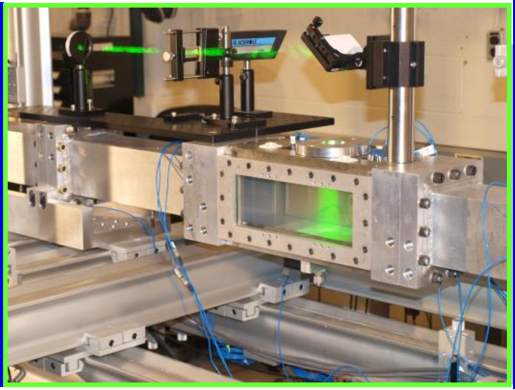
SAND2015-9418PE

Experiments on the shock-induced transport of a dense particle curtain



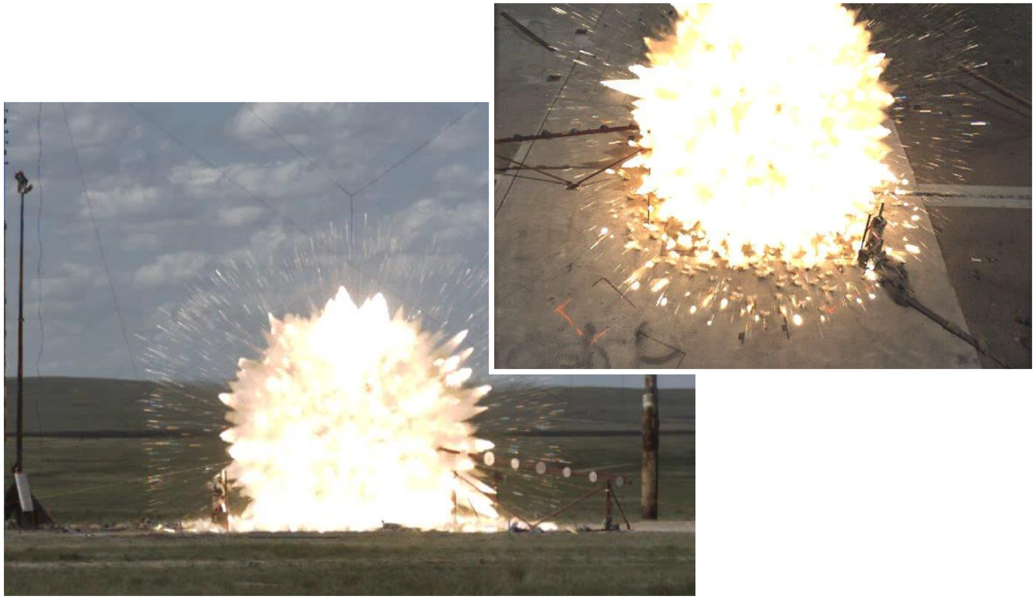


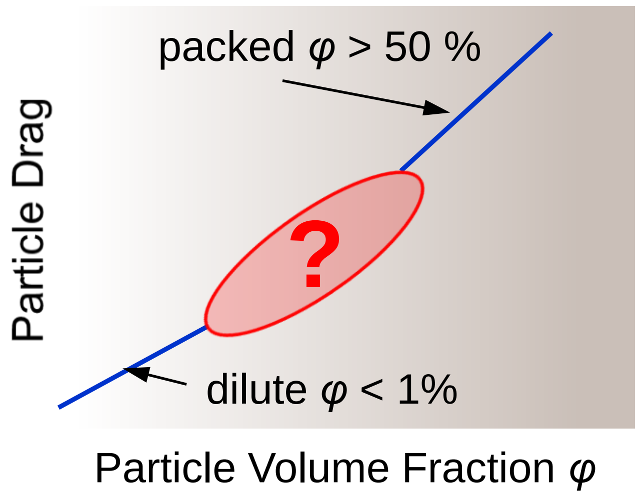

Justin L. Wagner, Steven Beresh, Sean Kearney, Edward DeMauro, Brian Pruett, Paul Farias

Ejecta Workshop

November 2nd, 2015

Motivation for Solid Particle Experiments





Explosive Particle Dispersal

- Dynamics of densely packed particles influence heterogeneous explosive processes [1, 2]

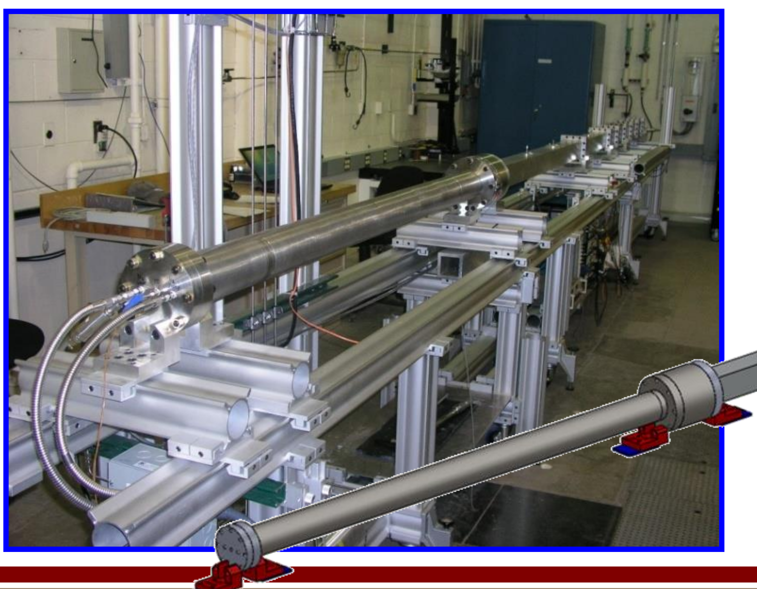
Gas-Particle Dynamics

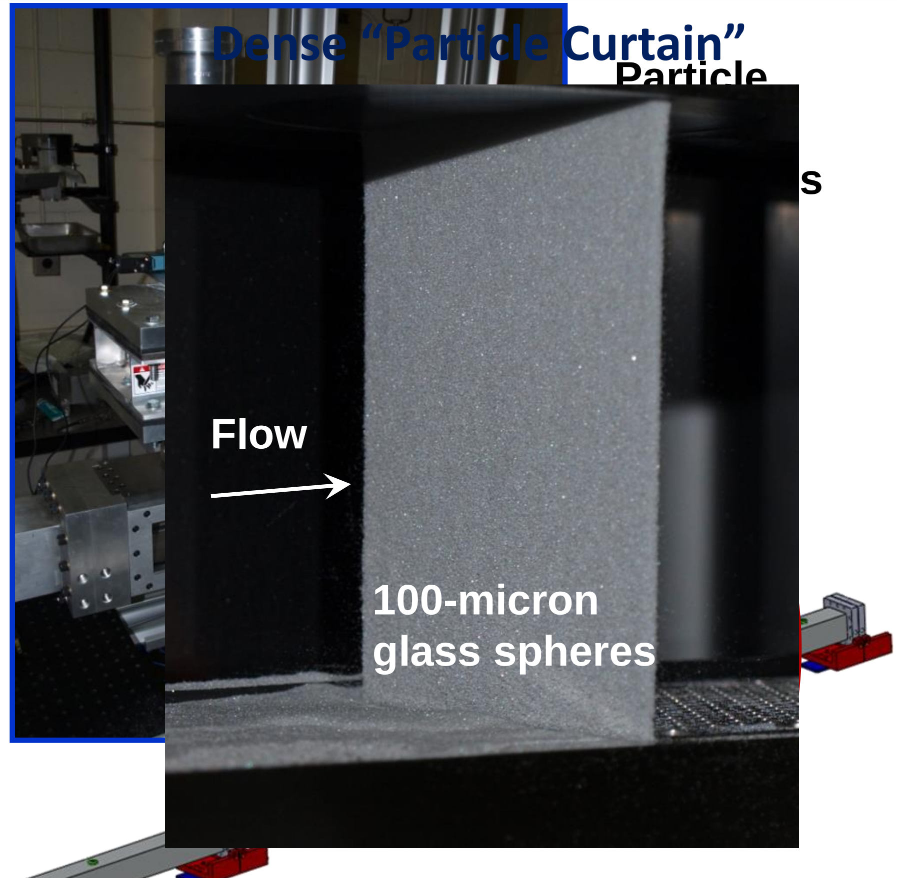
- Dynamics governed by volume fraction φ [2]
- Very little data in "dense" regime ($1\% < \varphi < 50\%$)

Particle Curtain Experiments in MST

Multiphase shock tube facility

- MST allows study of shock-particle interactions in dense gas-solid flows.
- Shock Mach #s up to about 2, driven section at atmosphere
- 76 mm × 76 mm test section

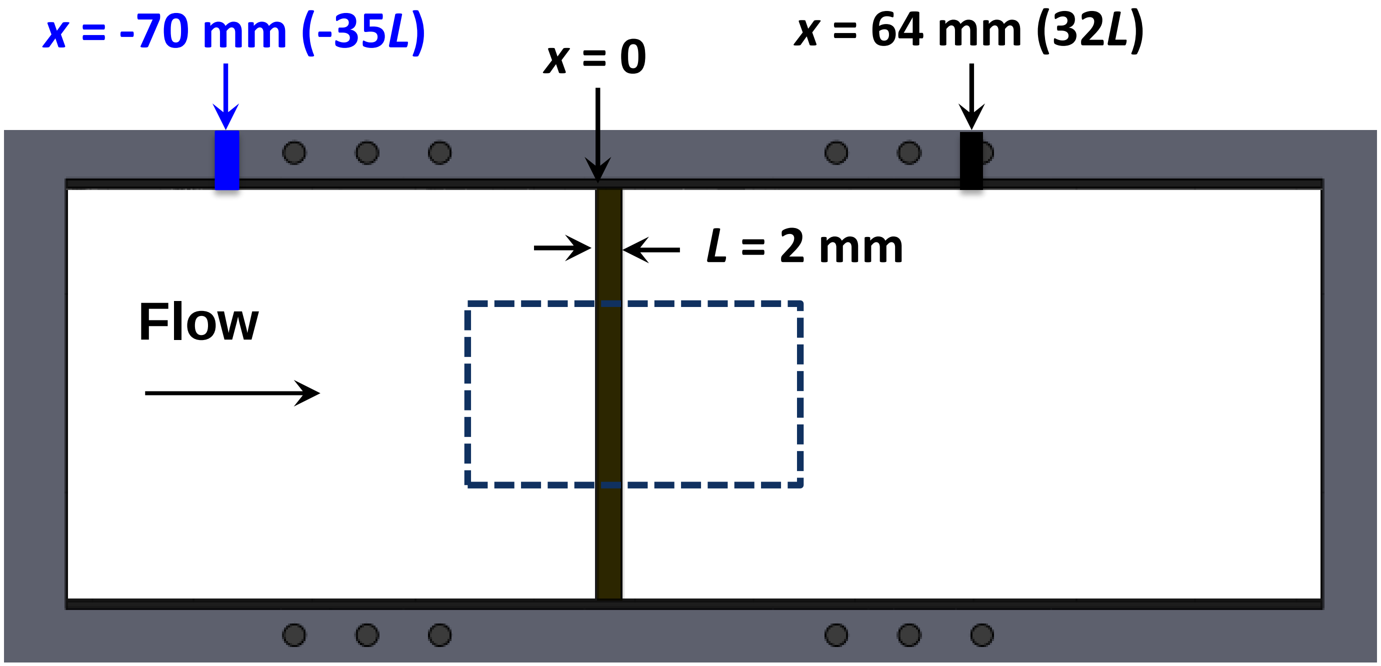




Particle volume fraction ≈ 20%

Curtain Measurements

Test Section



Pressure Measurements

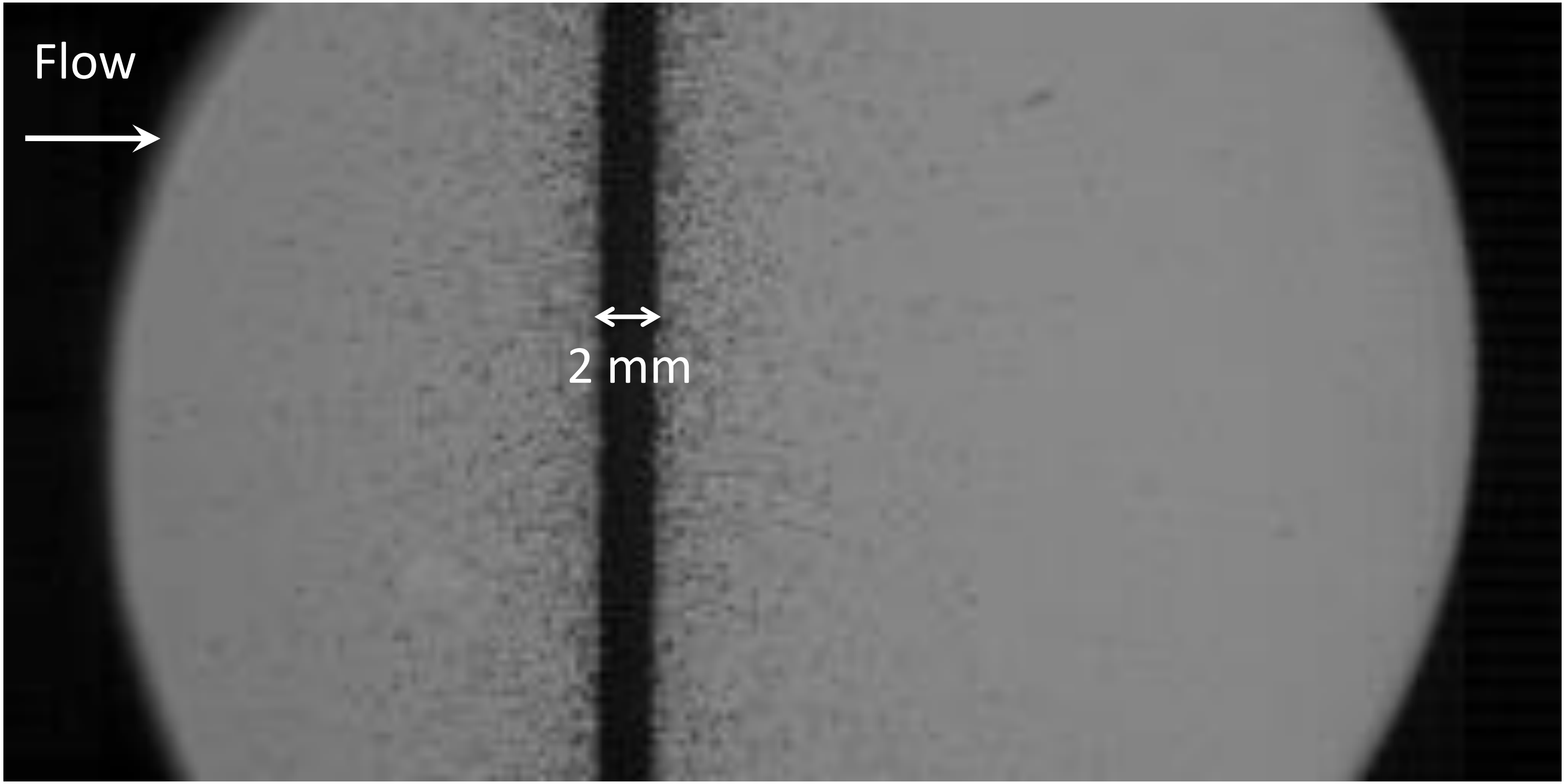
- PCB sensors upstream and downstream of curtain

High-Speed Schlieren

- Continuous LED source and Phantom v12.1 camera

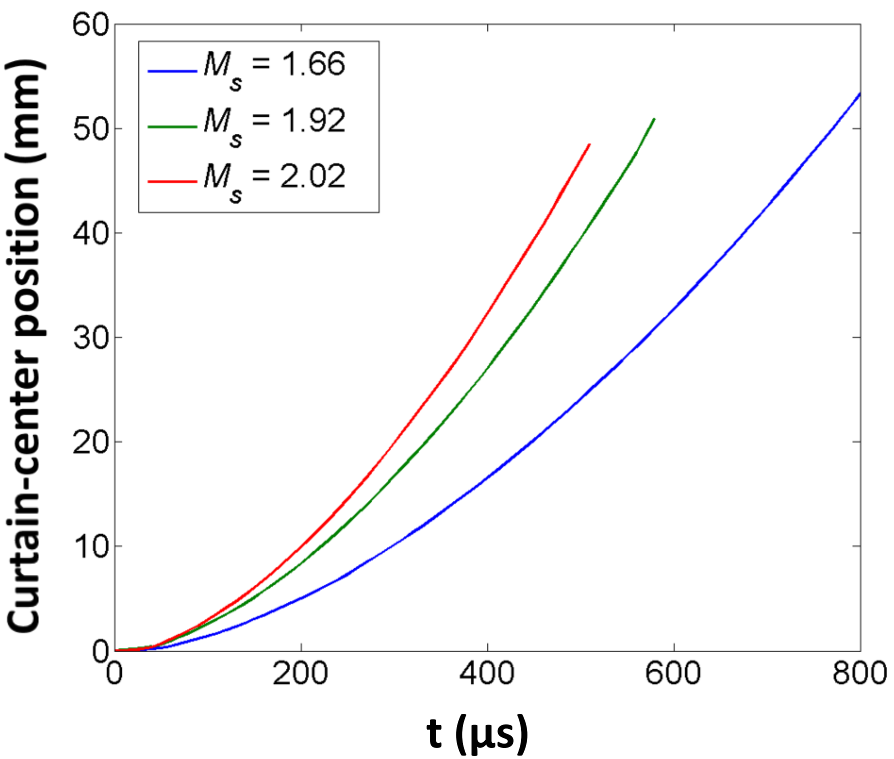
High-speed Schlieren (130 kHz)

Interaction at shock Mach number = 1.67



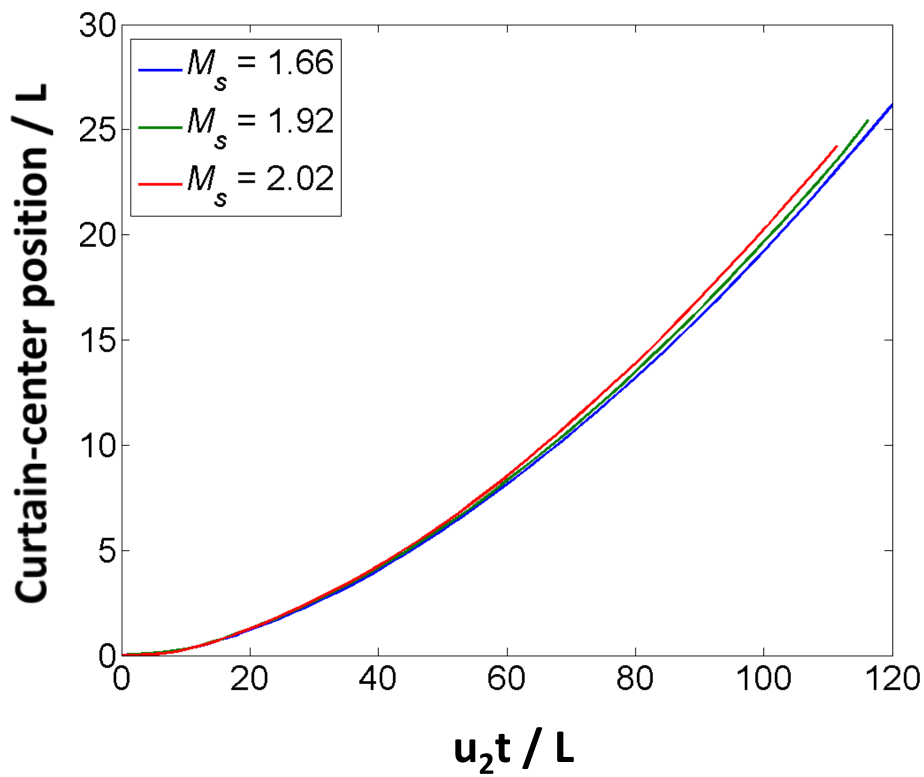
Particle Trajectories

At all three Mach #s



As expected, particles travel faster for stronger shocks.

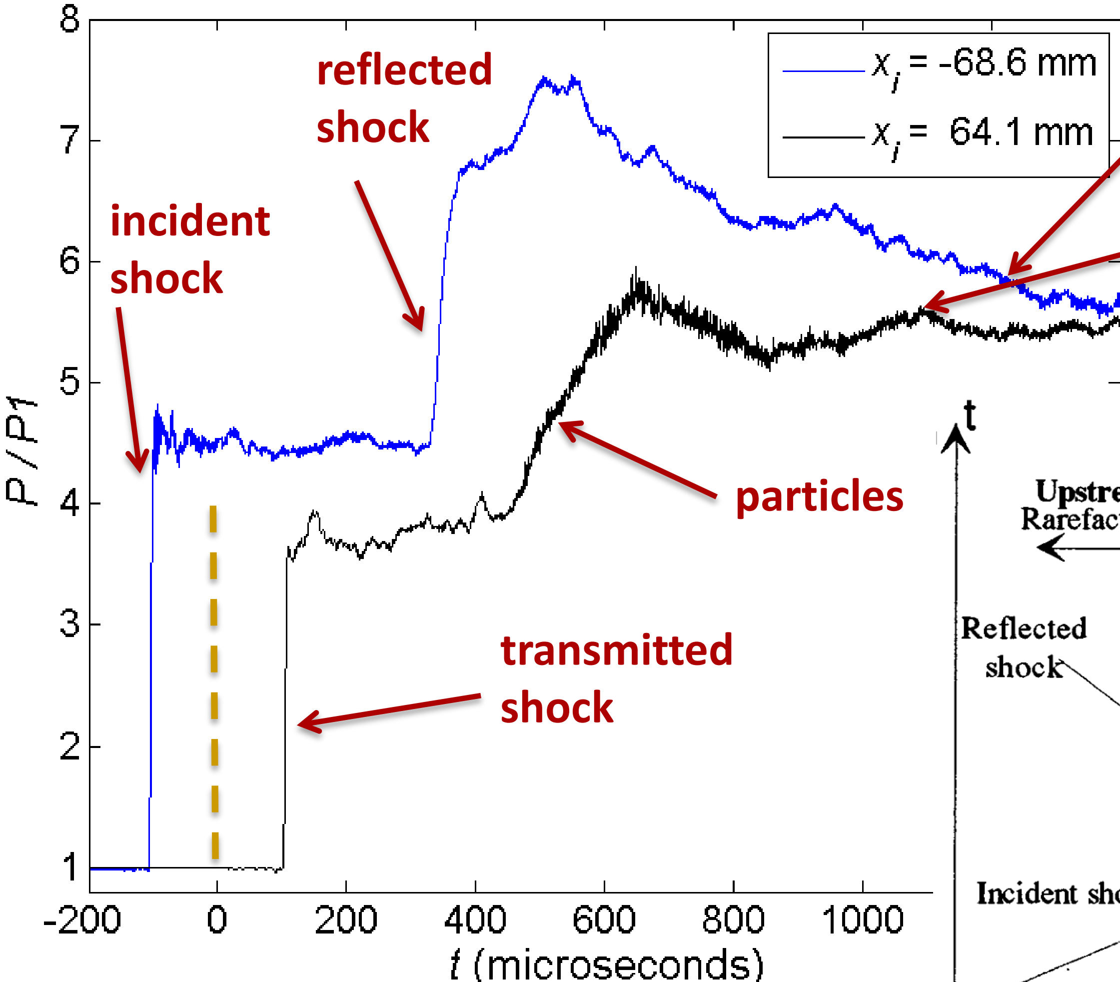
Time normalized by u_2



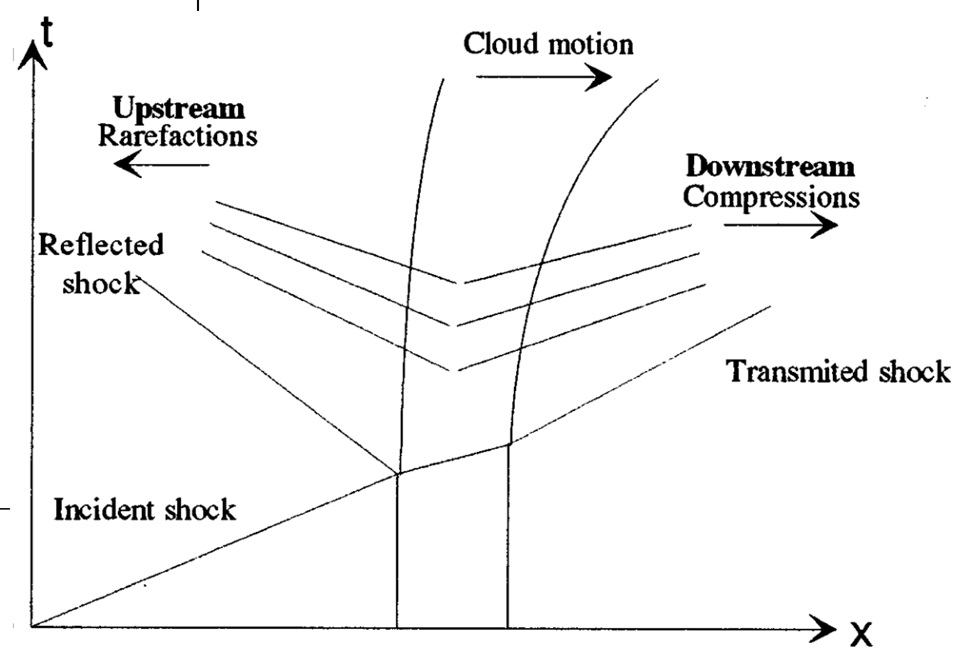
Trajectories collapse with shock-induced velocity u_2 [1]

[1]Ling, Wagner, Beresh, Kearney, Balachandar, *Physics of Fluids*, 24, 2012

Pressures (Mach 2.02 Interaction)



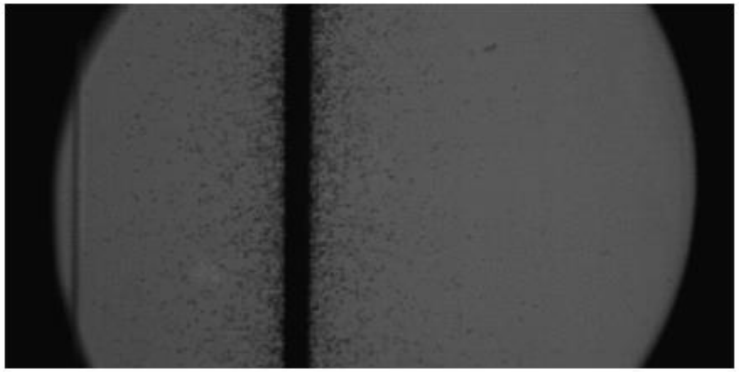
x-t diagram (Rogue et al)



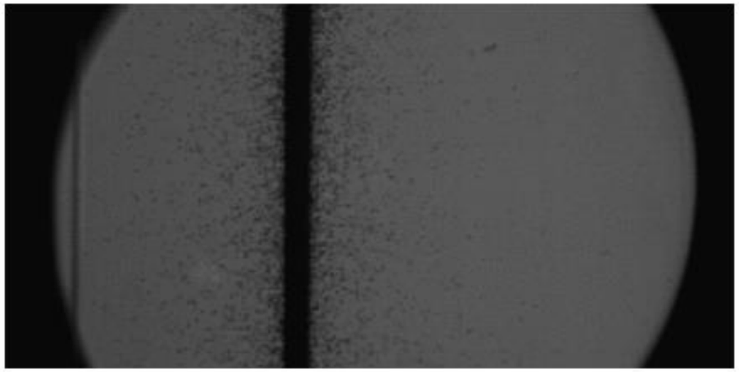
Rogue et al, *Shock Waves*, **8**, 1998

Compare to modeling of *Balachandar et al.*

Standard Drag Model



New Drag Model



Particle trajectories substantially under predicted by Re # model

Results including dense volume fraction effects much improved, *though new data are needed*.

Ling, Wagner, Beresh, Kearney, Balachandar, *Physics of Fluids*, 24, 2012

Modeling (University of Florida, Balachandar et al)

Where does the additional interphase momentum come from [1]?

$$\sum F^{gp} = F_{qs}$$

total force on a particle imparted by the gas — **quasi-steady drag**

Each term increased by two effects:

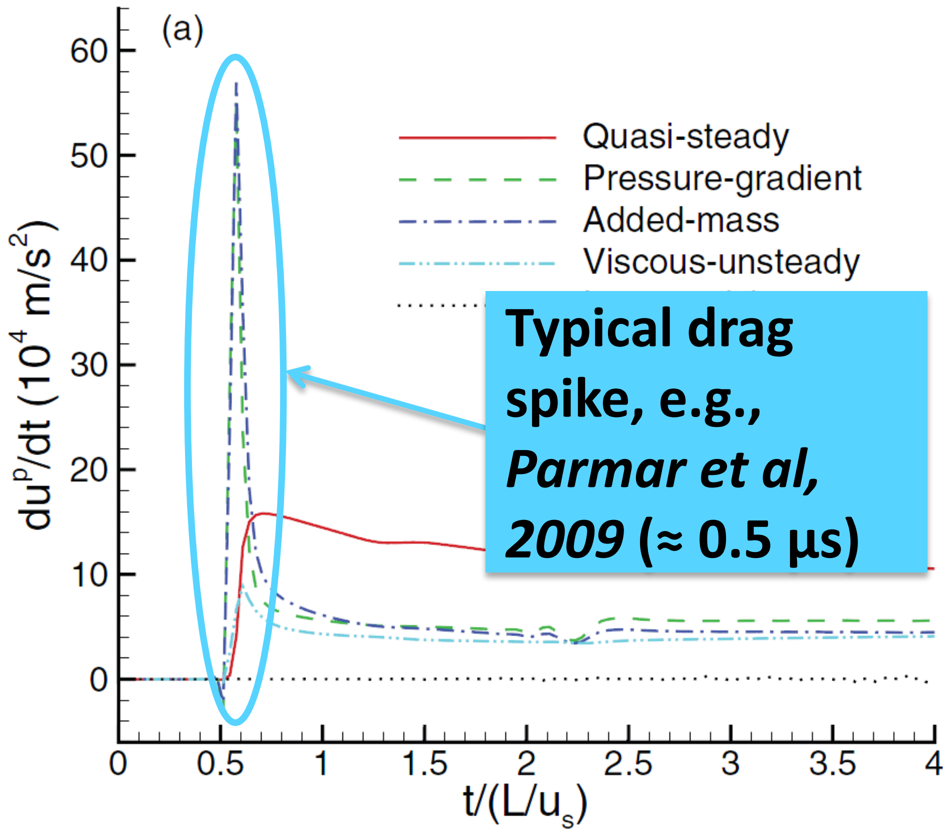
1) ***Volume fraction effects*** **(Sangini et al, 1991)**

2) ***Compressibility effects*** **(Parmar et al, 2010)**

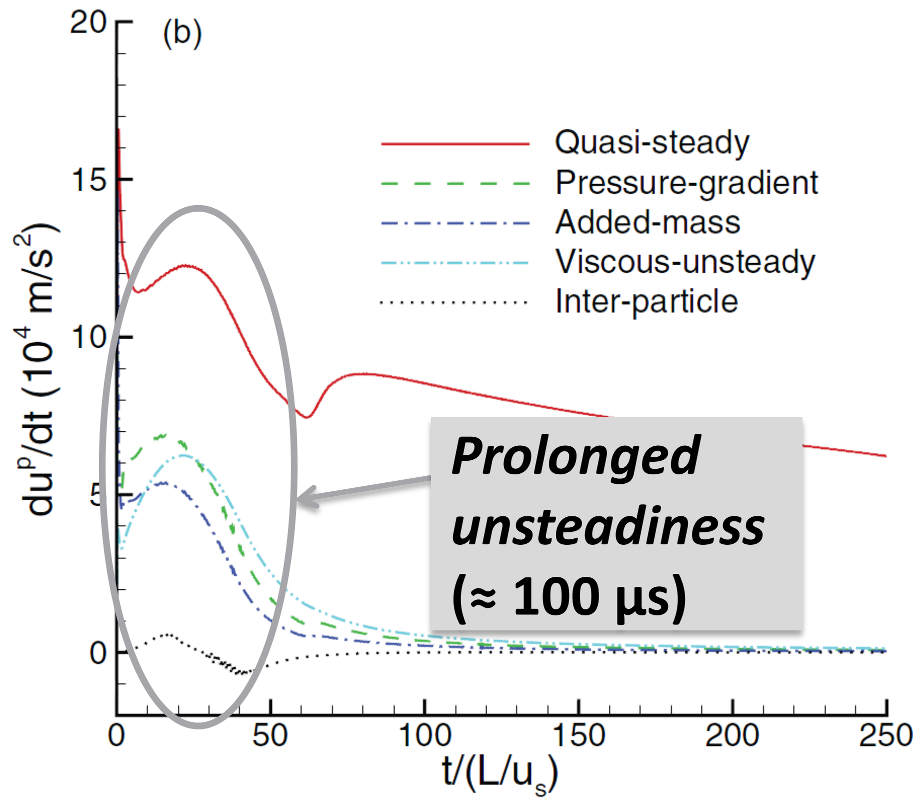
[1] Ling, Wagner, Beresh, Kearney, Balachandar, *Physics of Fluids*, 24, 2012

Modeling (University of Florida, Balachandar et al)

Early times (shock passage)



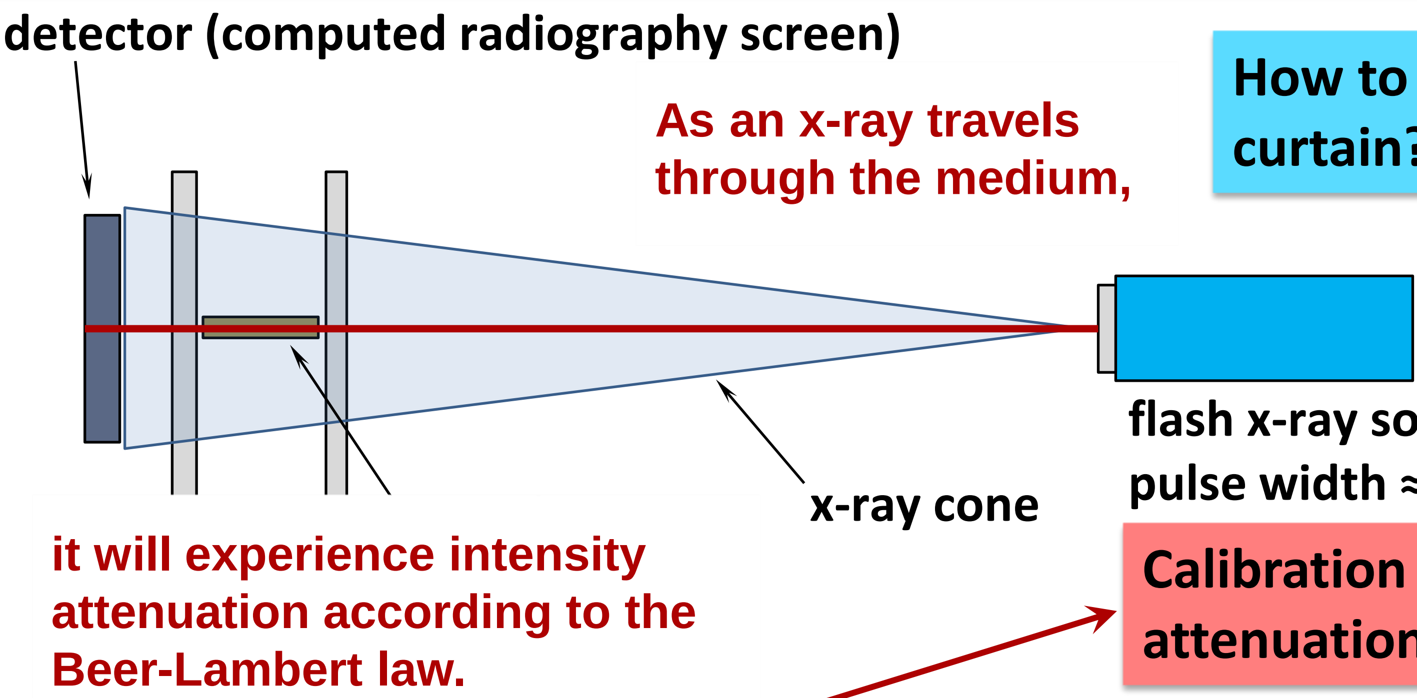
Later interaction times



The dense particle curtain causes increased quasi-steady drag, a prolonged unsteadiness and a more rapid spread.

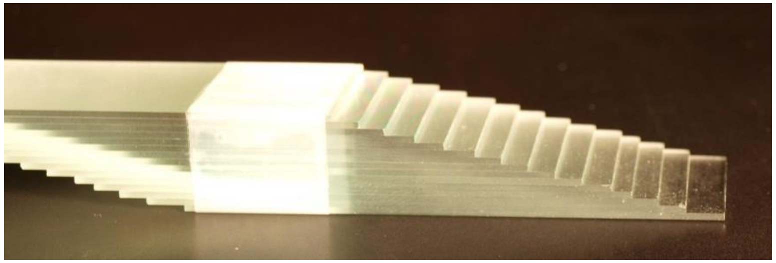
[1]Ling, Wagner, Beresh, Kearney, Balachandar, *Physics of Fluids*, 24, 2012

Volume Fraction Measurements



How to see inside curtain?

Calibration to find attenuation coefficient



Beer-Lambert

$$I/I_0 = e^{-A\rho w}$$

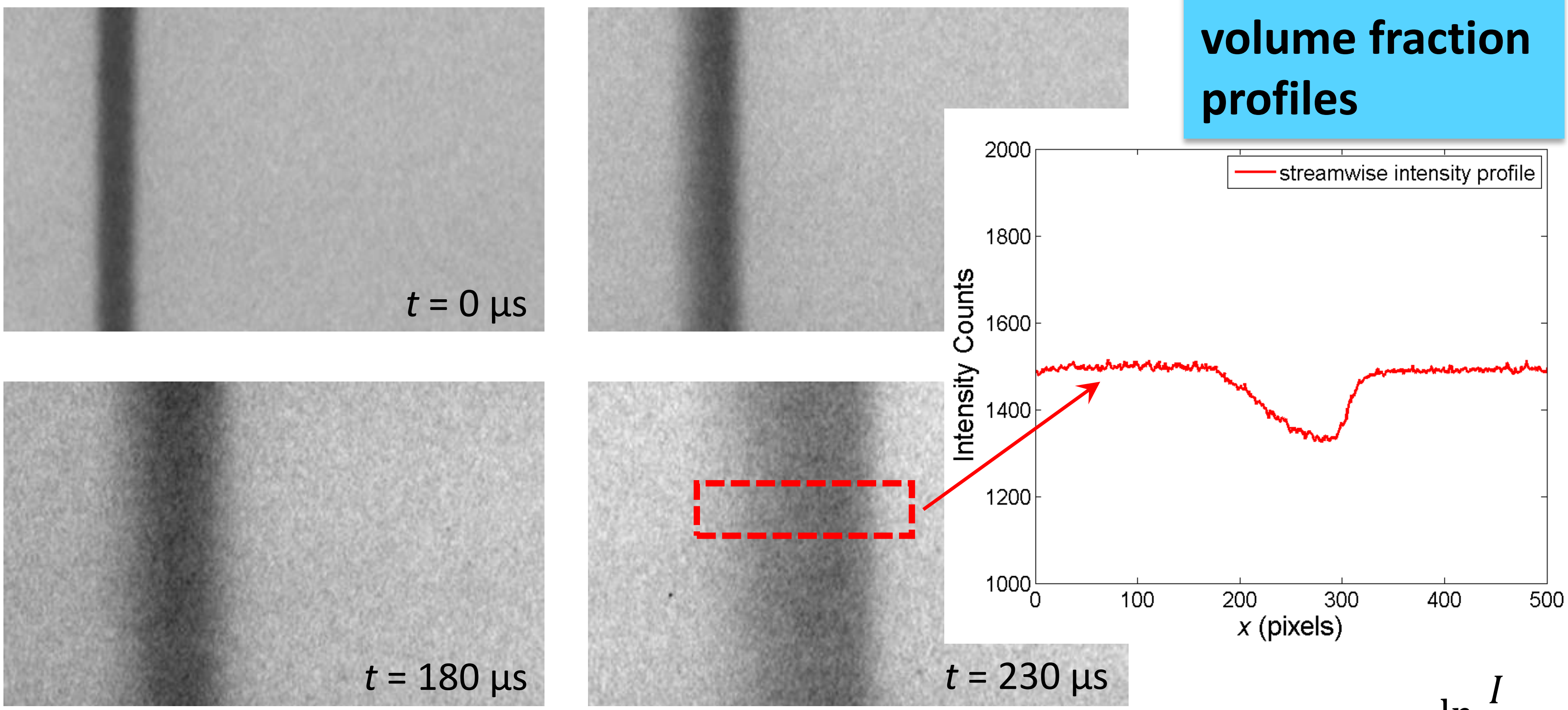
where ρ is the medium density, w is its optical path length, and A is its mass attenuation coefficient

Calculate φ assuming constant curtain width w_0

Interaction Radiographs (Flash X-Ray)

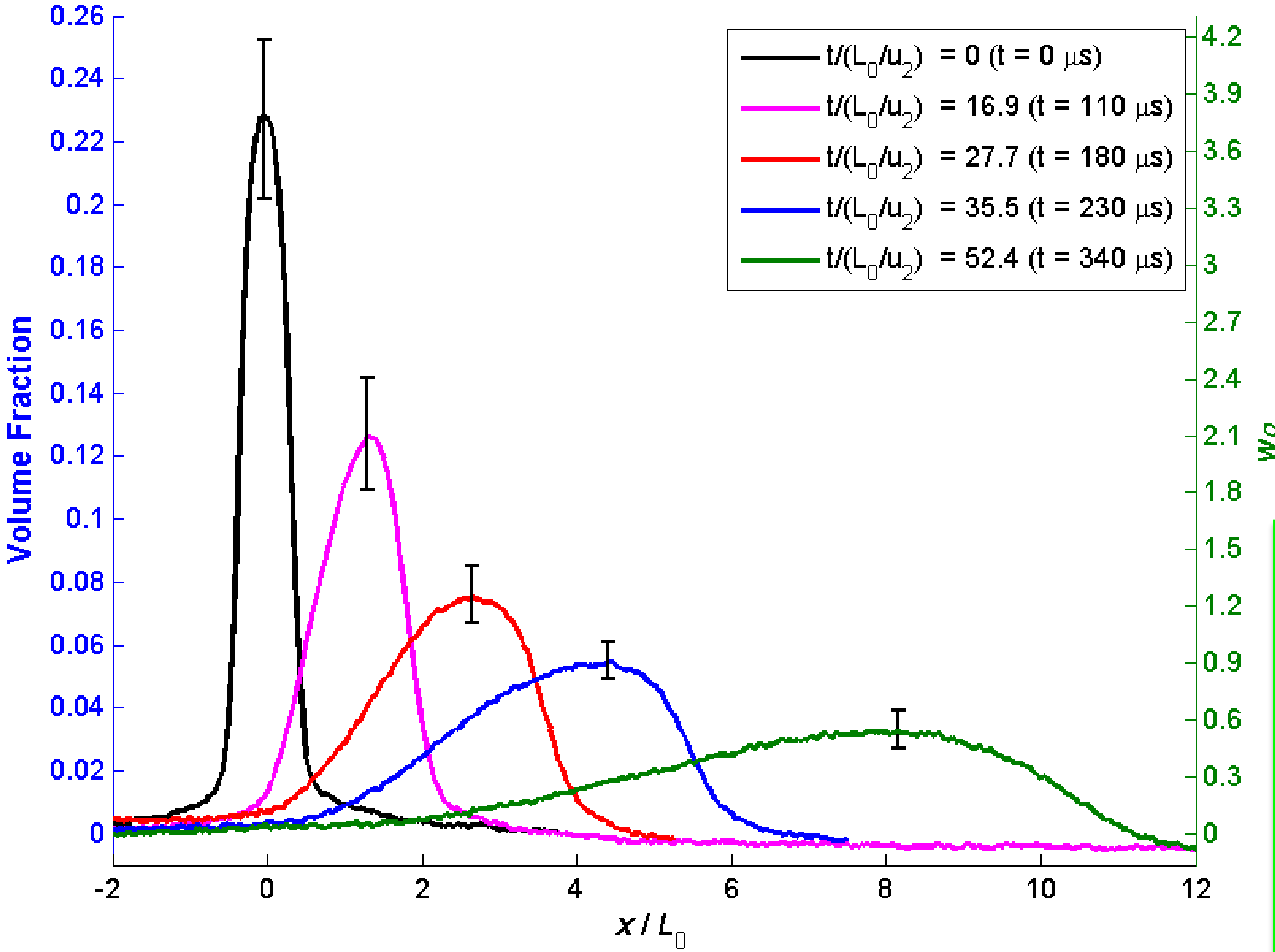
<u>**0-230 µs**</u>

Apply Beer's law to back out volume fraction profiles



$$\varphi = \frac{w}{w_0} = \frac{\ln \frac{I}{I_0}}{-A w_0 \rho}$$

Volume Fraction Profiles



Curtain spreads in asymmetric fashion with the downstream-side exhibiting steeper gradients

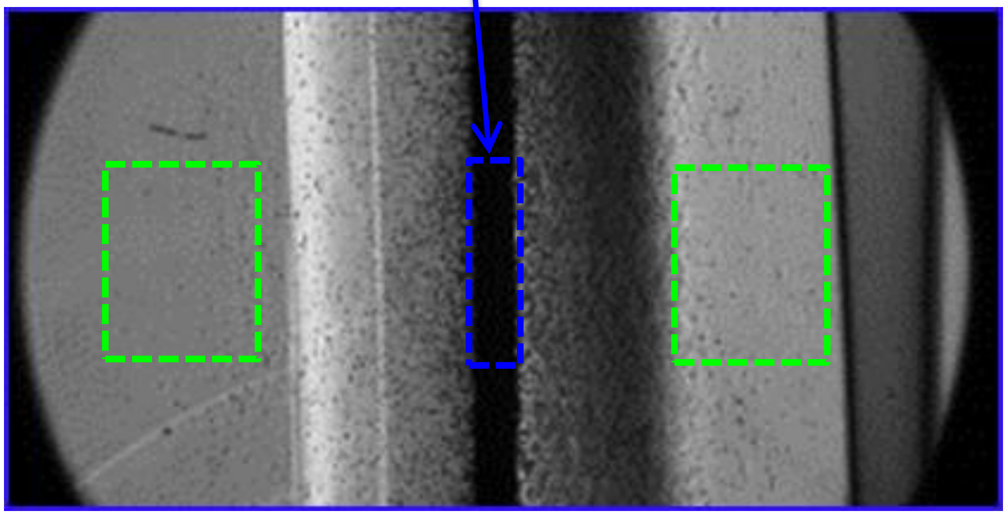
We've focused on diagnostics for solid particles, need gas-phase data too….

Wagner, Kearney, Beresh, DeMauro, Pruett, *accepted for publication in Experiments in Fluids*, 2015

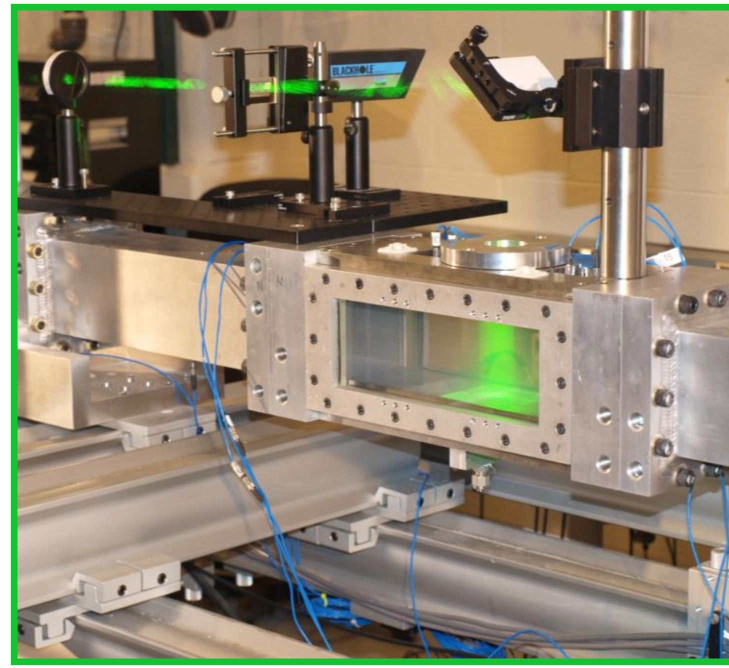
Gas Phase Particle Image Velocimetry (PIV)

Sandia National Laboratories

We've previously focused on the solid particles.



PIV Setup

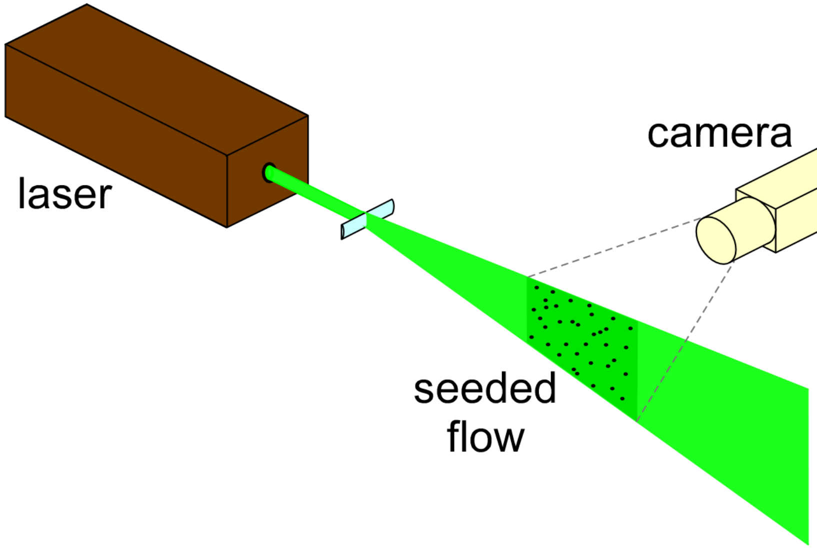


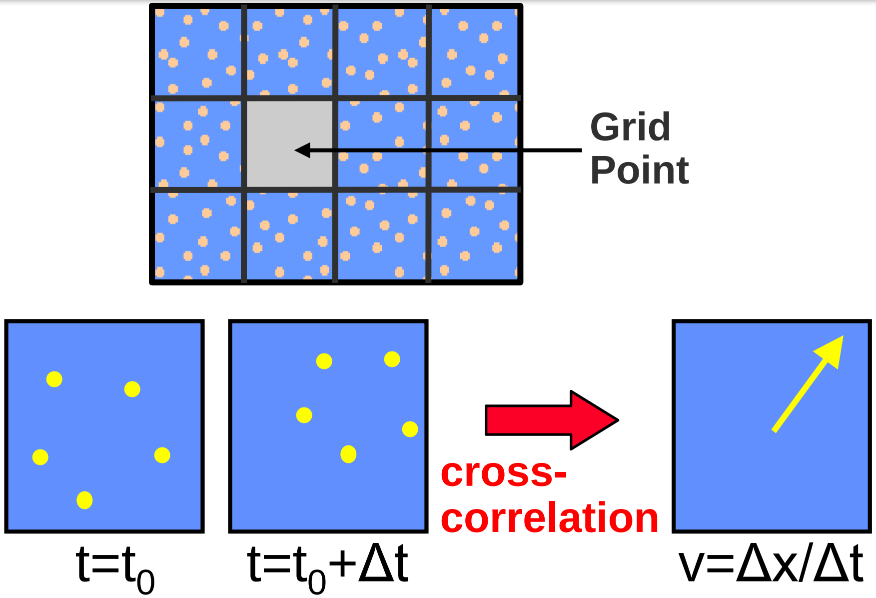
We need gas phase data to measure:

1. **Interaction Unsteadiness**
2. **Interphase Momentum Transfer**
3. **Particle-Induced Turbulence**

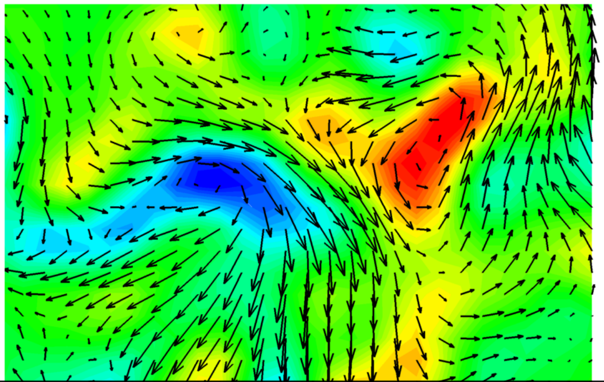
Seed the *gas* with micron size particles

PIV Principle





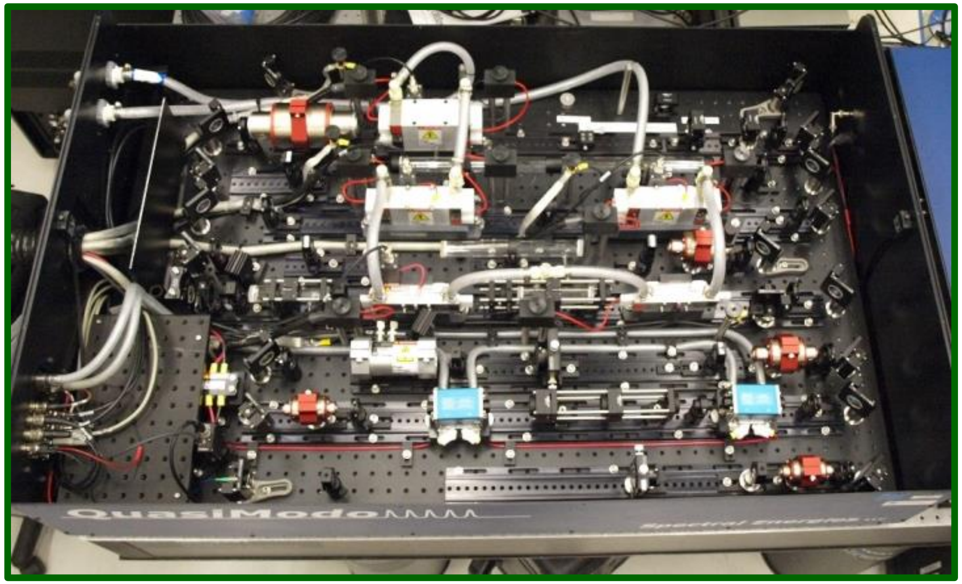
- Seed a large quantity of small **particles** into the wind tunnel
- Illuminate with a double-pulsed laser sheet and **image** with a specialized digital camera
- Grid the images into smaller windows
- In each grid window, track a pattern of particles as they move from the first exposure to the second
- Compute a field of **velocity** vectors



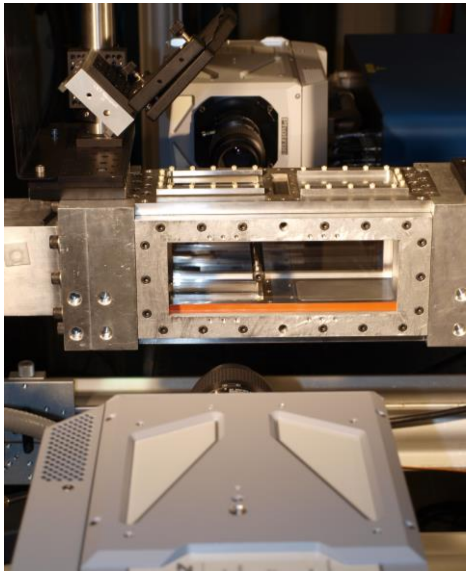
But a conventional PIV systems allow only one realization in the millisecond test times of a shock tube...

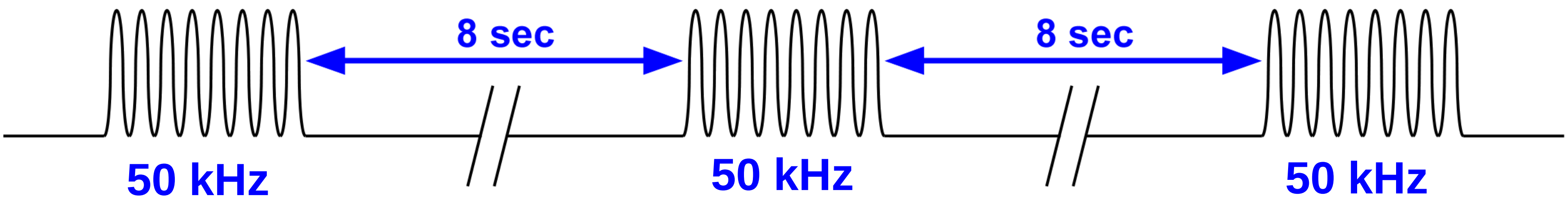
Solution: Pulse-Burst PIV

Spectral Energies Burst-Mode Laser



Photron SA-Z Cameras





Bursts of high repetition rate pulses last up to 10.2 ms, *plenty long in a shock tube flow.*

As a start, we applied this tool to particle-free flows in the MST.

Transient Flowfields of Interest

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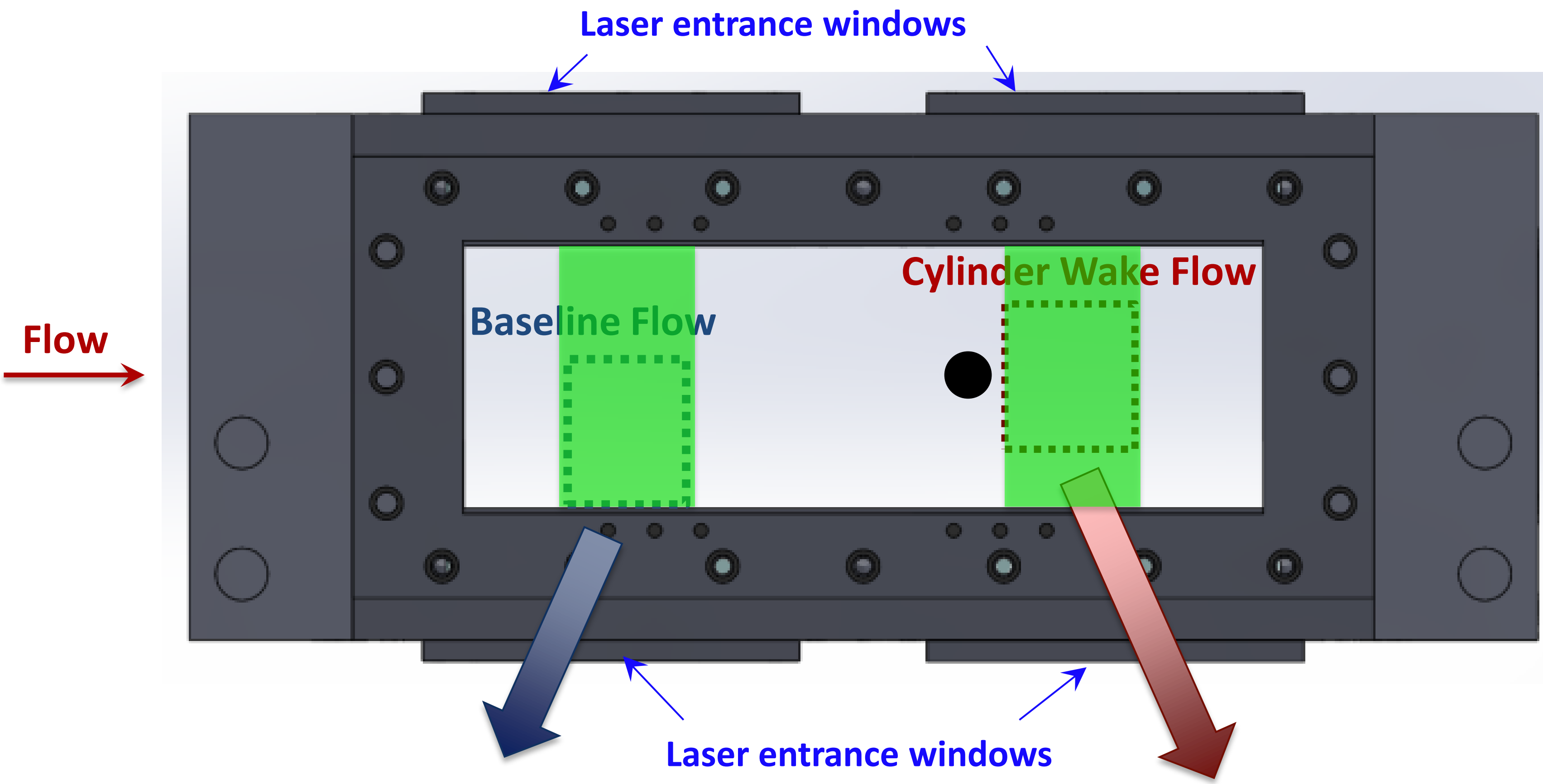
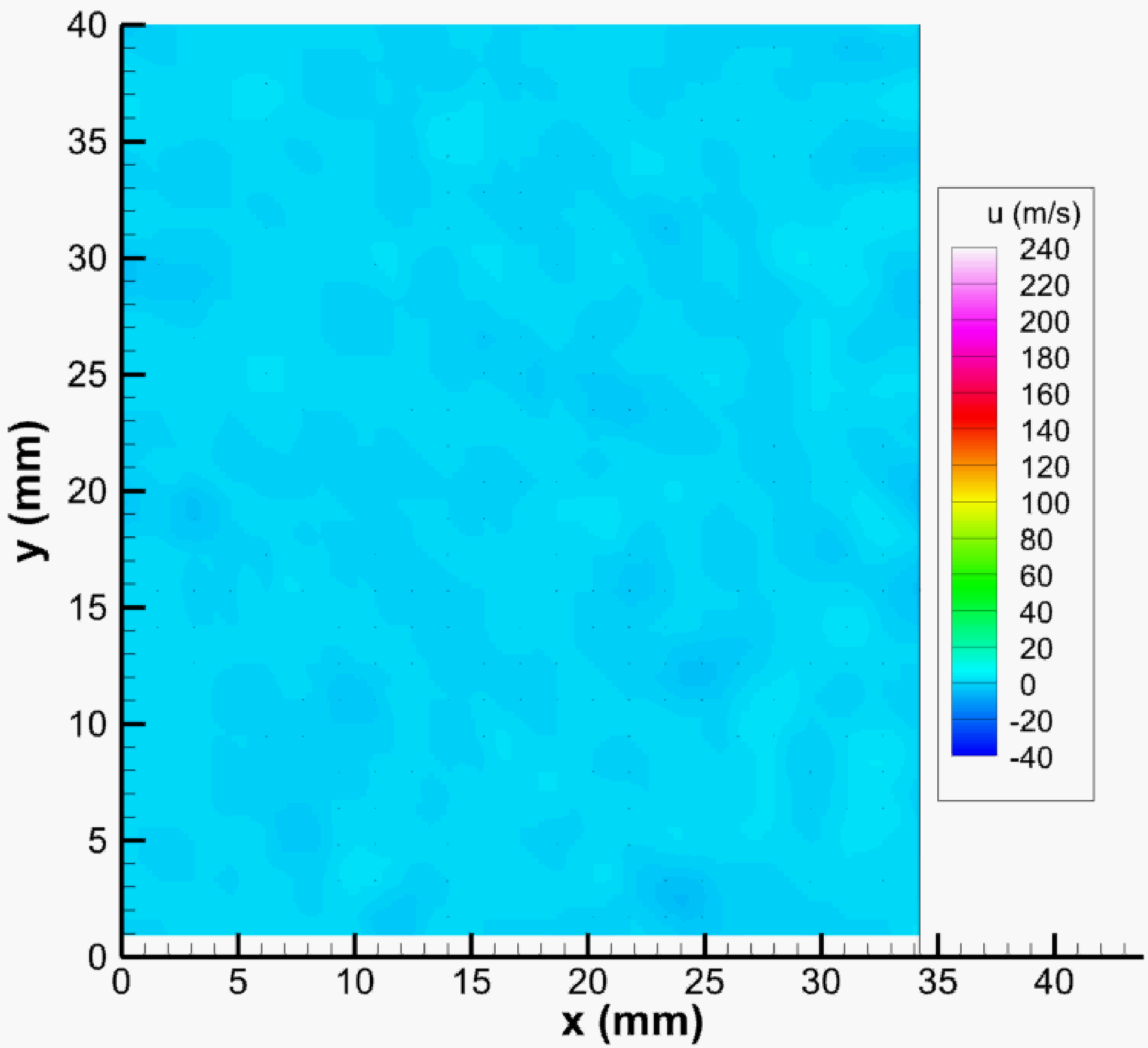


1. Incident and reflected shocks
2. Boundary layer growth
3. Core flow acceleration (non-ideal)

1. Shock deformation due to cylinder
2. Transient wake growth
3. Wake response to reflected Shock

Baseline Transients (M_s = 1.45, M_2 = 0.56)

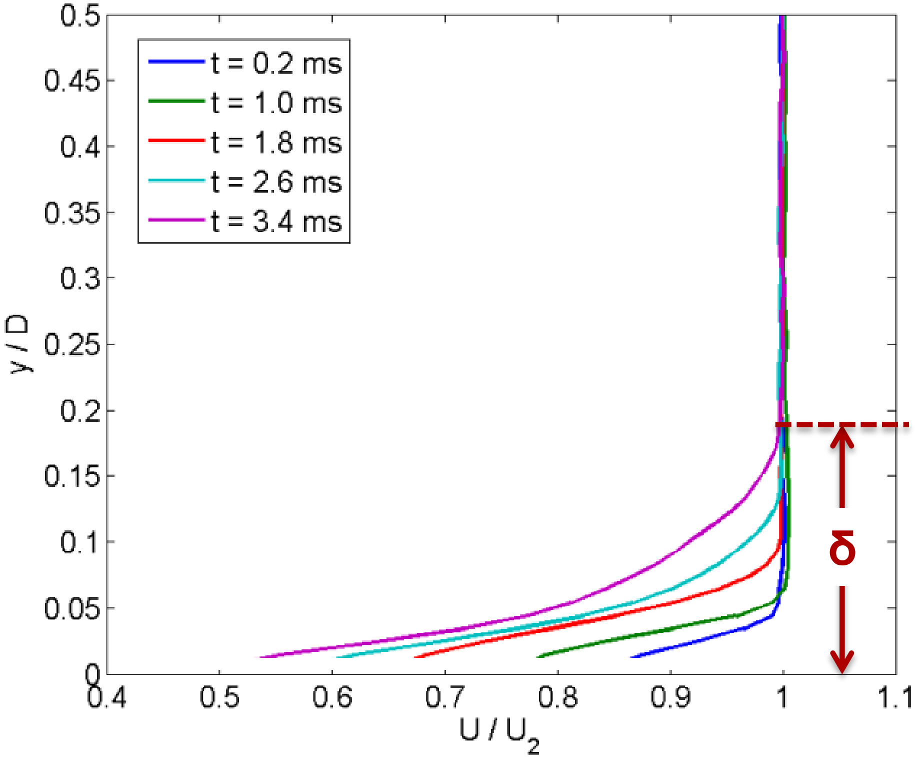


First TR-PIV in MST

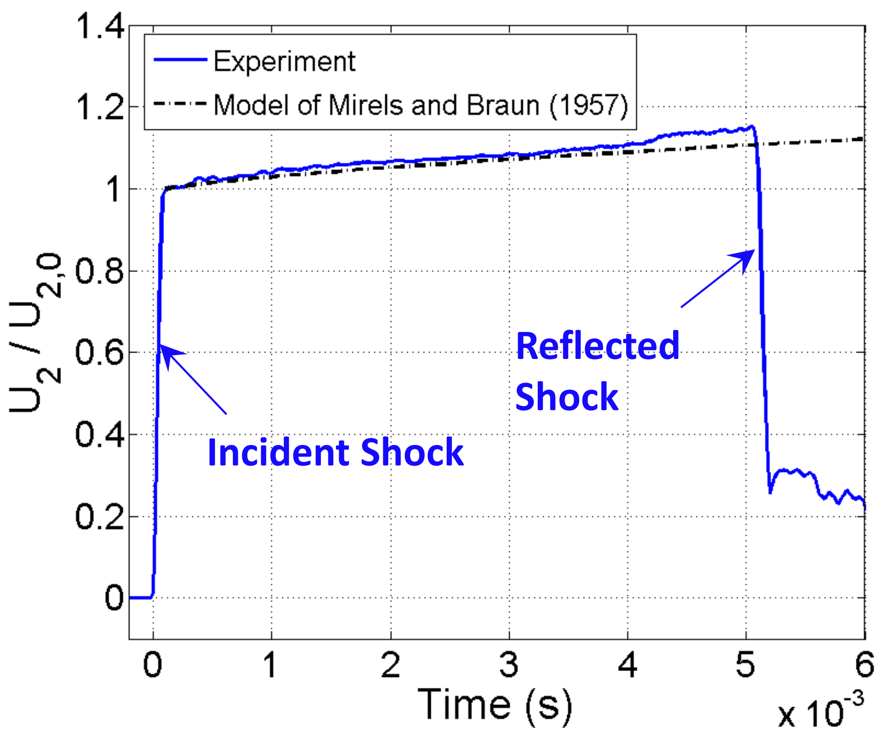
- **Data every 20 microseconds.**
- We capture:
  - Incident shock
  - Boundary layer growth
  - Core flow acceleration
  - Reflected shock wave-boundary layer interaction.

Boundary Layer Growth Effects

Normalized Streamwise Velocity Profiles



Core Flow Acceleration



Pulse-Burst PIV quantifies the spatial and temporal variations in the baseline flow, important information in our multiphase experiments.

Transient Wake ($M_s = 1.32$, $M_2 = 0.43$)

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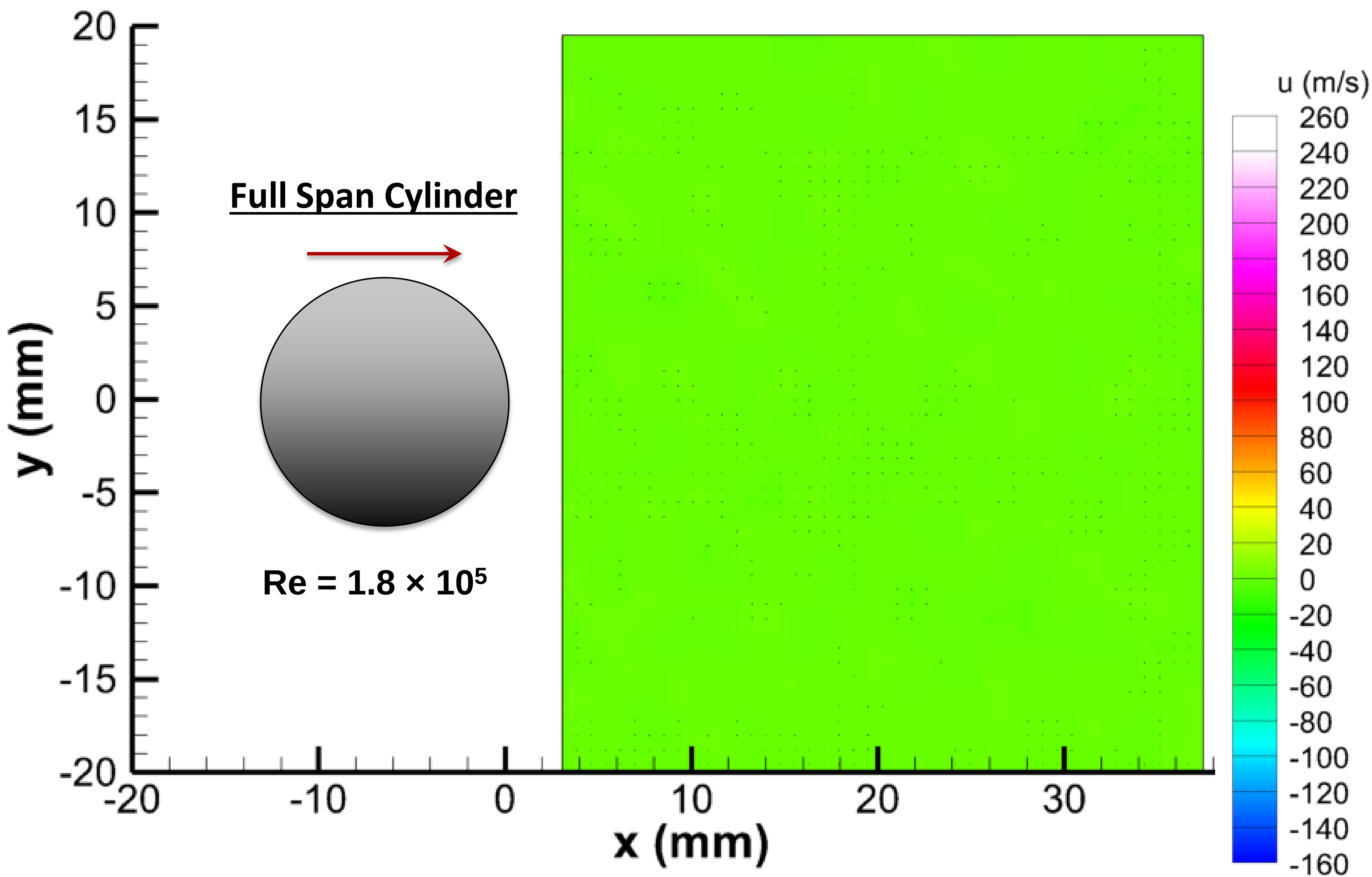
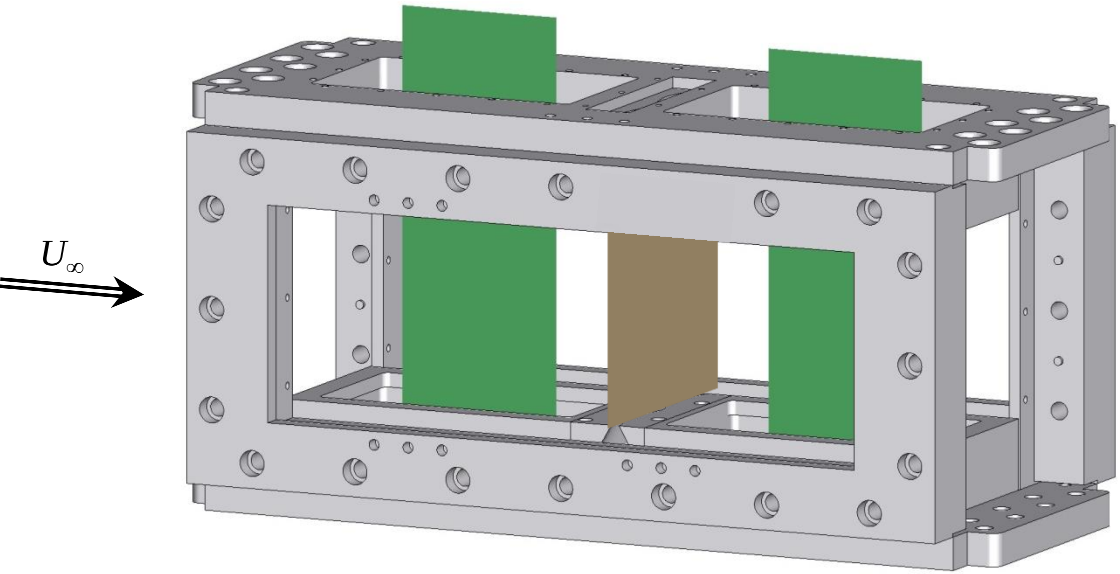
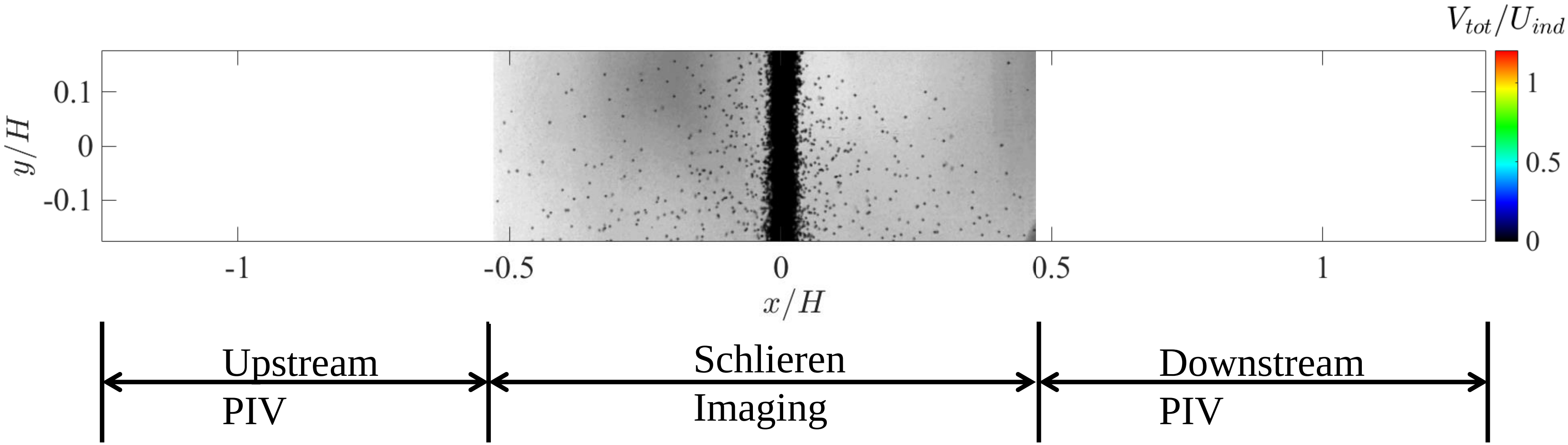


Particle Curtain Pulse-Burst PIV



- Data capture gas jetting through the curtain and angled shock waves
- Control volume analysis ongoing to back out the particle drag



Conclusions

1. MST is available to test the dynamics of dense gas-solid mixtures subjected to shock-induced flows.
    a. Diagnostic capabilities for quantitative measurements of solid particles and surrounding gas
2. In comparison to dilute flows, particle dispersal is greatly increased by dense volume fraction effects.
    a. New models by Professor Balachandar's group at UF capture the key drag terms responsible.
3. Volume fraction profiles show asymmetric dispersal.
    a. Work is ongoing with UF to understand profile shapes

Future work will focus on reacting particles.

Acknowledgements

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Questions?