laser fusion efforts in the United States

Snapshot: Research activities in laser fusion over the past 30 years have evolved into the next generation of Inertial Confinement Fusion—the National Ignition Facility.

By Roy R. Johnson

By 2002, scientists anticipate achieving ignition in the laboratory.· The National Ignition Facility (NIF) is the next generation Inertial Confinement Fusion (ICF) laser, beginning a new era for laser fusion research capabilities.

Laser fusion ignition is the process by which very high temperatures are reached in the center of a sphere of very dense nuclear fuel. This high temperature causes fuel to begin fusion, which subsequently burns

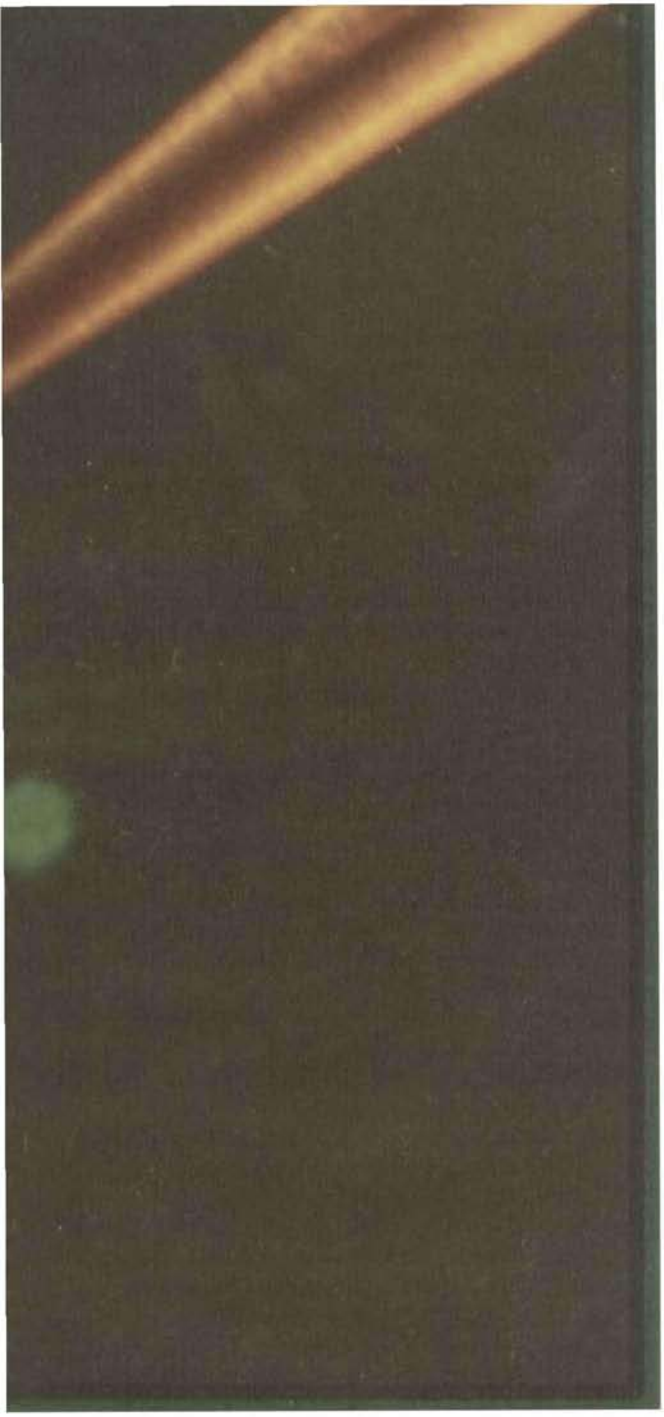
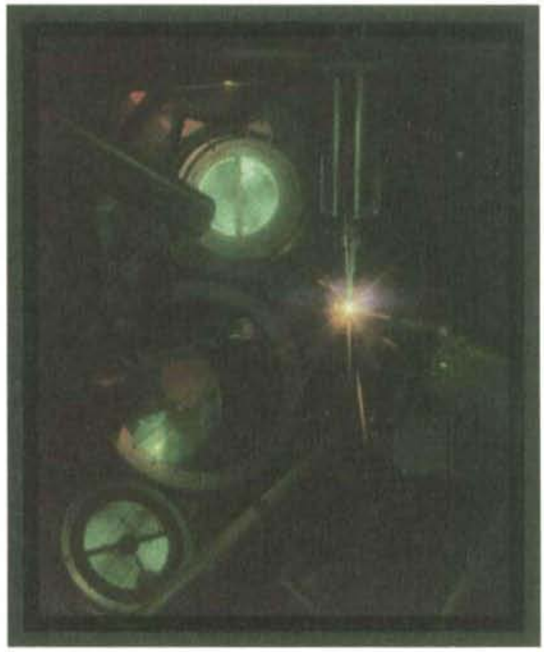


Photo credit: Thomas A. Leonard



Above: This photograph was taken during the laser irradiation of a cryogenic target on February 9, 1977, looking through the gap in the ellipsoidal-mirror illumination system used at KMSF. The target was a hollow, spherical glass shell, 51 μm in diameter, with a 0.7 μm wall, containing 1.3 ng of deuterium-tritium condensed in a liquid layer on the inside surface of the shell.

Left: The 10-beam Nova laser directly irradiating a deuterium/tritium-fueled glass microsphere to produce 2×10^{13} neutrons in January 1986.

through and heats the remaining cooler fuel as a deflagration wave. This process is analogous to a spark occurring in the center of a sphere of combustible material. The appropriate conditions in both cases must be achieved to burn a significant portion of the fuel. It has been a major effort over the years to determine precisely, what conditions are required for laser fusion ignition to occur. The NIF is the next step to achieving this long-sought goal of producing net energy gain from nuclear fusion.

The quest for fusion

The discovery that the sun was a pure fusion source of energy led many scientists to speculate that pure fusion energy on earth could be achieved. Unlike the sun,[1] a terrestrial fusion source could not be contained with gravity, but containment in a magnetic bottle was possible. Alternatively, it was thought that fusion did not have to be contained, but rather produced dynamically like a Supernova. During World War II, progress was made in understanding fission energy with the ultimate demonstration of the atomic bomb. With this enormous source of energy available, it became possible to achieve fusion energy through the hydrogen bomb. The Atomic Energy Commission (AEC) classified all work in the Controlled Thermonuclear Program until 1957-58 when Project Sherwood was declassified. On November 1, 1952, the first fission/fusion device was demonstrated on the shot called Mike. In 1957, John Nuckolls [Lawrence Livermore National Laboratory, (LLNL)] expanded on this approach by conceiving a fusion power plant driven by a series of fusion explosions in a giant steam-filled hole encased in granite. To make the design attractive, the fusion explosions needed to be as small as possible and ignited without a fission explosion. Since the driving energy had to be delivered in a few nanoseconds, it was not feasible to meet these criteria by conventional pulsed power supplies or explosives, although an implosion driven by high energy electrons from an accelerator was considered. This later approach was pursued by Sandia National Laboratory (SNL).

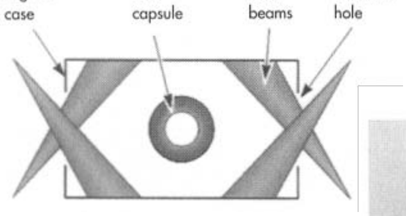
Along with the magnetic confinement approach to fusion in the laboratory, many approaches to inertial confinement have been investigated. Specifically, the driver used for the initial compression and heating of the fuel capsule has been envisioned as either a laser (solid-state Nd:Glass, KrF, CO_2), or a particle beam (light-ion or heavy ion). Presently, the solid-state Nd:Glass driver is carrying out the only laboratory experiments that have a direct impact in determining the conditions required to achieve ignition.

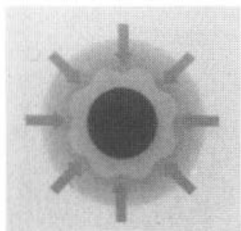
The proponents of inertial fusion were stymied by the lack of an adequate driver other than a nuclear weapon. It was also clear that for inertial fusion to work, energy had to be delivered to the target quickly. With Maiman's[2] invention of the short-pulse ruby laser, inertial fusion was on track to a new driver.

However, for national security reasons, the introduction of the laser presented a threat from two different areas: (1) The high energy, multi-second duration of laser emission, as achieved with the gas dynamic laser, could be used to burn through materials and thus be a threat to the offensive assets of the military, and (2) The short pulse length of solid-state lasers made them viable for nuclear weapons applications. As a result, the U.S. government classified research in both areas. The Department of Defense (DoD) classified research in high-energy long-pulse lasers; the AEC classified research in high-power short-pulse lasers.

In the early 1960s, the AEC and the National Weapons Laboratories considered using lasers to ignite fusion fuel. LLNL scientists Stirling Colgate, Ray Kidder, and John Nuckolls, among others, studied the possibility of using powerful, short-duration laser pulses to compress and ignite a small quantity of deuterium-tritium (D-T) fuel. At that time, some aspects of this work needed to be classified, because many of the concepts, much of the physics, and the calculational methods used in laser fusion were derived from nuclear weapons work.

With the discovery of a high power laser, it became possible to do experiments with small targets and reach plasma temperatures in the keV range. In 1963, Basov and Krohkin[3] offered the first open literature discussion of laser fusion followed independently by John Dawson[4] in 1964. These early analyses stressed heating small spheroids of D-T to thermonuclear temperatures before they could disassemble. However in the classified community, the process of ignition and radial propagating burn was included and theoretical work by Kidder and Nuckolls continued, which showed that energy breakeven could be achieved at rather modest energies of the order of kilojoules. It was this concept, independently confirmed by Keith Brueckner,[5]





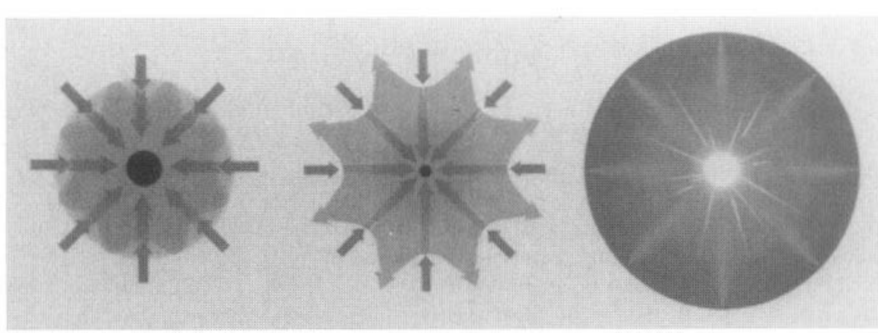


Figure 1. Indirect- and direct-drive targets heat and ablate the surface of a fuel capsule to drive it to ignition and burn. The differences are in the coupling of the laser light to the capsule through the laser interaction physics.

that convinced Keeve Siegel in October 1969 to eventually invest $25 million of KMS Industries' assets in laser fusion for energy applications. At the time, the U.S. had grave concerns about Middle East supplies of oil and worldwide energy shortages.[6]

Throughout the 1960s, there were a number of laser interaction experiments performed in France, England, Japan, Germany, USSR, and the U. S. to understand the basic coupling of laser radiation with matter. It was very important to understand the energy absorption process and to determine the amount of laser light scattered or reflected. Much of the plasma theory developed in the Magnetic Fusion Program was used in laser-matter interaction. Once it had been demonstrated that lasers could heat matter to temperatures in the keV range, there was a concerted effort to produce neutrons from the fusion reactions.[7-10] The targets were primarily CD_2 slabs since the polymer could be easily fabricated by substituting deuterium for hydrogen.

In 1962, LLNL began an experimental program (led by Ray Kidder) to study laser fusion. They used a 12-beam ruby laser to heat deuterium gas to produce neutrons. By 1971, the LLNL 10-20 GW Nd:Glass long-path laser produced 4×10^4 neutrons from a CD_2 target. A Laser Fusion Program was started at the University of Rochester (U/R), led by Moshe Lubin, and the Naval Research Laboratory (NRL), led by John Emmett, which used an Nd:Glass laser to make neutrons from CD_2 targets. Although these experiments were interesting, the neutrons were coming from interactions of hypervelocity particles that resulted from deuterium being accelerated by the large electric fields associated with the laser interaction with the CD_2 slab. Since the process was not thermal, it could not be scaled and the dependence on laser energy was weak.

In the early 1970s, a new generation of code calculations by John Nuckolls, George Zimmerman, Lowell Wood, and Ron Theissen[11] showed that interesting laser fusion experiments could be done with lasers as small as 100 kJ and that gains of 100 could be achieved with a megajoule-sized laser. At that time, the ICF Program was formalized at LLNL, and in 1972 John Emmett was hired to lead LLNL's new Laser Division.

In 1972, an experimental program was also started at KMS Fusion (KMSF). As time progressed, the National Weapons Laboratories concentrated on indirect-drive targets that used x-rays generated in hohlraums to uniformly illuminate the spherical capsule. The others (KMSF, U/R, NRL) pursued the direct-drive approach that required uniform illumination of the spherical capsule to reach high compression. Figure 1 shows the direct- and indirect-drive approaches.

Achieving fusion

At the beginning of 1973, there appeared to be only two major physics issues that could put a roadblock in the path of laser fusion: (1) a concern of poor laser light absorption by the target as a result of stimulated Brillouin scattering (SBS) and (2) the failure to reach high densities as a result of hydrodynamic instabilities. These problem areas still exist, but careful studies over the past 20 years have defined their limits so that there is high confidence in achieving ignition with laser fusion.

By late 1973, a number of other physics issues, previously thought to be insignificant, were becoming problem areas for targets irradiated by 1.06-μm laser light. The sequences of events that caused these issues to be reassessed are listed as they were discovered.

- The direct-drive capsule was only absorbing 20% of the incident laser energy. This was considerably less than 80-90% that had been predicted for inverse bremsstrahlung including SBS and from experiments that measured high absorption with planar targets. The cause was the relative short plasma scalelengths in these small capsules, which made absorption by inverse bremsstrahlung inefficient.
- The presence of fast ions that accounted for approximately 50% of the absorbed energy. Since the fast ions represented only a very small percentage of the ablated mass, the presence of fast ions had the effect of lowering the hydrodynamic coupling efficiency. The cause was poor thermal transport in the target because of flux inhibition of the electron energy in the plasma.
- The least obvious, but of more ultimate significance to target design, was the presence of a significant amount of energy in hard x-rays. It was already known that x-rays were detrimental since they could penetrate the spherical shell and preheat the fuel, thereby reducing the amount of fuel compression. These high-energy x-rays were not expected and they resulted in a serious re-evaluation of the Laser Fusion Program. Although there was some question about their origin, it is generally accepted that they were caused by high-energy electrons resulting from stimulated Raman scattering and that these electrons could cause significant preheat of the fuel. This effect was more severely felt in indirect-drive targets where the plasma scalelengths were longer. Experiments and theory have shown that these three effects will not be important for ignition experiments because they can be ameliorated by using 0.35 μm laser light.

On May 1, 1974, the dawn of laser fusion occurred when neutrons from laser driven implosions were produced for the first time.[12] These neutrons resulted from imploding a 60-μm diameter glass shell filled with deuterium. Two days later, the KMSF experiment was repeated with a 73-μm diameter target filled with D-T gas and the first neutrons from the D-T reaction were made. After being informed of this success

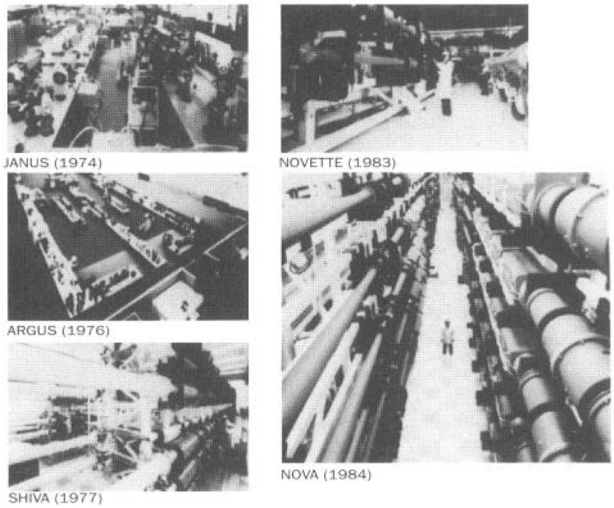


Figure 2. Since 1974, LLNL has used master oscillator power amplifiers to construct solid-state lasers.

on May 13, 1974, the AEC arranged a meeting at KMSF that included a top-level review committee to examine the data and eventually the results were accepted. These experiments were later duplicated using the Janus laser at LLNL in which the fuel ion temperature of 3.2-3.7 keV was measured.

In August 1974, the AEC issued guidelines that declassified essentially all work with directly irradiated fusion targets. This allowed release of much of the work at KMSF and removed the AEC from the awkward position of classifying a general concept that was already generally known to the interested scientific community and often considered an obvious next step in target design. The indirectly driven targets at LLNL, SNL, and Los Alamos National Laboratory (LANL) remained classified.

The two-beam Argus laser became operational at LLNL in 1976 and was the workhorse for laser-plasma interactions for several years. Subsequently, LLNL built the first major laser facility in November 1977—the 20-beam Shiva laser that delivered 10 kJ in a nanosecond at 1.06 μm. One year earlier, a prototype of one arm of Shiva was built called Cyclops, which attained the first implosion, neutrons, and copious hard x-ray emission with indirect-drive targets. The Shiva indirect-drive target experiments at this laser wavelength demonstrated conclusively that future lasers must be operated at shorter wavelengths to reduce Raman scattering. Although direct-drive target experiments had already shown that shorter laser wavelengths were required, the indirect-drive experiments made it imperative to use shorter wavelengths. Experiments at LANL at 10.6 μm showed that the hot x-ray temperature increased rapidly with laser intensity and wavelength.

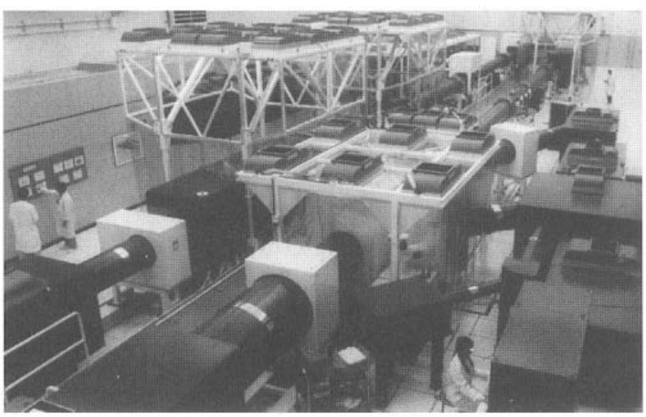


Figure 3. Beamlet has 11 amplifier modules in the multi-pass cavity and 5 in the booster position.

The KMSF program continued with experiments that used 0.53-μm laser light for the direct-drive implosion of cryogenic D-T targets in 1976-77.[13] In December 1983, indirect-drive cryogenic experiments were performed at LLNL. In 1988, the University of Rochester performed direct-drive cryogenic experiments using 0.35-μm laser pulses that were able to reach 200 times liquid density of D-T.[14]

In January 1983, LLNL developed the Novette laser (the prototype beamline of Nova), which operated at either green or ultraviolet wavelengths. Its success paved the path to completing the 10-beam Nova laser in December 1984. Nova continues as the workhorse of the National ICF Program, delivering up to 120 kJ of 1.05-μm light and routinely performing experiments with up to 50 kJ of 0.35-μm laser light in nominally 1-2 nsec pulses. Figure 2 shows the evolution of LLNL lasers since 1974.

On August 26, 1988, the Department of Energy (DoE) declassified the association of Halite and/or Centurion with ICF experiments using nuclear explosives at the Nevada Test Site. Excellent performance with those experiments resolved fundamental questions about basic feasibility to achieve high gain. The latest declassification occurred on December 7, 1993, when DoE declassified nearly all experimental data and analytical calculations on indirect-drive targets.

As the Laser Fusion Program grew in scope, it became apparent that it must be reviewed periodically by groups other than the DoE. Beginning in October 1979 with the Foster Committee, there have been a number of reviews that have provided full-assessment report on the National ICF Program.[15-18] All of these reviews endorsed the quality and value of the ICF program. In December 1992, the Inertial Confinement Fusion Advisory Committee (ICFAC), chaired by V. Narayanamurti, was formed to oversee the ICF Program and report to the DoE Assistant Secretary for Defense Programs.

The national ignition facility

On October 21, 1994, the DoE's Secretary Hazel O'Leary announced the approval to proceed with the NIF, which will deliver 1.8 MJ of 0.35 μm light.

Like Nova, the NIF laser is a flash-lamp-pumped Nd:Glass laser harmonically converted from 1.05 μm to 0.35 μm. The NIF will use the output from an array of 192 individual beamlets, each configured in a multipass architecture, to compress and ignite a small cryogenic capsule filled with D-T. In preparation for the NIF, LLNL has built and tested the prototype Beamlet. Figure 3 shows the Beamlet configuration. Beamlet uses state-of-the-art fiber optic and integrated circuit technology in the oscillator and preamplifiers to produce the desired laser pulse shape in time and space. The laser pulse is then multipassed four times in the large amplifier section, where it is then switched out by a $(35\text{-cm})^2$ plasma Pockels cell and polarizer. The laser pulse then passes through the final amplifiers and is frequency tripled using a type I/II KDP/KD*P crystal array. The Beamlet has met most of its performance specifications and has recently produced 6.4 kJ in 3 nsec at 0.35 μm with an 80% frequency conversion efficiency.

As stated earlier, the NIF target design must operate in a region of energy and intensity space that meets target physics requirements and still be accessible to the NIF laser performance. Figure 4 shows the conditions for reaching ignition with the NIF capsule and estimates the degree of robustness with regard to plasma instabilities and hydrodynamic instabilities. The yield from this target is approximately 15 MJ. The NIF target design has been evaluated by both LLNL and LANL and endorsed by the ICFAC. In addition to the mainline indirect-drive approach, the NIF also provides the capability to do direct-drive and Fast Ignitor experiments that have the potential to reach ignition at lower laser energies.

The DoE has budgeted $55 million for FY 1996 to do a preliminary design and to start negotiating contracts with firms to design and build the NIF's lasers and optics.

A facility the size of the NIF requires a detailed plan that extends

Optics Production for the National Ignition Facility

L. Jeffrey Atherton

Approximately 7,500 meter-class optics are required for the NIF with a nominal square aperture of 40 cm. These optics include neodymium-doped phosphate glass amplifier slabs, lenses for spatial filtering/image relaying and focusing, mirrors to form the multipass cavity and transport the beam to the target chamber, full-aperture thin-film polarizers for use in the optical switch, KDP and KD*P crystals for use in the optical switch and harmonic generation, and fused silica windows for a debris shield, noble gas isolation, and the optical switch. Table 1 summarizes the sizes and quantities of these optical components. Approximately 5-10% spares will also be purchased for construction and initial operation, so a total of about 8,500 large optics will be procured for the NIF. In addition, approximately 30,000 smaller optics, ranging in size from 5 to 30 cm, are required for the optical pulse generation system, and for alignment and diagnostics.

Table 1. Optical subsystems and quantities

Subsystem	Component	Size (cm)	Quantity
Amplifiers	Amplifier slab	46 x 81 x 3.4	3648
Lenses	Spatial Filter	43 x 44 x 2.6	768
	Focus	39 x 41 x 4.3	192
Mirrors	Cavity	39 x 41 x 8.0	384
	Elbow (Switch)	41 x 69 x 8.0	192
	Transport*	49 x 65 x 8.0	798
Polarizers	Polarizer (Switch)	42 x 77 x 9.0	192
Crystals	Switch	40 x 41 x 1.0	192
	SHG	39 x 41 x 1.1	192
	THG	39 x 41 x 0.9	192
Windows	Debris Shield	39 x 41 x 1.0	192
	Gas Box	50 x 51 x 1.0	192
	Switch	41 x 42 x 3.0	384
Total			**7518**

*Largest of the transport mirrors

The requirements for the large NIF optics are similar to those for the Beamlet laser (a scientific prototype of NIF) recently completed at LLNL. For all optics in transmission (except the crystals), the transmitted wavefront error specification (peak-valley) is λ/6 at 633 nm; for the crystals the transmitted wavefront specification is λ/4. The reflected wavefront specifications (peak-valley) for the mirrors and polarizer are 0.4 λ and 0.8 λ, respectively, confined to low-power aberrations. The reflectivities of the mirrors and polarizer (*s*-polarization) must exceed 99%; the transmission of the polarizer must also be greater than 98% for *p*-polarized light. The damage threshold requirement for these optics is extremely demanding. For intracavity and transport optics (1 μm wavelength), the damage threshold requirement ranges from 15 J/cm^2 to 20 J/cm^2 for a 3 nsec pulse, depending on location. The damage threshold of the harmonic conversion crystals, focus lens, and debris shield must exceed 12 J/cm^2 at 351 nm. For the NIF, we plan to use the ISO 10110 standard for optics drawings; we are in the process of converting the NIF optics drawings into this format.

Production of most of these optics will begin in late 1998 to early 1999, and continue into early 2002. Crystal production is expected to begin in early 1998. While the U.S. optics industry can readily manufacture optics meeting the technical specifications (and did so for Beamlet), it lacks the capacity to meet the production schedule. Furthermore, in some areas, such as laser glass, the present manufacturing technology is not cost effective for the quantity of optics needed for the NIF. LLNL has started a comprehensive multi-year development program with leading optics manufacturers to improve the U.S. optics industry's ability to meet the cost and schedule requirements for the NIF. This development program started in mid-1994, and will continue through late-1997. Toward the end of development, equipment will be purchased and installed at the optics manufacturing sites, production teams will be formed, and a pilot production campaign initiated to address any remaining issues prior to the start of production.

L. Jeffrey Atherton is the associate program leader for Laser Materials Technology at Lawrence Livermore National Laboratory.

over eight years. In FY97, the final site selection will be made and construction begins. Currently, the preferred site location by DoE is at LLNL. The NIF's construction costs are presently estimated at $700 million (in 1994 dollars) for a six to seven year construction project. The total project cost is $1.1 billion, which includes all the non-construction costs. The 15-year operational life of the project raises the overall cost of the NIF to $1.8 billion. Under the present schedule, the NIF is to be completed in 2002, and will begin experiments with cryogenic D-T fueled capsules to demonstrate fusion ignition and energy gain in 2003. Figure 5 is an artist's rendering of the NIF upon completion.

The NIF will allow the U. S. to retain its leadership role in the development of Inertial Fusion Energy (IFE) for future electrical power plants and will provide new basic scientific research capabilities for the nation and its economy. The multiple applications of the NIF could create an enormous number of high-technology jobs in the 21st century.

Essentially, the NIF will have three essential missions—defense, energy, and science.[19]

- In the absence of underground testing, the NIF will be among the most important of the aboveground experimental facilities necessary for maintaining the reliability, safety, and effectiveness of the remaining nuclear stockpile.
- The NIF demonstration of fusion ignition and energy gain will be the final step required to establish the scientific feasibility of electric power generation by IFE.
- The NIF will accelerate the science and technology derivatives of ICF that have resulted both in developing new research areas (*e.g.*, x-ray holography, high-energy density physics) and new technologies (*e.g.*, advanced laser materials, optical detectors, x-ray optics for x-ray lithography).

Consistent with the NIF time scale, a parallel path development can merge the ICF defense mission and IFE capabilities by 2005 to provide a timely and cost-effective strategy for a commercial power plant demonstration in 2025. Such cost sharing between Defense Programs funding for ICF and Energy Research Programs funding for IFE represents a national security and energy "dual benefits" approach to congressionally approved DoE research.

Because of the inherent separability of IFE technologies, the ICF ignition and energy gain demonstration within Defense Programs' proposed NIF can be joined with the Energy Research Programs' development of the heavy-ion driver.[20] Figure 6 is a timeline to illustrate the parallel path development plan for ICF ignition and gain, IFE technologies, and IFE power plant demonstration.

To keep development time and costs to a minimum, the IFE technologies should be accomplished with as few major facilities as possible. A viable scenario for IFE would include a power plant demonstration decision in 2005 based on the ICF ignition and energy gain data from the NIF and the heavy-ion driver development data from the Induction Linac Systems Exper-iments (ILSE).[21]

The NIF target physics and ILSE driver technology results and those from an IFE target fabrication and fusion chamber program would be integrated in an Engineering Test Facility (ETF).[22] The heavy-ion driver for the ETF would be built in two phases. Driver Stage 1 would be an intermediate facility between the ILSE

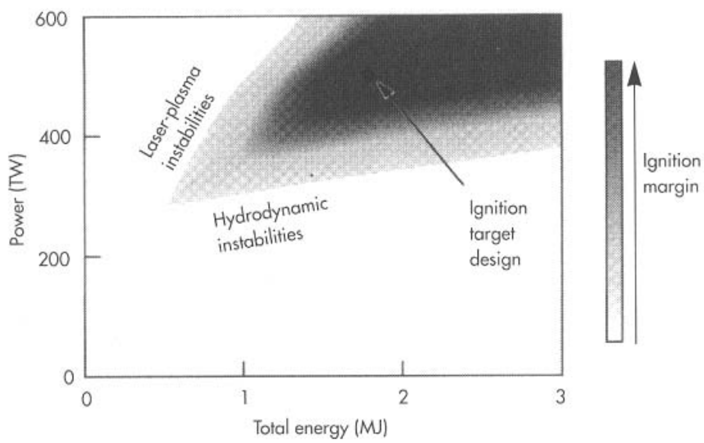


Figure 4. The National Ignition Facility's Indirect-drive target design meets the criteria of acceptable target performance for hydrodynamic and laser-plasma instabilities.

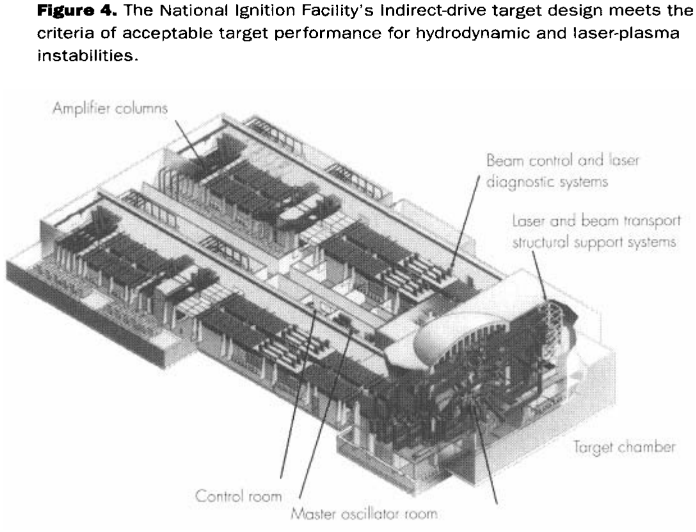


Figure 5. Schematic diagram of the 192-beam National Ignition Facility.

facility and Driver Stage 2, which would meet the full needs of the ETF.

The modularity and inherent separability of the IFE technologies would allow the possibility of the ETF to be upgraded to a Demonstration Power Plant (DPP), commonly referred to as the DEMO. All heavy-ion driver, target fabrication, fusion chamber development, and testing will be done at the DEMO site.

Scientists and engineers at LLNL and Lawrence Berkeley Laboratory (LBL) have estimated a $400 million total cost for developing the heavy-ion driver, target fabrication, and fusion chamber IFE technologies necessary, combined with a NIF ignition demonstration, for a 2005 ETF decision. Depending on how activities are grouped, the heavy-ion driver portion would account for 25-50% of the $400 million. The total cost for the IFE Program between 2005 and 2025, including the ETF/DEMO facilities that are necessary to reach fusion power plant demonstration, has been estimated at $4 billion.[23] The heavy-ion driver portion would account for approximately 25% of the $4 billion.

In the quest for a laser fusion power plant capability, the Inertial Fusion Program has led to a number of important derivative technologies. Similar to other scientific R&D programs, the Inertial Fusion Program comprises a multiple collection of scientific and engineering disciplines. Such spin-off technologies include new laser materials, diffraction gratings, and x-ray lithography.

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Roy R. Johnson is the Inertial Confinement Fusion Program Authorized Declassifier at Lawrence Livermore National Laboratory, Livermore, Calif.

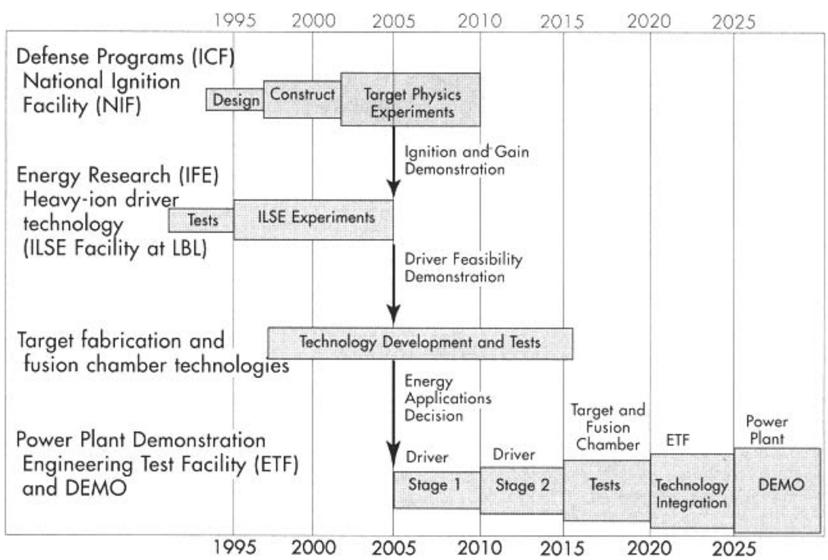

Figure 6. Timeline for ICF ignition/gain, IFE technologies, and the IFE power plant.