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ABSTRACT

This paper analyzes x-ray-driven implosions that are designed to be less sensitive to 2D and 3D effects in *Hohlraum* and capsule physics. Key performance metrics including the burn-averaged ion temperature, hot-spot areal density, and fusion yield are found to agree with simulations where the design adiabat (internal pressure) is multiplied by a factor of 1.4. These results motivate the development of a simple model for interpreting experimental data, which is then used to quantify how improvements in compression could help achieve ignition.

I. INTRODUCTION

Implosion performance in inertial confinement fusion (ICF) is generally considered to be a function of hot-spot mix, x-ray symmetry, velocity, and pulse shaping, which is a factor in the adiabat (compressibility) of the deuterium–tritium (DT) fusion fuel.[1,2] We define the design adiabat α_v by the pressure in the fuel relative to Fermi degenerate DT at the peak velocity of the implosion (as calculated by simulations). To maximize compression, it is important to avoid mechanisms that disturb or (pre)heat the fuel and thereby minimize the effective adiabat. Relative to the first experiments on the National Ignition Facility (NIF),[3,4] improvements in stability have led to increased yield and self-heating as detailed in previous work.[5–7] Still, it is relatively difficult to explain and project performance since these advances have convolved improvements in target quality, the power and energy delivered by the laser, and a reduction in compression, which are not fully understood (individually). Most experiments can only be reconciled with 3D calculations that include features unique to each target[8,9] that may not capture (or be aware of) other important aspects in target physics. In addition, it is not easy to control or maintain implosion symmetry, or velocity, at the level necessary to interpret other factors.[10] As a consequence, the primary limitations to temperature, areal density, and self-heating are not yet known, nor the changes needed to increase fusion yield.

This paper uses results from the so-called "BigFoot" campaign, which was designed to simplify several aspects of *Hohlraum* and capsule physics.[11] Calculations were not used to optimize yield but instead to select a parameter space that would allow for systematic studies and to reduce reliance on 3D simulations to interpret and extrapolate data. Nonetheless, these implosions do not perform as expected, and in the first half of this paper, we show that measurements are in good agreement with calculations at a higher design adiabat ($\alpha_v = 5.6$) than intended ($\alpha_v = 4.0$). These results are important because they demonstrate a persistent and significant deficit in compression relative to modeling. At the same time, these data achieve areal densities (and yields) that represent some of the highest-performing experiments on the NIF. To understand the importance of compression more generally, we use the second half of this paper to develop a simple model for interpreting data. We find that a deficit in compression is common to x-ray-driven implosions on the NIF and that even small improvements ($\geq 10\%$) could present a pathway to ignition.

II. EXPERIMENTAL DATA

Details of the BigFoot target, laser pulse, and strategy can be found in Fig. 1 and previous work.[11–13] The platform has been used to test hypotheses in physics since implosions (1) behave as expected with respect to laser energy, target scale, and implosion symmetry and (2) show little to no sensitivity to target quality and engineering features.[14] These data are also unusual in that experiments have been performed over a large range in laser energy without changes in design. This makes it possible to study individual data and trends in a manner that is statistically significant. Performance should be a function of implosion velocity and compression and requirements for ignition at a given target scale.[1,2] These quantities are not measured on all experiments (with accuracy) or can only be inferred. As a consequence, we report results vs the laser energy per unit ablator mass (E/M) and neutron down-scatter ratio (DSR). E/M is a surrogate for velocity (and energy density), and DSR is proportional to neutron scattering at 10 to 12 MeV. Both are measured on all experiments, and the burn-averaged areal density in g/cm^2 is given by $\rho R_{\rm b} = 20\,{\rm DSR}$ (Ref. 4). Experiments used a capsule inner radius R of 844 (950) μm, which we define as target scale $S = R/844 = 1$ (1.125). In Figs. 2 and 3, we report the burn-averaged ion temperature T, hot-spot areal density $\rho R_{\rm h}$, neutron yield Y, and ignition metric χ_α[15] as the open black squares. All implosions are the same type except for changes in scale,[16] so we normalize $\rho R_{\rm h}$, Y, DSR, and χ_α by a factor of S, S^4, S, and S, respectively, to simplify visualization. (Hot-spot volume V and burn width τ should increase as S^3 and S, respectively, so $Y \sim n^2 T^N V \tau \sim S^4$ for small changes in S.) The burn-averaged ion temperature is derived from time-of-flight measurements and averaged across all diagnostic lines of sight. Most implosions are symmetric, or nearly so (time-integrated neutron emission data are shown in Fig. 1), and the measurements of yield and DSR are averaged in the same way. The areal density of the hot spot is inferred from the ion temperature, neutron yield, neutron burnwidth, and time-integrated neutron hot-spot radius (defined by the 17% intensity contour in emission at 13 to 15 MeV) as outlined in Cerjan *et al.*[17] This approach avoids ambiguities with respect to x-ray emission (and hot-spot volume) that can lead to unphysical values for the inferred hot-spot density, pressure, etc. The parameter χ_α is a simple function of the burn-averaged areal density, yield, and DT mass and can be used to estimate the distance to ignition with the formula in Ref. 15. Consistent with these interpretations, these data include the highest-performing implosions done on the NIF and have a yield amplification from alpha heating that agrees with $\chi_\alpha \approx 1$. (Recent experiments confirm these findings and will be published separately.[18]) No data appear to deviate from the trend even though we have inferred asymmetries in the ion temperature of 200 to 300 eV and residual motion(s) in the hot spot of 40 to 120 km/s. The experiments shown here have used capsules from different batches, thick and thin capsule supports (30- vs 45-nm tents), and capsule fill tubes (10- vs 5-μm) as available. Despite these variations, the data are highly monotonic in E/M, and performance does not appear to depend on small changes in target fielding and engineering. We have considered other factors and will focus our discussion on the DT adiabat.

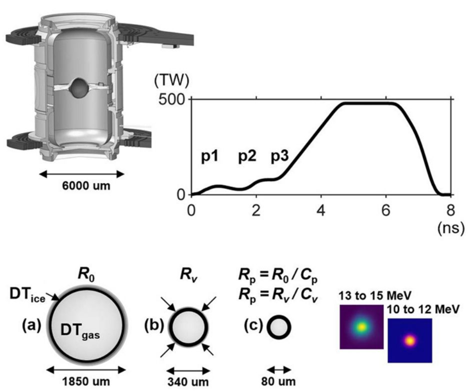

FIG. 1. BigFoot experiments use a high-density carbon ablator and low-gas-fill density (0.3 mg/cm^3) Au *Hohlraum* to minimize the length of the laser pulse, avoid laser-plasma instabilities, and simplify fabrication. They also employ changes to the laser pointing and *Hohlraum* entrance hole to reduce laser propagation in high-Z plasmas. Here, we show the target, laser pulse, and time-integrated neutron emission from shot 180128 in two energy bands. Three pulses (labeled p1 to p3) are designed to put the DT shell at a relatively high adiabat ($\alpha_v = 4.0 \pm 0.1$) and increase stability at the fuel-ablator interface. For the purposes of this paper, the phases of an implosion are defined by (a) the initial radius R_0, (b) the radius at maximum implosion velocity R_v, and (c) the radius at peak compression R_p.

III. RADIATION-HYDRODYNAMIC SIMULATIONS

We note that fitting an ensemble of data with few assumptions can provide more confidence in any interpretation. It is difficult to make predictions when experiments have different and unique sources of degradation. Also problematic, high-resolution calculations have to make approximations in physics (e.g., in transport) to estimate the importance of microscopic imperfections. When simulations reach a certain level of complexity and computational expense, they have to be validated by experiments. Since the metrics in Figs. 2 and 3 are very regular, our efforts have focused on finding a methodology that is insensitive to small details. For the experiments reported here, we find that the best fit to data is achieved in simulations that increase the DT fuel adiabat by a factor of 1.4 relative to expectations. This "effective adiabat" lets us reduce the compressibility of all simulations in the same way and is the functional replacement for physics mechanisms that may not be known. We are unable to attribute this change to errors in the x-ray drive,[19] instabilities,[20] or mix/preheat[21] as currently understood. This is accomplished by adding 80 J of internal energy (proportional to the laser power) to capsules that absorb 200 to 250 kJ of x rays without changing the strength or timing of shocks within the shell. To compare with data, we use integrated calculations in LASNEX,[22] which reproduce the x-ray drive inferred by VISAR[23] with the measured laser pulse (i.e., no multipliers[24,25]). There are no changes in these calculations relative to previous work, other than to increase the resolution by a factor of 4 in r and z to improve convergence. Calculations of this type also reproduce the measured implosion velocity, the burn-averaged ion temperature, and the neutron yield in experiments that lack a cryogenic DT layer and have fewer sources of uncertainty. There is no single explanation for why these calculations are predictive, except to say that these implosions are relatively simple compared to previous data.[5–7] We forward-simulate all diagnostics (as discussed above) and interpret each in the same way. The results are also provided in Figs. 2 and 3. Simulations with a design adiabat of 5.6 are given by the solid black squares and provide a good match to data even though the expected design adiabat is 4.0. To address requirements for ignition (and standard expectations), we also show the result

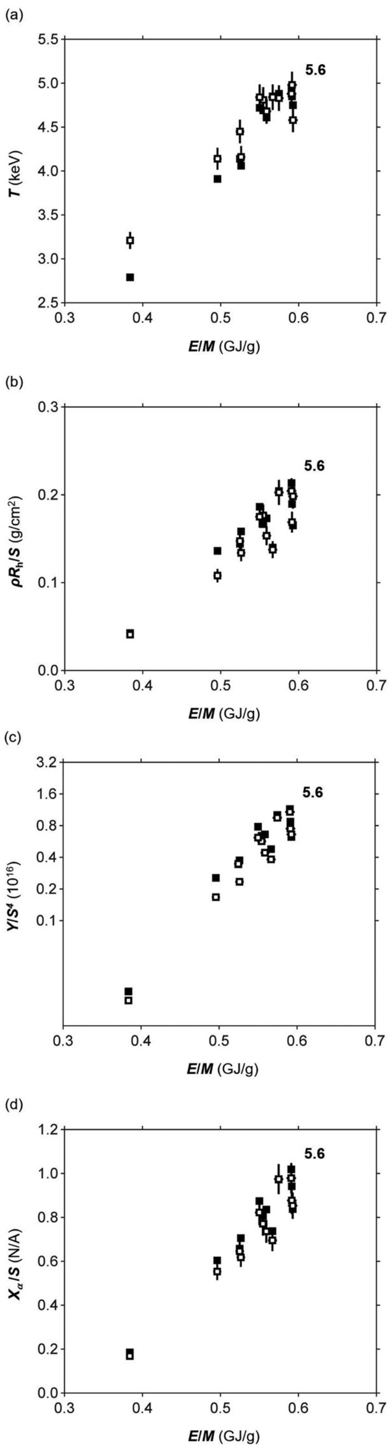

FIG. 2. (a) Burn-averaged ion temperature, (b) hot-spot areal density, (c) neutron yield, and (d) χ_α for BigFoot implosions (open black squares) as a function of laser energy per unit ablator mass *E*/*M*. We have normalized for small differences in target size/scale *S* to simplify visualization. Measurements are a close match to calculations in LASNEX (solid black squares) having a design adiabat $\alpha_v = 5.6$. The nominal design adiabat is 4.0.

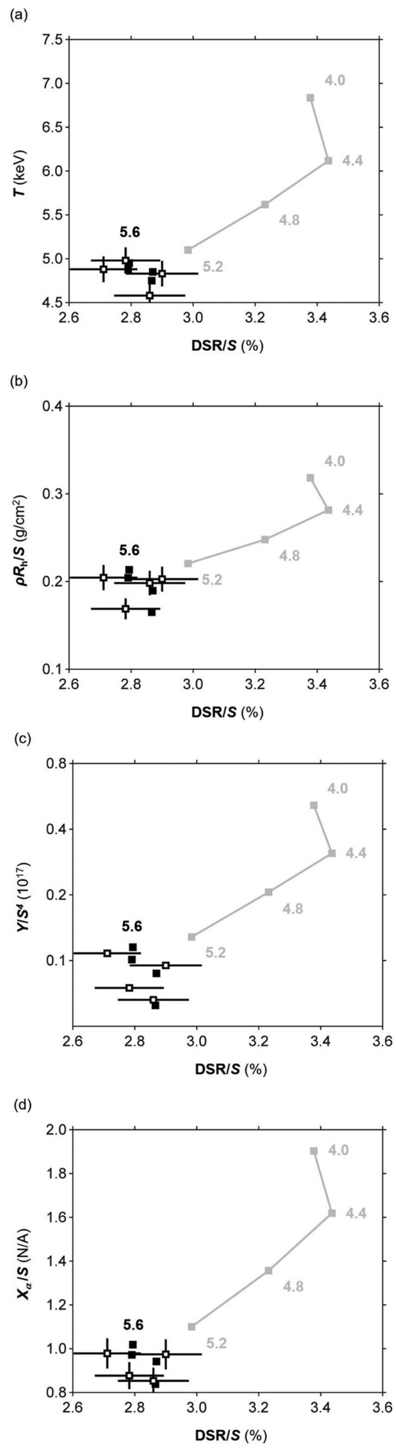

FIG. 3. The four highest-performing BigFoot experiments (open black squares) are compared to calculations in LASNEX at a design adiabat of 5.6 (solid black squares) and 5.2 to 4.0 (solid gray squares) on (a) burn-averaged ion temperature, (b) hot-spot areal density, (c) neutron yield, and (d) χ_α as a function of the neutron down-scatter ratio (DSR). The discontinuity coincides with common criteria for ignition: $T \sim 5$ keV and $\rho R_h \geq 0.3$ g/cm^2.

of calculations at $\alpha_v = 5.2$ to 4.0 by the solid gray squares. Simulations predict the burn-averaged ion temperature to exceed 5 keV and for the onset of ignition when the hot spot has sufficient areal density to rapidly self-heat ($\approx$0.3 g/cm^2).[1,2] The burn-averaged compression ratio of the DT fuel is directly related to the DSR. Per previous work,[26] a lower bound for the no-burn compression ratio is $C_p \approx (20\,\mathrm{DSR}/\rho_0 t_0)^{1/2}$, where $\rho_0 t_0$ is the initial areal density of the cryogenic layer. Typical values for ρ_0 and t_0 are 0.25 g/cm^3 and 40 to 75 μm, respectively. BigFoot experiments are consistent with 20% deficit in DSR, or 10% in compression, and are otherwise predicted to ignite. Once ignition is achieved in simulation (as observed), then we expect all performance metrics to be discontinuous in DSR and for the burn-averaged compression ratio to decrease (a large fraction of the yield is generated as the shell expands).

IV. SIMPLE THEORY

We have developed a reduced model to better understand and extrapolate these results. If we assume that the control volume that defines the hot spot during compression has mass m_h, an energy at peak implosion velocity is $\approx \frac{1}{2} m_h v^2$ and is compressed radially by a factor C_v with $\gamma = 5/3$ (from peak implosion velocity to peak compression, as shown in Fig. 1), then the energy in the hot spot at peak compression is $E_h \approx \frac{1}{2} m_h v^2 C_v^2$. We have assumed that kinetic energy dominates other factors (to first order), and it is not necessary to treat the origin in detail. If the cold DT shell has mass m_c and stagnation adiabat α_s, then the energy in the cold fuel at stagnation is $E_c \approx \alpha_s\, e_F(\rho_c) m_c$, where $e_F(\rho)$ is the energy density of Fermi DT. Assuming that alpha heating is negligible prior to peak compression, we expect $E_h + E_c$ to equal the kinetic energy of the cold fuel, $\frac{1}{2} m_c v^2$, and for

$$C_v^2 \approx \frac{m_c}{m_h} \frac{1}{1+x}, \tag{1}$$

where $x = E_c/E_h$ at stagnation. This formula can be used to estimate the peak compression ratio of an implosion without detailed hydrodynamic calculations. It also predicts physics scalings that are similar to previous work (Ref. 27). If an implosion is far from ignition, then we expect $m_c \approx$ mass of the initial DT fuel layer and $m_h \approx$ mass of the initial DT gas in pressure equilibrium (in the central void). The energy and mass of the hot spot will increase due to alpha heating and electron conduction, but we assume that neither alters the pdV work by the cold shell. To avoid confusion with respect to the stagnation adiabat, α_s, we define the internal energy in the cold fuel at peak velocity as $E_v = \alpha_v e_F(\rho_v) m_c$ and estimate $E_c/E_v \approx 2.5(V_v/V_c)^{2/3}$. The change in volume during stagnation is V_v/V_c and $\alpha_s e_F(\rho_c) \approx 2.5\alpha_v e_F(\rho_v)(V_v/V_c)^{2/3}$. This formulation agrees with previous research[28] and the behavior of a monotonic ideal gas as explained in Meyer-ter-Vehn.[29] For an implosion at Mach number M, the density and pressure at stagnation should increase by $2.4M^{3/2}$ and $3.6M^3$, respectively. This results in $E_c/E_v \approx 0.8M^{1/2}(V_v/V_c)^{2/3}$, which we evaluate at $M \sim 10$ to approximate data. If we also assume that the volumetric compression of the hot spot and cold fuel are comparable (self-similar and adiabatic), then $x \approx 2.5E_v/\frac{1}{2} m_h v^2$. High compression should result from small(er) values of x. This expression is easy to compare to calculations and can be modified to include different estimates for the gamma law or m_h. We can predict the compression ratio relative to peak implosion velocity C_v although we would prefer to know the compression ratio relative to the initial radius, C_p (see Fig. 1). This is not an obstacle since C_p/C_v is typically calculated to be 5 to 6, and we will assume a factor of 5.5. Higher values are preferred but are limited by the distance the shell can travel before it stagnates. The areal density and DSR at peak compression follow from mass conservation and are proportional to C_p^2.

The yield should increase as $n^2 T^N V \tau$ (Refs. 1 and 2). If we assume that the confinement time τ increases with the hot-spot radius and temperature as $\sim R_h/T^{1/2}$ (the time for hydrodynamic disassembly holding other factors constant), nV and nR_h are proportional to the hot-spot mass and areal density, respectively, and $T \sim v^2 C_p^2$ ($E_h \approx \frac{1}{2} m_h v^2 C_v^2$), then $Y \sim m_h \rho R_h T^{N-1/2} \sim m_h \rho R_h (v C_p)^{2N-1}$. These derivations demonstrate the processes involved and show that scaling(s) can be a function of parameter space. For example, $C_p^2 \sim v^2/\alpha_v$ if $x \gg 1$ and $C_p^2 \sim (v^2/\alpha_v)^{x/x+1}$ if x is arbitrary. To make sure that our estimates of $Y(C_p)$ are conservative, we will also assume $x \gg 1$ and neglect any benefit from alpha heating, tamping by the cold shell, and any increase(s) in m_h and ρR_h. The burn-averaged temperature is commonly 4 to 5 keV, and it is reasonable to set $N \approx 3$ (Ref. 15). With these assumptions, we expect $Y \sim C_p^5$ and $\chi_\alpha \sim (\rho R)^{0.61} Y^{0.34} \sim C_p^3$, at a minimum.

V. DISTANCE TO IGNITION

BigFoot (NIF) implosions are meant to have a velocity of 430 (380) km/s and have typically been characterized by a DT mass of 140 (200) μg. The design adiabat is not measured but is predicted to depend on the velocity of the first shock in the fusion fuel, u_1, in km/s.[19] A simple fit to the published literature[3,5,11] suggests $\alpha_v \approx 1.2 + 1.0 \times 10^{-3} u_1^2$ for $u_1 \leq 60$ km/s. Subject to these assumptions, Fig. 4(a) provides the expected compression ratio for BigFoot (NIF) implosions as the black (gray) solid line. Data are given by the black (gray) open squares. BigFoot implosions have relatively high compression ($C_p \approx 22$ to 23) but are below theory by at least 10%, in agreement with detailed calculations (see Fig. 3). The estimated impact(s) on areal density, yield, and χ_α is given in Figs. 4(b)–4(d). The minimum deficit relative to expectations is −15%, −30%, and −20%, respectively. The deficit in these quantities is larger at small u_1 and could help explain why these experiments show little or no alpha heating. If we extrapolate using the upper envelope of all data (which appears to be continuous), then we expect measurements to approach theory at $u_1 \approx 60$ km/s. Many experiments are below the upper envelope of data and could be sensitive to details that are not known or not included (e.g., a precise estimate of the implosion velocity). If instabilities were to result in cold fuel near the center of the hot spot (and shot to shot variations in C_p), this could help explain the scatter at small(er) u_1. Considering Fig. 3, BigFoot implosions are designed to approach ignition if they achieve a compression ratio that agrees with theory. According to Ref. 28, the laser energy needed to ignite E_{ign} should scale as $\approx v^{-6}\alpha_v^2$. Since we expect $x \gg 1$ and $C_p^2 \sim v^2/\alpha_v$, this suggests $E_{ign} \sim v^{-2} C_p^{-4}$. It is clear that errors in compression are important and that even small improvements could increase the likelihood of ignition. A 10% deficit in compression (as shown here) is equivalent to 20% in pdV work. If future efforts are unable to find and correct this discrepancy, then the data in this paper can also be used to motivate other changes in target design. High-performing experiments already

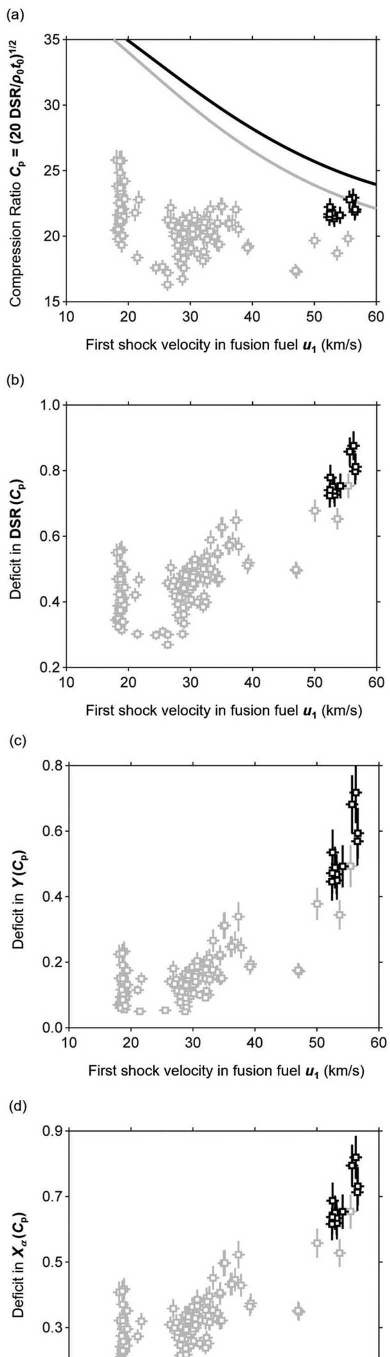

FIG. 4. (a) The peak compression ratio C_p as a function of first shock velocity u_1 (a surrogate for adiabat) in BigFoot implosions (open black squares) and previous NIF data (open gray squares). Theoretical expectations are given by the black (gray) line assuming an implosion velocity of 430 (380) km/s and a DT mass of 140 (200) μg. These estimates imply a deficit in (b) DSR, (c) yield, and (d) χ_α that is strongly correlated with adiabat.

achieve 5 keV, and it is only necessary to determine the energy per unit mass or target scale that would allow a hot-spot areal density of 0.3 g/cm^2 or higher. Above this threshold, we expect fusion alpha particles to strongly couple to the hot spot and for the burn fraction to depend on the total areal density of the fuel (primarily). If we extrapolate linearly using Fig. 2(b), this would appear to require an increase in E/M of 20%, which would exactly offset the observed deficit in pdV work. We also note that $\rho R_\mathrm{h}/S \approx 0.22$ g/cm^2 at $E/M = 0.6$ GJ/g. With no other improvements, this suggests that $\rho R_h \geq 0.3$ g/cm^2 at $S \approx 1.5$. This would represent a 30% increase in scale over the largest implosions reported here. Laser energy E for a perfect hydrodynamic scale is $\sim S^3$, and this would require a factor of 2.2 more laser energy than was used on shot 180128 (1.8 MJ). $2.2 \times 1.8\,\mathrm{MJ} = 4\,\mathrm{MJ}$. Both approaches have been demonstrated in design calculations using indirect drive[11,14] and are a central aspect of current proposal(s). These conditions could also be achieved with other schemes, such as laser direct drive, which provide a factor of 3 to 4 more coupled energy.

VI. CONCLUSION

We have analyzed experiments using the BigFoot platform on the NIF and find that performance metrics including ion temperature, hot-spot areal density, and neutron yield are monotonic in laser energy, and calculations are a good match to data if the adiabat is increased by a factor of 1.4 relative to expectations ($\alpha_\nu = 5.6$ vs 4.0). Even so, these experiments achieve relatively high compression and yield, and a simple model is used to explain observations. Implosions are proposed at higher laser energy per unit mass and larger scale(s) to address requirements for ignition. We also plan to test the sensitivities reported here and will make small/iterative changes in the laser pulse to study and optimize the compression ratio in existing implosion designs.[26]

ACKNOWLEDGMENTS

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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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