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The National Ignition Facility and the Golden Age of High Energy Density Science

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***Abstract*—The National Ignition Facility (NIF) is a 192-beam Nd:glass laser facility being constructed at the Lawrence Livermore National Laboratory (LLNL) to conduct research in inertial confinement fusion (ICF) and high energy density (HED) science. When completed, NIF will produce 1.8 MJ, 500 TW of ultraviolet light, making it the world's largest and highest-energy laser system. The NIF is poised to become the world's preeminent facility for conducting ICF and fusion energy research and for studying matter at extreme densities and temperatures.**

***Index Terms*—Inertial confinement fusion, High energy density science, National Ignition Facility**

I. Introduction

Construction of the NIF project, which began in 1996, is currently over 93% complete and scheduled for completion in 2009 [1,2]. More than half of the 192 main laser beams have been fully commissioned and are operational. Installation and commissioning of the remaining optics and electronics will be completed over the next year and a half, leading to the beginning of ignition experiments in 2010.

The NIF will provide opportunities to explore regimes of high energy density physics never before possible. In concert with other national facilities such as Z at Sandia National Laboratories and OMEGA at the University of Rochester and with several university laboratories, the U.S. will have unique opportunities to expand the forefront of science in areas that will safeguard our national security, enhance our ability to understand our universe, and provide alternatives for clean energy in the future.

II. National Ignition Facility

The NIF laser is comprised of 192 laser beams, each delivering over 20 kJ of optical energy at 1053 nm. The Nd:glass NIF laser utilizes a multi-pass laser architecture to achieve a total system gain of greater than 10^{15}. An aerial view of NIF is shown in Fig. 1, and one of the two laser bays is shown in Fig. 2.

A schematic of a beam line is illustrated in Fig. 3. The NIF laser starts as a single beam generated by the master oscillator, a highly stable fiber oscillator with the capability of generating

Fig. 1. Aerial view of the National Ignition Facility.

Fig. 2. View of one of two laser bays showing two clusters of 48 beams.

arbitrary optical pulse shapes. This single beam is amplified and split into 48 separate beams to drive the injection laser system.

The injection laser system, one of the most challenging and sophisticated laser amplifiers on NIF, amplifies the nanojoule optical pulses from the master oscillator by a factor of over 10^{10}. The several hundred-millijoule output optical pulses from the injection laser system are then split into four separate beams and injected into the main laser beam lines at the transport spatial filter.

[1]**Work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.**

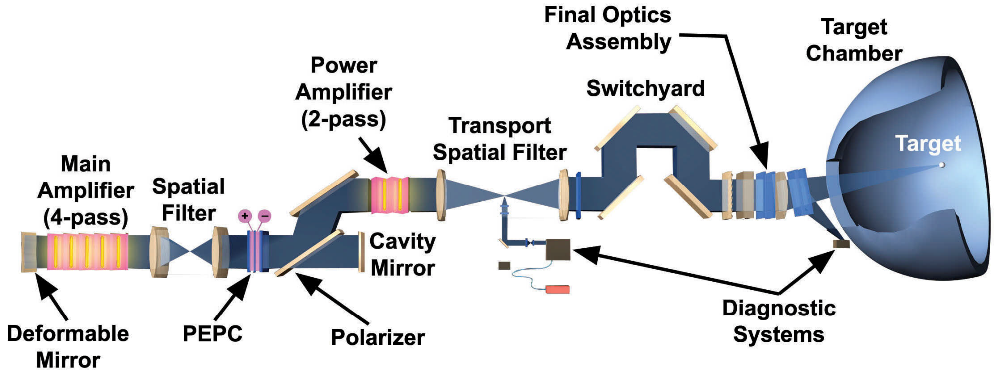


Fig. 3. Simplified diagram of NIF laser architecture.

Once in the main laser, the individual beams are expanded to 40×40 cm and amplified to over 20 kJ through a multi-pass configuration. This multi-pass configuration is implemented utilizing a large-aperture plasma electrode Pockels cell (PEPC) to switch the optical pulses through the amplifier system. After four passes through the main amplifier and two passes through the power amplifier, the beam is directed to the target chamber through a system of optics in the switchyards.

All laser, target and diagnostic systems are controlled from a single control room through an advanced and complex distributed control system. Over 60,000 control points are carefully orchestrated with over 1.5 million lines of code to precisely execute each shot and experiment on NIF.

At the target chamber (Fig. 4), the beam enters the final optics assemblies where it is converted to ultraviolet at 351 nm and focused on the target suspended in the center of the target chamber.

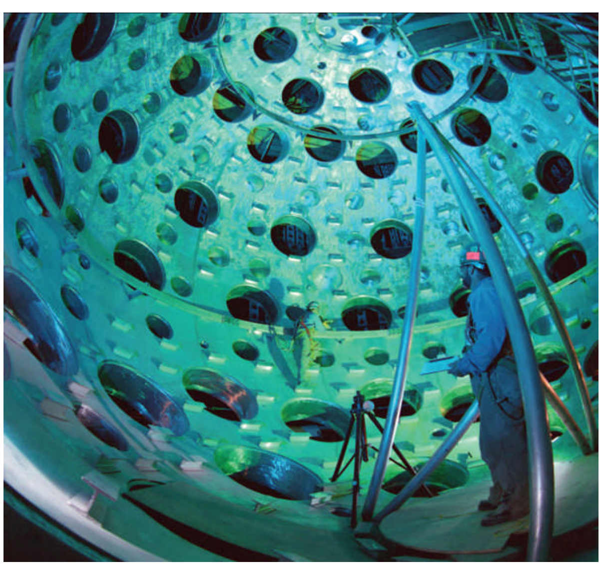


Fig. 4. The NIF target chamber is constructed from 4-inch-thick aluminum and coated with a 16-inch-thick shielding concrete shell. The entire assembly weighs about one million pounds.

III. IGNITION TARGETS

All experiments on NIF have one common requirement: illuminating a sub-centimeter scale target, precisely centered in the target chamber. Creating a NIF target is a complex interplay among target designers, materials scientists, and engineers. Designers understand the goals for each experiment and must establish specifications for the target. Components for making NIF targets are typically only a few millimeters in size, and their complicated shapes must be machined to meet precise requirements, including specifications for density, concentricity, and surface smoothness.

Targets for the ICF experiments are being fine tuned by a large collaboration that includes scientists and engineers from LLNL, General Atomics, the University of Rochester's Laboratory for Laser Energetics, Los Alamos National Laboratory and other industrial partners. This team is perfecting the target materials and methods to fabricate them. Nanoscale materials developed for NIF experiments include high-density carbon, very low-density copper and gold foams, and graded-density foams. The point design is illustrated in Fig. 5.

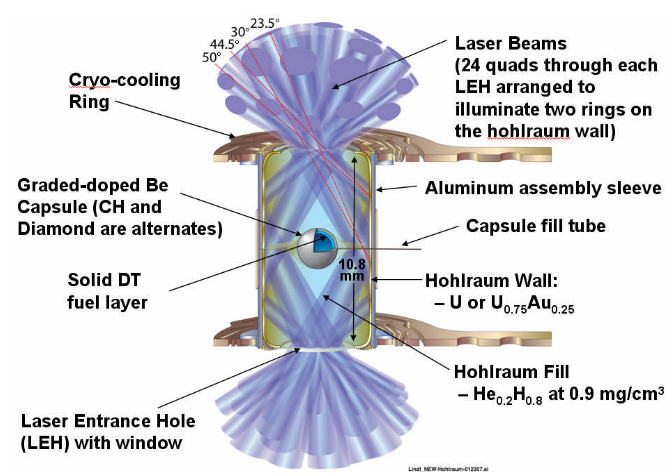


Fig. 5. The NIF point design has a DT-filled capsule in a high-Z hohlraum.

The indirect-drive target has a high-Z radiation case with a capsule in the center filled with cryogenic DT fuel. The present point design has a maximum radiation temperature of 285 eV and uses 1.3 MJ of 3ω laser energy. Alternate designs have been developed for 270 to 300 eV. The hohlraum wall is a composite of uranium and gold. The hohlraum is filled with low density mixture of helium and hydrogen gas to control plasma filling. The point design capsule has a copper-doped beryllium shell, and alternate designs with high density carbon are being developed. The capsule is filled with cryogenic DT fuel using a fill tube. DT filling and layering are done in the target chamber just prior to the shot.

Target fabrication requirements are very stringent for ignition designs. Components must be machined to within an accuracy of 1 µm. Joints can be as small as 100 nm, which is just one-thousandth the width of a human hair. In addition, the margin of error for target assembly is less than 8 µm. The extreme temperatures and pressures the targets will encounter during experiments make the results highly susceptible to imperfections in fabrication. We have successfully fabricated and assembled an engineering prototype that meets the requirements (see Fig. 6.).

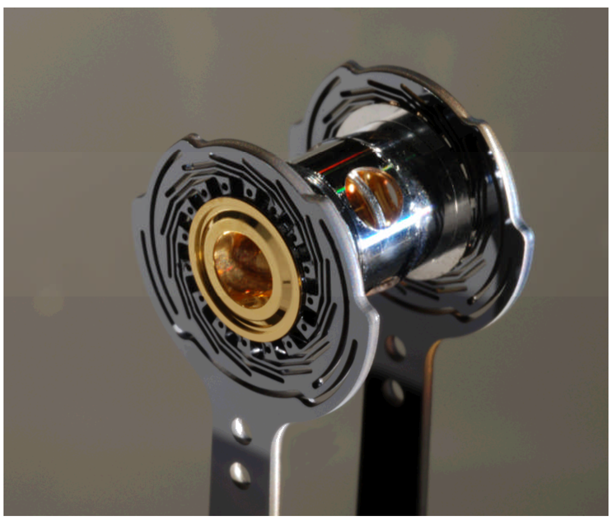


Fig. 6. Prototype NIF target showing SiC attachment arms that aid in precision temperature control.

The Be capsule is 2 mm outer diameter. The capsule's surfaces must be smooth to within 10's nm, and the thickness and opacity of the copper-doped layers must be carefully controlled. Each capsule is made by depositing beryllium on a smooth, near-perfectly spherical plastic mandrel. As the mandrel is rotated, a 150-µm-thick layer of beryllium slowly builds up on its surface. After a capsule is polished, a laser is used to drill a 5-µm fill hole. An oxidation technique removes the mandrel through the drilled hole, and a 10-µm tube is attached to the capsule so it can be filled with D-T gas. The fill tube meets surface specifications and in simulations does not significantly perturb the implosion.

A key requirement for a successful ignition target is the DT fuel layer on the inside of the capsule. Researchers at LLNL, LANL and LLE have pioneered procedures to form the frigid layer of D-T fuel inside the fuel capsule. The DT ice is

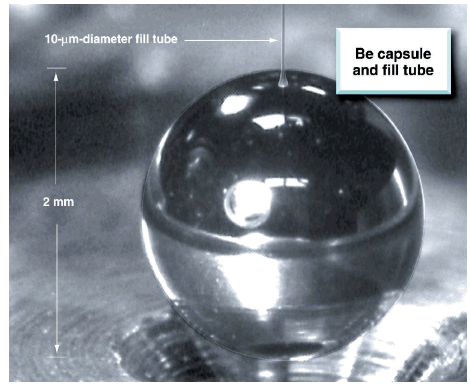


Fig. 7. A prototype Be ignition capsule. The capsule is 2 mm outer diameter with a 10 µm diameter tube attached for DT filling.

1.5 degrees below the triple point of the hydrogen isotope mixture—the temperature at which all three phases of the substance can coexist in equilibrium. Beta decay of the tritium helps smooth the layer by selectively heating thicker regions and evaporating hydrogen from them. NIF researchers found that the DT ice can be shaped by precisely controlling heat transfer within the hohlraum, including contributions from thermal convection of helium. A thermomechanical package encases the hohlraum to accurately control the position and temperature of the hohlraum–capsule assembly. With the thermomechanical package, the target assembly can maintain its position to within 2 µm, and at 18 to 20 K, temperature fluctuations are limited to only 1 mK. This system integrates the ICF target with a cryogenic layering and characterization station and a target positioner attached to NIF's target chamber. The system includes a positioning boom to center the target in the chamber. An ignition-target inserter cryostat attached to the positioner cools the target and the DT fuel to meet temperature and uniformity requirements. The layering and characterization station can image the DT fuel layer in three directions within a few minutes.

IV. Campaign to Ignition

A. *The National Ignition Campaign*

When NIF's laser beams impinge on the hohlraum's inner cavity, laser energy is converted to X-ray energy. These X-rays bathe the capsule and ablate its outer layer. Conservation of momentum requires that the remaining material implode or compress. Compressing the D-T fuel to extraordinarily high temperature, pressure, and density ignites a burning hydrogen plasma.

A detailed plan called the National Ignition Campaign (NIC) has been developed to begin ignition experiments in 2010. NIC is a collaborative effort involving LLNL, the University of Rochester Laboratory for Laser Energetics, General Atomics, LANL, and Sandia National Laboratories (SNL). Components of the NIC plan include target physics, systems engineering and operations, target fabrication, and equipment development such as target diagnostics, cryogenic target positioner, and user optics required for the ignition experiment.

Target designs, which are the product of over 3 decades of research on indirect drive ICF [3,4] calculate to ignite with a laser energy as low as 1 MJ. Experiments using the OMEGA laser at the University of Rochester, and the Z-machine at Sandia, are helping to further refine these designs. Development of manufacturing capability is well under way for producing targets to the required tolerances. Diagnostics and other support equipment are being designed and fabricated to help perform the ignition experiments.

The NIF Project and NIC activities are merging at a rapid rate. The NIF laser and the equipment needed for ignition experiments, including high-quality targets, will be available in 2009. We have already started commissioning laser beams to the target chamber. In 2008, prior to the ignition campaign, we will begin a series of experiments with 96 beams (called early operation shots, EOS) to choose a drive temperature and to test symmetry and shock timing. These tests will provide information to select the best target scale, laser energy, and focal spot size for the initial ignition campaign to begin in FY10. (*Eos*, the Greek goddess of the dawn, is a fitting name because NIF represents the dawn of a new era in physics research, especially in the field of HED science.)

B. Investigating Performance Margins and Uncertainties

Most of the simulation effort and planning has been focused on the point design that uses 1.3 MJ to drive a hohlraum to 285 eV. We have developed a complete set of requirements for this design that describe all aspects of the target, its fabrication and fueling, the laser pulse delivered to it, etc. Recently, we completed an extensive set of analyses to determine the impact on target performance of designs and operational uncertainties [5]. A target performance model has been developed, based on a large number of 1, 2 and 3D simulations of capsules, hohlraums, multi-mode Rayleigh Taylor instability growth, and more [4]. We are using the model to estimate the probability of ignition based on statistical variability in the laser performance, target fabrication, and target experimental campaigns.

An example of performance modeling is shown in Fig. 8, which plots laser energy versus stimulated Brillion scattering (SBS) growth that gives constant target robustness (measured as the maximum allowed hot spot degradation fraction, ε, where ε is the radial fraction of the hot spot at the center of the compressed fuel cooled by 3D perturbations to the implosion). Initial operation of the NIF laser will be limited to

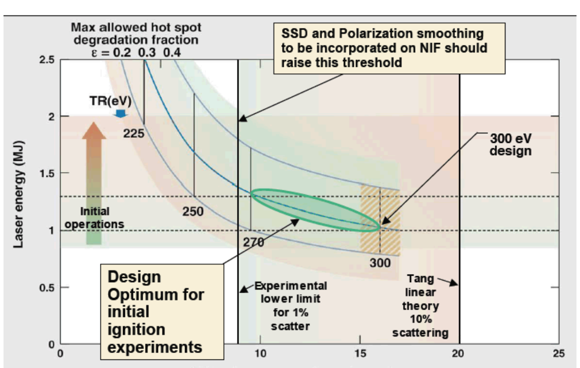
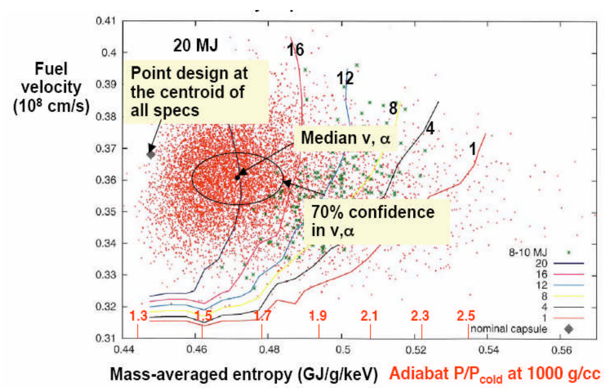


Fig. 8. Ignition point design optimization must balance LPI effects, laser performance impacts, and capsule robustness

about 1.3 MJ while we develop operational experience. For a robustness factor ε=0.3, hohlraums in the range of 270-300 eV are possible with laser energies of 1-1.3 MJ. The corresponding SBS gain exponents are about 10-17, which covers the range of LPI uncertainty. Laser Plasma Interaction (LPI) effects for ignition target designs are being investiagated in detail using the code pF3D [6]. LPI effects in a NIF ignition hohlraum are quite complex. Obtaining a predictive capability for ignition relevant plasma conditions has been an experimental, theoretical, and computational grand challenge. Recent advances in massively parallel computing, along with methods such as Thomson scattering for characterizing laser produced plasmas, have allowed us to make significant advances toward this objective in experiments on the Omega laser [7,8,9]. Based on this progress, we have chosen a range of of target designs with hohlraum temperatures which vary from 270 eV to 300 eV. The optimal design will be chosen following the EOS experiments discussed earlier.

Figure 9 shows an example of a statistical analysis of target performance based on the expected statistical distribution functions for 34 capsule fabrication and laser pulse shape parameters [10,11]. Lines of constant target yield are plotted in the fuel-implosion-velocity versus entropy design space which determine capsule heating and compressibility. Each red dot is a 1D simulation, and we have varied 34 1D parameters spanning the range of possible values for target and laser characteristics. The median result for the 285 eV NIF point design is a 20 MJ yield.



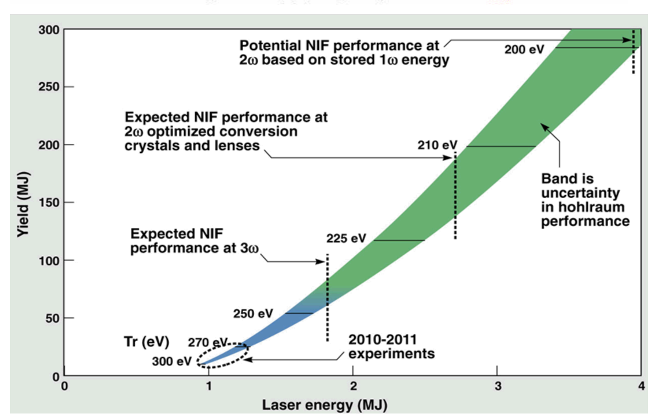


Fig. 10. Target yield versus laser energy. Ultimately, yields over 100 may be possible on NIF.

The overall conclusion from these analyses is that the 285 eV point design has a credible chance for ignition if the required precision of target experiments, laser performance and target fabrication is achieved. Subsequent to the initial ignition experiments, target with other ablators (CH and diamond) and experiments at higher laser energy may be conducted, increasing the likelihood of successful ignition.

The initial ignition experiments will only scratch the surface of NIF's potential, which includes high yields with green light and greatly expanded opportunities for the uses of ignition by decoupling compression and ignition with the Fast Ignition approach [12]. Figure 10 shows the range of target yield that is being investigated for future experiments and operating scenarios.

C. Diagnostics

NIF will include a large assortment of diagnostics. Many of the diagnostics for the initial experiments have been installed and operated on four beam experiments. During recent tests in the Precision Diagnostic Station (PDS) all of NIF performance requirements have been demonstrated on a single-beam basis. The modular control system concept dovetails well with plans for NIF experiments. For example, although achieving ignition will require all 192 beams, many experiments will require fewer laser beams. Each NIF experimental series will require different laser parameters such as wavelength, energy, and pulse duration; different configurations of the laser beam; different laser targets; and different diagnostic instruments. By taking advantage of the facility's experimental flexibility, teams will be able to create an extraordinary range of physical environments, including densities ranging from one-millionth the density of air to ten times the density of the core of the sun, temperatures ranging from a terrestrial lightning bolt (about 10^4 K) to the core of a carbon-burning star (10^9 K) and pressures from 1 to 100 TPa (1 gigabar). Researchers will study phenomena at timescales ranging from fractions of a microsecond (10^{-6} s) to picoseconds (10^{-12} s).

Diagnostics for the ignition experiments will be installed beginning in 2009. An important capability will be an advanced radiographic capability (ARC) for making high energy radiographs of the ignition core. These radiographs can be used to measure the areal density and symmetry of the core near time for ignition. X-ray energies greater than 20 keV are needed to penetrate the dense core. Lasers with pulse lengths of about 1 ps have been shown to produce high energy electrons and protons. The particles can be used to probe material directly or be used to produce efficient high energy x-ray sources. One quad of NIF will be converted to short pulse operation for ARC. Mirrors will be used to redirect one quad of NIF beams in the target area to a compressor vessel. Chirped pulse amplification will be used to produce picosecond pulses that will be focused on backlighter targets through a port on the midplane of the chamber. This will provide important imaging information especially of the high density fuel assembly stage where there are few other diagnostics.

ARC will also provide an opportunity to explore the concept of fast ignition [12], where an intense shot pulse beam (~20 ps) is used to ignite fuel that has been compressed by long-pulse (~10 ns) beams. LLNL has begun an internally funded study that will culminate in a fast ignition experiment on NIF shortly after the initial ignition campaign. Fast ignition is of significant interest to IFE since it will allow higher target gains at lower drive energy and open up the possibility of using thick liquid wall protection with laser drivers.

V. Exploring the Frontiers of Science

In addition to supporting the DOE's Stockpile Stewardship Program, NIF will provide researchers from universities and DOE national laboratories unparalleled opportunities to explore basic science in astrophysics, planetary physics, hydrodynamics, nonlinear optical physics and materials science [13]. Approximately 15% of NIF facility time and a larger percentage of its shots will be devoted to science experiments in these fields. The first science studies will focus on recreating in the laboratory the properties of celestial objects under scaled conditions. With its 192 beams together generating up to 1.8 MJ of ultraviolet energy, the giant laser will allow scientists to explore some of the most extreme conditions in the universe such as the hot, dense plasmas found in stars. NIF experiments will help scientists understand the mechanisms driving new stars, supernovae, black holes and the interiors of giant planets. The physical processes of stars have long been of interest to LLNL researchers because the prime stellar energy mechanism, thermonuclear burn, is central to the Laboratory's core mission. For decades, researchers have advanced astrophysics by applying their expertise in HED physics and computer modeling of the nuclear processes that take place in these regimes.

Once NIF attains ignition (a burst of fusion reactions in which more energy is liberated than is input), a flux of 10^{32} to 10^{33} neutrons per square centimeter per second will be generated, a rate that may allow excited-state nuclear reactions to occur. This neutron flux will also enable scientists to extend their understanding of the nucleosynthesis of heavy elements, those nuclei more massive than iron. Scaled NIF experiments will permit studies of the entire life cycle of a star, from its birth in a cold, dense molecular cloud through its subsequent stages of evolution to an explosive death such as a supernova.

Once formed, stars are heated by nuclear fusion in the interior and cooled by radiation emissions at their surface, called the photosphere. Opacities of each layer control the rate at which heat moves from the core to the surface. In this way, opacity plays a major role in understanding the evolution, luminosity, and instabilities of stars. Experiments will mimic stellar plasma to obtain information on the opacities of key elements such as iron and determine how opacity changes with plasma density and temperature throughout a star's lifetime. Experimenters plan to simultaneously measure the radiation transmission, temperature, and density of a material sample.

VI. Use of NIF for Inertial Fusion Energy

Achieving ignition, burn and gain in an ICF target will be a major milestone opening up the possibility of using inertial fusion for energy [14]. NIF will only be capable of a few target shots per day and therefore will not be able to ignite targets at high pulse repetition rate as will be required for IFE. Nonetheless, NIF will be able to make significant contributions to IFE [15]. Foremost is the area of advanced target development. Many target designs have been proposed for IFE and most can be tested to some degree on NIF. Besides the baseline indirect-drive (hohlraum) targets, NIF will also be able to test fast ignition, shock-ignition and polar direct drive concepts. Although it would take a significant effort, NIF has been designed to allow reconfiguration of the beams for uniform illumination direct drive. Not only will NIF be able to do experiments with different target concepts, experiments can be conducted to quantify the impact on target performance that different target materials (e.g., used in capsules and hohlraums) and fabrication techniques have. This will help in specifying the requirement for the automated target fabrication facility that will be required for IFE power plant.

The emissions (neutrons, x-rays and energetic ions) of an ignition target will also be useful for certain IFE-relevant chamber and optics experiments. Experiments to test the single-shot response of candidate IFE chamber first wall materials (solids and liquids) can be conducted at IFE relevant fluences by placing test samples close to the target. These experiments will also help benchmark IFE codes that have been developed to predict post-shot conditions in an IFE chamber. It should also be possible to test concepts to protect sensitive final optics from target debris, e.g., magnetic deflection and use of gas puffs.

Some preliminary consideration has also been give to the possibility of retrofitting a single quad or bundle of NIF for high rep-rate operation by replacing the flash lamps with diodes and adding high pressure He gas for cooling. Such a project would address some of the key technology integration challenges for developing high repetition rate solid state lasers in a large scale facility.

VII. Conclusions

NIF was designed specifically to meet the needs of three missions: strengthening stockpile stewardship for a safe and reliable nuclear stockpile without nuclear testing, advancing ICF as a clean source of energy, and making significant strides in HED science. These three missions share the need to expose materials to extraordinarily high pressures, temperatures, and densities—as much as 100 billion atmospheres pressure, 100 million degrees Centigrade temperature, and 1,000 g/cm^3 density. These conditions are similar to those occurring in exploding nuclear weapons, in supernovae, and in the fusion reactions that power our Sun and other stars and that may one day provide an inexhaustible power supply on Earth. Because of the similarities of these phenomena, the results of some NIF experiments will be applicable to all three missions.

We cannot venture inside stars, planets, or black holes, nor can we traverse billions of light years across the universe to examine a supernova explosion. However, with NIF, we can re-create, on a vastly smaller scale, the same physical processes that astronomers can only glimpse through a telescope. Our goal is to demonstrate ignition and burn, in turn launching a new era of high energy density science and energy research.

Acknowledgment

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