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The National Ignition Facility (NIF) and the National Ignition Campaign (NIC)

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***Abstract*—The National Ignition Facility (NIF), the world's largest and most powerful laser system for inertial confinement fusion (ICF) and experiments studying high-energy-density (HED) science, is now operational at Lawrence Livermore National Laboratory (LLNL). NIF construction was certified by the Department of Energy as complete on March 27, 2009. NIF, a 192-beam Nd:glass laser facility, will ultimately produce 1.8-MJ, 500-TW of 351-nm third-harmonic, ultraviolet light. On March 10, 2009, total 192-beam energy of 1.1 MJ was demonstrated; this is approximately 30 times more energy than ever produced in an ICF laser system. The principal goal of NIF is to achieve ignition of a deuterium-tritium (DT) fuel capsule and provide access to HED physics regimes needed for experiments related to national security, fusion energy and broader frontier scientific exploration.**

NIF experiments in support of indirect-drive ignition began in August 2009. These first experiments represent the next phase of the National Ignition Campaign (NIC). The NIC is a national effort to achieve fusion ignition and is coordinated through a detailed execution plan that includes the science, technology, and equipment. Equipment required for ignition experiments includes diagnostics, a cryogenic target manipulator, and user optics. Participants in this effort include LLNL, General Atomics (GA), Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL), and the University of Rochester Laboratory for Energetics (LLE). The primary goal for NIC is to have all of the equipment operational, integrated into the facility, and ready to begin a credible ignition campaign in 2010. With NIF now operational, the long-sought goal of achieving self-sustained nuclear fusion and energy gain in the laboratory is much closer to realization.

Successful demonstration of ignition and net energy gain on NIF will be a major step towards demonstrating the feasibility of Inertial Fusion Energy (IFE) and will likely focus the world's attention on the possibility of an ICF energy option. NIF experiments to demonstrate ignition and gain will use central-hot-spot (CHS) ignition, where a spherical fuel capsule is simultaneously compressed and ignited. The scientific basis for CHS has been intensively developed [1]. Achieving ignition with CHS will open the door for other advanced concepts, such as the use of high-yield pulses of visible wavelength rather than ultraviolet and Fast Ignition concepts [2, 3]. Moreover, NIF will have important scientific applications in such diverse fields as astrophysics, nuclear physics and materials science. The NIC will develop the full set of capabilities required to operate NIF as a major national and international user facility. A solicitation for NIF frontier science experiments is planned for summer 2009.

This paper summarizes the design, performance, and status of NIF and plans for the NIF ignition experimental program. A brief summary of the overall NIF experimental program is also presented.

***Keywords*—National Ignition Facility, National Ignition Campaign, Inertial Fusion Energy, Inertial Confinement Fusion, High Energy Density Science, and Laser Inertial Fusion Energy**

I. Introduction

NIF is the U.S. Department of Energy (DOE) and National Nuclear Security Administration (NNSA) national center[1] to study inertial confinement fusion (ICF) and the physics of extreme energy densities and pressures. [4] NIF concentrates all the energy of its 192 laser beams onto a centimeter-scale fusion target, driving it to conditions under which it will ignite and burn, liberating more energy than is required to initiate the fusion reactions. NIF is designed to achieve target temperatures of 100 million K, densities of 1,000 g/cm^3, and pressures exceeding 1 Gigabar. These conditions have never been created in a laboratory and exist naturally only in the interiors of the stars and during thermonuclear burn.

NIF ignition experiments will initially operate in the "indirect-drive" configuration (Fig. 1-a) in which the fusion capsule [5], filled with a deuterium-tritium (DT) mixture, is mounted inside a cylindrical hohlraum. Laser beams enter the hohlraum through a hole in each end of the cylinder, are absorbed by the interior wall and converted to x-ray energy. These x-rays bathe the capsule and ablate its outer layer. Conservation of momentum requires that the remaining material implode or compress. Compression of the DT fuel to extraordinarily high temperature, pressure, and density causes the central hot spot to ignite, and a burn wave propagates through the remaining fuel. NIF can also be configured in a "direct-drive" arrangement (Fig. 1-b) wherein the laser beams are directed onto the surface of the DT fuel capsule. Fig. 1-c illustrates the fast ignition concept.

The mission to achieve thermonuclear ignition in the laboratory was identified in the early 1990s by DOE's Fusion Policy Advisory Committee and the National Academy of Sciences Inertial Fusion Review Group as the next important step in inertial fusion research. The experimental program to accomplish ignition [6] is detailed in the NIC Execution Plan [7], including all required science, technology, and experimental equipment. The central goal of the NIC Program is to perform credible ignition experimental campaigns on the NIF beginning in FY2010 and to demonstrate a reliable and repeatable ignition source by the end of FY2012.

[1] NIF web site, http://www.llnl.gov/nif/

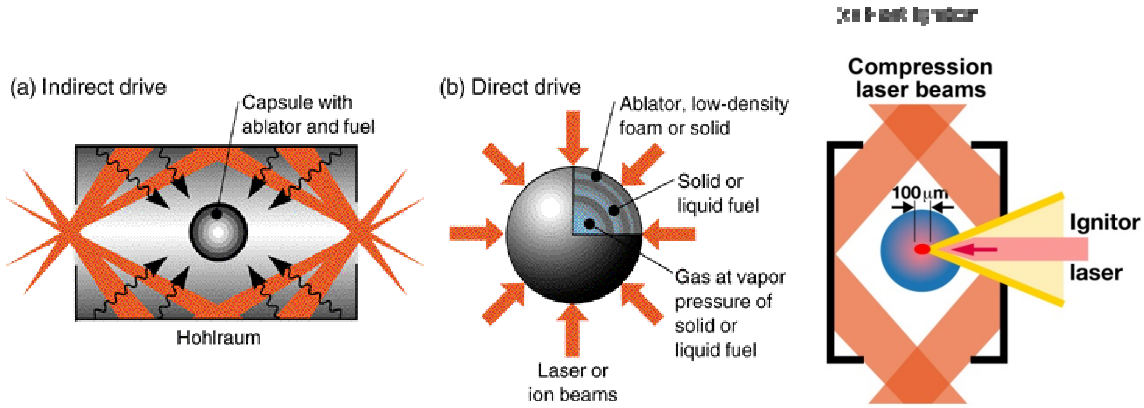

Figure 1. Illustration of ICF target concepts (a) indirect drive, (b) direct drive (c) fast ignition.

To prepare for the FY2010 ignition campaign, many activities are under way at NIF and other medium-scale facilities including OMEGA at LLE, Z at SNL, Trident at LANL, and Jupiter at LLNL. Experiments at these facilities are being used to develop and demonstrate shock timing, laser ablation and the diagnostics techniques needed to achieve ignition. In addition, the NIC team is conducting a simulated campaign that is stepping through the processes of preparing and executing the NIC to refine requirements on targets, diagnostics, lasers, optics, data collection and analysis, and to optimize the NIC strategy and shot plans to balance risk and resources.

II. The National Ignition Facility

The NIF is designed to achieve ignition of a DT nuclear fusion target. NIF's 192 laser beam lines are housed in a building with a volume of about 350,000 m^3 (Fig. 2). Each laser beam line contains 36 to 38 large-scale precision optical elements, depending on beam line configuration (Fig. 3), and hundreds of smaller optical components. The combined total area of precision optical surfaces is 3600 m^2, and the total radiating aperture is 22 m^2. For purpose of comparison, the combined optical surface area of the two Keck Telescopes, the world's largest, is 152 m^2, approximately 4% of NIF's. The NIF 10-meter-diameter high-vacuum target chamber (Fig. 4) 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. About 35 different types of diagnostics are planned for NIC. For indirect-drive fusion studies, all 192 beams will be focused into a cylindrical hohlraum through two round entrance holes 2.5 mm in diameter. The conditions created in the hohlraum will provide the necessary environment to explore a wide range of high-energy-density physics experiments, including laboratory-scale thermonuclear ignition and burn. All of the 192 beam lines have been operated at the fundamental 1053-nm wavelength (1ω), delivering greater than 19 kJ per beam line.

A continuous-wave Yb-fiber master oscillator produces the initial laser pulse. The initial pulse passes through an array of fiber-optical components used to provide the required precise temporal shape and bandwidth, then is split 48 ways, sending pulses into the preamplifier modules. Pulses from each of the 48 preamplifier modules are further split and delivered into the 192 beam lines. Each beam line, illustrated in Fig. 2, operates as a four-pass amplifier, enabled by the LLNL invention of the large aperture plasma-electrode Pockels cell (PEPC) [8]. The PEPC functions as follows: a pulse is injected into each beam

(a) (b) (c)

Figure 2. (a). NIF facility aerial photograph, (b) cut-away drawing, and (c) Laser Bay 2.

line near the focal plane of the transport spatial filter (TSF), from where it expands to the full, square-aperture beam size of 37.2 × 37.2 cm, then passes through the spatial filter lens, which collimates the beam. The pulse passes through the power amplifier (PA), reflects from a mirror and a polarizer, and then passes through the cavity spatial filter (CSF) and main amplifier (MA). It reflects from a deformable mirror used to correct wavefront distortions and then makes a second pass through the MA and CSF. During the time required for the pulse to make this double pass, voltage is applied to the PEPC that rotates the polarization of the pulse by 90 degrees. It then passes through the polarizer, reflects from a second mirror, and makes another double pass through the PEPC, CSF and main amplifier. Before the pulse returns to the PEPC, its voltage is switched off, so the pulse reflects from the polarizer and mirror and makes a final pass through the PA and TSF and propagates on to the switchyard. There, beam transport mirrors direct the pulse through a final optics assembly (FOA), shown in Fig. 5, consisting of a 1ω vacuum window, focal-spot beam conditioning optics, two frequency conversions that change the wavelength to 351 nm, a focal lens, main debris shield that also serves as a diagnostic beam splitter and a thin, disposable debris shield used to protect the optics from debris produced by irradiation of the target.

Also, new for NIF is the introduction of the line-replaceable unit (LRU) design concept [9]. In this concept, developed at LLNL for the Atomic Vapor Isotope Separation Program, the laser is assembled using modular components that are easily removed for maintenance, thus allowing the laser to maintain nearly continuous operation. Other key developments essential to the success of NIF are: a continuous pour method for producing extremely low-defect laser glass [10], rapid growth of large, frequency conversion crystals of potassium dihydrogen phosphate (KDP) and deuterated KDP [11], and the LLNL-developed strategy for increasing damage resistance and economically managing optical damage. Complete description of these key developments is beyond the scope of this paper; details can be found in the cited references.

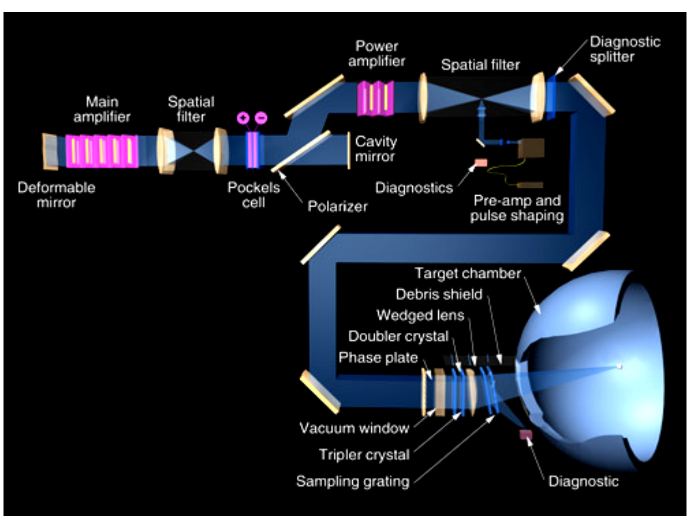

Figure 3. Schematic of one of NIF's 192 beamlines.

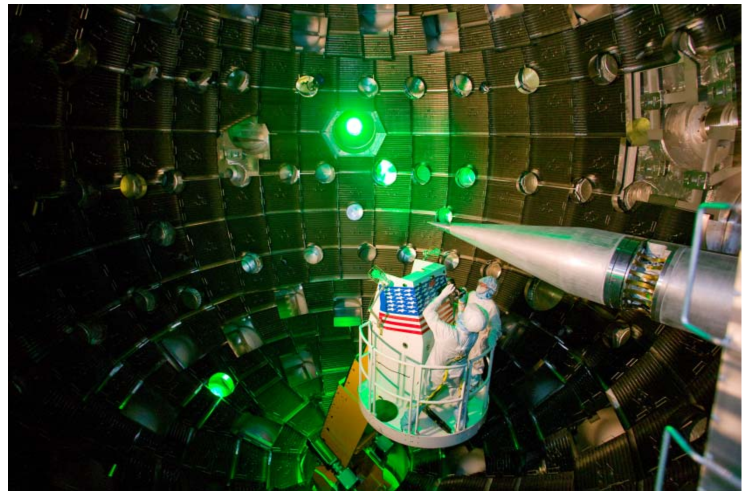

Figure 4. Inside the NIF target chamber, a 10-m-diameter sphere of 10-cm-thick aluminum coated with a 40-cm-thick neutron shielding concrete shell. The entire assembly weighs about one-half million kilograms. The target positioner is on the right.

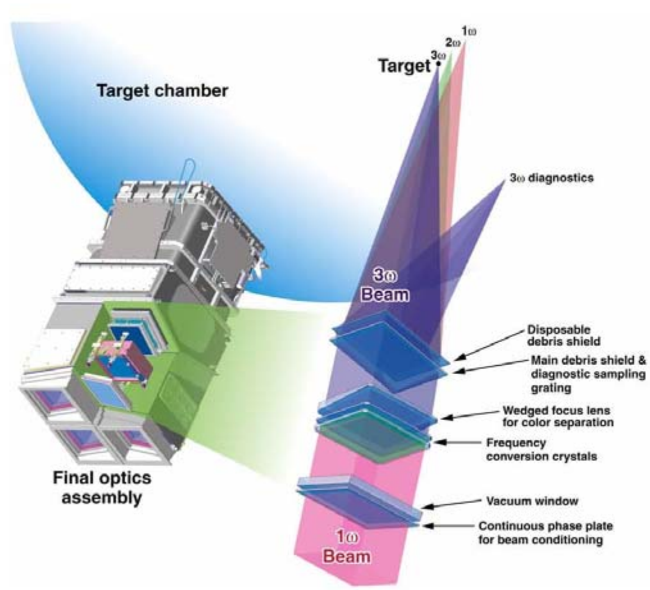

Figure 5. NIF final optics assembly containing a beam-conditioning phase plate, KDP frequency conversion crystals, a fused-silica focus lens and two fused-silica debris shields.

III. THE NATIONAL IGNITION CAMPAIGN

A. Overview

The National Ignition Campaign (NIC) is a collaborative effort by LLNL, GA, LLE, LANL and SNL with two major goals: execution of DT ignition experiments starting in FY2010 with the goal of demonstrating ignition and a reliable, repeatable ignition platform by the end of the NIC in Q4FY2012. The NIC will also develop the infrastructure and other support required to operate NIF as a user facility.

The NIC ignition campaigns will use the “indirect-drive” configuration, in which the laser beams are directed into either end of a cylinder coated with gold or other high-Z materials mounted vertically within the target chamber. The laser irradiation of the cylinder produces a radiation field inside the cylinder that implodes a mm-scale capsule filled with a mix of deuterium and tritium. As shown in Fig. 6 (left), the laser beams are deployed in multiple cones so as to control the time-dependent symmetry of the radiation drive. The resulting asymmetry is maintained to less than 1% on average. The high degree of symmetry of the NIF implosion coupled with a precisely tailored target design and corresponding laser pulse results in the high peak fuel ρR required for alpha heating of the fuel and capsule ignition. Fig. 6 (right) shows the ρR regime expected on NIF vs. those achieved at OMEGA.

Initial NIF ignition experiments will commence by late FY2010 at total 192-beam ultraviolet laser energies of approximately 1.2 MJ. This energy level is consistent with the laser-commissioning plan that ramps up the planned routine 192-beam operating energy of NIF to 1.8 MJ by late 2011. The target design to be used in initial ignition experiments is shown in Fig. 6 (left). Two capsule ablator materials (Be with Cu dopant and CH with Ge dopant) are under consideration for initial ignition experiments. Both capsules are filled with DT gas via a 10-µm-diameter SiO_2 fill tube to a density of 0.3 mg/cm^3 with a DT solid layer at 18.3 degrees Kelvin. The Cu and Ge dopant density is varied through the ablator and is typically present at less than 1% concentration. Calculated one-dimensional yields for the CH/Ge and Be/Cu capsules are 16.5 MJ and 21 MJ, respectively. Maintaining these two design options reduces risk and allows the choice of a target optimally configured to the precise laser and target fabrication capabilities available.

Ignition target development and fabrication has made strong progress since the start of NIF construction in 1997; indeed, ignition target development and fabrication is a research 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 particular long-standing challenge for ignition target fabrication is the frozen DT fuel layer [12]. This layer must be formed at approximately 1.5 degrees 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, and spherical isotherms must be maintained at the layer surface via auxiliary heating. These challenges have been addressed, and ignition targets meeting all specifications are now in production [13]. Fig. 7 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 includes a characterization station capable of imaging the DT layer in three spatial dimensions within minutes.

The diagnostic suite for NIC is also a major focus of NIC efforts in FY2009 and FY2010. Approximately 35 diagnostics measuring x-ray, neutron, charged particle, optical, and other emissions will be installed by the end of FY2010. 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. Further information regarding NIF diagnostics is available at the NIF website.[2]

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

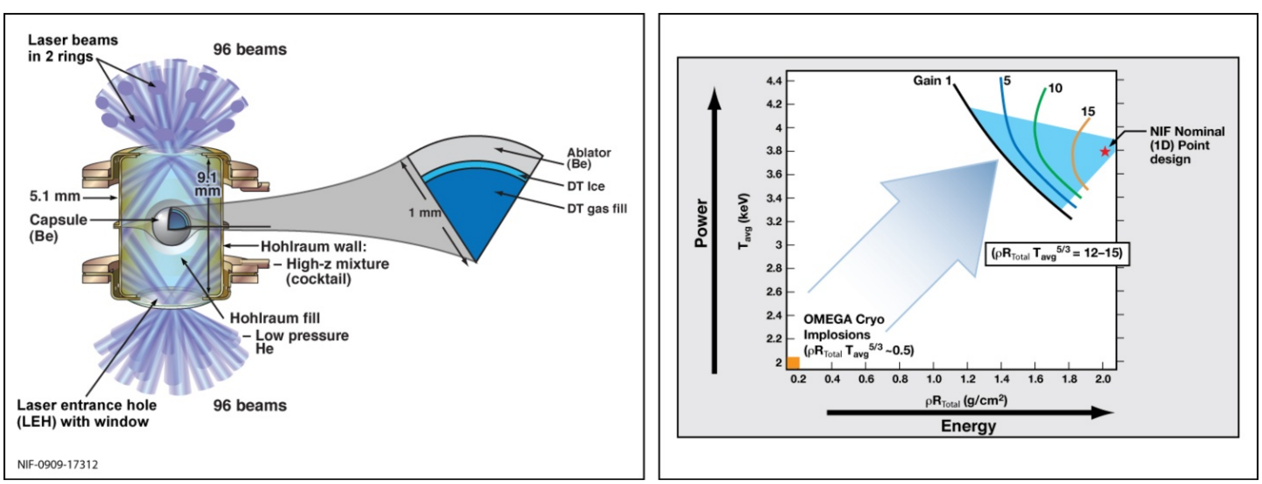

Figure 6. (left). Schematic of NIF ignition target. (Right) ρR regimes expected at NIF and OMEGA.

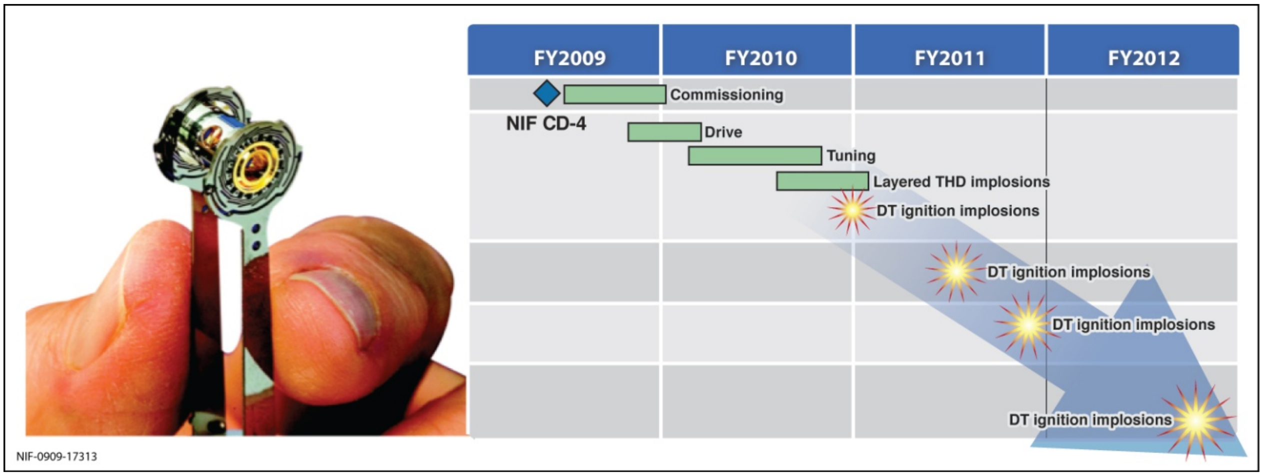

Figure 7. (left). NIF fusion target thermo-mechanical package, (right) schedule for NIC experimental campaigns.

B. NIC Experimental Plan

The NIC experimental plan consists of a series of implosion experiments as shown in Fig. 7 (right). The first series will culminate with the first attempts at inertial fusion ignition in late FY2010. Subsequent series 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.

Each NIC experimental series involves setting 14 laser and 3 target parameters to those required for ignition conditions via a combination of experiments and computational simulations. The laser and target parameters to be tuned are shown in Fig. 8. The tuning of these parameters corresponds to tailoring the capsule adiabat, velocity, symmetry, and degree of hydrodynamic instability to that required for ignition. These 17 parameters are tuned in four phases designed to tailor the laser and cryogenic deuterium-tritium target to ignition conditions. In the first or "drive" phase, the empty hohlraum is tuned to produce the necessary radiation drive on the capsule as a function of time. In the "tuning" phase, 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" conditions required for ignition. The third phase consists of layered cryogenic implosions conducted with a 74%/24%/2% mix of tritium, hydrogen, and deuterium ("THD") respectively. The reduced yield from these 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 deuterium-tritium ignition implosions with expected gains of up to 10-20. The FY2010 layered-target ignition experiments will be conducted with E_{laser} ~1.2 MJ. Laser energies of 1.8 MJ should be available for subsequent experimental series.

NIC experiments on NIF commenced with hohlraum energetics experiments in August FY2009. These first crucial experiments are measuring backscattered laser energy from NIF hohlraums and directly address the issue of laser-plasma instabilities, a key area of risk examined by JASON and other review committees.

In preparation for execution of the ignition experimental series, the NIC team has conducted a "simulated campaign" to exercise the experimental team and develop the ability of NIC scientists to quickly tune the ignition target to the correct conditions. The "Blue Team" specified and executed simulated experiments that exercised much of the NIF laser, target, and operational infrastructure, while the "Red Team" provided synthetic data that took into account specified target fabrication errors, laser power imbalance, backscatter, and cross-beam energy transfer. Over a several month period, the Blue Team 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 to ignition conditions.

IV. NIF EXPERIMENTAL PROGRAM

While ignition experiments will be the primary focus of the ICF Campaign and NIC through FY2012, as shown in Fig. 8, NIF will execute other experiments in support of stockpile stewardship, national defense, and fundamental science. Experiments conducted in collaboration with the Defense Threat Reduction Agency (DTRA) and the Missile Defense Agency (MDA) will validate NIF as an ultra-low debris soft x-ray (E < 15 keV) simulator. Nuclear survivability tests of specific components will also be conducted. NIF will also execute initial experiments in fundamental high-energy-density science; a solicitation for such experiments was issued in early September 2009. Potential NIF users will be encouraged to develop experiments leveraging the various experimental capabilities evolved to date for NIC and other high energy density science activities.

The achievement of ignition at NIF will demonstrate the scientific feasibility of ICF and motivate more detailed consideration of ICF as an option for clean, sustainable energy. Both pure fusion and fusion-fission hybrid schemes for energy production are under consideration and have been described elsewhere [14]. The latter appears considerably attractive given the closed nature of the fuel cycle and the possibility of burning spent nuclear fuel and excess weapons plutonium and highly enriched uranium.

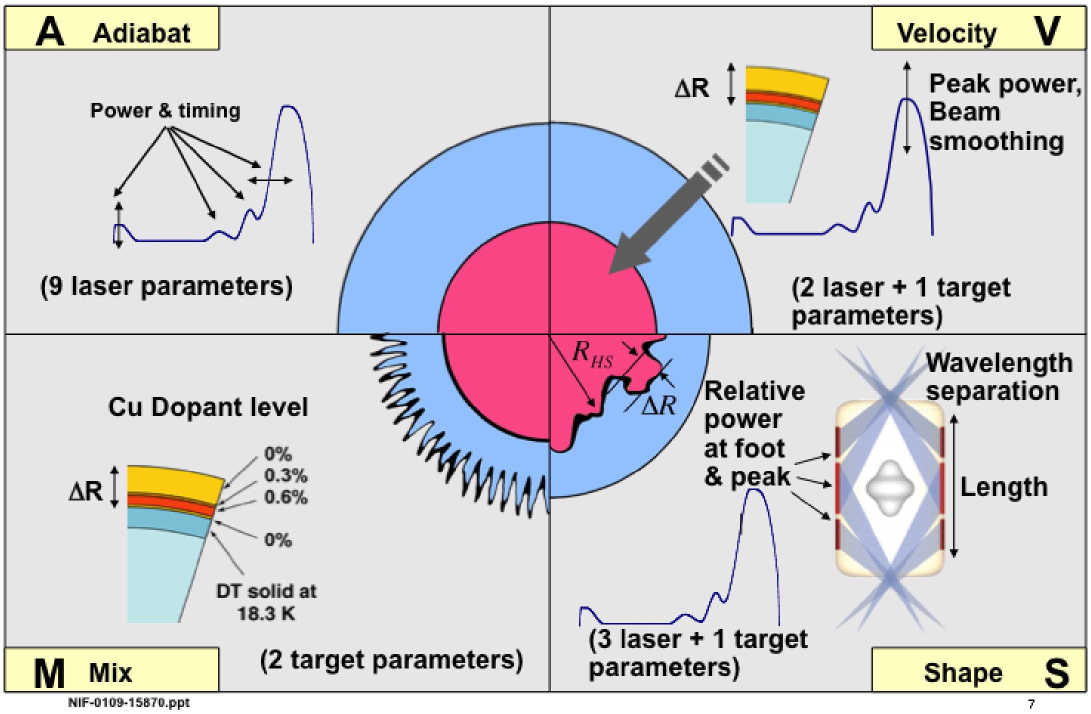

Figure 8. Laser and target parameters to be tuned in the NIF ignition campaigns.

V. CONCLUSION

After many years of R&D, most of the pieces needed for demonstrating ignition at NIF are in place, including the NIF laser, a detailed point design with adequate margin, high-quality targets meeting all specifications, and advanced diagnostics capable of precision tuning of capsule performance to ignition conditions. The National Ignition Campaign is the centerpiece of the NIF experimental program. NIF ignition will allow access to the burning plasma regime for the first time, enabling important stockpile stewardship studies and demonstrating the scientific feasibility of ICF. More generally, NIF's ability to expose materials to 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 the Department of Energy's national security, energy, and fundamental science missions. NIF and other major facilities worldwide will launch a new era in high-energy-density science. The demonstration of ignition may one day lead to an inexhaustible power supply on earth.

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