ICF-Related Hydrodynamic Instabilities in a Shocked Spherical Gas Bubble

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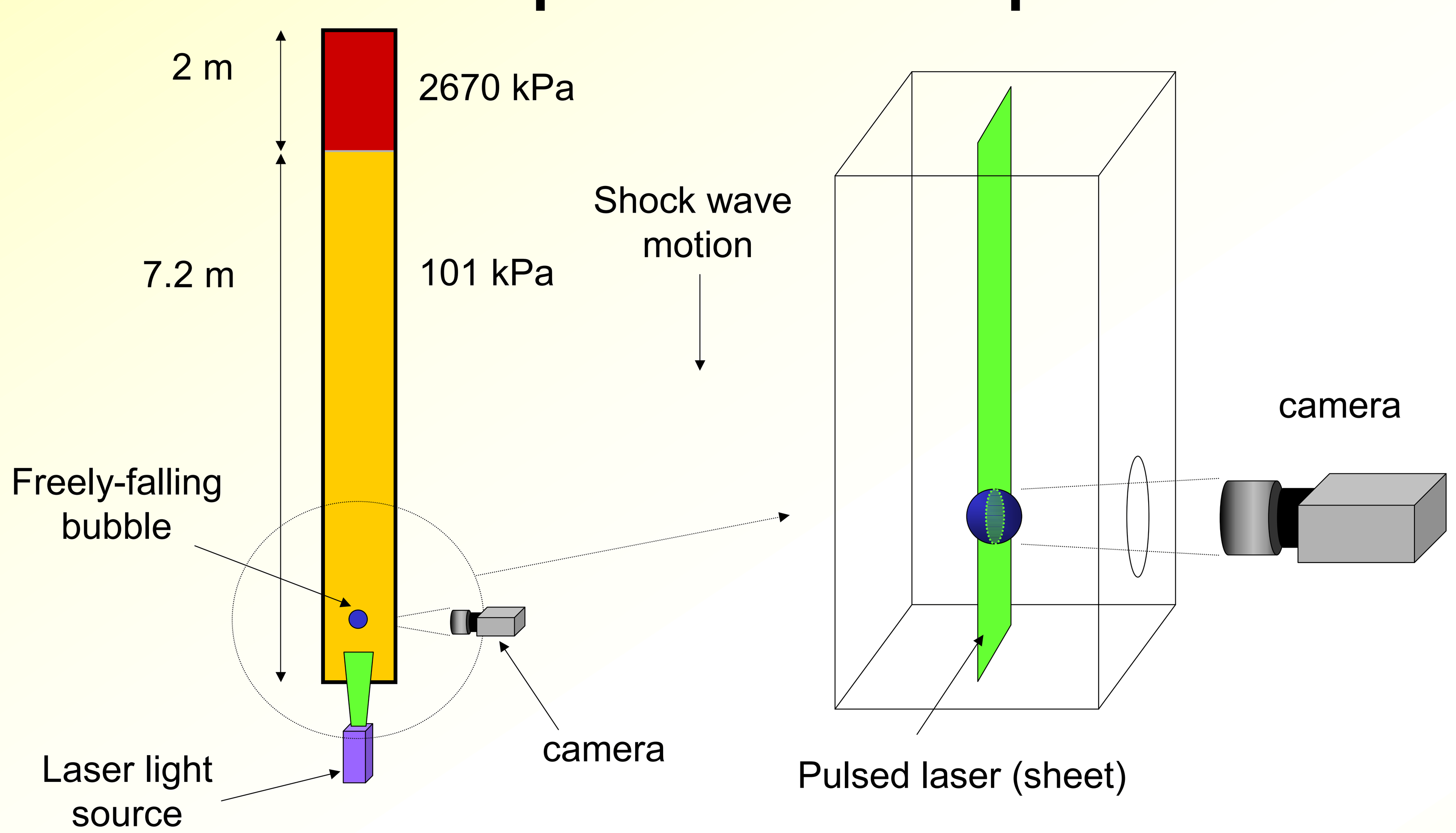
Introduction:

In laser, heavy-ion, or z-pinch-driven ICF ignition, compression of the target is accompanied by fluid instability growth. This instability is key to the understanding of the ignition and yield from the target. The surface of the DT target becomes unstable due to Richtmyer-Meshkov and Rayleigh-Taylor growth. Vorticity is generated baroclinically at the interface, causing the interface to deform and allowing the materials to mix after the shock has passed. This turbulent mixing between the DT and the ablator surface and the asymmetry associated with the compression can alter the yield from the target.

Shock tube experiments are currently underway at the University of Wisconsin-Madison in an effort to characterize the growth of these instabilities, for the special case of a dense spherical bubble. The high structural capacity of the shock tube facilitates experiments at Mach numbers exceeding those achieved in previous hydrodynamic shock-induced-mixing experiments. Richtmyer-Meshkov and Kelvin-Helmholtz instabilities on the bubble surface lead to the formation of large vortical structures in the post-shock flow, which are analyzed here and can be used in testing the hydrodynamics in radiation hydrodynamics codes.

Experimental Setup:



Wisconsin Shock Tube Laboratory
Madison, WI

Shock tube:
- Vertical, modular
- 20 MPa impulsive load capability
- 25.4 cm square cross section
- Planar laser imaging ports
- Retractable bubble dropper

Imaging:
- Nd:YAG pulsed laser sheet
- CCD cameras
- Mie scattering or PLIF
- Dual exposure

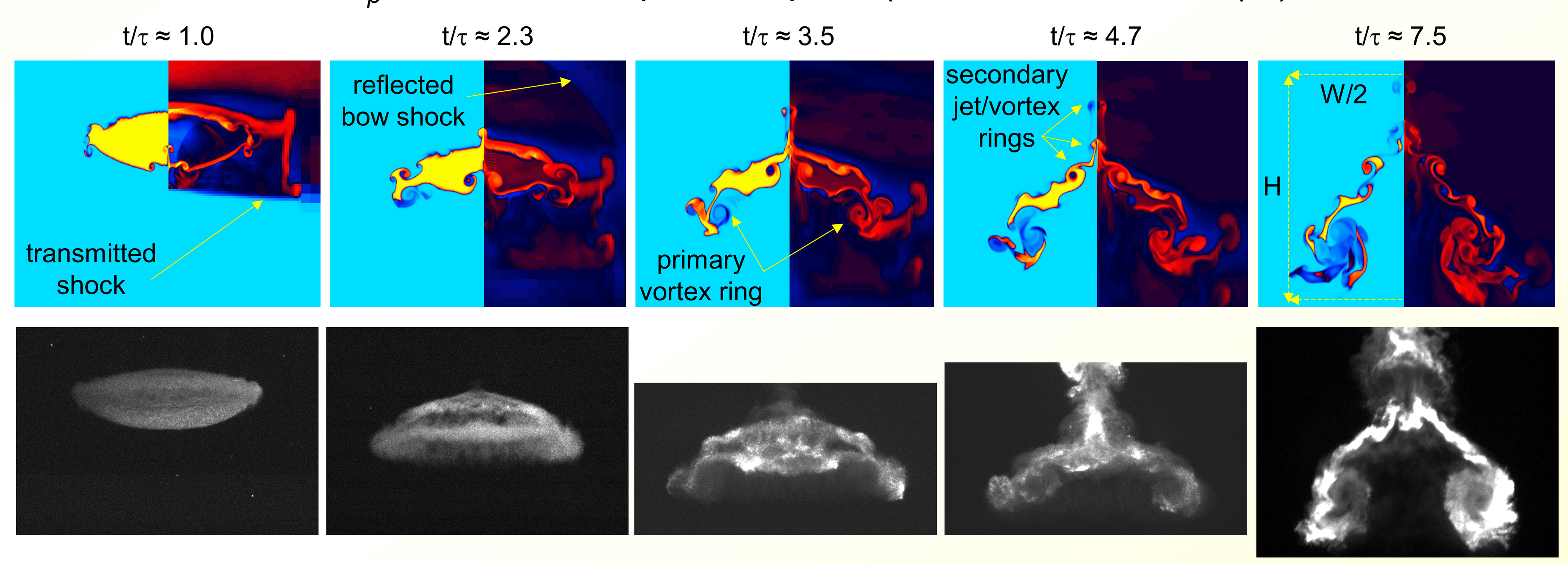
Abstract:

Experiments studying the unstable growth of a dense spherical bubble in a gaseous medium, subjected to a strong planar shock wave (2.8 < M < 3.4), are performed in a vertical shock tube. The test gas is contained in a freely-falling spherical soap-film bubble, and the shocked bubble is imaged using planar laser diagnostics. Concurrently, simulations are carried out using a 3-D compressible hydrodynamics code.

Experiments and computations show consistent results, indicating the formation of characteristic vortical structures in the post-shock flow. The results emphasize the significance of 3-D effects, and of small non-uniformities in the initial bubble geometry. Further, the time-behavior of flow features is analyzed, showing that, under some conditions, the development of the unstable interface can be parameterized for variable shock strength.

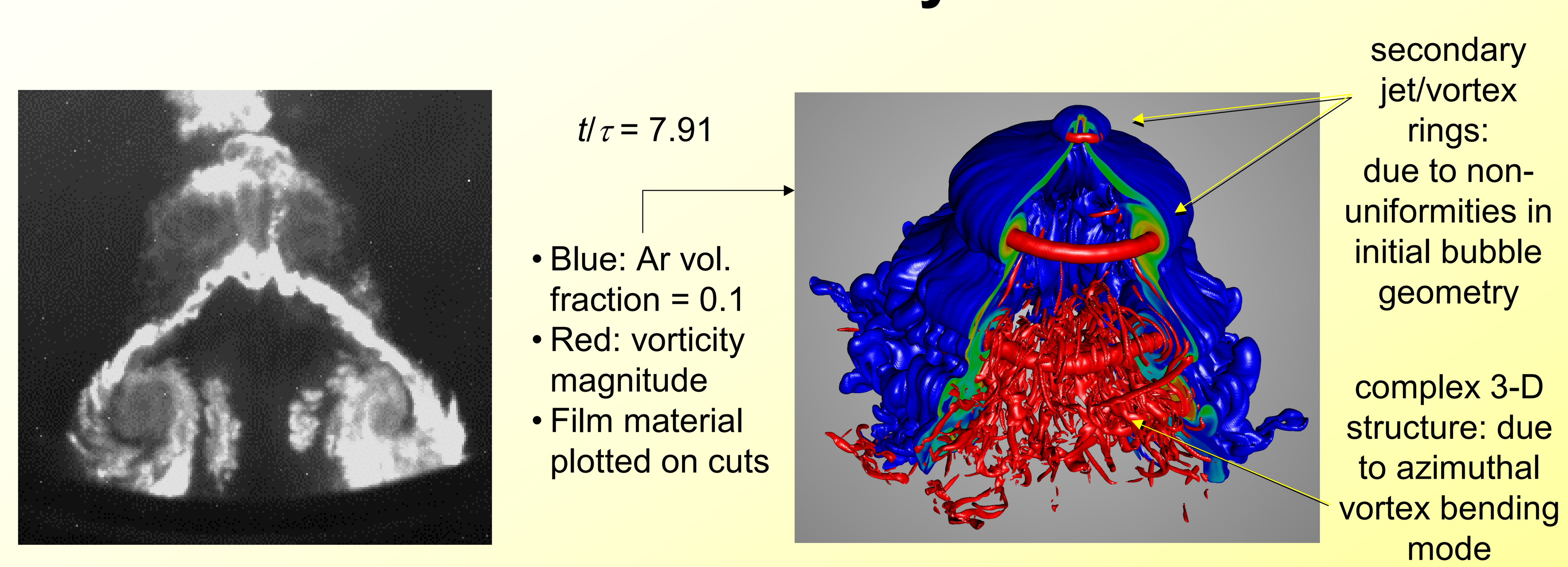
Bubble Evolution:

t = time since initial shock/bubble contact
τ = characteristic time, defined as D/u_p, where D is the initial bubble diameter, and u_p is the shocked particle speed (M = 2.88 → τ = 68.2 μs)

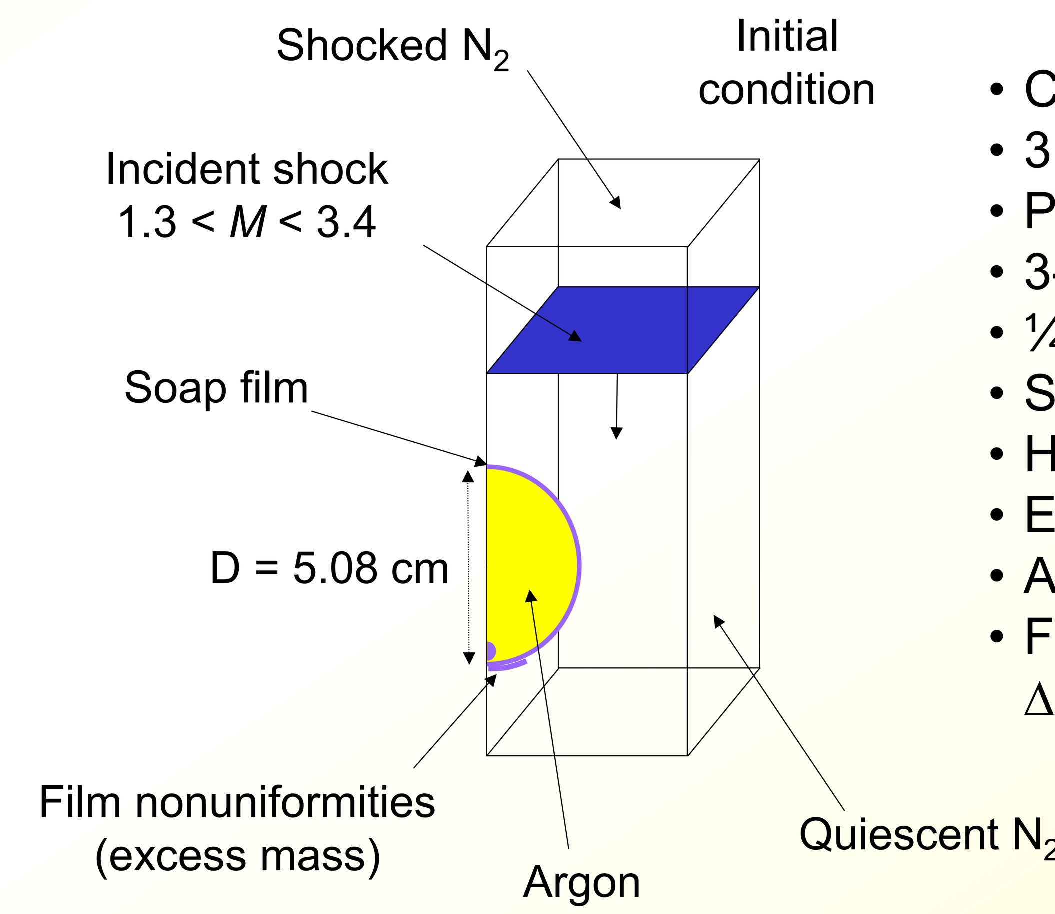


Top: Numerical results; Ar volume fraction (left) and total density (right) plots at midplane, for M = 2.88.
Bottom: Experimental shock tube images obtained using laser light scattered at bubble midplane.
Below: Late-time image and 3-D rendered plot showing multiple vortex rings and complex 3-D structure.

3-D and Secondary Effects:

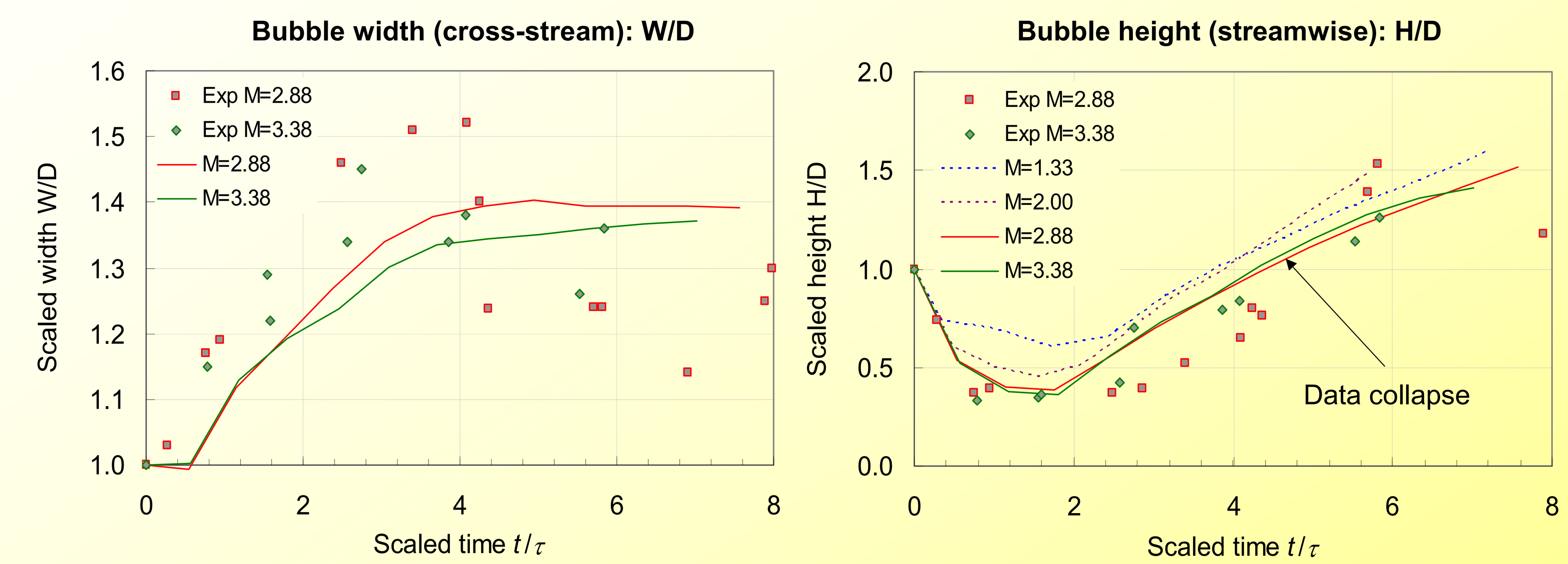


Simulations with Raptor:



- Compressible Euler equations
- 3 fluids
- Perfect equation of state
- 3-D Cartesian grid
- ¼ symmetry
- Shock-capturing scheme
- Higher-order Godunov solver
- Eulerian framework
- Adaptive mesh refinement (AMR)
- Finest-level grid spacing: Δx = 195 μm (R_{130})

Growth Trends:



To investigate the possibility of parameterizing the shock-bubble interaction, integral length measurements for varying incident Mach number M are analyzed on the nondimensional timescale t/τ, where $\tau = D/u_p$. Data shown here are the maximum cross-stream and streamwise dimensions of the bubble ("width" and "height"), normalized by the initial diameter D. For M = 2.88 and 3.38, both experimental and computational results are shown. In the width data, a recompression of the bubble is seen around t/τ = 4, due to shock wave reflections from the side walls. In the height data, the growth trends collapse to nearly a single curve for the two higher Mach numbers. However, this parameterization fails for M = 1.33 and 2.00, due to compressibility effects in the post-shock flow.

Discussion:

- Novel experimental approach:
  - Strong shocks, free-falling bubble, planar imaging, dual exposure
- Key observed feature:
  - Heavy spherical bubble in a light gas, accelerated by a shock wave, forms a large vortex ring in the shocked flow, due to fluid instabilities.
- Other important features seen in experiment and/or computations:
  - 3-D effects, film non-uniformity effects, side wall reflections
- Collapse of time data is possible within higher Mach number range studied here, using parameterization by shocked particle speed, u_p. This may allow future studies to be scaled to the regime of laser-driven experiments.

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