Constraining fundamental plasma physics processes using doped capsule implosions[*]

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Abstract. A standard technique in inertial confinement fusion research is the use of low levels of spectroscopic dopants as a passive diagnostic of fuel conditions. Using higher dopant levels it becomes possible to modify the plasma conditions. Doped capsule experiments may thus provide a way to control and study fundamental plasma physics processes in the inertial fusion regime. As a precursor to eventual experiments on the National Ignition Facility (NIF) we have performed a series of capsule implosions using the Omega laser. These are intended to guide the modelling of high-Z dopants and explore the feasibility of using such capsule implosions for quantitative physics experiments. We have fielded thin glass shells filled with D-He^3 fuel and varying levels of Ar, Kr and Xe dopants. X-ray emission spectroscopy is combined with simultaneous measurements of primary neutron and proton yields and energy spectra in an attempt to fully constrain capsule behaviour.

1. Introduction

The use of spectroscopic dopants as a diagnostic in ICF implosions is an established technique [1] used to provide information on fuel conditions or to aid the study of hydrodynamic mix. By using low levels of low atomic number (low-Z) dopant, emission spectra can be obtained without significantly perturbing capsule performance. However, as we approach ignition on the US National Ignition Facility (NIF) increased fuel temperatures will necessitate the use of higher-Z dopants, which have much greater potential to modify implosion behaviour.

A series of directly driven implosion experiments has been performed at the Omega laser to examine the effects of fuel dopant on capsule performance as both dopant concentration and atomic number (Z) are varied. These experiments are intended to guide the modelling of capsule fuel dopants ahead of future application on NIF. In addition however, such experiments also provide a means to control or manipulate the plasma environment. It may thus be possible to use the implosion data set to study and constrain fundamental plasma physics processes.

In this paper we apply the experimental results to explore the feasibility of using doped capsule implosions for quantitative plasma physics experiments. As an example the sensitivity of performance

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to the electron-ion energy exchange rate is considered. This has been the subject of recent theoretical work [2], which suggests that deviation from conventional ideal plasma theory [3] may be significant.

2. Experiment

Thin shell glass capsules (nominally 5um thickness, 950um diameter) were imploded at Omega in direct drive using a 23kJ, 1ns square laser pulse. The capsules were filled with 10atm of D-He^3 fuel (80:20 by number) plus an additional quantity (up to 0.7atm) of higher Z dopant gas. The D-He^3 fuel was intended to improve characterisation of the implosion by providing both 2.45MeV D-D neutron and 14.7MeV D-He^3 proton primary yields. Particle yields and energy spectra were measured using standard techniques [4].

The higher Z dopant gas, which was alternately Ar, Kr or Xe, was used to modify the plasma conditions. At the highest dopant pressures the dopant comprised up to 75% of the fill mass, significantly perturbing the implosion. A small quantity of Kr was maintained in all doped capsules to facilitate spectroscopic diagnosis of electron temperature [4]. In this paper we focus on the results obtained using the high-Z Kr and Xe dopants, which have been more comprehensively modelled than the more recent Ar data.

Neutron and proton yield data is shown in figure 1. At low dopant levels ($\leq 10^{-2}$ atm) capsule performance is little changed from the undoped case. At higher levels the yield falls off rapidly with increasing dopant pressure. Both Kr and Xe filled capsules appear to follow the same trend, despite quite different Z. However Ar data (not shown) shows little decrease in yield over this range, indicating that fall-off is reduced at much lower Z as expected.

In order to quantify the position of the cliff edge it is important to take account of shot-to-shot variation of the experimental configuration. Even when averaged for each target type, there remain statistically significant differences which must be corrected for. Such corrections rely on accurate capsule modelling.
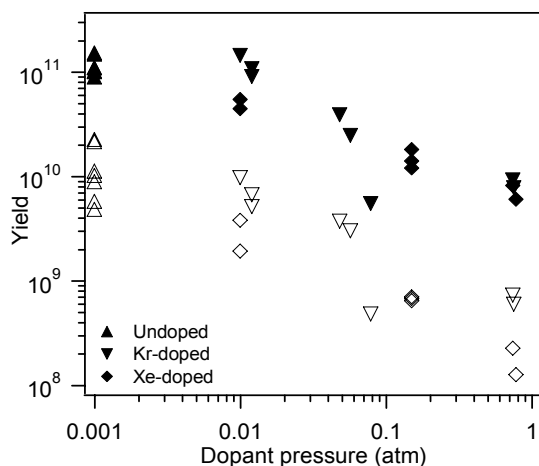
Figure 1. Neutron (solid) and proton (unfilled) yields vs. dopant pressure. Undoped values are plotted at 0.001atm on the log scale for convenience.
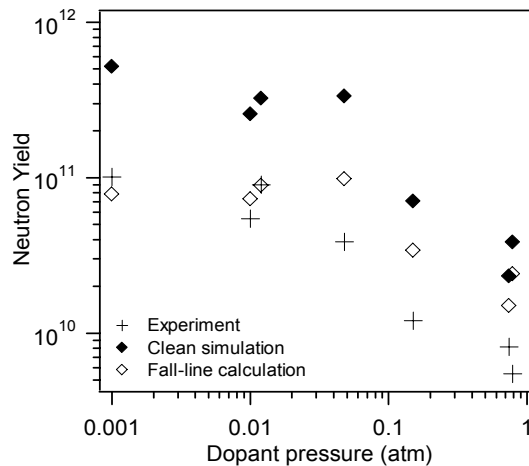
Figure 2. Observed neutron yields for selected capsules have been compared to clean and fall-line mix simulations.

3. Modelling

Capsules were modelled in 1D spherical geometry using the radiation-hydrocode nym [5]. The simulations provide a qualitative understanding of capsule dynamics. Ablatively-driven implosion of the shell gives rise to two distinct yield phases: a high temperature, low density shock phase and a dense compression phase. Compression yield dominates in all simulations. Ion and electron

temperatures become separated by the passage of the shock, and then relax toward equilibrium as the fuel is compressed. As dopant concentration is increased the inward shock becomes weakened by radiation loss and the compression phase becomes even more dominant. At high dopant levels temperature separation is severely reduced, so that capsule yield is produced under equilibrium conditions. This transition to temperature equilibrium is observed experimentally.

Comparison of simulated and measured neutron yields shows reasonable agreement (figure 2). The experimental yield over calculated clean (YoC) ranges from ~10-35%. This is consistent with results achieved in other high convergence capsule implosions [6], demonstrating a first order understanding of capsule behaviour. However, if these results are to be used to draw quantitative conclusions about the physics models it is important to fully account for the outstanding yield discrepancy.

Calculated proton yields match the data well at low dopant concentrations (YoC 20-50%). Agreement rapidly becomes less good as dopant is added, with YoC falling off to ~5%. Simulated ion temperatures, derived by post-processing calculations to produce a synthetic neutron time-of-flight signal, successfully reproduce the data trend, but consistently underestimate the measured values.

3.1. Hydrodynamic mix

In general the particle diagnostic data is more consistent with conditions during the shock phase than over the entire implosion; measured yields and areal density are lower than expected from calculations, whilst ion temperatures are higher. This suggests that the compression phase is significantly degraded compared to clean simulations, an interpretation reinforced by recent reaction history measurements on similar DT-filled capsules [7].

Fall-line calculations [8] have been used to provide a worst-case estimate of mix degradation (figure 2). At low dopant levels fall-line degradation is sufficient to account for the observed yields. The treatment removes much of the late-time compression phase yield predicted in clean simulations. However, at higher dopant levels there is little effect. These results suggest that within the context of a 1D model the yield data cannot be explained by hydrodynamic mix alone.

3.2. Uncertainties

The effect of various measurement uncertainties has been considered. Uncertainties in the capsule shell dimensions (both thickness and radius) contribute ~10% uncertainty to neutron yield and ~20% for proton yield. Gas fill uncertainties, arising from both measurement uncertainty in the initial fill and in calculated leakage during storage and fielding, contribute ~5-10% in total for each yield.

The combined uncertainty is dominated by uncertainty in the neutron bang time, which is used to calibrate the electron conduction flux limiter. The quoted measurement uncertainty of ±50ps is normally sufficient to constrain capsule energetics. However, the thin shell high convergence capsules used here appear extremely sensitive to timing variation. The resulting uncertainty is typically 40-60% in neutron yield, whilst proton yield may vary by as much as a factor three.

At high dopant levels the combined effects of measurement uncertainty and mix are insufficient to account for capsule performance, suggesting that dopant modelling may be inadequate. Modelling dopant opacity presents a significant challenge since partially ionised high-Z dopants are not in local thermal equilibrium (LTE) and cooling is dominated by bound-bound (line) transitions. Available non-LTE models consider only principal quantum number levels which raises concerns about their ability to properly calculate radiative loss. To assess the importance of energy level structure, the sensitivity of capsule performance to spectral resolution has been considered. Doped capsule simulations typically require ~1-5eV resolution in the spectral lines to achieve convergence. This implies that line structure on this scale must be included in calculations.

3.3. Plasma model sensitivities

A simple parameter scaling was used to assess the sensitivity of capsule performance to variation in the electron-ion energy exchange rate. Theory [2] suggests that the exchange rate could deviate from that predicted by ideal plasma models by about a factor two under inertial fusion conditions.

Yield sensitivities were found to be similar for most capsules, except at the highest dopant levels where they are significantly reduced. In all cases proton yield shows greater sensitivity than neutron yield (figure3). Although the effect of a factor two scaling exceeds random error uncertainties at low dopant levels (figure 4) the overlapping error bars mean that it will be difficult to distinguish model effects from random uncertainty. At high dopant levels there seems little prospect of such distinction. In addition model sensitivities are of similar order of magnitude to mix uncertainty. These results imply that reduced error bars, via improved energetics constraints, and improved mix modelling will be necessary in order to properly constrain plasma models.
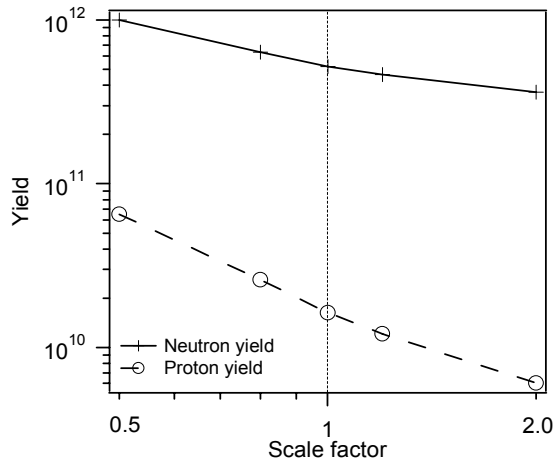
Figure 3. Simulated neutron and proton yields for a Kr-doped capsule plotted as a function of electron-ion energy exchange rate scaling factor.
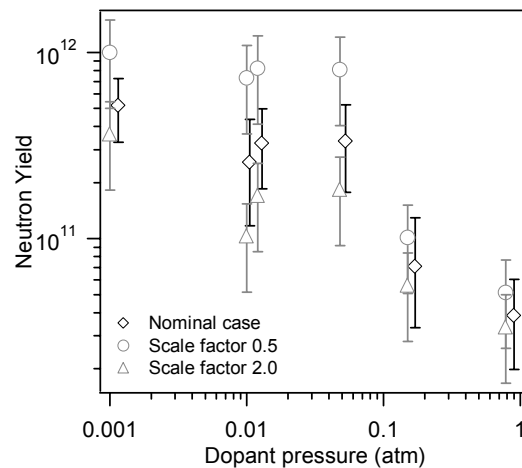
Figure 4. Simulated neutron yield vs. dopant pressure, plotted for the nominal plasma model and model scaling factors of 0.5 and 2.0. Error bars represent total random error uncertainty.

4. Summary

A series of implosion experiments has been performed at the Omega laser to examine the effects of fuel dopant on capsule performance. 1D simulations of the experiment agree with the neutron yield to the level expected for such high convergence implosions. Uncertainty in the modelling is dominated by uncertainties in hydrodynamic mix and in the capsule energetics. Neutron bang time does not appear to be a good constraint on the energetics of these capsules. We have not quantified the effect of opacity modelling uncertainties, but resolution studies indicate that this may be a concern. The feasibility of using these experiments to constrain fundamental plasma physics models has been assessed, considering electron-ion energy exchange as an example. Model sensitivity is found to be of the same order as the dominant capsule uncertainties. This work suggests that further efforts are necessary to reduce uncertainties before these experiments are usefully able to constrain the physics model.

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