Diagnostic Signatures of Performance Degrading Perturbations in Inertial Confinement Fusion Implosions

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We present 3D radiation-hydrodynamics simulations of indirect-drive inertial confinement fusion experiments performed at the National Ignition Facility (NIF). The simulations are carried out on two shots from different NIF experimental campaigns: N130927 from the high foot series and N161023 from the ongoing high density carbon series. Applying representative perturbation sources from each implosion, synthetic nuclear diagnostics are used to post-process the simulations to infer the stagnation parameters. The underlying physical mechanisms that produce the observed signatures are then explored. We find that the radiation asymmetry and tent scar perturbations extend the nuclear burn width; this is due to an asymmetric stagnation of the shell that causes the delivery of mechanical PdV work to be extended compared to an idealised implosion. Radiation asymmetries seed directed flow patterns that can result in a difference in the inferred ion temperature ranging from 80 eV to 230 eV depending on the magnitude and orientation of the asymmetry considered in the simulation; the tent scar shows no such temperature difference. For N130927 radiation asymmetries dominate the yield and inferred ion temperature and the tent scar has the largest influence on the neutron burnwidth. For N161023, the fill tube decreases the burn width by injecting mix into the hot spot, leading to a smaller hot spot and increased energy losses. Both the radiation asymmetry and the fill tube generate directed flows that lead to an anisotropic inferred temperature distribution. Through existing and novel synthetic neutron imaging techniques we can observe the hot spot and shell shape to a degree that accurately captures the perturbations present.

I. INTRODUCTION

The National Ignition Facility (NIF)¹ at the Lawrence Livermore National Laboratory (LLNL) has worked towards achieving thermonuclear fusion using an indirect-drive Inertial Confinement Fusion (ICF) scheme^{2,3}, where 192 laser beams incident on a hohlraum deliver a tailored x-ray pulse that drives the collapse of a cryogenic deuterium-tritium (DT) fuel pellet. Upon stagnation, the kinetic energy of the capsule is converted to thermal energy and the high densities and temperatures achieved initiate hot spot ignition before the capsule disassembles under its own pressure.

In recent years significant progress has been made in increasing the yield of experiments fielded at NIF. After the National Ignition Campaign (NIC)^{4,5} was thought to under-perform due to hydrodynamic instabilities, the redesign to a higher trough radiation temperature and shorter pulse length (known as the high foot shot series)⁶ saw large improvements, leading to shots that achieved a fuel gain of unity⁷. After the high foot series, experiments moved on to look at High Density Carbon ablators (HDC)⁸ that used a near-vacuum hohlraum with shorter laser pulse lengths, reducing laser-plasma instabilities which lead to a more symmetric implosion. This has increased the neutron yield to approximately 2×10^{16} neutrons, equivalent to a $\times 2 - 3$ yield enhancement from alpha deposition⁹. Despite these improvements, progress is still ongoing to achieve the MJ neutron yields first predicted during the NIC.

The performance of NIF experiments are affected by a variety of perturbation sources. During the capsule's implosion, blow-off from the gold wall crosses over and

intercepts the propagating laser beams causing premature absorption within the hohlraum. This leads to a time and angle dependent radiation field¹⁰ that affects the global shape of the capsule. The support tent¹¹ (two thin films of Formvar which hold the capsule within the hohlraum) explode when they are first irradiated, causing two annular trenches to develop which become Rayleigh-Taylor (RT) unstable. The fill tube stalk¹², which feeds the DT into the inside of the ablator, also becomes RT unstable like the tent supports but can be significantly more damaging. The fill tube is composed of a silicon dioxide tube that is held in place by glue and filled in with cryogenic DT. These different materials cause a low density channel to form which can promote mixing and shearing as the shock propagates through it, entraining contaminants into the RT bubble that forms. Due to the density contrasts between the ablator and channel, the effect of the fill tube is more pronounced for recent HDC experiments¹³. The non-uniformity¹⁴ of the different capsule layers are a RT unstable system which affects the whole capsule and can promote mixing of the ablator and fuel, alongside the cold DT shell and hot spot, quenching the fusion reactions. When all perturbations are present at once, their interdependency and feedback on each other make interpreting the 3D time-varying roles in an implosion's performance a complicated process.

Quantifying the performance of an ICF experiment relies on looking at the products that are released during the implosion. Neutrons from the fusion reactions are the most studied due to their ability to escape the fusing capsule. Using these products to understand the role and influence of perturbations is critical in improving the per-

formance of experiments, and an advanced suite of diagnostic tools are available to do this. The Neutron Imaging System (NIS)¹⁵ images the primary and scattered neutrons coming from the hot spot, allowing the shape of both the hot spot and dense fuel layer to be inferred. The neutron Time-of-Flight (nToF)¹⁶ detectors produce an energy-resolved spectrum that contains information about the hot spot's ion temperature and bulk velocity. The flange Neutron Activation Detectors (fNADS)¹⁷ are a series of neutron counters that inform on the neutron flux asymmetry, which can be related back to the areal density of the fuel.

Apart from neutrons, x-rays and γ -rays are also produced during fusion and can be used as diagnostics. X-ray self emission from the hot plasma can be imaged using gated x-ray detectors¹⁸ and time-resolved hot spot dynamics can be observed with the Dilation X-ray Imager¹⁹. γ -rays produced from DT reactions are used to determine the nuclear burn width of the fusing hot spot. When γ -rays are produced from inelastic neutron scattering from the ablator they can image the remaining ablator mass, although this is not regularly carried out.

Detailed understanding of the perturbations present in an implosion requires a comparison of experiments to simulations. Discrepancies between the code and experiment are an indication for further physics models or perturbation sources that need to be included. Current 3D modelling ongoing at LLNL^{20,21} has had great success in reproducing the integrated metrics of a capsule's performance. Using simulations as a stand-in for the experiment allows constraints to be placed on what can be inferred from diagnostics, as well as aiding in the development of new analysis techniques with the current diagnostics available. Finally it provides a way to establish what new diagnostics need to be developed to maximise our understanding of experiments.

Previous work^{22–24} in the development of synthetic neutron diagnostics to post-process 3D radiation-hydrodynamics simulations at Imperial College have looked at the impact and role of different perturbations on implosion quality. This has been accomplished using an inverse ray trace method, where neutrons are tracked back from a detector to where they were produced. Only including neutrons that reach the detector greatly reduces the computational expense and improves the statistics. However, these have been performed using ad-hoc perturbations which may not be representative of a NIF experiment. In this paper, we extend this work to examine perturbation scenarios and amplitudes that are known to occur in experiments and characterise their performance through existing neutron diagnostics. We look to see if any of these perturbations provide a hallmark diagnostic signature in isolation and if they still persist when multiple perturbations are included simultaneously. Section II shows the implosion's performance in 1D, and considers issues arising from numerical constraints. Section III examines the role of each perturbation individually: subsection A deals with radiation asymmetries,

FIG. 1. One-dimensional density maps as a function of radius and time for N130927 and N161023. The black dashed lines denotes the ablator/DT interface. The radiation pulse is included for each implosion.

subsection B with the tent scar and subsection C with the fill tube. Sections IV and V combine these perturbations together, studying how their collective behaviour affects the capsule's performance and whether diagnostic signatures present individually will persist. This work will focus upon two particular NIF shots, the high foot shot N130927 and the HDC shot N161023.

II. 1D RADIATION HYDRODYNAMICS

All simulations presented in this paper are produced using the 3D Eulerian radiation magnetohydrodynamics code Chimera^{22,25,26}. Chimera uses $P_{1/3}$ Automatic Flux Limiting²⁷ for the radiation transport algorithm, allowing it to numerically transition between optically thick and thin media. The opacities and emissivities are read in as look up tables created by the SpK code²⁸,

Performance Metric	N130927	N161023
Neutron Yield (10^{15} Neutrons)	260	9.03
Neutron Bang Time (ns)	16.82	7.82
Neutron Burn Width (ps)	100	98
Neutron Average Ion Temperature (eV)	7939	4494
DSR (%)	3.51	3.27

TABLE I. Neutron parameters from 1D Chimera simulations for shots N130927 and N161023

which uses Detailed Configuration Accounting (DCA) with energy levels calculated from a Screened Hydrogenic Model (SHM), supplemented by experimental levels from the NIST atomic database²⁹. The x-ray drive uses a frequency dependent spectrum that includes the m-band component of the radiation flux. We use 54 energy groups chosen non-uniformly to ensure adequate resolution around important spectral features such as the carbon K-edge. The alpha transport burn package uses a Monte-Carlo Coulomb collision method³⁰ with a Maynard-Deutsch³¹ stopping model. The hydrodynamics use a second-order Van Leer advection scheme, with a Von Neumann artificial viscosity and the equation of state is supplied by FEOS³². The non-magnetised thermal transport uses the Braginskii co-efficients³³ with flux limited conduction.

Shot N130927 was a high performing shot as part of the high foot campaign, achieving a fuel gain of unity⁷. It has a 1.13 mm outer radius using a 3 stage Si doped (2%, 4%, 2%) CH ablator capsule. Shot N161023 was a 0.8 $\times$ scale capsule fielded early in the HDC campaign; it was a 860 μ m outer radius W-doped HDC capsule. In our atomic modelling, we use a surrogate Si dopant in place of W and the concentration is increased so that it creates agreement with shock timing data and nuclear metrics such as yield and bang time of Hydra simulations.

Figure 1 shows the mass density of an idealised 1D implosion of N130927 and N161023 with the radiation profiles inlaid. Differences between the pulse designs are pronounced, with N161023 having a much shorter (relative to its pulse length) and hotter trough compared to N130927, which will set it on a higher adiabat. The overall shorter radiation pulse of N161023 is due to HDC being 3 $\times$ denser than CH and so less time is needed to compress the ablator material before driving the implosion. Additionally, N161023 is a subscale target and can be driven to stagnation quicker. Despite these early time differences, both pulses reach approximately the same peak radiation temperature, although N161023 rises slower to its peak. The implosion time (time between the shock breakout of the ice and the 1st shock landing on axis) is longer for N130927, allowing more time for RT growth.

The performance of these implosions is quantified in terms of their nuclear parameters and these are summarised in table I. N130927 has a neutron yield of 500

FIG. 2. Converge of neutron yield as a function of cell size for N161023. N130927 shows a similar yield-resolution scaling.

kJ with an inferred temperature approaching 8 keV, compared to the 25 kJ of N161023 which shows a more modest 4.5 keV. The DSR values between implosions are within 10% of each other despite N130927 having almost double the areal density of N161023. This is due to N130927 having significant alpha deposition and so the peak areal density is before peak neutron production causing the scattered neutrons to sample a lower areal density. These stagnation conditions are consistent with using Hydra calculations⁶. The values in table I are for a radial resolution of 250 nm; figure 2 shows the neutron yield as a function of cell size and shows convergence at 250nm resolution.

Due to computational constraints, the multidimensional simulations shown in the upcoming sections are run at a resolution that may be insufficient to fully resolve certain phenomena. For example, the early time ablation front scale length which suppresses large wavelength Rayleigh-Taylor growth is of order 2-3 μ m. Using a spatial resolution that is similar to this scale length will do a poor job in resolving it and can lead to incorrect instability growth and radiation energy deposition. However, resolving these lengths in 3D simulations is not always feasible, as to do so would approach 10^9 computational cells.

III. PERTURBATION SOURCES

The ICF capsule calculations presented in this paper are carried out in a two step process. First a subsection of the capsule, typically a 2D/3D wedge, is initialised and simulated in spherical geometry up until a convergence ratio (CR) of approximately 3. At this time the leading shock in the DT has nearly encountered the centre of the capsule. The spherical geometry allows a section of the problem to be simulated whilst minimising the influence that grid imprint can have on the numerical algorithms. Additionally these wedges are routinely run with an axis

that does not start at the origin. This is done to increase the time-step as the angular length of the cell is $\propto r d\theta$.

At the end of this spherical mesh phase, the simulation is remapped to a cubic Cartesian mesh. For the anisotropic radiation fields and tent membrane perfect azimuthal symmetry is assumed and so the hydrodynamic, thermodynamic and radiative variables of the 2D spherical wedge are interpolated onto a 3D Cartesian mesh by matching the radial and polar co-ordinates between meshes. More care must be taken for the fill tube which breaks the azimuthal symmetry. For this the first polar section of computational cells are mapped onto the Cartesian mesh creating the initial shell, after this the fill tube is then placed and aligned with one of the primary axes along the waist. Running on a cubic mesh allows the origin of the capsule to be resolved. For the simulations presented here, the final stagnation resolution is a $2\text{ }\mu\text{m}$ cubic mesh, with an initial radial resolution of $1\text{ }\mu\text{m}$ in the ablation and initial implosion phase on the spherical mesh. The key neutron metrics of all the 3D simulations reported here are summarised in table II.

The following sections use perturbation sources that have been derived from high resolution HYDRA simulations for ease of implementation. While these will recover the gross properties of the physics at play, these approximate models will fail to capture the true evolution that occurs in experiment. For example, the simplified fill tube in section C will not capture the double jetting structure when an ab initio fill tube calculation is performed¹³. Despite this, these models serve as a starting point to start investigating such perturbation scenarios.

A. Anisotropic Radiation Fields

The performance of the high foot campaign was thought to be dominated by the large-scale shape of the hot spot²¹. These long wavelength perturbations are caused by an angle and time dependent radiation field coming from the hohlraum wall. The gold ablates outward as it is heated causing premature absorption and redirection of the laser energy. Assuming that the laser absorption is symmetric around the azimuth, radiation incident on the capsule can be described by a Legendre polynomial expansion:

$$T_r(\theta, t) = T_r^0(t)(1 + a_2(t)P_2(\theta) + a_4(t)P_4(\theta)) \quad (1)$$

where $T_r(\theta, t)$ is the angular dependant radiation field, $T_r^0(t)$ is the initial symmetric field, $a_{2/4}(t)$ are the Legendre amplitudes and $P_{2/4}(\theta)$ are the 2nd and 4th Legendre polynomials. A positive P2 means a higher drive temperature at the pole, and a negative P2 drives harder at the waist. A positive P4 drives harder at the poles and waist simultaneously, and a negative P4 at the polar angles $\theta=45/135/225/315^\circ$. It should be noted this treatment is not valid if the laser absorption is non-symmetric in the

FIG. 3. Time-dependent P_2 and P_4 Legendre amplitudes for shots N130927 and N161023. The radiation pulse for both are included in blue for reference (in arbitrary units).

azimuth, which would either require spherical harmonics to describe the full angular dependence or a 3D hohlraum capsule simulation. There has been some experimental evidence for a azimuthally asymmetric radiation field when looking at re-emission from the gold hohlraum³⁴.

The modulation amplitudes (a_2 and a_4) are derived from 2D hohlraum simulations and are consistent with the shape measured from convergent ablator experiments in flight and hot spot emission from symcaps³⁵. These are shown in figure 3 for both implosions. As N161023 uses the HDC ablator and therefore can be driven to stagnation in a shorter time period, the gold has less time to expand from the hohlraum wall and intercept the laser, which reduces the Legendre amplitudes.

A major consequence of this non-symmetric radiation field is the redistribution of mass due to a difference in the driving ablation pressure. With the amplitude of the Legendre coefficients changing in time, this redirection of mass changes throughout the implosion. Although the mass redirection is seeded at the ablation front, the shock that propagates through the capsule is embedded with this flow pattern and can redistribute the DT fuel mass. For the case of N130927, the mass is primarily driven to the poles and to the waist of the capsule; this is a consequence of the radiation being dominated by the P_4 Legendre amplitude. The angular component of the velocity reaches a maximum of 10 % (50 km s^{-1}) of the radial component at CR=3 in the leading shock within the DT gas, the dense DT shell reaches a more modest 2-3 %. These values are achieved just before the implosion is reinitialised on the Cartesian mesh.

Figure 4 shows a time sequence of the capsule implosion with radiation asymmetries applied. At 16ns the DT shell is just about to enter its deceleration phase and shows a squaring of the shell at a convergence ratio of 4, with the re-expanding shock having an oval shape. The

FIG. 4. Density slices of N130927 with the radiation asymmetry perturbation applied. The times are just before the re-expanding shock interacts with the shell, 500 ps later and then peak neutron output. The black line denotes the ablator/DT interface. The final image shows velocity stream lines overlaid in the x-z plane that are coloured by the v_z component (running up and down the page).

FIG. 5. Ion temperature skymap inferred from the primary DT spectrum for N130927 with the radiation asymmetry perturbation. Overlaid are the positions of the SpecE (pink), SpecA (yellow) and the South pole (green) nToF diagnostic. The skymap is centred on $\phi = 90^\circ$.

middle image shows the capsule 500 ps later as it decelerates and enters its stagnation phase. Redirected material at the poles and waist of the capsule are beginning to emerge and run ahead of the shell, which itself now shows a clear angular density variation. The final image at 16.7ns shows the conditions at peak neutron output: mass accumulated at the poles and waist of the capsule, forming polar jets and an equatorial ring that lead the implosion, with the jets prematurely stagnating.

Due to the redistribution of mass, the asymmetric implosion has a strong effect on the ion temperature in the hot spot. At bang time, while a small portion of the hot spot achieves a temperature of 6 keV (at the region compressed by the polar spikes), the average is at a much lower temperature of 3.5 keV. A final consequence of the asymmetric stagnation is the introduction of residual kinetic energy into the capsule. This is highlighted by the streamlines (right hand side, grey scale) which instantly

FIG. 6. (top) Primary neutron image for the radiation asymmetry perturbation at a NIS detector position of $\theta = 90^\circ$, $\phi = 315^\circ$. (bottom) The corresponding fluence compensated image along the same direction.

neously trace out the velocity field within the hot spot. It is apparent that significant vorticity has been introduced into the hot spot cavities, as evidenced by the rotation and roll up of the streamlines. There are directed flow patterns aligned with the polar jets and the waist, indi-

cating bulk motion.

This implosion's performance is characterised by post-processing the simulation with synthetic nToF and neutron imaging diagnostics. For the nToF, the directed flows will cause a broadening of the DT spectrum, leading to an inferred ion temperature that is larger than its thermal value. Figure 5 shows a skymap of the inferred ion temperature, with the position of the Spec E/A and southpole detectors overlaid. The fast moving polar jets induce a large Doppler broadening causing a higher neutron inferred temperature of 3.59 keV compared to the slower equatorial ring value of 3.36 keV. Both of these are higher than the non Doppler-broadened temperature of 3.22 keV. From their current positions the nToF detectors capture both the maximum and minimum temperature seeded by the perturbation.

The NIS captures time integrated primary and scattered neutron images of the implosion, which give an indication of the hot spot and shell shape respectively. Figure 6 (top) shows the perturbed primary neutron image along the $\theta = 90^\circ, \phi = 315^\circ$ line of sight detector. With this and the scattered image (not included), the work of Casey³⁶ has utilised a fluence compensation technique which separates out the primary fluence from the scattered image, allowing the DT shell to be imaged. This is shown in figure 6 (bottom) and has favourable agreement with the cross-sectional density image taken directly from the simulation, shown in figure 4. The neutron image from the second equatorial NIS detector ($\theta = 90^\circ, \phi = 213^\circ$) shows quantitatively the same image as figure 6 owing to the symmetry of the perturbation. Imaging along the north pole NIS detector ($\theta = 5.25^\circ, \phi = 225^\circ$) shows the dense shell and polar spike, but gives no information on the radiation asymmetries due to the azimuthal symmetry.

B. Tent Membrane

Another perturbation source thought to be a significant contributor to yield degradation during the high foot campaign is the tent membrane which holds the capsule in place within the hohlraum³⁷. Radiation ablating the contact point between the membrane and the capsule causes material to blow out and create a trench on the surface that becomes Rayleigh-Taylor unstable. A consequence of this is an areal density deficit at these contact points on the ablator surface that can feed through and imprint onto the DT fuel.

For this simulation, a surrogate tent scar perturbation is applied, derived from high fidelity capsule simulations that match convergent ablator (2DConA) data³⁸. A surrogate is required as the tent membrane is 45nm in thickness, which is computationally intractable. When applied to Chimera simulations, due to the small amplitudes involved relative to the normal Chimera cell size, the radial displacement is turned into a density modulation that can be applied to the capsule's surface. This

technique has been verified by comparing to larger amplitude harmonic perturbations that were measured using the Hydro Growth Radiography platform³⁹. The surrogate used is a function of the polar angle only and symmetry is assumed in the azimuth.

The scar created by the tent membrane seeds a non-radial velocity flow that becomes embedded into the transmitted shock as it traverses the DT. Unlike the radiation asymmetry, this flow is more isolated and is localised around the scar, with no flow towards the pole or waist of the capsule. These non-radial flows have short scale structures that change sign within the cavity created by the tent scar. The maximum magnitude of these angular flows (30 km s^{-1}) in the leading DT shock are almost half the value of the angular flows seeded by the radiation asymmetry.

Figure 7 shows a time sequence of the capsule implosion with the tent scar. At 16ns the shock has begun to re-expand from the centre. The ablator material along the tent direction has been ablated strongly, leading to a slight perturbation on the DT fuel inner edge. At 16.4 ns the shell is decelerating and the tent scar has begun to close up on the outer edges of the ablator material due to the shell's convergence. The DT shell shows a strong variation in radius with dense rings of material forming. While the outer DT shell remains round at 16.7 ns (i.e. peak neutron output) the inner surface has been perturbed, showing an angular variation in the hot spot / ablator interface. The velocity flows present show no jetting structure like the radiation asymmetries.

The time sequence shown in figure 7 has discrepancies when compared to the behaviour of other simulations¹¹ which shows more growth during the final stagnation phase. We attribute this to two effects, the spatial resolution of the grid and the imprint associated with stagnating on a Cartesian mesh. Near stagnation the width of the tent scar becomes comparable to the resolution used in simulation. Additionally, as the tent is coming in at approximately 45° to the axes it will be affected by the mesh structure which will diffuse mass into the low density channel.

The inferred ion temperature in figure 8 shows no variation owing to the lack of jets and flows generated in the hot spot, although there is a slight increase at the poles. The non Doppler-broadened temperature is 3.67 keV, so the flows have only added an extra 70 eV. The primary neutron image in figure 9 (positioned at $\theta = 90^\circ, \phi = 315^\circ$) shows a round hot spot compared to figure 6, with only a small perturbation on the outer edges which is hard to detect. The fluence compensated image however shows an enhancement in inferred areal density along the tent scar directions.

C. Fill Tube

The final perturbation scenario considered is the fill tube that feeds the DT fuel into the capsule⁴⁰. For

FIG. 7. Density slice of N130927 with the tent scar perturbation applied. The times are just before the re-expanding shock interacts with the DT shell, 400 ps later and then peak neutron output. The black line denotes the ablator/DT interface. The final image shows velocity stream lines overlaid in the x-z plane that are coloured by the v_z component (running up and down the page).

FIG. 8. (left) Ion temperature skymap inferred from the primary DT spectrum for N130927 with the tent scar perturbation. Overlaid are the positions of the SpecE (pink), SpecA (yellow) and the South pole (green) nToF diagnostic. The skymap is centred on $\phi = 90^\circ$.

this perturbation we move onto the HDC shot N161023, which used a silicon dioxide fill tube $10 \mu\text{m}$ in diameter. Similar to the tent membrane, when irradiated the fill tube explodes, creating a density channel that becomes RT unstable^{12,41}. However, there are substantial differences between the fill tube and tent scar. The fill tube extends all the way down into the ablator and is not constrained to the surface of the capsule. This channel allows it to easily penetrate through to the DT compared to the tent perturbation.

The fill tube perturbation applied is a surrogate derived from a highly resolved 2D capsule simulations that is matched in its growth from radiography⁴². The surrogate perturbation is a $2 \mu\text{m}$ amplitude, $25 \mu\text{m}$ FWHM Gaussian divot that is applied on the waist of the capsule on a $90^\circ \times 90^\circ$ wedge. The wedge size is chosen such that the perturbation can grow unhindered by numerical boundary conditions up until $\text{CR}=3$, shown in figure 10,

FIG. 9. (top) Primary neutron image for the tent scar perturbation at a NIS detector position of $\theta = 90^\circ$, $\phi = 315^\circ$. (bottom) The corresponding fluence compensated image along the same direction.

while still remaining small enough for computational expediency. Unlike previous simulations, for this spherical mesh a static but variable resolution is used in the azimuth and polar directions, starting at 0.5° around the fill tube and eventually feathering out to 1° . It is then

FIG. 10. A cutaway showing two perpendicular density slices of the fill tube perturbation at a convergence ratio of 3, just before it is remapped onto a Cartesian grid. The black line denotes the Ablator/DT interface.

remapped onto a $2\mu\text{m}$ Cartesian mesh at $\text{CR}=3$.

Figure 11 shows a time sequence of the fill tube implosion beginning at 7.2ns, before the shock re-interacts with the shell. There is a clear left-right asymmetry in the re-expanding shock which is due to the fill tube. The initial divot has now grown into a non-linear RT bubble cavity that is filled with ablator material and is running far ahead of the DT shell. The next image 200ps later shows the interaction of the reversed shock with the fill tube. The shock has penetrated into the centre of the fill tube bubble, causing velocity shear and initiating the Kelvin-Helmholtz instability. The fill tube has begun to disintegrate and is no longer a coherent jet of ablator material. The final image at peak neutron output (7.7ns) shows a flattening of the outer edge of the DT shell at the fill tube position. The inner edge of the DT fuel / hot spot interface has penetrated deeper into the centre and ablator material has embedded itself into the DT along the fill tube opening. The velocity streamlines show a coherent flow through the centre of the hot spot due to the fill tube.

The fill tube injects ablator and dopant material into the DT fuel which will lead to enhanced x-ray emission from the hotspot. However for our simulations the ablator and dopant are largely confined to the DT shell, with very little pushing further into the hot spot. This is due to the relatively small amount of ablator and dopant material becoming one cell in extent within the simulation. When this happens the material is no longer advected with flow. This physically corresponds to atomic mixing of the material into the DT fuel. Although this means detailed synthetic x-ray measurements will not be accurate in reproducing experiment results, the bulk hydrodynamics should remain relatively unchanged, allowing neutron analysis of the perturbation to be performed unaffected.

Figure 12 shows the inferred ion temperature sky map for the implosion with a variation of 100eV in temperature. The dominant feature is the increased inferred temperature along the fill tube axis, denoted by the cross on the sky map. Although the ablator material has broken up due to the rebounding shock, a directed flow still remains along the fill tube direction as shown in figure 11. The position of SpecE detector makes it possible to measure the temperature inferred along the fill tube axis. The primary neutron image (positioned at $\theta = 90^\circ, \phi = 315^\circ$) in figure 13 shows a reduced hot spot size due to the mix of cold DT fuel. The fluence compensated image reveals a round shell with a small amount of the flattening and increased areal density. The NIS detector at $\theta = 90^\circ, \phi = 215^\circ$ will be looking almost parallel to the fill tube, making it hard to image the perturbed shape. The north pole detector at $\theta = 5.25^\circ, \phi = 225^\circ$ highlights the asymmetrically converged DT shell in a similar way to figure 13.

Imaging the fill tube directly with neutron imaging would be possible under the condition that it is aligned with a pair of antipodal (180° separated) detectors. Taking the primary neutron images, their ratio differs due to an attenuation factor $\propto \exp(-\sigma\Delta(\rho R))$, where σ is the attenuation coefficient. The antipodal imaged fill tube in figure 14 shows that material has been pushed out of the centre, leading to a large increase in areal density around the fill tube with a dip along it. The fill tube perturbation is only $20\mu\text{m}$ in diameter and would be challenging to image when the instrument response is considered. In general, antipodal neutron images could enable the possibility to quantify perturbations that affect one hemisphere of a capsule preferentially, whether it be a fill tube or a odd mode radiation asymmetry such as a P_1 drive.

IV. COMBINING PERTURBATIONS

Each perturbation was considered in isolation; in this section they are combined to determine their effect on the implosion dynamics and the diagnostic signatures inferred. For this two final perturbation scenarios will be considered: N130927 with the tent scar and the radiation asymmetry perturbation, and N161023 with the radiation asymmetries and the fill tube perturbation.

Note that for the comparisons that follow, the values of the symmetric implosion differ from those in table I. This is to be expected as the simulations were ran with different resolutions and geometries. Whilst knowing what information is lost between these different set ups, what is more important are how the diagnostics respond to different perturbation scenarios that are ran under the same conditions. To aid in the comparison, the symmetric implosions were simulated in the same methodology to the perturbed scenarios, i.e. a $1\mu\text{m}$ spherical grid until a $\text{CR} \approx 3$ and then stagnated on a Cartesian grid at a resolution of $2\mu\text{m}$.

FIG. 11. Timelapse of N161023 with the fill tube perturbation applied. The times are just before the re-expanding shock interacts with the fill tube, 200 ps later and then peak neutron output. The black line denotes the ablator/DT interface. The final image shows velocity stream lines overlaid in the x - z plane that are coloured by the v_x component (running left and right along the page).

FIG. 12. Ion temperature skymap inferred from the primary DT spectrum for N161023 with the fill tube perturbation. Overlaid are the positions of the SpecE (pink), SpecA (yellow) and the South pole (green) nToF diagnostic. The black cross denotes the fill tube position. The skymap is centred on $\phi = 90^\circ$.

A. Highfoot N130927

With both radiation asymmetry and the tent scar applied, the early time drive behaviour of the implosion shows some minor differences from their individual counterparts. The angular velocity field at CR=3 is a superposition of the two individual perturbations. Disruption of the mass flow due to the tent scar shows itself in the reduced velocity magnitude in the leading shock wave.

The inferred temperature skymap shows essentially no difference from figure 5 and so it is omitted. The primary neutron image in figure 15 shows that the outer edges of the hot spot have been squashed towards the waist compared to radiation asymmetry of figure 6 due to the addition of the tent scar. The fluence compensated image shows the tent scar weakly along the negative P4 directions, but is largely dominated by the polar spikes and equatorial ring of the radiation asymmetries.

FIG. 13. (top) Primary neutron image for the fill tube perturbation at a NIS detector direction of $\theta = 90^\circ, \phi = 315^\circ$. (bottom) The corresponding fluence compensated image along the same detector. The fill tube is at an orientation of $\theta = 90^\circ, \phi = 0^\circ$

B. HDC N161023

The early time behaviour of the combined perturbations is a superposition of the radiation asymmetry and fill tube; around the fill tube there is no influence of the

	Simulation & Performance	Neutron Yield (10^{15} Neutrons)	Neutron Bangtime (ns)	Neutron Burn width (ps)	T_{ion} max (keV)	T_{ion} min (keV)	Burn-averaged T_{ion} (keV)	Average DSR %
1	Highfoot P_0	61.45	16.81	125	5.60	5.60	5.47	3.77
2	Highfoot Radiation Asymmetry	3.75	16.70	142	3.59	3.36	3.22	N/A
3	Highfoot Tent Scar	6.43	16.70	152	3.74	3.73	3.67	N/A
4	Highfoot Combined	3.48	16.66	155	3.58	3.40	3.27	2.87
5	HDC P_0	4.89	7.83	120	3.97	3.97	3.88	2.40
6	HDC Radiation Asymmetry	2.65	7.76	135	3.77	3.69	3.51	N/A
7	HDC fill tube	1.95	7.67	111	3.62	3.52	3.43	N/A
8	HDC Combined	1.72	7.67	116	3.77	3.63	3.47	2.12

TABLE II. Neutron metrics of N130927 and N161023 with different perturbation sources.

FIG. 14. Line of sight areal density difference for the fill tube perturbation, imaged by antipodal primary neutron imagers.

radiation asymmetry owing to P_4 Legendre mode vanishing at that point and the P_2 Legendre mode being weak.

Including both effects, the primary and fluence compensated neutron images are shown in figure 16. In contrast to N130927 (figure 4), the effect of the radiation asymmetries has been to cause mass redistribution into a negative P_4 arrangement and form two rings which are captured well by the fluence compensated image. The fill tube has then disrupted one side of these material rings causing a source of azimuthal asymmetry into the shell. The primary image shows a smaller emitting region on one side due to the combined perturbations.

Figure 17 shows the inferred temperature skymap of the radiation asymmetry perturbation alone, together with the combined perturbations. Although both skymaps reach the same maximum inferred temperature, the radiation asymmetry has the highest temperature at the poles whereas the combined scenario still has its peak along the fill tube axis. The inferred minimum temperature is higher than in the case where only the fill tube is included; this is due to the induced motion within the hot spot.

FIG. 15. (top) Primary neutron image for N130927 with the tent scar and radiation asymmetries at a NIS detector direction of $\theta = 90^\circ, \phi = 315^\circ$. (bottom) The corresponding fluence compensated image along the same detector.

V. DISCUSSION

Now that each simulation has been investigated to understand their hydrodynamic evolution, the task is now to determine if these perturbations have left an observable diagnostic signature. The effect that these perturbations have on the neutron diagnostics is shown in table II. Rows 1-2 and rows 5-6 compare the effect of radiation

FIG. 16. Primary neutron image for N161023 with the fill tube and radiation asymmetries at a NIS detector direction of $\theta = 90^\circ$, $\phi = 315^\circ$. (bottom) The corresponding fluence compensated image along the same detector.

asymmetries for N130927 and N161023 respectively. The dominant effect is an increase of the neutron burn width and an earlier bangtime. This elongation of the burn pulse is due to the asynchronous convergence that different parts of the DT shell experience. This extends the period over which mechanical PdV work is done on the hot spot by the DT shell, and limits the maximum power that can be delivered to the hot spot. Additionally, the larger surface area due of perturbed shell can lead to increased thermal conduction losses, further lowering the hotspot temperature. The hot spot volume (defined by the 1keV ion temperature contour) is constantly shrinking throughout the burn pulse, indicating that the alpha heating and PdV work delivered are unable to overcome the thermal and radiative losses. The largest effect of radiation asymmetries is for N130927, with a $20\times$ decrease in the neutron yield compared to the P_0 result alongside a shift in bang time of 10ps.

The tent scar for N130927 (row 3) has a qualitatively similar effect on the neutron diagnostics, elongating the pulse by an extra 10ps compared to the radiation asym-

FIG. 17. Ion temperature skymap inferred from the primary DT spectrum of N161023 with the radiation asymmetry (top) and filltube and radiation asymmetry perturbation (bottom). Overlaid are the positions of the SpecE (pink), SpecA (yellow) and the South pole (green) nToF diagnostic. The black cross denotes the fill tube position. The skymap is centred on $\phi = 90^\circ$.

metries; however a more symmetric implosion lead to a higher ion temperature by 400eV. The yield is reduced by $10\times$ compared to the P_0 result and once again their is extended delivery of the PdV work which leads to a larger neutron burn width. When the radiation asymmetry and tent are combined simultaneously (row 4), the effect on the neutron signal is dominated by the radiation asymmetry in terms of yield and ion temperatures. The DSR has dropped significantly compared to the P_0 case and is thought to be due to three reasons. The first is that with the polar spikes cutting the hot spot in half, neutrons are emitted closer to the fuel layer, providing a shorter path of escape from the capsule. The second is that this mass redistribution has lead to substantial areas of weak areal density, providing a path for the neutrons to escape. The third is that bang time is occurring earlier in time and so the areal density should be lower as it has converged less.

For N161023 the fill tube perturbation (row 7) reduces the neutron burn width instead of elongating it. The rate of PdV work delivered by the shell is comparable to the symmetric case so there is not an asynchronous implosion occurring. The 1keV volume of the hot spot follows

FIG. 18. fNAD sky map for N130927 (top) and N161023 (bottom) with all perturbations included. The black cross denotes the fill tube position. The sky map is centred on $\phi = 90^\circ$.

a qualitatively similar trend to the symmetric case; however it is substantially smaller due to the cooling caused by the fill tube. This reduced hot spot volume due to mix leads to a smaller burn width. When the fill tube and radiation asymmetry are simulated together (row 8), the neutron signatures take on aspects from both implosions, having a burn width that is dominated by the fill tube and the spread of inferred ion temperature by the radiation asymmetries. The DSR decrease in this case is largely attributed to the weak areas of areal density that have been seeded by the radiation asymmetries, especially along the polar axis.

The DSR's calculated here are low when compared to experimental results, for example N130927 had a measured DSR of 3.5% compared to Chimera's 2.87%. This is thought to be due to the single scatter approximation that is used in our 3D neutron transport. When multiple scattering events are included in 1D calculations, the DSR value can increase by up to 20%.

One point to consider that has been neglected thus far has been the spatial and temporal response of the diagnostics. The NIS has a spatial resolution of approximately $10 \mu m$ ⁴³ and so large shape defects such as radiation asymmetries should be measurable. The fill tube and tent scar would prove more challenging due to their localised extent. The high temporal resolution of the nToF detector will allow the spectral features discussed to be resolved. For the fNAD, fits to the detectors are performed for Legendre modes to a P2 and this will there-

fore lose some of the higher mode content. The extended nature of the hot spot will also alias high mode content to lower modes, making the results hard to interpret. Despite this, for a large isolated feature such as the P4 present from N130927, the unfitted fNAD signal should be able to resolve this.

VI. CONCLUSION

When multiple mechanisms for yield degradation are included in a single simulation, it is challenging to interpret the changes in their inferred parameters. Each of the added perturbations distort the hot spot and further decreases the neutron yield. Once the hot spot is heavily distorted, additional perturbations have a negligible effect. This is due to the hot spot having already become heavily distorted, and additional perturbations have a reduced impact. The tent scar and radiation asymmetries extend the burn width of the neutron pulse, due to an asynchronous implosion delivering work to the hot spot at different times. This is in contrast to the fill tube, which reduces the burn width due to mix quenching one side of the hot spot (causing the PdV work to be delivered to a smaller volume). Which perturbation dominates the neutron signals is non-trivial to determine due to the placement of the current nToF diagnostics, but the NIS orientation can reproduce the shell shape which helps to infer the perturbations present.

One significant source of disagreement between simulations and experiments is in the fNAD diagnostics, shown in figure 18. With all the different perturbation sources considered, the variation seen by the fNAD's are at the 1-2% level, this is much lower than experimentally observed values of $\pm 5\%$ ¹⁷. This discrepancy in magnitude seems to indicate missing perturbation sources that further distort the shape of the capsule at stagnation. The form that these perturbations can take are restricted by the signatures discussed in this paper. Creating a large deficit in the fNAD is possible with the fill tube, as asymmetric cooling of the hot spot allows the dense fuel shell to compress more. This reduced the burn width of our simulations, and it has been reported that simulations consistently under predict the nuclear burn width of the experiments²¹. Increasing the burn width of the simulations may therefore require further shape defects. Finding a combination of these perturbation scenarios that can explain both the fNAD signal and the nuclear burn width is a current ongoing research area.

The work throughout has used artificial symmetries by forcing the perturbations (except the fill tube) to have no dependence on the azimuth. The fill tube itself was restricted to a symmetric Gaussian divot and ignored effects such as shadow casting by the early time drive. The HDC campaign ongoing at NIF has consistently found signals in the fNAD that suggest there are more symmetry breaking perturbations happening in the implosion. A natural extension of this work would be

to introduce deviations from symmetry in the azimuth, possibly by considering a spherical harmonic modulation of the radiation field that would include an azimuthal dependence. Since these long wavelength asymmetries appear to lengthen the burn pulse, this could help to understand the discrepancy of experiments consistently reporting longer burn widths than their simulated counterparts.

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N130927 Implosion Map

N161023 Implosion Map

Yield Convergence for N161023

N130927

N161023

Inferred Temperature (keV)

3.36

3.42

3.48

3.53

3.59

Inferred Temperature (keV)

3.728

3.730

3.733

3.735

3.737

Density (gcm^{-3})

450 μm

Inferred Temperature (keV)

3.52 3.54 3.57 3.59 3.62

Fluence Compensated Neutron Image

Fill tube antipodal imaging

Inferred Temperature (keV)

3.63 3.67 3.70 3.73 3.76

Inferred Temperature (keV)

3.69 3.71 3.73 3.75 3.77

$$Y_{fNAD} / \langle Y_{fNAD} \rangle$$

0.977 0.988 1.000 1.012 1.023

$$Y_{fNAD} / \langle Y_{fNAD} \rangle$$

0.987 0.994 1.000 1.006 1.013