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Recent Advances in Indirect Drive 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, Commissariat a l'Energie Atomique (CEA), and Laboratory for Laser Energetics at the University of Rochester, has performed a broad range of experiments on the Nova and Omega lasers to test the fundamentals of the NIF target designs. These studies have refined our understanding of the important target physics, and have led to many of the specifications for the NIF laser and the cryogenic ignition targets. Our recent work has been focused in the areas of hohlraum energetics, symmetry, shock physics, and target design optimization & fabrication.

1. Introduction

In preparation for ignition on the NIF, we are performing a range of experiments on the Nova and Omega lasers to refine our understanding in key areas of target physics. This work is divided into 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 it's 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. Due to limited space, we will briefly describe work in some of these areas below.

2. Energetics

We can relate the quantity of x-rays absorbed by a NIF indirect drive ignition capsule, E_{cap}, to the laser energy, E_L, via 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 believed that the overall coupling efficiency of absorbed laser light to the capsule, $\eta_{CE}\eta_{HR\text{-}cap}$, might prove to be as much as a factor of two greater than we had originally thought 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 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% (ie, a 20% improvement in coupling efficiency).

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 reemited x-ray flux to incident x-ray flux) at distinct

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photon energies. To perform this temperature scaling we use single ended hohlraums (or "halfraums") comprised of a gold cylinder and an split-disc endcap, 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 4800 μm diameter ("scale 3") down to 1000 μm diameter (scale 5/8) while irradiating them with a 1ns pulse of ~10TW we were able to vary the radiation temperature from ~100eV to >250eV. 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 450eV. The open circles and black line plot the experimental and theoretical emission at 1000eV photon energy. The reasonably good agreement between the theoretical and experimental scaling is consistent with wall losses scaling the way theory indicates they should..

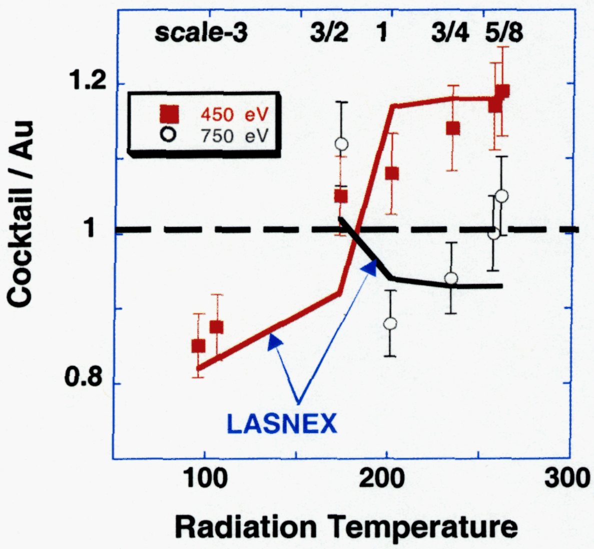


FIG. 1. Ratio of measured x-ray flux from Cocktail and Au endcap vs. radiation temperature

Complementing the temperature scaling of relative albedo are experiments to measure the absolute albedo at low temperature. Here the object is two fold. First, to see if the albedo of pure gold is as high as indicated by predictions (this result would have important implications for early time symmetry). Second is to provide a peg-point for the relative albedo scaling supported by the data of *FIG. 1*. 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.

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 has been emulated using the Omega laser. Both backlit foam balls [5] and thin shells [6][7] have been 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) has been 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 are 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 are performed at the few micron 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 its 10 beam, single-cone predecessor - the 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)Æn(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 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 still tolerable, giving only a ≈40% degradation in neutron yield. For the highest convergence targets (C≈23) we find evidence for a rapid decline in performance where 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). Other sources of degradation such as long-wavelength ($\ell=2$) capsule nonuniformities 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. However, most of this degradation can be explained by the effects of a plausible 0.5 mm $\ell=1$ shell thickness variation which alone can contribute a 20% degradation in yield [19].

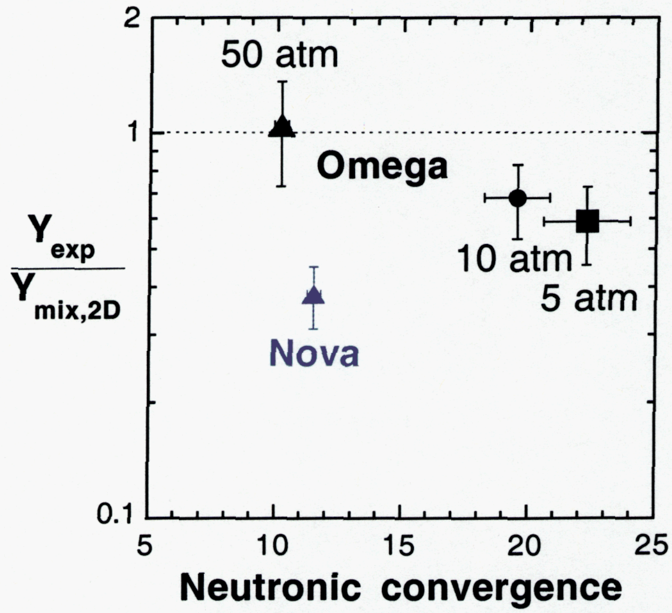


FIG. 2. Averaged ratio of measured primary (DD) neutron yield to 2D simulated yield with 1D mix model versus inferred fuel convergence from secondary (DT) neutrons.

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, these three materials have differences in robustness in ignition designs, in their levels of development, and in other aspcts of tarfget fielding.

4.1 Target design simulations

We have concentrated our design simulations in three areas: the beginnings of a systematic reoptimization of the capsules; simulations of ignition diagnostics, and developing more detailed specifications for targets.

To reptimize 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 unoptimized designs, as shown in *FIG. 4*. Further optimization is being done for the 300 eV plastic capsules, and in the near future we will examine beryllium capsules and other drive temperatures.

For target fabrication, the reoptimization 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 of ice roughness, and of material inhomogeneity. Specifications continue to be challenging — for example, fill holes should be smaller than 5 μm diameter — but appear to be feasible in all cases.

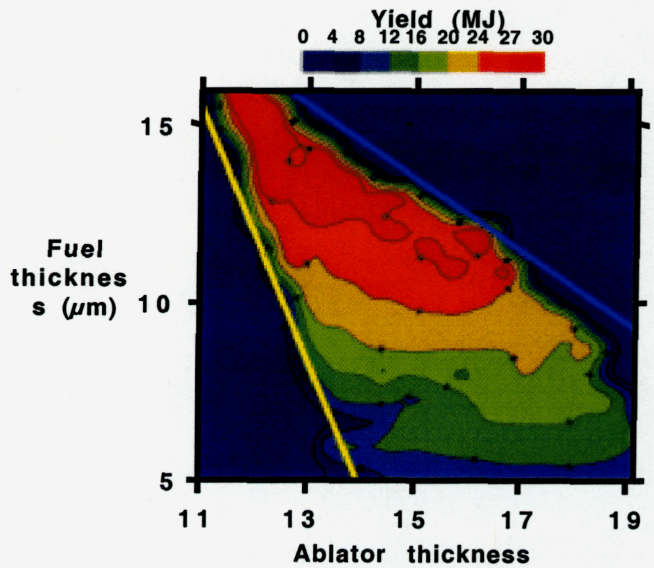


FIG. 3. 1-D calculated yield for polyimide target for varying thickness of DT fuel and ablator, for 1.3 MJ laser energy.

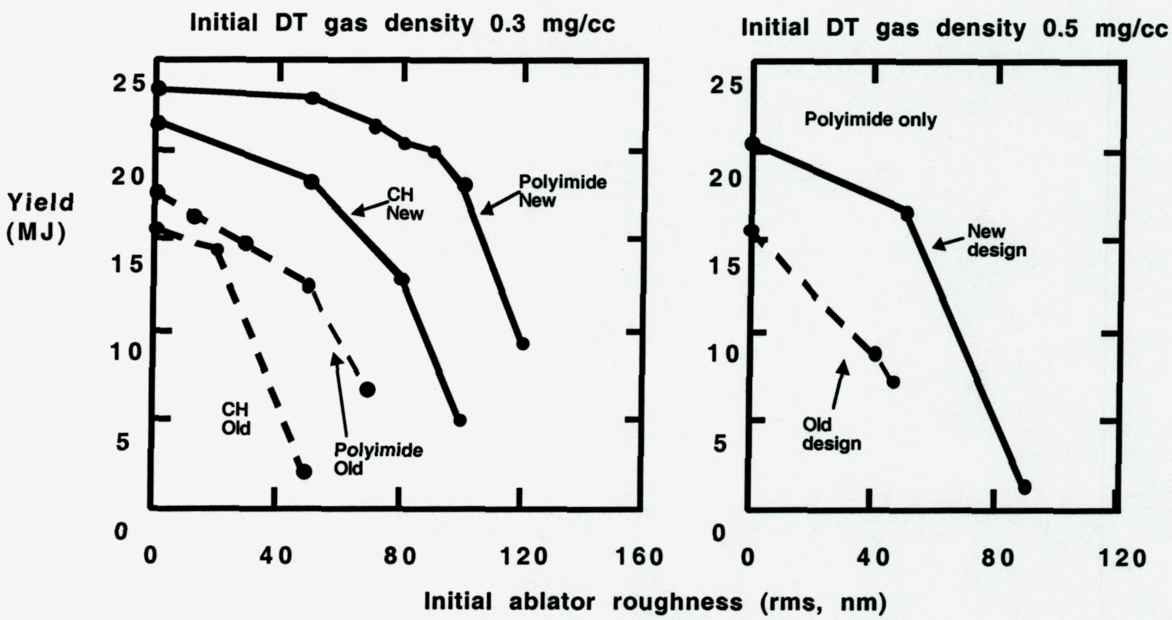


FIG. 4. 2-D simulations of modes > 12, for twp possible gas interest

4.2. Beryllium Capsules

As we have reported previously, at Livermore we are attempting to make beryllium capsules by sputter deposition onto thin spherical plastic mandrels, while at Los Alamos, 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. A secondary issue is the capsule strength.

We have found that ion-assisted sputter deposition onto a voltage-biased substrate controls the coating morphology. The columnar structure becomes much finer with an 80 V bias and an ion-bombardment current of 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 microns. We plan to polish the capsule surfaces, but have only started to investigate this. Preliminary data indicates that capsules produced with high bias voltages and currents have strengths close to that of bulk beryllium.

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-to-4 micron diameter holes through 120 micron 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

As we have discussed previously[20], we are forming polyimide ablators by vapor depositing two monomer precursors onto polymer mandrels which are subsequently heated to form polyimide. By carefully mixing and balancing the monomer fluxes to assure stoichiometry, good capsules can be produced. However even with our best designs of the polyimide coater, however, we are not able to obtain smooth enough capsules.

We have reported invention of a novel technique to smooth the polyimide surfaces[21]. Unimidized coated shells are levitated on a gas stream saturated with dimethyl sulfoxide vapor. The vapor is absorbed, liquifying the outer portions of the coating allowing surface-tension-driven flow. This smooths 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.

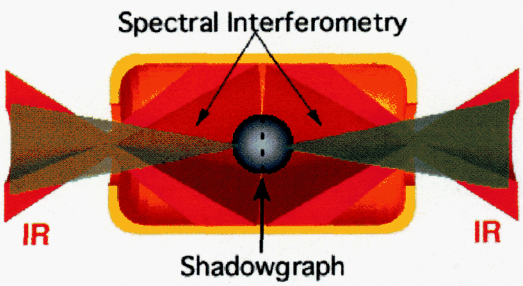
Both sputter deposited beryllium and vapor deposited polyimide shells require good coating mandrels. The quality of the mandrels limit the quality of the final capsule, so we must have mandrels that are "NIF quality", which means that their surface mode amplitudes are les than those required for ignition. 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 (PαMS) by microencapsulation. is overcoated with a thin layer of plasma polymer. Upon heating the PαMS decomposes and diffuses through the plasma polymer wall, leaving the plasma polymer as the final mandrel. The plasma polymer mandrel largly conforms to the PαMS pre-mandrel. We thus focused our effort on the PαMS pre-mandrels. 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 have interior vapor densities requiring the target temperature to be 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. For a D_2 layer in a plasma polymer capsule with the same thickness as the layer, the ratio of capsule heating to D_2 heating is as large as to 2.5 for the best-tuned infrared wavelength, while for DT the ratio is up to 7. The thermal performance of a He/H_2 gas-filled hohlraum limits the total capsule plus fuel heating to less than 10 Q_{DT}, so we may not be able to reach the higher heating levels in the D-T solid.

All of our layering studies during the past few years have been performed with capsules centered in spherical cavities which serve as infrared integrating spheres and establish the spherical isotherms necessary for a layer with uniform thickness[24]. A major recent accomplishment is demonstration of 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), as indicted in *FIG. 5*, where they diffusely scatter from specially roughened interior hohlraum walls. The diffuse reflection isotropizes the infrared, which 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 earlier[25].



A

B

FIG. 5 A. Infrared layering in a hohlraum; B. shadowgraph of a uniform D2 layer. The capsule is filled and supported by a very small fill tube.

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