Keeping Laser Development on Target for the National Ignition Facility

The NIF laser technology and engineering team is making steady progress developing the advanced laser components and systems for the giant facility, scheduled for startup in 2003.

No facility in the 46-year history of Lawrence Livermore has triggered the level of publicity, public and Congressional scrutiny, and sheer scientific excitement as the Department of Energy's forthcoming National Ignition Facility (NIF), by far the world's largest laser. This enormous $1.2-billion facility, the size of a modern sports stadium, is the largest construction project and permanent facility in the Laboratory's history (see box, p. 10).

Because NIF represents such a large advance in laser size and performance, a formal four-year laser development program was launched in 1995. So far, the effort has tapped 250 scientists, engineers, designers, and technicians, all working to provide validated designs that will be transferred to industry for manufacturing. Over the past three years, the designs of hundreds of components have been steadily evolving, incorporating numerous advanced materials, technologies, and cost-saving features.

The sheer scale of the undertaking is not lost on the NIF laser technology development team. "Every month for two years, we're going to be building the equivalent of approximately two Novas—Livermore's 10-beam laser and, for many years, the world's most powerful," notes Dick Hackel, associate program leader for Livermore's Laser Science and Technology (LS&T) Program.

Taking a Big Leap

Physicist Howard Powell, head of the LS&T Program, points out that NIF's projected power, enough for laboratory fusion experiments to achieve energy break-even and gain for the first time, necessitates a laser facility with unparalleled levels of sophistication. "We're going from working with Nova's 10 beams to manipulating 24 sets of 'bundles' containing 8 beams apiece. That's a big leap."

The size of NIF has required new, multibeam components and controls and new techniques for troubleshooting and maintaining the giant laser. The effort includes readying component replacement strategies based on the concept of modular line-replaceable units. Additionally, unprecedented attention is being paid to maintain cleanliness throughout the huge system to prolong the life of all components.

Powell points out that some of the laser technology development has been done in collaboration with colleagues from the French Commissariat à l'Energie Atomique (CEA), other DOE national laboratories, and the University of Rochester. The French agency plans to build its Ligne d'Intégration Laser by 2001 and its Laser Mégajoule with specifications similar to NIF's by 2010. Other productive collaborations include those forged with literally hundreds of vendors. Beginning next year, these companies will be manufacturing tens of thousands of NIF components, many of them to unprecedented levels of performance.

Fundamental to the development work has been a one-beam scientific testbed called Beamlet (see box, p. 8) that has permitted the online evaluation of the NIF laser design and operating specifications. Complementing Beamlet is Amplab, a complete working prototype of a NIF amplifier module for an eight-beam bundle.

As final design changes are made and prototypes are built and tested, an important focus has been on ensuring performance and reliability. "We're going to be buying at least 192 of most items, so we want to make sure the parts work exactly as we specify," notes Powell.

Driving Down Costs

Another major focus has been substantial cost reduction. New approaches to component design were required to reduce costs without impacting performance.

"Cost drives every design. We're always questioning whether we can make it more compact or with fewer parts. Although the NIF facility will be enormous, it will be literally packed with components," says Richard Sawicki, NIF associate project engineer for special equipment.

Some cost-effective measures have been relatively simple, such as making the laser beams square so they can be packed closer together to save space and multiplexing some components, such as the flashlamps in the main amplifiers. Other cost-saving measures, such as the multipass laser design, in which the beams are passed through the same amplifiers several times, are more complex; yet this design will save millions of dollars by reducing the number of amplifiers and facility space needed. Other designs emphasize the sharing of components wherever possible or mechanical structures that support several systems simultaneously.

Cost-cutting efforts rely increasingly on computer-aided design. "When we built Nova, the designers used pencil and paper and built a lot of full-scale models," notes Sawicki. In contrast, NIF parts are designed and scrutinized on computer by a team of a hundred designers using the latest three-dimensional engineering software. Even entire systems, on the scale of hundreds of meters, are modeled on computers to make sure there is adequate room to move equipment in and out.

Another major computer role is simulating the evolution of the beam as it propagates through every laser system. Livermore codes that model the work of the flashlamps and amplifiers as well as the beam itself are saving crucial development time. After analyzing the predicted performance, cost, and safety of over 100,000 design variations of the amplifier systems, the codes also were used to choose the optimum laser design.

Birth of a Pulse

The main laser components in NIF (Figure 1) take a low-power laser pulse from the master oscillator, shape and smooth it, amplify it enormously, and precisely direct it at a minuscule target called a hohlraum. Major laser components include the optical pulse generator, the amplifiers, the pulsed-power system to drive the amplifiers, the optical switch, a final optics assembly to convert frequency to ultraviolet and focus the beams, and the beam control system. Each of these key components has required significant technology advancements.

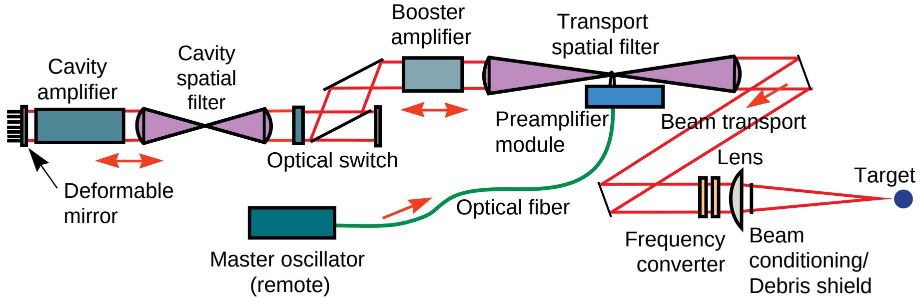


Figure 1. The layout of NIF's major components through which a pulse of laser light travels from injection to final focus on the target.

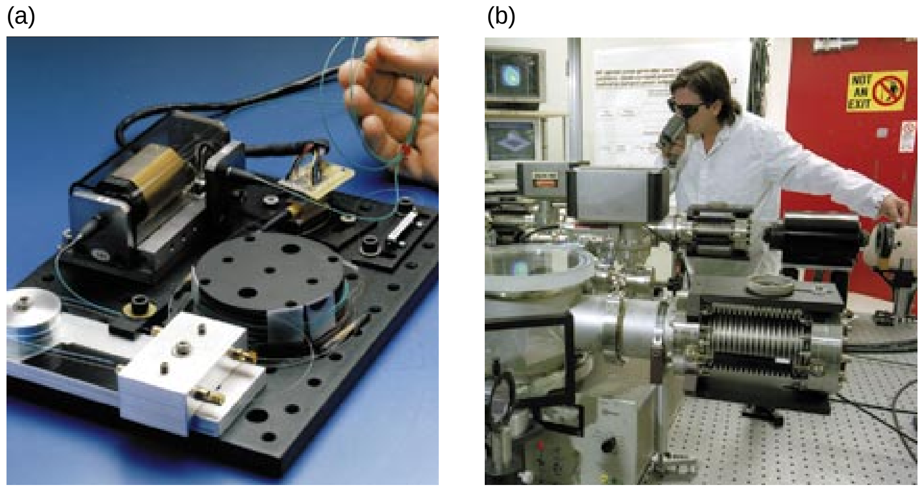


Figure 2. (a) NIF's low-power pulse is first amplified by these ytterbium-doped optical fibers (seen glowing blue at lower left). (b) The pulse is then amplified to 22 joules by four-pass amplifiers (here tested in the laboratory by technician Mike Martinez), which are part of the preamplifier module (PAM).

The primary function of the optical pulse generation (OPG) system, NIF's "front end," is to generate, amplify, and shape the laser beams before they enter the main amplifiers. The OPG system, which uses fiber optics technology extensively, was designed to be highly versatile to satisfy the broad range of NIF experimental requirements.

NIF's laser pulse will be born in the master oscillator room (Figure 2). Here, a small, compact oscillator made of ytterbium-doped optical fiber generates weak laser pulses (a few nanojoules with a beam diameter of a few micrometers). The oscillator pulse is shaped in time and broadened over multiple colors, which are used to smooth the intensity of the laser spot on the target. Each of the pulses is then transported to preamplifier modules (PAMs) for amplification and beam shaping.

Each PAM first amplifies the pulse by a factor of about a million, to a millijoule, and then boosts the pulse once again, this time to a maximum of 22 joules, by passing the beam four times through a flashlamp-pumped amplifier (Figure 3). The most challenging aspect of OPG development, according to engineer John Crane, has been the four-pass amplifier design. With an eye on cutting costs, NIF managers decided last year to reduce the number of PAMs from 192 to 48, with one PAM feeding four separate beamlines. As a result, the PAM's output energy requirement went up substantially. Laboratory testing of complete PAM prototypes with more powerful amplification has been validated, says Crane.

To perform the range of experiments needed on NIF, the PAMs must perform three kinds of shaping of the input laser beams.

- Spatial shaping to make the square beam more intense around the edges to compensate for the higher gain profile in the center of the large amplifiers.
- Spectral shaping and beam smoothing to eliminate both hot spots and dark spots at the focus by manipulating the focal beam pattern with fast changes in wavelengths.
- Temporal shaping to ensure that the laser pulse delivers energy to the target with a prescribed time-history for efficient ignition.

Amplifying the Beam

The two large amplifier units in each NIF beamline are designed to efficiently amplify the nominal 1-joule input pulse from the OPG system to each of the 192 beams to the required power and energy, maintaining the input beam's spatial, spectral, and temporal characteristics.

The amplifiers, with 16 glass slabs per beam, are arranged in two units—the so-called cavity amplifier and the booster amplifier. Together, they are the laser system's central component. "The main amplifiers provide 99.9% of NIF's power and energy, so their performance is crucial," says development scientist Chris Marshall. When fully integrated with optics, flashlamps, pulsed power, and other related components, the amplifiers are also the costliest NIF system.

"We've never built laser amplifiers on this scale," comments NIF system engineer Doug Larson. "These are truly huge." Indeed, at eight times the size of Nova's amplifiers, NIF's amplifiers use 42-kilogram slabs, 3.4 by 46 by 81 centimeters, of neodymium-doped phosphate glass set vertically on edge at Brewster's angle, to create a polarizing effect, so that the laser beams have very low reflective losses while propagating through the glass. The slabs are stacked four high and two wide to accommodate a bundle of eight beams (Figure 4).

The slabs are surrounded by vertical arrays of flashlamps. Measuring nearly 180 centimeters (6 feet) of arc length,

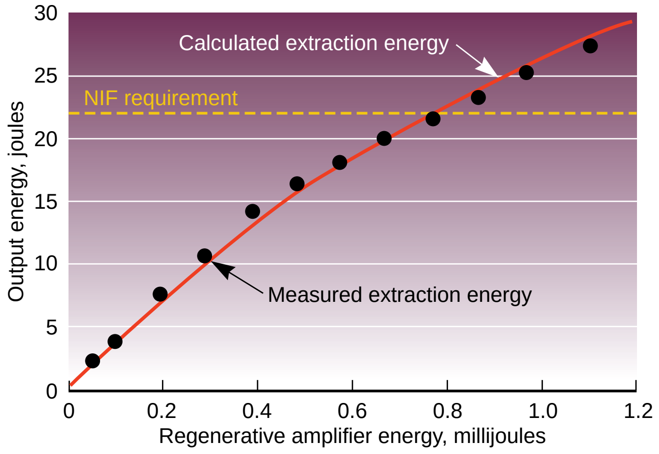


Figure 3. Demonstrated output energy of the prototype PAM exceeds the required 22 joules. The circles indicate measured output energy, while the continuous line indicates calculated energy.

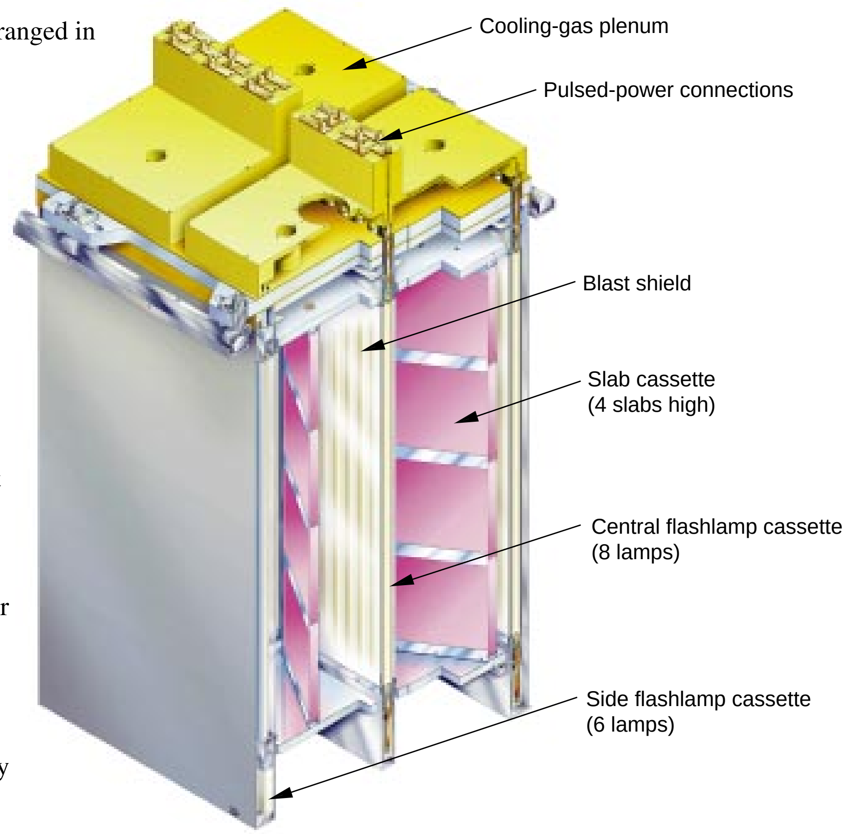


Figure 4. This cross section of a NIF amplifier module shows how the neodymium-doped phosphate glass slabs accommodate a bundle of eight beams traveling in parallel. The beams pass through 16 such amplifiers on their way to the target.

NIF's 7,680 flashlamps are the largest commercial units ever made (Figure 5). Each driven with about 30,000 joules of electrical energy, the flashlamps excite the neodymium in the laser slabs to provide optical gain in the infrared spectrum. Some of the energy stored in the neodymium is released when the laser beam passes through. With a combination of increased efficiency, fewer amplifiers, and the use of larger flashlamps, NIF will need less than twice the number of flashlamps of Nova, even though the laser system will produce some 40 times more output energy.

The flashlamps will be cooled with nitrogen gas between shots to indirectly cool the amplifier slabs and reduce beam distortions in order to meet the requirement of one shot every 8 hours. This is the first time such active cooling will be used in Livermore's fusion lasers. To ensure cleanliness, hermetically sealed blast shields will protect the laser slabs from possible contamination generated in the flashlamp cavities.

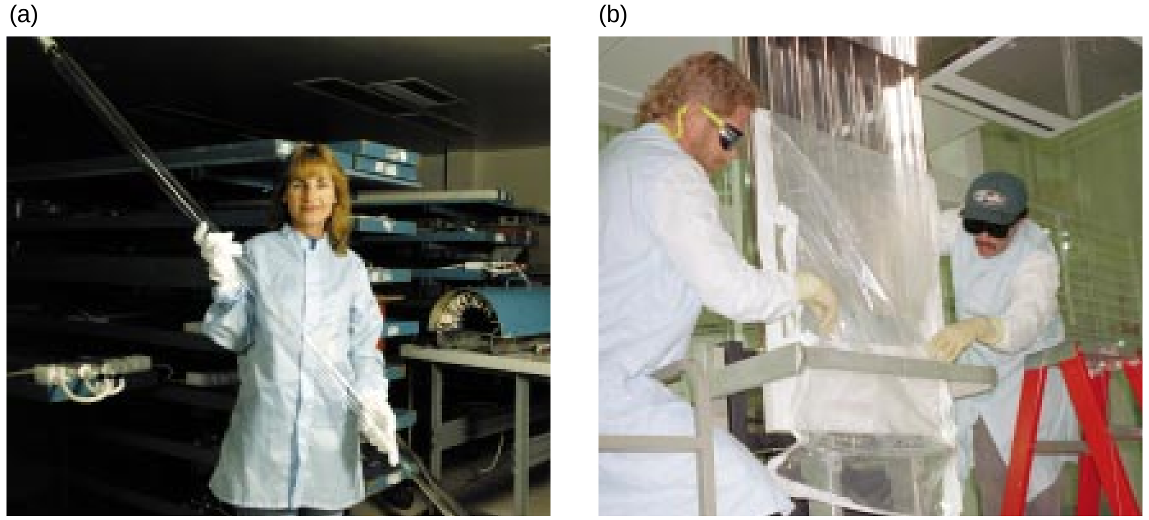


Figure 5. (a) Technician Wanda Dallum holds a flashlamp, the largest commercial unit ever manufactured. (b) Technicians install a cassette of flashlamps in Livermore's Amplab.

Beamlet: An Invaluable Testbed for NIF

To be sure that NIF's major laser design will function as proposed, Laser Programs' project leaders decided in 1990 to develop and assemble a scientific prototype well in advance of construction. Completed in 1994, the Beamlet laser has been used to test and refine NIF's laser design and to test early prototype parts.

Because constructing a full bundle of beams and associated amplifiers was not feasible, Beamlet consists of a single beam. Beamlet does, however, include the main laser amplifiers as an array stacked two high and two wide, a prelude to the four-high, two-wide amplifiers now being developed for NIF. To reduce Beamlet costs, only one of the four apertures in the array contains high-quality laser glass. In addition, the amplifiers and other hardware rest on the floor rather than hang from a support frame as in the NIF design.

By simulating NIF operating conditions, Beamlet has demonstrated the viability of most of the NIF laser requirements, including the output power and focal parameters of the laser light and high-efficiency conversion of the laser light from 1.05 to 0.35 micrometers for illuminating the target. The results from Beamlet, Amplab, dozens of small laboratories, and computer design codes give laser scientists and engineers substantial confidence that NIF will meet its projected performance specifications.

The Beamlet Demonstration Project has been ongoing since 1990 to develop, test, and refine NIF's laser design and hardware.

The amplifiers' frame assembly units are supported from an overhead aluminum space frame to enable bottom access for cleaning and maintenance. A cassette of four slabs stacked one above the other and an eight-wide flashlamp cassette slide into the unit to form an amplifier column. These cassettes are installed and removed using a special ultraclean maintenance and assembly cart being developed at Livermore (see Figure 6).

Amplab, one of the most visible centers of the entire development program, is the key facility for testing the main amplifiers. A multimillion-dollar facility jointly developed by Livermore and the French CEA, Amplab began construction in 1996, with full-scale testing commencing in 1997.

Amplab consists of a miniature laser bay, with a full-scale 4-by-2 amplifier bundle, is only three slabs long and has flashlamps and a prototype cooling system. "We're using the minimum number of amplifier modules needed to validate the performance of our design," explains Marshall. He points out that Amplab complements the function of Beamlet, which is testing a single, complete, integrated beamline with the same optical arrangement as planned for NIF but with different hardware.

Amplab testing is providing essential information on the energy gain and performance of the amplifiers; extent to which they distort the laser light; mechanical fit of a myriad of associated components; thermal recovery of the transmitted beam after a shot; and degree of cleanliness in assembly, maintenance, and use. The testing regime is also revealing important differences in hardware provided by various vendors.

Storing the Energy

The power conditioning system provides the energy for the flashlamps with the highest-energy array of capacitors ever built. The system's design is a collaboration among Sandia National Laboratories in Albuquerque, Lawrence Livermore, and industry. Sandia is responsible for designing the system, developing the switch, and testing the integrated module at its dedicated facilities, while Livermore is responsible for developing capacitors, power supplies, and other components. Ultimately, Sandia will lead the assembly installation and checkout of the NIF power-conditioning modules (Figure 7).

The power-conditioning system will occupy four capacitor bays, each 15 by 76 meters (50 by 250 feet), adjacent to each laser cluster. The system must deliver three pulses to each flashlamp: a triggering test pulse, a preionization pulse to prepare the lamps for main discharge, and a main pulse to provide energy to the flashlamps.

Twenty capacitors will be housed in 1.7-megajoule modules that power the flashlamps in parallel. Eight such modules are needed to power each laser bundle of eight beams. All together, NIF's capacitor bank will store some 330 megajoules of energy, several times larger than Nova's bank.

According to engineer Mark Newton, "We're working to reduce the system

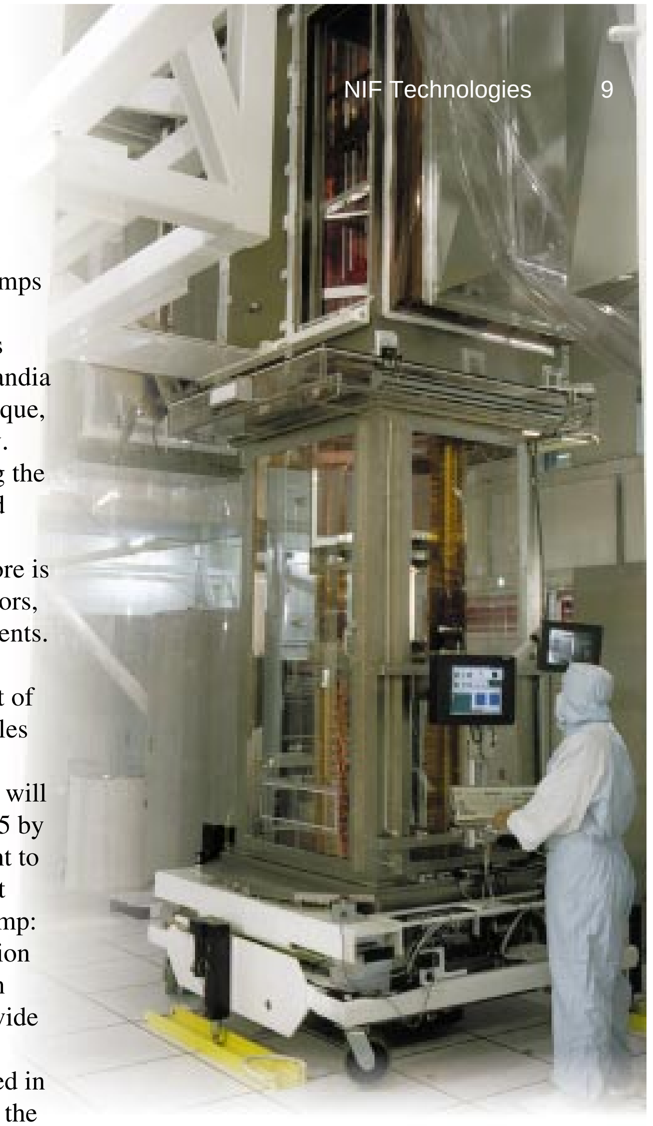


Figure 6. A technician, using a specially designed, ultraclean maintenance and assembly cart, inserts a cassette of four slabs into a frame assembly unit in the Amplab.

Figure 7. NIF's 1.7-megajoule power conditioning modules, each housing 20 advanced capacitors, are being tested by Sandia National Laboratories, Albuquerque.

At a Glance: the National Ignition Facility

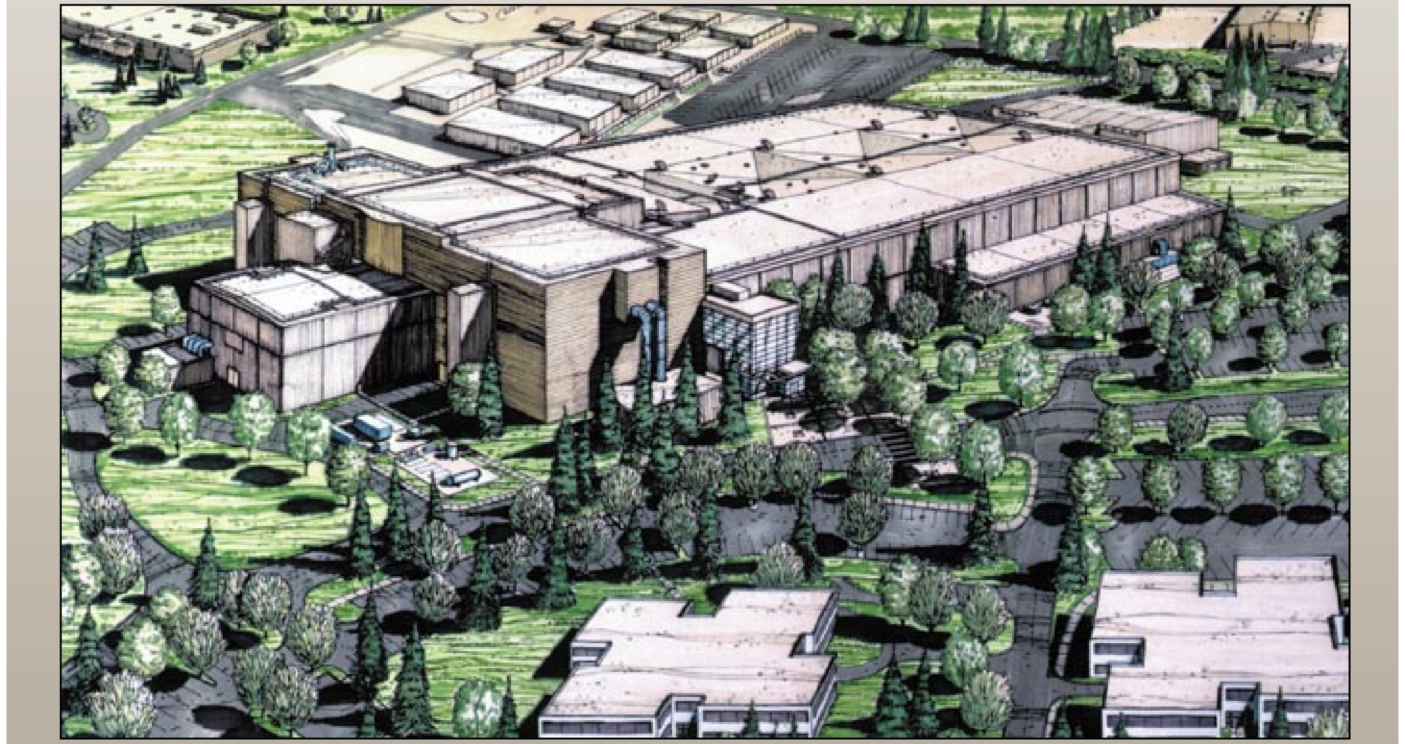
The Department of Energy's National Ignition Facility will be an enormous facility, about 200 meters long by 85 meters wide (550 by 300 feet), a little smaller than a typical domed football stadium. NIF's laser system will have 192 beams, each with a square aperture of about 40 centimeters per side and arranged in 24 beamlines of 8 beams each. Together the beams will produce 1.8 million joules (about 500 trillion watts of power, greater than 100 times the U.S. peak generating power) of laser light in the ultraviolet region at a wavelength of 0.35 micrometer for four billionths of a second.

To achieve this power, the beams will precisely compress and heat to 100 million degrees a capsule 1 to 3 millimeters in diameter containing deuterium–tritium fuel. The result will be ignition (self-heating and enhanced combustion of the fusion fuel) for the first time in a laboratory, liberating up to 10 times the energy required to initiate the reaction.

This sequence of events will last long enough for researchers to make accurate measurements of the nuclear reaction's temperature, pressure, and other properties. By providing these data, NIF will play a significant role in the DOE's science-based Stockpile Stewardship Program to assure the safety and reliability of the nation's nuclear weapons. The facility will also be used by scientists researching inertial confinement fusion energy and basic science such as astrophysics.

As Department of Energy Secretary Federico Peña commented at groundbreaking ceremonies last April, "NIF will unleash the power of the heavens to make Earth a better place."

NIF's total project cost is $1.2 billion, with design and construction managed by a partnership of Lawrence Livermore, Sandia, and Los Alamos national laboratories, and the University of Rochester. Engineering design began in 1996, construction began in 1997, and startup of one bundle of eight beams is planned for 2001. All 192 beams should be available for experiments by the end of 2003.



Artist's rendering of NIF illustrates the facility's immense scale. The two facilities in the foreground currently house Livermore's Business Operations and Human Resources departments.

cost to well below that of Nova in terms of dollars per joule." To that end, Newton and associates are incorporating the latest capacitor technologies, handling the energy in larger units, and qualifying as many vendors as possible.

The capacitors will use a "self-healing" technology previously tested on Beamlet. Developed over the past decade for various national security uses, this technology has failure characteristics that are more predictable than those of conventional capacitors, resulting in better capacitor bank designs at lower cost. This type of capacitor is known as self-healing because its "soft" failure mode (small internal faults) causes a gradual loss of capacitance over the capacitor's lifetime.

The pulsed power is switched via giant current-capacity switches and transmitted overhead to the amplifiers via coaxial cables. The NIF switches, one per capacitor module, must reliably handle 500 kiloamperes. NIF engineers are also working with U.S. and Russian experts to develop switches that could have a longer lifetime.

A Large Optical Switch

A key component in the laser chain is a kind of optical switch called a Pockels cell, which allows the beam to pass four times through the main amplifiers. This device uses electrically induced changes in the refractive index of an electro-optic crystal, made of potassium dihydrogen phosphate (KDP). When combined with a polarizer, the Pockels cell allows light to pass through or reflect off the polarizer. The NIF Pockels cell will essentially trap the laser light between two mirrors as it makes four one-way passes through the main cavity amplifiers before being switched out.

The Pockels cell used in the NIF laser is a new type, called the plasma electrode Pockels cell (PEPC, like the soft drink), developed at Lawrence Livermore (Figure 8). "The PEPC makes possible NIF's multipass architecture," says engineer Mark Rhodes.

Rhodes explains that Pockels cells used to be limited to small diameters (Nova's was 5 centimeters) because conventional designs required a KDP crystal about the same thickness as the beam diameter. NIF beams are 40 centimeters square, so crystals this thick would take too much space.

Instead, the PEPC uses a thin plate of KDP sandwiched between two gas-discharge plasmas that are so tenuous they have no effect on the laser beam passing through the cell. Nonetheless, the plasmas serve as conducting electrodes, allowing the entire surface of the thin crystal plate to charge electrically in about 100 nanoseconds so the entire beam can be switched efficiently.

The NIF design calls for four PEPCs stacked vertically in a single replaceable

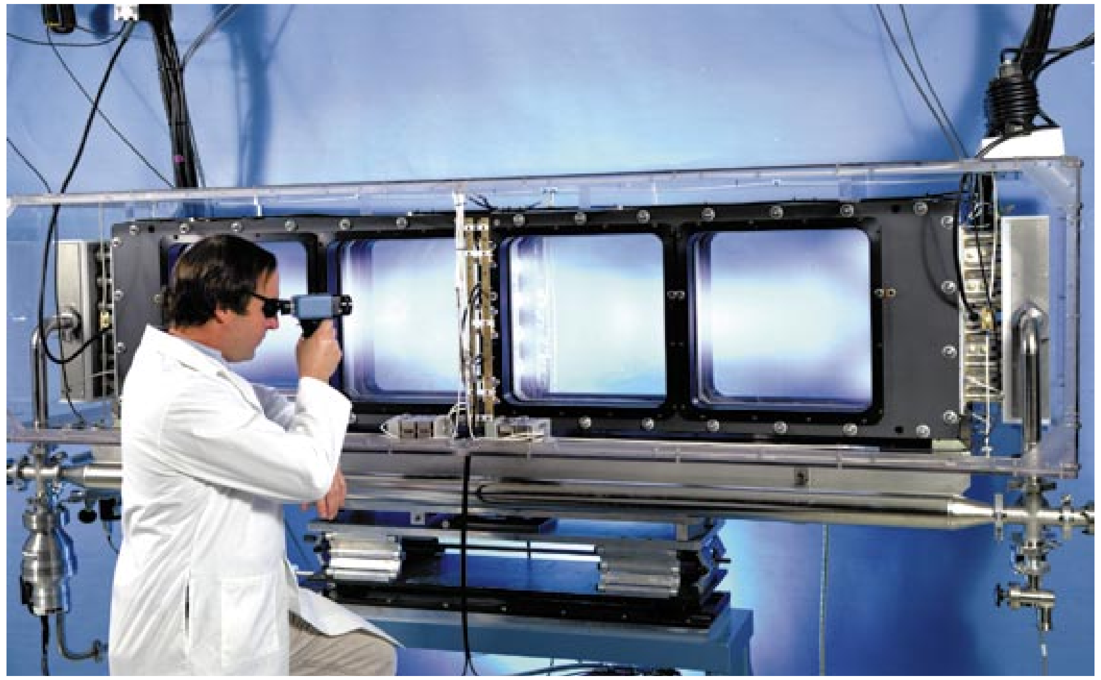


Figure 8. Each of NIF's plasma electrode Pockels cells (being tested here horizontally), acting as a giant light switch for four beams, will be arranged vertically in a single replaceable unit.

unit, but electrically the PEPCs are two independent 2-by-1 Pockels cells. The Beamlet's Pockels cell, which successfully uses a 37-centimeter aperture, continues to function reliably after nearly three years of operation.

Laser Alignment and Control

As the NIF beams make the four passes through the amplifiers, they accumulate wavefront aberrations due to distortions in the amplifier glass and other optics. As a result, NIF engineers needed to develop a way to compensate for these distortions to produce a well-controlled, focused beam.

The answer lay in a device called a deformable mirror, an adaptive optic that uses an array of actuators to bend its surface to compensate for wavefront errors. Advances in adaptive optics in the atomic vapor laser isotope separation (AVLIS) program demonstrated that a deformable mirror could meet the NIF performance requirement at feasible cost. Livermore researchers, led by physicist and systems engineer Erlan Bliss, developed a full-aperture (40 centimeters square), deformable mirror that was installed on Beamlet in early 1997 (Figure 9). Prototype mirrors from two vendors are scheduled to be tested in March 1998.

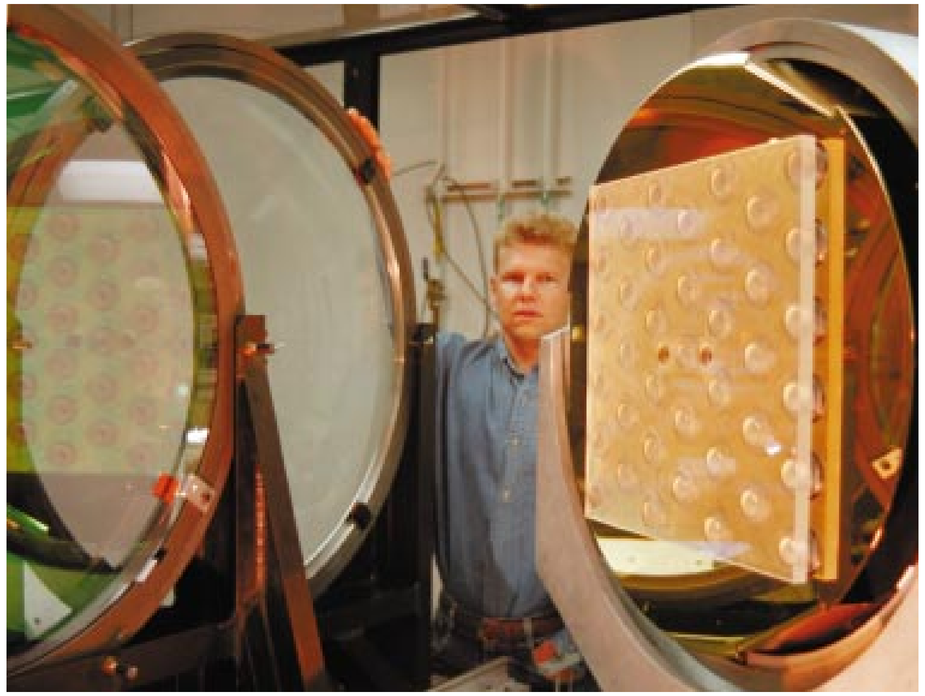


Figure 9. This full-aperture, 40-centimeter-square, deformable mirror (tested here by engineer Scott Winters) uses an array of 39 actuators to bend its surface to compensate for wavefront errors picked up by the beam.

The deformable mirror is but one element of a comprehensive, computerized system to align and control each beam so that it accurately delivers its energy to the target. New alignment concepts and simplifications of previous laser systems were designed for more reliable performance at reduced cost per beam. Aiding the effort is a one-tenth-scale layout of a NIF beamline, built to test new alignment concepts and components and software. The model uses full-size components at most critical locations, allowing the alignment system to be validated using prototype NIF hardware.

The scope of beam control for NIF is well beyond that of Nova or any other laser because of the 192 beams. That means that the alignment time per beam must be reduced to achieve a reasonable shot rate, which will help to control costs.

"With 192 beams, the challenge is to build a very reliable, simple, and robust system so we can align the main laser section easily and confidently in about 30 minutes," says engineer Rich Zacharias. "The system has to be autonomous because we can't afford an army of technicians to baby each beam." Zacharias says each of the beams must be aligned at multiple points along the way, requiring a system of 12,000 actuators.

Heading toward 2001

"The laser development and engineering design team has done a terrific job," says NIF project manager Jeff Paisner, "but it still has to meet a challenging schedule in order to complete detailed designs by the end of fiscal 1998." Procurement of laser hardware is slated for 1999, and preliminary laser assembly in the facility is scheduled for 2000. By 2001, a complete bundle of eight beams is scheduled to be installed and thoroughly tested. Once the installation team has been trained and the bundle's performance demonstrated, the 23 other bundles will be installed.

"The year 2001 may sound like it is way off in the future, but for us," Paisner says, "it's just around the corner."

—Arnie Heller

Key Words: Amplab, amplifier, Beamlet, beamline, deformable mirror, flashlamp, fusion, laser, National Ignition Facility (NIF), Nova, Pockels cell, power conditioning, pulsed power.

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About the Scientist and Engineer

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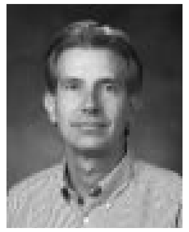

RICHARD H. SAWICKI, associate project engineer for NIF special equipment, has supported NIF development since joining the Laser Systems Engineering Division in 1983. His duties include having responsibility for the precision laser and target-system hardware. Since joining the NIF project in 1994, he has been involved with planning the conceptual design and technology development. Prior to those assignments, Sawicki had responsibility for R&D and production planning for the dye laser and uranium separator systems in the Atomic Vapor Laser Isotope Separation project and evaluated the dynamic structural response of various weapon and target systems in the Nuclear Test Engineering Division. Prior to joining the Laboratory in 1980, Sawicki worked on design and thermostructural analyses for high-technology systems in the aerospace industry. He received his B.S. in engineering from Dartmouth University in 1971 and his M.S. in machine design from the University of California, Los Angeles, in 1974.