# Code-to-Code Comparisons for the Problem of Shock Acceleration of a Diffuse Dense Gaseous Cylinder

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# Motivation

• Focus on computational issues as cause for disagreement between Rage and ongoing LANL shock/cylinder experiments:

- Large scale (dipole aspect ratio) differences
- Quantitative velocity measurements (PIV)

• Remove experimental uncertainities/unknowns:

- Use well-defined initial conditions
- Analysis and comparisons based on computational data
- Use different codes for comparison

# Motivation

- Use this research to also examine:
  - What does convergence mean for evolving flows & instabilities?
  - What are the resolution requirements for “fully-resolved” calculations of this class of flow?
  - What quality of results can we obtain from low-order codes (second-order) in this regime?
- Our guide will be existing & on-going experiments

# Experimental Configuration

• "Pour" $SF_6$ in the shocktube as a laminar stream

• LANL experiments seed gas with glycol/water droplets (original CalTech experiments used biacetyl)

• Laser sheet illumination with multiple frames per experiment

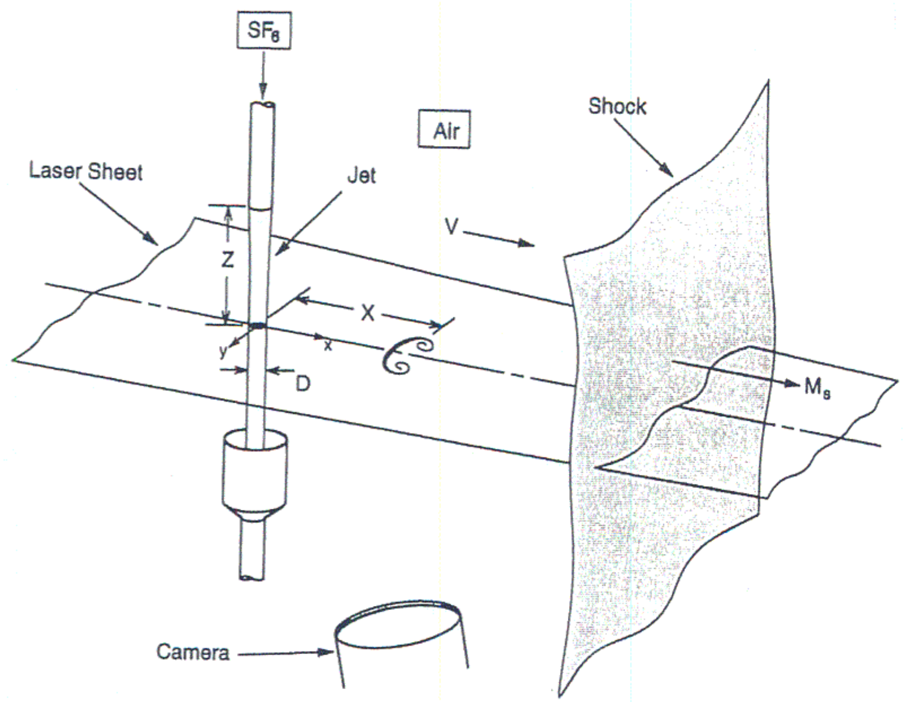
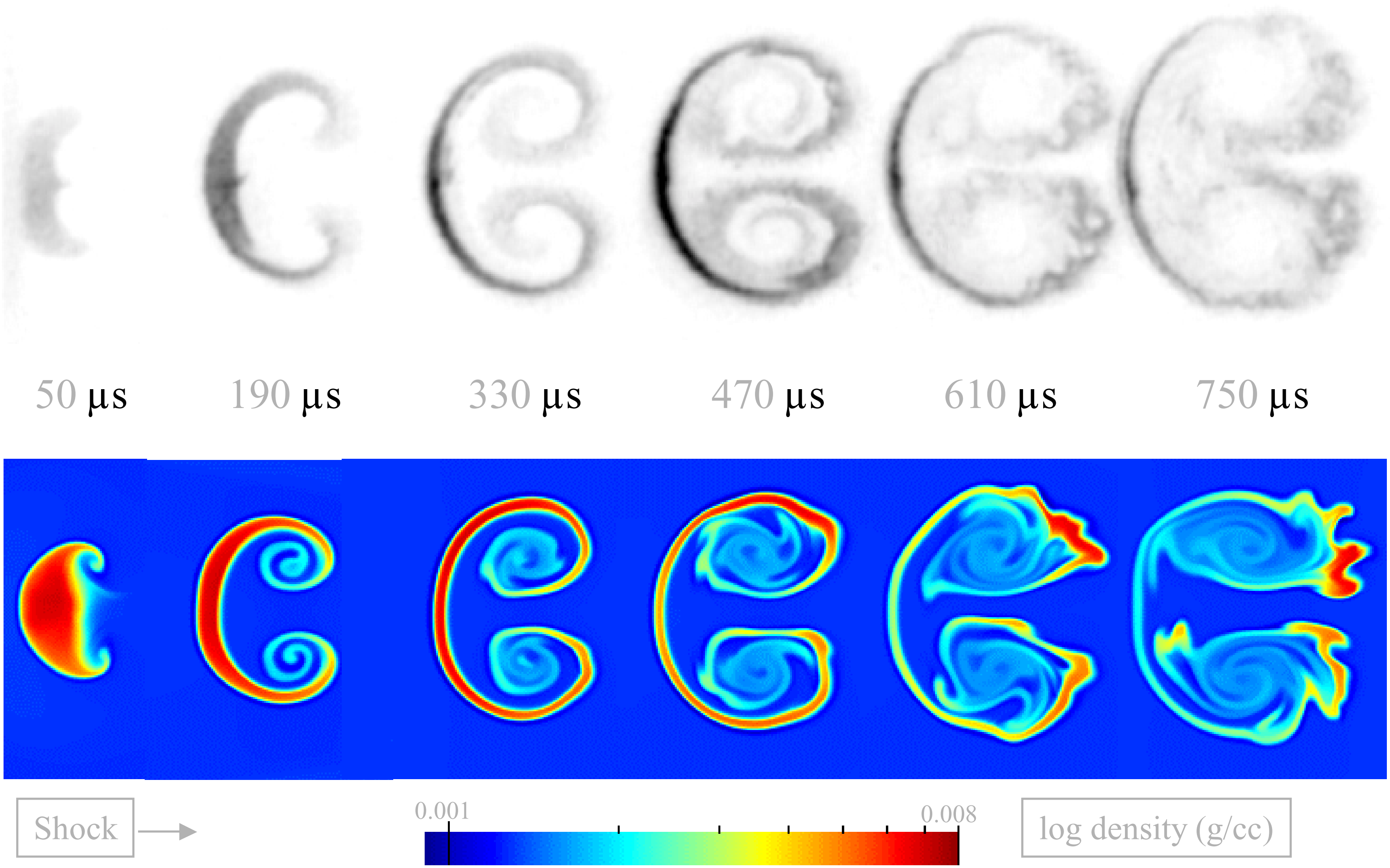
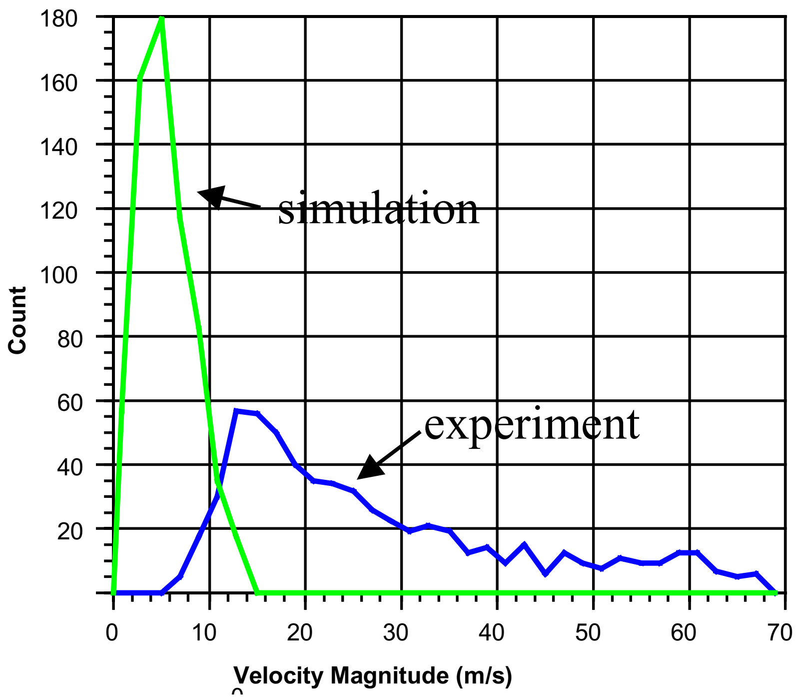


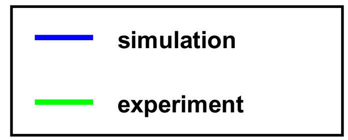

FIG. 1. Drawing of the jet/PLIF configuration.

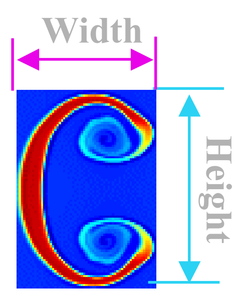
# Comparison Between Experiment and Simulation

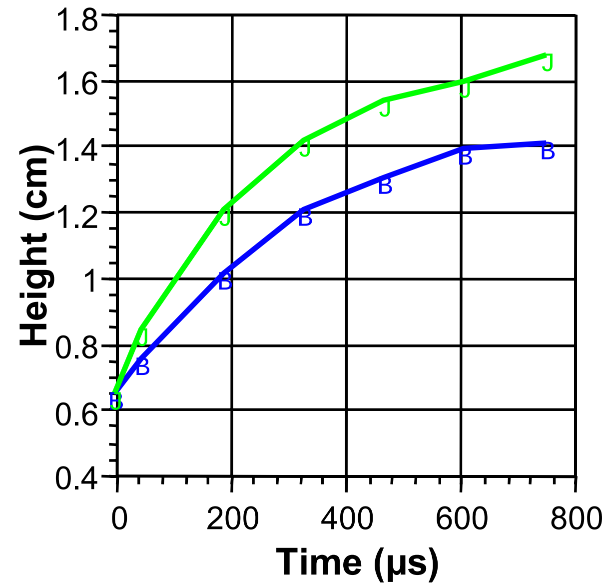


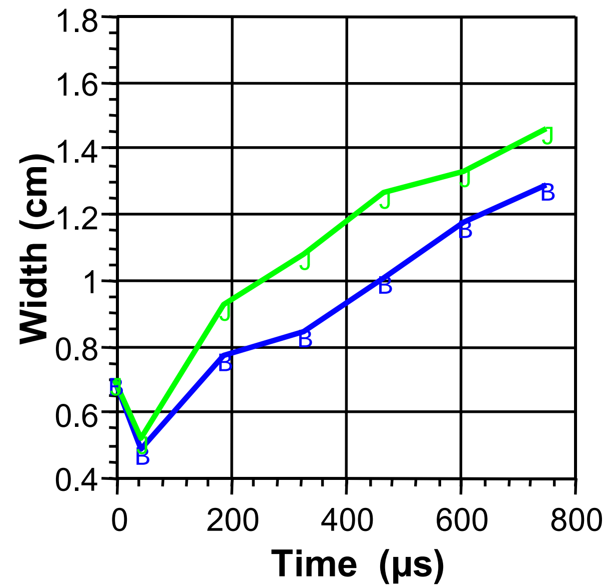
# Quantitative Measurements




Simulation has larger velocities and smaller lengths compared to the experimental data.

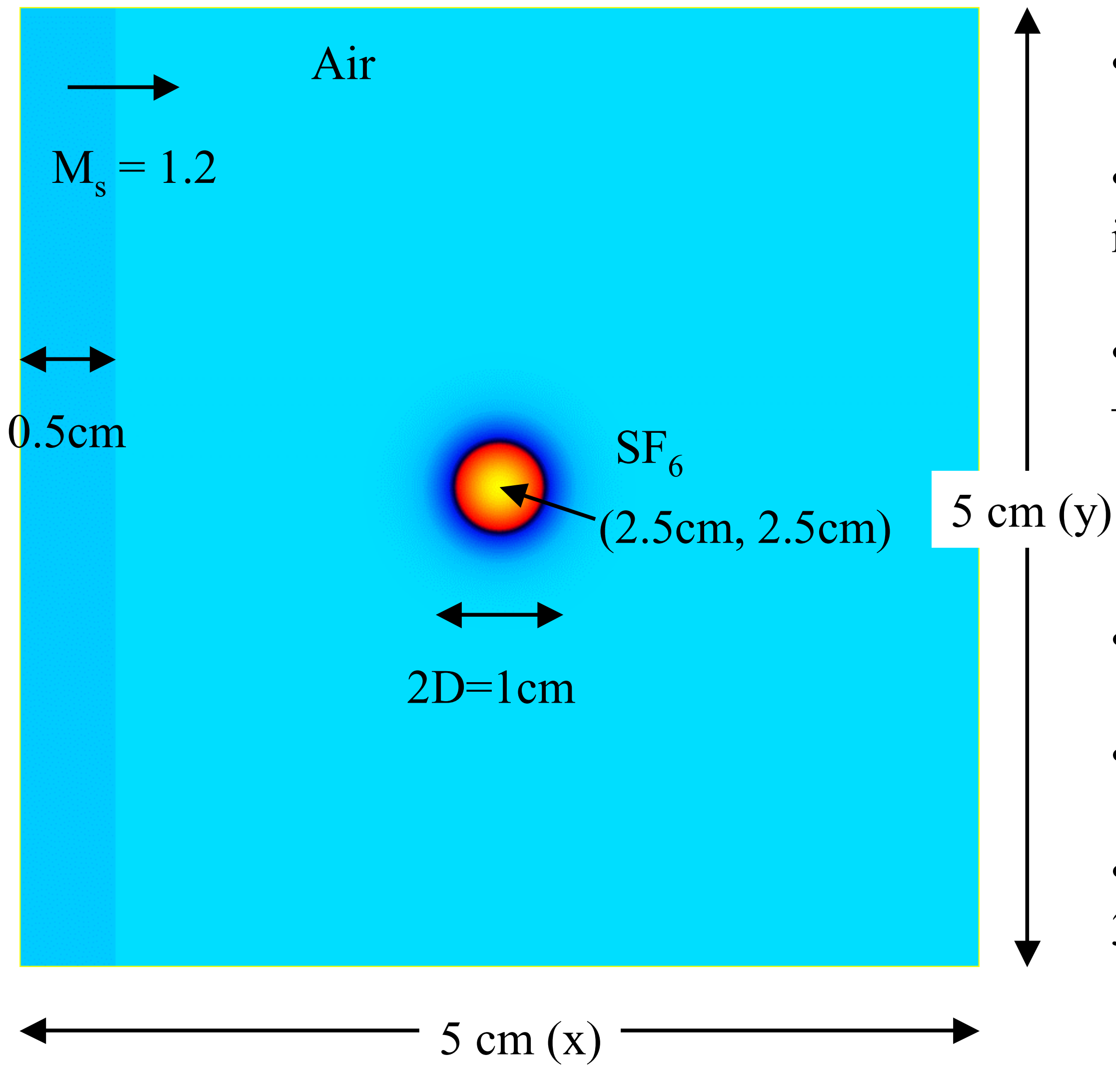
# Codes

- Rage (LANL; Gittings et al.)
  - Eulerian (Lagrange + Remap); directionally split
  - Unstructured AMR (point-wise adaptivity)
  - Multi-component formulation (mass fraction); one energy equation
  - Euler equations (inviscid)

- Cuervo (LANL; Rider & Kamm)
  - Eulerian (direct); directionally and temporally unsplit
  - Rectangular uniform grids
  - single-component formulation (gamma blending); one energy equation
  - Navier-Stokes equations (constant properties)

- Raptor (LLNL; Greenough et al.)
  - Eulerian (direct); directionally split
  - Block-structured AMR (patch-based adaptivity)
  - VOF formulation (volume fraction); N energy equations
  - Navier-Stokes equations (Chapman-Enskog, Sutherland’s formula)

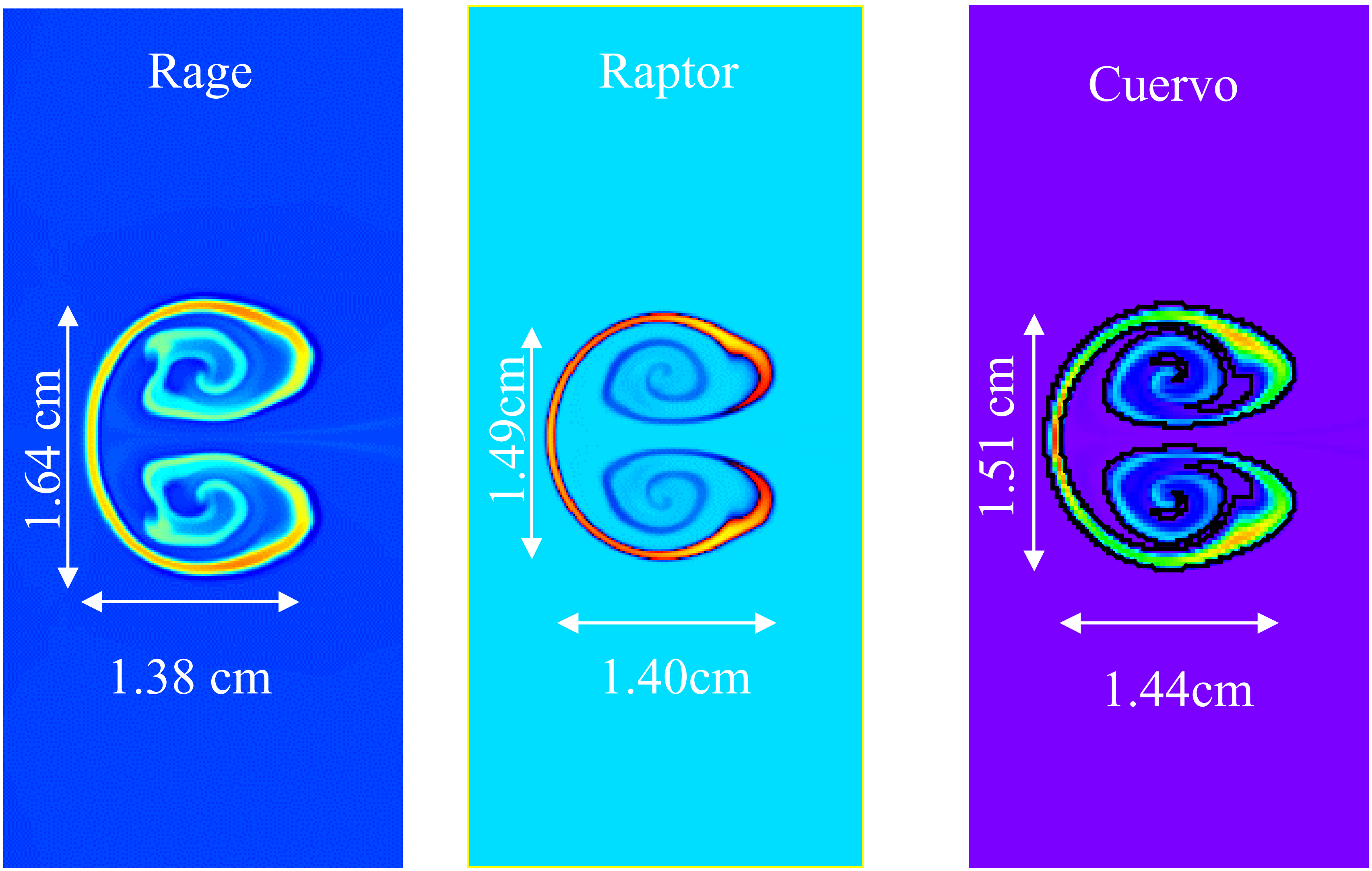
# Model Problem




- Inflow/outflow B.C.'s
- Moving frame with post-interaction velocity near zero
- $\rho_{SF_6} = \rho_0 \exp(-r^2/\delta)$, $r=\sqrt{(x-x_0)^2 + (y-y_0)^2}$, $\delta=0.0902$; D=0.5cm
- LANL pre-shock conditions
- $t_{final} = 0.8$ msec
- $\Delta x$ = 125µm, 62.5µm, 31.25µm, 15.625µm, 7.8125µm

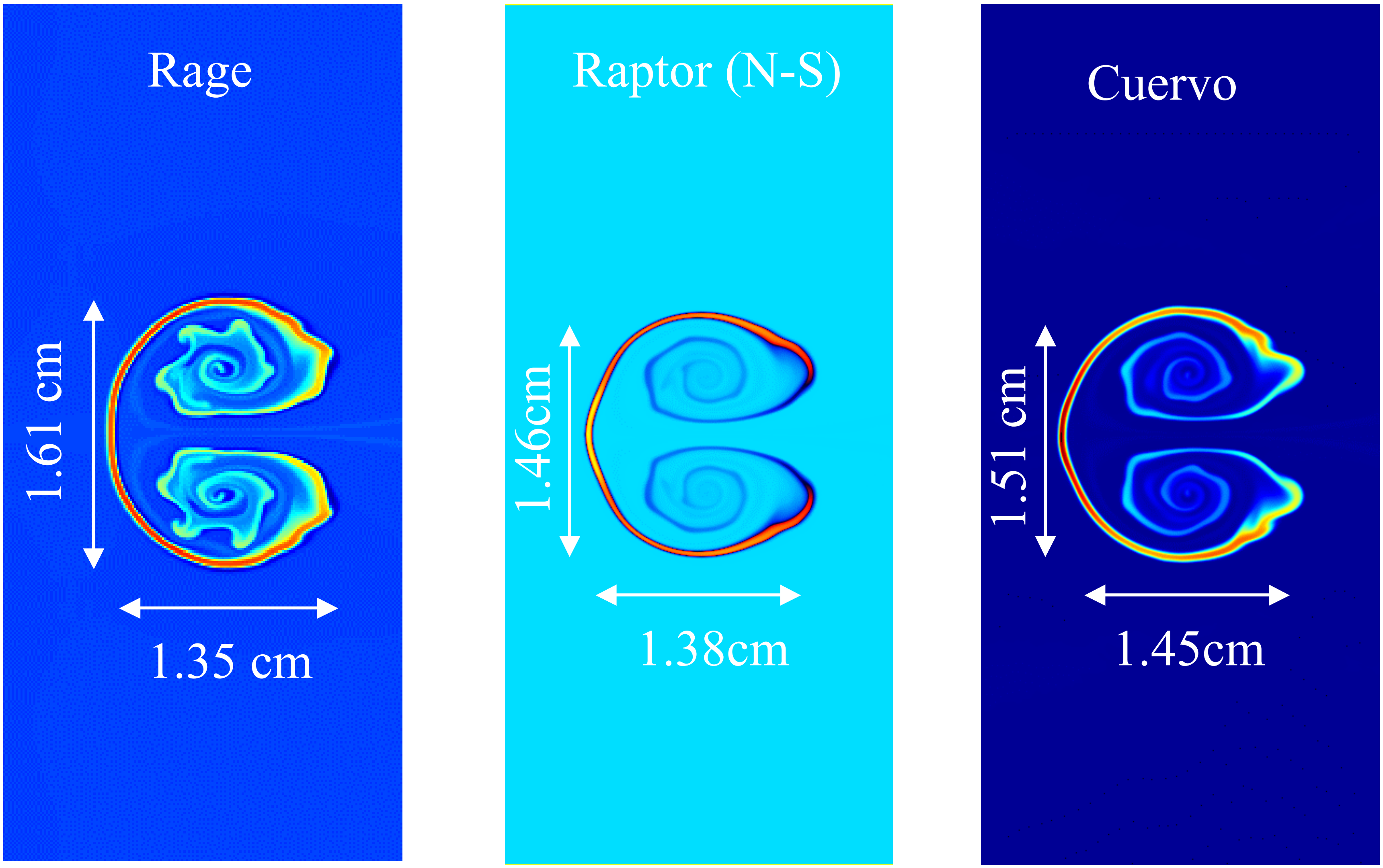
# Integral Lengths/Flow

125 micron zoning, t = 0.8 msec



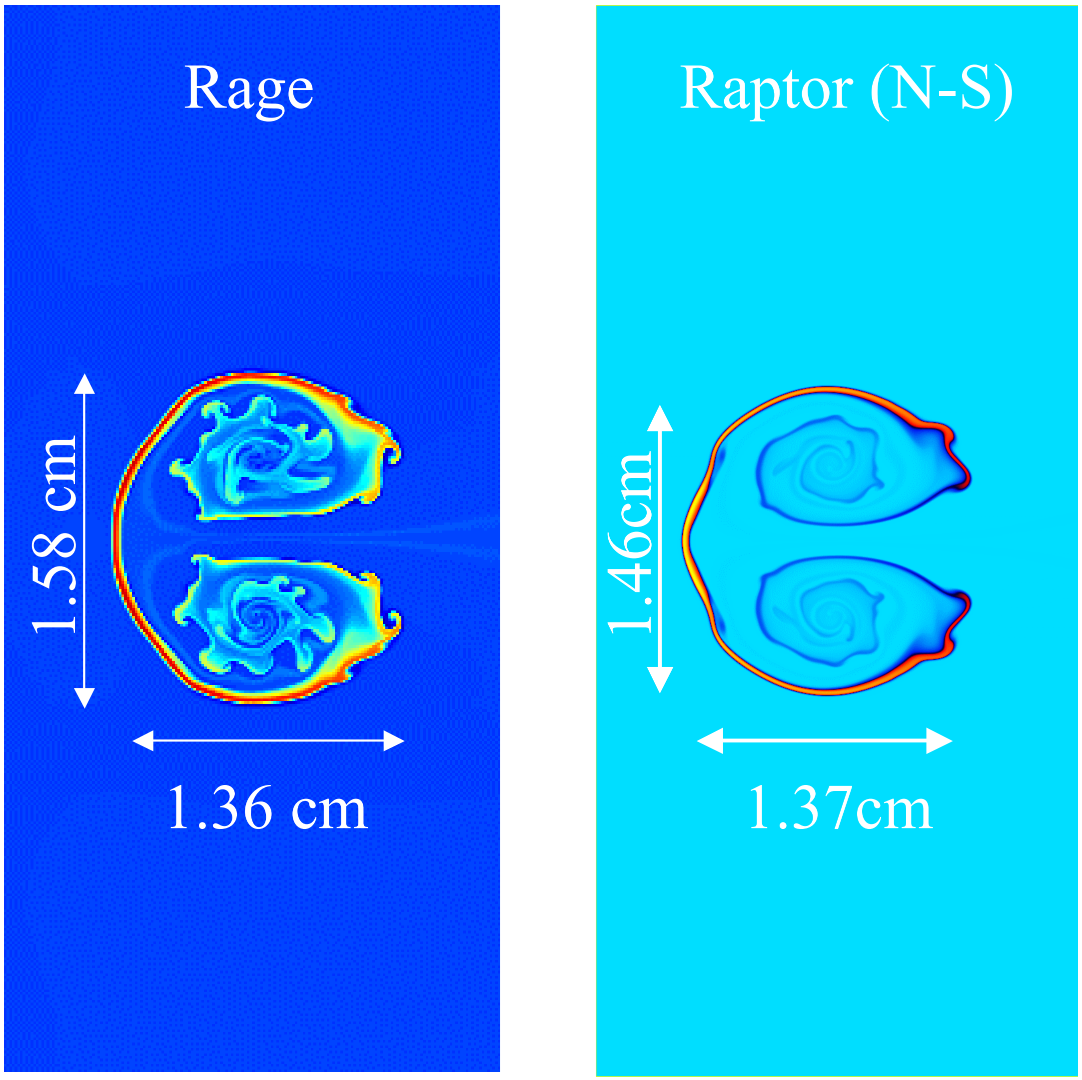
# Integral Lengths/Flow

62.5 micron zoning, t = 0.8 msec



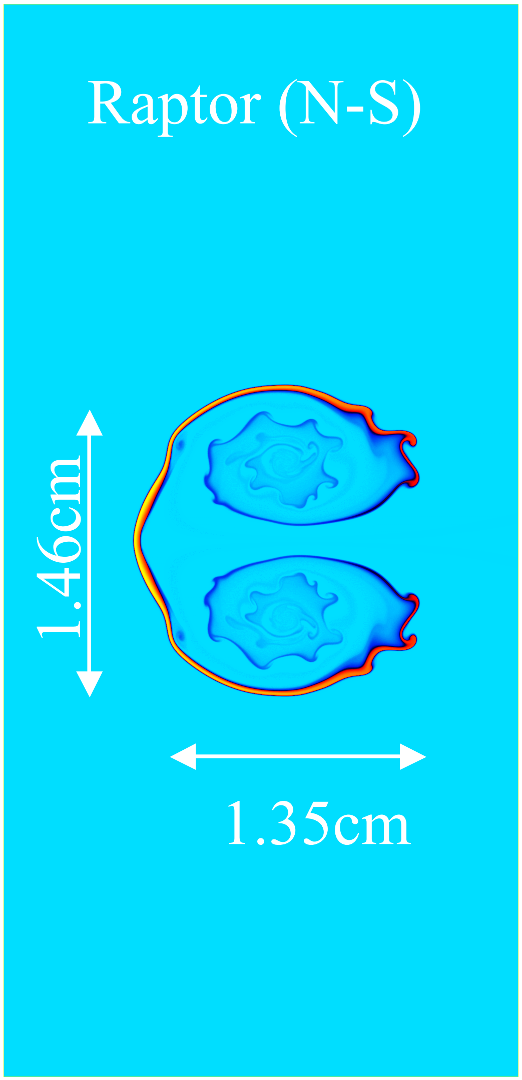
# Integral Lengths/Flow

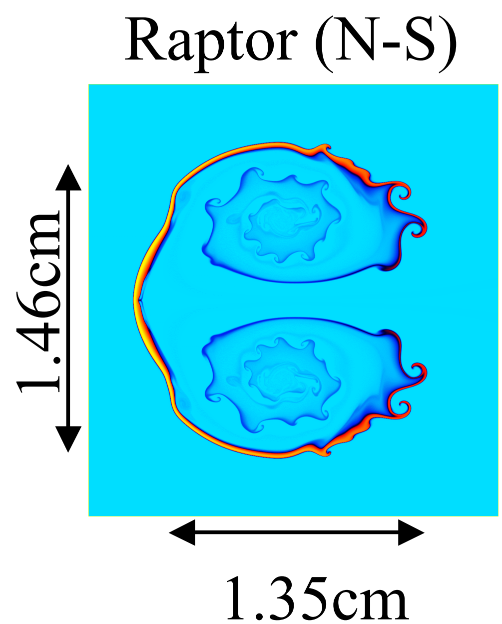
31.25 micron zoning, t = 0.8 msec

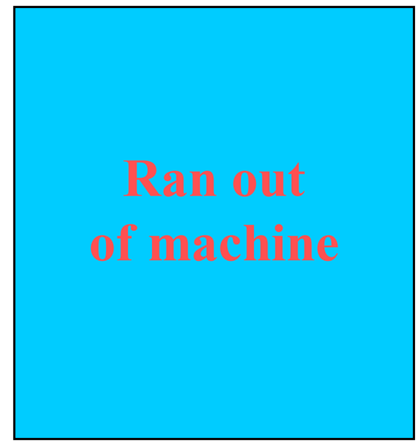


# Integral Lengths/Flow

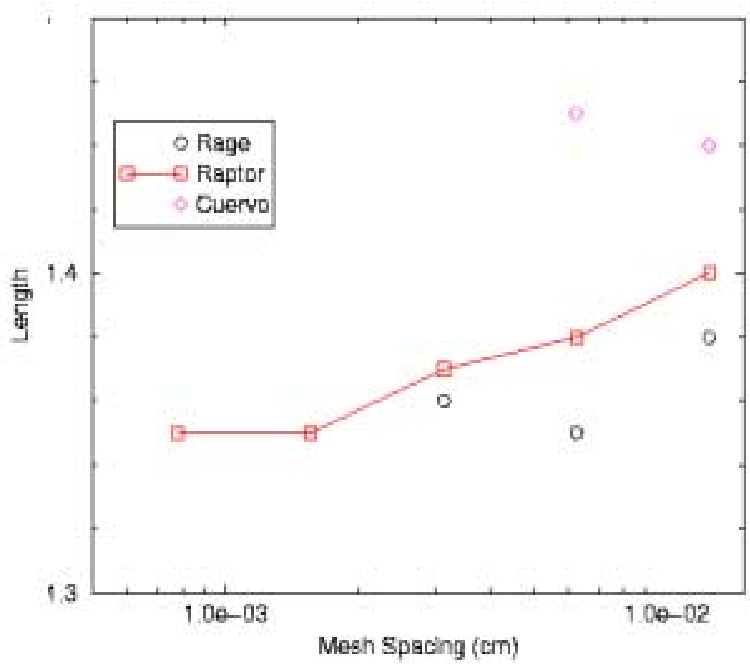
15.125 micron zoning — 7.8125 micron zoning — 3.90625 micron zoning

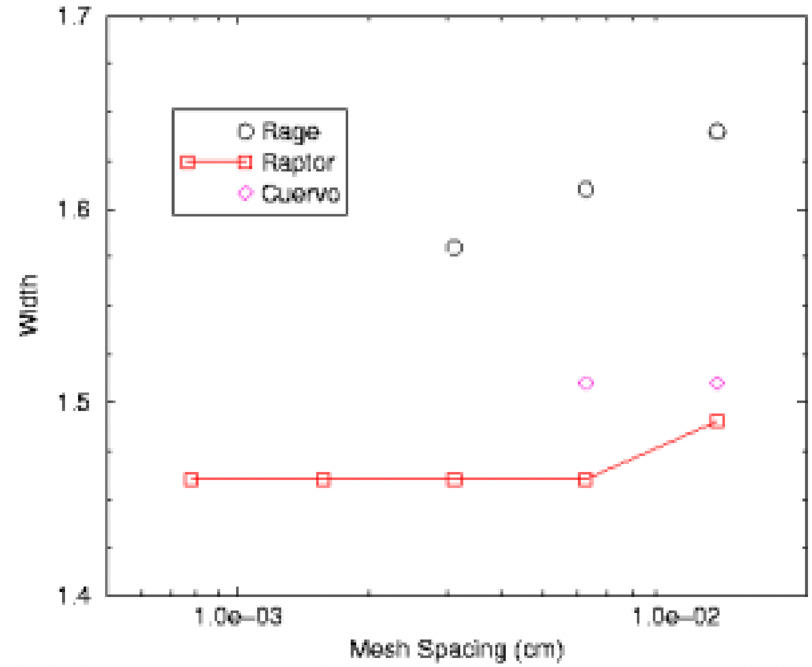


# Integral Lengths - Summary

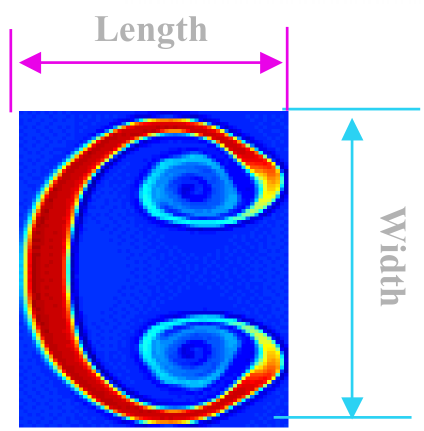



**Convergence Rates**

Cuervo ~ $\Delta x^{1.28}$

Raptor ~ $\Delta x^{1.58}$

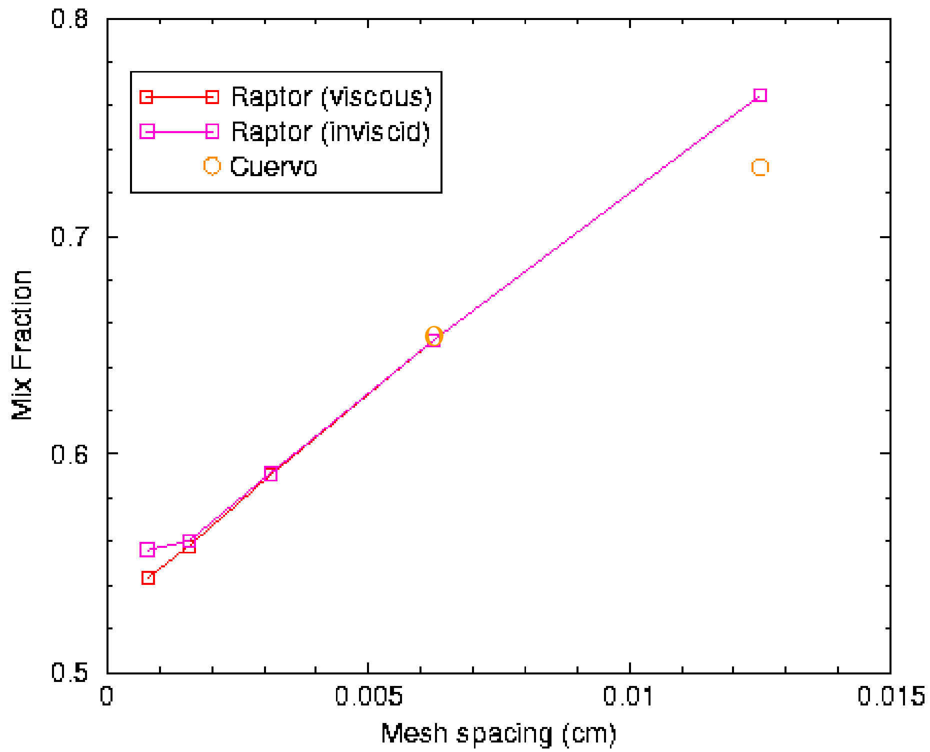



**Convergence Rates**

Cuervo ~ $\Delta x^{0.74}$

Raptor ~ $\Delta x^{0.28}$

# Mixing Fraction



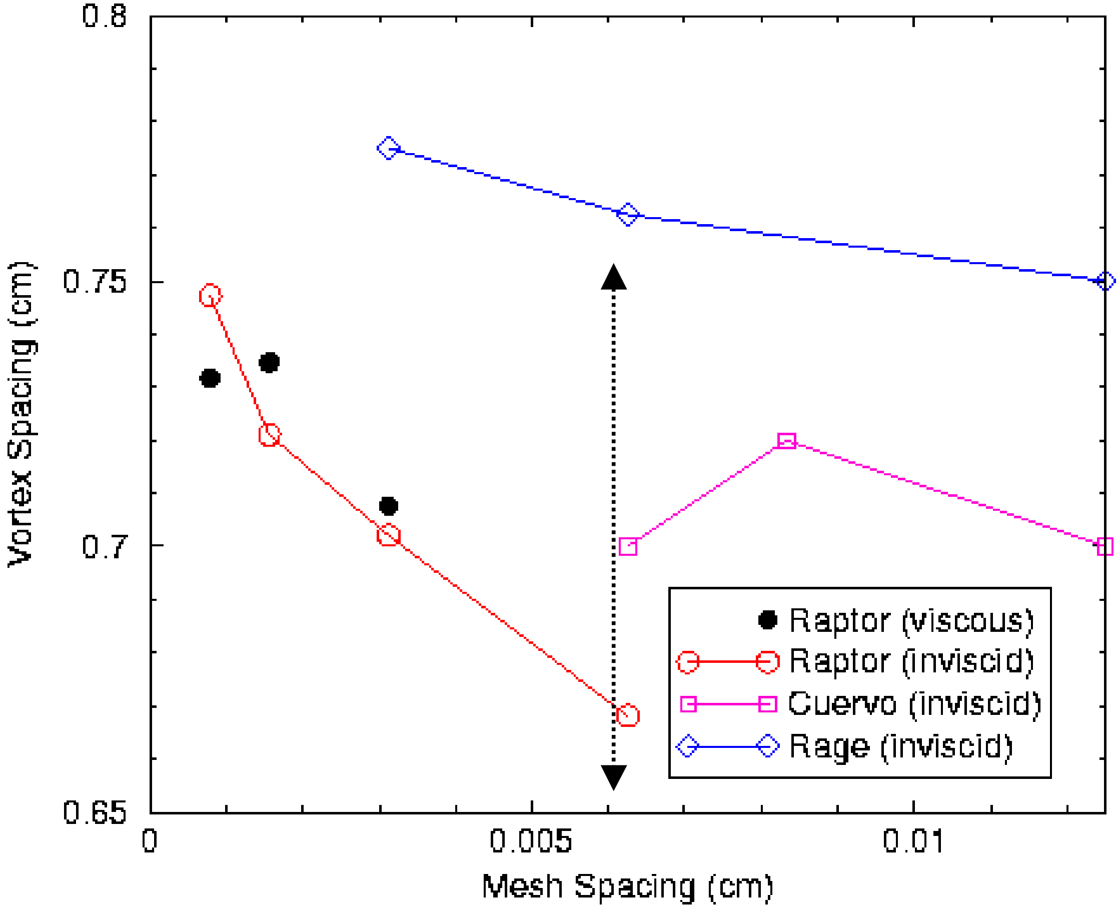

$$\theta = \frac{\Sigma f_{SF_6} (1-f_{SF_6}) \Delta x \Delta y}{(\Sigma f_{SF_6} \Delta x \Delta y) (\Sigma (1-f_{SF_6}) \Delta x \Delta y)}$$

**Convergence Rates**

Cuervo ~ $\Delta x^{0.28}$

Raptor ~ $\Delta x^{1.02}$

# Vortex Spacing



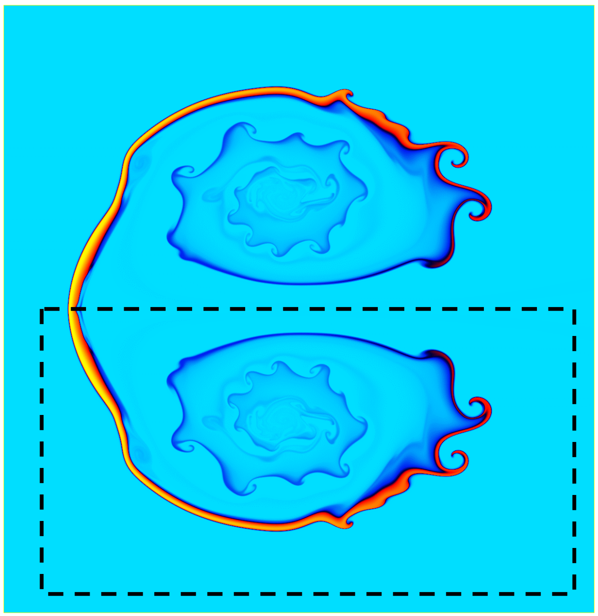

• Experimental data range shown for comparison

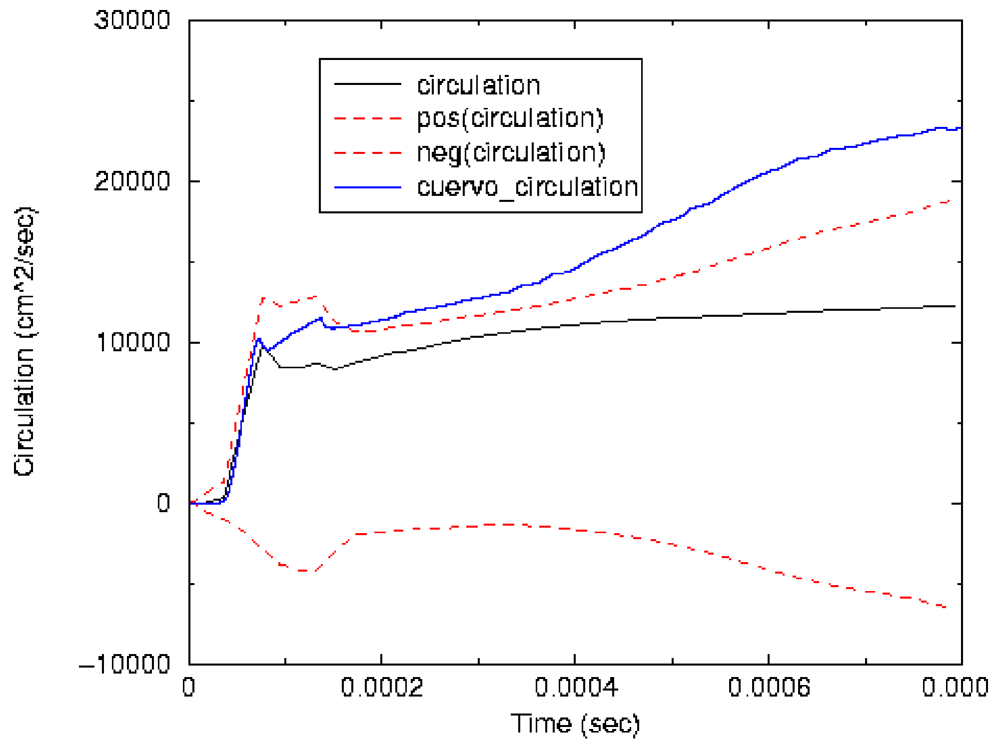
• cf. J.W. Jacobs, Phys. Fluids 1993; M=1.095, D=0.43

**<u>Convergence Rates</u>**

Raptor ~ $\Delta x^{0.87}$

# Circulation Budget






- Deposition by shock (positive)
- Counter-sign production (baroclinic)
- Late-time equilibration

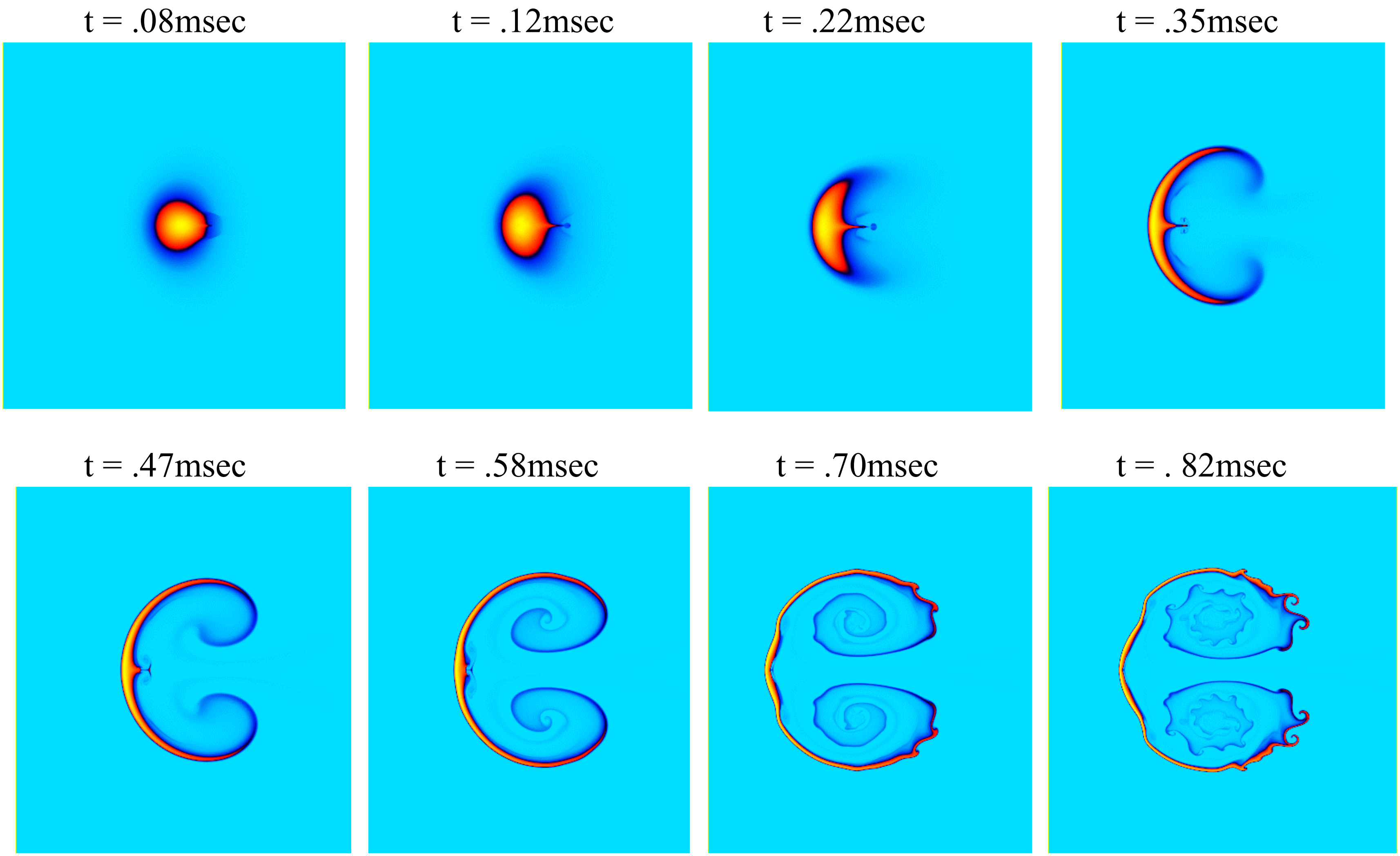
# Flow Dynamics

- Early time
    - Vortex blob deposition (shock-passage time ~ 30 μsec)

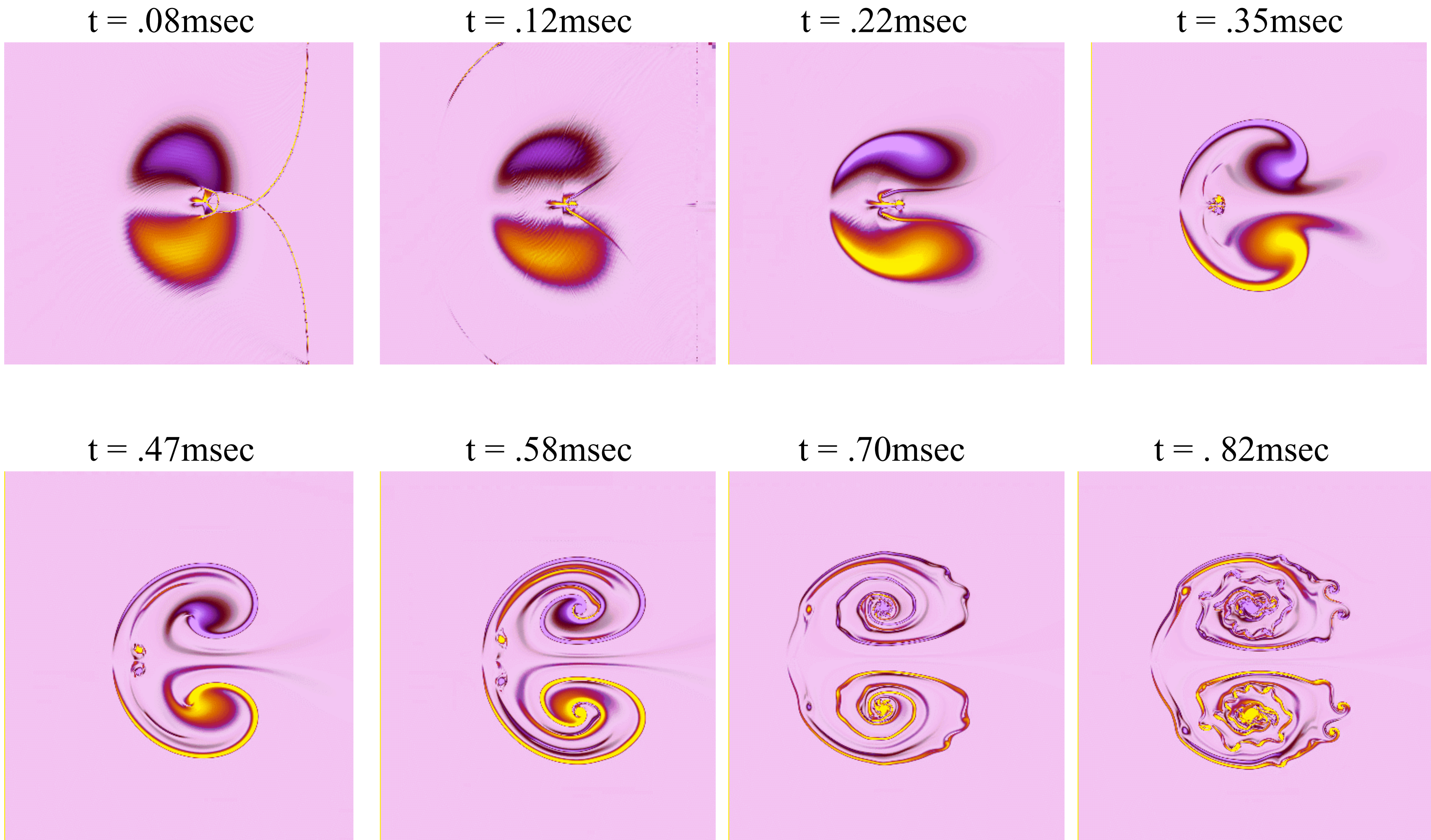
- Intermediate time
    - Blob      dipole transformation
    - Counter-sign production

- Later time
    - Dipole configuration established
    - Balanced net vorticity (i.e. $\Gamma$ ~ constant)

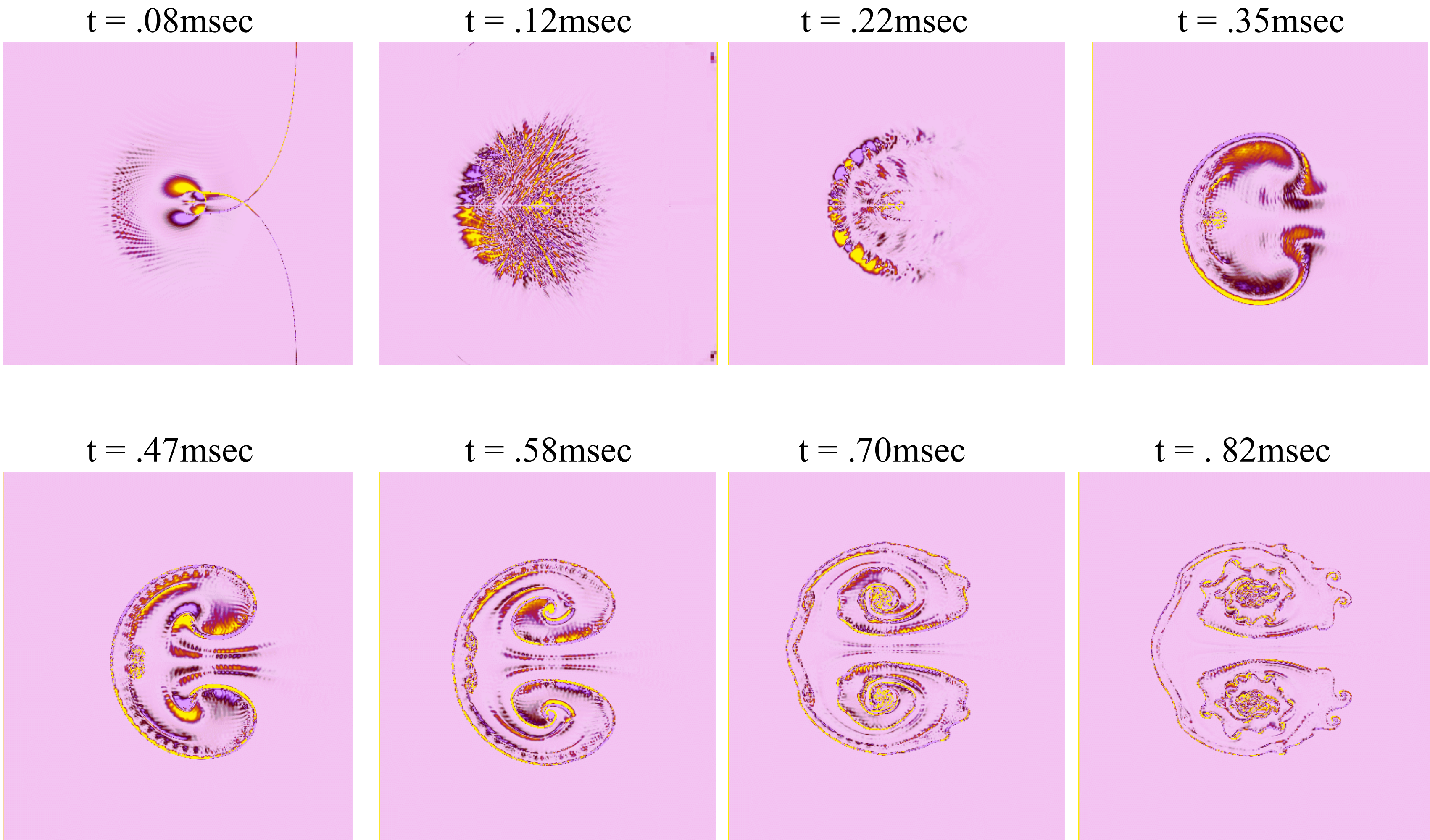
# Flow Dynamics - Density



# Flow Dynamics - Vorticity

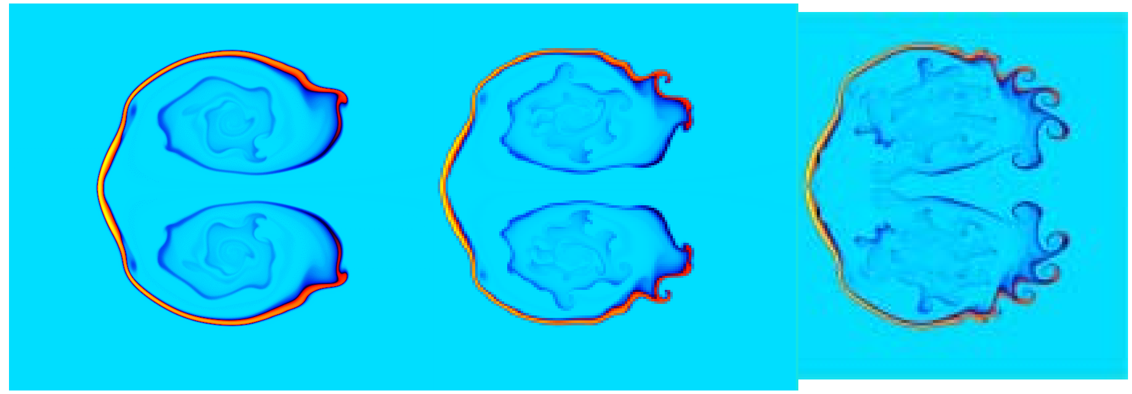


# Flow Dynamics – Baroclinic Generation



## Raptor Summary

31.25μm, 15.625μm, 7.8125μm

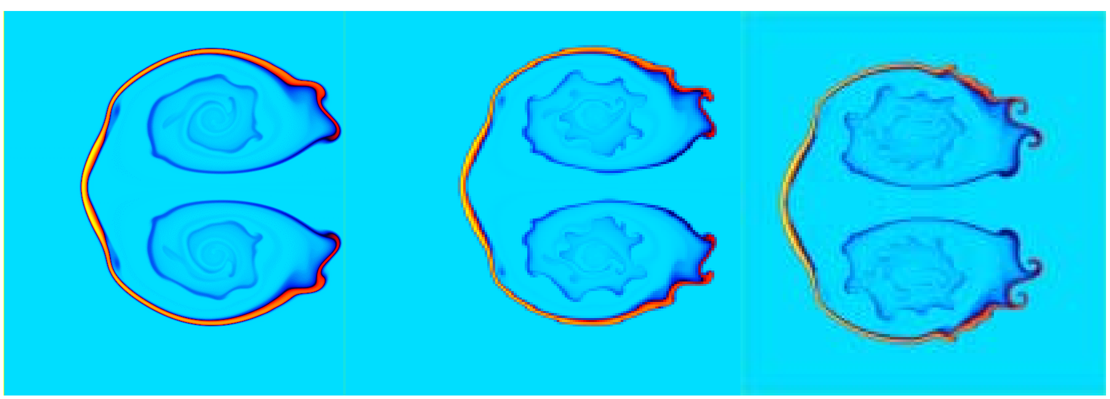


Increasing Resolution

Inviscid

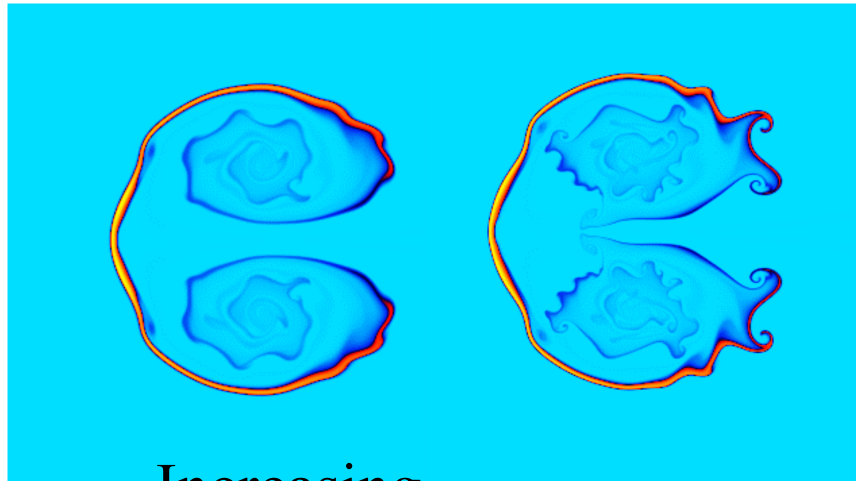
Increasing Resolution

Viscous



# NEW Raptor Summary
# No prelax, viscosity fix

31.25μm, 15.625μm, 7.8125μm

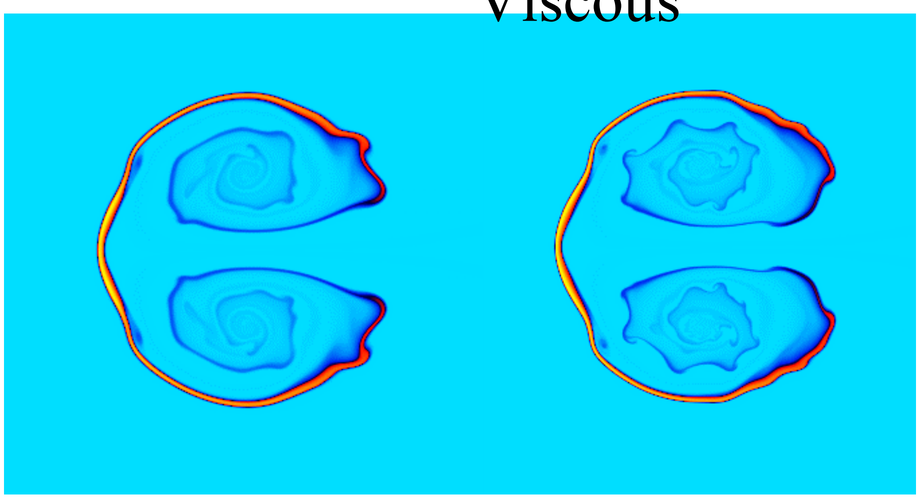


Increasing Resolution

Inviscid

Increasing Resolution

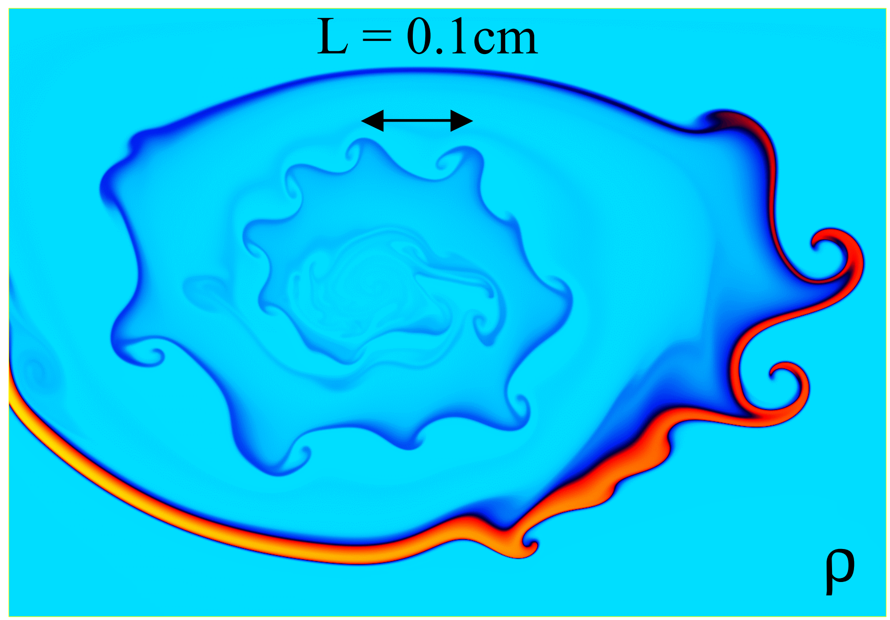
Viscous



# Lengthscale estimates

- Using order of magnitude considerations (Tennekes and Lumley)
  - $U \approx 2{,}000$ cm/sec, $\nu \approx 0.1$ cm$^2$/sec, $L = 0.1$ cm    Re = 2,000
  - $\eta/L \sim Re^{-0.75}$    $\eta \sim 3\ \mu m$ (Kolmgorov scale)
  - $\lambda/L \sim Re^{-0.5}$    $\lambda \sim 90\ \mu m$ (Taylor scale)

- At 7.8125 µm resolution, we have about 12 points/$\lambda$    resolvable



# Conclusions

• Have we demonstrated convergence?

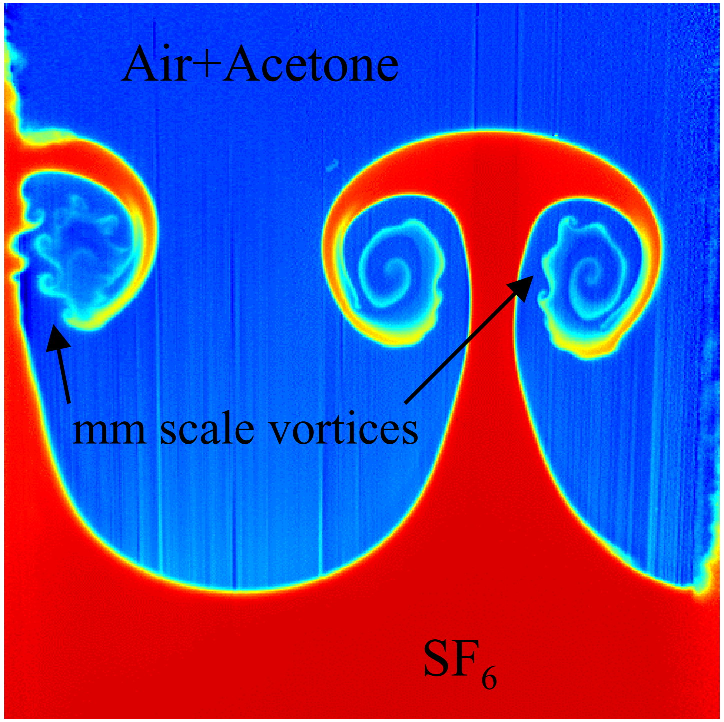
- Maybe.  Some diagnostics show convergence while others do not.
- Include addition diagnostics (statistical, wavelet analysis).

• Have demonstrated what resolutions and physics are required for resolved calculations.

•  Directly compute mm wavelength vortices.  This is a robust feature present in analogous flow (Jacobs' Diffuse Interface R-M).

• Rage calculations appear to be the out-lier;  much more structure and different integral measurements. Vorticity?

M=1.2 Diffuse Interface R-M

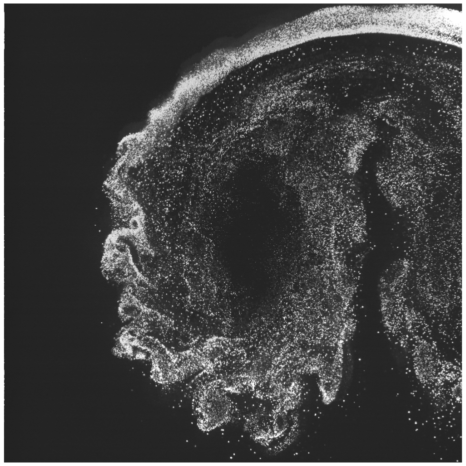



Courtesy of Prof. J.W. Jacobs

# NEEDS

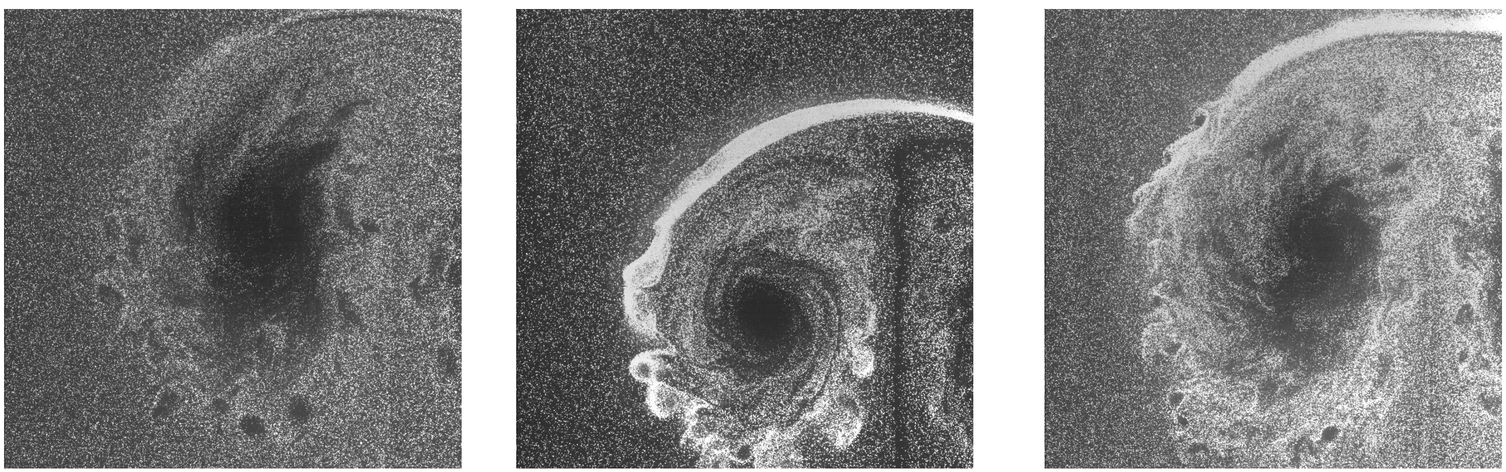
- High(er) resolution experimental imaging
  - PLIF visualization. LANL facility appears to generate a "more stable" evolving flow better pictures. Isolate mm-scale vortices
- More direct measurements
  - Mixing measurements (Rayleigh scattering). Complementary to Helium jet work by J. Budzinski.
- More computing resources (never have enough) would allow definitive simulations.
  - e.g. highest resolution run took ~ 70 hrs wall clock on 128 CPU's of an SP-3; AMR required 4.7 Mzones compared to 43 Mzones single grid.

# LANL Experimental Activity



• No outer flow seeding

Varying the seeding densities & light intensity



Images courtesy C. Tomkins, LANL, DX-3