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# Stockpile Stewardship and the National Ignition Facility

E. Moses

January 18, 2012

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# Stockpile Stewardship and the National Ignition Facility (U)

E. Moses[a]

Lawrence Livermore National Laboratory, Livermore, CA 94450

**Abstract.** The National Ignition Facility (NIF), the world's most energetic laser system, is operational at Lawrence Livermore National Laboratory (LLNL). Since the completion of the construction project in March 2009, NIF has completed nearly 150 target experiments for the National Ignition Campaign (NIC), High Energy Density Stewardship Science (HEDSS) in the areas of radiation transport, material dynamics at high pressure in the solid state, as well as fundamental science and other national security missions. NIF capabilities and infrastructure are in place to support all of its missions with over 50 X-ray, optical and nuclear diagnostic systems and the ability to shoot cryogenic targets and DT layered capsules. NIF is now qualified for use of tritium and other special materials as well as to perform high yield experiments and classified experiments. DT implosions with record indirect-drive neutron yield of $4.5 \times 10^{14}$ neutrons have been achieved. A series of 43 experiments were successfully executed over a 27-day period, demonstrating the ability to perform precise experiments in new regimes of interest to HEDSS. This talk will provide an update of the progress on the NIF capabilities, NIC accomplishments, as well as HEDSS and fundamental science experimental results and an update of the experimental plans for the coming year. (U).

## 1. Introduction

The National Ignition Facility (NIF), located at Lawrence Livermore National Laboratory in Livermore, California, is the world's largest and most energetic laser facility for Inertial Confinement Fusion (ICF) research. NIF is the first laser system designed to obtain ignition and thermonuclear burn of deuterium-tritium filled ICF capsules [1]. High-powered, high-energy lasers such as NIF, the OMEGA laser at the University of Rochester, and other facilities around the world can compress and heat material, producing unique states of matter and unique radiation environments in the laboratory. These conditions are of interest for High Energy Density Science (HEDS) supporting the NIF missions in national security and fundamental science [2]. Ignition on NIF will support the national security mission as well as demonstrating the viability of inertial fusion for energy production.

The NIF has been operational and conducting experiments since late in 2009. In the most recent fiscal year (October 2010–September 2011), NIF operated 24/7 and executed 286 system shots. The combination of laser, target, and diagnostic capabilities available at NIF make it an unprecedented instrument for advancement of ICF and other areas of HEDS.

A key mission driver for the Stockpile Stewardship Program (SSP) is to deliver predictive, physics-based capabilities to enable the assessment of the safety, reliability, and performance of the U.S. nuclear stockpile in an era without nuclear testing. During the operation of a thermonuclear weapon, temperatures, pressures, and densities are reached that do not occur anywhere else except in the interior of stars and in specially designed HEDSS experiments on NIF. The region of SSP interest of NIF operations as well as an example a platform used for support of HEDSS (in this case for radiation transport experiments) is shown in Fig. 1. The National Ignition Facility (NIF) gives the nuclear design laboratories in the U.S. [Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL)] and the U.K. [United Kingdom's Atomic Weapons Establishment (AWE)] access to an experimental platform that can reach the extreme temperature and density regimes previously inaccessible without the aid of a nuclear explosive. NIF has already completed several HEDS campaigns in support of SSP in radiation transport, complex hydrodynamics, and materials dynamics.

NIF experiments to demonstrate fusion ignition are part of the National Ignition Campaign (NIC). The NIC approach to ignition uses indirect drive with a cryogenic-filled capsule inside of a high-Z hohlraum [3]. Experiments have begun to study the four major control variables for ignition: symmetry, fuel adiabat, shell velocity, and mix. Initial results have demonstrated that the techniques developed can

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[a] e-mail moses1@llnl.gov

observe and control the effects of the different variables. Cryogenic layering of the DT fuel has been demonstrated and symmetric implosions have been demonstrated with 1.3- to 1.6-MJ experiments with good absorption and low fast-electron preheat.
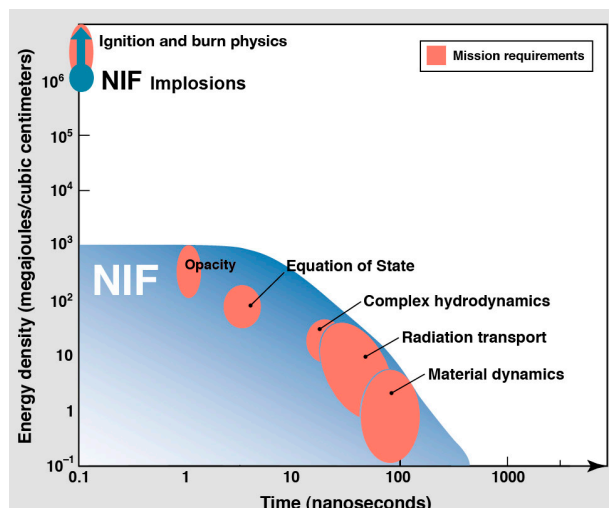


**Fig. 1.** Phase space for SSP applications of NIF and experimental configuration for radiation transport experiments.

## 2. National Ignition Facility

The NIF is a 192-beam Nd-glass laser for ignition experiments. The facility, shown in Figure 2, consists of two laser bays, a control room and the target area as well as two switchyards and four capacitors bays.
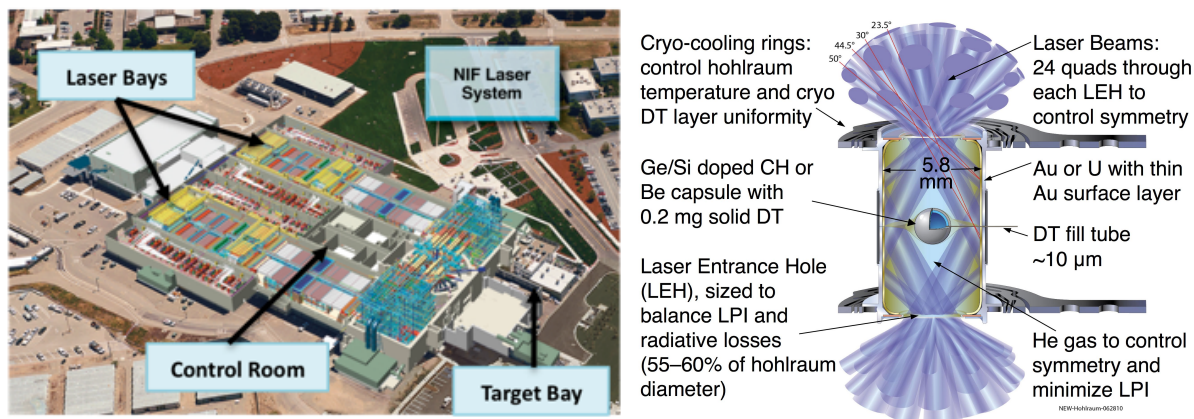


**Fig. 2.** On the left, the NIF facility with its major areas designated and a cutaway showing the beam path and on the right, the NIC indirect-drive ignition point design.

The laser is designed to deliver 1.8 MJ of frequency-converted 0.35-μm light to target with pulse lengths up to 33 ns. The beams irradiate the target in two cones from top and bottom for indirect-drive implosions of ICF capsules. Ignition physics experiments have been done with up to 1.6 MJ of laser energy on target. Laser experiments have demonstrated beam line performance for operating at 1.8 MJ [4]. The plan is to increase laser energy during 2012 to perform 192-beam experiments with 1.8 MJ and 500 TW of 0.35-μm light using optics with improved performance.

Approximately 50 optical, x-ray, gamma, neutron and charged particle diagnostics are available at NIF, with additional advanced diagnostics planned. These diagnostics are either fixed or inserted into the target chamber via Diagnostic Instrument Manipulators or "DIMs." The DIM mount is used at a variety of facilities worldwide and facilitates broad collaboration in NIF diagnostics. A number of these diagnostics have been developed to handle conditions associated with high fusion yield and NIF is now qualified for use of tritium and to conduct fusion ignition experiments with single-shot yields up to 45 MJ. The NIF diagnostic team is international and includes individuals from the academic, industrial, and national laboratories in the US and several international collaborations.

During the past year, additional hardware has been added to manage the unique conditions produced by ignition experiments. Target experiments sometimes contain beryllium and uranium. Equipment and procedures have been developed to safely handle these hazardous materials. Tritium processing and handling equipment have also been installed to manage the tritium from ignition targets. An ignition shot at full yield of 20 MJ of fusion energy produces nearly $10^{19}$ neutrons. Shielding and monitors have been installed to ensure safe operations. The facility is now qualified for full yield ignition experiments with hazardous materials.

## 3. National Ignition Campaign (NIC) and progress towards Ignition

The NIC was formed in 2005 as a comprehensive program to provide all of the capabilities for performing ignition experiments, to develop the physics basis for ignition, and to conduct the initial ignition experimental campaign. The goal of NIC program is to demonstrate a reliable and repeatable ignition platform and to develop NIF as a user facility for its multiple missions the end of FY2012. NIC is a national effort that includes General Atomics (GA), LLNL, LANL and Sandia National Laboratories (SNL), the University of Rochester Laboratory for Laser Energetics (LLE), and a number of other collaborators including Lawrence Berkeley National Laboratory, the Massachusetts Institute of Technology, the U.K. AWE, and the French Atomic Energy Commission (CEA) [5]. The capabilities for performing ignition experiments include development of the diagnostics, targets, target cryogenic system, phase plates and other optics, and personnel and environmental protection equipment. Experiments on OMEGA, NIF and other facilities provide the technical basis for ignition experiments. Initial ignition campaign began in 2010 with the first cryogenic implosion experiments.

The first experiments to demonstrate ignition and gain use 0.35-μm laser light with a central hot spot ignition (HSI) target in an indirect-drive configuration (see Figure 2). HSI relies on simultaneous compression and ignition of the spherical DT-filled capsule in an implosion. In the indirect-drive configuration, the capsule is placed inside a cylindrical cavity of a high-Z metal (a hohlraum), and the implosion pressure is provided by focusing the laser energy onto the interior walls of the hohlraum and converting it to x-rays. The small (few % of the total DT fuel mass), high-temperature central part of the imploded fuel provides the "spark," which ignites the cold, high-density portion of the fuel. The scientific basis for HIS targets has been intensively developed over the last 40 years, and ignition and gains equal to or great than 1(fusion yield/laser input energy) with HSI targets is expected by 2012. The NIF ignition experiments use a centimeter-scale Au/U hohlraums containing a 2-mm-diameter, thin-walled plastic or beryllium capsule filled with a mixture of deuterium and tritium (see Figure 2).

NIF scientists have demonstrated that NIF can meet the ignition energy performance goals simultaneously with the requirements for temporal pulse shaping, focal-spot conditioning, and peak power of 500 TW for representative ignition pulses. The goal of the ignition campaign is to demonstrate a repeatable ignition platform with indirect-drive HSI targets by the end of 2012.

The NIC is proceeding in four phases. In the first "drive" phase, the empty hohlraum was tuned to produce the necessary radiation drive on the capsule as a function of time. In the second "capsule tuning" phase, non-cryogenic and cryogenic capsules are used to adjust the hohlraum symmetry, shock timing, velocity and mass ablated to produce the conditions in the imploding capsule required for ignition when a cryogenic fuel layer is incorporated. The third phase uses layered cryogenic implosions with a mixture of T, H, and D in a ratio 74:24:2 to make the THD capsules hydrodynamic analogues to DT implosions. The

low D content leaves them unaffected by thermonuclear energy production, yet their radiation and hydrodynamic transport mirror that of DT implosions up to the point at which DT implosions become perturbed by alpha particle production and deposition. The reduced yields allow the full diagnostic suite to be used and the required pre-burn temperature and fuel areal density ($\rho r$) to be verified. The fourth and final phase is ignition with cryogenic-layered DT implosions.

The first two phases measured drive temperatures of 300 eV with backscatter of less than 15%, and radiation symmetry control was demonstrated to compressed cores to <10% [6]. In these hohlraums, beam propagation in underdense plasma and underdense plasma production from hohlraum blow off was more important than in previous Nova and OMEGA experiments and have brought new understanding to hohlraum performance. Energy transfer between crossing laser beams is an important effect and can be controlled and used to modify the hohlraum environment. New models have been developed for the radiating plasma and are being used to refine the ignition target design [7, 8, 9, 10, 11].

The third phase began in September 2010, and THD capsule implosion results with 1.3 MJ at 0.35 µm demonstrated the hohlraum temperature of 300 eV and symmetric x-ray environment required for high convergence.
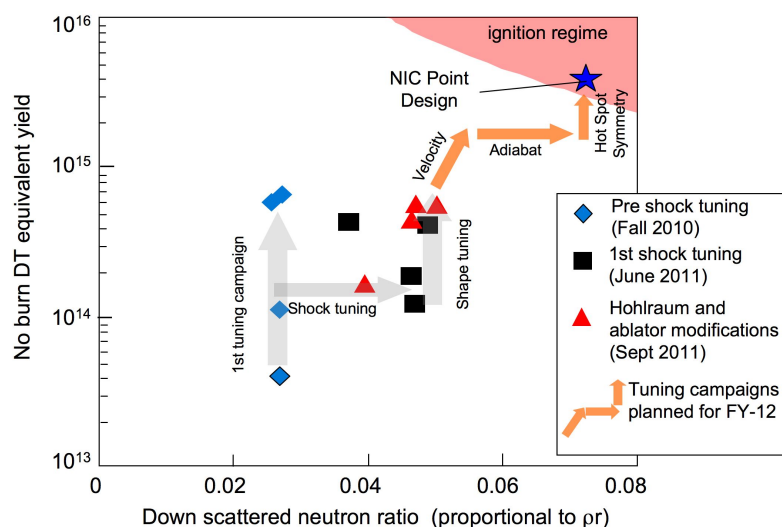


**Fig. 3**. Progress in the NIC tuning campaigns and anticipated path forward to ignition.

The DT ignition campaign began in Sept. 2011 and implosions have been conducted with laser energies of 1.3–1.6 MJ, resulting in hot spot ion temperatures of 3.7 keV, a main fuel $\rho r$ of 1 g/cm$^2$ and neutron yields of 7 x 10$^{14}$. The progress in target performance can be summarized by plotting the neutron yield vs. the fuel compressed $\rho r$, as shown in Figure 3. The $\rho r$ is not measured directly, but can be inferred from the ratio of downscattered to primary 14-MeV neutrons. Figure 3 shows the results of the first three tuning campaigns. By increasing the implosion velocity (increasing laser input power to 450–500 TW), moving to lower adiabat implosions (modifying the detailed pulse shape and shock timing), and fine tuning the drive symmetry, it is anticipated that the main fuel $\rho r$ will increase to the ignition levels of 2–2.5 g/cm$^2$, and fusion yields of 10 to 25 MJ are expected. This path is indicated on Figure 3.

## 4. NIF Experiments in support of SSP

NIF is rapidly emerging as the premier facility in the world for the study of matter at extreme conditions of temperature and pressure. The NIF laser's unprecedented power, precision, and reproducibility, coupled with sophisticated target fabrication and diagnostic capabilities put in place via NIC and other ongoing experimental campaigns, is enabling leading-edge experiments in support of the SSP as well as fundamental science.

The LLNL, LANL, and the U.K. have developed experimental campaigns to study the physical phenomena that are created during the implosion of nuclear weapon and use them to validate physics-based models of stockpile weapon performance. These experimental campaigns also serve as a tool to develop SSP personnel's skills, knowledge, and abilities. This year, several different experimental campaigns totaling 43 shots in support of SSP have studied aspects of weapons physics. Below we summarize key results from some of these campaigns.

**Radiation Hydrodynamics Campaign**

We have developed an experimental platform on NIF for radiation hydrodynamics experiments. The capability to measure radiation burnthrough, radiography of hydrodynamic features and radiation transport via calorimetry will allow a variety of experiments, such as ionization of molecular clouds, protostar formation in interstellar clouds, radiation transport through inhomogeneous materials and density perturbations.

The first Radiation Transport experimental campaign on NIF was successfully conducted in 2009. An experimental platform was commissioned for calorimetry, and initial data was acquired from radiation transport through 2D and 3D features. The experimental team included members from LLNL, AWE, LANL, NSTeC, and General Atomics.

In 2011 these experiments were continued to obtain a set of physics data for radiation transport. The experimental geometry is shown in figure 4. A cylindrical gold hohlraum is used to produce the source x-rays. The hohlraum shown is 5 mm in diameter and 3.6 mm long with a 4 mm diameter laser entrance hole (LEH). The hohlraum is illuminated through one end with 80 NIF laser beams to generate an x-ray temperature of ~ 180 eV for > 8 nsec. A target package is placed on the upper wall of the hohlraum, with various features cut into the target. Another half-hohlraum functions as a calorimeter, capturing the radiation transported from the x-ray source through the target package. The calorimeter halfraum is 4 mm in diameter, 2 mm high with a 2.5 mm diameter viewing aperture centered on the hohlraum axis.

These experiments used a variety of axisymmetric slot patterns to test the dependence of the slot width (from 200 $\mu$m to 400 $\mu$m), adjacent slots to test the burn-through time of the material separating the slots, and slanted slots. Y-shaped slot patterns with area equal to that of axisymmetric patterns were also tested to observe the effect of intersections. The experimental measurements of the radiation passing through the slots match predictions to within the 16% absolute accuracy of the Dante instrument and albedo uncertainties in the calorimeter.
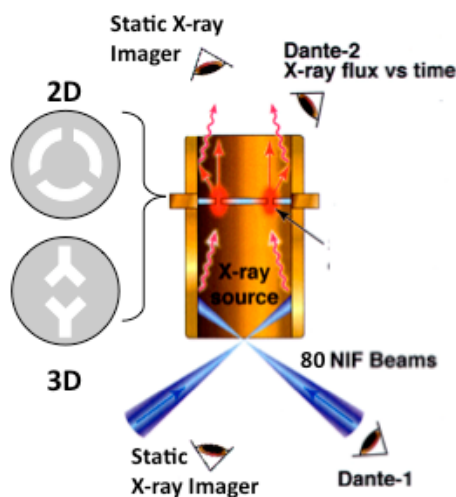


**Fig. 4.** Experimental configuration on NIF for radiation transport experiments

Streaked radiography measurements of the density profile within the slot were also performed. This used an 8-ns-duration 9 keV backlighter. Successful measurements were made on 6 patterns.

The x-ray flux generated in the hohlraum is measured by a multichannel x-ray spectrometer (DANTE1) that views the holhraum interior through the LEH at an angle of 37° from the axis of the hohlraum. A second x-ray flux diagnostic (DANTE-2) measures the temperature of the calorimeter viewing the wall of the calorimeter at an angle of 26°.

The target package consists of a 200-$\mu$m-thick, 500 mg/cc tantala aerogel with open slots and is opaque (with the exception of the slots) to the x-ray drive. As plasma is generated on the inner edges of the slots and begins to fill in, the radiation transport through the slots is modified by the evolving density profile. The x-ray energy passing through the slots heats a gold calorimeter half-hohlraum that is located on the down-stream side of the foam.

A VISAR system was used to measure the shock breakout from an aluminum witness plate placed at the location of the target package. The experimental configuration is shown in figure 5a.
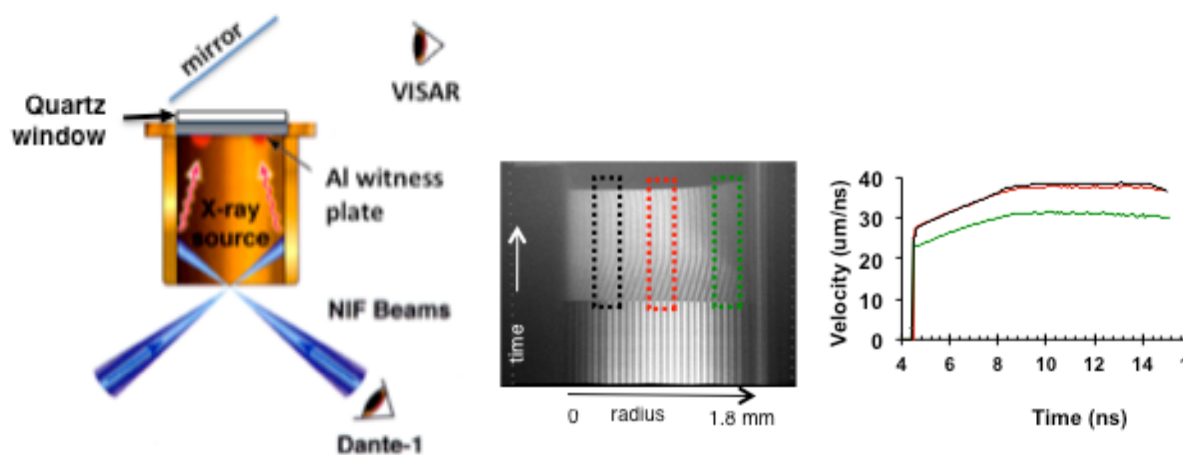


**Fig. 5a** Experimental configuration for drive characterization at the position of the target package.
**Fig 5b** Flux measured from a slanted feature compared to that from two straight features of different widths

This allows a complementary measurement of the drive incident on the target package and was used to more precisely characterize the actual drive at the location of the feature. It also provides a measurement of the drive planarity across the feature. A shock is created from x-ray drive in a Al disk. It breaks out the rear surface and enters a quartz window. The shock propagates through the quartz and creates a reflective surface at the shock front. The VISAR laser reflects off the shock front and the velocity of the shock can be measured. Since Al has a well-known equation-of-state, measurements of the shock velocity can be correlated to the drive at the Al surface. However, at these high pressures, there were considerable uncertainties in the transmission of quartz and the mirror reflectivity in this environment. Experiments were first conducted at the Omega facility to identify mirror materials that would survive the environment of NIF and the transmission of quartz under an x-ray environment. With that information, measurements were made on NIF using a Au mirror. Results are shown in figure 5b. The shock velocity and planarity were within ~ 2% of predictions. X-ray images of four different feature topologies taken from a time-integrated soft x-ray imager on a NIF shot is shown in figure 6.
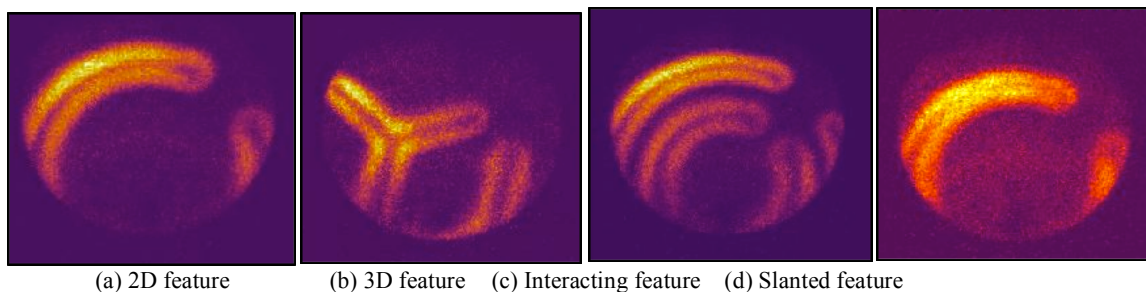


(a) 2D feature      (b) 3D feature     (c) Interacting feature    (d) Slanted feature

**Figure 6.** Time-integrated X-ray images of x-ray self emission from different feature topologies

A time-resolved x-ray streak camera was fabricated to allow measurement of the hydrodynamic evolution of the feature. Radiation transported through a feature is the result of the hydrodynamic evolution of the feature and radiation transported through the feature. By measuring the hydrodynamic evolution, the two effects can be isolated. The experimental configuration is shown in figure 7(a). A 8 keV, 8 nsec X-ray line source is generated by 16 NIF beams, which is used to radiograph the target. The data is shown in 7(b) along with a lineout at 4 ns compared to simulations.
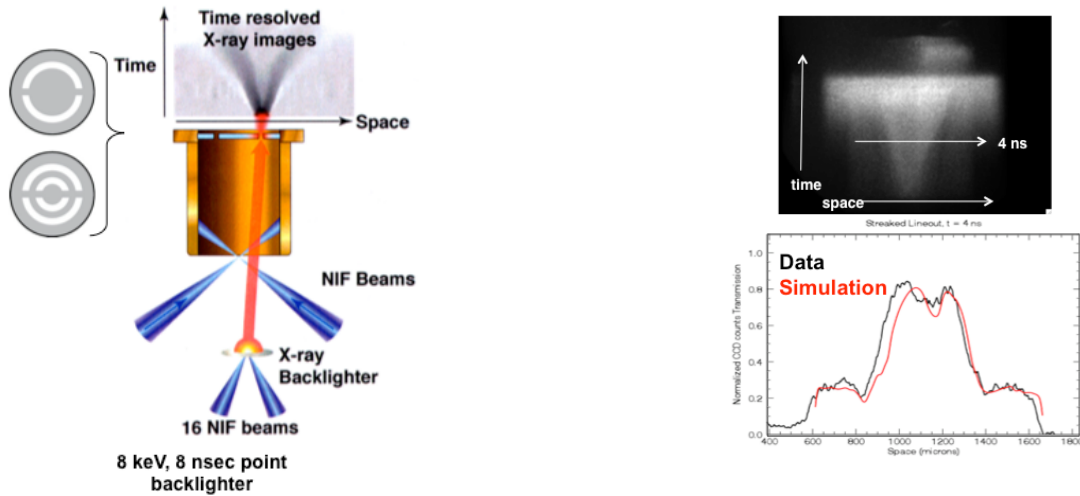


**Fig. 7a** Experimental configuration for measure,ment of the hydrodynamic evoluation of the target package.
**Fig. 7b.** Data froma slanted feature compared to simulations.

## Equation-of-state Experimental Platform

An experimental platform was commissioned on NIF during 2011 to reach >5 MBars in quasi-isentropic compression on a planar sample for equation-of-state (EOS) measurements. The configuration is shown in figure 8a. Laser beams from NIF enter a gas-filled hohlraum, which converts the laser power to x-ray power. An EOS target package is placed on the side of the hohlraum. The package consists of an ablator (diamond) and the material whose EOS is to be measured. X-rays ablate the diamond, driving a pressure pulse into the EOS material. By carefully tailoring the time-dependence of the laser power entering the hohlraum, the x-ray power incident on the ablator gradually increases, with a gradually increasing pressure in the EOS sample. This method potentially provides very high quasi-isentropic conditions inside planar EOS samples. A velocity interferometer (VISAR) reflects off the rear surface of the EOS sample. By using different sample thicknesses, the EOS can be deduced.
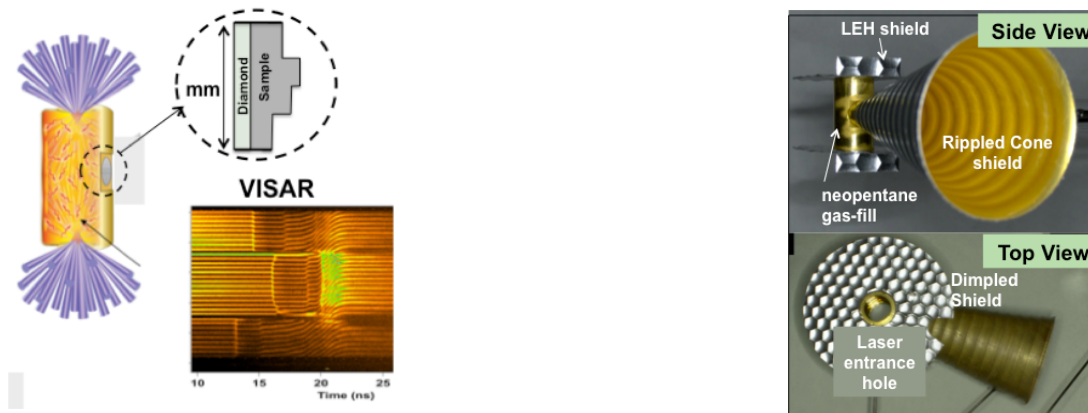


**Fig. 8a** Experimental configuration for Equation of State experiments of the hydrodynamic evoluation of the target package.
**(8b)** Data froma slanted feature compared to simulations.

The target is shown in figure 8b. A rippled cone shield is attached around the EOS target package to prevent unconverted light from the laser from illuminating the EOS package. A pair of circular dimpled shields surrounding the laser entrance holes prevent unconverted light from illuminating the sides of the hohlraum. Dimples are placed on reflecting surfaces to disperse the reflected light. A preliminary analysis of EOS data acquired in shown in figure 9. Future experiments will increase the laser power and hence reach higher pressures.
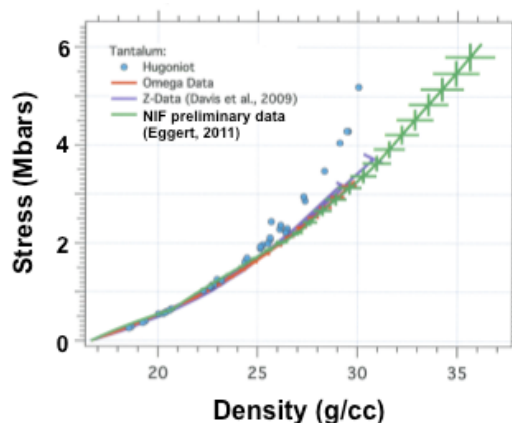


**Fig. 9** Preliminary analysdis of OES data acquired for Ta

**Material Strength Experimental Platform**

Commissioning experiments began on NIF during 2011 using an experimental platform to reach >5 MBars in quasi-isentropic compression on a planar sample for material strength measurements. The experimental configuration is shown in figure 10a. The hohlraum configuration is similar to that used for EOS expeiments. The target package, consists of an ablator , reservoir and material strength sample. The ablation pressure created is used to heat and expand the reservoir. Once heated into a plasma, the reservoir expands across a gap and ramp compresses a sample quasi-isentropically whose material strength is of interest. An imposed rippled on the front surface of the sample grows via the Rayleigh-Taylor instability. An x-ray source is used to radiograph the growth and compared to predictions using different models of strength. The instability growth increases with decreasing strength.
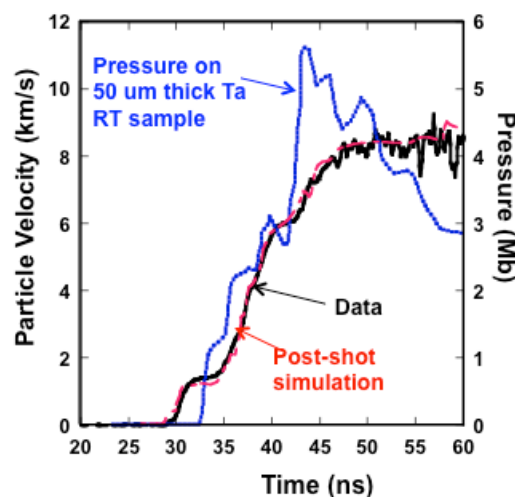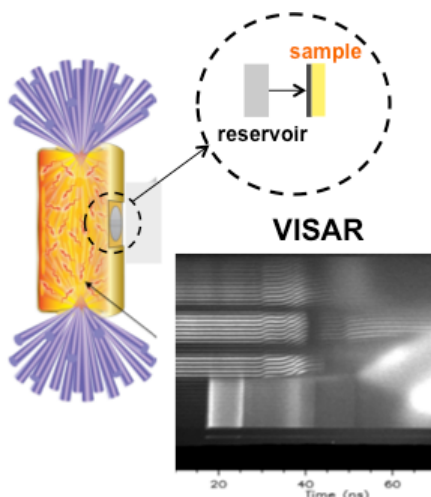


**Fig. 10a** Experimental platform for quasi-isentropic compression experiments onto a planar sample for materials strength.
**Fig. 10b.** Visar data compared to simulations consistent with 4Mbar pressure on a Ta sample.

A planar, quasi-isentropic drive platform was demonstrated during 2011 using 740 kJ of NIF laser energy into a 10 mm diameter x 13.5 mm long, thin walled hohlraum. The drive shots utilized thin-wall hohlraums, one with a vacuum and the other gas-filled, to measure the drive on a 14 μm thick Ta witness sample. The drive was diagnosed via VISAR for both targets (with corroborating data from the measured radiation drive (Dante) and laser power history. The quasi-isentropic drive was achieved via a stack of two different densities of carbon foam layers and a final CH(12.5%Br) layer for the reservoir. Differences between the gas and the vacuum hohlraums were evident at late-times and in the Soft X-ray Imager (SXI) images. The gas-filled hohlraum delivered a smooth drive profile out to ~70 ns whereas the vacuum hohlraum shows a non-uniform pressure spike late in time at ~50 ns which correlates with late-time stagnation physics in the hohlraum. The VISAR measurements utilized two separate window materials, LiF and quartz, to span the entire pressure range of the drive. The LiF window was used to measure the lower part of the drive in the vacuum hohlraum and appears to have measured the entire drive out past peak pressure in the gas-filled hohlraum target. The z-cut quartz tamper region returned data in two pressure regions: it remained transparent to the VISAR laser for quartz pressures < 1.4 Mbar and then returned data for the high pressure portion of the drive by reflecting from the > 2 Mbar shock front located inside of the quartz. The analysis of VISAR data shown in figure 10b is consistent with a 4 Mbar peak pressure achieved inside a Ta sample. This is an equivalent drive pressure of ~5 Mbar in a thicker 50 μm Ta sample planned for strength measurements. The first two drive shots were very repeatable and in agreement with simulations in terms of pressure ramp-timing and peak pressure. The transparency of the LiF window allowed for the entire drive up to peak pressure to be measured with one VISAR trace.

We performed another shot measuring the 22 keV backlighter brightness, demonstrating that the laser to x-ray conversion using the NIF 88 ps, UV pulse is comparable to the short pulse conversion efficiencies at the same intensity. Together with the drive measurements, the strength platform has been commissioned for experiment at 5 Mbars. Future experiments will be used to acquire strength data and extend the drive to higher pressure.

A second set of experiments on NIF is exploring how materials in the solid state behave when subjected to unprecedented pressures. Valuable high precision data on material dynamics are central to improving computational simulations of nuclear weapons performance. NIF experiments can be used to study the dynamical behavior of materials at high pressures and density conditions. These experiments include material strength, equation of state, material phase, phase transitions and melt. Recent NIF experiments are developing the platform for characterizing material behavior in extreme density regimes by measuring material properties in shocked solid state tantalum and carbon. In tantalum, we collected equation of state data up to 6 Mbar and material strength data up to 5Mbar. In carbon, NIF reached a record of 50 MBars pressure. We will be able to use this data from previously inaccessible regimes to develop a better fundamental understanding of material dynamics. These experiments are important stepping stones toward understanding the more complex material behavior of substances like plutonium.

## 6. Summary and Conclusion

NIF has been completed and demonstrated performance at its design goals of 1.8 MJ and 500 TW, and the facility is being prepared for ignition and fusion yield experiments. A full set of diagnostics has been commissioned for initial ignition experiments, and the next phase of radiation-hardened diagnostics are being installed.

The NIC has begun its ignition campaign. The first results on ignition-scale targets show excellent performance with good energy coupling and good radiation symmetry control. Experiments are continuing to optimize the ignition target design for four major control variables for ignition: symmetry, fuel adiabat, shell velocity, and mix. Cryogenic layered experiments with DT have shown that the facility can successfully field ignition experiments. Further ignition experiments are planned throughout the year to improve performance and demonstrate alpha heating of the fuel, the next step in ignition demonstration. NIF scientists have also begun experiments supporting the NIF's national security and fundamental science missions and is in the process of transitioning to a national user facility.

The first experiments in support of SSP on NIF have been remarkably successful. Throughout these experimental campaigns, NIF laser drive has proved to be extraordinarily reproducible, giving high confidence in the results obtained, as well as enabling high-accuracy quantitative comparisons between consecutive target shots with a single controlled design variable.

The NIF HEDSS experiments have already provided valuable data and have demonstrated its value to help the U.S. from having to return to underground testing to overcome a stockpile challenge. Future classified experiments, dependent on achieving the energy densities available with ignition, will be able to address fundamental physics surrounding nuclear weapon boost. Creating a predictive, physics-based capability to enable the assessment of the safety, reliability, and performance of the U.S. nuclear stockpile in an era without nuclear testing requires removing all of the major uncertainties associated with nuclear weapons performance including boost.

## Acknowledgements

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