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The national ignition facility: path to ignition in the laboratory

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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 US nuclear weapons stockpile. Four of the NIF beams have been commissioned to demonstrate laser performance and to commission the target area including target and beam alignment and laser timing. 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. This talk will provide NIF status, the plan to complete NIF, and the path to ignition.

PACS. 42.55.-f Lasers – 42.60.-v Laser optical systems: design and operation – 52.57.-z Laser inertial confinement

1 Introduction

The National Ignition Facility (NIF) is a 192-beam laser system for inertial confinement fusion (ICF) and to study the physics at high energy densities and pressures [1,2]. NIF is presently under construction at the Lawrence Livermore National Laboratory (LLNL) and when completed in 2009 will produce 1.8 MJ, 500 TW of ultraviolet light for target experiments. This is sixty times as energetic as present laboratory capabilities. The Project is approximately 80% complete with eight beams in a bundle operational in the main laser bay. These eight beams have produced 152 kJ of 1.05-μm light making it already the most energetic infrared laser. Status and schedule of the Project is reviewed in Section 2.

Beginning in late 2002, four beams of NIF were activated to the target chamber for target experiments in an initiative called NIF early light (NEL). A beam could also be directed to a laser precision diagnostic system (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.

A principal mission of NIF is achieving ignition of deuterium-tritium plasmas in ICF targets. A plan has been developed to begin the first ignition experiments in 2010 after completion of the project in 2009. The integrated plan includes the target physics, diagnostics, user optics, target systems, personnel and equipment protection systems, and systems support as well as NIF operations. Section 4 presents a summary of the plan.

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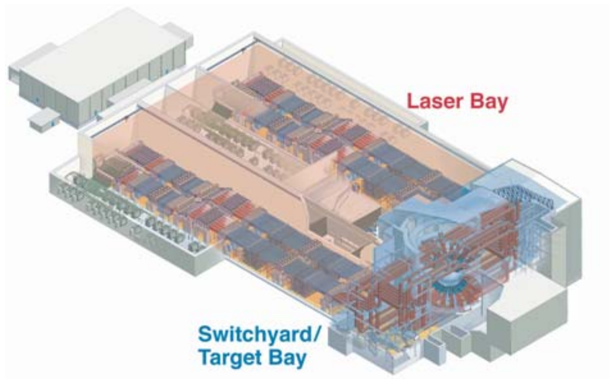

Fig. 1. (Color online) Layout of the national ignition facility.

2 NIF project status

The NIF Project began in 1995 with a mission to construct a facility to achieve ignition by ICF in the laboratory and to perform high energy density experiments. The facility contains a 192 beam Nd-glass laser system. The laser will produce 1.8 MJ, 500 TW for target experiments. The layout of the facility is shown in Figure 1. It consists of two

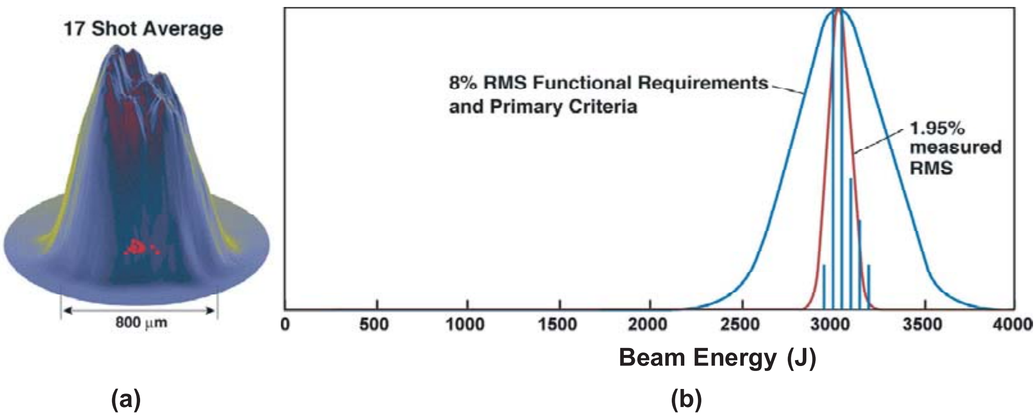

Fig. 2. (Color online) The 3D contour shows a 17-shot average of the beam spot for a NIF quad with 800 μm phase plates. The data points show the pointing accuracy. (b) Variation of beam energy for the 17 shot campaign showing a 2% rms power balance.

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 and bottom of the target chamber. 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 completing installation of the laser components. 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 prealigned 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. These are 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 2009. Overall, the Project is over 80% complete. Nearly 20% (over 1000) of the LRUs have been installed.

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.

3 NIF early light (NEL) experiments

Beginning in 2002, NIF activated a quad of four beams throughout the laser system to the target chamber experiments. Also, one of the four beams could be directed to the Precision Diagnostic System (PDS), to fully characterize laser performance at full energy. The NEL experiments demonstrated 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 in the PDS characterized the performance of a NIF beam at full energy and power [3]. All Project completion criteria and long-term functional requirements and primary criteria were demonstrated on a beam line basis. NIF performance for producing 1ω light was demonstrated over a range of pulse lengths varying from 1 ns to 10 ns. 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.

Target experiments also demonstrated NIF beam performance. In target experiments, the laser energy repeatability for the four beams in a quad was better than 2% rms, exceeding the 8% rms power balance requirement as shown in Figure 2a. Figure 2b 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. Beam synchronicity was also demonstrated to be better than 20 ps.

Laser performance required for ignition was also demonstrated. Figure 3 shows a 3ω ignition design pulse. This pulse has a contrast of better than fifty to one between the peak and the foot. Along with the data, the desired pulse shape as predicted by the Laser Performance Model is shown. The agreement between experiment and prediction is better than 8% averaged over 2 ns consistent with ignition requirements for power balance. At best focus, over 70% of the 3ω energy is focussed to better than a 200 μm diameter spot and over 98% of the energy is contained in a 600 μm diameter spot. This exceeds the design specifications. Beam smoothing by SSD and by polarization smoothing desired for ignition experiments and other users were also demonstrated.

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

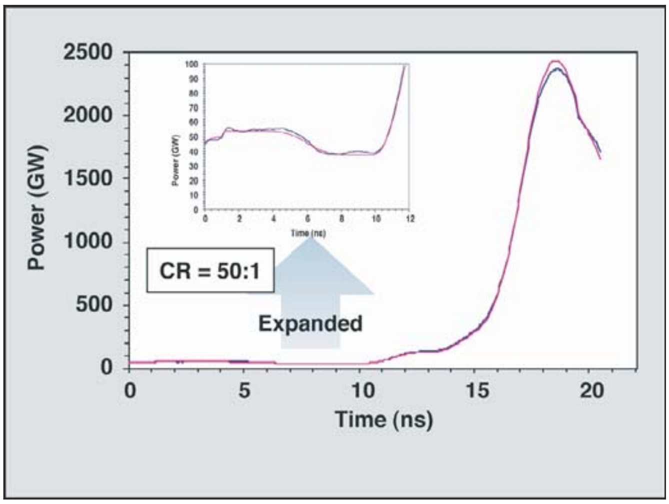

Fig. 3. (Color online) Example of an ignition pulse. The two curves are data from one NIF beam and the preshot prediction of the pulse.

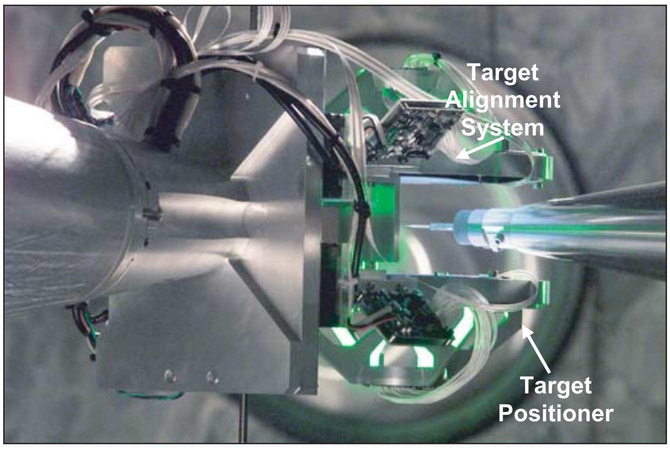

Fig. 4. (Color online) Target on the target positioner being aligned using the target alignment system.

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. Two diagnostic instrument manipulators (DIMs) were commissioned. These are general purpose instruments used to insert diagnostics such as streak cameras and framing cameras into the target chamber. Diagnostics operated with a 98% success rate during the lifetime of NEL experiments. Additionally several other X-ray and optical diagnostics were commissioned. These include a soft X-ray power diagnostic for measuring absolute X-ray fluxes from 0.1 to 5 keV and a hard X-ray energy diagnostic for measuring X-ray intensity from 10 to 90 keV. A full aperture backscatter diagnostic was commissioned to measure scattered light

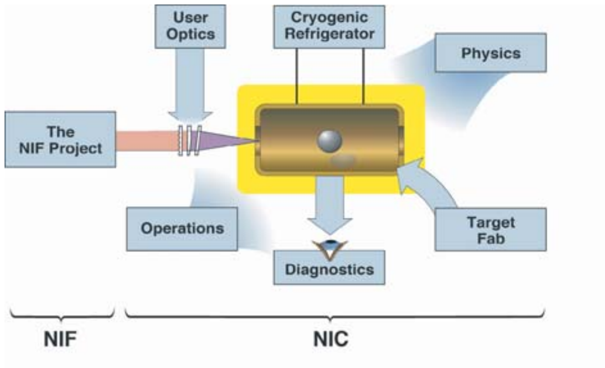

Fig. 5. (Color online) Schematic showing the various subsystems of the national ignition campaign (NIC).

from the four beams of the quad, and a near backscatter imager measured the light scattered outside of the lens.

4 National ignition campaign

An integrated plan called the National Ignition Campaign has been developed to integrate all of the activities required to begin ignition experiments after project completion. 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 $\sim$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, shown schematically in Figure 5, needed to begin ignition experiments include diagnostics, user optics, cryogenic target capability, and personnel and environmental protection systems. Diagnostic systems are needed in addition to those commissioned for the NEL experiments. These include implosion diagnostics for pre-ignition and ignition experiments [8]. The user optics include phase plates, polarization smoothing crystals, debris shields and other special optics required for experiments. Beam smoothing capability was demonstrated on NEL and this capability needs to be extended to all 192 beams [3]. The cryogenic target system is required for fielding ignition targets. The system 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 building 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.

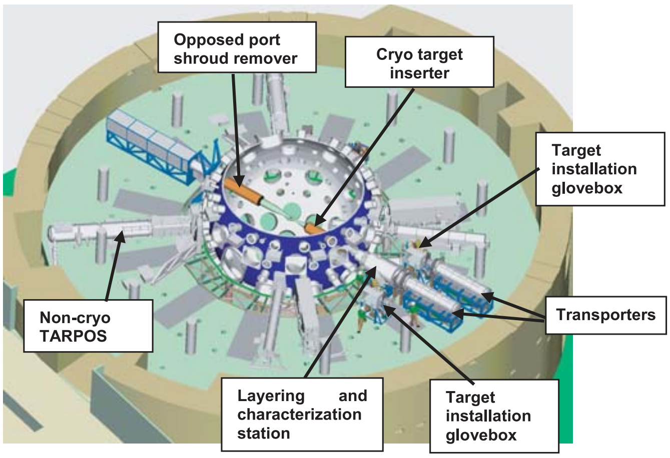

Fig. 6. (Color online) Layout of the NIF cryogenic target system in the NIF target bay.

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.

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