Experimental study of the interaction of a strong shock with a spherical density inhomogeneity

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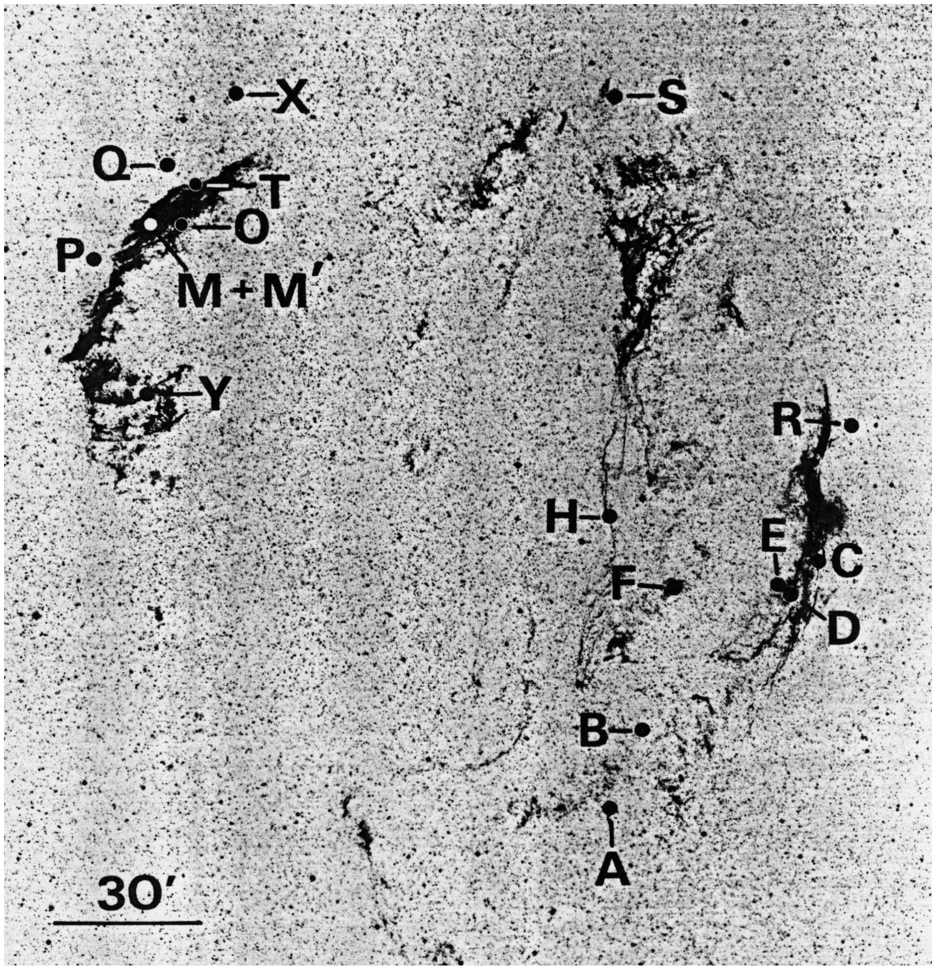
Summary

- Experiments have been conducted on the Omega Laser to study the interaction of a strong shock (M>10) with a spatially localized density inhomogeneity (Cu sphere)
- The interaction is diagnosed with x-ray radiography simultaneously from two orthogonal directions
- The evolution of the shocked sphere is observed to proceed as an initial roll-up into a double vortex ring structure followed by the appearance of an azimuthal instability which ultimately results in the three-dimensional breakup of the sphere.
- Numerical simulations are performed in both two and three-dimensions, and results are in good agreement with experiment.

Outline

- Background / motivation
- Omega Experimental Results
- Numerical simulations
- Conclusions

These experiments recreate in a controlled setting the interaction of a strong shock with a dense molecular cloud

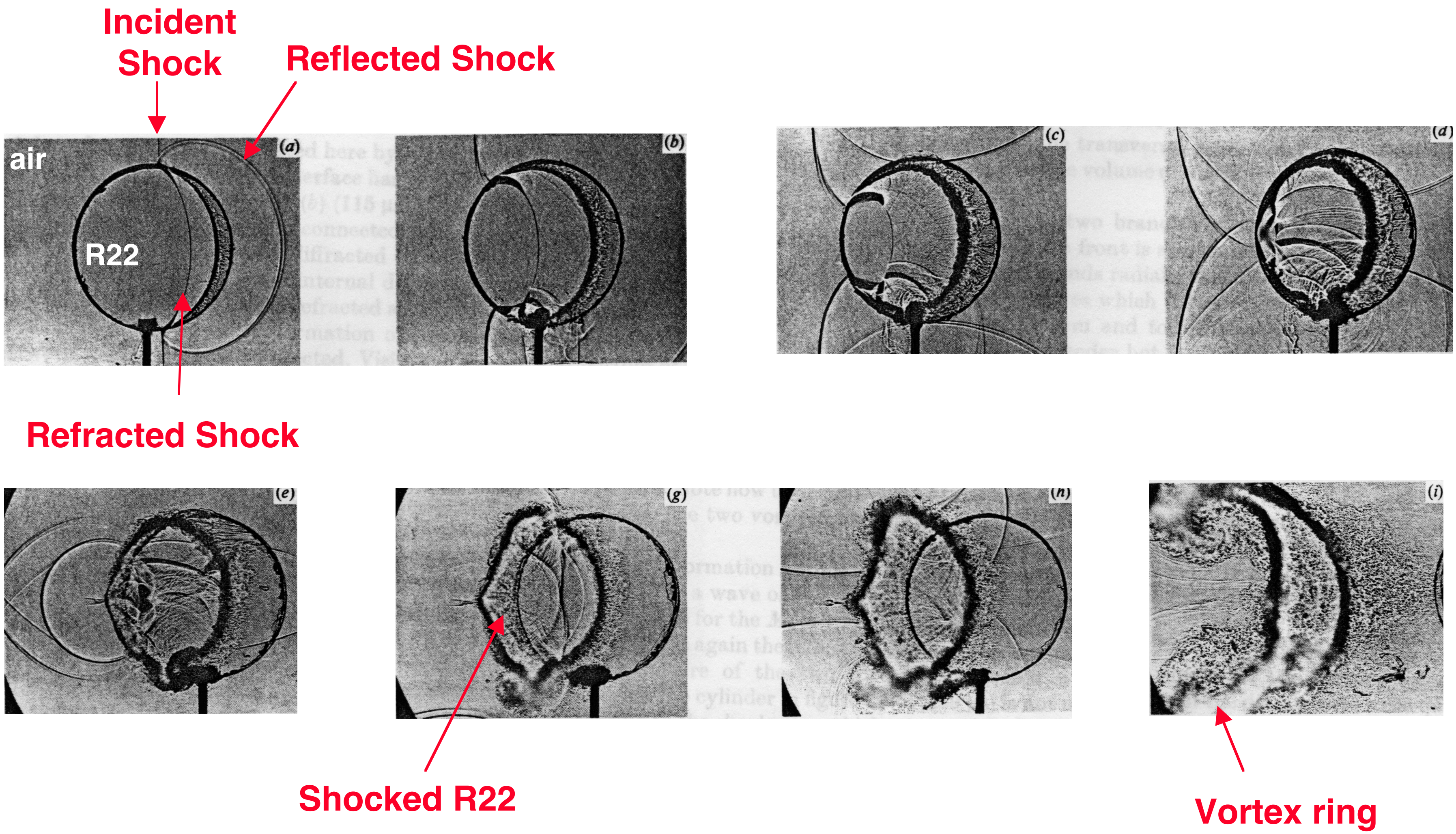


From Fesen el al., Ap.J. 262, 171 (1982):

"The Cygnus Loop is the classic example of a moderately old supernova remnant (SNR). its structure and physical properties are the result of a supernova-generated shock wave interacting with the surrounding interstellar medium."

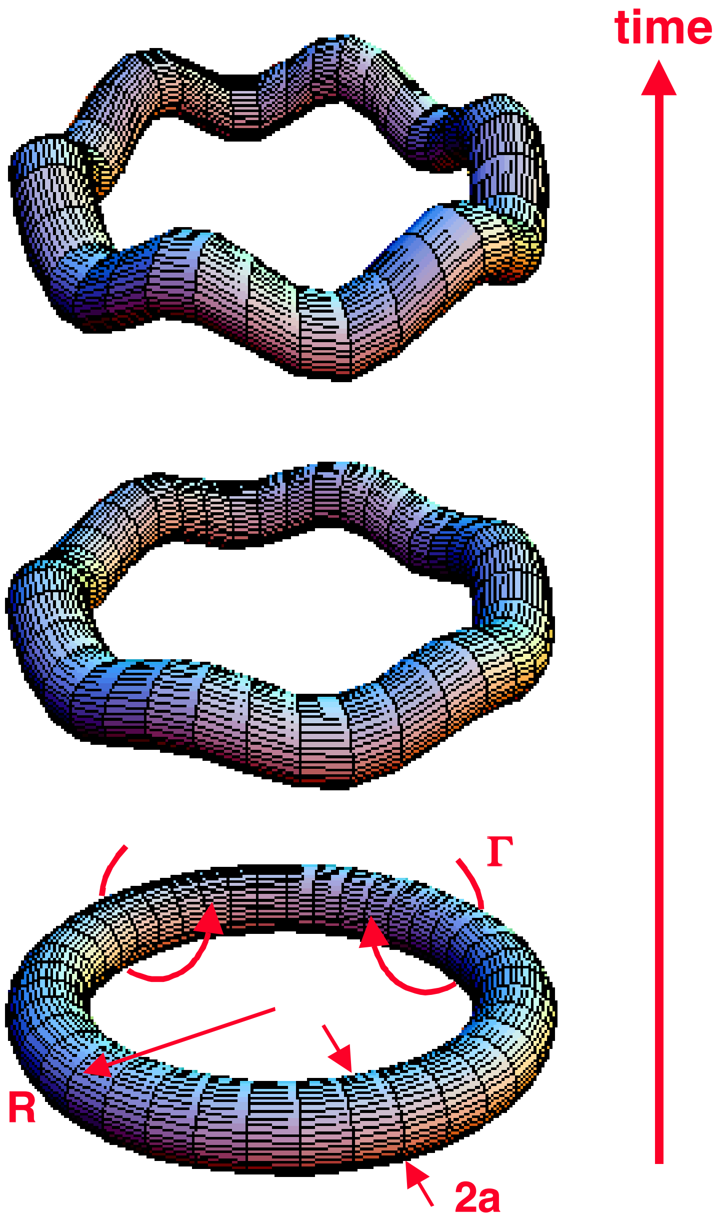
"Comparisons with published shock models indicate significant differences between the models and observations …"

The interaction of a shock with a dense spherical inhomogeneity has previously been studied only at low mach number

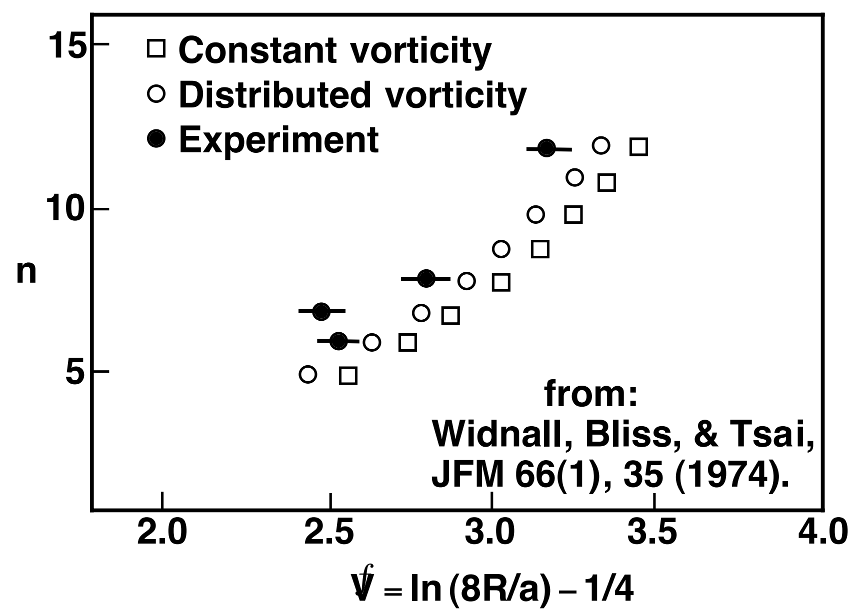


From M = 1.2 shock tube experiments of Haas & Sturtevant, JFM 181, 41 (1987)

Once formed, a vortex ring is subject to a 3D azimuthal bending mode instability



Mode number, n vs. non-dimensional ring translation velocity, $\tilde{V}$



The mode number is a function of the ring radius R and thickness a

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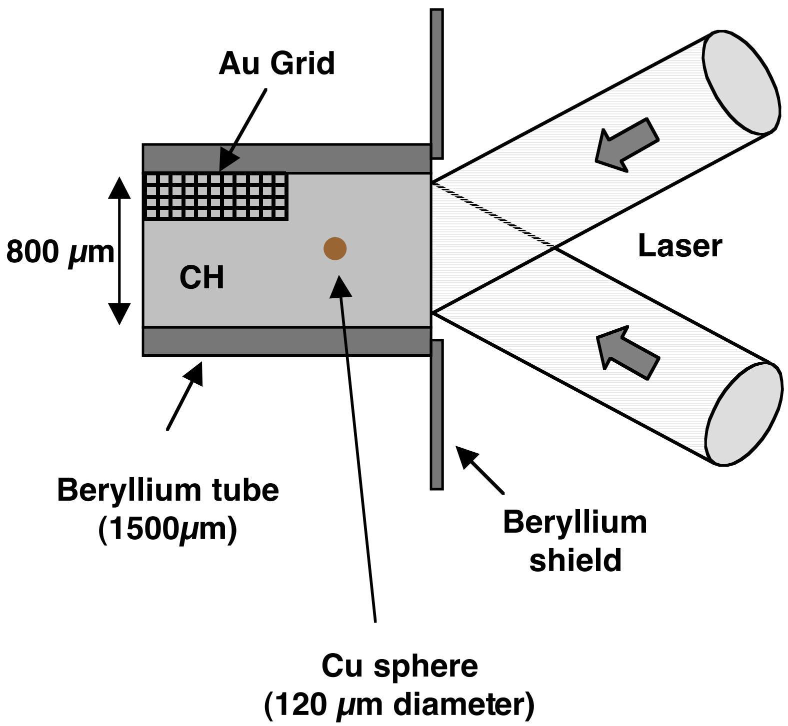
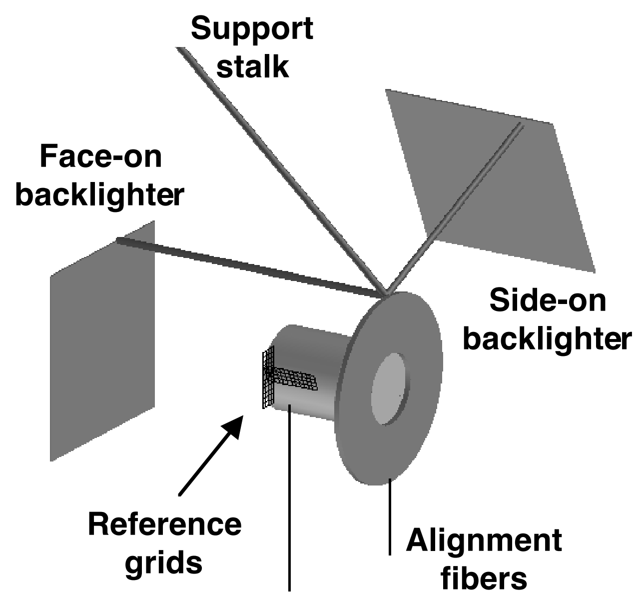
The Omega experiments are conducted in a very small Beryllium shock tube

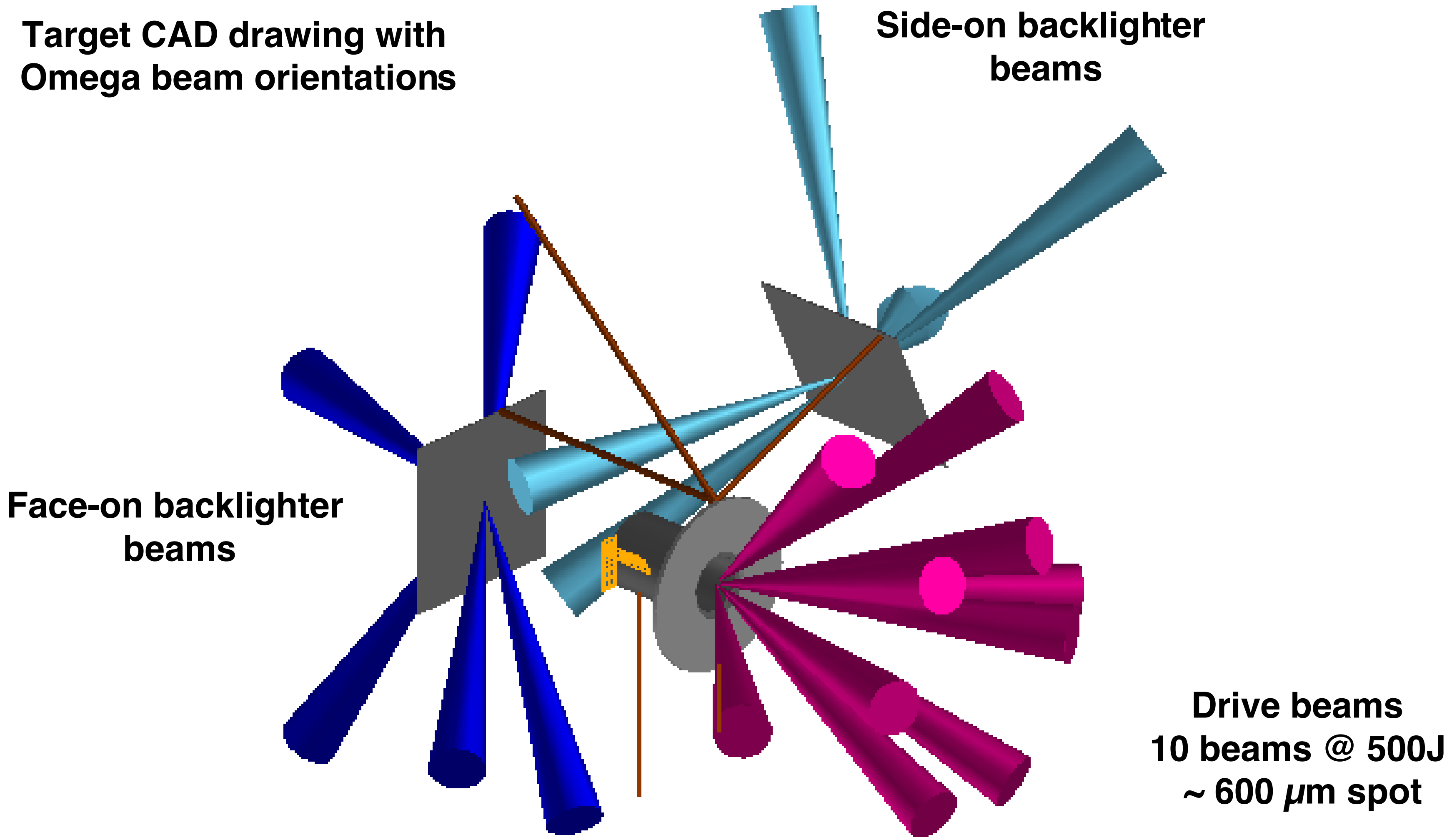
2D slice through target



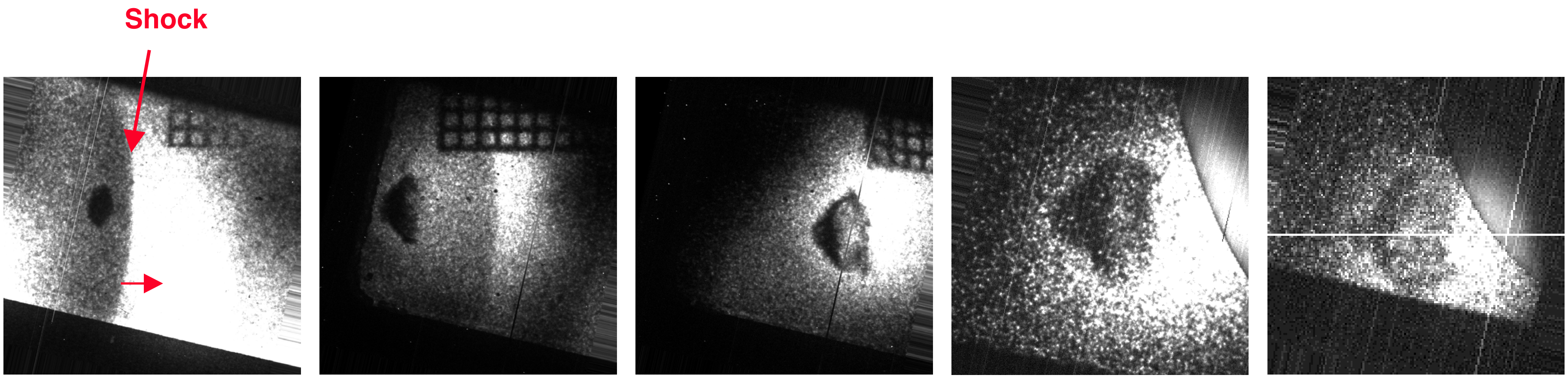
3D view of target



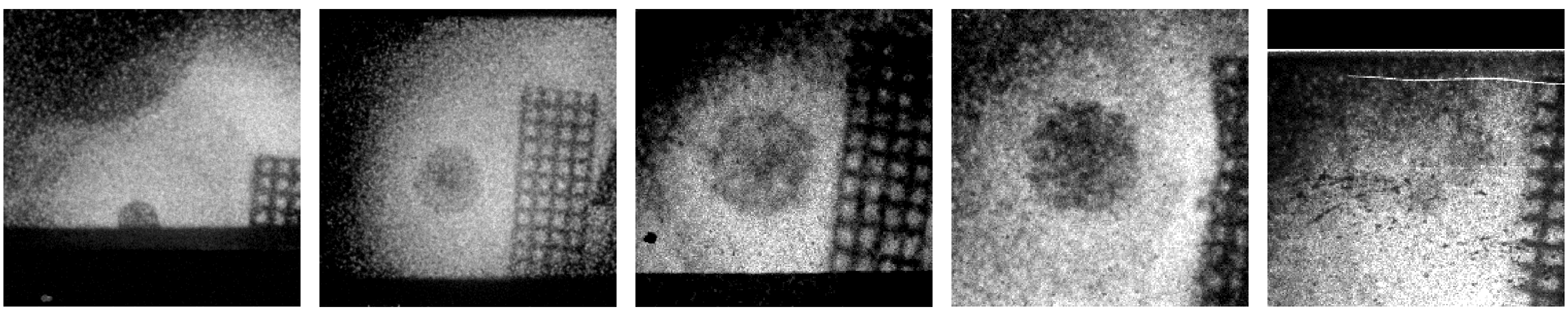
Multiple beams of the Omega laser are used to both drive the strong shock and diagnose the interaction



Simultaneous side-on and face-on images of shock / sphere interaction with 120 μm diameter Cu sphere



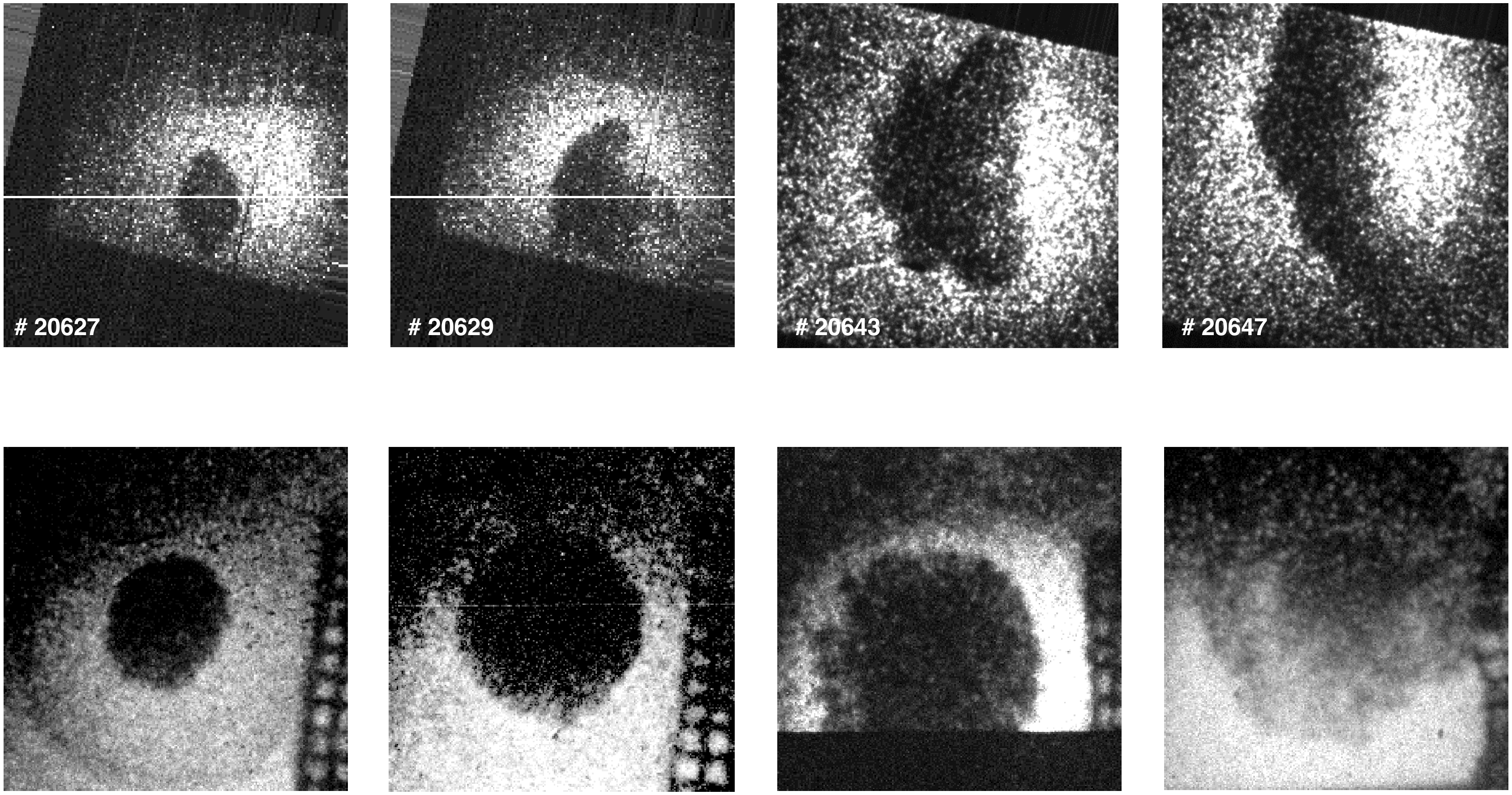
19728 # 19736 # 19732 # 20637 # 20645



t = 13 ns t = 26 ns t = 39 ns t = 52 ns t = 78 ns

Omega data of April, 2000 **Omega data of Aug 2-3, 2000**

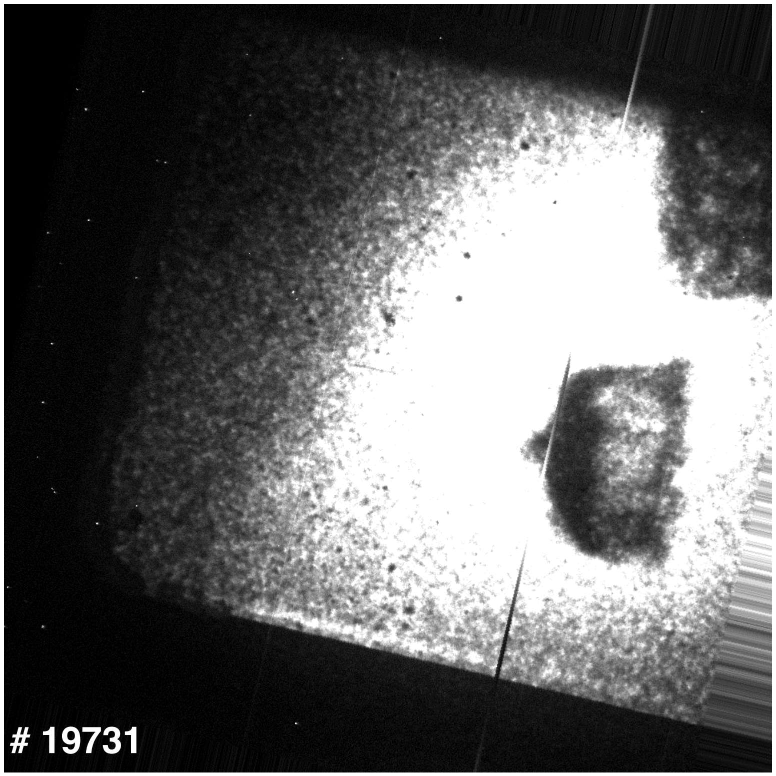
Simultaneous side-on and face-on images of shock / sphere interaction with 240 μm diameter Cu sphere



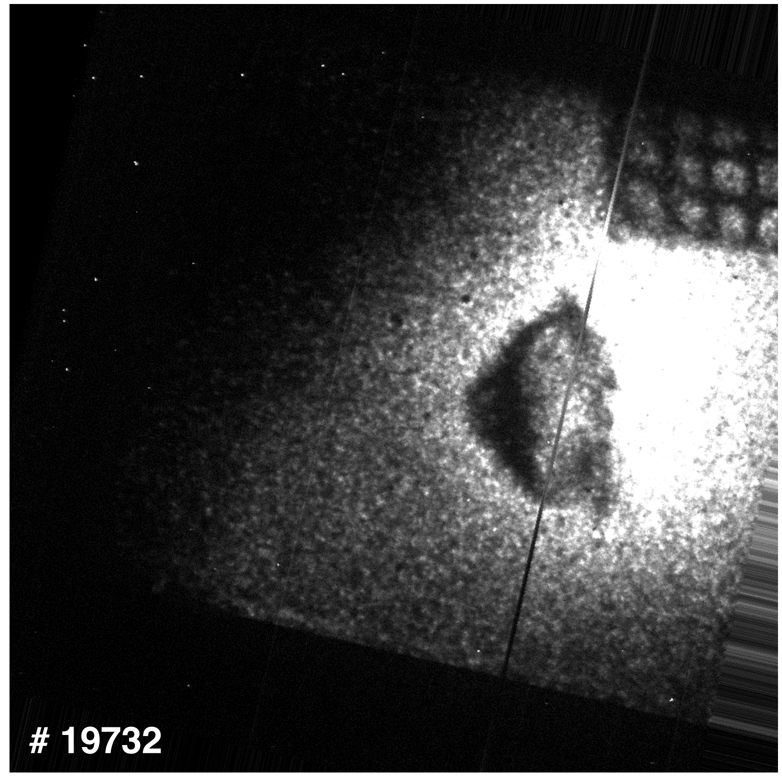
t = 27 ns   t = 54 ns   t = 78 ns   t = 105 ns

Omega data of Aug 2-3, 2000

Large-scale features appear repeatable from shot-to-shot, but small-scale details differ



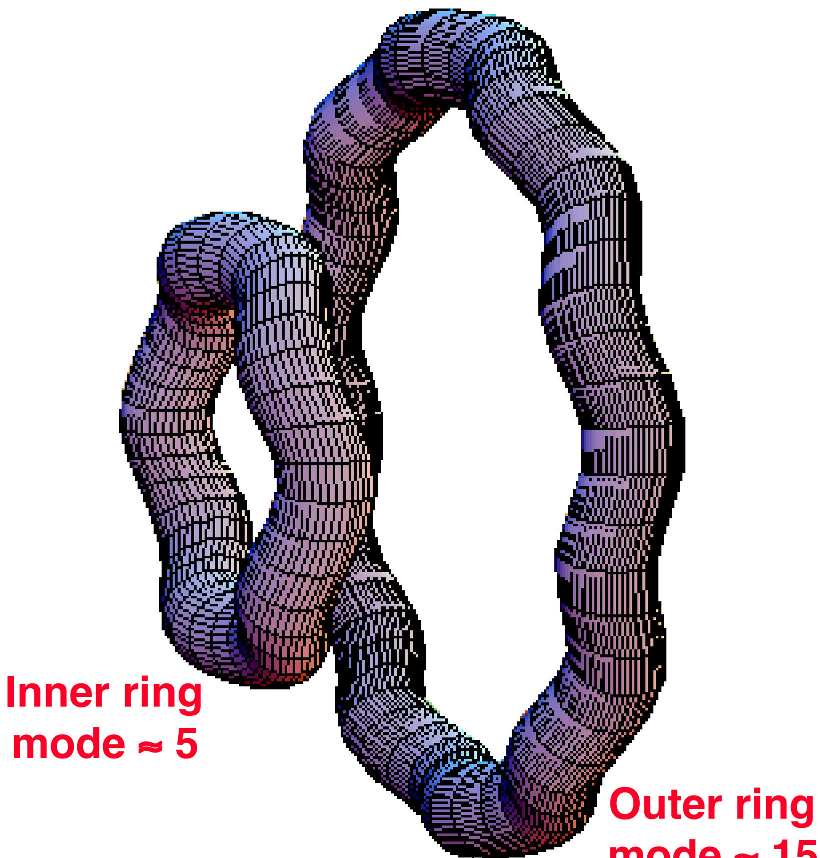
t= 39 ns
V-backlighter

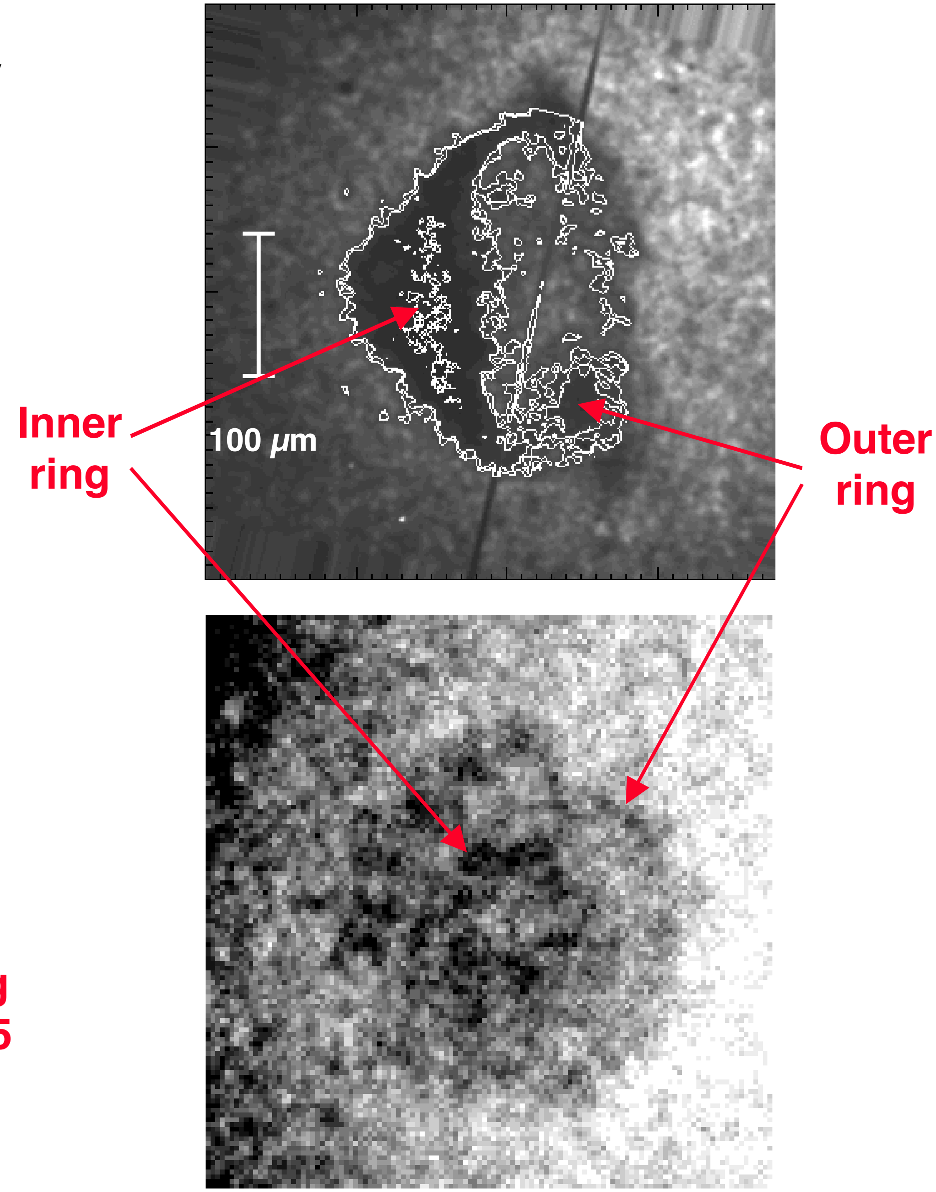


t= 39 ns
Fe-backlighter

The two orthogonal diagnostic views help to reveal the 3D morphology of this flow

Illustration of 3D morphology



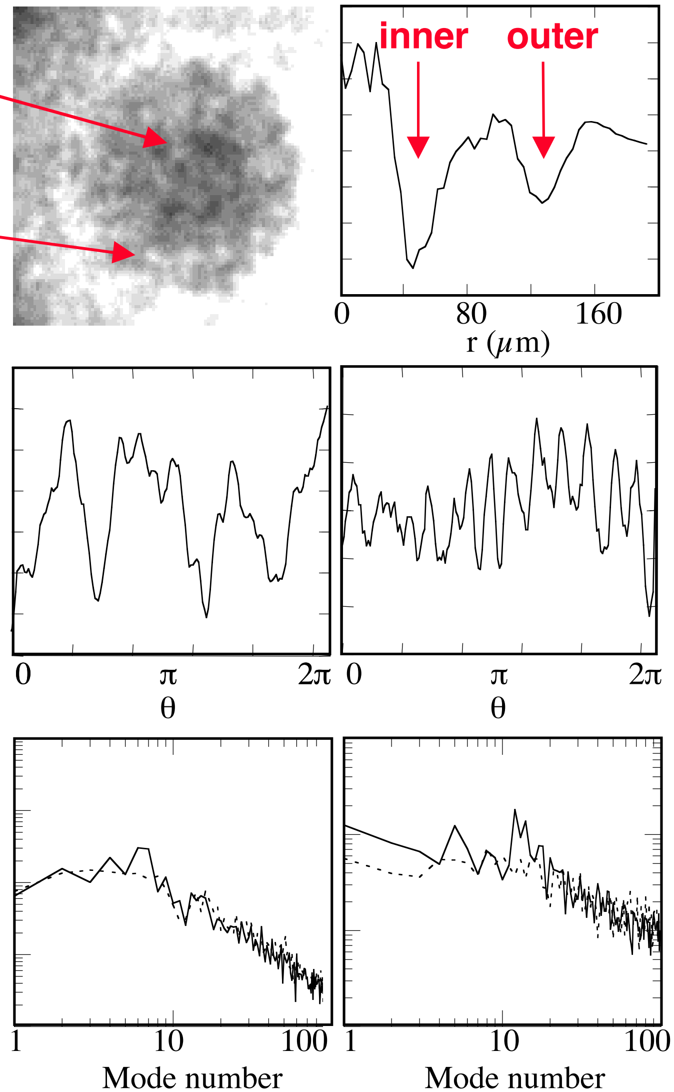


Analysis of Omega shock / sphere data quantifies the three-dimensional instability and breakup of the sphere

inner ring

outer ring

Azimuthally averaged radial lineout



Azimuthal lineout through inner ring

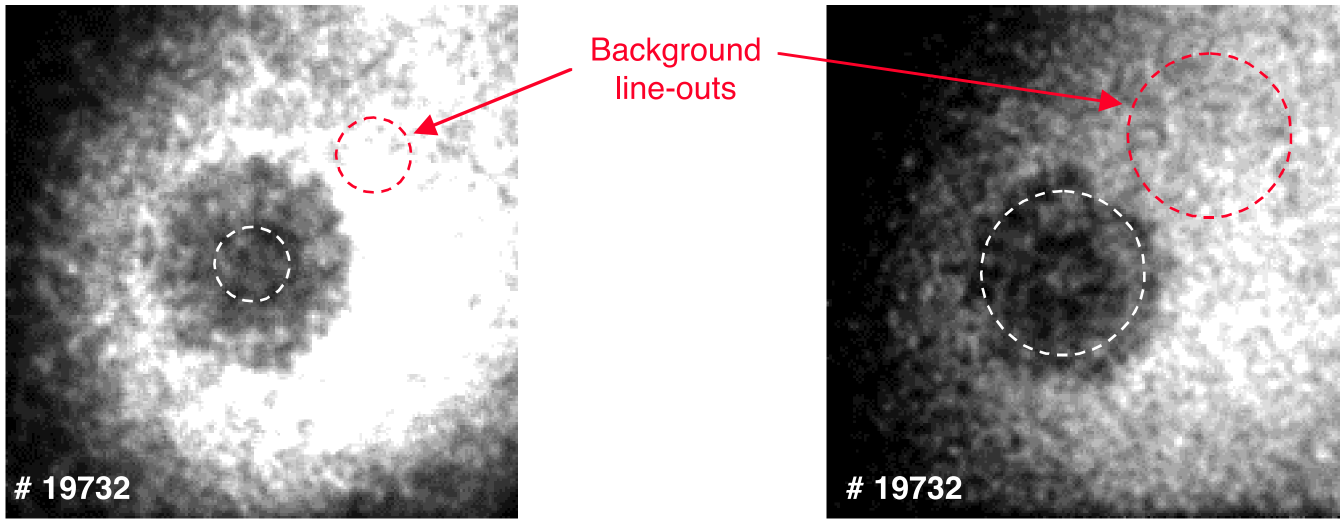
Azimuthal lineout through outer ring

Spectrum of inner azimuthal lineout

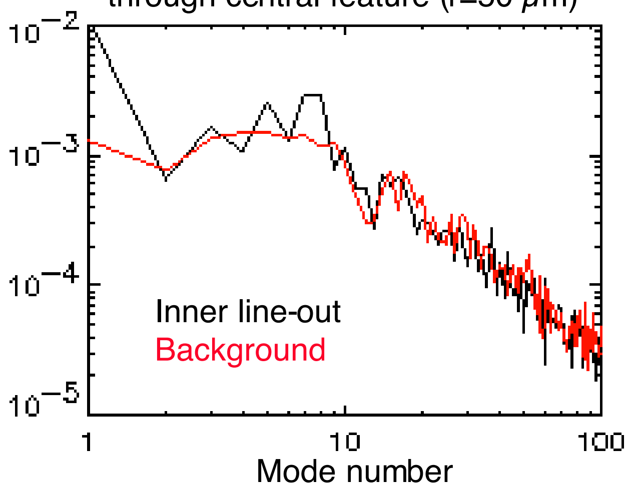
Spectrum of outer azimuthal lineout

From Robey et al., submitted to PRL (May, 2001)

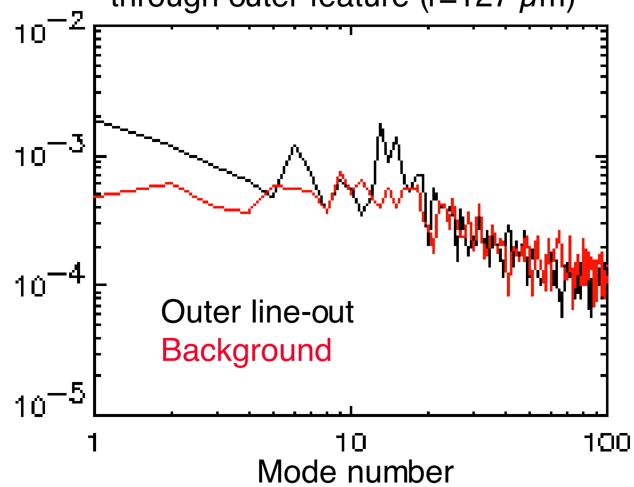
Mode number spectra from face-on images of shock / sphere interaction reveal a dominant azimuthal mode



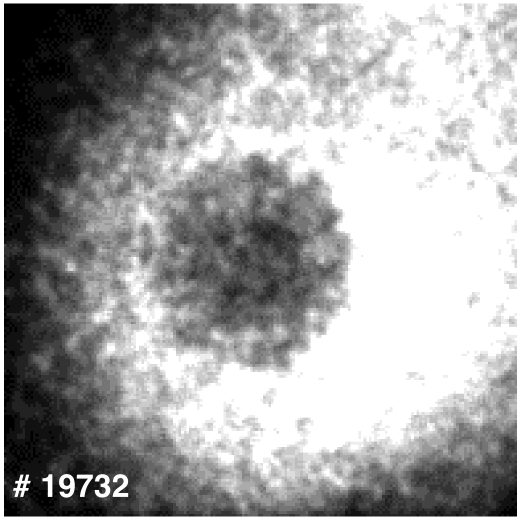
Power spectrum of circular line-out through central feature (r=50 μm)

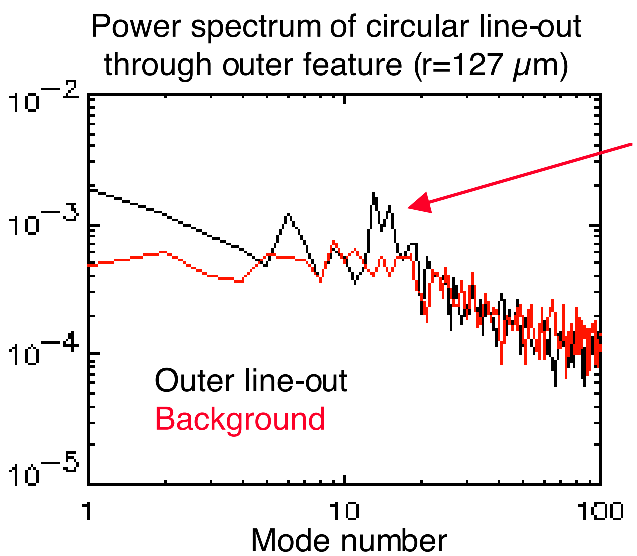


Power spectrum of circular line-out through outer feature (r=127 μm)



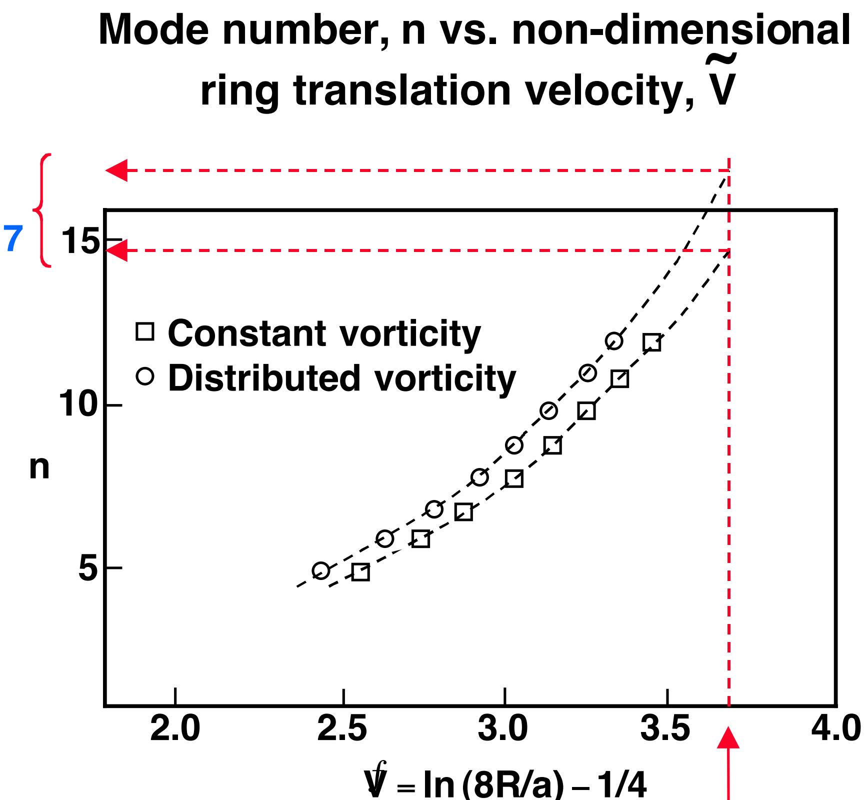
The observed azimuthal mode number agrees well with the prediction from Widnall's theory





Observed peak at 15

Predicted Mode = 14-17

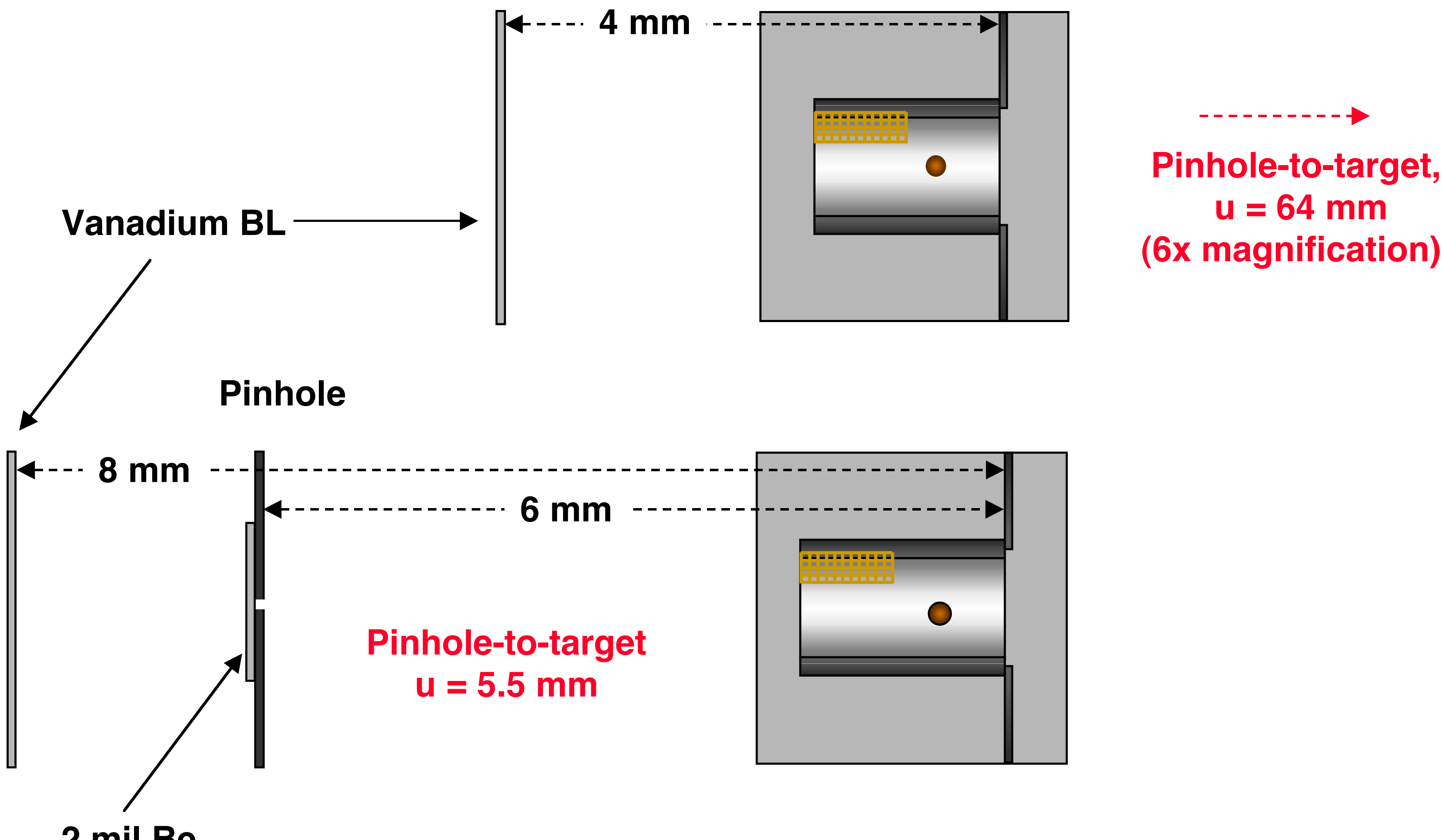


From azimuthal lineouts

a = 20 μm
R = 127 μm

$\tilde{V}$ = 3.67

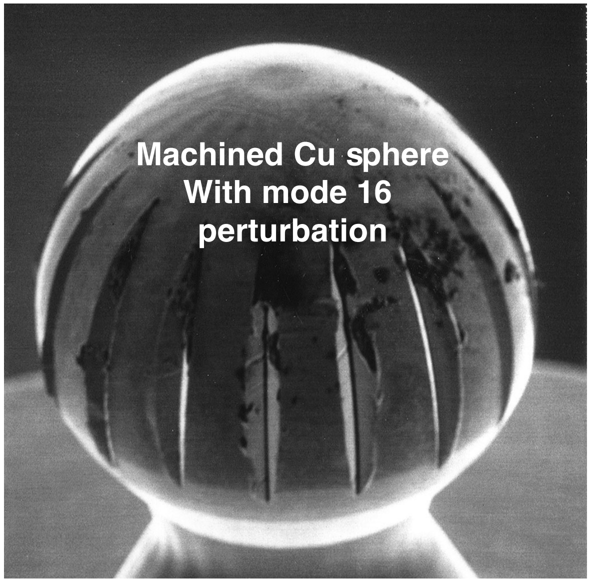
SNR should be greatly improved using a backlit pinhole due to greatly decreased pinhole-to-target distance

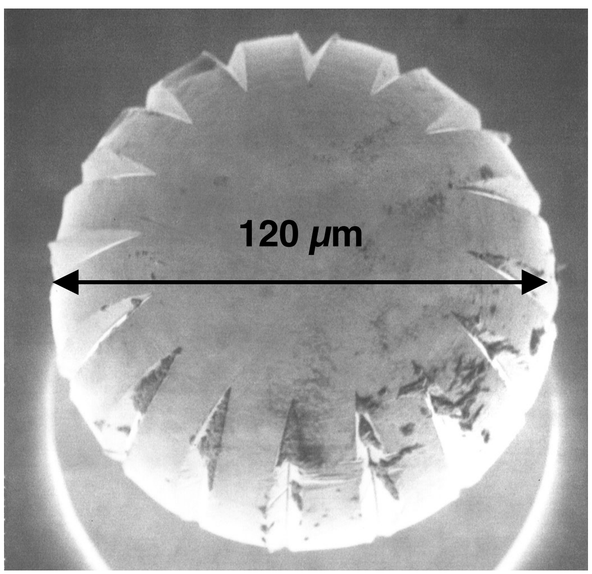


photons / resolution element ~ u^{-2}, and SNR = $\sqrt{\#\ \text{photons}}$

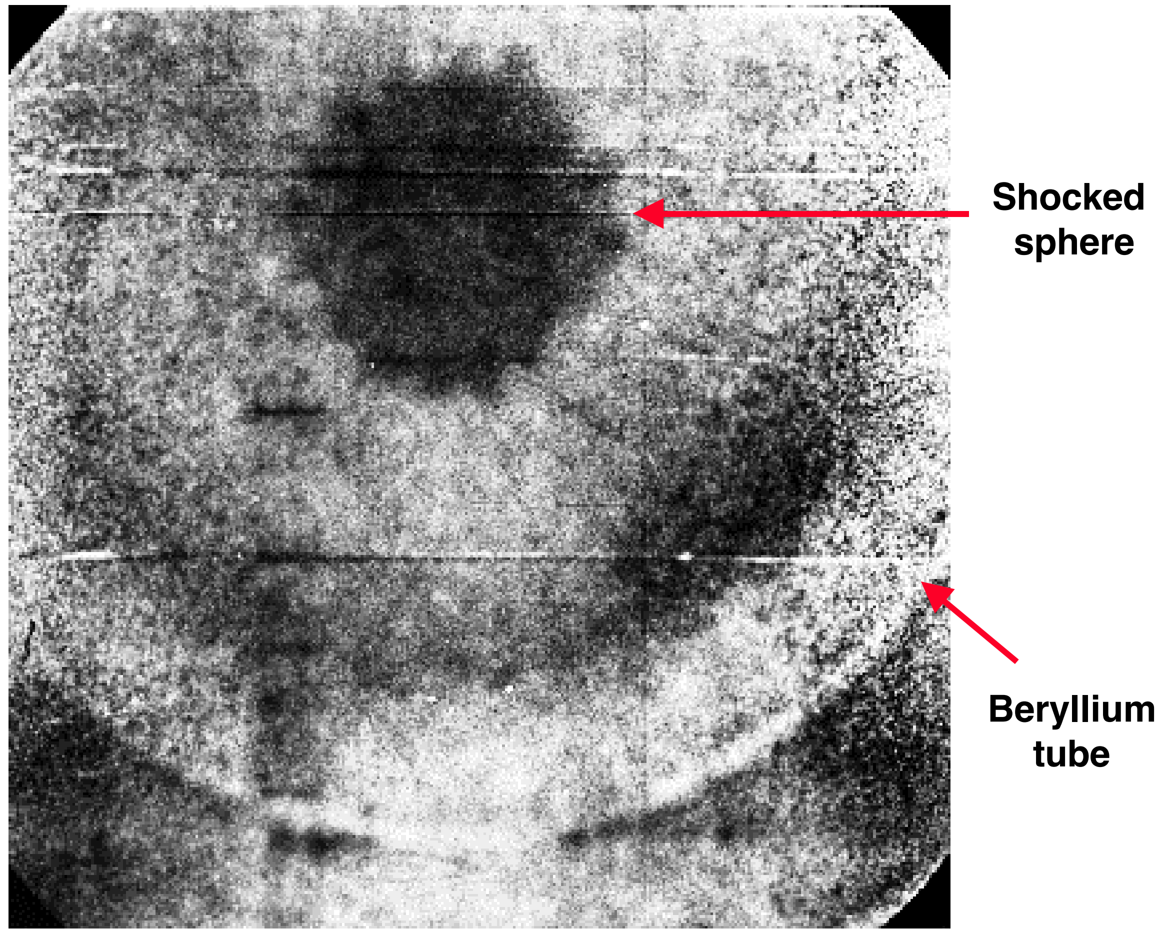
Backlit pinhole increases SNR by factor of 11

We have begun investigating the ability to seed the azimuthal instability with machined initial perturbations





Face-on view using point projection backlighting



Shot #24527

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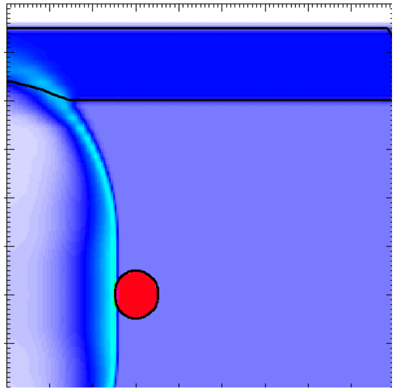
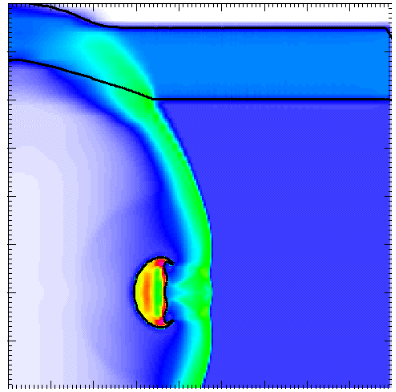
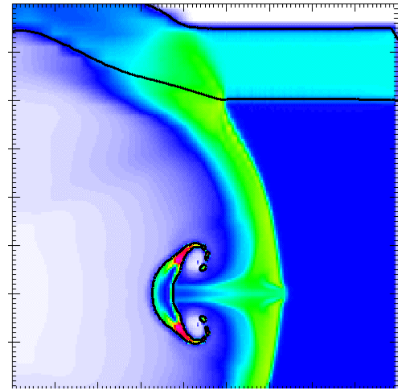
2D simulations of the experiment performed with CALE predict the basic evolution of the sphere into a vortex ring



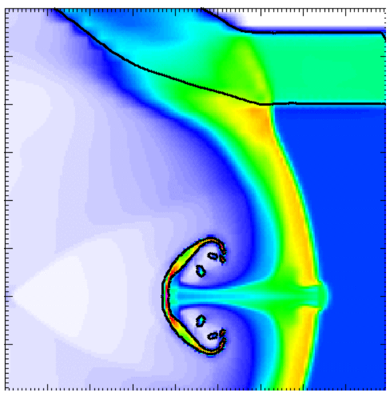
t= 10 ns



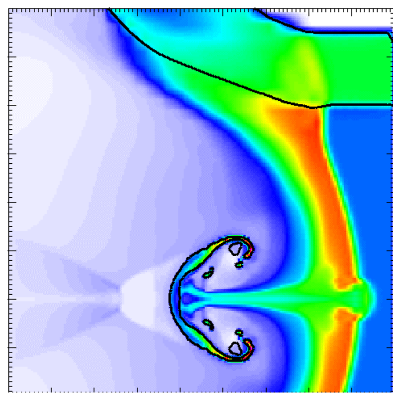
t= 20 ns



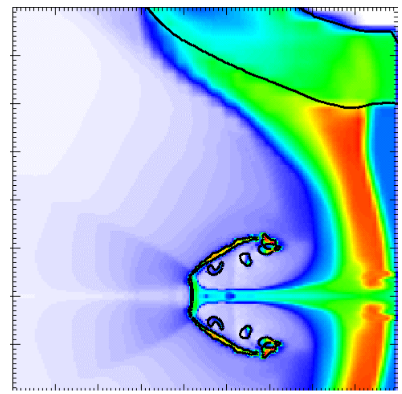
t= 30 ns



t= 40 ns



t= 50 ns



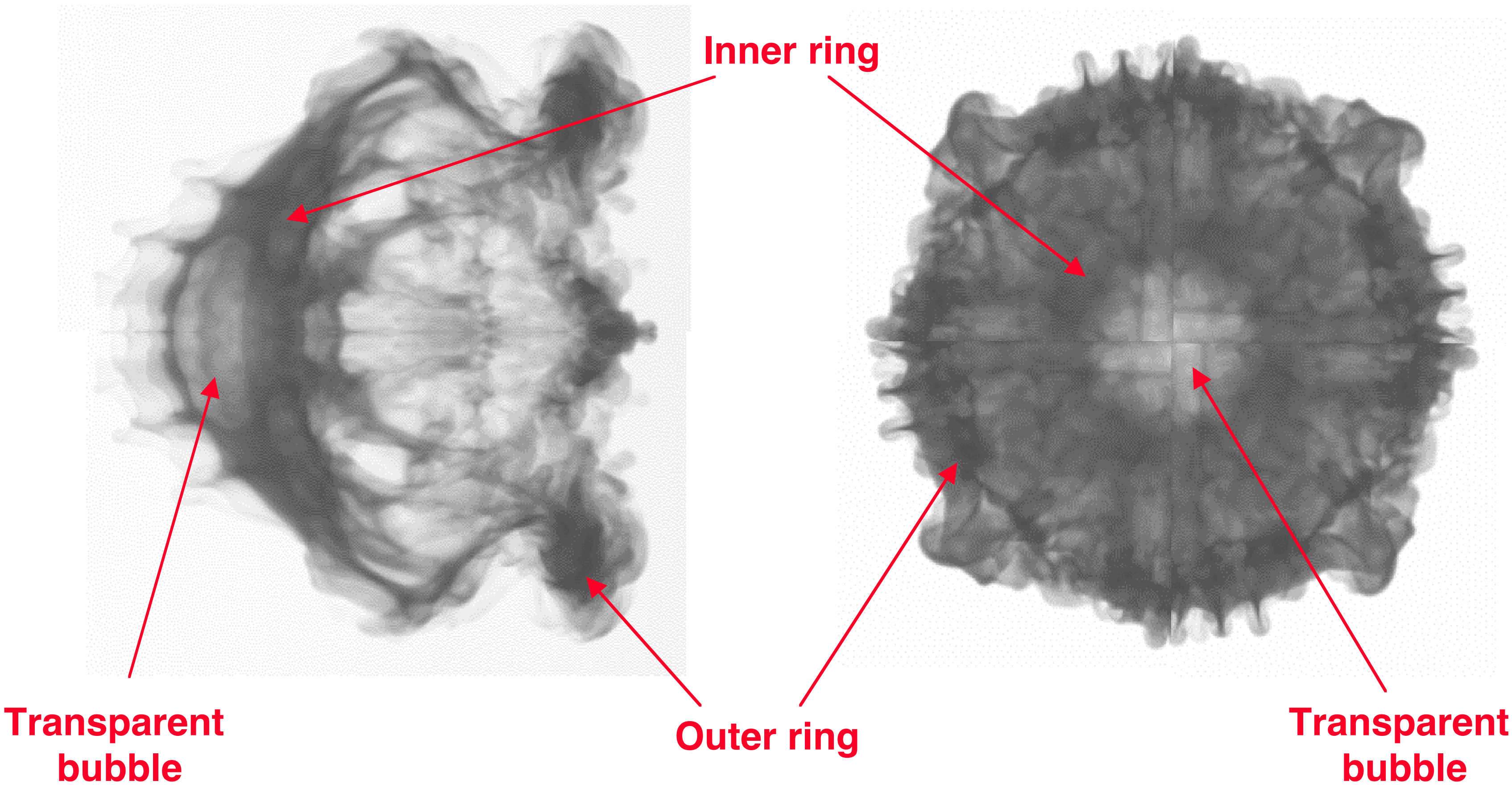
t= 60 ns

Simulations by J. O. Kane

3D simulations of the experiment have been performed with an AMR code

Simulated radiograph of side-on view

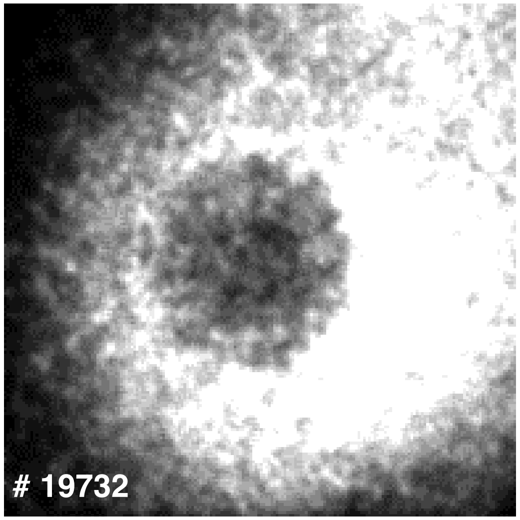
Simulated radiograph of face-on view



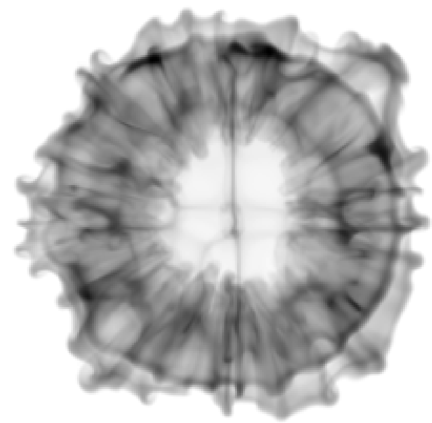
Simulations by J. A. Greenough

Mode number spectra of the experimental and the AMR face-on images are in good agreement

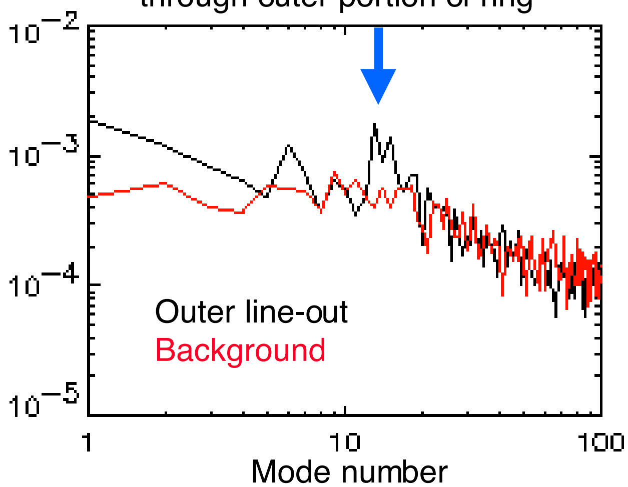
Experiment

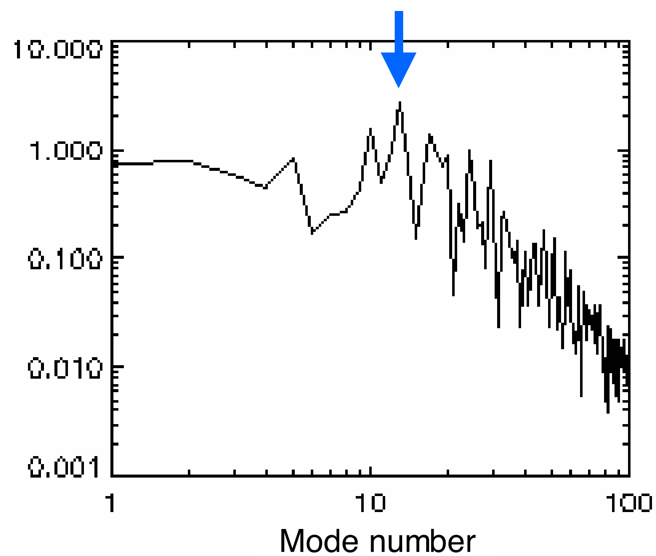


AMR simulation



Power spectrum of circular line-out through outer portion of ring





Conclusion

- Experiments have been conducted on the Omega laser to explore the interaction of a strong shock with a dense sphere

- The experiment has been diagnosed simultaneously from two orthogonal directions

- The experimentally observed azimuthal mode number is in good agreement with both incompressible theory of Widnall and 3D numerical simulations.

- Future work will focus on shock interaction with less-dense objects and interactions with multiple objects