The first capsule implosion experiments on Orion*

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Abstract. Direct drive capsule implosions are being developed on the Orion laser at AWE as a platform for ICF and HED physics experiments. The Orion facility combines both long pulse and short-pulse beams, making it well suited for studying the physics of alternative ignition approaches. Orion implosions also provide the opportunity to study aspects of polar direct drive. Limitations on drive symmetry from the relatively small number of laser beams makes predictive modelling of the implosions challenging, resulting in some uncertainty in the expected capsule performance. Initial experiments have been fielded to evaluate baseline capsule performance and inform future design optimization. Highly promising DD fusion neutron yields in excess of 10^9 have been recorded. Results from the experiments are presented alongside radiation-hydrocode modelling.

1. Introduction

Direct drive capsule implosions are being developed on the Orion laser [1] at AWE as a platform for ICF and HED physics experiments. Although the energy scale of the facility (~5kJ) precludes access to very high yield implosions, there is significant potential to study relevant aspects of the implosion physics as well as more fundamental physics of ICF plasmas; an area of current interest being the use of implosions as a source of energetic charged particles for plasma stopping power experiments. The Orion facility is configured with ten long pulse (ns) beams and two additional PW (ps) beams, which make it well suited for studying the physics of alternative ignition approaches, including both fast ignition and shock ignition. Orion implosions also provide the opportunity to study aspects of polar direct drive [2], with particular relevance to configurations being explored for direct drive shock ignition at LMJ [3].

Limitations on drive symmetry from the relatively small number of laser beams, together with the complexity of polar drive configurations, makes predictive modeling of Orion implosions challenging, resulting in some uncertainty in the expected capsule performance. Accordingly initial experiments have been fielded to evaluate baseline capsule performance and inform future design and optimization.

Implosions were performed using thin-shell, deuterium-filled, silica glass capsules. These were intended to produce exploding pusher-like dynamics, in which the fusion yield is mainly produced during the initial shock phase, in order to minimize the impact of mix and asymmetry. A substantial suite of diagnostics was fielded to characterize the implosions, which included the first use of Orion's neutron total yield (NTYD) and time-of-flight (NTOF) diagnostics, and time-gated x-ray imaging (GXD) on multiple axes.

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2. Capsule design

Suitable capsule designs were identified by a 1D study of capsule phase space using the Nym radiation-hydrocode [4]. As expected, clean yield was generally found to decrease rapidly with increasing shell thickness (figure 1), as shell inertia is increased and the drive shock is both delayed and weakened. The variation of yield with capsule radius is not monotonic, such that there is an optimal radius for a given shell thickness. Based on this study it does not appear possible to simultaneously achieve low convergence, high fusion yields and exploding pusher-like dynamics at the Orion energy scale without recourse to very high aspect ratio shells.

Consideration of drive uniformity requires a smaller capsule radius than the 1D optimum. The existing Orion phase plates are relatively small, being intended primarily for indirect drive, and at best focus result in a very low ratio of spot size to capsule radius, providing far from optimal illumination [5]. Improved illumination can be achieved by operating at ~2mm defocus, although this does compromise the quality of the beam spot. Polar drive is also necessary to optimize equatorial symmetry (figure 2).

The resulting nominal capsule design was a 250μm radius, 2.5μm thick silica glass shell with 10atm D_2 gas fill. These were imploded using a 600ps FWHM square pulse with ~2.5kJ laser energy.

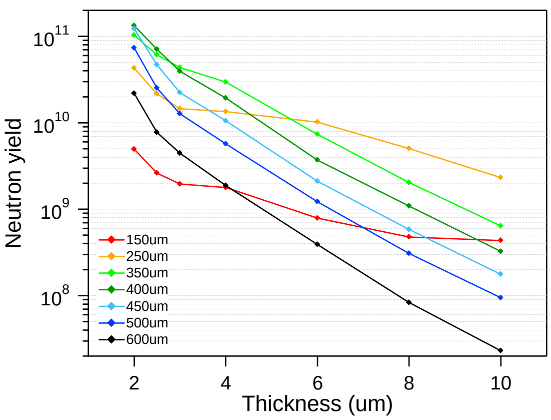

Figure 1. Clean neutron yield as a function of shell thickness and radius, as determined from 1D Nym simulation study. Only a subset of these capsules produce exploding pusher-like dynamics.

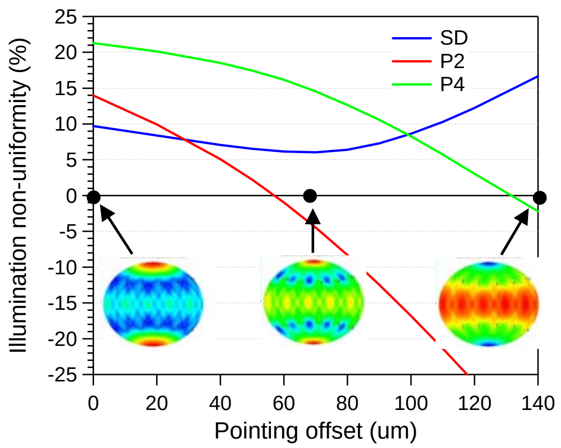

Figure 2. Static view-factor calculations show improved drive uniformity with polar drive pointing offset. Curves show standard deviation of incident laser power over the capsule surface (blue), with Legendre P2 (red) and P4 (green) modes. Inset images show incident power map at selected offsets.

3. Experimental results

Experimental fusion yields were measured using three different diagnostic methods: CR39 nuclear track detection for absolute proton yield; NTYD using activation of an indium sample for absolute neutron yield; and an NTOF spectrometer, which provided relative neutron yields. Excellent correlation between the different diagnostic yields (figure 3) provides confidence in the measured performance. This is particularly important for the highest yield shot, a single data point significantly separated from the others, which might otherwise be interpreted as anomalous. The highest recorded yield was 1.7 x 10^9 neutrons and corresponds to the thinnest capsule. A large increase in performance near this shell thickness was anticipated from design simulations (figure 1). However, it is difficult to definitively attribute this behaviour to the thinner shell; in general the yield data shows large variability and is not well-correlated with any single input parameter.

The experimental yields have been compared to post-shot modeling of the experiments using Nym (figure 4), which takes account of simultaneous variations in the 1D experimental parameters. The simulations were calibrated to the time of peak emission, as measured by the Dante diagnostic, by tuning the thermal conduction flux limiter and input laser energy, compensating for limitations in laser absorption modeling [6]. The use of existing GXD self-emission images to further constrain the modeling is also underway. Experimental neutron yields are typically ~15-35% of post-shot mix simulations. This difference indicates some variability or degradation mechanism not adequately captured in the 1D simulation model.

Ion temperatures ⟨Ti⟩ derived from the NTOF measurements of the neutron spectra range from ~3-5keV (figure 5). Although the line of best fit shows an upward trend, there is no strong correlation between ⟨Ti⟩ and neutron yield, which suggests that thermal broadening at the neutron source does not dominate the measured spectrum. Synthetic neutron spectra from post-processed simulations produce inferred temperatures significantly lower than the experiment, even when the effect of 1D bulk plasma velocity is included. This discrepancy could suggest additional motion due to asymmetry or turbulence that is not captured by the simulations.

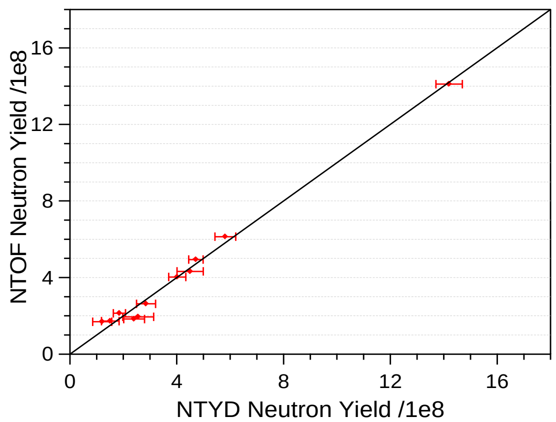

Figure 3. Comparison of NTOF and NTYD neutron yields, showing excellent correlation. The best-fit line has R^2=0.99.

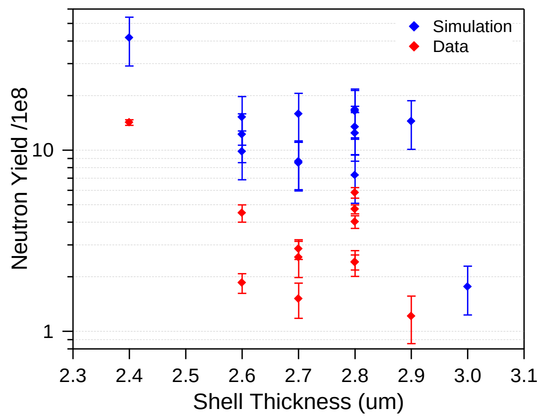

Figure 4. Measured (red) and simulated (blue) neutron yields as a function of capsule shell thickness. Although a large increase in performance is seen at 2.4µm, there is significant variability in the data.

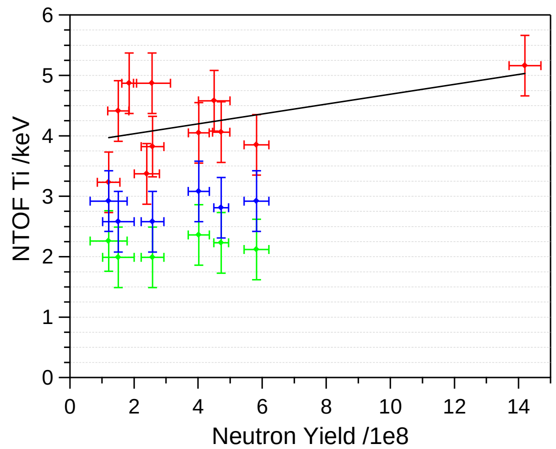

Figure 5. Ion temperature determined from NTOF (red) shows no significant correlation with neutron yield. Simulated ⟨Ti⟩ with (blue) and without (green) motion Doppler effects are significantly lower.

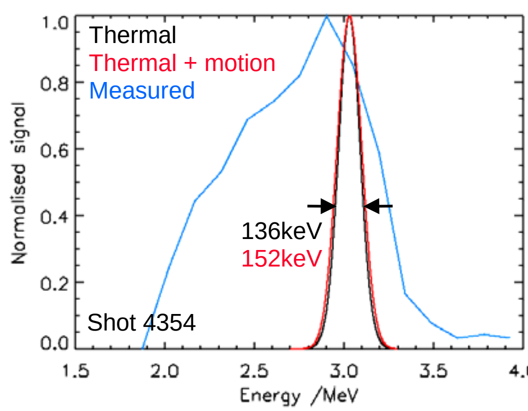

Figure 6. Preliminary proton spectral data (blue) shows significant broadening which is consistent with downshift through the residual shell material. Calculated source spectra with (red) and without (black) motion Doppler broadening are shown for reference.

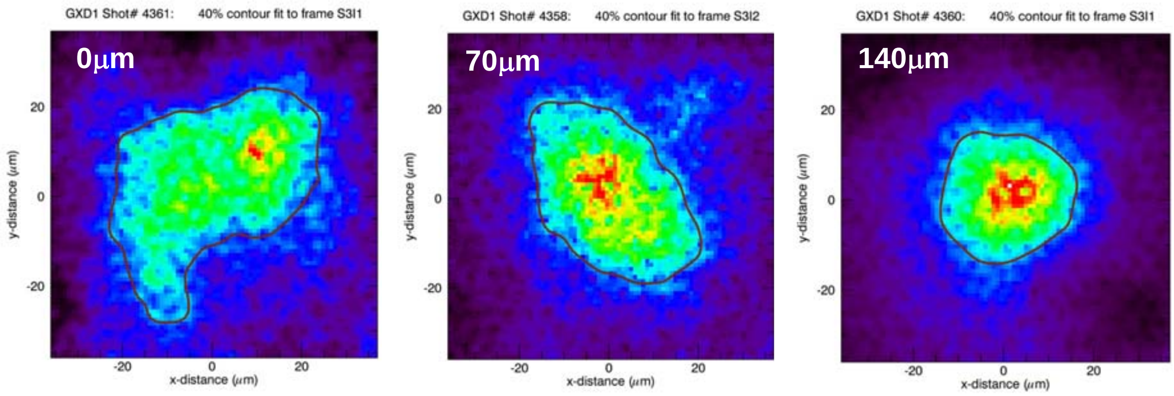

Figure 7. Gated x-ray images of the implosion self-emission taken from the equatorial view at bang time for three different polar drive pointing offsets (0, 70 and 140μm). Although implosion symmetry appears to improve with increased pointing offset, as expected, the experiment shows significant shot-to-shot variation.

Proton spectra from the DD reaction were obtained using the LLNL IPS magnetic spectrometer [7]. Preliminary analysis shows a small downshift in the peak energy ~100-200keV, but significant broadening which gives rise to a low energy tail (figure 6). Spectral data was obtained only for the thickest shells (2.7-2.8μm) for which simulations predict significant residual shell areal density at fusion bang time. The observed broadening is consistent with a simple energy loss calculation through this residual shell.

GXD images of the x-ray self-emission from the implosion core show obvious signs of asymmetry (figure 7). The data shows varying degrees of implosion asymmetry, with some shots appearing quite spherical, although this could also reflect cooling of perturbed peripheral regions due to mixed shell material. There is no significant correlation between neutron yield or convergence and symmetry. Gated equatorial images may hint at improved symmetry with an increase in the polar drive laser pointing offset, which is consistent with expectations from view-factor calculations. However, the data is inconclusive since these images exists for relatively few shots and there is significant shot-to-shot variation.

4. Conclusion

Direct drive capsule implosions are being developed on the Orion laser at AWE as a platform for ICF and HED physics experiments. Initial experiments have been fielded to evaluate the baseline capsule performance and inform future design and optimization. These experiments have successfully demonstrated the first use of Orion's neutron total yield and neutron time-of-flight fusion diagnostics. Data from multiple yield diagnostics confirms highly promising DD neutron yields up to ~10^9. Differences between 1D post-shot modeling and the experimental data are expected to be largely due to asymmetries in the implosions, as GXD images show asymmetric implosion cores on most shots. 2D post-shot modeling is now being undertaken. Future experiments will benefit from additional diagnostics and from new larger Orion phase plates, which will improve on-target beam quality.

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