Implosion and Ignition Physics

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Introduction

- For the last decade AWE has maintained a small effort on ICF implosions and ignition as part of a broader plasma physics programme

- The imminent prospect of ignition at the US National Ignition Facility (NIF) has stimulated increased interest at AWE in a formal UK approach to ICF & IFE

- An understanding of, and the ability to model, ICF implosions and ignition is a core capability for a fusion programme

- In addition NIF will offer exciting opportunities to study ignition physics and access new experimental regimes

- A broad range of fundamental plasma physics and nuclear physics experiments may be possible

- This talk presents an overview of some of the implosion research undertaken by AWE
High-Z doped capsule experiments

• Collaborative experiments performed with LANL at the Omega laser

• Thin-shell glass capsules fielded in direct drive with variety of gas fills

• Experiments intended to guide modelling of fuel dopants ahead of future applications on NIF.
  • use as spectroscopic diagnostic of fuel conditions,
  • study of hydrodynamic mix
  • study NLTE physics.

• Experiments also intended to develop in-house expertise in direct drive implosions
High-Z experiment results

- A large database of doped capsule data now exists at a range of concentrations and dopant Z.

- Even small amount of high-Z dopant produces significant degradation.

- Experimentally determined ion and electron temperatures show transition to equilibrium as Kr dopant is increased.
Comparison to simulations

- Experiments have been simulated using Nym rad-hydrocode.

- Neutron YoC ranges over 10-35%, consistent with that achieved in other high convergence implosions

- Fall-line calculations provide a worst-case estimate of mix degradation

- At high dopant levels performance cannot be accounted for by hydrodynamic mix or experimental uncertainty

- Suggestive of errors in dopant modelling
Capsule modelling

- A large range of diagnostics is being used to constrain capsule modelling

- There is some evidence that capsule compression is over-predicted by simulation:
  - Proton downshift
  - Self-emission images
  - DT/DD neutron ratio

High-Z capsules offer a platform to study fundamental plasma physics

- As example have assessed capsule sensitivity to electron-ion coupling

- Recent theory suggests exchange rate could be in error by a factor 2 in ICF capsules

- Neutron and proton yields show different sensitivities; measuring both uniquely determines model

- Currently at Omega experimental uncertainties exceed model sensitivity

- Potential for improvement at NIF

Double shell capsule experiments

- AWE were involved in early work on double shell capsules with LANL at Omega³

- Double shells provide an alternative non-cryogenic route to ignition that avoids many complexities of the single-shell approach

- Much of our effort was aimed at explaining the varied performance of different double shell targets

- Improved understanding has allowed development of designs which control and mitigate mix

- LLNL now have credible ignition designs⁴

Double shell capsule modelling

- Simulations provide an understanding of double shell dynamics

- The main design challenge is to control the effects of mixing between the high-Z inner shell and the DT fuel.

- Detailed modelling was undertaken using the 2D Eulerian code Petra, to study the impact of different perturbations

- Multimode perturbations using modes up to 100 showed increased mix degradation compared to 1D models
Various degradation mechanisms were explored through detailed 2D modelling.

Perturbations due to foam pore structure were expected to seed mix at the outer surface of the inner shell.

This was calculated to have a significant effect on capsule performance.

Effect on yield was later confirmed experimentally using two different types of foam.

Expansion of high density foam regions during preheat phase.

Instability occurs along main shock front, not along material interfaces as before.
Fusion diagnostic development

- AWE has been collaborating with LANL on the development of gamma bang time and reaction history diagnostics for Omega and NIF

- The GCD and GRH both work by detecting 16.7MeV gamma rays from an alternative DT fusion reaction.

- AWE is also involved in developing the NIF neutron time-of-flight (nToF) diagnostics, which will provide ion temperature measurements for the ignition campaign.

GCD application

• Application of the GCD has been demonstrated in recent experiments at Omega.

• We have used the GCD to explore the anomalous behaviour of $^3$He, reported in experiments by MIT$^6$.

• Our experiments reproduce the anomalous yield behaviour.

• GCD measurements will complement other data to help constrain capsule modelling.

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The GCD provides low noise, time resolved measurements of the fuel burn. (~75ps resolution after deconvolution)

Two yield phases are apparent in all curves; identified as shock and compression burn.

Signal evolves as $^3$He fraction is increased; compression phase clearly reduced.

Excellent shot-to-shot reproducibility gives confidence that observed features are real.
• Clean simulations match initial shock phase, but overestimate compression phase.

• Youngs’ mix model\textsuperscript{7} predicts little yield degradation

• Fall-line calculation does surprisingly well for simple model, particularly at 36\% \(^3\)He.

\textsuperscript{7} D.L. Youngs, Physica D 37, W Garbett, AWE

Ignition Opportunities

• NIF will offer exciting opportunities to study ignition physics and access new experimental regimes

• AWE has begun to explore potential applications of the ignition platform:
  • Physics of ignition
    • Study alpha physics / fundamental plasma physics models
  • Improved ICF designs
    • Fast ignition, shock ignition, double shells etc
  • Nuclear physics
    • Cross-section measurements, exotic processes
  • NLTE physics
THD experiments

• NIC THD experiments may help constrain alpha physics models

• Recent calculations\(^8\) suggests alpha range could be around 30% larger than Spitzer theory

• This can significantly impact self-heating; effect most obvious in marginal fuels

• THD experiments provide more comprehensive diagnostics which help confirm origin of effect.

Orion opportunities

- Orion also offers opportunities for studying ICF physics
- The combination of short and long pulse beams is ideal for studying the physics of fast ignition
- Orion will be of similar size to the Gekko XII laser, used for the integrated fast ignition experiments of Kodama et al.
- Will allow exploration of beam coupling to compressed matter
Summary

• AWE is looking to develop a more formal approach to ICF and IFE

• AWE has a demonstrated capability in modelling ICF implosions, which is a core capability for a fusion programme

• AWE is gaining experience in operating at NIF and is involved in several aspects of the ignition effort

• NIF and Orion will offer opportunities to study ignition physics and access new experimental regimes