X-ray drive of beryllium capsule implosions at the National Ignition Facility

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Abstract. National Ignition Facility experiments with beryllium capsules have followed a path begun with “high-foot” plastic capsule implosions. Three shock timing keyhole targets, one symmetry capsule, a streaked backlight capsule, and a 2D backlight capsule were fielded before the DT layered shot. After backscatter subtraction, laser drive degradation is needed to match observed X-ray drives. VISAR measurements determined drive degradation for the picket, trough, and second pulse. Time dependence of the total Dante flux reflects degradation of the of the third laser pulse. The same drive degradation that matches Dante data for three beryllium shots matches Dante and bangtimes for plastic shots N130501 and N130812. In the picket of both Be and CH hohlraums, calculations over-estimate the x-ray flux > 1.8 keV by ~100X, while calculating the total flux correctly. In beryllium calculations these X-rays cause an early expansion of the beryllium/fuel interface at ~3 km/s. VISAR measurements gave only ~0.3 km/s. The X-ray drive on the Be DT capsule was further degraded by an unplanned decrease of 9% in the total picket flux. This small change caused the fuel adiabat to rise from 1.8 to 2.3. The first NIF beryllium DT implosion achieved 29% of calculated yield, compared to CH capsules with 68% and 21%.

1. Introduction
Beryllium ablators [1] were chosen for the first ignition target design for the National Ignition Facility [2], but the challenges of handling beryllium contamination in the target chamber and diagnostics led to selecting glow discharge polymer (GDP). The first implosion of a DT filled beryllium capsule at NIF required a sequence of shots to understand the interaction of the beryllium capsule with the hohlraum and to experimentally tune the timing and velocity of shocks within the capsule. The first beryllium DT capsule experiment was designed to be similar to the first high-foot CH DT capsule (N130501). Both were fielded in a now standard, 5750 µm diameter Au hohlraum, supported by a 45 nm thick tent, and filled through a similar glass tube glued to a 10 µm dia. hole in the capsule. This similarity in laser drive, hohlraum dimensions, and capsule parameters allows us to compare these two experiments, and the performance of beryllium vs. plastic capsules in general.
2. Drive reduction for keyhole, 1D and 2D convergent ablator targets

Our HYDRA [3] calculations began with subtracting the backscattered energy, assuming it never reached the hohlraum. The plastic capsules have ~ 2% less backscatter than beryllium: less SRS in the 30° beams and no SBS in the 50° beams. Keyhole targets have a gold cone penetrating the hohlraum wall and into a capsule filled with liquid D₂. A VISAR (Velocity Interferometer System for Any Reflector) reflected off the moving shock front to measure its velocity versus time [5] at both the equator and pole. Ad hoc reduction to laser power and energy transfer between the laser cones is needed to bring the calculations into agreement with experiment. Implosions are backlighted with copper x-rays to give streaked radius vs. time (1DConA) [6] or time-gated images of transmission (2DconA) [7]. Measurements of the time of peak X-ray emission at the south pole [8] (bangtime) further constrain power reduction. Jones et al. [4] introduced time dependent multipliers on the laser power incident into the hohlraum as a calculational tool to match better the measured shock speeds, shock merger times, peak implosion velocity, capsule bangtime, and other experimental data. Experiments have shown that the radiation flux within the hohlraum is actually depleted [9]. The hohlraum physics in the calculations [10] is thought to be in error. Figure 1 shows the drive degradation derived from keyhole, 1D and 2DConA targets and by matching Dante flux measurements. The 0.3 value at 12ns is required to explain the low VISAR 3rd shock velocity and the late bangtime with 0.9 MJ.

N150222 was a 1DConA target, using ~8.3 keV emission from a copper backlighter foil to measure in transmission the radius vs. time of the imploding Be/Cu shell. From this the implosion velocity of the unablated mass is derived [6]. The observed velocities those calculated for the unablated mass agree within experimental error bars. Table I summarizes the results.

Table I- Post Shot Simulations of N150222 vs. Observations

|              | Bangtime (ns) | Yield (e+11) | X-ray fwhm (ps) | DD Tion (keV) | ConA peak V (km/s) | P0 (um) | P2/P0 (%) | Mass Remaining (%) |
|--------------|---------------|--------------|-----------------|---------------|--------------------|---------|------------|-------------------|
| Calculated   | 17.437        | 6.28         | 300             | 2.17          | 285                | 67.9    | -10.3      | 11                |
| Data         | 17.44±0.02    | 2.31±0.16    | 377±20          | 2.11±0.2      | 282±9              | ~60     | -16        | 10±1.5            |

N150420 was a 2DConA target, again using a copper backlighter to image the implosion within about 1ns of peak X-ray emission (bangtime) [7]. From these time-dependent images the radii of minimum transmission, and of the points of maximum slope in the transmission are derived. The former corresponds roughly to the radius of the inner copper doped beryllium layer, and the latter to its outer radius. The calculated and measured points differ by an ~30ps shift of the measured points to earlier times, within the 80ps uncertainty. The velocity derived from the measured minimum radii is 285 ± 20 um/ns compared with 270 um/ns calculated 0.62ns before bangtime. As with the 1DConA, N150222, the observed implosion is slightly earlier than calculated. A calculated velocity for the maximum slope point is 245 km/s compared to the measured 223 km/s.

2.1. Dante Flux modelling in the second and third laser pulses

Dante [11], an 18 channel soft x-ray spectrometer, uses filters, mirrors, and X-ray diodes to measure the absolute flux emitted out the hohlraum laser entrance hole between 50 eV and 20 keV. The power and spectrum are sensitive to laser drive degradation. Figure 2 compares calculated and observed Dante spectrally integrated flux, and in figure 3 the flux >1.8 keV for the 1DConA. The 2DConA and the DT capsule also agree with calculations.
Since calculated drive degradation is thought to be a consequence of inadequate hohlraum, not capsule, modeling, the same degradation could apply to hohlraums with plastic (CH) as well as with beryllium capsules. Applying the degradation in figure 1 in the third pulse to CH capsules also brings both total and m-band fluxes into agreement with the observations.

The Dante instrument is not spatially resolved, but integrates all the X-ray emission within its field of view. Typically this emission comes from within the LEH, but the effective aperture of the LEH to X-rays changes with time. Images of the LEH with the Static X-ray Imager (SXI) [12] can measure the amount of this closure. The calculated image has a slightly smaller diameter (2750 vs. 2950 µm) than the experiment. Thus the hohlraum brightness (flux/unit area) is about 13% less than calculated from the spatially integrated flux, or, in a time integrated sense, the drive degradation is ~13% too high.

2.2. Laser picket modelling

One of the deficiencies in HYDRA hohlraum modeling is the over-prediction of M-band flux in the picket of the laser pulse. A drive multiplier in the picket is thought to represent errors in the equation of state. It is set to obtain the 1st shock velocity observed by the VISAR: 0.93 for beryllium capsules and 0.85 for CH. The M-band is then over-predicted by about a factor of 100 compared to Dante data for both CH and Be capsules, suggesting an error in hohlraum modeling. HYDRA calculates that a thin hohlraum wall layer is being heated to high temperature at low density. The data suggest that softer X-rays are being emitted at lower temperatures. The total Dante flux is correctly calculated. We don’t know how to correct this error. For beryllium capsules this over-prediction has a measurable consequence in VISAR measurements. Unlike CH, which transmits VISAR light, the metallic beryllium/DD surface reflects the VISAR. M-band X-rays can penetrate through the ablator, preferentially heating the copper doped layers that expand. HYDRA calculations predict an interface velocity of 2-4 km/s, but VISAR measurements show only 0.2-0.3 km/s, reflecting about 1/100 the kinetic energy.

3. Sensitivity to the laser picket

With the drive degradation determined from VISAR, 1DconA and 2DconA experiments, the hohlraum radiation drive could be calculated for the DT layered beryllium shot N150617. However a small but important difference occurred between the intended laser picket and that delivered by the NIF laser. The delivered energy in the picket was 9% low (within NIF specifications), but the second and third pulses were as requested. This caused a slower first shock in the beryllium. The second and third shocks then over took the first shock 20 µm inside the DT ice/gas interface, instead of just inside the gas. This increased the entropy of some of the fuel, changing the total fuel adiabat from an intended 1.9 to 2.3 times the Fermi degenerate. The final ρR was decreased. The expected down-scattered ratio
(DSR) dropped from 5% to 4%, and the calculated yield was reduced a factor of ~2. This unfortunate picket deficit also affected the first CH DT layered capsule as well, N130501, allowing us to still compare the relative performance of beryllium to plastic.

4. Conclusions
Using the discussed drive degradation and saturated cross beam energy transfer [13], we calculated the performance of both beryllium and plastic DT layered implosions. In the absence of heating from alpha deposition asymmetric radiation drive alone accounts approximately a factor of two degradation. This leads to less alpha particle deposition and less heating, which accounts for N130812 not igniting. Driven by 1.37 MJ (vs. 1.27 and 1.69 for CH), the performance of the beryllium ablator DT layered capsule gave a 3.8% measured down-scattered ratio (vs. 3.1 and 4.1%), a lower implosion velocity 285 km/s (vs. 310 and 350), a lower inferred un-ablated mass, 200 µg (vs. 280 and 420), and an intermediate 29% ratio of observed yield/ calculated 2D asymmetric (vs. 68 and 21%). Within the uncertain degradations from drive and fabrication asymmetry, such as M1 asymmetry in the DT ice, the beryllium and plastic implosions are similar. The laser-hohlraum interaction is only slightly different with Be than with CH capsules. Drive degradation for the 3rd pulse is similar, perhaps identical for Be and CH. Similar saturation of crossbeam energy transfer is needed for both Be and CH capsule hohlraums to replicate observed x-ray and neutron images. In summary when driven similarly the Be capsules performed much like a CH capsules. Performance degradation for both seems dominated by drive and target fabrication asymmetries. The advantages of beryllium are its low opacity, higher mass ablation rate, and greater stability to high frequency surface perturbations. These advantages were not emphasized in the first experiments comparing beryllium and CH.

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