Theory and Modeling of Blast-Wave—Driven Interfacial Hydrodynamic Instability in OMEGA Planar Experiments

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Summary

Modeling of shock-driven highly nonlinear interfacial perturbation growth shows agreement with experimental mixing length but not perturbation morphology.

- A Fresnel zone plate was used to obtain time-gated x-ray images with a resolution of ~1 μm, of a single-mode perturbed interface between brominated plastic and low-density foam.
- This platform is being developed to study interfacial instability growth, which may be a source of fuel-ablator mix in direct-drive ICF implosions.
- As in the experiment, DRACO simulations show a high level of growth and roll-up but predict a greater blast-wave speed in the foam.

CRF: Carbonized resorcinol-formaldehyde
Collaborators


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Fuel-ablator mix due to interfacial instability growth is a possible cause of performance degradation in LDD ICF implosions

- Radiation from tritium decay in permeation-filled targets can cause localized perturbations at the inner ablator shell surface
- OMEGA cryo targets are estimated to have dozens to over 100 of these features
- Voids in the ice and defects at the fuel ablator interface may also contribute to mixing
- Isolated features at the ablation surface and in the shell have been shown by simulation to be capable of transporting ablator material into the core*
- Experimentally, excess photon yield in OMEGA cryo implosions is correlated with low shell adiabat and inferred ablator mix fraction in the hot spot**, evidence of fuel-shell mixing


See S. Miller et al., JO04.00007
A planar shock-driven platform has been developed on OMEGA and OMEGA EP to study interfacial growth

- A multilayer planar target is driven with a 2.25-kJ, $7 \times 10^{14}$ W/cm², 1-ns pulse, using SG650 DPPs
- The interface between brominated plastic and CRF foam is perturbed with a single-mode, 5- or 10-µm peak-to-valley, $\lambda = 50$ µm wavelength perturbation (so $A/\lambda \sim 0.2$)
- This platform uses ambient targets, with the goal of transitioning to D₂ cryogenic cells, multiple shocks, and ICF-relevant perturbations

See P. Nilson et al., BO03.00008
These experiments use high-resolution, late-time imaging of perturbation growth

- A Ti He\(_\alpha\), 4.75-keV area backlighter is used, with a 100-ps exposure time
- The x-ray CCD uses a high-magnification zone plate for ~1 \(\mu m\) resolution
- Radiographs are taken late in time when spike speed is small, minimizing motion blurring: \(V_{\text{spike}} \Delta t_{\text{exp}} \sim (53 \text{ km/s}) \times (100 \text{ ps}) \sim 5 \mu m\)
- Experiments allow determination of the mix-region size, to test modeling in the challenging, highly nonlinear growth regime
The interface is unstable to both Richtmyer-Meshkov and Rayleigh-Taylor growth

- Growth of the pre-imposed modulation is due to both RMI from the primary shock and slow deceleration (RTI) due to the end-of-pulse rarefaction fan
- At the interface, $Kn \ll 1$, $Re \ll 1$; vorticity deposited during shock transit is conserved
- Neither RMI nor RTI is expected based on linear theory to dominate (and $A < 0$, so a phase inversion occurs):
  - $G_{RT}(10 \text{ ns}) \approx \exp \int dt \sqrt{Agk} \sim 20$; $A \sim 1/2$, $g \sim 3 \mu m/\text{ns}^2$, $k = 2\pi/50 \mu m = 0.12 \mu m$
  - $G_{RM}(10 \text{ ns}) \approx 1 + Ak(\Delta u)t \sim 14$; $\Delta u \sim 30 \mu m/\text{ns}$
- The combination of these leads to a growing mix region at the interface which quickly becomes nonlinear

\[ \text{RMI: Richtmyer-Meshkov Instability} \]
\[ \text{RTI: Rayleigh-Taylor Instability} \]
Simulations predict resolvable instability growth

- DRACO is run in Eulerian mode using a 2nd-order accurate PPM hydro solver
- Simulations also show qualitative agreement in the nonlinear perturbation growth, but with discrepancies in the width of the spike head
- Timing between experiment and simulation needs to be confirmed
- The blast-wave position differs between simulation and experimental data

PPM: Piecewise Parabolic Method
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*PPM: Piecewise Parabolic Method*
An “air gap” between the perturbed CHBr and the foam affects the spike morphology

- Little is known about the region where the two layers meet, which can have an observable effect

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No gap  Gap, truncated peaks  “Air” gap

• “Air” gap causes a high initial At ~ 1
• This is followed by a reshock due to the reflected shock off the CRF, during the RMI phase reversal
• The result is greater amplitude and deeper rollup structure

Shot 99046
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Foam porosity may be the cause of an over-prediction of the blast-wave speed

- The observed spike tip-to-blast wave position is much greater in simulation than experiment
- This may be due to modeling the foam using SESAME tables as a homogenous mixture (89% C, 7% H and 4% O)
  - The CRF foam has a high porosity: \( \varphi = \rho_{\text{ave}}/\rho_C \approx 0.95 \)
  - Shocked porous materials can exhibit initial void collapse leading to an increase in post-shock internal energy and, for sufficiently high porosity, an “anomalous” Hugoniot where post-shock density decreases with increasing shock strength*
  - The compressive Young’s modulus of CRF is \( \sim 5 \text{ MPa} \ll P_{\text{shock}} \)**
- However, there are reasons to believe porosity is not playing a significant role:
  - The shock is predicted to be strong even long after the end of the pulse: \( P_{\text{shock}} \sim 4 \text{ Mbar} \)
  - Radiation from the shock front is estimated to cause void closure and homogenize shocked foams***

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