

Empowering Light


Historic Accomplishments in Laser Research


"The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them."

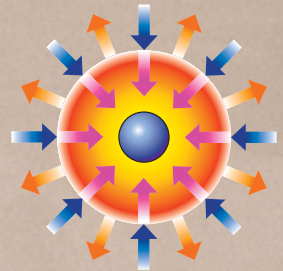
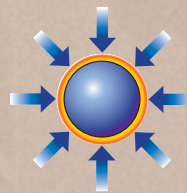
**—Sir William Henry Bragg,
Nobel Prize for Physics, 1915**

WITH the flash of the first ruby laser in 1960, a new technology was born that would come to play a major role at Lawrence Livermore National Laboratory. At the time of the laser's first demonstration, the Livermore branch of the University of California's Radiation Laboratory was eight years old. A moratorium on nuclear weapons testing was in effect, and Livermore's weapon designers were deploying systems, such as the warhead for the Polaris missile, that had been tested before the moratorium took effect in 1958, and devising increasingly sophisticated computer codes to investigate the extremely complex physical phenomena involved in nuclear explosions.

The steps of an inertial confinement fusion reaction, in which more energy is produced than is used to initiate ignition. Under laboratory conditions, the sequence produces energy gain equivalent to the power of a miniature star lasting for less than a billionth of a second.

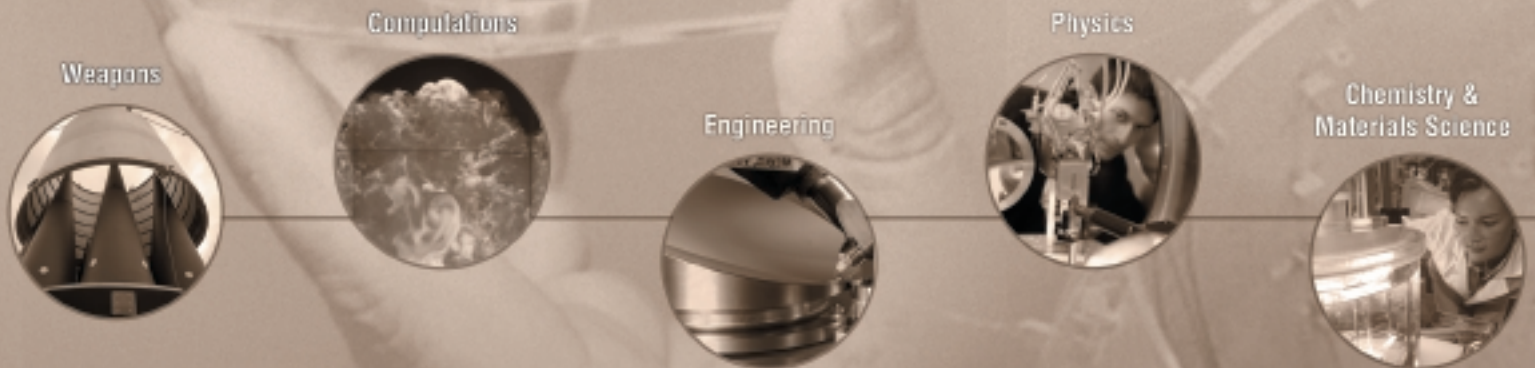
 Radiation

 Blowoff



Laser beams or laser-produced x rays rapidly heat the surface of the fusion target, forming a surrounding plasma envelope.

Fuel is compressed by the rocketlike blowoff of the hot surface material.



The laser—with its highly coherent and focusable light—caused Livermore scientists to sit up and take notice. Several, including physicist John Nuckolls, began postulating possible uses for this amazing invention. Their musings reflected Livermore’s ongoing work in nuclear weapons design and controlled thermonuclear reaction (fusion) research. How small a thermonuclear reaction could be created in a controlled laboratory environment? Could a laser be used to create such a reaction? Such controlled reactions held out the promise of understanding better the complex interactions within nuclear weapons and the possibility of developing a new source of energy through fusion.

A Frontier Beckons

For half a century, the Laboratory has explored ways of producing energy from fusion, the nuclear reaction that powers the Sun and stars and gives nuclear weapons their awesome power. Fusion holds out the promise of providing a clean and inexhaustible source of commercial electric power production. From the start, Livermore pursued the magnetic confinement concept for producing fusion power, in which intense magnetic fields trap a plasma long enough to achieve

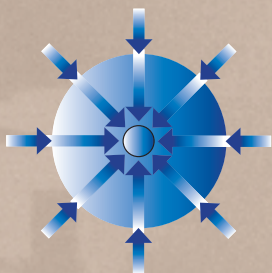
fusion. (See *S&TR*, May 2002, pp. 16–21.) The laser presented another option for obtaining energy from the fusion process. Shortly after the laser’s invention, Livermore used weapon design codes to study the possibility of using powerful, short laser pulses to compress and ignite a small quantity of fusion fuel composed of tritium and deuterium—two isotopes of hydrogen—in a process dubbed inertial confinement fusion (ICF).

These original calculations revealed that just heating the fusion fuel with the energy from laser light would not be enough to generate net energy, even with lasers as large as 1 million joules. To achieve energy gain—that is, more fusion energy released than energy required to initiate the fusion reaction—the laser would also have to compress the fuel to about 1,000 times its liquid density. Just scaling up existing lasers appeared no mean task, given that, at its inception, the laser’s top energy production was about 1 joule and its power about 1 kilowatt. It was also a high-risk task both scientifically and financially. A great deal of cutting-edge science and technology had to be developed at a cost difficult to estimate.

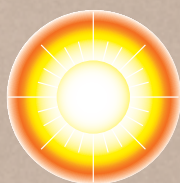
In 1962, the Laboratory started a small laser fusion project in its physics organization. The project focused on building more powerful and efficient lasers, exploring basic aspects of light–plasma interactions, and developing high-power, short-pulse lasers. Another group of physicists focused on designing fuel pellets and upgrading calculation methods. From 1962 to 1970, these early efforts produced a number of firsts including a computer program specifically designed for laser implosion calculations and a multibeam laser system for irradiating various targets. Long Path, a neodymium-doped glass (Nd:glass) laser completed in 1972, was designed to provide 40 to 50 joules of energy in 10-billionths of a second and was part of early laser and target research at Livermore.

As the decade turned, major advances in laser technology presented the possibility for high-energy systems, and new computer calculations suggested that by carefully shaping the laser pulse, targets could be ignited with less energy than originally predicted. In 1971, Laboratory Director Michael May asked Associate Director for Plans Carl Haussmann to draw all the Laboratory’s laser efforts together. (See *S&TR*, January/February 1999, pp. 4–11.) Haussmann moved swiftly

➔ Inward transported thermal energy



During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.



Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

Nonproliferation



Energy & Environment



Stockpile Stewardship



Lasers



Biotechnology





The 4 pi laser system, dating from the mid-1960s, had 12 ruby laser beams arranged around a gas-filled target chamber about 20 centimeters in diameter. Physicist Frank Rainer (inset), who has been involved in laser research and development at the Laboratory since 1966, holds the target chamber seen at the center of the larger picture.

to focus Livermore's laser work. With a few phone calls and visits to the Division of Military Application at the Atomic Energy Commission (predecessor of the Department of Energy), he committed Livermore to building a 10-kilojoule laser system, the largest laser fusion facility in the country. He then brought in John Emmett and Bill Krupke—who were responsible for advanced laser research at the Naval Research Laboratory and Hughes Aircraft, respectively—to get the program up and running. The era of increasingly large and more energetic solid-state lasers at the Laboratory began.

Paving the Way with Big Laser Systems

In the early 1970s, various types of lasers were being studied for ICF: carbon dioxide, Nd:glass, hydrogen fluoride, and atomic iodine. Basic considerations of plasma physics, coupled with Livermore computer calculations, indicated to Laboratory scientists that delivering the laser energy to the target at shorter wavelengths was extremely important. Under

Hausmann and Emmett, the Laboratory decided to focus on solid-state laser systems, in which the energy in laser light is amplified in a solid material such as glass disks. For amplifiers, they chose Nd:glass, which had a relatively short wavelength in the infrared portion of the spectrum, stored energy well, and could be made in large sizes. Nd:glass amplification made for lasers with high flexibility in pulse duration, wavelength, and bandwidth.

Over three decades, the Laboratory designed and built a series of lasers, each bigger, more complex, and more powerful than the last, beginning with one that delivered 10 joules in a single beam to one that will deliver 1.8 million joules in 192 beams. (See the [box on p. 23](#).) These unprecedented projects drew on expertise from nearly every area of the Laboratory and were the basis for numerous collaborations with outside industry and the larger fusion research community. Concurrently, researchers also developed increasingly sophisticated diagnostic instruments needed for measuring and observing what was happening in the laser systems and their experiments. (See the [box on p. 25](#).)

In 1974, Livermore finished the one-beam, 10-joule Janus laser and used it to conduct the first fusion experiments at the Laboratory. It was used to demonstrate for the first time the thermonuclear reaction in laser-imploded deuterium–tritium fuel capsules. Starting in 1974, the two-beam Janus laser was used to gain a better understanding of laser–plasma physics and thermonuclear physics. It was also used to improve the LASNEX computer code, a hydrodynamics code developed in the 1970s for laser fusion predictions, which is still in use today.

The one-beam Cyclops was also completed in 1974. Its beamline was a prototype of the yet-to-be built Shiva laser. Cyclops was used as a test bed for optical designs, including those aimed at negating a nonlinear phenomena that occurs with intense light. Krupke explains, “If the intensity of the light gets high enough—as in fusion lasers—the electric field in the light perturbs the atoms of the glass so strongly that the glass responds in a nonlinear way.” As a result, the beams tended to self-focus to the point of boring holes through the glass. A team of lasers scientists measured the phenomenon in glass of different compositions. In 1974, they connected their measurements to the types of measurements routinely made by glass companies to characterize their glass. “It was like the Rosetta stone,” says Krupke. “With this quantitative correspondence, they were able to plot the nonlinear refractive performance of millions of glasses and find the one with the lowest possible value. We then worked with our industrial partners to make a composition with the characteristics we needed.”

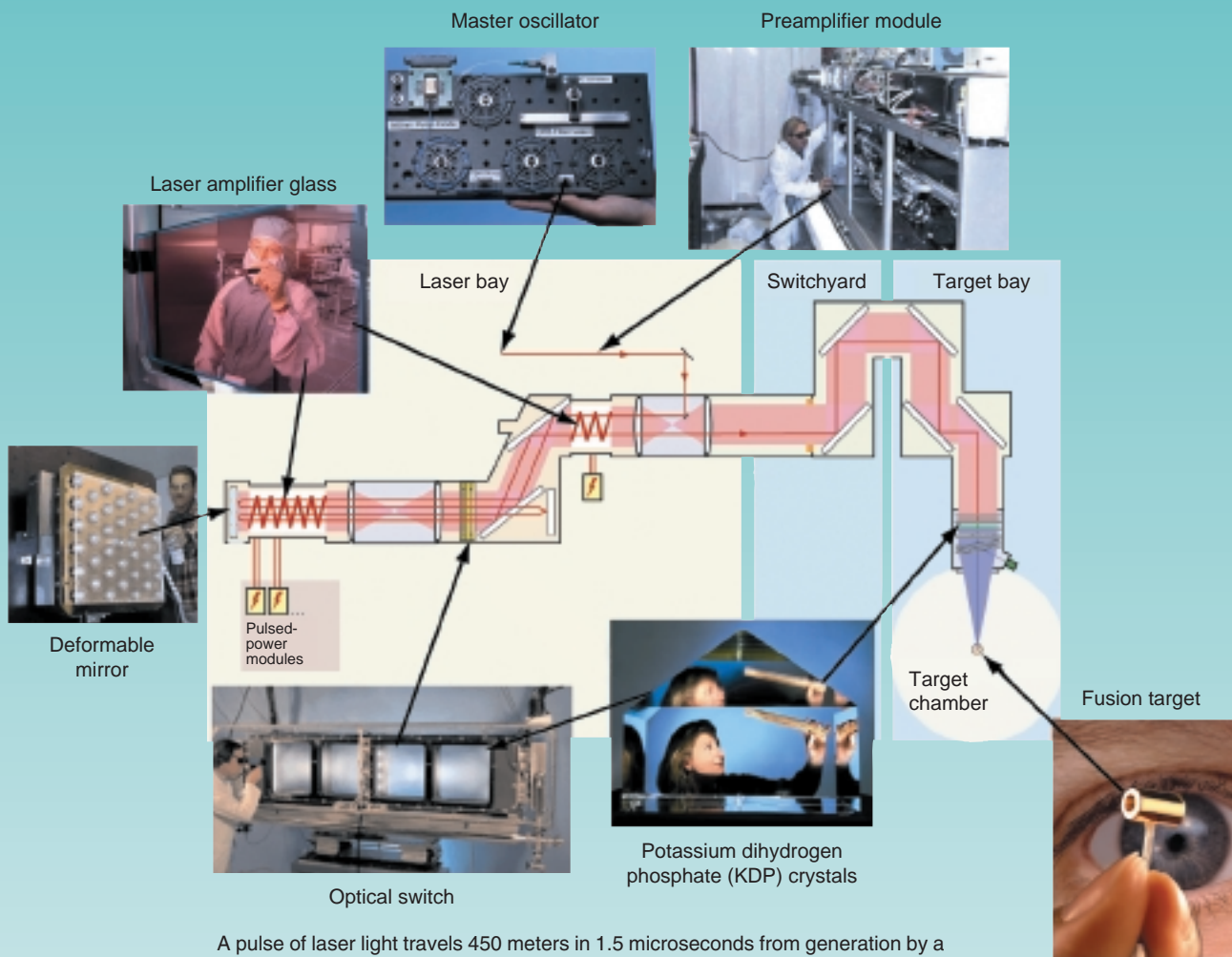
Laser scientists also used Cyclops to demonstrate how spatial filters could be used to remove nonlinear “noise.”

The Path of a Laser Pulse

Generating enough laser energy to cause fusion, thereby simulating the physical interactions in the Sun, stars, and nuclear weapons, is an exacting process. In Livermore's National Ignition Facility (NIF), the journey begins with a weak infrared laser pulse, with energy of about 1 nanojoule and a diameter of 1 micrometer produced by the master oscillator. That pulse is amplified by the preamplifier and split into 192 pulses of 10 joules each. The pulses enter the main laser system, where each light pulse makes four passes in a beampath containing mirrors, optical switches, lenses, spatial filters, and laser amplifier glass. This multipass concept was one of the design breakthroughs of NIF. Without it, the facility would have had to be over 300 meters long for the pulses to be amplified to the required energy. Each pulse reflects off a

deformable mirror to correct for aberrations that accumulate in the beam as a result of minute distortions in the optics.

Once the beams—now 40 centimeters square—have been amplified to the required energy level (about 20 kilojoules per beam for routine operation for inertial confinement fusion experiments), they enter the switchyards where mirrors turn, or redirect, the beams into a radial, three-dimensional configuration around the target chamber. Just before entering the chamber, each pulse passes through a final optics assembly where the pulses are converted from infrared to ultraviolet light with potassium dihydrogen phosphate crystals and focused to deliver a total of 1.8 megajoules of energy to the target. Each NIF laser pulse will travel 450 meters from start to finish, a journey taking 1.5 microseconds.



A pulse of laser light travels 450 meters in 1.5 microseconds from generation by a master oscillator to delivery on the target.

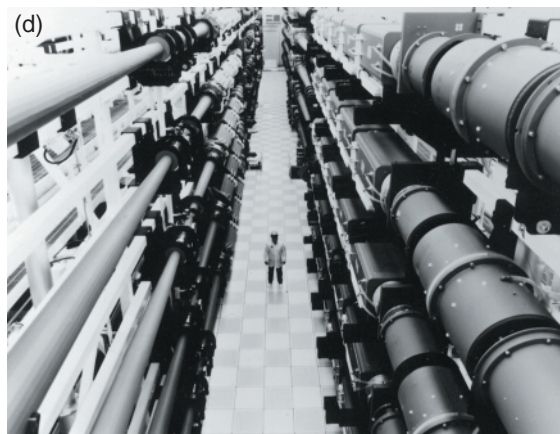
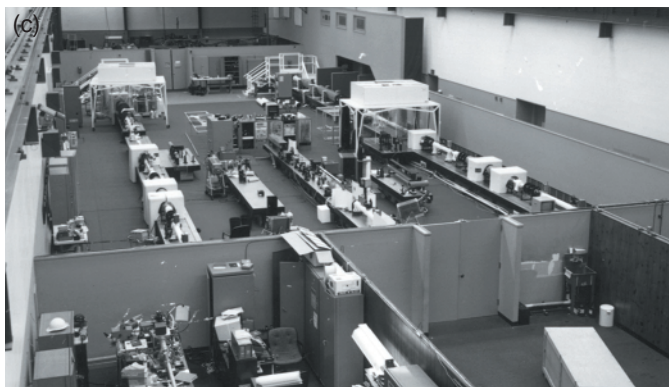
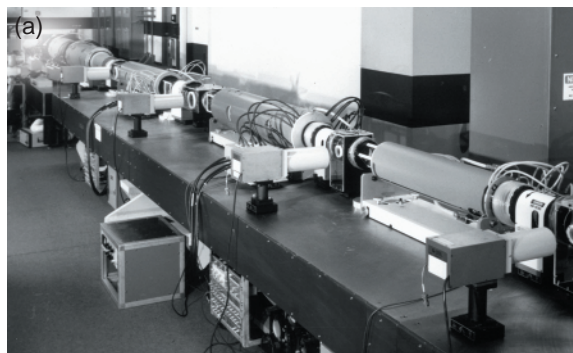
Imaging spatial filters are, in effect, small inverted telescopes inserted in laser beamlines to focus the laser light through pinholes, thus stripping away the noise, or residual nonlinear self-focusing instabilities of the beam that accumulate in the pulse during amplification. These filters essentially “freeze” the noise level of the laser beam and do not permit it to develop further. The beam can thus be relayed from one amplifier to another virtually noise-free. Janus target experiments confirmed the improved beam quality.

In 1976, the two-beam Argus came online. Use of Argus increased knowledge about laser–target interactions and laser propagation limits and helped program researchers develop technologies needed for the next generation of laser fusion systems. Argus was the first laser to have spatial filters engineered into it so that the beam could be relayed from one amplifier to another while preventing the amplification of the intensity fluctuations, or spikes, that led to optical damage known as angel’s hair, or filamentation.

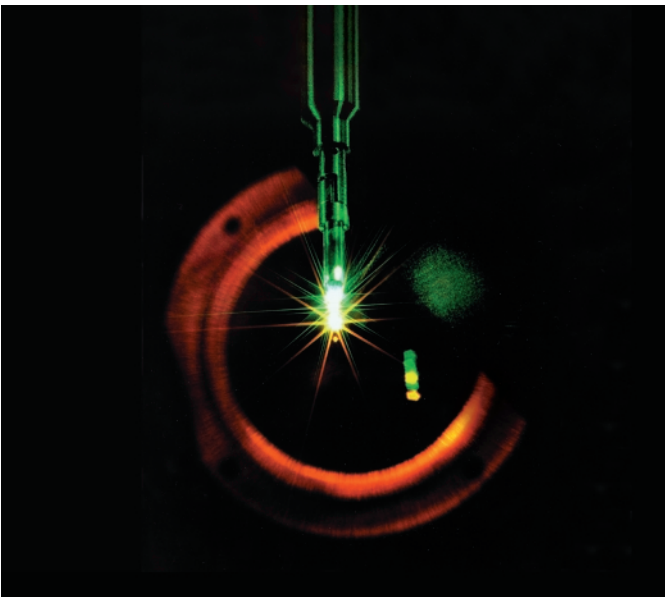
The 20-beam Shiva became the world’s most powerful laser in 1977, delivering 10.2 kilojoules of energy in less than

a billionth of a second in its first full-power firing. In June 1979, Shiva compressed fusion fuel to a density of 50 to 100 times greater than its liquid density. Even more important, according to John Holzrichter, who was responsible for the laser and ICF programs at the time, Shiva proved once and for all that infrared laser light was too long a wavelength to reach fusion energy gain. Says Holzrichter, “The laser beam generates a dense plasma where it impinges on the target material. The laser light gives up its energy to the electrons in the plasma, which absorb the light. The rate at which that happens depends on the wavelength and the intensity. On Shiva, we were heating up electrons to incredible energies, but the targets were not performing well. We tried a lot of stuff to coax the electrons to transfer more of their energy to the target, with no success.”

Results from computer codes and physics theory led ICF researchers to believe that pulses of shorter wavelength were



From 1973 to 1977, the Laboratory built four laser systems: (a) the one-beam Cyclops; (b) the one- and two-beam Janus system, which is still in use; (c) the two-beam Argus; and (d) the 20-beam Shiva. Each new laser provided more power and better control over the target-irradiation conditions as well as produced higher temperatures and greater compression and density in the deuterium–tritium fuel than its predecessor.



This miniature “star” was created in the Nova laser target chamber as 300 trillion watts of power hit a 0.5-millimeter-diameter target capsule containing deuterium–tritium fuel.

needed to suppress the production of these hot electrons and transfer that energy to the target. Frequency conversion crystals were added to Argus to change the laser light to a shorter wavelength, and experiments began to validate the benefits of the shorter wavelength.

Novette, which began operation in 1983, was the first laser to be engineered with optical frequency converters made of potassium dihydrogen phosphate (KDP) crystals, which converted the infrared light to shorter wavelengths. (See the [box on p. 26.](#)) Novette was a test bed and an interim target facility between Shiva and the 10-beam Nova, the next system in line.

Ten times more powerful than Shiva, Nova became the world’s most powerful laser. In 1986, Nova produced the largest laser fusion yield to date—a record 11 trillion fusion neutrons. The following year, Nova compressed a fusion fuel

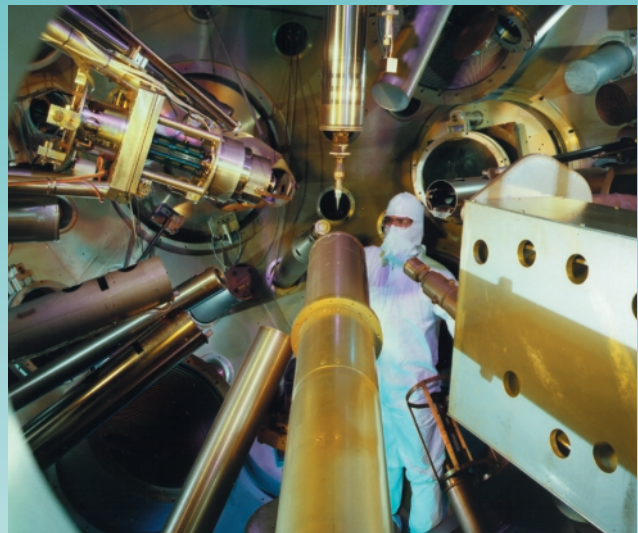
Measurements Fast and Small

Experiments are all about measurement. From the beginning, those who developed lasers and conducted experiments on them have wanted to measure properties such as the shape of the laser pulse, the interactions of laser light with materials, and the physics of the target. Most of these measurements occur over brief time scales (less than billionths of a second) and short distances (micrometers) and involve measuring a variety of particles such as protons, neutrons, electrons, and photons at energies from infrared to x-ray. In the early 1960s and 1970s, diagnostic systems that could obtain information on these scales were considered extremely challenging to build and field. To develop its diagnostics, the new laser program turned to the Laboratory experts in measuring extreme conditions—the physicists, engineers, and technicians who developed and fielded diagnostics for weapons-related tests.

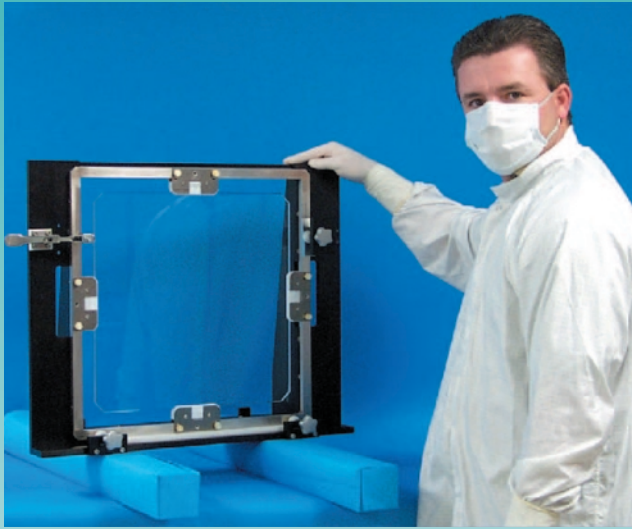
A variety of instruments evolved. A compact, ultrafast version of an optical streak camera helped laser designers determine whether their lasers were generating pulses of the right duration and shape. Zone plates, or coded apertures, measured alpha particle emissions, capturing the first images of alpha particles from thermonuclear burn of deuterium–tritium. X-ray streak cameras helped inertial confinement fusion (ICF) researchers define the compression physics of the ICF process. Neutron time-of-flight systems measured velocity variation in neutron bursts to help determine target performance. Photoconductive detectors measured how long fusion reactions lasted.

The National Ignition Facility (NIF) will use hundreds of cameras, detectors, and sensors to diagnose each beam from its first weak infrared pulse to its final, full-power ultraviolet configuration at the center of the target chamber. Other diagnostics that will gather information about ICF and high-energy-density experiments include the world’s fastest optical

camera, operating with an electronic shutter speed of 30-trillionths of a second, and possibly miniaturized diamond detectors to detect neutrons. Development continues on systems for experiments, including a velocity interferometer that will be used in NIF’s first physics experiment to measure the velocity of the shock wave on a foil. The experiment, scheduled for 2003, will direct the energy of four NIF beams—equivalent to the total energy of Nova—on a foil to explore the equation of state of materials.



Inside the main chamber of Nova (the predecessor system to the National Ignition Facility), diagnostics surround the target mounted at the end of the rod in the chamber’s center.



To get from the “as grown” crystal shown at the bottom of p. 23 to the finished pieces shown above—some as large as 41 centimeters across—requires precision machining and finishing. Plates sawed from the crystal are machined to the proper size and flatness before the final finishing, which is an exacting process. (See *S&TR*, January/February 1998, pp. 12–19.)

Fast-Growing Crystals

Beginning with the Argus system, thin plates of potassium dihydrogen phosphate (KDP) crystals have been used to convert the infrared laser light (at a wavelength of 1,053 nanometers, often referred to as 1-omega light) to high harmonic, shorter frequencies—green-blue (527 nanometers, or 2-omega) and ultraviolet (351 nanometers, or 3-omega).

The crystals are also used to rotate the light’s polarization for switching laser light in and out of the amplifier sections. The development of a technology to quickly grow high-quality crystals stretches back more than a decade. The fast-growth method was pioneered by Natalia Zaitseva at Russia’s Moscow State University and perfected at Livermore by Zaitseva and Laboratory scientists in the 1990s. In 1994, this effort garnered an R&D 100 Award for developing the process that produced high-quality KDP crystals for inertial confinement fusion lasers. (See *Energy & Technology Review*, November 1994, pp. 5–6.) In 1996, the team produced in only 27 days a KDP crystal measuring 44 centimeters across. (See *S&TR*, November 1996, pp. 12–20.) Under standard growing conditions, such an accomplishment would have taken up to 15 months. The following year, the Livermore team produced the world’s largest single-crystal optical element—a pyramid-shaped KDP crystal measuring about 1 meter tall and weighing nearly 180 kilograms—in 6 weeks. Previous methods would have required a growing period of 12 to 24 months to achieve the same result.

target to about one-thirtieth of its original diameter, close to that needed for ignition and fusion gain. In 1996, one arm of Nova was reconfigured as a petawatt laser. (See *S&TR*, March 2000, pp. 4–12; December 1996, pp. 4–11.) Record-setting laser shots produced pulses with more than 1.3 quadrillion watts, or 1.3 petawatts, of peak power. The laser pulse lasted less than 0.5 trillionth of a second—more than a thousand times shorter than shots typically produced by Nova’s 10 beams.

When the United States ceased nuclear testing, laser facilities became even more important for defense research, and the portion of Nova shots dedicated to the weapons program increased considerably. Researchers using Nova continued obtaining high-energy-density data necessary to validate the computer codes used to model nuclear weapons physics.

The Next Step Up

Work on Nova prepared the Laboratory to tackle construction of the 192-beam National Ignition Facility (NIF), where scientists expect to apply the lessons learned from past laser research to achieve fusion ignition and energy gain. (See *Energy & Technology Review*, December 1994, NIF special issue). Beamlet, the prototype of NIF, was also essential to demonstrating the viability of the new laser system. Operated

at the Laboratory between 1994 and 1998, Beamlet showed that the multipass laser architecture conceived for NIF was capable of meeting the fluence (energy per unit area) requirements prescribed by the National Academy of Sciences—5 to 6 kilojoules of ultraviolet energy in a 3-nanosecond pulse with a 30-centimeter beam. In August 1994, Beamlet achieved 6.4 kilojoules in a 29.6-centimeter beam. Eight months later, Beamlet improved its performance to produce 8.3 kilojoules in a 34-centimeter beam. Both of these milestones demonstrated the viability of NIF’s multipass laser architecture and other critical enabling technologies.

Groundbreaking for the stadium-size NIF took place in May 1997. (See *S&TR*, September 1999, pp. 21–23.) An extremely ambitious and technically challenging project, NIF is the culmination of 30 years of building increasingly powerful and complex Nd:glass lasers. NIF’s primary goal is to achieve ignition—a feat necessary for its role in stockpile stewardship and inertial fusion energy (IFE) development. NIF is a key component of the nation’s Stockpile Stewardship Program to ensure the safety and reliability of the nuclear deterrent and will allow weapon scientists to perform vitally needed physics experiments to validate aspects of the physics of thermonuclear weapons. Additionally, NIF will serve as a national and international center for the study of IFE and the

physics of matter under conditions of extreme temperature, energy density, and pressure.

NIF is both the largest laser and the largest optical instrument ever built, requiring 7,500 large optics (more than 30 centimeters across) and more than 30,000 small optics. The design, manufacture, and assembly of these important pieces have called for innovative ways to make optics of higher quality than ever before and to do so at unprecedented speeds and at lower cost. Livermore scientists, working with two industrial partners, met this challenge by developing the Continuous Laser Glass Melting Process. This process converts high-purity, powdered raw materials into one continuously moving strip of high-optical-quality laser glass, 1 meter long and 0.5 meter wide. This award-winning process is 20 times faster and 20 percent less expensive than the one-at-a-time process it replaces. And the resulting glass has 2 to 3 times better optical quality.

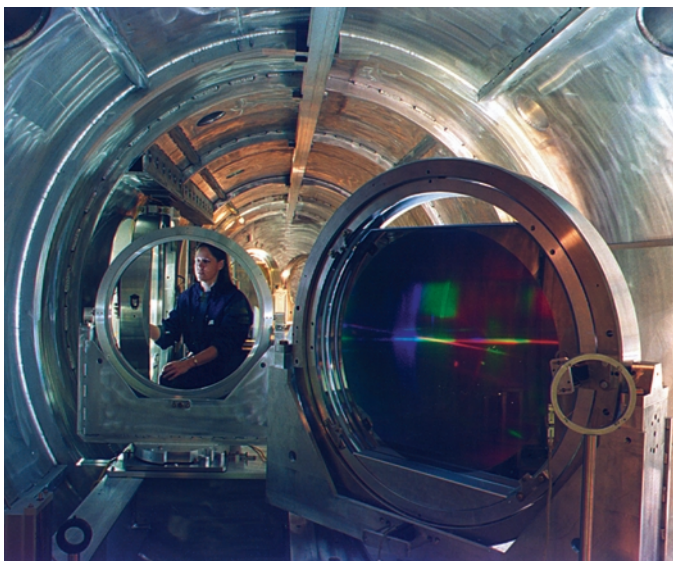
NIF is designed to deliver a total energy of 1.8 million joules of ultraviolet light to the center of a 10-meter-diameter target chamber. This energy, when focused into a volume less than a cubic millimeter, can provide unprecedented energy densities in a laboratory setting. In ICF experiments, NIF's laser beams will converge on a target containing a BB-size capsule of deuterium-tritium fuel, causing the capsule to implode and release about 10 times the energy used to drive the implosion. (See the [box on p. 29](#).) The NIF schedule calls for project completion at the end of fiscal year 2008; the NIF

team's goal is to achieve "early light" in 2003 by delivering four laser beams to the target chamber.

Other Roads Taken

In the 30 years that the Laboratory has pursued its goal of developing increasingly powerful Nd:glass lasers for basic science, energy, and nuclear weapons research, other roads have opened up, roads that sometimes have led in serendipitous directions. The innovations of Livermore's laser researchers have led, for example, to the invention of the x-ray laser in the 1980s; extreme ultraviolet lithography in the 1990s, which will soon be used to produce integrated circuits; isotope separation technology in the 1970s and 1980s; "guide stars" in the 1990s to aid ground-based astronomical observation; and numerous applications for the Department of Defense and industry.

The x-ray laser concept dates to the 1970s when physicists realized that solid-state lasers could produce high enough power to ionize x-ray laser targets. (See *S&TR*, [September 1998](#), pp. 21–23.) Livermore's Novette, the precursor of the Nova laser, was used for the first demonstration of a laboratory x-ray laser in 1984. In 1997, as a result of this research and other technical and engineering developments such as Livermore's laser isotope separation efforts, the Laboratory entered an industry-government collaboration to develop extreme ultraviolet light for making future computer chips smaller, faster, and with more storage. (See *S&TR*, [November 1999](#), pp. 4–9.) The collaboration involves Lawrence



Laser physicist Deanna Pennington adjusts a diagnostic lens within the Petawatt's compressor chamber. In May 1996, the laser reached more than a petawatt (a quadrillion watts) of peak power, more than 10 times the peak power of Livermore's Nova laser.

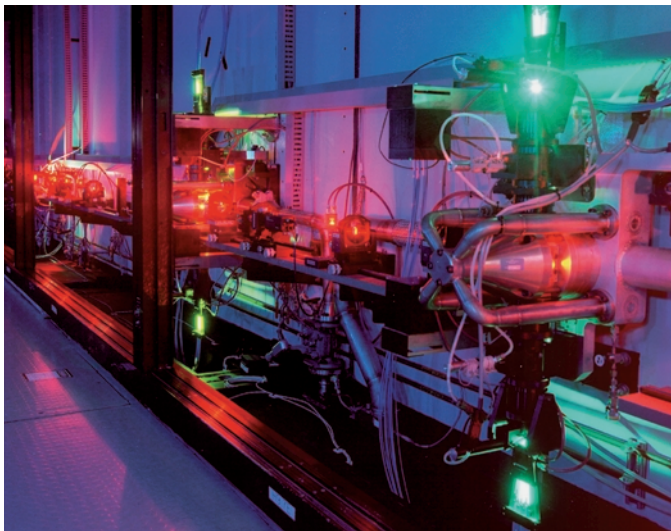


The 10-meter-diameter target chamber of the National Ignition Facility was assembled from 18, 10-centimeter-thick aluminum sections. It is located in a 7-story target bay, weighs about 450,000 kilograms, and has been precision aligned to better than 1-millimeter accuracy.

Livermore, Lawrence Berkeley, and Sandia national laboratories and a consortium of semiconductor companies including Intel, Motorola, Advanced Micro Devices, Micron Technology, Infineon Technologies, and IBM.

In the early 1970s, many analysts were projecting that there would soon be a shortage of electricity. One option was to expand the use of fission energy, which would require an inexpensive source of enriched uranium fuel. At the same time, the inherent properties of lasers were recognized as having the potential of leading to a low-cost method to produce such fuel.

The Uranium Atomic Vapor Laser Isotope Separation (U-AVLIS) program began at Livermore in 1973 to help maintain the U.S. market share of enriched uranium fuel for the nuclear power plants that would be required to meet the world's energy needs. (See *S&TR*, May 2000, pp. 13–21.) The process used dye lasers to produce a broad and almost continuous range of colors, and an optical system selected, or “tuned,” the laser to the precise color needed to separate the desired isotope. Every isotope has a unique spectroscopic signature defined by the color of light absorbed by its atoms.



During laser isotope separation, plant-scale dye laser chains absorb green light from solid state lasers and reemit it at a color that can be tuned to the isotope of interest. In the atomic vapor laser isotope separation (AVLIS) process for uranium enrichment, green light is converted to red–orange light of three different wavelengths that are absorbed only by uranium-235. Livermore's progress in large-scale engineering development and demonstration of AVLIS for uranium enrichment led the Department of Energy in 1985 to select the technology for further development. Large-scale laser programs such as AVLIS and the Nova laser brought greater industrial involvement with advanced lasers.

By precisely tuning lasers to the color signature of a specific isotope of uranium, those atoms were selectively photoionized and then electrically separated.

Based on the success of Livermore's AVLIS program, Congress created the United States Enrichment Corporation (USEC) in 1992 to move this reactor fuel enrichment process into the private sector. By the late 1990s, however, the energy economies of the world and the need for enriched uranium had changed. USEC suspended the AVLIS program in 1999.

Laser isotope separation technology is now finding other important applications in energy, medicine, astronomy, and industry. One application uses a compact dye laser similar to that used in uranium enrichment to create a laser guide star to compensate for the effects of atmospheric turbulence that blurs the images taken by Earth-bound telescopes. (See *S&TR*, July/August 1999, pp. 12–19; June 2002, pp. 12–19.) Livermore physicist Claire Max led the team that created the first upper-atmosphere guide star at the Laboratory in 1993. Since then, the technology has been installed at several leading telescopes worldwide.

Livermore's laser researchers have also developed many Department of Defense and industrial applications from this remarkable tool over the years. For the Army, researchers have developed and demonstrated a solid-state heat-capacity laser that burned a 1-centimeter-diameter hole through a 2-centimeter-thick stack of steel plates in 6 seconds. (See *S&TR*, April 2002, pp. 19–21.) This prototype of a laser tactical weapon shows promise as the first high-energy laser compact enough in size and weight to be considered part of the Army's future combat system for short-range air defense.

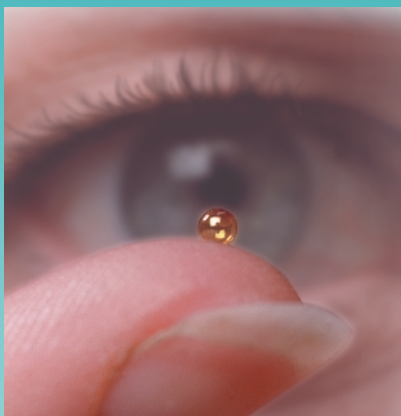
On the industrial side, a team led by physicist Lloyd Hackel collaborated with colleagues at Metal Improvement Company to develop a high-energy pulsed laser system that acts as a shock-peening tool for treating metal surfaces. (See *S&TR*, October 1998, pp. 12–13.) This system, which promises to extend the service lifetime of critical metal parts, from aircraft engine fan blades to hip joints, is rapidly becoming an industrial tool for improvement of critical components. Another laser-based system imprints permanent, high-resolution identification marks that are difficult to counterfeit, can be read by machine, and strengthen the part at the site of the mark. (See *S&TR*, September 2001, pp. 8–10.)

Frontiers Beckon Bright

Throughout its years of exploration into laser systems and technology, the laser organization at the Laboratory has contributed breakthrough after breakthrough. In the last five years alone, Livermore has been responsible for the world's most powerful laser (the Petawatt in 1996), the brightest (JanUSP in 1999), and the largest (the National Ignition Facility, under construction). The future beckons bright.

Focusing on Targets

One NIF target design resembles a typical Nova target, but at 2 millimeters in diameter, it will be four times bigger and will contain a layer of frozen deuterium-tritium to help achieve conditions supporting ignition. (See *S&TR*, July/August 1999, pp. 4–11.)

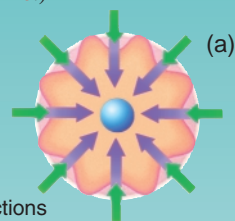


For nearly 30 years, researchers have explored and refined the design, production, and performance of targets for Livermore's Inertial Confinement Fusion Program.

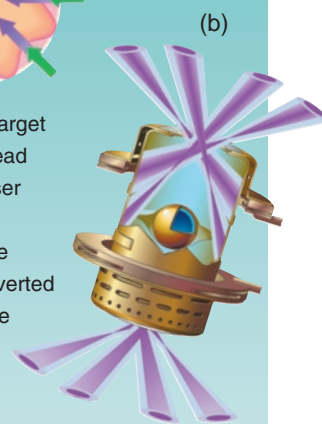
Current target design efforts build upon thousands of experiments on Nova and predecessor laser systems, which led to an ever-increasing capability in target design and fabrication, diagnostic instrumentation, and computer simulation as well as a firmer grasp of physics issues affecting ignition. Computer modeling has always been an important tool for exploring target design options at Livermore. Because no single code can simultaneously model all ignition phenomena, researchers today

use several Livermore-developed codes, including the radiation hydrodynamics codes LASNEX, HYDRA, and F3D, which simulate the interactions of the laser light with the electrons and ions in the plasma. Target design continues to evolve, and researchers are exploring target designs not only for the National Ignition Facility but also for inertial confinement fusion power plants of the future. (See *S&TR*, November 2001, pp. 24–26.)

(a) The direct-drive target, a small capsule containing deuterium-tritium fuel, is uniformly illuminated from all directions



by laser beams. (b) The indirect-drive target has an outer metal cylinder of gold or lead containing a plastic fusion capsule. Laser beams enter the cylinder, or hohlraum, through holes at its end caps and hit the inside surface where the energy is converted to x rays. The x rays heat and ablate the capsule surface, causing a rocketlike pressure on the capsule and forcing it to implode.



For instance, a NIF short-pulse initiative, funded by the Laboratory Directed Research and Development program, shows promise in obtaining extremely bright x-ray sources for stockpile stewardship experiments. Another area of research involves diode-pumped lasers, which may provide nearly continuous high-energy laser operation for fusion power production. (See *S&TR*, September 1996, pp. 4–11.) And, of course, NIF and beyond.

About NIF, George H. Miller, associate director for NIF Programs notes, "MIT physicist Sam Ting [Nobel Prize for Physics, 1976] has been quoted as saying no big facility is ever known for the thing that it was originally designed to do. The people learning to use facilities come up with ideas and inventions that were never conceived of by those who first put the facilities together. So I can't possibly guess what NIF is going to be known for 15 years from now, much less 30 years from now. But one of the things I do know is that NIF is going to be an absolutely remarkable machine in terms of its flexibility, its power, its ability to do the kind of quality experiments that are just going to excite and challenge all varieties of science."

—Ann Parker

Key Words: 4 pi laser, atomic vapor laser isotope separation (AVLIS), Beamlet, Cyclops, Continuous Laser Glass Melting Process, direct-drive target, extreme ultraviolet lithography, hohlraum, indirect-drive target, inertial confinement fusion (ICF), Janus, laser guide star, laser peening, LASNEX, Long Path, National Ignition Facility (NIF), neodymium-doped glass (Nd:glass), Nova, Novette, Petawatt, potassium dihydrogen phosphate (KDP) crystals, Shiva, solid-state heat capacity laser, spatial filters, x-ray laser.

For more information about the National Ignition Facility Programs Directorate:

www.llnl.gov/nif/

For details about the history of lasers at Livermore:

www.llnl.gov/timeline/

For further information about the Laboratory's 50th anniversary celebrations:

www.llnl.gov/50th_anniv/