SAND2007-5746C

Status and plans of the United States ICF Program

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Abstract. Inertial confinement fusion research in the United States is focused on demonstrating ignition in the laboratory at the beginning of the next decade and a broader high energy density science research program. Three experimental facilities (OMEGA EP, the refurbished Z, and the NIF) will be completed in the next two years. The US approach emphasizes lasers and pulsed power and both direct- and indirect-drive target configurations. Since IFSA 2005 in Biarritz, France significant advances have been made in preparing to demonstrate ignition on the NIF. An active research program in high energy density science will 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 towards the demonstration of ICF ignition on the National Ignition Facility early in the next decade. A detailed plan to execute ignition experiments in 2010, the National Ignition Campaign (NIC), has been developed. NIC is a national effort among LLNL, LLE, LANL, SNL, and General Atomics (GA) that includes evaluating the target physics and developing the necessary equipment—such as diagnostics, the cryogenic target system, and the user optics—to conduct the ignition experiments.

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 National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) will be completed 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. In September 2007 the refurbishment project (figure 1) will complete 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 updated 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

(ZBL). 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

OMEGA EP, scheduled for completion in April 2008 (figure 2), will create a flexible experimental platform 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 for HEDS physics, advanced radiography, and fast ignition studies. 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 either the existing OMEGA target chamber or the new OMEGA EP target chamber, while long pulse beams can only be directed to the latter chamber.

Figure 1. Overhead view of the refurbished Z.

Figure 2. Overhead view of OMEGA EP.

2.3. NIF

NIF is a 192-beam neodymium-glass laser facility that will be completed in 2009 and will produce 1.8 MJ and 500 TW of ultraviolet light, making it the world's largest and most powerful laser system.[1] The NIF Project is 93% complete, with the entire beam path nearly finished. Single-beam experiments have attained a laser energy equivalent to over 1.8 MJ. Experiments in 2005 with one bundle (8 beams) demonstrated laser performance that meets or exceeds ignition requirements.[2]

The optical and electronic laser equipment is being installed, including the transport and final optics, and two clusters (96 beams) have been commissioned. The NIF Project has demonstrated the capability to produce over 2.1 MJ of 1ω light, which is nearly 40 times that possible on Nova or OMEGA. The transport of the first beams to the target chamber center is planned for the fall of 2007. Half of the 192 beams will be activated by the end of 2008 in a symmetric configuration for early opportunity shots in order to begin ignition experiments.

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 an indirect-drive configuration. Several target designs use 1.0 - 1.3 MJ of laser energy. The capsule designs use a variety of low-Z ablators (Be, high-density carbon, or doped-CH). Figure 3 shows the baseline. All the designs are calculated to ignite with a reasonable margin for hydrodynamic and laser plasma instabilities. The designs are being validated experimentally by evaluating drive symmetry techniques, characterizing ablator performance, and studying laser-plasma interactions in long-scale-length plasmas. The shape of an imploding, D_2-filled CH capsule inside a 0.7-NIF-scale hohlraum has been detected in OMEGA experiments by imaging the x-ray emission, and the imploding core shape can be controlled by varying the beam pointing of the inner and middle laser cones.[3] The x-ray ablation rates in candidate capsule materials have been measured in OMEGA experiments.[4] 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, and this data is being used 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 [5] has directly compressed a cryogenic D_2 capsule (with a ~100 µm thick ice layer) to 202 ± 7 mg/cm^2 [6] as shown in figure 4. A smooth (<2-µm rms) inner ice-layer surface was required to achieve this areal density, which is the highest ever measured in an ignition-relevant laboratory implosion.

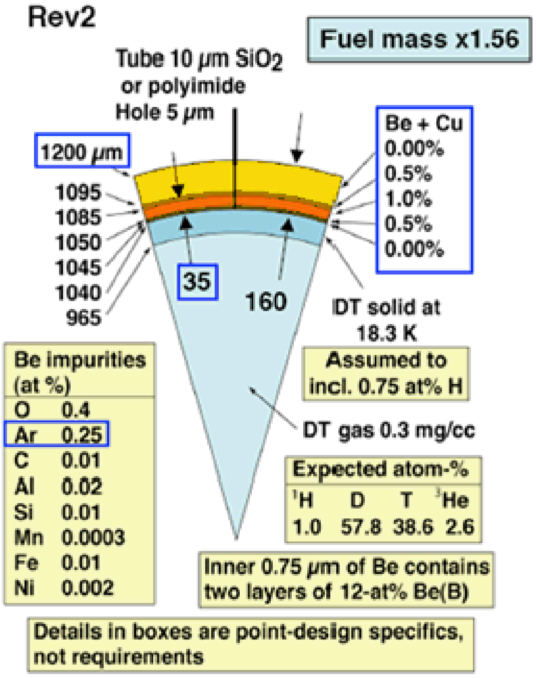

Figure 3. Capsule point design for indirect-drive ignition on NIF.

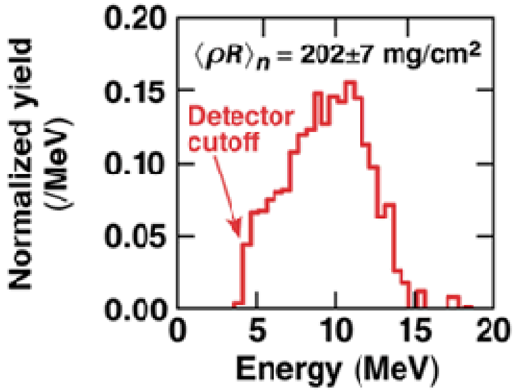

Figure 4. Measurement of fuel ρr with D^3He fusion proton energy loss in compressed cryogenic D_2 capsule.

4. High Energy Density Science

Z's unique capability is to produce copious x rays, large plasma environments, and controlled high pressures to evaluate high energy density science (HEDS) phenomena.[7] In the z-pinch mode, Z has produced the earth's most powerful (200 TW before the refurbishment) and most efficient (15%) laboratory source of x rays. The MJ-class x-ray sources are used to validate radiation transport algorithms and opacity models. In the short-circuit mode, the magnetic fields enable material samples to be driven to high pressures without shock formation. Z's material property capability was recently used to obtain accurate data on the melt properties of two capsule ablators (Be and high density carbon) whose microstructure in a solid state can seed instabilities that could prevent ignition.[8].

After ignition is demonstrated, NIF will become the premiere laser facility for exploring new HEDS regimes, with greater than 50 times more energy and 20 times more power than present laser facilities. Questions in astrophysics, high–pressure material properties, radiation transport, and other areas will be addressed. Studies of the nuclear processes that formed the heavy elements in the periodic table may become possible using the unprecedented neutron fluxes that will be produced. NIF will transition to a shared national facility by 2012. Plans for governance of NIF as a shared national facility are being developed and initial experiments in HEDS and basic physics are being planned.

5. Inertial Fusion Energy (IFE)

The High Average Power Laser Program is developing the science and technologies for a laser fusion power plant and builds upon the results from the ICF program (Sec. 3). Key components of the power plant are being developed in concert while closely coupling the science, technology, and final purpose to ensure that the IFE source is economically attractive. A diode-pumped solid state laser (DPSSL) at LLNL and a krypton fluoride (KrF) gas laser at the Naval Research Laboratory (NRL) have demonstrated 2.5 - 10 Hz operation during long-duration, high-energy runs (>10,000 shots at 300 J for KrF and >100,000 shots at 60 J for DPSSL). Progress has been made by both lasers in achieving the >7% wall plug efficiency required for an energy application. Other achievements include bench tests of a system to track and engage the injected target, continuous production of foam shells that can meet target specifications, demonstration of high-damage-threshold (>15 J/cm^2 at 5×10^5 shots) grazing-incidence metal mirrors for the final optics, 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 design is based upon 3 GJ target yields and fusion gains of 50 - 100. This approach 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. Target Fabrication

The specification sheets for the point design for the ignition target are now under change control. There are hundreds of entries, with tolerances, for the target in terms of the detailed size (Legendre modes and isolated defects), surface finish, cleanliness, impurities concentration, cryogenic temperature, gas fill, leak rates and shelf life. The specifications are for the beryllium ablator, the fill tube and glue fillet, the DT ice, tenting structures, hohlraum material and target ice validation access. All of the specification for the Be ablator point design have been individually achieved as reported in accompanying papers at this conference. We are now entering into the pilot production phase in which we are demonstrating acceptable yield and throughput of the components and assembly of the ignition targets. Of particular note in achieving specifications are: (1) the graded doped Be ablators, (2) the 5-micron fill hole in the 150 micron ablator, (3) attaching the specified 10-micron-diameter fill tubes to full thickness shells, (4) making the cocktail hohlraum wall with alternating layers of Au and U with a shelf life of > 28 days, (5) all of the above processes are now in pilot production.

7. 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 of the target fabrication requirements have been met. The new facilities will provide unprecedented HEDS regimes for laboratory basic science research. Complementary research on repetitive laser and pulsed power drivers, target chamber dynamics, and new target concepts are strengthening the inertial fusion energy program.

Acknowledgments

Contributions from S. Batha, J. Kilkenny, D. Meyerhofer, E. Moses, and J. Sethian are appreciated.

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