

The National Ignition Facility: Transition to a User Facility¹

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Abstract. The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) has been operational since March 2009 and has been transitioning to a user facility supporting ignition science, high energy density science (HEDS), national security applications, and fundamental science. The facility has achieved its design goal of 1.8 MJ and 500 TW of 3ω light on target, and has performed target experiments with 1.9 MJ at peak powers of 410 TW. The facility is on track to perform over 200 target shots this year in support of all of its user communities. The facility has nearly 60 diagnostic systems operational and has shown flexibility in laser pulse shape and performance to meet the requirements of its multiple users. Progress continues on its goal of demonstrating thermonuclear burn in the laboratory. It has performed over 40 indirect-drive experiments with cryogenic-layered capsules. New platforms are being developed for HEDS and fundamental science. Equation-of-state and material strength experiments have been done on a number of materials with pressures of over 50 MBar obtained in diamond, conditions never previously encountered in the laboratory and similar to those found in planetary interiors. Experiments are also in progress investigating radiation transport, hydrodynamic instabilities, and direct drive implosions. NIF continues to develop as an experimental facility. Advanced Radiographic Capability (ARC) is now being installed on NIF for producing high-energy radiographs of the imploded cores of ignition targets and for short pulse laser-plasma interaction experiments. One NIF beam is planned for conversion to two picosecond beams in 2014. Other new diagnostics such as x-ray Thomson scattering, low energy neutron spectrometer, and multi-layer reflecting x-ray optics are also planned. Incremental improvements in laser performance such as improved optics damage performance, beam balance, and back reflection control are being pursued.

1. Introduction

The National Ignition Facility (NIF), located at Lawrence Livermore National Laboratory (LLNL) in Livermore, California, is the world's largest and most energetic laser facility for research in inertial confinement fusion (ICF) and high energy density science (HEDS) in support of its national security

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mission [1]. NIF also performs experiments for fundamental science and other national security missions as well as ICF as a potential source of renewable energy. NIF is the first laser system designed to achieve ignition and thermonuclear burn of deuterium-tritium-filled ICF capsules. NIF has developed an unprecedented experimental capability, much of it developed as part of the National Ignition Campaign (NIC) [2]. NIC, started in 2005 and completed in 2012, was a comprehensive program for developing NIF as an ignition platform and transitioning NIF to a user facility. NIF is now a fully operational facility with users performing experiments for multiple missions

Significant progress has been made since the last conference in developing NIF capabilities and in the science being performed at NIF. NIF laser performance has been demonstrated above its design goal of 1.8 MJ and 500 TW. NIF operability has improved increasing its shot rate each year and broadening the number of experimental platforms. NIF continues to expand its capabilities with an increasing number of diagnostics and facility enhancements. NIF has transitioned from NIC into a user facility and has broadened its HEDS program both for national security and fundamental science. In addition, progress continues on reaching its ICF goal of ignition in the laboratory. Recent experiments have measured neutron yields greater than 10^{15} neutrons and are greater than 50% of predictions from simulations. Analysis indicates that a significant fraction of the yield is from self-heating by alpha deposition.

This paper summarizes some of these advances since the last conference and provides an overview of capabilities that have been developed. Progress made in HEDS and toward ignition is reviewed. In depth analysis can be found in other papers in this conference and publications elsewhere.

2. NIF Facility

NIF is the most recent laser facility constructed at LLNL for ICF research. NIF consists of a 192 beam Nd-glass laser system installed in two laser bays, two switchyards to redirect the beams for indirect drive target irradiation, a target area designed for ignition experiments producing 20 MJ of fusion yield, and a control room for operations. NIF is designed to produce 1.8 MJ and 500 TW of 3ω light on target in a highly shaped pulse for indirect-drive fusion ignition experiments [3]. The NIF facility includes diagnostics systems, cryogenic target fielding capabilities, integrated control systems, and contamination controls systems required for performing integrated ignition experiments.

Since the last conference NIF has demonstrated that it meets all of its performance requirements and has transitioned to an operational facility. Since commissioning, NIF has steadily increased its power and energy as shown in Figure 1. At the time of Project completion in 2009, NIF was operating at 500 kJ and 200 TW of 3ω light. At the time of the last conference, NIF had attained ~ 1.3 MJ and 400 TW of 3ω light. In 2012, NIF demonstrated that it could achieve its design goals of 1.8 MJ and 500 TW of 3ω light on target in an ignition shaped pulse. Laser performance at these energy and power levels was demonstrated in the course of normal operation [4]. This improvement in performance and operations at the design point shown in Figure 1 is attributable to several advances in technology. Much of the increase has been enabled by improving optics quality and their resistance to

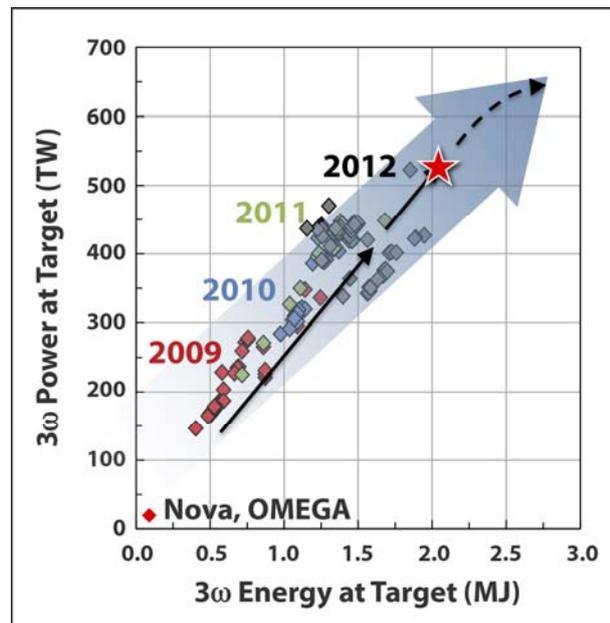


Figure 1. Progress in power and energy on NIF continues increasing to the NIF design point

damage. NIF is designed to operate at fluences of 8 J/cm^2 for 3ω light. When NIF was designed, damage levels for optics were $\sim 2 \text{ J/cm}^2$. Through years of research, new processing techniques have been developed for improving NIF optics quality allowing NIF to operate at its design energy [5]. A system has been developed to block damage sites when damage does occur to prevent the damage site from increasing in size [6]. Techniques have also been developed to repair damage sites allowing optics to be recycled reducing overall operating costs [7]. Along with an active damage inspection program, other improvements in performance include controlling amplitude modulation in the laser pulse to reduce peak fluence and increase of the clear aperture of the beams to propagate more energy for a given fluence [8]. Additional improvements have been identified that could potentially allow NIF to operate at energy above 2 MJ.

The NIF facility has also greatly improved its experimental capabilities from Project completion and even since the last conference two years ago. For example, Figure 2 shows the number of target diagnostics available for experiments as a function of years. The number of diagnostics has increased by around a factor of five since Project completion and approximately 20 diagnostics have been added since the last conference. All of the NIC partners: LLNL, Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), University of Rochester Laboratory for Laser Energetics (UR-LLE), General Atomics as well as a number of other collaborators including Lawrence Berkeley National Laboratory, the Massachusetts Institute of Technology (MIT), the U.K. Atomic Weapons Establishment (AWE) in England, and the French Atomic Energy Commission (CEA) in France have contributed to this effort. Some of the new capability recently added include the South Pole Bang Time (SPBT) diagnostic to measure the x-ray bang time of the capsule [9], additional neutron time-of-

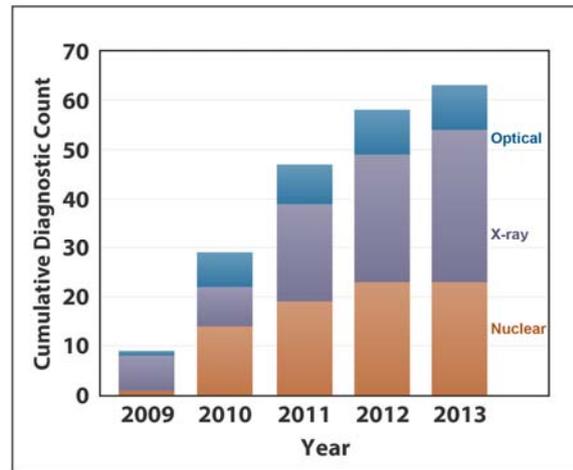


Figure 2. Target diagnostics on NIF continue to increase each year

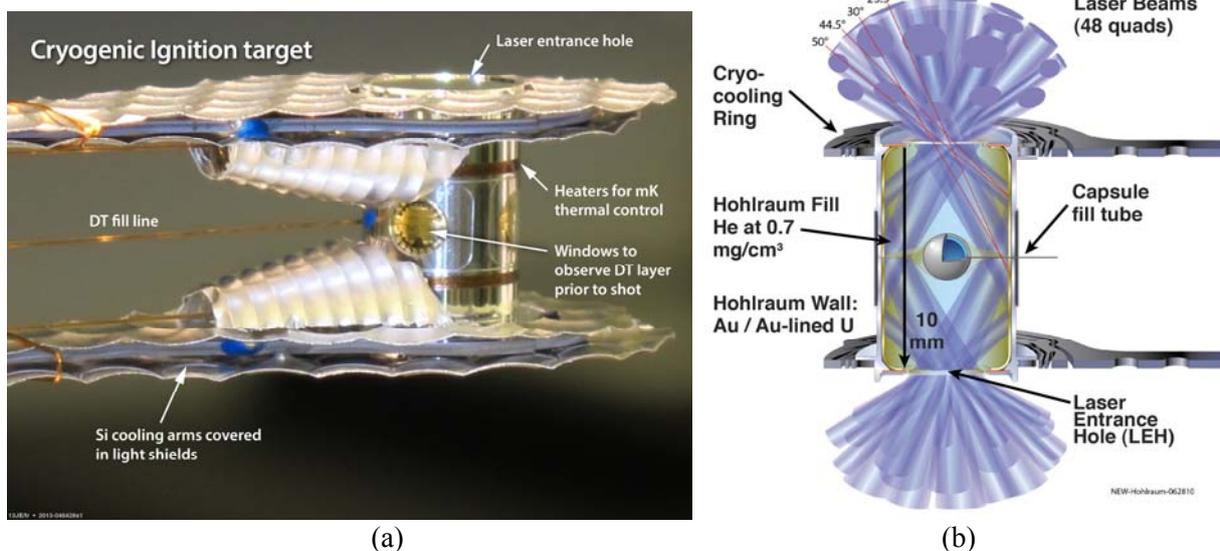


Figure 3. A cryogenic hohlraum for ignition experiments (a) and a schematic of the target showing the irradiation geometry (b).



Figure 4. The large compressor vessel that will contain the full aperture gratings for compressing the ARC pulse to 30 ps.

flight (nToF) detectors to measure drift velocity of the implosion [10], an array of flanged-mounted neutron activation detectors (fNADS) to measure isotropy of the neutron emission [11], and Radioactive Gas Spectrometer (RAGS) fielded by SNL and LLNL to measure gaseous activation products [12]. More than 20 diagnostics may be fielded on a single experiment.

Advances also continue in target fabrication. Cryogenic targets are one of the most complex targets fielded at any facility. An example is shown in Figure 3 along with a schematic of an ignition target. The target contains apparatus for cooling, temperature monitoring, and thermal control needed for producing cryogenic deuterium-tritium (DT) layers inside of the capsule in the hohlraum. The target

contains viewing windows for measuring the layer quality. The layer is characterized by x-ray radiography along three orthogonal axes in the hohlraum. Ignition quality layers can now be grown routinely. New capsule characterization methods have recently been developed that measure the surface of each capsule before being mounted in the target. Surface finish, manufacturing defects, and contamination particles can be detected and tract to correlate with target experiments data.

Laser capabilities are also expanding. Recently, the capability to delay beams up to 100 ns for producing x-ray backlighters was installed for radiography of hydrodynamic instability experiments. NIF is now installing the capability for producing short-pulse beams for high-energy x-ray radiography. ARC, advanced radiographic capability is being installed on four NIF beams, or a quad [13]. Each NIF beam is divided into two ARC beams that propagate pulses independently to target. ARC uses chirped pulse amplification to amplify and temporally compress the beam to produce a 1.5 kJ pulse of 1 μ m energy in a 30 ps pulse in each ARC beam. Beam path hardware is presently being installed in the large compressor chamber that holds the large gratings for pulse compression shown in Figure 4. The chirped pulse oscillator has been installed and beams are being propagated through the main laser chain. The first four of the eight beams are planned to be operational in 2015.

3. NIF User facility

Since it was established as a construction project in 1995, NIF has been envisioned as a national user facility. Built in support of the Stockpile Stewardship Program (SSP) most of the experiments support SSP either for Inertial Confinement Fusion (ICF) research or for High Energy Density Stewardship Science (HEDSS). NIF also performs experiments supporting other national security applications and fundamental science. As NIF transitions to a user facility, management structures are being developed to serve the broad user community. Shot proposals from the different user groups are being peer reviewed for technical excellence and reviewed by the facility for execution. A NIF User group has been formed and has held two meetings for developing proposals for fundamental science. The first round of fundamental science proposals has been reviewed and ten proposals with sixteen principal investigators have been chosen. Experiments for some of the proposals have begun.

One of the fundamental science experiments is to measure the equation of state of carbon up to a Gigabar along its Hugoniot [14]. The experiment is a collaboration of scientists from University of California Berkeley, SLAC Accelerator National Laboratory, AWE, and LLNL. The experiment uses a hohlraum platform developed for ICF ignition experiments with the ICF capsule being replaced with a solid CH sphere. X-rays from the hohlraum ablate the outside of the sphere producing a spherically convergent shock in the CH sphere. The velocity of the shock front is measured using x-ray radiography as shown in Figure 5. The shock front is tracked by the increased absorption of the x-ray backlighter as the density of the material increases due to the shock front. When the shock converges at the center an x-ray flash is observed. By fitting the trajectory, the equation of state (EOS) of CH can be extracted. For this shot the pressure is derived to be 720 Mbars at the center of convergence.

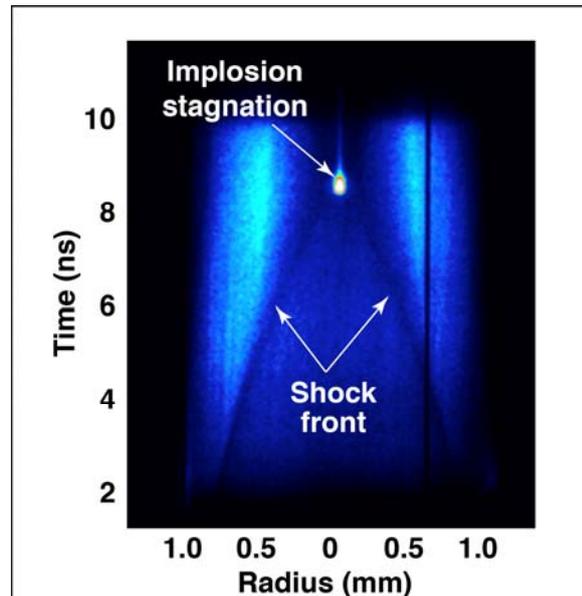


Figure 5. A streaked radiograph of a CH sphere show the radiation-driven shock front converging to produce a stagnation flash. Analysis shows that pressures of 720 Mbars were attained.

There is much synergy among the different user communities for developing experimental capabilities. For example, many of the platforms developed for ICF are used for HEDSS and fundamental science experiments. The same platform is used for studying EOS as part of the HEDSS Program and for fundamental science experiments. Of course diagnostics are used across all of the different users and much of the target fabrication development is applicable to many different research areas. An example of the cross connection of different research areas is illustrated in Figure 6. Solid Radiochemistry Collectors were being developed by ICF to measure activation products produced in

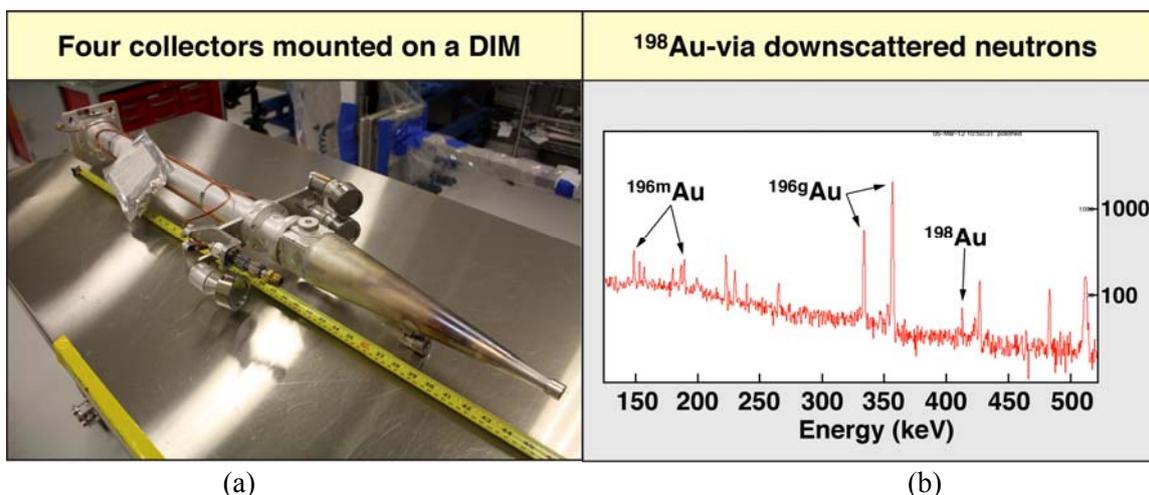


Figure 6. Activated Au from the hohlraum has been collected on NIF. (a) Collectors are mounted on the x-ray imaging diagnostic. (b) An activated Au spectrum is shown. The relative abundance of activated products depends on the flux of low energy neutrons.

ICF ignition experiments. The collectors are discs of solid material placed near the target as shown in Figure 6a. After the shot the collectors are taken to a nuclear counting facility to measure the activated products. In testing the collectors, activated Au from the hohlraum debris is found as shown in Figure 6b. The ratio of Au activation products depends on the flux of low energy neutrons produced by down scattering the 14 MeV DT neutrons in the high-density shell material indicating that excitation of excited nuclear states of Au are involved. This data is presently being analyzed to extract cross sections of excited state nuclei. NIF is the only facility in the world that can produce neutron flux densities allowing studying excited nuclear states.

4. NIF Progress on Ignition

Achieving ignition and burn continues to be a major effort on NIF. Achieving ignition requires assembling the fuel to a hot spot areal density of $\sim 0.3 \text{ g/cm}^2$ at temperatures of $\sim 5\text{-}10 \text{ keV}$. Implosion velocities of $3\text{-}4 \times 10^7 \text{ cm/s}$ and fuel pressures of $\sim 200 \text{ Gigabars}$ are required in a low mix implosion [15,16]. The implosion is controlled by a combination of laser pulse shaping and target geometry that optimizes the fuel adiabat, implosion velocity, implosion shape, and hydrodynamic mix.

Initial experiments were done as part of the NIC. NIC experiments used indirect drive and a CH capsule with a laser pulse shape that produced an implosion having a low adiabat, close to Fermi degeneracy [17]. During NIC, there were 38 cryogenic layered ignition experiments in addition to a large number of experiments for measuring shock timing, shape, shell velocity, and hohlraum symmetry. A summary of progress in NIC is shown as the blue points in Figure 7 [18]. Initial experiments, begun in September 2010, used Ge-doped capsules and performed orders of magnitude below predictions from integrated simulations. After a number of experiments for optimizing shock timing and implosion symmetry and changing to Si-doped capsules that were found to be more efficient, capsule yields approaching 10^{15} neutrons were obtained. These yields were still nearly an order of magnitude below the simulation predictions. Experiments then tried to improve performance by going to higher compression and higher velocity. Instead of improving performance, these experiments did not perform as well. In analyzing these results, it appeared that low-mode implosion asymmetry and hydrodynamic mix were degrading performance more than predicted by the simulations.

Experiments since the end of NIC have focused on understanding the implosion physics for improving target performance. New experimental platforms have been developed to investigate detailed physics of the implosion. One new platform is two-dimensional radiography of the imploding shell. These radiographs have shown that the implosions on NIC had a significant P4 inflight asymmetry. This asymmetry is shown in Figure 8 measured when the implosion is about 20% of its initial radius. More symmetric implosion can be produced if the hohlraum length is increased by 0.7-1.0 mm from the standard NIC length of 9.4 mm [19]. Symmetry on NIC was adjusted by

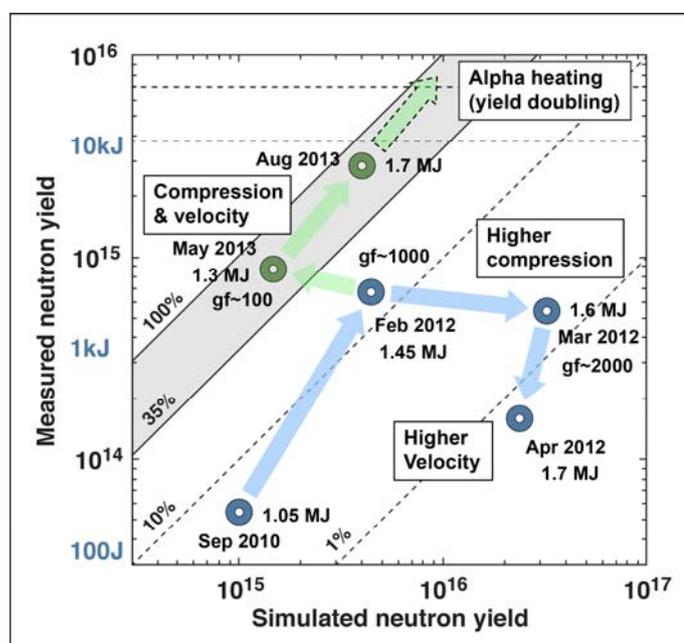


Figure 7. Progress toward ignition is shown as measured neutron yield versus yield predicted by simulations. The blue points show the progress during NIC with low adiabat implosions. The green points show the progress made recently with high adiabat implosions.

measuring the asymmetry of the hot spot at peak compression. These images only measured the shape of the hot central fuel. The surrounding cold fuel can have significant asymmetries reducing confinement and fuel areal density. These in-flight radiography experiments also showed that the support structure, or tents, that hold the capsule in place provided a seed for hydrodynamic instabilities. Effort is under way to reduce the mass of the tents to reduce the seed for hydrodynamic instabilities.

Another example of experiments studying the underlying physics of ignition implosions is a campaign to measure the growth rate of hydrodynamic instabilities. In these experiments, single mode perturbations are imprinted onto an ignition capsule as shown in Figure 9 [20]. The capsule is mounted onto a reentrant cone and placed in the center of a hohlraum. The reentrant cone allows access for x-ray radiography of the imploding shell. The hohlraum is driven

with a typical ignition pulse. Eight beams are used to produce a 5 keV backlighter source. Examples of x-ray radiographs taken when the shell has imploded to about half of its initial radius is shown in Figure 9. Single mode periods are clearly visible in the radiographs. Intensity modulations are analyzed to extract growth factors for comparison with simulations. Preliminary results indicate that the growth factors in CH capsules using the NIC ignition pulse are large as predicted by simulations. Also, these experiments show that implosions using pulses that produce a higher adiabat implosion are more stable with respect to mix as predicted by simulations.

Recent experiments have begun exploring the performance of higher adiabat implosions. These experiments use Si-doped CH capsules similar to those used for NIC experiments and are driven with laser pulses that have a “high foot”, a higher initial pulse, compared to NIC experiments [17]. The initial pulse produces a shock that sets the initial adiabat of the cryogenic fuel. The higher adiabat implosion calculates to be more stable to ablation front hydrodynamic instabilities and have been confirmed in experiments as discussed above. The higher adiabat implosions are less efficient and calculate not to obtain as high of gain as NIC targets. Initial experiments show good performance and are summarized as the green data in Figure 7. Implosions have produced yields of greater than 10^{15} neutrons and are greater than 50% of predictions from simulations. These experiments indicate that a significant fraction of the yield is from self-heating by alpha deposition, a first for ICF implosions. Experiments are continuing extending the performance to higher intensity and higher velocity to understand the limits due to hydrodynamic instabilities and mix.

Experiments are also planned to explore alternative ablaters. High-density carbon (HDC) and Be ablaters calculate to produce more efficient implosions than CH ablaters. HDC, or diamond capsules have been fabricated [21] and initial experiments have begun and have obtained high implosion velocities and good performance in gas-filled capsules [22]. Plans for cryogenic capsule implosions are being developed. Designs for Be ignition experiments are also being developed [23] and experiments are planned to begin next year.

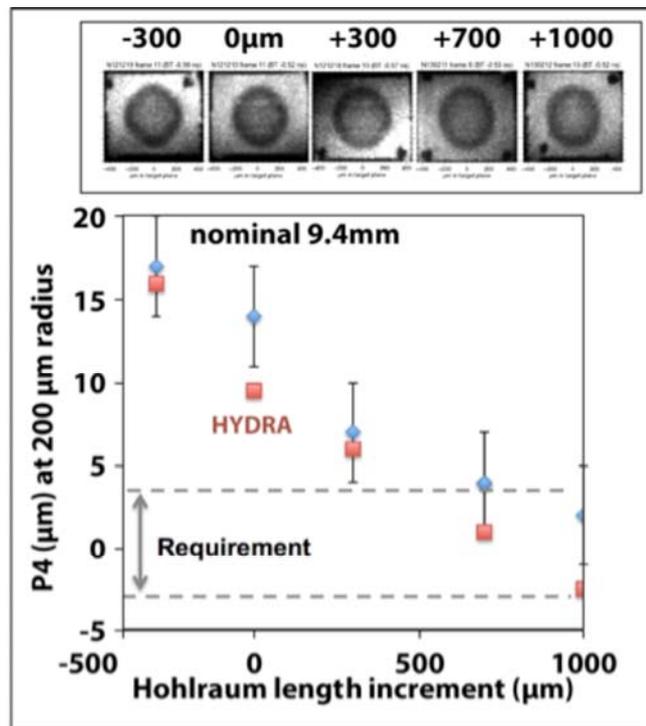


Figure 8. X-ray radiography measures the shape of the shell in flight.

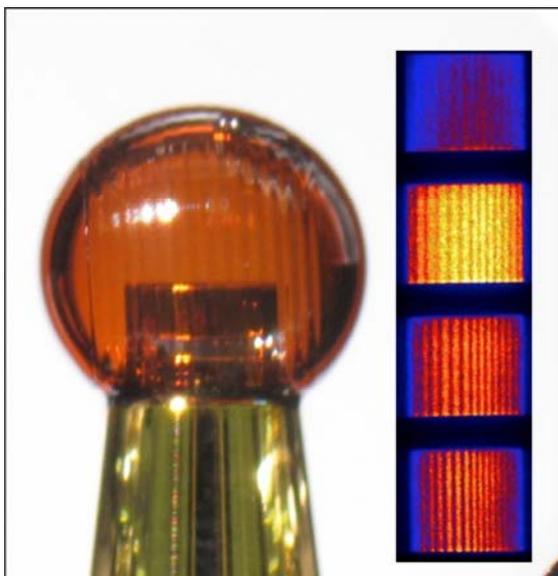


Figure 9. Capsules with imprinted periodic perturbations are used to study hydrodynamic instabilities.

5. Summary

NIF is a fully operational facility supporting experiments for ICF and HEDS as well as fundamental science and other national security missions. It has demonstrated that it meets design goals of 1.8 MJ and 500 TW of 3ω light on target in a shaped ignition pulse. It can perform at design levels as part of routine operations. This high level of performance is a result of a number of advances for maintaining optics performance operating at design fluences. NIF has developed a vast array of experimental capabilities. It has commissioned over 60 different diagnostic systems. It routinely fields cryogenic layered targets for ignition experiments and has developed a number of other experimental platforms for use by its diverse user community. It continues to develop capability and plans to have four ARC

beams operational in 2015 for short pulse high-energy x-ray backlighting capability.

NIF is transitioning into a national user facility for supporting its users in SSP, fundamental science, and other national security missions. NIF is developing a peer review process for ensuring that it produces world-class science. NIF has completed its first set of reviews of fundamental science proposals; ten experiments (with sixteen principal investigators) have been chosen. Experiments have begun on some of the proposals and they are already producing unique results.

Progress continues toward attaining ignition. At the completion of NIC, neutron yield was nearly an order of magnitude below predictions from integrated simulations. Low-mode implosion symmetry and hydrodynamic mix appeared to be degrading performance more than predicted by the simulations. Experiments since the end of NIC have focused on understanding the implosion physics for improving target performance. These include measurement of the inflight symmetry of the imploding capsule and quantitative measure of the mix growth factors. Implosion platforms have been developed that are more stable to mix although they do not calculate to perform as well as the NIC design. These have performed close to predictions from simulations in experiments to date. In recent experiments, a significant fraction of the yield appears to be from self-heating by alpha deposition, a first for ICF implosions. Experiments are continuing extending the performance to higher intensity and higher velocity to understand the limits due to hydrodynamic instabilities and mix. Target designs are being developed for alternative ablaters such as HDC and Be that are potentially more efficient and experiments are planned to test these in the future.

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