Deficiencies in Compression and Yield in X-Ray–Driven Implosions

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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 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 at the National Ignition Facility (NIF),[3,4] improvements in stability have led to increased yield and self-heating as detailed in prior 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 that are not fully understood (individually). Most experiments can be reconciled only with 3-D 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] The primary limitations to temperature, areal density, and self-heating are not yet known, nor are the changes needed to increase fusion yield.

This summary uses results from the so-called "BigFoot" Campaign, which was designed to simplify aspects of hohlraum and capsule physics.[11] Calculations were not used to optimize yield but, instead, to select a parameter space that would reduce reliance on 3-D simulations to interpret and extrapolate data. Nonetheless, these implosions have not performed as expected, but in the first half of this summary, we show that measurements are in good agreement with calculations at a higher design adiabat (α_v = 5.6) than intended (α_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) representing some of the highest-performing experiments on the NIF. To understand the importance of compression more generally, we use the second half of this summary to develop a simple model for interpreting data and find that even small improvements in compression (≥10%) could present a pathway to ignition.

Details of the BigFoot target, laser pulse, and strategy can be found in prior 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 (within standard specifications).[14] These data are also unusual in that no changes were made in design (shot-to-shot), even though experiments were performed over a large range in laser energy. This makes it possible to study individual data in a manner that is statistically significant, as well as trends. Figures 1 and 2 show the burn-averaged ion temperature *T*, hot-spot areal density ρR_h, neutron yield *Y*, and ignition metric χ_α (Ref. 15) versus the laser energy per unit ablator mass (*E*/*M*) and neutron down-scatter ratio (DSR) as the open black squares. *E*/*M* is a surrogate for velocity (and energy density) that is measured on all experiments, and DSR is a common measure of compression proportional to neutron scattering at 10 to 12 MeV. The burn-averaged areal density (in g/cm^2) is given by ρR_b = 20 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). All implosions were designed

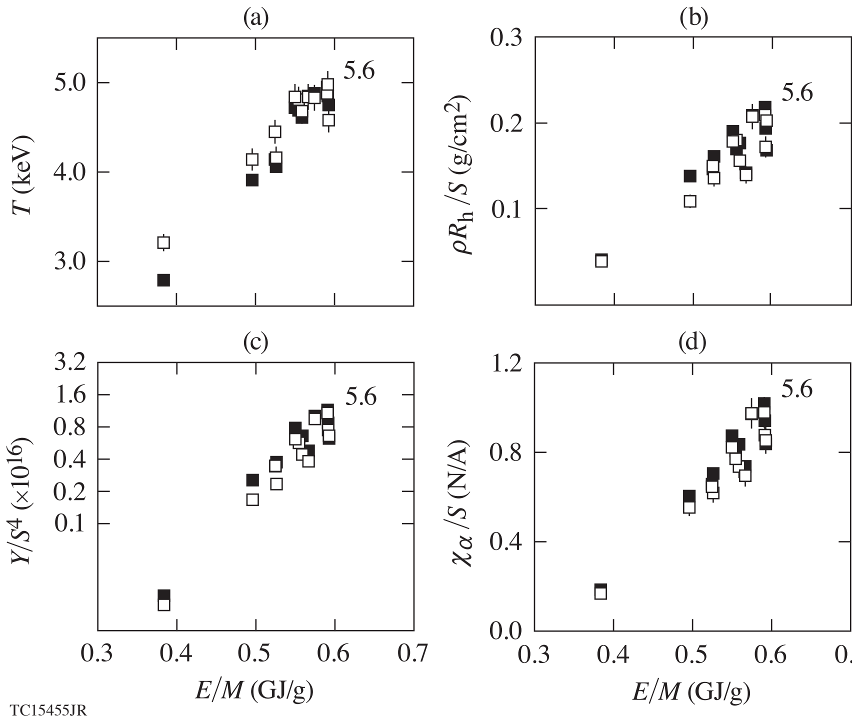

Figure 1
The (a) burn-averaged ion temperature, (b) hot-spot areal density, (c) neutron yield, and (d) χ_α for BigFoot implosions (open black squares) as a function of laser energy per unit ablator mass *E*/*M* normalizing for small differences in target size/scale *S*. Measurements are a close match to calculations in *LASNEX* (solid black squares) having a design adiabat α_v = 5.6. The nominal design adiabat is 4.0.

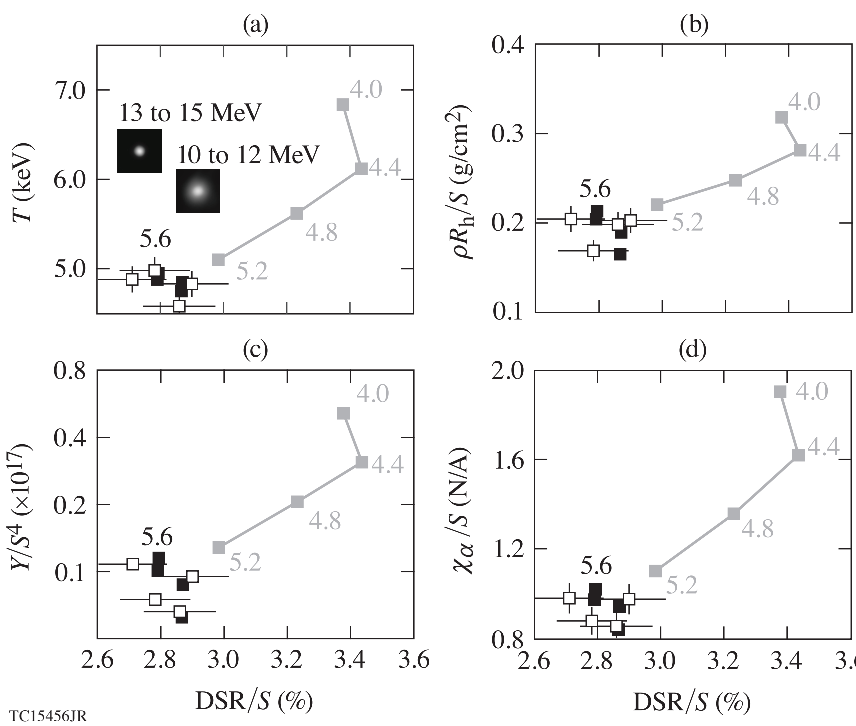

Figure 2
The four highest-performing BigFoot experiments (open black squares) are compared to calculations in *LASNEX* at a design adiabat of 5.6 (solid black squares) and 5.2 to 4.0 (solid gray squares) on (a) burn-averaged ion temperature, (b) hot-spot areal density, (c) neutron yield, and (d) χ_α as a function of 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).

to be self-similar except for the change in scale,[16] so we normalize all of these metrics as appropriate. This simplifies visualization but does not adjust interpretation. The burn-averaged ion temperature is derived from time-of-flight measurements and averaged across multiple lines of sight. Most implosions are symmetric, or nearly so [time-integrated neutron emission data are shown inset to Fig. 2(a)], so measurements of yield and DSR are averaged in the same way. No data stand out from the series, 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 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 that cause uncertainty in the volume of the hot spot and can lead to unphysical values for the inferred hot-spot density, pressure, etc. 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 $\chi_\alpha \approx 1$. (Separate experiments confirm this result and will be published separately.[18]) The experiments shown here have used capsules from different batches, thick and thin capsule supports (30- versus 45-nm tents), and capsule fill tubes (10 μm versus 5 μm) as available. Despite these variations, the data are highly monotonic in *E*/*M*, which suggests that engineering details do not dominate performance. This summary will consider other factors, including the DT adiabat.

We note that fitting an ensemble of data with few assumptions provides more confidence in any interpretation. It is difficult to make predictions if each implosion has a unique source of degradation, particularly if multiple mechanisms play a role. This is common in ICF because (1) implosions tend to be complicated and (2) high-resolution calculations must make approximations in physics (e.g., in transport) to study the importance of microscopic imperfections. When simulations reach a certain level of complexity, and/or computational expense, they can be validated only by experiments. Since the metrics in Figs. 1 and 2 are very regular, our efforts have focused on finding a methodology that is insensitive to small details. For the experiments reported here, we find 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 serves as the functional replacement for a 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 to capsules that absorb 200 to 250 kJ of x rays. To make the best comparisons with data, we use integrated calculations in *LASNEX*[22] that reproduce the x-ray drive inferred by VISAR data[23] and the times of peak neutron and x-ray emission ($\pm$100 ps) using the measured laser pulse.[24,25] 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. We forward-simulate all diagnostics (as discussed above) and interpret them in the same way. Results are also provided in Figs. 1 and 2. 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 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 along with the onset of ignition when the hot spot has sufficient areal density to rapidly self-heat ($\approx$0.3 g/cm^2) (Refs. 1 and 2). The neutron DSR is directly related to the burn-averaged compression of the DT fuel. Per prior work,[26] a lower bound for the no-burn compression ratio is $C_\mathrm{p} \approx (20\ \mathrm{DSR}/\rho_0 t_0)^{1/2}$, 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 a deficit in DSR of 20% (or a deficit in compression of 10%) and are otherwise predicted to ignite. Once ignition is achieved in simulation, all performance metrics are discontinuous in DSR, so it is no longer an accurate measure of peak compression.

To understand these results, this summary provides simple models for compression as a function of velocity, DT adiabat, and other details of a given implosion. It also develops simple estimates for the areal density, yield, and χ_α as functions of the same. These derivations are not included in this summary to reserve space for data and will be provided upon request. To make comparisons with data, we note that BigFoot (NIF) implosions are meant to have velocities 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 it is predicted to depend on the velocity of the first shock in the fusion fuel, u_1, which is measured in km/s (Ref. 19). If we fit published literature,[3,5,11] then $\alpha_v \approx 1.2 + 1.0 \times 10^{-3} u_1^2$. Figure 3(a) provides C_p as a function of u_1 for BigFoot (NIF) implosions as the solid black (gray) line, whereas data are the open black (gray) squares. BigFoot implosions have relatively high compression ratios ($C_\mathrm{p} \approx 22$ to 23) but are below theory by at least 10%, consistent with the calculations in Fig. 2. The estimated impacts on areal density, yield, and χ_α is given in Figs. 3(b)–3(d) as C_p^2, C_p^5, and C_p^3, respectively. The minimum deficit relative to expectations is –15%, –30%, and –20%, respectively. (The maximum deficit is considerably larger.) If we extrapolate using the upper envelope of all data (which appears to be continuous), it seems that measurements would approach theory at $u_1 \geq 60$ 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., reduced implosion velocity). We note that 3-D calculations tend to result in higher DSR since cold fuel can approach the center of the hot spot and increase the mass-average ρR_b. If so, the formula used here could overestimate the compression ratio in experiments that are unstable. If we consider Fig. 2, BigFoot implosions are designed to approach ignition if compression were to agree with theory. According to Ref. 27, the laser energy needed to ignite E_{ign} should scale as $\approx v^{-6}\alpha_v^2$. Since we expect $x \gg 1$ and $C_p^2 \sim v^2 / \alpha_v$, then $E_{ign} \sim v^{-2} C_p^{-4}$. It is clear that (1) errors in compression are critical to understanding and (2) even small improvements could enable ignition. A 10% deficit in compression (as shown here) is equivalent to 20% in *PdV* work on the hot spot. If future efforts are not able to find and correct this discrepancy, the data in this paper can also be used to motivate other changes in target physics. High-performing experiments already achieve 5 keV, so it is only necessary to find an increase in energy per unit mass (or target scale) that 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 the DT burnup fraction to depend on the total areal density of the fuel (primarily). If we extrapolate linearly using Fig. 1(b), this would require an increase in *E*/*M* of 20% $\left(\text{to overcome the deficit in } C_p^2\right)$ or an increase in *S* of 30% (equivalent to a factor of 2.2 in additional laser energy or laser-capsule coupling). Both of these changes can be made in design calculations and are the subject of existing proposal(s).[11,14]

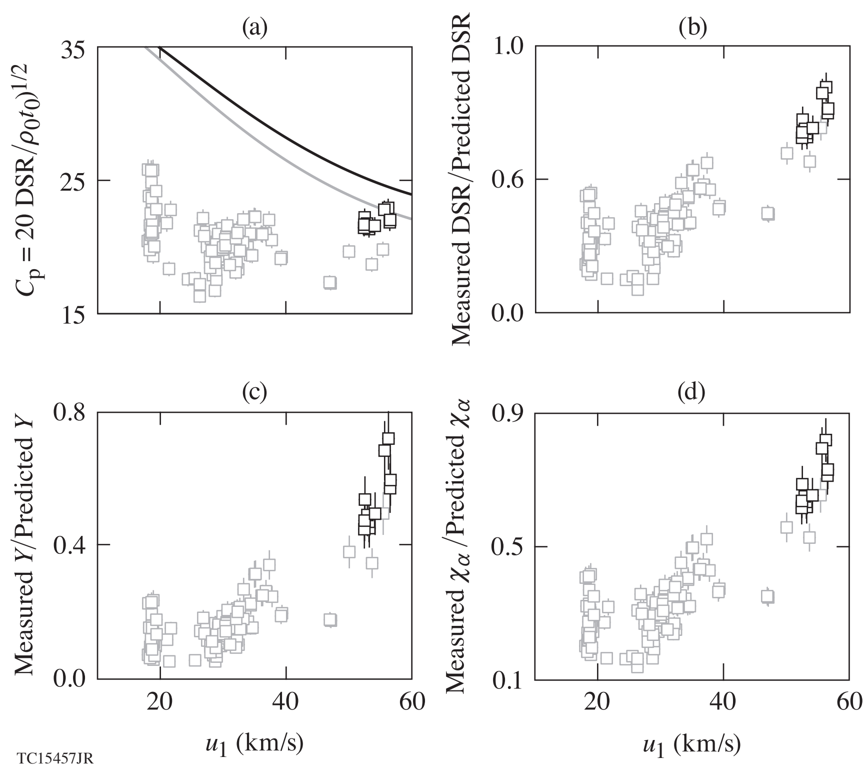

Figure 3
(a) The peak compression ratio C_p as a function of first shock velocity u_1 (a surrogate for adiabat) in BigFoot implosions (open black squares) and prior NIF data (open gray squares). Theoretical expectations are given by the black (gray) line assuming an implosion velocity of 430 (380) km/s 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 to adiabat.

In conclusion, we have analyzed x-ray-driven implosions 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 the data if the adiabat is increased by a factor of 1.4 relative to expectations (α_v = 5.6 versus 4.0). Even so, these experiments achieve relatively high compression and yield, and we have developed a simple model to interpret observations. We have proposed implosions at higher laser energy per unit mass, some of which would include larger targets, to provide more insight into potential performance limitations on the NIF. We also plan to test the sensitivities reported here and will make small/iterative changes to the laser pulse in an attempt to improve compression.[26]

This work was made possible by the operations team at the NIF, target fabrication efforts at General Atomics and LLNL, and the encouragement and support of J. H. Nuckolls, J. D. Lindl, W. L. Kruer, and G. B. Zimmerman. We also thank the Senior Leadership Team at the NIF and note that future communications with the first author should be addressed to the Laboratory for Laser Energetics at the University of Rochester. The data that support the findings of this study are available from the corresponding author upon request. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

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