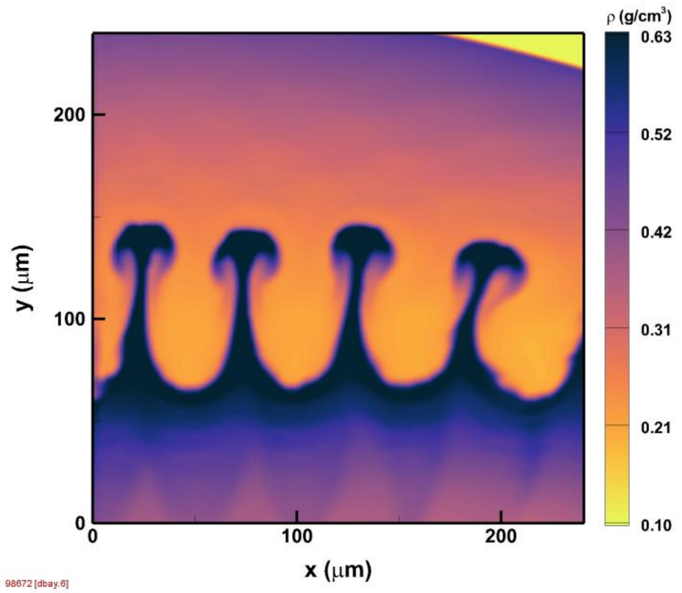
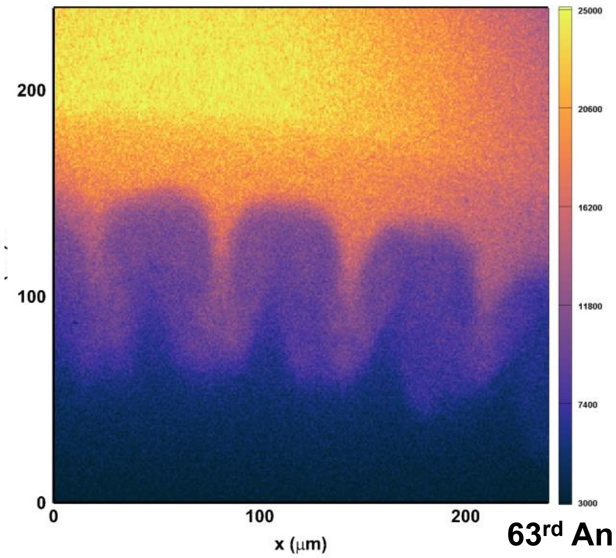
Theory and Modeling of Blast-Wave—Driven Interfacial Hydrodynamiclinstability in OMEGA Planar Experiments





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Summary

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

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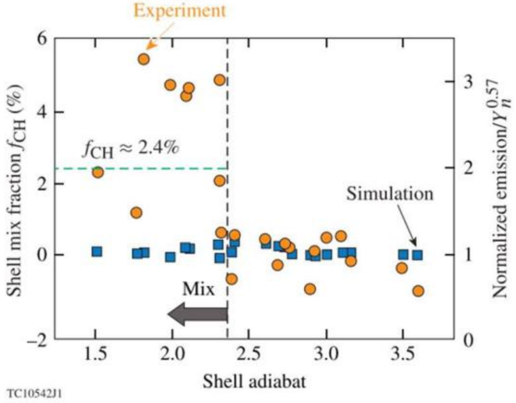
Fuel-ablator mix due to interfacial instability growth is a possible cause of performance degradation in LDD ICF implosions

- 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

Excess photon yield: indicator of fuel-shell mix



See S. Miller et al., JO04.00007

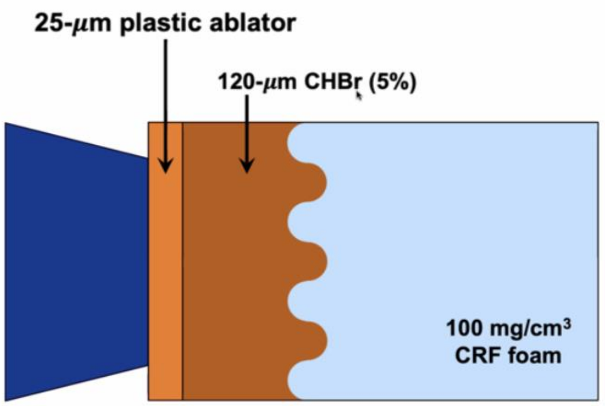
LDD: Laser direct-drive

* I. V. Igumenshchev, V. N. Goncharov, W. T. Shmayda et al., Phys. Plasmas 20, 082703 (2013).

** T. C. Sangster, V. N. Goncharov, R. Betti et al., Phys. Plasmas 20, 056317 (2013); R. Epstein, V. N. Goncharov, F. J. Marshall et al., Phys. Plasmas 22, 022707 (2015); see also V. N. Goncharov, T. C. Sangster, R. Betti et al., Phys. Plasmas 21, 056315 (2014).

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, 7×10^{14} W/cm^2, 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, λ = 50 μm wavelength perturbation (so $A/\lambda \sim 0.2$)
- This platform uses ambient targets, with the goal of transitioning to D_2 cryogenic cells, multiple shocks, and ICF-relevant perturbations

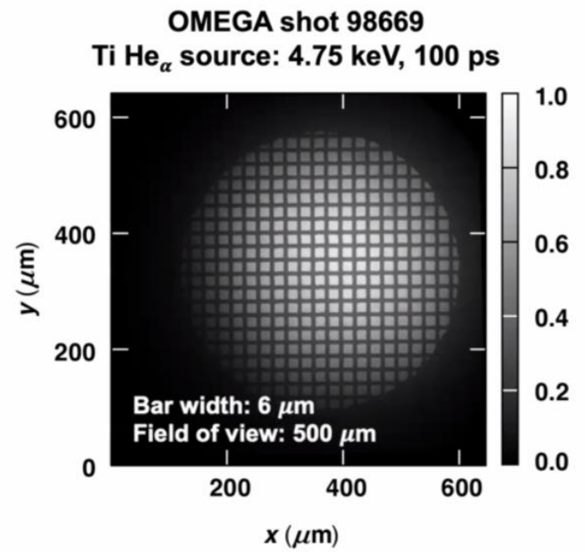


See P. Nilson et al., BO03.00008

DPP: Distributed Phase Plate
CRF: Carbonized resorcinol-formaldehyde

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 μm resolution
- Radiographs are taken late in time when spike speed is small, minimizing motion blurring: $V_{spike}\Delta t_{exp}$ ~ (53 km/s)×(100 ps) ~ 5 μm
- Experiments allow determination of the mix-region size, to test modeling in the challenging, highly nonlinear growth regime

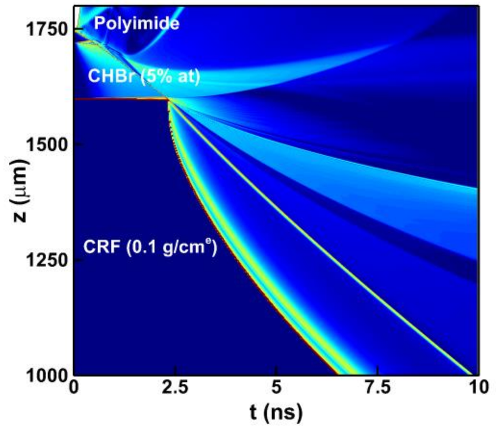


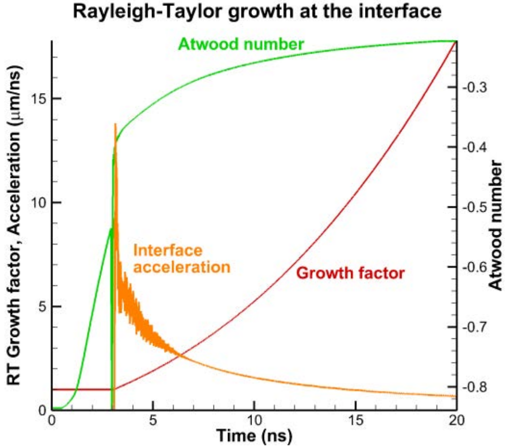
FZP grid test image

FZP: Fresnel Zone Plate

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, $\text{Kn} \ll 1,\ \text{Re} \ll 1$; 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):
  - $G_{RT}\left(10\ \text{ns}\right) \approx \exp\int dt\sqrt{Agk} \sim 20$; $A \sim 1/2$, $g \sim 3\ \mu\text{m/ns}^2$, $k = 2\pi/50\ \mu\text{m} = 0.12\ \mu\text{m}$
  - $G_{RM}\left(10\ \text{ns}\right) \approx 1 + Ak\left(\Delta u\right)t \sim 14$; $\Delta u \sim 30\ \mu\text{m/ns}$
- The combination of these leads to a growing mix region at the interface which quickly becomes nonlinear

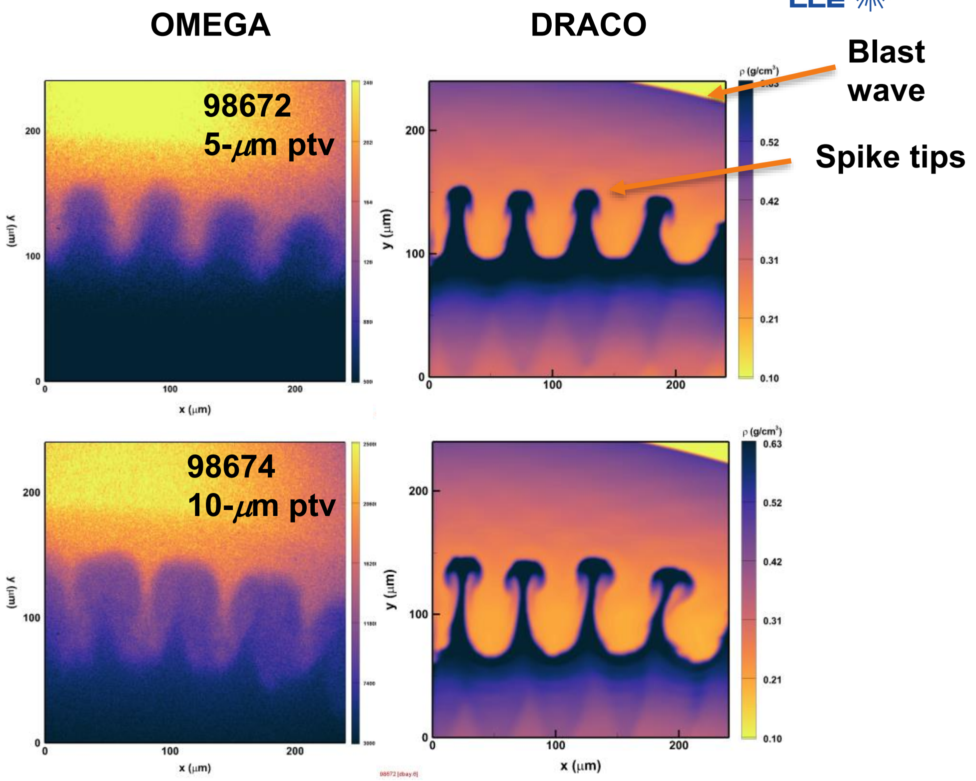




RMI: Richtmyer-Meshkov Instability
RTI: Rayleigh-Taylor Instability

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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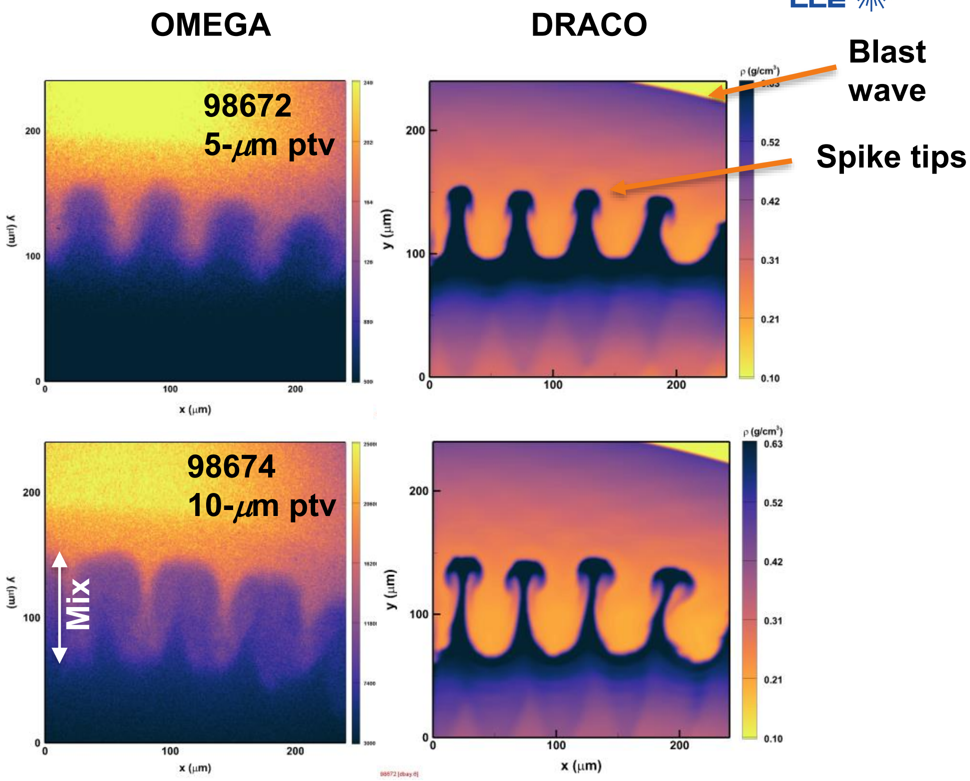


PPM: Piecewise Parabolic Method

An “air gap” between the perturbed CHBr and the foam affects the spike morphology

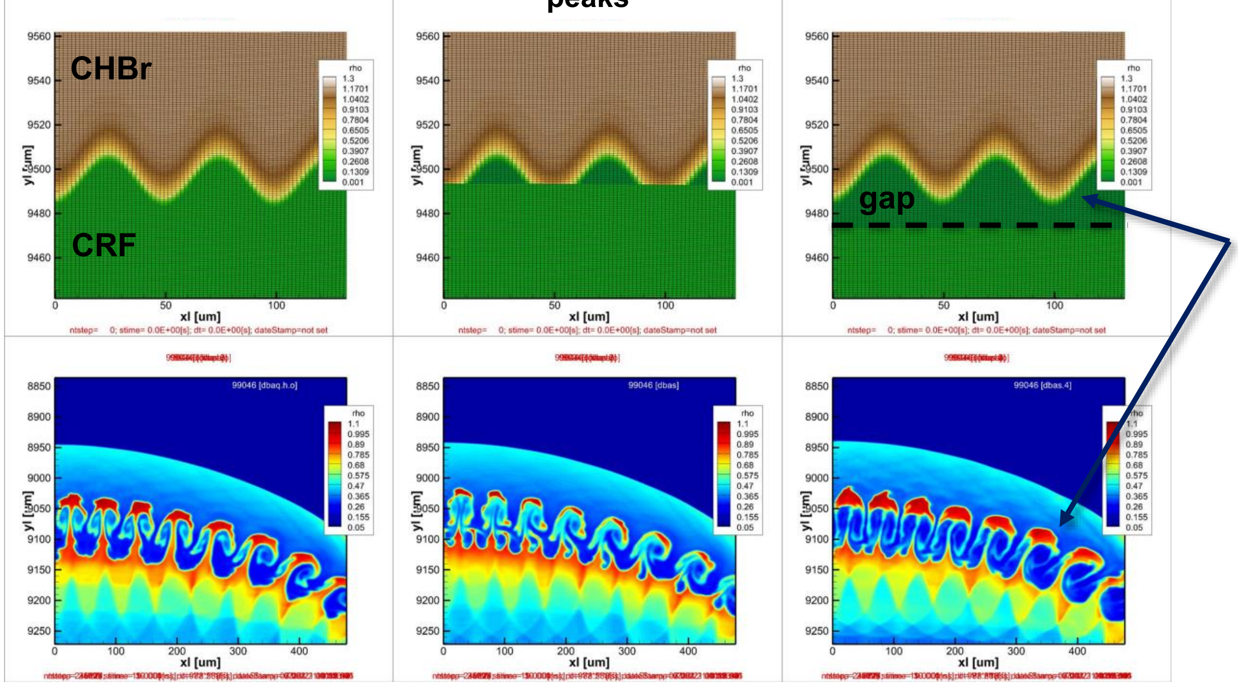
- Little is known about the region where the two layers meet, which can have an observable effect

No gap

Gap, truncated peaks

“Air” gap

Shot 99046



- “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

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: $\varphi = \rho_{\text{ave}}/\rho_{\text{C}} \approx 0.95$
  - 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 ~ 5 MPa << P_{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_{shock} ~ 4 Mbar
  - Radiation from the shock front is estimated to cause void closure and homogenize shocked foams***

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* Ya. B. Zel'dovich, Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*
** F.-M. Kong, S. R. Buckley, C. L. Giles, Jr. et al., UCRL-LR-106946 (1991).
*** P. Belancourt, "Strong Shock Waves in Highly Porous Materials, Ph. D. thesis, U. Michican (2019).

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