Experiments to explore the influence of pulse shaping at the National Ignition Facility

Cite as: Phys. Plasmas 27, 112708 (2020); https://doi.org/10.1063/5.0019193
Submitted: 23 June 2020 . Accepted: 25 September 2020 . Published Online: 09 November 2020


AIP Advances
Fluids and Plasmas Collection

Phys. Plasmas 27, 112708 (2020); https://doi.org/10.1063/5.0019193
© 2020 Author(s).
Experiments to explore the influence of pulse shaping at the National Ignition Facility

Cite as: Phys. Plasmas 27, 112708 (2020); doi: 10.1063/5.0019193
Submitted: 23 June 2020 · Accepted: 25 September 2020 ·
Published Online: 9 November 2020

C. A. Thomas,1,a) E. M. Campbell,1, K. L. Baker,2, D. T. Casey,2, M. Hohenberger,2, A. L. Kritcher,2, B. K. Spears, S. F. Khan,2 R. Nora,2 D. T. Woods,2 J. L. Milovich, R. L. Berger,2 D. Strozzi,2 D. D. Ho,2 D. Clark,2 B. Bachmann,2 L. R. Benedetti,2 R. Bionta,2 P. M. Celliers,2 D. N. Fittinghoff,2 G. Grim,2 R. Hatarik, N. Izumi,2 C. Kyrala,2 T. Ma,2 M. Millot, C. A. Thomas,1,a) G. Kyrala,2 T. Ma,2 M. Millot,2 J. L. Milovich,2 R. L. Berger,2 D. Strozzi,2 D. D. Ho,2 D. Clark,2 B. Bachmann,2 L. R. Benedetti,2 R. Bionta,2 P. M. Celliers,2 D. N. Fittinghoff,2 G. Grim,2 R. Hatarik, N. Izumi,2 C. Kyrala,2 T. Ma,2 M. Millot,2 J. L. Milovich,2 R. L. Berger,2 D. Strozzi,2 D. D. Ho,2 D. Clark,2 B. Bachmann,2 L. R. Benedetti,2 R. Bionta,2 P. M. Celliers,2 D. N. Fittinghoff,2 G. Grim,2 R. Hatarik, N. Izumi,2 C. Kyrala,2 T. Ma,2 M. Millot,2 J. L. Milovich,2 R. L. Berger,2 D. Strozzi,2 D. D. Ho,2 D. Clark,2 B. Bachmann,2 L. R. Benedetti,2 R. Bionta,2 P. M. Celliers,2 D. N. Fittinghoff,2 G. Grim,2 R. Hatarik, N. Izumi,2 C. Kyrala,2 T. Ma,2 M. Millot,2 J. L. Milovich,2 R. L. Berger,2 D. Strozzi,2 D. D. Ho,2

AFFILIATIONS
1Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA
2Lawrence Livermore National Laboratory, Livermore, California 94550, USA
3Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
4Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
5Author to whom correspondence should be addressed: cliff.thomas@stanfordalumni.org

ABSTRACT
The shaping of the drive pulse in time is a key tool in the design of fusion experiments that use inertia to confine burning plasmas. It is directly related to the adiabat and compressibility of the DT fuel and the characteristics of the laser and target that are needed to ignite. With this in mind, we have performed experiments at the National Ignition Facility that test small changes in the shape of the pulse. In contrast to theory, we find implosions at lower adiabats can have reduced yield and areal density. We discuss implications to performance and the mechanism(s) that could be responsible.

Published under license by AIP Publishing. https://doi.org/10.1063/5.0019193

I. INTRODUCTION
A primary goal of the National Ignition Facility (NIF) is to determine the laser and target requirements needed to achieve thermonuclear ignition and propagating burn.1 In detailed calculations, performance is predicted to depend on the shape of the laser pulse and the design adiabat, a, of the DT fusion fuel.2,3 By convention, the adiabat is defined by the pressure in the cold fuel relative to Fermi-degenerate DT at the maximum velocity of the implosion.4 In the absence of mechanisms that disturb the fuel such as preheat, the shape of the laser pulse should determine the compressibility of the shell and the terms “pulse shaping” and adiabat are interchangeable. So far, experiments on the NIF have primarily reported tests at a = 1.5 ± 0.1 and a = 2 to 2.5 using indirect drive. The integrated performance has improved as issues with hot-spot mix5 and target engineering features6,7 have been identified and corrected. Changes in the shape of the laser pulse have also played a role but have not proven as easy to study. In part, this is because uncertainties in hohlraum and capsule physics complicate the interpretation of simple tests.8 Small and unpredictable changes in implosion velocity and symmetry confuse results. In addition, most experiments are subject to multiple sources of degradation, and sophisticated calculations are needed to unfold the importance of each. If aspects of these calculations are inaccurate, this would be expected to convolve changes in the pulse with other aspects of physics and make optimization difficult.

To provide new insight(s), this paper takes advantage of the “BigFoot” platform, which was developed to facilitate single-variable studies.9 This design uses features that are conservative and reduces the number of mechanisms that impact data. As shown in prior work,10 the yield is a simple and expected function of laser energy per unit target mass, target size/scale, and implosion symmetry. This relationship makes it possible to correct for variations in these quantities and study other aspects of physics such as pulse shape. As a consequence, we have used this platform to perform implosions at two design adiabats (a = 4 and 3 ± 0.1) and find that yield and areal density can decrease when the adiabat is reduced. These findings suggest the optimum design adiabat is above 3 (presently) and that one or more aspects of simulation are incomplete. We have not been able to explain these results in high-resolution calculations using
known details of the targets or facility. At the same time, these experiments provide the first direct evidence that performance can increase with compression and that further improvements could require non-intuitive changes to the drive.

For background, we briefly explain features of the BigFoot design that make it useful for this work [see Fig. 1(a)]. First, the length of the laser pulse is shorter (and the radius of the hohlraum entrance hole is larger) than conventional target designs.\(^8\) This not only reduces the energy coupled to the target and the expected yield but also makes it considerably easier to control and maintain implosion symmetry. There is less time for high-Z plasma to move toward and impede the propagation of the laser. Second, BigFoot experiments have minimal laser–plasma instabilities and show no evidence of hot-electron pre-heat.\(^1\) It is not necessary to account or correct for either when changes are made in the length, power, or energy of the laser pulse. Third, the first shock in the ablator is also considerably stronger (\(>12\)-Mbar) than in prior studies. This should reduce the maximum possible compression of the DT fuel but, more importantly, should also reduce the instabilities seeded by target flaws and imperfections that can vary shot to shot (e.g., the capsule support, fill tube, and other debris). Fourth, calculations in LASNEX\(^17\) are able to predict the time of peak emission (\(\pm 100\) ps) and implosion symmetry (\(\pm 5\) \(\mu\)m in \(P_4\)) using the measured laser pulse.\(^18,19\) Together, these features allow us to maintain implosion velocity and symmetry\(^20,21\) while testing expectations vs pulse shape with fewer sources of uncertainty.

### II. CHANGES TO THE PULSE

As an example, this paper reports the result of two experiments where the length of the laser foot (the low power section of the pulse) is increased by approximately 400 ps, as shown in Fig. 1(a). This change could appear to be small but is exceedingly important to the calculated yield and areal density. A shock is launched by each rise in the pulse (labeled \(p_1–p_3\)), and the adiabat of the fuel at peak velocity is a function of their relative timing. For the experiments described here, the adiabat of the fuel should decrease (increase) when the delay between \(p_1\) and \(p_2\) is lengthened (reduced). In the limit the second shock catches the first at the inner radius of the DT shell (an additional 400 ps delay) these implosions are calculated to ignite. The rise to peak laser power is slow (~2 ns) to minimize the impact of \(p_3\) on the calculated adiabat. We seek to study and optimize \(p_1\) and \(p_2\) first. According to integrated calculations in LASNEX (in 2-D), the change in Fig. 1(a) should lower the mass-average design adiabat from 4 to 3 \(\pm 0.1\) and increase the neutron yield and DT areal density by a factor of 2.9 and 1.3, respectively. The target and laser pulse are otherwise identical, modulating a small increase in the laser cone fraction (the power on the inner laser cones of the NIF divided by the total) of 3%. The time of peak emission is delayed by 400 ps (as expected), and x-ray measurements confirm that the velocity and symmetry of these implosions are otherwise unchanged.\(^21\) This makes it possible to isolate the influence of the pulse shape at a given laser energy, \(E\). In Fig. 1(b), we show the primary neutron yield \(Y\) measured at 13–15 MeV, and in Fig. 1(c), the neutron down scatter ratio (DSR) averaged across multiple measurements. The DSR is a function of neutron emission at 10–12 MeV and is related to the burn-average DT areal density (in \(g/cm^2\)) by \(\rho R_0 = 20\ DSR\).\(^6\) (We average the DSR since most implosions are symmetric, and because diagnostics with a common line of sight can vary by more than the uncertainty in each.) In contrast to calculations, the yield and DSR are found to decrease when the pulse is lengthened and \(a_r\) is reduced. The statistical significance of these results is addressed in Fig. 2. In Ref. 15, we have shown the outcome of BigFoot experiments at \(a_r = 4\) is a simple function of laser energy per unit ablator mass \(E/M\), target size/scale \(S_t\), and the time-integrated shape of the hot-spot \(P_2\). \(S_t\) is defined by \(R/944\) (where \(R\) is the radius of the capsule in \(\mu\)m), and Legendre \(P_2\) characterizes the dominant asymmetry. This analysis lets us account for small changes in each shot to shot, while comparing new results to the aggregate of prior findings. We find data at \(a_r = 3\) are below trend by 40–50%, or \(4–5\sigma\) (40% \(9\% \approx 4\)), and are not explained by normal variations in target physics. Though not shown here, the yield and DSR at \(a_r = 3\) are even below prior implosion results at \(a_r = 4\) using smaller capsules at reduced laser energy.
III. THEORY AND ANALYSIS

We can illustrate the principles involved with simple models. It is only necessary to assume the mass that forms 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 \( C_R \sim (v^2/x_a)^{1/2} \) (Ref. 22). If so, the energy in the hot spot \( E_h \) should increase as \( v^2 C_R^2 \sim v^2 x_a^{-1} \) without accounting for alpha deposition. If self-heating is included, then we assume \( E_h \sim (v^2 x_a^{-1})^f \) with a feedback \( f \geq 1 \). The neutron yield \( Y \sim n^2 T^2 V \tau \sim E_h^2 \) for NIF-scale experiments at 4–5 keV (Refs. 2 and 3). Since the kinetic energy of the shell is roughly proportional to laser energy \( E \) (when the coupling between the hohlraum and capsule is fixed), this is roughly comparable to \( Y \sim (E/M)^n (x_a)^{-j} \), where \( M \) is the initial mass of the ablator. This derivation clearly outlines the expected relationship between yield and adiabat and shows that self-heating should have multiple signatures in data. \( E/M \) is measured to \( < 1 \) and \( x_a \) is a function of design. Calculations have validated this relationship, and expect \( f \sim 2 \) in current experiments, i.e., \( Y \sim (E/M)^n (x_a)^{-j} \). Since areal density \( \sim C_R^2 \), it follows that \( DSR \sim (E/M)^j (x_a)^{-1} \). The yield and DSR should increase when adiabat is reduced, and it is imperative to study and quantify these behaviors in data.

If we assume the measured yield follows a power law in \( E/M \) and \( x_a \) (in the same way), then best-fit exponents can be found with a least-squares fit. In this manner, we can quantify the importance of each without relying on detailed calculations or theory. To account for other small changes shot to shot, we also include a correction for the target size/scale \( S \) and implosion symmetry (hot-spot pulse \( P_2 \)) as explained in Ref. 15. We then repeat this exercise for the DSR but include no dependence on \( P_3 \). (The data in Fig. 1(c) show little or no sensitivity.) In Fig. 3(a), we assume \( Y \sim (E/M)^{N_1} (S)^{N_2} (1 - 0.05 P_2/S) (x_a)^{N_3} \) and find \( N_1 = 7.5 \pm 0.3 \) and \( N_2 = 2.0 \pm 0.1 \) with a \( \chi^2 = 1.2 \) (per degree of freedom). In Fig. 3(b), we assume \( DSR \sim (E/M)^{N_1} (S)^{N_2} (x_a)^{N_3} \) and find \( N_1 = 0.9 \pm 0.2 \) and \( N_2 = 0.6 \pm 0.1 \) with a \( \chi^2 = 1.1 \). These fits are a good representation of data and behave as expected with the exception of adiabat. Figures 4(a) and 4(b) demonstrate the significance of these results (again). In this case, we go through the same process but include no information with respect to \( x_a \). For \( Y \sim (E/M)^{N_1} (S)^{N_2} (1 - 0.05 P_2/S) (x_a)^{N_3} \) and \( DSR \sim (E/M)^{N_1} (S)^{N_2} (x_a)^{N_3} \), then we find \( N_1 = 5.1 \pm 0.2 \) and \( N_2 = 0.3 \pm 0.3 \). Neither model is a good fit to data and \( \chi^2 \gg 1 \). (The residuals in the yield and DSR are increased by a factor of 2 or more.) It would appear that higher performance is possible at even higher adiabat. As a consequence, we have proposed to extend this work to \( x_a \) = 5 and 6. We expect a more complicated relationship than shown here, with a local maximum in the yield and DSR at a design adiabat other than 4. Subsequent experiments would change other aspects of the pulse, such as the delay between \( p_2 \) and \( p_3 \).

BigFoot implosions have been designed to reduce the number of mechanisms that degrade performance. This should make it easier to perform and interpret experiments that test expectations. Here, a small change in the pulse shape is found to reduce the yield (DSR) by a factor of 0.56 (0.84) although both were expected to increase. The value of this approach is evident. Had we performed these experiments with changes in the pulse shape, laser energy, and/or implosion symmetry (at the same time), it is not guaranteed that calculations would arrive at the same interpretation. It would be even more difficult to reach these conclusions if experiments were sensitive to small changes in target quality. If calculations are unable to capture the primary sensitivities in data, then it is unclear how they can unfold combined effects. That said, it is possible to study the effect of the pulse shape in experiments with additional sources of degradation. If we assume the shot-
to-shot variability (or reproducibility) is \( \sigma \) and we can average over multiple experiments, \( N \), then we expect the accuracy of our inferences to scale as \( \sigma / \sqrt{N} \). It is only necessary to increase the total number of experiments by \( \sigma^2 \).

IV. IMPLICATIONS TO IGNITION

We now examine the peak compression ratio \( C_p \) in BigFoot data to check for self-consistency. This quantity is estimated from the areal density of the cold fuel since observations of the hot spot do not have to correlate with pdV work. We begin by defining the areal density at peak compression as \( \rho R_{bc} \) and the areal density at peak burn as \( \rho R_{bc} + \rho R_{bh} \), with contributions from the cold shell (c) and hot spot (b), respectively. We measure the latter, but note that alpha heating and electron conduction tend to offset the time(s) of peak compression and peak burn. As a consequence, we expect \( \rho R_{bc} \geq \rho R_{bc} + \rho R_{bh} \). If we also assume that the cold fuel at peak compression has the same mass as the initial DT layer (with areal density \( \rho_{c,b} \)) and is relatively thin (corrections for a finite hot spot and cold shell are typically 3% or less), then we can put a lower bound on \( C_p \) as

\[
C_p^2 = (\rho R_{bc} + \rho R_{bh})/\rho_{c,b} = 20 \text{ DSR} / \rho_{c,b}.
\]

This formula can be used to compare implosions of different sizes and types when alpha heating is modest, and \( \rho R_{bh} \ll \rho R_{bc} + \rho R_{bh} \), Figure 5 shows \( C_p \) as a function of the mass-average first shock velocity in the fusion fuel, \( u_1 \), in km/s. The first shock is the primary source of entropy in calculations and can be viewed as a surrogate for adiabat.\(^{23,24}\) Energy deposition should increase as \( u_1^2 \), and in simulations, we find \( u_1 \approx 1.2 \times 10^{-3} u_0^2 \) for \( u_1 \leq 60 \text{ km/s} \). We remind the reader that the goal of pulse shaping is to control (and minimize) the adiabat to maximize compression. BigFoot implosions with a mass-average \( x_e = 4 \) \((u_1 \approx 55 \text{ km/s})\) have a compression ratio of 22–23. When BigFoot implosions are performed at a lower adiabat \((x_e = 3 \text{ and } u_1 \approx 40 \text{ km/s})\), the compression ratio is 20 and more consistent with prior results. It is clear that performance correlates with compression but not as we typically expect. This analysis can also be used to infer discrepancies relative to theory. It is only necessary to decide which data can serve as a reference and project \( C_p \sim x_e^{-1/2} \). If we assume implosions at high adiabat are closer to theory, then this type of extrapolation is given by the solid line in Fig. 5. BigFoot data at \( x_e = 3 \) appear to be deficient in compression by 25%. This is equivalent to 50% in the DSR, and significant, as the laser energy needed to ignite \( E_{ign} \sim v^4 u_0^4 \) \((\text{Ref. 25})\). If \( C_p \sim (v^2 / x_e)^{1/2} \), then we expect \( E_{ign} \sim v^{-2} C_p^{-4} \sim v^{-2}(20 \text{ DSR} / \rho_{c,b})^{-1} \). Disparities in compression should have a significant impact on performance and the probability of ignition.

Given these results, we will briefly discuss the mechanisms that could play a role. This could include one or more errors in the strength or timing of shocks, as explained in Ref. 24. We find this unlikely, as these inferences have repeatedly been validated.\(^{25,26}\) It is also possible that we do not fully understand the DT equation of state, the stagnation adiabat, or both. Although not presented here, simulations can match the measured yield, temperature, and DSR of BigFoot implosions if they use a higher adiabat than intended by a factor \( \geq 1.4 \). For capsules that absorb 200 kJ of x rays, this is equivalent to adding 80 J to the cold DT shell. Simulations would have to underestimate sources of instability, mix at the fuel–ablator interface, or vorticity at small scales.\(^{27}\) An increase in the effective adiabat would result from residual motion in the cold DT proportional to \( u_1 \), which would increase internal energy as \( u_1^2 \) after hydrodynamic growth (compression and thermalization). Calculations expect instability to increase at lower adiabats (in general) but do not predict the results shown here. Mix

---

FIG. 4. The best models for (a) yield and (b) areal density vs laser energy per unit mass, target scale, and hot-spot symmetry without accounting for design adiabat.

The residuals are 23.0% and 8.0%, respectively. Data at \( x_e = 4 \) \((3)\) are shown by the open black squares (solid black squares).

FIG. 5. BigFoot data (open black squares) are compared to previous results (open gray squares) on aspects of pulse shaping. Experiments at \( u_1 \) of 18, 32, 40, and 55 km/s correspond to \( x_e \) of 1.5, 2.3, 3.0, and 4.0, respectively. The solid line is the expected value for a BigFoot-type implosion assuming \( C_p \sim x_e^{-1/2} \) at a given velocity and DT mass.
between the ablator and DT fuel would increase its absorption of hard x rays and further reduce compressibility. Any impact(s) would be magnified if the ablator were to emit photons that directly couple to DT fuel at 10–100 eV. This part of the spectra is not a focus of most calculations. For insight, we will continue to quantify sensitivities in pulse shaping and work to characterize the state of the DT fuel. We have also proposed to test aspects of stability and, as a start, have made capsules with different levels of high-Z dopant and crystallinity to address hypotheses regarding preheat and microscopic sources of turbulence.

V. CONCLUSION

We have used an implosion platform that simplifies experimental interpretation(s) to test small changes in the shape of the drive pulse. If the laser energy per unit mass, hydrodynamic scale, hot-spot symmetry, and design adiabat are given by \( E/M, S, P_0, \) and \( \alpha_w \) respectively, then we find \( Y \sim (E/M)^{7/5} (S)^{4} (1 - 0.05[P_2/S]) (\alpha_w)^{2.0} \) and DSR \( \sim (E/M)^{0.9} (S)(\alpha_w)^{0.6} \). All terms behave as expected with the exception of the adiabat. This is important to the optimization of NIF because calculations are typically used to set the strength and timing of p1–p3. We will use these findings to interpret future work, and this will be particularly helpful when small and inadvertent changes are made in the laser pulse. If we consider Fig. 5, this should have important implications to compression and the proximity of ignition. For the experiments reported here at \( \alpha_w = 3 \) having a laser energy \( E = 1.8 \text{ MJ} \), a 25% deficit in compression should increase the energy needed to ignite by a factor of \( 1.25^{1} \approx 2.4 \).

ACKNOWLEDGMENTS

This work was made possible by the operations team at NIF, target fabrication efforts at General Atomics and LLNL, and the encouragement and support of J. H. Nuckolls, J. D. Lindl, W. L. Krueer, 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 No. DE-AC52-07NA27344, the U.S. Department of Energy National Nuclear Security Administration under Award No. DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority. This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof and shall not be used for advertising or product endorsement purposes.

REFERENCES


