Status and plans of the United States ICF Program

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Abstract. Inertial confinement fusion research in the United States focuses on demonstrating ignition on the NIF at the beginning of the next decade and on broad high energy density science (HEDS) research. Three facilities (OMEGA EP, the refurbished Z, and NIF) will be completed in the next two years. The US approach emphasizes lasers and pulsed power and both direct and indirect drive. Since IFSA 2005 in Biarritz, France significant advances have been made towards demonstrating ignition in a joint effort by LLNL, LLE, LANL, SNL, and GA. An active HEDS research program will also be pursued on these new facilities.

1. Introduction
The three major US inertial confinement fusion (ICF) facilities (OMEGA, Z, NIF) provide complementary capabilities for studies of radiation flow, radiation hydrodynamics, instability and mix, opacity, equations of state, target physics, and inertial fusion concepts, leading to the demonstration of ignition on the National Ignition Facility (NIF) early in the next decade. A detailed plan to execute ignition experiments in 2010, the National Ignition Campaign (NIC), has been developed. The NIC is a national effort among LLNL, LLE, LANL, SNL, and General Atomics (GA) that includes optimizing the symmetry and shock timing techniques and developing the necessary equipment—such as targets, diagnostics, the cryogenic target system, and user optics—to achieve ignition.

2. Status of ICF facilities
Upgrades to two ICF facilities are nearly complete: the refurbished Z pulsed power facility at Sandia National Laboratories (SNL) and the OMEGA Extended Performance (OMEGA EP) laser at the Laboratory for Laser Energetics (LLE) at the University of Rochester. The NIF at Lawrence Livermore National Laboratory (LLNL) is 93% complete and will be fully operational in 2009.

2.1. The Z facility
Before its refurbishment, Z’s high current (20 MA) electrical pulse power was 50 TW with a rise time of <100 ns.[1] In September 2007 the refurbishment project (figure 1) completed the replacement of the 22-year-old components on Z to enhance its reliability and improve the high energy performance. This shared national facility will retain the name Z and is expected to have 30% more current (26 MA) and twice the electrical power (100 TW) with a pulse duration that can be varied between 100 - 300 ns. The refurbished Z will be capable of conducting experiments with improved data quality and reproducibility and at a higher shot rate than the 240 annual rate that was achieved in 2006. A short-pulse, high-energy enhancement (10 ps, 2 kJ by 2009) is being implemented on the Z-Beamlet laser, a core diagnostic on Z. This petawatt capability will create new opportunities to explore advanced radiography, a fast ignition ICF concept, and the basic science of matter under extreme conditions.
2.2. OMEGA EP
Scaled direct-drive experiments are performed on OMEGA as a complement to indirect-drive experiments. OMEGA EP, scheduled for completion in April 2008 (figure 2), will create a flexible experimental platform for HEDS, advanced radiography, and fast ignition studies by adding four NIF-scale laser beams and a separate target chamber to the existing 30-kJ, 60-beam OMEGA laser system. Two of the beams can operate as short-pulse, petawatt-level (2.6 kJ, 1 - 100 ps) beams. All four beams can operate as long-pulse, UV beams, producing up to 6.5 kJ in a 10-ns laser pulse. The two short-pulse beams can be directed to the existing OMEGA target chamber or to the new OMEGA EP target chamber, while the long-pulse beams can only be directed to the new chamber.

![Figure 1. Overhead view of the refurbished Z.](image)

![Figure 2. Overhead view of OMEGA EP.](image)

2.3. NIF
NIF is a 192-beam neodymium-glass laser facility to be completed in 2009 that will produce 1.8 MJ and 500 TW of ultraviolet light, making it the world’s largest and most powerful laser system.[2] The NIF Project is 93% complete, with the entire beam path nearly finished. Single-beam experiments have attained a laser energy equivalent to over 2 MJ in an ignition pulse. The modular design has allowed tests to validate the capability of the full facility to meet and exceed ignition requirements.[3] The optical and electronic laser equipment is being installed, including the transport and final optics, and two clusters (96 beams) have been commissioned through their 1ω sections. The NIF Project has demonstrated the capability to produce over 2.1 MJ of 1ω light, which is nearly 40 times that possible in routine operation on Nova or OMEGA. The transport of the first beams to the target chamber center is planned for the fall of 2007. Half the 192 beams will be activated by the end of 2008 in a symmetric configuration in order to begin evaluating the hohlraum energetics and capsule symmetry as a step towards ignition experiments. An Advanced Radiographic Capability, consisting of four beams operating at >13 kJ in 10 ps, will be used to diagnose the ignition cores and for HEDS and fast ignition research.

2.4. Nike
Nike is a krypton fluoride (KrF) laser at the Naval Research Laboratory (NRL) that has the advantage of a short wavelength, broad bandwidth, and uniform illumination. These characteristics enable reduced laser energy and higher gain for direct drive and should be beneficial for evaluating advanced target schemes such as shock ignition and fast ignition.

3. Inertial Confinement Fusion
Significant progress has been made in the last two years towards the goal of performing the first ignition experiments on NIF in 2010 with indirect drive. Several target designs using 1.0 - 1.3 MJ of laser energy have been developed. The baseline “point design” (figure 3) uses a Cu-doped Be ablator.
High-density carbon and Ge-doped CH are being evaluated as alternative ablators. The various ablators are calculated to ignite with different degrees of sensitivity to hydrodynamic and laser plasma instabilities. Understanding and managing the tradeoffs among these sensitivities and the requirements for target fabrication, laser performance, and diagnostics is a major activity of the NIC that is rooted in large-scale simulations coupled with a suite of experimental measurements and diagnostic technique validations on OMEGA and Z. An example is the detailed equation of state and melt characterization data for Be and high-density carbon.[4] Effort is also being expended in benchmarking predictive capabilities related to laser plasma interactions and in validating the symmetry and shock timing techniques that will be used to tune the ignition target on NIF. Target designs are being validated experimentally by assessing drive symmetry techniques, characterizing ablator performance, and studying laser-plasma interactions in long-scale-length plasmas. For example, the shape of an imploding, D₂-filled CH capsule inside a 0.7-NIF-scale hohlraum has been detected on OMEGA by imaging the x-ray emission, and the imploding core shape has been controlled by varying the beam pointing of the inner and middle laser cones.[5] The x-ray ablation rates in candidate capsule materials have been measured in OMEGA experiments.[6] The critical intensity for onset of Backward Stimulated Raman Scattering has been examined on OMEGA for NIF-relevant hohlraums as a function of plasma density and laser intensity to guide target design in order to mitigate this effect.

All ignition designs require the implosion of a thick DT ice layer. A complex pulse shape on OMEGA with a high-intensity picket before the main pulse[7] has directly compressed a cryogenic D₂ capsule (with a ~100-µm-thick ice layer) to 202±7 mg/cm²[8] as shown in figure 4. A smooth (<2-µm rms) inner ice-layer surface was required to achieve this areal density, the highest ever measured in an ignition-relevant laboratory implosion.

4. Target Fabrication
The ignition target point design has been specified in detail for the Be ablator, the fill tube and glue fillet, the DT ice, tenting structures, hohlraum material, and target ice validation access. There are hundreds of entries in specification sheets, with tolerances, in terms of the size (Legendre modes and isolated defects), surface finish, cleanliness, impurities concentration, cryogenic temperature, gas fill,
leak rate, and shelf life. All Be ablator specifications have been individually achieved, as reported in the accompanying conference papers. We are entering the pilot production phase for demonstrating acceptable yield and throughput of the target components and assembly. Particular achievements are: (1) low-leak-rate, graded-dopant Be ablator, (2) a 5-µm fill hole in a 150-µm-thick ablator with a cofinear larger hole for gluing the 10-µm-diameter fill tube to the ablator, (3) a cocktail hohlraum wall with alternating Au and U layers and a shelf life of >28 days, (4) precision thermo-mechanical packages that allow centering of a shell in a hohlraum to within 8 µm while providing the proper thermal environment for layering, (5) sub-millikelvin temperature stability over many weeks for the first article of the indirect-drive target inserter cryostat, and (6) demonstration of a “fast quench” approach to creating smoother cryogenic DT layers.

5. Inertial Fusion Energy (IFE)
The High Average Power Laser Program is developing the science and technologies for a laser fusion power plant that builds upon results from the ICF program (Sec. 3). The key components for a power plant are being developed in concert, closely coupling the science, technology, and final purpose to ensure the IFE source is economically attractive. The Mercury diode-pumped solid state laser (DPSSL) at LLNL and the Electra KrF gas laser at NRL have demonstrated high-energy, rep-rated (2.5 – 10 Hz) operation of long duration (>10,000 shots at 300 J for KrF and nearly 300,000 shots at 60 J for DPSSL). Both lasers have made progress in achieving the >7% wall plug efficiency required for an energy application. Other achievements include bench demonstrations of tracking and engaging the injected target, continuous production of foam shells that can meet target specifications, demonstration of high-damage-threshold (>15 J/cm² at 5 × 10⁷ shots) grazing-incidence metal mirrors, and a reactor chamber concept that uses magnetic fields to divert ions from the first wall. The pulsed power approach to a z-pinch power plant, based on 3 GJ target yields and fusion gains of 50 - 100, relies on recyclable transmission lines and a reliable and efficient linear transformer driver architecture for petawatt-class z-pinch accelerators.[9] A prototype module has been tested on more than 13,000 shots without failure.

6. Summary
We are entering an exciting time for ICF with the upgrades to Z and OMEGA and the completion of NIF. Improved target designs and experiments are providing confidence in the NIC plans for the first ignition experiments in 2010, and most target fabrication requirements have been met. The new facilities will provide unprecedented HEDS regimes for basic science research. Complementary research on repetitive laser and pulsed power drivers, target chamber dynamics, and new target concepts are strengthening the IFE program.

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References
[1] Matzen M K et al. 2005 Phys. Plasmas 12 055503-16
[2] Moses E I, Miller G H and Kauffman R L 2006 J. Phys. IV France 133 9-16
[3] Haynam C et al. 2006 J. Phys. IV France 133 575-585
[4] Knudson M D 2007 J. of Physics Conf. Series, TuO8.2, these proceedings
[5] Hoffman N M 2007 J. of Physics Conf. Series, MO1.4, these proceedings; Regan SP, et al. 2007, MP03, these proceedings
[6] Olson R E 2007 J. of Physics Conf. Series, TuO1.4, these proceedings
[7] Goncharov V, Knauer J P, McKenty P W et al. 2003 Phys. Plasmas 10 1906-1918
[8] Harding D 2007 J. of Physics Conf. Series, TuP11, these proceedings
[9] Stygar W A, Cuneo M E, Headley D I et al. 2007 Phys. Rev. ST Accel. Beams 10 030401-24