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A direct experimental comparison of rugby-shaped and cylindrical shaped gas-filled hohlraums on the Omega laser facility demonstrates that higher coupling and minimal backscatter can be achieved in the rugby geometry, leading to significantly enhanced implosion performance. A nearly 50% increase of x-ray drive is associated with earlier bangtime and increase of neutron production. The observed drive enhancement from rugby geometry in this study is almost twice stronger than in previously published results. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4890485]

In the current effort to reach thermonuclear ignition in the indirect drive approach to inertial confinement fusion,[1] the efficient conversion of laser energy to x-rays in a high-Z enclosure (the hohlraum) plays a central role. Because a major part of the energy losses occurs at the hohlraum wall, optimizing its shape in order to reduce its area has been suggested as a way to achieve higher efficiency.[2,3] A typical example of such a change in geometry is shown in Fig. 1. A wide range of advanced hohlraum designs, to be fielded on the National Ignition Facility (NIF)[4] and the Laser MegaJoule (LMJ),[5] rely on this "rugby hohlraum" concept.[6] A first experimental test was successfully conducted in vacuum hohlraums, for low convergence implosions driven by square pulses, validating the concept in this simple case.[7–11] However, it has since been shown that extrapolating the modeling of vacuum hohlraums[12] to gas-filled hohlraums can be problematic.[13] An experimental test in a more ignition-relevant gas-filled configuration with shaped laser pulses is thus critical to assess all the aforementioned ignition design proposals. In this Letter, we present a direct comparison of rugby-shaped and cylindrical hohlraums in such a configuration, demonstrating a strongly enhanced performance in rugby geometry.

The experiment was performed on the Omega laser facility at the laboratory for Laser Energetics,[14] with 40 beams arranged in 3 cones on each side of the hohlraum (10 beams at 21°, 10 at 42°, and 20 at 59° incidence from the axis), delivering 12 kJ in a high contrast 2.6 ns laser pulse. The beams were optically smoothed using elliptical phase plates,[15] double polarization,[16] and smoothing by spectral dispersion.[17]

We compared millimetric rugby-shaped and cylindrical hohlraum targets with the same inner diameter and laser entrance holes diameter (LEHs) (Fig. 1). An arc of a circle wall profile was chosen for the rugby hohlraum as sufficiently representative of this class of designs. Because the outer cone of laser spots is viewed at a lower angle from the capsule, the rugby-shaped hohlraums can be 10% shorter to achieve equivalent symmetry. This accounts for about a third of the area reduction and thus of the expected energetic benefits. A diagnostic hole is drilled on the side of the hohlraum and covered with a thin 2 μm gold patch to allow the imaging of hot-spot x-ray emission while limiting flux losses. Previous experiments have shown that such a patched diagnostic hole has negligible impact on the radiation temperature in this regime. All hohlraums considered in this Letter are filled with 0.8 atm of CH_4 gas at room temperature, held by 700 nm thick CH windows. In simulations, the partition of x-ray losses between wall, laser entrance holes, and light materials (gas/capsule) for these conditions is shown to be similar to corresponding ignition scale designs. Capsules of nominal 666 μm outer diameter are mounted at the center of each hohlraum, made of 35 μm thick, 2.8% at. doped CH(Ge), and filled with 30 atm of deuterium gas doped with 0.25 atm of argon (to boost X-ray emission and enable imaging).

The main result of this Letter is the dramatic increase of x-ray flux observed in the rugby-shaped geometry, as shown in Fig. 2. The x-ray flux exiting the hohlraum was measured with two independent arrays of filtered, absolutely calibrated x-ray diodes, Dante[18] and DMX.[19] Both diagnostics are looking at one of the LEHs at 37° from the hohlraum axis. The absolute accuracy of flux measurement is evaluated to be ±10% from monte carlo simulations of the analysis using calibration uncertainties for each channel. Relative comparisons are more accurate (±5%), as confirmed by the low dispersion of results for a given hohlraum shape. The two independent diagnostics give measurements that are consistent within their error bars.

A 40%–50% enhancement of the flux compared to cylindrical geometry is observed, which is larger than the

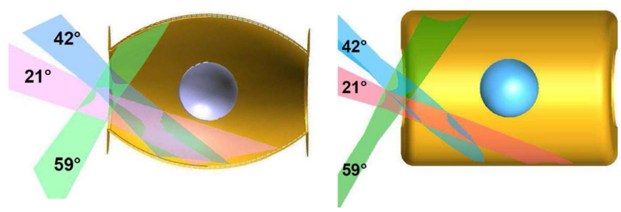

FIG. 1. Cut view of targets (not to scale). Only one beam of each cone is shown for clarity. Beam pointing is optimized to produce symmetric implosion.

effect previously observed in vacuum hohlraums, because the use of better optical smoothing led to reduced backscatter. It is also higher than would be naively expected from the reduction of gold wall surface area and share of energy losses at the wall.

Large differences in neutron yield were observed for the implosion of the same capsules used in a rugby hohlraum compared to a cylindrical one, as measured by the neutron time of flight diagnostic and summarized in Table I. Up to 60% of simulated 2D clean yield is achieved, the best rugby shot reaching 1.4e10 neutrons, improving on the already excellent performance of vacuum hohlraums. The higher neutron yields and earlier bangtime observed in rugby are also manifest on neutron time detector[25] measurements of the neutron production rate (cf. Figure 3). This is consistent with a higher drive on the capsule in the rugby.

We stress that the measured ion temperatures are the yield-averages of two very different components: a shock convergence phase, associated with high temperature over a small volume, and a compression phase associated with lower temperatures over a larger volume. A less efficient compression phase, for instance, would reduce the weight of the corresponding low ion temperature component. Therefore, as seen here, the total yield does not necessarily scale directly with the observed ion temperature, particularly when differences in symmetry or shock timing are present. Here, such a difference in shock timing (due to small pulseshape variations) overlap with a difference in drive (between rugby and cylinders), leading to a complex picture.

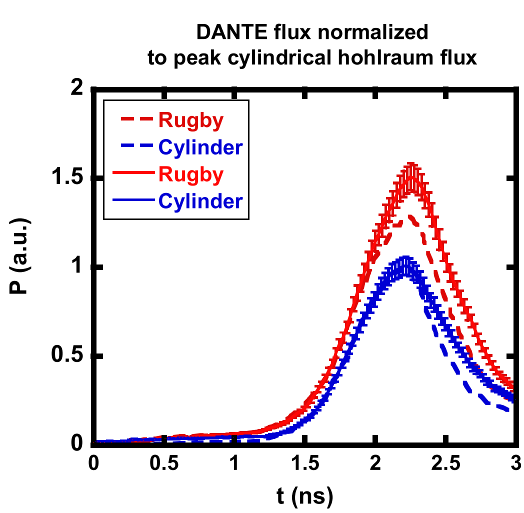

FIG. 2. X-ray flux seen from Dante for both hohlraum types, normalized to the cylindrical hohlraum case. The observed (full line) 40%–50% enhancement of the drive is 15% stronger than predicted (dashed line).

A second important result of this experiment is the observation of a low backscatter. Time-resolved backscatter was measured on all laser cones with the full aperture backscatter stations (FABS),[20] which collect light backscattered in the focusing lens aperture on a streaked spectrometer and a calibrated calorimeter. The fixed position of FABS on the target chamber allows a backscatter measurement on at most two beams on a given shot. In order to evaluate the laser plasma interaction conditions for all three cones, we conducted the experiment in two steps (designated as parts A and B), measuring inner cone (21°) and outer cones (42° and 59°) backscatter on different shots. Based on shot-to-shot reproducibility, we then infer backscatter for all cones in each hohlraum type. Because of the low level of observed backscatter, possible variations would have little impact on simulation results. Near Backscattering Imagers[21] providing filtered, time-integrated images of Spectralon (a lambertian, high diffusive reflectance material) scatter plates around the lenses, allow us to correct for the fraction of backscattered light outside of the lens aperture. We only observe significant deviation for the inner cone, which is refracted in the expanding ablator material. The fraction of backscattered light outside the lens is evaluated to be close to 50% by a supergaussian fit. Assuming the deviation is constant, we obtain an upper bound of the total backscatter and a corrected laser power history (Fig. 4). Note that because the experiment had to be carried in two parts over different days, small variations in pulseshape were present, leading to slightly different performance between part A shots and part B shots.

Stimulated Brillouin backscatter is found to be negligible on all cones except for a brief burst (3 GW over 100 ps) during initial interaction of the beams with the cold, dense hohlraum window. In cylindrical geometry, Stimulated Raman backscatter (SRS) is also negligible on all cones. In rugby geometry, SRS is negligible on the outer cone and weak (<2%) on the 42° cone, whereas 6% of laser beam energy is lost to backscatter on the innermost (21°) cone. The overall loss from backscatter is still less than 4% of the total laser energy.

We note that the use of beam-smoothing and gas-fill lead to significantly reduced backscatter in comparison with the previous vacuum hohlraum experiment, for which up to 7% outer cone backscatter was observed and 10%–20% backscatter on the inner cones was inferred. In contrast to the previous experiments with vacuum hohlraums, Hard X-ray Detectors (a set of 4 filtered diodes covering the 10–50 keV range)[22] also show strongly reduced signal at high energies, consistent with the low observed SRS.

Integrated radiation hydrodynamics simulations of the hohlraums, using the actual experimental laser pulseshapes for each shot, were conducted with Lasnex, postprocessed to simulate the diagnostics view of the hohlraum wall and laser hot spots through the LEH. A physics model including detailed configuration accounting non-equilibrium atomic physics and a strong limitation of thermal conduction ($f = 0.05$) was used, as investigations indicated that such a

TABLE I. Nuclear diagnostics measurements. Quoted error bars on ion temperature do not include the ±0.5 keV uncertainty on absolute calibration of the instrument.

Part	Hohlraum	Bangtime (ns)	Total yield (neutrons)	Ion temperature (keV)	Secondary yield (DT neutrons)
A	Rugby	3.12 ± 0.05	1.37e10 ± 2.5e8	3.0 ± 0.3	2e7 ± 5e6
B	Rugby	3.21 ± 0.05	8.1e9 ± 1.6e8	3.5 ± 0.3	1.6e7 ± 4.5e6
A	Cylinder	3.42 ± 0.05	1.1e9 ± 5.8e7	2.3 ± 0.1	Below threshold
B	Cylinder	3.47 ± 0.05	3.54e9 ± 1.65e8	3.0 ± 0.5	6.78e6 ± 3e6
A	Reduced power rugby	3.27 ± 0.05	5.79e9 ± 1.65e8	2.1 ± 0.1	1.1e7 ± 3.7e6

model was able to predict some features of ignition-scale gas-filled hohlraums better than the "high flux model" which gives good results for vacuum hohlraums[23] but overestimates the drive in full scale gas-filled hohlraums.[13] This is only a simple approximation of possible limitations, by 3D magnetic fields or kinetic effects, of the physically nonlocal thermal transport. Cross beam power transfer[24] was assessed in the simulations, but was found to have negligible impact in our experimental conditions for realistic saturation levels.

With this model, the simulations predict a 30%–35% increase in observed radiation flux, which is slightly lower than measured (Fig. 2).

Simulations also confirm that for these hohlraums, a higher Dante flux is associated to a higher x-ray drive on the capsule: in the cylinder case, the peak internal temperature is almost identical to the predicted Dante temperature, whereas in a rugby, the simulated internal temperature is 18% higher than the predicted Dante value. In other words, the simulations would indicate that the difference in x-ray flux seen by Dante strongly underestimates the difference in central temperature. This is related to predicted differences in laser entrance hole closure, leading to a 20% smaller area of the rugby LEH viewed from Dante at 2.35 ns. However, LEH closure is known to be overestimated in simulations,[13] and this may explain part of the remaining discrepancy between experiment and simulation. Less LEH closure would indeed lead to a higher predicted drive enhancement, a smaller difference in central temperature, and thus a later bangtime, as observed.

Experimentally, the LEH was imaged on a frame camera equipped with a low magnification soft x-ray nose. The angle of observation for this diagnostic is 37, identical to DMX and Dante. No difference in LEH radius between hohlraum types is discernible at peak emission (Fig. 5), and the diagnostic resolution (30 μm) provides an upper bound on LEH closure at peak emission. Hence, the observed drive enhancement cannot be attributed purely to a source size effect, as this would require a nearly 50% smaller clear aperture in the cylinder case and would therefore not be consistent with measurements. Such a large LEH closure would also strongly hinder beam propagation and would have a clear signature on all diagnostics, including backscatter.

In simulations, the small pulseshape variations between the two parts of the experiment lead to better performance for the rugby hohlraum in the first part, and for the cylindrical hohlraum in the second part. Simulated yields (Table II) are higher for the rugby hohlraums in both cases, as observed, but with better yield-over-clean for rugby hohlraums, increasing the yield difference in the experiment.

The core shapes at peak emission, obtained by time-resolved observation of the capsule emission with an X-ray framing camera, exhibit equivalent, slightly "pancake" symmetry both in the rugby and the cylinder. A negative mode 2 amplitude close to 18% is inferred from the decomposition in Legendre modes of image contours at 17% of maximum emission, for implosions achieving a convergence close to 12 (as deduced from the 24 μm radius of x-ray images). This behavior, however, is not captured by simulations, which predict the opposite sign for mode 2 in the cylinder

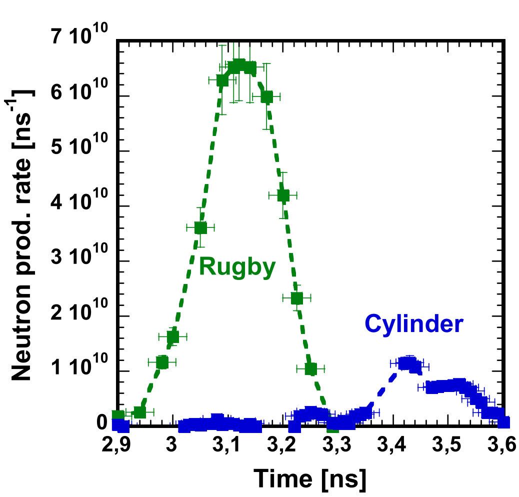

FIG. 3. Neutron production rate for part A full-power rugby and cylinder shots, from NTD measurement.

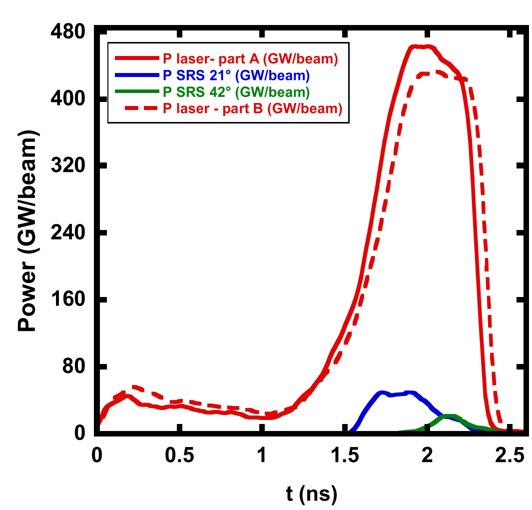

FIG. 4. Average pulseshape for one beam (full line: part A shots, dashed line: part B shots) and backscattered power in rugby hohlraums for all cones. The use of a gas-fill improved the backscatter compared to vacuum hohlraums.

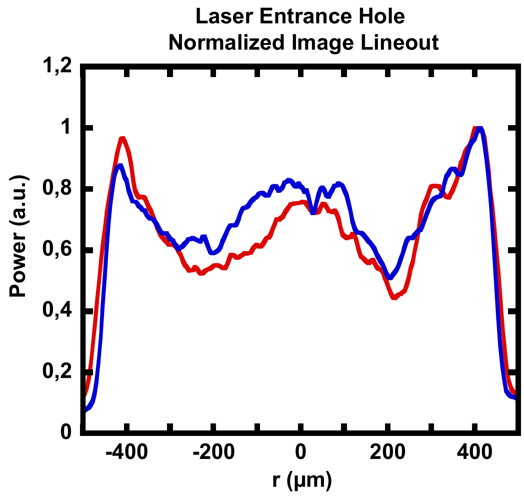

FIG. 5. Comparison of radial lineouts for soft x-ray images of rugby and cylinder hohlraums LEH, viewed from the same angle as DMX and Dante.

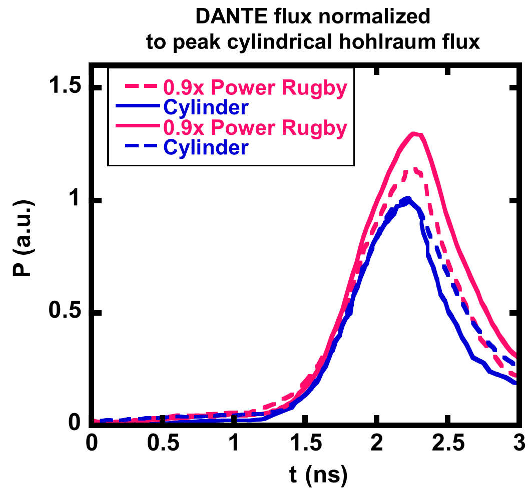

FIG. 6. X-ray flux seen from Dante for a reduced power rugby, normalized to the full powercylindrical hohlraum case. The observed (full line) 20% enhancement of the drive is stronger than predicted (dashed line).

hohlraum. The strong difference between predicted and observed symmetry may be a cause of the low values of yield-over-clean in the cylinder.

To further test the x-ray drive enhancement, a shot was performed with intentionally reduced laser power in a rugby-shaped hohlraum (90% of peak power). This was found to lead to a drive that is still 20% higher than the cylindrical case (Fig. 6), better lowest-order symmetry (Legendre mode 2 reduced to 5%), 150 ps earlier bangtime, and a higher neutron yield. The Legendre mode 2 symmetry in the cylindrical hohlraum could be similarly tuned by an intentional reduction of power, but this would again increase the difference in drive compared to the rugby hohlraum.

In conclusion, it has been experimentally demonstrated that the use of rugby-shaped gas-filled hohlraums can lead to significantly better hohlraum coupling compared to the classical cylindrical shape, enhancing both x-ray drive and implosion performance while retaining minimal laser backscatter. The higher efficiency achieved with hohlraum shaping is a valuable resource, which offers design options for either better propagation, increased geometrical smoothing of the drive, higher radiation temperature, lower required laser power, or a combination of those. Current simulations underestimate the observed difference in flux between hohlraum shapes and appear to overestimate the difference in central drive, indicating the need for improvements of physical models, including more accurate thermal transport modelling. Because simulation-based extrapolations are not reliable at this stage, an experimental test at ignition-scale would still be needed to fully validate the rugby hohlraum concept.

TABLE II. Nuclear diagnostics simulations.

Part	Hohlraum	Bangtime (ns)	Total yield (neutrons)	Ion temperature (keV)
A	Rugby	2.91	2.2e10	2.8
B	Rugby	3.03	1.6e10	2.7
A	Cylinder	3.41	8.0e9	1.6
B	Cylinder	3.53	1.0e10	1.7
A	Reduced power rugby	3.02	2.0e10	2.6

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