Experimental and computational investigations of shock-accelerated gas bubbles

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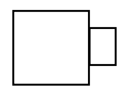
Overview

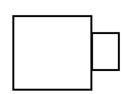
- Planar shock wave accelerates spherical soap bubble: Ar inside, N_2 outside, A_{init}=0.176
- Time evolution of geometrical properties
- Mach number effects
  - M=2.88, u_p=745 m/s, A_{shock}=0.00216
  - M=3.38, u_p=907 m/s, A_{shock}=-0.0219
- Laboratory and computational experiments
- Comparison with RAPTOR (2D and 3D model)

Details of R-M experiment

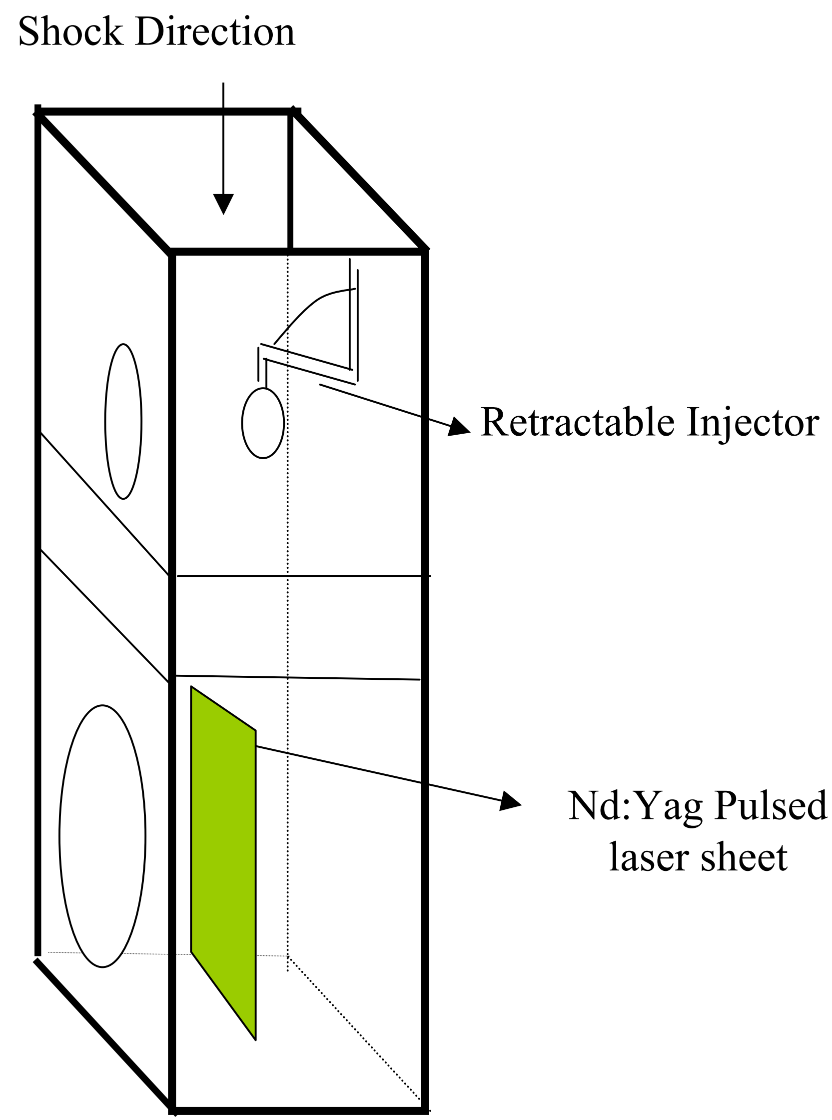
Planar shock wave
Spherical soap bubble D = 5 cm
Driver: He Driven: N_2 Test: Ar



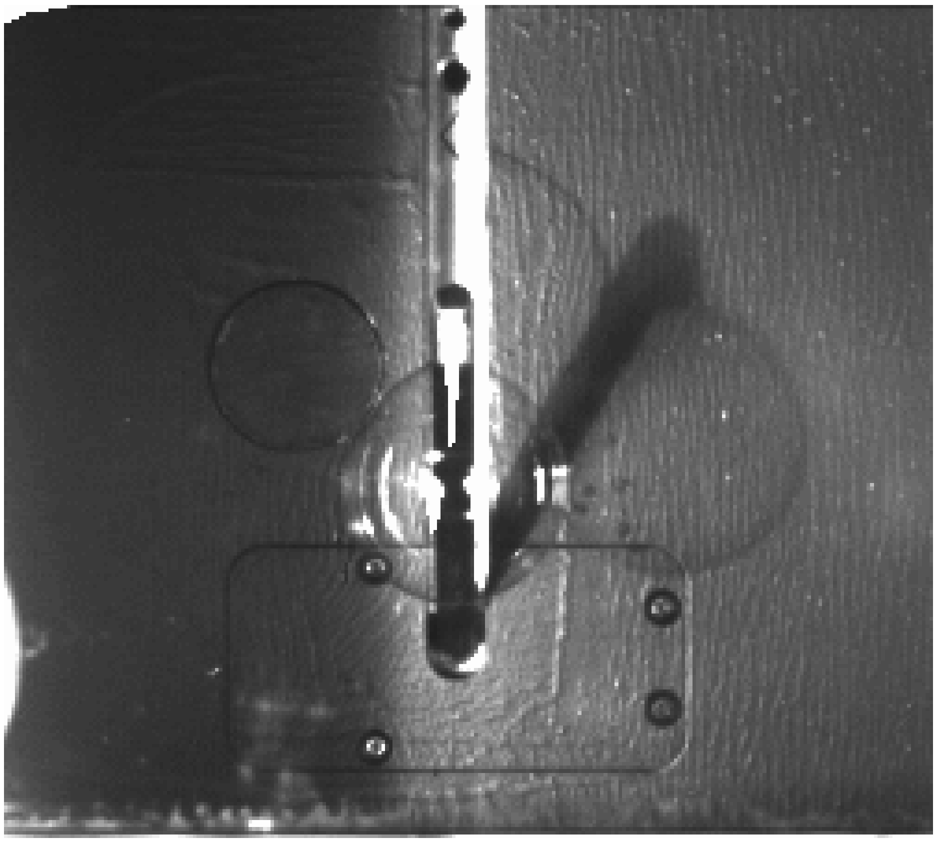
Initial conditions:
Continuous white light from the front
Motion picture at 220 fps



Post shock:
Mie-scattering from the soap film acting as flow tracer
2 laser pulses
2 images per run on same frame



Initial conditions

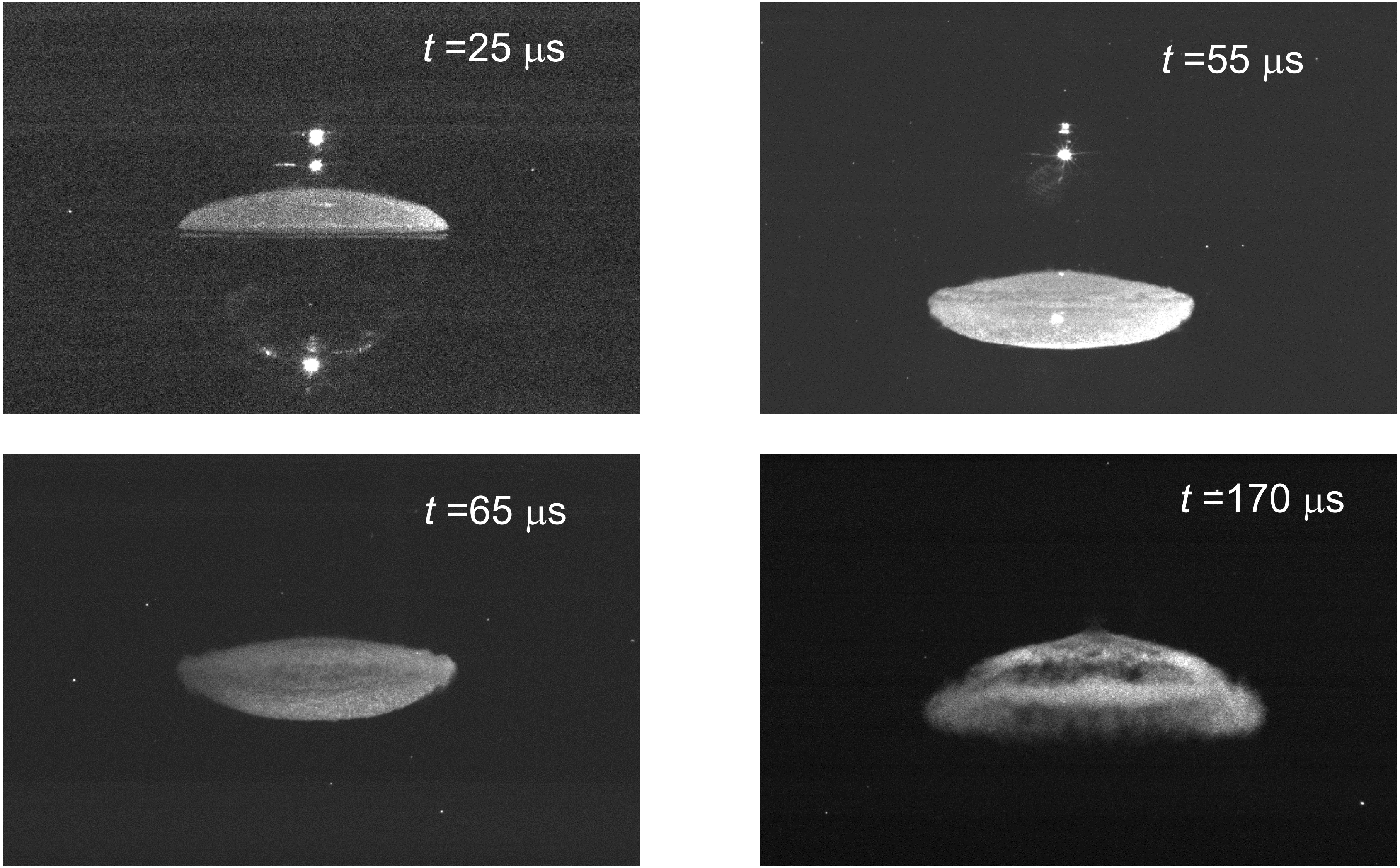


In free fall, bubble exhibits almost no left to right motion

Deduce that front to back motion is also negligible

Laser sheet intersects bubble in diametral plane

Shock Accelerated Bubble M#2.88



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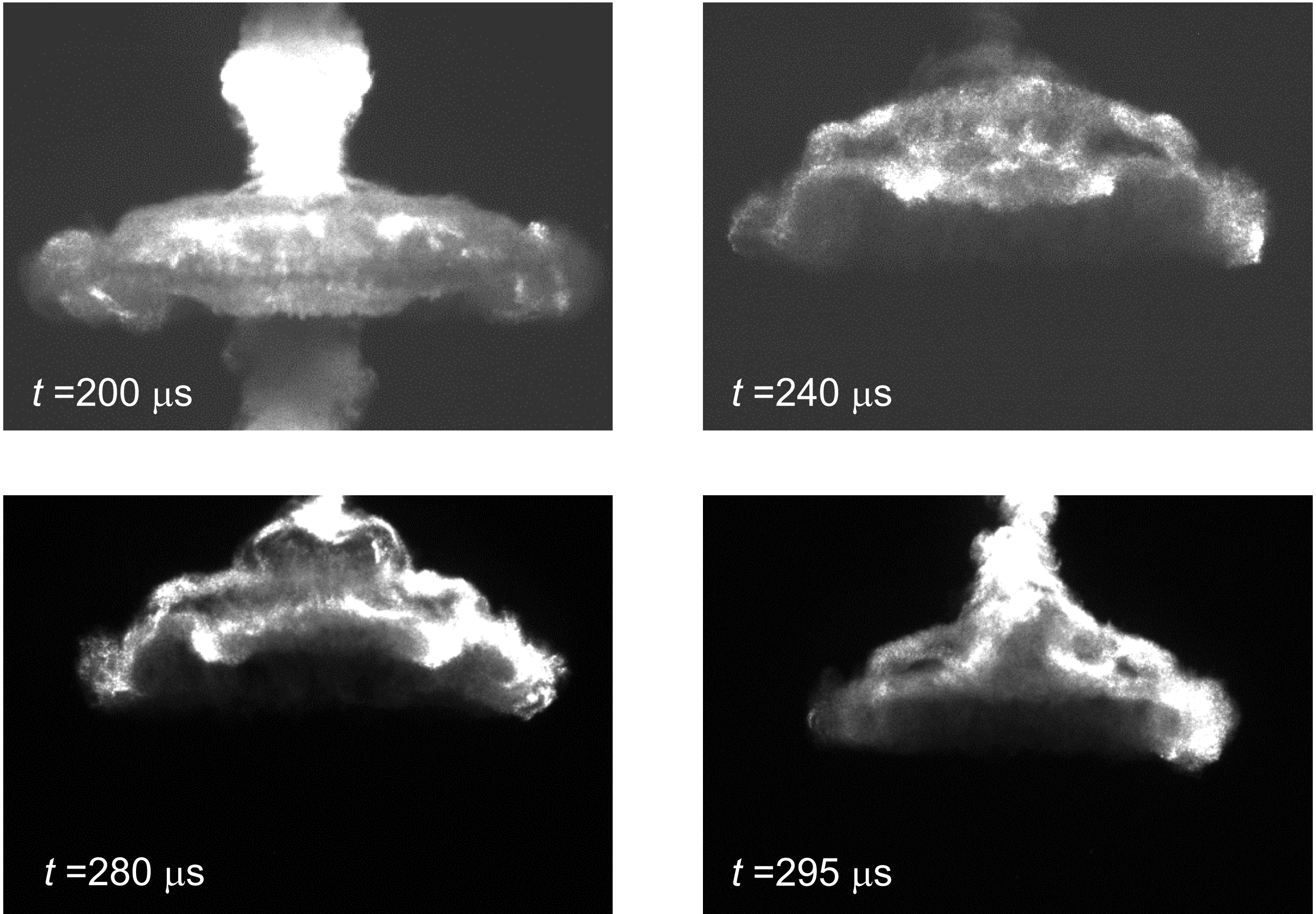

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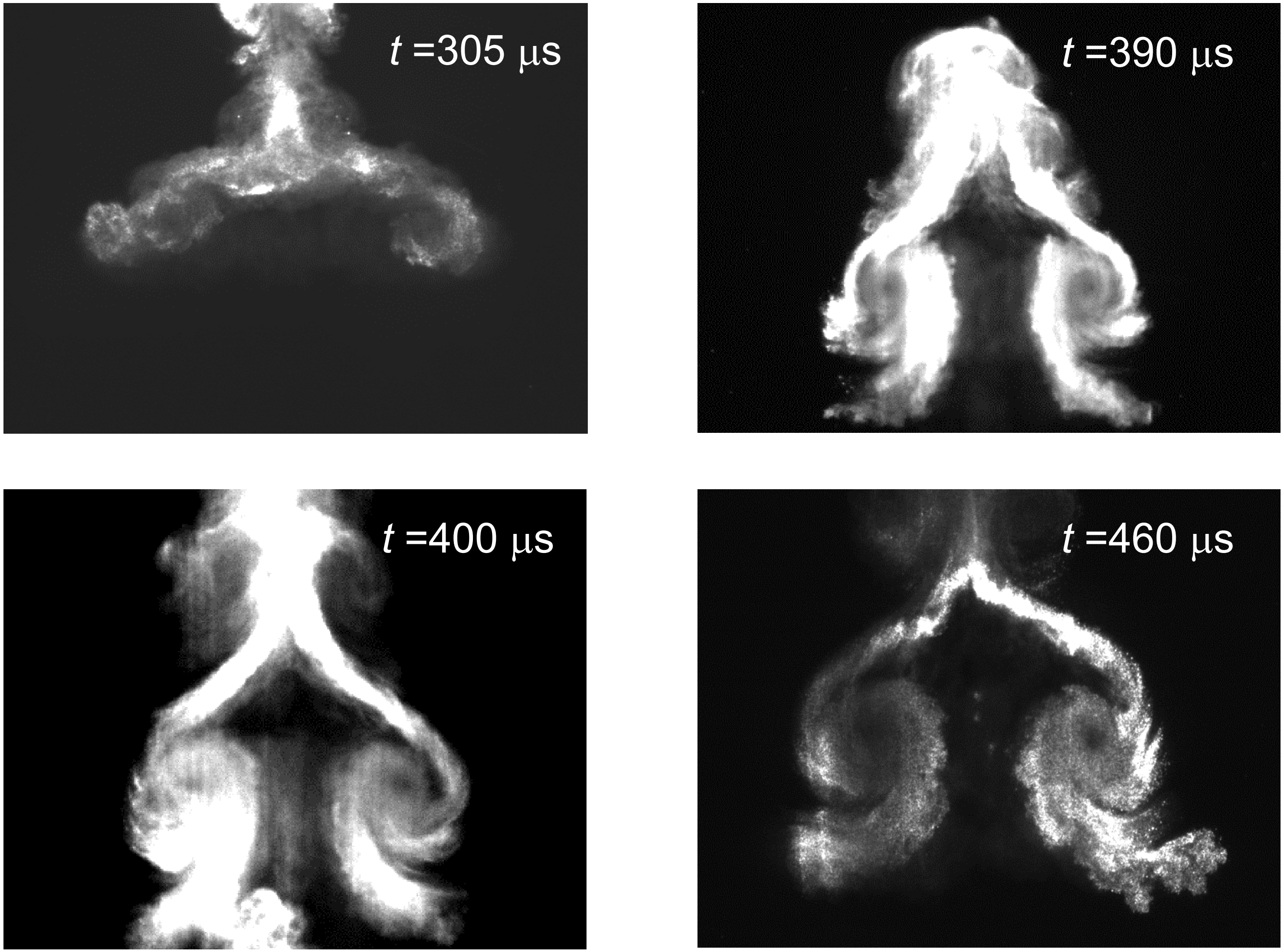

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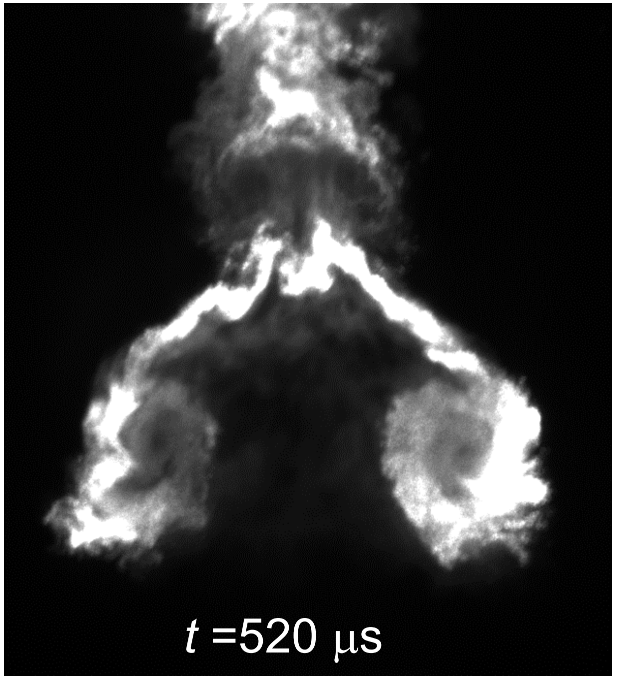

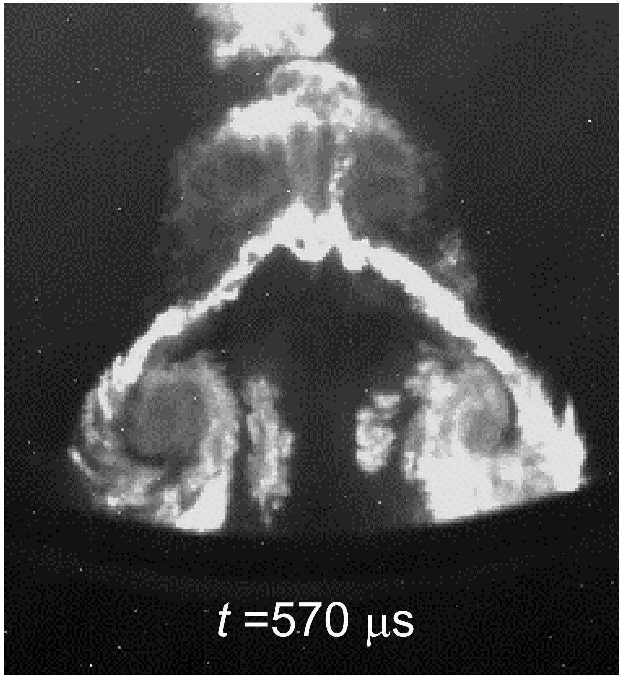

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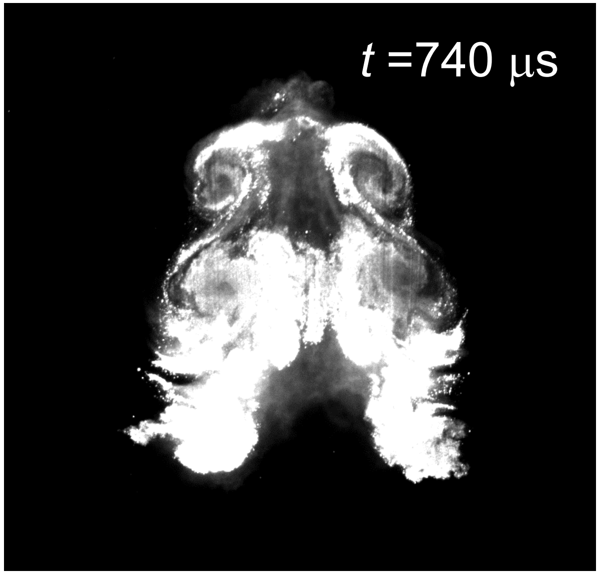
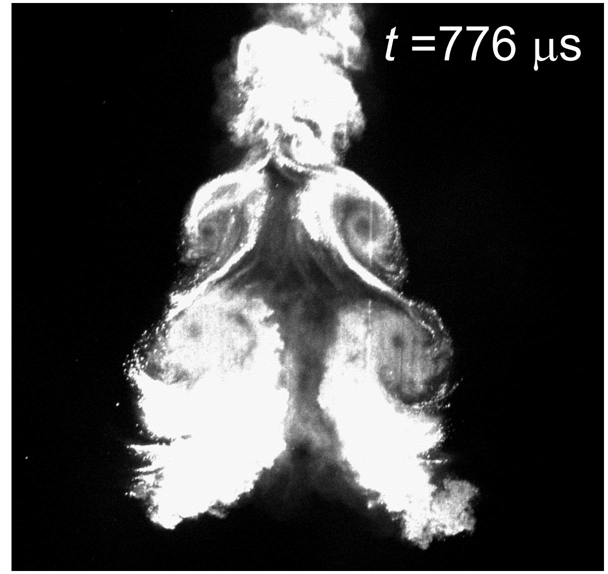
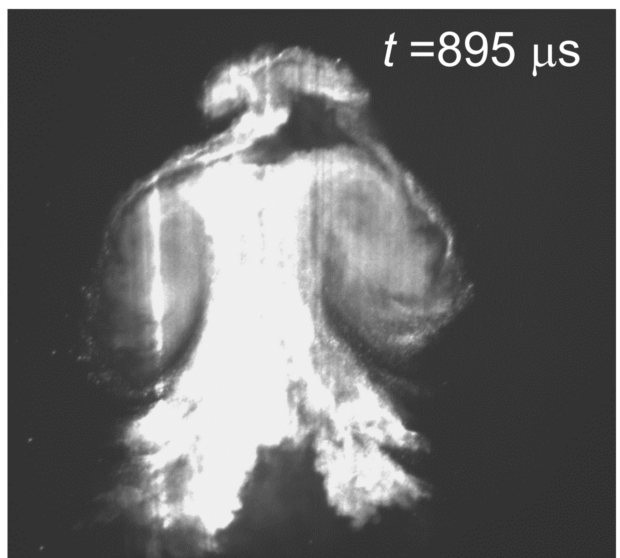
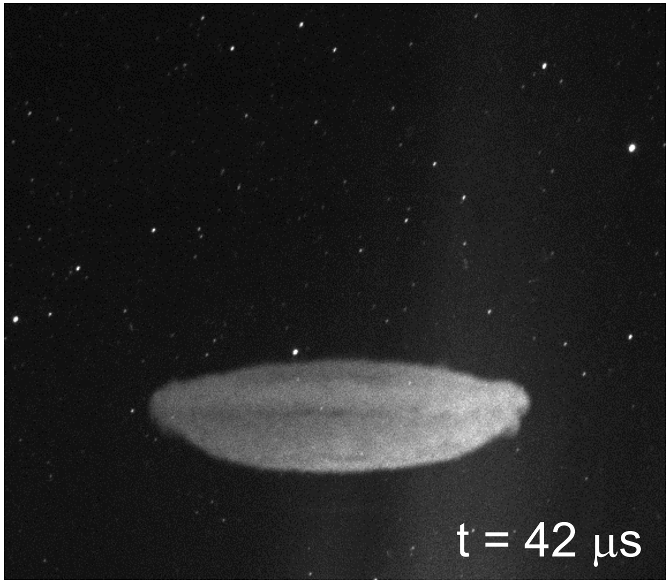
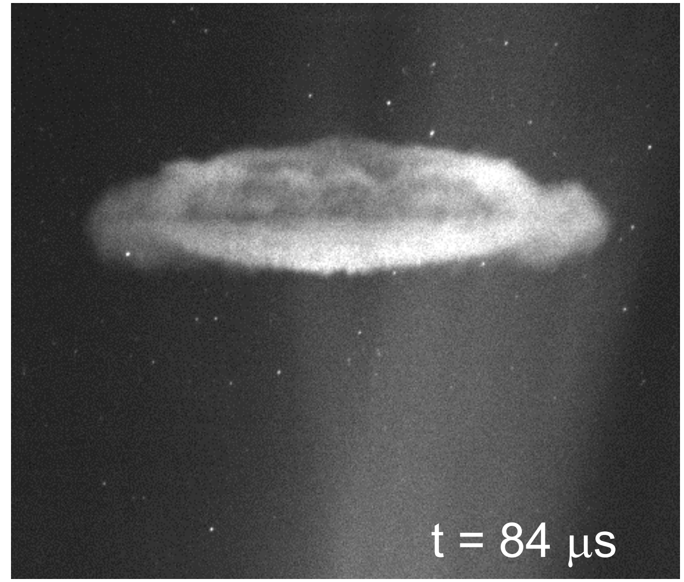


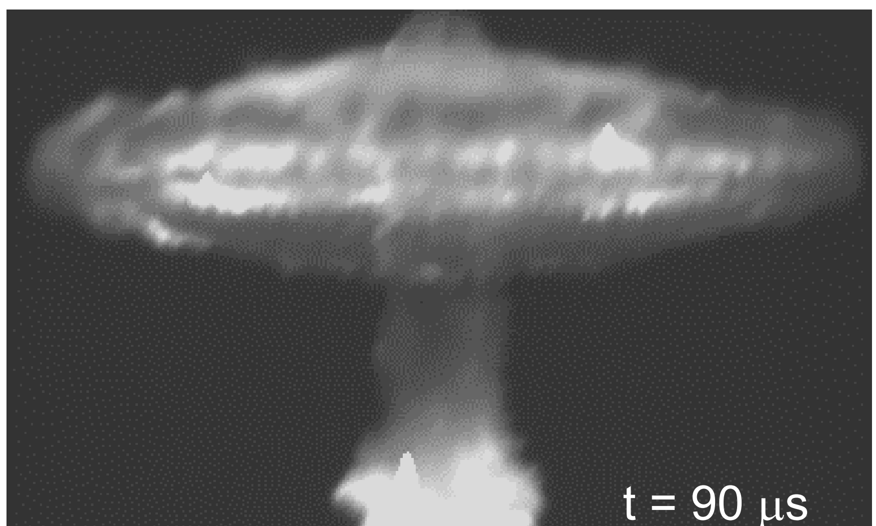




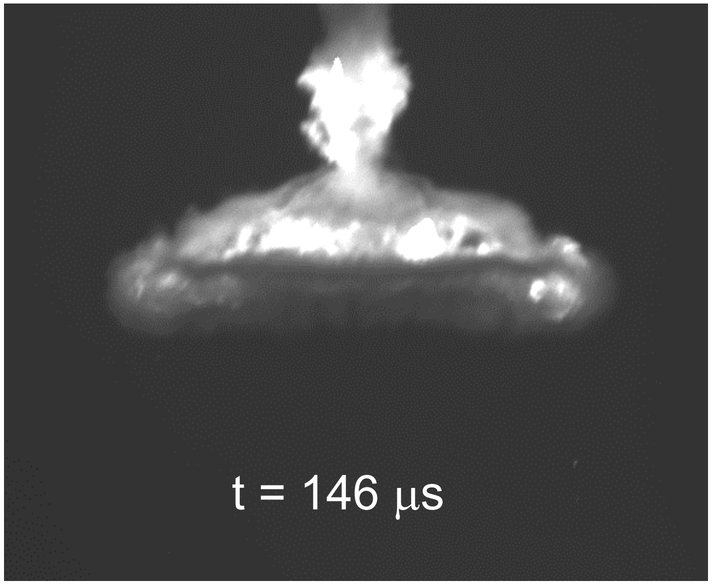
Shock Accelerated Bubble M#3.38

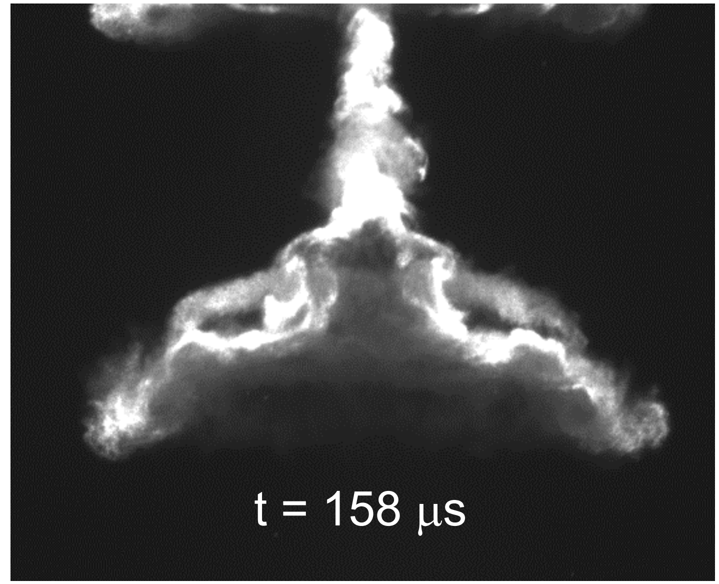


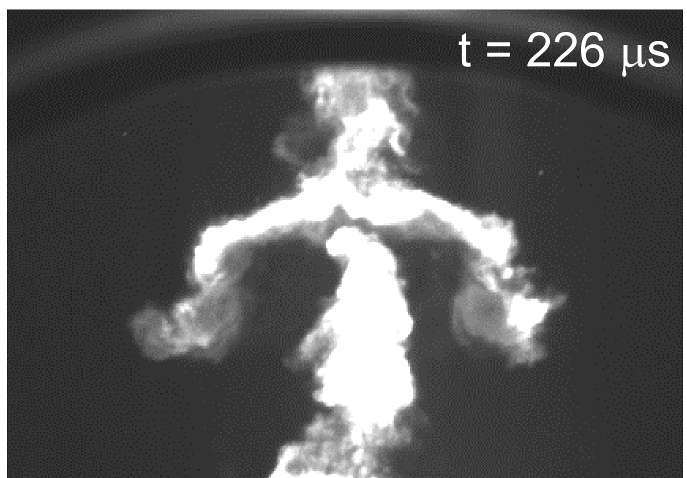




Shock Accelerated Bubble M#3.38







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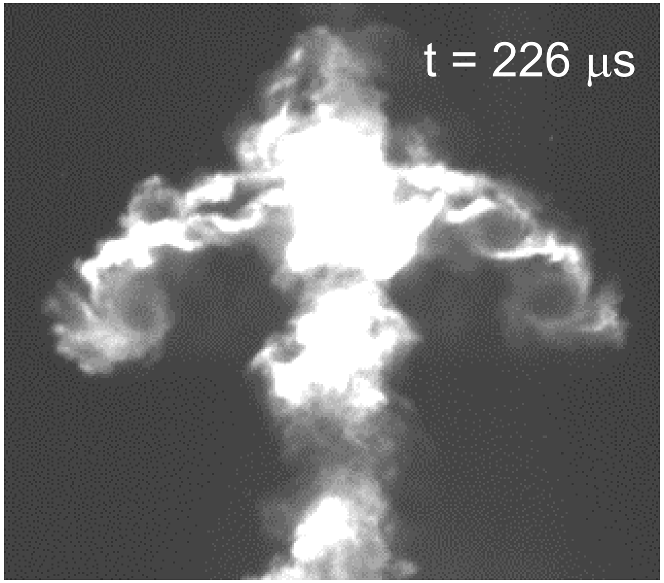
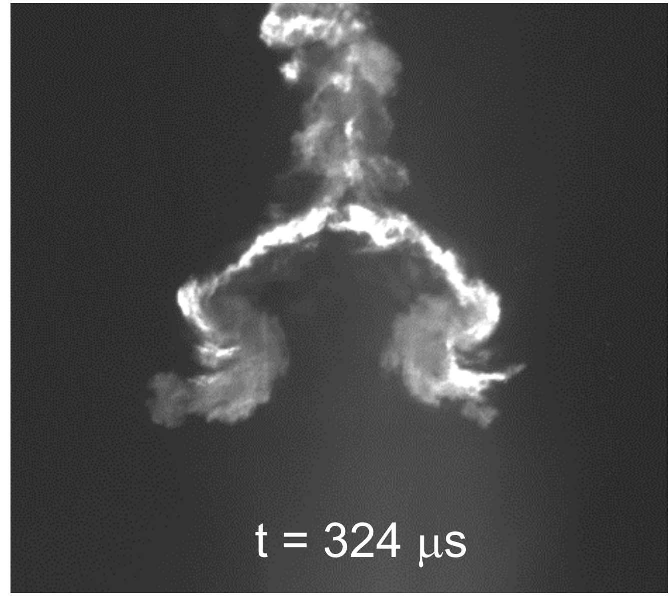
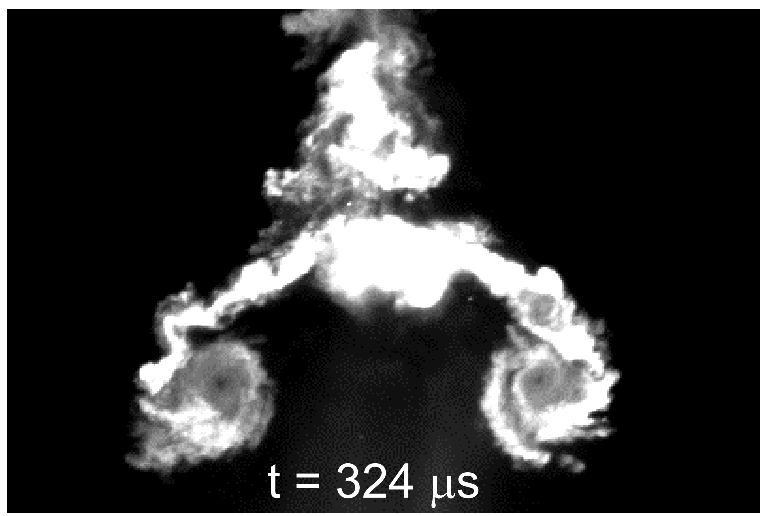


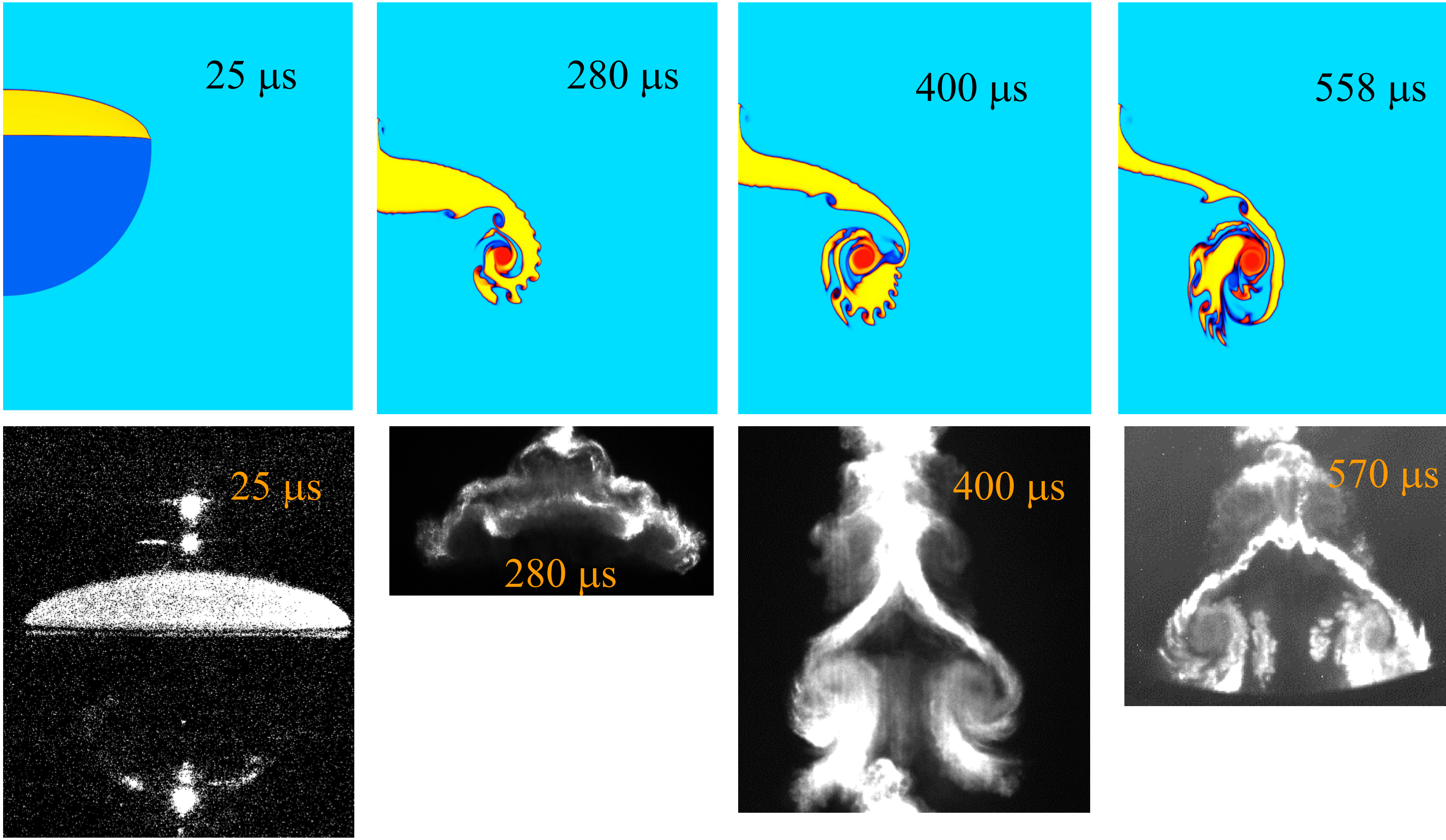




2-D Computational experiments

- Raptor code (LLNL)
- Navier-Stokes; Godunov with PLM; Richardson's error estimation
- 2-D cross section (w/ axial symmetry)
- Grid:
  - 3 AMR levels (4,4,2)
  - $\Delta xmin = 0.078$ mm
- M = 2.88,3.38
- 2-inch-dia. Ar bubble in N_2 initially at 98.274 kPa
- No soap film; sharp interface
- Richardson on only while shock interacts
- Times given relative to initial shock-bubble interaction (±4 μs error)

Qualitative laboratory/computational comparison M#2.88



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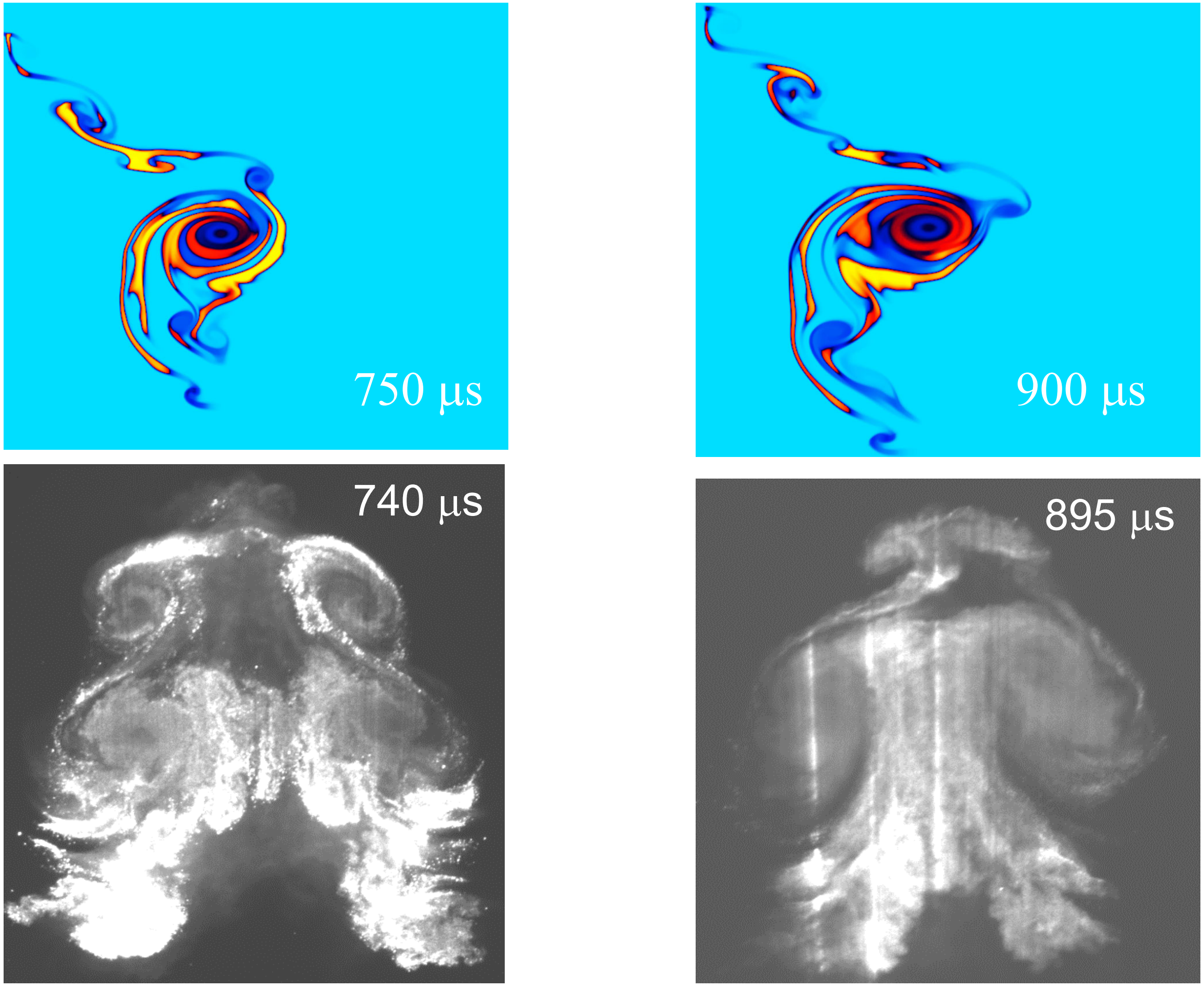

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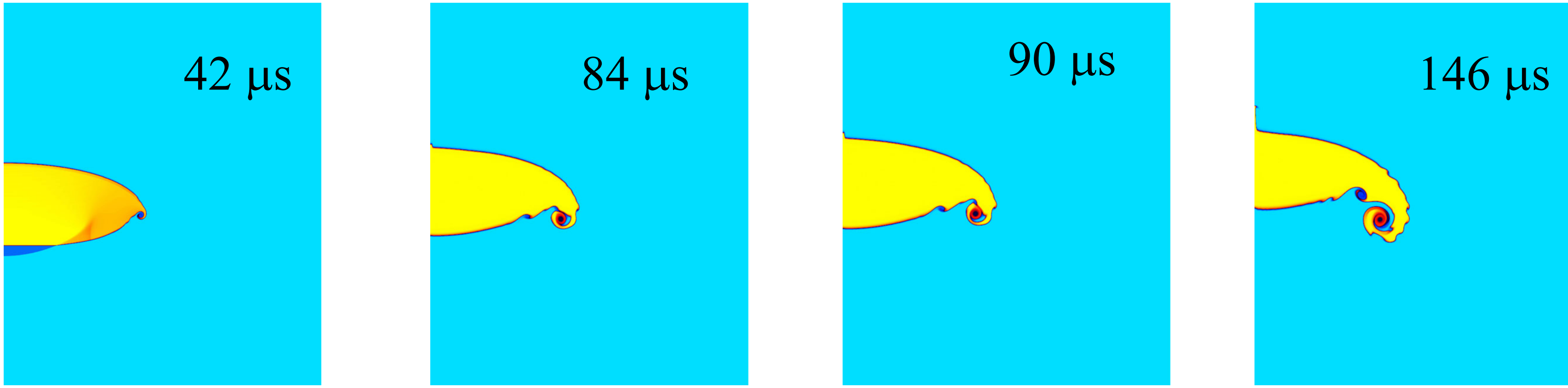

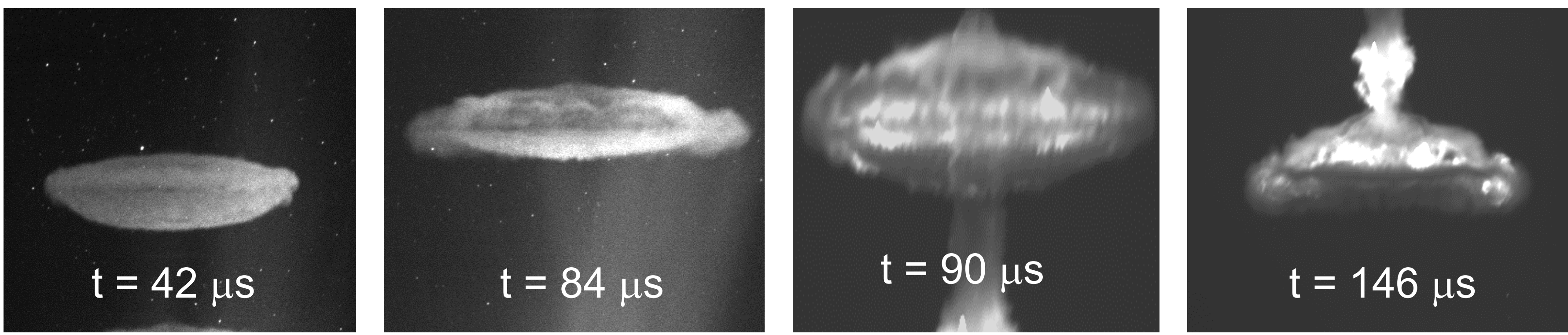

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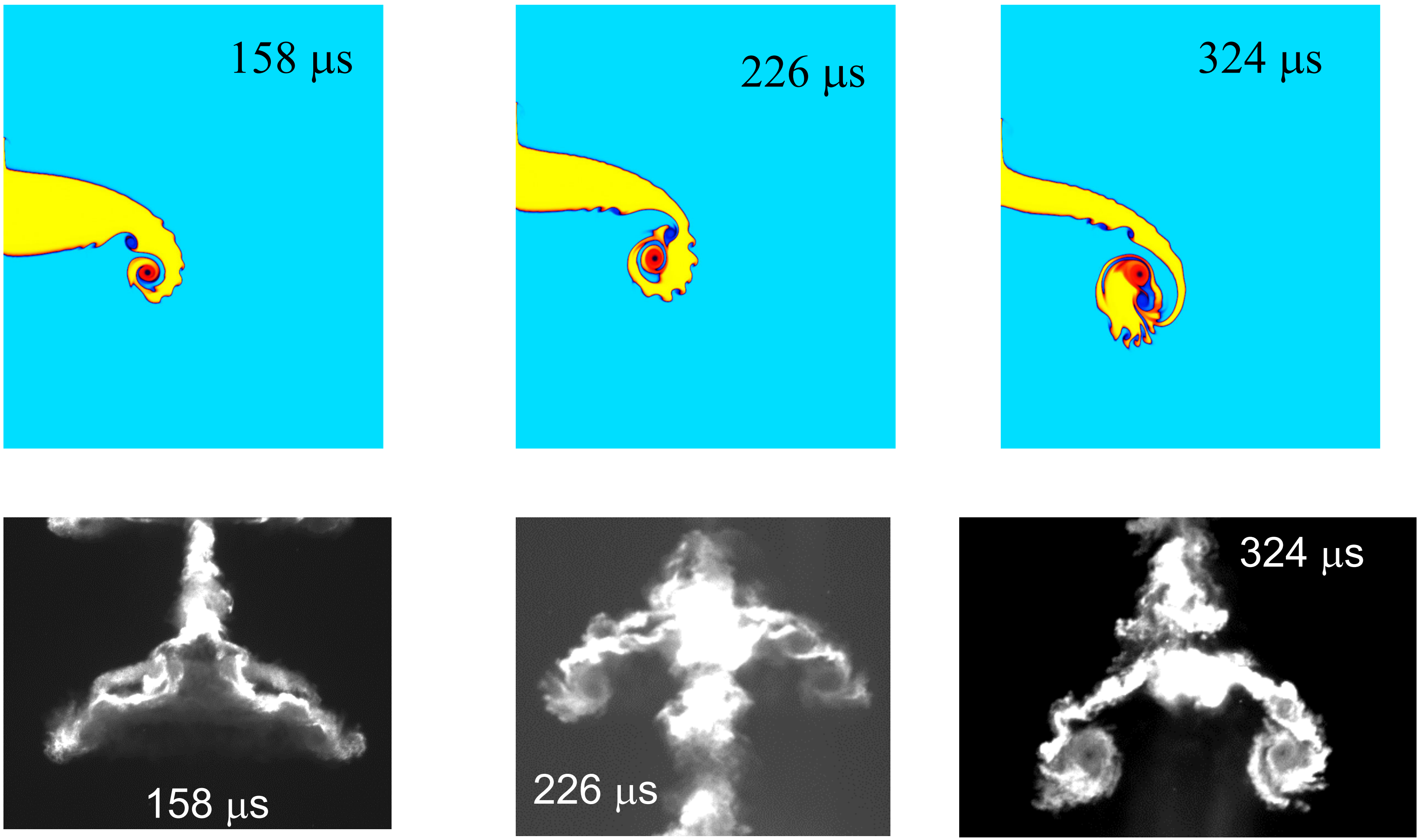
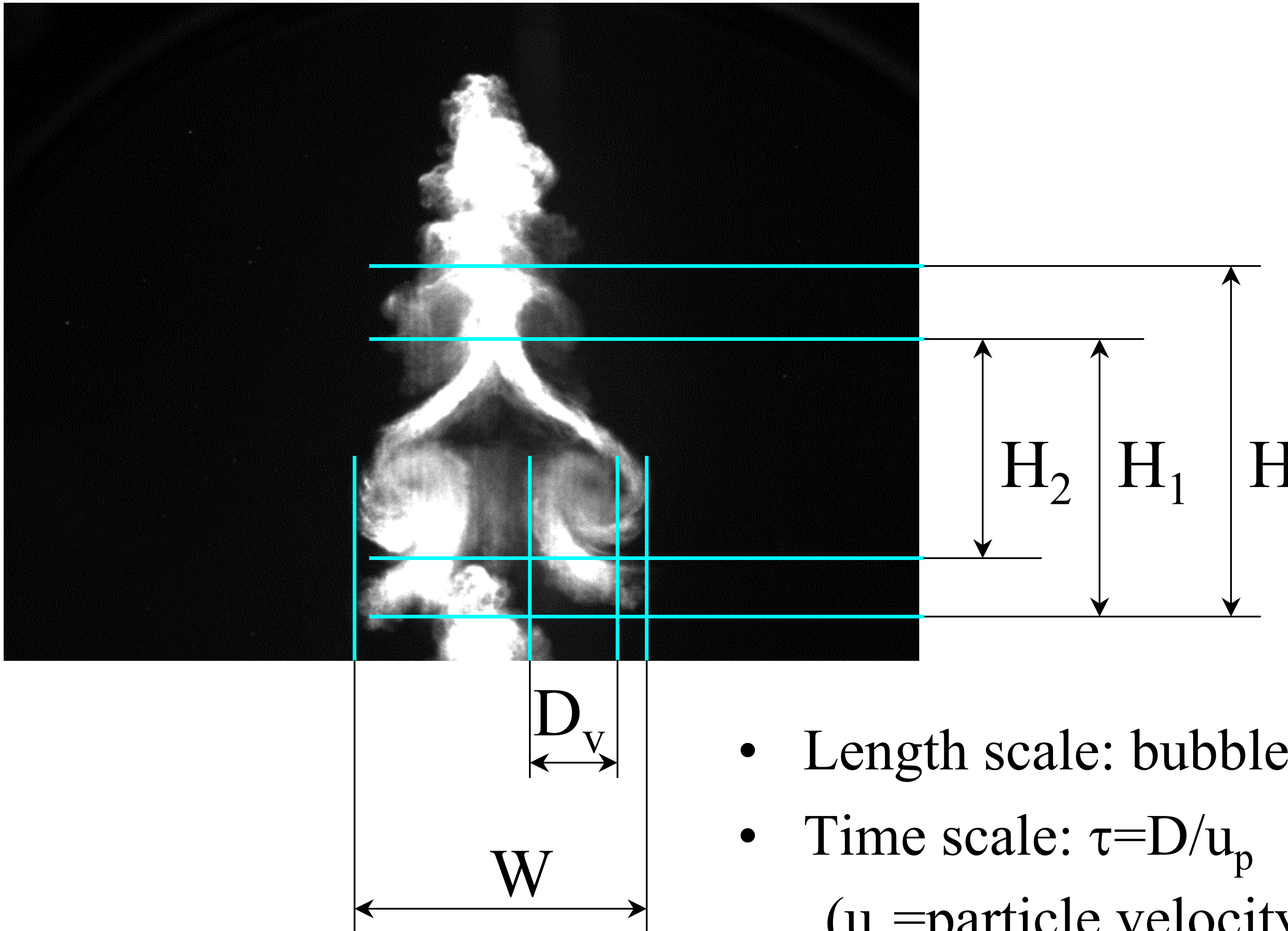
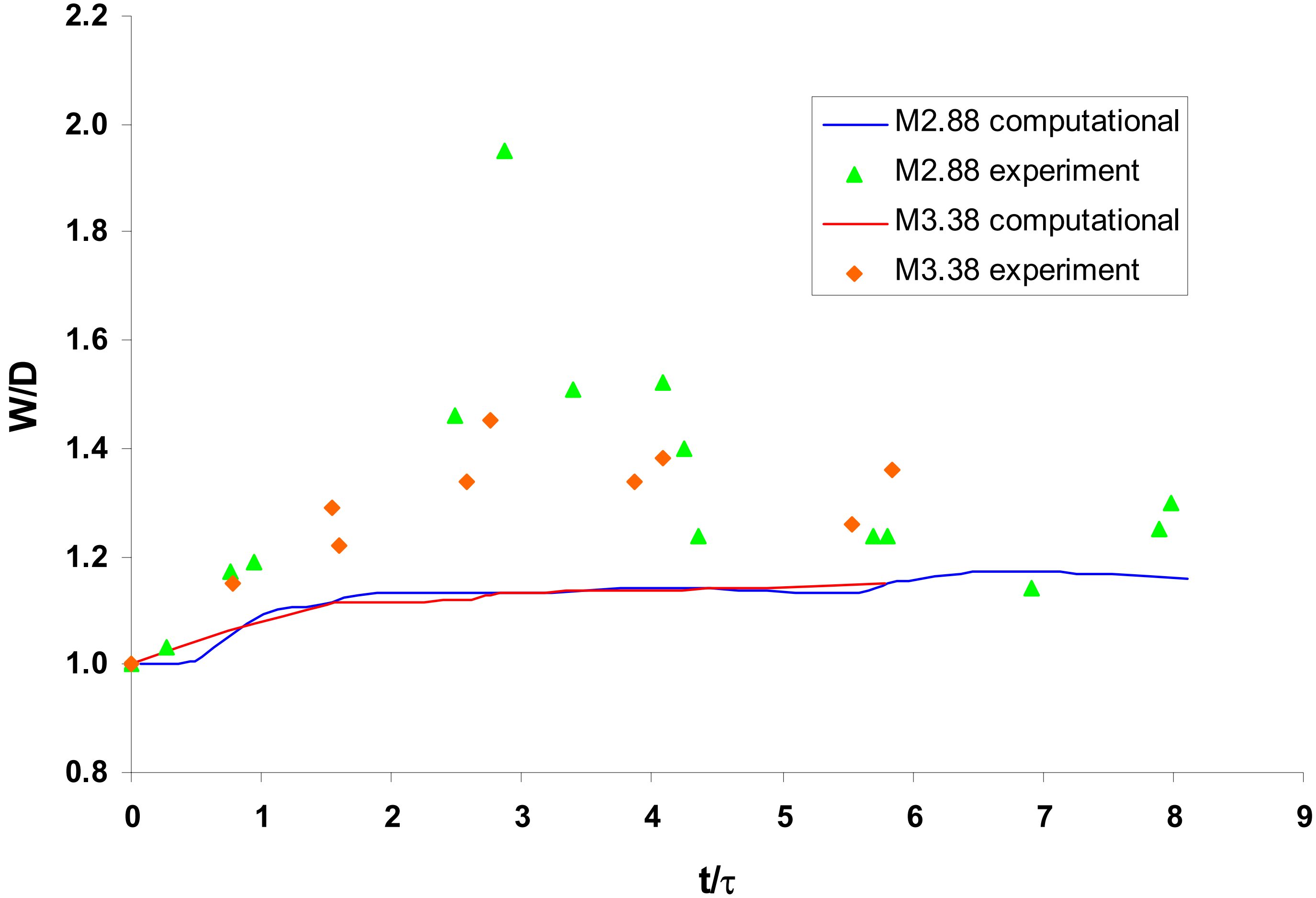


Geometrical features

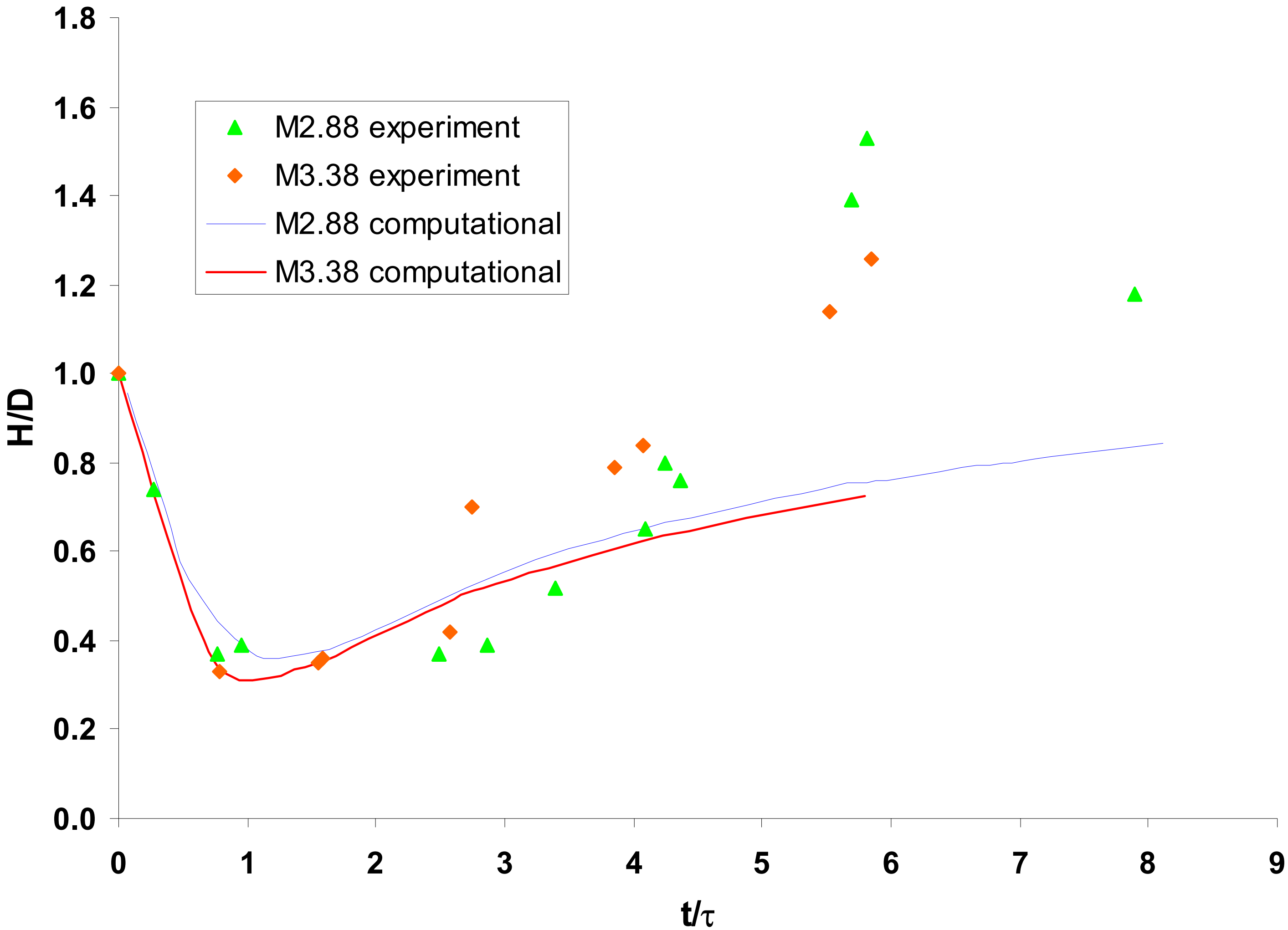


- Length scale: bubble diameter D
- Time scale: $\tau = D/u_p$
  (u_p=particle velocity behind shock)

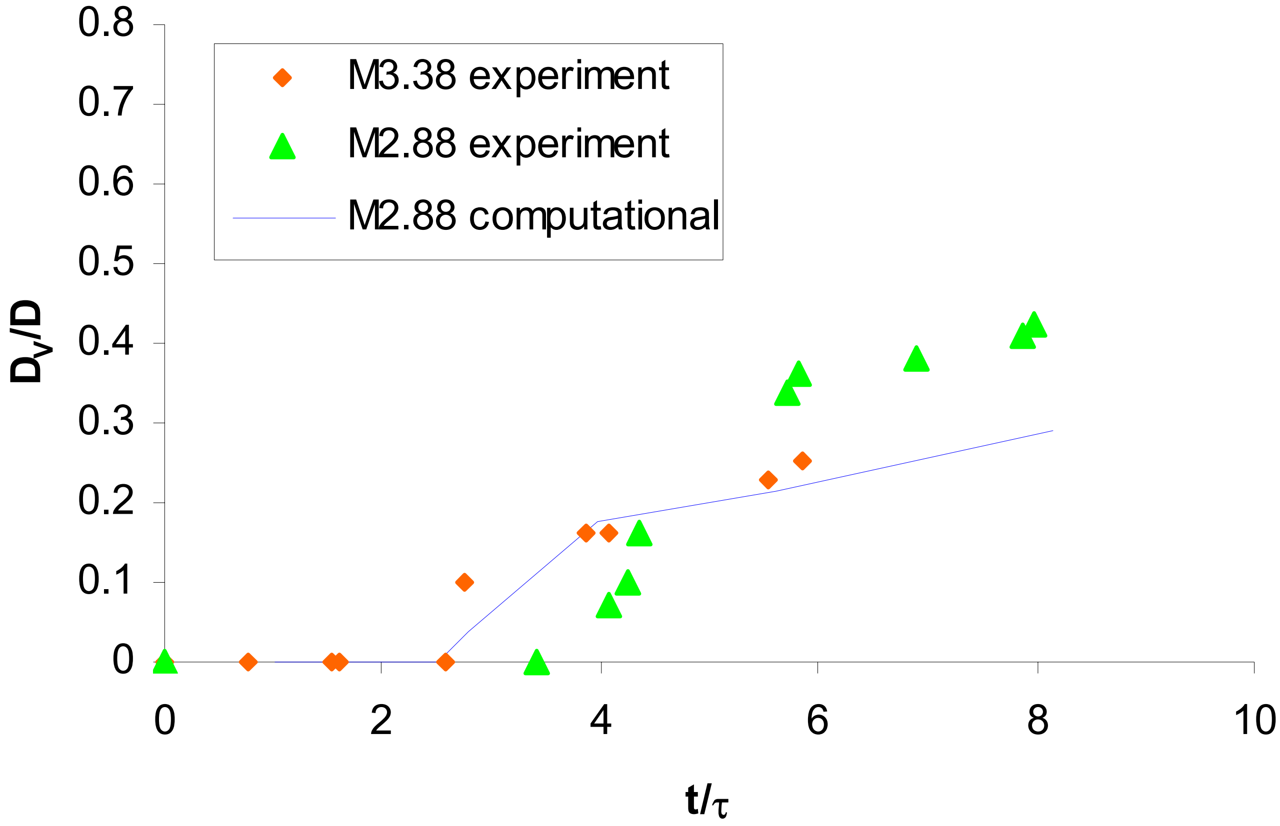
Width growth rate



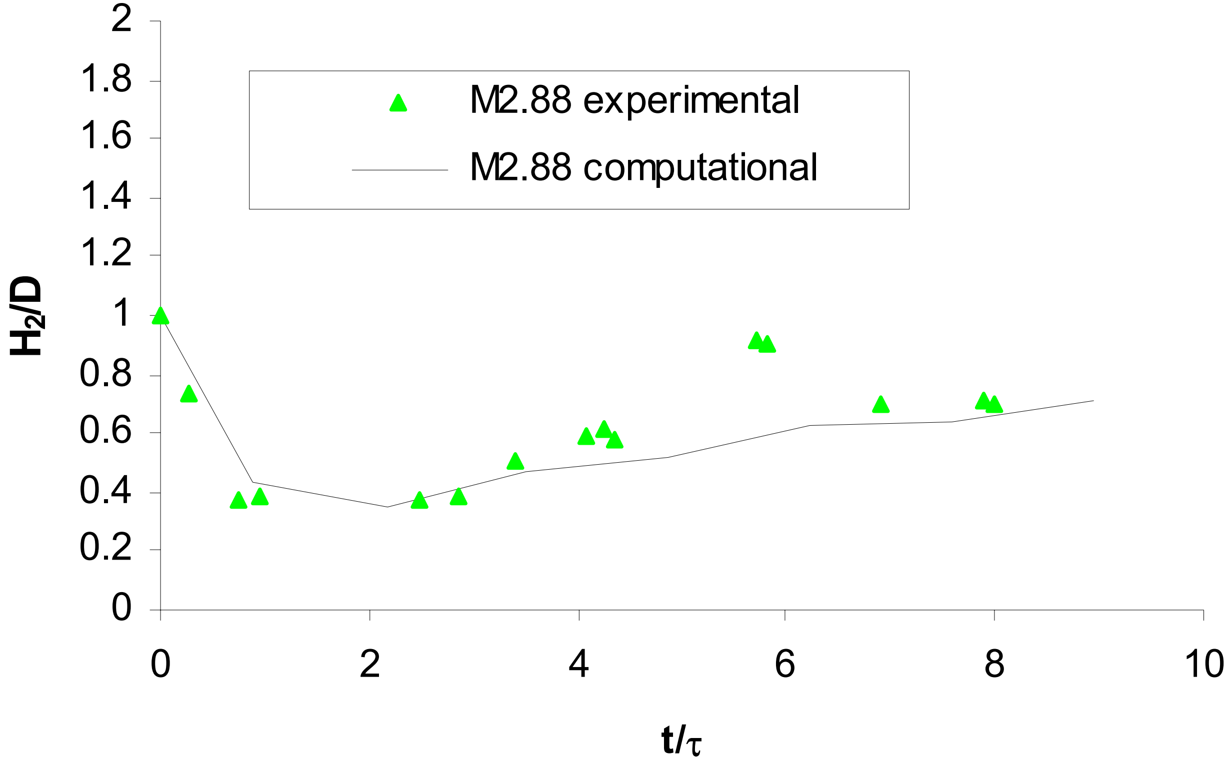
Height growth rate



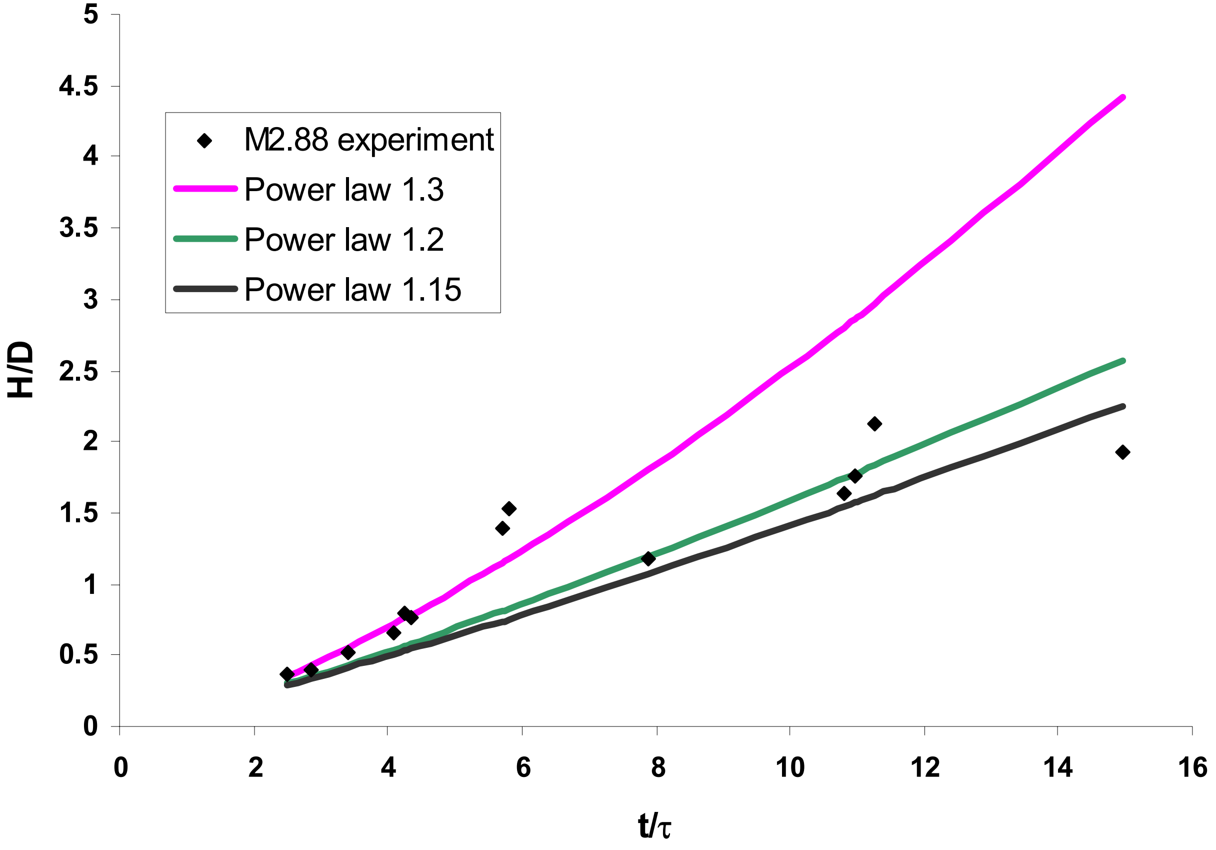
Vortex diameter growth rate



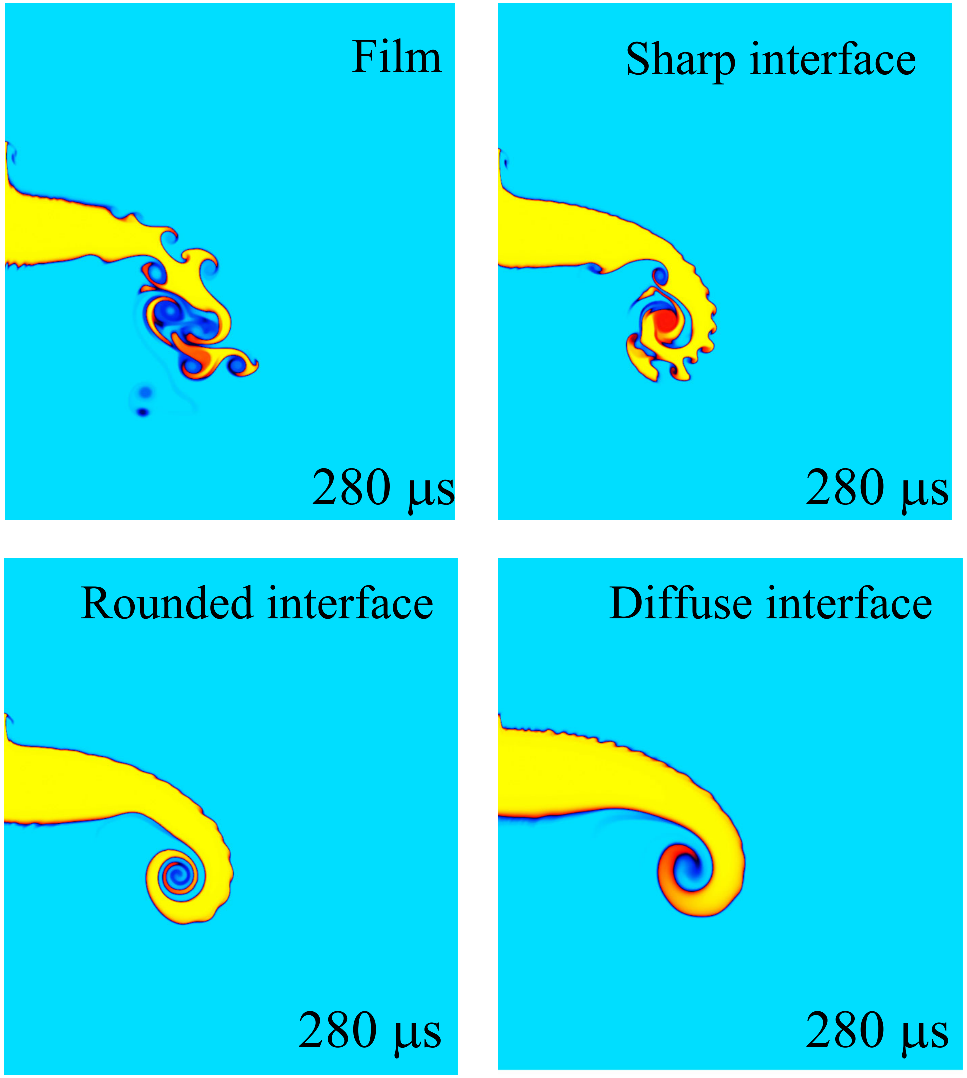
Experiments vs. computations (H_2; M=2.88)

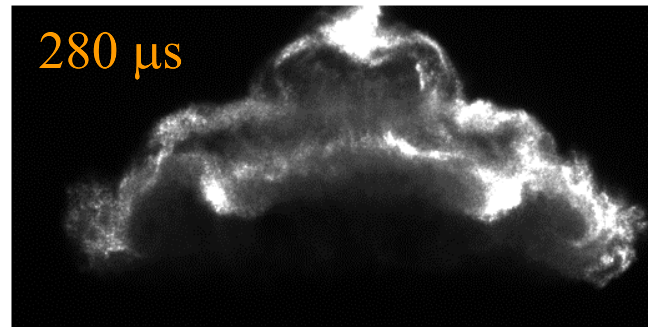


Height growth rate (power law fit)



2D Simulation with different initial conditions





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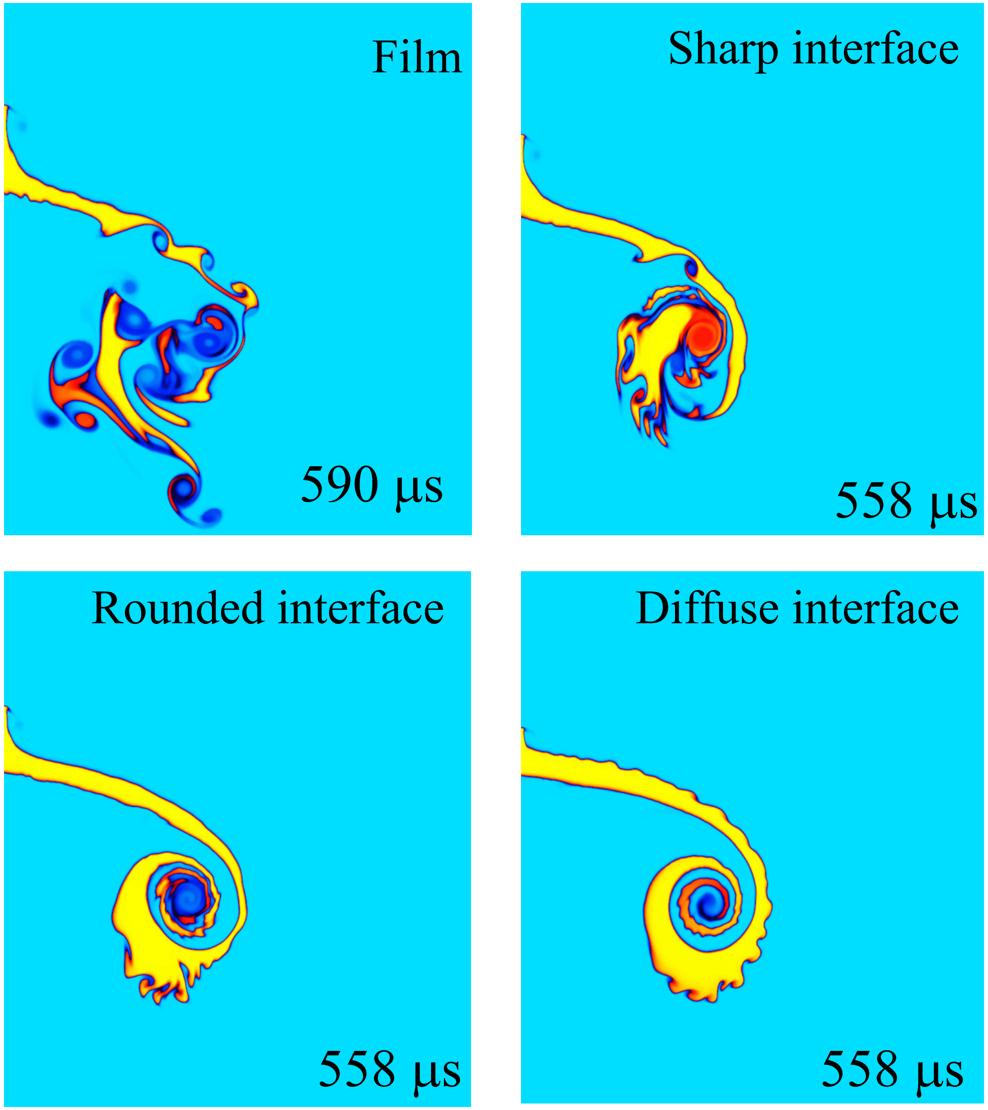
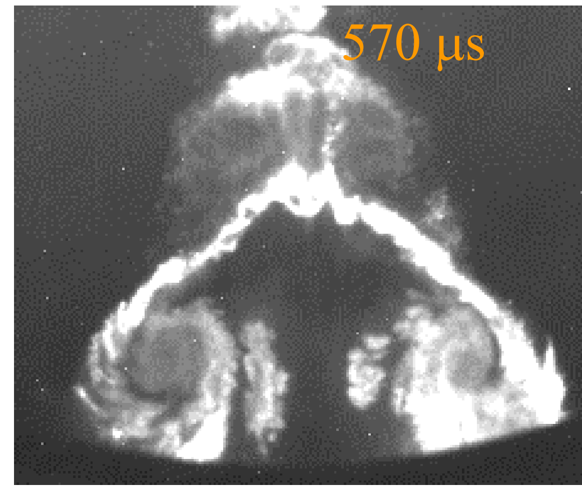
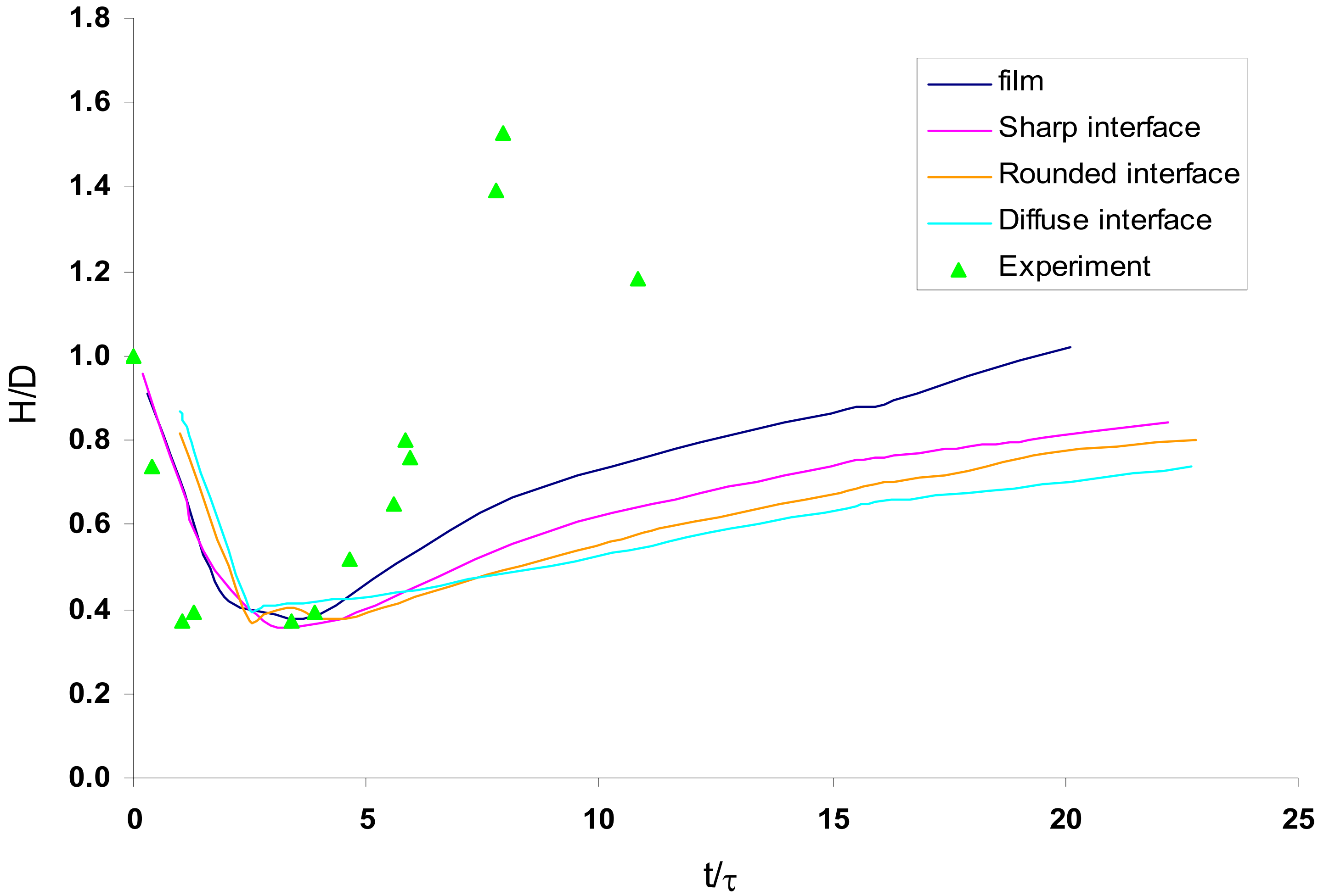
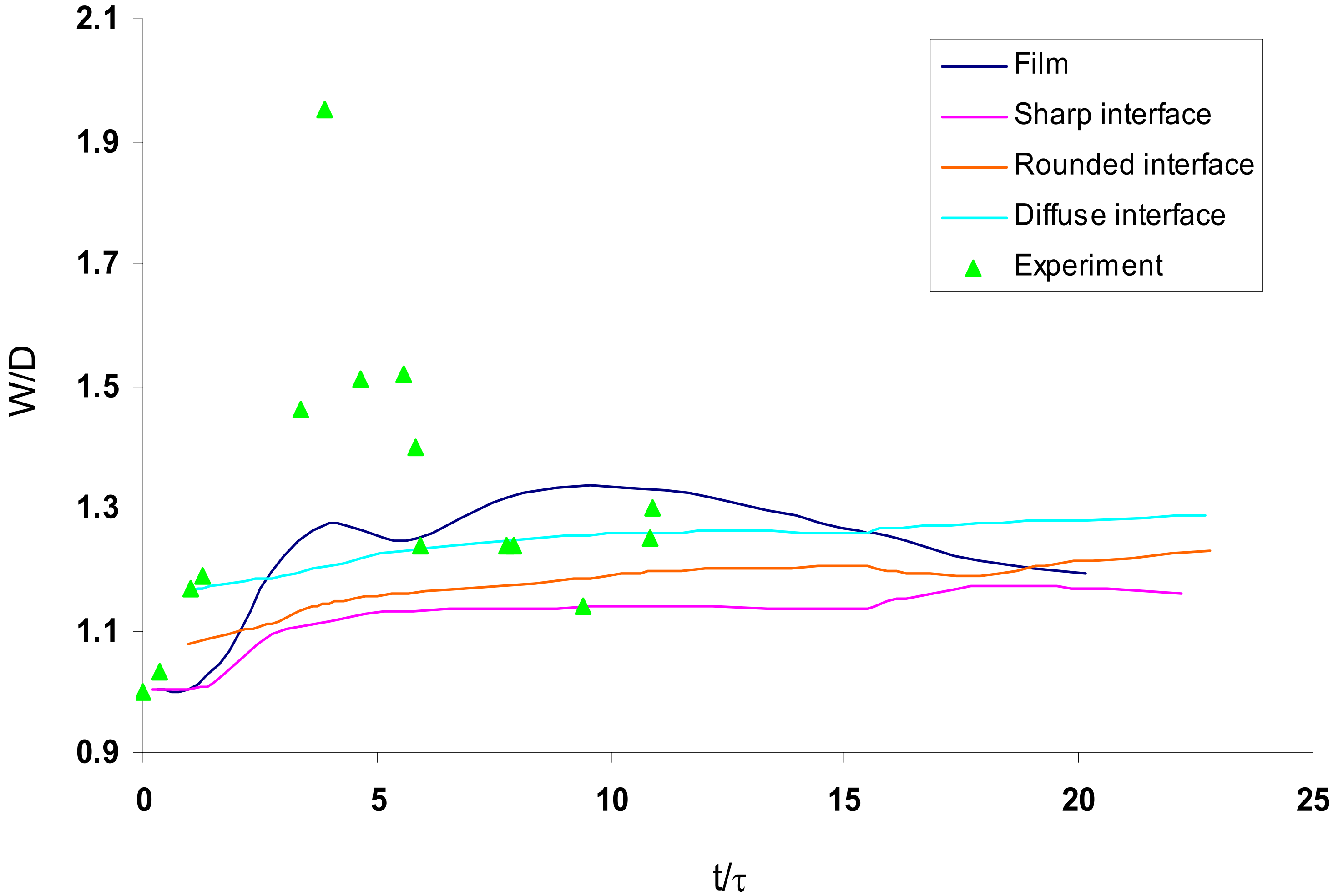




Height growth rate M#2.88



Width growth rate M#2.88



Conclusions from comparison with 2D simulation

- Observed bubble distortion, formation of vortex ring
- Measured growth rates of relevant large scale features
- Axial compression and expansion is observed
- Growth rate predicted are good for early timings
- No upstream vortex or jet is observed in simulation
- Absence of small scale features in simulation

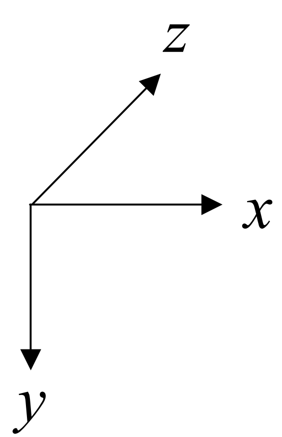
- Need 3-D numerical simulations

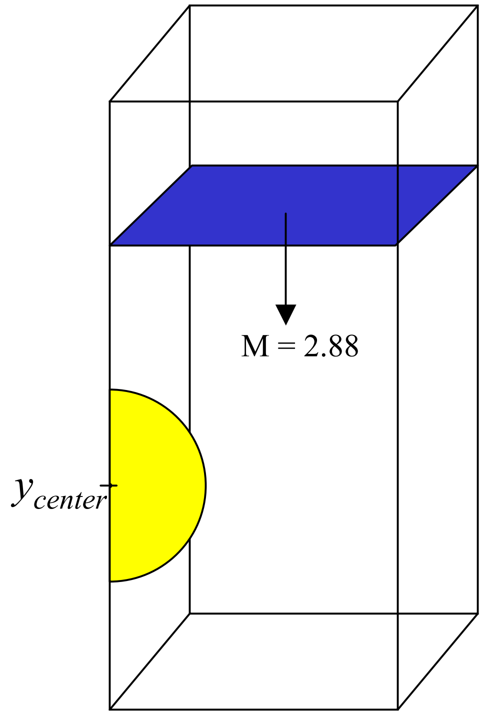
3-D Computational experiments

- Raptor code (LLNL): 3-D
- Euler (no artificial viscosity used in 3-D runs); Godunov with PLM; Richardson's error estimation
- 3-D Cartesian, ¼ symmetry about bubble center
- Grid:
  - 2 AMR levels (4,4)
  - $\Delta xmin$ = 0.195 mm (factor of >2 coarser than 2-D runs)
- M = 2.88
- 2-inch-dia. Ar bubble in N2 initially at 98.274 kPa
- Film:
  - Thickness: 1 cell-width
  - Density: 0.1 g/cm3
- Times given relative to initial shock-bubble interaction (±4 ms error)

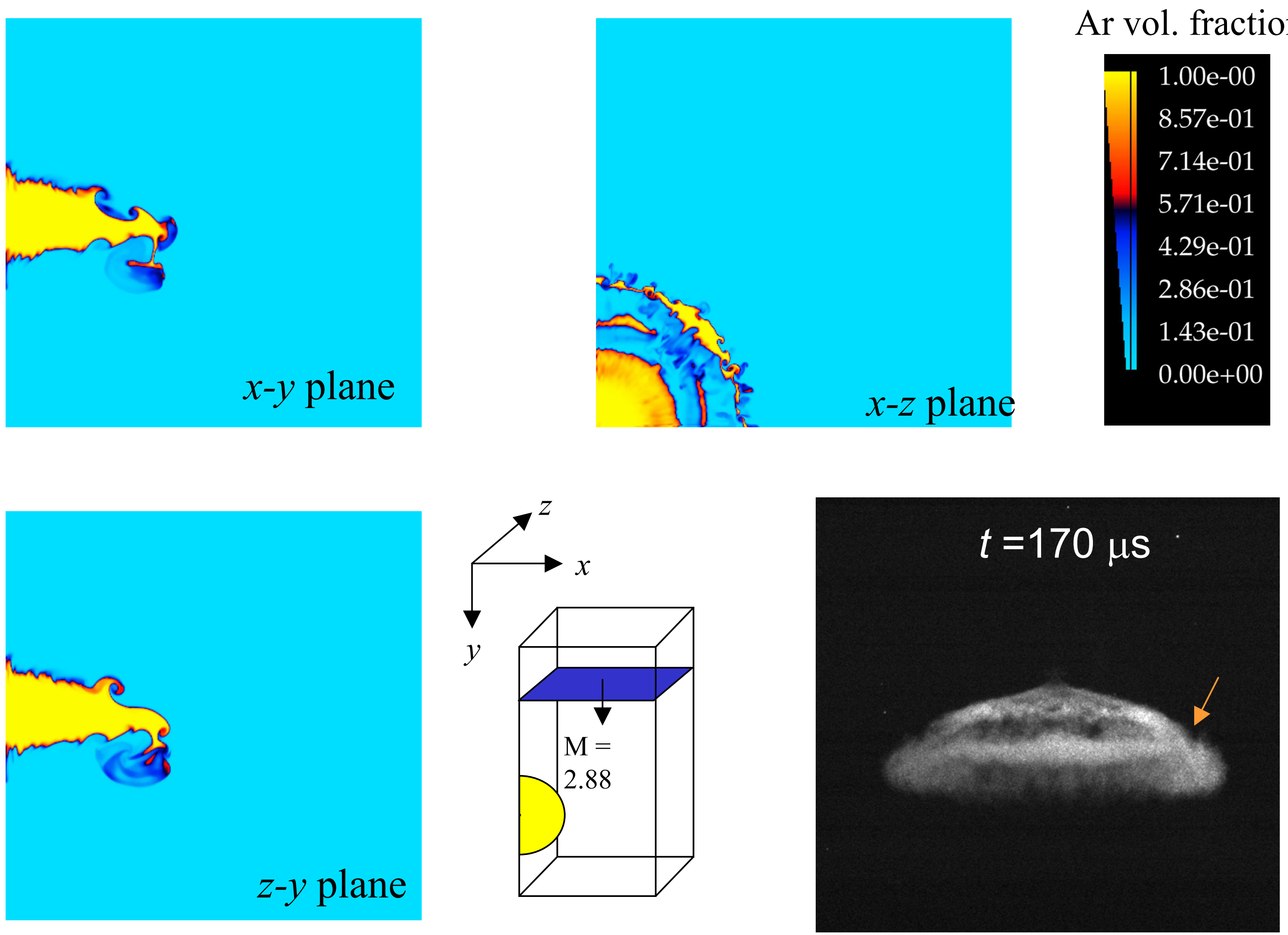
3-D Computational experiments

- Shock propagates along the *y*-axis
- Bubble is centered at (0,*ycenter*,0)
- Results are viewed using 3 planar slices: one perpendicular to each axis, at a selected location on that axis.
- *x*-*y* and *z*-*y* plots are shown at $z = 0$ and $x = 0$ locations, respectively.
- *x*-*z* plots are shown at a *y* location selected to be near the main vortex ring (indicated by red line).





Qualitative laboratory/3-D computational comparison



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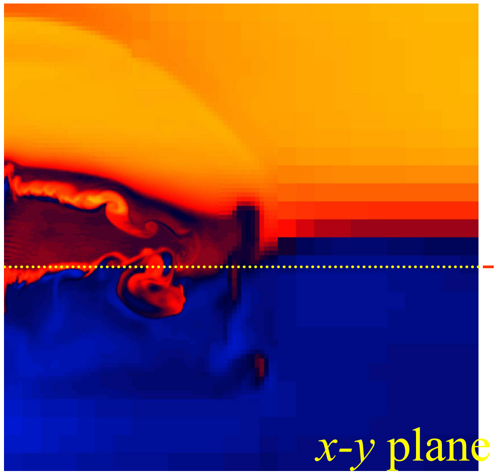

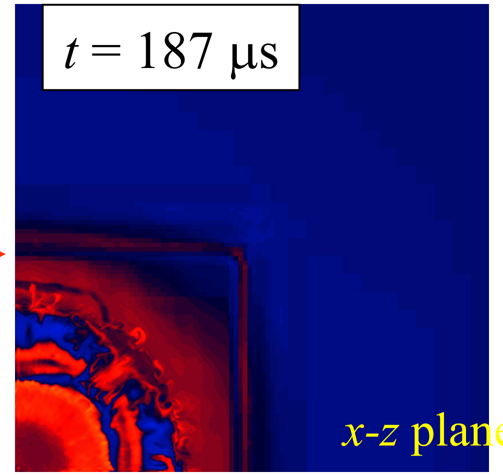

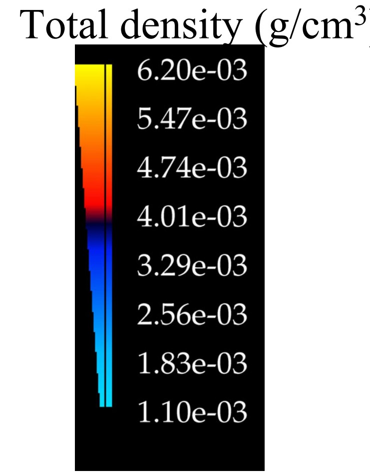

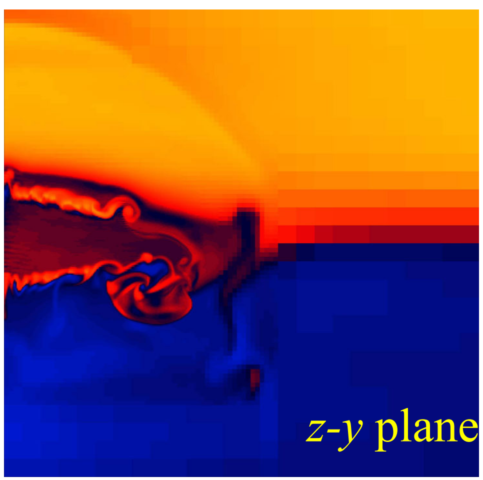

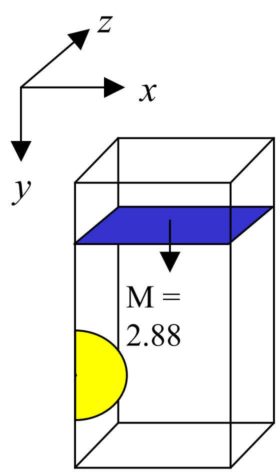

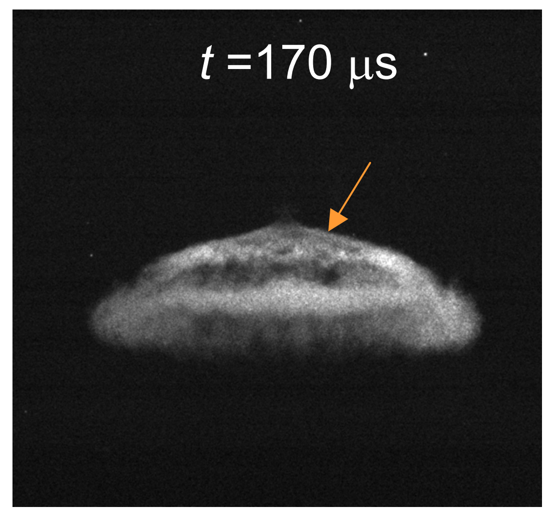

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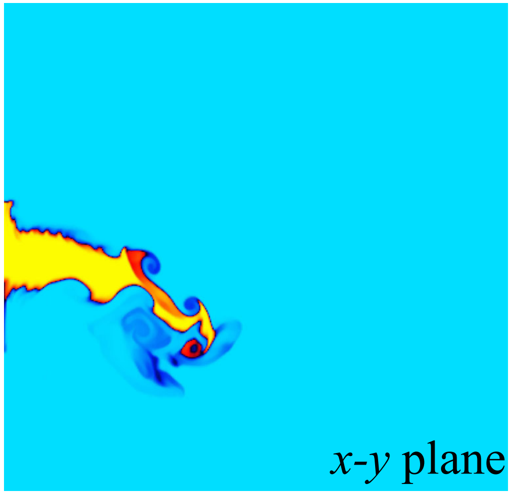
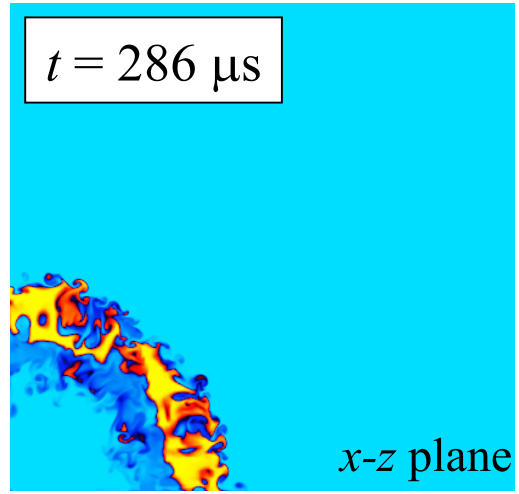
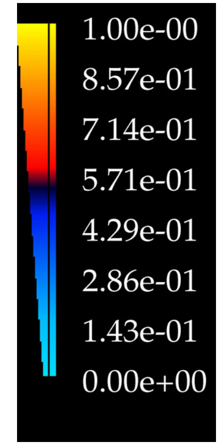
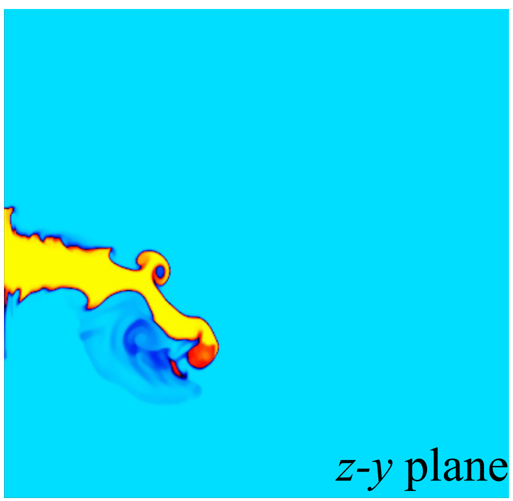
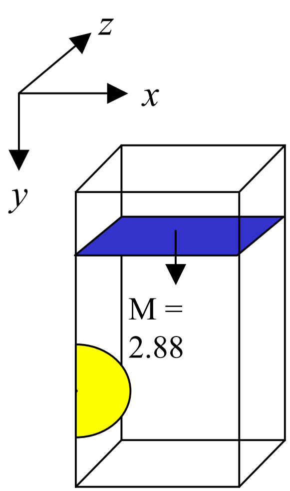


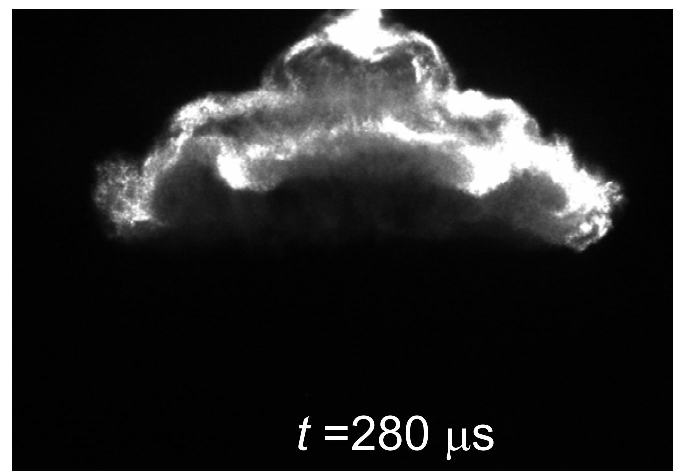


Ar vol. fraction









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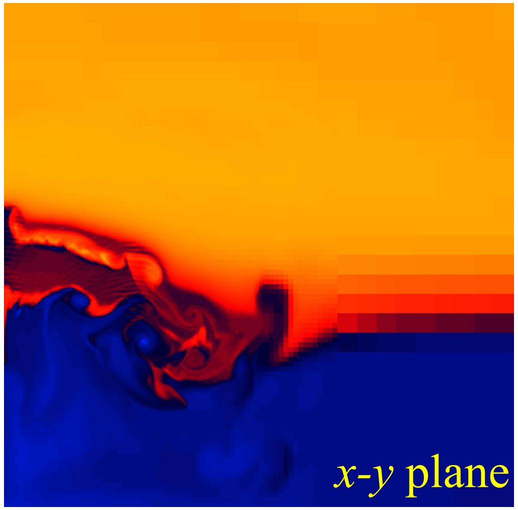
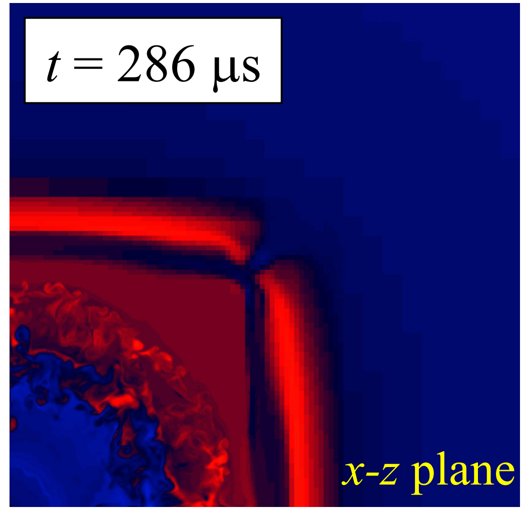
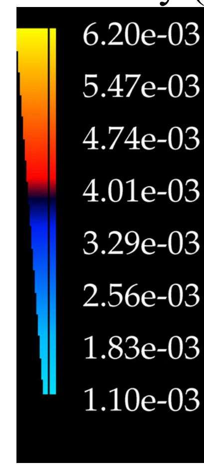
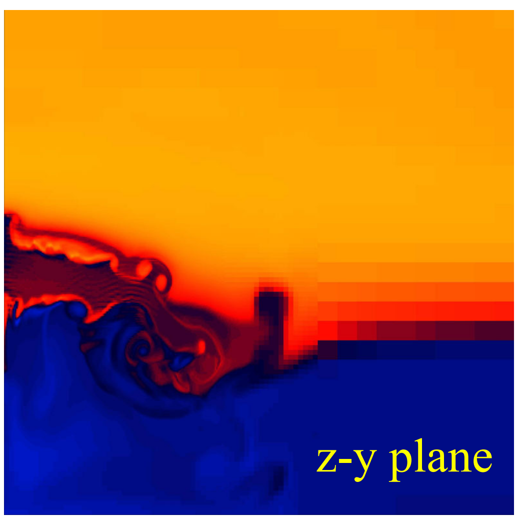
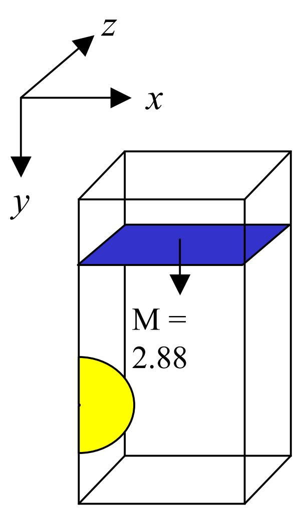


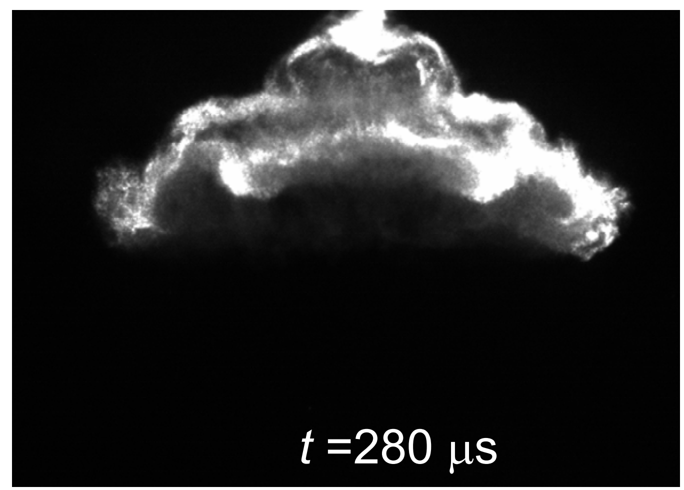


Total density (g/cm³)

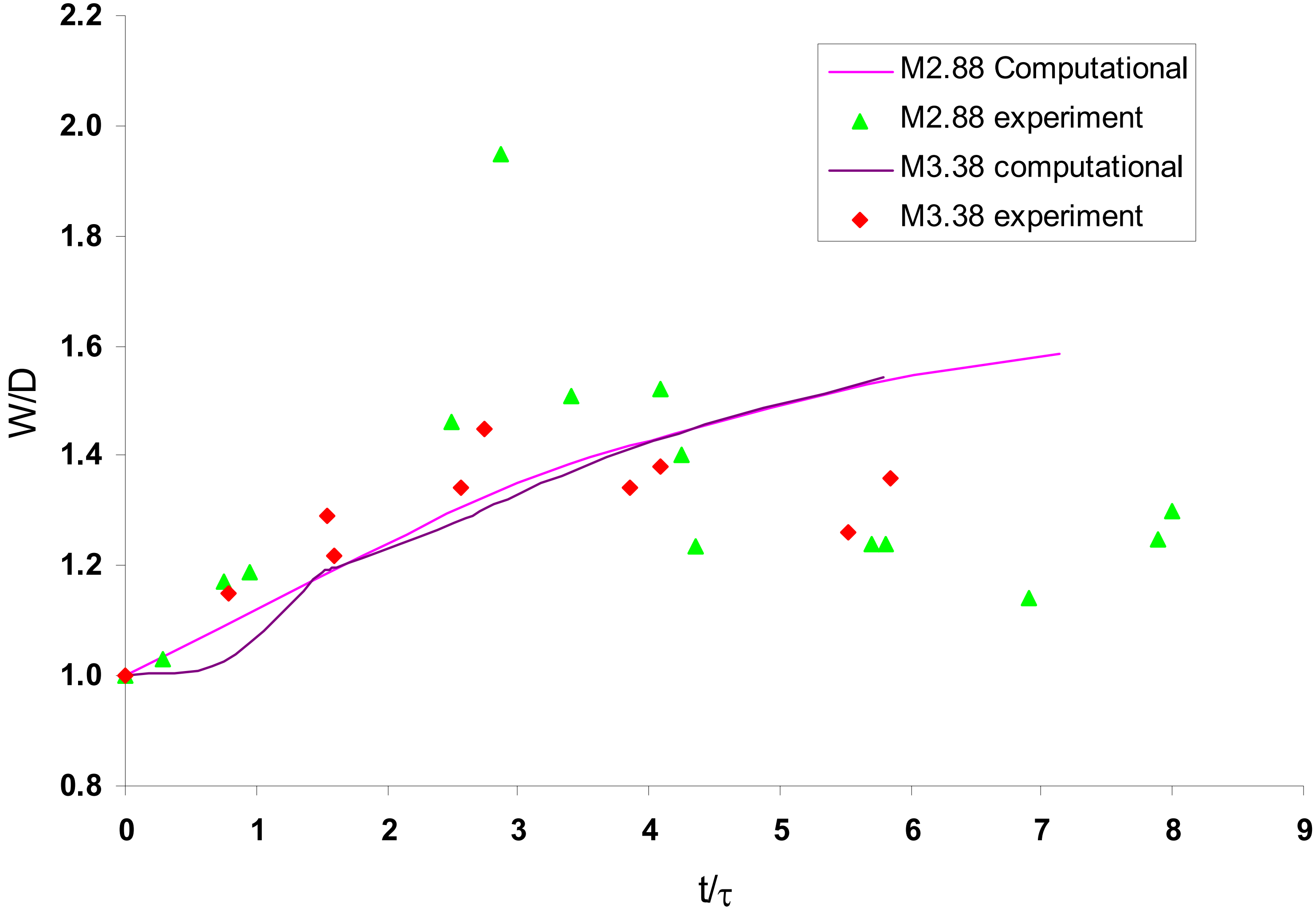




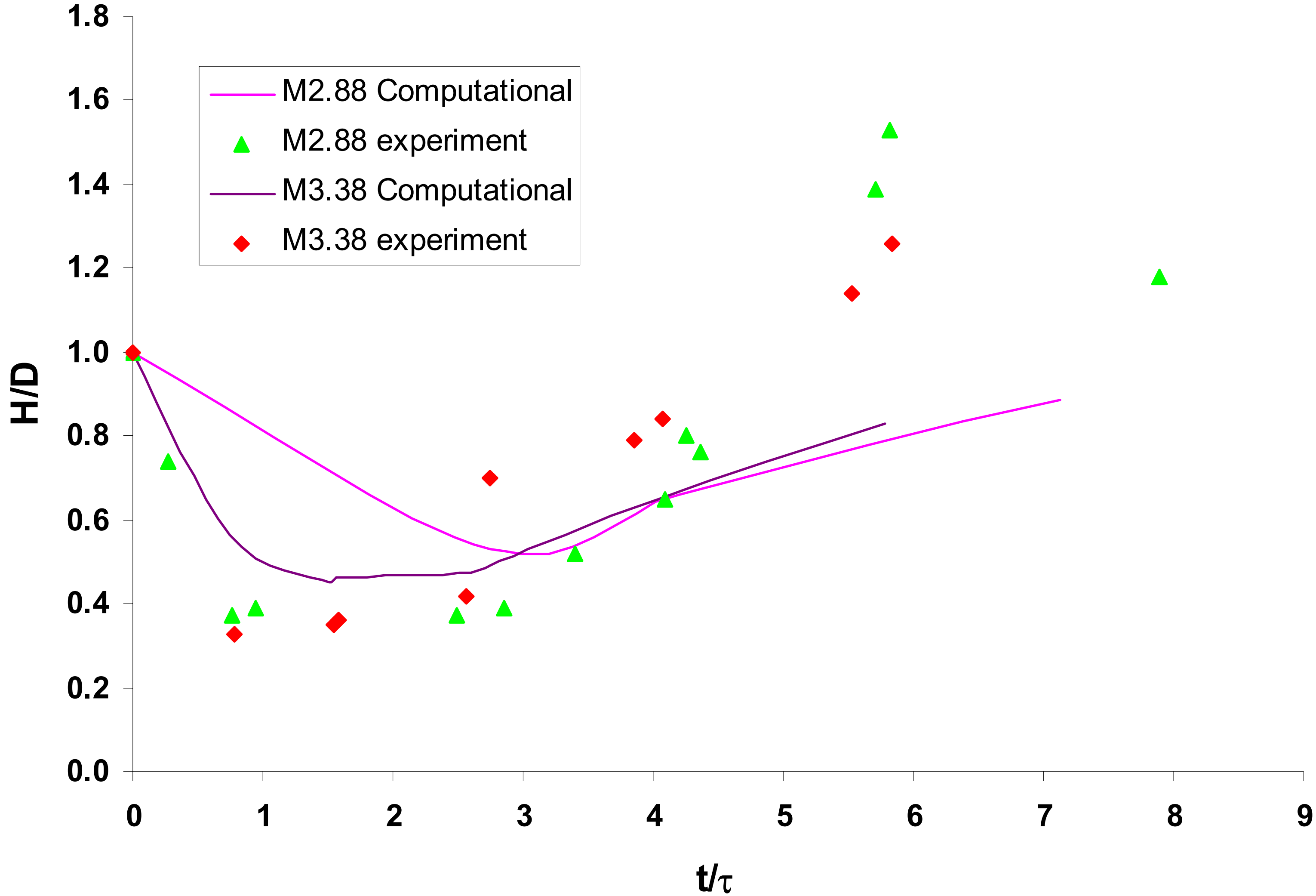




Width growth rate



Height growth rate

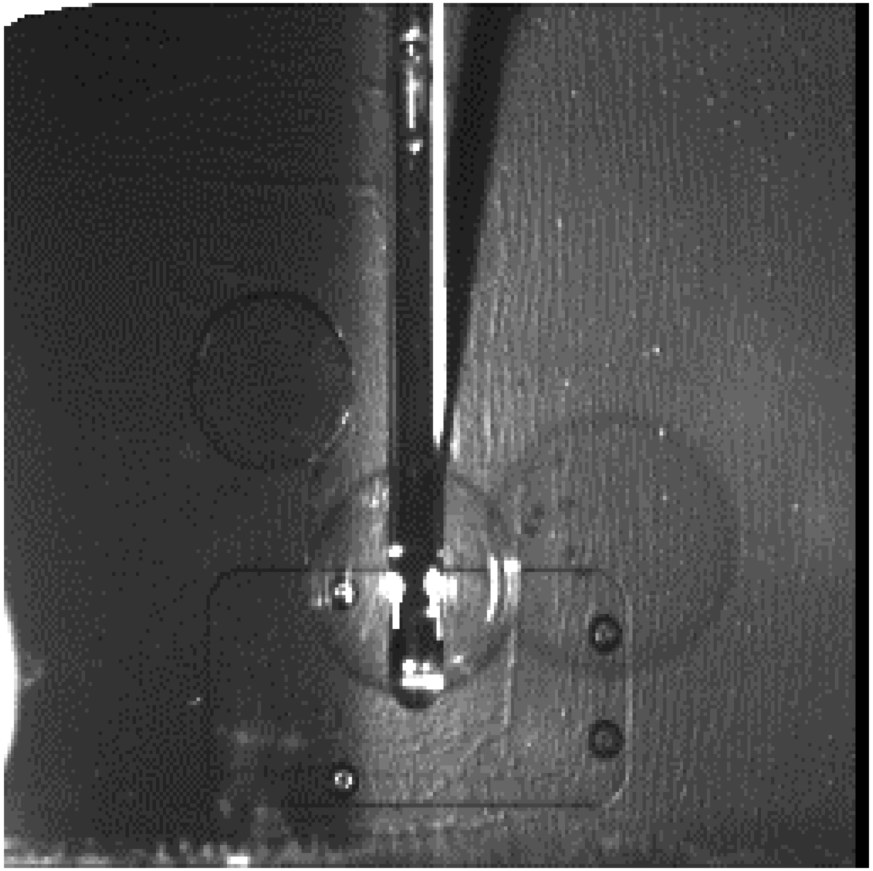


Conclusions

- Developed new bubble-release technique
- Used strong (M>2.5) shocks
- Observed bubble distortion, formation of vortex ring
- Measured growth rates of relevant large scale features
- $\tau = D/u_p$ appears to be appropriate time scale
- 3D simulation with film resolved internal structures and small scale perturbations.

- Need full 3-D numerical simulations
- Develop "tomography" experiment
- Develop experiment to measure species concentration

Initial conditions



In free fall, bubble exhibits almost no left to right motion

Deduce that front to back motion is also negligible

Laser sheet intersects bubble in diametral plane