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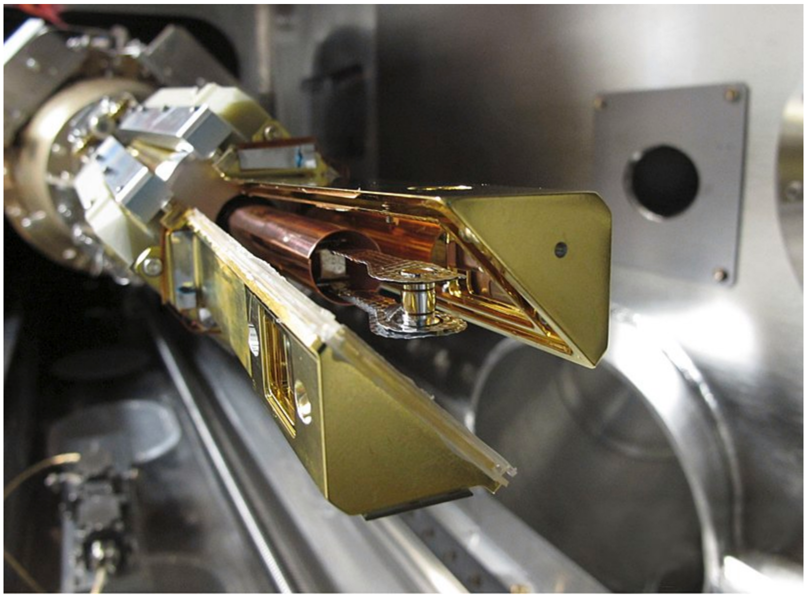
# National Ignition Facility


The National Ignition Facility, located at Lawrence Livermore National Laboratory.


The target assembly for NIF's first integrated ignition experiment is mounted in the cryogenic target positioning system, or cryoTARPOS. The two triangle-shaped arms form a shroud around the cold target to protect it until they open five seconds before a shot.

The **National Ignition Facility** (**NIF**), is a large laser-based inertial confinement fusion (ICF) research device, located at the Lawrence Livermore National Laboratory in Livermore, California. NIF uses lasers to heat and compress a small amount of hydrogen fuel with the goal of inducing nuclear fusion reactions. NIF's mission is to achieve fusion ignition with high energy gain, and to support nuclear weapon maintenance and design by studying the behavior of matter under the conditions found within nuclear weapons.[1] NIF is the largest and most energetic ICF device built to date, and the largest laser in the world.

The basic concept of all ICF devices is to rapidly collapse a small amount of fuel so the pressure and temperature reach fusion-relevant conditions. NIF does this by heating the outer layer of a small plastic sphere with the world's most powerful laser. The energy from the laser is so intense that it causes the plastic to explode, squeezing down on the fuel inside. The speed of this process is enormous, with the fuel reaching a peak around 350 km/s,[2] raising the density from about that of water to about 100 times that of lead. The delivery of energy and the adiabatic process during collapse raises the temperature of the fuel to hundreds of millions of degrees. At these temperatures, fusion processes occur very rapidly, before the energy generated in the fuel causes it to explode outward as well.

Construction on the NIF began in 1997 but management problems and technical delays slowed progress into the early 2000s. Progress after 2000 was smoother, but compared to initial estimates, NIF was completed five years behind schedule and was almost four times more expensive than originally budgeted. Construction was certified complete on 31 March 2009 by the U.S. Department of Energy,[3] and a dedication ceremony took place on 29 May 2009.[4] The first large-scale laser target experiments were performed in June 2009[5] and the first "integrated ignition experiments" (which tested the laser's power) were declared completed in October 2010.[6]

Bringing the system to its full potential was a lengthy process that was carried out from 2009 to 2012. During this period a number of experiments were worked into the process under the National Ignition Campaign, with the goal of reaching ignition just after the laser reached full power, some time in the second half of 2012. The Campaign officially ended in September 2012, at about $\frac{1}{10}$ the conditions needed for ignition.[7] Experiments since then have pushed this closer to $\frac{1}{3}$, but considerable theoretical and practical work is required if the system is ever to reach ignition.[8] Since 2012, NIF has been used primarily for materials science and weapons research.

## Contents

# Description

## ICF basics

Inertial confinement fusion (ICF) devices use *drivers* to rapidly heat the outer layers of a *target* in order to compress it. The target is a small spherical pellet containing a few milligrams of fusion fuel, typically a mix of deuterium (D) and tritium (T). The energy of the laser heats the surface of the pellet into a plasma, which explodes off the surface. The remaining portion of the target is driven inward, eventually compressing it into a small point of extremely high density. The rapid blowoff also creates a shock wave that travels toward the center of the compressed fuel from all sides. When it reaches the center of the fuel, a small volume is further heated and compressed to a greater degree. When the temperature and density of that small spot are raised high enough, fusion reactions occur and release energy.[9]

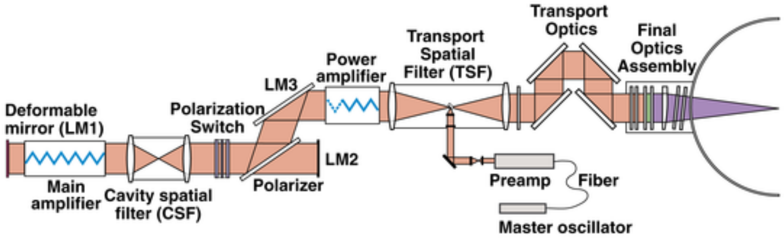
The fusion reactions release high-energy particles, some of which, primarily alpha particles, collide with the surrounding high density fuel and heat it further. If this process deposits enough energy in a given area it can cause that fuel to undergo fusion as well. However, the fuel is also losing heat through x-ray losses and hot electrons leaving the fuel area, so the rate of alpha heating must be greater than these losses, a condition known as *bootstrapping*.[10] Given the right overall conditions of the compressed fuel—high enough density and temperature—this bootstrapping process will result in a chain reaction, burning outward from the center where the shock wave started the reaction. This is a condition known as *ignition*, which will lead to a significant portion of the fuel in the target undergoing fusion and releasing large amounts of energy.[11]

To date most ICF experiments have used lasers to heat the target. Calculations show that the energy must be delivered quickly in order to compress the core before it disassembles. The laser energy also must be focused extremely evenly across the target's outer surface in order to collapse the fuel into a symmetric core. Although other drivers have been suggested, notably heavy ions driven in particle accelerators, lasers are currently the only devices with the right combination of features.[12][13]

## Driver laser

NIF aims to create a single 500 terawatt (TW) peak flash of light that reaches the target from numerous directions at the same time, within a few picoseconds. The design uses 192 beamlines in a parallel system of flashlamp-pumped, neodymium-doped phosphate glass lasers.[14]

To ensure that the output of the beamlines is uniform, the initial laser light is amplified from a single source in the Injection Laser System (ILS). This starts with a low-power flash of 1053-nanometer (nm) infra-red light generated in an ytterbium-doped optical fiber laser known as the Master Oscillator.[15] The light from the Master Oscillator is split and directed into 48 Preamplifier Modules (PAMs). Each PAM contains a two-stage amplification process. The first stage is a regenerative amplifier in which the pulse circulates 30 to 60 times, increasing in energy from nanojoules to tens of millijoules. The light then passes four times through a circuit containing a neodymium glass amplifier similar to (but much smaller than) the ones used in the main beamlines, boosting the nanojoules of light created in the Master Oscillator to about 6 joules. According to Lawrence Livermore National Laboratory (LLNL), the design of the PAMs was one of the major challenges during construction. Improvements to the design since then have allowed them to surpass their initial design goals.[16]



Simplified diagram of the beampath of a NIF laser beam, one of 192 similar beamlines. On the left are the amplifiers and optical switch, and on the right is the final spatial filter, switchyard and optical frequency converter.

The main amplification takes place in a series of glass amplifiers located at one end of the beamlines. Before firing, the amplifiers are first optically pumped by a total of 7,680 xenon flash lamps (the PAMs have their own smaller flash lamps as well). The lamps are powered by a capacitor bank which stores a total of 422 MJ (117 kWh) of electrical energy. When the wavefront passes through them, the amplifiers release some of the light energy stored in them into the beam. To improve the energy transfer the beams are sent though the main amplifier section four times, using an optical switch located in a mirrored cavity. In total these amplifiers boost the original 6 J provided by the PAMs to a nominal 4 MJ.[9] Given the time scale of a few billionths of a second, the peak UV power delivered to the target is correspondingly very high, 500 TW.

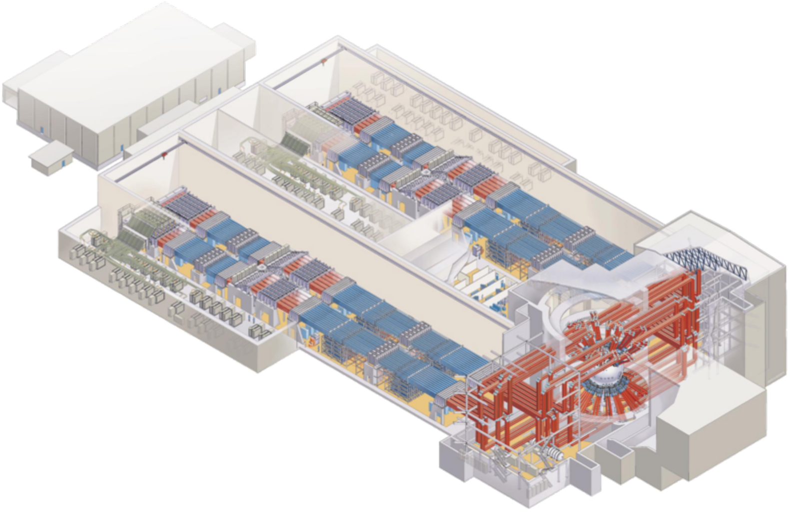
Near the center of each beamline, and taking up the majority of the total length, are *spatial filters*. These consist of long tubes with small telescopes at the end that focus the laser beam down to a tiny point in the center of the tube, where a mask cuts off any stray light outside the focal point. The filters ensure that the image of the beam when it reaches the target is extremely uniform, removing any light that was misfocused by imperfections in the optics upstream. Spatial filters were a major step forward in ICF work when they were introduced in the Cyclops laser, an earlier LLNL experiment.

The total length of the path the laser beam propagates from one end to the other, including switches, is about 1,500 meters (4,900 ft). The various optical elements in the beamlines are generally packaged into Line Replaceable Units (LRUs), standardized boxes about the size of a vending machine that can be dropped out of the beamline for replacement from below.[17]

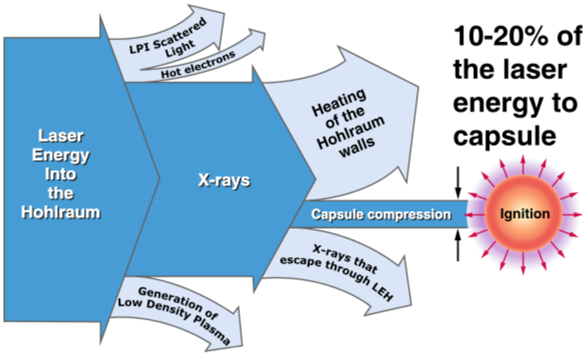
After the amplification is complete the light is switched back into the beamline, where it runs to the far end of the building to the *target chamber*. The target chamber is a 10-meter-diameter (33 ft) multi-piece steel sphere weighing 130,000 kilograms (290,000 lb).[18] Just before reaching the target chamber, the light is reflected off various mirrors in the *switchyard* and target area in order to impinge on the target from different directions. Since the length of the overall path from the Master Oscillator to the target is different for each of the beamlines, optics are used to delay the light in order to ensure all of them reach the center within a few picoseconds of each other.[19] NIF normally directs the laser into the chamber from the top and bottom. The target area and switchyard system can be reconfigured by moving half of the 48 beamlines to alternate positions closer to the equator of the target chamber.

One of the last steps in the process before reaching the target chamber is to convert the infrared (IR) light at 1053 nm into the ultraviolet (UV) at 351 nm in a device known as a frequency converter.[20] These are made of thin sheets (about 1 cm thick) cut from a single crystal of potassium dihydrogen phosphate. When the 1053 nm (IR) light passes through the first of two of these sheets, frequency addition converts a large fraction of the light into 527 nm light (green). On passing through the second sheet, frequency combination converts much of the 527 nm light and the remaining 1053 nm light into 351 nm (UV) light. Infrared (IR) light is much less effective than UV at heating the targets, because IR couples more strongly with hot electrons which will absorb a considerable amount of energy and interfere with compression. The conversion process can reach peak efficiencies of about 80 percent for a laser pulse that has a flat temporal shape, but the temporal shape needed for ignition varies significantly over the duration of the pulse. The actual conversion process is about 50 percent efficient, reducing delivered energy to a nominal 1.8 MJ.[21]

One important aspect of any ICF research project is ensuring that experiments can actually be carried out on a timely basis. Previous devices generally had to cool down for many hours to allow the flashlamps and laser glass to regain their shapes after firing (due to thermal expansion), limiting use to one or fewer firings a day. One of the goals for NIF is to reduce this time to less than four hours, in order to allow 700 firings a year.[22]


NIF's basic layout. The laser pulse is generated in the room just right of center, and is sent into the beamlines (blue) on either side. After several passes through the beamlines the light is sent into the "switchyard" (red) where it is aimed into the target chamber (silver).

## NIF and ICF



Sankey diagram of the laser energy to hohlraum x-ray to target capsule energy coupling efficiency. Note the "laser energy" is after conversion to UV, which loses about 50% of the original IR power. The conversion of x-ray heat to energy in the fuel loses another 90% - of the 1.9 MJ of laser light, only about 10 kJ ends up in the fuel itself.

The name National Ignition Facility refers to the goal of igniting the fusion fuel, a long-sought threshold in fusion research. In existing (non-weapon) fusion experiments the heat produced by the fusion reactions rapidly escapes from the plasma, meaning that external heating must be applied continually in order to keep the reactions going. Ignition refers to the point at which the energy given off in the fusion reactions currently underway is high enough to sustain the temperature of the fuel against those losses. This causes a chain-reaction that allows the majority of the fuel to undergo a nuclear *burn*. Ignition is considered a key requirement if fusion power is to ever become practical.[11]

NIF is designed primarily to use the *indirect drive* method of operation, in which the laser heats a small metal cylinder instead of the capsule inside it. The heat causes the cylinder, known as a hohlraum (German for "hollow room", or cavity), to re-emit the energy as intense X-rays, which are more evenly distributed and symmetrical than the original laser beams. Experimental systems, including the OMEGA and Nova lasers, validated this approach through the late 1980s.[23] In the case of the NIF, the large delivered power allows for the use of a much larger target; the baseline pellet design is about 2 mm in diameter, chilled to about 18 kelvins (−255 °C) and lined with a layer of frozen DT fuel. The hollow interior also contains a small amount of DT gas.

In a typical experiment, the laser will generate 3 MJ of infrared laser energy of a possible 4. About 1.5 MJ of this is left after conversion to UV, and about 15 percent of this is lost in the x-ray conversion in the hohlraum. About 15 percent of the resulting x-rays, about 150 kJ, will be absorbed by the outer layers of the target.[24] The coupling between the capsule and the x-rays is lossy, and ultimately only about 10 to 14 kJ of energy is deposited in the fuel itself.[25]

The resulting inward directed compression is expected to compress the fuel in the center of the target to a density of about 1,000 g/cm$^3$ (or 1,000,000 kg/m$^3$);[26] for comparison, lead has a normal density of about 11 g/cm$^3$ (11,340 kg/m$^3$). The pressure is the equivalent of 300 billion atmospheres.[10]

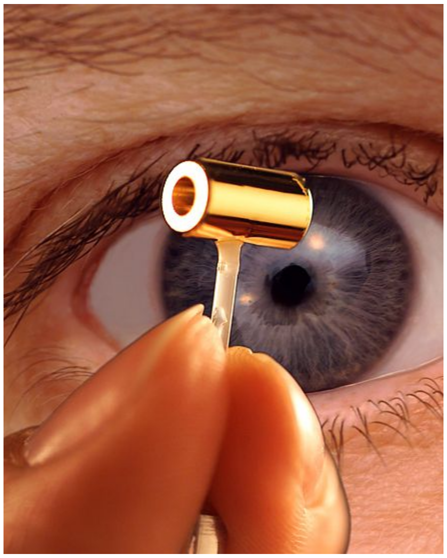
Based on simulations, it was expected this would produce about 20 MJ of fusion energy to be released, resulting in a net fusion energy gain of about 15 (G=Fusion energy/UV laser energy).[24] Improvements in both the laser system and hohlraum design are expected to improve the energy absorbed by the capsule to about 420 kJ (and thus perhaps 40 to 50 in the fuel itself), which, in turn, could generate up to 100-150 MJ of fusion energy.[26] However, the baseline design allows for a maximum of about 45 MJ of fusion energy release, due to the design of the target chamber.[27] This is the equivalent of about 11 kg of TNT exploding.

These output energies are still less than the 422 MJ of input energy required to charge the system's capacitors that power the laser amplifiers. The net wall-plug efficiency of NIF (UV laser energy out divided by the energy required to pump the lasers from an external source) would be less than one percent, and the total wall-to-fusion efficiency is under 10% at its maximum performance. An economical fusion reactor would require that the fusion output be at least an order of magnitude more than this input. Commercial laser fusion systems would use the much more efficient diode-pumped solid state lasers, where wall-plug efficiencies of 10 percent have been demonstrated, and efficiencies 16-18 percent are expected with advanced concepts under development.[28]

## Other concepts

NIF is also exploring new types of targets. Previous experiments generally used plastic ablators, typically polystyrene (CH). NIF's targets also are constructed by coating a plastic form with a layer of sputtered beryllium or beryllium-copper alloys, and then oxidizing the plastic out of the center.[29][30] In comparison to traditional plastic targets, beryllium targets offer higher overall implosion efficiencies for the indirect-drive mode where the incoming energy is in the form of x-rays.

Although NIF was primarily designed as an indirect drive device, the energy in the laser is high enough to be used as a *direct drive* system as well, where the laser shines directly on the target. Even at UV wavelengths the power delivered by NIF is estimated to be more than enough to cause ignition, resulting in fusion energy gains of about 40 times,[31] somewhat higher than the indirect drive system. A more uniform beam layout suitable for direct drive experiments can be arranged through changes in the switchyard that move half of the beamlines to locations closer to the middle of the target chamber.



Mockup of the gold-plated hohlraum designed for the NIF.

It has been shown, using scaled implosions on the OMEGA laser and computer simulations, that NIF should also be capable of igniting a capsule using the so-called *polar direct drive* (PDD) configuration where the target is irradiated directly by the laser, but only from the top and bottom, with no changes to the NIF beamline layout.[32] In this configuration the target suffers either a "pancake" or "cigar" anisotropy on implosion, reducing the maximum temperature at the core.

NIF's fuel "target", filled with either D-T gas or D-T ice. The capsule is held in the hohlraum using thin plastic webbing.

Other targets, called *saturn targets*, are specifically designed to reduce the anisotropy and improve the implosion.[33] They feature a small plastic ring around the "equator" of the target, which quickly vaporizes into a plasma when hit by the laser. Some of the laser light is refracted through this plasma back towards the equator of the target, evening out the heating. Ignition with gains of just over thirty-five times are thought to be possible using these targets at NIF,[32] producing results almost as good as the fully symmetric direct drive approach.

# History

## Impetus

Lawrence Livermore National Laboratory's (LLNL) history with the ICF program starts with physicist John Nuckolls, who started considering the problem after a 1957 meeting on the peaceful use of nuclear weapons arranged by Edward Teller at LLNL. During these meetings, the idea later known as PACER first developed. PACER envisioned the explosion of small hydrogen bombs in large caverns to generate steam that would be converted into electrical power. After identifying several problems with this approach, Nuckolls became interested in understanding how small a bomb could be made that would still generate net positive power.[34]

There are two parts to a typical hydrogen bomb, a plutonium-based atomic bomb known as the *primary*, and a cylindrical arrangement of fusion fuels known as the *secondary*. The primary releases significant amounts of x-rays, which are trapped within the bomb casing and heat and compress the secondary until it undergoes ignition. The secondary consists of lithium deuteride fuel, which requires an external neutron source to begin the reaction. This is normally in the form of a D-T "spark plug" in the center of the fuel. Nuckolls's idea was to explore how small the secondary could be made, and what effects this would have on the energy needed from the primary to cause ignition. The simplest change is to replace the LiD fuel with D-T gas, essentially making the spark plug the entire secondary. At that point there is no theoretical smallest size - as the secondary got smaller, so did the amount of energy needed to reach ignition. At the milligram level, the energy levels started to approach those available through several known devices.[34]

By the early 1960s, Nuckolls and several other weapons designers had developed the outlines of the ICF approach. The D-T fuel would be placed in a small capsule, designed to rapidly ablate when heated and thereby maximize compression and shock wave formation. This capsule would be placed within an engineered shell, the hohlraum, which acted similar to the bomb casing. However, the hohlraum did not have to be heated by x-rays; any source of energy could be used as long as it delivered enough energy to cause the hohlraum itself to heat up and start giving off x-rays. Ideally the energy source would be located some distance away, to mechanically isolate both ends of the reaction. A small atomic bomb could be used as the energy source, as it is in a hydrogen bomb, but ideally smaller energy sources would be used. Using computer simulations, the teams estimated that about 5 MJ of energy would be needed from the primary, generating a 1 MJ beam.[34] To put this in perspective, a small fission primary of 0.5 kt releases 2 million MJ in total.[35][36][37]

## ICF program begins

While Nuckolls and LLNL were working on hohlraum-based concepts, former weapon designer Ray Kidder was working on the direct drive concept, using a large number of laser beams to evenly heat the target capsule. In the early 1970s, Kidder formed KMS Fusion to directly commercialize this concept. This sparked off intense rivalry between Kidder and the weapons labs. Formerly ignored, ICF was now a hot topic and most of the labs soon started ICF efforts of their own.[34] LLNL decided early on to concentrate on glass lasers, while other facilities studied gas lasers using carbon dioxide (e.g. ANTARES, Los Alamos National Laboratory) or KrF (e.g. Nike laser, Naval Research Laboratory).

Throughout these early stages of development, much of the understanding of the fusion process was the result of computer simulations, primarily LASNEX. LASNEX greatly simplified the reaction to a 2-dimensional simulation, which was all that was possible given the amount of computing power at the time. According to LASNEX, laser drivers in the kJ range would have the required properties to reach low gain, which was just within the state of the art. This led to the Shiva laser project which was completed in 1977. Contrary to predictions, Shiva fell far short of its goals, and the densities reached were thousands of times smaller than predicted. This was traced to issues with the way the laser delivered heat to the target, which delivered most of its energy to electrons rather than the entire fuel mass. Further experiments and simulations demonstrated that this process could be dramatically improved by using shorter wavelengths of laser light.

Further upgrades to the simulation programs, accounting for these effects, predicted a new design that would reach ignition. This new system emerged as the 20-beam 200 kJ Nova laser concept. During the initial construction phase, Nuckolls found an error in his calculations, and an October 1979 review chaired by John Foster Jr. of TRW confirmed that there was no way Nova would reach ignition. The Nova design was then modified into a smaller 10-beam design that added frequency conversion to 351 nm light, which would increase coupling efficiency.[38] In operation, Nova was able to deliver about 30 kJ of UV laser energy, about half of what was initially expected, primarily due to limits set by optical damage to the final focusing optics. Even at those levels, it was clear that the predictions for fusion production were still wrong; even at the limited powers available, fusion yields were far below predictions.

## Halite and Centurion

With each experiment, the predicted energy needed to reach ignition rose, and it was not clear that post-Nova predictions were any more accurate than earlier ones. The Department of Energy (DOE) decided that direct experimentation was the best way to settle the issue, and in 1978 they started a series of underground experiments at the Nevada Test Site that used small nuclear bombs to illuminate ICF targets. The tests were known as Halite or Centurion depending on which lab ran it, LLNL or LANL.

Each test was able to simultaneously illuminate many targets, allowing them to test the amount of x-ray energy needed by placing the targets at different distances from the bomb. Another question was how large the fuel assembly had to be in order for the fuel to self-heat from the fusion reactions and thus reach ignition. Initial data were available by mid-1984, and the testing ceased in 1988. Ignition was achieved for the first time during these tests, but the amount of energy and the size of the fuel targets needed to reach ignition was far higher than predicted.[39] During this same period, experiments began on Nova using similar targets to understand their behaviour under laser illumination, allowing direct comparison against the results obtained from the bomb tests.[40]

Data from the tests suggested that about 10 MJ of x-ray energy would be needed to reach ignition.[39][41][42][43][44] If this energy is supplied by an IR laser to a hohlraum, as in Nova or NIF, this corresponds to an original laser energy on the order of 100 MJ, well beyond the reach of existing technologies.[39]

A great debate broke out in the ICF establishment as a result.[39] One group suggested that they attempt to build a laser of this power; Leonardo Mascheroni and Claude Phipps designed a new type of hydrogen fluoride laser that was pumped by high-energy electrons that would be able to reach the 100 MJ limit. Others used the same data and new versions of their computer simulations based on these experiments that suggested that careful shaping of the laser pulse and using more beams spread more evenly showed that ignition and net energy gains could be achieved with a laser between 5 and 10 MJ.[45][46]

These results prompted the DOE to request a custom military ICF facility they called the "Laboratory Microfusion Facility" (LMF). LMF would use a driver on the order of 10 MJ, delivering fusion yields of between 100 and 1,000 MJ. A 1989/90 review of this concept by the National Academy of Sciences suggested that the LMF was too large a step to make at once, and that fundamental physics issues still needed to be explored. They recommended further experiments before attempting to move to a 10 MJ system. Nevertheless, the authors were aware of the potential for higher energy requirements, and noted "Indeed, if it did turn out that a 100 MJ driver were required for ignition and gain, one would have to rethink the entire approach to, and rationale for, ICF".[47]

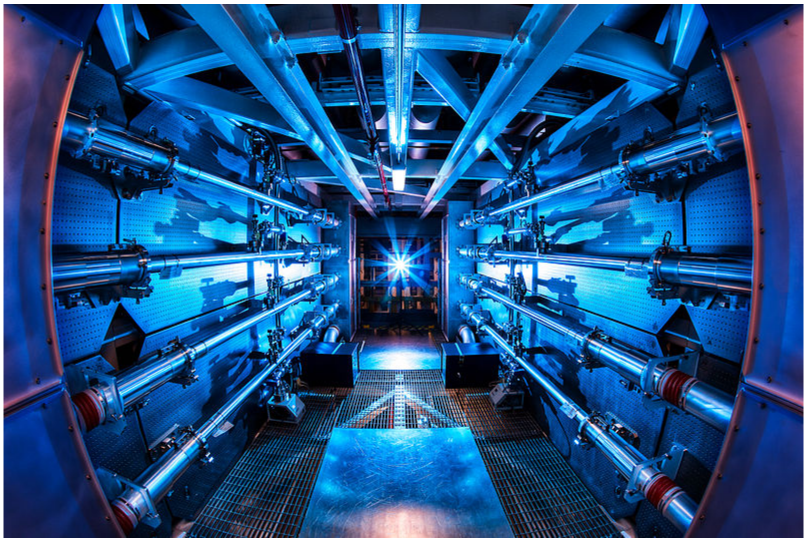
## LMF and Nova Upgrade

Building the LMF was estimated to cost about $1 billion.[48] LLNL initially submitted a design with a 5 MJ 350 nm (UV) driver laser that would be able to reach about 200 MJ yield, which was enough to attain the majority of the LMF goals. The program was estimated to cost about $600 million FY 1989 dollars, and an additional $250 million to upgrade it to a full 1,000 MJ if needed, and would grow to well over $1 billion if LMF was to meet all of the goals requested by the DOE.[48] Other labs also proposed their own LMF designs using other technologies.

The National Academy of Sciences review led to a reevaluation of these plans, and in July 1990, LLNL responded with the Nova Upgrade, which would reuse the majority of the existing Nova facility, along with the adjacent Shiva facility. The resulting system would be much lower power than the LMF concept, with a driver of about 1 MJ.[49] The new design included a number of features that advanced the state of the art in the driver section, including the multi-pass design in the main amplifiers, and 18 beamlines (up from 10) that were split into 288 "beamlets" as they entered the target area in order to improve the uniformity of illumination. The plans called for the installation of two main banks of laser beamlines, one in the existing Nova beamline room, and the other in the older Shiva building next door, extending through its laser bay and target area into an upgraded Nova target area. The lasers would deliver about 500 TW in a 4 ns pulse. The upgrades were expected to allow the new Nova to produce fusion yields of between 2 and 10 MJ.[48] The initial estimates from 1992 estimated construction costs around $400 million, with construction taking place from 1995 to 1999.

## NIF emerges

Throughout this period, the ending of the Cold War led to dramatic changes in defense funding and priorities. As the need for nuclear weapons was greatly reduced and various arms limitation agreements led to a reduction in warhead count, the US was faced with the prospect of losing a generation of nuclear weapon designers able to maintain the existing stockpiles, or design new weapons.[50] At the same time, progress was being made on what would become the Comprehensive Nuclear-Test-Ban Treaty, which would ban all criticality testing. This would make the reliable development of newer generations of nuclear weapons much more difficult.


The preamplifiers of the National Ignition Facility are the first step in increasing the energy of laser beams as they make their way toward the target chamber. In 2012 NIF achieved a 500 terawatt shot—1,000 times more power than the United States uses at any instant in time.

Out of these changes came the Stockpile Stewardship and Management Program (SSMP), which, among other things, included funds for the development of methods to design and build nuclear weapons that would work without having to be explosively tested. In a series of meetings that started in 1995, an agreement formed between the labs to divide up the SSMP efforts. An important part of this would be confirmation of computer models using low-yield ICF experiments. The Nova Upgrade was too small to use for these experiments,[51][a] and a redesign emerged as NIF in 1994. The estimated cost of the project remained just over $1 billion,[52] with completion in 2002.

In spite of the agreement, the large project cost combined with the ending of similar projects at other labs resulted in several highly critical comments by scientists at other weapons labs, Sandia National Laboratories in particular. In May 1997, Sandia fusion scientist Rick Spielman publicly stated that NIF had "virtually no internal peer review on the technical issues" and that "Livermore essentially picked the panel to review themselves".[53] A retired Sandia manager, Bob Puerifoy, was even more blunt than Spielman: "NIF is worthless ... it can't be used to maintain the stockpile, period".[54]

A contrasting view was expressed by Victor Reis, assistant secretary for Defense Programs within DOE and the chief architect of the Stockpile Stewardship Program. Reis told the U.S. House Armed Services Committee in 1997 that NIF was "designed to produce, for the first time in a laboratory setting, conditions of temperature and density of matter close to those that occur in the detonation of nuclear weapons. The ability to study the behavior of matter and the transfer of energy and radiation under these conditions is key to understanding the basic physics of nuclear weapons and predicting their performance without underground nuclear testing.[55] Two JASON panels, which are composed of scientific and technical national security experts, have stated that the NIF is the most scientifically valuable of all programs proposed for science-based stockpile stewardship.[56]

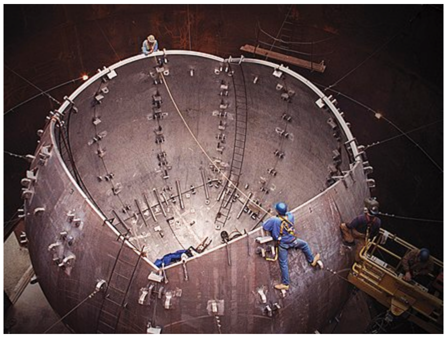
Despite the initial criticism, Sandia, as well as Los Alamos, provided support in the development of many NIF technologies,[57] and both laboratories later became partners with NIF in the National Ignition Campaign.[58]

## Constructing NIF

Work on the NIF started with a single beamline demonstrator, Beamlet. Beamlet operated between 1994 and 1997 and was entirely successful. It was then sent to Sandia National Laboratories as a light source in their Z machine. A full-sized demonstrator then followed, in AMPLAB, which started operations in 1997.[59] The official groundbreaking on the main NIF site was on May 29, 1997.[60]

The Beamlet laser tested the design and techniques that would be used on NIF.

At the time, the DOE was estimating that the NIF would cost approximately $1.1 billion and another $1 billion for related research, and would be complete as early as 2002.[61] Later in 1997 the DOE approved an additional $100 million in funding and pushed the operational date back to 2004. As late as 1998 LLNL's public documents stated the overall price was $1.2 billion, with the first eight lasers coming online in 2001 and full completion in 2003.[62]



The NIF target chamber was so large it had to be built in sections.

The physical scale of the facility alone made the construction project challenging. By the time the "conventional facility" (the shell for the laser) was complete in 2001, more than 210,000 cubic yards of soil had been excavated, more than 73,000 cubic yards of concrete had been poured, 7,600 tons of reinforcing steel rebar had been placed, and more than 5,000 tons of structural steel had been erected. In addition to its sheer size, building NIF presented a number of unique challenges. To isolate the laser system from vibration, the foundation of each laser bay was made independent of the rest of the structure. Three-foot-thick, 420-foot-long and 80-foot-wide slabs, each containing 3,800 cubic yards of concrete, required continuous concrete pours to achieve their specifications.

There were also unexpected challenges to cope with: In November, 1997, an El Niño weather front dumped two inches of rain in two hours, flooding the NIF site with 200,000 gallons of water just three days before the scheduled concrete foundation pour. The earth was so soaked that the framing for the retaining wall sank six inches, forcing the crew to disassemble and reassemble it in order to pour the concrete.[63] Construction was halted in December, 1997, when 16,000-year-old mammoth bones were discovered on the construction site. Paleontologists were called in to remove and preserve the bones, and construction restarted within four days.[64]

A variety of research and development, technology and engineering challenges also had to be overcome, such as working with the optics industry to create a precision large optics fabrication capability to supply the laser glass for NIF's 7,500 meter-sized optics. State-of-the-art optics measurement, coating and finishing techniques were needed to withstand NIF's high-energy lasers, as were methods for amplifying the laser beams to the needed energy levels.[65] Continuous-pour glass, rapid-growth crystals, innovative optical switches, and deformable mirrors were among the technology innovations developed for NIF.[66]

Sandia, with extensive experience in pulsed power delivery, designed the capacitor banks used to feed the flashlamps, completing the first unit in October 1998. To everyone's surprise, the Pulsed Power Conditioning Modules (PCMs) suffered capacitor failures that led to explosions. This required a redesign of the module to contain the debris, but since the concrete structure of the buildings holding them had already been poured, this left the new modules so tightly packed that there was no way to do maintenance in-place. Yet another redesign followed, this time allowing the modules to be removed from the bays for servicing.[38] Continuing problems of this sort further delayed the operational start of the project, and in September 1999, an updated DOE report stated that NIF would require up to $350 million more and completion would be pushed back to 2006.[61]

## Re-baseline and GAO report

Throughout this period the problems with NIF were not being reported up the management chain. In 1999 then Secretary of Energy Bill Richardson reported to Congress that the NIF project was on time and budget, following the information that had been passed onto him by NIF's management. In August that year it was revealed that NIF management had misled Richardson, and in fact neither claim was close to the truth.[67] As the GAO would later note, "Furthermore, the Laboratory's former laser director, who oversaw NIF and all other laser activities, assured Laboratory managers, DOE, the university, and the Congress that the NIF project was adequately funded and staffed and was continuing on cost and schedule, even while he was briefed on clear and growing evidence that NIF had serious problems".[61] Richardson later commented "I have been very concerned about the management of this facility... bad management has overtaken good science. I don't want this to ever happen again". A DOE Task Force reporting to Richardson late in January 2000 summarized that "organizations of the NIF project failed to implement program and project management procedures and processes commensurate with a major research and development project... [and that] ...no one gets a passing grade on NIF Management: not the DOE's office of Defense Programs, not the Lawrence Livermore National Laboratory and not the University of California".[68]

Bill Richardson began a review process that brought NIF construction back under control.

Given the budget problems, the US Congress requested an independent review by the General Accounting Office (GAO). They returned a highly critical report in August 2000 stating that the budget was likely $3.9 billion, including R&D, and that the facility was unlikely to be completed anywhere near on time.[61][69] The report, "*Management and Oversight Failures Caused Major Cost Overruns and Schedule Delays*," identified management problems for the overruns, and also criticized the program for failing to include a considerable amount of money dedicated to target fabrication in the budget, including it in operational costs instead of development.[67]

Early technical delays and project management issues caused the DOE to begin a comprehensive "Rebaseline Validation Review of the National Ignition Facility Project" in 2000, which took a critical look at the project, identifying areas of concern and adjusting the schedule and budget to ensure completion. John Gordon, National Nuclear Security Administrator, stated "We have prepared a detailed bottom-up cost and schedule to complete the NIF project... The independent review supports our position that the NIF management team has made significant progress and resolved earlier problems".[70] The report revised their budget estimate to $2.25 billion, not including related R&D which pushed it to $3.3 billion total, and pushed back the completion date to 2006 with the first lines coming online in 2004.[71][72] A follow-up report the next year included all of these items, pushing the budget to $4.2 billion, and the completion date to around 2008.

## Progress after rebaselining

A new management team took over the NIF project[73][74] in September 1999, headed by George Miller (who later became LLNL director 2006-2011), who was named acting associate director for lasers. Ed Moses, former head of the Atomic Vapor Laser Isotope Separation (AVLIS) program at LLNL, became NIF project manager. Since the rebaselining, NIF's management has received many positive reviews and the project has met the budgets and schedules approved by Congress. In October 2010, the project was named "Project of the Year" by the Project Management Institute, which cited NIF as a "stellar example of how properly applied project management excellence can bring together global teams to deliver a project of this scale and importance efficiently."[75]


Laser Bay 2 was commissioned in July 2007

Recent reviews of the project have been positive, generally in keeping with the post-GAO Rebaseline schedules and budgets. However, there were lingering concerns about the NIF's ability to reach ignition, at least in the short term. An independent review by the JASON Defense Advisory Group was generally positive about NIF's prospects over the long term, but concluded that "The scientific and technical challenges in such a complex activity suggest that success in the early attempts at ignition in 2010, while possible, is unlikely".[76] The group suggested a number of changes to the completion timeline to bring NIF to its full design power as soon as possible, skipping over a testing period at lower powers that they felt had little value.

### Early tests and construction completion

In May 2003, the NIF achieved "first light" on a bundle of four beams, producing a 10.4 kJ pulse of IR light in a single beamline.[22] In 2005 the first eight beams (a full bundle) were fired producing 153 kJ of infrared light, thus eclipsing OMEGA as the highest energy laser (per pulse) on the planet. By January 2007 all of the LRUs in the Master Oscillator Room (MOOR) were complete and the computer room had been installed. By August 2007 96 laser lines were completed and commissioned, and "A total infrared energy of more than 2.5 megajoules has now been fired. This is more than 40 times what the Nova laser typically operated at the time it was the world's largest laser".[77]

On January 26, 2009, the final line replaceable unit (LRU) was installed, completing one of the final major milestones of the NIF construction project[78] and meaning that construction was unofficially completed.[79] On February 26, 2009, for the first time NIF fired all 192 laser beams into the target chamber.[80] On March 10, 2009, NIF became the first laser to break the megajoule barrier, firing all 192 beams and delivering 1.1 MJ of ultraviolet light, known as 3ω, to the target chamber center in a shaped ignition pulse.[81] The main laser delivered 1.952 MJ of infrared energy.

## Operations

On 29 May 2009 the NIF was dedicated in a ceremony attended by thousands, including California Governor Arnold Schwarzenegger and Senator Dianne Feinstein.[4] The first laser shots into a hohlraum target were fired in late June 2009.[5]

### Buildup to main experiments

On January 28, 2010, the facility published a paper reporting the delivery of a 669 kJ pulse to a gold hohlraum, setting new records for power delivery by a laser, and leading to analysis suggesting that suspected interference by generated plasma would not be a problem in igniting a fusion reaction.[82][83] Due to the size of the test hohlraums, laser/plasma interactions produced plasma-optics gratings, acting like tiny prisms, which produced symmetric X-ray drive on the capsule inside the hohlraum.[83]

After gradually altering the wavelength of the laser, they were able to compress a spherical capsule evenly, and were able to heat it up to 3.3 million kelvins (285 eV).[84] The capsule contained cryogenically cooled gas, acting as a substitute for the deuterium and tritium fuel capsules that will be used later on.[83] Plasma Physics Group Leader Dr. Siegfried Glenzer said they've shown they can maintain the precise fuel layers needed in the lab, but not yet within the laser system.[84]

As of January 2010, the NIF could run as high as 1.8 megajoules. Glenzer said that experiments with slightly larger hohlraums containing fusion-ready fuel pellets would begin before May 2010, slowly ramping up to 1.2 megajoules—enough for ignition according to calculations. But first the target chamber needed to be equipped with shields to block neutrons that a fusion reaction would produce.[82] On June 5, 2010 the NIF team fired lasers at the target chamber for the first time in six months; realignment of the beams took place later in June in preparation for further high-energy operation.[85]

## National Ignition Campaign

With the main construction complete, NIF started working on the "National Ignition Campaign" (NIC), the quest to reach ignition. By this time, so sure were the experimenters that ignition would be reached that articles began appearing in science magazines stating that it would be announced only a short time after the article was published. Scientific American started a 2010 review article with the statement "Ignition is close now. Within a year or two..."[86]

Technician works on target positioner inside National Ignition Facility (NIF) target chamber.

The first test was carried out on 8 October 2010 at slightly over 1 MJ. However, a number of problems slowed the drive toward ignition-level laser energies in the 1.4 to 1.5 MJ range.

Progress was initially slowed by the potential for damage from overheating due to a concentration of energy on optical components that is greater than anything previously attempted.[87] Other issues included problems layering the fuel inside the targets, and minute quantities of dust being found on the capsule surface.[88]

As the power was increased and targets of increasing sophistication were used, another problem appeared that was causing an asymmetric implosion. This was eventually traced to minute amounts of water vapor in the target chamber which froze to the windows on the ends of the hohlraums. This was solved by re-designing the hohlraum with two layers of glass on either end, in effect creating a storm window.[88] Steven Koonin, DOE undersecretary for science, visited the lab for an update on the NIC on 23 April, the day after the window problem was announced as solved. On 10 March he had described the NIC as "a goal of overriding importance for the DOE" and expressed that progress to date "was not as rapid as I had hoped".[88]

NIC shots halted in February 2011, as the machine was turned over to SSMP materials experiments. As these experiments wound down, a series of planned upgrades were carried out, notably a series of improved diagnostic and measurement instruments. Among these changes were the addition of the ARC (Advanced Radiographic Capability) system, which uses 4 of the NIF's 192 beams as a backlighting source for high-speed imaging of the implosion sequence.

ARC is essentially a petawatt-class laser with peak power exceeding a quadrillion ($10^{15}$) watts. It is designed to produce brighter, more penetrating, higher-energy x rays than can be obtained with conventional radiographic techniques. When complete, ARC will be the world's highest-energy short-pulse laser, capable of creating picosecond-duration laser pulses to produce energetic x rays in the range of 50-100 keV for backlighting NIF experiments.[89]

NIC runs restarted in May 2011 with the goal of timing the four laser shock waves that compress the fusion target to very high precision. The shots tested the symmetry of the X-ray drive during the first three nanoseconds. Full-system shots fired in the second half of May achieved unprecedented peak pressures of 50 megabars.[90]

In January 2012, Mike Dunne, director of NIF's laser fusion energy program, predicted in a Photonics West 2012 plenary talk that ignition would be achieved at NIF by October 2012.[91] In the same month, the NIF fired a record high of 57 shots, more than in any month up to that point.[92] On March 15, 2012, NIF produced a laser pulse with 411 trillion watts of peak power.[93] On July 5, 2012, it produced a shorter pulse of 1.85 MJ and increased power of 500 TW.[94]

## DOE Report, July 19, 2012

The NIC campaign has been periodically reviewed by a team led by Steven E. Koonin, Under Secretary of Science. The 6th review, May 31, 2012 was chaired by David H. Crandall, Advisor on National Security and Inertial Fusion, Koonin being precluded to chair the review because of a conflict of interest. The review was conducted with the same external reviewers, who had previously served Koonin. Each provided their report independently, with their own estimate of the probability of achieving ignition within the plan, i.e. before December 31, 2012. The conclusion of the review was published on July 19, 2012.[95]

The previous review dated January 31, 2012, identified a number of experimental improvements that have been completed or are under way.[95] The new report unanimously praised the quality of the installation: lasers, optics, targets, diagnostics, operations have all been outstanding, however:

> The integrated conclusion based on this extensive period of experimentation, however, is that considerable hurdles must be overcome to reach ignition or the goal of observing unequivocal alpha heating. Indeed the reviewers note that given the unknowns with the present 'semi-empirical' approach, the probability of ignition before the end of December is extremely low and even the goal of demonstrating unambiguous alpha heating is challenging. (Crandall Memo 2012, p. 2)

Further, the report members express deep concerns on the gaps between observed performance and ICF simulation codes such that the current codes are of a limited utility going forward. Specifically, they found a lack of predictive ability of the radiation drive to the capsule and inadequately modeled laser-plasma interactions. These effects lead to pressure being one half to one third of that required for ignition, far below the predicted values. The memo page 5 discusses the mix of ablator material and capsule fuel due likely to hydrodynamics instabilities in the outer surface of the ablator.[95]

The report goes on to suggest that using a thicker ablator may improve performance, but this increases its inertia. To keep the required implosion speed, they request that the NIF energy be increased to 2MJ. One must also keep in mind that neodymium lasers can withstand only a limited amount of energy or risk permanent damage to the optical quality of the lasing medium. The reviewers question whether or not the energy of NIF is sufficient to indirectly compress a large enough capsule to avoid the mix limit and reach ignition.[96] The report concluded that ignition within the calendar year 2012 is 'highly unlikely'.[95]

## Ignition fails, focus shifts, LIFE ends

The NIC officially ended on September 30, 2012 without achieving ignition. According to numerous articles in the press,[97][98] Congress was concerned about the project's progress and funding arguments may begin anew.[99][100][101] These reports also suggested that NIF will shift its focus away from ignition back toward materials research.[102][103]

In 2008, as NIF was reaching completion, LLNL began the Laser Inertial Fusion Energy program, or LIFE, to explore ways to use the NIF technologies as the basis for a commercial power plant design. Early studies considered the fission-fusion hybrid concept, but from 2009 the focus was on pure fusion devices, incorporating a number of technologies that were being developed in parallel with NIF that would greatly improve the performance of the design.[104]

All of these, however, were based on the idea that NIF would achieve ignition, and that only minor changes to the basic design would be required to improve performance. In April 2014, Livermore decided to end the LIFE efforts. Bret Knapp, Livermore acting director was quoted as saying that "The focus of our inertial confinement fusion efforts is on understanding ignition on NIF rather than on the LIFE concept."[104]

## Breakeven claims

A memo sent on 29 September 2013 by Ed Moses describes a fusion shot that took place at 5:15 a.m. on 28 September. It produced $5\times10^{15}$ neutrons, 75% more than any previous shot. Alpha heating, a key component of ignition, was clearly seen. It also noted that the reaction released more energy than the "energy being absorbed by the fuel", a condition the memo referred to as "scientific breakeven".[105] This received significant press coverage as it appeared to suggest a key threshold had been achieved, which was referred to as a "milestone".[106]

A number of researchers pointed out that the experiment was far below ignition, and did not represent a breakthrough as reported.[107] Others noted that the definition of breakeven as recorded in many references, and directly stated by Moses in the past, was when the fusion output was equal to the laser input.[108]

In this release, the term was changed to refer only to the energy deposited in the fuel, not the energy of the laser as in previous statements. All of the upstream loss mechanisms were ignored, and the comparison was between the approximately 10 kJ that reaches the fuel and the 14 kJ that were produced, a $Q$ of 1.4. Using the previous definition, this would be 1.8 MJ in and 14 kJ out, a $Q$ of 0.008.[108]

The method used to reach these levels, known as the "high foot", is not suitable for general ignition, and as a result, it is still unclear whether NIF will ever reach this goal.[109]

Since 2013, improvements in controlling compression asymmetry have been made, with $1.9\times10^{16}$ neutrons produced in 2018, resulting in 0.054 MJ of fusion energy released by 1.5 MJ laser pulse.[110]

## Stockpile experiments

Since 2013, NIF has shifted focus to materials studies. Experiments beginning in 2015 FY have used plutonium targets, with a schedule containing 10 to 12 shots for 2015, and as many as 120 over the next 10 years.[111] Plutonium shots simulate the compression of the primary in a nuclear bomb by high explosives, which has not seen direct testing since the Comprehensive Test Ban. Tiny amounts of plutonium are used in these tests, ranging from less than a milligram to 10 milligrams.[112] Similar experiments are also carried out on Sandia's Z machine.[113] The director of LLNL's Primary Nuclear Design Program, Mike Dunning, noted that "This is an opportunity for us to get high-quality data using a regime that was previously unavailable to us".[112]

One key development on NIF since the Ignition Campaign has been an increase in the shot rate. Although designed to allow shots as often as every 4 hours,[b] in 2014 FY NIF performed 191 shots, slightly more than one every two days. This has been continuously improved, and in April 2015 NIF was on track to meet its goal of 300 laser shots in 2015 FY, almost one a day.[115]

### MagLIF experiments

On 28 January 2016, NIF successfully executed its first gas pipe experiment intended to study the absorption of large amounts of laser light within 1 centimetre (0.39 in) long targets relevant to high-gain Magnetized Liner Inertial Fusion (MagLIF). In order to investigate key aspects of the propagation, stability, and efficiency of laser energy coupling at full scale for high-gain MagLIF target designs, a single quad of NIF was used to deliver 30 kJ of energy to a target during a 13 nanosecond shaped pulse. Data return was very favorable and analysis is ongoing by scientific staff at Lawrence Livermore and Sandia National Laboratories.

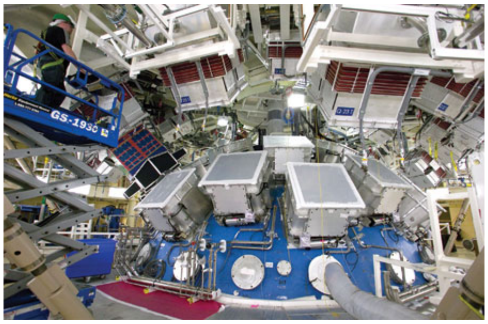
## Similar projects

Some similar experimental ICF projects are:

- Laser Mégajoule (LMJ).[116]
- Nike laser
- High Power laser Energy Research facility (HiPER).[117]
- Laboratory for Laser Energetics (LLE).
- Magnetized Liner Inertial Fusion (MagLIF).[118]
- Shenguang-II High Power Laser[119]

## Pictures

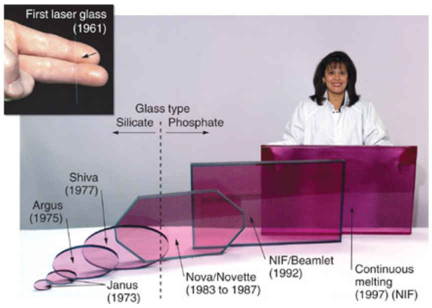
Viewing port allows a look into the interior of the 30 foot diameter target chamber.



Exterior view of the upper 1/3 of the target chamber. The large square beam ports are prominent.

A technician loads an instrument canister into the vacuum-sealed diagnostic instrument manipulator.

The flashlamps used to pump the main amplifiers are the largest ever in commercial production.



The glass slabs used in the amplifiers are likewise much larger than those used in previous lasers.

## In popular culture

The NIF was used as the set for the starship *Enterprise*'s warp core in the 2013 movie *Star*

*Trek Into Darkness*.[120]

## See also

- Chain reaction
- HiPER
- Inertial confinement fusion
- ITER
- Laser Mégajoule
- Nuclear fusion
- Nuclear reactor

## Notes

a. It is not clearly stated why Nova Upgrade would be too small for SSMP, no reason is given in the available resources.

b. One source suggested the ultimate aim was one shot per hour.[114]

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## External links

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