Lasers for Fusion Research

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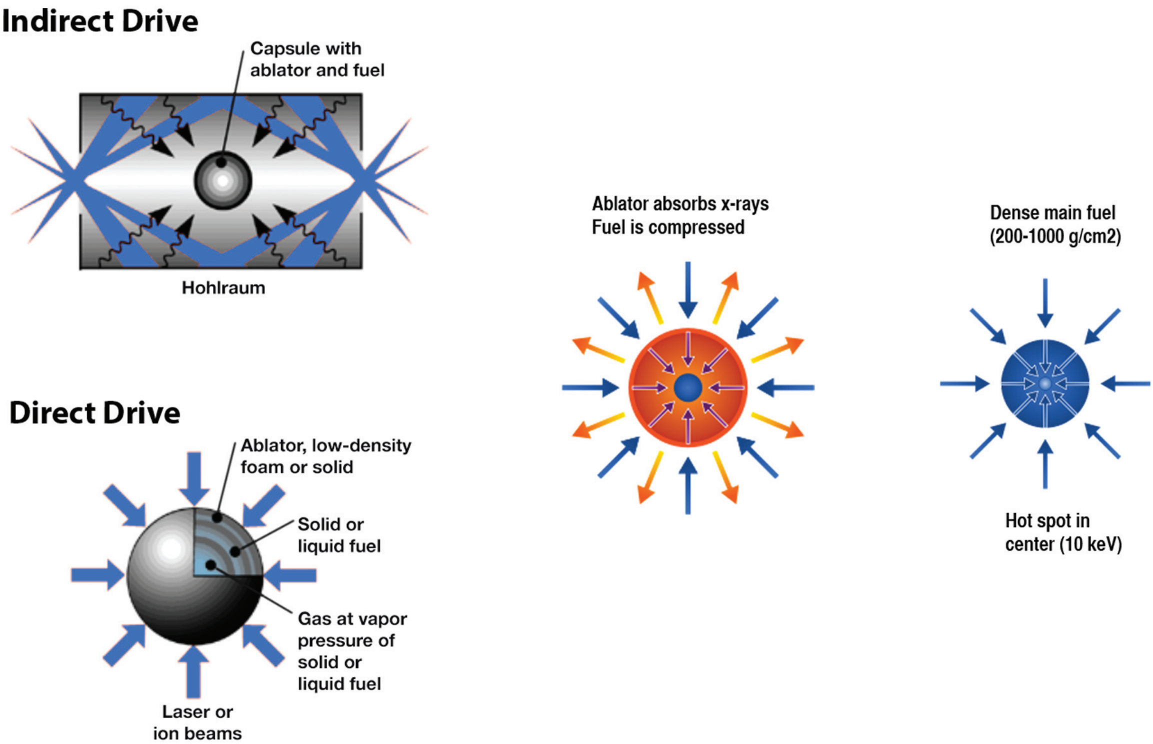
Laser fusion research began [1] at several establishments shortly after the first laser operated in 1960. John Nuckolls of the Lawrence Livermore National Laboratoroy and others around the world quickly recognized that the laser had the potential to concentrate power to the extreme levels required for small-scale fusion tests. Theoretical analysis showed [1,2] that achieving fusion and significant energy yield with the easiest targets to ignite, a mixture of deuterium and tritium (DT), would require imploding them to extremely high density—perhaps ten thousand times normal liquid density—with nanosecond-scale pulses in the kilojoule to megajoule range. Producing the extreme pressure and fuel implosion velocity required to reach the required density would require irradiance of 10^{14} W/cm^2 with lasers expected to be available in the near term. The challenge was to achieve significant energy yield at a size that looked reasonable for laboratory experiments.

Two basic concepts for laser-driven fusion explosions were quickly developed, as shown in Fig. 1. The direct-drive implosion uses laser energy that impinges directly on a spherical target containing DT fuel within an ablator shell that absorbs laser energy and expands, compressing the remaining ablator and fuel to a small volume in the center of the target and heating it to initiate DT fusion. The indirect-drive implosion absorbs the laser energy on the inside of a heavy metal cavity or hohlraum, producing soft x-rays that illuminate the ablator and implode the fuel capsule as in the direct-drive fusion.

The direct-drive implosion requires extremely uniform irradiance to achieve spherical symmetry. Indirect-drive fusion eases that requirement by converting the laser light to soft x-rays that with proper design uniformly irradiate the central capsule. X-ray absorption in the ablator is also simpler and less subject to nonlinear processes than laser absorption. However, indirect drive couples only 10%–20% of the drive energy to the fuel capsule, so it needs a higher laser drive energy.

Laser sources for such small targets should store energy from a long pump pulse and deliver a carefully shaped nanosecond pulse. Development of the Q-switch and the neodymium-glass laser were important milestones, providing a nanosecond pulse source and an amplifier that could be made in large sizes and had rather low gain so that it did not break into spontaneous oscillation from stray light before the nanosecond extraction pulse. Those developments encouraged Ray Kidder of Livermore to estimate that a pulse of at least 100 kJ lasting less than 10 ns might be able to ignite a small amount of DT fuel [1].

The glass laser is not a perfect solution, however, and in the early years of inertial fusion many other options were explored. The photolytically pumped iodine laser at 1.3 μm was identified as a promising fusion driver as soon as it was demonstrated in the early 1960s. The gas medium makes the laser less limited by nonlinear processes and much less expensive than a solid. The Asterix laser system [3] at the Max Planck Institute for Quantum Optics in Garching, Germany, and the Iskra laser system [4] at the Research Institute of Experimental Physics in Sarov, Russia (formerly Arzamas-16), were used in fusion research. Asterix, now operating in Prague, Czech Republic [5], produces up to 1 kJ in 350 ps, with frequency conversion to 657 and 438 nm. Iskra-5 reached 120 TW in 12 beams in 1991. Pumping a photolytic iodine laser with explosive-driven light sources, looked very appealing as a low-cost (but single-shot) route to megajoule energies [6], but precision control proved too difficult for use in fusion experiments.



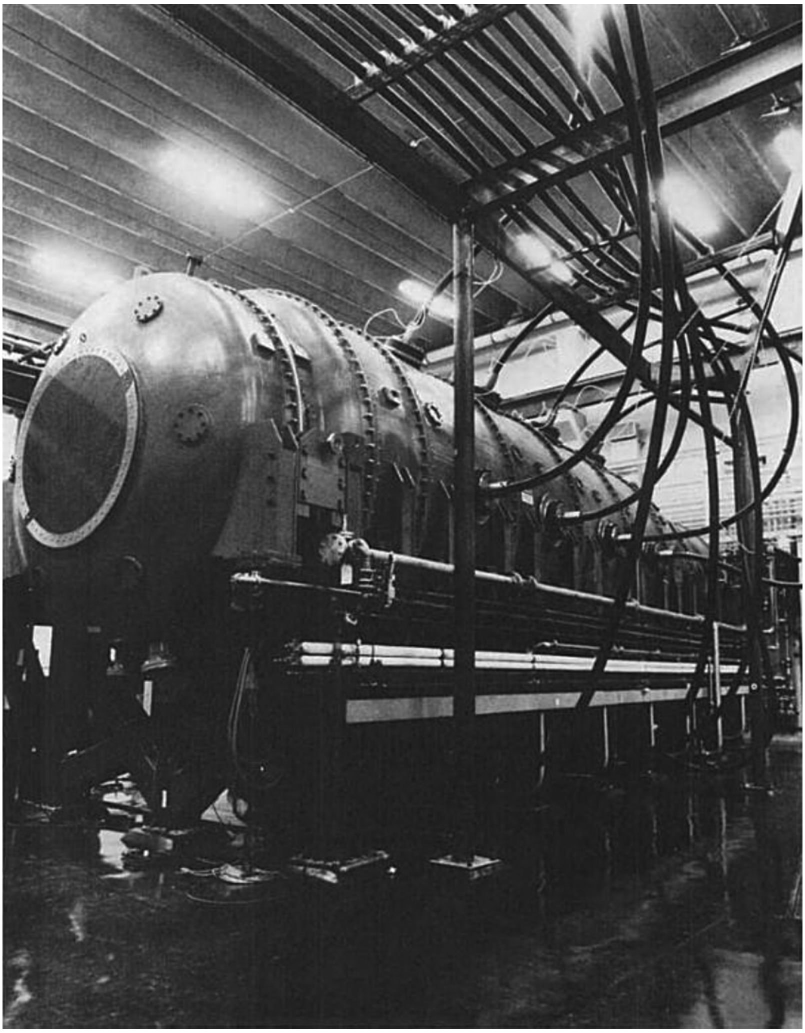
▲ **Fig. 1.** In a direct-drive target, laser beams illuminate a fuel capsule uniformly. In an indirect-drive target, they illuminate the inside of a heavy metal hohlraum surrounding the target and are converted to soft x-rays. The x-rays then implode the fuel capsule.

The 10.6-μm carbon dioxide laser initially seemed an excellent candidate, with high efficiency, the potential for large amplifiers in large sizes, and relatively inexpensive construction. The Antares project (see Fig. 2) [7] at the Los Alamos National Laboratory directed nanosecond CO_2 pulses of up 40 kJ on a fusion target from two final amplifiers, each with 12 roughly square 30-cm subapertures. Unfortunately, the long wavelength of the CO_2 laser proved a severe handicap because laser-plasma instabilities scale with the square of the wavelength, so they are two orders of magnitude larger at 10.6 μm than at 1.06 μm; therefore CO_2 laser fusion was abandoned in 1985.

The 248-nm krypton fluoride laser has also been explored as a fusion driver. The short wavelength is desirable for target interaction, but optics that far in the ultraviolet are difficult to develop. The KrF laser has broad bandwidth, which is desirable for beam smoothing in direct-drive fusion. At the power levels needed for fusion, it generates pulses of 100 ns or longer, which must be optically compressed to the few nanosecond pulses required for fusion. The Nike laser system [8] at the Naval Research Laboratory has explored KrF technology by stacking 56 pulses through an amplifier to give up to 4 kJ on target in 4 ns, and the Ashura laser system [9] at the Electrotechnical Laboratories, Tsukuba, Japan, has operated with up to 2.7 kJ in 20-ns target pulses. Figure 3 shows the 60×60-cm final amplifier of the Nike system.

The neodymium glass laser emerged as the most versatile and successful laser system for fusion research. A major advantage was that its 1.06-μm pulses can be converted efficiently to the second and third harmonics at 532 and 355 nm, which proved less vulnerable to laser-plasma instabilities than longer wavelengths. Xenon flashlamps excite neodymium ions in the glass, which drop to the upper level of the 1.06-μm laser transition. The transition has a lifetime of 300–400 ms and a gain cross-section high enough that energy can be extracted efficiently in short pulses with fluences tolerable for laser optics.

Early glass laser systems used cylindrical rods similar in concept to the first laser, a small cylindrical rod of flashlamp-pumped synthetic ruby crystal. The Del'fin laser system [10] at the Lebedev Institute, Moscow, Russia, used a large array of cylindrical rods serving as subapertures



◀ **Fig. 2.** Final amplifier of the Antares CO_2 laser system. (Courtesy of Los Alamos National Laboratory.)

within a single beamline. Amplifiers that used zig-zag laser beam propagation through large laser glass slabs were also explored [11].

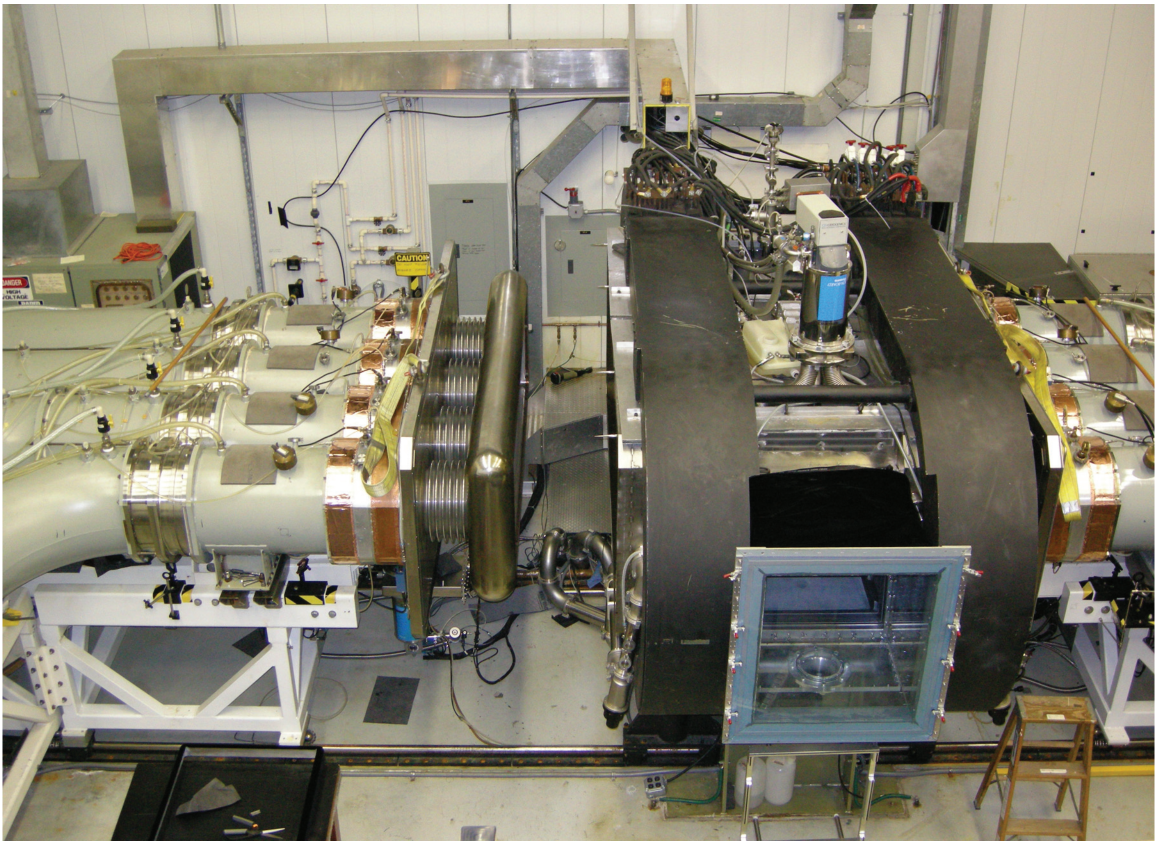
Fusion experiments in the U.S. began in the early 1970s, with three laboratories building a series of neodymium-glass lasers initially operated at 1.06 μm.

Moshe Lubin established the Laboratory for Laser Energetics at the University of Rochester in 1970 and built the four-beam Delta laser in 1972. When the lab's new building was completed in 1978, the six-beam Zeta laser began operation, performing experiments for universities, government agencies, and industry.

The promise of laser fusion also attracted a private company, KMS Fusion, founded by physicist and entrepeneur Keeve M. Siegel in Ann Arbor, Michigan. KMS built its own glass laser, and had some early experimental success, but the company ran short of money. Siegel suffered a fatal stroke while asking Congress for government support in 1975, and KMS Fusion survived for a time on government contracts.

John Emmett and Carl Haussmann led development of a series of glass lasers for fusion experiments at Livermore. The one-beam, 10-J Janus laser conducted the first fusion shots in 1974. The one-beam Cyclops laser followed, a prototype of one beam in the 20-beam Shiva laser. The two-beam Argus laser came on line in 1976, followed in 1977 by Shiva, which reached 10 kJ.

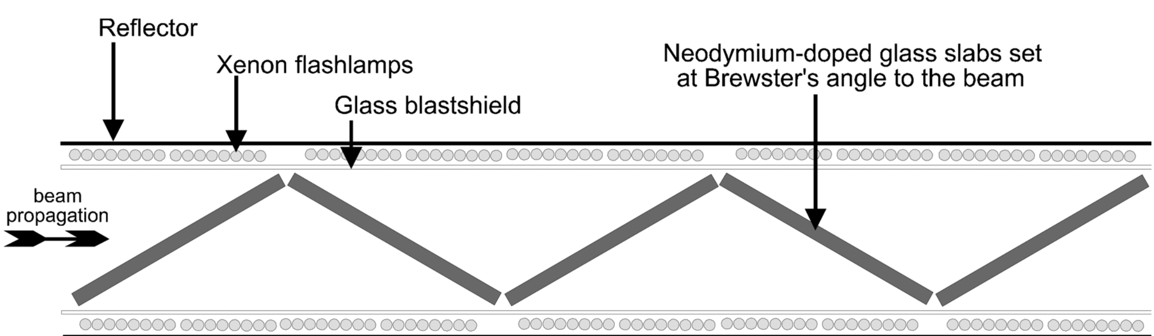
The most popular design for modern neodymium glass lasers with apertures larger than 10-cm is the Brewster's-angle slab amplifier shown in Fig. 4. A laser beam polarized in the plane of the figure



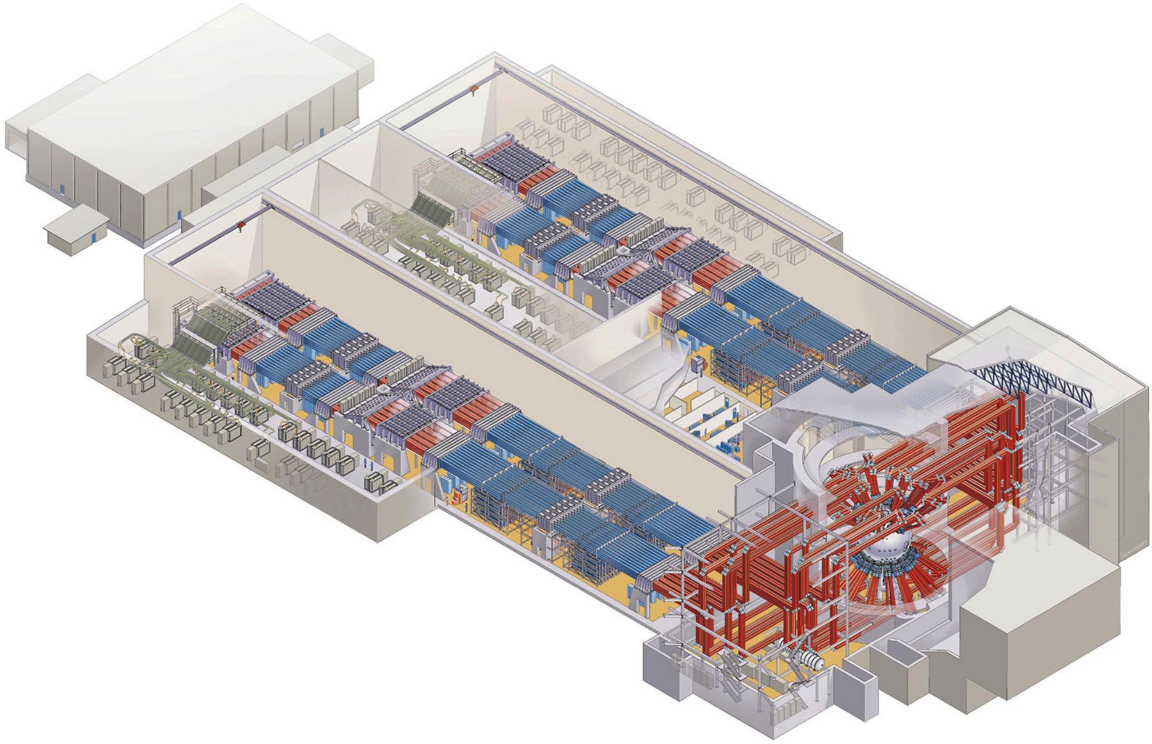
▲ **Fig. 3.** The 60-cm aperture final amplifier of the Nike KrF laser. The amplifier is pumped from two sides by electron beams generated by the cylindrical pulse-forming lines. (Courtesy of Naval Research Laboratory.)

sees no loss when it strikes the slab surfaces at Brewster's angle, and the slab faces are also easily accessible for flashlamp pumping. Early examples [12] used circular disks of glass, forcing elliptical beam profiles. More modern designs use elliptical or rectangular slabs so that the laser beam can be circular or square.

Many large glass fusion lasers have been built with those amplifiers, such as Gekko [13] at Osaka University, Japan; Vulcan [14] at the Rutherford-Appleton Laboratory, Didcot, UK; Omega [15] at the University of Rochester; Phebus at the Commissariat a l'Energie Atomique, Limeil-Valenton, France; and the sequence of lasers [16] leading to the Nova laser at Livermore completed in 1984. There



▲ **Fig. 4.** A Brewster's angle slab amplifier using neodymium glass. The laser beam sees no loss if it propagates through this series of slabs with polarization in the plane of the figure. (Courtesy of Lawrence Livermore National Laboratory.)



▲ **Fig. 5.** The NIF laser fusion facility. NIF has 192 laser beams of 40-cm aperture and a 10-m diameter target chamber seen at the right end of the picture. (Courtesy of Lawrence Livermore National Laboratory.)

have been many others [17]. Nova was the largest of its generation, with ten 46-cm beamlines able deliver up to 30 kJ at 351 nm in shaped pulses of a few nanoseconds duration for indirect-drive experiments.

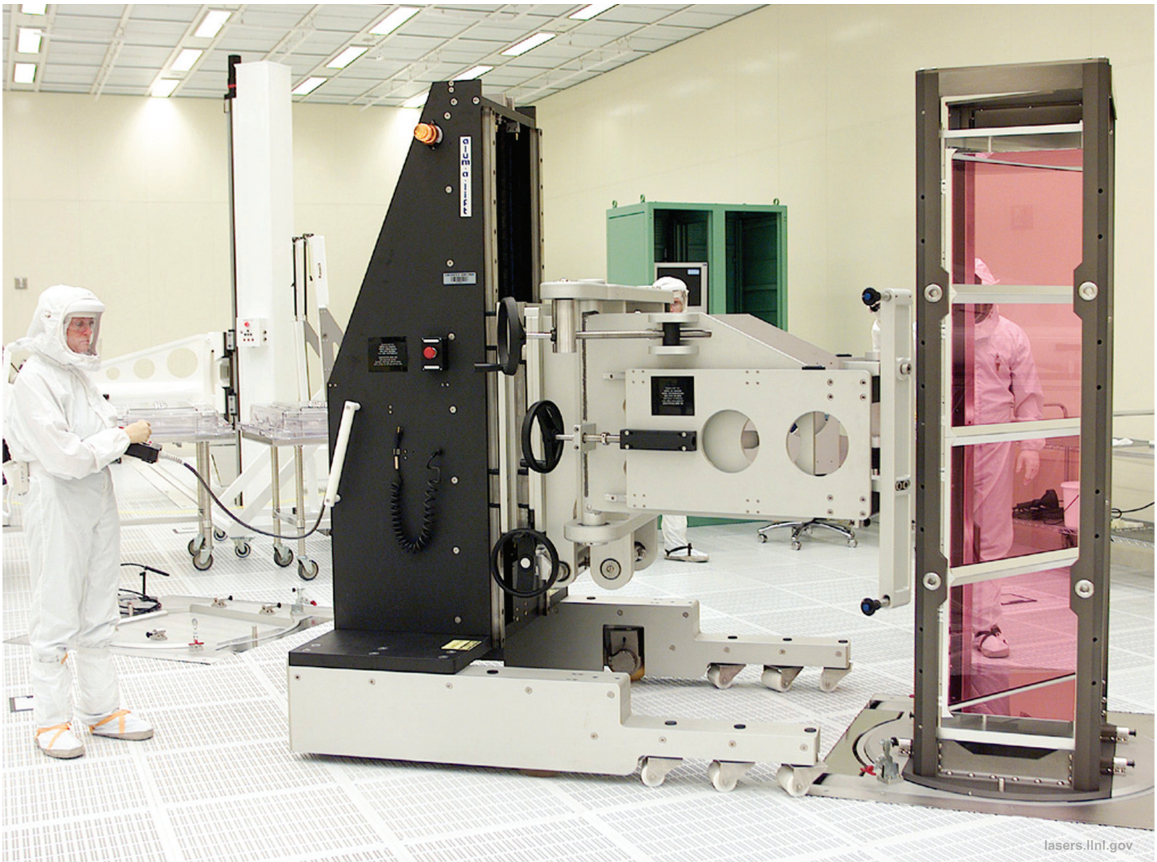
The Omega Upgrade laser at Rochester [15] began experiments in 1995. It delivers 30 kJ in 20-cm diameter beams at 351 nm in a 64-beam geometry optimized for direct-drive targets. The beams use a technique [18] called "smoothing by spectral dispersion" (SSD) to smooth the irradiance to give a very uniform profile on the target.

The largest fusion laser system now operating [19] is the National Ignition Facility at Lawrence Livermore National Laboratory (LLNL). Figure 5 is an artist's sketch of the facility. It contains 192 laser beamlines of 40-cm square aperture and was designed to irradiate targets with pulses to 1.8 MJ at the third harmonic (351 nm), and to have very flexible output pulses for a wide variety of target experiments [20].

NIF irradiates indirect-drive targets with conical arrays of beams that illuminate three rings of 64 beam spots each on the inside of a cylindrical hohlraum. This allows experimenters to tune the x-ray distribution within the hohlraum to optimize target implosions. The NIF beam arrangement can also be used to drive some direct-drive targets [21–23]. SSD smoothing is available if required.

Each beamline includes sixteen slabs, with the beam making four passes through the final amplifier (see Fig. 6) before exiting and being diretected into the target chamber. Such multipass amplifiers reduce the number of intermediate amplifiers and reduce cost of the facility, though they are harder to design and control than the single-pass amplifier chains used for most fusion laser systems in the past. Each preamplifier module in NIF injects about 1 J into each of four adjacent beamlines. The oscillator that drives the preamplifiers is a fiber laser that uses modulators and other hardware derived from those developed for fiber-optic communications systems.

The Laser Megajoule (LMJ) project under construction [23] by the Commissariat a l'Energie Atomique at Le Barp near Bordeaux, France, will have amplfiers similar to NIF, but will have 240



▲ **Fig. 6.** A stack of four NIF slabs ready for insertion into the final amplifier. (Courtesy of Lawrence Livermore National Laboratory.)

beamlines with 18 slabs each, and somewhat higher energy output capability. An eight-beam prototype called Ligne d'Intégration Laser (LIL) is currently operating.

Omega Upgrade, NIF, and LMJ also will have the capability to deliver kilojoule-class, petawatt-power picosecond beams to target from beamlines that use grating compression of frequency-chirped pulses [24]. This capability allows them to explore an advanced target design [25] called the "fast ignition" target that uses the main laser output to compress a target, and a separate petawatt picosecond beam to heat the central spot of the target sufficiently for ignition. Target implosion simulations suggest that such targets will offer higher net gain (fusion energy out divided by laser energy in) than conventional targets, highly desirable for future applications of laser fusion to energy production. Other laser facilities also have experimental programs investigating fast ignition. Petawatt beams are also useful for other experiments such as x-ray backlighting of imploding targets.

The National Ignition Facility succeeded in delivering pulses of more than 1.8 mJ to targets in 2012. However, that design energy proved insufficient to ignite fusion targets. Further experiments have increased yield, and Livermore researchers are focusing on improving target compression and reconciling theory with experimental results.

Researchers have long hoped to use laser fusion for electric power generation. The HiPER project [26] in the European Community, FIREX [27] in Japan, and LIFE [28,29] in the U.S. are all exploring energy applications of advanced laser fusion concepts. These projects are developing concepts for high-average-power facilities to follow NIF and LMJ, either with advances from NIF/LMJ-like technologies or with advanced diode-pumped solid-state lasers that offer higher efficiency and better thermal properties. Large slabs of laser-grade transparent ceramics [30,31], if developed in time, would be very valuable for advanced laser fusion projects since they offer the laser and thermal properties of laser crystals without the difficulty of growing large crystals. There are numerous other studies of conceptual designs for laser fusion power plants using solid-state [32] or KrF [33,34] lasers.

Fifty years after its origins, fusion research with lasers is a vibrant research area that has sparked many developments in both fusion and laser technology, and continues to do so.

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