Simulations of fill tube effects on the implosion of high-foot NIF ignition capsules

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Abstract. Encouraging results have been obtained using a strong first shock during the implosion of carbon-based ablator ignition capsules. These "high-foot" implosion results show that capsule performance deviates from 1D expectations as laser power and energy are increased. A possible cause of this deviation is the disruption of the hot spot by jets originating in the capsule fill tube. Nominally, a 10 μm outside diameter glass (SiO_2) fill tube is used in these implosions. Simulations indicate that a thin coating of Au on this glass tube may lessen the hotspot disruption. These results and other mitigation strategies will be presented.

1. Introduction

The high-foot series of ignition capsule experiments [1,2,3] on NIF has shown encouraging results and indicate the achievement of alpha-particle heating of the fusion fuel. A superior performer in this series, shot N140520 (May 20, 2014), imploded the capsule shown schematically in Fig. 1 by means of a 297 eV peak x-ray radiation drive pulse, also shown in Fig. 1. This x-ray pulse was achieved in a depleted uranium hohlraum driven by a 388 TW, 1.76 MJ laser pulse. The capsule had a 178 μm thick graded doped shell enclosing a 69 μm thick layer of solid DT. Silicon doping of the capsule [4,5] varied radially in five steps, (0.00, 0.01, 0.02, 0.01 and 0.00, atomic fraction) as shown in Fig. 1. The structure of the x-ray drive pulse causes a three-shock implosion of the capsule. Shot N140520 produced a neutron yield of 7.6×10^{15} neutrons (13-15 MeV) with a peak neutron emission at 15.96 ns, a burn-weighted ion temperature of 5.5 keV and a DSR (down-scatter-ratio, an indicator of peak fuel ρr) value of 0.041. All quoted times are referenced to 0.0 ns in the laser pulse. This neutron production value is significantly lower than the simulated performance value of 1.2×10^{18} neutrons (1D, ignites) or 7.8×10^{17} neutrons (2D, no fill tube, ignites). The non-linear process of ignition can be removed from these simulations by turning off alpha-particle deposition; this results in a 1D yield of 1.0×10^{16} neutrons and a 2D no-tube yield of 8.9×10^{15} neutrons.

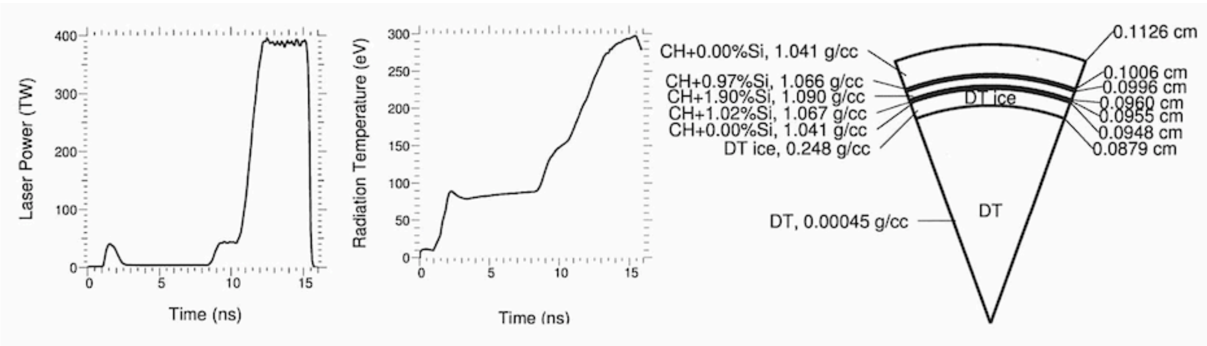

Figure 1. Laser pulse, x-ray drive pulse and schematic diagram and for NIF shot N140520 high-foot ignition capsule. All quoted times are referenced to 0.0 ns in the laser pulse.

This capsule had a fill tube attached in order to load the DT fuel prior to implosion. In this case, the tube was SiO_2 with an outside diameter of 10 μm and an inside diameter of 6 μm. The tube was inserted 44 μm radially into the CH shell. A tapered fill hole through the rest of the shell had a diameter of 3.6 μm at the inner shell surface next to the DT ice. Polar self-emission snapshot x-ray images from N140520 are shown in Fig. 2 before, at and after peak emission. The middle image occurs slightly before peak neutron production. Each image in Fig. 2 has its own emission-level to color-scale correspondence, with dark red corresponding to high emission and blue corresponding to low emission. In these images, the fill-tube orientation is at approximately 2:30 o'clock. The observed structure in the images appears to roughly align with the tube orientation.

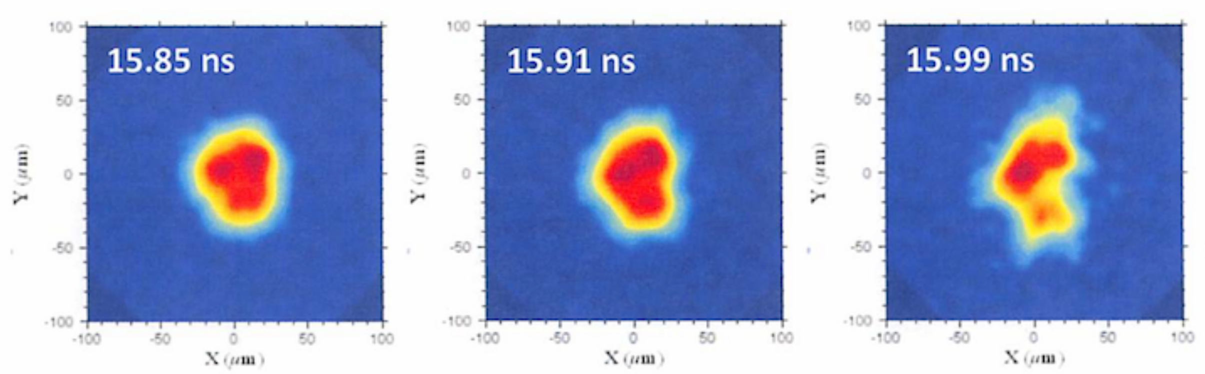

Figure 2. Polar self-emission x-ray images at three times for NIF shot N140520.

2. Simulation Technique

Implosion simulations of N140520 used a radiation-hydrodynamic computer code, LASNEX [6], to model the implosion of the capsule only, i. e., an x-ray source was applied to the outside of the ablator surface. An alternate approach would be to simulate the conversion of laser light to x-rays in the DU hohlraum that would then implode the capsule. In this two-dimensional, axially symmetric simulation a technique of "wedge expansion" was used that starts with an initial cone, or wedge angle of 5.625°; this was expanded to 11.25° at 3.4 ns, 22.5° at 8 ns, 45° at 13 ns, 90° at 14 ns and 180° at 14.7 ns. Since the number of angular zones in the simulation was held fixed the zonal angular resolution decreased at each wedge expansion. This technique allows high angular resolution at the start of the simulation when the fill tube and its perturbation are relatively small. Radial mesh management uses a technique called "donor line" remapping. The upper boundary of the simulation wedge is assumed (and verified) to be unperturbed by the tube evolution located on the symmetry axis; this upper boundary is called the "donor line". Wedge expansions are timed to maintain a one-dimensional (radial only)at the donor line. Radial node positions from this donor line are periodically broadcast over the entire simulation wedge using a uniform distribution of angular zones. This technique maintains concentric radial zoning. The wedge expansions are timed so that nodes on the donor line behave similarly to those in a 1-D implosion simulation. At late times, no-tube 2D simulations exhibit some non-symmetric behavior much reduced from that seen in 2D tube simulations. Efforts are continuing to achieve a more symmetric null simulation.

Results from simulating the implosion of N140520 are shown in Fig. 3, which depicts only "region-of-interest" density maps at eight times during the implosion, from initial configuration to bang time. Position coordinates and density-to-color-scale correspondence are not shown. The cylindrical axis of symmetry is at the bottom edge of each individual picture. The density map at 0.0 ns shows the initial configuration around the joint between the tube and capsule shell. The tube and capsule fill hole are contain solid DT; an epoxy glue fillet is shown at the tube-shell joint. Shell and tube ablation proceed at 1.8 ns. At 3.6 ns, a shaped-charge effect can be seen where the tube and shell meet; a non-radial shock is formed which reflects from the axis of symmetry, moving material azimuthally outward and creating a jet of material ahead of the main shock as seen clearly at 5.4 ns. By 15.6 ns this azimuthal movement of material has created a hole in the imploding shell. Further implosion causes this hole to collapse and create a large jet that penetrates the hotspot, as seen at 15.9 ns.

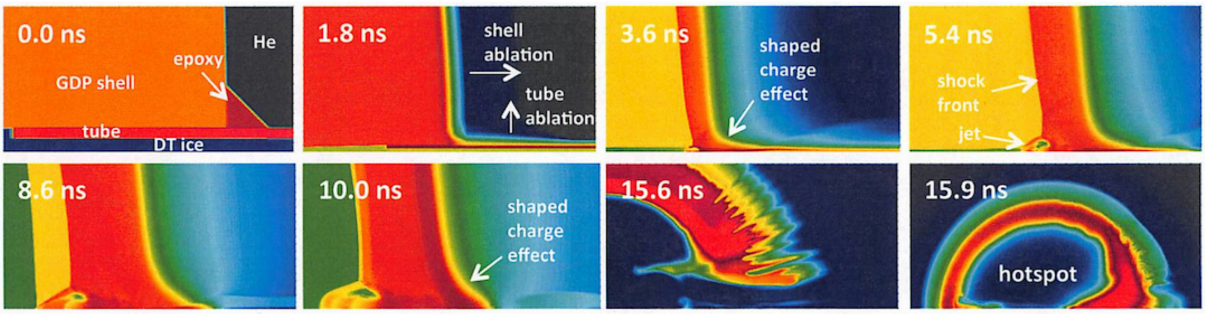

Figure 3. Density snapshots at eight times during the simulated implosion of N140520. No density-to-color-scale correspondence or position coordinates are shown. Dark red corresponds to high density; dark blue to low density.

3. Comparison of Data and Simulation

Figure 4 compares the observed polar x-ray emission of N140520 (Fig. 4a) with a simulation-generated image of the x-ray emission (Fig 4b) at the time of peak emission. The snapshot in Fig. 4a is at time 15.91 ns in the implosion and has the fill-tube orientation at 2:30 o'clock; the snapshot in Fig. 4b is at time 15.85 ns and has fill tube orientation at 3:00 o'clock. The two images are approximately the same size and show similar intensity fall-off from the image center to the outside of the emitting region. The non-symmetric structures seen in the two images are not inconsistent; each image has a flattening on the right-hand side and a dark region off the axis of the fill tube perhaps originating in the tube jet. Here dark red corresponds to areas of high x-ray emission and dark blue and gray correspond to areas of low emission.

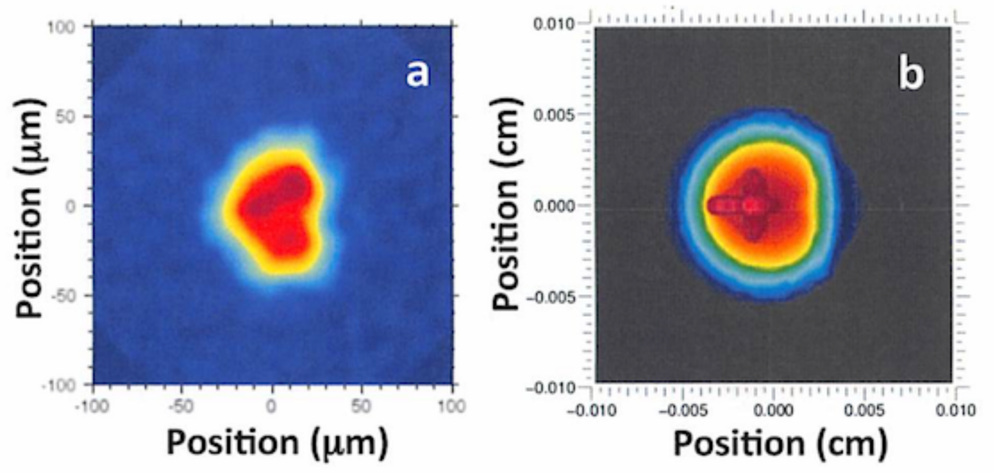

Figure 4. Observed (a) and simulated (b) x-ray images at peak emission for NIF shot N140520.

The simulation shown in Figs. 3 and 4 predicts a neutron output of $8.0x10^{16}$ (13-15 MeV). This is significantly lower than the no-tube igniting 2D simulation result of $7.8x10^{17}$ neutrons but more than the no-tube, alpha-deposition-off simulated result of $8.9x10^{15}$ neutrons. Removing alpha deposition from a simulated 2D implosion with the as-shot fill tube predicts a yield of $6.3x10^{15}$ neutrons.

4. Mitigation Strategies

Alternate fill-tube configurations may help mitigate the effects of the fill tube on capsule performance. Smaller diameter tubes may produce a smaller perturbation but would present additional fabrication and fielding difficulties. Larger diameter tubes would likely increase the size of the perturbation. Implosion simulations of a capsule with a gold-coated glass tube as well as simulations configured with the tube truncated at the capsule surface have predicted 30% and 100% improvement in neutron yield, respectively, compared with the nominal SiO_2 tube implosion.

5. Summary

Fill-tube hydrodynamic effects in high-foot ignition implosion N140520 may be responsible for degraded performance as compared with unperturbed implosion simulations. Both wedge-expansion and donor-line mesh-management techniques offer advantages for the simulation of this implosion.

The neutron output observed in high-foot shot N140520 is about 10% of the predicted output from a simulation of the as-built tube and capsule configuration. A polar x-ray image of this high-foot implosion shows hot-spot perturbations consistent with simulated hydro effects originating in the DT fill tube and fill hole.

Acknowledgments

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