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Design of a High-Foot/High-Adiabat ICF Capsule for the National Ignition Facility

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The National Ignition Campaign’s [M. J. Edwards, P. K. Patel, et al., *Phys. Plasmas*, **20**, 070501 (2013)] point design implosion has achieved DT neutron yields of 7.5×10^{14} neutrons, inferred stagnation pressures of 103 Gbars, and inferred areal densities (ρR) of 0.90 g/cm^2 (Shot N111215), values that are lower than expectations by factors of $10\times$, $3.3\times$, and $1.5\times$ respectively. In this paper, we present the design basis for an inertial confinement fusion capsule using an alternate indirect-drive pulse shape that is less sensitive to issues that may be responsible for this lower than expected performance. This new implosion features a higher radiation temperature in the “foot” of the pulse, 3-shock pulse-shape resulting in an implosion that has less sensitivity to the predicted ionization state of carbon, modestly lower convergence ratio, and significantly lower ablation Rayleigh-Taylor instability growth than that of the NIC point design capsule. The trade-off with this new design is a higher fuel adiabat that limits both fuel compression and theoretical capsule yield. The purpose of designing this capsule is to recover a more ideal one-dimensional implosion that is in closer agreement to simulation predictions. Early experimental results support our assertions since as of this writing a high-foot implosion has obtained a record DT yield of 2.4×10^{15} neutrons (within $\sim 70\%$ of 1D simulation) with fuel $\rho r = 0.84 \text{ g/cm}^2$ and an estimated $\sim 1/3$ of the yield coming from alpha-particle self-heating.

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The National Ignition Campaign’s (NIC) [1] point design has focused upon keeping the DT fuel adiabat as low as possible, with a four-shock, indirect-drive implosion, to obtain the maximum amount of convergence thereby reducing the energy required for ignition [2, 3]. Achieving this state requires very precise control over hohlraum issues such as drive-related asymmetries and the desired time dependent ablation pressure as well as capsule issues such as managing hydrodynamic instability and mix, delivering the required hot-spot formation (set by thermal conductivity of implosion kinetic energy) and attaining sufficient hot-spot stagnation pressure (strongly affected by implosion speed) [4, 5].

Presently, two-dimensional integrated design simulations (capsule + hohlraum) can only approximately predict the capsule ablation pressure history which can reach a peak of ~ 100 Mbars over a period of ~ 10 - 20 ns. NIF experiments [1, 6] indicate that the ablation pressure of the NIC implosion is currently over-predicted by $\sim 1.5\times$ during the 2nd pulse, the 4th rise acts as if delayed and reduced, and the peak radiation drive is over-predicted by $\sim 15\%$ in flux. This flux deficit in the peak of the drive may be the result of inconsistencies between simulated and actual inner-laser-beam hohlraum penetration

and laser entrance hole closure. [3, 7].

High-mode mix and inadequate hot spot formation likely contribute to less-than-ideal performance of the NIC point design implosion. Implosion velocities > 370 km/s are necessary to create the fuel densification ($\rho R > 1 \text{ g/cm}^2$) and stagnation pressure (> 400 Gbars) required for high yield but can lead to hydrodynamic instabilities [8–10]. In the few NIC shots where the implosion speed was pushed up above ~ 300 km/s, and which had less than 8% ablator mass remaining, hot spot ion temperature and yield both dropped significantly and x-ray brightness increased, consistent with ablator material mixing into the center of the implosion [11, 12].

Simulations in 2D have not been able to assess correctly the observed mix [2, 11] perhaps by overestimating the smoothing effects of ablation-front stabilization or by insufficiently representing the structure on and in the ablator and ice (coming from manufacture or from physics such as species separation effects [13]). Simulations may also underestimate the mass ablated at a given velocity, leading to perhaps more instability feed-through from the ablation front [9]. Of course the 2D simulations do not include 3D effects such as isolated defects in the ablator and/or ice and fill-tube perturbations.

Evidence from nuclear spectra from multiple lines of sight in NIC implosions suggests significant ρR asymmetry in the assembled cold fuel (with the ρR at the pole of the capsule measured to be $\sim 2\times$ that of the waist) [5].

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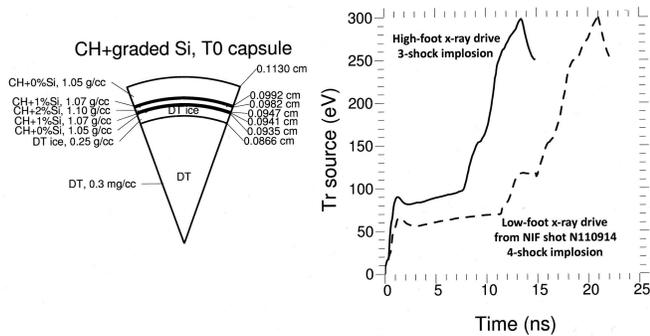


FIG. 1: The “T0” capsule (left) used in the high-foot implosions described here is identical to that used in the majority of the NIC implosions. The radiation temperature (right) driving the high-foot capsule (solid curve), however, is significantly different from that used by the low-foot NIC campaign (dashed curve).

This can reduce the efficiency with which implosion kinetic energy is converted to stagnation pressure resulting in lower stagnation pressures, densities, and yields. For the inferred in-flight fuel adiabat of the NIC implosion, $\alpha \sim 1.5 \pm 0.1$, the inferred hot spot density is $\sim 2 - 3\times$ too low, and the fuel ρR is low by $\sim 15\%$. A number of factors could contribute to this including mix, low mode asymmetry (hot-spot volume) and associated vortex flows, kinetic effects as well as a significant 5th shock.

Stiffer fuel (higher adiabat) [14] implosions would converge less (one can easily show that Convergence Ratio, $(CR) \sim p_{abl}^{1/15} v_{imp}^{3/5} / \alpha^{2/5}$) and likely suffer less from mix since lower CR rapidly decreases an implosion’s sensitivity to drive non-uniformities and decreases the ultimate growth of instabilities. Experiments at LLE with directly driven cryogenic implosions [15, 16] support the assertion that high adiabat implosions perform closer to 1D model expectations. This assertion may be weakened, however, if increased fuel adiabat is achieved by shock mistiming. Of course, since the energy required for ignition scales as CR^{-6} [17], one cannot completely relax the need to obtain high CR ’s with facility scale energies of MJ’s or less.

This paper gives a description of a three-shock implosion called the “high-foot” – referring to the temperature of the radiation drive in the early part of the drive pulse. The capsule geometry used in this study (see Fig. 1) is identical to the T0 capsule used in the NIC, with a $195\mu m$ thick ablator [8]. By design, this high-foot implosion is well tuned in that the high-adiabat is largely set by the strength of the 1st shock, with the 2nd and 3rd shocks adding a relatively small amount of entropy to the fuel. The pulse shape difference between the high-foot design and a comparison pulse-shape taken from a representative implosion fielded by the NIC (shot N110914) is shown in Fig. 1. Characteristic differences are noted in that the high-foot pulse has a higher T_r (90 eV vs. 60 eV) and shorter duration (6 ns vs. 10 ns) foot and less

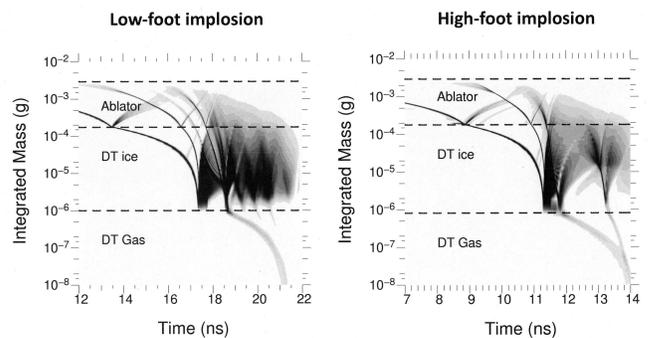


FIG. 2: The low-foot implosion shock structure (left) has four drive generated shocks and numerous shock reflection and rarefaction features that are not present in the three shock high-foot implosion design (right).

structure in the main rise to 300 eV radiation temperature, resulting in two additional shocks launched into the ablator rather than three. Figure 2 shows simulated shock plots for a low-foot implosion (left) and a high-foot implosion (right). The gray-scale shown is proportional to the log derivative of the pressure. Horizontal dashed lines mark interfaces between DT gas, DT ice and CH ablator. The low-foot implosion exhibits at least four drive-generated shocks, while the high-foot implosion exhibits three drive-generated shocks.

While the higher foot temperature shown in Fig. 1 does in fact raise the fuel adiabat, α , the initial motivation for the raised foot temperature was to escape an observed opacity modeling sensitivity in the ablation pressure profile (see Fig. 3). Modeling the low-foot ablation process with a Detailed Configuration Accounting (DCA) opacity model [18] shows disturbing structure in the pressure profile as the second shock propagates through the ablator. This pressure profile structure coincides with the presence of a large amount of carbon in a lithium-like state (ionization energy of 63 eV). Figure 3 illustrates, in normalized units, the profiles of the Charge State Distributions (CSD) of carbon, i.e., the fractions of carbon that exist in H-like (black solid), He-like (black dashed), and Li-like (black dotted) states. The normalized radiation temperature (red curve), electron temperature (green curve) and pressure (blue curve) all show effects of the abundance of Li-like carbon. For the high-foot implosion the double peak feature in the ablation pressure profile is reduced significantly as the second shock propagates through the ablator, recovering a more ideal profile shape. Other opacity models, such as Super Transition Arrays (STA) [18] do not exhibit such ablation pressure structure. It is anticipated that this structure, if correct, would significantly effect shock timing during capsule implosion. More importantly, this unexpected ablation pressure profile structure could frustrate attempts to “re-tune” [1] the implosion.

Various ideal 1D model performance metrics for two different α versions of the high-foot design and the char-

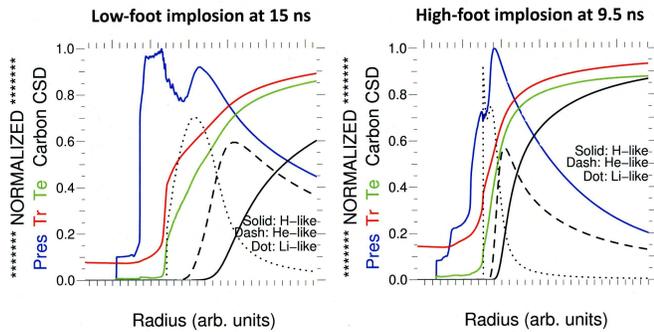


FIG. 3: For the low-foot implosion (left), DCA modeling of the ablation process shows a distinct double-peak feature in the simulated ablation pressure profile (blue curve) correlated with the location of the carbon Li-like ionization state (black dotted curve). For the high-foot implosion (right) the double peak feature in the ablation pressure profile is reduced significantly recovering a more ideal profile shape. In each case, the snapshot is taken just before the third drive-generated shock is launched.

TABLE I: Simulated ideal 1D performance for a low-foot implosion (N110914) and two higher-adiabat, high-foot implosions

	60 eV-foot	80 eV-foot	100 eV-foot
Y(MJ)	16.4	3.2	0.45
Neutrons	5.8×10^{18}	1.1×10^{18}	1.6×10^{17}
E_{abs} (kJ)	160	167	168
CR^* at ignition	36	27	24
CR^* at bangtime**	47	36	40
Fuel v_{imp} (km/s)	340	380	390
P_{stag} (GB)	408	285	294
ρR fuel (g/cm^2)	1.6	1.1	1.1
ΔS_{fuel} (MJ/g/keV)	454	536	564
α	1.45	2.28	2.8
Normalized v_{imp}^8/α^4	1 ⁺	0.4	0.16

* $R_{abl}(t=0)/R_{hotspot}$, ** α deposition off, ⁺Unity by definition

acteristic NIC design are shown in Table I. Ideal 1D performance declines with the high-foot designs, which have lower potential yield (Y), stagnation pressure (P_{stag}), and ρR . The high-foot designs have higher implosion speed for roughly the same amount of absorbed energy (E_{abs}) than the low-foot N110914 (the physics of which is easily understood by recognizing that the high-foot designs ablate more plastic early in time resulting in less ablator mass when the main part of the drive starts). Even with the increased implosion speed, it appears that 1D margin has been lost in the high-foot designs as measured by the scaling of v_{imp}^8/α^4 (a key component of the ignition threshold metric, “ITF”) [8] while only a modest reduction in CR has been gained. It is not until the 2D stability consequences are examined that the potential benefits and robustness of the high-foot implosion

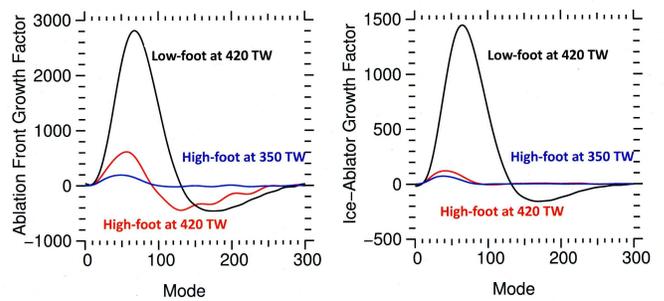


FIG. 4: The figure compares calculated growth factors (GF’s) at the ablation front (left) and ice-ablator interface (right) for the low-foot implosion and high-foot implosion. These GF’s are sampled at the time of peak implosion velocity. The primary comparison is between the black curve (low-foot at a nominal drive and capsule thickness) and red curve (high-foot at nominal drive and capsule thickness) for a 380 km/s implosion and 290 km/s implosion respectively. The blue curve shows results for a high-foot, low-power implosion as in NIF shot N130501.

become apparent.

Linear stability analysis of the high-foot implosion has been performed and the growth-factor results (GF , a ratio of initial to final amplitude per mode) are shown in Fig. 4 for the ablation front and fuel-ablator interface. These GF’s are sampled at the time of peak implosion velocity. The key comparisons in Fig. 4 are between the red curves (T0 capsule with high-foot pulse-shape) and the black curves (T0 capsule with the NIC low-foot nominal power pulse-shape). The blue curves represent the GF for the first high-foot DT layered implosion on NIF, shot number N130501 (May 1, 2013).

For the nominal cases of the high-foot pulse versus the low-foot pulse, it is clear that at the ablation front (Fig. 4, left frame) between modes 2-150, the high-foot pulse shows uniformly lower linear instability growth by a factor of about 5. The fuel-ablator interface (Fig. 4, right frame) shows a factor of ~ 10 less growth for the high-foot over the same range of modes from 2-150. The reduced instability growth is rationalized by three primary factors: more ablative stabilization due to the higher foot temperature at early times, less Richtmyer-Meshkov instability growth stemming from 3 rather than 4 shocks, and a large ablator density gradient scale-length (a fluffing out of the ablator) that is sympathetic with the higher adiabat achieved with the higher foot (Fig. 5). Stability gains in the high-foot implosions come at the cost of density compression, for example, at ignition time, the $\alpha = 2.7$ peak density is 50% that of the $\alpha = 1.5$ peak density.

Nonlinear radiation-hydrodynamics simulations up to mode 100 (calculated with the ASC code ARES) confirm the expectation of reduced instability growth (Figs. 6 and 7). These simulations were performed with a multi-mode specification of the NIC Rev. 5 surface roughness spectrum [8]. Figure 6 shows the results for the $\alpha = 1.5$

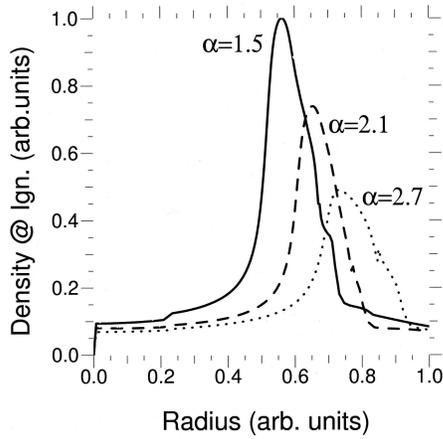


FIG. 5: Density profiles at ignition time (defined as time when central fuel reaches 12 keV) for various adiabat capsules illustrate reduction in peak ablator density and increase in ablator width as adiabat increases. Values are normalized to peak value of the $\alpha = 1.5$ curve.

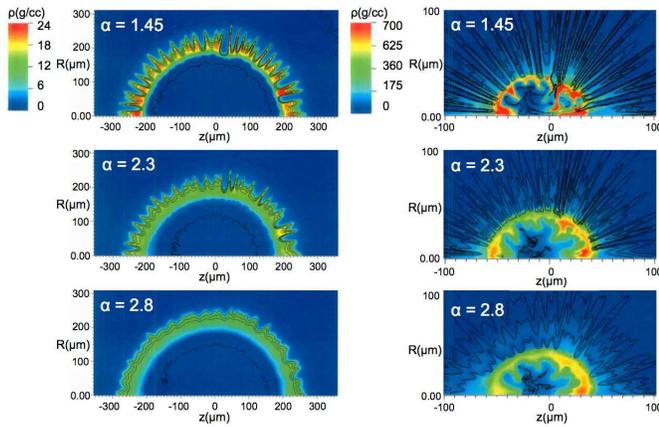


FIG. 6: 2D multimode (up to mode 100) simulations with a spectrum of imposed surface roughness ($4\times$ nominal) show, in density, the expected instability growth on the capsule. From top to bottom implosions with $\alpha = 1.45$ (low-foot), $\alpha = 2.3$ (high-foot), and $\alpha = 2.8$ (high-foot) are shown at $R \sim 200 \mu\text{m}$ (left column) and $R \sim 50 \mu\text{m}$ (right column).

N110914 capsule (top two images), the $\alpha = 2.3$ high-foot (middle row), and the $\alpha = 2.8$ high-foot (bottom row). For clarity, the density color scales in Fig. 6 are fixed for each of the two columns. As α increases, improved stability properties are evident in the reduction in amplitude of correlated RT spikes and bubbles and reduction in high mode number structures at the ablation front and fuel-ablator interface. Figure 7 shows the effect on capsule yield as the initial NIC Rev. 5 surface roughness is arbitrarily increased to a factor of $4\times$ nominal. These hydrodynamic advantages of the high-foot design may be realized if one assumes that the high-foot pulse shape does not substantially degrade the hohlraum or laser-plasma instability (LPI) physics that control the

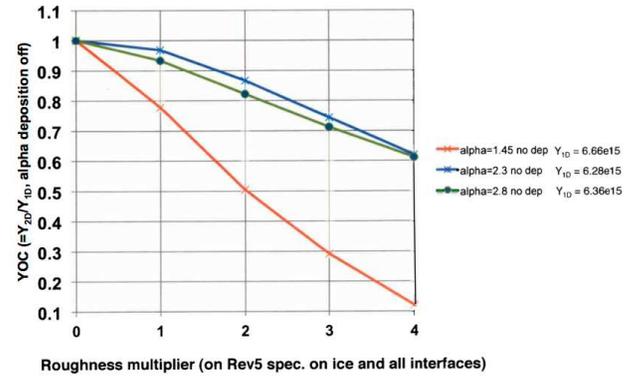


FIG. 7: Ratio's of 2D multimode (up to mode 100) model yields over 1D model yields are plotted vs. a multiplier of the capsule surface roughness for implosions with $\alpha = 1.45$ (low-foot, red), $\alpha = 2.3$ (high-foot, blue), and $\alpha = 2.8$ (high-foot, green) are shown. Even for a roughness multiplier of 4, which drops the simulated 2D yield to $0.1\times$ the 1D yield for the low-foot case, the high-foot implosions only drop to $0.6\times$ the 1D yield consistent with more resistance to ablation front RT instability.

TABLE II: Performance of three high-foot NIF implosions

	N130501	N130710	N130812
Laser Power (TW)	351	430	355
Laser Energy (MJ)	1.27	1.50	1.69
Yield (13-15 MeV neutrons)	0.77E15	1.0E15	2.4E15
Bangtime (ns)	16.7	16.4	16.7
T_{ion} (keV)	3.0	3.5	4.2
ρR fuel (g/cm^2)	0.6	0.7	0.9
Neutron Burn Width (ns)	0.172	0.180	0.156

drive on the implosion.

Table II summarizes results from several recent high-foot shots on NIF. The first cryogenic DT high-foot shot, N130501, generated a measured yield within 60% of 1D simulation. Shot N130710 used significantly higher laser power with a yield 46% of 1D simulation but had large asymmetries in the observed neutron images. High-foot shot N130812 (Aug. 12th, 2013) returned to low laser power but had high laser energy and generated a yield within 70% of 1D simulation. For N130812, 10.3 kJ of energy (kinetic + internal both at peak velocity + pdV work on fuel between the time of peak velocity and peak burn) was delivered to the DT fuel, with 8 kJ of fusion energy produced. About 3 kJ of this fusion energy is estimated to originate in alpha-particle self-heating. This estimate is based on 1D implosion simulations with alpha-heating enabled compared with simulations with alpha-heating disabled. Details of these high-foot DT experiments are presented in a companion paper by Park, *et al.* [20].

It is likely that the high-foot inertial confinement fusion capsule described here is not an end unto itself. This capsule implosion was designed to be insensitive to 2D

and 3D hydrodynamic defects and demonstrate performance close to 1D expectations; this prediction has been verified by recent experiments. However, according to simulations, the ultimate performance of this simplified implosion is limited. The superior results obtained from these high-foot experiments allow several aspects of the integrated ignition platform to be examined and understood. Future variations in capsule design (such as thinning the ablator) and hohlraum parameters (such as increasing the peak laser power) from that presented here may be able to increase implosion velocity and lead to further improvements. Making these variations in small incremental steps from the demonstrated performance

points of the high-foot capsule described here will help identify and perhaps improve the limits of predictive capabilities of models used in the design process.

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