Capsule modeling of high foot implosion experiments on the National Ignition Facility

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Abstract
This paper summarizes the results of detailed, capsule-only simulations of a set of high foot implosion experiments conducted on the National Ignition Facility (NIF). These experiments span a range of ablator thicknesses, laser powers, and laser energies, and modeling these experiments as a set is important to assess whether the simulation model can reproduce the trends seen experimentally as the implosion parameters were varied. Two-dimensional (2D) simulations have been run including a number of effects—both nominal and off-nominal—such as hohlraum radiation asymmetries, surface roughness, the capsule support tent, and hot electron pre-heat. Selected three-dimensional simulations have also been run to assess the validity of the 2D axisymmetric approximation. As a composite, these simulations represent the current state of understanding of NIF high foot implosion performance using the best and most detailed computational model available. While the most detailed simulations show approximate agreement with the experimental data, it is evident that the model remains incomplete and further refinements are needed. Nevertheless, avenues for improved performance are clearly indicated.

Keywords: inertial confinement fusion, National Ignition Facility, radiation hydrodynamics

(Some figures may appear in colour only in the online journal)

1. Introduction

What is the state of ‘understanding’ of indirect drive inertial confinement fusion (ICF) implosion experiments on the National Ignition Facility (NIF) [1]? Do the experiments agree with expectations based on the known experimental conditions, or are there discrepancies to suggest that the current physical picture of these implosions is incomplete? This paper attempts to answer this question with a focus on the database of high foot implosions [2–5] shot on NIF during 2013–2014. While broader interpretations are certainly possible, for the sake of this paper, ‘understanding’ is interpreted as how well the experimental results are reproduced by the best available numerical simulations and the known conditions at shot time.

The objective of this paper is to make as quantitative as possible the current state of this understanding by a detailed comparison of simulations against various experimental observables. A wealth of data is returned for each NIF experiment, and it is prohibitive to compare simulation results against every datum. Moreover, more than thirty high foot implosions have now been shot on NIF, and the resources are unavailable to model each shot in complete detail. Nevertheless, this paper aims to summarize results for a large enough database of shots, and in enough detail, to provide a review of current understanding that is comprehensive but without becoming incomprehensible.

The simulations described here were run with sufficient resolution to capture the anticipated dominant perturbation sources. Previous lower resolution two-dimensional (2D) simulations have been described in [6], and selected high-resolution, three-dimensional (3D) results have been reported in [7]. This paper compliments [6, 7] by describing more completely the 2D and 3D higher resolution simulations run to model the high foot database. Assessing a larger dataset of...
Simulations against experiment is important to determine whether the trends observed in high foot experiments (as laser and capsule parameters were varied) can be reproduced by the simulations. If the observed trends are approximately captured, then the simulation model can be judged adequate to identify the failure mechanisms limiting the performance in current experiments. Correctly identifying those failure mechanisms is obviously essential to planning future experiments striving to improve performance. If the observed trends are not captured, then further refinements of the model are clearly required.

Implosion experiments on the NIF aim to achieve ICF ignition by indirect drive in which a deuterium-tritium (DT) fueled capsule is imploded by x-ray ablation within a surrounding high-Z hohlraum [8, 9]. The high foot implosion design [10] was an evolution of the preceding low foot implosion design tested during the National Ignition Campaign (NIC) [11] in which the leading part of the radiation pulse driving the capsule (‘the foot’) was increased. Design studies conducted prior to the NIC [12] suggested this higher foot level would improve the stability of the implosion but at an unacceptable cost of reduced compressibility of the DT fuel. For this reason, high foot-type designs were not pursued during the NIC, and the low foot design was chosen instead [13]. More recent modeling of low foot implosions [7, 14], guided by experimental data from NIF, indicates that these low foot implosions were unacceptably unstable given the perturbation sources present. In particular, for the low foot, the perturbation seeded by the plastic membrane or ‘tent’ used to support the capsule in the hohlraum [15–17] appears to have had a devastating impact on the integrity of these implosions. Simulations suggest that, by itself, the tent accounted for more than an order of magnitude reduction in the neutron yield in these implosions. The improved stability of the high foot reduces the growth of this perturbation source and results in a much better performing implosion, albeit at lower overall compression. The tent is not the only source of yield degradation in NIF implosions, however, and a secondary aim of this paper is to assess the relative importance of the various degradation sources, known and hypothesized, for high foot implosions.

With these aims in mind, this paper summarizes a database of 2D simulations of selected high foot implosion experiments including various perturbation sources both individually and in combination. Nominal perturbations such as the capsule surface roughness, the capsule support tent, and the long wavelength radiation asymmetries resulting from the hohlraum geometry are assessed, as well as more speculative effects like hot electron pre-heat. So as to resolve all of the relevant perturbation scales, the simulations described here include only the imploding capsule and treat the surrounding hohlraum as a spherical, X-ray-emitting boundary. A subset of the simulations are also rerun in full 3D geometry to assess the impact of the genuinely 3D character of actual implosions on NIF. All simulations were run using the multi-physics, arbitrary Lagrangian-Eulerian (ALE) radiation hydro-dynamics code HYDRA [18].

Surveying the database of 2D and 3D simulation results, it is found that 2D simulations generally over predict the observed neutron yields by roughly a factor of two for these implosions, particularly at the highest laser powers and energies. At low laser energies, the hohlraum asymmetries are the dominant source of yield degradation. As the laser energy is increased, however, simulations accounting for only the hohlraum asymmetries overestimate the yield by up to an order of magnitude and the perturbation seeded by the capsule support tent is found to be as large a degradation source as the hohlraum asymmetries. Indeed, this reemergence of the tent defect as a large perturbation appears to explain the apparent plateau in high foot performance: with increasing velocity, the ablation front instabilities that were brought under control at low velocities reassert themselves and ultimately compromise high foot implosions. For the highest velocity implosions, however, even accounting for the effect of the tent, the 2D approximation is not adequate, and fully 3D simulations are required to reproduce the observed yields.

While these 3D simulations succeed in approximately reproducing the neutron yields observed in experiment, it is nonetheless clear that the simulation model is incomplete. In particular, even in fully 3D simulations, the hot spot ion temperature, as inferred from the Doppler-broadened width of the neutron spectrum [19], is consistently lower than observed by up to ~1 keV. Though less pronounced, the neutron down scatter ratio (DSR) [20], a measure of the burn-averaged fuel compression, is also slightly but consistently over-predicted in simulations compared to experiment. This is notable since these simulations represent the current best understanding of these implosions and fully account for the 3D character of the hot spot stagnation and all of the sources of asphericity identified so far. Even accounting for realistic 3D hot spot flow, discrepancies in the simulated ion temperature and DSR are persistent.

These consistent discrepancies have prompted speculation about various effects missing from the current simulation model, in particular hot electron pre-heat as an explanation of the reduced compression and reduced thermal conductivity in the hot spot to account for the higher hot spot temperatures. The latter could be due to a simple error in the calculated conductivity of DT at the relevant hot spot density and temperature, self-generated magnetic fields in the hot spot, or other effects that can also manifest themselves as an increased hot spot temperature. All of these effects are currently under investigation separately, but to assess their relative importance in the current simulations, 2D simulations with reduced hot spot thermal conductivities and added hot electron pre-heat have also been run. Based on these results, very large amounts of hot electron pre-heat, roughly an order of magnitude larger than currently estimated from experiment, appear to be necessary to explain the observed compression. On the other hand, a reduction in the DT thermal conductivity by one half yields hot spot ion temperatures (and other observables) in better agreement with experiment than the nominal model. Interestingly, this deviation in the conductivity is not unreasonable given the uncertainties in conductivity models for this density and temperature regime.
Table 1. NIF implosion experiments simulated in this study. Here the simulated convergence ratio is defined as the ratio of the initial outer capsule radius to the hot spot radius at bang time in a 1D no-burn simulation. $T_{\text{ion}}$ refers to the burn-weighted temperature inferred from the width of the primary emitted neutron spectrum, and the down-scattered ratio (DSR) is the ratio of the 10–12 MeV to 13–15 MeV components of the emitted neutron spectrum. $Y_{13-15\,\text{MeV}}$ refers to the primary neutron yield in the energy range of 13–15 MeV. All values are experimentally measured unless noted otherwise.

|                  | N130812 | N130927 | N131119 | N140120 | N140520 | N140819 |
|------------------|---------|---------|---------|---------|---------|---------|
| Hohlraum         | Au      | Au      | Au      | DU      | DU      | DU      |
| Shell thickness ($\mu$m) | 195.5  | 195.0  | 193.9  | 195.3  | 178.5  | 164.8  |
| $E_{\text{laser}}$ (MJ) | 1.7    | 1.8    | 1.9    | 1.9    | 1.8    | 1.8    |
| $P_{\text{laser}}$ (TW) | 350    | 380    | 410    | 410    | 390    | 390    |
| Simulated fuel velocity (km s$^{-1}$) | 329    | 353    | 356    | 356    | 391    | 390    |
| Simulated fuel adiabat | 2.7    | 2.7    | 2.2    | 2.4    | 2.4    | 2.7    |
| Simulated convergence ratio | 35    | 37    | 40    | 38    | 37    | 36    |
| $T_{\text{ion}}$ (keV) | 4.0 ± 0.2 | 4.4 ± 0.2 | 4.8 ± 0.2 | 5.1 ± 0.2 | 5.5 ± 0.2 | 5.5 ± 0.2 |
| DSR (%)          | 4.0 ± 0.2 | 3.5 ± 0.2 | 3.4 ± 0.3 | 3.7 ± 0.2 | 4.1 ± 0.2 | 3.5 ± 0.2 |
| $Y_{13-15\,\text{MeV}}$ | $2.4 \pm 0.05 \times 10^{15}$ | $4.4 \pm 0.1 \times 10^{15}$ | $5.2 \pm 0.1 \times 10^{15}$ | $8.0 \pm 0.1 \times 10^{15}$ | $7.6 \pm 0.1 \times 10^{15}$ | $5.5 \pm 0.1 \times 10^{15}$ |
| Yield/symmetric simulated | 0.23 | 0.05 | 0.002 | 0.005 | 0.02 | 0.02 |
Clearly many effects and their associated uncertainties can be assessed for the current simulation model; this paper summarizes the relevant sensitivities that have been assessed so far, but further work is needed.

This paper is organized as follows. Section 2 summarizes the experimental details of the individual high foot experiments modeled in this study. Section 3 then assesses the linear stability characteristics of each of these implosions as a starting point for more detailed nonlinear 2D and 3D simulations. Section 4 presents the results of the nominal 2D simulation model for these implosions and assesses the relative importance of the leading degradation sources. Section 5 extends this simulation model into 3D for a subset of the highest velocity implosions. Section 6 then considers the effect of hot electron pre-heat, both at the level believed to be consistent with experiment and at a much higher level as has been speculated to account for some of the performance discrepancies. Section 7 summarizes and concludes. Finally, the appendix summarizes some of the numerical convergence tests used to verify the results discussed in the preceding sections. Numerical convergence is, of course, crucial to the validity of any modeling results, and it is often assumed that convergence test have been run but they are not specifically described. For completeness and as a matter of record, these convergence tests are included here.

2. Implosion experiments simulated in this study

The individual high foot experiments modeled in this study are summarized in table 1. The NIF naming convention is used where NYYYMMDD refers to the NIF shot fired on day DD of month MM in year YY. As shown in the table, these shots span from very early in the high foot campaign (N130812), with modest laser powers and energies [2], to near the conclusion of the high foot campaign when implosions were driven with the maximum laser energy available on NIF and using ablators shells that had been thinned by up to 30 μm compared to those used at the start of the campaign [3]. For all of these shots, the capsule configuration remained essentially the same as that tested during the closing phase of the NIC: A ∼70 μm thick DT ice layer was enclosed by a plastic (CH) shell 165–195 μm thick and doped with up to 2 at% silicon in the inner part of the shell to control hard x-ray pre-heat. The inner edge of the DT ice layer was at a radius of ∼870 μm, and the interior volume of the capsule was filled with equilibrium DT vapor at a density of ∼0.3 mg cm⁻³.

Over the course of these six shots, not only was the laser power and energy increased and the CH ablator thickness reduced from 195 to 165 μm, but the hohlraum was changed from pure gold (Au) to gold-coated depleted uranium (DU) to increase its radiative efficiency [4]. In combination, all of these modifications had the effect of increasing the simulated implosion velocity from ∼330 km s⁻¹, similar to the implosions tested during the later phase of the NIC, to ∼390 km s⁻¹. As shown in the table the primary neutron yield (the yield in the 13–15 MeV energy range) increased from ∼2 x 10¹⁵ to ∼8 x 10¹⁵ and the hot spot ion temperatures from ∼4 to 5.5 keV with these modifications. Although this represents a net yield increase of ∼4x over the campaign, given the strong scaling of neutron yield with velocity for 1D implosions, the yield relative to the 1D prediction dropped from ∼25% for the earliest shot in this series to a percent or less later in the series. Clearly, large and growing 2D or 3D degradation mechanisms must be impacting these implosions as the velocity increased. The following sections describe modeling results aimed at understanding these 2D and 3D degradations.

3. Linear stability simulations

As a starting point for subsequent 2D and 3D simulations, this section summarizes the results of 2D linear stability simulations for the six implosion experiments in table 1. As shown in figure 1, the linear stability of these implosions is quantified by comparing their ablation front growth factors. These growth factors are defined as the ratio of the perturbation amplitude at the time of peak implosion velocity relative to the initial perturbation amplitude for an individual Legendre mode [21–23]. For all cases, the simulations were run using a 2D wedge initialized with a small Gaussian bump (15 μm wide by 1 nm in height) on the ablator surface at the axis of symmetry. By choosing a sufficiently small initial amplitude, the perturbations remain in the linear regime throughout the simulation, and by simulating a multimode initial perturbation, the entire mode spectrum as shown in figure 1 can be generated from a single simulation for each implosion. Of course, growth factors can be defined at surfaces other than the ablation front and at other times than peak implosion velocity to capture the impact of different phases of instability growth or different seeds. For the implosions described here, however, acceleration phase ablation front growth is the dominant perturbation source, and the ablation front growth factor is a very effective metric for assessing overall implosion stability. As discussed below, realistic surface perturbations grow into the weakly nonlinear regime in NIF implosions and invalidate the approximation of linearity. Nonetheless, linear growth factors provide a convenient framework for comparing the relative stability of different implosions as well as for understanding which wavelengths are amplified most.

The left panel of figure 1 shows the various x-ray radiation temperatures versus time used as drive inputs for the simulations list in table 1. These x-ray drives are tuned as described in [14, 24] such that 1D implosion simulations match the measured shock timings, implosion velocities, and bang times (time of peak neutron production) from experiment. This tuning procedure gives the best possible constraint on the 1D x-ray drive on the capsule. The trend from lower to higher peak laser power and energy is evident in the increasing peak radiation temperatures from N130812 to N140120. The reduced ablator thicknesses in N140520 and N140819 necessitate a retuning of the timing of the laser pulse to maintain correct shock timing as can be seen in the different rise times in these two x-ray drives. The slight
variations in the radiation temperature in the foot between all six drives reflect the variability in the laser delivery shot-to-shot, but otherwise the first $\sim 8$ ns of the radiation pulse are intended to be identical between all six shots.

The right panel of figure 1 compares the various ablation front growth factor spectra for the six implosion experiments. The predictable trend of decreasing stability (increasing peak growth factor) with increasing acceleration (either with higher power or with thinner ablators) is obvious. In progressing from N130812 to N140819, the maximum ablation front growth factor more than doubles from $\sim 170$ to $\sim 430$. Also evident in these spectra is the importance of the ablative Richtmyer-Meshkov (RM) oscillation \[25\] in setting the node in the growth factor spectrum \[22, 23, 26-30\]: as the ablator was thinned in N140520 and N140819, and the pulse length consequently shortened, the time for this RM oscillation was reduced and the location of the growth factor node moved from $\ell \sim 80$ to $\sim 120$, resulting in enhanced growth of shorter wavelength features.

Figure 2 plots the maximum of each growth factor spectrum from figure 1 versus simulated peak implosion velocity. The maximum growth factor correlates in a very linear fashion with velocity.

4. 2D nominal simulations

A variety of perturbation sources are now known to degrade the performance of NIF implosions. These perturbation
sources include the interior and exterior surface roughness of the ablator and DT ice layer, the capsule support membrane or ‘tent’ used to hold the capsule in the center of the hohlraum at shot time, the fill tube used to fill the capsule with DT fuel, and time-dependent asymmetries in the driving radiation field imprinted on the capsule from the hohlraum. Depending on the implosion type, each of these perturbation sources can be more or less important to the overall implosion performance. For low velocity high foot implosions (<340 km s\(^{-1}\)), simulations indicate that asymmetries in the hohlraum drive are the leading degradation source. As a starting point for 2D modeling of high foot performance, this perturbation source is included first, and the results are summarized in figure 3. The capsule-only simulations described here treat the x-ray drive on the capsule as a boundary condition and do not \textit{a priori} predict the asymmetries generated by the hohlraum. The radiation asymmetries used in these simulations are extracted from the lower-resolution hohlraum simulations described in [6]. These hohlraum simulations do not currently accurately predict the asymmetries present in NIF hohlraum experiments but, like the 1D x-ray drive on the capsule, are ‘tuned’ by artificially adjusting the laser power and cone fraction in the simulation to match the measured asymmetry characteristics of the implosion. This tuning includes matching the measured pole-to-waist shock asymmetries from VISAR measurements [31], in-flight shell asymmetries as measured by 2D convergent ablator (ConA) experiments [32], and finally the hot spot x-ray self-emission at bang time [33].

The results of including the tuned radiation asymmetries as the only perturbation source are summarized in figure 3. In each of the four panels, the simulated quantity is plotted on the vertical axis and the experimentally measured quantity is plotted on the horizontal axis. For the neutron yield, the error bars are smaller than the symbol size. Agreement between simulation and measurement, of course, corresponds to the symbols lying on the 45° line. The upper left panel of figure 3 plots the simulated versus experimental neutron yield, the lower left panel shows the burn-averaged hot spot ion temperature as inferred from the width of the primary neutron spectrum, the lower right panel shows the DSR, a measure of the burn-averaged fuel compression, and the upper right panel shows the hot spot symmetry as quantified by the second Legendre moment of the hot spot x-ray self-emission. As intended by the tuning of the radiation asymmetries used as inputs to these simulations, the agreement between the simulated and measured hot spot symmetry is quite close for all shots. Note that the agreement is not perfect given residual differences between these capsule-only simulations and the lower-
resolution hohlraum simulations that were used to tune the asymmetries; however, the agreement is adequate. The agreement between simulated and measured neutron yields is much poorer, however, with the highest velocity implosions resulting in an order of magnitude over prediction of the neutron yield. Despite this, the simulated hot spot ion temperatures are on averaged in agreement with the measured values, if not slightly under predicted in simulation. Finally, the DSR values are over predicted in simulation by ~20% for all of the implosions except for the lowest velocity case. The 2D simulations summarized in this figure follow a similar methodology to that described in [7, 14]. Further details of the simulation methodology are given in the appendix.

The inset in the upper left panel shows the material density at bang time for the representative shot N140520. The large hot spot distortions resulting from the hohlraum asymmetries are obvious. Despite the large distortions shown in the inset, these simulations in which hohlraum asymmetries are the only perturbation source clearly miss important effects that must be impacting the higher velocity implosions. Nevertheless, they give an indication of the relative importance of these asymmetries for these implosions. Namely, for the lowest velocity implosion N130812, the neutron yield and DSR are reasonably well matched and the hot spot ion temperature is only slightly low compared to experiment, suggesting that this implosion is fairly well described by this asymmetries-only model. For the remainder of the implosions, however, other effects must be present.

To assess these added effects, figure 5 shows a similar four-panel summary of the results of simulations including the capsule support tent, capsule and DT ice surface roughness, and the capsule fill tube in addition to hohlraum asymmetries. Comparing the inset in the upper left panel to figure 3 illustrates the impact of these added perturbations. Note that these simulations are not sufficiently resolved to model directly such fine-scale features as the tent (~50 nm) and fill tube (~10 μm), so the simulations described here use surrogate models that are tuned to reproduce the results of fully resolved 2D simulations. The details of these surrogate perturbations are described further in the appendix. Note, also, that the presence of the added perturbation sources, in particular the tent, changes the apparent hot spot symmetry predicted by the simulations. The hohlraum radiation asymmetries that have been tuned to reproduce the measured hot spot symmetry in the absence of the tent are hence not an accurate estimate of the actual implosion asymmetries. This discrepancy is illustrated in figure 4 where the blue symbols repeat the simulated hot spot symmetry results shown in figure 3 but the red symbols show the results of including the other perturbation sources with these asymmetries. As can be seen, the presence of the tent and other perturbations skews the hot spot symmetry to be ~10% more negative on average than without these perturbations. This is a significant deviation in the hot spot symmetry and is inconsistent with the measured hot spot shapes.

To address this discrepancy, the simulations shown in figure 5 have been retuned so that the measured hot spot asymmetry is matched in the simulations when the tent and other perturbations are included. Specifically, since the earlier parts of the x-ray drive asymmetry are constrained by separate shock timing and in-flight asymmetry measurements, only the P2 asymmetry during the peak of the x-ray drive was adjusted to regain agreement with the measured hot spot P2 asymmetry. This agreement is shown by the upper right panel of figure 5 and is within the error bars for all but one of the implosions.

Compared with the results in figure 3, the simulation results shown in figure 5 are in closer agreement with experiment, in particular for the neutron yield. While the highest velocity implosions were over predicted by an order of magnitude in figure 3, the yield discrepancy is reduced to less than a factor of three for all implosions when all perturbation sources are included, and in many cases the agreement is much better. The simulated ion temperature shows a similar level of agreement as in figure 3, although the simulation results are on average low relative to the measurement. The simulated DSRs remain ~20% high relative to the measurements except for the lowest velocity shot N130812.

As suggested by the improved agreement in neutron yield in figure 5, and also the increasing growth factors shown in figures 1 and 2, the surface perturbations play an increasingly significant role in the higher velocity implosions. The growing importance of these other perturbation sources is illustrated by figure 6. Here the bars show simulated neutron yield over symmetric neutron yield for the sequence of implosions with increasing implosion velocity. The blue bars show the results for simulations with hohlraum asymmetries as the only perturbation source, and the red bars show the results of simulations with the support tent as the only perturbation source. For both perturbation types, the degradation with respect to the symmetric simulation increases as shot number (or velocity) increases. What is notable in this plot, however, is that while the perturbation from the tent is only marginal in the lowest velocity implosion and the hohlraum...
asymmetries amount to more than a factor of three yield degradation, the impact of the tent increases more rapidly than does the effect of the asymmetries as implosion velocity increases. Indeed, for the highest velocity implosion, these two degradation sources have become comparable, and the degradation due to the tent is as large as that from the hohlraum asymmetries.

It is important to note that the increased ablation front instability indicated by figures 1 and 6 need not be associated with mix of ablator material into the hot spot, a phenomena not observed for high foot implosions [3]. Even without directly mixing ablator material into the host spot, increased ablation front modulations can feed through to the hot spot, distort the hot spot, and lead to reduced hot spot volume and hence reduced yield. This scenario appears to apply in these high foot implosions. Lastly, note that the results for shots N131119 and N140120 have been omitted in this figure since these implosions ignite without any perturbations producing a highly skewed yield over symmetric ratio.

5. 3D simulations

To address the remaining yield discrepancies in several of the 2D simulations shown in figure 5, selected higher velocity implosions were simulated in 3D. The 3D simulations are analogous in simulation methodology, resolution, and perturbation sources to their 2D counterparts except for their obvious added degree of freedom. This includes the simulated
3D hohlraum asymmetries based on the as-delivered 3D laser power imbalance and measured 3D surface roughness. The added dimensionality increases the simulation zone count by a factor of \(\sim 1000\), and hence each 3D simulation may be thought of as equivalent to running \(\sim 1000\) 2D simulations. This added computational cost clearly limits the number of fully 3D simulations that can be run, so the results for only four of the six high foot experiments are summarized in figure 7.

Despite its computational cost, the gain in physical realism in 3D is significant, however. In particular, 2D axisymmetric simulations enforce an artificial stagnation of the flow on the symmetry axis since the radial velocity component must remain zero there. This effect is clearly absent in real 3D geometry where flows can cross the origin unless they are improbably balanced by an exactly opposing flow. Additionally, 2D axisymmetric simulations model only the growth of 2D ridge- and valley-type perturbations as opposed to genuinely 3D spikes and bubbles. These 3D features are known to grow faster than their 2D counterparts and can therefore penetrate the hot spot more deeply [34–37]. For both of these reasons, the degradation in realistic 3D implosions can be expected to be greater than in the 2D axisymmetric idealization.

As seen in the upper left panel of figure 7, the added degree of freedom in the 3D simulation does reduce the simulated neutron yield from twice the measured value, in some cases, to less than, or even half of the measured value. While this is clearly an improvement with respect to the experimental data, it is also clear from the figure that the simulations do not capture the gross trend in the data, with the simulated yields appearing to roughly decrease as the measured yields increase. Indeed, in an average sense, the simulations slightly under predict the observed yields. Furthermore, the 3D simulations continue the trend of under predicting the hot spot ion temperatures and over predicting the implosion DSRs, although the 3D DSR results are clearly closer to agreement. This is notable in that the 3D simulations fully account for the current best prediction of the 3D hot spot flows that are hypothesized to account for the measured ion temperatures [38, 39]. That is, the realistic stagnation process in the presence of hohlraum asymmetries and capsule perturbations is modeled fully in these simulations and yet continues to disagree with the measured hot spot ion temperature. This result appears to lend further credence to experimental results suggesting that hot spot flows cannot explain the unexpectedly high hot spot ion temperatures inferred for these implosions [40].

As an alternative explanation of the origin of the high hot spot ion temperatures, the cyan points in figure 7 show the results of rerunning three of the four 3D simulations but with the DT thermal conductivity artificially reduced by a factor of
one half. Modifying the conductivity in this way is particularly motivated by the observation that both the yield and the hot spot temperature are under predicted in these simulations, and both of these discrepancies may be reduced by reducing the hot spot conductivity. These simulations are run with a simple, static multiplier on the thermal conductivity, which is clearly the most simplistic modification possible to the hot spot physics. As a numerical experiment to gauge the effect of uncertainties in the conductivity, however, this simple modification is informative.

Note that there are many reasons to suspect that the hot spot conductivity could be inaccurate. Foremost, models of the thermal conductivity of a DT plasma at the conditions of the hot spot boundary (∼1 keV and ∼100 g cm⁻³) have never been confirmed against direct experimental data. Furthermore, a comparison of various theoretical models for the conductivity suggest an uncertainty of ∼25% in this regime [41–50]. The possibility of self-generated magnetic fields in the hot spot has also long been hypothesized to result in a reduced effective hot spot thermal conductivity [51–54], while simulations have shown that plasma kinetic effects [55, 56] can increase the apparent hot spot temperature in a manner similar to inhibited conductivity. Lastly, it can be shown in 1D simulations that uncertainties in the α-particle stopping power can lead to yield and ion temperature enhancements indistinguishable from the effect of reduced thermal conductivity. Of course, it is also possible that the perturbation sources included in the nominal simulations are somehow exaggerated, and the correct model of these implosions is somewhat less perturbed than the results described here with the resulting higher yields and ion temperatures. Taken at face value, however, with the perturbation sources as they are currently understood, the results in figure 7 do suggest a closer agreement with the data when the hot spot conductivity is reduced. Note that this is true not only for the neutron yield and hot spot temperature, but also for the implosion DSR. While plausible, substantiating whether an inhibited thermal conductivity is the correct model for high foot hot spots remains a subject of ongoing work.

For completeness, figure 8 summarizes four other leading observables for these implosions, namely, the hot spot size as measured by the zeroth moments of the x-ray self-emission in the equatorial ($P_0$) and polar directions ($M_0$), the nuclear bang times, and the nuclear burn widths [57]. The agreement is reasonable for the first three quantities with the exception of the polar x-ray image size for N130927. Note that this image is believed to be saturated, and a value of ∼40 μm is estimated to be more realistic and also in agreement with simulation. By contrast, the nuclear burn widths are under
predicted for all of the implosions, although the discrepancy is of the order of the uncertainty in the measurement.

Finally, figures 9 and 10 show renderings of the four 3D simulations (with the nominal thermal conductivity) at their respective bang times. In each rendering, the outer surface shows the ablation front colored by the local temperature, while the cutaways show ion temperature on the left and density on the right. Note that the 3D simulation of N130927 is the same as that described in [7] and is included for completeness. The 3D simulation of N140819 is slightly updated from that discussed in [7] with a more accurate model of the hohlraum asymmetries.

To illustrate the importance of the added perturbation sources, in particular the tent, figure 9 shows the results of low-resolution simulations including only the hohlraum asymmetries as a perturbation source. Figure 10, by contrast, includes all perturbation sources and corresponds to the salmon-colored points in figures 7 and 8. For the first two implosions, N130927 and N140120, it is apparent that the tent and other perturbation sources only slightly modify the state of the implosion at bang time. Note, however, that their impact on the yield in 2D is quite significant in comparing figures 3 and 5. By contrast, the higher velocity, thinner shell implosions N140520 and N140819 are clearly very substantially perturbed by the presence of the tent and surface roughness as shown in figure 10. Comparing figures 9 and 10, it is clearly a serious oversimplification to include only the hohlraum asymmetries in any assessment of these high velocity high foot implosions.

6. Simulations including hot electron pre-heat

Consistent discrepancies between the simulated and measured DSRs, such as shown in figures 3 and 5, have prompted speculation about the role of high-mode fuel-ablator mix and hot electron pre-heat in high foot implosions. It has been speculated that mixing of hot ablator material into the DT fuel [22, 58] or direct pre-heating of the fuel by energetic electrons generated from laser–plasma interactions in the hohlraum [13, 59, 60] could raise the effective adiabat of the fuel and reduce its compressibility, thereby explaining the apparent
DSR discrepancies. Highly resolved simulations modeling fuel-ablator mix suggest that this is not a substantial effect for high or low foot NIF implosions \cite{19} and make this an unlikely explanation. The importance of hot electron pre-heat remains an open question, however, and this section describes 2D simulations meant to assess its significance. Uncertainty in the equation of state of DT is another possibility, particularly at high compression where experimental data is lacking, but this effect is difficult to quantify and the subject of ongoing work.

Hot electron populations in NIF hohlraums are inferred by hard x-ray measurements made with the FFLEX diagnostic \cite{20, 21}. The data suggests two hot electron populations with distinct temperatures of $\sim 18$ and $\sim 100$ keV. The lower temperature population is believed to be generated by Landau damping of the electron plasma waves that accompany stimulated Raman scattering (SRS) of laser light inside of the hohlraum \cite{22}. The time evolution of this hot electron population is then expected to follow the time dependence of reflected SRS light from the hohlraum, as measured by backscatter diagnostics, and the total population is estimated to amount to an energy of 50–100 kJ depending on the shot. The higher temperature (‘super-hot’) population is less well understood but believed to result from two plasmon decay instabilities deep in the hohlraum \cite{22}. Time resolved FFLEX measurements suggest a highly peaked distribution in time localized at the end of the laser pulse with a width of $\sim 1$ ns and a total energy of $\sim 5$ kJ. The left panel of figure 11 illustrates the time dependence of both the low temperature (blue) and high temperature (red) hot electron populations for the representative shot N130927. In this case, both populations have been normalized to a total energy of 50 kJ.

Hot electron slowing down in NIF implosions can be modeled using the non-local electron transport package in HYDRA. This package implements the Schurtz model for multi-group slowing down \cite{23} and includes the effects of the increase in the scattering cross-section of electrons as they slow down (‘cascading’) as well as the contribution of bare ions and bound electrons to the electron scattering cross-section. Further details of the modeling methodology for hot electrons are given in the appendix.

The right panel of figure 11 shows the effect of hot electrons in 1D HYDRA simulations of the high foot implosion N130927. Note that $\alpha$-particle stopping is artificially switched off in these simulations since the very high

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**Figure 10.** Renderings of the imploded hot spots for the four 3D high foot simulations at their respective bang times including all 3D perturbations. These include as-shot ablator and DT ice surface roughness, tent and fill tube perturbations, and the 3D hohlraum radiation asymmetries shown in figure 9. The tent and fill tube perturbations are visible in all four cases but are much more pronounced in the two later, higher velocity implosions, N140520 and N140819. The slower T0 implosions N130927 and N140120 show only slight additional shell perturbations in comparison to figure 9. The faster T-1 and T-1.5 implosions are very strongly perturbed by the tent and other effects. Reproduced from \cite{19}, with the permission of AIP Publishing.
yields simulated in 1D with $\alpha$-particle stopping strongly affect the simulated DSR and are entirely inconsistent with the experimental yields. As expected, for both the 18 keV hot electrons (blue) and the 100 keV hot electrons (red), the simulated 1D DSR decreases as the hot electron total energy is increased. The low temperature hot electrons only very weakly impact the DSR, however, and an extremely large hot electron energy (a significant fraction of the incident laser energy) would be required to match the measured DSR in 1D, as shown by the dashed line and error bar. A super-hot electron source of $\sim$50 kJ, an order of magnitude greater than inferred from FFLEX, is required to match the observed DSR.

Figure 11. Hot electron pre-heat sources and their simulated impact on 1D DSR. The left panel shows the radiation temperature versus time used in simulations of N130927 and the low-energy (18 keV) hot electron time dependence taken from the measured SRS time dependence (blue) and super-hot (100 keV) time dependence taken from the FFLEX measurement (red). The right panel shows the effect of these two different sources on simulated 1D DSR as the total hot electron energy is varied. Extremely large low-energy sources (blue) are required to match the measured DSR in 1D, as shown by the dashed line and error bar. A super-hot electron source of $\sim$50 kJ, an order of magnitude greater than inferred from FFLEX, is required to match the observed DSR (red).

Given these uncertainties, and as a broader assessment of the consequences of super-hot electron pre-heat, 2D simulations were run including 50 kJ of pre-heat with a super-hot temperature of 100 keV. Other than the pre-heat source, these simulations include all 2D perturbation sources and are similar to those shown in figure 5. In experiment, the inferred amount of pre-heat varies, in particular increasing with laser power and energy. This was not accounted for in these simulations, however, and only a fixed pre-heat energy of 50 kJ was used for all simulations. There is, however, considerable sensitivity to the arrival time of the pre-heat, and so the timing of the pre-heat was adjusted for each simulation to coincide with the end of the laser pulse, as observed experimentally and illustrated for N130927 in figure 11. Note that simulations with the experimentally inferred super-hot pre-heat level of 5 kJ are essentially indistinguishable from the nominal simulations without pre-heat, shown in figure 5.

The results of the 2D simulations including 50 kJ of 100 keV pre-heat are summarized in figure 12. As intended, the simulated DSRs are decreased compared to those from figure 5 and show reasonably good agreement with the data. The inset in the upper left emphasizes the lower compression and thicker shell that results from the added pre-heat when compared to figure 5. Notably, the 2D neutron yields are also reduced to be in fair agreement with the data while the hot spot shapes are only slightly altered. Like the previous results in sections 4 and 5, however, the simulated ion temperatures are all below the experimental data.

As a further numerical experiment, the 2D pre-heated simulations were rerun with the DT thermal conductivity reduced by a factor of one half, as in the 3D simulations in figures 7 and 8. The results of these simulations with both 50 kJ of super-hot pre-heat and a reduced DT thermal conductivity are summarized in figure 13. It is interesting that when both effects are included there is fairly good agreement on three of the four observables shown, and only the neutron yield is notably discrepant for the higher performing shots. This discrepancy suggests again the 3D character of these higher velocity implosions, and that, even in the presence of this very large pre-heat source, the added perturbations that accompany 3D are likely necessary to explain the observed
neutron yields. Note, however, that the lowest power and energy shot of this dataset, N130812, was reasonably well matched in 2D without pre-heat or modification of the DT thermal conductivity. This may suggest that these more anomalous effects of pre-heating and inhibited heat conduction occur only in the most strongly driven, hotter implosions that represent the higher energy end of the dataset. Finally, although the agreement suggested by figure 13 is interesting, recall that these simulations use a pre-heat level that is an order of magnitude larger than supported by the FFLEX data. In this sense, the agreement in figure 13 remains conjectural.

7. Summary and conclusions

This paper has summarized the current state of understanding of high foot implosions as quantified by a comparison of detailed 2D and 3D simulations against the experimental data. Figures 5, 7, and 8 attempt to encapsulate this understanding at a glance by plotting 2D and 3D simulation results against measurement for several shots and for various experimental observables. Note that figures 5, 7 and 8 extend previous detailed simulation results by modeling a range of implosion energies, powers, and shell thicknesses. This is important since the ability of simulations to reproduce the trends seen in experiment must be validated against a range of conditions if the simulations are to be relied on for extrapolation of future implosion designs.

As shown in figures 5, 2D simulations agree fairly well with experiment for low velocity implosions (low laser power and energy) but deviate by factors of several in neutron yield at higher velocities. 3D simulation results, as shown in figures 7 and 8 improve the agreement with the data but clearly do not reproduce experimental trends exactly. As a whole, the 3D simulations approximately capture the average neutron yield seen in the high foot database but not the specific scaling of performance with laser power, energy, or shell thickness. Figures 5, 7 and 8 also compare a number of other experimental observables with the simulations. It is seen that, while the hot spot shape and size in x-ray self-emission is reasonably well matched by the simulations, the hot spot ion temperature is consistently under predicted, the implosion DSR is slightly but consistently over predicted, and the nuclear burn width is under predicted. To address the first two discrepancies, and noting that the neutron yield is on average slightly under predicted, the 3D simulations were rerun with the DT thermal conductivity artificially reduced by a factor of one half. This improves the agreement for the neutron yield, hot spot temperature, and DSR and is an interesting suggestion that the physics of the hot spot is not correctly captured in
the nominal model. Of course, it is also possible that inaccuracies in the modeling of one or more of the perturbation sources present in these implosions could account for the discrepancies. Taken at face value, however, and given the current understanding of the perturbation sources, the experimental results are more consistent with simulations assuming modified hot spot physics. Substantiating whether additional effects, such as magnetic fields, plasma kinetics, or anomalous charged particle stopping, could modify the apparent hot spot properties in NIF implosions is a subject of ongoing work.

To address the question of whether hot electron pre-heat could account for some of the discrepancies seen between simulated and measured DSRs, the dataset of 2D simulations was rerun with a constant amount of super-hot, 100 keV pre-heat. A total super-hot pre-heat energy $\sim 5$ kJ is inferred from FFLEX measurements for these implosions, but simulations show that this pre-heat source has no influence on the simulated DSR. Given the large uncertainties in the pre-heat magnitude, and to gauge the effect of this perturbation source, the simulations were rerun with an exaggerated pre-heat source of 50 kJ for all shots. The artificially pre-heated simulations show reasonable agreement on neutron yield in 2D, in addition to DSR, but remain discrepant in the hot spot ion temperature. To resolve this last discrepancy, the pre-heated simulations were rerun with the DT thermal conductivity again decreased by a factor of one half. As in the 3D simulations, this modified conductivity brings the simulations into agreement with the measured ion temperatures but at the cost of over predicting the neutron yield by up to a factor of two for the highest energy implosions. It is possible that the remaining yield discrepancy could be resolved by the added perturbation growth present in 3D, but these simulations are not yet feasible in HYDRA.

Finally, these simulations confirm previous results that the asymmetries imprinted from the hohlraum radiation drive and the perturbation seeded by the capsule support tent are the largest degradation sources in high foot implosions. As illustrated in figure 6, while at low velocities the hohlraum asymmetries are the dominant degradation source, for the highest velocity high foot implosions, the tent becomes as large a degradation source as the asymmetries with each amounting to an order of magnitude degradation in yield in isolation.

Looking ahead, current experiments aim to mitigate both of these largest perturbation sources. Alternate capsule support strategies, such as replacing the tent with a stalk or shrinking the contact area of the tent with the capsule, are being tested [65]. Simultaneously, alternative hohlraum designs with larger case-to-capsule ratios [66], or other more
cases, the predicted yield exceeds $10^{16}$ neutrons, although it is still
leads to a factor of eight improvement in the predicted yield. In both
asymmetries and including the tent as the only perturbation source
hohlraum asymmetries are the only perturbation results is a factor of
factor of three improvement in neutron yield according to
numerator of three improvement in the predicted yield. In both
cases, the predicted yield exceeds $10^{16}$ neutrons, although it is still
well below the predicted symmetric yield for this implosion of
$4 \times 10^{17}$.

speculative techniques, such as capsule shimming [67], are being explored to mitigate hohlraum asymmetry imprint. As illustrated by figure 14, completely removing the tent perturbation from the N140520 implosion could result in up to a factor of three improvement in neutron yield according to simulation. Analogously, completely eliminating any asymmetry imprint from the hohlraum could give a factor of eight improvement in yield for this implosion. It is hoped that one of the strategies currently being tested will realize some of these large potential gains and enable further progress toward
ignition.

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Appendix

This appendix summarizes some of the numerical details of the results from the previous sections. Typically, these details are assumed and not explicitly discussed. In the spirit of fully
describing the verification, as well as validation, of the simulation model, these details are summarized here.

The bulk of the simulations described above are 2D simulations using ALE hydrodynamics [68], multi-group radiation transport in the diffusion approximation [69], tabular equation of state [70–72] and opacity data [73], and Monte Carlo transport of fusion products. These characteristics raise the necessity of demonstrating convergence of the simulations with respect to the computational mesh used to resolve the hydrodynamic motion, the number of radiation groups used to transport x-ray radiation, and the number of Monte Carlo particles used to model the slowing down of fusion products. Additionally, there is the question of the accuracy of the x-ray flux used to drive the simulated implosion.

Regarding the 1D x-ray flux used to drive the simulated implosion, this x-ray source is tuned to match shock timing data [31], 1D convergent ablator data [74], and finally bang time data from various companion experiments to the DT implosion being modeled. All of these data are matched within their respective error bars using multi-group full radiation transport in 1D as described in [24]. While not perfectly unique, the resulting x-ray drive is nonetheless highly constrained. An effective x-ray drive is then tuned using diffusive radiation transport that very closely reproduces the original results with full transport. This diffusive x-ray drive is then suitable for low-noise and very efficient 2D simulations of implosion instability growth. The level of agreement between the tuned diffusive transport results and the full transport results is illustrated in figure A1. Here snapshots of density as a function of radius during the implosion of the shell are over plotted from 1D simulations of N140520. The fuel-ablator Atwood number and ablation front scale length are also plotted as a function of ablation front radius in the right panel. While not perfect, the agreement is quite close, especially considering the rapidly varying density gradient at the ablation front and the fuel-ablator interface.

Once a 1D diffusive x-ray drive is established, the questions of convergence with respect to mesh refinement, number of groups for diffusive x-ray transport, and number of Monte Carlo fusion product particles can be assessed. Figure A2 shows the convergence characteristics of the nominal 2D simulations as the number of angular and radial zones in the mesh is increased. The four panels show the measurable of neutron yield, nuclear burn width, DSR, and burn-averaged ion temperature as a function of angular zone count for the two implosions N130927 and N140819. The solid curves show the results of simulations including all perturbations and starting at the nominal resolution of $393 \times 1024$ (radial \times angular) zones. The dashed curves show lower resolution simulations beginning with $300 \times 72$ zones but including only the longer wavelength effects of the hohlraum asymmetries. (The latter resolution is characteristic of the zoning used in low-resolution hohlraum simulations.) As shown in the figure, the effect of doubling the mesh resolution in the nominal simulation including all perturbations is insignificant for all four observables indicating that these simulations are converged. By contrast, the lower
Figure A1. Comparison of 1D simulation results for shot N140520 illustrating the close agreement between a full radiation transport simulations using $S_6$ (black) and a retuned simulation using the diffusive approximation (red). The left panel shows a sequence of density snapshots as the shell implodes, and the right panel shows the fuel-ablator Atwood number (left scale) and ablation front density gradient scale length (right scale) as functions of the ablation front radius. While the agreement is not perfect, diffusion clearly provides a very close approximation even for such rapidly varying quantities as the Atwood number and scale length. This level of agreement between full transport and diffusion is typical of the simulations described above and underlies the 2D and 3D instability modeling in sections 3–6.

Figure A2. Sensitivity of four simulated observables to 2D mesh refinement. The dashed lines show simulations with the hohlraum asymmetries as the only perturbation source, while the solid lines include all 2D perturbations. The nominal resolution of $393 \times 1024$ is converged in both cases, although lower resolutions are not.
resolution case with $300 \times 72$ zones and the hohlraum asymmetries as the only perturbation is not converged.

Figure A3 shows the results of a similar convergence test with respect to the number of radiation transport groups. The nominal simulation uses sixty logarithmically-spaced photon groups. Similar to the case of mesh refinement, doubling and quadrupling the resolution in photon energy leads to only small changes in the burn-averaged ion temperature, DSR, and burn width. There is a slightly larger impact on the simulated neutron yield, particularly for the higher velocity implosion N140819, but this is to be expected given the highly nonlinear dependence of yield on the hot spot temperature and that this simulation is at the threshold of the α-heating regime. It is interesting to note that the DSRs slightly decrease under refinement and the ion temperatures slightly increase. Though the effects are quite small, these are both in the direction of improving agreement with the experimental data.

Also included in figure A3 are points at nine photon groups. This case corresponds to the photon group structure used in the 3D simulations where computer memory limitations necessitate using a specially tuned, few-group radiation transport scheme. The points shown in figure A3 correspond to 2D simulations using this few-group scheme for the sake of comparison to the other 2D simulations and indicate that there is little loss in fidelity using this scheme in terms of neutron yield and nuclear burn width. For the DSR and ion temperature, a further approximation must be made in the 3D simulations. As with the number of photon groups, memory limitations prevent running the Monte Carlo fusion product package in-line in 3D, so that the DSR and ion temperature from the 3D simulations are computed by instantaneously transporting Monte Carlo neutrons through the simulation at bang time in a post-processing step. The results of applying this procedure in 2D are shown by the diamonds in figure A3. For both simulations, the post-processing procedure results in a computed DSR that is $\sim$0.5% higher than the result of running the Monte Carlo package in-line. This suggests that, if they could be computed in-line, the 3D DSR values would actually be slightly lower than shown in figure 7 and nearly in agreement with the data. On the other hand, the hot spot ion temperature is inflated by $\sim$0.2 keV using the simplified scheme, suggesting that the 3D ion temperatures are likely even further from the data than shown in figure 7.

Similar to the case of convergence under radiation group refinement, the convergence of simulations including hot
electron pre-heat was verified with respect to the number of hot electron groups. 1D simulations with 30, 60, and 120 hot-electron groups were run, and a 60 group structure was found to be converged for the low-energy hot electrons, while only 30 groups were needed to converge the high-energy hot electron simulations.

The final convergence test shown in figure A4 is with respect to the number of Monte Carlo particles used to model fusion products. The nominal 2D simulation model uses 150,000 Monte Carlo particles. As shown in the figure, the neutron yield and ion temperature, as well as other observables, are all but insensitive to increasing the number of Monte Carlo particles.

As discussed in section 4, the nominal 2D and 3D simulations are not sufficiently resolved to capture the very fine-scale features represented by the tent (∼50 nm) and fill tube (∼10 μm). To model these extremely fine-scale features, specialized high-resolution 2D simulations must be run [22]. To include the important effects of the tent and the fill tube in nominal resolution simulations, surrogate perturbations are then derived from these high-resolution simulations, and their longer-wavelength features can then be initialized in the lower resolution cases. The validity of this approximation procedure for the case of the capsule support tent is shown in figure A5 for the high foot implosion N140520. The left panel shows the result of a full resolved simulation where the tent is the only perturbation source. This simulation required 1600 × 12,288 zones to resolve the 45 nm thick tent feature. Such resolution is feasible for these specialized 2D simulations but impractical for the large number of 2D simulations discussed above and totally unworkable in 3D. However, the right panel shows the result of a nominal resolution simulation (393 × 1024 zones) using the surrogate tent perturbation, and fortunately the visual agreement is quite good. In fact, the simulated neutron yields from these two simulations are with 15%, validating the utility of the lower resolution model. Note that these simulations are run with α-particle deposition switched off to avoid the high sensitivity of yield amplification in this range and its feedback on the hydrodynamics of the hot spot.

A similar methodology and similar results apply for the surrogate perturbation used for the fill tube. Note, however, that very recent NIF radiography experiments [75] suggest that an additional perturbation may be seeded by the radiation shadow cast by the fill tube. This shadowing effect was not anticipated before these radiography experiments were performed and likely results in a larger effective perturbation from the fill tube than previous modeling suggests. The impact of this fill tube shadow, as well as its precise origins,
are the subject of ongoing work and could explain some of the remaining discrepancies.

An additional detail is that the 2D and 3D simulations presented above initially use a spherical polar mesh configuration that is converted to a multi-block ‘butterfly’ mesh during the stagnation phase of the implosion. This butterfly mesh configuration significantly improves the speed and fidelity of the simulation for modeling the complex, compressing flows in highly distorted hot spots. In some cases, however, meshes not aligned with the global flow can introduce artificial mesh imprinting on the flow, for example, when a spherically converging flow is modeled on a Cartesian mesh. To verify that this type of mesh imprinting was not occurring, unperturbed implosion simulations were run in HYDRA with a butterfly mesh. These tests verified that the asphericity induced by the mesh was less than a fraction of a percent of the perturbations being modeled from physical sources and confirmed that mesh imprinting does not corrupt the simulation results above.

Finally, all of the simulations described above were run in the inviscid approximation. This is despite the strongly stabilizing effect that viscosity has been found to exert on short wavelength flows in NIF hot spots [76]. However, given that the impact of viscosity on the experimental observables is generally smaller than the experimental error bars [14], and that the simulation run time increases significantly when viscosity is included, the inviscid approximation is thoroughly justified for the results discussed above.

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