Recent Advances in Indirect Drive ICF Target Physics *

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Abstract. In preparation for ignition on the National Ignition Facility, the Lawrence Livermore National Laboratory's Inertial Confinement Fusion Program, working in collaboration with Los Alamos National Laboratory, Sandia National Laboratory, General Atomics, Commissariat a l'Energie Atomique (CEA), and the Laboratory for Laser Energetics at the University of Rochester, is conducting research in a broad range of areas, including: experiments on the Omega laser to develop improved experimental methods for ignition, refinements of ignition target designs, fabrication of target components, and studies of cryogenic targets required for ignition. Our recent work has been focused in the areas of hohlraum energetics, symmetry, shock physics, target design optimization, and fabrication.

1. Introduction

In preparation for ignition on the NIF, we are conducting research in four principal areas; 1) Hohlraum Energetics and the optimization of laser/hohlraum coupling; 2) X-ray drive symmetry and the development of techniques to measure and control its time dependence; 3) the development of techniques to accurately time the four shock compression of the fuel; and 4) the refinement of ignition capsule designs and the fabrication of cryogenic targets. In this proceedings article we will briefly describe work in some of these areas.

2. Energetics

The quantity of x-rays absorbed by a NIF indirect drive ignition capsule, E_{cap}, can be related to the laser energy, E_L, by the expression

$$E_{cap} = \eta_{abs}\eta_{CE}\eta_{HR\text{-}cap}\, E_L \qquad (1)$$

where η_{abs} is the fraction of incident laser energy absorbed by the hohlraum, η_{CE} is the conversion efficiency of laser light into x-rays and $\eta_{HR\text{-}cap}$ is the fraction of generated x-rays which are actually absorbed by the capsule. For several years we have investigated the possibility of increasing the overall coupling efficiency of absorbed laser light to the capsule, $\eta_{CE}\eta_{HR\text{-}cap}$, by as much as a factor of two over what we had originally assumed in the early 1990's, when NIF was first specified. This increase is not due to any one improvement but, rather, to a compound effect of several small improvements [1]. One of these improvements is

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the reduction of wall losses compared to what we originally expected by replacing the gold wall with a mixture of materials specially selected so the opacity "holes" in one material is filled in by an opacity peak in another material [2,3]. For example, changing the hohlraum walls from pure gold, as modeled in the early 90's, to a mixture of 60%U:20%Au:20%Dy increases the coupling efficiency from 15% to 18% (a 20% improvement).

We have been experimentally studying wall losses for various materials the Omega laser over a range of temperatures. Here we describe measurements to study the temperature scaling of gold and cocktail relative albedo (or ratio of re-emitted x-ray flux to incident x-ray flux) at distinct photon energies. To perform this temperature scaling we use single ended hohlraums (or "halfraums") comprised of a gold cylinder and a split-disc end-cap, where half the split disc is pure gold and the other half is the U:Au:Dy mixture prepared by a co-sputtering technique [4]. By varying the size of the halfraum from 4.8 mm diameter ("scale 3") down to 1.0 mm diameter (scale 5/8) while irradiating them with a 1 ns pulse of ~10 TW we were able to vary the radiation temperature from ~100 eV to >250 eV. Relative albedo information comes from observing the emission of the split disc with a spectrally resolving, soft x-ray framing camera. *FIG.1*, below, shows the results of this scaling series. The red squares and line plots the experimental and theoretical emission of cocktail to gold as a function of temperature at a photon energy of 450 eV. The open circles and black line plot the experimental and theoretical emission at 750 eV photon energy, showing reasonable agreement.

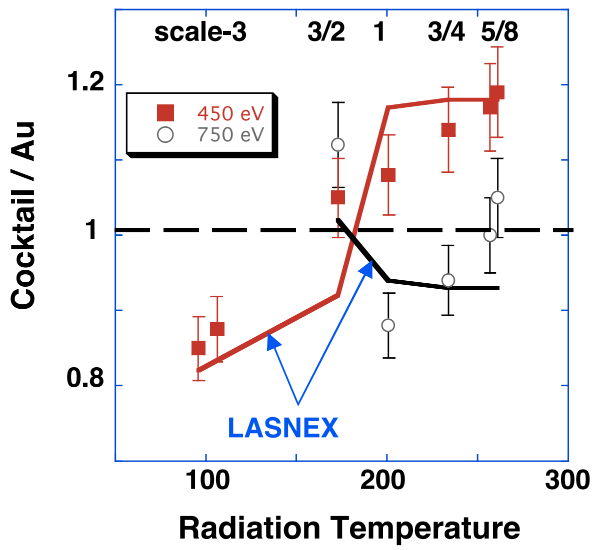

FIG. 1. Ratio of measured x-ray flux from Cocktail and Au endcap vs. radiation temperature.

Complementing the temperature scaling of relative albedo are experiments to measure the absolute albedo at low temperature. These experiments involve putting a known amount of x-ray flux into large hohlraums made of different materials and accurately measuring the resulting radiation environment. Preliminary results from these experiments, which will be published elsewhere, indicate that the low temperature wall losses for pure Au is very close to that predicted by our models.

In addition to work to improve the coupling efficiency, we have also been exploring strategies, beyond those described in reference 1, to extract more energy from the laser in useful ignition pulses (E_L in equation 1, above). This now includes work to explore the use of 2ω, green light, on NIF for ignition; a branch of exploration based on the assumption that the NIF final optics will support significantly higher fluence at 2ω than at 3ω. Our explorations of 2ω, which are ongoing, includes numerical simulation of NIF targets and 2ω interaction experiments on both the Helen Laser at AWE and, now, the Omega laser at the University of Rochester. The results of this work will be reported at future meetings.

3. Symmetry

Ignition of future high convergence implosion targets at NIF will require accurate understanding, control and measurements of hohlraum flux asymmetries. Over the last two years, two campaigns aimed at demonstrating finer symmetry control and measurement than were possible at Nova were completed at the 60-beam Omega facility. First, we have demonstrated better than 1% symmetry measurement accuracy for inferring the first ten Legendre flux asymmetry modes during the foot portion of the NIF ignition hohlraum drive. Second, we have demonstrated near-1D performance for up to convergence ratio 20 (initial capsule-to-final fuel radius) high growth factor implosions by using the NIF-like multiple-cone illumination capability available at Omega. This allows us to bridge the gap between understanding the performance of hydrodynamically equivalent Nova convergence ratio ≈10 implosions and NIF convergence ratio >30 implosions.

We have now routinely demonstrated flux symmetry measurement techniques at larger scales (1.6 – 2.4-mm radius hohlraums) approaching NIF ignition hohlraum scale. In these hohlraums, the first 4 -7 ns of the 90 eV NIF hohlraum drive were emulated using the Omega laser. Both backlit foam balls [5] and thin shells [6][7] were used to infer early time flux asymmetries. Measured out-of-round shape deviations from such driven surrogate capsules are decomposed into Legendre moments (up to mode 8). The sensitivity to higher order asymmetry modes (3 – 8) was increased [8] intentionally by decreasing the ratio of case-to-surrogate capsule radius to as little as 1.6. In a recent series of experiments, surrogate capsules were backlit with 4.7 keV x-rays after the start of a 90 eV drive in a 1.6 mm radius Omega hohlraum illuminated in a NIF-like multiple cone geometry [9][10][11].The measurements were performed at the few µm accuracy, which translates to the ability to infer early time drive flux asymmetries at the < 1% level.

An integrated and stringent test of symmetry control on the Omega laser is the ability to achieve high-convergence (>20) implosions at NIF-like case-to-capsule ratios (≈3). Recent studies have confirmed a large improvement (≈3x) in capsule performance on Omega for moderate convergence (≈9) indirectly-driven capsules [12] compared to the 10 beam, single-cone, Nova laser [13]. Extending these results to significantly higher convergences provides further confidence in reaching the required convergences (>30) for demonstrating ignition on the NIF. We have exploited the improved hohlraum symmetry conditions on Omega to demonstrate high-convergence implosions for a NIF-relevant case-to-capsule ratio of ≈3. The reported high convergences (≈20) are inferred from secondary {D+T(<1.01MeV)→ n(11.8-17.1MeV)+He^4} neutron measurements with the Medusa detector [14] which provide a sensitive indicator of the compressed fuel areal density [15]. This result represents a factor-of-two improvement in the highest observed convergence to date of an indirectly-driven single-shell capsule for a NIF-like case-to-capsule ratio. Similar high convergences have been reported previously with indirect drive but either under conditions of large case-to-capsule ratio (>6) for flux asymmetry mitigation on Nova [16] and Omega [17] or in double-shell experiments on Omega where the fuel convergence is defined relative to the *outer* shell radius [18].

The 3x higher capsule performance can be attributed to the improved symmetry environment offered by the Omega laser system. For the high-convergence targets (C≈19) the effect of 2D flux asymmetry is responsible for ≈40% degradation in neutron yield. For the highest convergence targets (C≈23) the 2D flux asymmetry alone is responsible for a factor-of-3 degradation. Although readily calculable, such a level of flux asymmetry is not compatible with ignition and suggests a practical limit on the Omega laser for performing high-convergence indirect-drive experiments. The NIF is expressly designed to offer improved levels of x-ray drive symmetry for achieving the necessary hot-spot formation compatible with ignition (C>30).

Simulations of these experiments, that include the effects of both intrinsic radiation asymmetry and mix, are shown in *FIG. 2*. The performance of these targets is in good agreement with the predicted DD neutron yields, particularly at the lowest convergences. Other sources of degradation such as long-wavelength $l=2$ (where l is the Legendre mode number) capsule non-uniformities and random flux asymmetry from laser power imbalances exist, but are estimated to contribute less than 10% in total. Thus, for the higher convergence targets *FIG. 2* shows that a 20-30% yield degradation still remains. Most of this degradation can be explained by the effects of a plausible 0.5 μm $l=1$ shell thickness variation which alone can contribute a 20% degradation in yield [19].

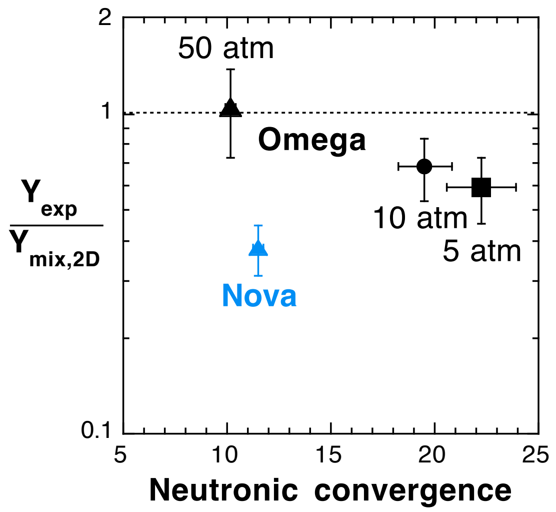

FIG. 2. Averaged ratio of measured primary (DD) neutron yield to 2D simulated yield with 1D mix model versus inferred fuel convergence from secondary (DT) neutron.

4. Ignition Capsules

We continue to investigate and develop three types of ignition capsules: beryllium, polyimide, and CH polymers. As reported at the 1999 IAEA conference [20], these three materials have differences in robustness in ignition designs, in their levels of development, and in other aspects of target fielding.

4.1 Target design simulations

We have concentrated our design simulations in three areas: the beginnings of a systematic re-optimization of the capsules; simulations of ignition diagnostics, and developing more detailed specifications for targets. To re-optimize our ignition designs, we have written a code that automatically determines an adequate low-entropy pulse shape for any set of capsule dimensions. We then scan over design parameters of possible capsules. We scan at fixed outer radius, and fixed integrated x-ray flux onto the capsule (the time-integral of T_R^4). Keeping these fixed ensures that the various capsules being compared will similarly stress the laser and the hohlraum physics. The absorbed energy varies somewhat, according to the variations in albedo of the ablator materials, with the lower albedo ablators absorbing more energy from a given laser-pulse/hohlraum configuration. *FIG. 3* shows a scan over shell thicknesses for polyimide-ablator capsules, at a size and drive energy that correspond to 150 kJ absorbed energy. After finding the optimum capsule at each set of dimensions, we perform 2D simulations of hydrodynamic instability growth for selected points that seem likely to be robust. This procedure results in targets that are significantly more robust than previous un-optimized designs, as shown in *FIG. 4*. Further optimization is being performed for the 300 eV plastic capsules, and in the near future we will examine beryllium capsules and other drive temperatures.

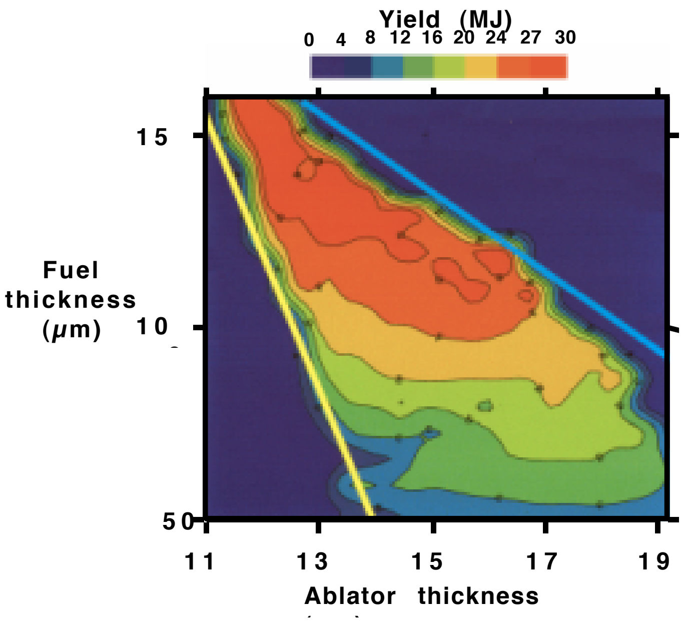

FIG. 3. 1D calculated yields for polyimide targets with varying thickness of DT fuel and ablator, for 1.3 MJ laser energy.

For target fabrication, the re-optimization described above affects many fabrication specifications. We are also simulating instability growth seeded by fill holes, the effects of long wavelength asphericity, the effects of ice roughness, and of material inhomogeneity.

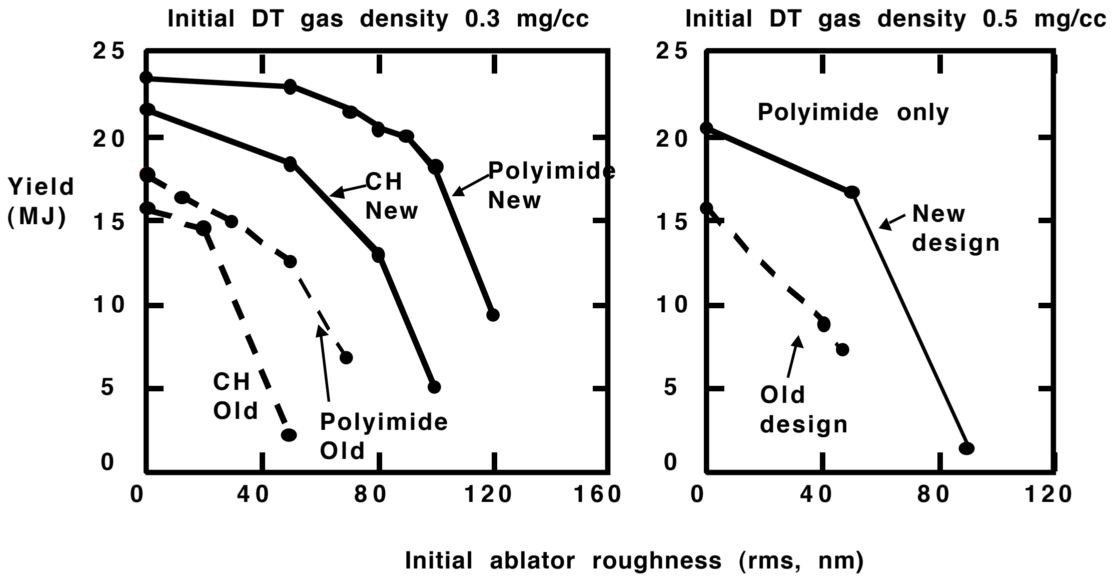

FIG. 4. 2D simulations of modes > 12, for two possible gas fills of interest

4.2. Beryllium Capsules

As we have reported previously, at LLNL we are attempting to make beryllium capsules by sputter deposition onto thin spherical plastic mandrels, while at LANL, machining and bonding of hemishells is being pursued. Our major concerns with sputter deposited beryllium are the microstructure of the material, the uniformity of the additives, the surface smoothness, and filling the capsules with the hydrogen-isotope fuel. We have found that ion-assisted sputter deposition onto a voltage-biased substrate controls the coating morphology. The columnar structure becomes much finer with a voltage bias (80 V) and an ion-bombardment (8 mA). The trace copper concentration is very uniform, with no evidence of micro voids. The surface roughness of the capsules also improves with bias and ion-bombardment, but does not become smooth enough to meet ignition specifications. Nevertheless, we have produced beryllium capsules doped with about 1% copper (atomic) at full NIF-design thicknesses of around 125 μm. We plan to polish the capsule surfaces, but have only started to investigate this.

We are investigating the possibility of filling beryllium capsules by drilling a tiny hole in the capsule, which could be resealed after filling. In a series of tests on flat beryllium foils, we were able to drill 3 - 4 μm diameter holes through 120 μm of beryllium using a highly focused short pulse laser. We are now investigating laser re-sealing by making a micro-weld.

4.3. Polyimide Capsules

We are forming polyimide ablators by vapor depositing two monomer precursors onto polymer mandrels that are subsequently heated to form polyimide [20]. Capsules are produced by carefully mixing and balancing the monomer fluxes to assure stoichiometry. An additional step is required to obtain smooth surfaces [21]. Un-imidized coated shells are levitated on a gas stream saturated with dimethyl sulfoxide vapor. The vapor is absorbed, liquefying the outer portions of the coating allowing surface-tension-driven flows, thus smoothing the bumps and valleys. The levitated shell is then imidized in place by raising its temperature. With this process, and using the best capsule coating apparatus and processes developed to date, we have produced capsules that are as smooth as the underling mandrel.

Both sputter deposited beryllium and vapor deposited polyimide shells require good coating mandrels. The quality of the mandrels limit the quality of the final capsule, so we must have mandrels that are "NIF quality", which means that their surface mode amplitudes are less than those required for ignition. A joint LLNL – General Atomics (GA) team, working at GA, has succeeded in this task. Mandrels are prepared by a two-step process. A "pre-mandrel" made from polyalpha methylstyrene (P□MS) by microencapsulation. is over-coated with a thin layer of plasma polymer. Upon heating, the P□MS decomposes and diffuses through the plasma polymer wall, leaving the plasma polymer as the final mandrel. The plasma polymer mandrel largely conforms to the P□MS pre-mandrel. The details are published elsewhere [22], but the results of optimizing the processing procedures and parameters has produced significant improvement in the modes ~10 to 20, with surfaces that meet requirements.

4.4. Cryogenic Fuel Layers

We have found that smooth solid D-T layers grown from a single nucleation point at the triple point (19.7 K), begin to roughen upon cooling below 19.3 K. However, current ignition designs perform best with interior vapor densities corresponding to target temperature of 18.3 K. Similarly, smooth HD and D_2 layers formed by solidifying at the triple point while heating with infrared at a level equivalent to the beta-heating rate in D-T (termed "1 Q_{DT}") also roughen if cooled more than a few tenths of a Kelvin. We found that raising the HD bulk infrared heating rate to 25 to 40 Q_{DT} preserves the initially formed smooth surface down to 1.5 K below the triple point [23]. Similar results have been seen at University of Rochester Laboratory for Laser Energetics, where direct-drive laser irradiation experiments of cryogenic targets are currently ongoing. We are preparing to test this with D-T, but may be limited somewhat by infrared absorption in the polymer capsule itself.

All of our layering studies during the past few years have been performed with capsules centered in spherical cavities that serve as infrared integrating spheres and establish the spherical isotherms necessary for a layer with uniform thickness [24]. We have recently demonstrated layering with infrared irradiation in a D_2 filled capsule in a cylindrical cryogenic hohlraum, where the isotherms for a uniform hohlraum wall temperature are not spherical. Cones of infrared are directed into the laser-entrance holes (LEHs) where they diffusely scatter from specially roughened interior hohlraum walls. The diffuse reflection of the infrared illumination provides uniform absorption in the solid layer. By changing the pointing and intensities of the infrared cones, guided by a sophisticated optical and thermal model, the layer uniformity can be controlled. The layer profile in the central plane perpendicular to the hohlraum axis is measured using shadowgraphy, while along the axis the layer thickness is measured using spectral interferometry. The details of the method of forming these layers has been published previously [25].

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