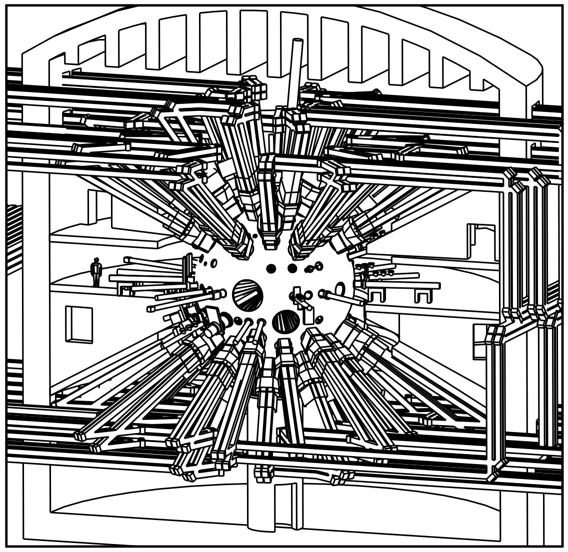
The Role of NIF in Developing Inertial Fusion Energy



The National Ignition Facility will demonstrate fusion ignition, which is central to proving the feasibility of inertial fusion energy. It will also help us determine the full potential of this alternate energy source.

AMERICA'S dependence on imported oil currently accounts for a trade deficit of $60 billion per year. As time passes, the world demand for energy will continue to grow, in part for demographic reasons, such as the rapidly increasing energy use per capita in developing Asian and Latin American countries together with the expected doubling of the world's population over the next 50 years. Our deficit and world energy demand will also grow for environmental reasons, particularly in the United States, which will need a substantial new source of energy to power zero-emission transportation and reduce urban air pollution, to charge batteries in electric cars, or to produce clean-burning hydrogen fuel by water electrolysis. Clearly, an alternative energy source is needed.

At present, there are only three known inexhaustible primary energy sources for the future: the fission breeder reactor, solar energy, and fusion. All are superior to coal or oil-based power plants because they are environmentally cleaner and ecologically safer. They will release little or no radioactivity per unit of power, as do coal mining and burning in the form of radon, uranium, and thorium,[1] and they will emit none of the gases (carbon dioxide and nitrogen dioxide) that contribute to greenhouse effects. Fusion, however, offers certain advantages over fission and solar energy. Unlike solar energy, which is only dependable in the limited desert regions of the world, some fusion fuels can be extracted from seawater, making them available to all countries of the world. Fusion power plants, if they can be developed economically, will also have many advantages over fission. The radiation hazard presented by fusion power plants can potentially be thousands of times smaller than that of fission power plants, with proper choice of materials.

Two Approaches to Fusion

Fusion combines nuclei of light elements into helium to release energy and is the same process that powers the sun. As noted, the fuel for fusion (deuterium and lithium, which can capture a neutron to regenerate tritium) can be extracted from seawater. The most likely fuel for any approach to fusion energy is DT (either liquid, gas, or a combination as in inertial fusion energy targets), which is a mixture of deuterium and tritium isotopes of hydrogen. This DT must be heated until it is hotter than the interior of the sun, but it fuses at the lowest temperature of any fusion fuel.

To explore the feasibility of economical fusion power plants, the Department of Energy is currently developing two primary approaches to fusion energy—magnetic fusion energy and inertial fusion energy (IFE). Both approaches use DT fuel and offer the potential advantages described above, but they must be developed more fully before economical fusion energy can be assured. Because the two approaches use different physics and present different technological challenges, the *National Energy Policy Act of 1992*[2] calls for both to be developed to the demonstration (DEMO) stage.

Magnetic fusion ignition is the goal of the proposed International Thermonuclear Experimental Reactor, which uses strong superconducting magnets to confine a low-density DT plasma inside a large, high-vacuum, toroidally-shaped vacuum chamber.[3] The IFE approach to fusion, in contrast, is one of the goals of the National Ignition Facility (NIF), the subject of this article. This approach uses powerful lasers or ion beams (drivers) to demonstrate fusion ignition and energy gain in the laboratory by imploding and igniting small, spherical DT fuel capsules (targets) to release fusion energy in a series of pulses (see box on p. 38). In its quest to accomplish this goal, the NIF supports a primary national security mission for science-based stockpile stewardship (see preceding article) and secondary missions supporting energy and basic science.

The IFE Power Plant

Figure 1 is a conceptual view of a generic IFE power plant, showing its four major parts—the driver, target factory, fusion chamber, and steam-turbine generator (balance of plant). This figure demonstrates some of the principal advantages of IFE as an energy source:

- The driver and target factory are separated from the fusion chamber to avoid radiation and shock damage to the most complex plant equipment. The separation between the driver and fusion chamber also allows a single driver to drive multiple fusion chambers, thus permitting flexibility in the required chamber pulse rate and lifetime and allowing for the staged deployment of several fusion chambers to achieve low-cost electricity.[4]
- Progress in inertial fusion experiments on the Nova laser facility at LLNL allows the most important target physics affecting target gain to be modeled successfully by computer codes such as LASNEX. When these computer models are better confirmed by target-ignition tests in the NIF, they can be used to design targets for future IFE power plants.
- IFE fusion chambers do not require a hard vacuum; therefore, a wider range of materials can be used to achieve very low activation and radioactive waste. IFE chamber designs that protect the structural walls with thick, renewable fluid flows are also possible, which will eliminate the need to replace the chamber's internal structural components periodically.[5,6]
- The cost of developing IFE can be diluted by sharing NIF for defense and energy missions.

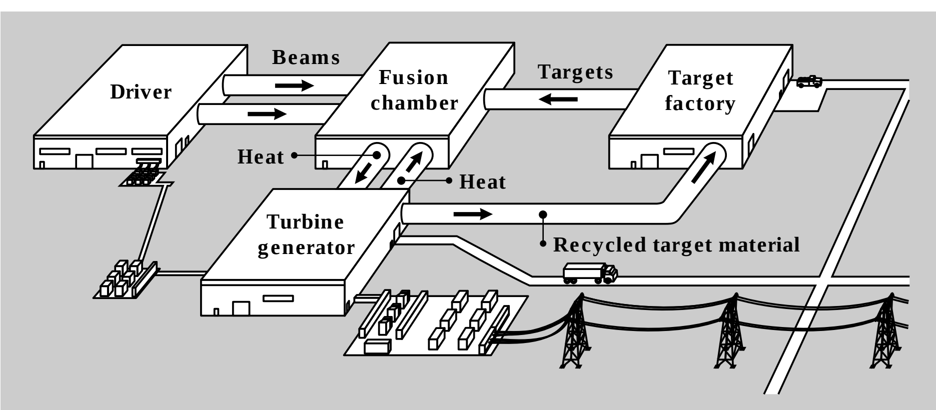


Figure 1. **Conceptual view of a four-part IFE power plant, showing the driver (either laser or ion particle beams), the target factory, the fusion chamber, and the turbine generator that produces electricity.**

How the NIF Can Help Develop IFE

In 1990, the Fusion Policy Advisory Committee[7] recommended that inertial fusion ignition be demonstrated in the NIF as a key prerequisite to IFE. In addition to ignition, IFE needs development in three major areas of technology:

- High-gain, injectable, mass-produced, low-cost targets.
- An efficient high-pulse-rate driver.
- A suitable, long-lasting fusion chamber.

A major facility following the NIF, to be called an Engineering Test Facility

(ETF), is planned to test the feasibility of these three areas of technology integrated together. The ETF will explore and develop the high pulse rate (several pulses per second) and overall system efficiency needed for economical IFE power production.

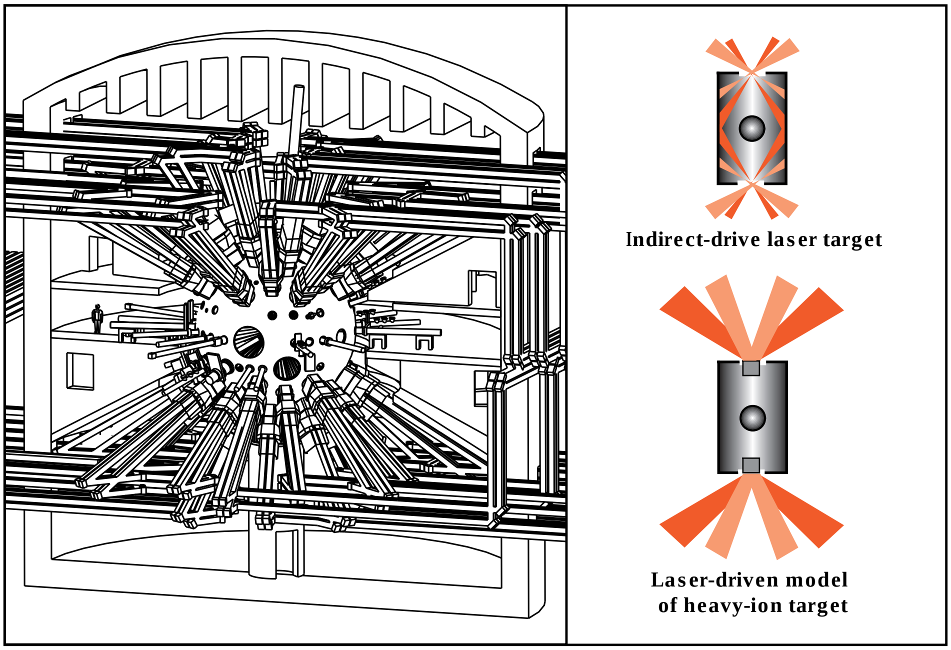
Filling Technological Needs

Targets. The targets for IFE must be capable of high energy gain. Energy gain is achieved when the fusion energy released from a reaction exceeds the energy that was put into the target by a laser or ion-beam driver. For high gain, the energy released from the target should be more than 50 to 100 times greater than the driver energy. Tests of inertial fusion target physics and ignition in the NIF will allow us to predict confidently the performance of several candidate IFE target designs.

For IFE targets to produce electricity at competitive rates (less than 5 cents per kilowatt-hour), they must be mass-producible at a cost of less than 30 cents each. This means new target-fabrication techniques must be researched and developed. In addition, we will have to develop and test methods of target injection and tracking for driver–target engagements at pulse rates of 5 to10 Hz. The NIF can test the performance of candidate mass-produced IFE targets and, at least for a limited number of pulses in a short burst, the associated target-injection methods.

The option of using direct-drive in addition to indirect-drive targets (see the box on pp. 38-39) is under consideration for the NIF. If direct-drive implosion experiments on the Omega Upgrade (an upgrade of the Omega glass laser to 60 beams) at the University of Rochester's Laboratory of Laser Energetics are successful, this option will be exercised, and both direct- and indirect-drive targets will be examined on the NIF. Figure 2

(a)



(b)

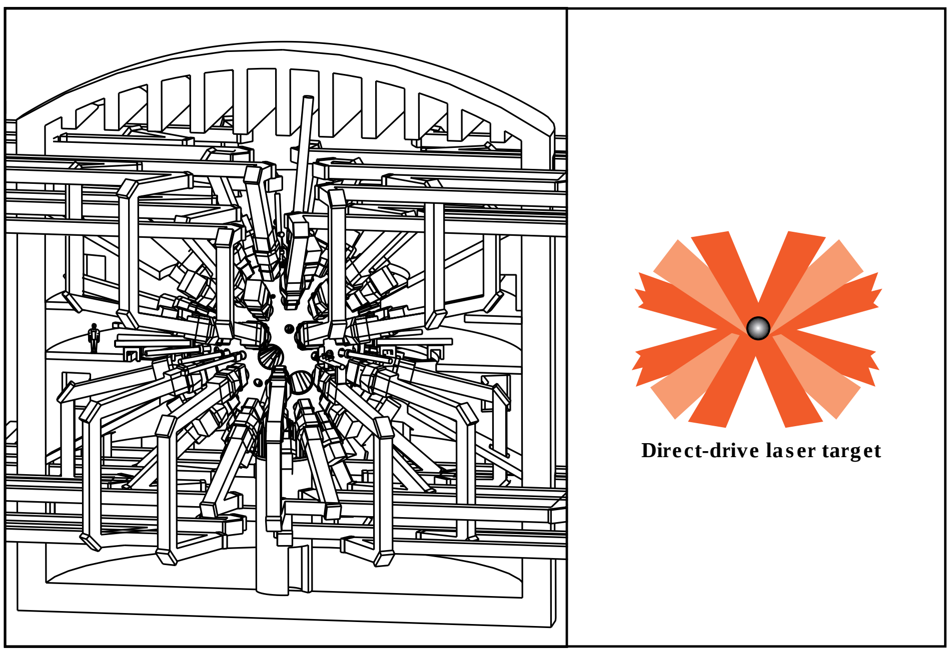


Figure 2. The NIF target area and beam-transport system (a) for indirect-drive experiments relevant to either laser or heavy-ion targets and (b) for direct-drive laser targets only. Note that the target area and beam-transport system in the baseline system (a) could be reconfigured to design (b) by the repositioning of 24 four-beam clusters, making direct-drive experiments possible.

shows the laser-beam configurations around the NIF fusion chamber that will be used to conduct indirect-drive (Figure 2a) and direct-drive experiments (Figure 2b). Figure 2 also shows examples of indirect- and direct-drive targets that can be tested in each configuration.

Figure 3 shows a heavy-ion-driven target for IFE (Figure 3a) compared with a modified laser-driven target (Figure 3b) that is designed to model more closely the IFE heavy-ion target. The latter (Figure 3b) illustrates how the NIF could use a laser to test the soft-x-ray transport and plasma dynamics inside a higher-fidelity hohlraum geometry similar to that in Figure 3a. Note that the capsule performance and implosion symmetry requirements for indirect-drive targets are independent of whether the x rays are generated with a laser or an ion-beam driver. We can also use the NIF for special laser-target experiments that simulate many aspects of heavy-ion targets.

Drivers. Although the key target-physics issues that NIF will resolve are largely independent of the type of driver used, it is essential in evaluating the potential of IFE to determine the minimum driver energy needed for ignition. Regardless of driver type, all IFE drivers for power plants need a similar combination of characteristics: high pulse-repetition rates (5 to 10 Hz) and high efficiency (i.e., driver output beam energy/electrical energy input to the driver greater than 10 to 20%, depending on target gain). In addition, they should be highly reliable and affordable when compared with nuclear generator plants.

The Energy Research branch of DOE is developing heavy-ion accelerators to meet the above requirements.[8] Heavy-ion drivers can be either straight linear accelerators (linacs) or circular (recirculating) beam accelerators like that shown in the box on p. 39. The Defense Programs branch of DOE, in contrast, is pursuing advanced solid-state lasers, krypton–fluoride lasers, and light-ion pulsed-power accelerators for defense applications that may, with improvements, lead to alternate IFE drivers. Diode-pumped solid-state lasers will be able to build on the laser technology being developed for the NIF.[9]

While other DOE research examines the direct-drive option and develops more efficient, high-repetition-rate IFE drivers (principally heavy-ion beam accelerators) for power plants, the NIF can be built and achieve its mission with current solid-state laser technology. Diode-pumped solid-state lasers (DPSSLs), which also build on NIF laser technology, may prove to be a backup to the heavy-ion accelerator. Using laser-diode arrays under development for industrial applications, DPSSL drivers may ultimately improve the efficiency, pulse rate, and cost of solid-state lasers enough for use as IFE drivers. Figure 4 shows a schematic DPSSL driver layout that, except for the diode pump arrays, has an architecture similar to that being developed for the NIF.

Fusion chambers. IFE needs fusion chambers where target fusion energy can be captured in suitable coolants for conversion into electricity. To allow high pulse rates, these chambers will have to be built so they can be cleared of target debris in fractions of a second. Further, they must be reliable enough to withstand the pulsed stresses of one billion shots (30 years of operation) without structural failure. They should also

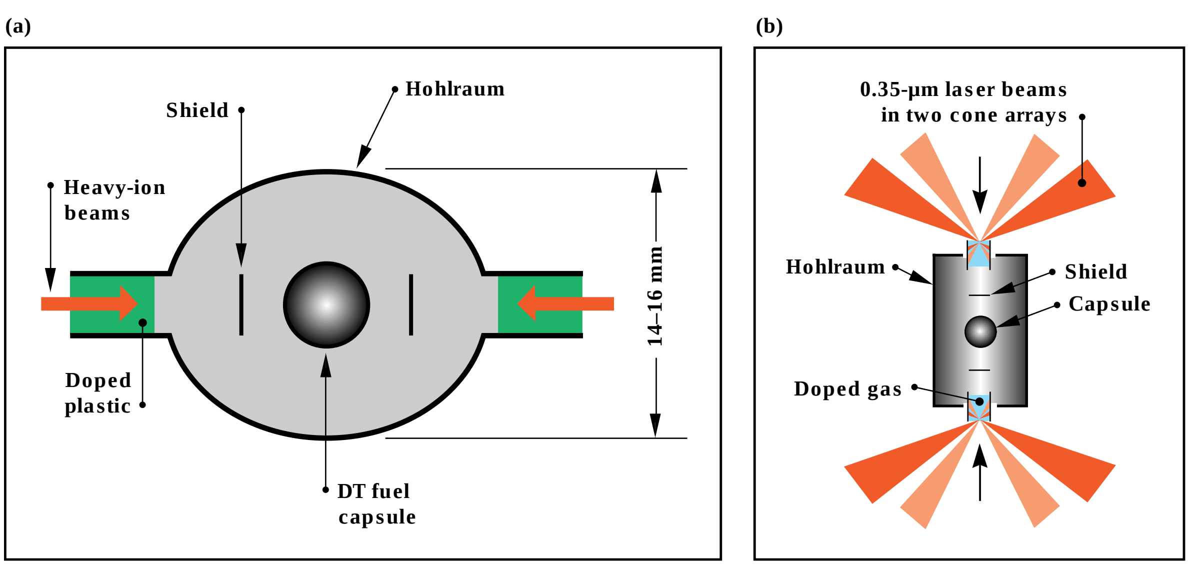


Figure 3. The NIF can test important heavy-ion physics issues, such as soft-x-ray transport and drive symmetry, hohlraum plasma dynamics, capsule-implosion hydrodynamics, and mix. Here the modified laser-driven target in (b) shows how the NIF could use a laser to test x-ray transport and plasma dynamics in a hohlraum geometry like that shown in (a).

use low-activation materials (such as molten salt coolants or carbon-composite materials) to minimize the generation of radioactive waste. Many IFE power plant studies have already found conceptual designs that meet these goals, but actual tests will be required. What we learn from the NIF fusion chamber can provide data to benchmark design codes for future IFE chamber designs.

Other Needs. In addition to fusion ignition, the NIF will provide important data on other key IFE power plant needs. These needs include wall protection from target debris and radiation damage, chamber clearing, rapid target injection, and precision tracking. The NIF will also be used to provide data that can benchmark and improve the predictive capability of various computer codes that will be needed to design future IFE power plants, to select among possible IFE technology options, and to improve our understanding of IFE target and chamber physics.

One predictive capability that can calculate and interpret material responses to neutron damage is a technique called molecular dynamic simulation (MDS).[10] MDS calculates responses at the atomic level by quantifying how a three-dimensional array of atoms responds to knock-on atoms that impinge on the matrix from a range of angles and with a range of energies as a result of an incident neutron flux. Potentially, MDS capabilities may include predicting, for a material, the number of vacancies and interstitials that will result from a neutron irradiation pulse, as well as the cluster fraction of defects, atomic mixing and solute precipitation, and phase transformations. Figure 5 shows how samples of materials exposed to the target neutron emission in a NIF shot can provide data that confirm the MDS model calculations.

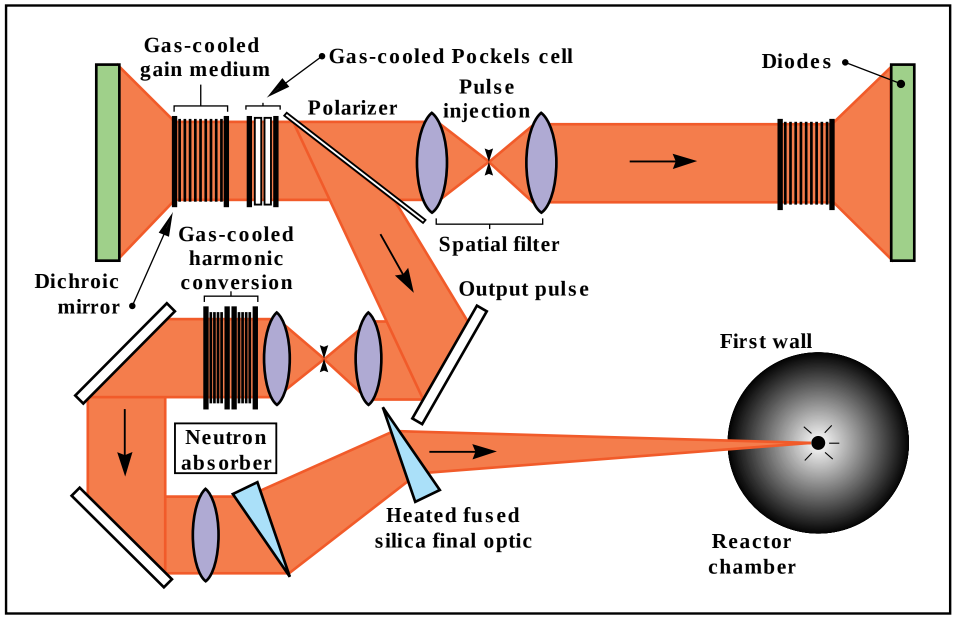


Figure 4. The diode-pumped, solid-state laser driver for IFE is similar in design to that being developed for the NIF. Although the NIF architecture will not include the diode pump arrays shown here, it will serve as an experience and technology base for the IFE driver. This figure shows a DPSSL IFE laser designed like the NIF in that it uses a multipass laser amplifier in which the laser beam is amplified by passing back and forth between the cavity mirrors four times before a Pockels cell optical switch sends the amplified beam out to the final optics and the target. However, the DPSSL uses light from arrays of efficient diode lasers to pump the amplifier from the ends rather than using light generated from flash lamps on the sides of the amplifier as in the present NIF design.

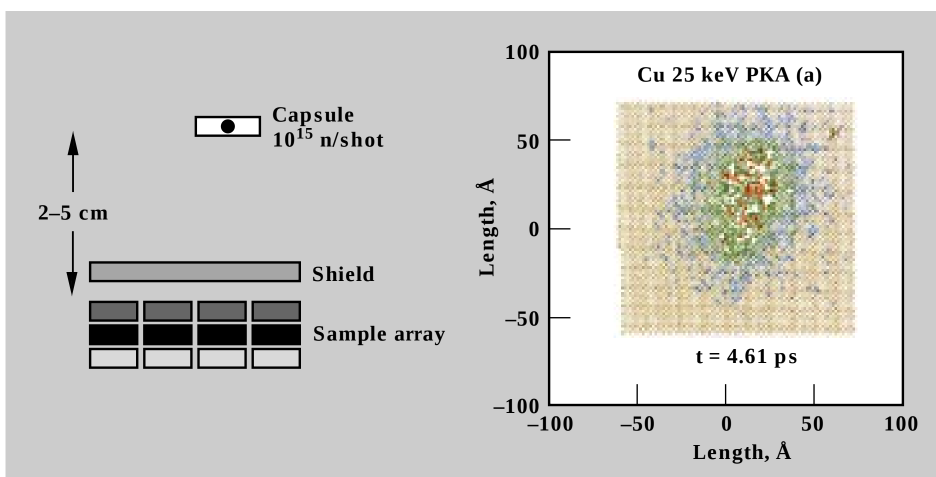


Figure 5. A molecular-dynamic simulation experiment on the NIF. Samples of 2- to 5-cm-width material placed within 20 cm of a NIF yield capsule (at left) will receive a significant exposure to 14-MeV neutrons (10^{15} neutrons per shot per square centimeter of sample area). The tantalum shield will stop most x rays. Electron microscope images of the damage sites will be compared to MDS code predictions as shown at right. The figure shows a typical damage site in a copper sample due to primary knock-on copper atoms (25 keV primary knock-on atoms [PKA]) arising from collisions of fast neutrons with copper atoms in the sample.

Producing Inertial Fusion Energy

An inertial confinement fusion (ICF) capsule or target is a small, millimeter-sized, spherical capsule whose hollow interior contains a thin annular layer of liquid or solid DT fuel (a mixture of deuterium and tritium isotopes of hydrogen). The outer surface of the capsule is rapidly heated and ablated either directly by intense laser or ion particle beams (drivers), called direct drive (a below), or indirectly by absorption of soft x-rays in the outer capsule surface. These soft x-rays are generated by driver beams hitting a nearby metal surface, a process called indirect drive (b below).

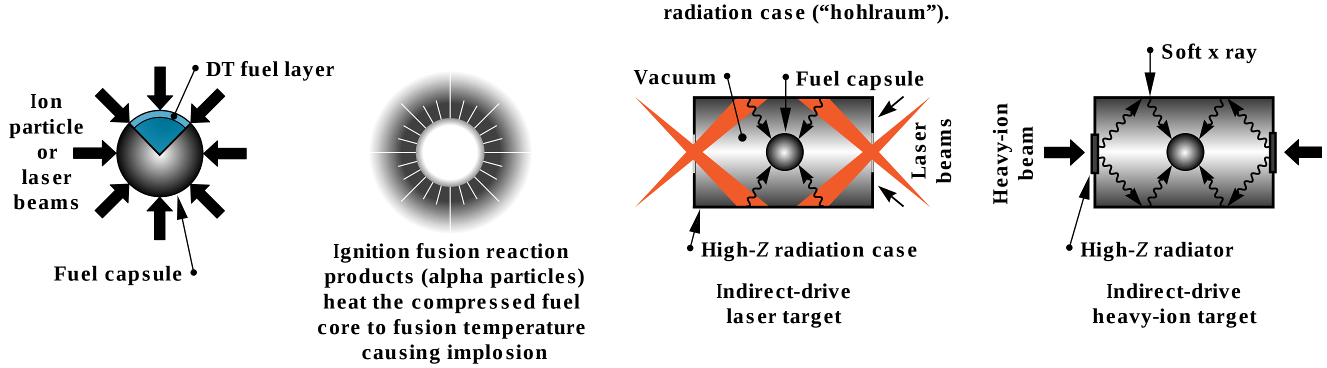
The rocket effect caused by the ablated outer capsule material creates an inward pressure causing the capsule to implode in about 4 nanoseconds (a nanosecond is one billionth of a second). The implosion heats the DT fuel in the core of the capsule to a temperature of about 50 million degrees Celsius, sufficient to cause the innermost core of the DT fuel to undergo fusion. The fusion reaction products deposit energy in the capsule, further increasing the fuel temperature and the fusion reaction rate. Core fuel ignition occurs when the self-heating of the core DT fuel due to the fusion reaction product deposition becomes faster than the heating due to compression. The ignition of the core will then propagate the fusion burn into the compressed fuel layer around the core. This will result in the release of much more fusion energy than the energy required to compress and implode the core.

An inertial fusion power plant would typically fire a continuous series of targets at a pulse rate of 6 Hz. The series of fusion energy releases thus created in the form of fast reaction products (helium alpha particles and neutrons) would be absorbed as heat in the low-activation coolants (fusion chamber) that surround the targets. Once heated, the coolants would be transferred to heat exchangers for turbine generators that produce electricity. The inertial fusion power plant example shown below uses jets of molten salt, called Flibe, surrounding the targets inserted into the fusion chamber. The molten salt jets absorb the fusion energy pulses from each target while flowing from the top to the bottom. The molten salt is collected from the bottom of the chamber and circulated to steam generators (not shown) to produce steam for standard turbine generators. This particular power plant example uses a ring-shaped ion beam accelerator as a driver, but there are also laser driver possibilities.

The minimum driver energy required to implode the capsule fast enough for ignition to occur is typically about a megajoule, the caloric equivalent of a large doughnut. Since this driver energy must be delivered in a few nanoseconds, however, a power of several hundred terawatts (1 terawatt = 1 million megawatts) will be needed. For reference, the entire electrical generating capacity of the United States is about one-half terawatt.

(a) Direct-drive targets are directly heated and imploded by intense driver beams.

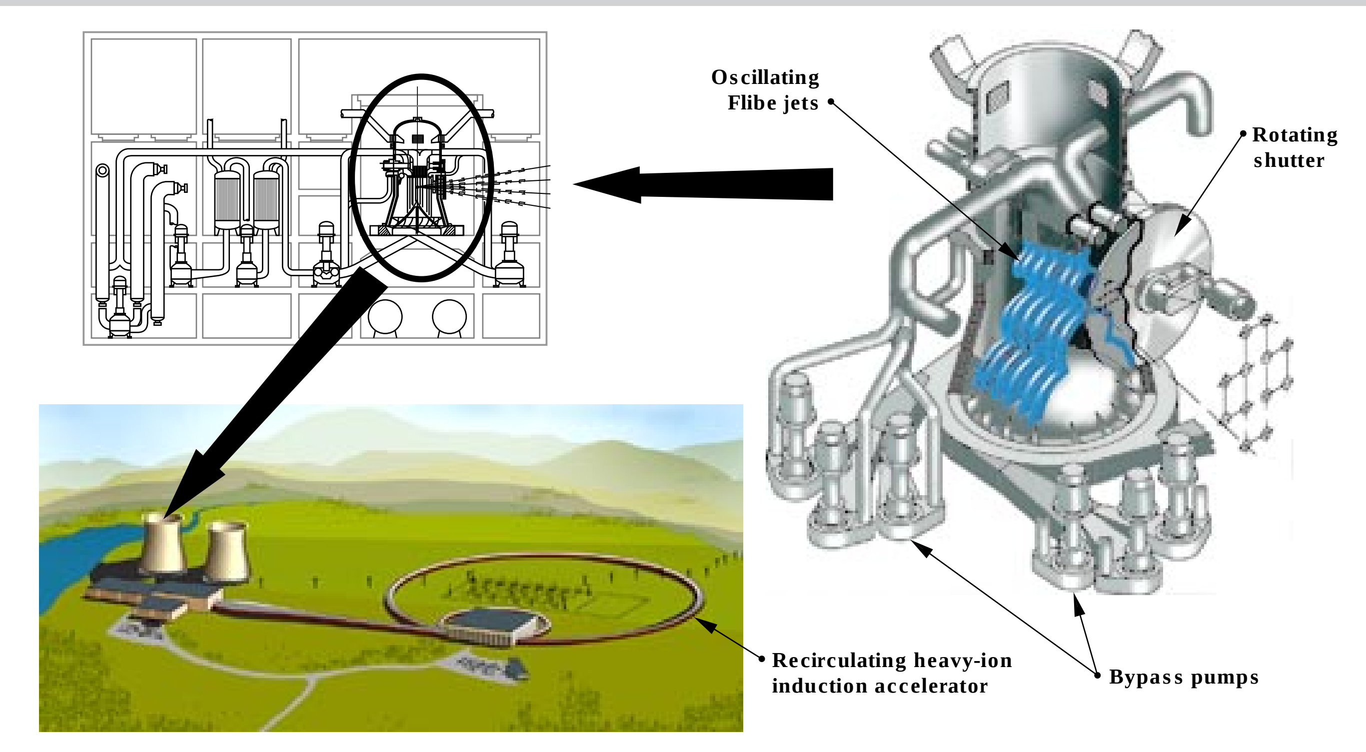
(b) Indirect-drive target fuel capsules are imploded by soft x rays generated by intense lasers or ion beams at the ends of a high-Z radiation case ("hohlraum").



The rapid thermal motion of the deuterium and tritium nuclei will cause a significant fraction of them to collide and fuse into helium ash before the compressed fuel mass from the implosion has had time to rebound and expand. The reaction products will fly away with several hundred times more kinetic energy than the thermal energy of the deuterium–tritium ion pair before fusion occurred. If some inefficiency in coupling the driver laser or ion-beam energy into compressing and heating the capsule is taken into account, the ratio of fusion energy produced by the target to the driver beam energy input to the target—called the target gain—can range from 50 to 100 in a typical power plant. Once this fusion heat is converted into electricity, the average amount of electricity needed to energize the driver would be 5 to 10% of the total plant output.

Inertial fusion targets are of two basic types: direct drive and indirect drive, both of which will be tested by the NIF to determine the best target for inertial fusion energy. A direct-drive target consists of a spherical capsule driven directly by laser or ion beams. So that the capsule will implode symmetrically and achieve high gain, it must be illuminated uniformly, from all directions, by many driver beams. In indirect-drive targets, the fuel capsule is placed inside a thin-walled cylindrical container (hohlraum) made from a high-atomic-number material, such as lead. Here a smaller number of driver beams (with a total energy similar to that required for direct drive) are directed at the two ends of the hohlraum cylinder, where the driver beam energy is converted to soft x rays, which, in turn, lead to the compression of the fuel capsule. The hohlraum spreads the soft x rays uniformly around the capsule to achieve a symmetric implosion.

For its driver, the NIF will use a solid-state glass laser to deposit the externally directed energy. This laser will deliver 1.8 MJ of laser light energy (in pulses spaced several hours apart) to test the minimum energy required for target ignition and the scaling of target gain so that any type of target optimized for future power plants can be designed with confidence. DOE–Energy Research is developing heavy-ion beam accelerators as its leading candidate drivers for future IFE power plants, while DOE–Defense Programs is developing other driver technologies for ICF research, including advanced solid-state lasers, that could lead to alternative IFE drivers as well.



Developing Fusion Power Technology

The NIF can also help develop fusion power technology (FPT), which includes the technologies needed to remove the heat of fusion and deliver it to the power plant. The primary functions of such components in IFE power plants are to convert energy, to produce and process tritium, and to provide radiation shielding. The dominant issues for FPT in IFE power plants concern component performance (both nuclear and material) so as to achieve economic competitiveness and to realize safety and environmental advantages. In this regard, NIF will provide valuable FPT information gained from the demonstrated performance and operation of the NIF facility itself, as well as from experiments designed specifically to test FPT issues. NIF's relevance to FPT has to do with both its prototypical size and configuration and its prototypical radiation-field (neutrons, x rays, and debris) spectra and intensity per shot. The most important limitation of NIF for FPT experiments is its low repetition rate (low neutron fluence), and its most important contributions to FPT development for IFE are related to:

- Fusion ignition.
- Design, construction, and operation of the NIF (integration of many prototypical IFE subsystems).
- Viability of first-wall protection schemes.
- Dose-rate effects on radiation damage in materials.
- Data on tritium burnup fractions in the target, tritium inventory and flow-rate parameters, and the achievable tritium breeding rate in samples.
- Neutronics data on radioactivity, nuclear heating, and radiation shielding.

The NIF will also be able to demonstrate the safe and environmentally benign operation that is important for IFE, including handling tritium safely and maintaining minimum inventories of low-activation materials. It is designed to keep radioactive inventories low enough to qualify as a low-hazard, non-nuclear facility according to current DOE and federal guidelines, thus setting the pattern for future IFE plants. Similar non-nuclear design goals will also be met for IFE power plants if the design selected for the fusion chamber is carefully followed and the low activation materials for it are used. The NIF will also demonstrate proper quality assurance in minimizing both

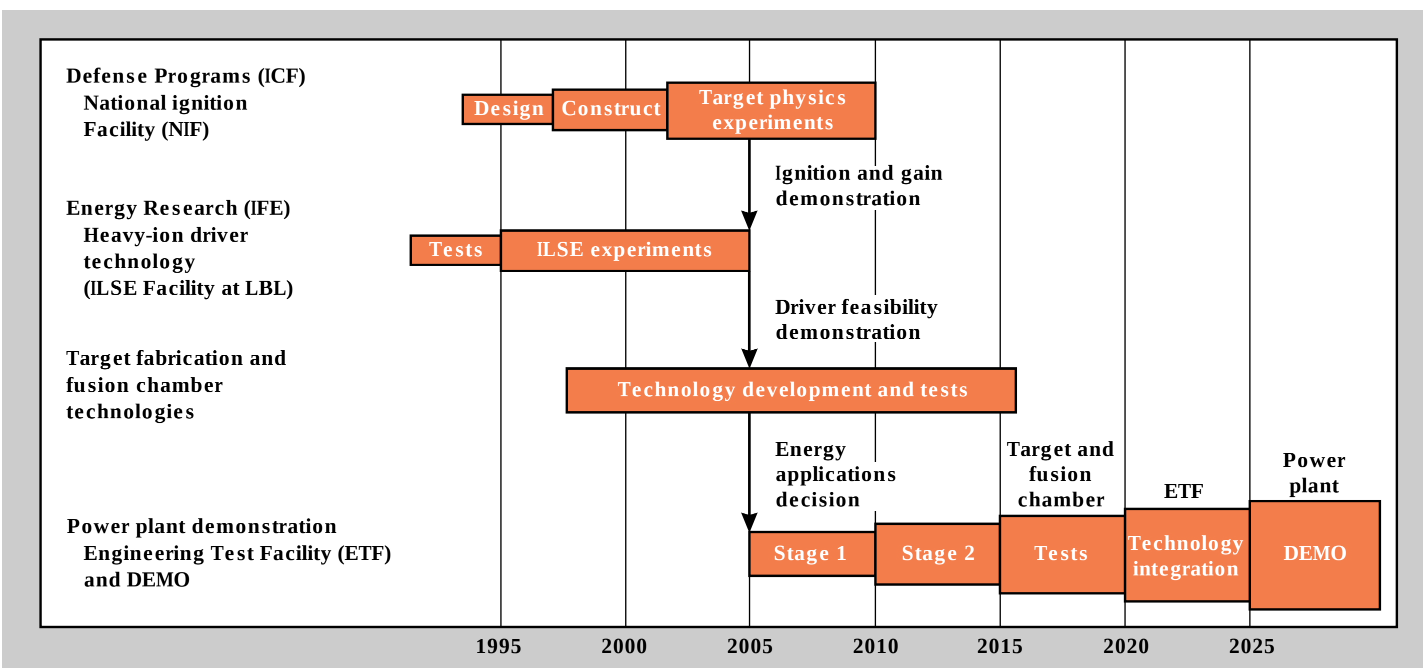


Figure 6. The timeline for IFE development includes ICF ignition and gain, IFE technologies, and the IFE power plant.

occupational and public exposures to radiation.

An Integrated IFE Development Plan

To capitalize on the success of fusion ignition in the NIF, which is expected to occur around the year 2005, an Engineering Test Facility (ETF) will be needed. This facility will test the fusion power plant technologies called for in the 1990 Fusion Policy Advisory Committee[7] the 1992 *National Energy Policy Act of 1992*[2] plans. A decision to move forward with the ETF will also depend on the timely demonstration of a feasible, efficient, high-repetition IFE driver.

Figure 6 shows existing and proposed facilities in an integrated plan for IFE development. In addition to the NIF, they include:

- **The Induction Linac Systems Experiment (ILSE).** Plans call for this proposed heavy-ion accelerator test facility to be built at the Lawrence Berkeley Laboratory. Its mission will be to demonstrate the feasibility of a heavy-ion driver for IFE by testing critical, high-current, ion-beam-induction accelerator and focusing physics with properly scaled-down ion energy and mass. ILSE may be built in two stages for a total construction cost of about $46 million. The ILSE experiments should also be completed by the year 2005.
- **The ETF/Laboratory Microfusion Facility (ETF/LMF).** This multiuser facility for both defense experiments and IFE technology development will be able to produce target-fusion energy yields at full-power plant scale (200 to 400 MJ) and high pulse rates (5 to 10 Hz). As indicated, it will also drive multiple test fusion chambers for defense, IFE (ETF), basic science, and materials research, using a single driver to save costs. Its total construction cost is expected to be $2 billion in today's dollars, and its life-cycle costs to the year 2020 are expected to be $3 billion. Then a successful IFE chamber from previous tests will be upgraded to a higher average fusion power level. This upgrade, which is expected to provide a DEMO (net electric-power demonstration) by the year 2025, is shown as the last phase of the upgradable ETF/LMF facility.

Note in Figure 6 that the decision to initiate the ETF/LMF facility, including selecting an ETF/LMF driver, will be made after ignition is demonstrated in the NIF. An ETF with a single driver can be designed to test several types of fusion chambers at reduced power, greatly reducing the cost of IFE development through a demonstration power plant. This parallel approach to IFE development has already been endorsed by many review committees, including the National Academy of Sciences,[11] the Fusion Policy Advisory Committee,[7] the Fusion Energy Advisory Committee, and the Inertial Confinement Fusion Advisory Committee.[12] DOE–Defense Programs (using the NIF for fusion ignition and gain demonstration) and DOE–Energy Research will play complementary roles in driver development and other IFE technologies.

Chairman Robert Conn, in reporting the recommendations of the 1993 Fusion Energy Advisory Committee to then DOE Energy Research Director Will Happer, wrote: "We recognize the great opportunity for fusion development afforded the DOE by a modest heavy-ion driver program that leverages off the extensive target program being conducted by Defense Programs. Consequently, we urge the DOE to reexamine its many programs, both inside and outside of Energy Research, with the view to embark more realistically on a heavy-ion program. Such a program would have the ILSE as a centerpiece, and be done in coordination with the program to demonstrate ignition and gain by Defense Programs."[8]

Summary

When the NIF demonstrates fusion ignition, which is central to proving the feasibility of IFE, it will tell us much about IFE target optimization and fabrication, provide important data on fusion-chamber phenomena and technologies, and demonstrate the safe and environmentally benign operation of an IFE power plant. In accomplishing these tasks, the NIF will also provide the basis for future decisions about IFE development programs and facilities such as the ETF. Furthermore, it will allow the U.S. to expand its expertise in inertial fusion and supporting industrial technology, as well as promote U.S. leadership in energy technologies, provide clean, viable alternatives to oil and other polluting fossil fuels, and reduce energy-related emissions of greenhouse gases.

Key Words: drivers—laser drivers, heavy-ion drivers; energy sources—fission breeder reactors, fossil fuels, inertial fusion energy, magnetic fusion energy, solar energy; fusion chambers; fusion power technology; International Thermonuclear Experiment; National Ignition Facility; targets—direct-drive targets, indirect-drive targets.

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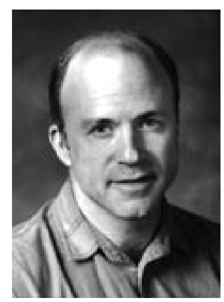

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