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NIF: A Path to Fusion Energy

E. Moses

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Disclaimer

The National Ignition Facility (NIF): A path to Fusion Energy*[1]

Edward I. Moses
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550
moses1@llnl.gov

Abstract

Fusion energy has long been considered a promising, clean, nearly inexhaustible source of energy. Power production by fusion micro-explosions of inertial confinement fusion (ICF) targets has been a long-term research goal since the invention of the first laser in 1960. The National Ignition Facility (NIF) is poised to take the next important step in the journey by beginning experiments researching ICF ignition. Ignition on NIF will be the culmination of over thirty years of ICF research on high-powered laser systems such as the Nova laser at Lawrence Livermore National Laboratory (LLNL) and the OMEGA laser at the University of Rochester, as well as smaller systems around the world. NIF is a 192-beam Nd-glass laser facility at LLNL that is more than 90% complete. The first cluster of 48 beams is operational in the laser bay, the second cluster is now being commissioned, and the beam path to the target chamber is being installed. The Project will be completed in 2009, and ignition experiments will start in 2010. When completed, NIF will produce up to 1.8 MJ of 0.35-μm light in highly shaped pulses required for ignition. It will have beam stability and control to higher precision than any other laser fusion facility. Experiments using one of the beams of NIF have demonstrated that NIF can meet its beam performance goals. The National Ignition Campaign (NIC) has been established to manage the ignition effort on NIF. NIC has all of the research and development required to execute the ignition plan and to develop NIF into a fully operational facility. NIF will explore the ignition space, including direct drive, 2ω ignition, and fast ignition, to optimize target efficiency for developing fusion as an energy source. In addition to efficient target performance, fusion energy requires significant advances in high-repetition-rate lasers and fusion reactor technology. The Mercury laser at LLNL is a high-repetition-rate Nd-glass laser for fusion energy driver development. Mercury uses state-of-the-art technology such as ceramic laser slabs and light diode pumping for improved efficiency and thermal management. Progress in NIF, NIC, Mercury, and the path forward for fusion energy will be presented.

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I. Introduction

Fusion energy can potentially provide a nearly unlimited source of clean sustainable power. Fusion of two light nuclei, normally deuterium and tritium, only occurs in plasmas at elevated temperatures where the particles have sufficient kinetic energy to overcome the Coulomb barrier. Materials cannot survive at these elevated temperatures, thus leading to innovative isolation and containment schemes. Two approaches to containment are magnetic fusion energy in which the fusion plasma is confined by magnetic fields [1] and inertial confinement fusion (ICF) [2] in which the fusion plasma is produced in the core of an imploded spherical capsule. Inertial fusion reactors use high-repetition-rate drivers such as lasers or heavy ion particle beams to produce ICF capsule implosions several times per second. [3] System studies show that reactors will generally operate at repetition rates of one to twenty hertz, targets need a gain of about one hundred, and the drivers need to be about ten percent efficient for commercial power applications. All of these present major challenges for realizing inertial fusion energy (IFE).

The National Ignition Facility (NIF) is preparing to make a significant step forward on one of these challenges. [4] NIF will be the first facility that produces ignition and gain of ICF capsules in the laboratory. [5] Ignition and gain in this context is the production of more fusion energy than the energy used to irradiate the target. NIF will be completed in 2009, and ignition experiments are planned to begin in 2010 as part of the National Ignition Campaign (NIC) that includes all of the required science and technology. These experiments will mark a significant step forward for realizing fusion energy. After the initial ignition experiments, NIF will continue ignition research, optimizing capsule performance as well as exploring alternate approaches such as fast ignitor [6] or direct drive [7] for uses of ignition, including fusion energy. In a complementary effort, LLNL is developing high-repetition-rate Nd lasers as fusion energy drivers. These efforts will position LLNL as a leader to fusion energy development.

II. National Ignition Facility

The National Ignition Facility (NIF) is a 192-beam laser facility that will produce 1.8 MJ and 500 TW of ultraviolet light for performing ignition target experiments. NIF is the most recent Nd-glass laser constructed at LLNL for ICF research. High-powered lasers have been shown to produce extreme states of matter having high energy density (HED) for studying hydrodynamics, radiative properties and material science at unique laboratory conditions. [8] These studies can provide insight into many astrophysical and planetary phenomena and nuclear explosions. NIF is poised to produce fusion ignition in the laboratory for the first time based on experiments on the Nova and OMEGA lasers. [9] At more than fifty times more energetic than these present facilities, NIF will be the world’s preeminent facility for performing experiments for ICF and HED science.

The lasers for NIF are based on flashlamp-pumped 1.05-μm Nd-doped glass architecture that has been used in ICF laser facilities at LLNL for more than 30 years. [4] At NIF, the main laser systems are installed in two laser bays. After being amplified to full energy, the beams are transported through two switchyards to the target area. At the target chamber, the beams are frequency converted to 0.35-μm light and focused on the target in the target chamber. An overview of the facility overlaid with a model of the beam transport system is shown in Figure 1.

Figure 1. Overview of the NIF facility with an overlay of the laser beampath.

The building is approximately 70,000 m^2. Each beam has a clear aperture of about 40 × 40 cm and the facility contains about 8,000 large optics. NIF is by far the largest and most complex optical system ever built.

The NIF began as a project in 1995 and is scheduled for completion in 2009. The project is currently over 90% complete. The building and nearly all of the beam path, shown in Figure 1, have been completed. To complete the project, optical systems and electronics are being installed in the beam paths, and the beams are then commissioned as operational to the target. The optics and electronics are installed as line replaceable units (LRUs) designed for ease of maintenance and replacement. Presently, over 80% of the LRUs have been installed in the laser bays, with installation in one of the laser bays nearly completed. The transport optics are being installed in the switchyard and target area to complete building out the laser beam path.

Beam commissioning qualifies the hardware for operation after installation. In the laser bay, the beams are grouped in sets of 8 beams called a bundle, and each laser bay has two clusters of six bundles each. Each bundle is split into two sets of four beams, or quads, as they are transported to the target area and focused on target. The schedule for commissioning the beams is shown in Figure 2. Presently, nine bundles, or 75% of the beams, in one laser bay have been commissioned. These lasers have demonstrated that they can produce 1.4 MJ of 1.05-μm light, making NIF the only megajoule-class laser system in the world. Commissioning of the rest of the beams in that laser bay will be completed by September 2007, with the beams in the other laser bay scheduled to be commissioned in 2008. Beginning in September 2007, beams will be commissioned through frequency conversion and final focusing in the target chamber. The plan is to have half of the beams commissioned by June 2008 to the target chamber in a symmetric geometry to begin indirect drive target experiments with 96 beams.

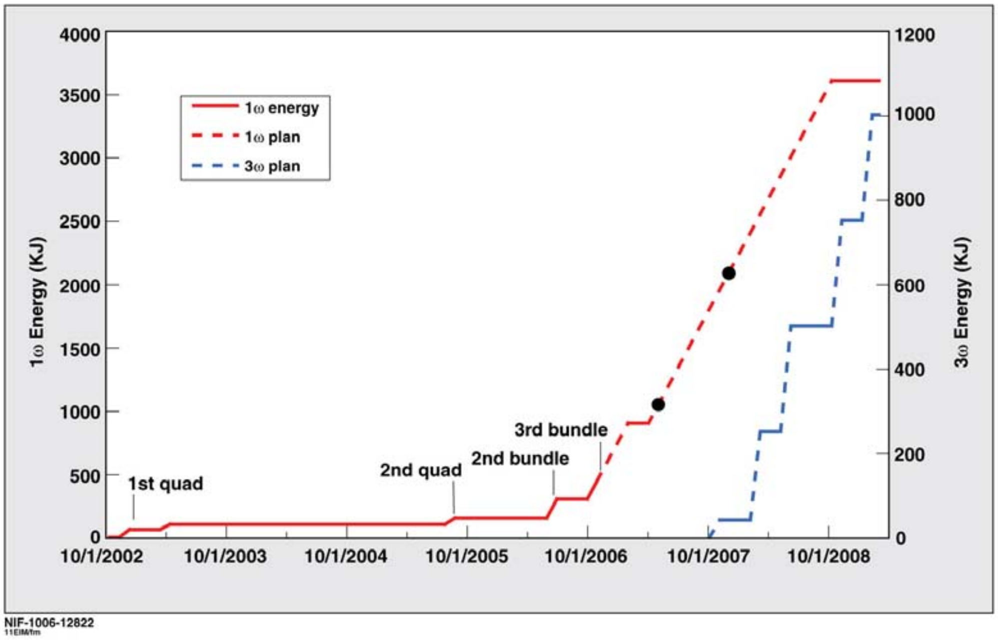

Figure 2. Schedule for commissioning NIF beams.

Experiments measuring beam performance have been done on one beam in the Precision Diagnostic System (PDS). [10] The PDS can fully characterize a beam at full energy in the near field and far field at 1.05-, 0.53-, and 0.35-μm wavelengths. Beam performance has been characterized over the entire operating range of NIF from 0.2 to 23 ns. Beam energy of 11.4 kJ of 0.53-μm light and 10.4 kJ of 0.35-μm light have been produced using 5-ns pulses. These are the highest energy levels ever achieved by a single laser beam. All of the functional requirements and primary criteria for a NIF beam line have been demonstrated. Ignition pulses with the equivalent of 1.8 MJ having contrast greater than 100 to one and desired beam smoothing have been produced. An example is shown in Figure 3. The complex pulse shape meets the power balance requirement, and the far-field focal spot is shown using an ignition-designed phase plate. These experiments provide confidence that NIF will be able to meet its performance required for ignition experiments.

III. National Ignition Campaign (NIC)

NIF will begin ignition experiments soon after the project is completed with a goal of performing the first experiment in 2010. A significant amount of equipment and technology is required beyond that provided by the project. In addition, understanding the target science and laser performance needs to be refined. A detailed plan called the National Ignition Campaign (NIC) has been developed. The plan includes the target physics and the equipment such as diagnostics, cryogenic target manipulator and user optics required for the ignition experiment. Effort in all of these areas has begun in preparation for the 2010 ignition experiments. The NIC is organized as a project with a defined set of scope, schedule and budget. It is a national effort with participation from Los Alamos National Laboratory, University of Rochester, Sandia National Laboratories, and General Atomics, in addition to LLNL. The plan is to begin preliminary experiments in 2008 when 96 beams are available in a symmetric configuration. Experiments with 192 beams will begin after project completion. These experiments will test the energetics, drive symmetry and ablator performance and optimize the target performance. Ignition experiments will begin after this optimization.

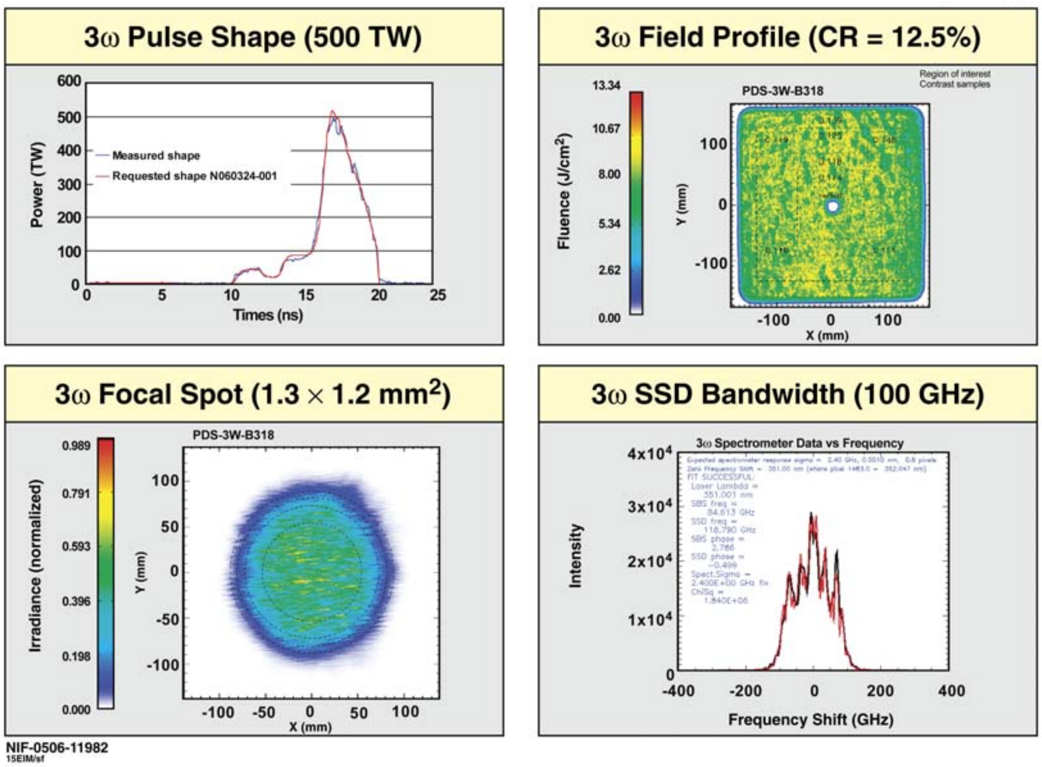

Figure 3. Example of ignition pulse measured in PDS experiments. Shown clockwise is a measured pulse for a 1.8-MJ ignition experiment compared with requested shape, a near-field image of the beam, the spectrum of the smoothing by spectral dispersion (SSD) bandwidth, and the 3ω far-field focal spot.

The NIC plan is organized around the ignition target point design. [11] A schematic is shown in Figure 4. 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 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. The filling and layer production is done at the target chamber just prior to the shot.

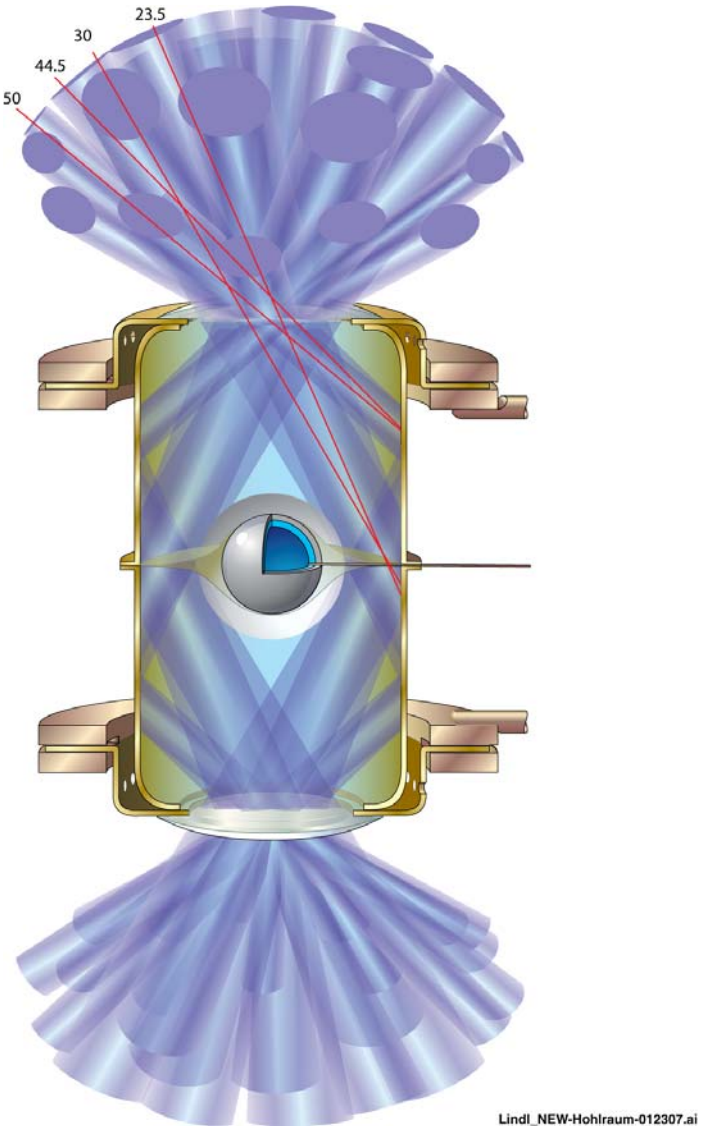

Figure 4. Example of an ignition hohlraum design.

The point design puts more stringent tolerances on target fabrication than previously required. Emphasis has been on developing the processes and characterization techniques to reliably produce ignition targets meeting specifications. Individual components have been fabricated and assembled into an engineering prototype. An example is shown in Figure 5. The Be capsule has a 2-mm outer diameter with a fill tube attached and meets surface finish specifications. In the future, manufacturing processes will be put in place to produce the components and assemble them to meet the NIF shot plan.

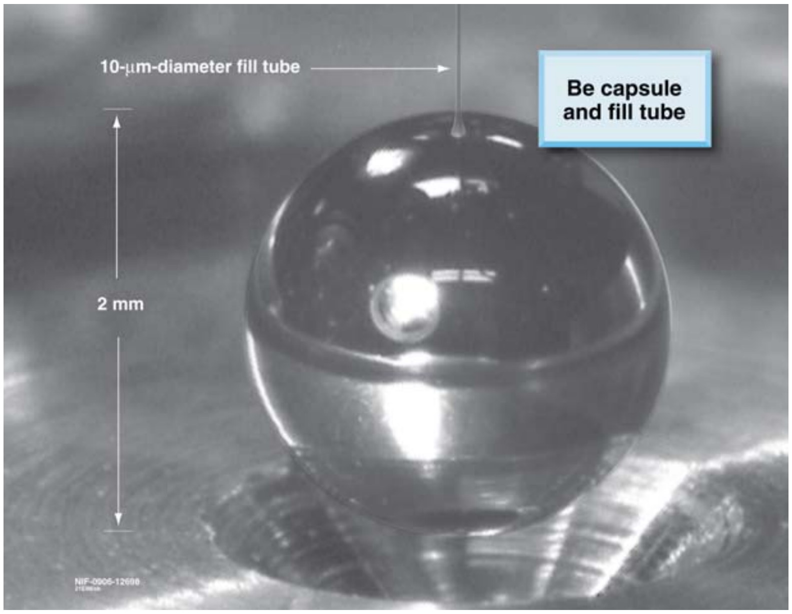

Figure 5. A prototype Be ignition capsule. The capsule has a 2-mm outer diameter with a 10-µm-diameter fill tube attached.

In the target area, diagnostics, cryogenic target fielding equipment, user optics, and radiation protection systems will be installed preparing for ignition experiments. Many of the diagnostics for the initial experiments have been installed and operated on four-beam experiments. [12] An example of a diagnostic manipulator for inserting x-ray streak cameras and framing cameras is shown in Figure 6. NIF diagnostics can be large, but they also have the precision for micron resolution with sub-nanosecond time resolution.

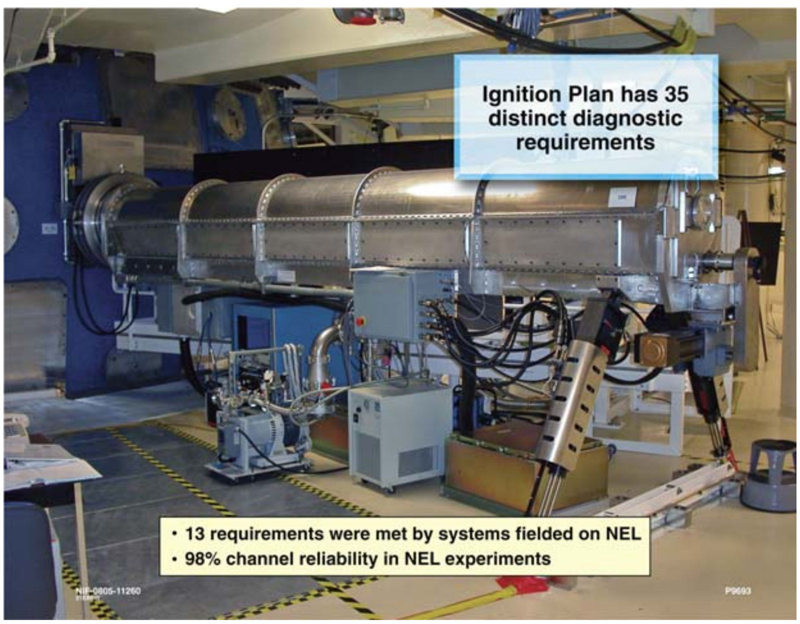

Figure 6. A Diagnostic Instrument Manipulator installed on the NIF target chamber. The manipulator is used to field x-ray streak cameras, x-ray framing cameras, and other diagnostics.

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 one picosecond have been shown to produce high-energy electrons and protons. The particles can be used to probe material directly or to produce efficient high-energy x-ray sources. [13] One quad of NIF beams will be converted to short-pulse operation for ARC. A schematic is shown in Figure 7. Mirrors will redirect one quad of NIF beams in the target area to a compressor vessel. Chirped pulse amplification [14] 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.

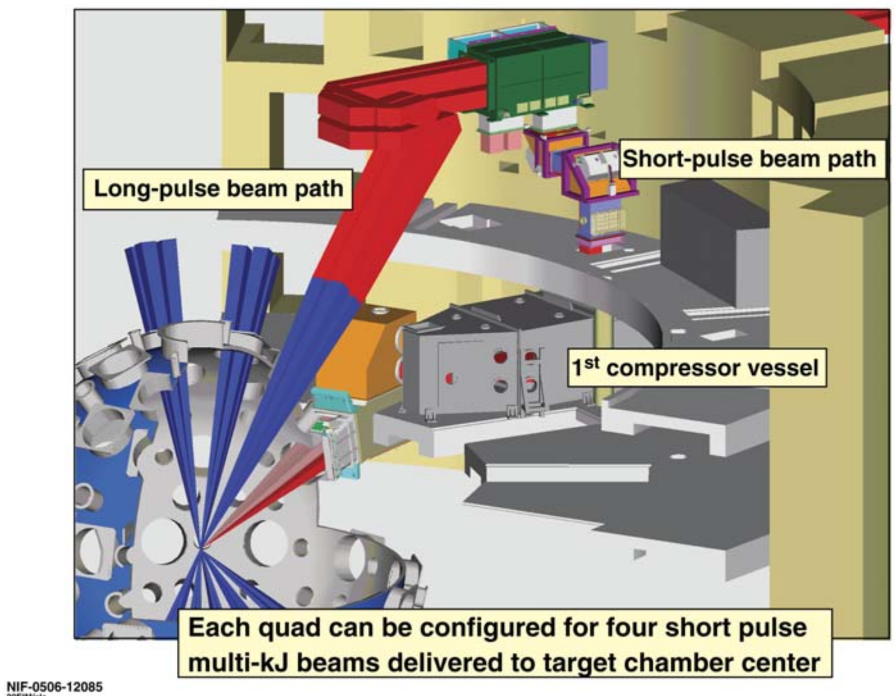

Figure 7. Model showing the plan for fielding an ARC short-pulse beam on NIF. Mirrors in the NIF beam path will redirect four NIF beams to a grating compressor vessel and transport them to the near mid-plane of the NIF target.

IV. Beyond NIC

Beyond the initial ignition experiments NIF offers the potential to become the world's premier facility in HED science. With more than fifty times the energy and ten times the power of present facilities, NIF can produce states of matter not previously available in the laboratory. NIF can accelerate more material for hydrodynamics experiments and heat more mass for radiation transport studies than present facilities. After ignition, the conditions in the hot dense core will be unique in the laboratory. The neutron yield environment will provide high flux densities for novel materials and nuclear physics studies. NIF will develop into a user facility by 2012 to broaden its scientific base and maximize its impact in the scientific community.

Optimizing target gain and investigating alternative ignition schemes is important for defense applications and basic science as well as for fusion energy. Some alternative approaches are direct drive [7] and ignition using 2ω light [15]. Direct drive offers the potential for higher gain, but reconfiguring the facility for direct drive is a major effort. Initial direct-drive research can be done using the polar direct-drive concept [16]. Ignition using 2ω light is interesting because NIF has the capability to produce about 50% more energy of 2ω light compared to 3ω light. Modeling indicates gains in excess of 100 MJ are possible [15]. Initial experiments can test the laser-plasma interaction issues with modest modification of the optics in a few beams. If this is promising, the laser can be converted to 2ω operation by changing some of the final optics LRUs.

One alternative ignition concept that has gained international interest is fast ignition [6]. In this concept, the fuel is assembled with a long-pulse driver, and electrons or protons produced by a short-pulsed laser heat and ignite the fuel. The concept is attractive because, computationally, the targets have higher gain at lower energy. The geometry requirements are also more relaxed, making this approach more amenable to reactor geometries. Initially, NIF can use the ARC beam to perform heating studies on dense fuel. NIF will be the only facility that can perform the heating studies at full scale and at full density. In the future, more NIF beams can be converted to short pulse for a full-scale fast ignition demonstration.

V. High Average Power Lasers

For inertial fusion energy, efficient high-repetition-rate drivers are required. LLNL has a continuing program in developing solid-state lasers for high-repetition-rate applications. The Mercury project is developing laser technology at sub-scale energy and apertures scalable to IFE drivers [17]. The laser shown in Figure 8 uses diode-pumped, gas-cooled, solid-state slabs for efficient operation. The laser uses eight diode arrays that produce 640 kW at 900 nm with 45% efficiency. They pump slabs of ytterbium doped strontium flourapatite (Yb:S-FAP) in a four-pass angular multiplexing and relay imaging geometry. The laser has been operated above 0.5 kW at 10 Hz for more than seven hours. Frequency conversion experiments using yttrium calcium oxyborate has produced 0.23 kW of 523-nm light.

In summary, the NIF project is nearing completion. The laser optics and electronics are being installed in the beam lines, and the beam lines are being commissioned. Nearly all of the equipment is installed in the laser bays, and nine of the 24 bundles have been commissioned. Hardware for transporting the beams to the target chamber is beginning to be installed. Half of the beams are planned for completion to the target chamber in a symmetric geometry in a little more than a year from now. Scientists will begin to prepare for ignition experiments by 2010. Equipment and technology required for ignition experiments have already begun to be developed. With its high energy and power, NIF will have unique laboratory capability for world class science. Ignition will provide unique laboratory capability for new areas of research. Optimizing ignition for higher gains will benefit a number of fields including inertial fusion energy. Along with other enabling technology such as high-repetition-rate lasers, NIF will be the gateway to the future for fusion energy.

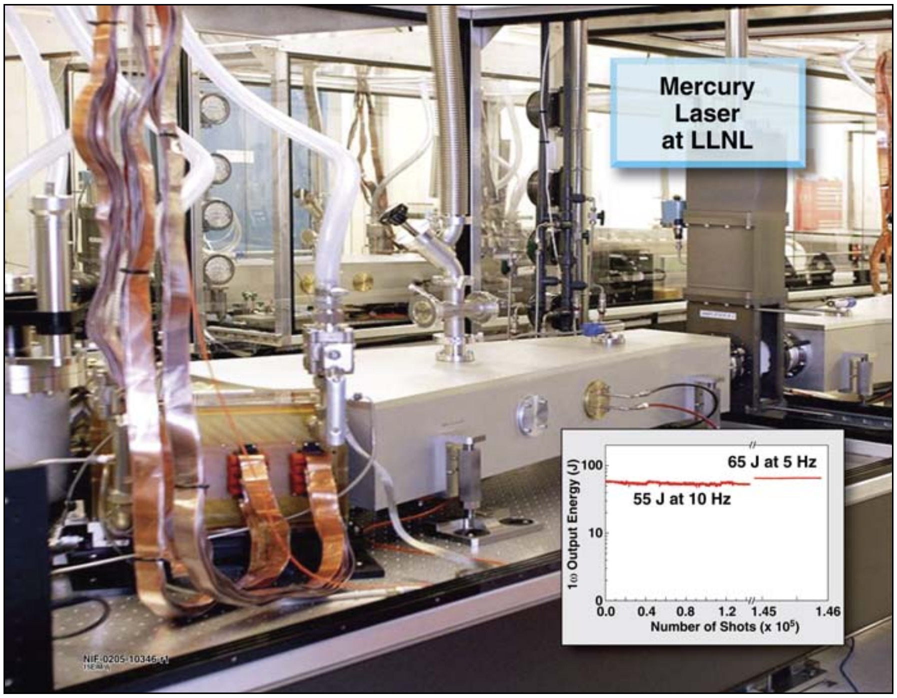

Figure 8. Mercury Laser at LLNL.

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