Principal Factors in the Performance of Indirect-Drive Laser-Fusion Experiments

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Experiments at the National Ignition Facility (NIF) are underway to test the physics and engineering limitations of thermonuclear burn at laboratory scales.[1] For an indirect-drive experiment, this begins by heating a high-Z cavity/hohlraum with a shaped laser pulse and ablating a low-Z pusher/capsule at ≈300 eV (Refs. 2 and 3). This process generates the pressures (≥100 Mbar) needed to implode a thin deuterium–tritium (DT) shell to high velocities (350 to 450 km/s) and make a central hot spot that self-heats. The primary goal of this work is to determine the characteristics of the laser and target that are needed for ignition. As documented elsewhere,[4–8] several advances have been made, but challenges remain. For example, it is still not possible to reliably relate performance to laser energy or implosion symmetry and account and correct for common variations in either. These sensitivities could suggest that one or more aspects of implosion physics are not understood or reproducible. In addition, it is still uncertain if all data can be taken at face value since multiple measurements of a given quantity can disagree, as shown in Fig. 1. Observations of the hot spot can be related to stagnation properties (and the proximity of ignition), but only if the state of the system is well defined. These issues complicate interpretation and present obstacles to predicting future data. Discrepancies could be due to errors in physics (theory or simulation) or variabilities in the target and facility that do not apply equally to all implosions.

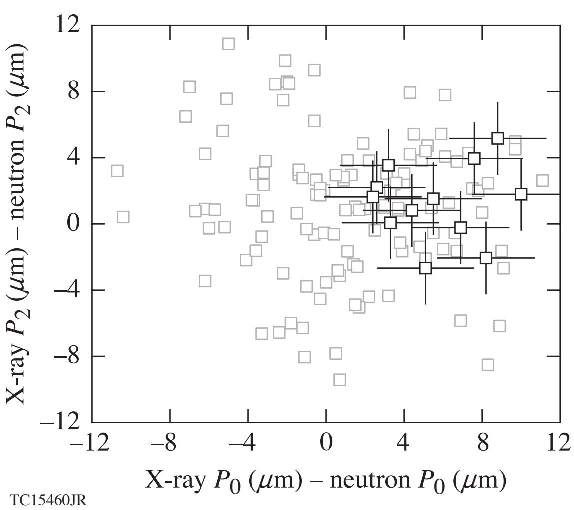

Figure 1
The size and shape of the hot spot (Legendre P_0 and P_2) can differ in independent measurements of x-ray and neutron emission. Inconsistency can be quantified by the scatter in both, as shown here. The inability to correlate hot-spot properties to yield could suggest these data do not resolve or characterize all possible sources of degradation. The expected deviation in the abscissa (ordinate) is 2.5 (2.2) μm, although data on the NIF (open gray squares) vary by 5.2 (4.6) μm. This has not been explained but could indicate small levels of high-Z material (mix) in the hot spot.[9] Recent data using the BigFoot Platform (open black squares) vary by 2.6 (2.4) μm and have an average abscissa (ordinate) that agrees with simulations.

In this summary, we focus our analyses on experiments using the so-called "BigFoot" platform (see Fig. 2) as described in Ref. 10. These experiments have been designed to reduce complex interactions in the laser, hohlraum, and capsule with the goal of simplifying the integrated system. This required new features in design (discussed below) that do not try to maximize performance. The result has been implosions that are relatively predictable and data that are more self-consistent. Performance compares favorably with theory and, as we show, is a simple function of laser energy per unit target mass (*E*/*M*), target scale (*S*), and low-mode implosion symmetry (hot-spot P_2). Neutron yield *Y* (measured at 13 to 15 MeV) is found to increase as $(E/M)^{7.6}(S)^4\left(1-0.05\left|P_2/S\right|\right)$ to ±8.7%. This analysis suggests that small target flaws and imperfections do not determine the yield, and we can account for small changes in *E*/*M*, P_2, etc. while testing other aspects of inertial confinement fusion (ICF). (Typically, yield can be explained only by detailed calculations in 3-D including flaws unique to each target.[11,12]) These results provide a useful perspective on data on the NIF and a new baseline for testing the physics of indirect drive.

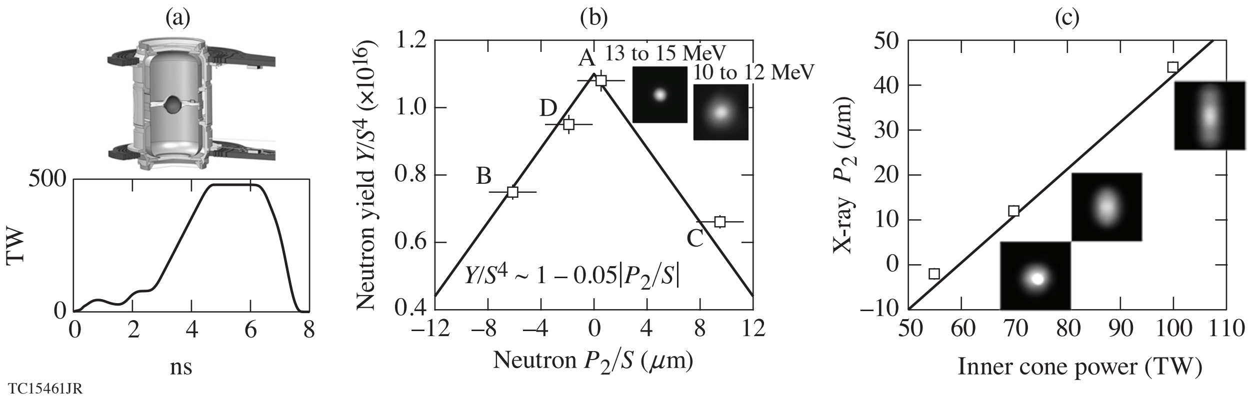

Figure 2
(a) The BigFoot target and laser pulse from shot 180128 at *S* = 1.125. (b) Yield versus hot-spot symmetry for data (open black squares) and simulations (solid line) after normalizing for small differences in target scale. (c) Hot-spot symmetry versus inner cone power at constant total power.

We begin by summarizing the BigFoot design and experimental campaign. The primary features and rationale are as follows: (1) a high-density carbon (HDC) ablator to substantially shorten the laser pulse; (2) a low-gas-fill (LGF) density hohlraum (0.3 mg/cm^3) to reduce laser–plasma instabilities at high power, tamp hohlraum-wall motion, and provide a well-understood radiation source; and (3) a ≥12-Mbar first shock to reduce phase coexistence in the ablator (liquid and solid) and increase hydrodynamic stability. This work also introduced changes in laser pointing, the geometry of the hohlraum, and the pulse shape, which are designed to produce a relatively high-adiabat implosion ($\alpha_v = 4$) as defined in Ref. 10. This shock-timing scheme was characteristic of early experiments in the National Ignition Campaign that gave unexpectedly high yield (e.g., shot 110212) and could reduce perturbations at the fuel–ablator interface. With these choices, the radiation-hydrodynamic code *LASNEX*[13] is able to predict key aspects of hohlraum performance, such as the time of peak capsule emission (±100 ps), with the measured laser pulse. This has allowed us to perform symmetric implosions near the power and energy limits of the NIF without employing cross-beam energy transfer.[14] The platform has also allowed us to collect data over a large range in laser energy (0.8 to 1.8 MJ) and primary yield (1.7×10^{14} to 1.7×10^{16}) as needed to study performance.

The first experiments used HDC capsules with an inner radius *R* of 844 μm and a total thickness of 64 μm that we define as target scale *S* = *R*/844 = 1. The equimolar DT layer was 40 μm thick to enable high implosion velocities and accurate characterization. The hohlraum was made of Au to avoid concerns with reproducibility (other materials oxidize) and simplify fabrication. The diameter of the hohlraum was 5400 μm and its length was 10,130 μm [see Fig. 2(a)]. The hohlraum is small so it can reach high radiation temperatures (≥330 eV) without using the maximum energy available on the NIF. This limits the damage to optics and maximizes the potential shot rate. Laser backscatter was limited for all experiments (≤1%), and the yield was found to increase monotonically with laser energy *E* (Ref. 10). Including recent data, the laser energy was increased from 0.8 to 1.3 MJ, and the primary yield from 1.7×10^{14} to 1.0×10^{16} at approximately E^8. To make a comparison with theory, we assume the mass forming the hot spot (1) has an initial energy $\sim v^2$ before compression by the cold fuel (it reaches the same implosion velocity as the shell prior to stagnation), (2) is compressed adiabatically with $\gamma = 5/3$ (losses relative to peak compression are small), and (3) achieves a radial compression ratio $\sim (v^2/\alpha_v)^{1/2}$, where the design adiabat α_v is a measure of compressibility.[15] The energy in the hot spot $E_\mathrm{h} \sim v^4$ without accounting for alpha heating. If self-heating is included, then we expect $E_\mathrm{h} \sim v^{4f}$ with a feedback f greater than 1. If we also assume yield $Y \sim E_\mathrm{h}^2$, consistent with $\langle\sigma v\rangle$ at 5 keV (Ref. 16), then we expect $Y \sim v^{8f}$. Scalings of this type are commonly used to explain performance in ICF,[2] but are difficult to apply to data since the uncertainty in velocity can be 4% to 5%. Alpha heating is not measured and must be inferred. To make more-precise comparisons, this summary uses a surrogate for velocity based on the laser energy E and the initial ablator mass M, which are both known to <1%. If the kinetic energy of the implosion is assumed to scale with E and its mass is proportional to M, then $v^2 \sim E/M$ and $Y \sim (E/M)^{4f}$. Calculations have been used to validate this approach and predict $f \sim 2$ for current experiments. Since implosions could be subject to additional instability or preheat, we will assume $Y \sim (E/M)^N$.

Experiments have also been done with HDC capsules having an inner radius of 950 μm at target scale $S = 950/844 = 1.125$. All dimensions of the capsule and hohlraum (and laser pulse) were increased by the same ratio. Peak laser power was increased by S^2 and laser energy by S^3. The first data of this type (shot number 170524) was compared to experiments at $S = 1$ and the yield was found to increase by a factor of $\approx S^4$ as expected;[17,18] including prior results, we expect $Y \sim (E/M)^N (S)^4$.

The data can also be used to address low-mode implosion symmetry, i.e., hot-spot P_2. This is the primary asymmetry on the NIF (laser-irradiation geometry) and two-sided cylindrical hohlraums. Calculations expect the primary loss mechanism to be conduction, and a small P_2 suggests a hot spot with more surface area. This should reduce the time-averaged number density and temperature of the burning plasma. To first order, the change in yield can be captured by an expansion in P_2/P_0 or P_2/S. Small changes in the system can cause asymmetry in P_2 (shot to shot) even for implosions that are designed to be symmetric. In Fig. 2(b) we report the primary neutron yield versus hot-spot P_2, in microns, for four experiments with the same E/M. The range is ± 8 μm in P_2 and a factor of 1.6 in yield. The experiments were done in the order shown: A through D. Small changes in the laser, target fabrication, and target alignment could cause this variation. Data and simulation are consistent, and both suggest $Y \sim 1 - 0.05 \left| P_2/S \right|$. To show the laser pulse can be adjusted to improve symmetry, we provide Fig. 2(c) in which ± 8 mm in P_2 is equivalent to $\pm 10\%$ on the inner cone energy (64 beams) or $\mp 5\%$ on the outer cone (128 beams). In net, $Y \sim (E/M)^N (S)^4 \left(1 - 0.05\left| P_2/S \right|\right)$.

We determine N with a least squares fit to all data accounting for changes in laser energy, ablator mass, target scale, and implosion symmetry. This analysis can use the x-ray or neutron P^2 since they are well correlated (see Fig. 1), but we choose the latter since neutron data are more directly related to the DT hot spot. In Fig. 3 we assume $Y \sim (E/M)^N (S)^4 \left(1 - 0.05\left| P_2/S \right|\right)$ and find $N = 7.6 \pm 0.3$ with a $\chi_\nu^2 = 1.2$ normalized per degree of freedom. Given the measurement uncertainty in laser energy is $\pm 0.5\%$ and neutron P_2 is ± 1.8 μm, then we should only fit data to $\approx 8.9\%$. Throughout this summary, we also fit data with subsets of this model and report the residuals. Data are consistent with high levels of alpha heating ($E^{7.6} > E^4$) and require all terms for a good fit. Two experiments are excluded from this process due to known problems with each target: E and F. In one of these experiments the capsule was found to have a defect/hole that would normally disqualify it from use; in the other, the capsule was found to be displaced from target chamber center by 200 μm (from one perspective). Most targets are centered to 25 μm. These issues were identified before each shot and could not be corrected. Both experiments are below trend and demonstrate that our analysis can identify outliers. Anomalies of this type should not be allowed to impact interpretations. All of the other targets met specifications and were not subject to selection effects. These targets used different capsule supports (30- and 45-nm plastic tents) and fill tubes (5- to 10-μm outer radius). Since the data are fit with a simple formula that follows expected sensitivities, it would appear these data can also provide constraints on other factors. Given that sensitivities in laser energy, target scale, and implosion symmetry have now been characterized, this platform can be used to study aspects of implosion physics with high precision. We have started a scan in pulse length that will look at adiabat ($\alpha_v = 2$ to 6) (Ref. 19) and other features in design. These tests will search for unexpected sensitivities and may help explain performance relative to prior data and expectations of ignition.[20]

To motivate additional work, we briefly discuss the terms in the fit and the physics mechanisms that could play a role. (1) The sensitivity of yield to laser energy reported here is fast relative to prior results[7] and simple theory with no alpha heating ($\sim E^4$).

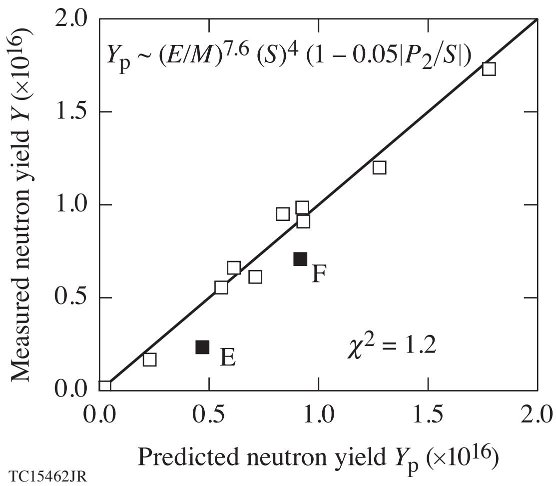

Figure 3
The best fit to data assuming yield is a function of laser energy per unit mass, target scale, and hot-spot symmetry. The residual excluding experiments E and F is 8.7%.

The accuracy of a power law (and its ability to extrapolate) should relate to the range over which it applies. If data are inconsistent with a single value of N or can only be fit over a small range in energy (for a few data points), this could suggest results that are variable (or stochastic). The sensitivity to E/M is a central aspect of performance and the interpretation of other physics. (2) Yield should increase with target scale. BigFoot experiments are intended to be robust and provide the requisite control (shot to shot) to interpret changes in target size. The required level of control is challenging since our analysis shows 6% in E/M can change the yield by a factor of 1.6, similar to a 12% change in S (or ± 8 μm in P_2). Understanding could be improved by performing experiments with more capsule radii and by making the sensitivity to scale a free variable in the fit to all data. (3) Performance should depend on low-mode symmetry and other observations of the hot spot. This is easy to demonstrate in BigFoot experiments since (a) P_2 is linear in the inner cone power [see Fig. 2(c)] and (b) the impact of target flaws and imperfections are reduced. A small amount of high-Z material can increase x-ray emission (locally), reduce neutron emission, and decorrelate these measurements from each other, and the yield.[9] Issues of this type would be expected to confuse interpretations of P_0 and P_2 as well as other integrated metrics, such as the burn-averaged pressure. Observations of the hot spot in BigFoot data are self-consistent (as shown in Figs. 1 and 2) and strongly correlate with yield. The uncertainty in subsequent inferences should be reduced. Experiments that make (large) intentional changes in implosion symmetry and stability could be used to extend this work and establish the experimental signature(s) for different failure modes.

Our results can also be used to suggest methods for increasing the yield and alpha heating. As shown in Fig. 4, a straightforward approach would be to increase laser energy by 10% to 20%. If we assume that laser–plasma instabilities do not grow significantly, this will increase the temperature in the hohlraum, the ablation pressure, and the energy coupled to the capsule. Experiments at scale 1 (1.125) have been designed to use 1.5 MJ at 400 TW (2.0 MJ at 500 TW). Using the scalings presented here, this could increase yield by as much as a factor of $(1.5/1.35)^{7.6} = (2.0/1.8)^{7.6} = 2.2$. We have also proposed targets that would use thicker capsules at higher power and energy to further increase E/M (Ref. 10). To determine the expected change in alpha heating, we calculate χ_α (a common metric for ignition[16]) and estimate yield amplification as $\exp\left(\chi_\alpha^{1.2}\right)$. For experiment 180128 (the highest point overall), the measured areal density is 0.620 ± 0.030 g/cm^2 and primary yield is 1.7×10^{16}. We estimate a total yield of 2.0×10^{16}, $\chi_\alpha = 1.13 \pm 0.06$, and a yield amplification of 3.2 ± 0.2. Since $\chi_\alpha \sim Y^{0.34}$, a factor of 2.2 in yield would increase χ_α by 30%. This implies that existing targets could demonstrate yield amplifications as high as a factor of $\exp(1.47^{1.2}) = 4.9$. To put this in perspective, the yield amplification in a burning plasma is commonly defined to be 3 to 3.5 (Ref. 16), and for ignition, a factor of 15 to 30. These implosions meet the criteria for an alpha-dominated plasma but are still far from ignition. Nonetheless, we recommend caution with respect to both extrapolations. The measured yield and areal density are consistently below integrated 2-D calculations by a factor of 4 and 1.3, respectively. Also, BigFoot implosions appear to have higher compression ratios than prior data despite having a higher design adiabat ($\alpha_v = 4$). This is inconsistent with theory and may indicate degradation mechanisms that are still unknown[21] that can be corrected.

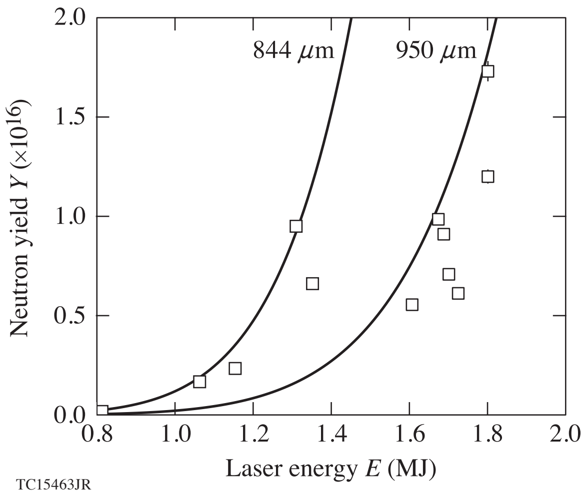

Figure 4
Yield versus laser energy for BigFoot implosions (open black squares) having a capsule inner radius of 844 and 950 μm. For context we show the fit from Fig. 3(a) at each scale [the solid line(s)] in the limit that $P_2 = 0$.

To conclude, we have analyzed implosions that simplify aspects of hohlraum and capsule physics and find that performance can be described by a simple function of laser energy per unit mass (E/M), target scale (S), and implosion symmetry (hot-spot P_2). Neutron yield Y is found to be expressible as $(E/M)^{7.6}(S)^4\left(\left|1-0.05P_2/S\right|\right)$ with a residual error that can be accounted for using measurements of E/M and P_2. This should improve the interpretation of future data and increase confidence in its extrapolation. To build on these results, we have started a scan in design adiabat that will use the same approach and make small changes in the pulse shape (only). We also propose experiments at greater energy per unit mass and will use both studies to address performance limits in indirect drive and criteria for ignition.

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