand the laws governing the equations of state of HED plasmas for both basic science and applications, Teller drove important developments such as the famous Metropolis Method, which is essential for making statistical mechanics calculations computationally feasible. This work was done with his former student Marshall Rosenbluth, their wives Mici Teller and Arianna Rosenbluth, and Nicolas Metropolis. Teller, Metropolis, Richard Feynman, and others are responsible for developing widely used models for hot dense matter.

At Livermore, Teller was a tireless champion of innovative HED research, knowing that this important field entwined basic science and major applications. He encouraged developments that showed promise for new ways to control and exploit HED matter and plasmas, thereby leading to much of Livermore's research on inertial fusion and lasers.



short-pulse capability. It allows researchers to study phenomena that occur in a material at different timescales, providing a more complete picture of material evolution. For example, structural changes to a material tend to occur on approximately the picosecond timescale, while electronic changes happen much faster, on approximately the femtosecond timescale." (See *S&TR*, July/ August 2006, pp. 4–10.)

Because very short pulses can overheat a laser system's glass amplifiers and thus damage them, Titan's short-pulse beam has an optical parametric chirped-pulse amplifier that temporarily stretches the pulse, reducing the beam intensity in the amplifier system. This stretched pulse is then compressed to its original duration using a pair of gratings in a vacuum, and a petawatt pulse of 400 joules in 400 femtoseconds is delivered to the target.

One of the major breakthroughs enabling petawatt capability was the development of multilayer dielectric optical gratings by CMLS scientist Jerry Britten in 1986 for the Laboratory's Nova laser. Previously, ultrashort-pulse lasers using gold optical gratings to compress pulses were limited in how much energy they could generate because of the optical damage threshold of the gold layer. The multilayer dielectric gratings provide up to five times improvement in damage threshold over gold. Titan uses two gratings, each measuring 80 by 40 centimeters wide, in its vacuum compressor.

The two Titan beams, which originate from the Janus laser, can operate independently or together. At full energy, the pulses can be produced once every 30 minutes. The short-pulse beam is directed through a dedicated port into Titan's 2.5-meter-diameter target chamber. It is focused onto a spot less than 10 micrometers in diameter (full width at half maximum). The long-pulse beam can be directed into the target chamber through different ports using an articulated beam transport. Inside the target chamber, researchers mount diagnostic equipment tailored for each experiment. Physicist Pravesh Patel of PAT designed the target chamber and worked with the Titan laser team to help ensure the new facility would meet all of the requirements for experiments. The Titan facility is also equipped with an array of other instruments, including radiation detectors, particle detectors, x-ray imagers and spectrometers, and charge-coupled-device and streak cameras for measuring and recording results.

Titan's long-pulse beam can be directed into the 2.5-meter-diameter target chamber through different ports. The short-pulse beam is directed through a dedicated port.

In February 2006, Titan delivered short pulses of 150 joules in 500 femtoseconds onto an 8-micrometer-diameter spot. Titan's combined short- and long-pulse beams were commissioned for experiments in July 2006.

Focusing Electrons and Protons

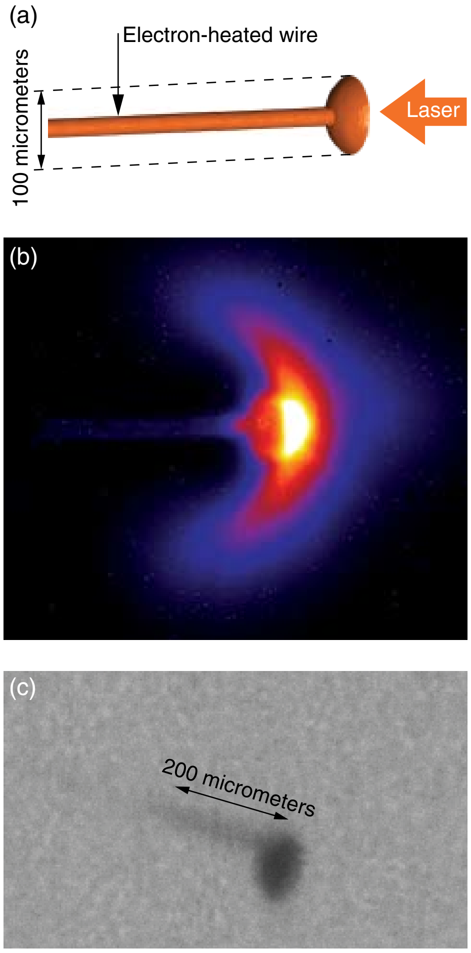
PAT and the Laboratory Directed Research and Development (LDRD) Program are funding Patel to conduct experiments that will further understanding of HED plasmas, which are relevant to the Laboratory's stockpile stewardship research. Plasmas are extremely hot states of matter that are difficult to probe when created by a laser because the plasma is always in transition from hydrodynamic expansion. A decade ago, Livermore researchers using the Petawatt laser unexpectedly discovered that when they fired a short pulse at a thin solid foil, the resulting relativistic electrons could interact with impurities in the foil to create a proton beam. (See *S&TR*, December 2003, pp. 11–14.) A few years later, Patel and his colleagues used a proton beam generated with the 100-terawatt Callisto laser to isochorically heat a plasma. During isochoric heating, a material's volume stays at a constant value. The proton beam heats the target to millions of degrees in a few picoseconds, which is too quick for significant hydrodynamic expansion to occur.

Patel and Andrew Mackinnon of the NIF Programs Directorate are studying the optimization of electron and proton transport for fast ignition. The Department of Energy Office of Science's (DOE/OS's) Fusion Energy Sciences Program and LDRD are funding the team. The team collaborates with John Pasley and Farhat Beg from the University of California (UC) at San Diego, Rich Stephens from General Atomics, and Rick Freeman and Linn Van Woerkom from Ohio State University, who are all supported by DOE/OS's Fast Ignition Advanced Concept Exploration grant, Livermore's Institute for Laser Science and Applications (ILSA), and DOE's Fusion Science Center at the University of Rochester. An important challenge for the viability of the fast-ignition approach to ICF energy is the transport of the ignition pulse energy to the target with high efficiency.

In one possible design for fast ignition, a gold cone is inserted radially into the fusion-fuel capsule, with the tip of the cone penetrating almost to the center of the capsule. Long-pulse laser beams 1 to 10 nanoseconds in duration compress the fuel capsule to a dense plasma core. A 10- to 100-picosecond petawatt laser pulse is then focused into the gold cone to generate energetic electrons at the top of the cone and ignite the fuel's plasma core. Mackinnon says, "We are using Titan to study materials at a density of 1 gram per cubic centimeter and a temperature of 25 electronvolts, but NIF will be used to study materials 300 times that density and temperatures between 100 and 200 electronvolts. Titan experiments test the physics requirements on a small scale and produce data needed to prepare for future experiments on NIF."

A common method researchers use to examine electron transport in short-pulse laser–matter interactions is K-alpha x-ray emission. When a short pulse with intensity greater than 10^{19} watts per square centimeter strikes a target, electrons with energies up to 3 megaelectronvolts are created. These energetic electrons interact with bound electrons in an atom. In K-alpha emission, an incident electron ejects an electron from an atom's innermost shell (called a K-shell electron). Then an outer-shell electron drops in to fill the vacancy, emitting a photon in the process. By studying K-alpha emission from the electron interactions, researchers can obtain information about the properties of electrons in a high-density plasma environment.

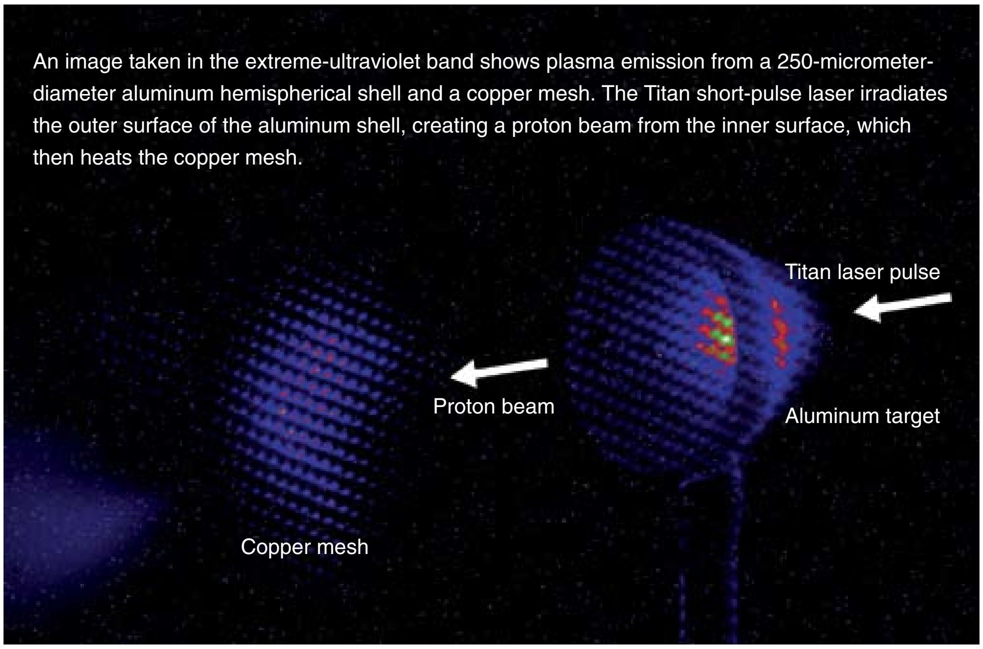
In one study, the team examined electron transport using a 20-micrometer-diameter copper-wire target covered with titanium. The team focused 100 joules of energy for 1 picosecond on a 10-micrometer spot at the end of the wire and measured the spatial distribution of



(a) A short laser pulse is fired onto the head of a titanium-covered copper wire to study electron transport. (b) A radiograph in the extreme ultraviolet band of 68 electronvolts shows heating by hot electrons along the wire. (c) An x-ray image of copper K-alpha fluorescence at 8 kiloelectronvolts shows hot electron penetration 200 micrometers into the wire.

University of California at San Diego researchers John Pasley and Farhat Beg participate in the Laboratory's Institute for Laser Science Applications. Pasley and Beg are collaborating on a team studying fast ignition for inertial confinement fusion energy.

the K-alpha emission for both copper and titanium. X-ray images showed the electrons' depth of penetration along the length of the wire. The images showed good agreement with simulations produced by the team using hybrid fluid-particle codes.


An image taken in the extreme-ultraviolet band shows plasma emission from a 250-micrometer-diameter aluminum hemispherical shell and a copper mesh. The Titan short-pulse laser irradiates the outer surface of the aluminum shell, creating a proton beam from the inner surface, which then heats the copper mesh.

Paving the Way to Fast Ignition

The advantage of using an electron beam for fast ignition is that electrons have a conversion efficiency of 30 to 50 percent (conversion of energy in laser pulse to energy in electron beam). However, electron transport is uncertain. "Electrons have a tendency to spray in a large angle," says Mackinnon. "For fast ignition to work, electrons must be concentrated on a small spot in the center of the plasma."

While the team is mainly concentrating on electron transport for fast ignition, it is also exploring the use of a proton beam. The earlier discovery that impurities in gold could generate a proton beam prompted studies for exploiting the phenomenon for fast ignition. Mackinnon explains, "Ultrashort laser pulses produce electrons and protons, either of which could potentially be used to ignite fusion fuel."

Protons offer attractive features. With a mass about 1,800 times the mass of electrons, protons are deflected less often than electrons and can be focused with curved targets as they travel through a plasma. However, the conversion efficiency for creating protons is only about 10 percent. The team is determining whether the conversion efficiency could be increased with the use of thin, hydrogen-rich layers on the rear target surface.

Some proton-focusing experiments have been conducted using an aluminum hemispherical shell target and a copper mesh. The Titan short-pulse beam was fired onto the aluminum target, producing a focused proton beam that simultaneously heated and radiographed the copper mesh. By measuring magnification (grid size) of the mesh projected onto a proton detector, researchers can determine the location of the focal spot of the proton beam generated from the spherical shell. These experiments showed that protons could be focused to an area less than 50 micrometers in diameter, creating solid-density plasmas with temperatures between 100 and 200 electronvolts.

These techniques will be applied at the University of Rochester's OMEGA EP (extended performance) laser facility, where the collaborative team may be able to isochorically heat plasmas to much higher temperatures and pressures. The 60-kilojoule OMEGA EP laser, which is scheduled to begin operation in 2007, is participating in the National Nuclear Security Administration's HED program. One of the facility's goals is to provide a staging ground for fast-ignition concepts that could be applied to NIF.

The Livermore results are also helping Pasley, Beg, Freeman, Stephens, and Van Woerkom with studies being conducted at UC San Diego and Ohio State University. Last year, academic collaborations at the Jupiter Laser Facility included more than 25 students and postdoctoral researchers. The students also collaborate on many other Livermore projects. Don Correll, director of Livermore's Institute for Laser Science Applications, says, "Engaging graduate students and postdoctoral researchers in HED science experiments on the Titan laser is a cornerstone of the institute's mission to strengthen collaborations between faculty and Laboratory researchers. The scientific breakthroughs benefit both the Livermore and academic HED science communities. The collaborations are also ideal for attracting the next generation of researchers to the Lab's scientific missions."

Measuring at the Extremes

Many of the shock wave techniques for obtaining EOS data were developed originally in gas-gun experiments, in which pressures are typically less than 100 gigapascals. One method, called impedance matching, relies on driving a shock wave through a reference material whose EOS is known into a test sample in contact with it. Because the materials share a common interface, the shock pressure and particle velocity will be the same in both materials. Using the measured shock velocities in each material and the known EOS of the reference material, researchers can determine the shock pressure and density of the sample. A major goal of Livermore researchers is to obtain experimental data up to very high pressures, densities, and temperatures.

However, HED regimes place extreme demands on the conventional impedance-matching technique.

Physicist Damien Hicks of PAT is conducting studies to improve Livermore's EOS database. Hicks says, "Impedance matching works well at low pressures. The compressions are much higher at pressures of hundreds of gigapascals, so highly precise velocity measurements are needed. Small errors in velocity measurements become large errors in density measurements." Problems also arise from using reference materials whose EOSs have been tested only at lower pressures. For example, the shock data on aluminum is patchy above 500 gigapascals. Even with additional data from theoretical models or extrapolations, uncertainties increase at these higher pressures.

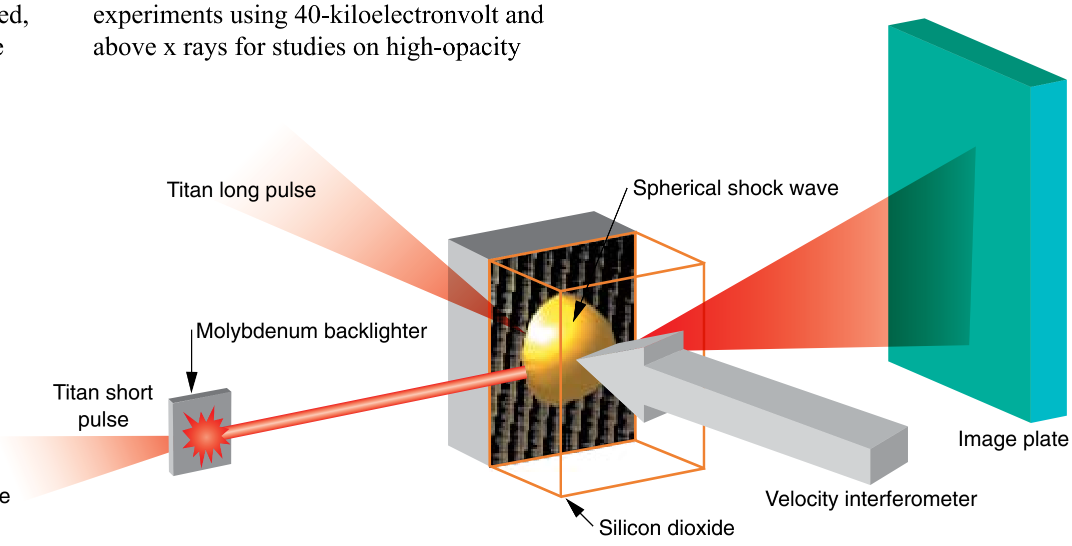
Hicks's team is developing a technique that eliminates these uncertainties by directly measuring the density of materials that are highly compressed by a shock wave. The team has conducted experiments in collaboration with researchers at the University of Rochester's Laboratory for Laser Energetics. It focused a nanosecond-long pulse from the OMEGA laser onto a 500-micrometer-diameter spot to generate a spherical shock wave in a polystyrene sample. Radiographic imaging using long-pulse-driven 5-kiloelectronvolt x rays produced a snapshot of the expanding shock wave. This two-dimensional (2D) image was then tomographically inverted, providing the density profile behind the shock front. By simultaneously measuring the shock velocity with a velocity interferometer, the team obtained absolute EOS data.

Last year, the team began experiments using Titan's long- and short-pulse beams to study silicon dioxide. They fired the long pulse to generate a shock wave, then the short pulse to produce higher energy and deeper penetrating x rays from a molybdenum foil adjacent to the silicon dioxide. The molybdenum x rays produced a radiograph of the shocked region. "The 2D picture of the symmetric, expanding shock wave enabled us to infer its density from the intensity of the transmitted x rays," says Hicks. The team estimates that the method accurately measures density to within 5 to 10 percent. The pressure in the shock wave is determined by measuring the shock velocity with an interferometer. "We bounce a probe laser pulse off the shock wave and measure the Doppler shift in the reflected light," says Hicks. "Combined with the density measurement, this measurement tells us the pressure of the sample."

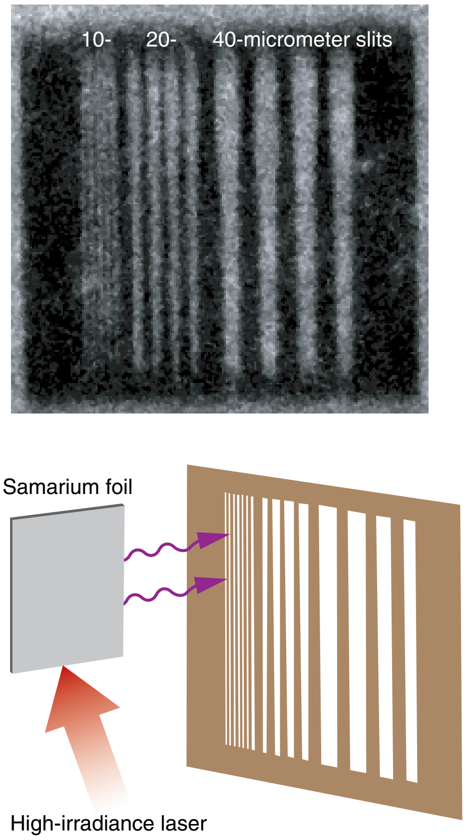
Unlike the conventional impedance-matching technique, where density is inferred from shock and particle velocities, the new direct density measurement does not demand increased precision at higher compressions. Therefore, the method readily scales to ultrahigh-pressure measurements. The team plans to conduct experiments using 40-kiloelectronvolt and above x rays for studies on high-opacity (high-*Z*) materials. The researchers also want to extend the EOS data for materials used as references. Hicks says, "Because so much information is known about aluminum at lower pressures, it makes sense to extend aluminum's EOS data to 1 terapascal and above so that the element can serve as a reliable reference at higher pressures."

Shedding Light on the Matter

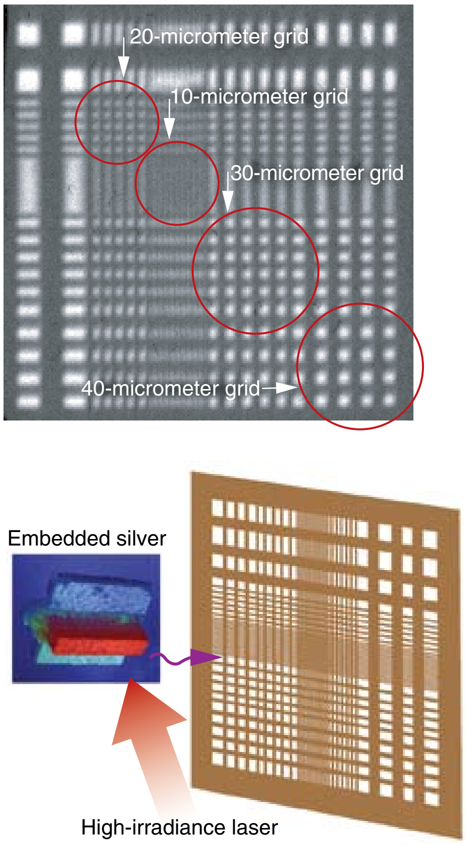
With funding from the Defense and Nuclear Technologies (DNT) Directorate and LDRD, physicist Hye-Sook Park of the NIF Programs Directorate is developing a high-energy backlighting technique to produce radiographs for x-ray energies up to 100 kiloelectronvolts. As NIF approaches completion, physicists will be conducting experiments that involve larger and denser targets than previously studied. NIF will need suitable diagnostics to ensure the dense materials are probed to specification. High-energy x-ray backlighting will be used in many HED experiments such as material strength, mid- to high-*Z* capsule implosions, and high-*Z* EOS studies. "NIF will fire single shots that are just several nanoseconds long," says Park. "The backlight needs to be bright enough to capture events occurring during that short time. We also need to differentiate small features at the surface of a material



This schematic shows a technique designed to directly measure the density in a shock wave. A long laser pulse drives a spherically expanding shock wave into silicon dioxide. Several nanoseconds later, a short laser pulse generates a burst of 17.5-kiloelectronvolt x rays from a molybdenum backlighter. The x rays project a snapshot of the spherical shock wave onto an image plate detector. A velocity interferometer measures the shock speed in the sample; shock speed and density provide data to determine the shock pressure.



Short pulses fired onto a 5-micrometer-thick sample of samarium provide a backlight for this one-dimensional radiograph of a 35-micrometer-thick tantalum grid. In this image, spatial resolution is clear at 10 micrometers.



Silver microwires are buried in a geometric-shaped material to produce two-dimensional (2D) radiographs of the x-ray emission of high-energy-density materials. In this image, 2D features at 20 micrometers are well resolved.

or within a thick and dense substrate, both of which require a high-energy x-ray backlighter with a spatial resolution less than 10 micrometers."

Traditional laser backlighters have energies less than 9 kiloelectronvolts. Park's team has developed 1D and 2D radiography methods with greater than 17-kiloelectronvolt x rays and a spatial resolution less than 20 micrometers. To produce 1D radiography of a 35-micrometer-thick sample of tantalum, researchers irradiated a 5-micrometer-thick samarium foil with a short-pulse laser, creating 40-kiloelectronvolt x rays. Edge-on views of the foils showed the technique could resolve features down to 10 micrometers.

The team is also testing microwire and microdot targets buried in different geometric shapes to create a small point source for 2D radiography. "Two-dimensional radiography is more difficult, because the K-alpha photon production in microwire volumes is not well understood," says Park. So far, they have tested the K-alpha emission from microdot samples of molybdenum and silver as well as x-ray emissions from various microwire targets made of molybdenum, silver, and samarium. A radiographed test grid using silver resolved 2D features clearly to 20 micrometers. Park says the technique could be scaled by using different materials for the type of energy required.

Park's team is also using high-energy backlighting techniques to study material strength. The NIF Programs and DNT directorates are funding research to examine material strength under high pressure and high strain rate. The experiments rely on the properties of instabilities in materials at HED conditions. "Perturbations always exist at the interface of two joining materials," says Park. "By studying the differences of the perturbation growth rate in various materials, we can measure the strength of the materials." The team has studied aluminum and vanadium and is conducting experiments on tantalum.

Each experiment using lasers requires specific laser parameters (wavelength, energy, and pulse duration) and configuration (illumination geometry). Titan and the other lasers in the Jupiter Laser Facility allow scientists to tailor experiments to obtain optimal results. "The parameters and configuration depend on the information we are trying to gather," says Ng. "Titan provides a cutting-edge environment to conduct a wide range of studies. It also facilitates collaborations with other scientists in HED research."

For scientists working on NIF, Titan experiments will help advance their understanding of issues facing fast ignition. The importance of Titan laser research will continue to grow as NIF begins full operation. Many Titan experiments will explore new concepts and serve as a test bed for more complex tests using NIF. Titan also will help train the cadre of young scientists who will use NIF over the next few decades.

—Gabriele Rennie

Key Words: backlighter, electron transport, equation of state (EOS), fast ignition, high-energy-density (HED) science, impedance matching, inertial confinement fusion (ICF), Janus laser, Jupiter Laser Facility, multilayer dielectric grating, Petawatt laser, proton transport, Titan laser.

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