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The National Ignition Facility: Experimental Capability

G. H. Miller

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THE NATIONAL IGNITION FACILITY: EXPERIMENTAL CAPABILITY

George H. Miller

Lawrence Livermore National Laboratory, P.O. Box 808 L-466, Livermore, CA 94551

The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory is a stadium-sized facility containing a 192-beam, 1.8-Megajoule, 500-Terawatt, ultraviolet laser system together with a 10-meter diameter target chamber with room for nearly 100 experimental diagnostics. NIF will be the world's largest and most energetic laser experimental system, providing a scientific center to study inertial confinement fusion and matter at extreme energy densities and pressures. NIF's energetic laser beams will compress fusion targets to conditions required for thermonuclear burn, liberating more energy than required to initiate the fusion reactions. Other NIF experiments will study physical processes at temperatures approaching 10^8 K and 10^{11} bar, conditions that exist naturally only in the interior of stars, planets and in nuclear weapons. NIF has completed the first phases of its laser commissioning program. The first four beams of NIF have generated 106 kilojoules of infrared light and over 16 kJ at the third harmonic (351 nm). NIF's target experimental systems are being commissioned and experiments have begun. This paper discusses NIF's current and future experimental capability, plans for facility diagnostics, cryogenic target systems, specialized optics for experiments, and potential enhancements to NIF such as green laser operation and high-energy short pulse operation.

I. INTRODUCTION

The National Ignition Facility (NIF) under construction at the Lawrence Livermore National Laboratory (LLNL) for the U. S. Department of Energy and National Nuclear Security Administration (NNSA) will be a scientific center for the study of inertial confinement fusion and the physics of extreme energy densities and pressures. Construction of the building that houses the laser system was completed in September 2001 and the installation of all 192 ultra-clean and precision aligned beam path enclosures was completed in September 2003. In late 2002 NIF began activating its first four laser beam lines. By July 2003 NIF had delivered world-record single laser energy performance in primary (1.06 micron), second, and third harmonic wavelengths. When completed in 2008, NIF will provide up to 192 energetic laser beams to compress deuterium-tritium fusion targets to conditions where they will ignite and burn, liberating more energy than is required to initiate the fusion reactions. NIF experiments will allow the study of physical processes at temperatures approaching 100 million K and 100 billion times atmospheric pressure. These conditions exist naturally only in the interior of stars and in nuclear weapons explosions. [1-6]

A detailed description of NIF and the performance of the laser system is presented in an accompanying presentation at this Conference.[7] In addition to the laser system, the first diagnostic systems to be used for both laser performance measurements and physics experiments have been installed and commissioned. These include static x-ray imaging, gated and streaked x-ray detectors mounted on the NIF target chamber and a full aperture back-scatter diagnostic that images scattered light through the final optical beampath of the first quad of four beams. With this initial suite of diagnostics NIF experimenters have completed the first studies related to ignition hohlraum energetics and hydrodynamics.[8]

II. HIGH ENERGY DENSITY PHYSICS ON NIF

The National Ignition Facility extends the experimental regimes of accessible high-energy-density (HED) by a significant amount compared to other current and planned high-energy laser and pulsed power facilities. Figure 1 shows one measure of NIF's physics reach for pressure versus pulse length. NIF, and the French Laser Megajoule (LMJ) system (recently approved for construction) can drive materials to tens of gigabars for pulse lengths of tens of nanoseconds. NIF is capable of providing a range

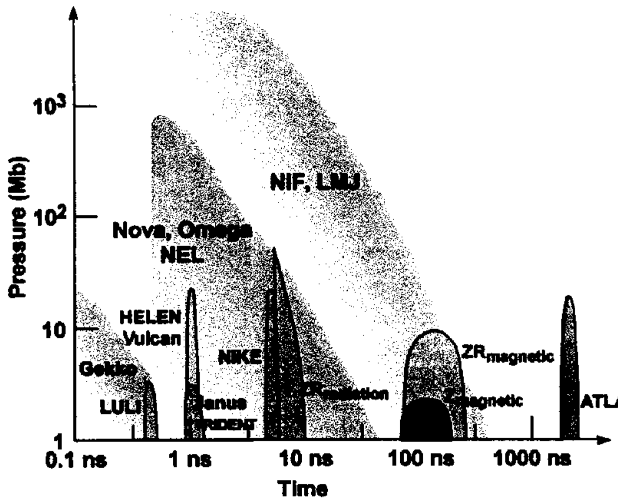


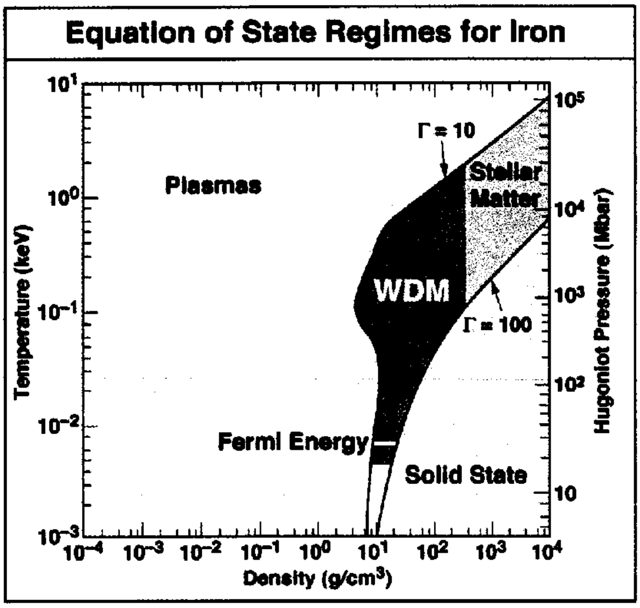
Fig. 1 Pressure-pulse length regimes accessible at different HED facilities currently operating or planned in the world.

pulse lengths that under certain configurations can be hundreds of nanoseconds. The ability to deliver extended high-energy drive allows experimental measurements of equation of state (EOS), materials at high pressures, hydrodynamics, and radiation transport that have not been possible in prior HED facilities.

NIF opens up new fields of study, for example in the area of warm dense matter (WDM) – approximately solid density matter at temperatures in the few eV to tens of eV range.[9,10] Figure 2a shows an example the EOS regimes for iron. In WDM ions are strongly coupled, electrons are partially degenerate, the thermal energy approaches the Fermi energy, and the material is partially ionized due to continuum lowering and pressure ionization. Currently there is no theory that adequately describes WDM.

Figure 2b shows how NIF can be used to provide high accuracy high-pressure measurements of WDM. NIF's high-energy laser beams can be tailored for driving relatively large uniform volumes. NIF beams can also be used to provide high x-ray fluences for high signal-to-noise radiography of dense matter. Recent experiments using isentropic plasma pistons (ICE drive) to steadily load materials have been demonstrated on the Omega Laser at the University of Rochester Laboratory for Laser Energetics and are being planned on NIF.[11-13] As more NIF beams become available it is expected that extremely high pressures can be generated using long-pulse generated shocks and ICE techniques along with unprecedented measurement accuracy associated with smoothing capability and new high precision target fabrication techniques. High-energy short-pulses can provide extremely high brightness and high-energy x-ray backlighter sources for radiographing WDM to fully resolve hydrodynamic features and materials states.[14,15]

Even with the first four beams of NIF experiments can reach tens to one hundred megabars in materials. Initial EOS experiments with the first four NIF beams are planned in the coming year that have a goal of exceeding 25 Mbar in aluminum[16] in a steady and uniform pressure wave. Isochoric heating with ignition neutrons or high en-



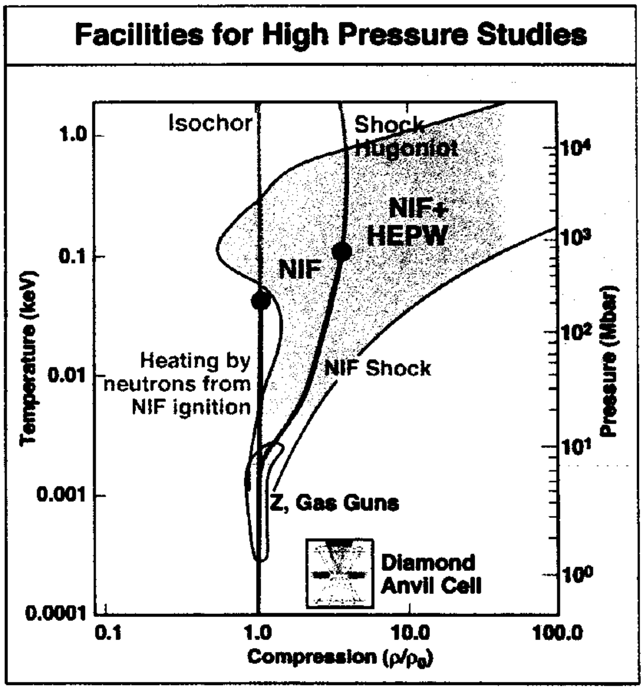


Fig. 2a, left, shows the phase space for iron with the warm dense matter (WDM) phase highlighted. Fig. 2b, right, details NIF's ability to reach high pressures using long pulse NIF, NIF plus HEPW and NIF ignition neutrons to isochorically heat materials to off-Hugoniot conditions. Other facilities such as z-pinch, gas gun, and diamond anvil cells are shown for comparison.

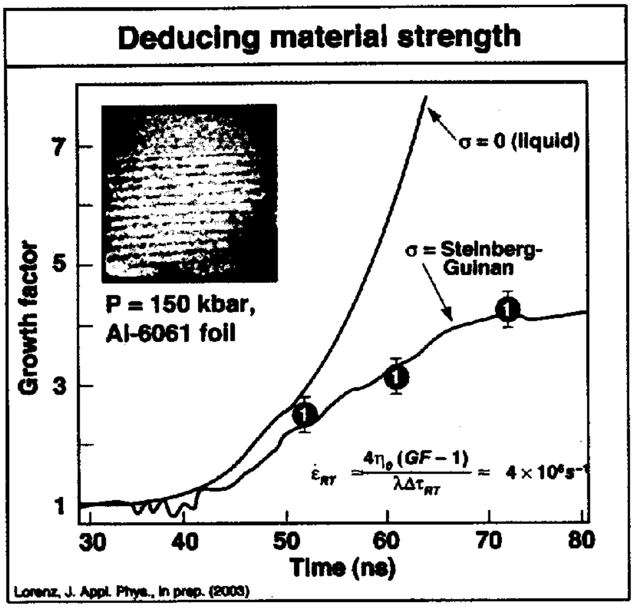


Fig. 3 Results from Omega on aluminum at 150 kbar shows the ability to use RT growth techniques to deduce materials strength at high strain rates.

ergy petawatt laser-generated ion beams when they become available in the coming decade provides an additional capability for heating materials off the Hugoniot.

Dynamic strength of materials at extreme pressure and strain rate is another area of great experimental and theoretical uncertainty. Large increases in materials strength are predicted as pressure and strain rate increase, however there is no controlled data currently available to support this prediction. Recent measurements on Omega have demonstrated Rayleigh-Taylor (RT) strength diagnostic techniques, which utilize laser driven plasma pistons to initiate and evolve RT instabilities over time with radiographic measurements of the induced deformation giving information on dynamic material strength. Figure 3 shows results from Omega demonstrating that aluminum departs from a liquid model at strain rates of 4×10^6/sec and pressures of 150 kbar for tens of ns, in agreement with a Steinberg-Guinan strength model.[17]

III. IGNITION ON NIF

Prospects for ignition on NIF continue to improve.[18,19] Designs supporting indirect-drive, or x-ray drive of ignition capsules in hohraums are becoming more robust as better modeling capability, including full 3-dimensional modeling of capsules and hohlraums allows design trade-off studies to be rapidly performed and design spaces to be optimized. For example, optimization studies have improved plastic capsule performance by a factor of two while allowing ablator roughness to increase by a factor of two, easing fabrication requirements.

New designs using beryllium with graded Cu dopant are spectacularly robust, with ablator roughnesses being relaxed by as much as a factor of 10-20 over previous designs and newly optimized polyimide designs.

In addition, significant progress has been made in fabricating smooth plastic and beryllium/copper capsules that nearly meet these new design specifications.

Precision control of cryogenic D_2 ice smoothness using infrared heating in an isothermal hohlraum has now been demonstrated. Progress is also being made in developing cryogenic hohlraums with convection mitigation and thermal control.

Diffusion filling of a capsule in a hohlraum has also been recently demonstrated and integration of infrared layering, thermal shimming, convection mitigation, and characterization in a D_2 test system is underway.[20]

Hohlraums driven with green or 2ω light from NIF are actively being studied.[21] Calculations suggest that as much as 1.5 MJ of energy may couple to a capsule at 250 eV drive temperature. However, physical data on 2ω laser plasma interactions is limited and more work is needed. NIF 2ω operation has been demonstrated and researchers are studying how to configure some of NIF's early beams for high energy 2ω LPI studies.

Direct drive on NIF is also making progress with new studies showing how adiabat shaping and off-pointing of the indirect-drive configuration of NIF beams (polar direct drive) can possibly meet symmetry requirements for direct drive implosions.[22]

Finally, fast ignition studies at the University of Osaka, Institute for Laser Engineering, and at Rutherford Laboratory in the UK are providing tantalizing glimpses of possible low energy symmetric heating combined with high power asymmetric drive to induce hot spot ignition conditions in cone-focused targets.[23,24]

A "proof-of-principle" fast ignition experiment at NIF is in the design phase. Laser physicists have determined how NIF's current injection laser, main amplifier, and beam transport system could be modified to allow up to 20 high energy petawatt-class (HEPW) beams to be directed to target chamber center. Initial experiments are being designed to utilize a single kilojoule-class HEPW beam line with 1-30 picosecond pulse width to drive electron or proton cone-focused ignition. NIF long pulse beams totaling 250 kJ into a hohlraum with 8-fold, 2-cone symmetry (8 quads of 4 beams in opposite laser entrance holes) would be used to compress the capsule. This capability on NIF could be in place in the 2006 time frame.[25] Additional HEPW beams in a quad could be installed to provide multi-kilojoule capability.

IV. EXPANDING SCIENTIFIC HORIZONS ON NIF

The National Academy of Sciences in the United States has recently recognized the exciting scientific frontiers becoming available at the next generation of

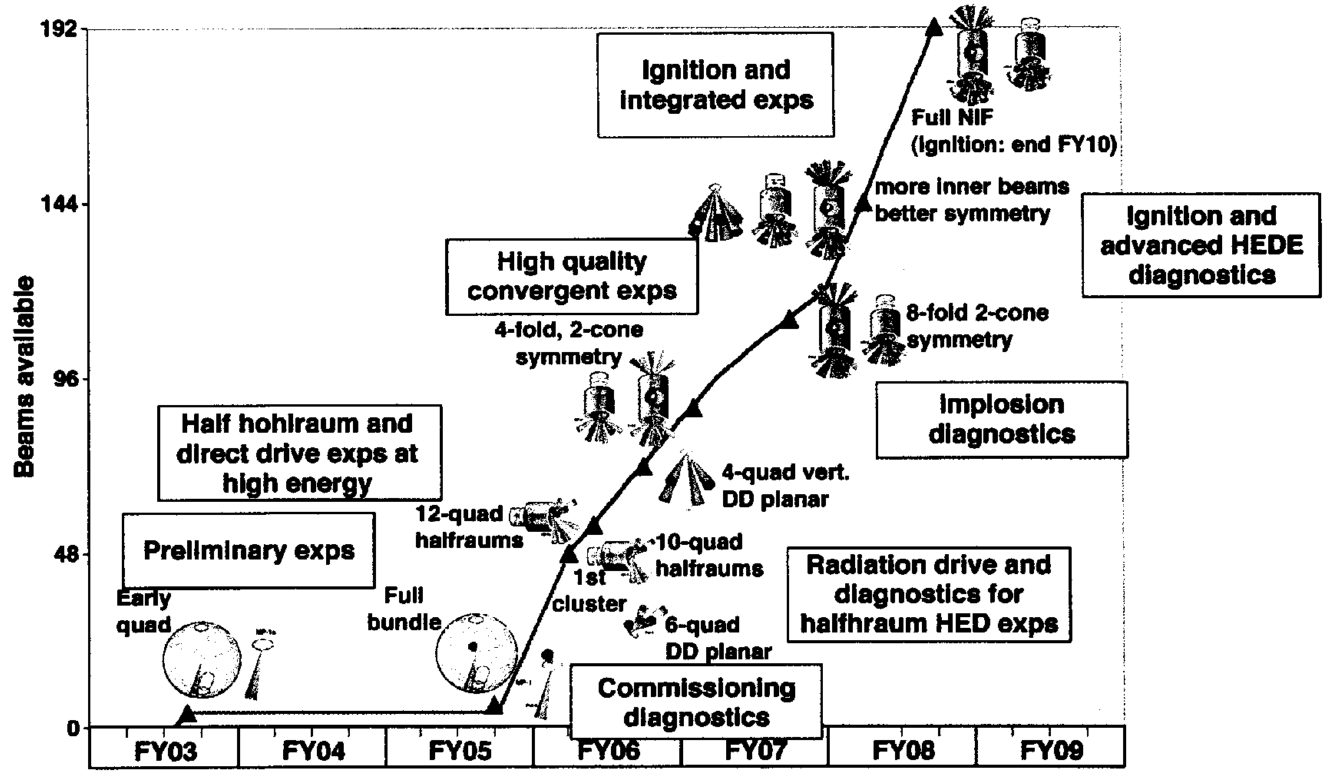


Fig. 4 The plan for completion of NIF provides increasing experimental capability over time for both experimental configurations and specialized diagnostics as more beams and symmetries become available.

high-energy-density experimental facilities.[26,27] Laboratory-based astrophysics, where extreme physics phenomena, heretofore inaccessible are now becoming accessible for the first time.

For example, supernovae explosion mechanisms remain uncertain. Recent planar and spherical RT experiments on Nova and Omega showed that instabilities produced in these systems can be quantitatively studied. NIF will provide the capability to study larger volume targets for longer times and high fluence, high energy time-resolved x-ray data will help to validate hydrodynamic models that can be scaled to stellar dimensions and times.

Other researchers are assessing NIF's potential for simulating exotic astrophysical systems such as the extended RT systems in the Eagle nebula, immense astrophysical radiative magnetohydrodynamic jets, and even possibly the incredible physical conditions that exist only near the surface of a neutron star.[28]

V. THE PATH FORWARD TO FULL NIF

Completion of all 192 laser beams is scheduled for September 2008. We have developed a plan for beam deployment that supports experiments with steadily increasing capability. The increasing symmetry and energy available enables a variety of target configurations including planar targets, horizontal and vertical half-hohlraums (halfraums), and vertical hohlraums with 4- and 8-fold symmetry that provides approximately 300 shots per year through 2008 for high-energy-density physics, inertial confinement fusion, and basic science. After project completion, NIF is expected to provide approximately 700 shots per year for a wide variety of experimental users as a national user facility. A recent shot campaign on NIF provided three target shots per day over a three-day period, demonstrating the ability to meet the planned 700 shots per year when NIF is fully operational.

We have also developed a baseline diagnostic plan that is synchronized to the increasing capability NIF provides. Figures 4 and 5 show these increasing capabilities to be provided by the time the first cluster of 48 beams are commissioned on NIF.

In addition to diagnostics, the NIF Program includes support for building and commissioning facility capabilities in diffractive optics (phase plates), cryogenic target systems, and target area operations. We are developing a non-ignition cryogenic target capability to be fielded around the time of first cluster. This will be followed with a full cryogenic target system for supporting the campaign of ignition experiments beginning the FY08 time frame.

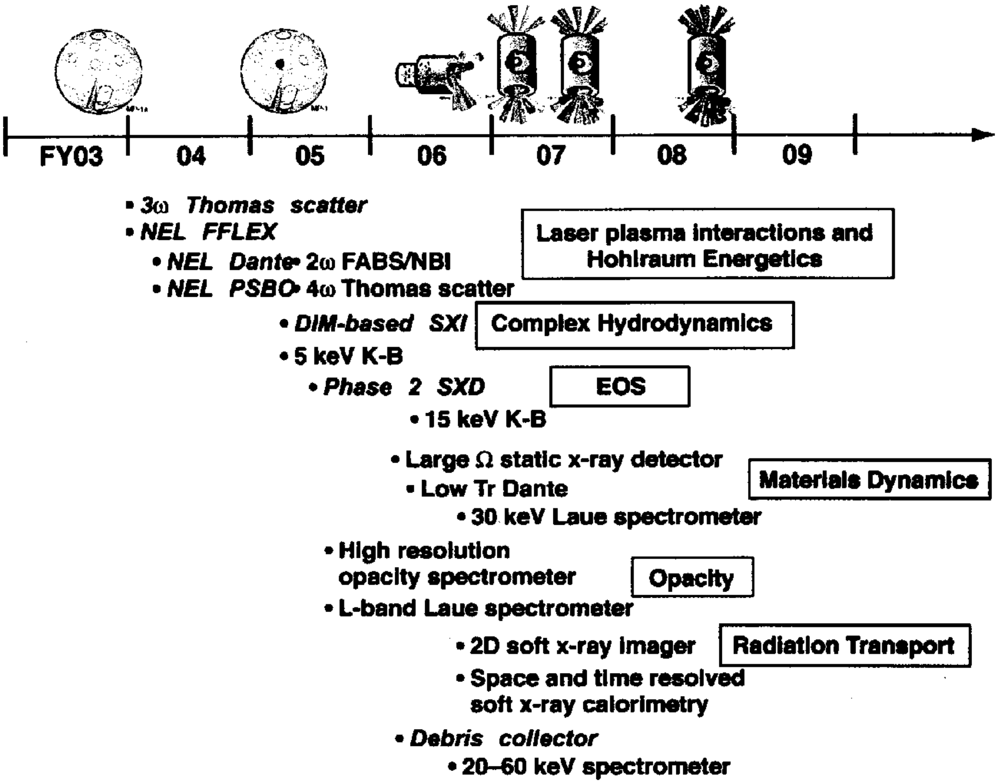


Fig. 5 Experimental diagnostics planned to be fielded on NIF through Project completion. Many diagnostics are key to experimental campaigns identified in the boxes to the right.

VI. CONCLUSIONS

The first physics experiments are already being performed on NIF. Initial experiments are studying laser-plasma interactions and hydrodynamics of shocked materials. In the coming year this unique facility will already be providing the first glimpses of conditions heretofore only found in the most extreme environments. This will be done under repeatable and well-characterized laboratory conditions for the benefit of a wide variety of scientific users.

To assist in the transition from a construction and technology project to a scientific user facility we have been working with the key user communities of NIF, academia, and NNSA to ensure that NIF is fully utilized to produce the highest quality physics data possible.

NNSA has created the position of NIF Director and charged him with developing the governance of user programs. This governance includes high-level NIF advisory committees, an Experimental Planning Advisory Committee (EPAC) with representation from all the user communities, and lower level scheduling committees. The NIF EPAC has begun meeting to familiarize itself with NIF's early capabilities in preparation for wider calls for proposals, the first of which is expected to be in FY05.

Current programmatic guidance for NIF shot allocations provide for approximately 40% for HED and ICF, 15% for basic science and military applications, and 5% for Director reserved contingency.

As NIF matures we fully expect the facility to evolve to include exciting new capabilities, some of which are mentioned briefly here. The NIF laser system and support buildings have been designed with maximum flexibility for future enhancements such as multi-wavelength operation and high-energy short pulse operation. NIF is ready to deliver the next generation of HED and ICF experimental capability for the US and international scientific communities.[28]

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29. For more information on the National Ignition Facility please visit the NIF web site at http://www.llnl.gov/nif