High-Energy-Density Physics Experiments at OMEGA 60: Evolution of the Rayleigh-Taylor Instability to the Highly Nonlinear Regime*

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Motivation

Potential flow models predict two growth stages of the Rayleigh-Taylor instability (RTI): 1) a linear stage characterized by exponential growth of spikes and bubbles, 2) a nonlinear stage where spikes and bubbles reach a terminal velocity and constant Froude number [1]. When the density contrast between the two fluids is small, numerical simulations show an unexpected re-acceleration phase and higher Froude number in the late nonlinear regime [2]. Experimental data is needed to understand the late-time evolution of RTI.

The Froude number is the ratio of the inertial force to the force due to acceleration. For classical RTI, the single-mode growth rate (γ_{RT}), bubble terminal velocity (u_b) and Froude number (Fr_b) are:

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

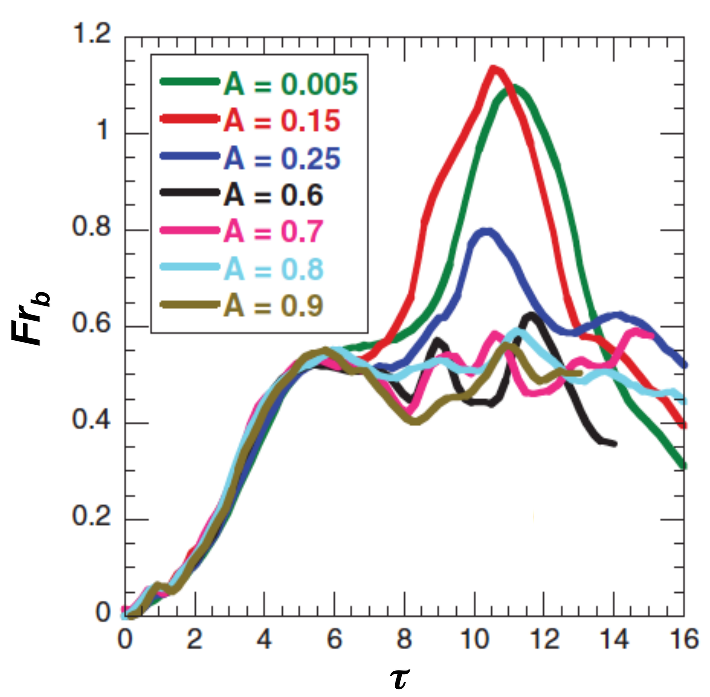
Atwood number:

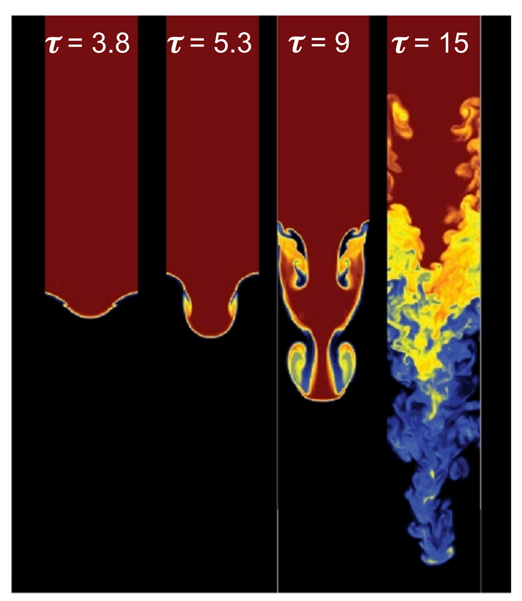
$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

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

$$u_b = \sqrt{\frac{Ag\lambda}{C\pi(1+A)}} \qquad Fr_b = \frac{u_b}{\sqrt{\frac{Ag\lambda}{1+A}}} = \frac{1}{\sqrt{C\pi}}$$

where $C = \begin{cases} 3 \text{ for 2D} \\ 1 \text{ for 3D} \end{cases}$





Temporal scaling:

$$\tau = \int \gamma_{RT}\, dt$$

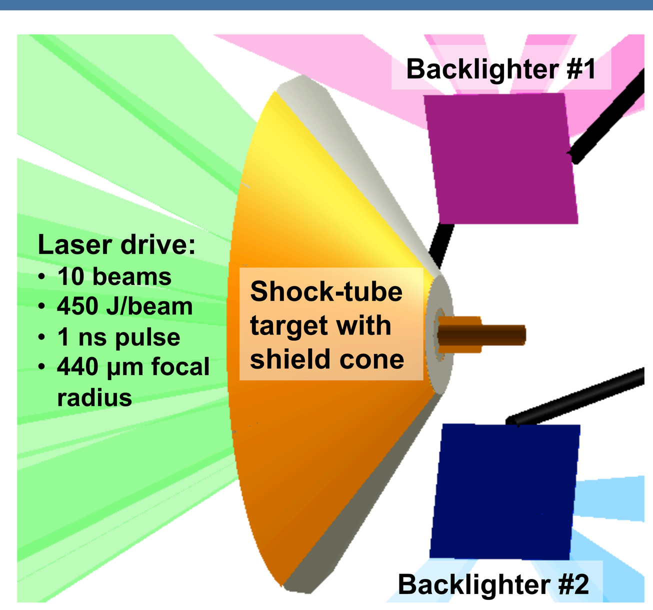
3D hydrodynamics simulations from Ramaprabhu *et al.* [2]:

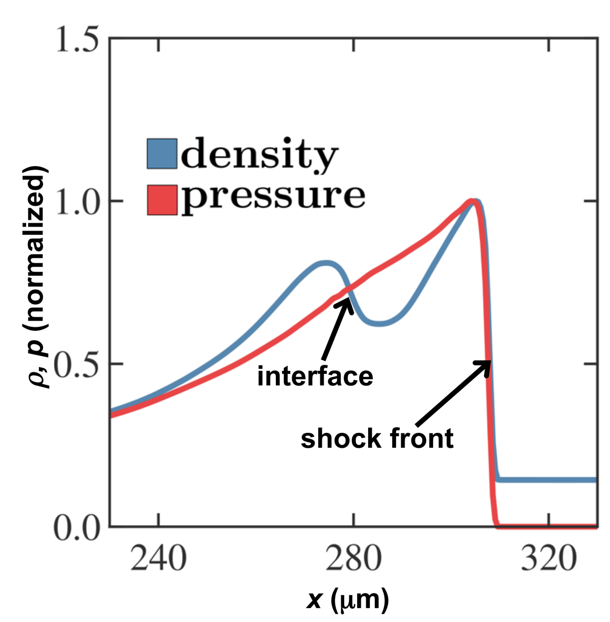
Left: evolution of bubble Froude number for various density contrasts.

Right: spike and bubble realizations for A=0.15 system in the linear (τ=3.8), nonlinear (τ=5.3), and highly nonlinear (τ=9) stages, and eventual chaotic mixing (τ=15).

We are developing an experimental platform at OMEGA 60 to drive single-mode RTI growth to the late nonlinear regime in low- and high-Atwood number systems.

Experimental Platform



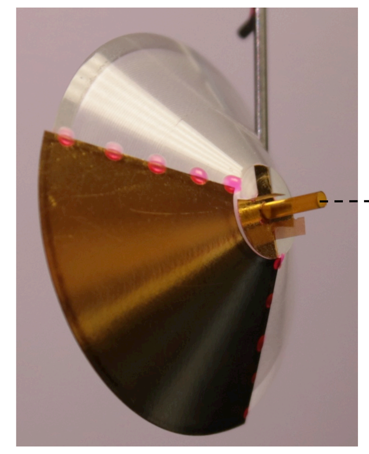


Left: Visrad model of OMEGA 60 target chamber setup.

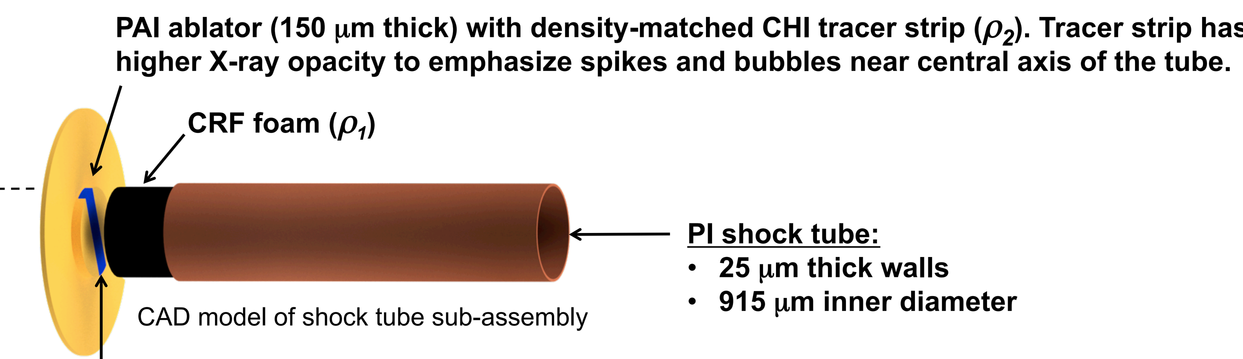
Right: 1D CRASH simulation: Behind the shock wave, the pressure gradient opposes the density gradient at the interface.

- Laser beams create a blast-wave that drives RTI growth at the 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 spikes and bubbles.

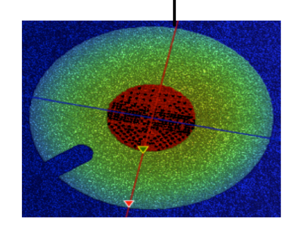
Target Design for First Experiment



Photograph of target



CAD model of shock tube sub-assembly

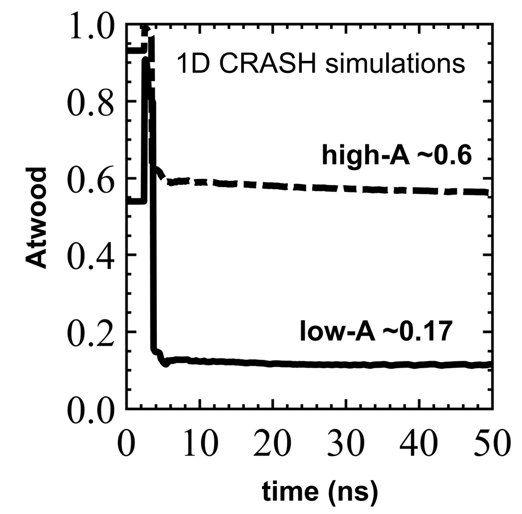


White-light interferometer scan of PAI surface pattern

3D single-mode sinusoidal seed perturbation is machined at interface:

$$h = a\cos\left(\frac{2\pi}{\lambda}x\right) + a\cos\left(\frac{2\pi}{\lambda}y\right)$$

where λ = 71 or 40 µm, a =1 µm



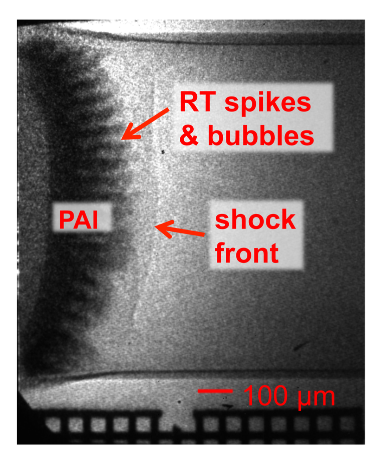
- **Shorter wavelength corresponds to later scaled time:**

$$\tau(t) = \int_0^t \sqrt{\frac{2\pi}{\lambda} A(t') g(t')}\, dt'$$

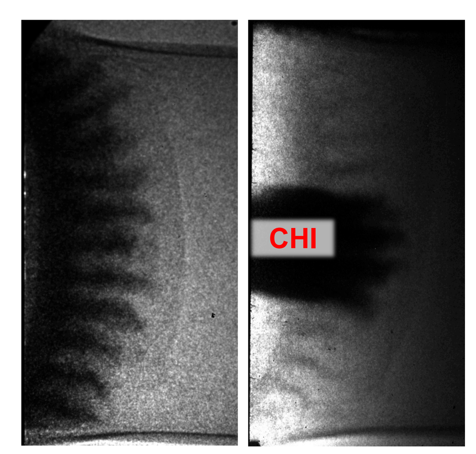
- **Post-shock Atwood number is predicted from simulations with initial densities:**

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

First Experimental Results: October 2016



High-A, λ=40 µm target at 15 ns

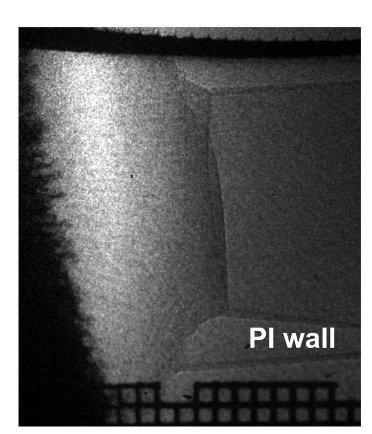


Simultaneous radiographs along orthogonal axes: High-A, λ=71 µm target at 15 ns

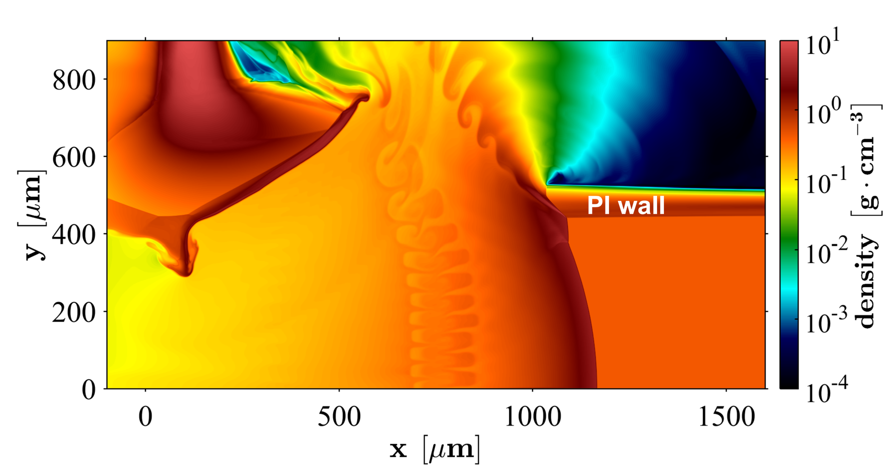
We successfully demonstrated:

- **Radiography on two orthogonal axes with image resolution ~10 µm.**
- **Observation of shock front, RT spikes and bubbles in λ=71 and 40 µm high-A targets.**

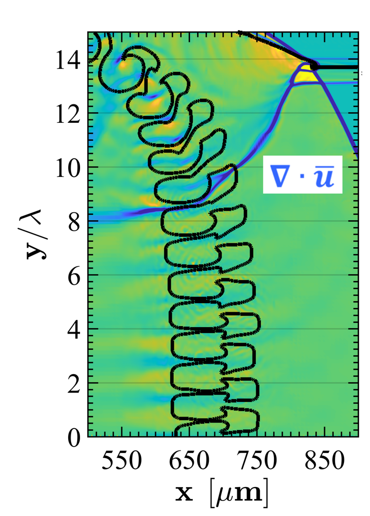
Higher internal pressure inside the low-A targets caused PI shock tubes to breach.



Radiograph of low-A target at 40 ns



2D CRASH simulation at 40 ns

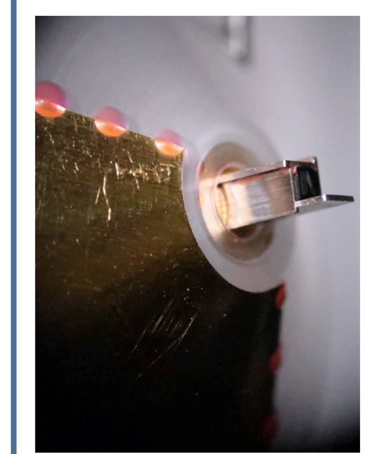


2D CRASH simulation: divergence of velocity field (blue contours)

2D CRASH simulations:

- **Confirmed initial experimental results**
- **Revealed transverse waves propagating inward from tube walls, which will limit observation of RTI growth at late times**
- **Guided a new shock tube design**

New Target Design for April 2017 Experiment



Photograph of target

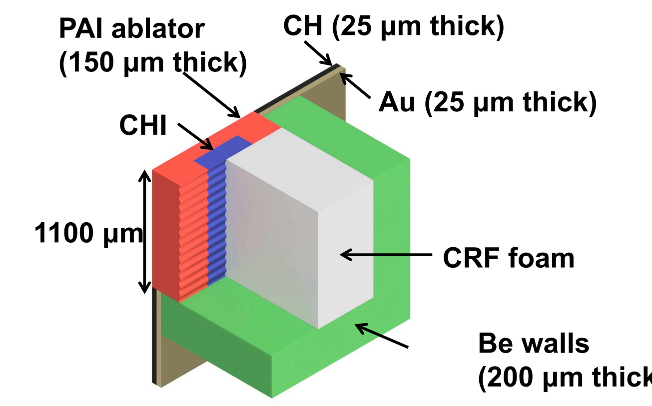


Illustration of new target features

- X-ray transmission through 200 µm Be is comparable to 25 µm PI, allowing walls to be much thicker
- Shock tube inner diameter increased from 915 to 1100 µm, extending time scale before transverse waves affect on-axis RTI growth

Targets with 3D and 2D perturbations:

- Useful to compare 3D and 2D growth rates to models
- 2D simulations aid experimental design and data analysis with faster turn-around time

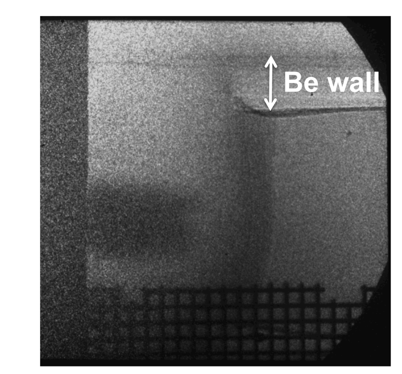
$$h_{3D} = a_{3D}\cos\left(\frac{2\pi}{\lambda}x\right) + a_{3D}\cos\left(\frac{2\pi}{\lambda}y\right)$$

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

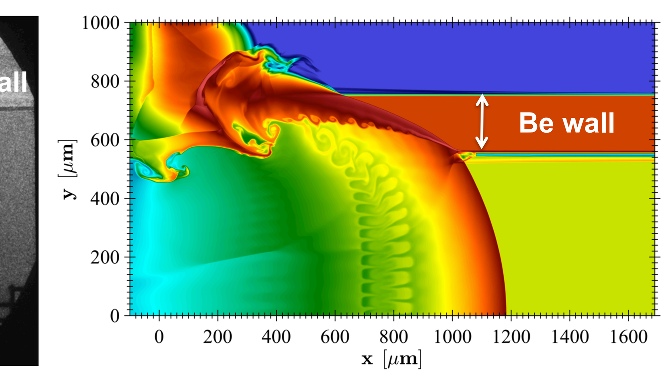
where λ = 40 µm, a_{3D} =2 µm and a_{2D} =4 µm

April 2017 Experimental Results

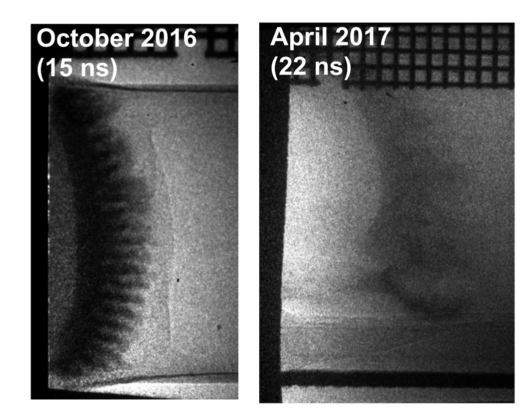
- **Shock tube walls maintained integrity, in agreement with simulations.**
- **Unfortunately, ablator manufacturing defects prevented observation of single-mode RTI growth.**



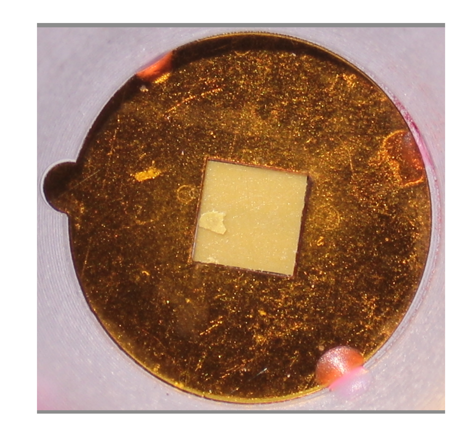
Low-A, 2D target at 40 ns



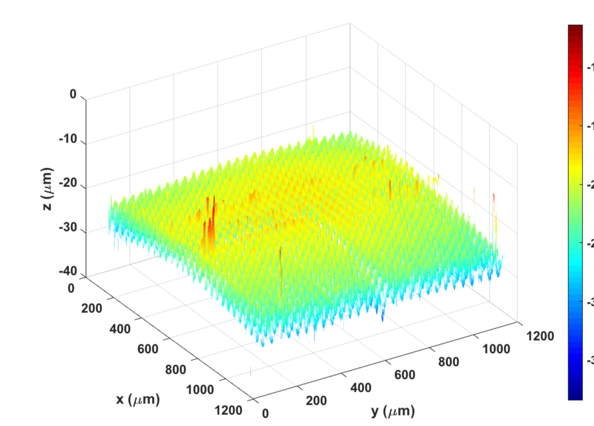
2D CRASH simulation at 40 ns



Comparison of high-A, 3D λ=40 µm data from both shot days



Laser-irradiated back surface of ablator (inside shield cone)



White-light interferometer scan of top surface of ablator with 3D pattern

- **Back surface defects introduced drive asymmetries**
- **Top surface patterns were not single-mode sinusoidal functions**
- **Macroscopic tolerance failures exposed gold shielding to laser irradiation, producing high-energy background noise in radiographs**

Future Plans

- Two more shot days are scheduled in 2018. We are working closely with the ablator manufacturer to improve parts quality.
- If we succeed in measuring RTI growth with short-wavelength, low-Atwood targets, this platform may be extended to higher energy facilities (such as NIF) to obtain data at even later scaled times.

References

1. V.N. Goncharov, Phys. Rev. Lett. **88**, 134502 (2002).
2. P. Ramaprabhu *et al.*, Phys. Fluids **24**, 074107 (2012).

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