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The National Ignition Facility: The World's Largest Laser

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The National Ignition Facility: The World's Largest Laser*

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Abstract. **The National Ignition Facility (NIF) is a 192-beam laser facility presently under construction at LLNL. When completed, NIF will be a 1.8-MJ, 500-TW ultraviolet laser system. Its missions are to obtain fusion ignition and to perform high energy density experiments in support of the U.S. nuclear weapons stockpile. Four of the NIF beams have been commissioned to demonstrate laser performance including target and beam alignment.. During this time, NIF demonstrated on a single-beam basis that it will meet its performance goals and demonstrated its precision and flexibility for pulse shaping, pointing, timing and beam conditioning. It also performed four important experiments for Inertial Confinement Fusion and High Energy Density Science. Presently, the project is installing production hardware to complete the project in 2009 with the goal to begin ignition experiments in 2010. An integrated plan has been developed including the NIF operations, user equipment such as diagnostics and cryogenic target capability, and experiments and calculations to meet this goal.**

Keywords-laser; fusion; ignition;

I. INTRODUCTION

The National Ignition Facility (NIF) is presently under construction at the Lawrence Livermore National Laboratory (LLNL). NIF is a 192-beam laser system to study inertial confinement fusion (ICF) and the physics of extreme energy densities and pressures [1,2]. When completed in 2009, NIF will be able to produce 1.8 MJ, 500 TW of ultraviolet light for target experiments. This is sixty times as energetic as present laboratory capabilities. At this power and energy, NIF is expected to ignite deuterium-tritium plasmas in ICF targets. Presently the Project is approximately 80% complete with eight beams in a bundle operational in the main laser bay. These eight beams have produced 150 kJ of 1.05-μm light making it already the most energetic infrared laser. The Project status and schedule is reviewed in Section 2.

Beginning in late 2002, four beams were activated to the target chamber for target experiments in a campaign called NIF early light (NEL). One of the beams could also be directed to a laser precision diagnostic station (PDS). On a beam line basis, NIF demonstrated operation at all Project completion criteria and long-term functional requirements and primary criteria. NIF also performed target experiments in four experimental campaigns. Results from NEL are summarized in Section 3.

In anticipation of the completion of the Project, planning has begun for the first ignition experiments. An integrated plan has been developed to begin ignition experiments in 2010. This plan includes the target physics, diagnostics, user optics, target systems, personnel and equipment protection systems, and systems support as well NIF operations. The plan optimizes all of the areas to balance the risks throughout the system. This plan is summarized in Section 4.

II. NIF PROJECT STATUS

The NIF facility layout is shown in Figure 1. The facility consists of two laser bays, four capacitor areas, two laser switchyards, the target area, and the building core. In addition, there is an Optics Assembly Building and a Diagnostics Support Building. Details of the laser and building designs can be found elsewhere [1,2]. The laser is configured in four clusters of 48 beams, two in each laser bay. Each cluster has six sets of eight beams called a bundle that is the fundamental beam grouping in the laser bay. In the switchyard, each bundle is split into two sets of four beams, or a quad, with one quad from each bundle directed toward the top of the chamber and the other quad directed toward the bottom. The irradiation geometry for an indirect-drive target is 24 quads through the top laser entrance hole and 24 quads through the bottom laser entrance hole.

Presently, the NIF Project is approximately 80% completed. The buildings were completed in 2001 and the beam path enclosures were completed in 2003. Almost all of the subsystem designs are completed. The laser components are assembled and installed in pre-aligned modules called line-replaceable units or LRUs. Over 5,700 LRUs need to be installed and commissioned. Completion of the Project involves primarily the assembly, installation, and commissioning of the LRUs and installing the supporting utilities and control systems.

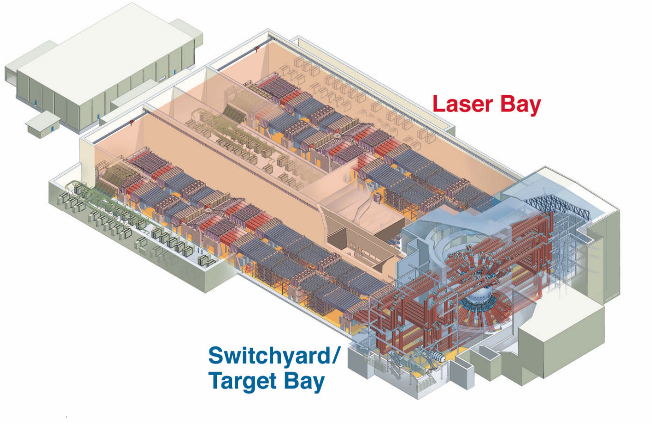

Figure 1. Layout of the National Ignition Facility.

The Project is being completed in two phases. In the first phase, the LRUs are being installed and beam lines activated in the laser bays to the switchyard wall. Beginning in 2007, the Project will begin to build out the beam lines to the target chamber. Project completion is planned for March 2009. Presently, nearly 1000 LRUs have been installed, and one bundle of eight beams has been commissioned to the switchyard wall. During the activation, the bundle produced over 150 kJ of 1ω light. This is the highest energy pulse produced by a laser system at 4% of NIF's capacity.

III. NIF EARLY LIGHT EXPERIMENTS

In 2002, NIF began activating a quad of four beams to the target chamber for NEL experiments. Any one of the four activated NIF beams could also be directed to a separate experimental area, known as the Precision Diagnostic System (PDS), to fully characterize NIF's laser performance. The NEL experiments were used to demonstrate the performance of NIF design architecture and the operability of the facility. Over 400 shots were performed during the lifetime of NEL from January of 2003 to October of 2004. By the end of NEL operations, the facility could routinely perform two shots per operations shift.

Experiments were performed in the PDS to characterize the performance of a NIF beam [3]. On a beam line basis, all Project completion criteria and long-term functional requirements and primary criteria were demonstrated. In separate PDS experiments, NIF produced 10.4 kJ of 3ω light and 11.4 kJ of 2ω light. This is equivalent to 2 MJ and 2.2 MJ, respectively, for 192 beams. The laser demonstrated its capability required for ignition. Figure 2 shows a 3ω ignition design pulse. Along with the data, the predicted output from the Laser Performance Model is shown. The good agreement between experiment and prediction is consistent with ignition requirements for power balance. Target experiments also demonstrated NIF beam performance. In hydrodynamics experiments, the laser energy repeatability was better than 2% rms, which is much better than the 8% rms power balance requirement as shown in Figure 3 (a). Figure 3 (b) shows the pointing stability during these experiments. The quad pointing showed pointing deviation of 30-µm rms for an 800-µm-diameter spot compared with the NIF requirement of 50-µm rms.

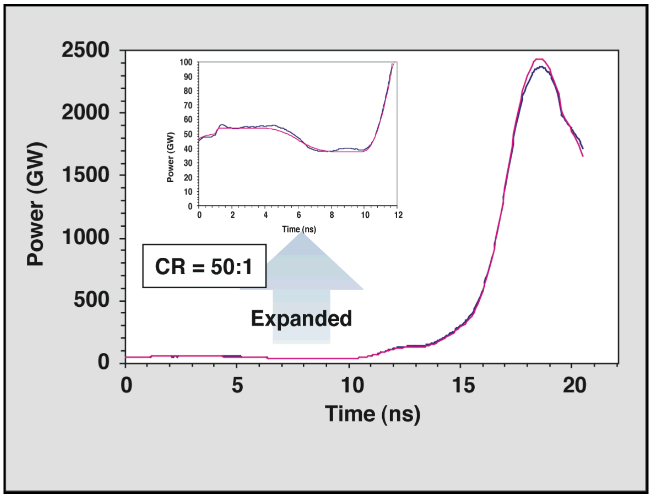

Figure 2. Example of an ignition pulse. The two curves are data from one NIF beam and the pre-shot prediction of the pulse.

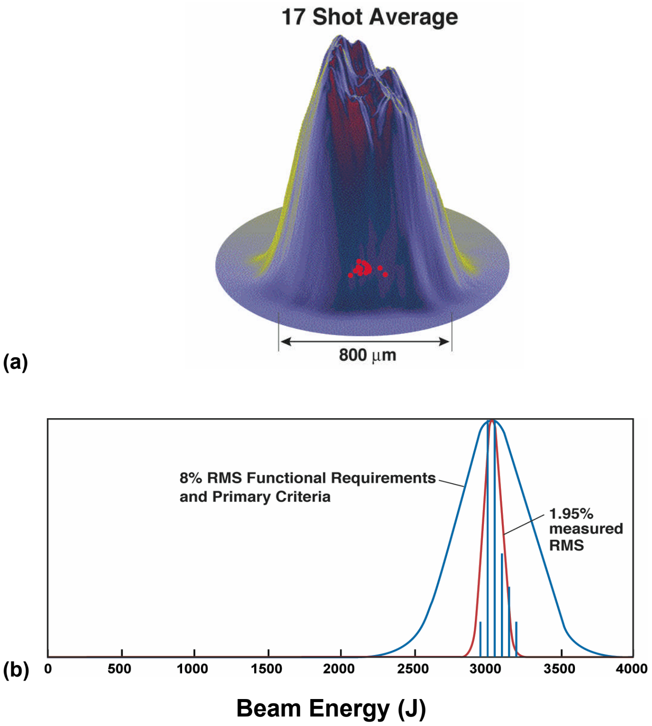

Figure 3. (a) The 3D contour shows a 17-shot average of the beam spot for a NIF quad with 800-µm phase plates. The data points show the pointing accuracy. (b) Variation of beam energy for the 17-shot campaign showing a 2% rms power balance.

Four experimental campaigns were performed on NEL. These experiments studied light propagation in a plasma [4], nonlinear hydrodynamics [5], hohlraum physics [6,7], and

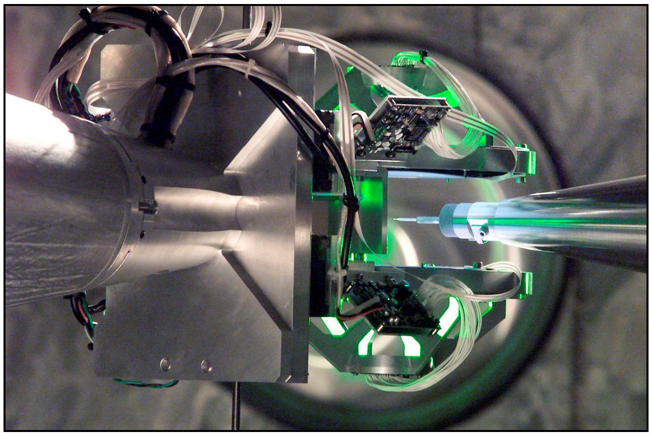

Figure 4. Target on the target positioner being aligned using the Target Alignment System.

equation of state. A major value of the experiments was to develop the target area and activate it for experiments. A picture of the target alignment system with a target in place is shown in Figure 4. This system is used for aligning the target and final beam alignment and was commissioned for doing these experiments. The initial diagnostics were also commissioned. A total of 13 diagnostic systems were commissioned [8]. These operated with a 98% success rate. Beam smoothing required for ignition experiments was also demonstrated. Continuous phase plates were deployed to shape the far field focal spot. Experiments used smoothing by spectral dispersion (SSD) and polarization smoothing to study the effects of beam smoothing on beam propagation and hohlraum coupling.

IV. NATIONAL IGNITION CAMPAIGN

After the NIF Project is completed in 2009, the goal is to begin ignition experiments in 2010. Significant effort is required after the end of the Project to prepare for these experiments. An integrated plan called the National Ignition Campaign (NIC) has been developed to meet this goal. The NIC plan coordinates the activities required to perform a credible ignition experimental campaign on the NIF in FY2010 and continued campaigns beyond 2010. The NIC is an integrated national effort involving several institutions that collectively work together to plan the activities and experimental campaigns. As shown in Figure 5, the plan integrates a number of subsystems with the target physics and NIF operations into a multiyear effort culminating in the initial ignition experiments in 2010. The 2010 ignition experiments begin using laser energy of ~1 MJ with the energy ramping up to the full 1.8 MJ in 2011 [9]. A pre-ignition campaign is planned at the beginning of 2010 to study the energetics, symmetry, ablator performance, and shock timing to optimize target performance.

The subsystems needed to begin the ignition experiments include diagnostics, user optics, cryogenic target capability, and personnel and environmental protection systems.

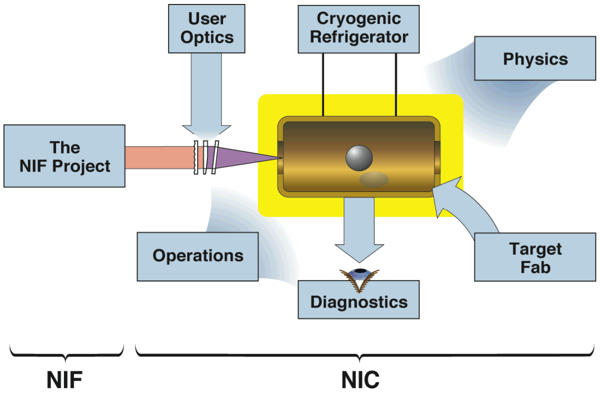

Figure 5. Schematic showing the various subsystems of the National Ignition Campaign (NIC).

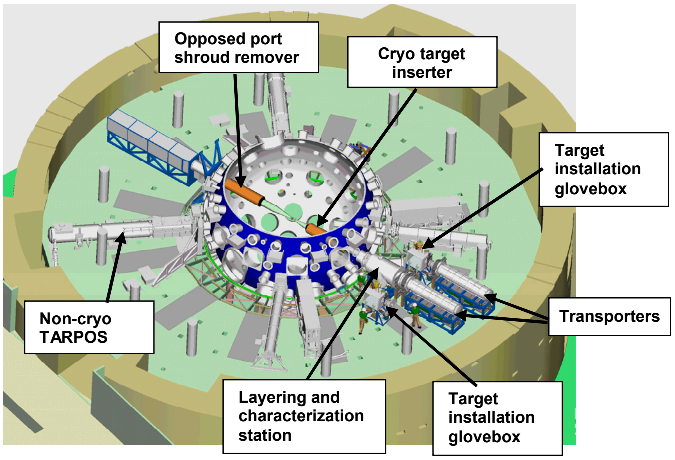

Figure 6. Layout of the NIF Cryogenic Target System in the NIF Target Bay.

Although a number of diagnostic systems were commissioned for the NEL experiments, additional systems are required, for the ignition experimental campaign in FY2010–2011[8]. The user optics include phase plates, polarization smoothing crystals, debris shields and other special optics required for conditioning the laser beam for optimizing target performance. During NEL, beam smoothing with SSD and polarization smoothing required for ignition were demonstrated [3]. The cryogenic target system is required for fielding ignition targets. It consists of a target positioner, a cryogenic shroud, target installation glove box, layering and characterization station, and a transport system. A schematic of the layout is shown in Figure 6. The plan is to fill the target reservoir in the LLNL tritium facility and transport it to NIF. The target will be cooled, filled, and layered next to the chamber and then inserted and aligned. Finally, the personnel and environmental protection systems are the neutron and tritium monitors, hazardous material handling systems, and shielding needed to manage the yield and hazardous materials in the target.

Figure 7. Mercury Laser; a system designed for 100J 10Hz operation.

V. FUSION SYSTEMS DEVELOPMENT

Hundred-joule, kilowatt-class lasers based on diode-pumped solid-state technologies, are being developed worldwide for applications in laser-plasma interactions and as prototype systems for fusion energy systems. The High Average Power Laser Program is developing many of the integrated technologies (lasers, target fabrication and injection, and chamber technologies, etc.) for laser-based fusion energy systems. As a part of this effort, LLNL is building a diode-pumped, gas-cooled 100-J, 10-Hz laser called Mercury (Figure 7).

The goals of the Mercury Laser Project are to develop the key technologies at sub-scale energies and beamline apertures, within an architectural framework that represents the building blocks of larger multi-kilojoule systems for inertial fusion energy applications. The system recently demonstrated 50 J at a 10 Hz repetition rate for several 1-hour runs with <5% energy fluctuations. Conversion to the second harmonic was performed with no indication of anomalous absorption or thermal degradation. The next experiments will focus on delivering 100 J at 10 Hz with beam smoothing, active wavefront optics, and conversion to the third harmonic.

Beyond this, future plans for the laser facility will include laser-plasma interaction experiments and conceptual laser designs for multi-kilojoule amplifiers. The kilojoules energy levels require increasing the Mercury aperture to a full size IFE beamline, demonstrating diode cost reduction and incorporating beam bundling. These designs have a set of challenging requirements that include: high efficiency, stringent reliability, and availability for large (109) shot counts.

VI. SUMMARY

In summary, the NIF project is on schedule for completion in 2009. The remaining activities are primarily the completion of LRU installation, utilities, and the control system. One bundle of eight beams has been commissioned to the switchyard wall. NEL experiments have demonstrated that NIF will be able to perform as designed. User experiments with four beams of NIF have demonstrated its ability to operate as a facility. The experiments provided important data showing NIF's value as an experimental facility. Plans are in place to begin ignition experiments in 2010, the year after Project completion. In parallel, we are developing the laser technologies to extend the NIF architecture into an efficient, high average power laser system for fusion energy applications.

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