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ABSTRACT

Experiments on imploding an Al capsule in a Au rugby hohlraum with up to a 1.5 MJ laser drive were performed on the National Ignition Facility (NIF). The capsule diameter was 3.0 mm with ∼1 MJ drive and 3.4 mm with ∼1.5 MJ drive. Effective symmetry tuning by modifying the rugby hohlraum shape was demonstrated, and good shell symmetry was achieved for 3.4 mm capsules at a convergence of ∼10. The nuclear bang time and the shell velocity from simulations agree with experimental data, indicating ∼500 kJ coupling with 1.5 MJ drive or ∼30% efficiency. The peak velocity reached above 300 km/s for a 120 μm-thick Al capsule. The laser backscatter inside the low-gas-filled rugby hohlraum was very low (<4%) at both scales. The high energy coupling allows implosion designs with increased adiabat, which, in turn, increases the tolerance to detrimental effects of instabilities and asymmetries. These encouraging experimental results open new opportunities for both the mainline single-shell scheme and the double-shell design toward ignition.

In the laser-driven indirect drive scheme for inertial confinement fusion (ICF), the capsule diameter is typically limited to ∼2 mm in order to attain quasi-spherical implosions in cylindrical hohlraums with the currently available laser energy.[1] Larger capsules would result in asymmetries that are detrimental to the implosion performance. This geometrical factor restricts the energy coupling efficiency from the hohlraum to the capsule to be ∼10%. There are on-going efforts to increase the capsule size for higher coupling while maintaining a good symmetry by modifying the shape of the hohlraum, such as oval-shaped or rugby-shaped hohlraum,[2,3] "I"-shaped I-raum,[4] and frustraum consisting of two truncated cones joined at their largest diameter.[5] Early experiments[6] on rugby hohlraum with high gas fill (He 1.2–1.6 mg/cc) suffered from large backscatter and optics damage. Recent experiments on NIF (N170629-002 and N170828-002) with low gas fill (He 0.3 mg/cc) have demonstrated for the first time ∼300 kJ coupled to a 3 mm Al capsule with 1 MJ drive in a Au rugby hohlraum.[7]

Here, we present a study of 3.4 mm-diameter Al capsules in a Au rugby hohlraum driven by 1.5 MJ laser energy. It is found that the shell symmetry during the implosion is sensitive to the rugby dimensions so that the rugby shape is an effective knob for symmetry tuning. A spherical imploded shell with P2/P0 = 1.6% has been observed near the bang time for 3.4 mm capsules. Measurements of the bang time, neutron yield, and in-flight capsule size show good agreement with simulations, consistent with ∼500 kJ coupled at 1.5 MJ drive. The peak velocity reached 350 km/s in an experiment using a thinner-shell (120 μm) Al capsule based on comparison of the simulation results with experimental data. This velocity is higher than our previous measurements for a shell thickness of 148–173 μm and is comparable to current ICF ignition designs.

The experiments were performed using a standard 2D X-ray radiography platform on NIF.[8] The setup is illustrated in Fig. 1(a). A Zr foil located at 12 mm from the target center was irradiated by 8 NIF beams to generate a 16 keV backlighter.[9] The X-ray radiographs were recorded by a framing camera at specified delays. The rugby wall shape is an arc of a circle, which is defined by the radius at the waist R_w, the radius at the laser entrance hole (LEH) R_{LEH}, and total length L_H.

In comparison to a conventional cylindrical hohlraum that has a straight wall, the curved wall of a rugby hohlraum affects the laser irradiation mainly in two aspects: enlarging the laser spot size on the hohlraum wall and enhancing the specular reflection of the outer beams. The incident angle relative to the wall is increased from 46° in a cylinder to ~67° in a rugby for 44° cones, and from 40° to ~65° for 50° cones. This results in an $\sim 1.4 - 1.8\times$ larger laser spot and lower intensity of the outer beams, which is helpful to reduce the wall bubble expansion.[10] The larger incident angle also leads to higher reflection, or glint, of the outer beams, which points toward the inside of the rugby hohlraum and is helpful to increase the inner beam transmission by heating the plasma there. Figure 1(b) shows a map of the simulated laser energy deposition for a 50° cone at 5 ns. It is clear that there is an ~10% energy deposition by the glint near the waist of the rugby. These beneficial effects, as well as the simulation setup, have been discussed in detail in Ref. 5 for frustraum, and they are applicable to rugby-shaped hohlraum as well.

The sensitivity of the laser energy distribution to the incident angle makes it possible to tune the implosion symmetry by adjusting the rugby wall shape. We have carried out 3 NIF shots with different rugby dimensions, as listed in Table I. The X-ray radiographs and the corresponding rugby shape, laser pulse shape, and measured radiation temperature are shown in Fig. 2. The pulse shape is a 4–5 ns long reverse ramp with peak power 300–400 TW. The peak radiation temperatures are 242–250 eV for the different rugby hohlraums. The wide rugby shown in Fig. 2(a) produced a quite prolate shell with P2/P0 = 13%, where P0 is the average size of the shell, and P2 is the second Legendre mode to represent a prolate ($P2 > 0$) or oblate ($P2 < 0$) shape.[11] A large positive P2 indicates more drive at the waist than at the LEH. A narrow rugby with reduced waist diameter shown in Fig. 2(b) reduced P2/P0 to 8%. This is consistent with less glint at a smaller incident angle. It was found in simulations that the shell symmetry is insensitive to the laser beam pointing because the effects of pointing change and the incident angle change along the curved wall are canceled. Therefore, the symmetry change is mainly due to the rugby shape change. Finally, a scale-up of the narrow rugby produced a very spherical implosion, as shown in Fig. 2(c), with P2/P0 only 1.6%. The hot spot symmetry, which can be different from the shell symmetry, was not measurable in these experiments due to the opaqueness of the Al shell. This symmetry tunability by rugby wall shape will be very useful for the design of future campaigns.

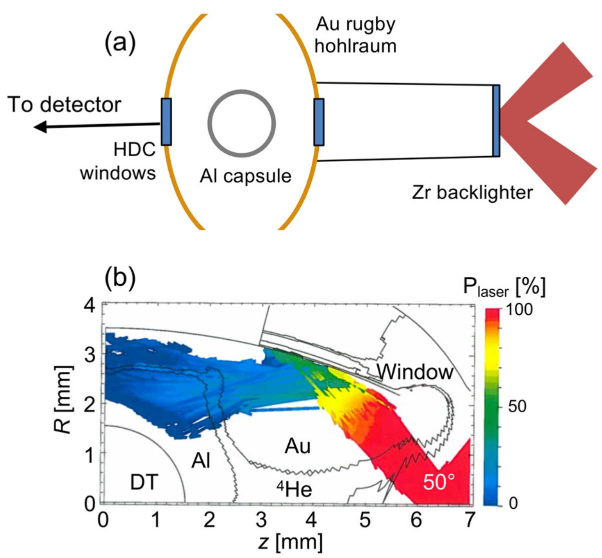

FIG. 1. (a) Experimental schematic. The 16 keV X-rays from the Zr backlighter produced a 2D image of the imploded capsule for symmetry assessment. The diagnostic windows are made of high-density carbon (HDC). (b) Simulated laser energy deposition of the 50° cone in the rugby hohlraum at 5 ns, showing the glint or specularly reflected light from the hohlraum wall.

TABLE I. Parameters for the 3 NIF shots shown in Fig. 2. The numbers in the bracket in the row of laser energy are the backlighter beam energy.

	N171030-001	N180624-002	N190428-002
Laser total energy (kJ)	1084 (BKL 66)	871 (BKL 67)	1505 (BKL 64)
Laser backscatter	3.3%	1.3%	0.4%
R_w (mm)	3.5	2.9	3.5
R_{LEH} (mm)	1.80	1.80	2.17
L_H (mm)	9.86	9.86	11.29
Capsule OD (μm)	3032	3032	3472
Capsule thickness (μm)	148	148	173
Probing time (ns)	12.9	13.3	15.1
P0 (μm) at maximum slope	420 ± 20	390 ±15	417 ± 9
P2 (μm)	55 ±6	30 ±11	7 ±2
P2/P0	13%	7.7%	1.6%

Nuclear diagnostics were enabled in shot N190122–002 with a 7 mg/cc DT gas fill in the Al capsule, providing measurements to infer the energy coupling to the capsule. The capsule and rugby hohlraum dimensions are the same as N190428–002, which is 0.9× scale in our design series. The laser energy was 1558 kJ in total, which includes the backlighter beam energy of 66 kJ. The measured nuclear bang time is 15.10 ± 0.15 ns, in good agreement with the simulated value 15.0 ns. The DT yield is $8.11 \pm 0.25 \times 10^{13}$, and the 2D simulated yield is 1×10^{14}, so the yield over clean (YOC) reaches 78%. The normalized burn history was measured by a gamma reaction history (GRH) detector.[12] The GRH generally operates at higher yields but was able to collect a relatively low-statistics signal (<8000 collected gamma rays). A 150ps-average smoothing was applied on the data to reduce noise. Figure 3(a) shows the comparison of the simulated and measured burn histories. The agreement is very good except for a bump at early time in the simulation that corresponds to the shock yield. The simulated burn width at FWHM is 900 ps, which is within the experimental uncertainty 753 ± 150 ps. The shell size, defined as the maximum slope in the X-ray radiograph taken at 15.1 ns, is $329 \pm 14\,\mu m$ in the measurement and 338 μm in the simulation, also in good agreement. Figure 3(b) shows the simulated energy absorption by the capsule at three scales, 0.7×, 0.9×, and 1.0×. The energy coupled to the capsule reaches 350, 500, and 650 kJ with 1.0, 1.5, and 2.0 MJ drives, respectively. The good agreement between multiple measurements and simulations indicates a coupling energy of ~500 kJ in the 0.9× scale experiments.

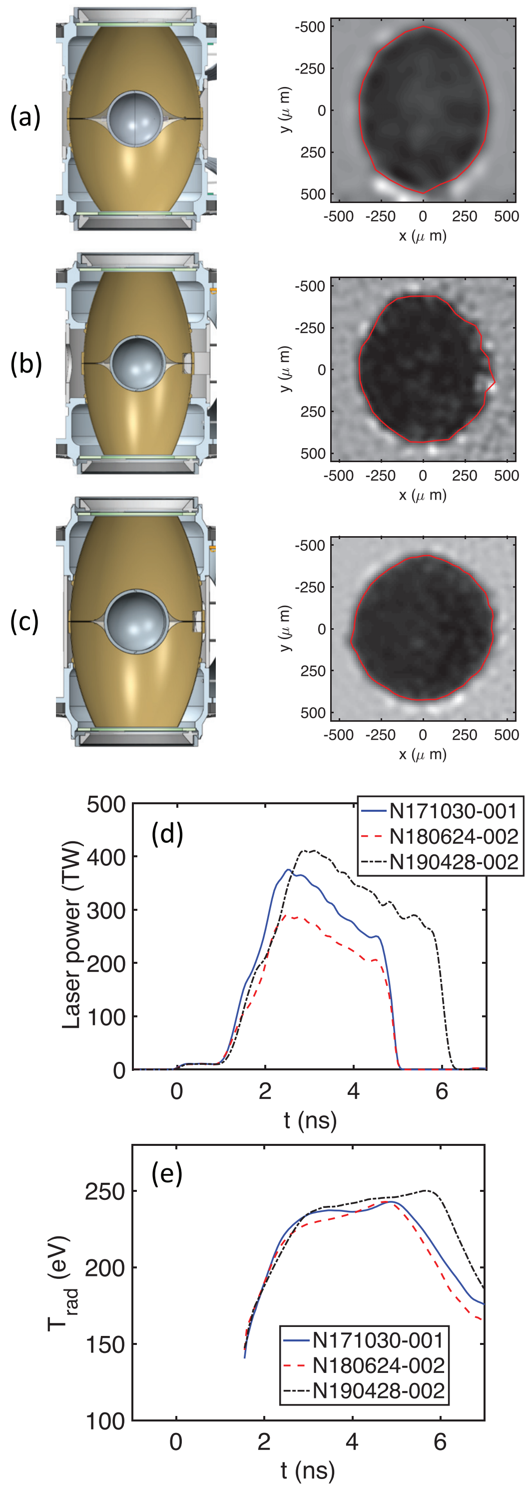

FIG. 2. (a)–(c) Rugby hohlraum shape and the 2D X-ray radiographs of the Al shell in three NIF shots, N171030-001, N180624-002, and N190428-002, taken at 12.9, 13.3, and 15.1 ns, respectively. (d) The corresponding pulse shape of the laser drive. (e) Measured radiation temperature vs time.

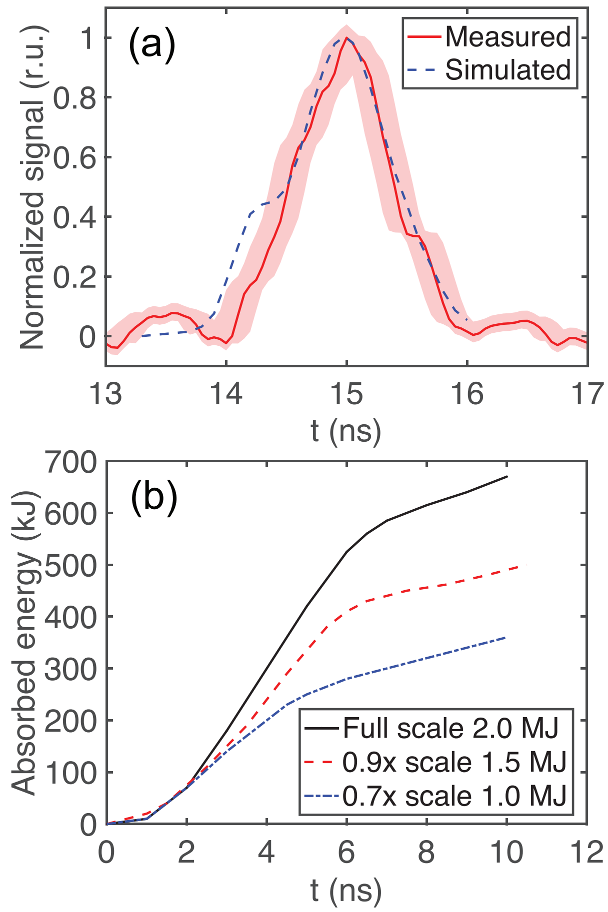

FIG. 3. (a) Comparison of the measured and simulated nuclear burn histories for shot N190122-002. Both are normalized by their maxima. (b) Simulated absorbed energy by the capsule at 0.7×, 0.9×, and 1.0× scales.

The Al capsule thickness was 173 μm in the above 0.9× scale experiments, which resulted in a low implosion velocity due to the massive shell. In the most recent shot N190630–002, the capsule thickness was reduced to 121 μm to boost the velocity. In this experiment, the laser energy was 1583 kJ, including the backlighter laser energy of 69 kJ. The framing camera was timed to record radiographs at ∼11.1 and ∼11.9 ns to measure the change in the shell size. The timing was chosen for the capsule to implode small enough to be within the diagnostic window. The measured P0 vs time is displayed in Fig. 4(a) together with the simulation result. The simulated trajectory is ∼300 ps earlier than the measured one, which is small compared to the 6 ns long coast time. The velocity is determined by a linear fit of the two data groups at the two delays. Figure 4(b) shows the measured and simulated velocities vs time, showing a reasonable agreement at the diagnostic window 11–12 ns. The peak velocity, although not measurable due to a limited diagnostic window, reaches 350 km/s in the simulation.

In summary, we have presented measurements of symmetry, nuclear bang time, neutron yield, in-flight capsule size, and velocity of Al capsules with a diameter of 3.0–3.4 mm in a Au rugby hohlraum.

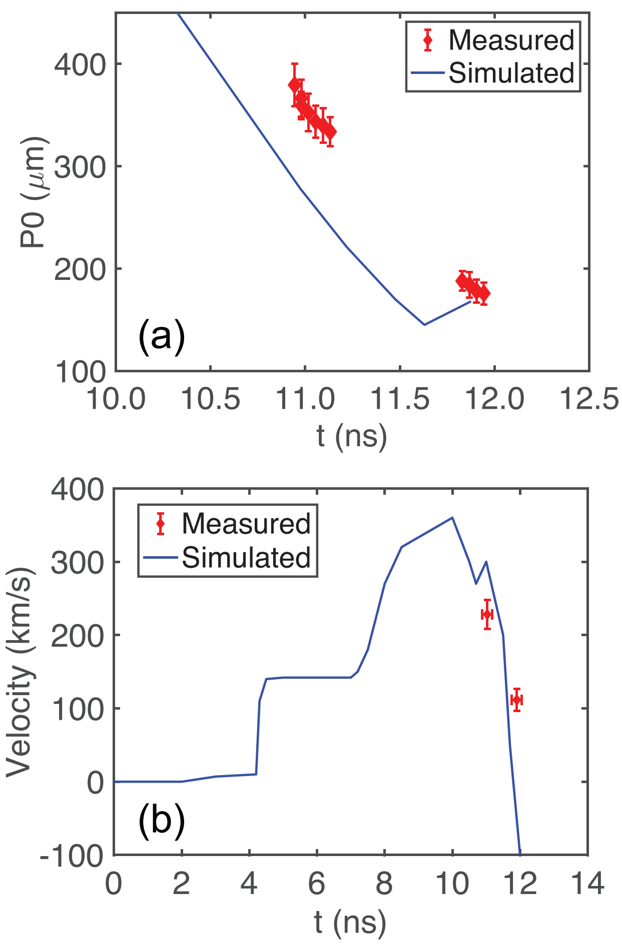

FIG. 4. Comparison of the measured and simulated P0 (a) and velocity (b) vs time for a thinner-shell shot N190630-002.

The good agreement between data and simulations indicates that $E_{cap} \sim 500\,\text{kJ}$ energy is coupled to the capsule out of 1.5 MJ of laser drive. It is also demonstrated that the implosion symmetry can be tuned effectively by adjusting the rugby shape. These results point to the potential for accessing volume ignition in low-Z ablator single shells by leveraging the high values of E_{cap} reported herein to operate at a high fuel adiabat ($\alpha = 4 - 10$) while preserving sufficient 1D performance margin.[13] This approach deviates from conventional hot-spot ignition by (1) having the entire fuel comprise the hot spot and (2) providing the majority of inertial confinement from the ablator instead of the fuel. The design work on the single-shell volume ignition scheme will be published in a separate paper.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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