Hotspot Parameter Scaling with Velocity and Yield for High Adiabat Layered Implosions on the National Ignition Facility

K. L. Baker\textsuperscript{1}, C. A. Thomas\textsuperscript{2}, D. T. Casey\textsuperscript{1}, M. Hohenberger\textsuperscript{1}, S. Khan\textsuperscript{1}, B. K. Spears\textsuperscript{1}, O. L. Landen\textsuperscript{1}, R. Nora\textsuperscript{1}, T. Woods\textsuperscript{1}, J. L. Milovich\textsuperscript{1}, R. L. Berger\textsuperscript{1}, D. Strozzi\textsuperscript{1}, C. Weber\textsuperscript{1}, D. Clark\textsuperscript{1}, O. A. Hurricane\textsuperscript{1}, D. A. Callahan\textsuperscript{1}, A. Kritcher\textsuperscript{1}, B. Bachmann\textsuperscript{1}, R. Benedetti\textsuperscript{1}, R. Bionta\textsuperscript{1}, P. M. Celliers\textsuperscript{1}, D. Fittinghoff\textsuperscript{1}, C. Goyon\textsuperscript{1}, R. Hatarik\textsuperscript{1}, N. Izumi\textsuperscript{1}, M. Gatju Johnson\textsuperscript{3}, G. Kyrala\textsuperscript{4}, T. Ma\textsuperscript{1}, K. Meaney\textsuperscript{4}, M. Millot\textsuperscript{1}, S. R. Nagel\textsuperscript{1}, P. K. Patel\textsuperscript{1}, D. Turnbull\textsuperscript{2}, P. L. Volegov\textsuperscript{4}, C. Yeamans\textsuperscript{1}, C. Wilde\textsuperscript{4}

\textsuperscript{1}Lawrence Livermore National Laboratory, Livermore, California 94550, USA
\textsuperscript{2}Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA
\textsuperscript{3}Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
\textsuperscript{4}Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

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Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

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Hotspot Parameter Scaling with Velocity and Yield for High Adiabat Layered Implosions on the National Ignition Facility

K. L. Baker¹, C. A. Thomas², D. T. Casey¹, M. Hohenberger¹, S. Khan¹, B. K. Spears¹, O. L. Landen¹, R. Nora¹, T. Woods¹, J. L. Milovich¹, R. L. Berger¹, D. Strozzi¹, C. Weber¹, D. Clark¹, O. A. Hurricane¹, D. A. Callahan¹, A. Kritcher¹, B. Bachmann¹, R. Benedetti¹, R. Bionta¹, P.M. Celliers¹, D. Fittinghoff¹, C. Goyon¹, R. Hatarik¹, N. Izumi¹, M. Gatu Johnson³, G. Kyrala⁴, T. Ma¹, K. Meaney⁴, M. Millot¹, S. R. Nagel¹, P. K. Patel¹, D. Turnbull², P. L. Volegov⁴, C. Yeamans¹, C. Wilde⁴

¹ Lawrence Livermore National Laboratory
² Laboratory for Laser Energetics, University of Rochester
³ Massachusetts Institute of Technology
⁴ Los Alamos National Laboratory

Abstract

This paper presents a study on hotspot parameters in indirect-drive inertially confined fusion implosions as they proceed through the self-heating regime. The implosions with increasing nuclear yield would reach the burning plasma regime, hotspot ignition and finally propagating burn and ignition. These implosions span a wide range of alpha heating from a yield amplification of 1.7 to 2.5. We show that the hotspot parameters are explicitly dependent on both yield and velocity and that by fitting to both of these quantities the hotspot parameters can be fit with a single power law in velocity. The yield scaling also enables the hotspot parameters extrapolation to higher yields. This is important as various degradation mechanisms can occur on a given implosion at fixed implosion velocity which can have a large impact on both yield and the hotspot parameters.
The yield scaling also enables the experimental dependence of the hotspot parameters on yield amplification to be determined. The implosions reported have resulted in the highest yield ($1.73 \times 10^{16} \pm 2.6\%$), yield amplification, pressure and implosion velocity yet reported on the National Ignition Facility.
For indirect drive inertial confinement fusion (ICF), x-rays impinging upon an ablator implode a spherical shell of deuterium-tritium fuel (DT) to reach fusion conditions, self-heating, and/or burn.\textsuperscript{1,2} At the National Ignition Facility (NIF), a high-Z cylindrical hohlraum is heated with 192 laser beams. The resultant x-rays ionize the exterior of the spherical ablator and launch shocks in the ablator that accelerate the remaining ablator and DT fuel inward compressing and heating a DT plasma, a hotspot, at its center. The fusion reaction that occurs between a deuterium and a tritium nucleus in the compressed hotspot generates a helium nucleus (alpha particle) and a neutron. To achieve high neutron yields, the hotspot must reach ion temperatures of $T_{\text{ion}}$>4 keV, and an areal density of $\rho r$>0.2-0.3 g/cm$^2$. At these areal densities, many of the alpha particles produced in the fusion reactions can then be stopped and absorbed in the hotspot, thereby increasing its temperature, a process known as alpha heating. For these particular implosions, a three-level laser pulse, as shown in Fig. 1a, produces three levels of x-ray drive in the hohlraum, which launch three primary shocks in the ablator. One of several characteristics distinguishing this implosion design from other HDC ablator implosions [3] is that the first two shocks merge in the ablator near the ice ablator interface.\textsuperscript{4-8} Figure 1a shows a comparison between two laser pulse shapes, one for a high adiabat (black), $\alpha$~4, BigFoot implosion, N180128, and a slightly lower adiabat (red) implosion, $\alpha$~3.5. The inset shock diagram in Fig. 1a displays a pie slice of the capsule along with a shock timing diagram for the implosions showing the first and second shock merger in the ablator (labeled as N180128). This has a substantial effect on the relative density difference between the DT ice and the ablator near the time of peak implosion velocity as seen in Fig. 1b. In particular, Fig. 1b shows the simulated density plot comparison between the adiabat 4, $\alpha$~4, shot, N180128, and an adiabat 3.5 implosion which has the second shock overtaking the first ~10 $\mu$m into the ice layer relative to the ice-ablator interface. Fig. 1b shows density lineouts of the two
implosions near the time of peak implosion velocity with the ice-ablator interface at a radius of ~200 µm. The adiabat of the fuel is defined as $\alpha = P/P_c$. $P$ is the mass-average DT fuel pressure at peak velocity, and $P_c$ is the minimum pressure at 1000 g/cm$^3$. In the $\alpha$~4 case, where the first two shocks merge in the ablator, the DT ice is only shocked two times and the ablator density remains at a slightly higher density than the DT ice making the ablator fuel interface stable. The $\alpha$~4 case, black line, is representative of the implosions presented in this paper. For the lower adiabat case shown, $\alpha$~3.5, the first and second shock overtake one another ~10 µm into the ice layer. The $\alpha$~3.5 case, red line, is more representative of previous ICF implosions where the first shock overtakes the second shock in the DT ice, usually at the ice-gas interface at lower adiabat closer to $\alpha$~2.5. For the lower adiabat case shown in Fig. 1b the ice layer next to the ablator is shocked three times and the DT ice density is higher than the ablator density near the time of peak implosion velocity. The lower density ablator pushing the higher density DT ice is classically unstable and drives mix at the fuel-ablator interface.

In this article, we determine the hotspot parameters explicit dependence on the yield, as well as on the velocity, as the implosions proceed through the self-heating regime. This yield dependence of the hotspot parameters, in conjunction with the dependence of yield amplification on yield, then provides a measure of the hotspot parameter dependence on yield amplification as well. We have chosen to determine the dependence on yield for the hotspot parameters, rather than yield amplification, because yield is a directly measured quantity with low error bars, ~3%, rather than an inferred quantity. The implosions described in this paper have a design adiabat of 4, $\alpha$~4, and were conducted in a hohlraum that was 6 mm in diameter and 11.3 mm in length. These hohlraums each contained a high-density carbon, HDC, capsule that had a 950 µm inner radius, was 72 µm thick and contained a tungsten, W, doped layer ranging between 0.13 and 0.28% W.
dopant. The W-doped layer shielded the ice-ablator interface from x-ray preheat.\textsuperscript{10-12} The particular specifics for each implosion are called out for each experiment in Table 1.

One of the most widely used metrics for layered implosions in ICF is the neutron yield. It is important, therefore, to understand how the yield and the hotspot parameters affecting the yield change as drive conditions on the capsule are varied and how the yield in turn affects the hotspot parameters. One straightforward effect of increased drive on the capsule is increased implosion velocity. Fig. 2a shows the measured yield, represented as black circles, as a function of the implosion velocity. The velocities used in the figures in this article were derived from postshot simulations of the shots performed with the radiation hydrodynamics code LASNEX.\textsuperscript{13} The simulation code was benchmarked by matching shock velocities and shock merger times inferred from VISAR measurements, temperature and yields in gas filled capsules, time-dependent backlit radiography in convergent ablator experiments and yield, ion temperature, hotspot size and bang time in layered implosions. The absolute uncertainty in matching the velocity of the convergent ablator experiments is \(\pm 15\) km/s and of the layered implosions \(\sim \pm 5\%\).\textsuperscript{14} For the figures in this paper, however, the velocity scalings of the hotspot parameters are obtained from a class of similar layered implosions linked to the same convergent ablator experiment and modelled with the same simulation code, with no changes to the deck between shots other than capsule and hohlraum parameters listed in Table 1 and the as delivered laser pulse. As such, the relative error bars on the velocity of the group of layered implosions, \(\pm 7\) km/s, is much lower than the absolute error bars or \(\sim \pm 60\) ps in bang time and the figures in the paper contain the relative velocity error bars. Table 1 also lists the implosion velocity, \(v_{\text{imp}}\), inferred from gated backlit x-ray radiography of the imploding shell taken with a convergent ablator platform \([15]\) with the same design and corrected for fuel vs ablator center-of-mass velocity offsets and any measured DT bang time offsets, again
with an expected relative error bar on the velocity of ±7 km/s. The experimentally derived velocities agree with the simulation values on average to within ~3 km/s, or <1%, over the entire set of shots. The hotspot shapes can be decomposed into Legendre polynomials, $P_n$, and the red (dark gray) circles in Fig. 2a represent a $P_2$ shape correction to the yields, $Y_{cp2}$, according to the formula $Y_{cp2} = Y/(1-(1.2*ABS(P_2/P_0)))$. This formula represents a fit to two-dimensional LASNEX simulations, at the yield amplification levels represented in this paper. The simulations varied the shape by changing the cone fraction, inner beam power/(outer+inner beam power), in the simulation to change the implosion symmetry and therefore the $P_2/P_0$. In the case of no alpha heating, $Y_{amp}=1$, the effect of shape on the yield is reduced according to the simulations with the yield decreased by the smaller factor $(1-(0.78*ABS(P_2/P_0)))$. Three velocity power-law scalings are included in Fig. 2a to compare with the data, a $v^{7.8}$ scaling as a dashed blue(lowest) line, a $v^{10}$ scaling as a dashed black(second lowest) line and a $v^{11.9}$ scaling as a dashed red(second highest) line. The $v^{7.8}$ scaling corresponds to the analytic no-alpha heating scaling in [17], assuming a hotspot mass scaling as $v^{0.1}$ and matches the three lower yield/velocity implosions. The $v^{10}$ scaling represents the best match over the entire data set, and the $v^{11.9}$ scaling is the best fit to the $P_2$ shape corrected yield using the simulation-determined correction formula.

In addition to shape effecting the yield from implosions, hotspot mix can also have a substantial effect on performance. If high-Z material from the shell is injected into the DT hot spot during the implosion, due to feedthrough of ablation front instabilities for instance, then those mixed regions experience enhanced bremsstrahlung emission and reduced yield. The injected mix causes an increase in x-ray emission from the hot spot relative to the neutron yield. In [20], the ratio of x-ray to neutron emissivity is given by
\[ \frac{X_\nu}{Y_{\text{DT}}} = \frac{4\pi}{f_D f_T A_v} \frac{e^{-h\nu/kT_e}}{\langle \sigma v \rangle^{0.33}} (1 + \sum x_i Z_i) \left(1 + \sum x_i \frac{j_i}{f_D \tau} \right) e^{-\tau_{\text{shell}}}, \]  

where \( X_\nu \) is the x-ray emission at a particular photon energy \((h\nu\) in units of keV), \( Y_{\text{DT}} \) is the total DT fusion yield, \( f_D \) and \( f_T \) are the fuel species fractions, \( A_v \) is Avogadro's number, \( \langle \sigma v \rangle \) is the temperature-dependent fusion reactivity, \( T_e \) is the electron temperature, and \( \tau_{\text{shell}} \) is the shell optical depth. The mix is characterized by a sum over mixed elements \( i \) that have atomic number \( Z_i \) and atomic fraction \( x_i \). The emissivity is represented by \( j_i \) which will scale as \( Z^2 \) for free-free continuum emission or as \( Z^4 \) for free-bound emission.

For these implosions a penumbral imaging system was used to measure the time-integrated x-ray emission utilizing an image plate detector. Penumbral pinholes with a 500 \( \mu\)m thick titanium filter were used to characterize the relative x-ray emission from each of the implosions and compare with the neutron yield. The energy corresponding to the peak detector response, assuming a 4.8 keV Bremsstrahlung source, was \( \sim24\) keV, which minimized shell opacity issues. The central part of the penumbral signal sampled all regions of the hotspot and was used to measure the total x-ray signal from the hotspot. Fig. 2b shows the ratio of the neutron signal to the x-ray signal, above 20 keV, for each of the implosions. Comparing the shot numbers with the parameters in Table 1, this figure shows that the lowest power and energy shot(N1704524), with the 0.13% tungsten doped capsules, had low relative mix, falling on the dashed line. After this shot, higher doped capsules, 0.21% W, were available and these capsules were pushed progressively harder, utilizing higher laser power and energy, to increase their velocity. As they were pushed harder they experienced more mix(N171015 to N171029 to N171119) according to Fig. 2b. After N171119, higher doped capsules became available, 0.28% W, and these capsules(N180128 and N180909) again experienced lower relative mix, falling on the dashed line. These capsules were then driven
to a higher implosion velocity by shooting them in a gold-lined uranium hohlraum for N180930, effectively increasing the energy and power by ~7% relative to N180128, and resulted in the lowest remaining mass and the largest level of mix. In Fig. 2b the dashed line is fit to the three shots which experienced the lowest mix in the series and is represented by $X_{RSfit} = -0.88 + \text{Yield}/2.64 \times 10^{15}$. We define a linear loss term to the yield as a function of how far the x-ray emission from the implosion is to the line denoting a “low mix” implosion, $(1-\eta) \cdot \text{ABS}(X-Ray \ Signal - X_{RSfit})/ X_{RSfit})$. A power law fit to the “P2 corrected” yields for the three implosions which had relatively little mix, $(X-Ray \ Signal - X_{RSfit}) \approx 0$, was made and then the value of $\eta$ was chosen which best enabled the remaining experimental points to fall on that same power law. We find that using $\eta = 1.2$ places all of the experimental points on a common power law, $\alpha_{15.7}^v$, represented by the dashed green (highest) line in Fig. 2a. The green (light gray) circles in Fig. 2a then represent both a correction due to shape, $Y_{cp2} = Y/(1-1.2 \cdot \text{ABS}(P2/P0))$, and a hypothesized correction from losses due to mix, $Y_{cm} = Y_{cp2}/(1-1.2 \cdot \text{ABS}(X-Ray \ Signal - X_{RSfit})/ X_{RSfit}))$, of the experimentally measured yield, black circles. We note that the experiment N180930 had both the largest correction for shape and the largest correction for mix. It is likely that the corrections do not remain linear for large corrections or in the presence of multiple large degradation mechanisms. As such, the overall correction to the yield for N180930, in particular, likely overestimates the actual yield in the absence of both of these degradation mechanisms. The data trends in Fig. 2b imply that the large degradation attributed to mix of the highest energy implosion, N180930, could be mitigated by decreasing the laser power in the Au-lined U hohlraum to maintain a larger remaining mass, or using a thicker HDC ablator, >72 µm, or increased dopant, >0.28% W, at full power to increase the remaining mass, perhaps also benefiting from an increase in picket energy to reduce the ablation front growth in the case of the increased dopant. If either of these
approaches were successful, they could appreciably increase the performance achieved to date with this platform by enabling it to perform closer to expectations at higher implosion velocities, between 432 and 453 km/s with lower mix than was observed in N180930. By applying both a shape correction and a correction for mix in the hotspot, the hypothesized “corrected” neutron yields can be fit with a single power law in velocity across all of the implosions.

More interesting quantities to judge how far away from ignition the implosions are operating are the ignition parameter, $\chi_\alpha$, and the yield amplification, $Y_{\text{amp}}$. These quantities are defined in equations 2 and 3 below.\(^{221}\)

$$\chi_\alpha \sim (\rho_{\text{R HDC}} + \rho_{\text{R DT}})^{0.61} \times (0.12 \times Y_T/(M_{\text{HDC}} + M_{\text{fuel}} - M_{\text{hs}}))^{0.34} \quad (2)$$

$$Y_{\text{amp}} \sim \exp(\chi_\alpha^{1.2}), \quad (3)$$

where $\rho_{\text{R HDC}}$ is the remaining ablator areal density, $\rho_{\text{R DT}}$ is the DT areal density, $Y_T$ is the total yield, $M_{\text{HDC}}$ is the remaining ablator mass, $M_{\text{fuel}}$ is the initial mass of the ice layer, and $M_{\text{hs}}$ is the mass of the hotspot. These quantities are all derived from experimental parameters and in the case of the remaining ablator mass, $M_{\text{HDC}}$, from a “rocket” model\(^{17}\) of the experimental measurements. The ablator areal density\(^{23}\), $\rho_{\text{R HDC}}$, is inferred from the gamma-ray reaction history diagnostic and the DT areal density, $\rho_{\text{R DT}}$, is inferred from the neutron time-of-flight detectors and the calculated hotspot areal density. The DT areal density is \~linearly dependent on the DT ice layer thickness, as seen in several different platforms, and increased about 7.4% between shots, N171029 and N171119 when the DT ice layer was increased by 4 um or 8.8%.\(^5\) $Y_{\text{amp}}$ indicates how much of the yield, $Y$, is due to alpha heating, where the no alpha heating yield, $Y_{\text{no-}\alpha}$, is simply $Y_{\text{no-}\alpha} = Y/Y_{\text{amp}}$.

Figure 3 shows the resulting yield amplification, as a function of implosion velocity, using equations 2 and 3 above, black circles. This implies that the yield amplifications for these
implosions span a range from 1.7 to 2.5. The velocity scaling for \(Y_{\text{amp}}\) was determined to be \(v^{2.6\pm2}\) with the yield and velocity scaling as \(Y_{\text{amp}} \propto v^{-1}Y^{0.325}\). This yield dependence is in agreement with eq. 2 and 3. This scaling of yield amplification with yield, \(Y_{\text{amp}} \propto Y^{0.325}\), can be used throughout the remainder of the paper to determine the scaling of the hotspot parameters with yield amplification.

The scaling of the yield with implosion velocity can be broken down by analyzing the velocity scaling of the parameters comprising the yield, \(Y\). The hotspot density, \(\rho\), is equal to:

\[
\rho = A \sqrt[7.04 \times 10^{-13}] {\frac{E_{\text{Fuel}}}{\langle \sigma v \rangle V_{\text{hs}} \tau_{\text{bw}}}}
\]

where \(A\) is the average atomic number, \(\langle \sigma v \rangle\) is the DT reaction rate per unit volume, \(V_{\text{hs}}\) is the hotspot volume, \(\tau_{\text{bw}}\) is the gamma ray burn width and \(E_{\text{Fuel}}\) is proportional to \(Y\). For the implosions discussed in this paper, the ion temperatures, \(T_{\text{ion}}\), range between 4.5 to 5.5 keV, as measured with neutron time-of-flight diagnostics, and \(\langle \sigma v \rangle\) over that range is proportional to \((T_{\text{ion}})^{3.6}\). The yield can therefore be expressed as \(Y \propto (\rho R)^2(T_{\text{ion}})^{3.6} \tau_{\text{bw}} P_0\), over this temperature range, where \(V_{\text{hs}} = (P_0)^3\) and \(P_0\) and \(R\) both represent the radius of the hotspot or more specifically the radial average of the 17% contour of the primary neutron emission. Using this expression for yield, the no-alpha heating velocity dependence of the primary yield can be determined from the equations in [17] as \(Y \sim (\rho R^*T_{\text{ion}})^2(T_{\text{ion}})^{1.6} (P_0)^2/v\) or \((v^{56/15})^2(v^{28/15}/M_{\text{hs}})^{1.6}(v^{-14/15})^2/v) \sim v^{7.96}/(M_{\text{hs}})^{1.6}\) with the approximation that \(\tau_{\text{bw}} = P_0/v\) and where \(M_{\text{hs}}\) is the mass of the hotspot. Using the analytic velocity scaling formulas in [17] along with the data in Fig. 4a and 4b, \(M_{\text{hs}}\) has a weak dependence on velocity, \(\alpha \sqrt{\frac{\rho R(v)}{T_{\text{ion}}(v)}} = \sqrt{\frac{v^{2.2}}{v^2}} = v^{0.45}\), which is close to the value determined experimentally in Fig. 6 of \(M_{\text{hs}} \propto v^{0.26}\). Using the experimentally determined \(M_{\text{hs}}\) velocity scaling \(\alpha v^{0.26}\), which includes \(\alpha\)-heating, in the no \(\alpha\)-heating yield scaling suggests that
the yield would scale as \( Y \propto v^{7.96} / (v^{0.26})^{1.6} = v^{7.5} \). Since the yield can be expressed as a function of hotspot areal density \((\rho R)\), ion temperature \((T_{\text{ion}})\), radius of the primary neutron image \((P_0)\) and the gamma ray burn width \((\tau_{\text{bw}})\), we have chosen to look at the velocity scaling of these hotspot parameters, as shown in Fig. 4a, 4b, 4c and 4d, respectively. The value of the 17\% contour was chosen to represent the size of the hotspot throughout this article and to infer hotspot mass, energy and pressure. Fig. 4a represents the velocity scaling for \( \rho R \). The experimental data is represented by the black circles with the dashed black line representing a fit to the \( \rho R \) data, \( v^{2.2+2} \). The green (light gray) circles represent the implosion velocity scaling of \( \rho R \) with the yield dependence removed such that \( \rho R \propto v^{-0.1} Y^{0.225} \). Throughout the paper, the yield dependence of a given hotspot parameter is determined by dividing the parameter by their yield to a given exponent and then fitting that modified parameter to a power law in implosion velocity and looking for the minimum variance between the modified parameter and the power law fit for all of the applied yield exponents. Fig. 4b shows the velocity scaling for \( T_{\text{ion}} \), as measured with neutron time-of-flight detectors, where the experimental data is again represented by the black circles and the dashed black line represents a fit to the ion temperature data, \( v^{2.20.3} \). The green (light gray) circles represent the implosion velocity scaling for \( T_{\text{ion}} \) with the yield dependence removed such that \( T_{\text{ion}} \propto v^{-1.75} Y^{0.026} \). In [17] using the author’s equations 4.58 through 4.60, the analytic scaling with velocity for ion temperature is given by \( T_{\text{ion}}(v) \propto v^{28/15} M_{\text{hs}} \) and for the hotspot areal density as \( \rho R(v) \propto v^{28/15} M_{\text{hs}} \). The measured power law velocity scaling of the product of these two quantities, \( v^{4.2} \), is slightly higher than the no-\( \alpha \) heating analytic scaling presented in [17] as \( v^{56/15} \). The analytic no-\( \alpha \) heating velocity scaling of \( M_{\text{hs}} \) can be expressed as proportional to the square root of the velocity scaling of \( \rho R \) divided by the velocity scaling of \( T_{\text{ion}} \) in [17], which using the experimental velocity scalings in Fig. 4a and 4b, which include \( \alpha \) heating, would suggest \( M_{\text{hs}} \) has a weak dependence on
velocity, proportional to $v^{0.45}$. Fig. 4c represents the velocity scaling for $P_0$, where the experimental data is represented by the black circles. The first four implosions are fit well by a $v^{-2}$ power scaling. The overall fit to $P_0$ for all the experiments is $v^{-1.2 \pm 1.3}$, which is very comparable to the no-$\alpha$ heating analytic scaling presented in [17] of $v^{-14/15}$. Fig. 4c also shows the images of the primary neutrons for each of the experiments, the $P_2$ and $P_0$ components of which were used in Fig. 2a for the shape-corrected yields. Fig. 4d represents the velocity scaling for the $\tau_{bw}$ where the experimental data is again represented by the black circles and a power law fit, $v^{-0.44 \pm 0.86}$, provides the best fit to all the data with a yield and velocity scaling, green (light gray) circles, of $\tau_{bw} \propto v^{-1.98} Y^{0.15}$. This is perhaps the furthest away from the no-alpha heating analytic scaling, which assuming $\tau_{bw} \sim P_0/v$ would be $v^{-29/15}$. We have also used the relative error bars for the burn width in Fig. 4d of $\pm 10$ ps rather than the absolute error bars of $\pm 30$ ps. When we put these experimentally-fit velocity scalings into the yield formula we get the yield scaling as $Y \propto (v^{2.1})^2 (v^2)^3 v^{-0.44} v^{-1.2} = v^{9.8}$, which is in good agreement with the overall fit to the data in Fig. 2a of $v^{10}$.

We can also look at the average radius of the primary neutron image, $P_0$, and the down scattered neutron image, $R_{ds}$, to infer the thickness of the DT shell, $R_{ds}-P_0$, as a function of yield and velocity. Fig. 5a represents the velocity scaling for $P_0$. The experimental data is represented by the black circles with the dashed black line representing a fit to the $P_0$ data, $v^{-1.2 \pm 1.3}$. The green (light gray) circles represent the implosion velocity scaling of $P_0$ with the yield dependence removed such that $P_0 \propto v^{-4.1} Y^{0.3}$. The thickness of the DT shell is then shown in Fig. 5b. The experimental data is represented by the black circles with the dashed black line representing a fit to the $R_{ds}-P_0$ data, $v^{-0.2 \pm 0.9}$. The no-alpha heating velocity scaling was calculated to be $v^{-14/15}$, which falls within the large range of the 10 to 90% confidence bands. The green (light gray) circles represent the implosion velocity scaling of $R_{ds}-P_0$ with the yield dependence removed such that
This scaling demonstrates higher compression with increasing yield. The convergence ratio, \( C_R \), can be defined as the initial inside radius of the DT ice layer divided by the measured hotspot radius, \( P_0 \). From that definition it is easy to see that the convergence ratio velocity scaling should look like the inverse of the \( P_0 \) scaling in Fig. 5a. Indeed, this is what is seen in Fig. 5c for the convergence ratio. The experimental data is represented by the black circles with the dashed black line representing a fit to the \( C_R \) data, \( v^{1.1 \pm 1.3} \). The green (light gray) circles represent the implosion velocity scaling of \( C_R \) with the yield dependence removed such that \( C_R \propto v^{4.1 \pm 0.3} \).

In a recent paper the variation in hotspot mass has been used to distinguish between the various regimes of hotspot evolution as a result of the differing levels of alpha-heating and heat flow.\(^{25}\) The three regimes are the self-heating regime, the robust ignition regime and the propagating burn regime. The authors define the self-heating regime where alpha particles are deposited primarily in the hotspot but where the temperature drops after peak compression as the alpha heating is unable to compensate for energy losses.\(^{254}\) The robust ignition regime is represented by stronger levels of alpha heating that increase the hotspot temperature significantly but that cannot yet support a propagating burn.\(^{25}\) The propagating burn regime results when the robustly igniting hotspot is confined and consequently significant portions of the DT shell are ablated into the hotspot.\(^{25}\) In the simulations in [25], the hotpot pressure and \( P_0 \) increased with alpha heating levels/yield which resulted in increasing compression of the DT shell. These high adiabat implosions see this trend as well, as shown in Fig. 5a and 5b. The authors in [25] define the end of the self-heating hotspot regime when the hotspot contains 20% of the initial total DT mass, a robustly igniting hotspot regime between 20% to around 30% of the initial DT mass contained in the hotspot and the propagating burn regime when the hotspot contains between 30%
to almost the entirety of the DT fuel, though this would be a function of the initial DT shell thickness. The hotspot mass, $M_{hs}$, can be expressed as $M_{hs} = \rho V_{hs}$ and was calculated from the experimental measurables using the methods in [24] and is shown in Fig. 6. In this figure, the black circles represent the inferred data with the dashed black line representing a fit to the $M_{hs}$ data, $v^{0.26\pm0.2}$. This weak scaling with velocity is consistent with the analytic velocity scaling of $M_{hs}$ expressed as proportional to the square root of the velocity scaling of $\rho R$ divided by the velocity scaling of $T_{ion}$ in [17] as discussed above. The green (light gray) circles represent the implosion velocity scaling of $M_{hs}$ with the yield dependence removed such that $M_{hs} \propto v^{-7.8}Y^{0.8}$. The highest fraction of the DT mass in the hotspot to the initial mass of the DT fuel is $\sim 7\%$ at a total yield of $2x10^{16}$, which places it within the self-heating regime and a factor of 3 in yield from the robustly igniting hotspot regime. According to [25] this ratio of the hotspot mass to the initial ice mass ratio of 7%, along with their explicit scaling with yield, indicates that at yields of $1x10^{17}$ the hotspot would be well into the propagating burn regime, a factor of 5 in yield from the highest yield shot reported in this paper. The $\chi_{\alpha}$ ignition parameter in eq. 2 is related to the Lawson criteria and is a more traditional estimate of the criteria to reach the full burning-plasma regime. Fig. 7 indicates that the ignition parameter scales with velocity as $\chi_{\alpha} \propto v^{3.1\pm1.9}$ and with velocity and yield as $\chi_{\alpha} \propto v^{-0.2}Y^{0.325}$ with the highest value of $\chi_{\alpha} = 0.91$. This yield scaling implies that the yield would have to be increased a factor of $\sim 8$ to reach the full burning-plasma regime where $\chi_{\alpha} \sim 1.8$.

Other important measures of implosion performance include the hotspot pressure and the hotspot energy. The hotspot pressure, $P_{hs}$, for each of the implosions was calculated using techniques detailed in [24] and can be expressed as $P_{hs} \sim (Z+1)\rho T_{ion}/A$, where $Z=1$ and $A=2.5$ for a DT plasma. The resultant inferred data, black circles, is shown in Fig. 8 along with the experimental scaling with implosion velocity going as $P_{hs} \propto v^{5.1\pm2.1}$, represented by the dashed
black line. The green (light gray) circles represent the implosion velocity scaling of $P_{hs}$ with the yield dependence removed such that $P_{hs} \propto v^{5.4} Y^{-0.025}$, a very weak scaling with yield. This is consistent with the parameter scaling seen in Fig. 4, $P_{hs} \propto (\rho R) T_{ion}/P_0 \propto (v^2.2)/(v^{-1.2}) \propto v^{5.4}$, and is slightly faster than the no-alpha heating analytic pressure scaling of $P_{hs} \propto v^{14/3}$ derived in [17], and agrees with the $v^5$ scaling derived in [26] for the case where alpha heating balances hotspot losses. The hotspot energy, $E_{hs}$, is also an important quantity which was calculated for each of the implosions and can be expressed as $E_{hs}=(3/2)P_{hs}V_{hs}$.[24] The resultant inferred data, black circles, is shown in Fig. 9 along with the experimental scaling with implosion velocity going as $E_{hs} \propto v^{1.8+2.}$, represented by the dashed black line. The green (light gray) circles represent the implosion velocity scaling of $E_{hs}$ with the yield dependence removed such that $E_{hs} \propto v^{-6.1}Y^{0.825}$. This is in good agreement with the analytic no-alpha heating scaling of $v^{28/15}$.[17]

In summary, we have presented the experimental velocity and yield scaling of the hotspot parameters for a high adiabat ICF platform. These parameters include ion temperature, primary nuclear radius, burn width, yield, DT shell thickness and derived quantities such as the hotspot areal density, hotspot mass, pressure, energy, yield amplification and ignition parameter. Knowing the yield scaling for these parameters enables their dependence on yield amplification, $Y_{amp}$, to be determined using the fit determined in Fig. 3, $Y_{amp} \propto Y^{0.325}$. With the yield dependence on $\chi_\alpha$, we can, for instance, extrapolate the yield required to reach the full burning-plasma regime. Most of the velocity scalings of the experimental data agree well with analytic theory [17], generally having a slightly higher velocity dependence than the no-alpha heating scaling. We note that the hotspot parameters such as the hotspot mass, energy, radius, yield amplification and $\chi_\alpha$ and to a lesser degree the burn width and hotspot areal density, have large outliers with the velocity only fit, however, once the yield dependence is accounted for they are well fit by a power-law scaling.
showing a strong dependence on yield and hence on yield amplification. We observe an increase in the hotspot radius, $P_0 \propto Y^{0.3}$, and a thinning of the DT shell, $R_{ds} - P_0 \propto Y^{-0.325}$, as the yield increases, as well as, an increase in the hotspot mass, $M_{hs}$, and hotspot energy, $E_{hs}$, as the yield and alpha heating increase and the implosion moves through the self-heating regime.\textsuperscript{25} The maximum ratio of the hotspot mass divided by the initial DT mass was found to be 7\%, which is roughly a factor of 3 away in the hotspot mass ratio and yield from the robust hotspot ignition regime as defined in [25] and a factor of four to five away in the hotspot mass ratio and yield necessary to support a propagating burn into the DT shell. Using a more conventional ignition parameter\textsuperscript{22}, $\chi_\alpha$, the yield would need to be increased a factor of $\sim$8 to reach the full burning-plasma regime, $\chi_\alpha = 1.8$.

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FIGURE CAPTIONS

Figure 1 Laser pulse shape comparison for a high adiabat (black), $\alpha \sim 4$, BigFoot implosion, 180128, and a slightly lower adiabat (red–gray) implosion, $\alpha \sim 3.5$. The inset diagram in Fig. 1a shows a pie slice of the capsule along with a shock timing diagram for the high adiabat, N180128, implosion showing the first and second shock merger in the ablator. Fig. 1b shows the simulated density plot comparison between the adiabat 4 shot and the adiabat 3.5 which has the second shock overtaking the first $\sim 10 \mu m$ into the ice layer relative to the ice-ablator interface. The ablator-fuel interface is at 200 $\mu m$.

Figure 2 Hotspot yield as a function of peak implosion velocity (Fig. 2a), where the experimental data is represented by the black circles. The red (dark gray) circles then represent a $P_2$ shape corrected yield, $Y_{cp2}$, applying the correction $Y_{cp2} = Y / (1 - (1.2 \times \text{ABS}(P_2/P_0))$. The green (light gray) circles then represent both a $P_2$ shape and a mix corrected yield, $Y_{cm}$, applying the mix correction $Y_{cm} = Y_{cp2} / (1 - (1.2 \times \text{ABS}(X-Ray\ Signal - XRS_{fit}) / XRS_{fit}))$. Fig. 2b shows the neutron yield vs. the x-ray signal from each of the implosions as an indication of mix into the hotspot.

Figure 3 The yield amplification, $Y_{amp}$, as a function of implosion velocity, black circles, and yield. The green (light gray) circles denote $Y_{amp}$ divided by the yield dependence of $Y^{0.325}$.

Figure 4 The peak implosion velocity scaling vs. yield can be viewed from the perspective of the parameters affecting the yield. Fig. 4a shows the peak implosion velocity scaling with hotspot areal density, black circles, along with yield dependence removed, green (light gray) circles. Fig. 4b represents the peak implosion velocity scaling vs. ion temperature, black circles, along with
yield dependence removed, green (light gray) circles. Fig. 4c illustrates the peak implosion velocity scaling vs. radius and Fig. 4d provides the scaling for the peak implosion velocity vs. the burn width, black circles, along with yield dependence removed, green (light gray) circles.

Figure 5 Primary neutron hotspot radius (Fig. 5a), thickness of the DT shell (Fig. 5b) and convergence ratio (Fig. 5c) as a function of velocity. The black circles represent the raw data and the green (light gray) circles in each represent the value with the yield dependence removed as a function of implosion velocity.

Figure 6 Hotspot mass, $M_{hs}$, as a function of implosion velocity, black circles. The green (light gray) circles denote $M_{hs}$ divided by the yield dependence of $Y^{0.8}$.

Figure 7 $\chi_\alpha$, defined in eq. 1, is plotted as a function of velocity, black circles, and $\chi_\alpha$ divided by the yield dependence of $Y^{0.325}$ is denoted by the green (light gray) circles.

Figure 8 Derived hotspot pressure, $P_{hs}$, as a function of implosion velocity, black circles. The green (light gray) circles denote $P_{hs}$ divided by the yield dependence of $Y^{-0.025}$.

Figure 9 Hotspot mass, $E_{hs}$, as a function of implosion velocity, black circles. The green (light gray) circles denote $E_{hs}$ divided by the yield dependence of $Y^{0.825}$.

Table 1 Capsule and laser specifications for each of the seven layered implosions.
Figure 1
Figure 2
Figure 3
Figure 4
Figure 5
Figure 6
Figure 7
Figure 8
Figure 9
<table>
<thead>
<tr>
<th>Shot</th>
<th>HDC Ablator Thickness (µm)</th>
<th>W Dopant</th>
<th>Remaining Mass (ng)</th>
<th>DT ice Thickness (µm)</th>
<th>Laser Power (TW)</th>
<th>Laser Energy (MJ)</th>
<th>LASNEX Velocity (km/s)</th>
<th>Exp. Mod. Velocity (km/s)</th>
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Table 1