Measurement of inflight shell areal density near peak velocity using a self backlighting technique

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Abstract. The growth of perturbations in inertial confinement fusion (ICF) capsules can lead to significant variation of inflight shell areal density (ρR), ultimately resulting in poor compression and ablator material mixing into the hotspot. As the capsule is accelerated inward, the perturbation growth results from the initial shock-transit through the shell and then amplification by Rayleigh-Taylor as the shell accelerates inwards. Measurements of ρR perturbations near peak implosion velocity (PV) are essential to our understanding of ICF implosions because they reflect the integrity of the capsule, after the inward acceleration growth is complete, of the actual shell perturbations including native capsule surface roughness and “isolated defects”. Quantitative measurements of shell-ρR perturbations in capsules near PV are challenging, requiring a new method with which to radiograph the shell. An innovative method, utilized in this paper, is to use the self-emission from the hotspot to “self-backlight” the shell inflight. However, with nominal capsule fills there is insufficient self-emission for this method until the capsule nears peak compression (PC). We produce a sufficiently bright continuum self-emission backlighter through the addition of a high-Z gas (~ 1% Ar) to the capsule fill. This provides a significant (~10x) increase in emission at hν~8 keV over nominal fills. “Self backlit” radiographs are obtained for times when the shock is rebounding from the capsule center, expanding out to meet the incoming shell, providing a means to sample the capsule optical density though only one side, as it converges through PV.

Recent experiments at the National Ignition Facility (NIF)[1] have demonstrated sensitivity to instabilities seeded through surface density perturbations on the capsule ablator to the laser pulse shape. The growth of perturbations in ICF[2] capsules can lead to significant variation of inflight shell areal density (ρR) and ultimately result in poor compression and ablator material mixing into the hotspot degrading the neutron yield[3], [4].

This paper presents the initial measurements of growth from the first self backlighter experiments on the NIF measuring growth from a pre-imposed perturbation, mode 40 and amplitude 100 nm, at radii <200 µm driven by a low-adiabatic laser pulse shape[5].
The primary aim of the experiment is to observe a snapshot of the total growth arising from the native perturbations at the surface of the capsule. We wanted to qualify the technique with a known perturbation that would be visible at the time of the peak emission from the rebounding shock. A mode 40 sinusoid ripple was machined into the ablator surface as considerable growth was expected when the capsule had reduced to radii less than 300 µm or convergences greater than 3x.

To boost the self-emission at PV a high Z gas is added into the fill of the capsule. This provides an additional experimental challenge as higher Z gases condense at a higher temperature than a cryogenic target is normally fielded at (~24 K). Ar was chosen at the 1% level as this allowed the target to be fielded at a cryogenic temperature, 75 K, with minimal risk of Ar condensation. The enhancement of emission from the Ar begins ~400 ps prior to PC providing a temporal window in which a series of self-radiographs can be taken.

Figure 1(a) shows the dopant quantities in the CH capsule and the location of the 1.4% Cu doped layer. From simulations we calculate that during the peak Ar emission (~PC -350 ps) the ablator will have predominantly burnt off, yet enough will remain so that the perturbation has not penetrated into the Cu doped layer. Figure 1(c) shows a prediction of the perturbation in the shell when it is at a radius of ~150 µm, from a capsule only 2D simulation using HYDRA[6]. The ripples are clearly visible in the density map, grown to a peak-to-valley of ~55 µm, and the enhanced Te from the added Ar provides sufficient self-emission to radiograph them.

The added Cu dopant in the shell absorbs the enhanced continuum emission from the rebounding shock at the K-absorption edge, 8.9keV. At this energy the emission from the rebounding shock is a continuum with a distribution determined by the electron temperature (Te) of the capsule gas. A spectroscopic measurement can be made of the relative emission above and below the absorption edge to find the Cu dopant ρR as a function of time.

The self-radiographs are taken in a 0.8 scale ignition design with a modified low adiabatic laser pulse shape. The smaller scale of the capsule and hohlraum with the addition of the Ar-gas does not allow direct comparison to an ICF experiment designed to achieve ignition, however they show the validity of the technique to observe growth arising from the initial conditions of the capsule surface that may not be measurable with current target fabrication techniques. The target has been used to measure the largest areal density growth factors arising from acceleration Rayligh-Taylor of ~7000x[5].

The ripples on the capsule were orientated such that they were visible from the polar and equatorial lines of sight as shown in figure 1(b). A pinhole imaging system coupled to an Micro-channel plate (MCP) gated x ray detector (GXD)[7] captured the self emission of the implosion, a sample of the polar images are shown in Figure 2. The GXD provided a large number of images spanning the period between PC -400 ps and -100 ps that corresponds to the time when the shell reaches peak velocity. The images are observed though a 10 µm Cu filter which provided a pseudo narrow energy band.

Figure 1: (a) A plastic (CH) capsule is doped with Si and 1.4% Cu. A mode 40 ripple is machined in to the ablator with a 220nm peak-to-valley. The initial radius of the capsule is 920µm. (b) Cartoon showing the orientation of the ripples in the hohlraum, visible on both the polar and the equatorial lines of sight. (c) When the shock rebounds through the capsule gas fill the presence of ~1% Ar enhances the self-emission[5], shown here by a HYDRA[6] simulation indicating the enhancement of Te at R~ 150 µm, near to PV.
response allowing the modulation in optical depth to be found. The orientation of the ripples and identical setup of the two detectors allows a simultaneous measurement of growth from the mode 40 perturbations to be made on both the pole and equator. The growth observed from these measurements is discussed in detail in L.A. Pickworth, PRL 2016. Figure 2 shows the (vertical) ripples very clearly, and in addition some three-dimensional features are visible, clear as two regions of brighter emission on the central two ripples. These two spots can be followed frame-to-frame coming closer together as the capsule converges.

![Figure 2](image)

Figure 2: A series of self-radiographs taken with a 12 x magnification, 12 µm pinhole imaging system onto a gated x-ray detector with ~100 ps time resolution, from the polar line of sight.

Figure 3 shows the self-emission from the capsule on a ‘streaked’ spectrometer[8]. The record shown in figure 3(a) covers 1 ns around PC, viewing the equatorial region of the shell unperturbed by the ripples. Two bands of self-emission are clearly visible, and highlighted in the emission time history shown in figure 3(b), the enhanced emission from the rebounding shock near to PV and the self-emission from the ‘hot spot’ at PC. Figure 3(b) compares the experimental time history to two simulations on a relative intensity scale, one with additional Ar and one without. The order of magnitude enhancement in self-emission near PV is clearly visible. It can also be seen that the timing of the enhanced self-emission in the simulation matches well to the experiment. The exact intensity of the simulation and experiment is not matched, this is interesting and further work is ongoing to improve the diagnostic analysis and the predictive capability that will allow us to compare absolute emissivity during the shock rebound phase in future.

![Figure 3](image)

Figure 3. (a) Streaked spectrum, viewed equatorially through a region of the capsule unperturbed by the pre-imposed ripples. (b) Time history of the self-emission below the Cu edge compared to simulation, with and without Ar, on a relative intensity scale. (c) Spectrum averaged over 100 ps at PV (d) Spectrum averaged over 100 ps at PC from the spectrum shown in (a).
Two spectra are shown in Figure 3 averaging over 100 ps at the rebounding shock and 100 ps at PC. The $\rho R$ of the Cu dopant can be inferred by measurement of the change in self-emission at the Cu dopant K-edge. For the time of the rebounding shock self emission we estimate the density of the Cu to be $(5.7\pm0.4)\times10^{-3}$ g/cm$^3$. To arrive at this conclusion we used the cold opacity of Cu [9]. This corresponds to a capsule convergence of $5.1\pm0.2\times10^{-3}$, consistent with the expected capsule radius near PV.

There are other notable features visible in the spectrum that change over the course of the implosion. At the time of PV there is visible emission from the Cu K-alpha line emission. At the time of PC this is no longer clearly visible in the spectrum, however the Cu 1s-2p absorption feature is highly visible. The presence of the 1s-2p feature indicates the Cu is both ionized and dense in a similar manner as previously investigated in a direct drive configuration using Ti dopant[10-12]. We intend to utilize this feature in future analysis to better infer the shell $T_e$ and $\rho R$. The whole spectrum can be carefully compared to a model for the $T_e$ and average shell opacity allowing the $T_e$ to be more accurately inferred. Initial application of this simple method (dashed blue lines in Figure 3(c, d)) highlights the need of a more detailed comparison to simulation that we are currently perusing.

Areal density of the shell can be inferred from time resolved images (Figure 2) through Ross pair filter imaging[13] that was fielded during these experiments; these will be discussed in a separate publication[5]. In future we intend to apply this technique to observe the ‘native’ shell surface features that have ‘grown up’ at the time of PV. In order to make these measurements as accurately as possible an imaging system with higher spatial resolution, improved signal to the detector and spectral selectivity is desired. NIF has recently commissioned a Kirkpatrick-Baez Microscope[14], [15] which has <8 µm spatial resolution and a narrow band spectral response that we hope to apply to this experimental platform in the near future, replacing the use of Ross-Pair filtering.

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