Simulations of a Shock-Accelerated Gas Cylinder and Comparison with Experimental Images and Velocity Fields

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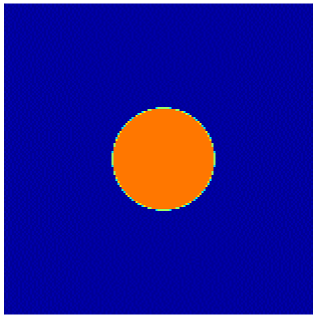

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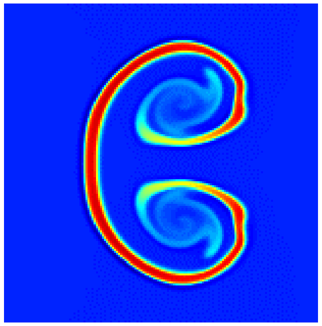

Collaborators

Experimenters:

Kathy Prestridge (LANL, DX-3)
Paul Rightley (LANL, DX-3)
Chris Tomkins (LANL, P-22/DX-3)
Bob Benjamin (LANL, DX-3)
Peter Vorobieff (UNM)
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Computational Scientists:

RAGE: Mike Gittings (LANL/SAIC, X-2)
Mike Steinkamp (LANL, X-3)

Cuervo: Bill Rider (LANL, CCS-2)
Jim Kamm (LANL, CCS-2)

CHAD: Barbara Devolder (LANL, X-5)
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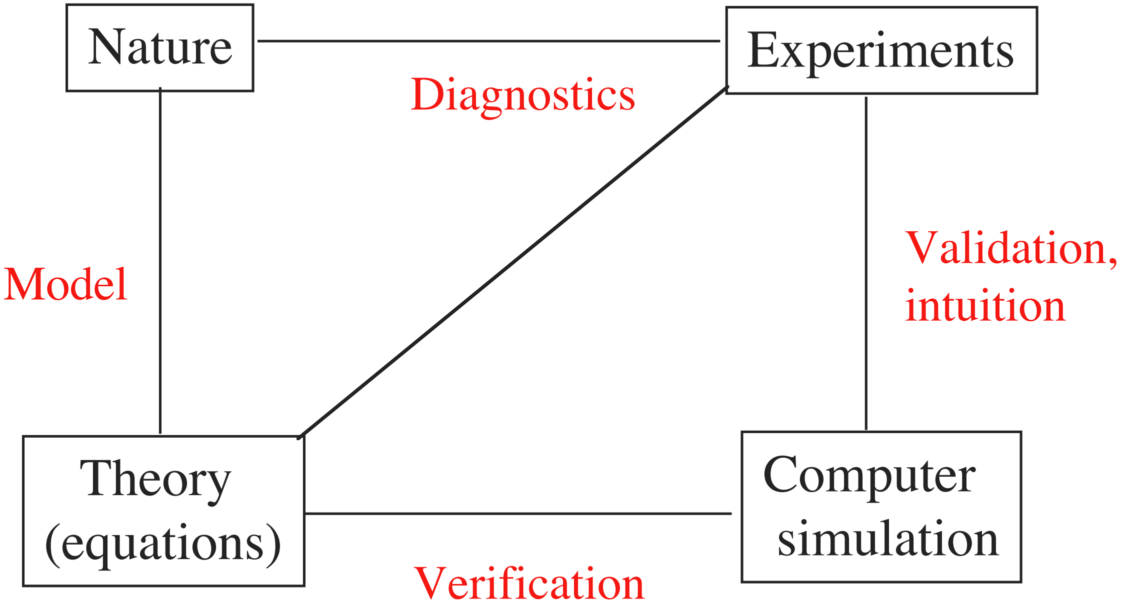
Thesis Advisors:

James Glimm (Stony Brook)
David Sharp (LANL, T-3)

Outline

- Purpose of research
- Experimental apparatus
- Simulation setup
- Qualitative and quantitative comparisons
- Future work

Our View of Scientific Modeling



Nature

Experiments

Diagnostics

Model

Validation, intuition

Theory (equations)

Computer simulation

Verification

How well do computer simulations approximate nature?

Richtmyer-Meshkov Instability

What is the Richtmyer-Meshkov instability?

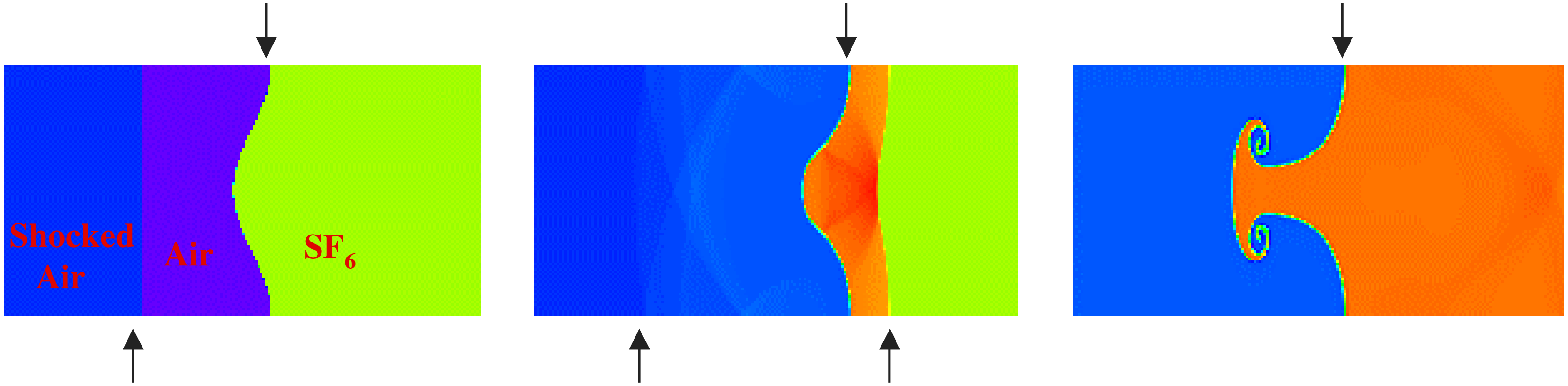
It occurs when a shock wave collides with an interface between two different materials causing perturbations on the interface to grow.

Example: Shock moving from air into SF$_6$ gas (Note: $\rho_{air} < \rho_{SF6}$)

Material Interface

Material Interface

Material Interface

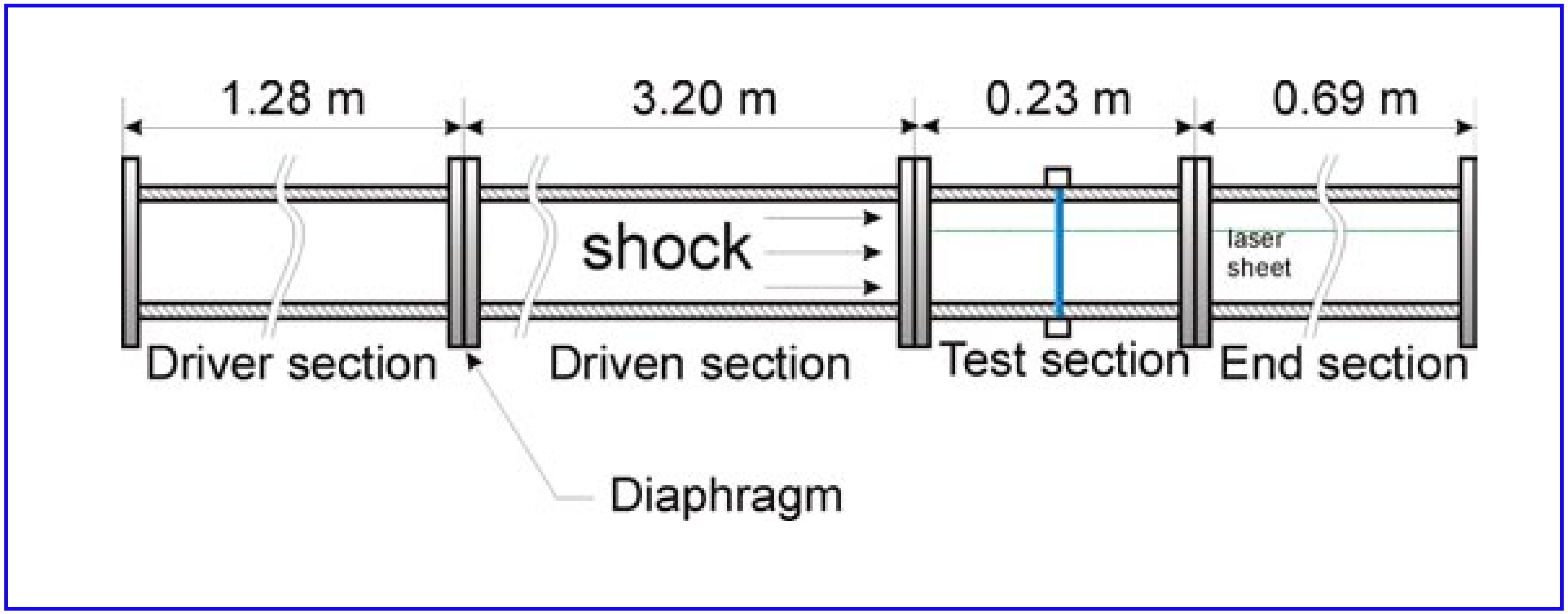


Incident Shock

Reflected Shock

Transmitted Shock

DX-3 Gas Shock Tube

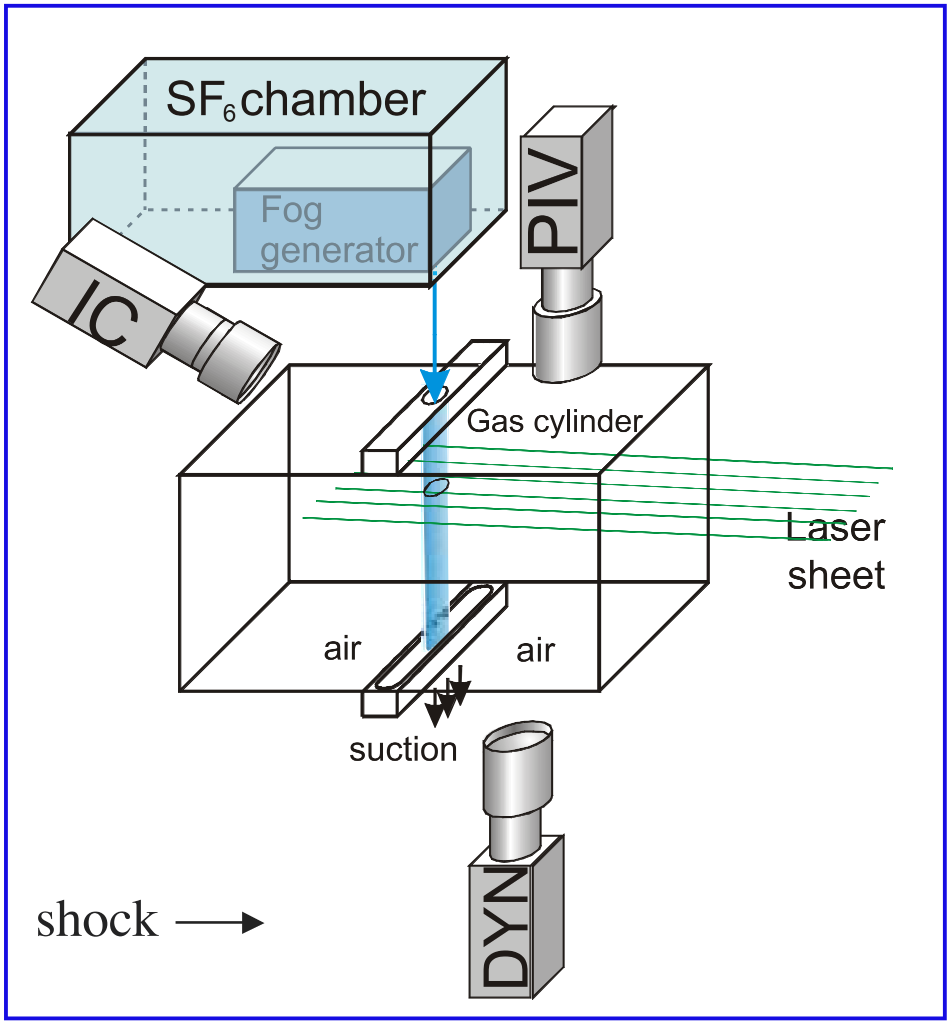


- Gas cylinder composed of SF_6 and surrounded by ambient air
- SF_6 seeded with glycol droplets to aid in visualizing the flow and to enable the PIV capability

Consult the following paper for more information on the experimental setup: P. M. Rightley, P. Vorobieff, and R. F. Benjamin. Evolution of a shock-accelerated thin fluid layer. *Phys. Fluids*, 9(6):1770-1782, 1997.

Test Section of the Shock Tube

- 2 lasers:
  - Customized, frequency doubled Nd:YAG
  - 10 Hz ‘New Wave’ at 532 nm
- 3 cameras:
  - Intensified CCDs, 1134x468
  - Initial Conditions (IC), Dynamic (DYN), and PIV
- 8 pulses:
  - 7 pulses for ICs and dynamic images with $\Delta t=140\mu s$
  - 8th pulse for PIV



RAGE: Radiation Adaptive Grid Eulerian Code

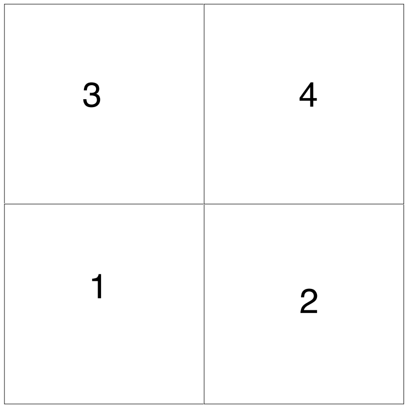
- Multi-dimensional Eulerian hydrodynamic code
- Directionally-split second order Godunov scheme

- Continuous adaptive mesh refinement (CAMR)
    - Each cell can be coarsened or refined by a factor of two in each timestep
    - Only one level of refinement change possible between adjacent cells
    - Refinement decisions can be modified for each material or defined for regions of computation

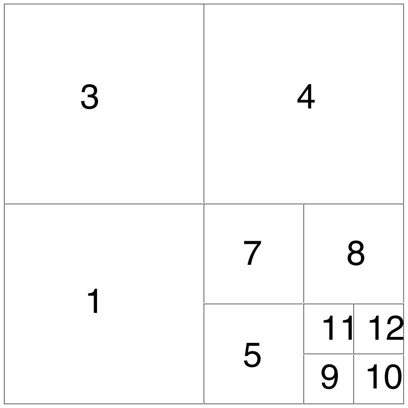
- Running in parallel on ASCI machines (Blue Mountain)
- Substantial validation has been performed on shocked interface problems
    - Shocked curtain, single mode RMI, NOVA experiments

RAGE was originally developed by Michael L. Gittings

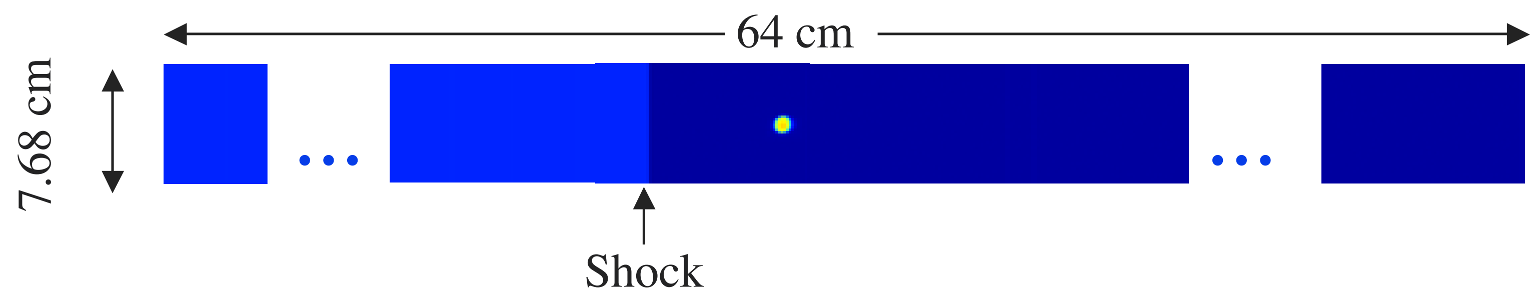
Initial grid -- level 1



Subdivided cells 2 and 6



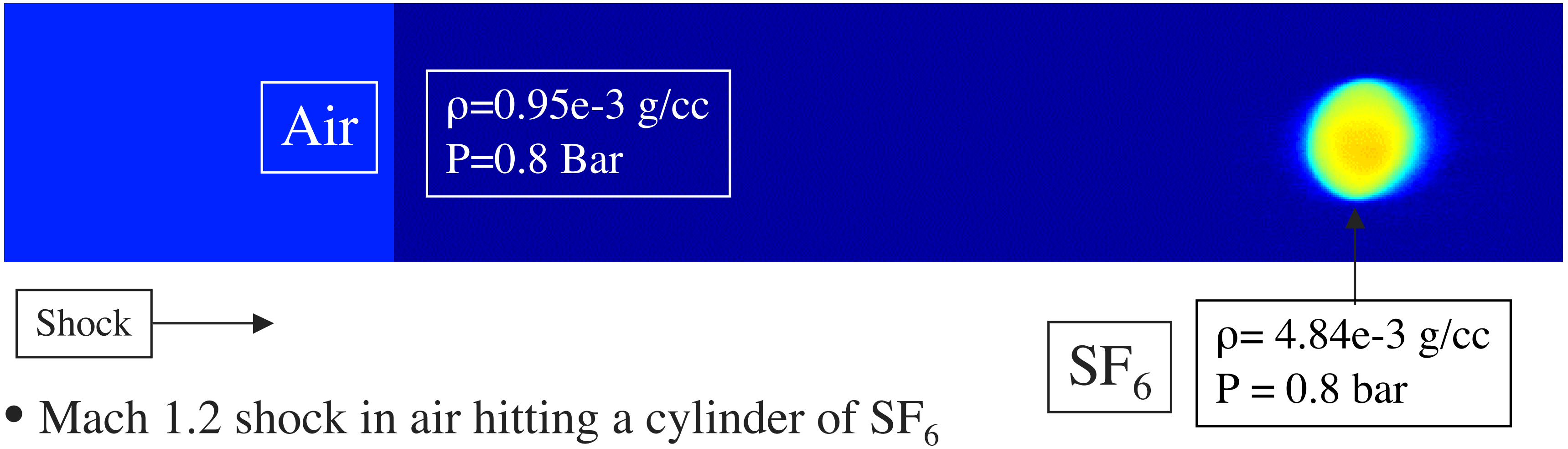
Cylinder Simulation Setup



64 cm

7.68 cm

Shock



Air

ρ=0.95e-3 g/cc
P=0.8 Bar

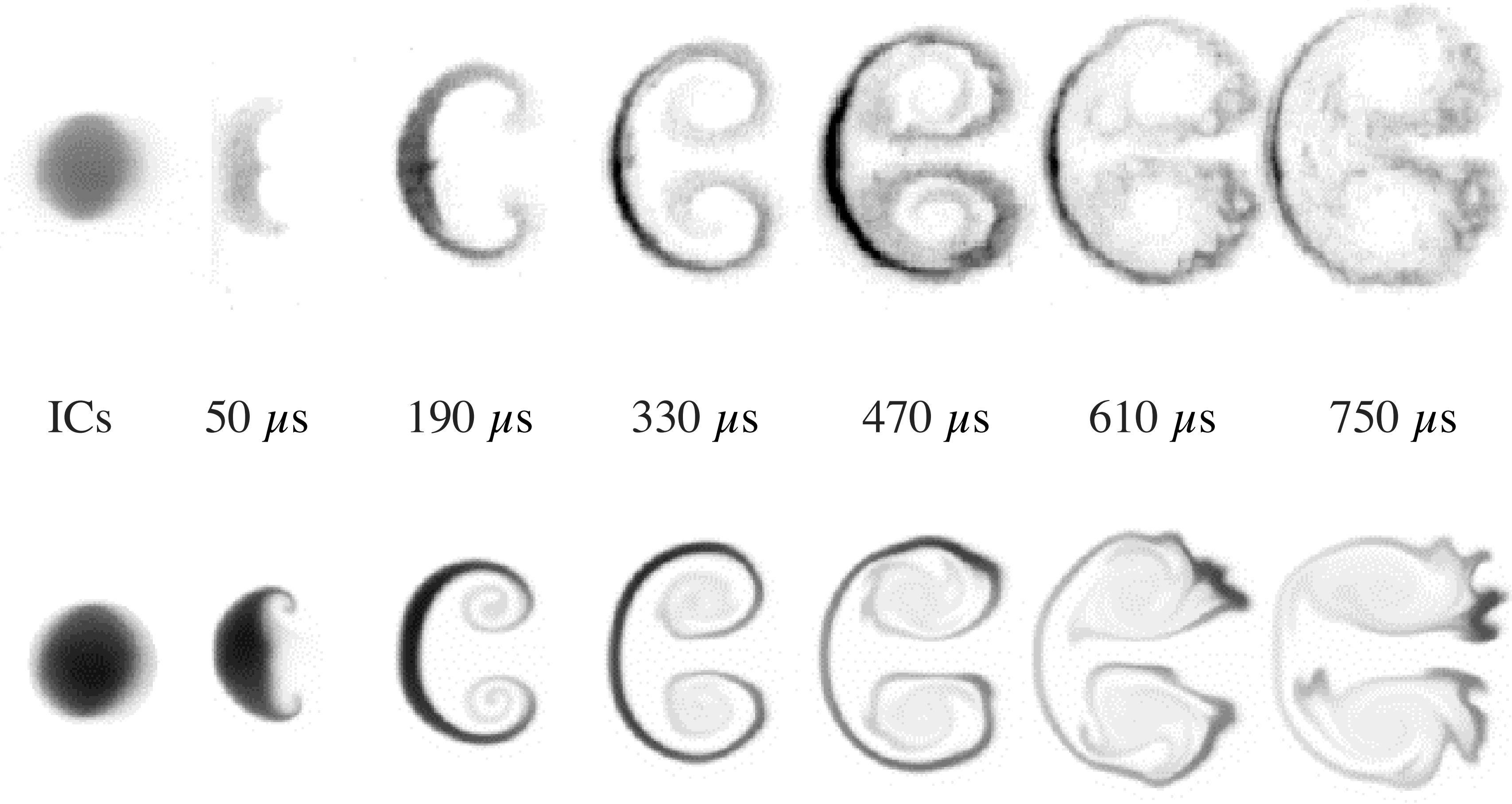
Shock

SF_6

ρ= 4.84e-3 g/cc
P = 0.8 bar

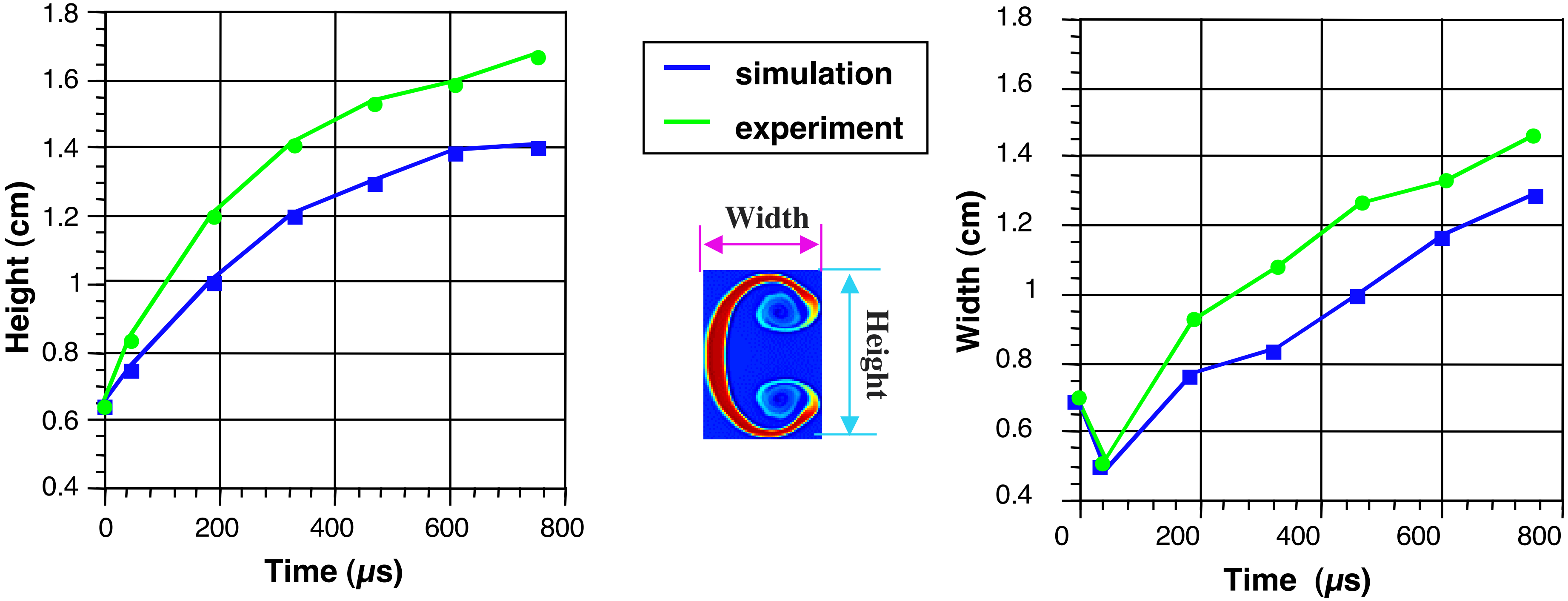
- Mach 1.2 shock in air hitting a cylinder of SF_6
- Ideal gases: $\gamma_{SF6} = 1.09$ $\gamma_{air}=1.4$
- RAGE grid: level 1 = 0.64 cm (approx 80 zones across the diameter
  level 7 = 0.01 cm of the initial cylinder)

Comparison Between Experimental and Computational Images



Shock ⟶

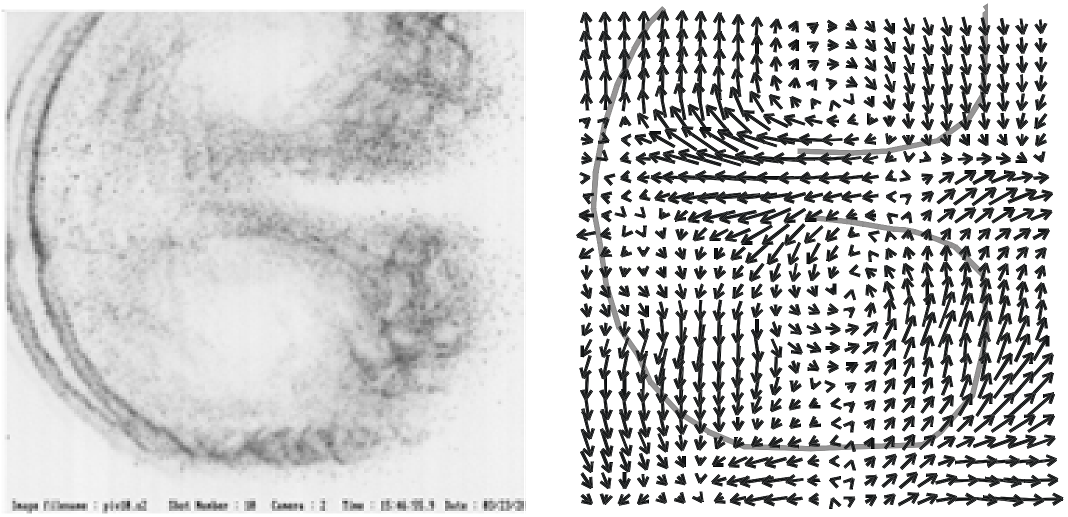
Quantitative Measurements



The height and width of the evolving cylinder are 15% larger in the experiment than in the simulation

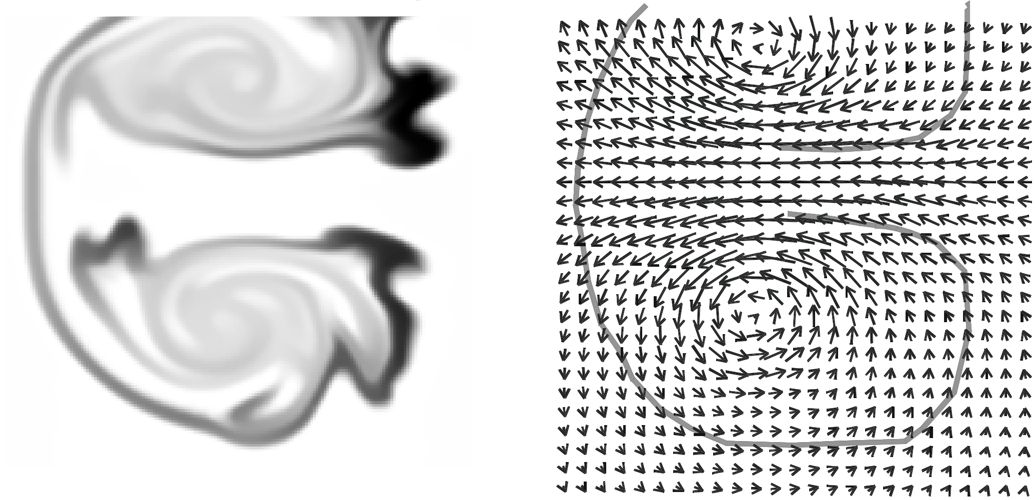
Velocity Fields

Experiment



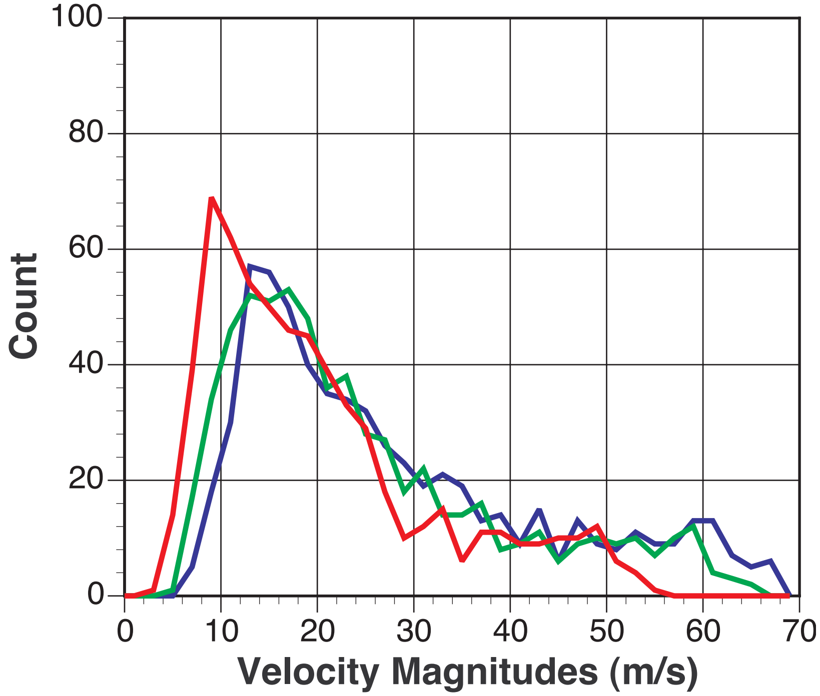
→ 10 m/s

Simulation

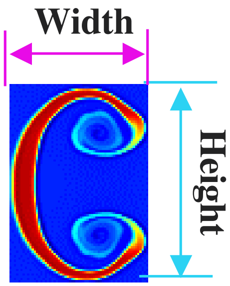


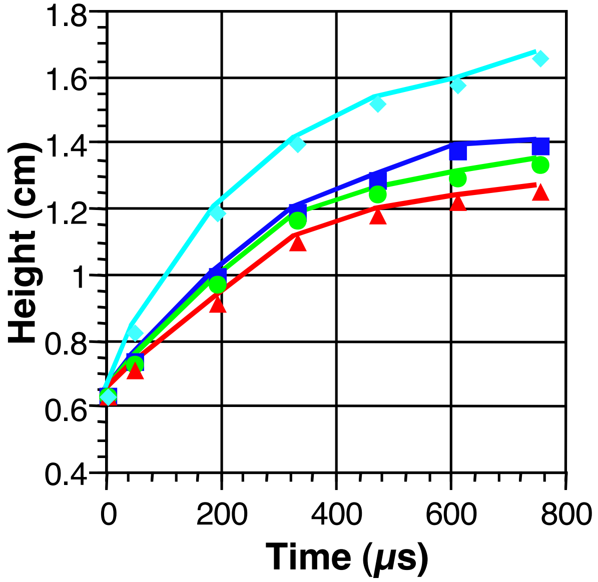
→ 50 m/s

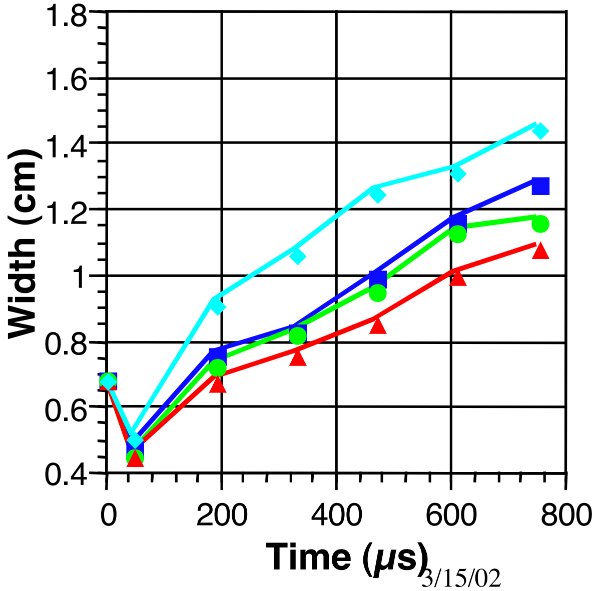
Varying Peak SF_6 Concentration



100% peak
80% peak
60% peak
experiment



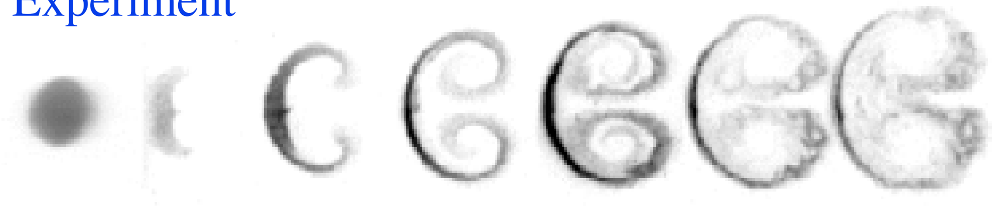




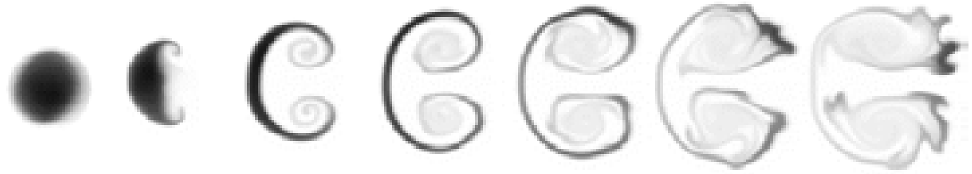
Smaller peak SF_6 concentrations result in smaller velocities and smaller lengths

Varying Density Gradient at the Air/ SF_6 Interface

Experiment



Experimental Initial Conditions



Sharp Interface

Diffuse Interface

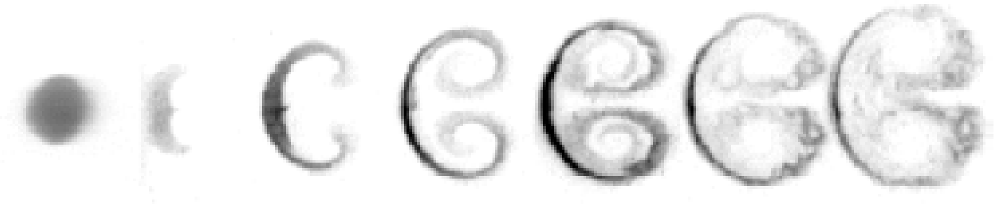
- Differences are visible in the density images with the initially diffuse interface producing the best visual agreement with the experiment

- No significant differences exist in the heights/widths and velocities

How well characterized are the experimental initial conditions?

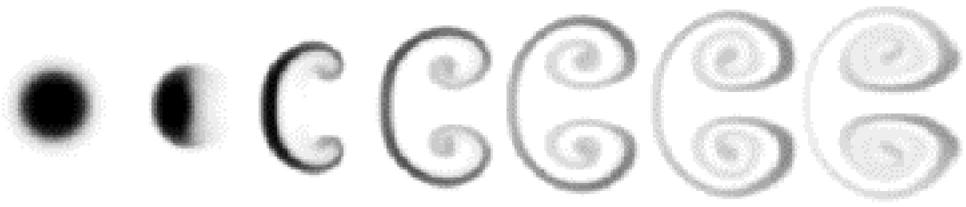
Mesh Refinement

Experiment



Diffuse Interface - fine Δx = 0.01

Diffuse Interface - coarse Δx = 0.02



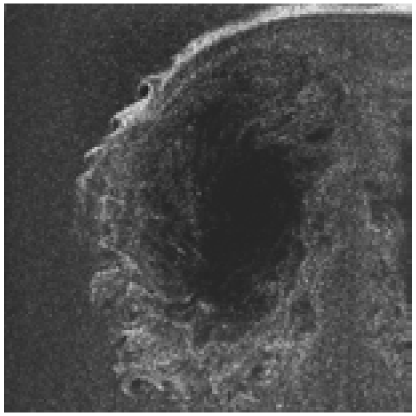
A coarser simulation shows “better” visual agreement with the experiment

Jet velocity:
coarse simulation: 62 m/s
fine simulation: 69 m/s

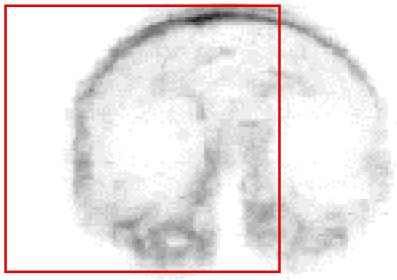
Coarser resolution:

- less rollup in vortex
- less evidence of secondary instability
- smaller jet velocity

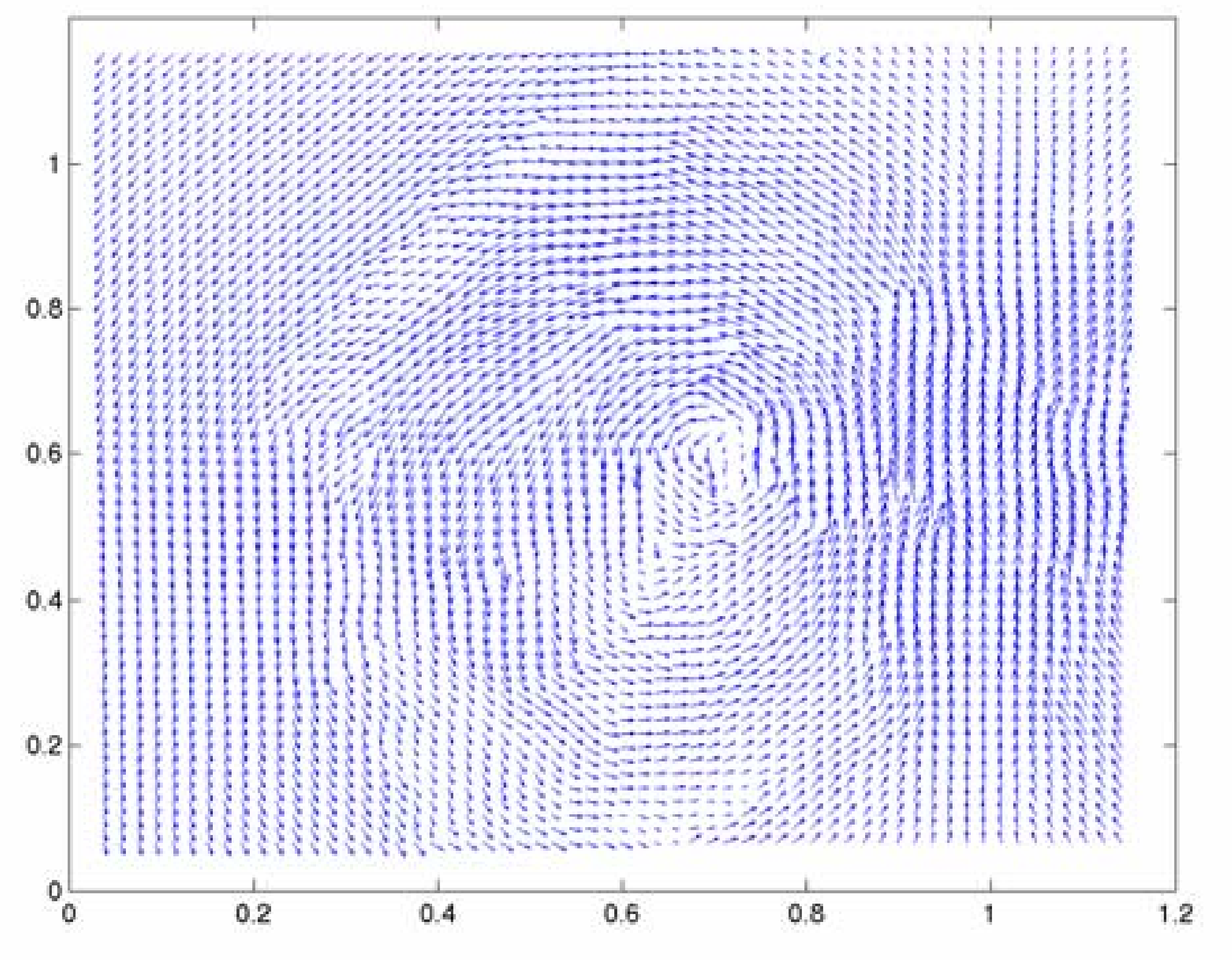
New Velocity Measurements



PIV image



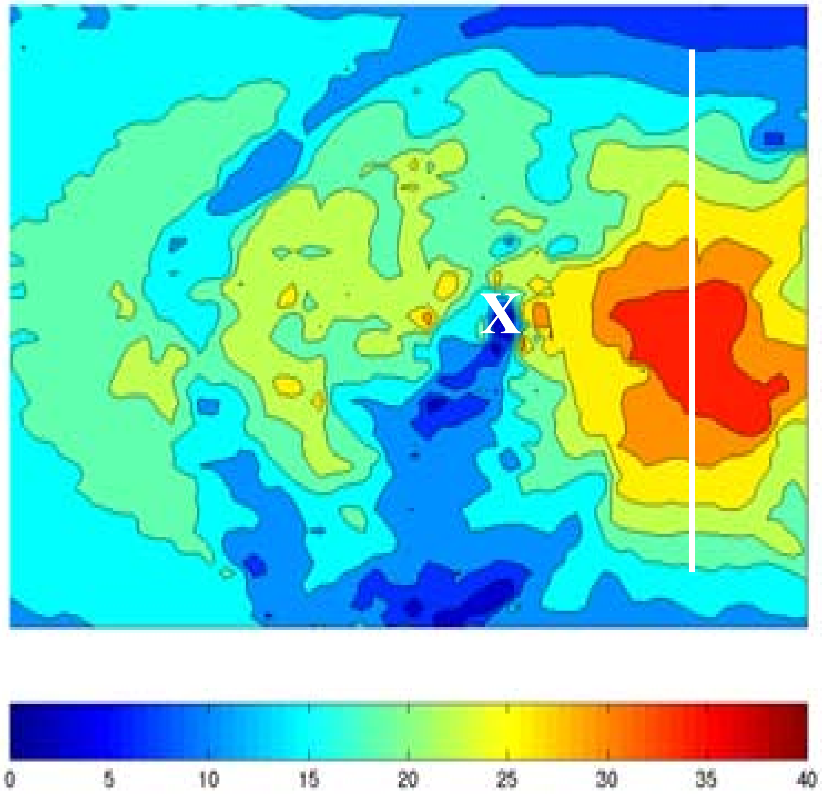
Last dynamic image



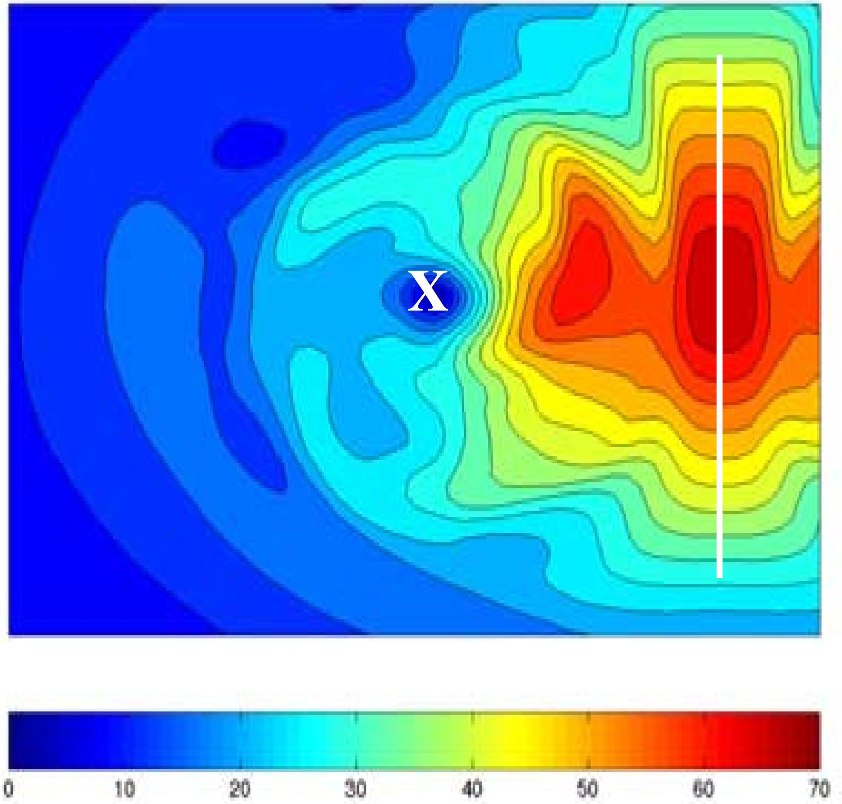
The new velocity field has vectors every 187 μm compared to every 537 μm obtained previously.

Location of Velocity Magnitudes

Experiment



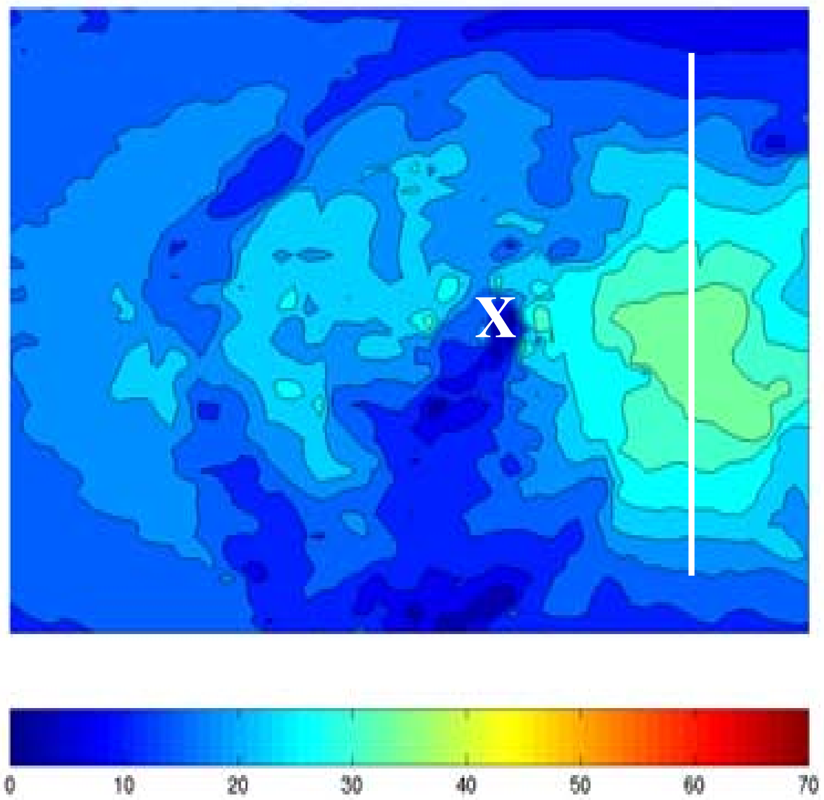
Simulation



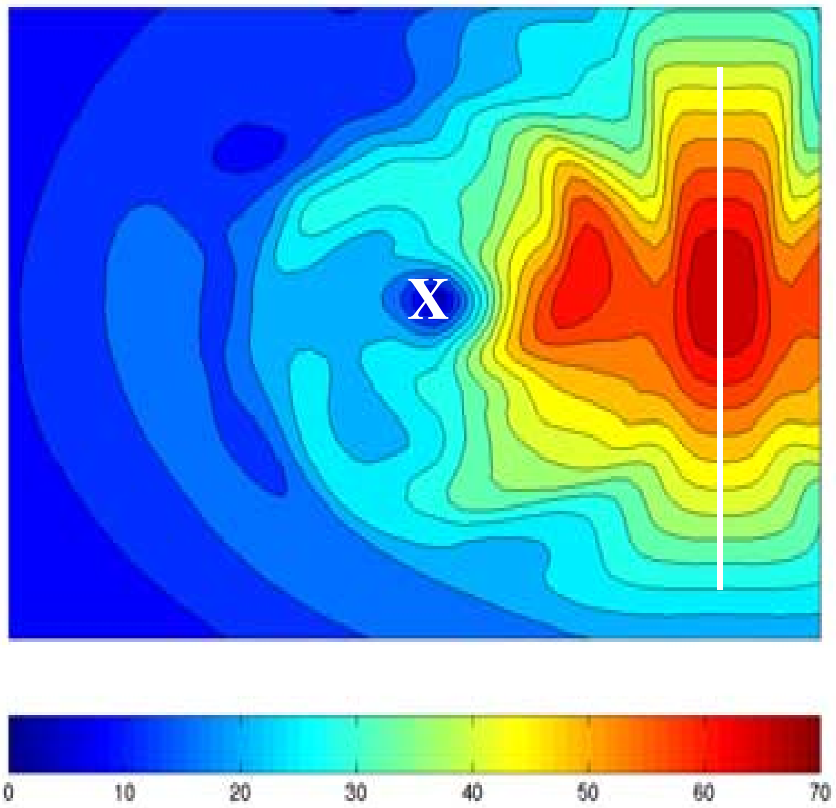
Largest velocities occur in the back-flow area and the smallest velocities occur in the vortex core

Comparison of Experimental and Computational Velocity Magnitudes

Experiment

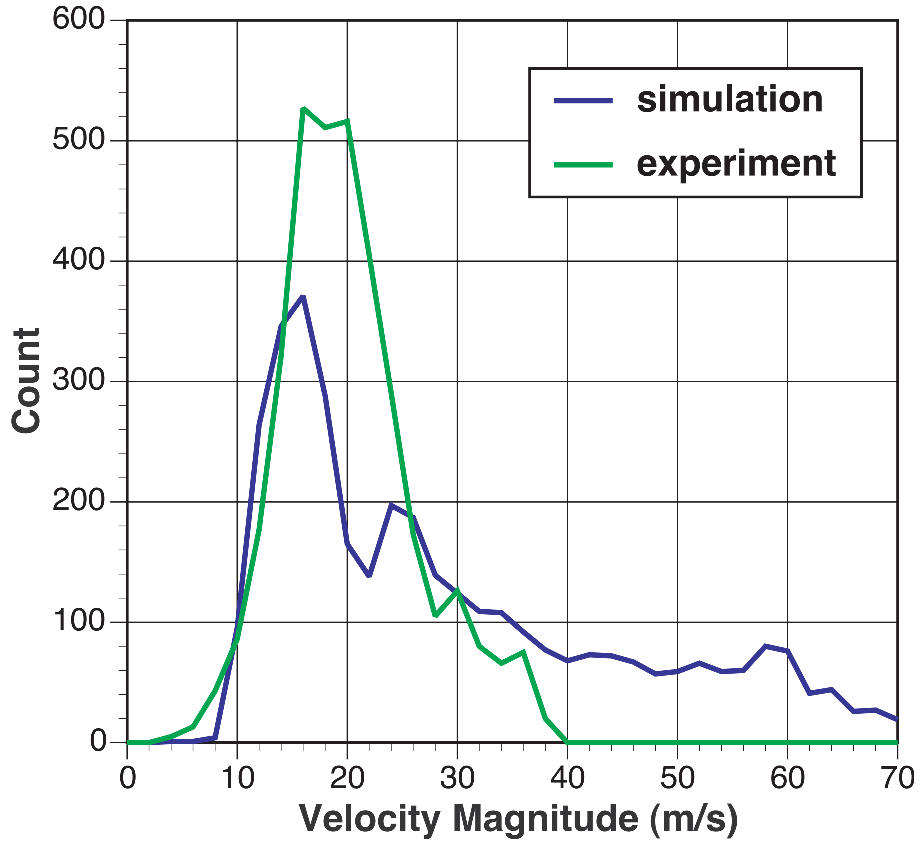


Simulation



The experiment and the computation have similar velocities in the vortex core

Histogram of Velocity Magnitudes

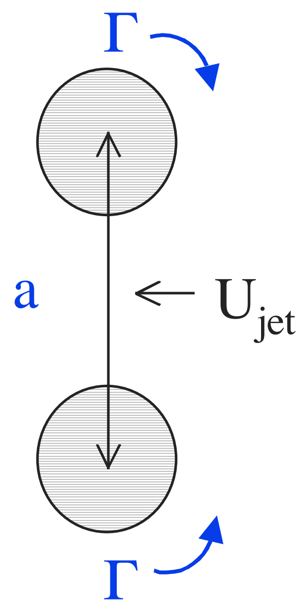


Both the experiment and the computation have a peak velocity of 15 m/s.

The magnitudes of the back-flow velocities form the tail of the histogram.

Large disagreement still exists between the experimental and computational back-flow velocities.

Jet Velocity of a Vortex Pair



Model the evolving cylinder as a vortex pair composed of two idealized incompressible rectilinear vortices with equal and opposite circulations

For steady state flow (i.e., vortices stationary), the jet velocity U_{jet} between the two vortices is equal to*:

$$\boxed{U_{jet} = 3\Gamma / 2\pi a}$$

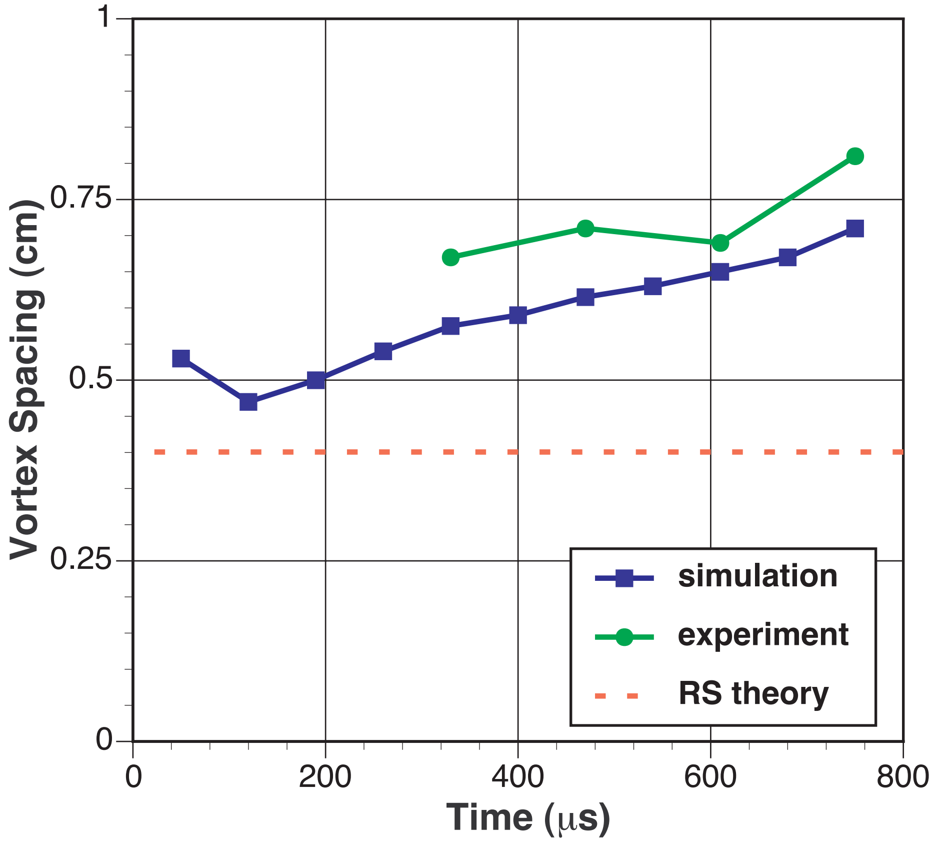
Simulation: U_{jet} = 59 m/s (predicted)
U_{jet} = 69 m/s (observed)

Experiment: U_{jet} = 37 m/s (predicted)
U_{jet} = 36 m/s (observed)

Are the predicted velocities qualitatively consistent with the circulation and vortex spacings measured in the experiment and the simulation?

*L. Prandtl and O.G. Tietjens. Fundamentals of Hydro- and Aeromechanics, McGraw-Hill Book, 1934.

Vortex Spacing



The experiment has larger vortex spacings compared to the simulation

The experimental and computational vortex spacings are in the range of Jacobs' measurements*

Note: The vortex spacing is determined using flow visualization

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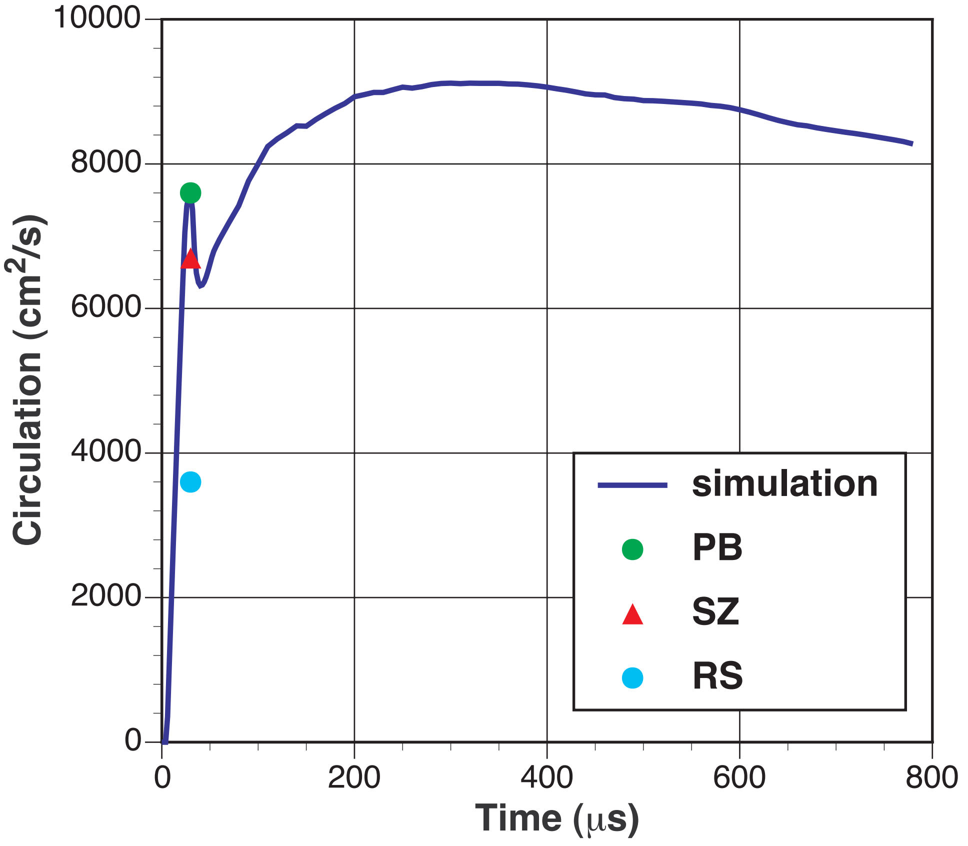
*J. W. Jacobs. The dynamics of shock accelerated light and heavy gas cylinders. *Phys. Fluids A*, 5(9):2239, 1993.

Circulation Values



Predictions of circulation:
RS: Rudinger & Somers (1960)
PB: Picone and Boris (1988)
SZ: Samtaney & Zabusky (1994)

The computational circulation value right after shock passage agrees well with the theoretical predictions of PB and SZ.

We need early-time PIV to determine the corresponding experimental circulation value.

Using the PIV results at 750 μs we find that: $\Gamma_{\text{experiment}} < \Gamma_{\text{simulation}}$

Summary

- Higher experimental velocities are observed with the improved PIV diagnostic, resulting in better agreement with the computational velocities
- The experiment and the simulation have similar velocities in the vortex core
- The computational jet velocity is approximately twice the value of the experimental jet velocity
- The differences in the jet velocities may be resolved by:
  - Examining the early-time shock-cylinder interaction in the experiment
  - Comparing the RAGE simulations with other hydrodynamics codes

Future Work

- Continue to investigate the length and velocity differences between the experiment and the simulation
- Redesign the experimental hardware to allow for high-resolution PIV at early time
- Obtain a better characterization of the experimental initial conditions
- Examine the effects of mix on the cylinder development using the new mix model added to the RAGE code
- Perform simulations using different computer codes
  - Cuervo (Bill Rider, Jim Kamm)
  - CHAD (Barbara Devolder, Manjit Sahota)
- Perform statistical analysis of the experimental and computational images (Bill Rider, Jim Kamm)