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2006 Plasma Phys. Control. Fusion 48 B497

(http://iopscience.iop.org/0741-3335/48/12B/S47)

Plasma Phys. Control. Fusion **48** (2006) B497–B506 doi:10.1088/0741-3335/48/12B/S47

The NIF Ignition Program: progress and planning

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Received 23 June 2006
Published 14 November 2006
Online at stacks.iop.org/PPCF/48/B497

Abstract

The first experimental campaign for ignition, beginning in 2010 after NIF construction and commissioning are completed, will include experiments to measure and optimize key laser and target conditions necessary for ignition. These 'tuning campaigns' will precede the first ignition shots. Ignition requires acceptable target performance in several key areas: energetics, symmetry, shock timing and capsule hydrodynamics. Detailed planning and simulations for 'tuning campaigns' in each of these areas is currently underway, as part of the National Ignition Campaign (NIC) Program. Tuning and diagnostic methods are being developed and tested on present facilities, including the OMEGA laser at the Laboratory for Energetics (LLE), the Z facility at Sandia National Laboratories (SNL), and the Trident laser at Los Alamos National Laboratory (LANL). Target fabrication development is underway at General Atomics (GA), Lawrence Livermore National Laboratory (LLNL), and LANL.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The plan under development for the first ignition experiments on NIF is designed to optimize specific laser and target conditions necessary for ignition. These 'tuning campaigns', which will precede the first ignition shots, will confirm the target performance in several key areas, and at the same time, be consistent with the facilities developing capabilities during its first several years of operation—including commissioning of the NIF laser, and the supporting technologies that are required for ignition [1]. These include the cryogenic target system, ignition diagnostics, and installation of special optics specific to the ignition target requirements. Operation in 2010 will be 'ramped up' during the year, to a maximum of $\sim$1 MJ laser energy (3ω) for the first actual ignition experiments late that year. Operation after 2010 will be extended to implode targets at higher energies.

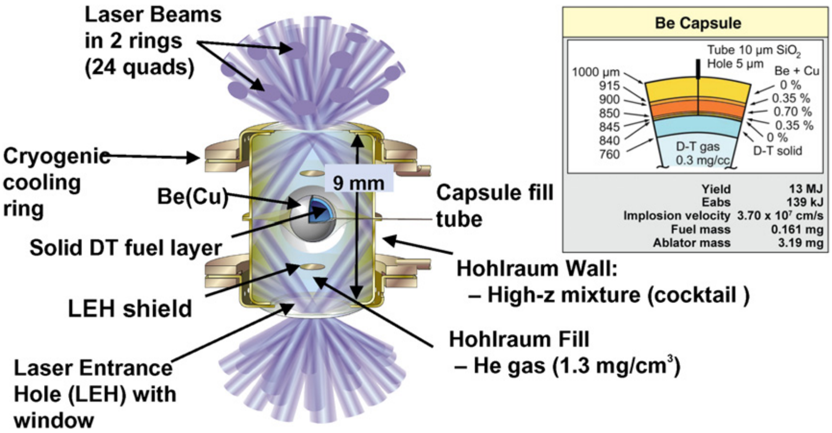

Figure 1. Schematic of ignition target.

The experimental 'tuning' campaigns will be conducted in two major phases, consistent with the facility commissioning, with operation at 0.35 MJ in early 2010, and up to 1 MJ in late 2010. The first phase will allow an assessment of target performance, under conditions relevant to 1 MJ targets, through the use of two types of targets; (a) '0.7-scale targets', where all target dimensions, the laser spot size and the laser pulse duration are reduced by a factor of 0.7, and the laser power is reduced by 0.5[6], and (b) full size targets ('Scale-1'), where the laser pulse is not scaled, but may be truncated in time.

2. Ignition target design

Ignition requires acceptable target performance in several key areas [2]: (1) energetics—the hohlraum must be heated to the required radiation temperature to drive the capsule implosion; (2) symmetry—the x-ray flux on the capsule must be sufficiently isotropic to implode the capsule with adequate sphericity; (3) shock timing—the time dependent x-ray flux in the hohlraum must drive four shocks through the capsule with the correct relative timing and pressure to compress the internal deuterium–tritium (D–T) fuel on a low isentrope. (4) Capsule hydrodynamics—the rate of x-ray driven ablation of the capsule material must implode the capsule to the correct velocity and with sufficient hydrodynamic stability.

The selection of the point design for the 2010 ignition targets is an optimization over all aspects of the system performance. The design must be consistent with the laser's maximum energy, peak power, beam-to-beam power balance and pointing accuracy. It must be consistent with a set of specifications and tolerances for the non-ideal aspects of the targets that will be shot, such as roughness of the capsule and fuel surfaces, and variations of target dimensions, material compositions and densities. Although a complete discussion of the full target specifications is beyond the scope of this paper, several of the important aspects are summarized below [3].

The 'Scale-1' ignition target for the 2010 ignition campaign is shown in figure 1. It consists of a 2 mm-diameter beryllium capsule, containing solid D–T, suspended inside of a high-Z cylindrical hohlraum. The D–T is introduced into the capsule through a small diameter

[6] For a fixed radiation temperature, the laser energy is approximately proportional to the cube of the hohlraum scale, and the laser power is approximately proportional to the square of the hohlraum scale.

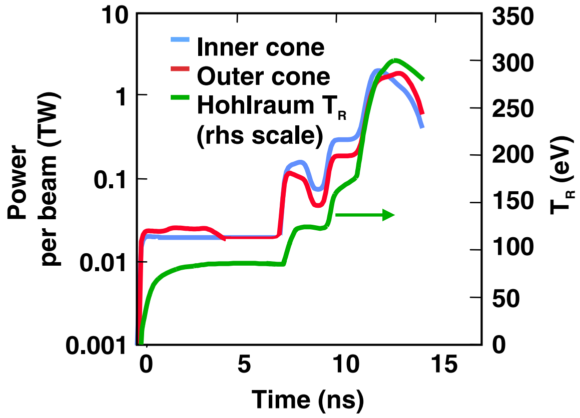

Figure 2. Time dependent laser power and hohlraum radiation temperature (eV).

fill-tube (SiO_2), prior to freezing and 'beta-layering' [4]. The Be capsule is doped with a small amount of Cu, with concentration varying in the radial direction, as shown in the insert in figure 1. This dopant distribution plays an important role in improving the hydrodynamic stability of the target, shielding the innermost Be layer from penetrating x-rays, and allowing it to remain at a density closer to that of the D–T fuel [5]. As a result, the 'graded Cu doped' Be target can tolerate approximately a factor of 3 times greater roughness of the outer surface than designs with constant Cu concentration[7]. Manufacture of these capsules is extremely demanding, but most of the specifications have been met [6].

The cylindrical hohlraum is ∼9 mm-long, and ∼5.2 mm in diameter. It is made from a mixture ('cocktail') of gold and uranium [7][8]. The hohlraum may also include 'laser entrance hole (LEH) shields', made from the high-Z cocktail mixture[9]. The hohlraum has thin plastic windows on the ends, and is filled with low-pressure He gas. The target will be illuminated with all 192 NIF beams, where each laser spot on the hohlraum wall is made up of four beams grouped together, forming a 'quad'. The 48 quads are arranged in 'inner' (8 quads) and 'outer' (16 quads) rings at each end of the hohlraum. 'Beam smoothing' techniques will be applied to the beams to minimize the laser intensity in the hohlraum. These include phase plates, to tailor the shape and size of the spot formed by each quad, smoothing by spectral dispersion (SSD), and polarization smoothing.

The 2010 ignition experiments will use ∼1 MJ of laser energy to heat the hohlraum to a radiation temperature of 300 eV. A typical time history of the laser pulse, showing the separate shapes for the inner and outer beams, and the resulting radiation temperature required to drive the ignition capsule, is shown in figure 2.

[7] The graded Cu doped capsule can withstand a root mean square (rms) roughness of 110 nm in modes 15–1000. This rms would result in a 50% yield reduction in a target that was perfectly tuned and unperturbed from other effects. To allow margin for other errors, the capsule smoothness requirement is set to 30 nm rms in modes 15–1000.

[8] The mixture serves to fill in gaps in the absorption at particular x-ray wavelengths, thereby reducing the energy lost in heating the wall material, and improving the efficiency of re-emission, however, the propensity of U to oxidize makes the manufacture and longevity of these hohlraums challenging.

[9] The overall benefit of adding LEH shields is under assessment. Shields can increase the radiation drive on the capsule because they block the capsule's view of the cold LEH, but they also impact the plasma conditions inside the hohlraum, potentially leading to less favourable laser-target coupling. The addition of shields affects the precise dimensions of the hohlraum. In particular, the length is reduced by ∼10% with shields due to the additional drive on the capsule poles.

Table 1. Summary of energetics efficiency for a range of target designs.

Energy (MJ)	Au hohlraum with CH capsule (1997)	Au hohlraum with Be capsule	Cocktail hohlraum with Be capsule	Cocktail hohlraum with diamond capsule
Laser light	1.45	1.08	1.0	1.0
Absorbed	1.30	0.97	0.9	0.9
X-rays	1.10	0.825	0.765	0.765
Wall loss	0.68	0.51	0.425	0.405
Hole loss	0.28	0.20	0.20	0.195
Capsule	0.14	0.14	0.14	0.165
Efficiency	9.7%	12.5%	14%	16.5%

3. Tuning campaigns

The 'tuning' campaigns will validate the important physics processes of the ignition design, leading to the 2010 integrated ignition experiments. Energetics is the first key area of optimization of the target. The overall coupling efficiency of laser energy to the capsule, for typical NIF designs, is in the range 10–15%. A summary of the energetics is shown in table 1. The absorbed capsule energy is 0.14 MJ for the designs in the first three columns. For the current 'point design' for the 2010 ignition experiments (cocktail hohlraum with Be capsule), this should be achieved with 1 MJ of laser energy. For all columns, 10% of the laser energy is assumed to be lost to backscatter from laser plasma instabilities and 85% of the remaining is converted to x rays when the beams interact with the high-Z wall. The fraction of the resulting x-ray energy that is lost from heating the walls is lower for the cocktail designs (55%) than the Au hohlraum designs (62%), due to the higher albedo of the mixed high-Z materials. Comparing the first two columns, the low-Z Be capsule is more efficient (17%) at absorbing the x rays than the CH capsule (13%). In each case the fraction of the total x-ray energy lost out to the LEHs is ~25%. The 2010 'point design' has an overall efficiency of 14%, significantly higher than our original designs from 1997 [8].

The fourth column in table 1 shows the energetics for a cocktail hohlraum with a diamond capsule. Although diamond has lower x-ray absorption than Be at the same *fixed* capsule radius, it has an overall energetics advantage. Due to its higher density, the shell is thinner for a given amount of ablator mass. For the same initial capsule radius, the *shock compressed* ablator is at larger radius for a longer time for diamond than for Be, allowing it to absorb more of the drive. Currently, the fabrication technology for Be is more mature than for diamond, [9, 10] therefore Be has been selected as the 'point design' for the 2010 ignition campaign. There continues to be excellent progress in the fabrication of these capsules[10] [11] and they will be reassessed in 2007.

The energetics 'tuning' experiments will demonstrate that the x-ray power in the hohlraum is within 10% of the time-dependent design specification (figure 2). These experiments will use a target nearly identical to the ignition target, but the capsule will contain D_2 gas rather than a solid D–T layer. The absorbed laser energy will be inferred by two instruments, full aperture backscatter station (FABS) and the near backscatter imager (NBI), which measure the backscattered laser light into and around the f-number of two of the beams (1 'inner' and 1 'outer'). The x-ray radiance (power/area/solid-angle) emitted from the hohlraum will be measured using an absolutely calibrated x-ray detector, which views a region of the interior wall through one of the LEH. Both of these instruments were activated in a series of early NIF experiments, using a single quad of beams [12–16]. Finally, the capsule absorbed energy will

[10] The capsules are produced by chemical vapour deposition, and then polished.

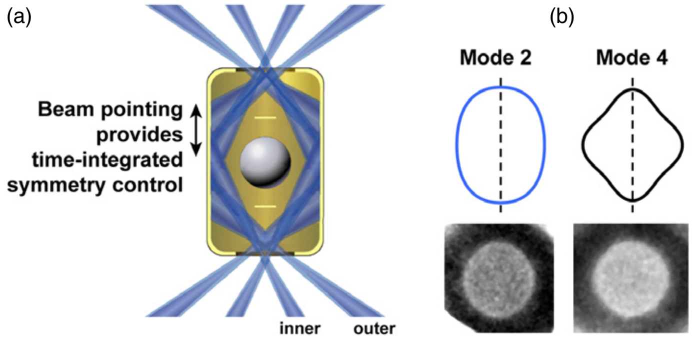

Figure 3. (*a*) Beam and hohlraum geometry showing inner and outer beams pointing. (*b*) The two lowest order asymmetries (P2 and P4), shown schematically, and in x-ray images from a foam surrogate target.

be inferred from a time resolved measurement of the x-rays and neutrons emitted when the imploded capsule reaches peak compression time ('bang time'). The majority of the energetics campaign will be performed in the 0.7 scale targets, where radiation temperature near 300 eV will be achieved. Performance will then be confirmed in Scale-1 targets at 1 MJ.

The symmetry 'tuning' experiments are designed to ensure that the capsule implodes with adequate spherical symmetry. Specifically, the time averaged variations in the x-ray flux symmetry must be less than 1%, and time dependent variations, of duration Δt, must be less than $\sim 10\%/\Delta t\,(\mathrm{ns})$ [17]. Initially, as the hohlraum heats, the albedo of the wall rises and the drive increases on the capsule waist. Later, as more plasma fills the hohlraum, the absorption of the laser beams occurs further back along the ray path, causing the drive to increase on the pole. The symmetry is 'tuned' by varying the laser beam pointing positions along the hohlraum wall, and the ratio of the laser power on the 'inner' and 'outer' beam cones (figure 3) [18].

A suite of symmetry methods has been developed to measure and tune the symmetry of the radiation drive throughout the duration of the x-ray drive. It makes use of several capsule 'surrogates' to enhance the effects of asymmetry and therefore the measurement sensitivity. At early times, a high-Z coated sphere will be used in place of the capsule. Asymmetry in the incident x-ray flux is enhanced in the high energy x-ray ($h\nu \gg kT_R$) Planckian re-emission from the high-Z sphere [19]. At intermediate times, the surrogate is either a low density ($\sim 0.1\,\mathrm{g\,cm^{-2}}$) foam ($SiO_2$) sphere or a Be capsule with a thinner ablator region [20]. In both cases the distortion of these surrogates, as they implode, is enhanced over that of an ignition capsule. The shape of the surrogate is imaged with a time-gated detector, using x-ray backlighting. A final technique, appropriate for the end of the drive pulse, relies on imaging the self-emission from the hot imploded capsule. The flux asymmetry sampled by the target can be varied by changing the thickness of the ablator, and therefore the capsule implosion time [21]. The symmetry tuning campaign will be naturally suited to the truncated pulse operation in early 2010, since symmetry must be tuned progressively throughout the time history of the x-ray drive. The final symmetry tune will then be confirmed in Scale-1 targets at 1 MJ.

In the shock timing campaign, we will adjust the strength and timing of the four shocks that are launched by the steps in the x-ray drive pulse (figure 2), so that the D–T fuel is compressed efficiently. The first three shocks must be timed so that they coalesce at the correct position in the D–T, to an accuracy of 50 ps. The arrival of the final shock must be timed relative to these to within 100 ps [22]. The first three shocks will be timed by measuring their coalescence in a surrogate target consisting of a Be capsule filled with liquid D_2. A hollow cone-shaped pedestal, joining the capsule to the hohlraum wall, will provide a vacuum line-of-sight to the interior D_2 filled region. The leading shock position in the D_2 will be determined with a laser interferometer (VISAR) [23], to observe the arrival of the subsequent shocks. This technique will not work for the fourth shock due to ionization ahead of the shock front. It's timing could be adjusted by stepping its launch time in decreasing increments down to 100 ps, but we are also developing approaches that are more deterministic. Tuning the first three shocks will require truncating the laser pulse, and is consistent with the planned operation in early 2010. The final tune will be confirmed in Scale-1 targets at 1 MJ.

The capsule hydrodynamics tuning campaign will be used to confirm aspects of the hydrodynamic stability of the ablator and to set the final ablator dimensions. The manufacturing process of the Be capsules leads to a material with a micrometre-scale crystalline structure. Diamond capsules also have a crystalline structure, but with nanometre-scale features. In their solid phase, the sound speed in both materials is anisotropic, raising the possibility that the crystalline morphology could seed perturbations that would grow hydrodynamically to unacceptable levels. The requirement set by the target design is that the fractional velocity perturbation, as the shock enters the D–T fuel, is small compared with the allowed fractional variation in ablator thickness, or $\sim 30\,\text{nm}/160\,\mu\text{m} \approx 2 \times 10^{-4}$. For Be, simulations and current models suggest a combination of x-ray pre-heat and the first shock ($\sim$3 Mbar) will melt the material, mitigating this risk. For the diamond design, the predicted melt pressure is higher ($\sim$5–8 Mbar), but the spatial scale of the crystalline features is smaller. Current estimates indicate that, for diamond, it will be sufficient if the second shock ($\sim$20 Mbar) melts the material. For both materials, there are uncertainties in the melt models and in the pressure range over which solid and melted phases coexist. The physics of this problem is highly complex and should be confirmed by experiment. Studies on existing experimental facilities are ongoing to test the models, and may provide sufficient confidence without a confirming experiment on NIF.

The second part of the capsule hydro-dynamics tuning campaign will be used to set the final ablator thickness. The requirement from the target design is that the remaining ablator mass, when the capsule reaches peak implosion velocity, be known to within 1% of its initial mass ($\sim$10% of its final mass). This tuning campaign will make use of a range of experiments and techniques. Experiments will measure 'burn-through' in a planar Be ablator sample, mounted on the side of a hohlraum, where x-ray emission is observed from the outside [24]. In spherical geometry, the remaining mass can be inferred by a combination of measurements from an imploded Be capsule, including 'bangtime' and nuclear activation of Cu in the Be [25]. These experiments require the desired 300 eV radiation drive, but the majority can be performed in the 0.7 scale targets, with final confirmation in Scale-1 targets at 1 MJ.

4. Recent progress and current research

Experiments are ongoing at a number of research facilities, in support of the National Ignition Campaign. These are focused on confirming key aspects of the target design and development of experimental methods for the tuning campaigns. Some highlights from this work are summarized below.

As summarized in table 1, the energy savings resulting from using a 'cocktail' of high-Z materials (Au and U) for the hohlraum wall rather than pure Au, is $\sim$100 kJ,—a significant advantage and an important feature in the 2010 ignition target design. In a series of experiments

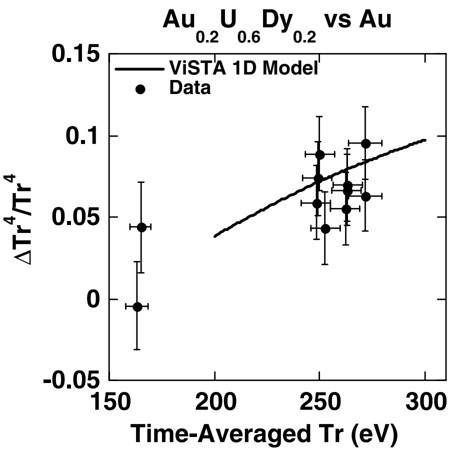

Figure 4. Increase in hohlraum soft x-ray radiation flux between cocktail hohlraum and gold hohlraum versus time-averaged radiation temperature. The line is a prediction from a 1D model incorporating the latest Equation of State and opacity models for the high Z elements used.

performed on the OMEGA laser at LLE, we verified the expected performance of cocktail hohlraums, over a range of radiation temperatures [26]. For these experiments we used a hohlraum made of a mixture of gold, uranium and dysprosium. Figure 4 shows the fractional increase in x-ray flux as measured by an absolutely calibrated soft x-ray spectrometer [27]. The key to the success of these recent experiments was in mitigating formation of lossy oxide layers in the uranium through improved fabrication, handling and storage procedures. These hohlraums were fabricated by co-sputtering materials on the inside two halves of a hohlraum mandrel that were rejoined during final assembly. An improved method of fabrication more suitable for routine production of ignition hohlraum assemblies, based on thin alternating layers of the high-Z materials, is under development by researchers at General Atomics [28].

In the area of capsule hydrodynamics, we are conducting experiments to test our hydrodynamic modelling of implosions. We have recently concluded an extended study, performed on the OMEGA laser at LLE, of the effects of capsule surface roughness on implosion performance [29]. These experiments used plastic capsules that were deliberately roughened by a laser-ablation technique[11]. To assess implosion performance, we measured neutron yield, and the shape of the x-ray emitting imploded core to ensure adequate implosion symmetry. The hohlraum illumination geometry allowed for symmetric implosions up to a convergence factor of 17, $2\times$ greater than for previous Nova implosions [30]. The experimental and calculated yields are shown in figure 5. Integrated simulations that include and do not include the effects of mix (i.e. 'clean') are shown for each shot. The simulated yields that include mix match the data within better than a factor of two over more than an order of magnitude variation in surface roughness and yields. Future experiments will assess the performance of other capsule ablators, including Cu-doped Be and diamond.

In another area of capsule hydrodynamics, we are developing techniques to confirm the expected performance of the 'as-fabricated' crystalline Be and diamond ablators. Direct melt measurements are underway on the Z-machine at Sandia National Laboratories, studying

[11] Capsules were fabricated from germanium doped (1% atomic fraction) plastic (CH), with approximately 440 μm inner diameters and 30 μm thick walls, and filled with 10 atm of deuterium. Surfaces were characterized by a rotary atomic force microscope, and simulations used the full spectrum of measured surface modes.

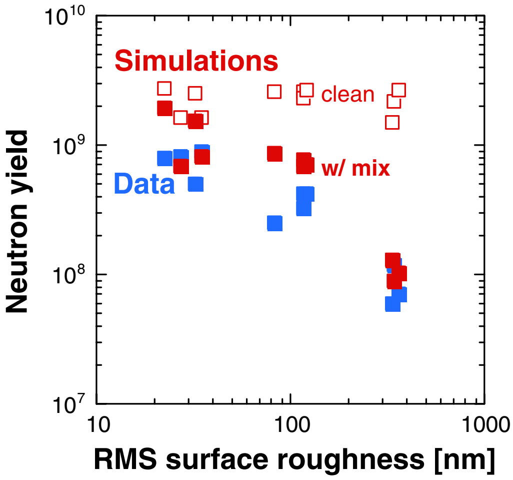

Figure 5. Neutron yield data, and simulations with and without mix ('clean'), plotted against surface roughness.

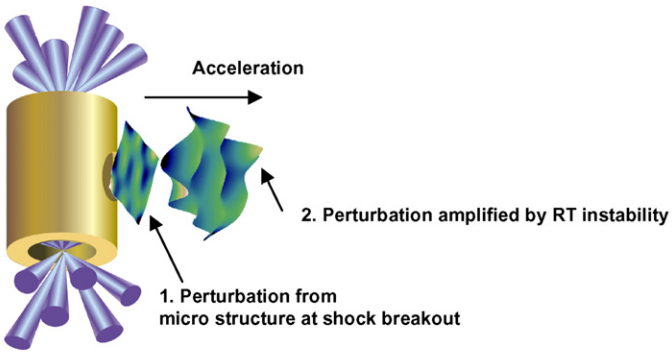

Figure 6. Schematic of experiment for measuring Rayleigh–Taylor growth of perturbations seeded by Be micro-structure.

shock transit though material that has been pre-shocked to pressures above and below the expected melt pressure [31]. At the OMEGA laser at LLE, experiments directly measure the hydrodynamic perturbations in an x-ray driven ablator. These experiments observe the amplified perturbation of a sample of the material, initially mounted on the hohlraum wall, after it has accelerated and grown by the Rayleigh–Taylor instability (figure 6). The resulting variations in the areal density ($\rho\ell$) are measured by x-radiographic imaging. A reasonable areal density modulation for measurement by radiography is $\sim$10%, requiring a 1000$\times$ amplification of the initial 10^{-4} fractional perturbation. In our current experiments on OMEGA, we have reached amplifications of $\sim$200 by staggering the laser beams in time to extend the duration of the x-ray drive, and using a small initial amplitude to avoid saturation. NIF experiments could extend this up to amplification of $\sim$1000 [32]. We are also investigating the possibility of optically measuring the perturbed shock front just as it enters a layer of liquid D_2 [33].

5. Conclusion

Through the expertise and contributions of all the participating laboratories, the National Ignition Campaign Team continues to make rapid progress in all aspects of the physics and technology required for ignition. Detailed planning and preparation for the first ignition experiments is underway.

Acknowledgment

This work was performed under the auspices of the US Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No W-7405-Eng-48.

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