

Blast-wave-driven Rayleigh-Taylor Instabilities

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Collaborators

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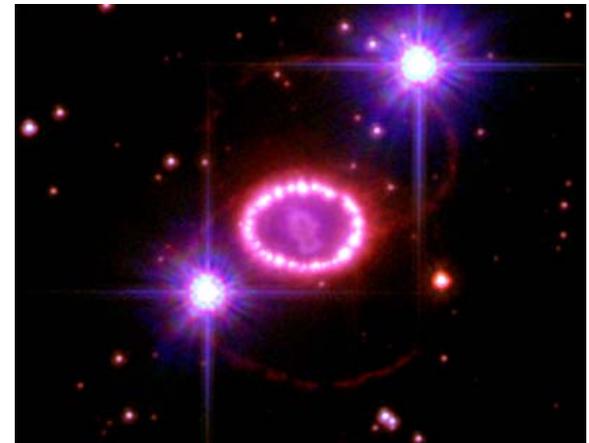
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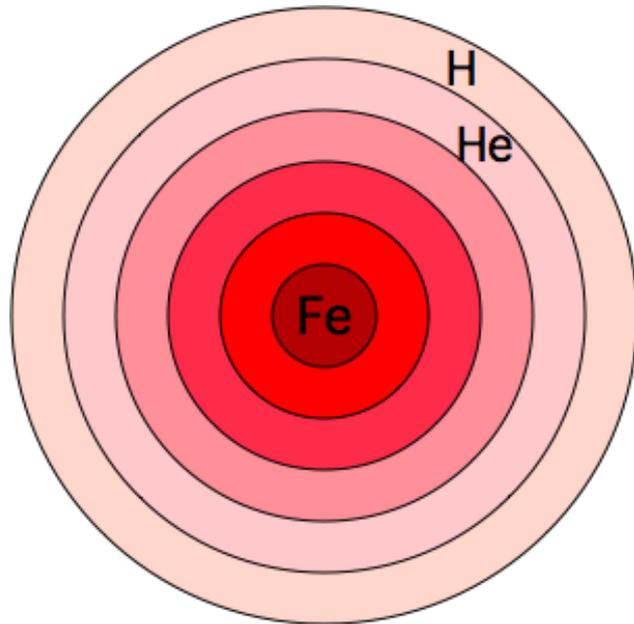
Understanding SN1987A motivates supernova hydrodynamics experiments

- Explosion occurred in February 1987
- Brightest supernova since invention of telescope
- First supernova in which progenitor star was observed prior to explosion
- About 50 kpc (168,000 light years) away
- 18 - 22 solar masses, ~ 43 solar radii
- Core-collapse supernova – first detection of neutrinos from a supernova
- Many significant discrepancies between theory and observations of light curve and spectra
- At least some of these discrepancies can be explained by mixing due to fluid instabilities during the explosion

SN1987A, Hubble Space Telescope



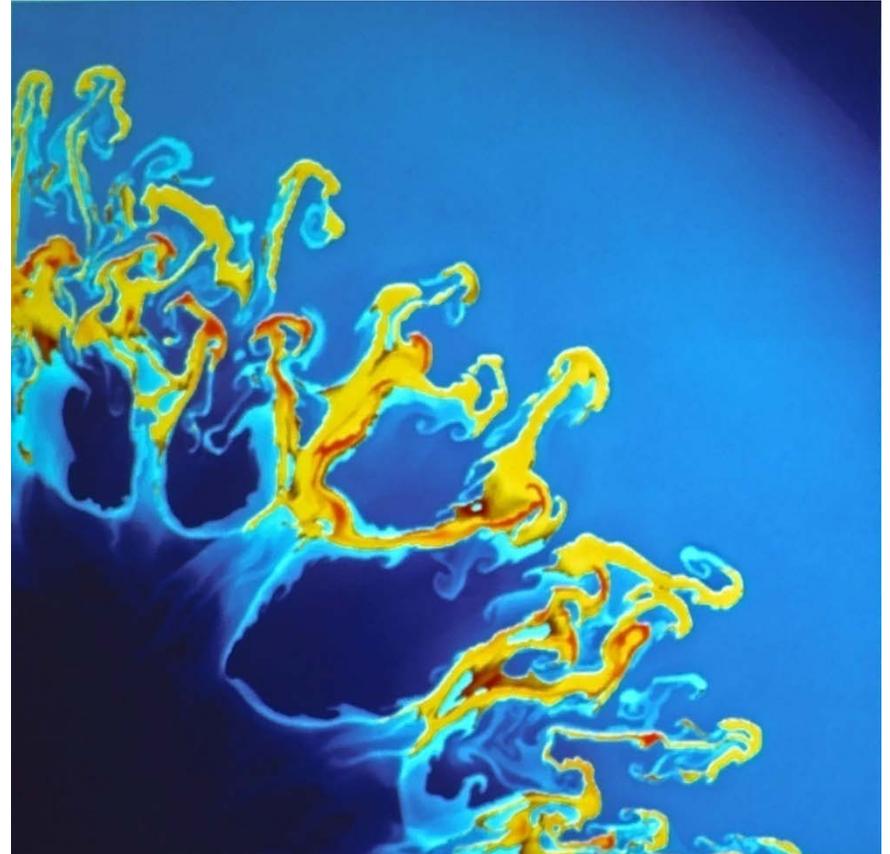
Mixing in supernovae



- Before the explosion, the star is thought to have a layered structure, with the lightest elements near the surface and the heaviest elements in the core
- In a spherically symmetric explosion, the lightest elements should have the largest expansion velocity, and the heavy elements in the core should have lower velocities
- This is contrary to what was observed, implying that there was significant large-scale mixing during the explosion
- Whenever the supernova shock crosses a composition interface, it may produce Richtmyer-Meshkov and Rayleigh-Taylor instabilities that could provide the mixing

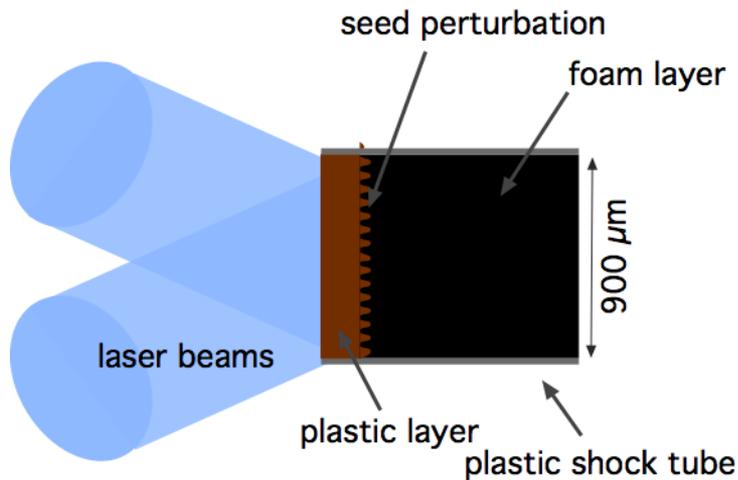
RT instability in supernova explosion

- **Simulation of RT instability in SN1987A**
- **In this model, there are instabilities at both the H-He interface and at the He-heavy element interface**

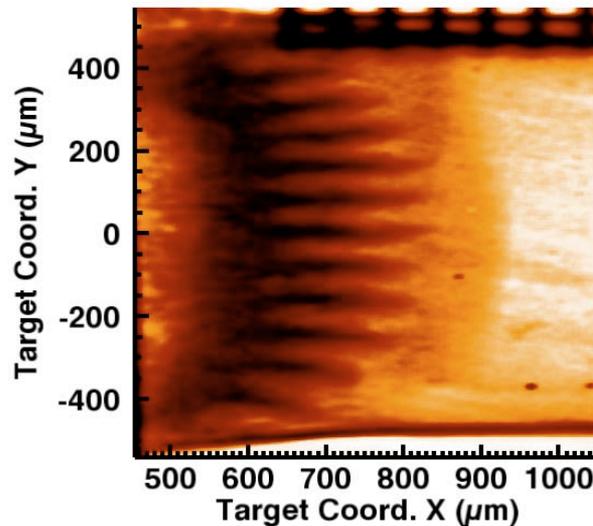


Well-scaled targets explore hydrodynamics of supernovae

- Targets scaled to conditions of blast-wave-driven H/He interface of SN1987A
- Planar blast wave leads to decelerating interface
- Interface unstable to Rayleigh-Taylor Instability



Scaled Target



Experimental Radiograph

Experiments performed at Omega laser facility

- **Ten Omega Laser beams to drive shock**
 - ~450 J each,
 - ~4.5 kJ total energy
 - 1 ns square pulse
- **Produce intensity of $\sim 9 \times 10^{14}$ W/cm²**
- **Pressure of ~50 Mbars**

The Omega Laser System



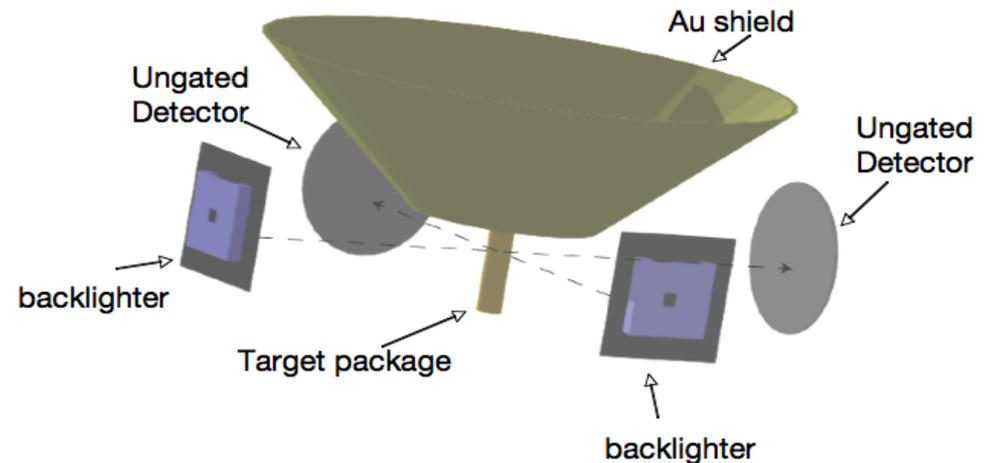
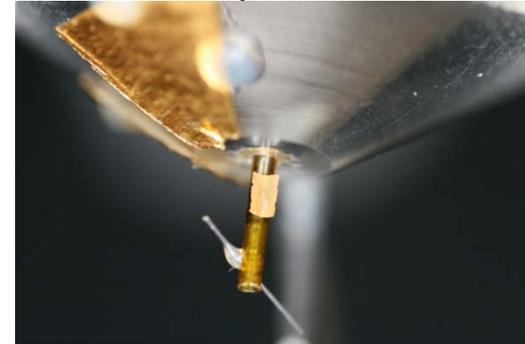
Inside the Omega target chamber

Key components of target

- **150 μm plastic (1.41 g/cc)**
 - Tracer strip material:
 $\text{C}_{500}\text{H}_{457}\text{Br}_{43}$ (1.42 g/cc)
 - Entire surface machined with seed perturbation
- **2-3 mm Carbonized Resorcinol Formaldehyde (CRF) foam (50 mg/cc)**

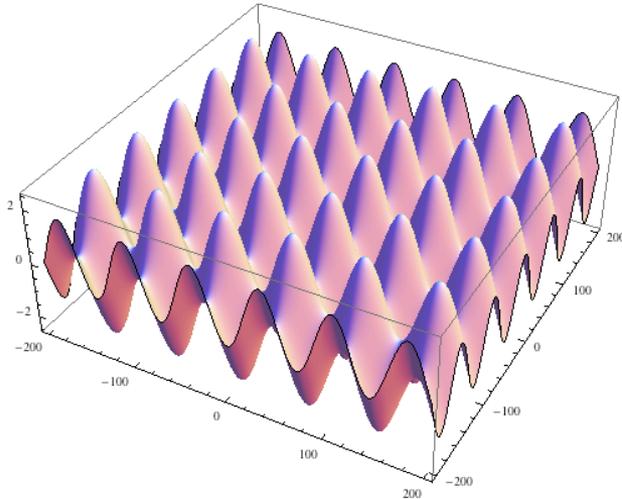
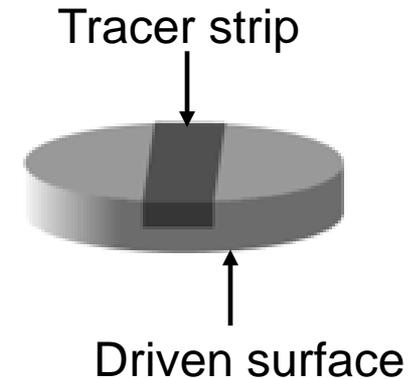


Target Fabrication:
M. Grosskopf, D. Marion

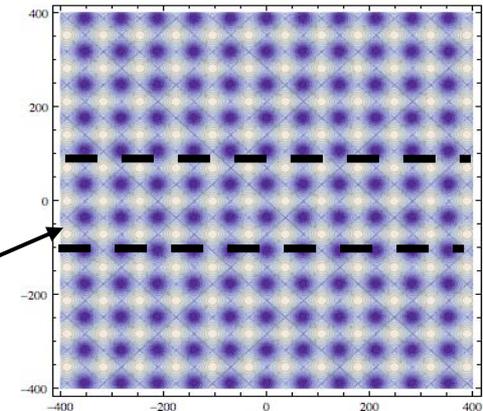


3D single mode Rayleigh-Taylor seed perturbations

- Two sine waves in orthogonal directions creates “egg crate” pattern
- Single mode:
 $a_o = 2.5 \mu\text{m}; k_x = k_y = 2\pi/(71 \mu\text{m})$

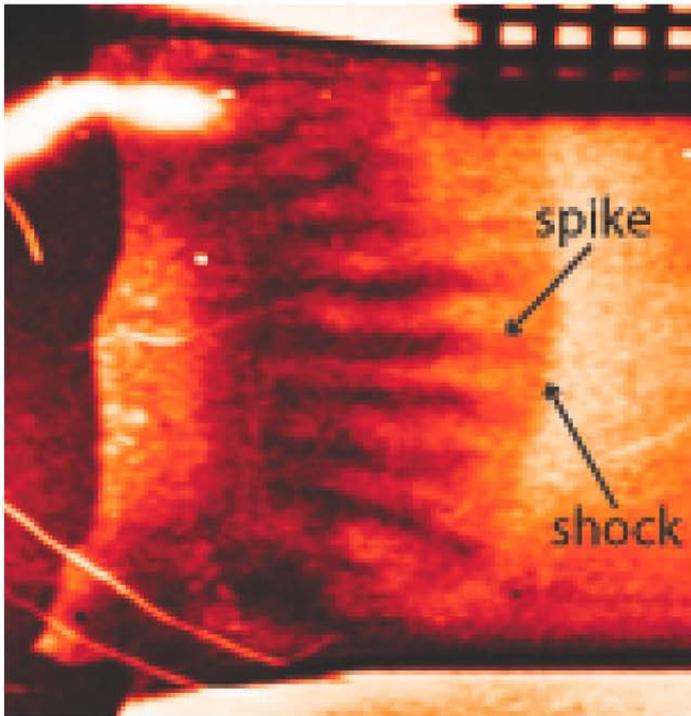


Tracer strip



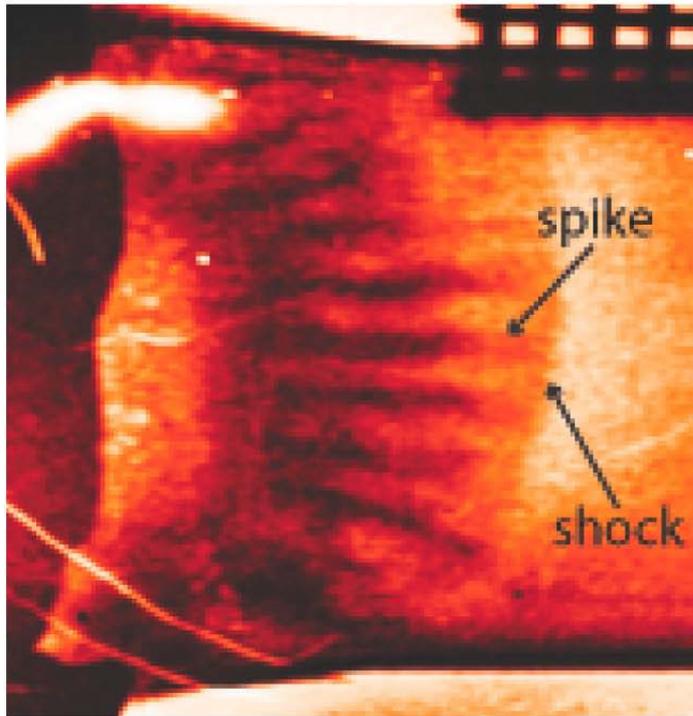
Amplitude enhanced
to show structure

Comparison of experiment to simulation

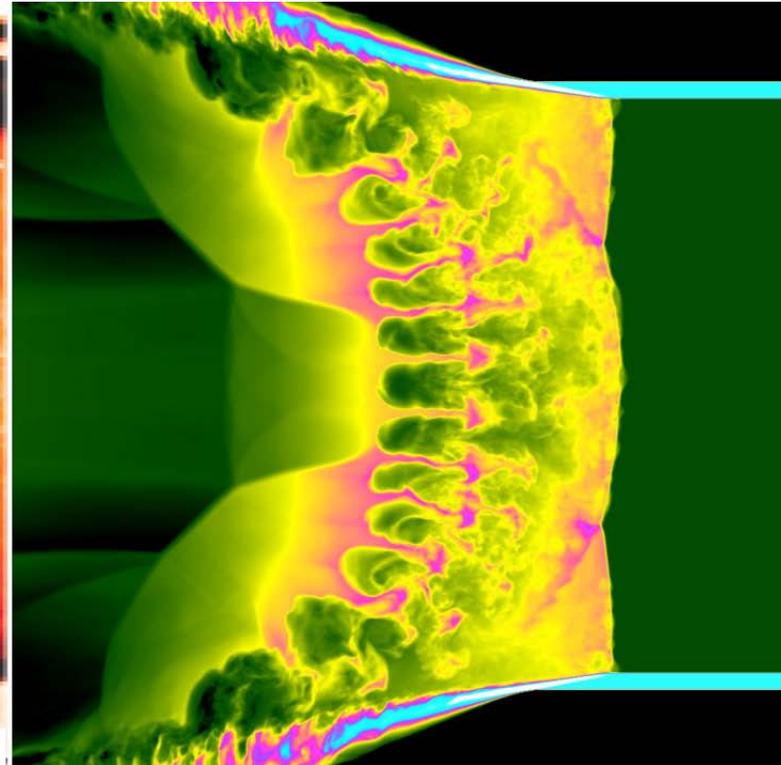


Experiment

Comparison of experiment to simulation

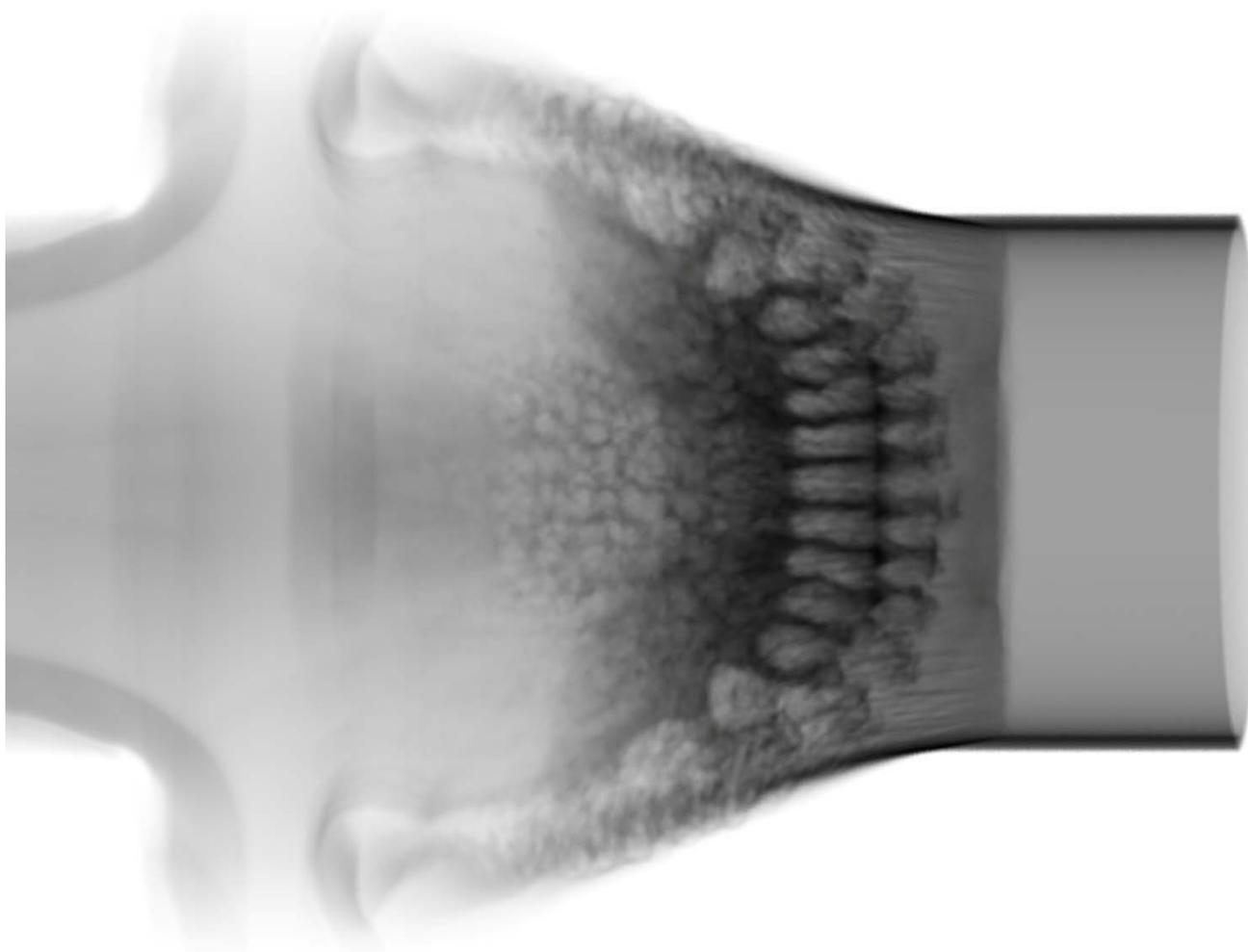


Experiment



3D FLASH simulation

Simulated radiograph



Differences between experiment and simulation

- **Spike extensions are observed in the experiment but not in the simulation**
- **Spikes penetrate to the shock front in the experiment but not in the simulation**
- **Mushroom caps at the ends of the spikes are seen in the simulation but not in the experiment**
- **Width of spikes and bubbles are comparable in the experiment, but spikes are much thinner in the simulation**

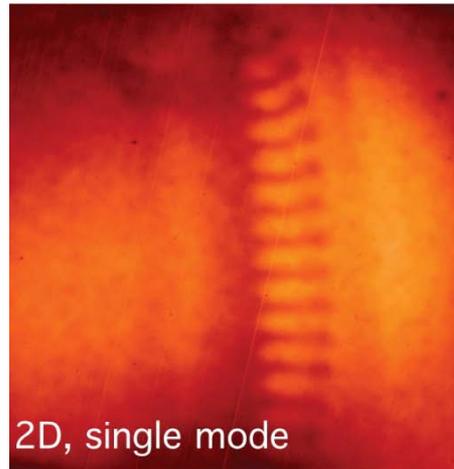


Possible causes of discrepancies

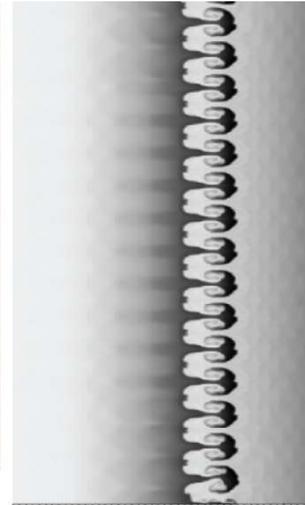
- **Mushroom caps are present in the experiment but can not be detected by the diagnostics**
- **Target alignment errors**
- **Error in simulation code**
- **Incorrect initial conditions or missing physics in simulation code**
 - **Presence of long-wavelength modes in initial conditions or gaps between components in target**
 - **Presence of a second shock wave**
 - **Turbulent mass stripping on a scale that the simulation code can not resolve**



Two-dimensional results



2D, single mode



FLASH 2D, single mode

- **Mushroom caps are seen in 2D experiments but are still smaller than predicted by simulations**
- **In 3D, mushroom caps are smaller and harder to see, but diagnostics in 3D experiments had higher resolution**

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 - **Generation of magnetic fields during the experiment**



Generation of magnetic fields

The magnetic-field generation mechanism that is relevant here is the Biermann battery effect.* An electric field is produced to balance the electron pressure,

$$\mathbf{E} = -\frac{1}{en_e} \nabla p_e$$

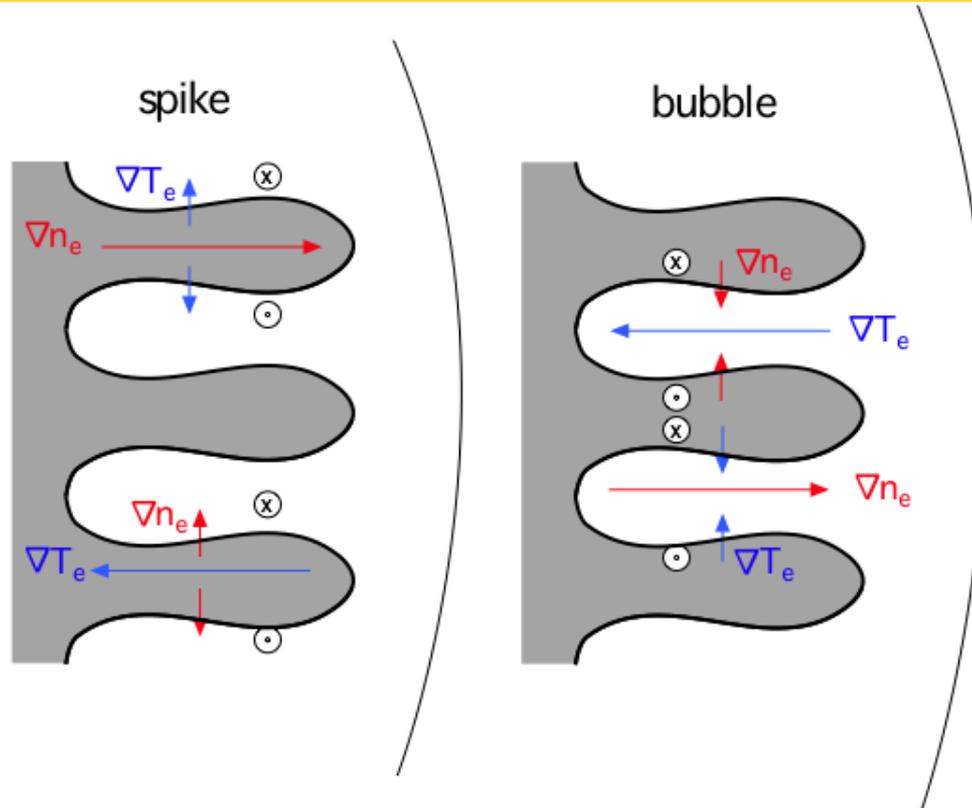
Using Faraday's law in cgs units, $\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{ck_B}{e} \left[\nabla T_e \times \nabla \ln n_e \right]$$

*Biermann (1950)



B-fields wrap around individual spikes and bubbles



An azimuthal magnetic field would have the effect of laterally confining both the spikes and bubbles and suppressing the mushroom cap formation

Approximated B-field from 1D Hyades is the same magnitude as the plasma pressure

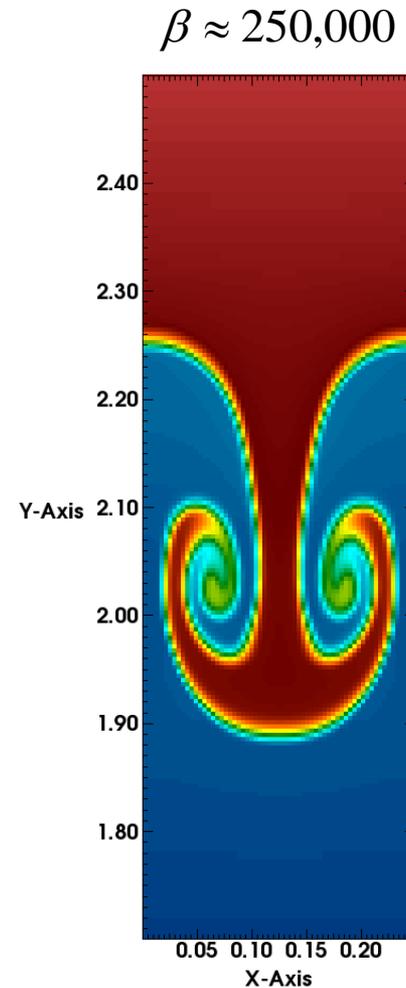
Magnetic field generation rate $\sim 2.5 \times 10^{14}$ Gauss/s
Magnetic field after 20 ns ~ 5 MGauss

Magnetic Pressure $\sim 10^{12}$ dynes/cm²
Plasma Pressure (ρu_s^2) $\sim 10^{12}$ dynes/cm²

Dissipation will likely reduce the field strength by at least an order of magnitude resulting in $\beta \geq 100$

Effect of magnetic field on spike morphology

Simplified 2D FLASH simulation of the effect of a magnetic field on spike morphology



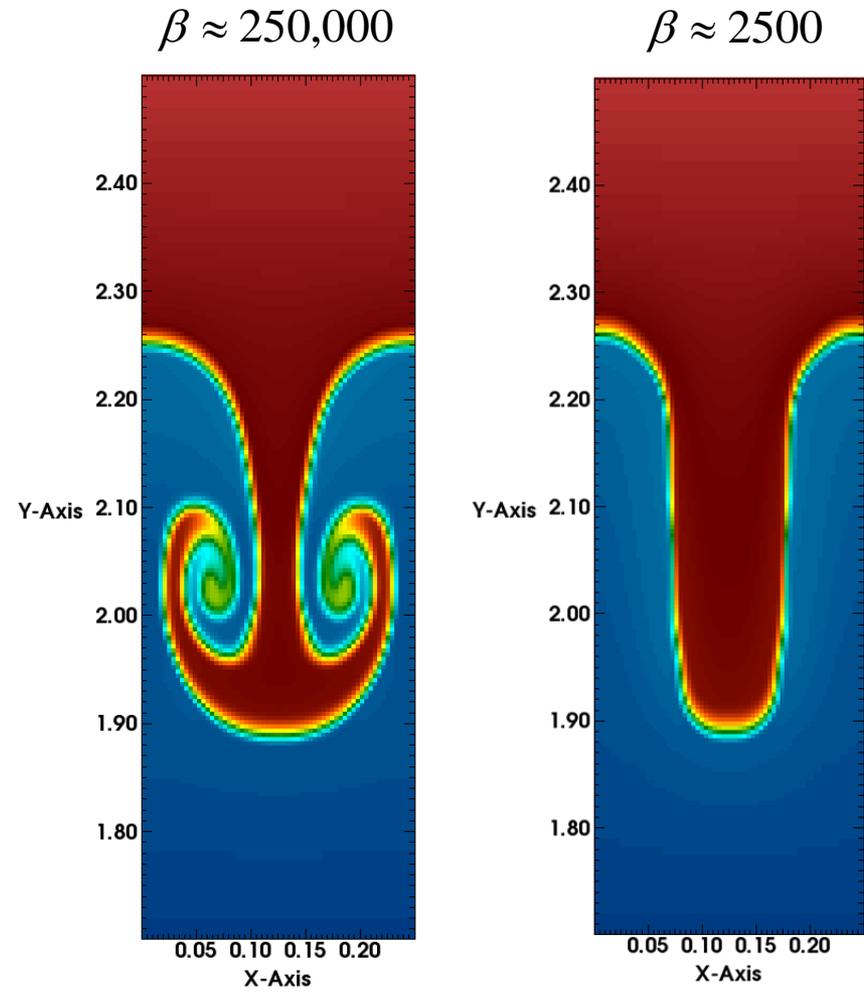
Effect of magnetic field on spike morphology

Simplified 2D FLASH simulation of the effect of a magnetic field on spike morphology

Even a fairly weak magnetic field can suppress the development of the mushroom cap

Magnetic field makes the width of the spike comparable to the width of the bubble

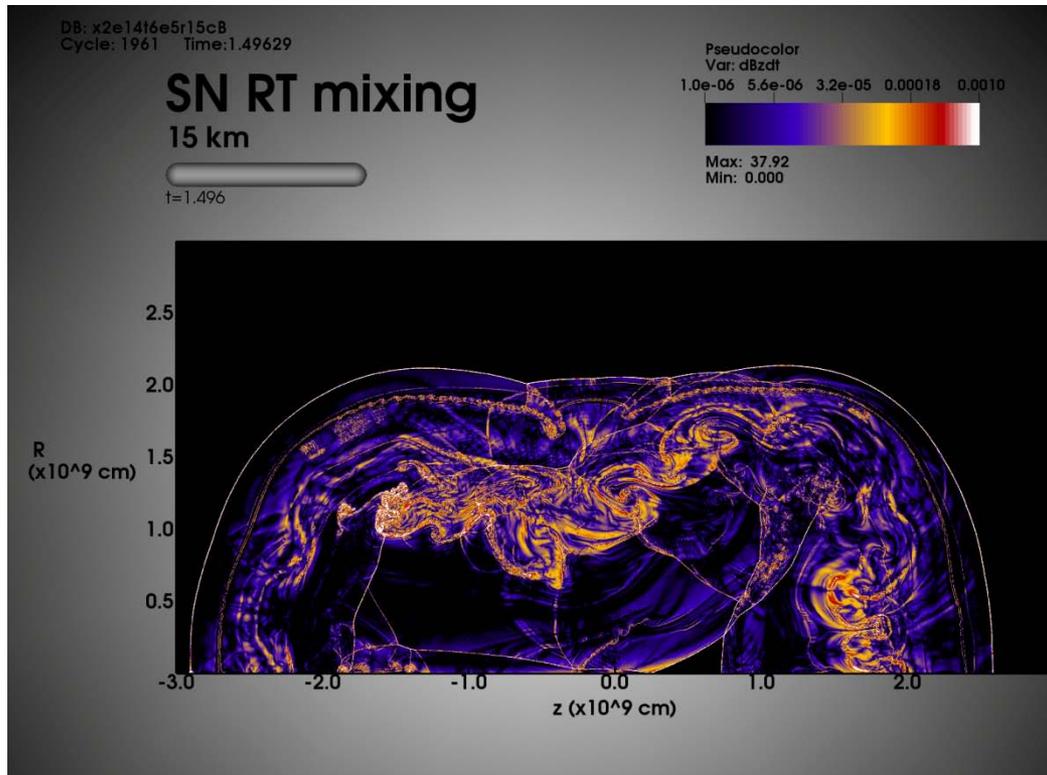
Magnetic field is likely to be more important in 3D than in 2D



Much more work is required

- In reality, dissipation may reduce the field strength considerably from simple estimates
- However, simulations show a significant effect on the morphology of the instability with $\beta \gg 1$
- A full simulation with all the relevant terms included will be required to determine the importance of magnetic fields
- Measurement of actual field strength in laser experiments is also planned

Magnetic field generation in supernova



Magnetic field generation rate in FLASH simulation of supernova explosion

Size of Biermann battery term in simulation is comparable to that obtained from simple order of magnitude estimate

Thermal pressure
 $\sim 6 \times 10^{11}$ dynes / cm^2
Magnetic pressure
 ~ 0.1 dynes / cm^2

Magnetic fields are not likely to be important for RT instability development during supernova explosions until very late in time

Conclusions

- **Laser experiments of blast-wave-driven RT instabilities show morphology which is very different from hydrodynamic simulations**
- **At least some of these differences may be caused by the generation of magnetic fields by the Biermann battery effect during the experiment**
- **If strong magnetic fields are generated during the experiments, it could have significant implications for the field of laser astrophysics**
- **The presence of magnetic fields may cause a breakdown of the scaling between laser experiments and astrophysical objects**
- **Much work remains (both experimental and computational) to determine the importance of magnetic fields in laser experiments**

