Progress toward Ignition with Noncryogenic Double-Shell Capsules

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Inertial confinement fusion implosions using capsules with two concentric shells separated by a low density region (double shells) are reported which closely follow one dimensional (1D) radiatively driven hydrodynamics simulations. Capsule designs which mitigate Au M-band radiation asymmetries appear to correspond more closely to 1D simulations than targets lacking mitigation of hohlraum drive M-band nonuniformities. One capsule design achieves over 50% of the unperturbed 1D calculated yield at a convergence ratio of 25.5, comparable to that of a double-shell design for an ignition capsule at the National Ignition Facility.

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It has been speculated that double-shell capsules are too hydrodynamically unstable to reach ignition and high gain because perturbations on the outside of the inner shell are Rayleigh-Taylor unstable during nearly the entire implosion phase and are not ablatively stabilized [1]. However, the simplicity of using noncryogenic high-pressure gaseous fuel, simple laser pulse shapes, and vacuum hohlraums makes it worth while to reconsider this type of capsule for the National Ignition Facility [2]. Although high gain may be difficult to achieve with double-shell capsules, it would still be useful to achieve ignition and burn in DT fuel with gains of the order of 1. One of the last major hurdles to overcome in the quest for ignition is to obtain symmetric implosions and nearly 1D behavior at convergences of 25–35, which are required for ignition. We describe the first experiments that have successfully achieved these high convergences with nearly one dimensional characteristics, using double-shell target designs.

We have fielded indirect-drive double-shell capsules on both the NOVA [3] laser at Lawrence Livermore National Laboratory and the OMEGA [4] laser at the Laboratory for Laser Energetics at the University of Rochester. The experiments at NOVA and the first set of experiments at OMEGA gave YOCs (experimental yields divided by calculated clean 1D yields) of 0.5%–3.0%. The NOVA experiments were fielded in cylindrical hohlraums, and the OMEGA experiments were fielded in tetrahedral hohlraums [5]. We had expected considerably better results in the tetrahedral hohlraums because of much better predicted symmetry of the thermal radiation drive [6,7]. Results in the first set of experiments at OMEGA were virtually identical to the earlier experiments in cylindrical hohlraums at NOVA. Since the thermal radiation in the tetrahedral hohlraums is expected to be very symmetric, the only potential drive symmetry issue is that of asymmetric preheat coming from the gold M-band radiation produced where high intensity laser radiation intersects the Au wall or Au plasma. Since the beams in a tetrahedral hohlraum are focused inside the hohlraum, M-band radiation is generated at variable locations closer to the capsule than the wall, and is hence not as uniform as is the thermal flux. The exact mode structure and time dependence of the M-band asymmetry can be determined only by a 3D radiation-hydrodynamics calculation, which we do not currently have the capability to do.

In the experiments reported here, two capsule designs were used to reduce the damaging effect of M-band asymmetry, one designed to reduce transmission of the M band through the outer shell, and one designed to reduce absorption of the M band in the inner shell. The *standard* double-shell target is shown in Fig. 1. This design is the target which has had the 0.5%–3% historical YOC and which has given the double-shell capsule such a questionable reputation. The *reduced M-band* (doped) target design

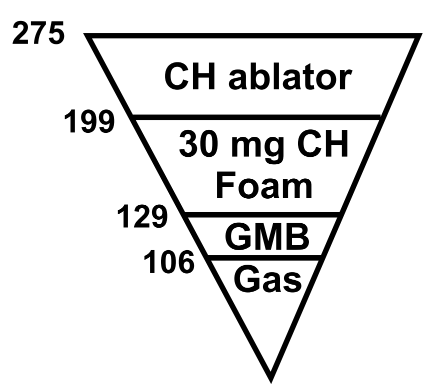

FIG. 1. *Standard* double-shell design used in earlier experiments with no effort at Au M-band mitigation.

replaced the CH ablator with a Br doped CH ablator (12% Br by weight). This doped ablator reduced transmission of the Au M band to the inner shell by approximately 80%. The *reduced absorption* (imaging) target design replaced the inner glass microballoon with a 3 μm thick glass gas bladder coated with 20 μm of CH and retained the pure CH ablator. Replacement of the outer 20 μm of the glass shell with CH virtually eliminated absorption of the 2.5 keV M-band radiation in the outer several microns of the inner shell, near the most unstable interface. The new glass/CH interface is stable due to preheat expansion of the glass. In addition this design allowed an x-ray image of the imploded *core* to be obtained.

Capsules were fielded in 2800 μm inside diameter spherical (tetrahedral) hohlraums with four 700 μm laser entrance holes arranged at the vertices of a tetrahedron, using all 60 beams from the OMEGA laser. Energy incident on the hohlraum was approximately 25 kJ in a 351 nm wavelength, unsmoothed, 1 ns square laser pulse. Backscattered laser energy was typically less than 5% and was accounted for in the simulations. DANTE [8,9] radiation drive measurements were made looking into an empty hohlraum to establish the experimental drive flux and spectrum. The quoted error for DANTE is 30% in flux (7% in radiation temperature). Figure 2 shows the measured radiation temperature (excluding the Au M-band part of the spectrum) for a 25 kJ drive shot. LASNEX [10] simulations used a calculated radiation flux which was scaled to agree with the DANTE measurements in both the thermal and M-band portions of the spectrum. A further scaling was done to correct for the laser energy delivered on each shot. About 6.9% of the flux during the laser pulse is in gold M-band radiation.

The primary measurement on these shots was neutron yield. Burn history measurements were made with an instrument ported from the NOVA laser, when high enough yield was present. The x-ray image of the imploded *core* was observed in the case of the *reduced absorption* target, whose shell density-thickness product ρR was low enough to allow escape of the x rays from the *core*.

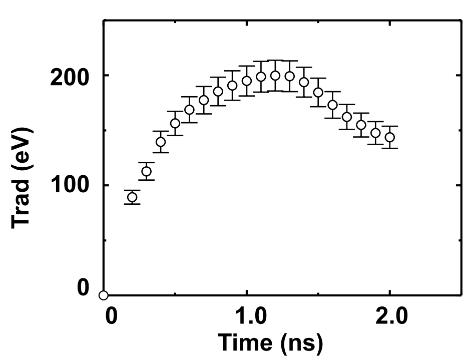

FIG. 2. Radiation temperature history for an empty tetrahedral hohlraum using a 1 ns square drive pulse at OMEGA with 25.5 kJ (including backscatter) incident on target.

Imaging was done with a gated x-ray pinhole camera with 9 μm spatial resolution and 80 ps temporal resolution [11]. The glass shell opacity combined with a 20 mil Be filter restricted the images to energies above 4 keV. (The *standard* and *reduced M-band* target design shell ρR was too large to allow an x-ray *core* image to be taken.) The total yield of the pure deuterium filled (DD) targets was insufficient to allow a core ρR measurement using the OMEGA neutron time of flight spectrometer system which was designed for much higher direct drive yields. Table I shows three representative results in this study.

Figure 3 shows the x-ray *core* image of the *reduced absorption* target. Measured peak compression and burn occur at approximately 2.5 ns in these implosions, more than 1 ns after the laser drive has turned off. The measured minimum *core* diameter is 32.2 μm at the 50% intensity point, in close agreement with the predicted image diameter of 32 μm at the time of peak fuel temperature from the post-processed clean 1D simulation of this shot, using the nominal DANTE flux. The diameter 60 ps later in both simulation and experiment increases, reaching approximately 40 and 36 μm, respectively. The calculated *fuel* diameter differs from the measured *core* diameter because the inner glass shell heats and radiates, increasing the effective *core* diameter beyond that of the fuel. Although the image is not exactly round, 2D yield calculations are quite insensitive to moderate low order mode fuel asymmetries. Simulations of this capsule using a radiation flux 30% above or below the nominal flux showed little sensitivity of the *core* diameter to the flux level (despite a large sensitivity in the total neutron yield), providing confidence in the calculated image diameter. Both *standard* and *reduced M-band* targets used DT gas to increase the yield, allowing operation of the neutron diagnostics where adequate signal levels allowed 10% errors on yield. The *reduced absorption* targets operated at significantly higher YOC and thus also operated in a reasonable region of diagnostic space despite using DD for fabrication reasons.

The results from those shots in which an effort was made to either reduce or mitigate the effect of M-band radiation on the implosion showed significant improvements in behavior relative to the historical few percent of clean yields for double-shell implosions. The best *reduced M-band* target had a YOC approximately 4 times larger than the

TABLE I. Representative results.

Shot	15 526	15 532	15 566
Type	Standard	Doped	Imaging
Gas	DT	DT	DD
YOC	0.022	0.075	0.61
Y_{calc}	1.87×10^{10}	4.95×10^{9}	2.68×10^{7}
$\mathrm{CR}_{\mathrm{calc}}$	31.4	27.7	25.5
$\rho_{\mathrm{fuel,calc}}$	12.8 gm/cm^3	8.8 gm/cm^3	5.51 gm/cm^3
$T_{\mathrm{ion,calc}}$	1.17 keV	0.94 keV	0.79 keV

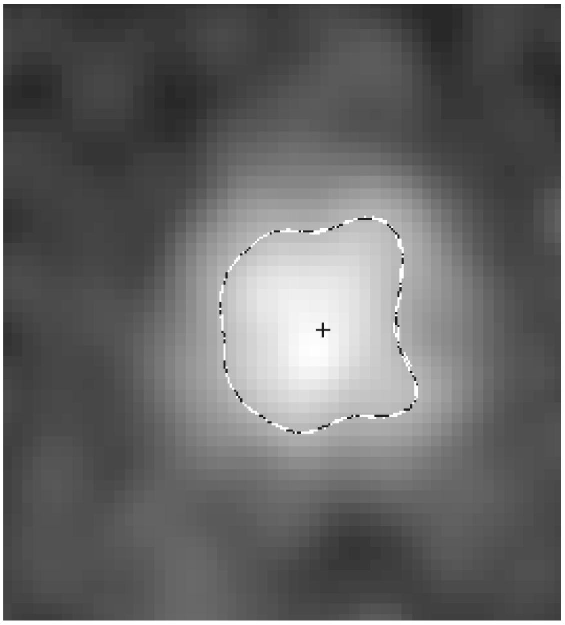

FIG. 3. Imploded *core* image for the *reduced absorption* double-shell design. The dashed line is the 50% intensity contour. The entire frame is 90 μm on a side.

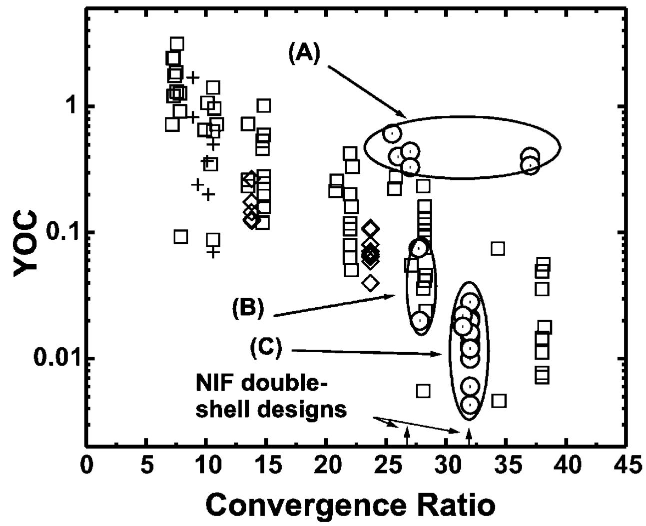

FIG. 4. YOC as a function of CR for 1–1.4 ns square drive pulses. Squares: 1 ns NOVA single-shell data. Diamonds: 1.4 ns NOVA single-shell data. Crosses: 1 ns OMEGA tetrahedral hohlraum single-shell data. Dot centered circles: 1 ns double-shell data (both NOVA and OMEGA shots). The encircled data: (A) *reduced absorption* target design, (B) *reduced M-band* design, and (C) *standard* double-shell design. Arrows indicate two NIF double-shell ignition target designs at CR 27 and 32 using 0.15 g/cm^3 and 0.1 g/cm^3 gas fill, respectively.

standard double-shell design, bringing it into the general YOC region occupied by the single-shell data. All of the *reduced absorption* targets had YOCs of approximately 50%, 25 times the historical double-shell standard. Application of three separate models, a linear mode saturation and superposition model [12], a 2D LASNEX model with all important modes explicitly resolved, and a turbulent transport model [13], all with 250 nm rms perturbation on the outer glass surface, gave 85%, 68%, and 50% of the 1D calculation, respectively, for the *standard* double-shell design. Surface perturbations, therefore, cannot explain the typical 1% performance of the *standard* double-shell targets.

While not conclusively demonstrating that the dominant degradation mechanism for double-shell implosions is indeed M-band asymmetries, the observations are consistent with that conclusion, particularly when the similarity in behavior between cylindrical and spherical hohlraums for targets without any M-band mitigation is noted. Figure 4 shows both the existing single-shell database and the double-shell target implosions from the last several years. The double-shell points use YOC and CR (defined as the ratio of the initial ablator diameter to the burn averaged fuel diameter) from simulations with the nominal DANTE flux. The single-shell data typically use a CR measured using secondary neutron analysis, which is essentially identical in content to the calculated quantity used for the double-shell data. This measurement was not possible in the double-shell implosions due to the low yields involved. If double-shell implosions remain at or above single-shell YOC values at the convergence ratios required for ignition, then the double-shell target can be viewed as a viable alternative to the cryogenic single-shell ignition target, at least for gains of the order of 1.

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