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Advances in Inertial Confinement Fusion at the National Ignition Facility (NIF)

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Abstract

The 192-beam National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in Livermore, CA, is now operational and conducting experiments. NIF, the flagship facility of the U.S. Inertial Confinement Fusion (ICF) Program, will achieve high-energy-density conditions never previously obtained in the laboratory—temperatures over 100 million K, densities of 1,000 g/cm^3, and pressures exceeding 100 billion atmospheres. Such conditions exist naturally only in the interiors of the stars and during thermonuclear burn. Demonstration of ignition and thermonuclear burn in the laboratory is a major NIF goal. To date, the NIF laser has demonstrated all pulse shape, beam quality, energy, and other specifications required to meet the ignition challenge. On March 10, 2009, the NIF laser delivered 1.1 MJ of ultraviolet laser energy to target chamber center, approximately 30 times more energy than any previous facility. The ignition program at NIF is the National Ignition Campaign (NIC), a national collaboration for ignition experimentation with participation from General Atomics, LLNL, Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), and the University of Rochester Laboratory for Laser Energetics (LLE). The achievement of ignition at NIF will demonstrate the scientific feasibility of ICF and focus worldwide attention on fusion as a viable energy option. A particular energy concept under

investigation is the LIFE (Laser Inertial Fusion Energy) scheme. The LIFE engine is inherently safe, minimizes proliferation concerns associated with the nuclear fuel cycle, and can provide a sustainable carbon-free energy generation solution in the 21st century. This talk will describe NIF and its potential as a user facility and an experimental platform for high-energy-density science, NIC, and the LIFE approach for clean, sustainable energy.

Key Words: National Ignition Facility, National Ignition Campaign, Inertial Fusion Energy, Inertial Confinement Fusion, High Energy Density Science, and Laser Inertial Fusion Energy.

1.0 The National Ignition Facility

The National Ignition Facility (NIF) is the U.S. Department of Energy (DOE) center for studying inertial confinement fusion (ICF) and high-energy-density (HED) science. NIF is the largest scientific project ever successfully completed by the DOE. NIF will be used to execute the science experiments necessary to ensure a safe, secure, and reliable strategic stockpile without underground testing, promote fundamental HED science and play a key role in the pursuit of clean fusion energy. The 192-beam football-stadium-sized NIF [1] is now operational at Lawrence Livermore National Laboratory (LLNL). A total 192-beam energy of 1.1 MJ at the third-harmonic (3ω) wavelength of 351 nm was demonstrated on March 10. 2009, over 30 times more energy than previously produced in any ICF laser system. In the next year, the energy out of NIF will approximately double to 1.8 MJ. Currently, NIF is conducting experiments to commission the laser drive, hohlraum, and fusion capsule and to develop the infrastructure needed to begin ignition experiments in FY 2010.

NIF's 192 beams are directed into a 10-meter-diameter, high-vacuum target chamber containing a ~1-cm-long cylindrical hohlraum target. The NIF target chamber contains entry ports for all the laser beams and over 100 ports for diagnostic instrumentation and target insertion. Sophisticated diagnostic instruments such as x-ray and neutron spectrometers, microscopes, and streak cameras can be mounted around the equator and at the poles of the target chamber. Laser interaction with the hohlraum will produce a radiation field with temperatures of approximately 300 eV. The resulting hohlraum conditions will provide the necessary environment to explore a wide range of HED science experiments, including laboratory-scale thermonuclear ignition and burn.

NIF is the most complex optical instrument ever constructed, with over 38,000 large and small optics and 60,000 points controlled by two million lines of software. The NIF 3ω energy specification of 1.8 MJ requires an order of magnitude increase in operating fluence over previous laser systems. Developing high-quality optics that can withstand the NIF environment has been a major research and development focus at LLNL. A systematic and robust approach for optics finishing improvement and optics maintenance has been developed to support the demanding requirements of ignition.

2.0 The National Ignition Campaign

2.1 Overview

The NIC has two major goals. The first is to execute layered target ignition experiments starting in FY2010. The second is to demonstrate ignition and provide a reliable and repeatable ignition platform at the completion of the NIC by the end of FY2012 [2]. The NIC will also develop the infrastructure and the processes required to operate NIF as a national user facility. The scope for NIC includes the ignition physics program, as well as the development of the diagnostics, targets, target cryogenic system, phase plates and other optics, and the personnel and environmental protection activities required to execute ignition experiments.

NIF ignition experiments will use a centimeter-scale hohlraum containing a millimeter-scale thin-walled plastic, nano-crystalline diamond or beryllium capsule filled with a mix of deuterium and tritium. Compression of the capsule by the ~280-eV radiation field in the ignition hohlraum drives the DT fuel to conditions under which it will ignite and burn, liberating more energy than is required to initiate the fusion reaction [3]. These conditions have never been created in a laboratory.

Initial experiments aimed at understanding the energetics of the NIF ignition hohlraum and capsule-tuning experiments began in the summer of 2009. Cryogenic ignition targets capable of yields in the 10–20 MJ range will be tested in late 2010–2012. Experiments at other laser facilities such as OMEGA at LLE, Z at SNL, Trident at LANL and Jupiter at

LLNL have been and continue to be used to develop and demonstrate tuning, shock timing, laser ablation and the diagnostics techniques needed to achieve ignition.

The NIC ignition campaign uses the “indirect-drive” configuration, where the laser beams are directed into the ends of a cylinder coated with gold or other high-Z material that is mounted vertically within the target chamber. Laser irradiation of the cylinder produces a radiation field inside that implodes the DT fuel capsule. As shown in Figure 1, the laser beams are deployed in multiple cones so as to control the time-dependent symmetry of the radiation drive to greater than 99%. The high degree of symmetry of the NIF implosion coupled with a precisely tailored target design and corresponding laser pulse shape results in the high, peak fuel ρR required for alpha heating of the fuel and capsule ignition.

Initial ignition experiments will begin in late 2010 at 192-beam ultraviolet laser energy of approximately 1.2 MJ. This energy level is consistent with the laser-commissioning plan that ramps up to the planned 192-beam operating energy in 2011. The target design to be used is shown in Figure 1. Two capsule ablator materials (Be with Cu dopant and CH with Ge dopant) are currently under consideration. Both capsules are filled with sufficient DT gas via a 10-mm-diameter SiO_2 fill tube to produce a solid DT layer on the inner wall of 0.3 mg/cm^3 density at 18.3 degrees Kelvin. The Cu and Ge dopant density, typically present at less than 1% concentration, is varied through the ablator. Maintaining these two design options reduces risk and allows the choice of a target that is optimally configured to the precise laser and target fabrication capabilities available.

2.2 Ignition Target Developments and Fabrication

Ignition target development and fabrication has achieved considerable progress since the start of NIF construction in 1997; indeed, ignition target development and fabrication is a research and development program in its own right. NIC ignition targets must meet demanding specifications. Components must be machined to within an accuracy of 1 μm, with joints as small as 100 nm. The margin of error for target assembly is less than 8 μm. Typically, the capsule outer surface must be smooth to within 1 nm, and the thickness and corresponding opacity of the doped layers must also be carefully controlled.

A long-standing challenge for ignition target fabrication is the frozen DT fuel layer. This layer must be formed at approximately 18.5K, 1.5 K below the triple point of the DT mixture. The layer temperature must fluctuate no more than 1 mK, the roughness of the inner layer surface must be maintained at 1-μm RMS roughness or better, with spherical isotherms maintained at the layer surface via auxiliary heating [4]. These challenges have been addressed, and ignition targets meeting all specifications are now in production. Figure 2 shows an actual ignition target assembly featuring the thermo-mechanical package used to maintain the target at the required specification. The target is held at the center of the NIF target chamber via a cryostat attached to the NIF target positioner. The system also includes a characterization station capable of imaging the DT layer in three spatial dimensions within minutes.

2.3 NIC Diagnostics

The diagnostic suite for NIC is also a major focus of the NIC efforts in FY2009 and FY2010. By the end of FY2010, it is anticipated that approximately 35 diagnostics measuring x-ray, neutron, charged particle, optical, and other emissions will be installed [5]. Examples of diagnostics include full-aperture backscatter measurement capability for use in hohlraum energetics experiments, velocity interferometers for shock timing, absolutely calibrated soft x-ray spectrometers to measure the radiation drive, gamma-ray detectors to measure the burn history of the ignition target, and magnetic recoil spectrometers for neutron spectroscopy. Diagnostics development is a national and international effort. Further information regarding NIF diagnostics is available at the NIF website.[*]

2.4 NIC Experimental Plan

The NIC experimental plan consists of four phases. The initial phase will culminate with the first experiments with layered cryogenic targets in late FY2010. The subsequent three phases will refine the target and laser parameters and investigate the physics of the ignition regime, with a goal of providing a reliable and repeatable ignition platform by the conclusion of NIC at the end of FY2012.

Based on many years of experimentation and simulations, it is believed that the NIC experimental campaign requires precise tuning of 14 laser and 3 target parameters to achieve ignition conditions. The tuning of these parameters corresponds to tailoring the

[*] NIF web site, https://lasers.llnl.gov/programs/nic/diagnostics.php

capsule adiabat, velocity, symmetry, and degree of hydrodynamic instability. These 17 parameters are tuned in four steps. In the first, or "drive" step, the empty hohlraum is tuned to produce the necessary radiation drive on the capsule as a function of time. In the second, "tuning" step, a variety of non-cryogenic and cryogenic deuterium-filled capsules are used to adjust the hohlraum symmetry and shock timing so as to produce the compressed fuel central "hot spot" required for ignition. The third step consists of layered cryogenic implosions conducted with a mixture of tritium, hydrogen, and deuterium (THD). The reduced yield from these THD targets allows the full diagnostic suite to be employed and the presence of the required temperature and fuel areal density to be verified. The final step is DT ignition implosions with expected gains of 10-20. Initial DT ignition experiments will be conducted with E_{laser} ~1.2 MJ. Laser energies of 1.8 MJ should be available for subsequent experiments.

To prepare for executing the ignition experimental series, the NIC team conducted a "simulated campaign" to exercise the experimental team and develop the ability of NIC scientists to quickly tune the ignition target to the required conditions. Over a several month period, the simulated campaigns demonstrated synthetic ignition by successfully adjusting laser and target parameters to compensate for detunings specified by the Red Team and reduced from days to hours the time required to examine a data set and experimentally tune the laser and target.

First Cryogenic Hohlraum Experiments: Early in September 2009, NIF conducted its first cryogenic hohlraum experiments. In the first shot, NIF fired 192 beams that delivered 508-kJ 3ω energy into a cryogenic hohlraum, imploding a helium-filled plastic capsule and marking the start of the hohlraum energetics and tuning campaigns. The helium/hydrogen-filled hohlraum was cooled to about 19 Kelvin. All target diagnostics acquired data, and the capsule implosion was recorded using a gated microchannel-plate detector.

The second 192-beam cryogenic hohlraum shot was fired at 494 kJ 3ω. Again, all target diagnostics acquired data and the capsule implosion was recorded (see Figure 3). The two concentric "cones" of laser beams entering each end of the hohlraum may have a small difference in wavelength. On this shot, the wavelength of the outer cone of beams was adjusted to considerably improve the symmetry of the imploded capsule at the time of peak compression. With the controls in place to fire low-level deuterium shots for symmetry tests and neutron diagnostic commissioning, the third cryogenic hohlraum shot fired 192 beams at 486 kJ 3ω into a 20-Kelvin hohlraum with a 10% deuterium-filled capsule, generating NIF's first neutrons. Neutron yield was successfully diagnosed by the first Neutron Time of Flight diagnostic constructed by LLE. This shot also successfully tuned the symmetry of the imploded capsule by further reducing the outer cone wavelength, demonstrating the effectiveness of the inter-cone energy transfer mechanism.

In the fourth cryogenic hohlraum shot, NIF fired 192 beams at 568 kJ 3ω into a 20-Kelvin hohlraum with another 10% deuterium-filled capsule. This shot maintained the same frequency separation between the cones, while increasing laser energy and power by 20 percent to test higher drive. This implosion had improved symmetry and increased D-D neutron yield, measured for the first time using an indium activation diagnostic.

3.0 NIF Multi-Mission Experimental Program

While ignition experiments will be the primary focus through FY2012, NIF will execute other experiments in support of its primary missions. NIF will provide national and international researchers unparalleled opportunities to explore fundamental astrophysics, planetary physics, hydrodynamics, nonlinear optical physics, and materials science. Examples of experiments planned for NIF include investigation of the physics of planetary interiors, the formation of elements with $Z>26$ via Type II supernovae explosions, excited state nuclear reactions, and ultra-intense laser-matter interactions. NIF will ultimately be a major international center for fundamental HED science.

4.0 Ignition and Inertial Fusion Energy

Achievement of ignition will motivate more detailed consideration of ICF as an option for clean, sustainable energy. The achievement of ignition at NIF will demonstrate the scientific feasibility of ICF and will likely focus the world’s attention on the possibility of an ICF energy option. New capabilities in high-repetition-rate, high-efficiency, solid-state lasers indicate that 1000-MW Inertial Fusion Energy (IFE) power plant could be attainable in the next decade.

Both pure fusion and fusion-fission hybrid schemes for energy production are under consideration. A key feature of the Laser Inertial Fusion Energy (LIFE) concept is the use of ICF-generated neutrons to be used as a pure fusion device or one to induce fission reactions in a cooling blanket that could extract virtually all its energy content and decrease long-lived actinide waste. This approach could close the nuclear fuel cycle without the need for chemical separation and reprocessing, while generating thousands of megawatts of carbon-free electricity. Such a scheme could also incinerate more than 99% of spent reactor fuel and extend the service life of deep geologic repositories by up to a factor of 20 [6]. The LIFE concept appears particularly attractive given its closed fuel cycle and the possibility of burning spent nuclear fuel, excess weapons plutonium, and highly enriched uranium.

5.0 Conclusion

NIF is now operational, conducting experiments and acquiring data to prepare for the cryogenic layered-target ignition experiments planned to begin in late FY2010. After many years of R&D, all systems needed to demonstrate ignition at NIF are scheduled to be in place, including the NIF laser, a detailed point design target with adequate margin, the capability to produce high-quality targets meeting all specifications, and advanced diagnostics to allow precision tuning of laser and capsule parameters to ignition conditions. NIF ignition will allow access to the burning plasma regime in the laboratory for the first time, enabling important stockpile stewardship studies and demonstrating the scientific feasibility of ICF. More generally, NIF's ability to create extraordinarily high pressures, temperatures, and densities—as much as 1 trillion atmospheres pressure, 100 million degrees K temperature, and 1,000 g/cm^3 density—will enable major fundamental advances in support of DOE's national security, energy, and fundamental science missions. NIF and other major facilities worldwide will launch a new era in HED science, and the demonstration of ignition may one day lead to an inexhaustible clean power supply for humanity.

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Figure Captions:

Figure 1. Schematic of NIF ignition target.

Figure 2. NIF fusion target thermo-mechanical package.

Figure 3. Capsule implosion recorded during 192-beam cryogenic hohlraum shot fired at 494 kJ 3ω.

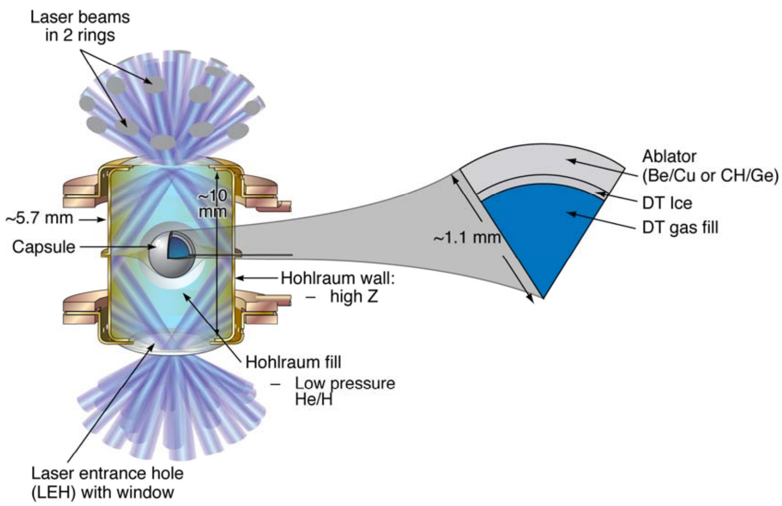

Figure 1. - 2/3 pp

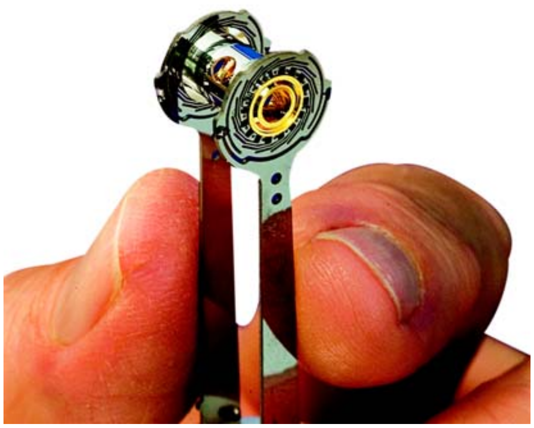

Figure 2. - 1/2 pp

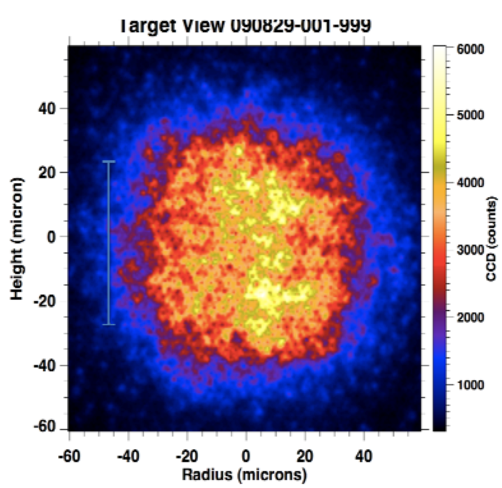

Figure 3. - 1/2 pp