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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 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 7.6E15 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. This neutron production value is significantly lower than the simulated performance value of 1.2E18 neutrons (1D, ignites) or 7.8E17 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 1.0E16 neutrons and a 2D no-tube yield of 8.9E15 neutrons.

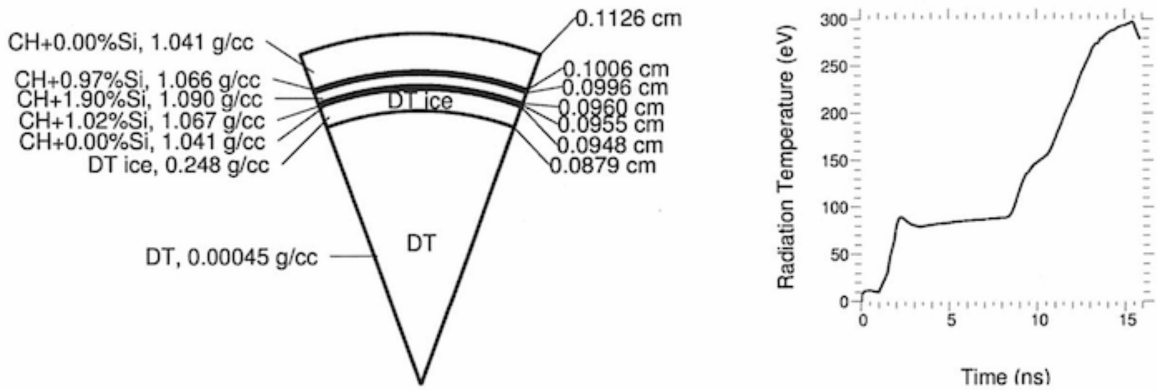

Figure 1. Schematic diagram and x-ray drive pulse for NIF shot N140520 high-foot ignition capsule.

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.

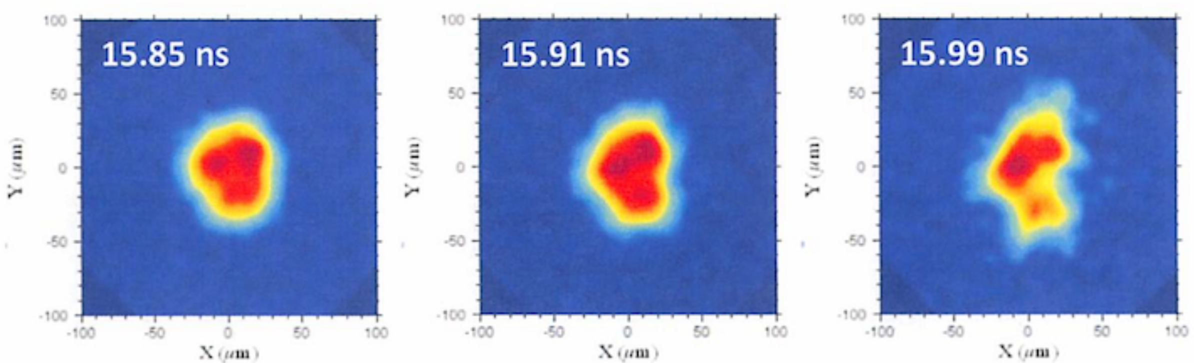

Figure 2. Polar self-emission x-ray images at three times for NIF shot N140520.

2. Simulation Technique

Implosion simulations of N140520 used a radiation-hydrodynamic computer code 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. A technique of "wedge expansion" was used for this simulation. Using two-dimensional symmetry, the initial simulation wedge angle was 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. The zonal angular resolution decreased at each wedge expansion since the number of angular zones was held fixed. 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 wedge boundary of the simulation is the donor line and is assumed to be unperturbed by the tube evolution on axis. Radial node positions from this donor line are periodically broadcast over the entire simulation wedge, with 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 filled with 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-concentric 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. These effects continue as the capsule converges, resulting in shell material being moved away from the simulation axis, thus creating a large hole in the shell, as seen at 15.6 ns. Shell convergence effects fill in this hole with imploding material, creating a large jet that penetrates the hotspot, as seen at 15.9 ns.

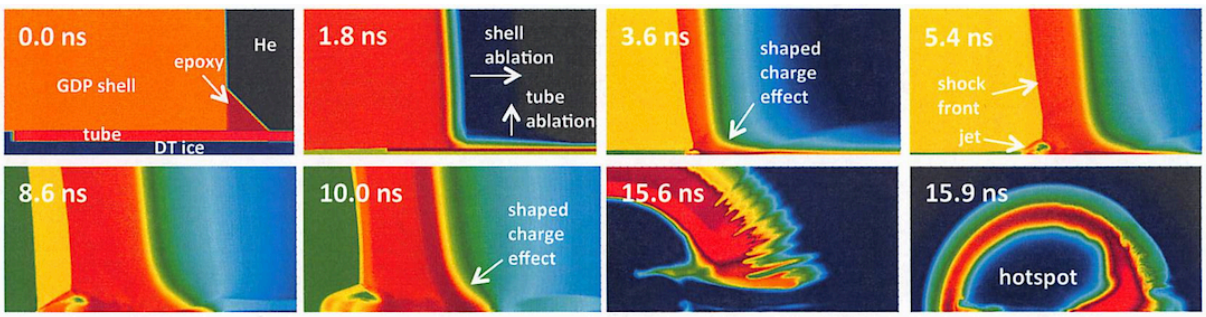

Figure 3. Density snapshots at eight times during the simulated implosion of N140520. No density-to-color-scale correspondence or position coordinates are shown. Dark red corresponds to high density, dark blue to low density.

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.

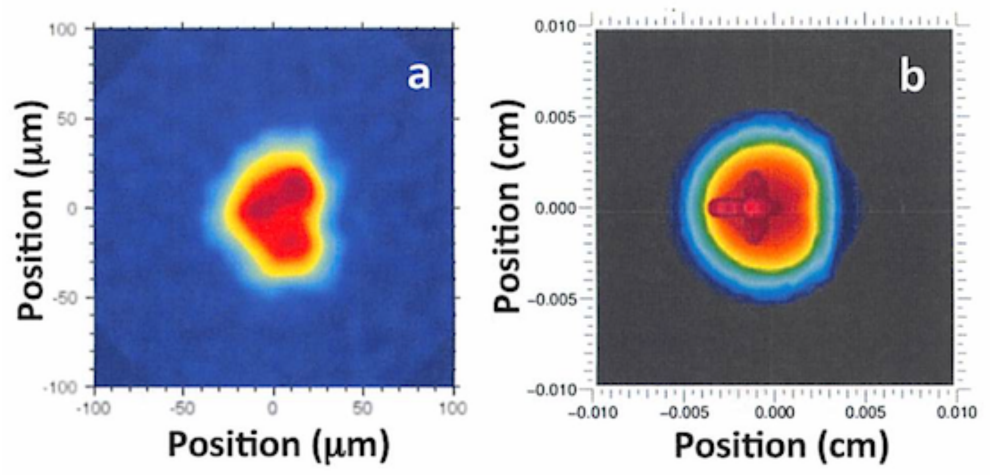

Figure 4. Observed (a) and simulated (b) x-ray emission from the implosion of NIF shot N140520.

The simulation shown in Figs. 3 and 4 predicts a neutron output of 8.0E16 (13-15 MeV). This is significantly lower than the no-tube igniting 2D simulation result of 7.8E17 neutrons but more than the no-tube, alpha-deposition-off simulated result of 8.9E15 neutrons. Removing alpha deposition from a simulated 2D implosion with the as-shot fill tube predicts a yield of 6.3E15 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. Alternately, 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 shown improved results.

5. Summary

Several high-foot ignition implosions on NIF have shown reduced performance when compared with expectations based on simulations. Fill-tube hydrodynamic effects may account for some of this discrepancy. Capsule implosion simulations using a wedge-expansion technique can provide early-time angular resolution at the location of the fill tube. In addition, a donor line radial remapping scheme maintains an orthogonal mesh throughout the simulation.

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. Polar x-ray images of these high-foot implosions show hot-spot perturbations consistent with hydro effects originating in the tube and hole used to fill the capsule with DT fuel.

According to simulations, fill tube induced perturbations of the hotspot may be reduced by coating the nominal fill tube with a thin layer of Au, or by truncating the tube at the capsule surface.

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