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June 2020

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This work was performed under the auspices of U. S. DOE by LLNL under contract number DEAC52-07NA27344. Y.P. acknowledges support from DOE OFES Early Career Research Program. Y.M.W. acknowledges LLNL LDRD (17-ERD-048) support. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States government is permitted.

Submitted to Physics of Plasmas
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Experiments on imploding an Al capsule in a Au rugby hohlraum with up to 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-fill rugby hohlraum was very low (<3%) 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 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 good symmetry by modifying the shape of the hohlraum, such as oval-shaped or rugby-shaped hohlraum 2, 3, “I”-shaped hohlraum, and frustraum consisting of two truncated cones joined at their largest diameter. Early experiments 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. 4

Here we present a study of 3.4 mm-diameter Al capsules in 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 implosion 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 inflight 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 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 5. 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 6. 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 Rwa, the radius at the laser entrance hole (LEH) RLEH, and total length Lh. 7

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 ∼1.4 – 1.8× larger laser spot and lower intensity of the outer beams, which is helpful to reduce the wall bubble expansion 8, 9. The larger incident angle also leads to higher reflection, or glint, of the outer beams, which points toward inside of the rugby hohlraum and is helpful to increase the inner beam transmission by heating the plasma there. Fig. 1 (b) shows a map of simulated laser energy deposition for a 50° cone at 5 ns. It is clear that there is ∼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

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FIG. 1. (a) Experimental schematic. The 16keV 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.

carried out 3 NIF shots with different rugby dimensions as listed in Table. 1. 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 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% while 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 opaqueness of the Al shell. This symmetry tunability by rugby wall shape will be very useful for the design of future campaigns.

Nuclear diagnostics were enabled in shot N190122-002 with 7 mg/cc DT gas fill in the Al capsule, providing measurements to infer the energy coupling to the capsule.
TABLE I. Parameters for the 3 NIF shots shown in Fig. 2. The numbers in the bracket in the row of laser energy is 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%         | 1.6%         | 0.4%         |
| RCE (mm)               | 4.5          | 2.9          | 3.5          |
| R_LEH (mm)             | 1.80         | 1.80         | 2.17         |
| I (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%         |

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

The capsule and rugby hohlraum dimensions are 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 laser energy of 66 kJ. The measured nuclear bang time is 15.10 ± 0.15 ns, in good agreement with simulated value 15.0 ns, 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 ± 14 µm in the measurement and 338 µm in the simulation, also in good agreement. Fig. 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 drive, respectively. The good agreement between multiple measurements and simulations indicates a coupling energy of ~500 kJ in the 0.9× scale experiments.

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. Fig. 4 (b) shows the measured and simulated velocity vs time, showing a reasonable agreement at the diagnostic window 11-12 ns. The peak velocity, although not measurable due to 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. The good agreement...
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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