

Progress in modelling ignition implosion experiments on the National Ignition Facility

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Abstract. The recently completed National Ignition Campaign on the National Ignition Facility showed significant discrepancies between 2-D simulations predictions of implosion performance and experimentally measured performance, particularly in thermonuclear yield. This discrepancy between simulation and observation persisted despite concerted efforts to include all of the known sources of implosion degradation within a reasonable 2-D simulation model, *e.g.*, using measured surface imperfections and radiation drives adjusted to reproduce observed implosion trajectories. Since this simulation study was undertaken, more recent experiments have brought to light several effects that can significantly impact implosion performance, in particular large inflight long-wavelength shell asymmetries and larger than expected perturbations seeded by the capsule support tent. These effects are now being included in the simulation model and show improved agreement with observation. In addition, full-capsule 3-D simulations with resolution adequate to model the dominant unstable hydrodynamic modes are being run and show further improvements in agreement with experiment.

1. Introduction

The National Ignition Campaign (NIC) [1, 2] on the National Ignition Facility (NIF) [3] was completed in September 2012. While substantial progress was made in experiments on NIF, the NIC ultimately fell short of its goal of demonstrating fusion ignition by indirect drive inertial confinement fusion [4, 5]. Implosions driven by record-breaking laser powers and energies on NIF and tuned with unprecedented precision and control achieved implosion velocities of 350 km/s, deuterium-tritium (DT) fuel densities of greater than 800 g/cm³, and hot spot pressures greater than 100 billion atmospheres. Nevertheless, DT fusion yields did not exceed $\sim 9 \times 10^{14}$ neutrons, well below the $\sim 5 \times 10^{16}$ threshold of unambiguous fusion ignition. Additionally, concentrated simulation efforts, analogous to those used in designing ignition experiments for NIF, consistently over-predicted the yields from NIC experiments [6]. This discrepancy persisted despite concerted efforts to include all of the known sources of implosion degradation present during NIF implosions in sophisticated 2-D as well as 3-D simulations [7]. Despite reproducing the observed implosion characteristics reasonably

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well (velocity, bang time, shell remaining mass) and approximately matching the measured burn-averaged ion temperatures, fuel areal densities, and hot spot x-ray image sizes, neutron yields averaged an order of magnitude higher in simulations than observed in experiment.

Since these simulation studies were completed, experiments have continued on NIF and have identified several important effects—absent in the previous simulations—that can likely resolve at least some of the large discrepancies between simulated and experimental yields. Foremost among these results were the 2-D ConA experiments that used germanium backlighting to image the shape of imploding shells in flight on NIF [8]. Time gated images from these 2-D ConA experiments revealed significantly larger low-mode asymmetries in NIF implosions at a converged radius of $\sim 200\ \mu\text{m}$. In particular, larger Legendre mode four (“P₄”) asymmetries were observed than had been expected or were included in previous simulations. The presence of these low-mode asymmetries in flight was also corroborated by the observation of large low-mode asymmetries in neutron down scattering signals from the burning hot spot. While these two indications of low-mode asymmetries are not easily connected, together they do strongly suggest the presence of larger asymmetries in the range of P₂ – P₄ than previously modeled.

Another important observation from the 2-D ConA experiments was the much larger role of the capsule support tent in seeding perturbation growth at the shell ablation front than had been expected. 2-D ConA images from experiments using various tent thicknesses (110 nm, 45 nm, and 15 nm) showed a clear “scar” across the face of the image that scaled weakly with tent thickness and vanished when the capsule was supported by a stalk instead of a tent. According to previous simulation-based estimates, the tent should have produced an essentially invisible perturbation in the ConA images. Such a large, coherent perturbation, again unanticipated and absent from previous simulations, can certainly be expected to impact implosion performance.

An additional effect omitted in previous systematic simulations of NIF implosion performance is the presence of deeply penetrating mix contaminating the DT hot spot with higher Z ablator material. While the effects of this “deep mix” have long been appreciated based on simulations [9, 10] and significant efforts have been made to measure it experimentally [11], sufficiently detailed shot-by-shot data on deep mix was only just becoming available at the time previous simulation studies were being run. Some scoping studies [7] and attempts to connect the inferred mix from NIF experiments to target quality were made [12], but only recently has a systematic analysis based on Ross pair x-ray images of NIF implosions produced a fairly comprehensive database on deep mix in NIF implosions [13]. These mix estimates, based on a model of the ratio of x-ray to neutron yield from the hot spot, still have considerable uncertainty and the origins of the large amounts of mix inferred on many NIF shots remains unexplained, but the presence of this mix is a clearly non-negligible effect in NIF implosions that must be included in any plausible simulation model.

This paper summarizes the results of a revised post-shot simulation of NIF shot N120321 incorporating the effects enumerated above. This shot was one of the best performing shots fired during the NIC featuring the highest combination of compression and yield, and as such has been the subject of much modeling work. While agreement between simulation and experiment is substantially improved by the inclusion of the effects listed above, some discrepancies remain indicating that some improvements in simulation technique are still required.

2. Revised 2-D post-shot simulations

With the identification of the effects described above, a sequence of 2-D simulation was undertaken to add these effect incrementally and assess their contributions to the degradation of implosion performance. Table 1 summarizes these results in the form of several simulated observables to compare with experiment. The last column in the table gives the experimental values for shot N120321. The first entry in the table lists the simulated observables of a 1-D simulation for which the x-ray drive on the capsule has been adjusted to match the measured shock timing and implosion trajectory from companion VISAR and 1-D ConA shots. The details of this technique have been described elsewhere [7]. The subsequent columns show the results of progressively adding the

Legendre P_2 and P_4 drive asymmetries tuned to match the inflight asymmetries from 2-D ConA experiments, adding a surrogate perturbation adjusted to model the observed effect of the tent in 2-D ConA radiographs, adding a similar surrogate perturbation to model the effect of the fill tube attached to the capsule, adding the effect of surface roughness, adding 200 ng of ablator material into the hot spot to model the effect of deep mix, and finally a Legendre P_1 ice layer asymmetry of $1.6 \mu\text{m}$ particular to this shot. All of the 2-D simulations used zoning sufficient to resolve Legendre mode numbers up to 100 and for the cases including roughness used the as measured ablator surface and ice surface roughness for this shot. Based on Ross pair imaging, the inferred mix mass for this shot is $409 \pm 143 \text{ ng}$ [14], while estimates based on linear regime growth factors suggest 200 – 500 ng could have been injected. Given the uncertainties in all of these estimates and the crudeness of the simulation models treatment of this effect, 200 ng was deemed a reasonable estimate.

Table 1. Summary of simulated observables for shot N120321 including a hierarchy of perturbation effects. Effects add sequentially from left to right from 1-D to 2-D to 3-D simulations. The right most column lists the experimentally measured values.

	1-D	P_2 & P_4	tent	fill tube	rough- ness	200 ng mix	ice P_1	3-D	expt.
bang time (ns)	22.93	22.89	22.88	22.86	22.86	22.85	22.86	22.83	22.83
burn width (ns)	121	119	119	118	112	118	106	116	158
x-ray P_0 (μm)	25.8	24.3	22.9	22.7	21.9	19.1	18.8	18.8	17.6
x-ray P_2 (μm)	—	0.34	0.03	0.00	- 0.05	- 0.01	- 0.02	0.07	0.06
DSR (%)	6.08	6.27	6.33	6.31	6.31	7.70	7.74	7.01	6.26
T_{ion} (keV)	4.49	3.88	3.73	3.09	3.20	2.16	2.19	2.48	3.07
neutrons (10^{14})	313	88.6	55.0	28.0	29.4	9.2	9.5	7.7	4.2

In progressing from a 1-D simulation to the 2-D simulation including all of the above effects, a substantial drop in yield is apparent with the presence of the tent perturbation, the fill tube perturbation, and the mix mass being leading contributors. When all of the effects are included, the simulated yield has dropped from two orders of magnitude greater than experiment to within a factor of two. The inclusion of these effects also influences several of the other observables as listed in the table. Namely, the burn-averaged ion temperature drops with increasing perturbation to a value close to experiment, but then drops below the experimental value with the addition of deep mix. Simultaneously, the neutron down-scattered ratio (DSR), a measure of compression or ρR , approximately matches the data in 2-D without mix, but is greater than the experimental value with mix. Both of these effects are suggestive that higher than simulated levels of instability growth that could break up the imploding shell and decrease the DSR while increasing the ion temperature via Doppler broadening could be present.

3. Progress in 3-D simulations

Also included in Table 1 are the results of a 3-D full sphere simulation of N120321. This simulation is analogous to the 2-D simulations in resolution and the various perturbation sources included. Since this simulation is fully 3-D, no approximations need be made in initializing capsule surface perturbations and the actual measured surface features from pre-shot imaging of the ablator are used. Most importantly, 3-D simulations relax the artificial symmetry constraints present in 2-D axisymmetric simulations and allow essentially arbitrary flows through the center of the capsule implosion. As such, these simulations give the most complete and faithful representation of the conditions present in the experiment.

As shown in the table, simulating in 3-D further degrades the yield toward the experimental value. The 3-D simulation also improves agreement with the measured ion temperature illustrating the importance of Doppler broadening due to flows within the 3-D hot spot. The agreement with the

experimental DSR value is somewhat improved as well. These continued discrepancies, however, again suggest that greater instability growth is occurring in experiment than is currently simulated leading to greater breakup of the imploded shell than currently modeled.

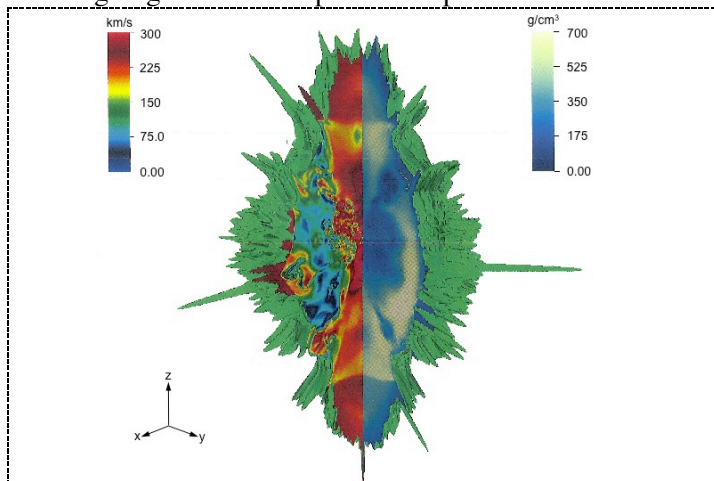


Figure 5. Rendering of the fuel ablator interface at bang time (22.83 ns) from a 3-D simulation of NIF shot N120321. The color scales show fluid flow velocity (left) and density (right) on corresponding slices.

As an illustration of the 3-D character of these implosions, Fig. 1 shows a rendering of the fuel ablator interface and hot spot conditions from this simulation.

4. Conclusions

While reasonable agreement can be shown between simulations and experimental results for the shot considered here, several caveats deserve to be borne in mind. Foremost, this analysis has considered only one of the three dozen ignition experiments conducted during the NIC. Performing a similar analysis for a significant fraction of these experiments would be necessary to validate or refute the conclusions reached for N120321. More importantly,

a number of shots during the NIC showed unexplainably large amounts of ablator mix into the hot spot. Similarly, the unexpectedly large perturbation seeded by the support tent cannot be explained based on current simulations. This effect, along with the unexplained mix mass for some shots, and the lingering discrepancies in the simulations discussed here are all suggestive of hydrodynamic instability growth rates, or the sources that initiate that growth, being larger than currently modeled. This hypothesis motivates direct measurement of these growth rates as is now being done via the Hydro. Growth Radiography (HGR) experiments on NIF [15] and further simulation and theoretical work to understand these discrepancies.

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