Ignition on the National Ignition Facility

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January 9, 2008

IFSA 2007
Kobe, Japan
September 10, 2007 through September 14, 2007
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Ignition on the National Ignition Facility

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Abstract. The National Ignition Facility (NIF), the world’s largest and most powerful laser system for inertial confinement fusion (ICF) and experiments studying high energy density (HED) science, is nearing completion at Lawrence Livermore National Laboratory (LLNL). NIF is a 192-beam Nd-glass laser facility that will produce 1.8 MJ, 500 TW of ultraviolet light, making it over fifty times more energetic than present ICF facilities. The NIF Project, begun in 1995, is over 90% complete and is scheduled for completion in 2009. The building and the entire beam path have been completed. The Project is presently installing the optics and electronics to build out the beams and is commissioning them in the laser bays. By September 2007, all of the lasers in one of the two laser bays will be commissioned with the capability of producing over 2 MJ of 1\(\omega\) (1.05 \(\mu\)m) light, making NIF the world’s first megajoule laser system. A year later, the laser system will be essentially complete. Experiments using one beam in the Precision Diagnostic System (PDS) have shown that NIF can meet all of its 3\(\omega\) light performance goals including energy, power, focusing, and shot rate and has the precision and accuracy required for ignition pulse performance. The plan is to have half of the beams commissioned to the target chamber in a symmetric geometry to begin 96-beam symmetric indirect-drive experiments. These first ICF experiments using more than 200 kJ of 3\(\omega\) light will have an order of magnitude more energy than presently available and represent the beginning of experiments preparing for ignition. This national effort for ignition experiments is coordinated through a detailed plan called the National Ignition Campaign (NIC) that includes the science, technology, and equipment such as diagnostics, cryogenic target manipulator, and user optics required for ignition experiments. The goal is to have all of the equipment operational and integrated into the facility soon after Project completion to begin ignition experiments in 2010. In addition, experiments will begin to investigate HED science for defense and basic science applications. With over 50 times more energy than present facilities and the ability to produce ignition, NIF will explore new physics regimes. Following project completion in 2009, facility time at NIF will be allocated to the broad user community using the process outlined in a formal governance plan. A NIF User Office has been established to coordinate use of NIF by the national security and other user communities.

1. Introduction
As the National Ignition Facility (NIF) nears completion at the Lawrence Livermore National Laboratory (LLNL), the long-term goal of attaining fusion ignition and burn in the laboratory is rapidly approaching [1]. NIF is a 192-beam laser system under construction for ignition experiments and, when completed in 2009, will be over fifty times as energetic as present laboratory capabilities. In single beam experiments on the Precision Diagnostic System (PDS), NIF has demonstrated that it can
meet the performance goals required for ignition. Preparation has begun for ignition experiments as a national effort organized as the National Ignition Campaign (NIC). The NIC is an integrated plan including the target physics, diagnostics, user optics, target systems, personnel and equipment protection systems, and systems support as well as NIF operations. In addition to ignition experiments, the unprecedented energy and power of NIF allows studies of matter in temperature and density regimes unobtainable by any other laboratory facility. Ignition will allow even larger-parameter space to be accessed as well as new experimental capabilities like high flux neutron experiments. Ignition also is the next step to developing inertial confinement fusion (ICF) as a future source of renewable energy.

2. NIF Project Status
The NIF Project, begun in 1995 and scheduled for completion in 2009, is funded by the National Nuclear Security Administration (NNSA) for research in ICF and high energy density science (HEDS) in support of its national security mission. NIF also will support the mission for ICF as a long-term source of renewable energy and use for basic science research. The facility contains a 192-beam Nd-glass laser system that will produce 1.8 MJ, 500 TW of 351-nm light for target experiments. The Project has gone through a number of phases including completion of design, building construction, and laser beam path installation. Presently, the laser optics and electronics are being installed and beams are being commissioned. Overall, the Project is more than 90% complete, is within budget, and is on schedule for completion in 2009.

The layout of the NIF facility consists of two laser bays, four capacitor areas, two laser switchyards, the target area, and the building core. Details of the laser and building designs can be found elsewhere [2,3,4]. The design of the NIF laser is highly modular for ease of construction and maintenance. The fundamental grouping of eight beams in the laser bay is called a bundle. Half of the beams, or 12 bundles, are located in each 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 laser components are assembled and installed in pre-aligned modules called line-replaceable units or LRUs. To complete NIF, over 5,700 LRUs need to be installed and commissioned. Presently, over 4000 of the LRUs have been installed, with all of the LRUs installed in one laser bay and over 96% installed in the other laser bay. Installation of LRUs has begun in the switchyards and target area.

![Figure 1. Near-field profiles of the commissioned beams in Laser Bays 1 and 2.](image)

After installation of LRUs, the bundles are aligned and commissioned. The modular design allows NIF to be commissioned on a single-bundle basis. All twelve bundles have been commissioned in one
of the laser bays, and three bundles have been commissioned in the other laser bay to the switchyard wall. The near-field profiles of the commissioned beams are shown in figure 1. Each bundle has produced over 150 kJ of 1ω light with a total capability of 2.5 MJ. This is more than twenty times the capability of any previous laser system. During the next year and half, the rest of the bundles will be commissioned in the laser bays, and the beam path will be commissioned to target chamber center for beginning experiments by 2009.

3. PDS Experiments
In addition to NIF being the most energetic and powerful laser for ICF research, it is also the most precise optical system. Ignition experiments have stringent requirements for laser energy, power, stability, pointing, and beam conditioning. A series of experiments have been performed in the PDS to understand NIF beamline performance [4,5]. PDS has a number of diagnostics to characterize the full aperture beam in both the near field and the far field for all three wavelengths. An example from a recent set of experiments in PDS is shown in figure 2. The goal of these experiments was to demonstrate NIF performance for a 1.8-MJ ignition pulse with beam smoothing. Figure 2a shows the 3ω ignition pulse shape having a dynamic range of over 100:1. Figure 2b and 2c show the near-field and far-field beam profile, respectively. The far-field profile is shaped using a continuous phase plate (CPP) designed for a 1.8-MJ ignition target. Figure 2d shows the bandwidth of the beam for smoothing by spectral dispersion. Effects of the bandwidth can be seen in figure 2c by the blurring of the speckle pattern. In summary, these experiments demonstrated that NIF can meet the ignition design requirements for energy, power, pulse shaping, and beam smoothing simultaneously.

![Figure 2](image-url)

Figure 2. NIC 1.8-MJ ignition point design, energy, power, pulse shape and smoothing were achieved simultaneously.
4. National Ignition Campaign

Ignition experiments are planned to begin in 2010, only eighteen months after the end of the Project. To expedite beginning of experiments, the NIC has already begun to manage all of the activities required for ignition experiments. This includes the hardware required as well as the supporting science for ignition. NIC is a combined national effort by General Atomics, the Laboratory for Laser Energetics at the University of Rochester, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratory.

The initial ignition experiments are planned to use ~1 MJ of laser energy consistent with the laser capability at the end of the Project, with experiments continuing to ramp up to the full energy of 1.8 MJ. The present point design for the initial experiments is shown in figure 3 [6,7]. The design uses 1.3 MJ of laser energy in a 15-ns shaped pulse with a peak radiation temperature of 285 eV. The target consists of a Be capsule in a hohlraum made of a uranium:gold composite. Designs for plastic (CH) and high-density carbon capsules have also been developed. The hohlraum is filled with a low-density helium and hydrogen mixture for beam propagation and to reduce plasma filling. Early experiments are planned using 96 beams in scaled targets to study beam propagation and laser plasma interaction (LPI) in order to optimize target irradiation parameters [8]. Preliminary experiments are planned using 192 beams to optimize the x-ray symmetry on the capsule, shock timing, and the capsule mass ablation before beginning the ignition experiments.

NIC provides all of the hardware including targets, diagnostics, user optics and facility modifications for performing the ignition experiments. This includes all of the off-line supporting capability as well as hardware installed in the facility. Examples are ignition targets that consist of a complex set of components requiring precise assembly to sub-micron tolerances and capsules with nanometer roughness surface finish [9,10]. An assembled prototype ignition target is shown in figure 4. The target has an Al cooling sleeve covering the high Z hohlraums, and the ring structures are for controlling the cooling to produce uniform cryogenic DT layers. NIC provides the infrastructure for manufacturing the targets and for cooling and fielding targets at NIF.

![Figure 3. NIF engineering prototype target.](image1)

![Figure 4. Schematic of the cryogenic ignition target showing the 48 “quads” of laser beams entering the hohlraum from above and below. There are 4 individual laser beams within each quad.](image2)
Target design and experiments on OMEGA and elsewhere are presently being done to better ensure success for the ignition experiments. For example, OMEGA experiments are developing scaling relations for LPI in long scalelength plasmas similar to conditions in NIF targets [11]. Other experiments study the effects of microstructure in beryllium and high-density carbon on shock propagation in capsule ablators [12]. Target design efforts continue to optimize the ignition target design and to study diagnostic signatures in simulated experiments. One result of these studies is understanding the importance of Advanced Radiographic Capability (ARC) to take high-energy x-ray radiographs of the imploding core for ignition experiments [13]. Examples of simulated images are shown in figure 5. These are a series of images of an imploding capsule with an imposed asymmetry on the x-ray drive flux. Images are taken using 50-keV or greater energy x-ray sources to penetrate the capsule and for reduced background signal. The x-ray source is produced using petawatt picosecond laser beams. The plan is to convert up to four NIF beams to short pulse, injecting them near the midplane of the target chamber. Each NIF beam will be split into two petawatt beams allowing up to eight radiography frames to be recorded on each shot.

![Multiple ARC Compton Radiographs (same gray scale at all times)](image)

Figure 5. Examples of simulated images from multiple ARC radiographs.

5. NIF-ignition and beyond
After the initial ignition experiments in 2010, NIF will continue ignition research with increasing energy and additional diagnostics as it transitions to a national user facility. The goal will be to optimize ignition targets for using ignition and DT burn as a new experimental capability. Optimized targets allow for potentially adding higher Z dopants to the capsule and fuel for studying their material properties at these extreme conditions and their effect on the burning DT plasma. Neutron flux densities of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in burning plasmas can be a unique platform for nuclear physics studies. The feasibility of alternative ignition designs such as using $2\omega$ light and fast ignition may be investigated.

A NIF User Office has been established to coordinate use of NIF by the national security and other user communities. Following project completion in 2009, facility time at NIF will be allocated via procedures outlined in a formal facility governance plan. By 2012, NIF will complete full-energy commissioning of all beams will be completed to support of a broad range of user experiments. In general, NIF and ignition at NIF will be the gateway to new avenues in scientific research and applications.
In summary, the NIF project is on schedule for completion in 2009 with the remaining activities being primarily the completion of LRU installation, utilities, and the control system. Thirteen of the twenty-four bundles have been commissioned to the switchyard wall, and hardware is being installed to transport the beams to target chamber center. PDS experiments have demonstrated that NIF will meet performance requirements for ignition point design experiments. The NIC is already preparing the facility for ignition experiments in 2010 with full user operations planned by 2012. Future experiments on NIF offer the opportunity to perform world-class science on a facility with unique capabilities.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

[10] Wilkens H et al. 2008 Recent success in fabrication of depleted uranium and cocktail hohlraums for the National Ignition Facility *Proceedings from the Fifth International Conference on Inertial Fusion Sciences and Applications* to be published
[12] Diol L et al. 2008 Benchmarking pF3D vs OMEGA experiments Proceeding from the Fifth International Conference on Inertial Fusion Sciences and Applications to be published
[13] Landen O et al. 2008 Experimental studies of ICF indirect-drive Be and high density candidate ablators *Proceedings from the Fifth International Conference on Inertial Fusion Sciences and Applications* to be published