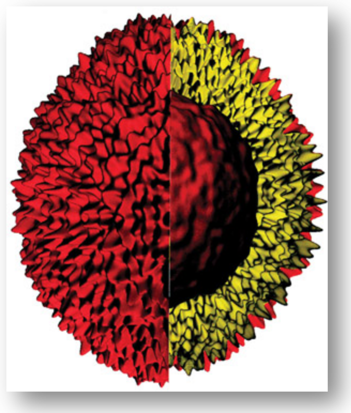
Blast-Wave-Driven Rayleigh-Taylor Instability Growth in Low-Density-Contrast Systems: Experimental Results and Future Directions

L. Elgin[1], T. Handy[1], G. Malamud[1,2], C.M. Huntington[3], S.R. Klein[1], M.R. Trantham[1], R.P. Drake[1], A. Shimony[2], C.C. Kuranz[1]

[1] University of Michigan, Ann Arbor, MI; [2] Nuclear Research Center – NEGEV, Israel; [3] Lawrence Livermore National Laboratory, Livermore, CA

Motivation



ICF capsule implosion [3]

The Rayleigh-Taylor instability (RTI) causes fluid layers to interpenetrate and mix during supernovae explosions and inertial confinement fusion capsule implosions, ultimately affecting the outcome of these systems. Potential flow models predict two RTI growth phases: 1) a linear stage characterized by exponential growth, 2) a nonlinear stage where heavy-fluid spikes and light-fluid bubbles reach a terminal velocity and constant Froude number [1]. When the density contrast of the two fluids is small, numerical simulations show an unexpected re-acceleration and higher Froude number in the late nonlinear stage [2]. Our goal is to obtain experimental observations of RTI growth in this regime.

Classical model of single-mode RTI growth in nonlinear stage [1]:

RT growth rate:

$$\gamma_{RT} = \sqrt{\frac{2\pi}{\lambda} A(t) g(t)}$$

Atwood number:

$$A = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$$

ρ_1 : density of heavy fluid
ρ_2 : density of light fluid
g : acceleration
λ : perturbation wavelength

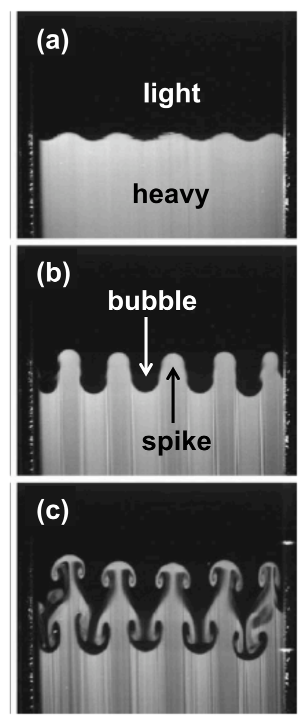
Terminal velocity:

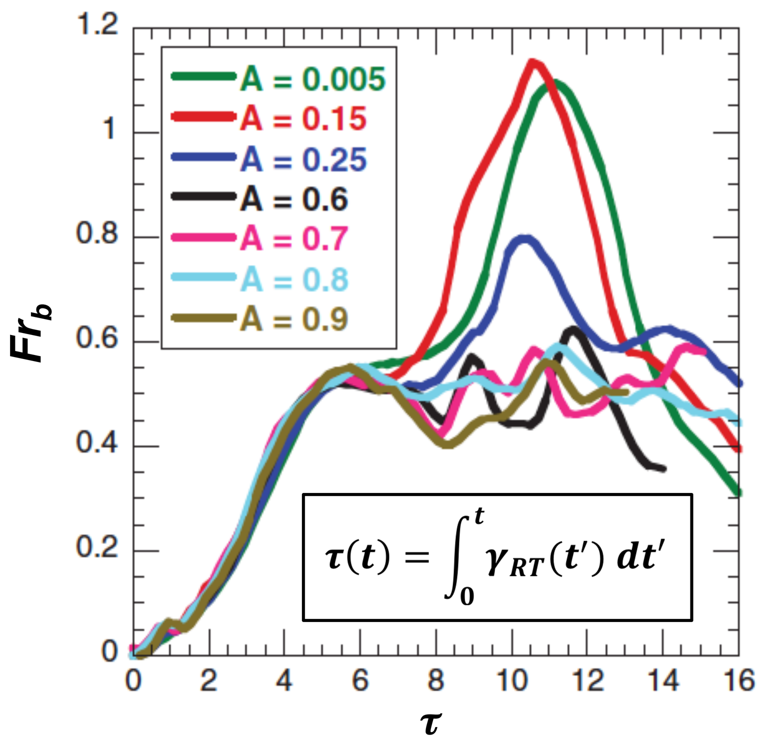
$$u_{b,s} = \sqrt{\frac{Ag\lambda}{C\pi(1 \pm A)}}$$

Constant Froude number:

$$Fr_{b,s} = \frac{u_{b,s}}{\sqrt{\frac{Ag\lambda}{1+A}}}$$

where
b: bubble tip, s: spike tip, $C = \begin{cases} 3 \text{ for 2D} \\ 1 \text{ for 3D} \end{cases}$

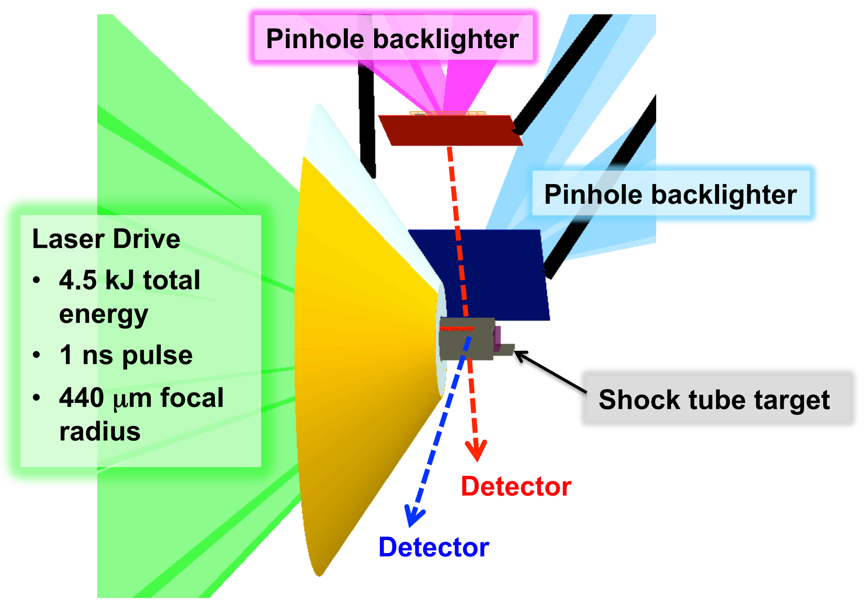


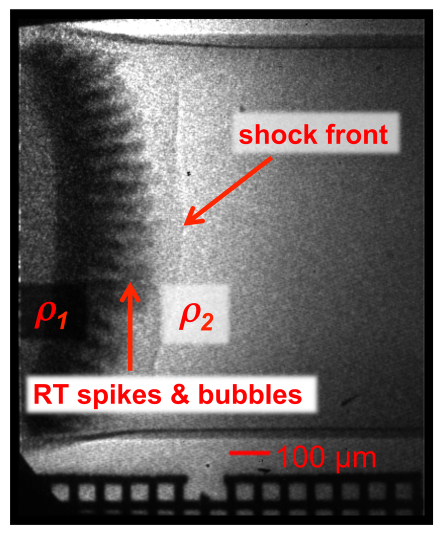


Left: Classical fluids drop-tank experiment by Wilkinson and Jacobs [4] showing RTI growth in (a) linear and (b,c) nonlinear stages

Right: 3D hydrodynamics simulations from Ramaprabhu *et al.* [2] showing evolution of bubble Froude number for various density contrasts. Reacceleration occurs in the late nonlinear stage (7 < τ < 11) for A ≤ 0.25

Experimental Platform at Omega 60





- **Laser beams create a blast wave that drives RTI growth at a planar interface between two materials of different densities inside a shock tube**
- **A series of X-ray radiographs along two orthogonal axes capture the evolution of the mixed fluid region**

Target Design

Photograph of target exterior

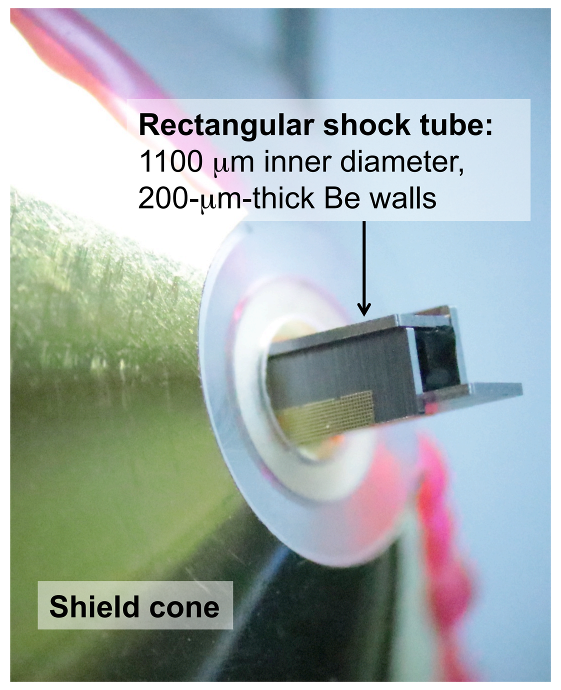
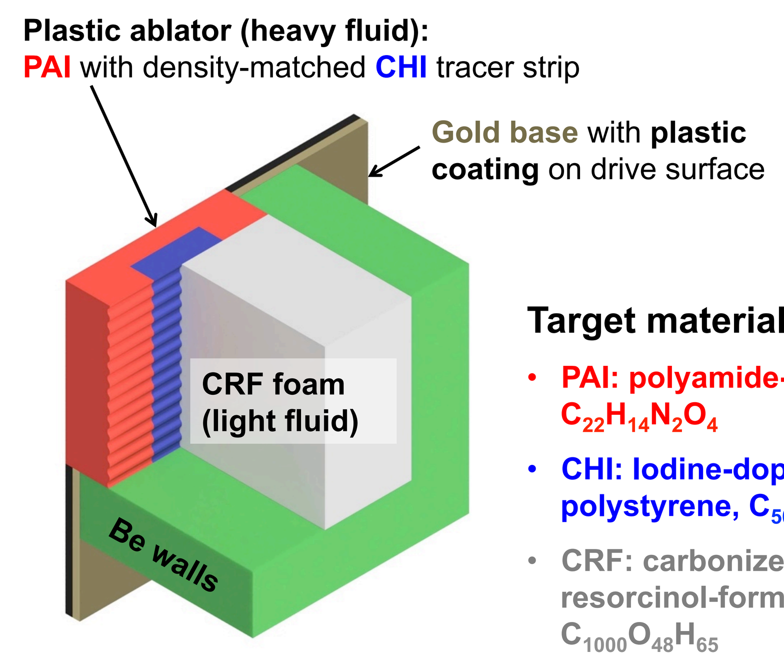


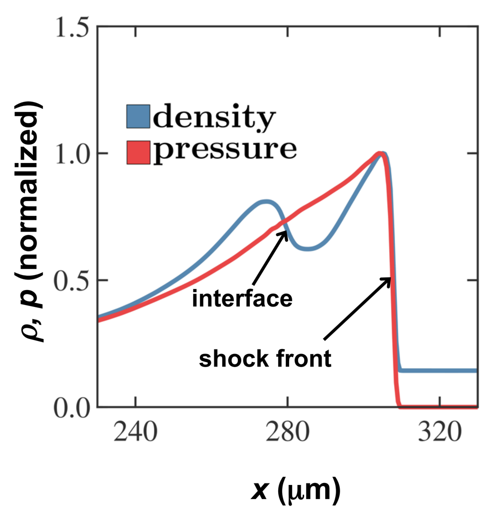
Illustration of target interior

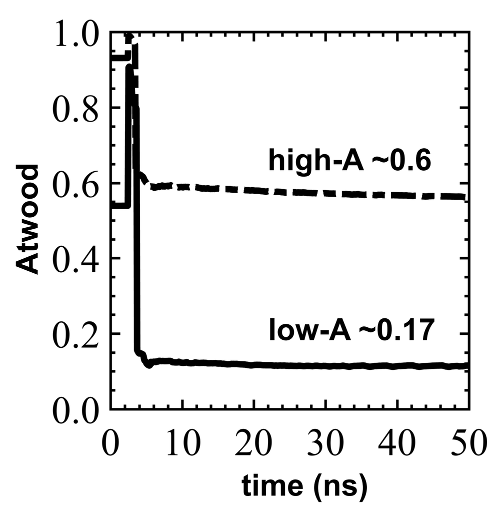


Target materials:

- **PAI: polyamide-imide, $C_{22}H_{14}N_2O_4$**
- **CHI: Iodine-doped polystyrene, $C_{50}H_{47}I_3$**
- **CRF: carbonized resorcinol-formaldehyde, $C_{1000}O_{48}H_{65}$**

1D CRASH simulations





- **Blast wave creates pressure gradient in opposition to density gradient at interface**
- **Post-shock Atwood number predicted from simulations with initial densities:**

PAI, CHI: ρ_1 = 1.4 g/cc
CRF: ρ_2 = 0.05 g/cc (high-A)
0.40 g/cc (low-A)

- **2D or 3D sinusoidal pattern machined at the interface seeds single-mode instability growth**

$$h_{2D} = a_{2D} \cos\left(\frac{2\pi}{\lambda} y\right)$$

$$h_{3D} = a_{3D}\left(\cos\left(\frac{2\pi}{\lambda} x\right) + \cos\left(\frac{2\pi}{\lambda} y\right)\right)$$

with:

- λ = 40 μm
- a_{2D} = 2 μm, a_{3D} = 1 μm
- a_{PTV} = 4 μm (2D and 3D)

- **Both RTI and material decompression contribute to growth of mixed region:**

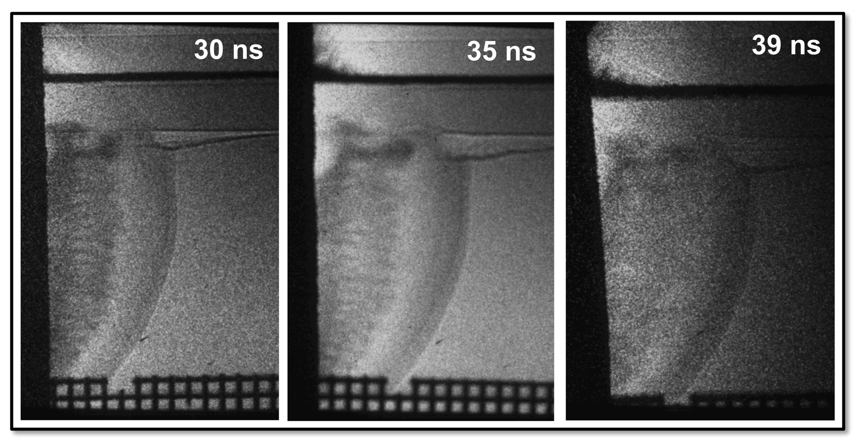
Bubble or spike height due to RTI growth:

$$h_{b,s}(t) = R_{b,s}(t) - R_{int}(t) - \int_0^t \left(u_{b,s}(t') - u_{int}(t')\right) dt'$$

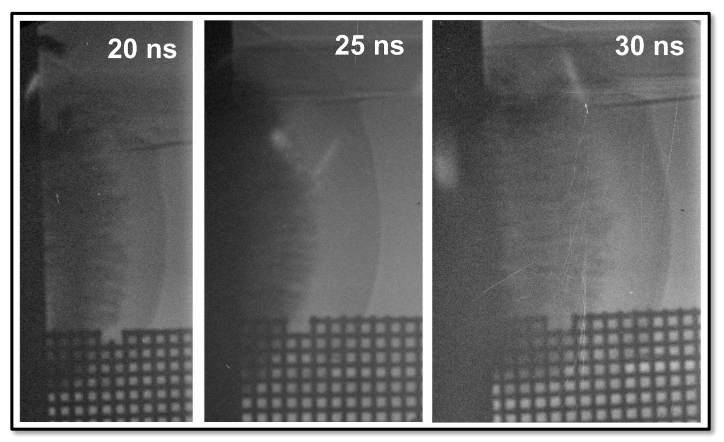
bubble or spike tip position; interface position; material decompression

Low-A Experimental Results

April 2018 experiment: 2D targets



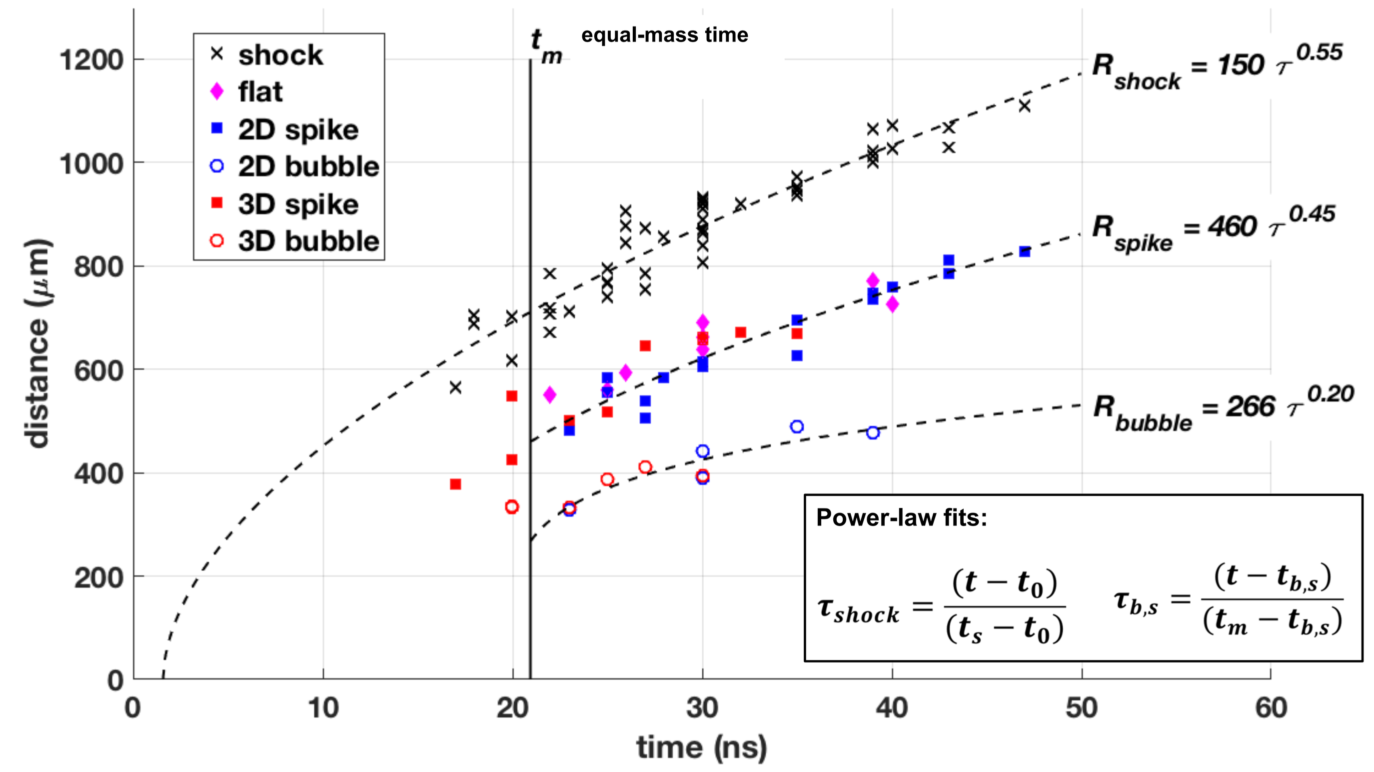
July 2018 experiment: 3D targets



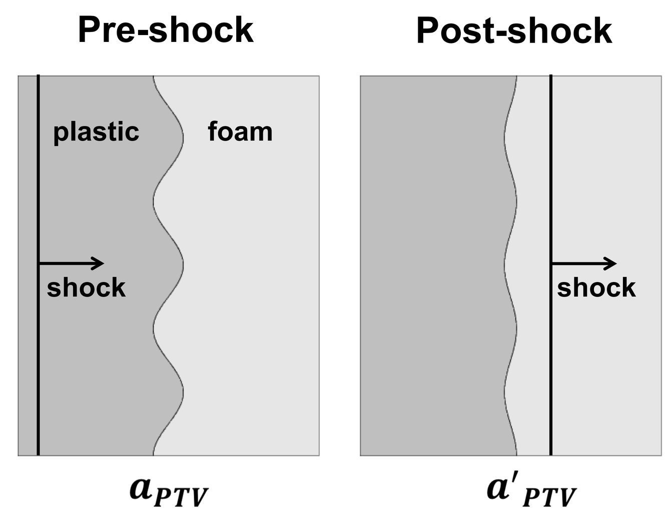
Fiducial grid: 64 μm pitch

Data Analysis

Combined Low-A Experimental Data (2017-2018)



- **Shock wave inverts and compresses initial modulation, prior to RTI growth phase [5]**



Initial interface position: $R_0 = 150\, \mu m$

Shock break-out time from plastic: $t_s = 2.7\, ns$

Shock velocity in plastic: $u_{s1} = \frac{R_0}{t_s} = 56\, \mu m/ns$

Shock transit time across interface: $\Delta t \approx \frac{a_{PTV}}{u_{s1}}$

Shock velocity in foam*: $u_{s2} = \begin{cases} 90\, \mu m/ns, & \text{high-A} \\ 73\, \mu m/ns, & \text{low-A} \end{cases}$

*Calculated from power-law fits to experimental data

Estimated post-shock peak-to-valley amplitude: $a'_{PTV} \approx u_{s2}\Delta t - a_{PTV} = \begin{cases} 2.4\, \mu m, & \text{high-A} \\ 1.2\, \mu m, & \text{low-A} \end{cases}$

Conclusions:

- After 25 ns, acceleration is negligible and material decompression dominates
- Spike and bubble fronts converge for 2D, 3D, and "flat" targets, indicating loss of single-mode initial conditions
  - Post-shock amplitude of λ=40 μm mode is small for low-A design
  - Target imperfections (of comparable magnitude) could seed RTI growth with complex, multi-mode spectrum

On-going and Future Work

- Refine simulations based on experimental results
- Analyze spectral content of radiography data
- Design experiment for NIF, which could drive single-mode RTI to later times

References

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