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# The National Ignition Facility and the Path to Fusion Energy

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The National Ignition Facility (NIF) is operational and conducting experiments at the Lawrence Livermore National Laboratory (LLNL). The NIF is the world's largest and most energetic laser experimental facility with 192 beams capable of delivering 1.8 megajoules of 500-terawatt ultraviolet laser energy, over 60 times more energy than any previous laser system. The NIF can create temperatures of more than 100 million degrees and pressures more than 100 billion times Earth's atmospheric pressure. These conditions, similar to those at the center of the sun, have never been created in the laboratory and will allow scientists to probe the physics of planetary interiors, supernovae, black holes, and other phenomena. The NIF's laser beams are designed to compress fusion targets to the conditions required for thermonuclear burn, liberating more energy than is required to initiate the fusion reactions. Experiments on the NIF are focusing on demonstrating fusion ignition and burn via inertial confinement fusion (ICF). The ignition program is conducted via the National Ignition Campaign (NIC)—a partnership among LLNL, Los Alamos National Laboratory, Sandia National Laboratories, University of Rochester Laboratory for Laser Energetics, and General Atomics. The NIC program has also established collaborations with the Atomic Weapons Establishment in the United Kingdom, Commissariat à l'Energie Atomique in France, Massachusetts Institute of Technology, Lawrence Berkeley National Laboratory, and many others. Ignition experiments have begun that form the basis of the overall NIF strategy for achieving ignition. Accomplishing this goal will demonstrate the feasibility of fusion as a source of limitless, clean energy for the future. This paper discusses the current status of the NIC, the experimental steps needed toward achieving ignition and the steps required to demonstrate and enable the delivery of fusion energy as a viable carbon-free energy source.

Keywords: ICF, Fusion, Lasers

## 1. Introduction

Inertial Confinement Fusion (ICF) is one of the two main approaches for developing fusion as an energy source. In ICF, high-powered lasers, or other pulsed energy sources, are used to compress and heat a spherical capsule containing deuterium–tritium (DT) fusion fuel. The concept of ICF was developed shortly after the development of lasers and has been an active area of research for nearly forty years [1]. The goal of the research is to ignite and burn the DT fuel to produce more thermonuclear energy than input driver energy. Ignition and thermonuclear burn in the laboratory will provide a pathway to development of Inertial Fusion Energy (IFE) for energy production.

The National Ignition Facility (NIF) located at Lawrence Livermore National Laboratory (LLNL) is the world's largest laser facility [2,3]. The 192 beams of NIF can heat targets to temperatures of more than 100 million degrees and produce pressures more than 100 billion atmospheres. These conditions, similar to those at the center of the sun, will allow scientists to probe the physics of planetary interiors, supernovae, black holes, and other phenomena of interest for High Energy Density (HED) science [4,5]. NIF is the first laboratory system designed to obtain ignition and thermonuclear burn. Completed in 2009, NIF has been operational for more than two years. It has demonstrated performance required for ignition experiments and has completed the infrastructure for supporting initial ignition experiments.

Experiments have begun on NIF for understanding ignition target performance [6,7]. These experiments study the four major control variables for ignition: symmetry, fuel adiabat, shell velocity, and mix [8]. Initial results have demonstrated that newly developed techniques can observe and control the effects of these ignition variables. Cryogenic layering of the DT fuel has been demonstrated, and the first experiments using these layers have been performed. Initial ignition experiments are planned for the coming year.

Successful ignition on NIF will achieve the long sought after goal of ICF and advance the goal of IFE as a carbon-free energy source. Technology advances in areas such as high-repetition-rate lasers, fusion chamber technology, and target fabrication will be needed to make IFE a reality. A path forward is being formulated called Laser Inertial Fusion Energy (LIFE) that provides a systems engineering methodology for this development. This path defines technology development parallel to target physics development on NIF to expedite developing IFE as a power source.

## 2. National Ignition Facility (NIF)

The NIF is a 192-beam Nd-glass laser system enclosed in a stadium-sized facility at LLNL. The facility, shown in Figure 1, consists of two laser bays, a control room and the target area, as well as two switchyards and four capacitors bays. The NIF Project started in 1995 and was successfully completed in March 2009. NIF has been operational for over two years, primarily performing physics experiments for ignition. Experiments have also been performed on NIF for HED science, x-ray effects, and other national security missions as well as for fundamental science. So far, over 200 target experiments have been executed.

The laser is designed to deliver 1.8 MJ of frequency converted 0.35-µm light to target, over 60 times more energetic than any previous laser system [10]. The architecture of each beam is a multi-pass flashlamp-pumped Nd-glass laser producing ~20 kJ of 1.05-µm light at the output of the laser bays. The laser pulse can be independently shaped for a set of four beams with pulse lengths up to 33 ns, having contrast ratios of over 100:1. The beams are transported to the target chamber and frequency converted producing ~10 kJ of 0.35-µm light per beam. Shot operations is computer controlled using the Integrated Computer Control System (ICCS) [11]. ICCS uses automated input provided by the experimental scientist to set laser parameters and diagnostics for shot execution. The NIF has over 60,000 control points that require setup for each shot. Shot execution occurs over a five-minute countdown period. Data recovery occurs within thirty minutes after the shot.

NIF has demonstrated that it meets all performance requirements for ignition experiments [12]. Energy and power performance required for 1.8 MJ and 500 TW operation has been demonstrated on a single-beam basis. Pulse shapes with contrasts of greater than 100:1 required for ignition experiments are routinely produced. Power balance, important for symmetric implosions, has been demonstrated to be 3% at peak powers. Beam pointing to target has been demonstrated with 60-µm rms accuracy. Ignition physics experiments have been performed with laser energy up to 1.4 MJ on target with plans to increase laser energy to 1.8 MJ during the next year.

Many new capabilities have been added in transitioning from project completion to an experimental facility. Systems have been commissioned to manage tritium and other hazardous materials such as beryllium and depleted uranium. Radiation shielding has been installed for operations at full ignition yield of $10^{19}$ neutrons. The facility is now fully operationally qualified for ignition experiments. Experiments have been done using tritium, producing neutron yields of $10^{15}$ neutrons with plans to increase to full yield over the next year.

NIF has an ever increasing diagnostic capability for ignition and other user experiments. About 40 different diagnostics are operational and additional diagnostics are planned in the coming years. Diagnostics have been developed by a broad scientific community, including the NIC participants and collaborators. State of the art optical, x-ray, and neutron measurements are being made with picosecond time resolution and micron spatial resolution. Some examples of the diagnostics are shown in Figure 2. All of the diagnostics have been designed for automatic operation. Diagnostic pointing and alignment are handled remotely using alignment sensors. The control system that controls the laser also handles data acquisition and processing. After a shot, data processing can occur automatically or by desktop processing using a central calibration and setup database. The processed data along with its reduction parameters are archived in a central data storage center for easy access and control.

## 3. National Ignition Campaign (NIC)

The NIC is a comprehensive program to develop the physics basis for ignition and to conduct the initial ignition experimental campaign. The goal of the NIC program is to demonstrate a reliable and repeatable ignition platform and develop NIF as a user facility for its multiple missions. NIC is a national partnership of LLNL, Los Alamos National Laboratory (LANL), Sandia National Laboratories, University of Rochester Laboratory for Laser Energetics, General Atomics and a number of other collaborators including Lawrence Berkeley National Laboratory, the Massachusetts Institute of Technology (MIT), the U.K. Atomic Weapons Establishment (AWE) in England, and the French Atomic Energy Commission (CEA) in France. NIC encompasses all of the capabilities required for ignition experiments including development of the diagnostics, targets, target cryogenic system, phase plates and other optics, and personnel and environmental protection equipment. Experiments on OMEGA, NIF and other facilities provide the technical basis for ignition experiments. The initial ignition campaign began in 2010 with the first cryogenic implosion experiments.

The schematic of an ignition target is shown in Figure 3. The laser beams are focused through laser entrance holes at each end of a high Z cylindrical case, or hohlraum. The lasers irradiate the hohlraum walls producing X rays that ablate and compress the fuel capsule in the center of the hohlraum. The hohlraum is made of Au, U, or other high Z material. For ignition targets the hohlraum is ~0.5 cm diameter by ~1 cm in length. The hohlraum absorbs the incident laser energy producing X rays for symmetrically irradiating the capsule. The fuel capsule is a ~2-mm-diameter spherical shell of CH, Be, or C filled with DT fuel. The DT fuel is in the form of a cryogenic layer on the inside of the shell. The outside of the capsule absorbs the X rays ablating the shell, producing a spherical implosion. The imploding shell stagnates in the center igniting the DT fuel.

The ignition target is a precision piece of equipment. The capsule and cylindrical case must be manufactured and assembled to micron tolerances. The surface finish of the capsule and cryogenic fuel require submicron smoothness to maintain good spherical implosions. A completed target ready for an experiment is shown in Figure 4. The large arms coming from the right are the cooling arms connected to a cryogenic refrigerator for cooling the target to ~18°K producing the cryogenic fuel layer. The cryogenic layer must be maintained to milli-kelvin tolerances for several hours before the shot. The cooling and temperature control is maintained through automatic control and feedback from temperature sensors on the target. Target cooling and layer formation is done through automated scripts of the thermal cycle. The cryogenic layer is measured using x-ray imaging before the shot. All of this is coordinated with the laser control system.

Experiments have begun for the initial ignition campaign, which will establish the physics basis for the first ignition experiments planned for the coming year. The initial ignition target design uses a Au hohlraum with a CH capsule. The design is based on results from large-scale radiation hydrodynamic simulations and experimental results from the Nova and OMEGA laser as well as other smaller facilities [13]. Experiments study the four major control variables for ignition: symmetry, fuel adiabat, shell velocity, and mix [8]. These variables are tuned by controlling the target geometry and laser pulse shape to optimize the radiation drive, ablator physics, shock physics, and preheat in the target. Initial experiments have demonstrated that these techniques can successfully diagnose the parameters affecting target variables and are sensitive to changes in the target or laser.

Experiments on NIF have demonstrated efficient coupling of the laser energy to x-ray heating of the hohlrum. Radiation temperatures of over 300 eV have been obtained with backscatter of less than 13%. The data is shown in Figure 5 for the scaling of drive with laser energy. A $T_r$ of 300 eV for 1.3 MJ of laser energy is obtained in an ignition-scale hohlraum [14].

Symmetric implosions are obtained by controlling the uniformity of the flux on the capsule. Symmetry control has been demonstrated both by varying the inner and outer cone beam energy and by varying the wavelength difference of the inner and outer cone beams [15,16]. Symmetry is measured by imaging the core emission from the stagnating implosion core. Recently, the first implosions were done using an equal mixture of deuterium and tritium to optimize the neutron yield. Images from both the neutron and x-ray emission were obtained from the implosion. The data are shown in Figure 6. Both the size and shape of the emission is similar for both images, although details of the structure differ. Results from these experiments as well as other experiments measuring the ablator and fuel performance are being used to optimize the target performance for the first ignition experiments planned for the coming year.

## 4. Path to IFE – LIFE

A long-term goal of ICF is using IFE for producing a clean carbon-free energy source. Ignition on NIF will achieve the next important step in developing this potentially revolutionary source of clean power. New power sources could have major impacts in the coming decades as developing countries satisfy their need for new energy sources and developed countries replace and enhance their existing energy infrastructure. Rapid development of IFE from ignition demonstration on NIF to commercial power production could make a significant impact on the world's future demands for a clean, safe, reliable energy source.

Significant technology development is required in addition to successful ignition demonstration to realize the goal of IFE. Technology advances in areas such as high-repetition-rate lasers, fusion chamber technology, and target fabrication will be needed. An approach to this development called Laser Inertial Fusion energy (LIFE) uses a systems engineering approach to systematically define the requirements and development path. LIFE activities focus on developing the technology in parallel with the target physics research to expediently attain a successful IFE demonstration.

A LIFE conceptual design for an IFE power plant has been produced that identifies and prioritizes the technology development. The design is based on extensions of proven technologies. The LIFE engine includes a reactor vessel with target and laser delivery systems, energy extraction and tritium breeding. The lasers are conceived as line replaceable units that can be exchanged during hot operations. The laser architecture is based on the NIF laser design, and the high-repetition-rate capability builds on the experience with the Mercury laser system [17]. The reactor vessel is designed for easy replacement to ensure high facility availability using current available materials. The turbine building houses a conventional electrical power plant driven by the thermal production from the LIFE engine. Also included in the design are maintenance and support facilities and office areas.

Fusion energy holds the promise of an energy source with no greenhouse gas emissions and a virtually inexhaustible, widely available fuel supply. It would remove the need for actinide enrichment and reprocessing and high-level waste storage required by fission power plants. While these and other features of fusion energy are attractive, scientific and technological challenges remain. Successful demonstration of ignition by the NIC, coupled with a robust LIFE technology development effort, could lead to the delivery of this plant in a 10- to 15-year time frame to meet the world's growing energy demands.

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## References

[1] J. Nuckolls, L. Wood, A. Theisen, and G. Zimmerman, *Nature* **239**, 139 (1972).
[2] G. H. Miller, E. I. Moses, and C. R. Wuest, *Nucl. Fusion* **44,** S228 (2004).
[3] E. I. Moses, *J. Phys.:* Conf. Series **112**, 012003 (2008).
[4] R. Davidson et al., Frontiers in High Energy Density Physics: The X-Games of Contemporary Science (The National Academies, Washington, DC, 2003).
[5] B. A. Remington, R. P. Drake, and D. D. Ryutov, *Rev. Mod. Phys*. **78**, 755 (2006).
[6] J. D. Lindl and E. I. Moses, Phys. Plasmas **18**, 050901-1 (2011).
[7] O. L. Landen et al., *Phys. Plasmas* **18**, 051002-1 (2011).
[8] M. J. Edwards et al., *Phys. Plasmas* **18**, 051003-1 (2011).
[9] J.D. Lindl, Inertial confinement fusion: the quest for ignition and energy gain using indirect drive (American Institute of Physics Press, New York, 1998).
[10] J. T. Hunt, K. R. Manes, J. R. Murray, P. A. Renard, R. Sawicki, J. B. Trenholme, and W. Williams, *Fusion Technol*. **26**, 767–771 (1994).
[11] L. Lagin et al., Fusion Engineering and Design **83**, 530 (2008); C. Marshall, Fusion Engineering and Design, this conference
[12] G. A. Haynam et al., *Appl. Opt.* **46**, 3276 (2007).
[13] S. W. Haan et al., *Phys. Plasmas* **18**, 051001-1 (2011).
[14] S. H. Glenzer et al., *Phys. Rev. Lett*. **106**, 085004 (2011).
[15] N.B. Meezan et al., *Phys. Plasmas* **17**, 056304 (2010).
[16] S. H. Glenzer et al., *Science* **327**, 1228 (2010).
[17] A. Bayramian et al., *Fusion Science and Technology* **52**, 383 (2007).

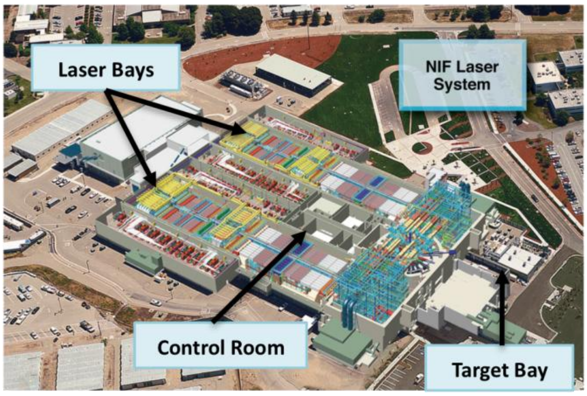

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Fig. 1. A cut-away drawing of the NIF beam path showing the major areas of the facility.

(a) (color reproduction on web and in print) (b) (color reproduction on web and in print)

Fig. 2. Examples of NIF Diagnostics: (a) Magnetic Recoil Spectrometer developed by MIT measures the neutron spectrum from an ignition capsule, (b) Gamma Reaction History developed by LANL measures the time history of neutrons from the imploded core of an ignition implosion.

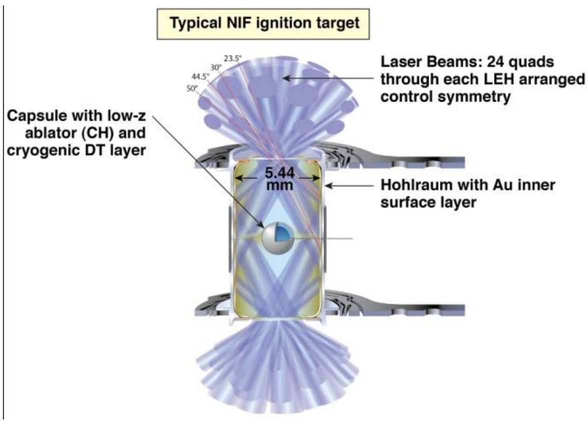

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Fig. 3. Schematic of the ignition target design.

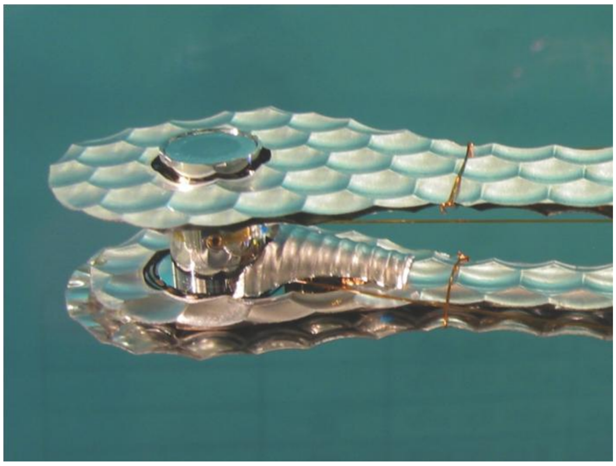

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Fig. 4. Photograph of an ignition physics target.

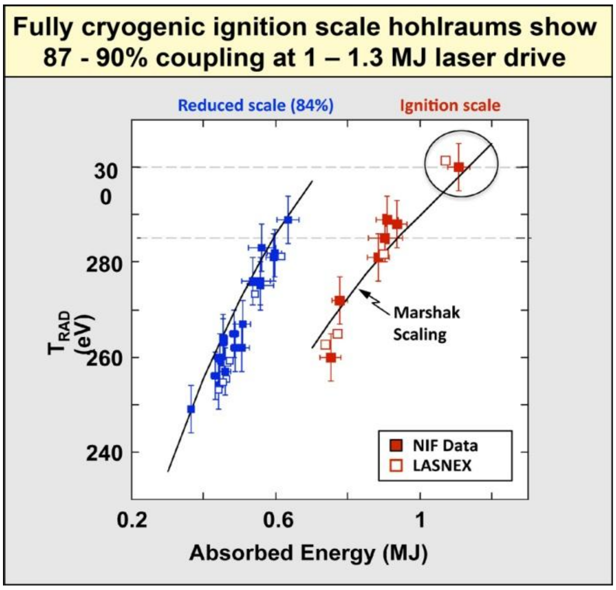


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Fig. 5. Hohlraum drive scaling shows 300-eV drive from an ignition-scale target with 1.3 MJ of laser energy.

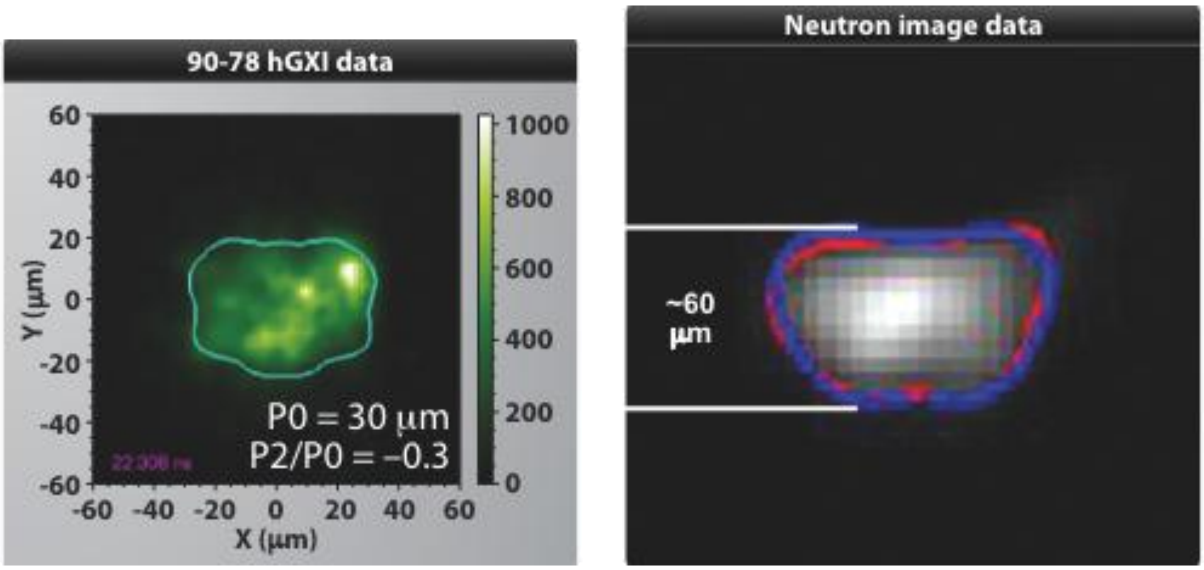


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Fig. 6. Images of the imploded core: (a) keV x-ray emission, (b) DT neutron emission.