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Preparing for Ignition Experiments on the National Ignition Facility

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Abstract
The National Ignition Facility (NIF) is a 192-beam Nd-glass laser facility presently under construction at Lawrence Livermore National Laboratory (LLNL) for performing ignition experiments for inertial confinement fusion (ICF) and experiments studying high energy density (HED) science. NIF will produce 1.8 MJ, 500 TW of ultraviolet light ($\lambda = 351$ nm) making it the world's largest and most powerful laser system. NIF will be the world's preeminent facility for the study of matter at extreme temperatures and densities for producing and developing ICF. The ignition studies will be an essential step in developing inertial fusion energy (IFE). The NIF Project is over 93% complete and scheduled for completion in 2009. Experiments using one beam have demonstrated that NIF can meet all of its performance goals. A detailed plan called the National Ignition Campaign (NIC) has been developed to begin ignition experiments in 2010. The plan includes the target physics and the equipment such as diagnostics, cryogenic target manipulator and user optics required for the ignition experiment. Target designs have been developed that calculate to ignite at energy as low as 1 MJ. Plans are under way to make NIF a national user facility for experiments on HED physics and nuclear science, including experiments relevant to the development of IFE.

Keywords: laser, inertial confinement fusion, inertial fusion energy

1. Introduction

The National Ignition Facility (NIF) is a 192-beam Nd-glass laser facility being constructed at LLNL [1,2]. When completed, NIF will begin an experimental campaign to demonstrate ignition (a burst of fusion reactions in which more energy is liberated than is input) and energy gain (>10×) in an inertial confinement fusion (ICF) target [3]. Achieving ignition will be a key milestone for the development of inertial fusion energy (IFE) [4]. Besides its primary mission of stockpile stewardship, NIF will become the world's preeminent user facility for conducting experiments studying high energy density (HED) science and nuclear science. It will be capable of producing conditions (temperatures, densities, and radiation fluxes) that are not achievable anywhere else on earth.

The NIF Project is over 93% complete and scheduled for completion in 2009. An aerial view of NIF is shown in Fig. 1. The building and all the infrastructures are complete and over 70% of the optical and electronics components have been installed. The 192 beams of NIF are divided into two large laser bays. The beams are grouped as four beams per quad, two quads per bundle, six bundles per cluster and two clusters per bay. Fig. 2 shows the beam path in one of the two laser bays. Two clusters, 96 beams, have been commissioned with the demonstrated capability of producing 2,000 kJ of 1053-nm light. (1053 nm is the fundamental frequency of Nd and is referred to as 1ω.) 2000 kJ is nearly 40 times the normal operating capability of Nova or OMEGA, the previous largest laser systems. The beams will be frequency tripled just prior to entering the chamber so the target will see 351-nm light (3ω).

2. National Ignition Campaign

The National Ignition Campaign (NIC) is a detailed plan to begin ignition experiments in 2010. NIC is a collaborative effort involving LLNL, the University of Rochester Laboratory for Laser Energetics (UR-LLE), General Atomics, Los Alamos National Laboratory (LANL), and Sandia National Laboratories (SNL). The plan includes the target physics, targets fabrication and the equipment such as diagnostics, cryogenic target manipulator and user optics required for ignition experiments. Preliminary experiments will be conducted in early fall of 2008 when 96 beams are available in a symmetric configuration. These "Early Opportunity Shots" will allow us to choose the optimum hohlraum temperature and laser energy for initial ignition experiments.

2.1 Ignition Targets

The NIC plan is organized around the ignition target point design shown in Fig. 3. 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 He gas to control plasma filling. The point design capsule has a 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. As part of the NIC, we have successfully fabricated and assembled an engineering prototype that meets the requirements.

An example target component is shown in Fig. 4. The Be capsule has a 2-mm outer diameter with a fill tube attached and meets surface finish specifications. The capsule's surfaces must be smooth to within 1 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, 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 DT gas.

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 DT fuel inside the fuel capsule. The DT ice is 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. Temperature can fluctuate no more than 1 mK. 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.

2.2 NIF 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 the NIF's 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 energy greater than 20 keV is 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 fuel assembly stage where there are few other diagnostics.

ARC will also provide an opportunity to explore the concept of fast ignition [5], where an intense short-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 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.

3. Science at the Extreme

NIF will provide researchers from universities and Department of Energy (DOE) national laboratories unparalleled opportunities to explore "frontier" basic science in astrophysics, planetary physics, hydrodynamics, nonlinear optical physics, and materials science [6]. About 15% of NIF shots will be devoted to science experiments in these fields. The first science studies will focus on re-creating in the laboratory the properties of celestial objects under scaled conditions. Scientists will be able 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 fusion, is central to the Laboratory's national security 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 flux of 10^{32} to 10^{33} n/cm^{2}s 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 determining 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.

4. Use of NIF for IFE

Achieving ignition, burn and gain in an ICF target will be a major milestone opening up the possibility of using inertial fusion for energy. 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 [7]. 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 given 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.

5. Conclusions

As the construction of NIF nears completion, efforts are under way to define details of the ignition campaign to demonstrate production of greater than 10 times more energy output in fusion than laser light input. This will be a major milestone on the path to energy applications of inertial fusion and will set the stage for a more concerted and focused effort on developing IFE as an alternative approach to fusion power. In addition to its stockpile stewardship mission, NIF will become an international user facility providing unprecedented capabilities to explore extreme states of matter. It will also be used for IFE-relevant experiments in the areas of advanced targets, chambers, optics and possible high-average-power laser technology development.

Acknowledgements

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Figures

Fig. 1. Arial view of the NIF.

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

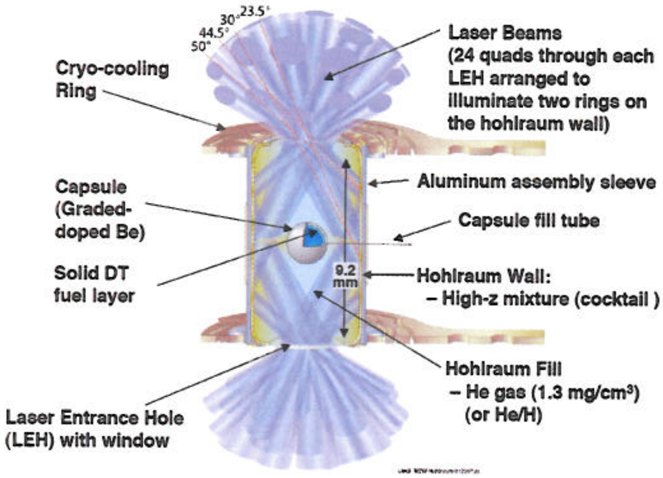

Fig. 3. The NIF point design has a DT-filled capsule in a high-Z hohlraum.

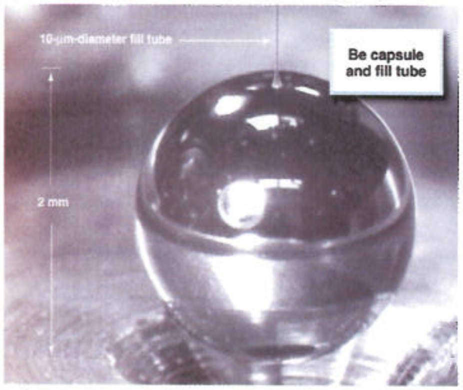

Fig. 4. A prototype Be ignition capsule. The capsule has a 2-mm outer diameter with a 10-μm-diameter tube attached for DT filling.

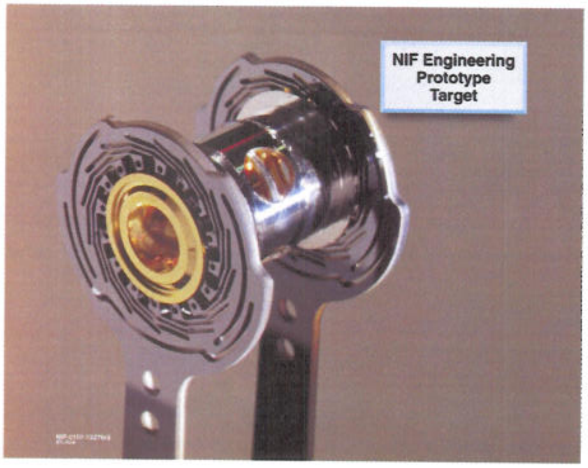

Fig. 5. Prototype NIF target showing SiC attachment arms that aid in precision temperature control.