The Path To Inertial Fusion Energy

E. I. Moses
Lawrence Livermore National Laboratory, Livermore, CA, U.S.A.94450
E-mail; moses1@llnl.gov

Abstract. The 192-beam National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in Livermore, CA, is now operational. Results from initial NIF ignition experiments have been very promising. In light of this strong progress and the start of layered target integrated ignition experiments at NIF later this year, the U.S. and the wider international community are currently examining the implications of NIF ignition for inertial fusion energy (IFE). A laser-based IFE power plant will require a repetition rate of 10-20 Hz and approximately 10% electrical efficiency, compared to the 10^{-4} Hz and 0.5% efficiency characteristic of NIF. The realization of IFE will also require further development and advances of large-scale target fabrication, target injection, target chamber, and other supporting technologies. It is important to realize that many of the scientific and technological advances made under the NIF ignition program in areas such as laser technology, target fabrication, and diagnostics are very significant and directly support the advancement of IFE. Examples include the demonstration of multi-pass laser architecture, the development of robust capsule and hohlraum manufacturing and target layering capability, and the development of hardened diagnostics suitable for the extreme ignition environment. These capabilities coupled with a robust IFE program could lead to a prototype IFE demonstration plant in the 10-15 year time frame. LLNL, in partnership with other institutions, is continuing to examine the Laser Inertial Fusion Engine (LIFE) concept and is looking in detail at the impact of various technology choices as well as the advantages of both pure fusion and fusion-fission schemes. This paper will review these topics as well as the overall progress of IFE technology and describe a 10-15 year plan to demonstrate integrated IFE operations. It is important that the IFE community develop an effective and implementable plan in the near term to be ready to immediately capitalize on the demonstration of ignition at NIF.

1. Introduction

The National Ignition Facility (NIF) is the U.S. Department of Energy (DOE) and National Nuclear Security Administration (NNSA) center to study inertial confinement fusion (ICF) and high energy density (HED) science [1], [2]. NIF is by far the largest scientific project ever successfully completed by the DOE. The 192-beam football stadium-sized NIF was certified as complete in March 2009 and is now fully operational and conducting experiments at Lawrence Livermore National Laboratory (LLNL). A total 192-beam energy of 1.1 MJ 3ω was demonstrated on March 10, 2009, over 30 times more energy than ever produced in an ICF laser system.

NIF's 192 beams are directed into a 10-meter-diameter vacuum target chamber containing a ~1-cm-long cylindrical hohlraum target. The NIF target chamber contains entry ports for all the laser beams and over 100 ports for diagnostic instrumentation and target insertion. Sophisticated diagnostic instruments such as x-ray and neutron spectrometers, x-ray imagers, and streak cameras are mounted around the equator and at the poles of the target chamber [3].

The laser interaction with the hohlraum produces a radiation field with temperatures of several hundred eV. NIF is designed to achieve target temperatures of 100 million K, radiation temperature over 3.5 million K, density of 1,000 g/cm^3 and 100 billion times atmospheric pressure. These conditions have never been created before in a laboratory and exist naturally only in astrophysical environments. The resulting hohlraum conditions will provide the environment to explore a wide range of high energy density science experiments, including laboratory-scale thermonuclear ignition and burn.

NIF is the largest optical instrument ever constructed, with over 38,000 large and small optics and 60,000 points controlled by two million lines of software. The NIF 3ω energy specification of 1.8 MJ requires an order of magnitude increase in operating fluence over previous laser systems. Developing high-quality optics that can withstand the NIF environment has been a major research and development focus at LLNL. A systematic and robust approach for optics finishing and maintenance has been developed to support the demanding requirements for ignition.

2. The National Ignition Campaign

The NIF ignition program is being executed via the National Ignition Campaign (NIC), a national effort that includes General Atomics (GA), LLNL, Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL), the University of Rochester Laboratory for Laser Energetics (LLE), and a number of other partners including Lawrence Berkeley National Laboratory, the Massachusetts Institute of Technology, the U.K. Atomic Weapons Establishment (AWE), and the French Atomic Energy Commission (CEA). The NIC has two major goals: beginning integrated ignition experiments with cryogenic, layered ignition targets in late 2010, and demonstration of a reliable and repeatable ignition platform by the conclusion of NIC at the end of FY2012. The scope for NIC includes the ignition physics program as well as the development of the diagnostics, targets, target cryogenic system, phase plates and other optics, and personnel and environmental protection activities required to execute ignition experiments. The NIC will also develop the infrastructure and processes required to operate NIF as a national user facility [4].

NIF ignition experiments use a centimeter-scale hohlraum containing a 2-millimeter-scale, thin-walled plastic or beryllium capsule filled with a mixture of deuterium and tritium [5]. Compression of the capsule by a >280-eV radiation field in the ignition hohlraum drives the DT fuel to conditions under which it will ignite and burn, liberating more energy than is required to initiate the fusion reaction.

The campaign to initially demonstrate NIF ignition is proceeding in four phases. In the first or “drive” step, the empty hohlraum is tuned to produce the necessary radiation drive on the capsule as a function of time. In the second step, “capsule tuning,” a variety of non-cryogenic and cryogenic capsules are used to adjust the hohlraum symmetry, shock timing, velocity and mass ablated so as to produce the conditions in the imploding capsule required for ignition when a cryogenic fuel layer is incorporated in follow-on experiments. The third step consists of layered cryogenic implosions conducted with a nominal 72%/22%/6% mixture of tritium, hydrogen, and deuterium (THD), respectively. The reduced yields from these THD targets allow the full diagnostic suite to be employed and the presence of the required pre-burn temperature and fuel areal density to be verified. The final step is DT ignition implosions with expected gains of 10-20. The initial DT ignition experiments will be conducted with E_{laser} ~1.3 MJ. Laser energies of up to 1.8 MJ will be available for subsequent experiments.

In the fall of 2009, experiments conducted in support of the NIC focused on the first two steps discussed above. These initial experiments were aimed at understanding the energetics of the NIF ignition hohlraum and initial capsule-tuning experiments. The results from these initial experiments have been outstanding and show great promise for achievement of ignition. Capsule implosion experiments at energies up to 1.2 MJ have demonstrated laser energy absorption, radiation temperatures, and symmetry control that scale to ignition conditions. Of particular importance is the demonstration of peak hohlraum temperatures near 300 eV, with overall backscatter of less than 10% and the ability to field cryogenic targets with tunable x-ray drive symmetry. Figure 1 shows images of the layered target before and after it was shot on September 29, 2010, on the NIF.

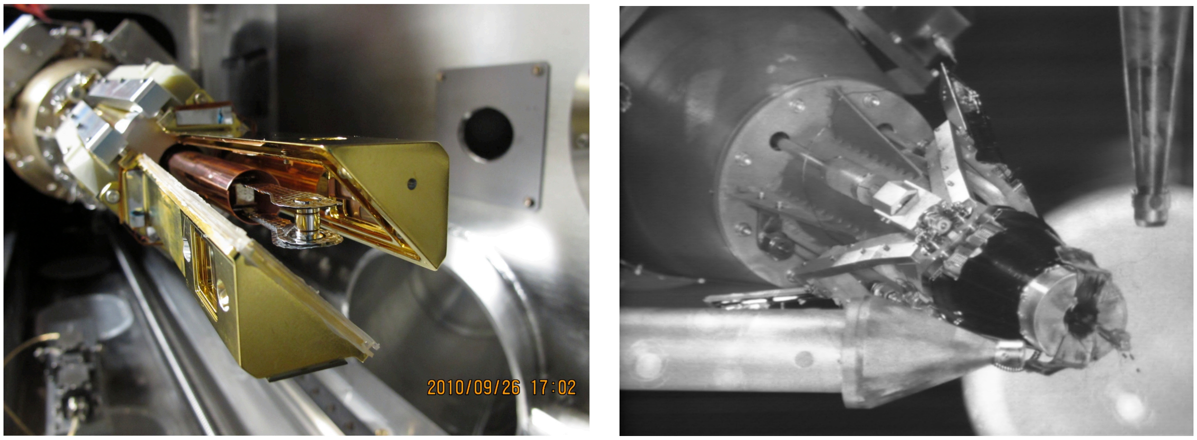

FIG 1. Cryogenic layered target shot on September 29, 2010 (a) before and (b) after being shot in the NIF target chamber.

3. Ignition Preparation Project (IPP)

Beginning in December 2009, many activities were undertaken at NIF to bring on-line the capabilities required to conduct a successful ignition campaign. Collectively, these activities are referred to as the Ignition Preparation Project (IPP). These included:

- Systems to support cryogenic, layered targets at Target Chamber Center (TCC)
- Personnel and Environmental Protection Systems (PEPS) to provide for proper handling of tritium, depleted uranium, beryllium, and nuclear yield
- Target diagnostics systems to support capsule tuning and ignition campaigns
- Robust, efficient operations with increasing levels of routine performance

Cryogenic Target Positioner (CTS). The CTS is a complicated piece of equipment that performs those functions necessary to shoot a cryogenically cooled, ignition target at the center of the NIF target chamber. The CTS holds the target in place while the capsule is being filled with liquid THD or DT, cryogenically cools the target to form the THD or DT “ice” layer within the capsule, characterizes and maintains the layer quality until the experiment is initiated, inserts and locates the target within the NIF chamber, and removes the protective shroud to expose the target just prior to the arrival of the laser pulse. The CTS was attached to the NIF target chamber and was operationally qualified in August 2010.

The Personnel and Environmental Protection Systems. Several PEPS systems were operationally qualified during the IPP including:

- Forty-four shield doors that were assembled, mounted, and filled with concrete; these doors, some weighing as much as five tons, provide neutron and radiation shielding for high-yield ignition experiments in and around the Target Bay (see Figure 2)
- The Tritium Processing System (TPS) used to remove tritium from the target chamber exhaust streams shown in Figure 3
- Contamination Control Systems, housed in the Hazardous Materials Management Area (HMMA), that provide areas (chemical hoods, glove-boxes and enclosures) to manage contaminated items coming from the target chamber
- Radiation Monitoring System to provide continuous monitoring of the radiation environment in the NIF facility

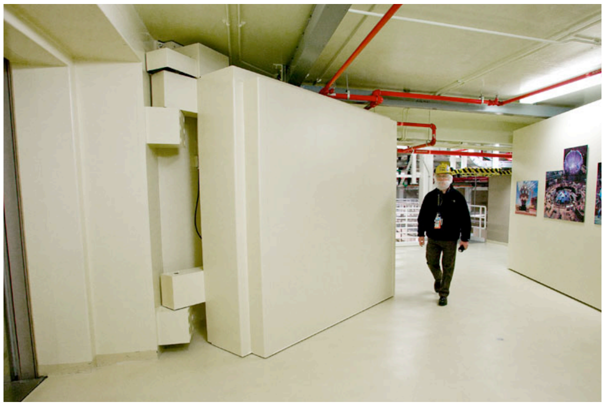

FIG. 2. One of 44 shield doors installed at the NIF.

Robust and Efficient Radiological Operations. During the IPP, plans and procedures for managing tritium, beryllium, depleted uranium and associated activation and fission products were developed and put into place. These flow down from regulatory requirements into practices and protocols. The required administrative controls were implemented through authorizing documents and work permits for specific activities at the NIF. A detailed training and qualification program was also developed to assure that workers understand the hazards and controls associated with their work and are qualified to work safely in the environment at NIF. This included extensive training and qualification as radiation and as beryllium workers.

FIG. 3. NIF's Tritium Processing System

Target Diagnostics. A large number of new target diagnostics were developed, calibrated, installed, and commissioned on NIF during FY2010. This includes ignition and hohlraum/capsule diagnostics including: Neutron Time of Flight, Neutron Activation Detector, Velocity Interferometer for Any Reflector and Static X-Ray Imagers. These new ignition diagnostics provide NIF with the capability to measure the important ignition parameters such as neutron yield, ion temperature, areal density, the shape and size of the imploding core, and the absolute burn history in neutron environments.

4. The Path to Inertial Fusion Energy

The successful commissioning of the NIF laser and the hohlraum energetics results to date represent the first essential steps in producing ICF ignition in the laboratory. The achievement of ignition at NIF will demonstrate the scientific feasibility of ICF and focus the world's attention on the potential of IFE as an energy source.

A laser-based IFE power plant will require a repetition rate of 10-20 Hz and approximately 10% electrical efficiency, compared to the 10^{-4} Hz and 0.5% efficiency characteristic of NIF. The realization of IFE will also require further development and advances of mass manufacturing of targets, injection and tracking of in-flight targets, and fusion chamber technologies. While NIF progress towards ignition has received significant attention, it is important to realize that many of the scientific and technological advances made under NIF in areas such as laser technology, target fabrication, and diagnostics also directly support the advancement of IFE.

The NIF laser architecture itself is a major step forward for IFE. NIF is the first ICF laser to use a multi-pass design; the validation of this design is essential to the success of both NIF ignition and solid-state laser-based IFE. The current laser designs under consideration for IFE rely on modifications of the NIF architecture, including the replacement of 400-W average power discharge-pumped flashlamps with 30-kW average power laser diodes and implementation of He-gas cooling. The validated NIF laser architecture, the performance of the 10-Hz, 50-J Mercury laser at LLNL and similar systems elsewhere in the world, and new ideas for compressing the physical size of the laser by over an order of magnitude, indicate the potential to achieve the desired performance characteristics for an IFE laser beamline. Alongside this, developments elsewhere in the semiconductor diode industry, including fabrication technology for LED backlit LCD televisions, have reduced the quoted price for bulk manufacture of laser diodes to a point where they would now represent only a small fraction of the cost of construction of an IFE plant.

Advances in target fabrication and target diagnostics made by the NIC team also have direct benefit to IFE. The NIC team has developed advanced capsule and hohlraum manufacturing techniques and robust layering methodologies applicable to the challenge of generating the approximately 300 million targets/year required for a 1000-MW scale IFE power plant. Additionally, the NIC diagnostics effort has spurred research into developing target and laser diagnostic systems capable of survival in the extreme neutron and x-ray environment associated with ignition conditions.

5. Laser Inertial Fusion Energy Requirements and Roadmap

The demonstration of ignition at NIF and the technology development undertaken by the NIC team provide a solid basis for future scientific and technological development in support of IFE. LLNL, in collaboration with many national and international partners, continues to actively pursue the Laser Inertial Fusion Energy (LIFE) concept and has now established a self-consistent point design that couples specific driver, target, chamber and other technologies required to implement a 1-GW commercialization demonstration in the 2030s, consistent with widespread fusion-based power production in the 2050 time frame. The requirements-based approach being undertaken is defining the areas in which further research and technology development are required as part of an integrated project to construct a high-repetition-rate IFE demonstration facility. NIC results coupled with a robust LIFE development program would lead to the delivery of this plant in the 10-15 year time frame.

The primary motivation for fusion energy research is the promise of an energy source with no greenhouse gas emissions and with a virtually inexhaustible, widely available fuel supply. It would remove the need for actinide enrichment and reprocessing and high-level waste storage. While these and other features of fusion energy are attractive, significant scientific and technological questions remain. Conceptually, ICF can be harnessed to generate electricity and other useful products from a steady sequence of ICF events. Fusion-power system studies indicate that the energy released per event could range from hundreds of megajoules to possibly as much as several gigajoules, with corresponding repetition rates from several per second to about once every ten seconds for a 1- GW(e) power plant.

Figure 4 shows a schematic of a LIFE plant. Four principal technical requirements are being considered to develop cost-competitive, environmentally attractive options for LIFE.

Driver Efficiency and Target Gain: The efficiency of the driver in converting energy from the electrical power grid to the energy needed to compress the capsule, coupled with the energy “gain” of the capsule, must be sufficient to yield substantial net energy. With the efficiency of a plant-scale laser driver currently projected to be about 12%, and a blanket gain of 1.25, a target gain of 60 to 70 leads to a commercially acceptable net electrical output and recirculating power fraction.

Current calculations indicate that gain in this range is achievable from indirect-drive capsules with a driver energy of about 2.5 MJ. Alternatively, direct drive could be adopted. In general, this is predicted to result in higher net efficiency, but has a greater degree of uncertainty for ignition scale performance due to a much lower level of effort invested to date in this approach. Both options can be tested on the NIF. A clear requirement for an integrated IFE demonstration facility will be to utilize an ignition scheme that has been demonstrated prior to construction. The NIF is able to field indirect-drive and polar direct-drive options in the near term. Over the longer term, symmetric direct-drive and other options may be available.

Durability: The components of the IFE system must sustain economic plant operations at high availability, reliability and ability to be inspected and maintained. In particular, the fusion environment must be able to cope with high fluences of charged particles, x-rays and neutrons while retaining structural integrity, low levels of activation, and high levels of performance in converting thermal energy to electricity and breeding tritium.

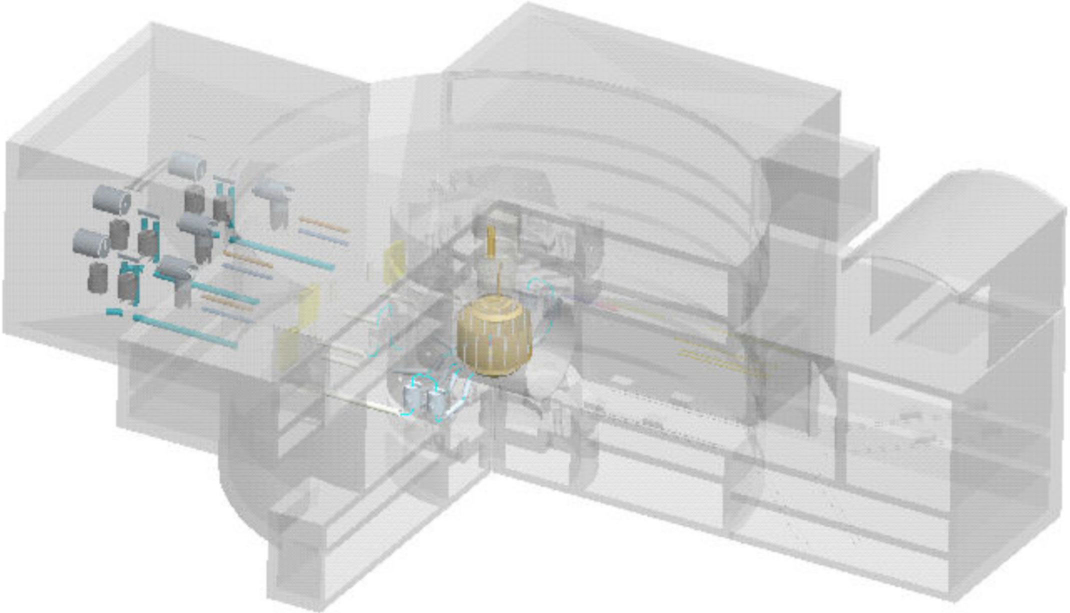

FIG. 4. Schematic of a LIFE plant.

The LIFE approach adopts the NIF concept of Line Replaceable Units (LRUs), [6] throughout the plant, which substantially decouples component reliability from plant availability, permitting the target value of 92% to be achieved. This concept is applied, for example, at the level of laser beamlines, which have been designed with an innovative new architecture to reduce their physical size by over an order of magnitude compared to the NIF. This allows remote manufacture, maintenance and changeover of individual beamlines while the plant is operational.

For the fusion chamber, the LIFE approach would maintain the scale used for NIF (~56 m radius) but with a relatively high-density gas fill to protect the solid wall. This is calculated to absorb the charged particle debris and redistribute the x-ray pulses such that there is no significant threat from debris at the first wall, and the pulsed temperature jump of the first wall is lowered to the point in which steel can be used without the need for a protective layer or the need for development of new excotic material. Moreover, the entire fusion chamber could be treated as a Line Replaceable Unit with a lifetime of about 4 years, keeping the thermal loading and neutron-induced damage rates to acceptable levels.

Repetition Rate: The driver, target fabrication, and fusion chamber must operate at a repetition rate that is sufficient to produce economically useful power. For the laser, the repetition rate and driver efficiency are strongly coupled, with substantial experience from industrial applications supporting the ability to operate at tens of kW average power for solid-state architectures. Integrated laser designs have recently been developed for LIFE that achieve the required performance characteristics using Nd:glass gain media, helium cooling and diode technology based on current production methods [7].

Power plant operations will require on the order of 10^6 targets per day depending on the gain that can be achieved. The ICF program has developed and used a wide range of techniques to produce targets to the required specifications, but at necessarily high cost per target given the very small production numbers. Techniques are being explored to produce large quantities of targets, including capsule fabrication, DT-fuel filling and layering, and hohlraum production, as well as methods to deliver them accurately to the center of the target chamber, but much work remains to be done. To date, models of target production factories that include capital amortization, personnel costs and operational consumables indicate that mass production will yield costs of $0.2-$0.3 per target, in which the material cost is <$0.05 per target. What remains is to demonstrate high volume production using such techniques while maintaining control over the specifications.

The chamber must be capable of being restored sufficiently to its initial condition after each shot to allow insertion of the next target, and for transmission and focusing of the next pulse of energy to that target. Detailed thermal calculations show that the use of indirect-drive hohlraum geometry allows the target to survive injection into the relatively high-density chamber gas, which itself is essential for the chamber to survive the subsequent target implosion.

Energy Conversion and Tritium Breeding: The energy released from the burning of DT fuel is mainly in the form of energetic neutrons, along with significant numbers of ions and x-rays. The neutron energy must be absorbed by the chamber and converted into thermal energy that can then be efficiently used to drive electric generators. The chamber must also utilize the emitted neutrons to breed sufficient new tritium to sustain the fuel supply.

The LIFE chamber design has been developed using an iterative set of models to consider the thermo-mechanical response, neutronic performance, economic viability, and operational availability and maintainability. The design yields an excess tritium breeding ratio (1.10) alongside substantial gain from secondary reactions in the blanket (1.25) and a coolant temperature that could drive efficient thermo-electric conversion (40–50%) if a suitable closed Brayton-cycle system can be demonstrated. Such systems are under development for a wide range of advanced fission, fusion, and solar-thermal applications.

The LIFE plan is designed to complement and build on the success of current and emerging nuclear energy technologies. An integrated design has been established that would lead to an operating demonstration plant by the mid-2020s, drawing from a substantial subsystem development program to demonstrate the required high levels of technology readiness on a time scale compatible with the construction requirement.

This demonstration plant would be used to further qualify and certify subsystems and components for the subsequent commercial fleet, while establishing the path forward for viable commercial operation.

6. Conclusion

After many years of R&D, all the pieces for ignition are in place: the NIF laser and the equipment needed for ignition, including high-quality targets and an ignition point-design target. Layered cryogenic targets are now being fielded that combine all the technologies for a full-scale ignition experiment. The National Ignition Campaign is on course to demonstrate a robust and repeatable ignition platform by 2012, marking the culmination of over 50 years of research.

Although significant technical challenges must still be met to incorporate this physics achievement into an IFE power plant, a self-consistent point design for a LIFE plant delivering 1-GW net electricity has been established, along with a development program that would enable a demonstration plant to be constructed in the early 2020s. Rollout of a commercial fleet would then be enabled for initiation in the early 2030s, with material choices such that the doubling time of the installed capacity should not be limited by material supply, including tritium.

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