Crossing the Petawatt Threshold

An extraordinarily powerful new laser promises to help make fusion power more easily attainable with "fast ignition." The laser beam's ultrashort pulses and extremely high intensities will also enable researchers to advance their understanding of the fundamental nature of energy and matter.

FOR more than three decades, Lawrence Livermore's Laser Programs have earned a worldwide reputation for pushing the limits of laser technology. But few accomplishments have rivaled the one celebrated in the early morning hours of May 23, 1996, by an exhausted but exuberant crew that just used a revolutionary laser that produced more than a quadrillion watts of energy, a world record.

The extraordinarily powerful laser is called the Petawatt because the prefix "peta" refers to a quadrillion, or 10^{15}. The laser reached a peak of 1.25 petawatts of peak power, about 25% more powerful than expected and more than ten times the peak power of Lawrence Livermore's Nova laser, the world's largest. The historic shots shattered the existing record for laser power (125 trillion watts) by more than a factor of 10, set by Livermore researchers using a Petawatt prototype during the summer of 1995.

Although the shots exceeded by more than 1,200 times the entire electrical generating capacity of the U.S., they lasted less than half a picosecond (a trillionth, or 10^{-12}, of a second). In that exceedingly fleeting moment, nearly 10,000 times shorter than the typical Nova laser shot, only enough energy (about 600 joules) was generated to keep a 100-watt light bulb burning for about 6 seconds.

By crossing the petawatt threshold, the laser heralds a new age in laser research. Lasers that provide a petawatt of power or more in a picosecond may make it possible to achieve fusion using significantly less energy than presently envisioned, through a novel Livermore concept called fast ignition. (See *Science & Technology Review*, September 1995, for more information.) The Petawatt laser will also enable researchers to study the fundamental properties of matter, thereby aiding the Department of Energy's stockpile stewardship efforts and opening entirely new physical regimes to study.

Coincidentally, University of California at Berkeley professor Charles Townes was visiting the Laboratory on the same day, May 23, as a member of a panel reviewing the Laser Programs (see Figure 1). Townes was awarded the Nobel Prize in 1964 for co-inventing the first laser, which generated only a few thousandths of a watt.

"When the laser first came along, I never imagined it getting up that high," Townes told reporters. "When we first invented them, I was thinking about very modest powers. It never occurred to me it would be in this kind of ballpark."

Indeed, the Petawatt is only the latest of a family of lasers with increasing irradiance (power per unit area) that began in the 1970s with LLNL's Argus, Shiva, and then Nova laser systems (see Figure 2). The introduction in the mid-1980s of a unique new laser material—titanium-doped sapphire (Ti:sapphire)—offered high gain over a broad range of wavelengths. Together with a new technology—chirped-pulse amplification (CPA) to minimize laser materials damage—they offered the possibility of creating high-power subpicosecond pulses directly from a solid-state laser. Lawrence Livermore researchers began work on short-pulse lasers in the mid-1980s and completed a 10-terawatt (TW) laser in 1989. The embodiment of most of the advances since that time resides in the Petawatt.

With its full-aperture beam of 58 centimeters in diameter (to be installed in early 1997 to replace a 46-cm beam), the Petawatt will produce about 1 kilojoule of energy in less than

Laser physicist Deanna Pennington adjusts a diagnostic lens within the Petawatt's compressor chamber. At right is one of the diffraction gratings, while behind her are a turning mirror and the second compressor grating.

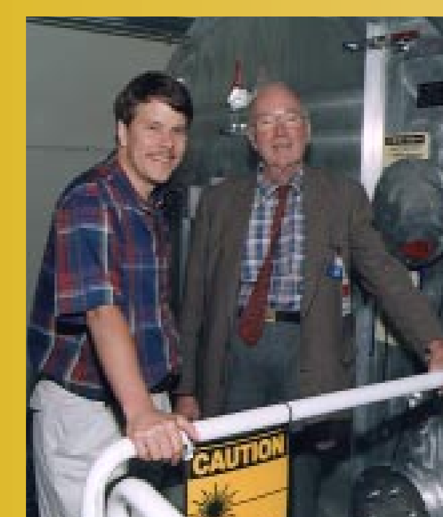

Figure 1. With the Petawatt is laser in the background, Livermore's Michael Perry (left) shows how far the technology has come to UC Berkeley Professor Charles Townes, who co-invented the laser.

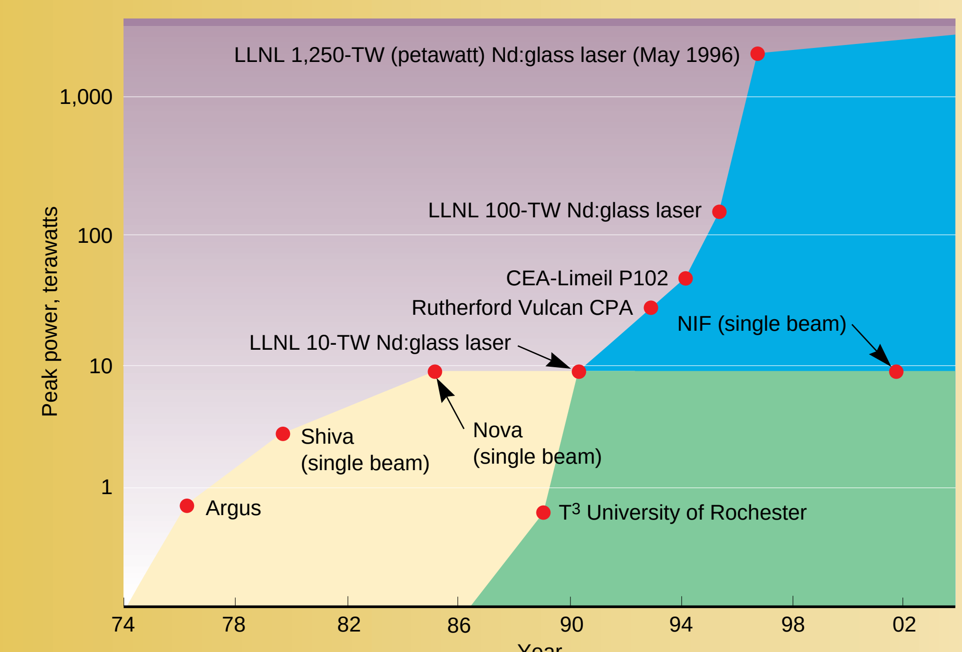

Figure 2. Milestones in laser development: early lasers (yellow), long-pulse technology (green), and chirped-pulse amplification technology (blue).

0.5 picosecond. In contrast, one beamline of Nova typically produces 10 kilojoules of energy in 1 nanosecond (billionth of a second), some 1,000 times slower. Nova and the National Ignition Facility (NIF) planned for Livermore are long-pulse lasers (nanoseconds and longer), specifically designed to produce high-pulse energy.

Petawatt Development

The Petawatt Advanced Fusion Project was proposed in 1992 as a high-risk, potentially high-payoff project to develop the capability to test the fast-ignitor concept for inertial confinement fusion (ICF) and to provide Livermore—and the world—with a unique capability in high-energy-density physics. Michael Perry, leader of Lawrence Livermore's Short-Pulse Lasers, Applications, and Technology Program, won a competitive grant in 1993 from LLNL's in-house Laboratory Directed Research and Development program to begin building the laser.

Perry formed a core team of physicists, engineers, and technicians with backgrounds in laser physics, optics, engineering, materials science, and atomic physics. Team members knew that success required advances in knowledge of the basic behavior of optical materials, development of new diffraction grating technology, substantial improvements in short-pulse laser technology, and advancement of a sound theoretical basis for the fast-ignitor concept. Finally, they recognized that although an all-Ti:sapphire laser could not provide sufficient power, a hybrid system starting with a Ti:sapphire laser and using new, smaller, and more efficient neodymium glass amplifiers could provide the necessary pulse energy and bandwidth to achieve a petawatt.

Much of the Petawatt's early effort was devoted to further developing CPA technology. CPA was first developed to increase the power of radar systems and was discussed for use in lasers in the middle 1970s. The first successful demonstration occurred for solid-state lasers in the late 1980s at the University of Rochester. Further developments at Rochester, Lawrence Livermore, and elsewhere along with the introduction of new laser materials (e.g., Ti:sapphire) have revolutionized high-power laser research. (See Figure 3.)

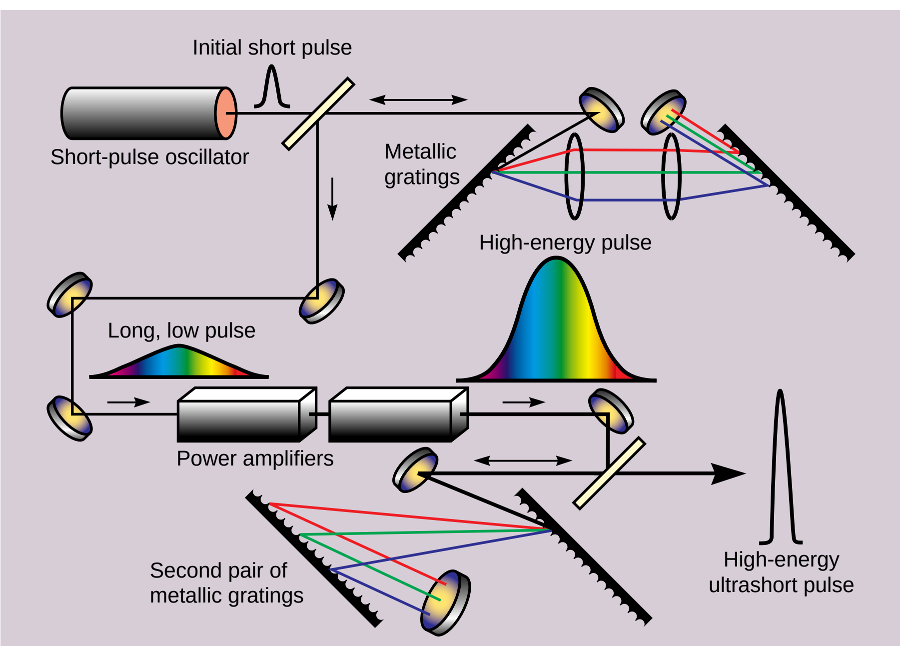

Figure 3. The concept of how chirped-pulse amplification and other new technologies enable the production of the petawatt (quadrillion-watt) pulses.

CPA is critical because laser pulses of extremely high power density (gigawatts/centimeter^2, or GW/cm^2) can severely damage optical components such as amplifiers, lenses, and mirrors. With CPA technology, it became possible to generate very short laser pulses with extremely high peak powers by stretching a low-energy laser pulse more than 10,000 times its duration prior to amplification and then recompressing the pulse back to near the original duration after amplification. Because passage through the laser optics occurs when the pulse is long, there is no damage.

Using this technology, the Petawatt laser begins with a broad-bandwidth, low-power pulse lasting less than 0.1 picosecond in a temperature-controlled clean room in the basement of the Nova building. Instead of consisting of a single, very specific wavelength (color) produced in conventional lasers, these ultrashort pulses contain a broad spectrum. Before amplification, the short-pulse beam is sent to the pulse stretcher. Here, the pulse is stretched by using a diffraction grating to spread out the different wavelengths (colors), separating each frequency component. By passing each color through a different optical path length (the red components travel a shorter length than the blue), the pulse is stretched in time by a factor of 30,000 to 3 nanoseconds. The pulse is then amplified more than a trillion times without damaging the laser glass as the pulse travels through a series of amplifier modules, including a portion of one arm of the Nova laser for the final amplifier stage.

After amplification, the beam is then sent to the vacuum chamber 3 × 11 meters long, where the pulse is compressed using a pair of diffraction gratings each 74 centimeters in diameter. By reversing the process of the stretcher (now the red components travel a longer length than the blue), the pulse is compressed down to less than half a picosecond (nearly its original duration), thereby increasing its peak power nearly 10,000 times to more than a petawatt. Such pulses must be compressed in a vacuum because the irradiance of the beam leaving the second grating is over 700 GW/cm^2, far too great to pass through any material (including air) without resulting in damage.

The Grating Challenge

One of the most challenging tasks was the fabrication of pulse compression gratings of sufficient size, optical quality, and ability to withstand the enormous power of the Petawatt laser pulse. Said Perry, "When the project began, there wasn't a facility in the world capable of making the required gratings, so we created one."

The diffraction gratings that are used in the Petawatt laser are nearly 1 meter in diameter, some eight times larger and twice as resistant to damage as the previous state of the art. Livermore's successful development of diffraction grating technology for the Petawatt led to the selection of gratings for many uses on the National Ignition Facility (NIF), a 192-beam laser facility planned for Livermore.

Initially, achieving a petawatt of peak power was expected to require an entirely new optical component—a high-efficiency, multilayer dielectric grating. That advanced technology was developed by the Petawatt team in 1993 and 1994, an achievement recognized in 1994 with an R&D 100 Award. However, the dielectric gratings were not used in the current experiments because new metallic gratings developed by the team have proven satisfactory for petawatt pulses at 0.5-picosecond durations. These metallic gratings are simpler to manufacture than the multilayer gratings. Multilayer gratings would be required to achieve the multikilojoule pulses necessary to achieve ignition if fast-ignitor capability is added to the NIF. Interestingly, the multilayer dielectric grating technology has already produced its own spinoff. (See this and other spinoff technologies discussed in the box below.)

With the grating technology in hand, the focus of the Petawatt team moved to installation of the petawatt system on the Nova laser. Numerous large-scale optical and mechanical components capable of working at extreme precision under vacuum had to be designed,

Petawatt Spinoffs

The technology developed for the Petawatt has provided many unexpected spinoffs. In particular, Lawrence Livermore's experimental and theoretical studies of laser-induced damage, carried out in support of the Petawatt laser's development, have created valuable new technologies. Researchers, led by Brent Stuart, using the petawatt front end made pioneering measurements of the laser damage threshold for a multitude of optical materials (crystal and glass) lasting from 0.1 picosecond to 1 nanosecond. A fundamental change in the damage mechanism is observed when the pulse length is less than approximately 20 picoseconds. This change in mechanism is accompanied by a dramatic change in the morphology of the damage site.

The discovery and explanation of this difference formed the basis of a collaborative program with medical researchers on the interaction of short laser pulses with human tissue. Laser ablation of tissue (removal of tissue by its being "blown off") has great promise in a number of therapeutic situations requiring precise material removal with minimal disturbance of the surrounding tissue. Potential applications include precision cutting (as in keratonomy), perforation (applicable to middle ear surgery), pressure release for hydroencephaly, and dental drilling. The advantage for surgery with lasers whose pulses last less than a picosecond is that the duration is far too short to transfer heat to surrounding tissue. (See the October 1995 *S&TR* for more on LLNL efforts to develop short-pulse lasers as safe and painless surgical tools.) The ability to cut and drill material with no heat or shock has also found important application in LLNL's role in nuclear weapon stockpile management.

Two R&D 100 Awards were earned as a result of the need to manufacture diffraction gratings to a size, precision, and resistance to optical damage never before attained. The first, earned in 1994, was the development of multilayer dielectric gratings for use in dispersing light into constituent colors, or wavelengths, for many different applications. These gratings, made of multiple layers of thin dielectric film, have much higher damage thresholds than metallic gratings and can be custom designed for narrow- or broad-bandwidth use. Besides their use in new generations of extremely high-powered lasers, they may be used in entirely new products in such areas as remote sensing and biomedical diagnostic systems. (See the September 1994 *E&TR* for more information.) Furthermore, the grating development laboratory and technology will be used for developing the extensive diffractive optics used throughout the final focus assembly of the planned National Ignition Facility.

The technology developed to produce the multilayer and metallic gratings with extremely small features (down to 0.1 micrometer) may also give a dramatic boost to American producers of flat-panel displays. The LLNL process to laser interference lithography enables the production of large-area field-emission displays (FEDs). This display can be thinner, brighter, larger, and lighter and can consume less power than traditional active matrix liquid crystal displays. The new technology earned its inventors an R&D 100 Award in 1996 (see the October 1996 *S&TR*).

fabricated, and installed. Significant modifications to the ten-beam target bay were performed over many weekends, when the Nova laser is usually not used for target experiments. A new beamline was installed to route the beam from the Petawatt's master oscillator room to the disk amplifier section of Nova's beamline number 6 for final amplification. A particularly challenging task was installation of the enormous compression chamber in the target bay without disrupting the normal operation of the Nova system.

With everything in place, three series of experimental shots were performed. In the first series, performed in December 1994, the Petawatt's beam was propagated to Nova's two-beam target bay to study CPA effects. For the second shot series, performed in March 1995, the beam was propagated into the newly constructed compression chamber to produce a short pulse length. Following the March 1995 shot series, the new injection beamline between the Petawatt's master oscillator room and the Nova preamplifier was activated, along with the compression chamber vacuum system and a full suite of optical diagnostics. The final test series performed in May 1996 produced the record-shattering result, but not without exceptionally hard work. "We had to work 16-hour days, 7 days a week for more than a month to make sure everything was ready for the demonstration shots. It was a true team effort between the Nova engineers, operations crew, and the Petawatt project team," recalls Perry, who furnished non-alcoholic champagne for the historic night. (See Figure 4.)

Four Options

As the Petawatt laser is now configured, the beamline from the underground master oscillator room can take one of four courses. First, it can be injected into the Nova chain to the Petawatt's compressor chamber and used along with nine of Nova's ten beams as a large-scale hybrid system to test the fast-ignitor concept and investigate new concepts in laser–matter interactions and plasma physics. Second, the beam can be shunted to a small room next door to the master oscillator room, where it is used for researching issues related to the use of lasers in medicine and material processing, development of plasma mirrors, and harmonic conversion to a shorter wavelength for Nova x-ray diagnostics development.

Third, through early next summer, the laser can be used as the core of a 100-trillion-watt laser to study plasma physics and begin research on fast-ignitor physics. Finally, early this winter, a target chamber will be installed between the Petawatt's compression chamber and Nova's ten-beam chamber. It will permit the Petawatt laser to be used independently of Nova.

The decision to develop a target chamber exclusively devoted to petawatt laser use, while retaining the ability to perform experiments in Nova's ten-beam target chamber, was prompted by the high level of interest expressed by researchers at LLNL and other centers.

Building a petawatt target chamber makes good sense, says Perry, "because it will allow us to work the bugs out of the Petawatt's focusing system and enable simple, single-beam experiments without impacting operation of the Nova chamber."

The 100-TW laser was constructed in early 1995 as a crucial stepping stone to the Petawatt. Using most of the Petawatt's components, but not taking advantage of the full complement of Nova's amplifiers, the 100-TW is connected to Nova's two-beam target area. It was successfully test fired for the first time on July 31, 1995, surpassing the 120 trillion watts produced by Nova and making it the most powerful laser ever tested at the time.

"The 100-TW was only a warm-up for the Petawatt," says project engineer Greg Tietbohl, noting that the laser has been used to test some of the basic concepts and advanced components underlying the Petawatt. Laser–plasma experiments being performed on the 100-TW laser are producing data that enable the design of a more comprehensive series of experiments to test the fast-ignitor concept on the Petawatt. The 100-TW laser continues to operate as the world's second most powerful laser, and it is now used extensively by researchers from LLNL and the international university community. The 100-TW operations will end in July 1997 because Nova's two-beam target bay will be disassembled in order to build an optics assembly area for NIF.

Figure 4. The Livermore crew after the first successful accomplishment of petawatt peak power (1,250 trillion watts) on May 23, 1996.

Focusing Petawatt Pulses

A significant problem with petawatt pulses is how to focus them. Conventional approaches such as lenses or mirrors with debris shields cannot be used because these both involve transmissive optics that would be damaged by the extreme power density of the petawatt pulse (over 700 GW/cm^2).

A radical concept proposed by Perry and Associate-Director-at-Large John Nuckolls was the use of a so-called "plasma mirror." The intense petawatt beam strikes the front surface of a piece of polished glass, creating a very-short-lived critical-density plasma in the early part of the pulse. Because the petawatt pulse is so short, the plasma does not have time to expand during the pulse. The remainder of the pulse then reflects off the critical-density plasma and strikes the target of interest.

The resulting detonation of the target creates a large amount of debris (typical of all target experiments) that hits the plasma mirror substrate instead of sensitive and expensive diagnostic equipment and optics. (See Figure 5 for the difference in optical- and plasma-mirror irradiances.) The curvature of the mirror can be easily changed to accommodate a wide variety of experimental conditions and targets. To date, over 90% reflectivity has been demonstrated in small-scale experiments conducted with the Petawatt's front end.

Possible Key to Fast Ignition

The Petawatt provides researchers with their first tools to explore the fast-ignitor fusion concept, conceived by Livermore's Max Tabak and others in 1992. Focusing a high-power laser pulse gives rise to an extremely high density of energy, or light pressure. This light pressure can enable the laser pulse to interact with very-high-density material at the core of an imploded fusion pellet instead of being stopped by lower-density plasma in the corona. These intense pulses also generate large amounts of energetic electrons. These high-intensity phenomena form the basis of the patented fast-ignitor fusion concept. (See Figure 6.)

In this scheme, laser energy compresses a spherical volume of fusion fuel to high density—exactly as in the conventional approach to ICF. However, conventional ICF relies on the formation of a hot central core

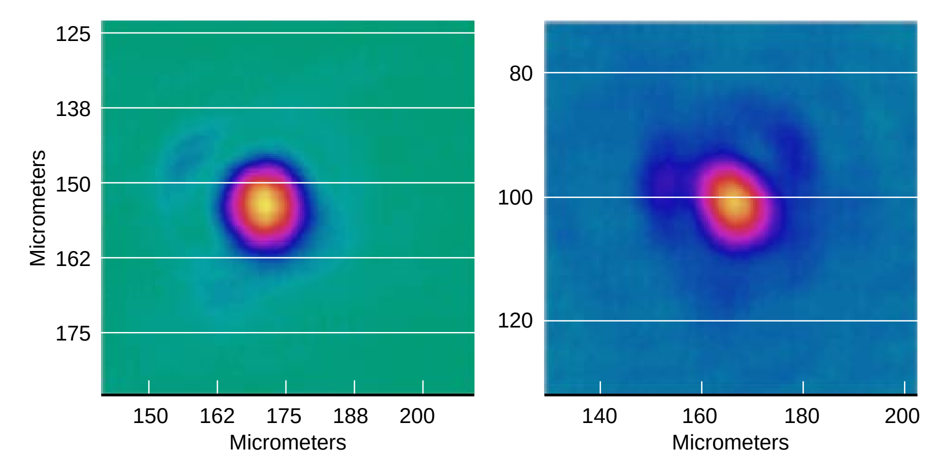

Figure 5. False-color contour plot of far-field irradiance distributions from (a) a precision optical mirror (diffraction-limited spot) and (b) a plasma mirror.

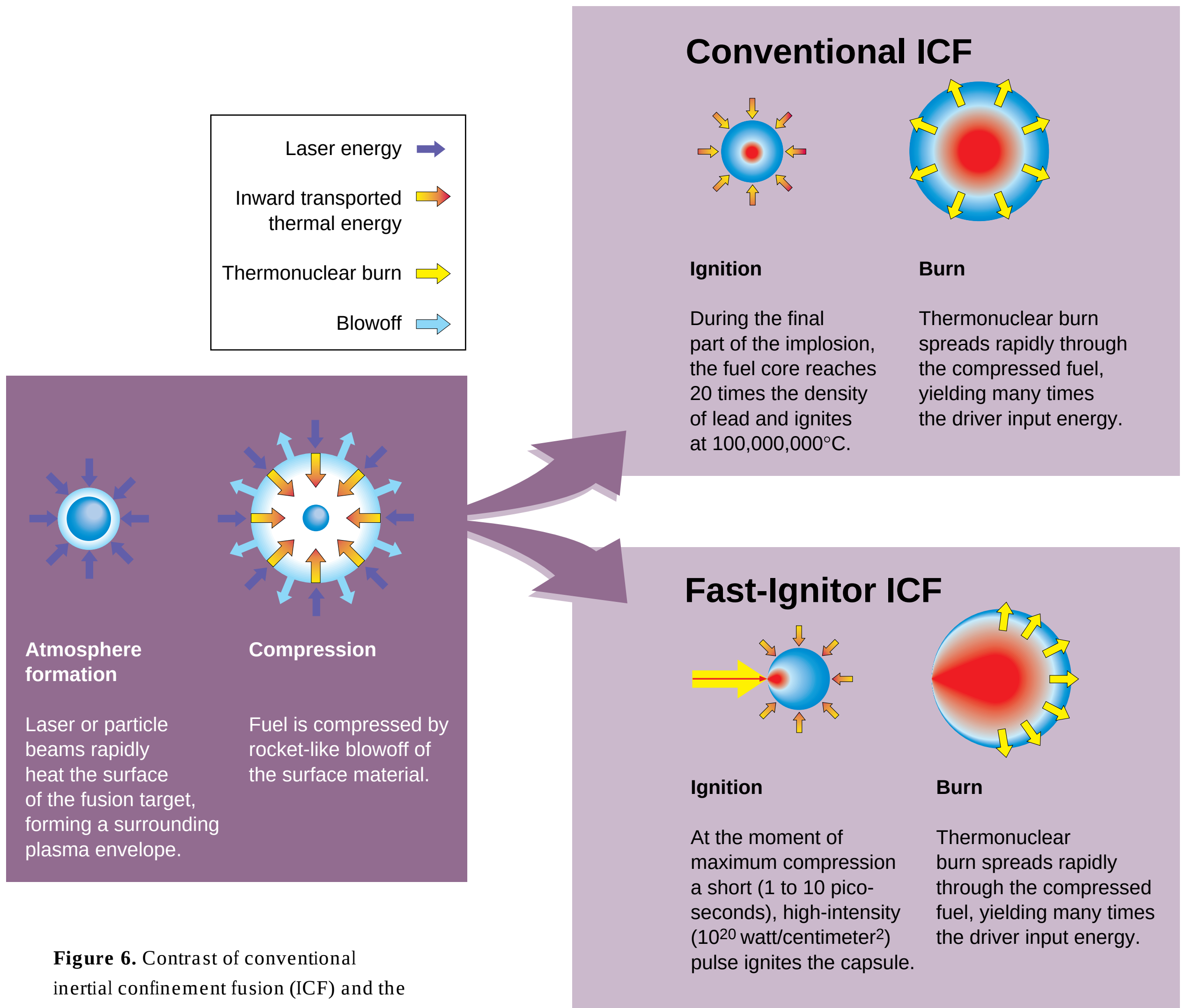

Figure 6. Contrast of conventional inertial confinement fusion (ICF) and the fast-ignitor ICF, which is used on the Petawatt laser.

within the dense deuterium–tritium fuel to spark ignition. This condition is achieved by the rapid, highly symmetrical and spherical implosion of the capsule driven by pulses delivered either directly by many laser beams or indirectly by x rays. Because of the extreme requirements on symmetry and the necessity to achieve both high temperature and density in the implosion, conventional ICF requires substantial energy and precision from the laser.

By contrast, the fast-ignitor concept adds two laser beams that are timed to strike the target at the moment of maximum compression. Because the Petawatt was conceived to use Nova, eight of Nova's ten beamlines would strike the target and form a plasma. Then a 1-TW, 100-picosecond channeling beam supplied by the Petawatt laser bores through the plasma and pushes the deuterium–tritium fuel in its path toward a higher density near the core of the target. At the optimum moment, a petawatt ignitor beam propagates through the channel formed by the channeling beam, striking the high-density, preimploded core. The petawatt pulse generates hot, high-energy electrons, which instantaneously raise a small region on the periphery of

the core to over 100 million degrees Celsius. The fusion burn propagates from this small volume on the edge throughout the remaining fuel before hydrodynamic disassembly of the core.

The fast-ignitor technique offers, in principle, a method of reducing the energy and precision required to achieve ignition compared with conventional ICF. Perry cautions that, compared with the firm scientific foundation of conventional ICF, the fast-ignitor concept is still in its infancy because it resides in a region of untested physics. If, however, upcoming fast-ignition tests prove successful, a petawatt laser could be added to the NIF for fast-ignitor capability at a moderate additional cost.

The Petawatt's beam would be fired to inject energy into a small region of the deuterium–tritium target capsule to initiate ignition a few billionths of a second after NIF's beams are fired. A Petawatt–NIF combination might enable the achievement of a higher fusion energy gain than currently envisioned.

A New Chapter in Physics

The ultrashort pulses and extremely high irradiance of the Petawatt laser will also enable researchers to advance their understanding of laser–matter interactions and, indeed, advance understanding of the fundamental nature of energy and matter. The enormous irradiance that will be generated by the Petawatt, some 10^{21} W/cm^2, will make possible an irradiance unlike any produced in the laboratory to date. These unprecedented laboratory conditions will be characterized by electric fields about 100 times stronger than the field that binds electrons to atomic nuclei. Such fields have the potential to trap electrons and accelerate them to high energies within just a few centimeters, instead of many kilometers as in conventional particle accelerators.

The enormous electric fields created by the Petawatt will impart enormous oscillatory ("quiver") energy to the free electrons in the plasma. At 10^{21} W/cm^2, the quiver energy of a free electron would be more than 10 million electron volts. The electrons would be moving at speeds approaching the speed of light and at densities never before seen in the laboratory.

These plasmas will be similar to those believed to exist in many astrophysical objects. Scientists could then study conditions predicted to exist in the center of stars and surrounding celestial bodies such as black holes and brown dwarves.

Additionally, high-energy photons (0.1 to 10 megaelectron volts) produced from the interaction of the petawatt pulse with high-atomic-number targets offer the potential for time-resolved radiography of dense objects. The short-pulse duration, potentially small source size, and simple production of multiple pulses separated in time make this an attractive source for multiple-exposure flash x-ray radiography. The plasmas themselves can provide important information to Lawrence Livermore scientists supporting DOE's Stockpile Stewardship and Management Program.

The Petawatt laser is currently undergoing a long series of tests as it is transformed into an operational facility for target experiments. Its development is expected to continue into the next decade as LLNL scientists continue to advance the state of the art in optics and the technology of short-pulse lasers. Perry notes that several years of hard work lie ahead in exploring the fast-ignitor concept with the Petawatt. The overall goal, as it was with the development of Livermore's first generation of lasers, is to speed the arrival of laser fusion as a source of virtually inexhaustible energy for society. Another goal, admittedly closer at hand, is to aid the nation's Stockpile Stewardship Program.

Key Words: chirped-pulse amplification, fast ignition, laser interference lithography, multilayer dielectric gratings, National Ignition Facility, Nova, Petawatt laser, plasma mirror, Ti:sapphire laser, 100-TW laser.

For further information contact Michael Perry (510) 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 (Summa Cum Laude, 1983), an M.S. in nuclear engineering (1984), and a Ph.D. in nuclear engineering/physics (1987). He is currently the leader of the Petawatt Laser Project and Associate Program Leader for Short-Pulse Lasers, Applications, and Technology. He has authored more than 70 professional publications.