SAND2016-1465PE

Pulse-Burst PIV in High-Speed Flows

Steven Beresh, Justin Wagner, Ed DeMauro,
John Henfling, Rusty Spillers, and Paul Farias
Sandia National Laboratories
Albuquerque, NM

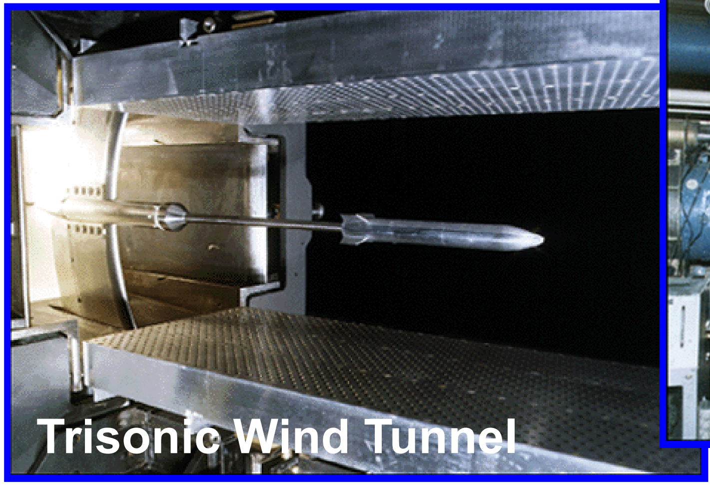
Michigan State University Seminar
February 25, 2016

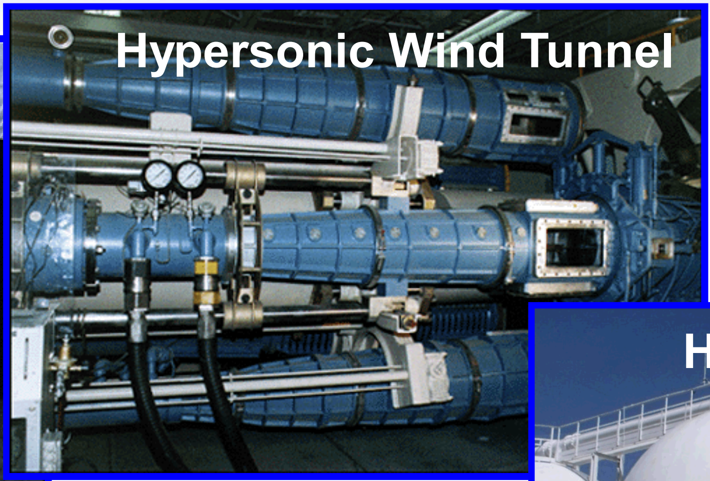
National Nuclear Security Administration

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Experimental Aerosciences Facility





Trisonic Wind Tunnel (TWT)

- Mach 0.5 – 3
- Gravity bombs, missiles

Hypersonic Wind Tunnel (HWT)

- Mach 5, 8, 14
- Re-entry vehicles, rockets

High-Altitude Chamber (HAC)

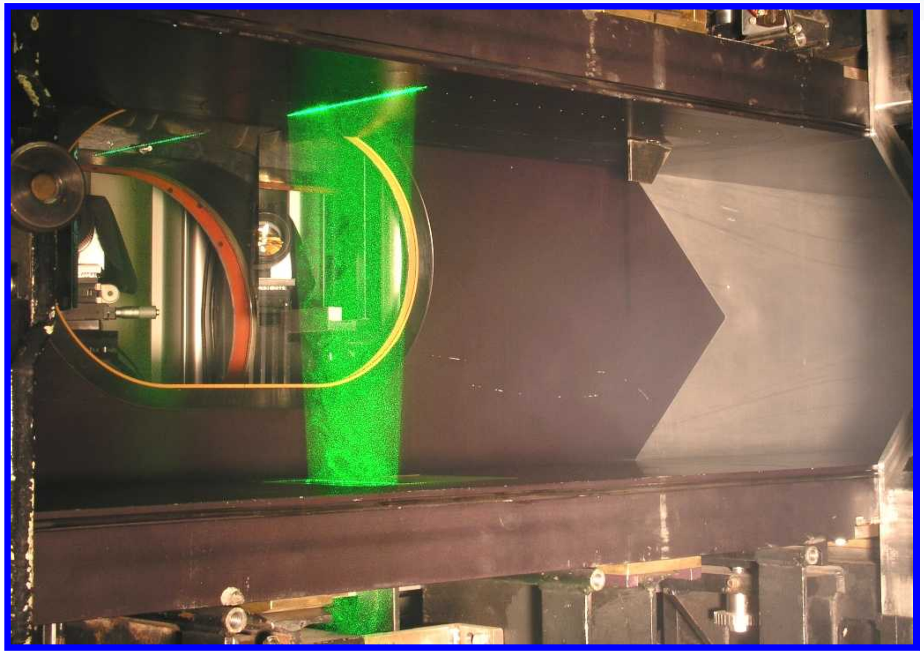
- Satellite components

Multi-Phase Shock Tube (MST)

- Explosives research

Much of the focus in our laboratory is on advanced diagnostics.

Data acquisition ~1950



Data acquisition ~21st century

Experimental data are necessary to develop and validate Sandia's modeling and simulation capability.

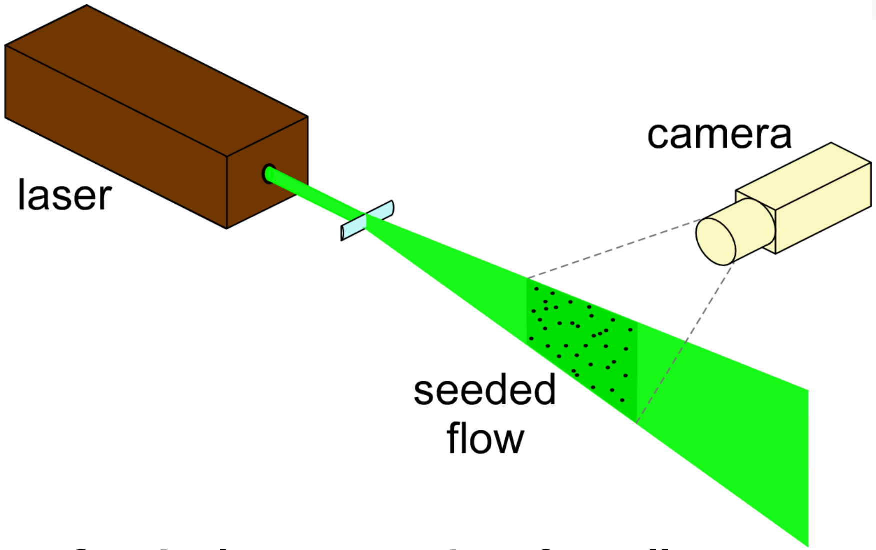
- Provide scientific discovery as well as validation data.

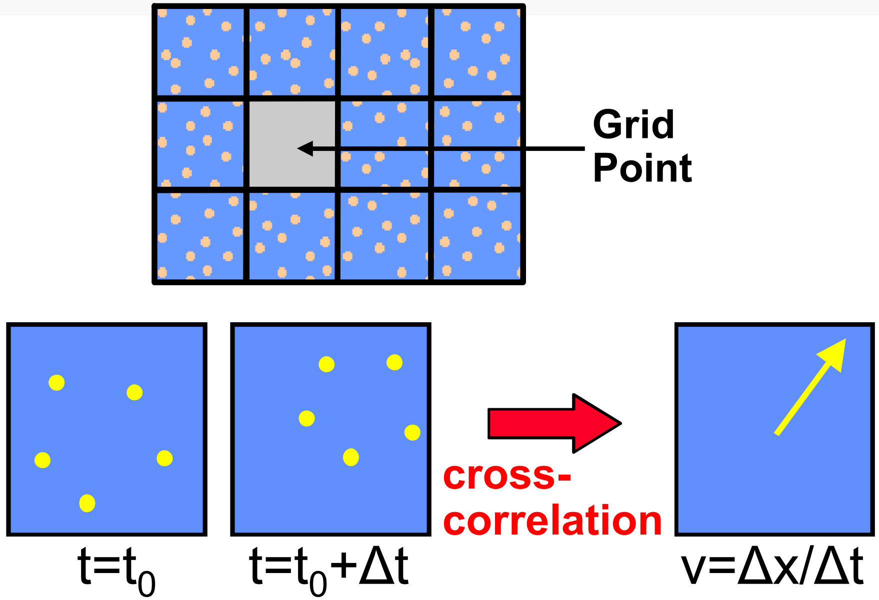
High-fidelity flowfield data are needed, not just aerodynamic coefficients and surface measurements.

- Adapt new diagnostic technologies to aero applications.

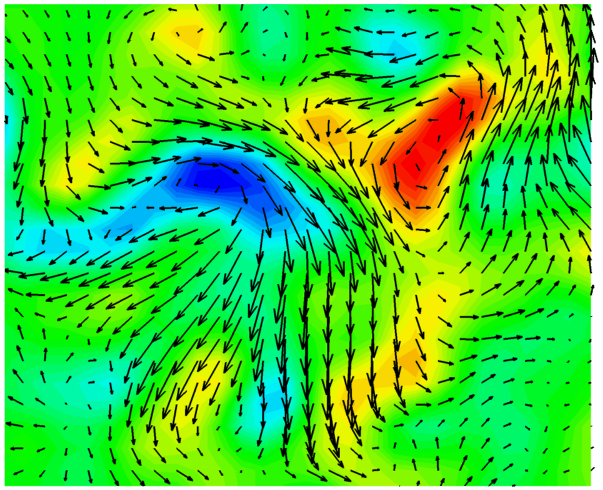
Sandia National Laboratories

What is Particle Image Velocimetry (PIV)?





- 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



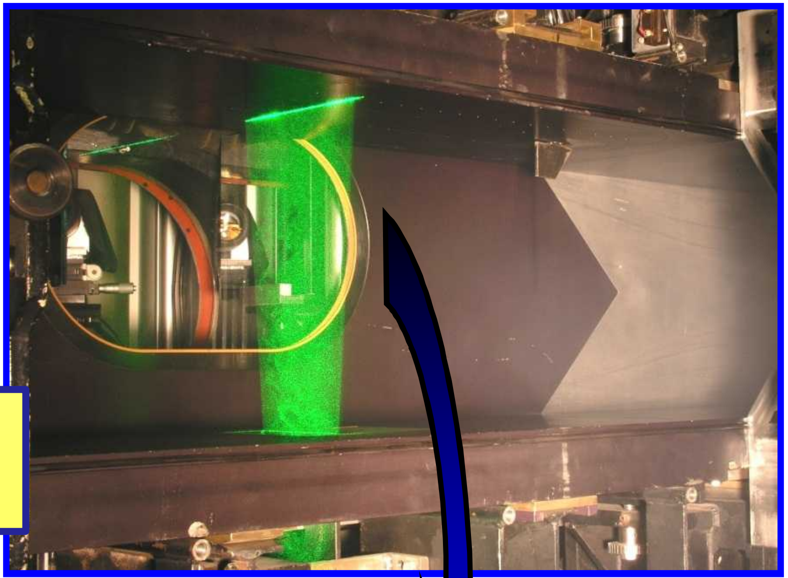
Sandia National Laboratories

Particle Image Velocimetry (PIV) has emerged as our most widely used measurement.

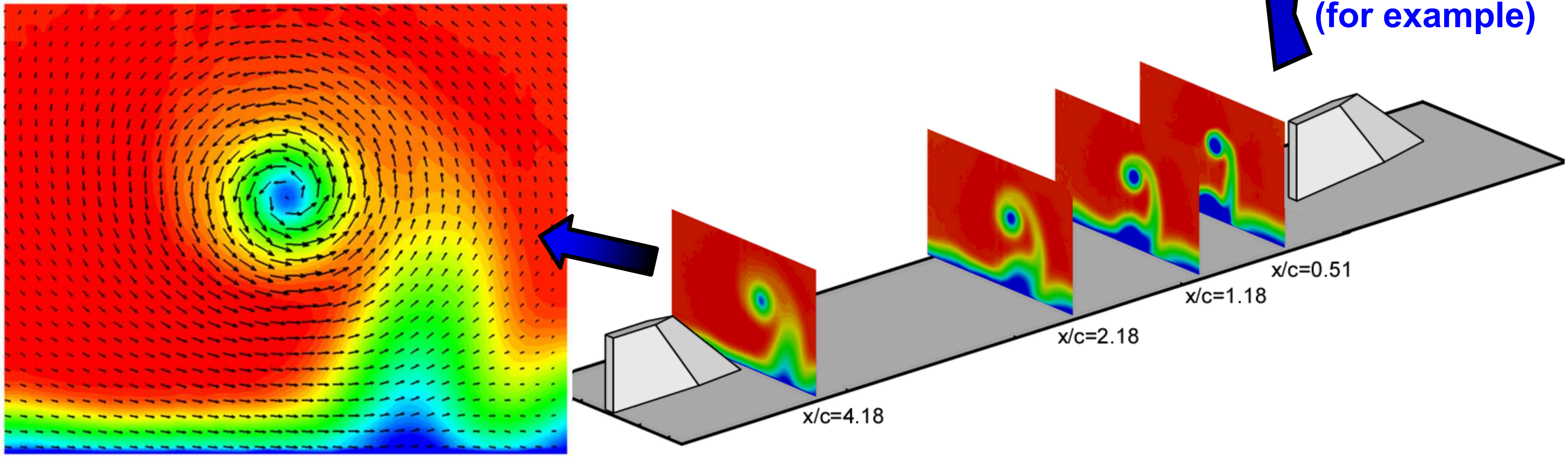
PIV data have been key to improving our understanding of the physics our codes must simulate.

- Can be reduced to mean velocity fields, turbulence quantities, flow structures, etc.
- Combined with a force balance or pressure sensors, it can explain aerodynamic forces.

But conventional PIV does not provide the time component to flow velocimetry.



(for example)



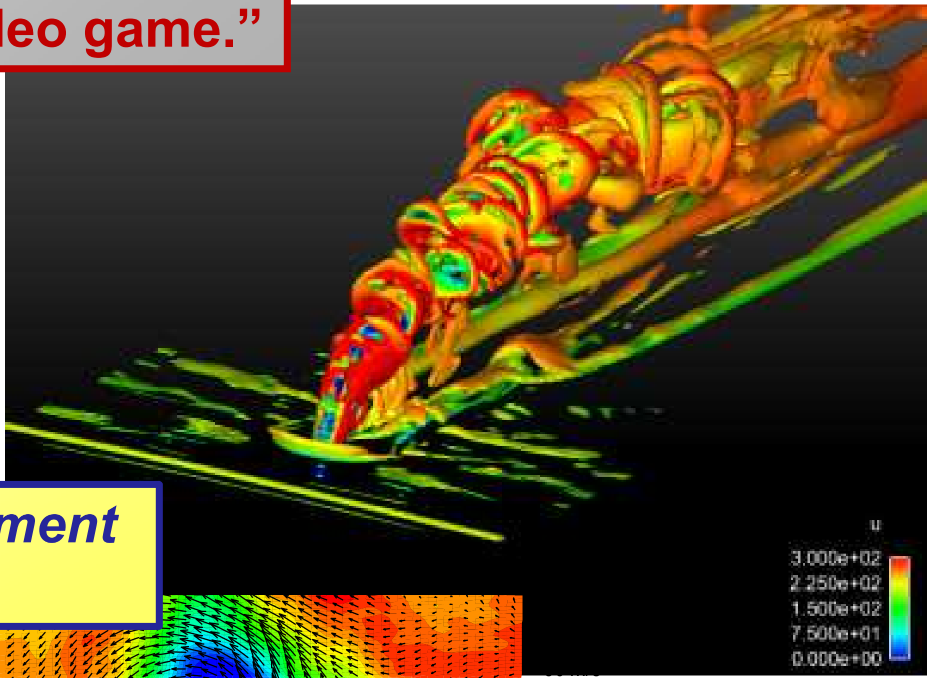
PIV Data for CFD Validation

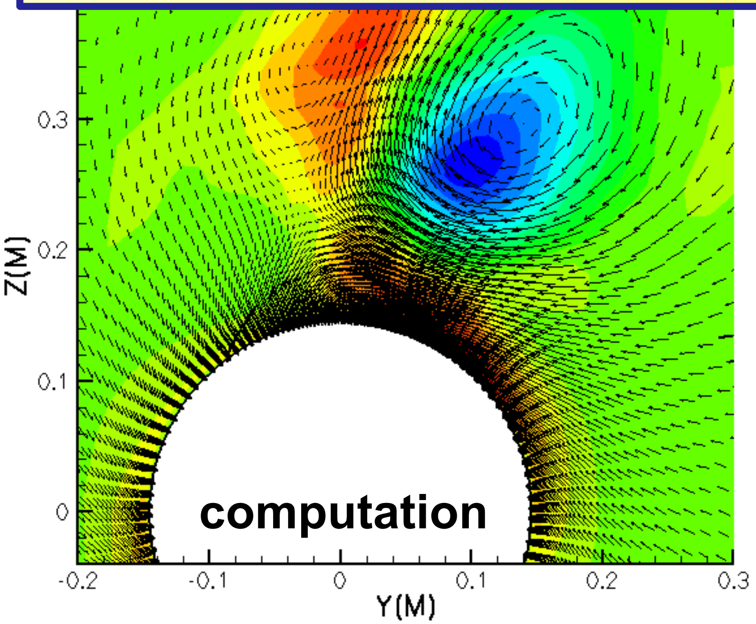
"Without validation, CFD is just a video game."

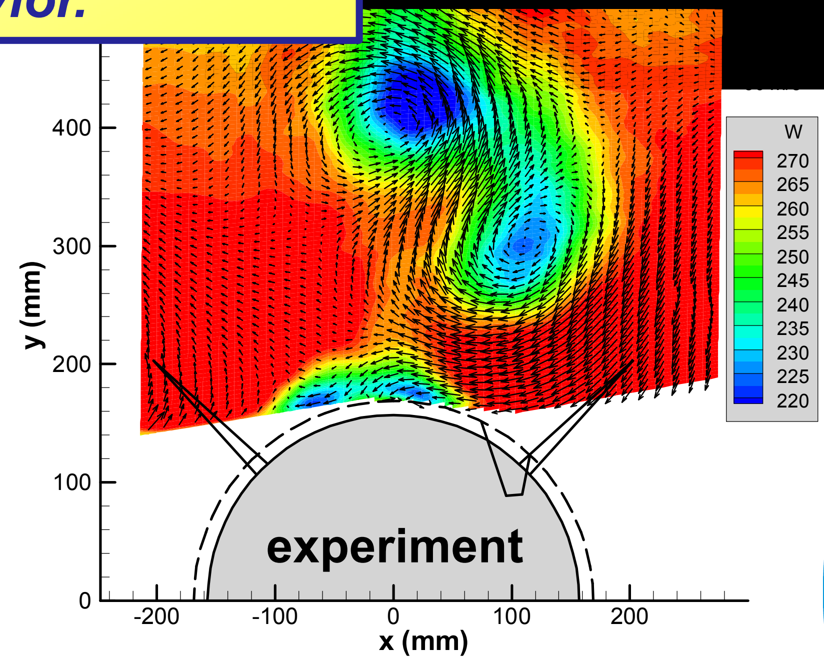
The physical models in our CFD codes must be shown to produce accurate results before we may use them to design flight vehicles.

Our PIV experiments provide key validation data.

Recent applications require development of models of unsteady behavior.







Sandia National Laboratories

Time-Resolved PIV (TR-PIV)

Provide temporally correlated velocity fields – that is, PIV movies.

The current state-of-the-art in TR-PIV:

- Diode-pumped solid-state (DPSS) lasers
  - Typically 1-10 kHz (16 kHz max)
  - Only a few mJ at high kHz
- Fast CMOS cameras to 20 kHz at 1 Megapixel
- Works fine for low-speed flows and small field of view.

This isn't good enough for a high-speed wind tunnel:

- Faster repetition rates for briefer time scales.
- Higher energy required.
  - Scatter light off smaller particles
  - Expand laser sheet for larger field of view

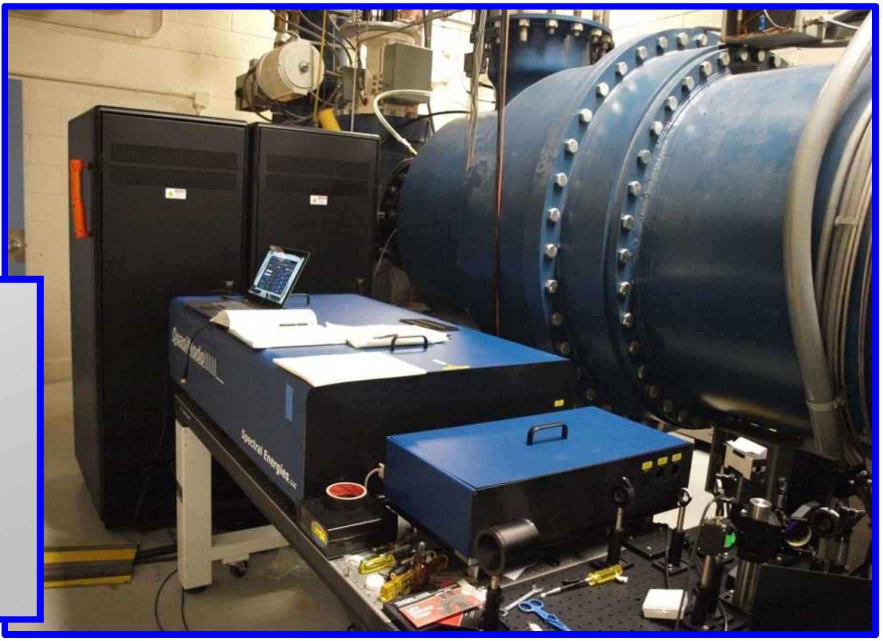
A pulse-burst laser is necessary.

Sandia National Laboratories

Pulse-Burst Laser

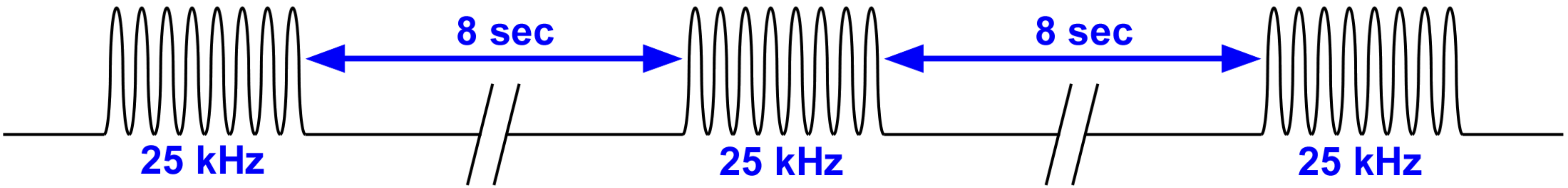
A pulse-burst laser allows high energy and high repetition rates.

But a very low duty cycle.



Pulse-Burst Laser:

- Manufactured by Spectral Energies, LLC
- Bursts of pulses for 10.2 ms
- Up to 500 kHz of pulse pairs, 20-500 mJ
- But only one burst every 8 sec

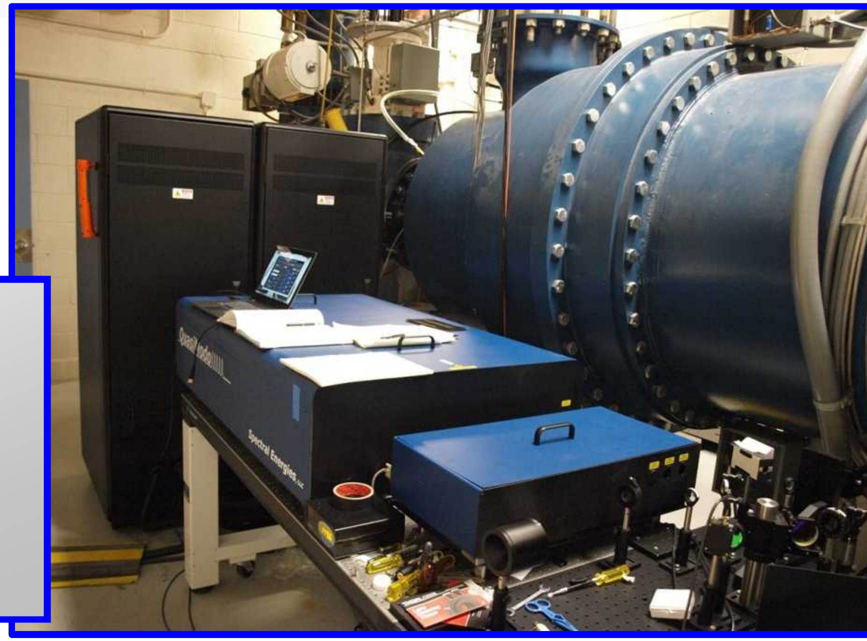


Sandia National Laboratories

Pulse-Burst Laser

A pulse-burst laser allows high energy and high repetition rates.

But a very low duty cycle.

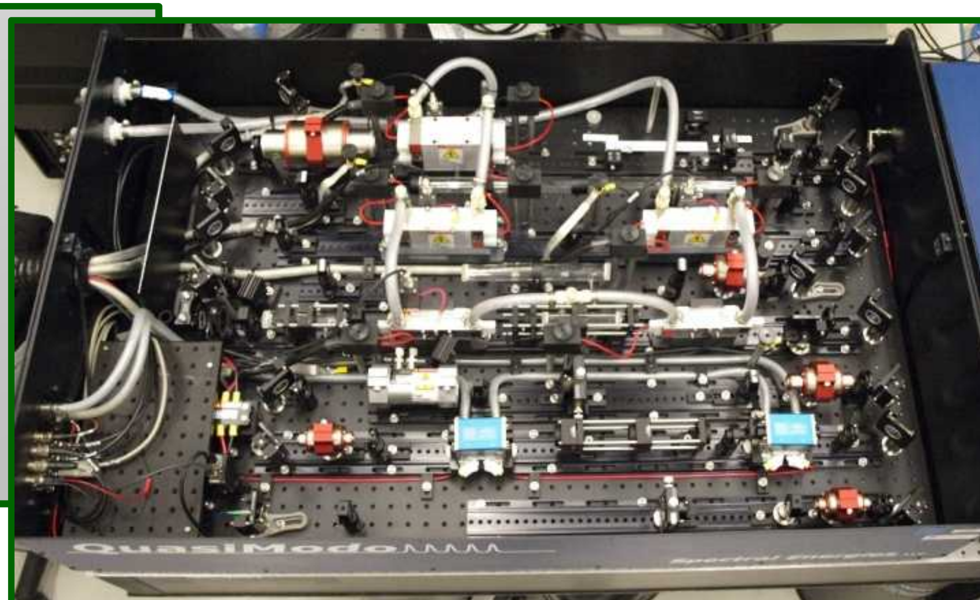


Pulse-Burst Laser:

- **Manufactured by Spectral Energies, LLC**
- **Bursts of pulses for 10.2 ms**
- **Up to 500 kHz of pulse pairs, 20-500 mJ**
- **But only one burst every 8 sec**

Laser Design:

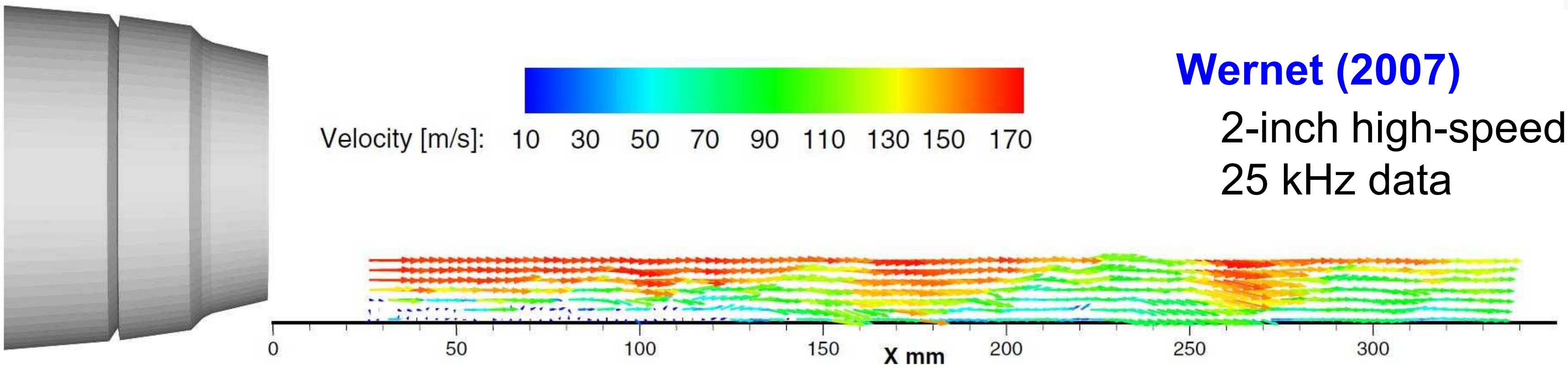
- **CW diode laser at 1064 nm**
- **Sliced by combined acousto-optic and electro-optic modulators**
- **Four diode-pumped amplification stages**
- **Four flashlamp-pumped amplification stages**



A Brief History of Pulse-Burst PIV

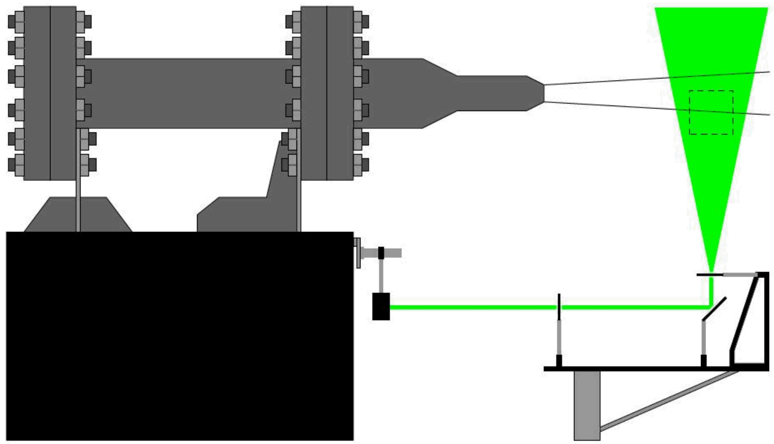
Wernet (2007)

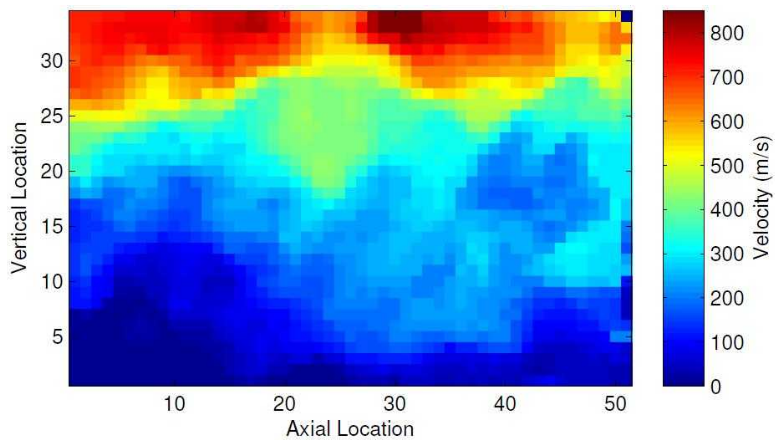
2-inch high-speed jet
25 kHz data



Brock et al (2014)

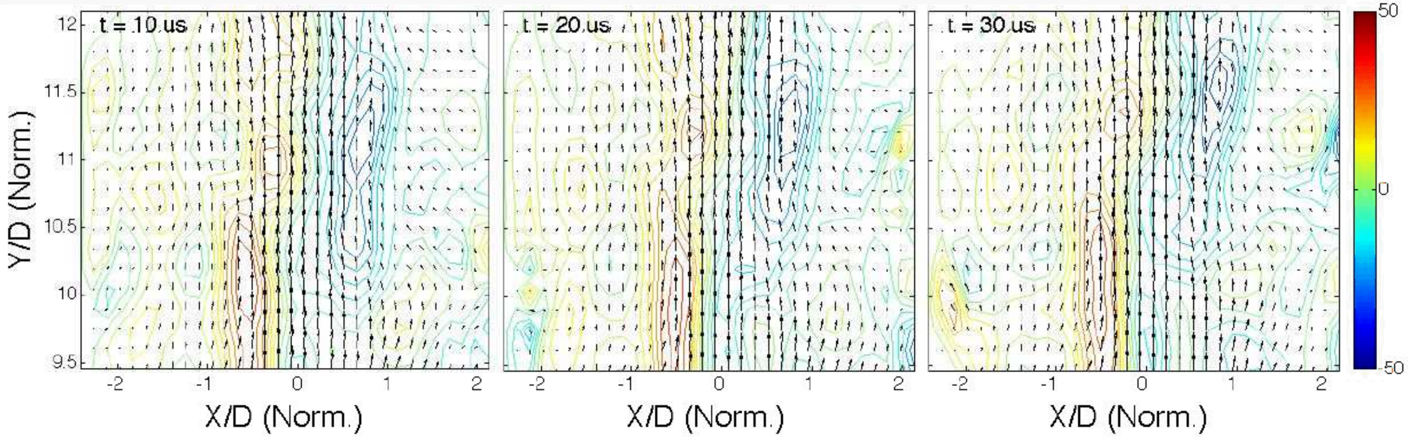
1 MHz data in a supersonic jet
But only 13 images of poor quality





Sandia National Laboratories

A Brief History of Pulse-Burst PIV



Miller et al (2013, 14)

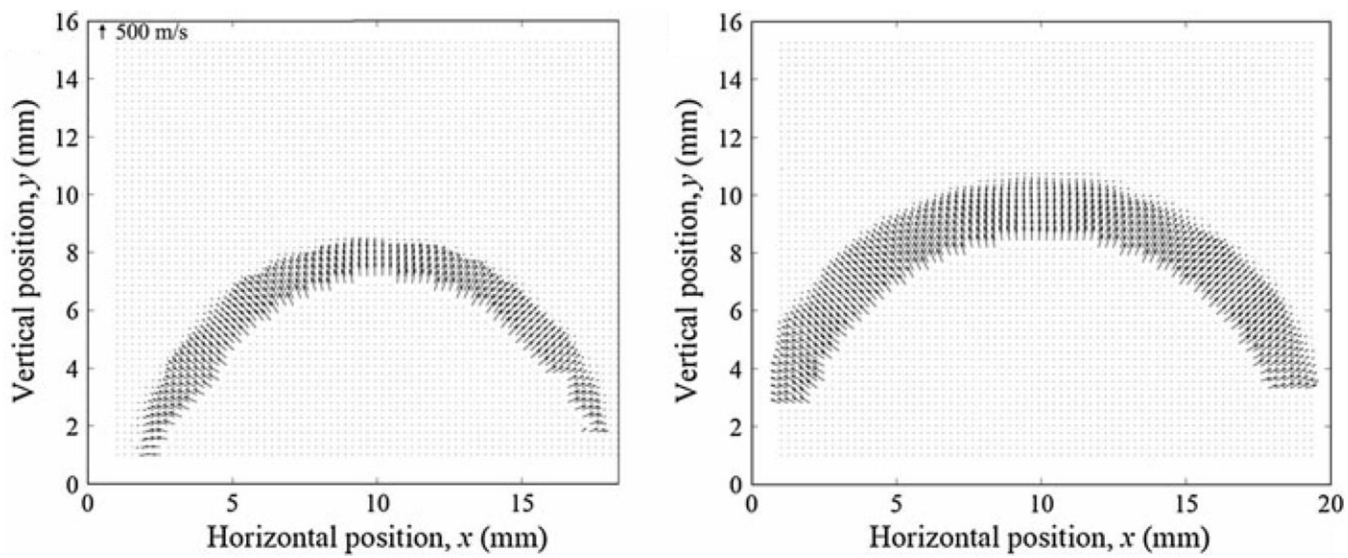
First at 10 kHz, then 100 kHz

4.6 mm jet at Mach 0.3

Murphy and Adrian (2011)

Chain together 8 Nd:YAG's

300 kHz of a blast wave



Our work is the first application of pulse-burst PIV in a ground-test facility.

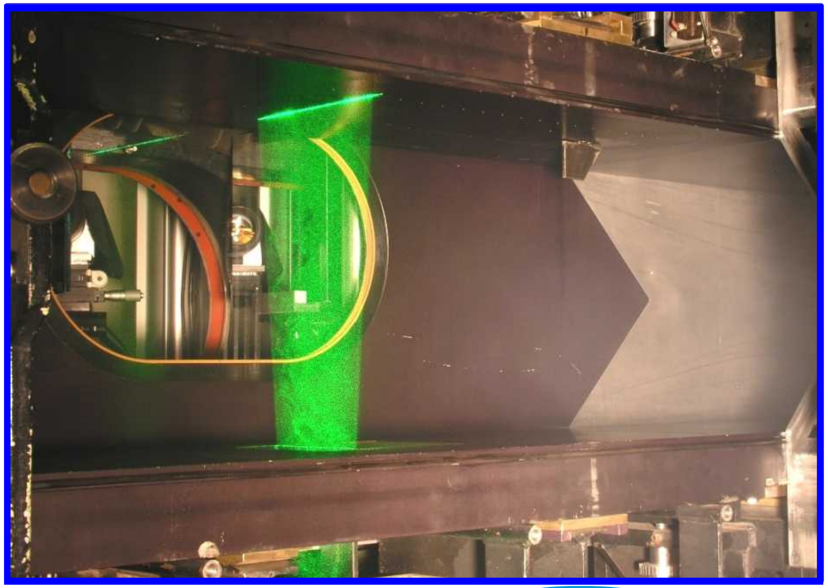
Trisonic Wind Tunnel (TWT)

Technical Characteristics

- Blowdown to atmosphere
- M_∞ = 0.5 - 1.3, 1.5, 2.0, 2.5, 3.0
- Re = 3 - 20 × 10^6 /ft
- Run times: 20 - 120 seconds
  at 20 - 30 minute intervals
- 12 × 12 inch test section

Transonic Test Section

- Multiple configurations
  - 4 porous walls
  - 3 porous & 1 solid wall (half-body models)
  - 2 porous walls, 2 solid walls (imaging)
  - 4 solid walls **Typical PIV Configuration**
- Test section enclosed in pressurized plenum



Sandia National Laboratories

The Particle Seeder

Particles generated from mineral oil and delivered into the TWT stagnation chamber.

In situ measurements of the particle size show $d_p = 0.7 - 0.8\ \mu m$.

Is the particle response time good enough?

Stokes Number = 0.04

- St < 1 is acceptable
- St < 0.1 is very good

particle response is excellent

Sandia National Laboratories

The Particle Seeder

Corona ViCount smoke generator:

- Particle diameter 0.2-0.3 μm
  - Generated from mineral oil
- Placed in pressure vessel to drive particles into stagnation chamber.

Particle Injection

- Deliver particles upstream of the TWT flow conditioning.
- Insert tubes slotted with holes to deliver particles into TWT.

The Particle Seeder

Corona ViCount smoke generator:

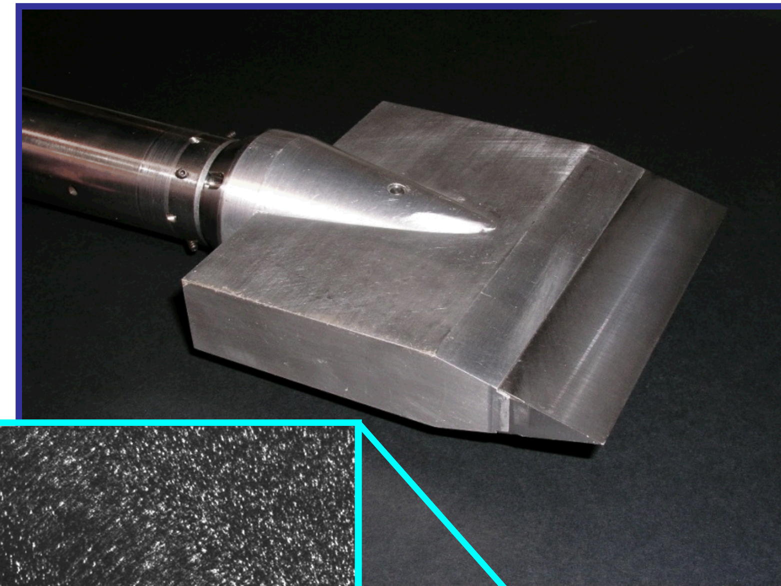
- Particle diameter 0.2-0.3 μm
  - Generated from mineral oil
- Placed in pressure vessel to drive particles into stagnation chamber.

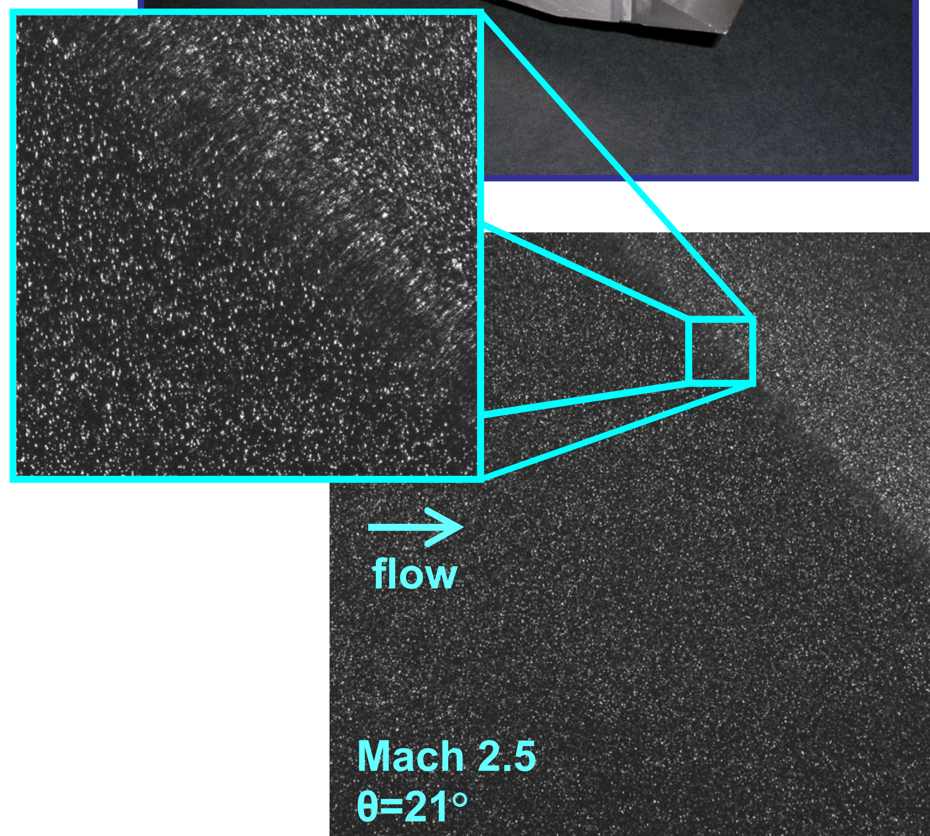
Particle Injection

- Deliver particles upstream of the TWT flow conditioning.
- Insert tubes slotted with holes to deliver particles into TWT.

Test the particle response across a shock generated by a 15° wedge.

- Machs 1.5, 2, and 2.5
- Pitch wedge to get different shock angle θ





Particle Response

Over a range of Machs and shock angles:

τ_p = 1 - 2 μs

d_p = 0.7 – 0.8 μm

Particle diameter is larger than the manufacturer specification.

- Probably due to agglomeration when the smoke is ducted to the stagnation chamber.

Is this particle size and response time good enough?

What is a typical turbulent velocity gradient?

- $(du/dx)_{max} \approx 3\%$ of the interrogation window
- At Mach 2.5, this yields **τ_f = 50 μs**

Stokes Number = τ_p / τ_f = 0.04

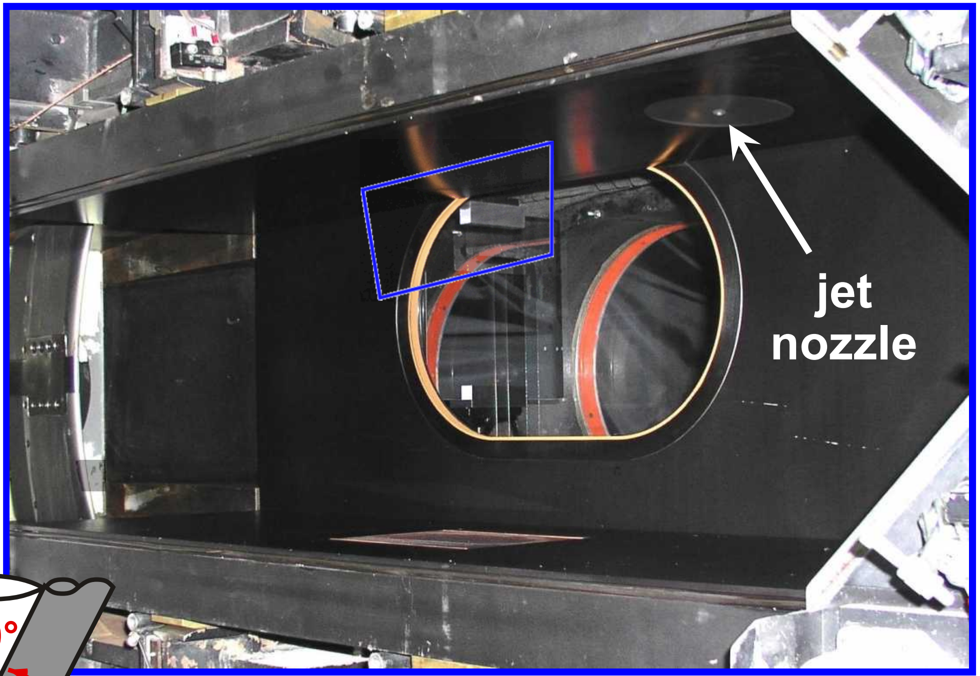
- $\tau_p / \tau_f < 1$ is acceptable
- $\tau_p / \tau_f < 0.1$ is very good

particle response is excellent

Sandia National Laboratories

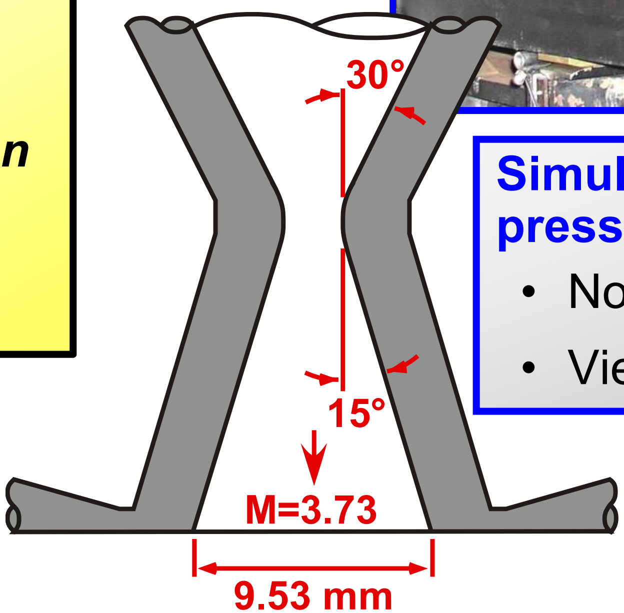
Our First Test Application

Supersonic Jet in Transonic Crossflow



Spin rockets control vehicle rotation.

An interaction between the jet plume and the fins alters the aerodynamics.

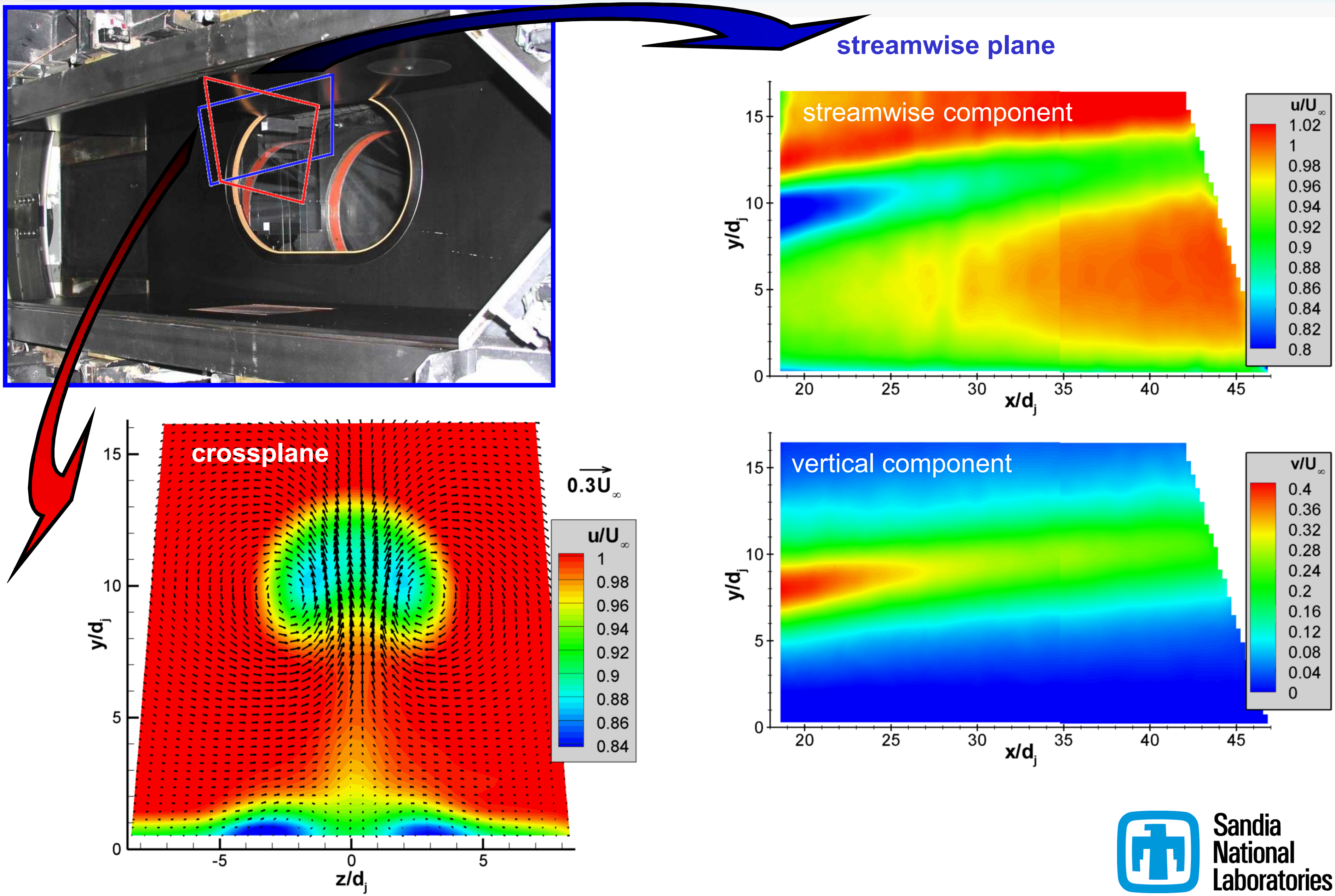


Simulate the spin rockets with high pressure air through a nozzle.

- Nozzle mounts on top wall of TWT.
- View the far-field of the interaction.

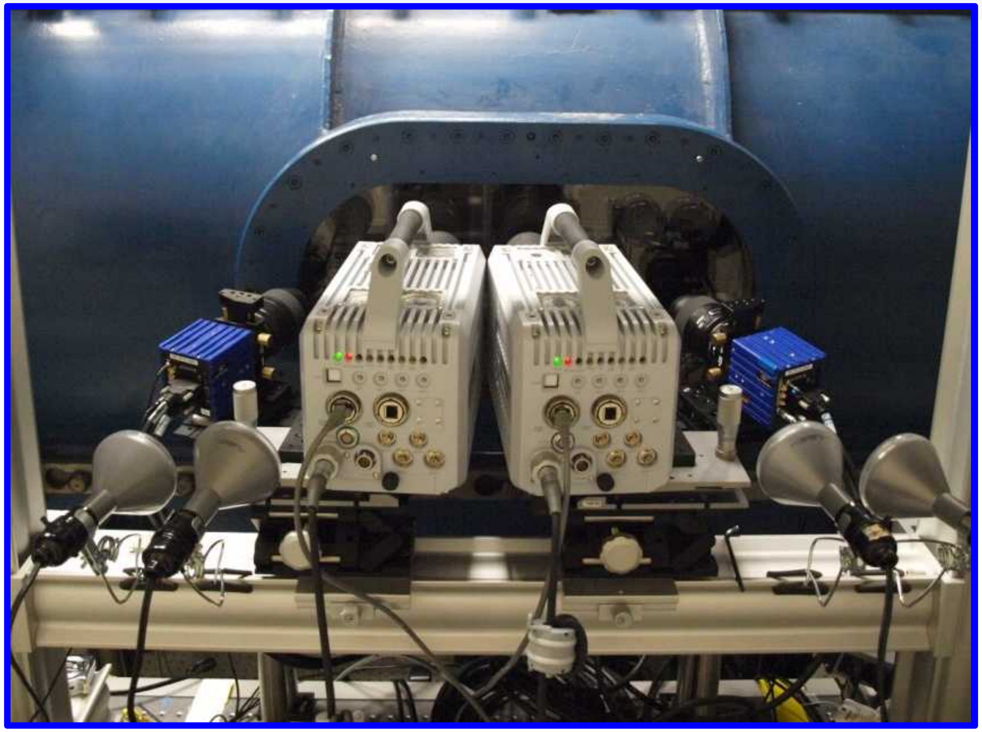
Sandia National Laboratories

We have a lot of previous data on this configuration.



Sandia National Laboratories

High-Speed Cameras



High-Speed Cameras

- Photron SA-X2
- Two side-by-side for wider field of view
- Two-component PIV

Camera Orientation

- Cameras canted at 5° due to large size of camera body.
- Max error in streamwise component is < 2%.

Present experiments:

- 50 kHz framing rate
- 640 × 384 pixels
- Frame straddle pulse pairs

Present laser settings:

- 25 kHz of pulse pairs
- Δt = 2.00 μs
- 2.5 ms burst, 175 mJ/pulse

Sandia National Laboratories

Field of View

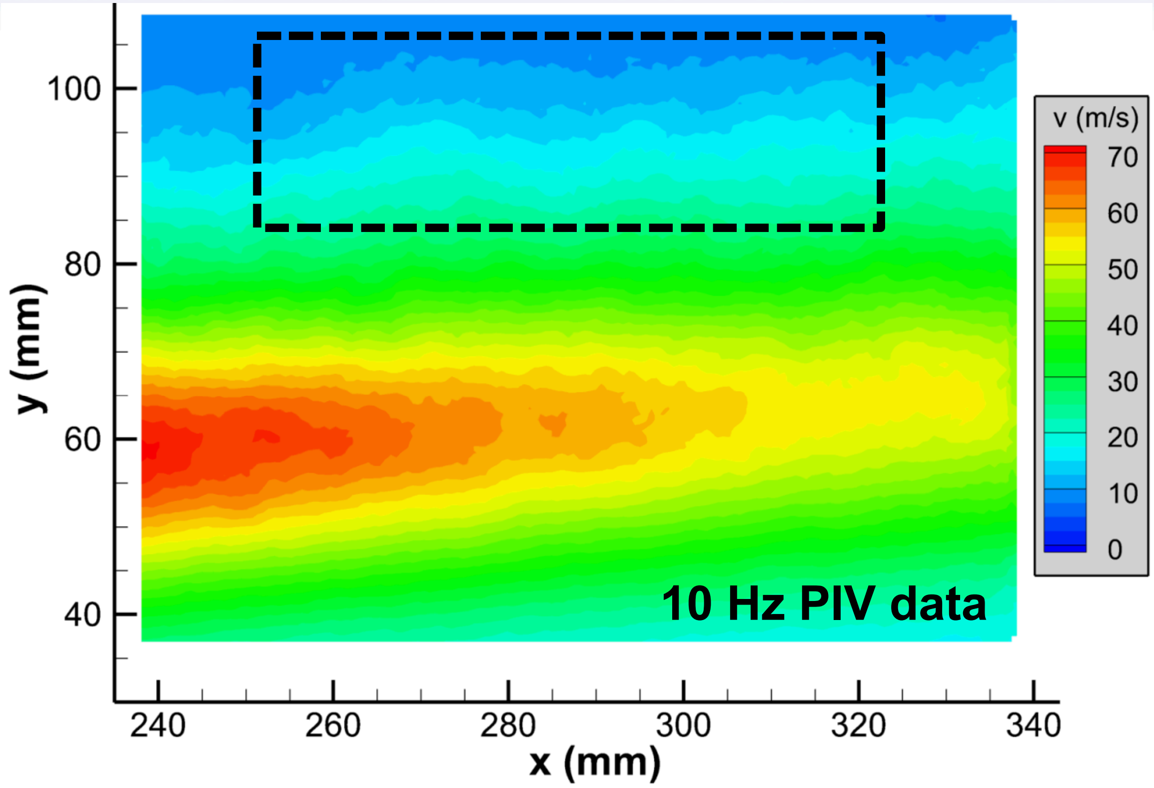
Combined field of view:

Image turbulent eddies at the outward mixing layer.

Today's data at J=8.1

Far from jet core and sparser turbulent eddies.

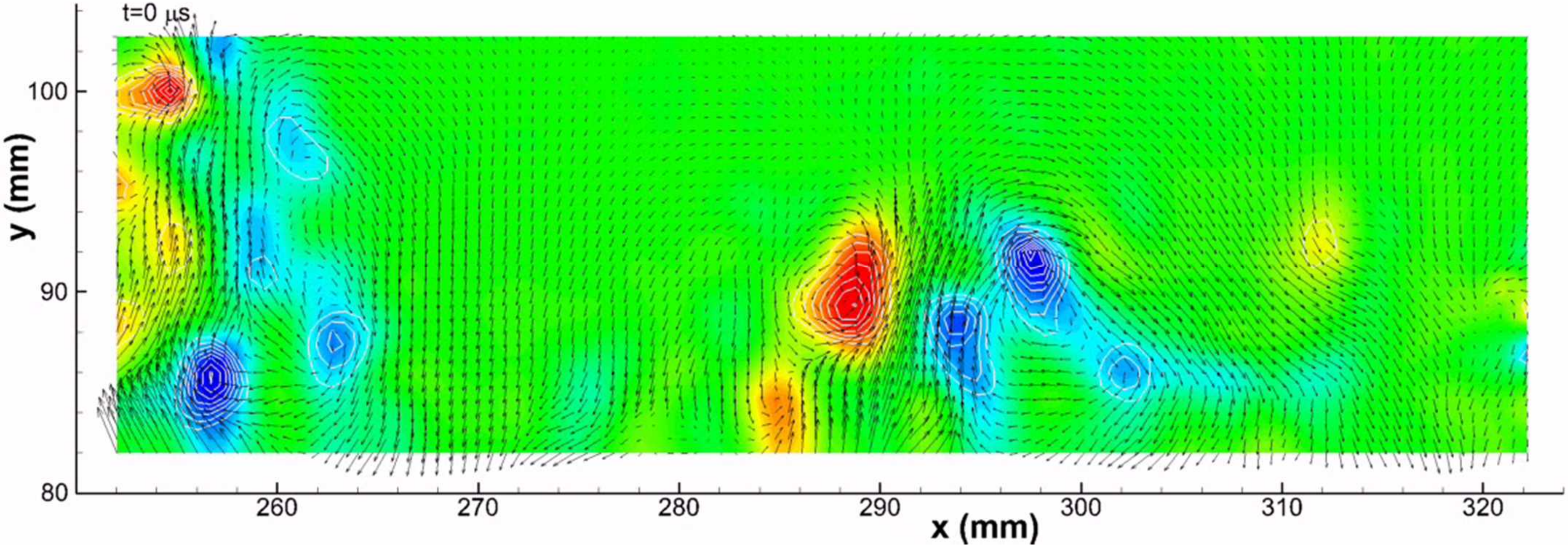
Makes data more visually interpretable.



Sandia National Laboratories

A Sample Pulse-Burst PIV Movie

This is a 2.5 ms movie with 63 vector fields acquired at 25 kHz.



(920)

Velocity fluctuations are shown.

Final pass uses 24 × 24 pixel interrogation windows.

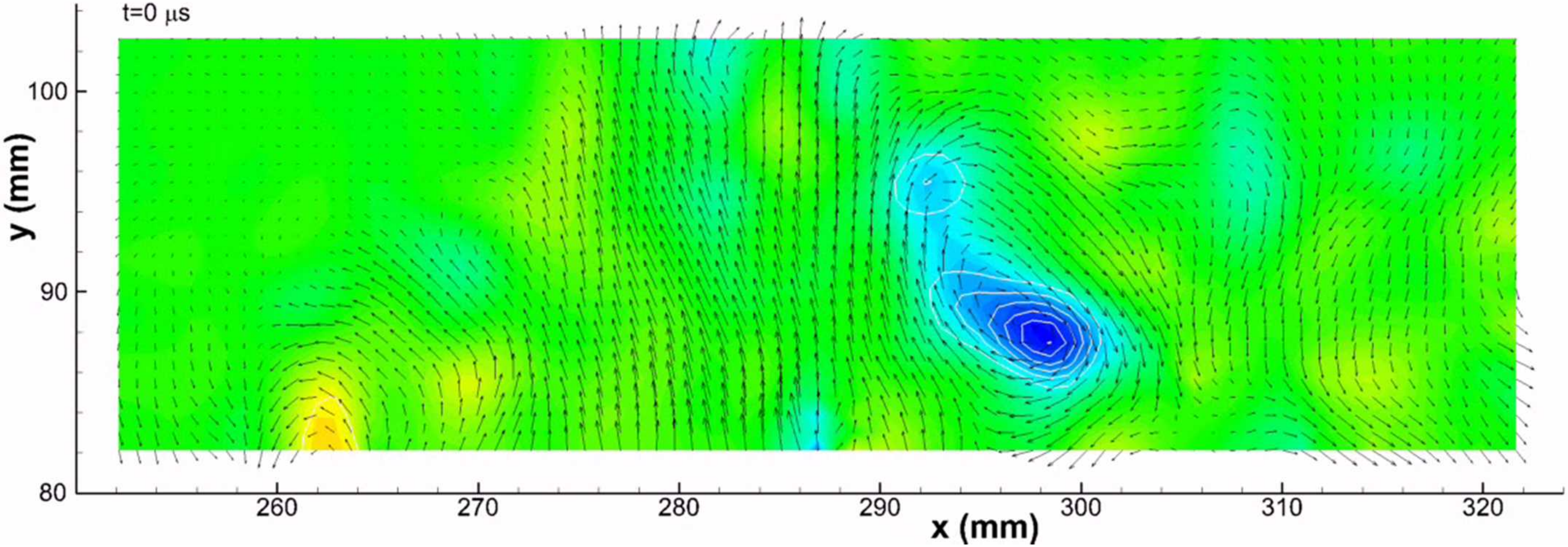
Counter-rotating eddies convect past, typically in pairs.

- **About 8-10 mm separating eddies in a pair**
- **About 20-30 mm separating pairs**

Sandia National Laboratories

Increase the Frequency with Double Exposures

Run the laser at 50 kHz, double-exposing pulse pairs on single images.



(1700)

Process using autocorrelations.

This works because there's no directional ambiguity.

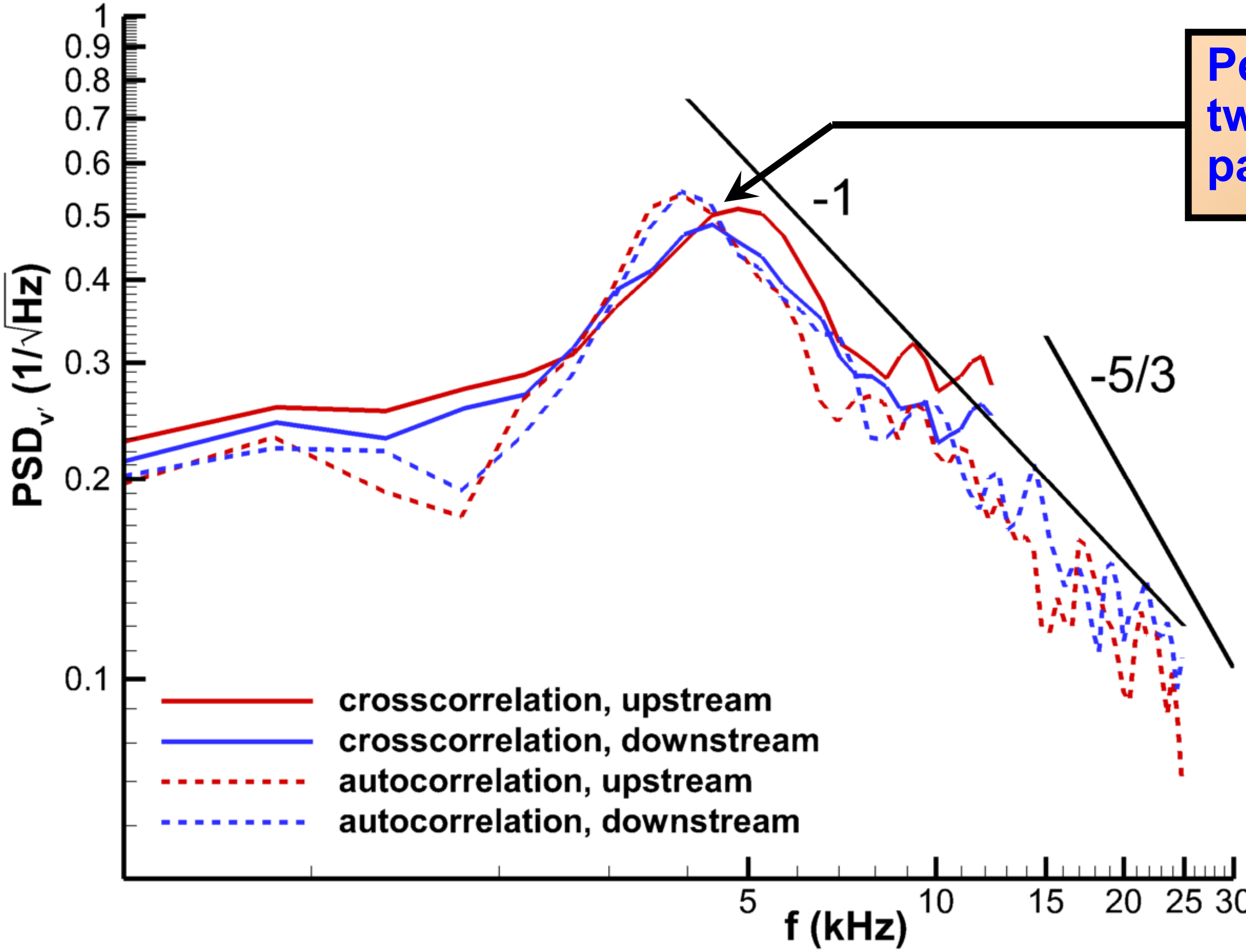
Final pass is 32 × 32 pixel due to increased noise.

Increased framing rate helps visualize vortex coalescence and decay.

Single eddies can become stable and long-lived.

What else can we do with Pulse-Burst PIV?

Compute power spectra from the time signal of each vector.



Peak corresponds to about twice the spacing of eddy pairs.

Inertial subrange should show -5/3 slope.

- **Does not begin until about 20-30 kHz.**

But we do see an apparent "-1" power law.

- **Historically elusive and controversial for velocity fields.**
- **Or is it a measurement artifact?**

Assembled from 53 bursts of 25 kHz data, 25 bursts of 50 kHz data.

Sandia National Laboratories

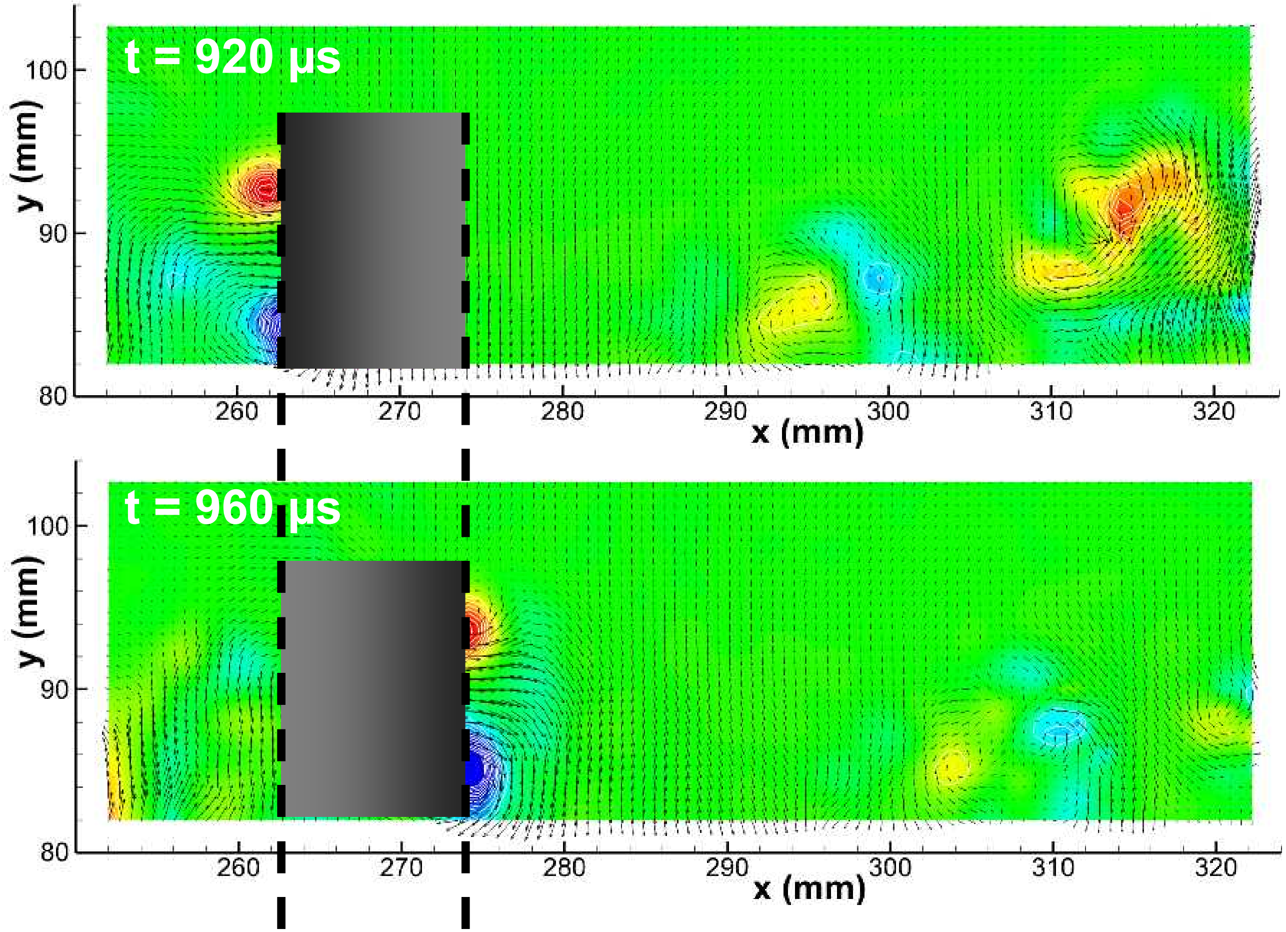
Velocity Supersampling

Use the supersampling algorithm of Scarano and Moore (2012).

"Pour space into time"

Between successive velocity fields, the flow convects by 16 vector spacings.

Use local convection velocity and Taylor's hypothesis to convert the intervening 15 vectors from space to time.



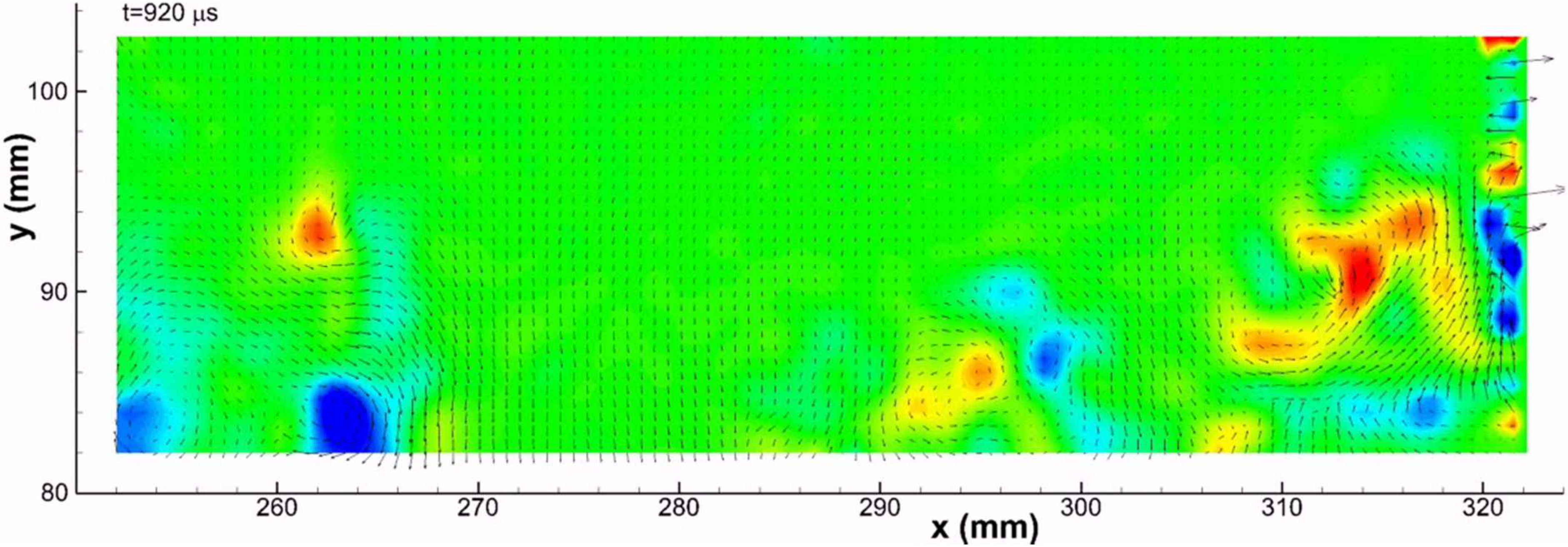
Follow the local streamlines

Interpolate into new intervening vector fields

Sandia National Laboratories

Velocity Supersampling

Use the supersampling algorithm of Scarano and Moore (2012).



We see a much smoother movie with more detail showing vortex rotation and deformation.

End effects are an artifact of extrapolating beyond the field of view.

What does supersampling reveal in frequency space?

Sandia National Laboratories

Velocity Supersampling Power Spectrum

This will extend the power spectrum to much higher frequencies.

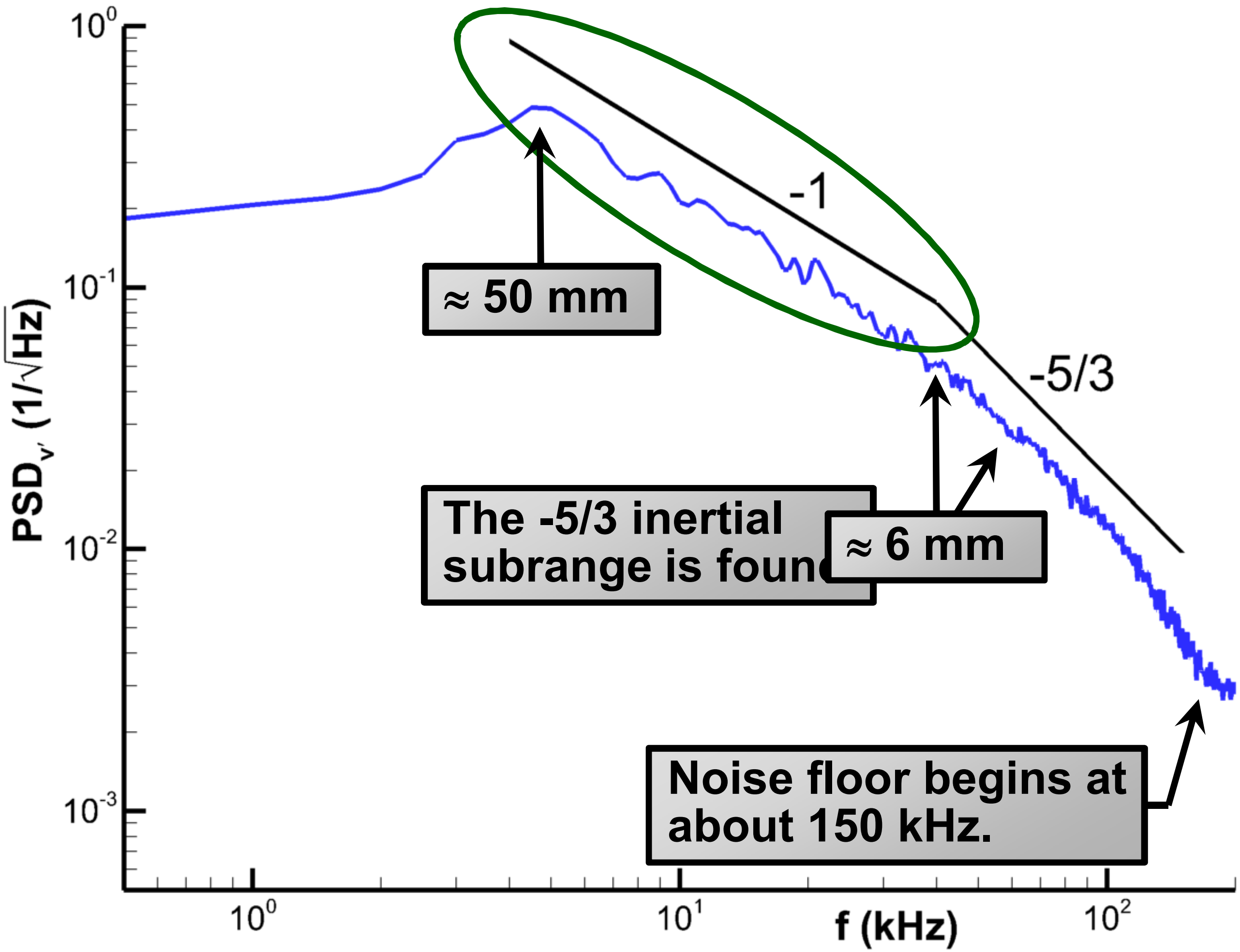
The -1 region is substantiated.

- **Lasts for one full decade.**
- **Any remaining aliasing or denoising effects ≥ 100 kHz.**

Scales of the -1 regime:

- **Pope predicts inertial subrange starts at Λ/6 = 40 kHz ≈ 6 mm.**
- **PIV spatial resolution is about 1 mm.**

Corresponds to the dominant turbulent eddies measured by PIV.



Sandia National Laboratories

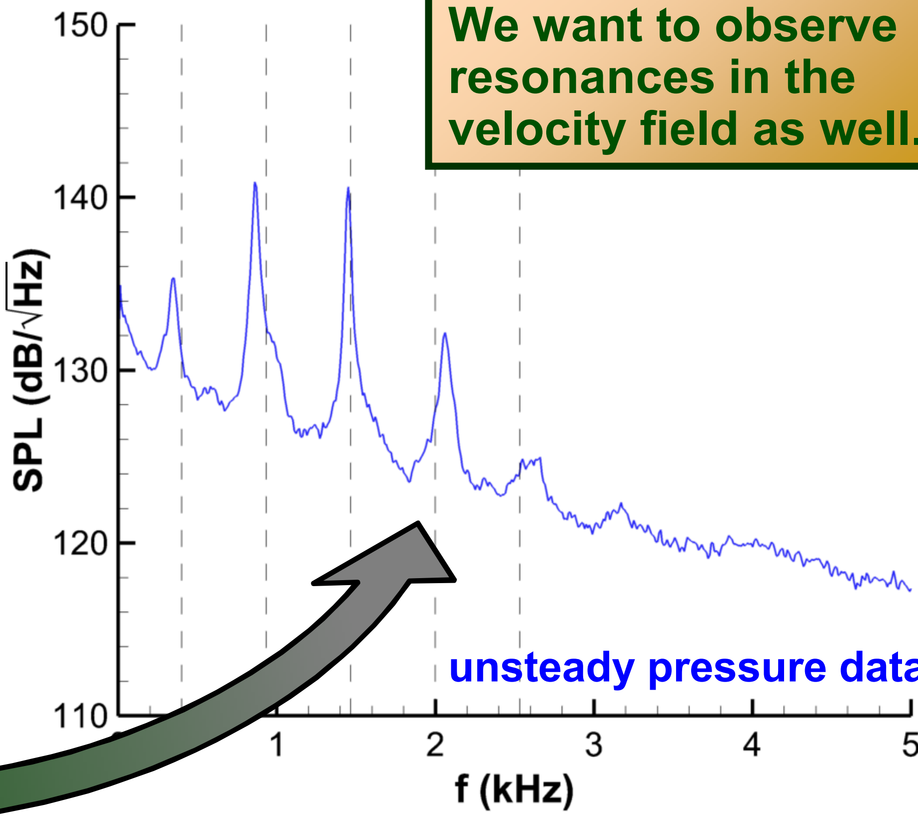
Next Application: The Acoustics of an Aircraft Bay

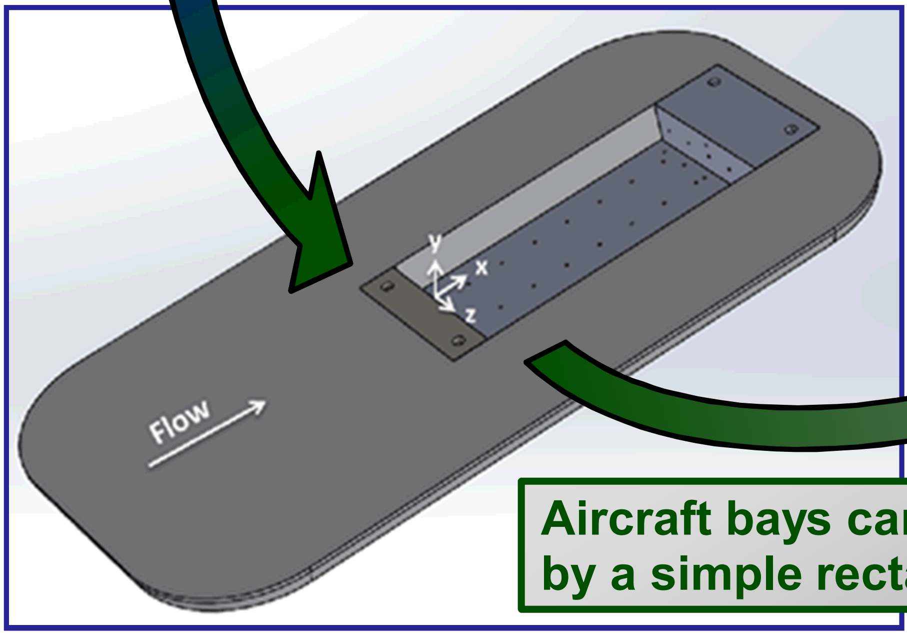
F-35 Weapons Bay
(photo: Lockheed Martin)

Flow over an aircraft bay creates a harsh aeroacoustic environment.

Multiple strong resonance tones.

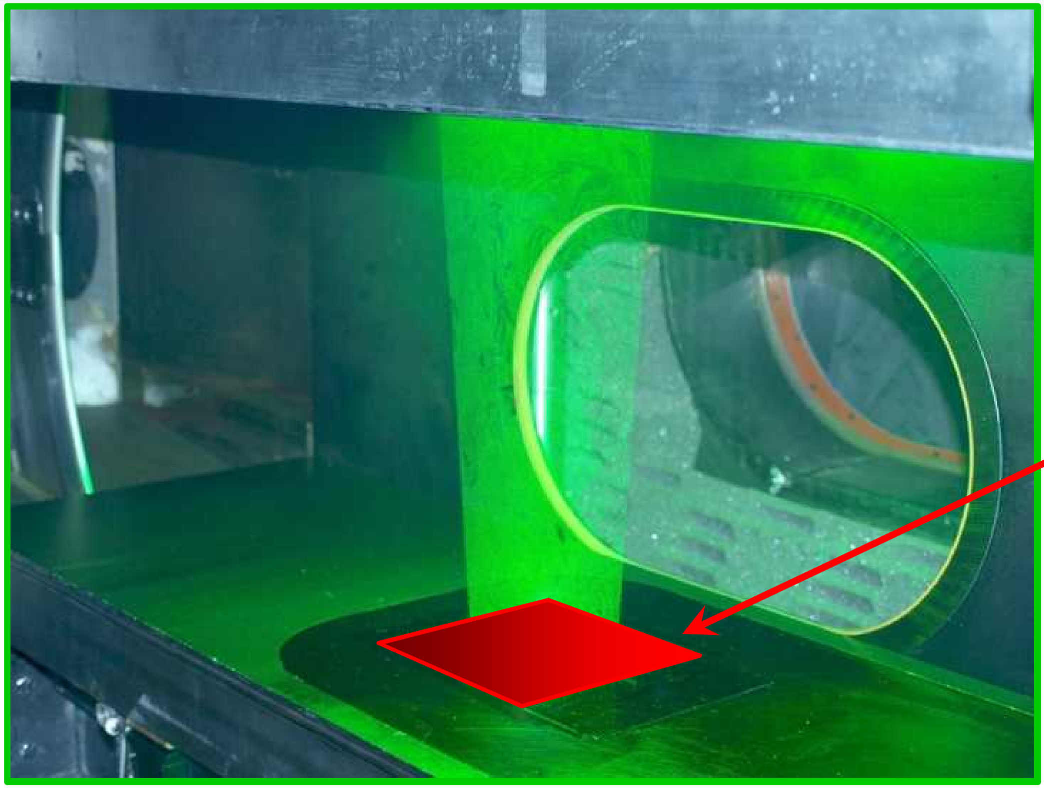
We want to observe resonances in the velocity field as well.

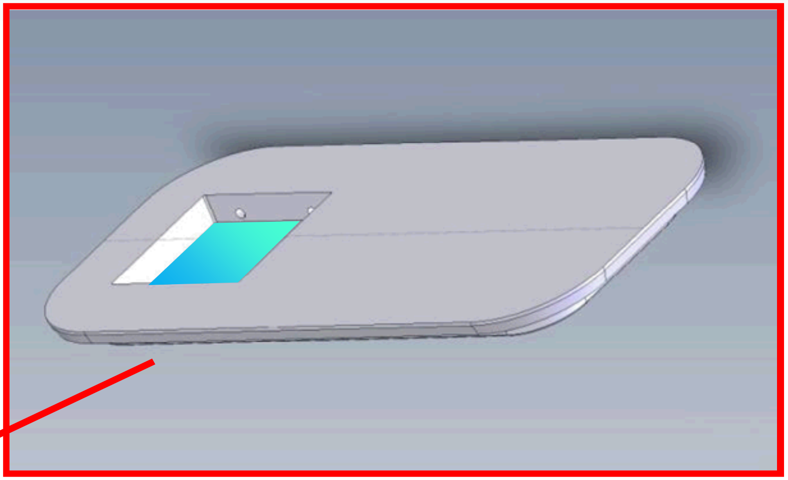




Aircraft bays can be well represented by a simple rectangular cavity.

Cavity Flow





Build a cavity into the test section wall.

Floor is glass for laser access.

Our cavity is a rectangular cutout:

- 5″ long × 5″ wide × 1″ deep

Tested at Mach 0.6, 0.8, and 0.94.

We have much acoustic and PIV data on this flow field.

Sandia National Laboratories

New High-Speed Cameras

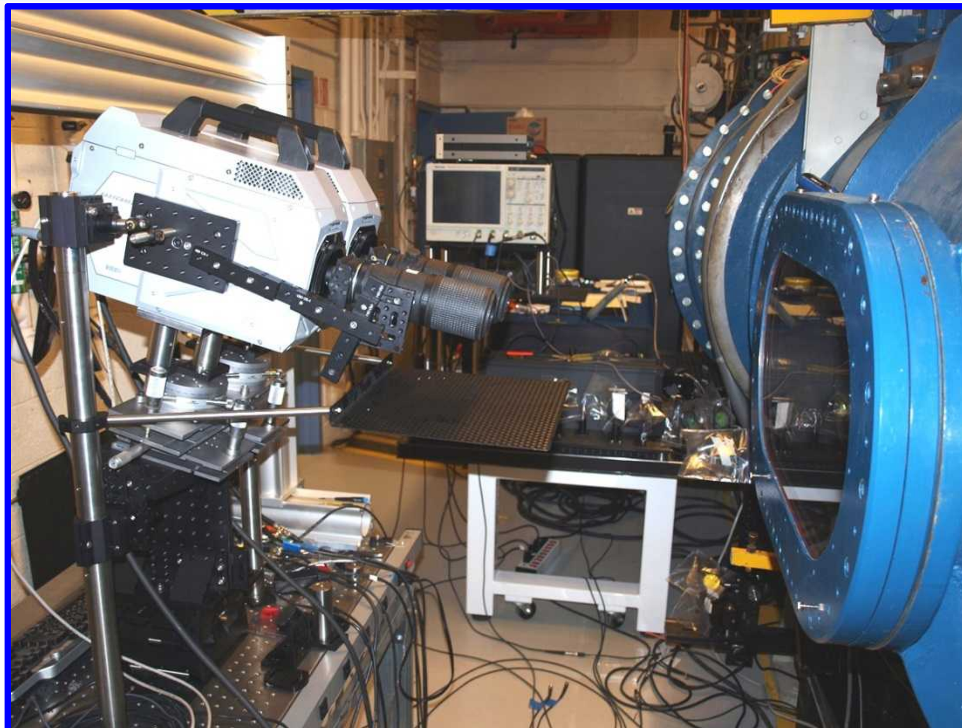
Two *Photron SA-Z's* placed adjacent for dual two-component PIV.

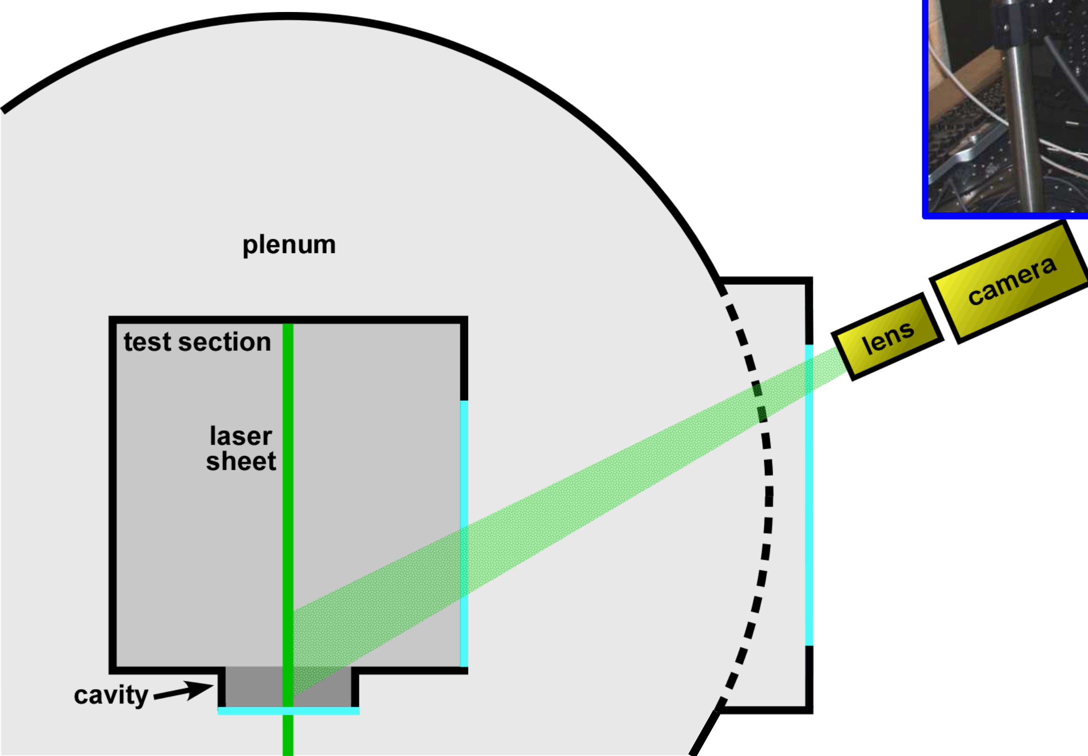
PIV framing rate now 37.5 kHz.

Tip cameras down by 12° to peer into the cavity.

Can reach about 55% depth.

Creates a bias error in vertical component.





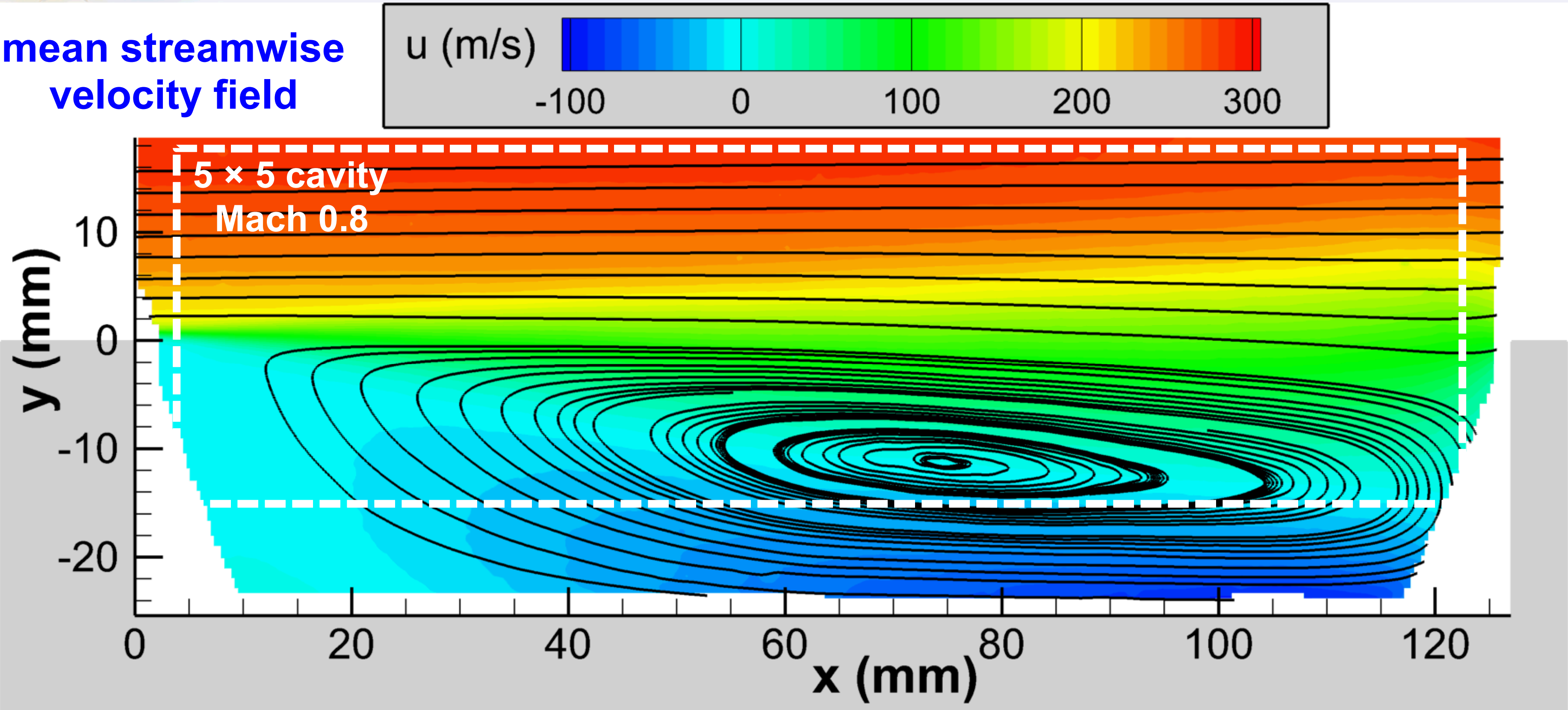
Previous 10-Hz PIV data were acquired similarly.

Bias error does not hinder visualization of the cavity flow or vortex detection.

Sandia National Laboratories

We have a lot of 10-Hz PIV data on this flow.

mean streamwise velocity field



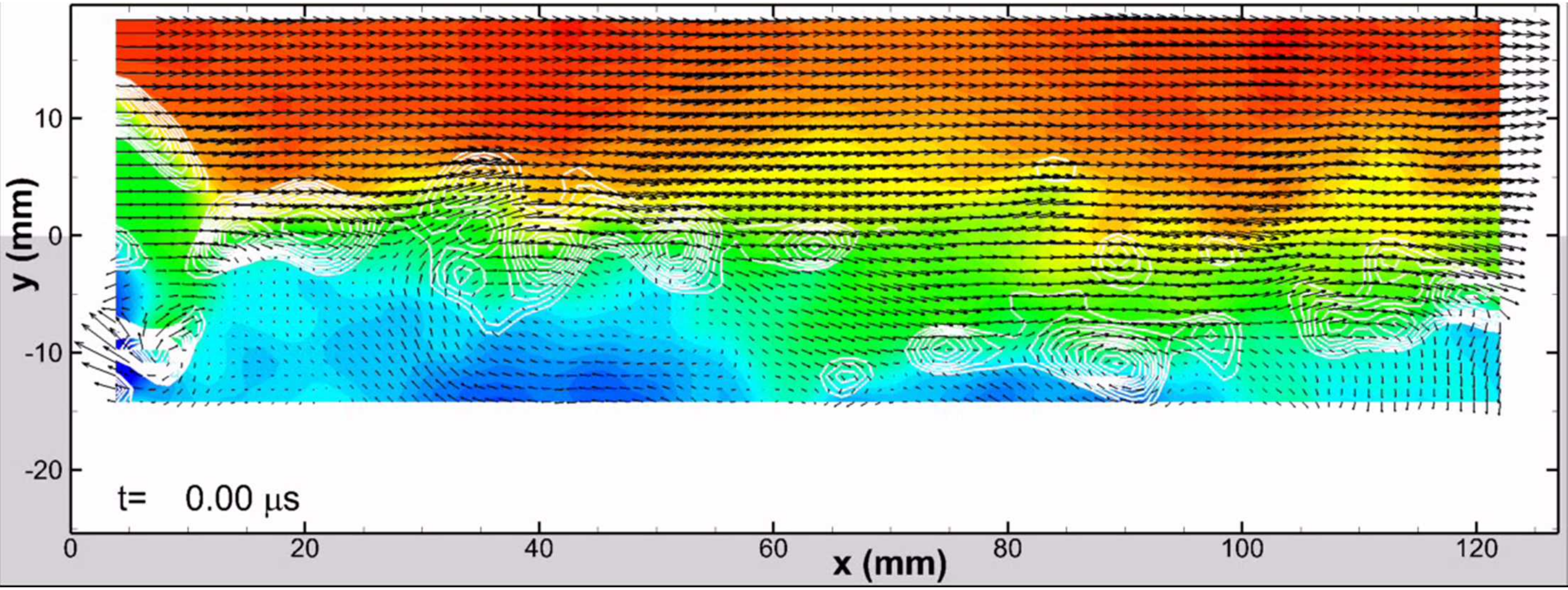
Streamlines clearly visualize the recirculation region and strong reverse velocities are evident.

The pulse-burst PIV field of view visualizes most of the recirculation region and will capture reverse velocities.

The behavior of large-scale structures is key to the acoustic tones produced by the cavity resonance

A Sample Pulse-Burst PIV Movie

This is a 10.2 ms movie with 386 vector fields acquired at 37.5 kHz.



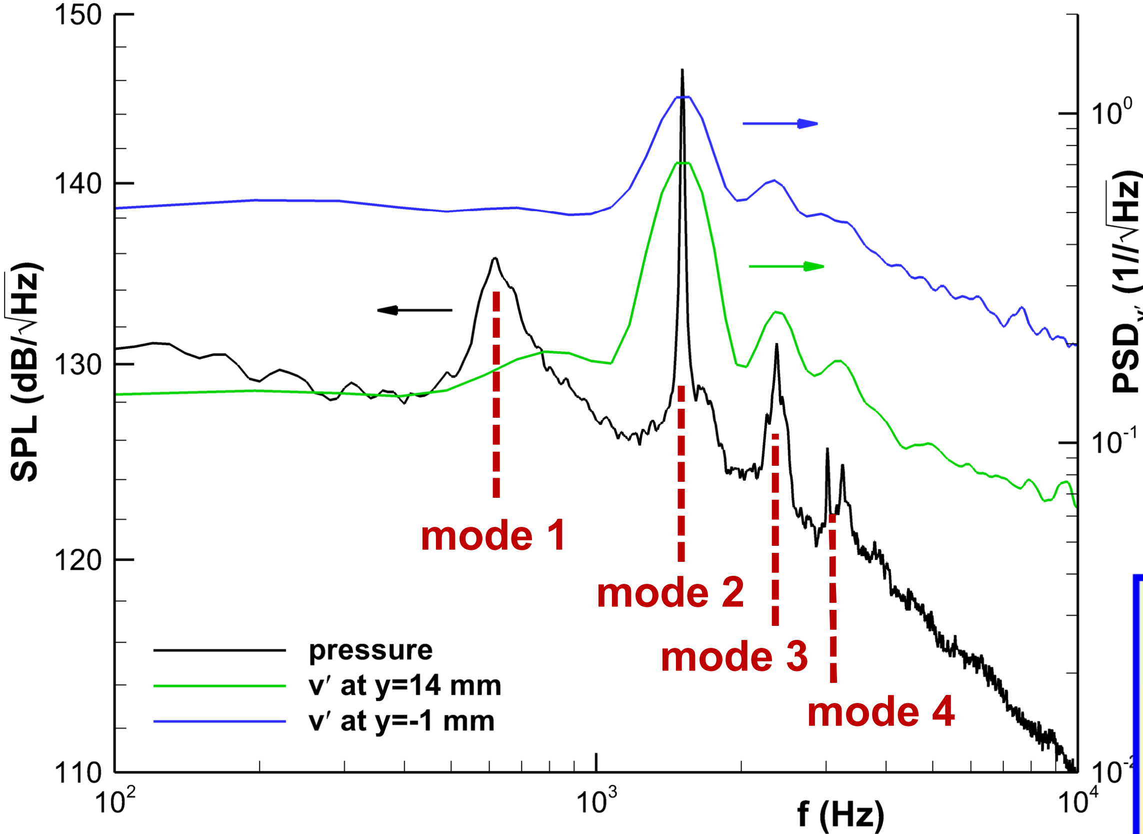
We can visualize:

- Recirculation region shifting position.
- Ejection and impingement events at aft end of cavity.
- Recirculation events enhancing shear layer flapping.
- Growth of shear layer structures and their recirculation.

Sandia National Laboratories

Can we identify the cavity resonances using Pulse-Burst PIV?

Compare power spectra to a pressure sensor in the aft wall.



Extract two velocity signals:

- One above the shear layer
- One within the shear layer

Velocity peaks broadened due to 100 Hz frequency resolution.

Pressure frequency resolution is 10 Hz.

Modes 2 – 4 match very well between pressure and velocity.

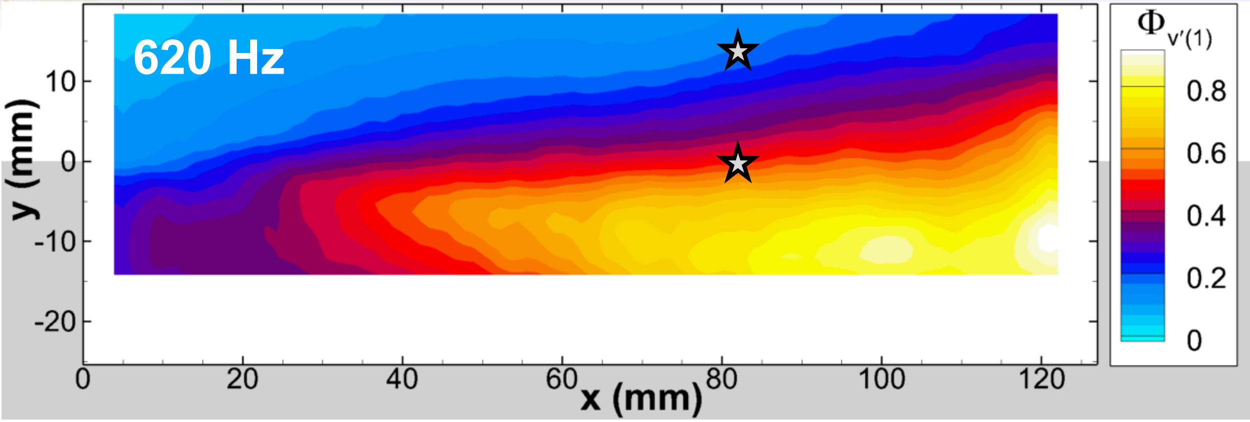
We can even see the bifurcated mode 4 peak in the shear layer velocity data.

Mode 1 is largely absent in the velocity data.

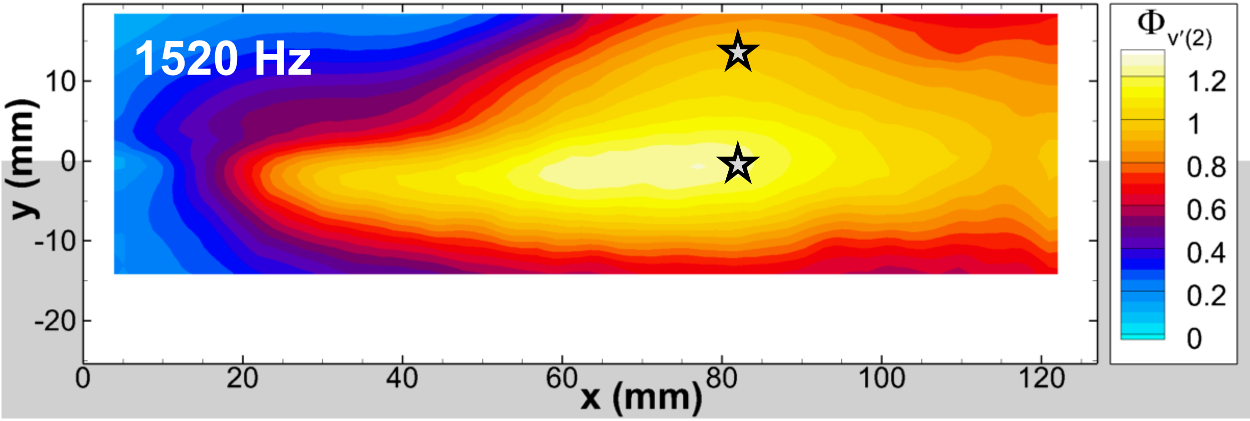
Pulse-burst PIV allows us to look at the *spatial distribution* of the resonance modes.

Sandia National Laboratories

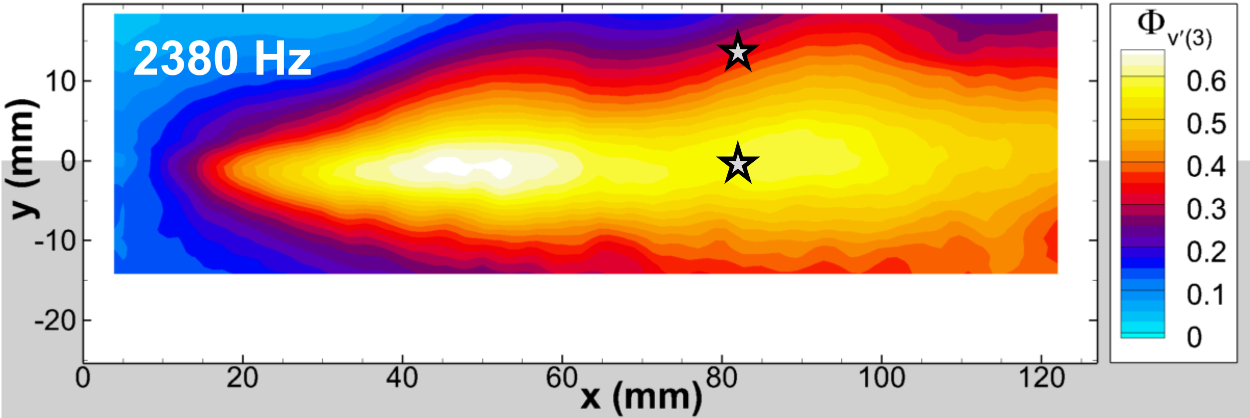
Spatial Distribution of Resonance Modes



Mode 1 concentrated in the recirculation region.



Mode 2 concentrated in the streamwise center of shear layer.



Mode 3 concentrated in the upstream shear layer.

Sandia National Laboratories

Can we identify the turbulent structures responsible for resonance?

Spatio-temporal correlations

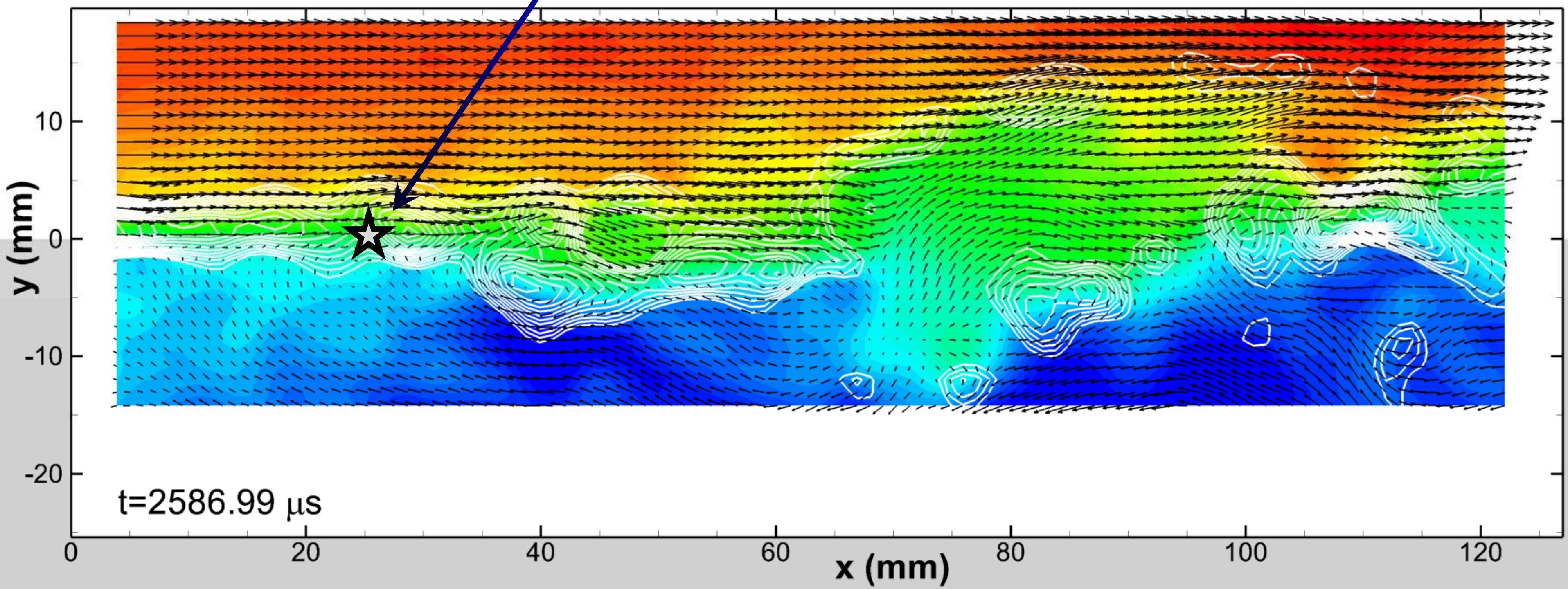
Correlate a reference vector with every vector in the velocity field.

Track correlation fields through space and time.

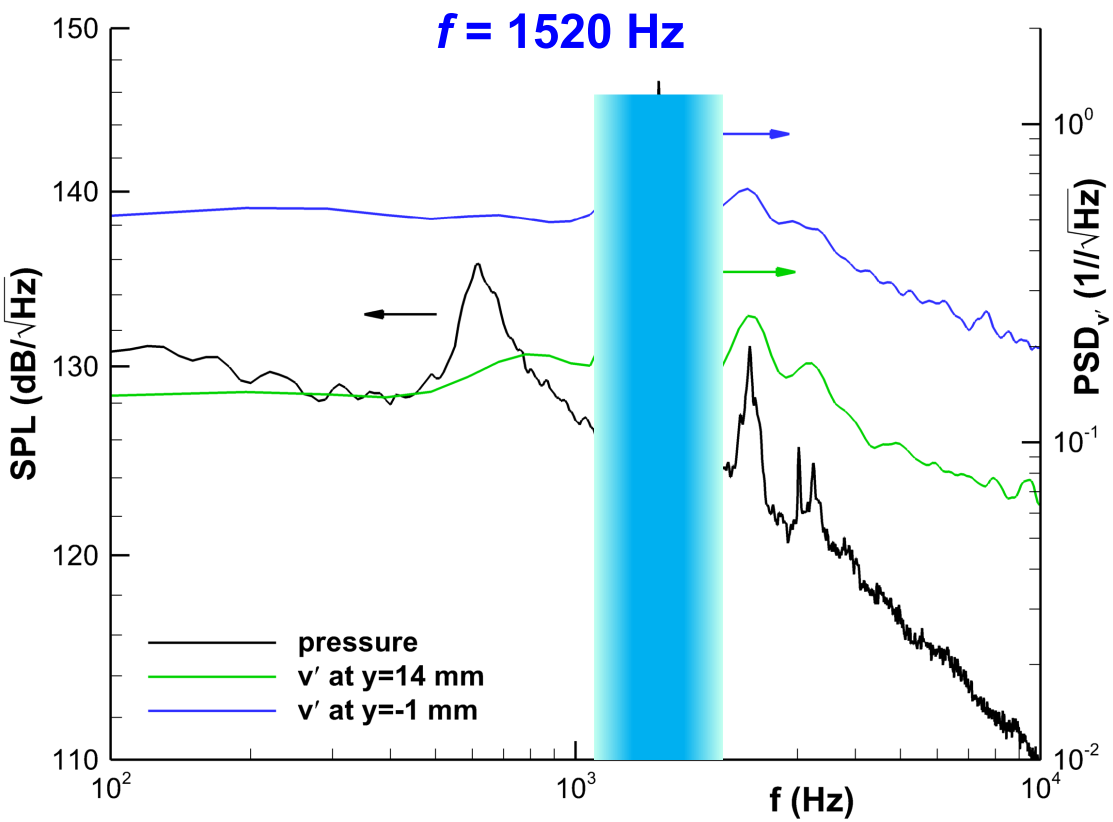
Choose a reference vector in the upstream shear layer.

But it turns out our conclusions are not dependent upon the reference.

Correlations of the vertical component turn out to be most useful.



Bandpass filter the velocity data.



Mach 0.8 is dominated by the second mode.

But all modes may be simultaneously active, plus turbulent fluctuations.

Clouds detection of flowfield associated with each mode.

Filter each velocity signal for a specific resonance mode.

Then, perform the correlations.

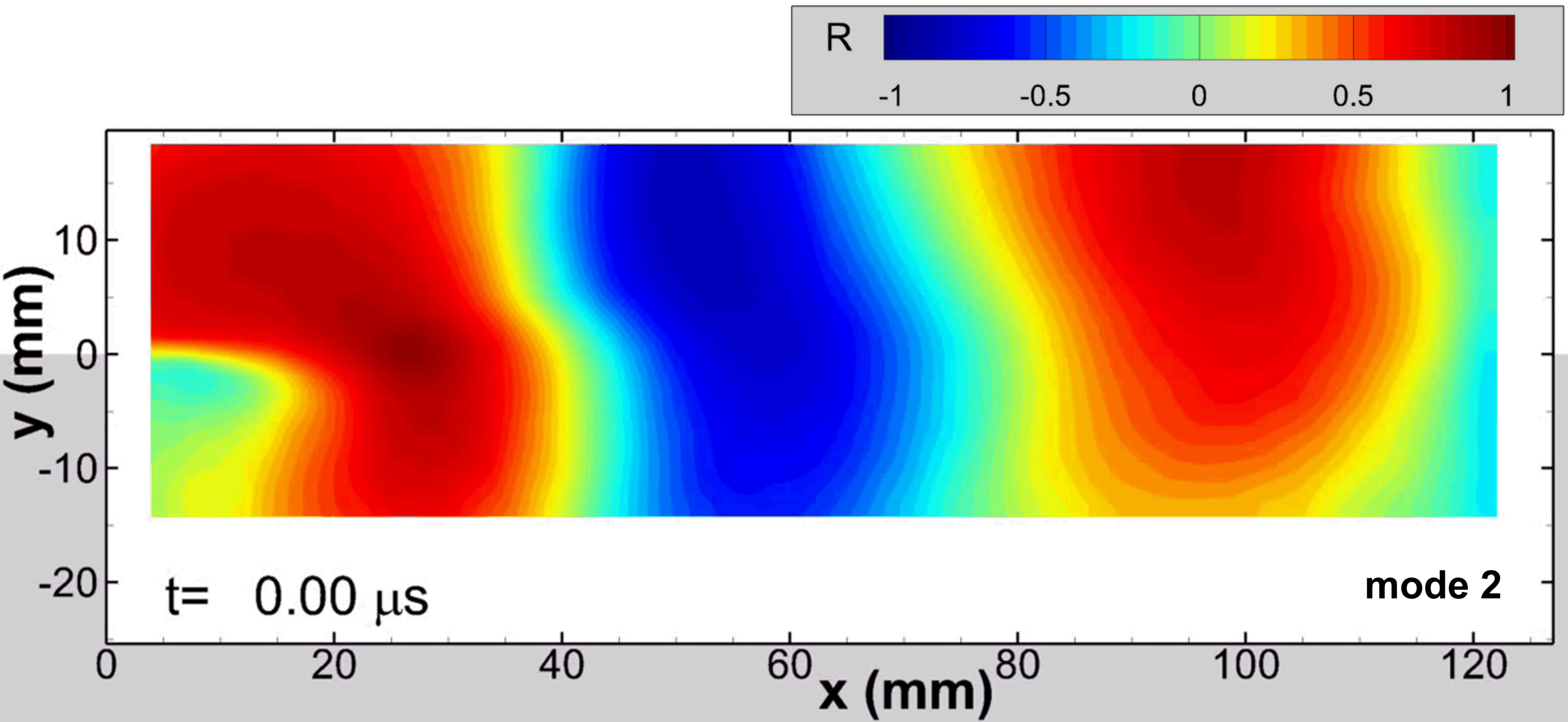
It turns out *mode 1* behaves differently than the rest, so let's start by discussing *mode 2*.

Sandia National Laboratories

Mode 2 Correlation Field

In a narrow frequency band, we can see the characteristic structures in the flow responsible for resonance.

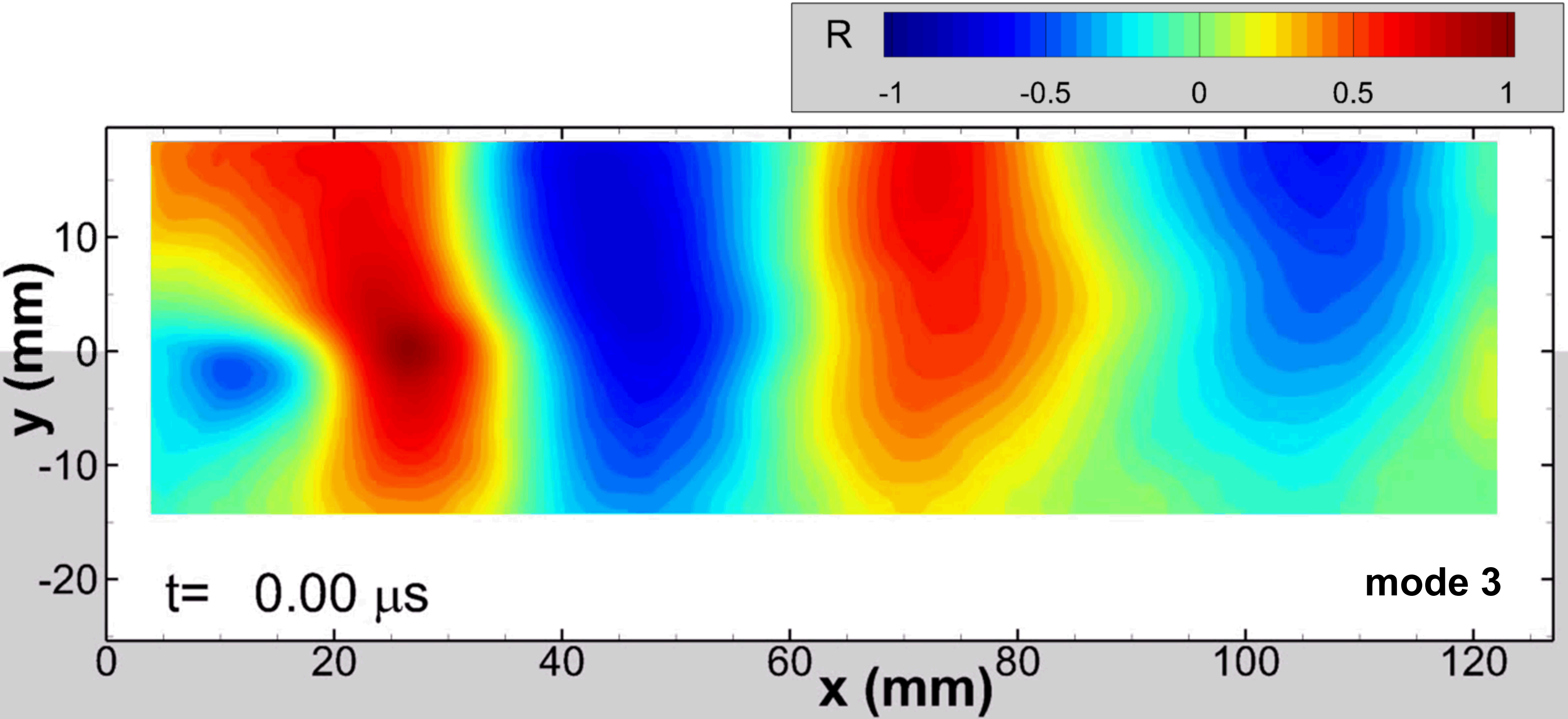
- **The spacing between the structures increases as they convect downstream.**
- **The structures tend to drift outward.**



Mode 3 Correlation Field

In a narrow frequency band, we can see the characteristic structures in the flow responsible for resonance.

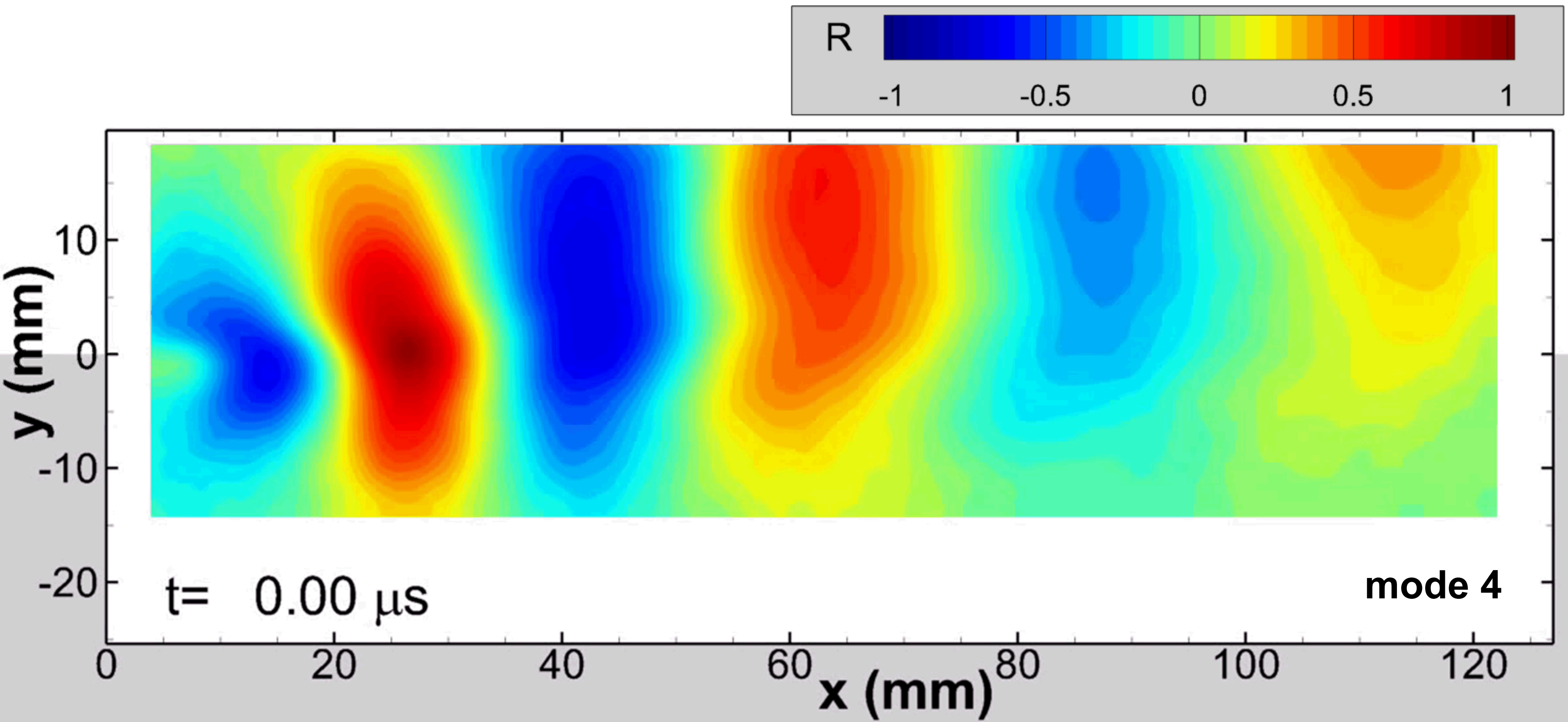
- **The spacing between the structures increases as they convect downstream.**
- **The structures tend to drift outward.**
- **The spatial scale of the coherent structures shortens as the mode increases.**



Mode 4 Correlation Field

In a narrow frequency band, we can see the characteristic structures in the flow responsible for resonance.

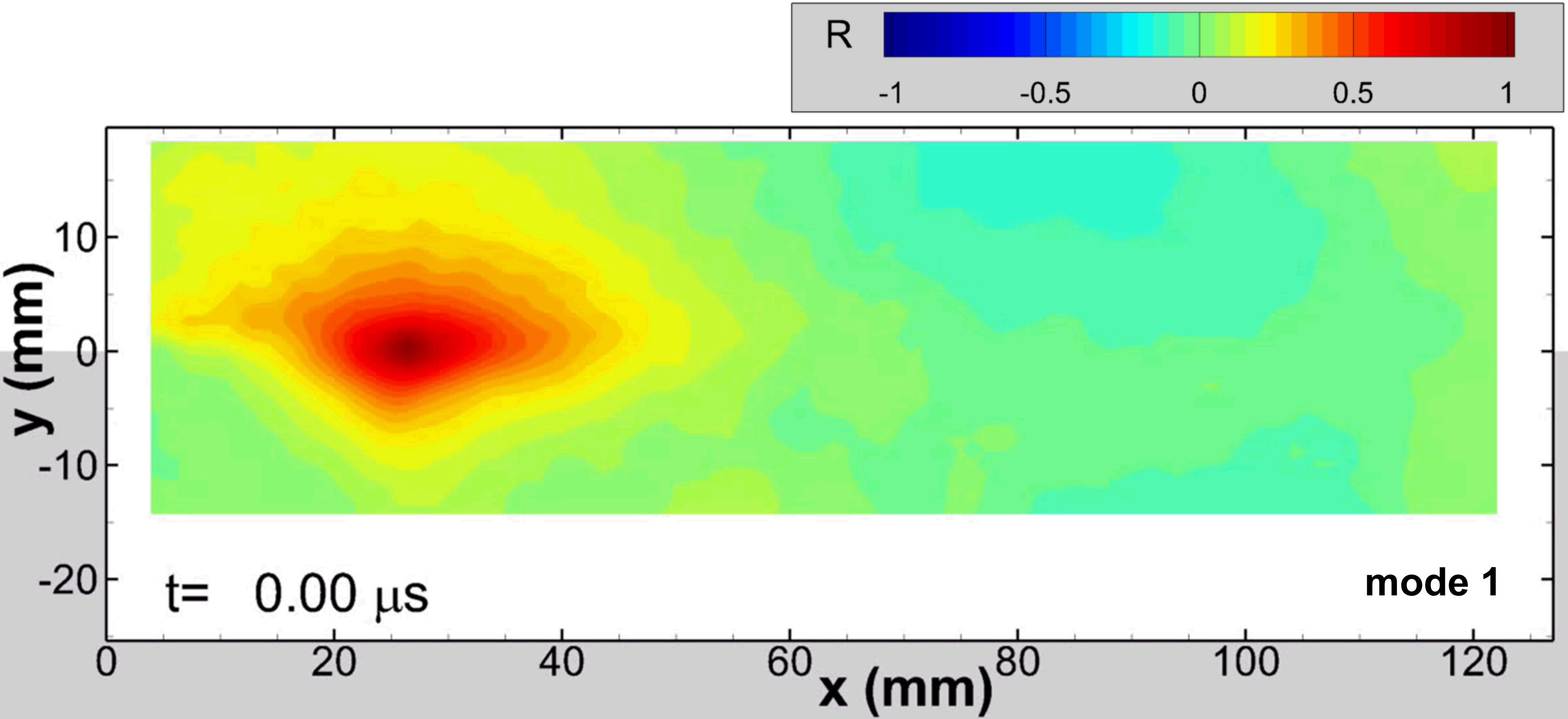
- **The spacing between the structures increases as they convect downstream.**
- **The structures tend to drift outward.**
- **The spatial scale of the coherent structures shortens as the mode increases.**



Mode 1 Correlation Field

Mode 1 shows properties of a localized standing wave.

No apparent spatial resonance or convection.



Mode 1 Correlation Field

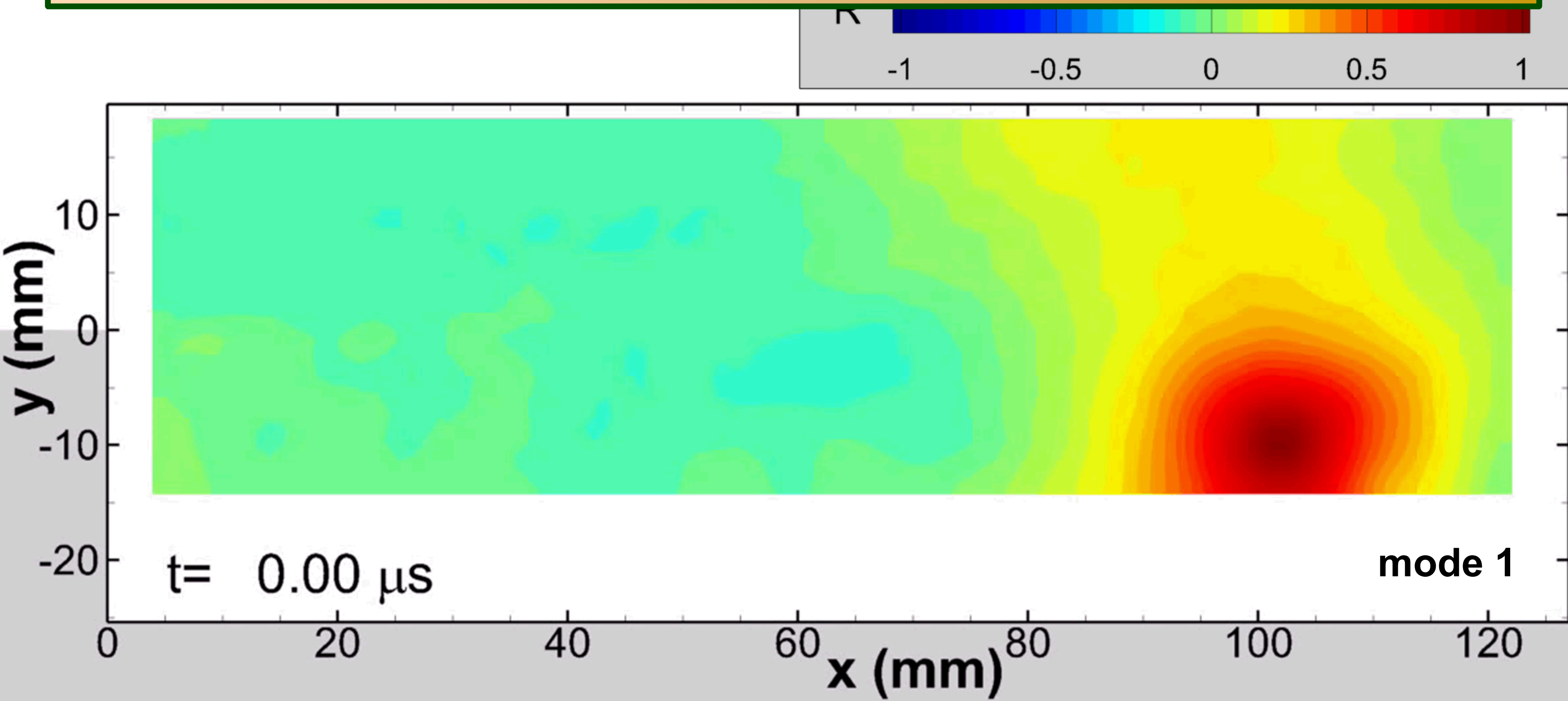
Mode 1 shows properties of a localized standing wave.

No apparent spatial resonance or convection.

Bandpass-filtered correlations do not detect mode 1 turbulent structure motion.

Because the mode 1 wavelength is longer than the cavity length.

Pulse-burst PIV provides unprecedented data for studying resonance in compressible cavity flows, and we're full of new ideas for it.



What's next in the wind tunnel?

Data up to Mach 2.5.

- We're working on it right now!

Add more cameras!

- Boost the framing rate without sacrificing spatial resolution.

Data analysis possibilities seem nearly endless:

- Conditional analysis and time/space correlation
- Bandpass-filtered movies for specific modes
- Joint Time Frequency Analysis
- Dynamic Mode Decomposition

We also are examining uncertainty issues.

- Peak locking is a notorious difficulty, but not the only one.

Pulse-burst lasers make TR-PIV feasible for high-speed flows.

- *This is the first application of Pulse-Burst PIV to a ground test facility.*

Sandia National Laboratories

Multiphase Shock Tube (MST)

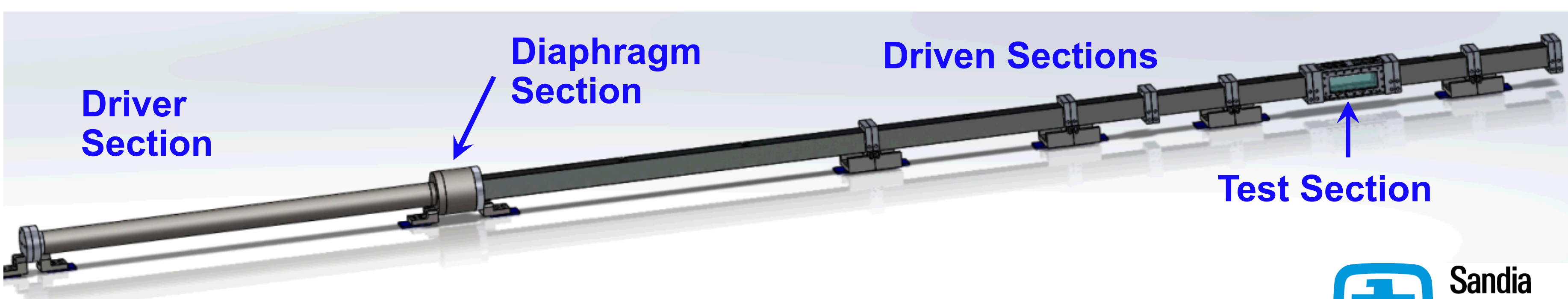
Can we implement pulse-burst PIV in our shock tube?

Shock Mach numbers M_s up to about 2.

Driven section is air initially at atmosphere.

Test section width D = 76 mm.

MST typically used for shock-particle interaction and liquid breakup experiments.



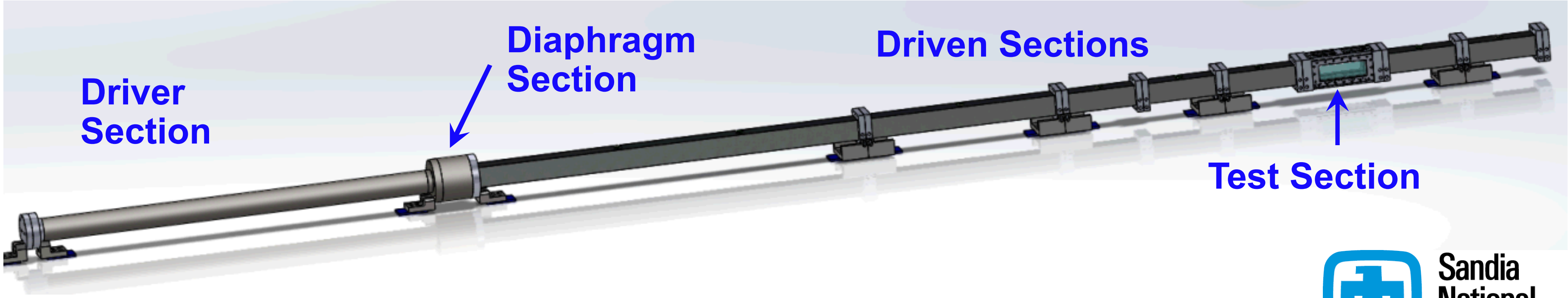
Sandia National Laboratories

Multiphase Shock Tube (MST)

Can we implement pulse-burst PIV in our shock tube?

Conventional PIV gives only one realization in the ~ 1 ms test time of a shock tube.

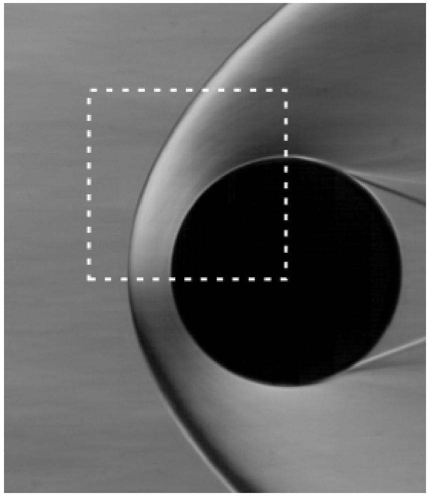
PIV pulse bursts last up to 10.2 ms, plenty long in a shock tube.

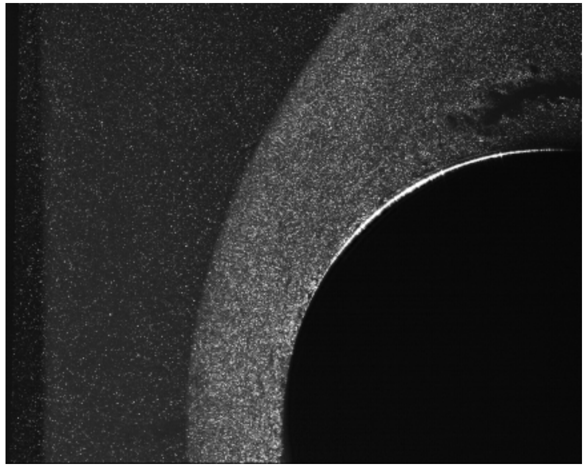


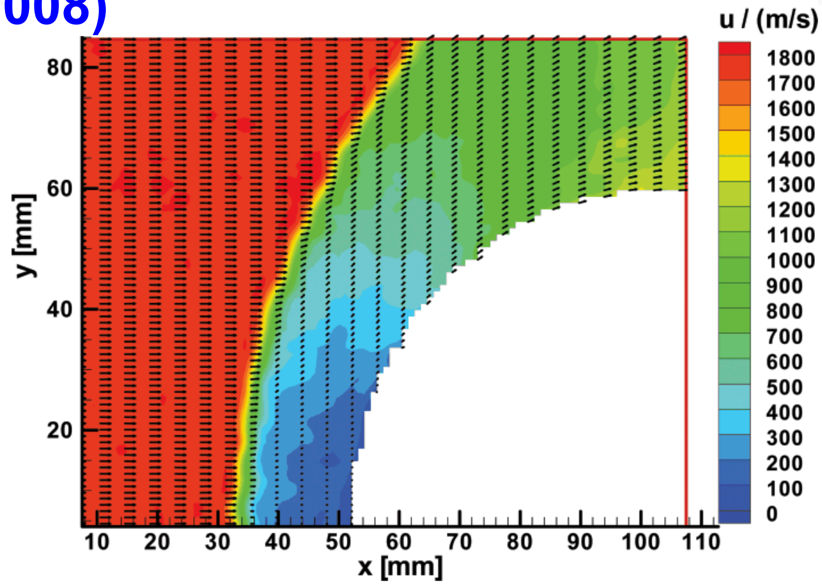
Sandia National Laboratories

Previous PIV in Shock Tubes and Shock Tunnels

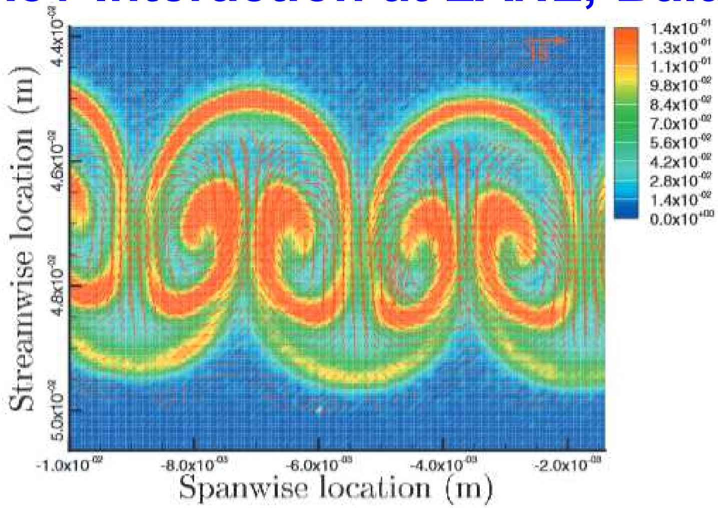
Cylinder Flow at ISL, Havermann et al. (2008)







Richtmeyer-Meshkov Interaction at LANL, Balakumar et al. (2008)



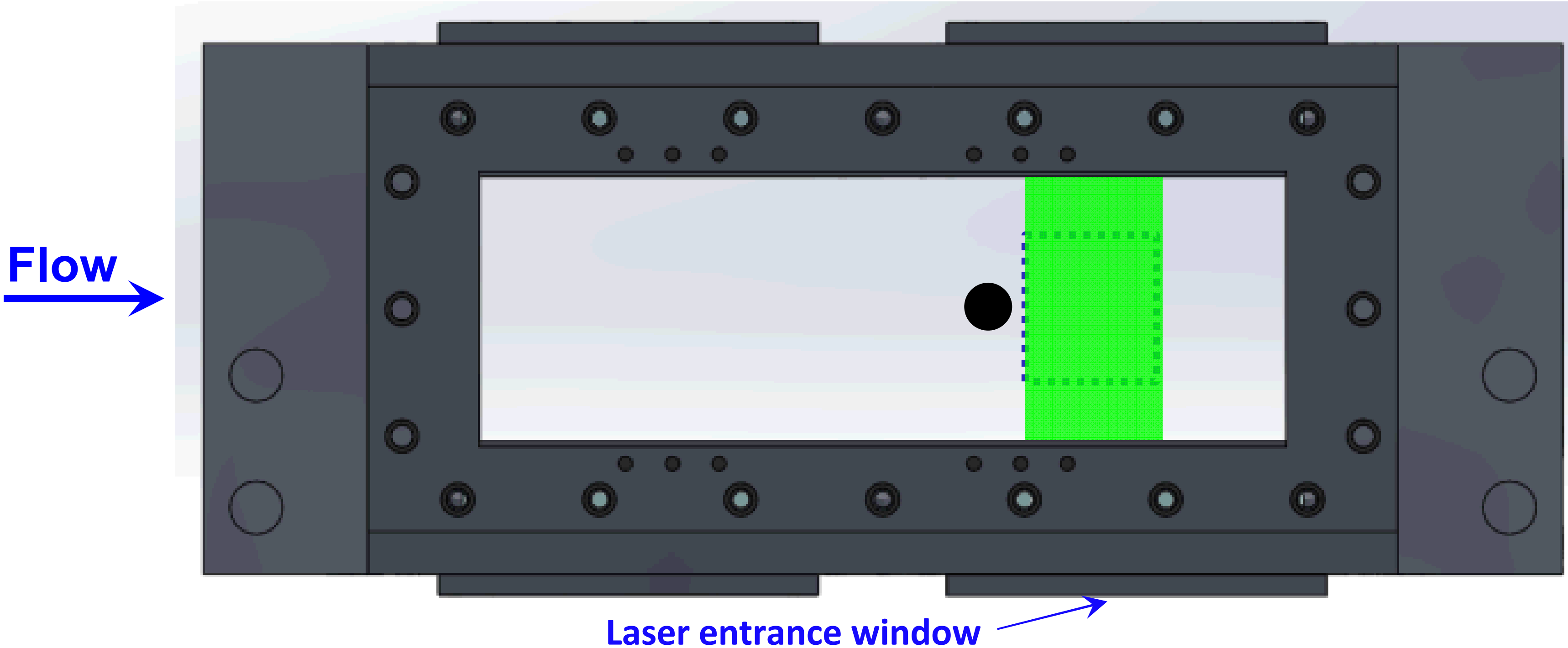
Insightful results, but conventional PIV gives only one realization in the ~ 1 ms test time of a shock tube.

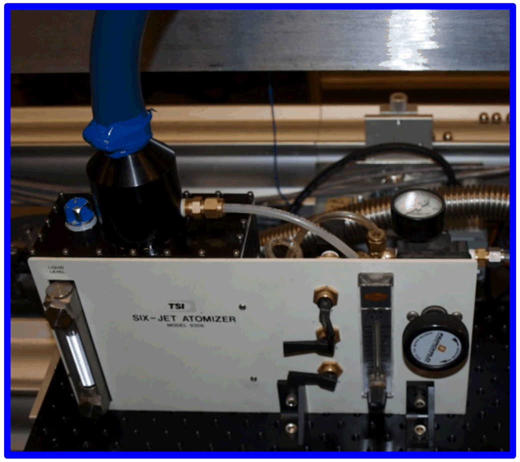
PIV pulse bursts last up to 10.2 ms, plenty long in a shock tube.

Also: Bonazzo et al at Wisconsin, Jacobs et al at Arizona, Vorobieff et al at New Mexico

Cylinder Wake Flow

Transient wake growth of a cylinder after an impulsively started flow.

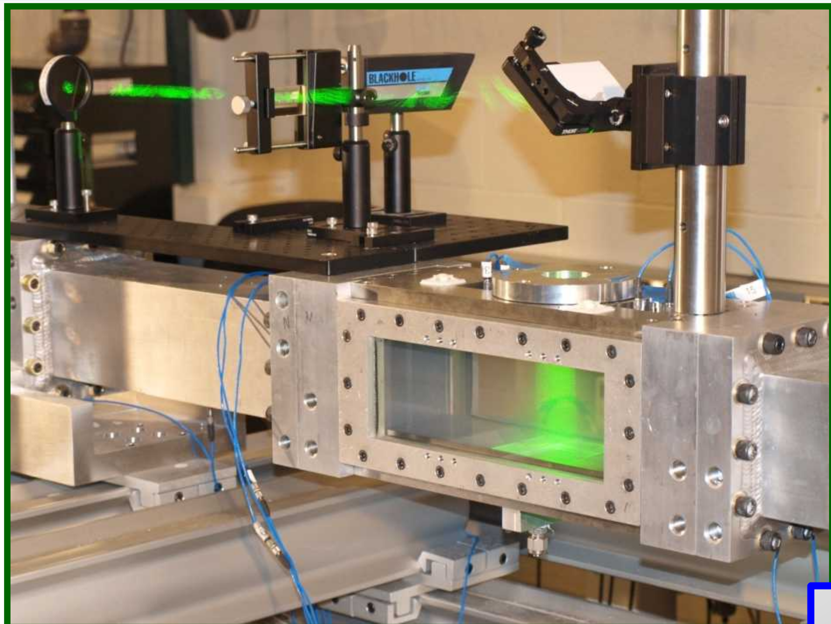




Particle seeding:

- TSI Six-Jet Atomizer
- Particles mixed into driver section prior to run.
- Particle size: d_p = 1.6 μm
- Stokes Number: 0.05 – 0.50

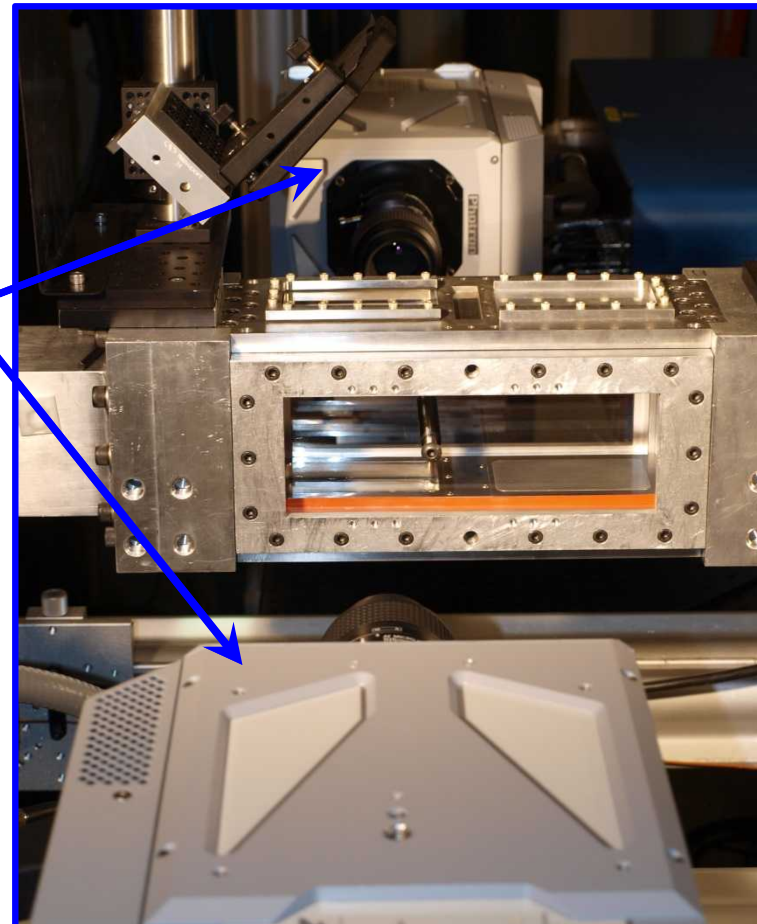
Imaging Details



Pulse-Burst Laser Settings:

- Pulse pairs at 50 kHz
- 20 mJ per pulse
- Burst duration = 10.2 ms

cameras

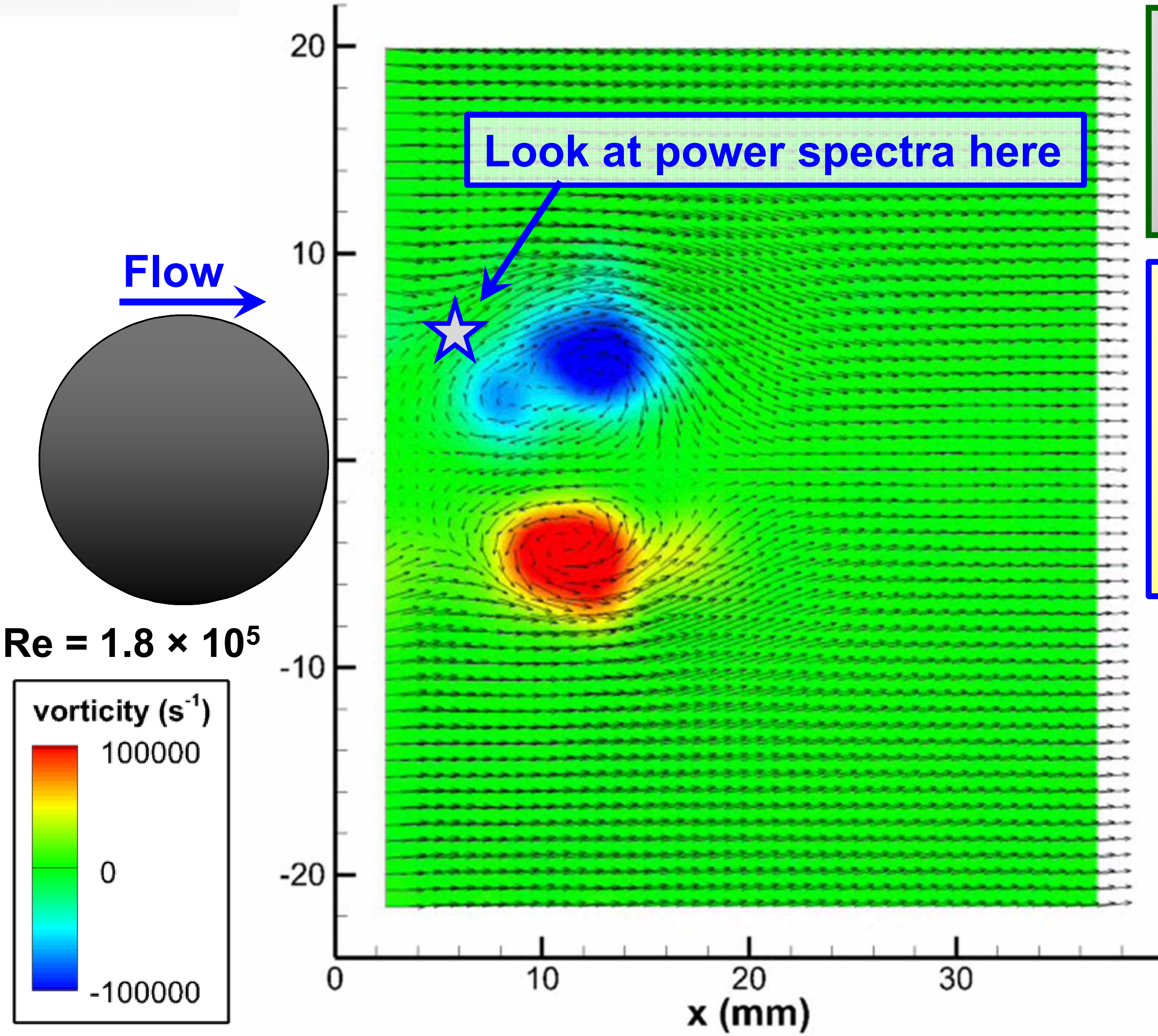


Two *Photron SA-Z's* placed adjacent to extend field of view

- Each 680 × 340 pixels
- Two-component vectors

Laser and cameras triggered off shock passage at upstream location.

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



50 kHz frame rate

Final interrogation window: 24 × 24 pix ($1.8 \times 1.8\ mm^2$)

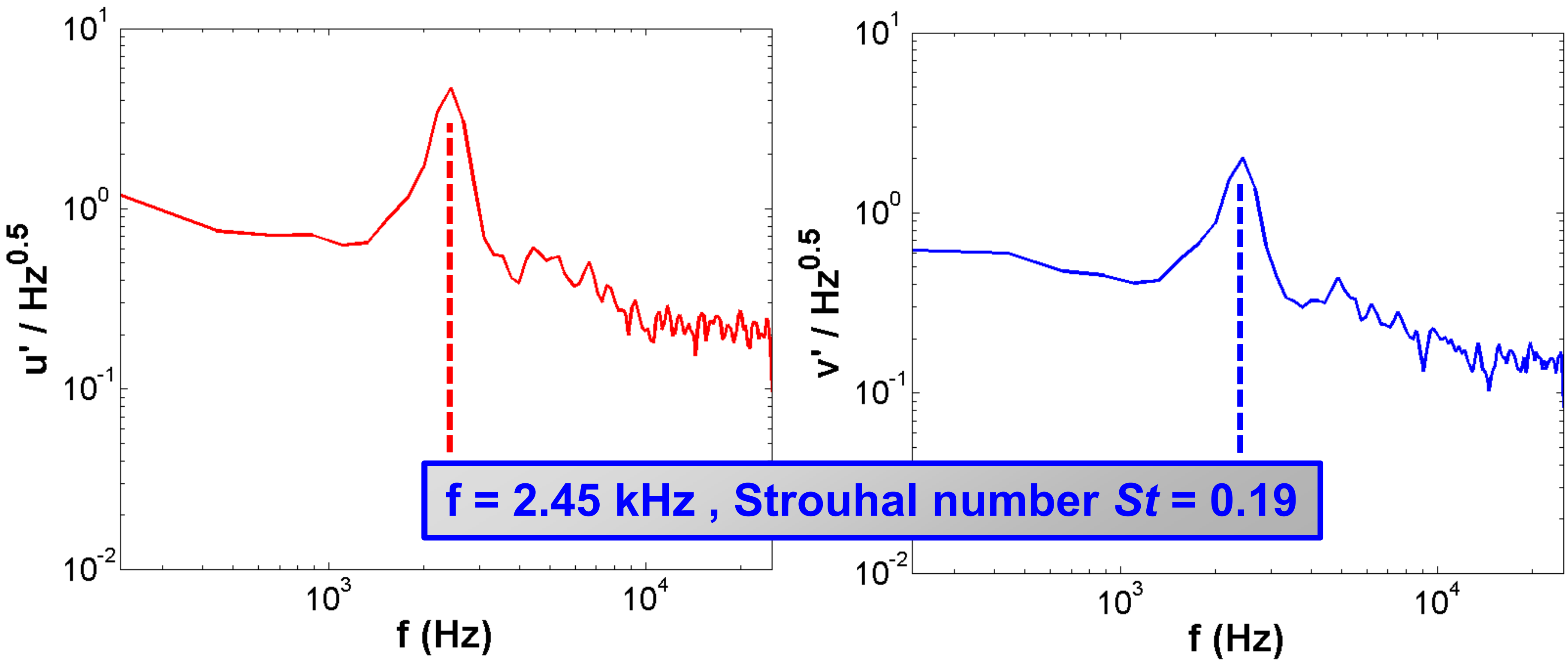
Vortex shedding starts symmetric, then becomes a von Kármán streeet.

Some historical precedent exists.

Sandia National Laboratories

Power Spectra of Vortex Shedding

Streamwise Velocity **Wall-Normal Velocity**



f = 2.45 kHz , Strouhal number *St* = 0.19

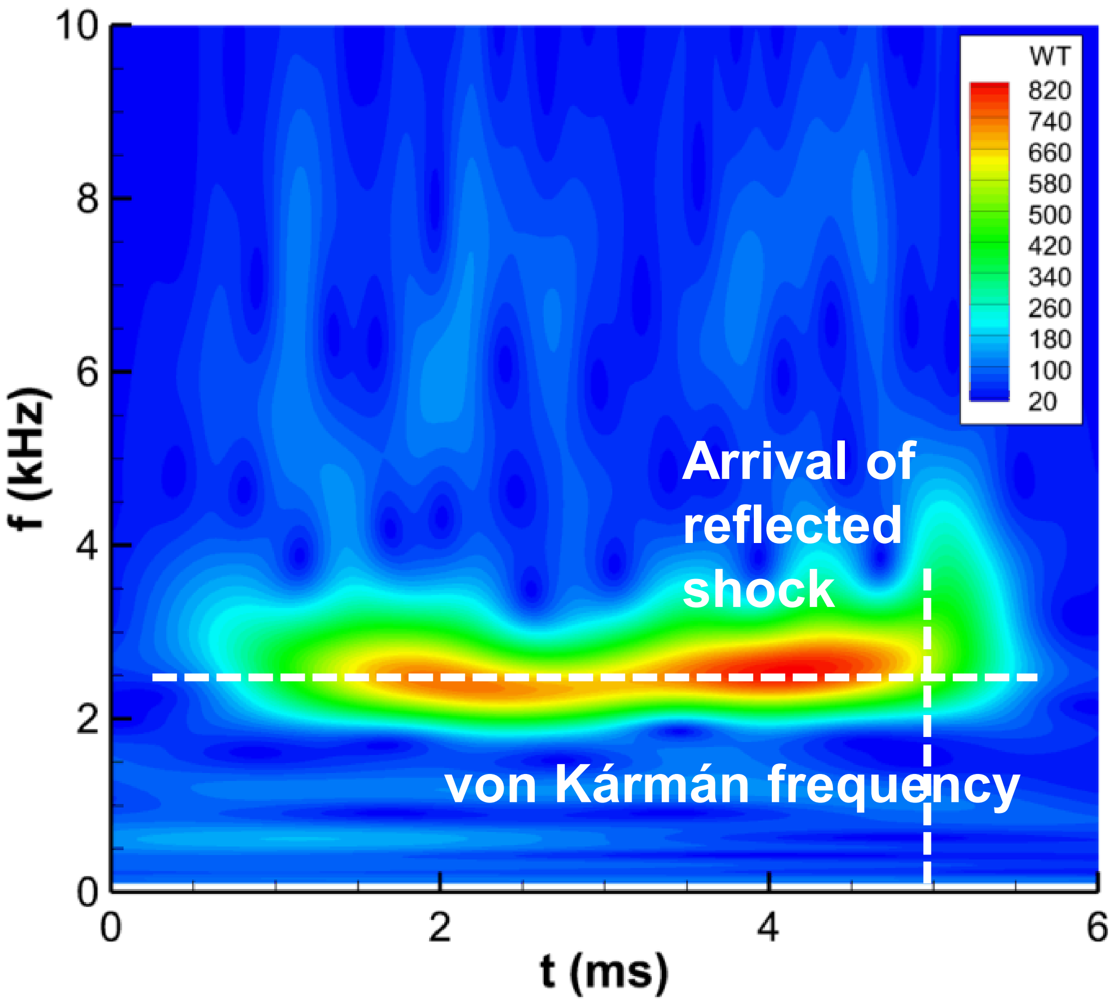
Similar *St* to previous studies at this Re (Roshko, 1961).

This is a time average. How does the frequency of vortex shedding change in time?

Sandia National Laboratories

Joint Time Frequency Analysis (JTFA)

Wavelet Transform of Wall-Normal Velocity



- It takes ≈ 0.5 ms for vortex street to become active.
- Street reaches local max at ≈ 2 ms, remains near maximum until ≈ 5 ms
- After the reflected shock at 5 ms, it takes ≈ 0.5 ms for shedding to dampen.

Pulse-burst PIV quantifies the transient nature of vortex shedding in a shock tube.

Sandia National Laboratories

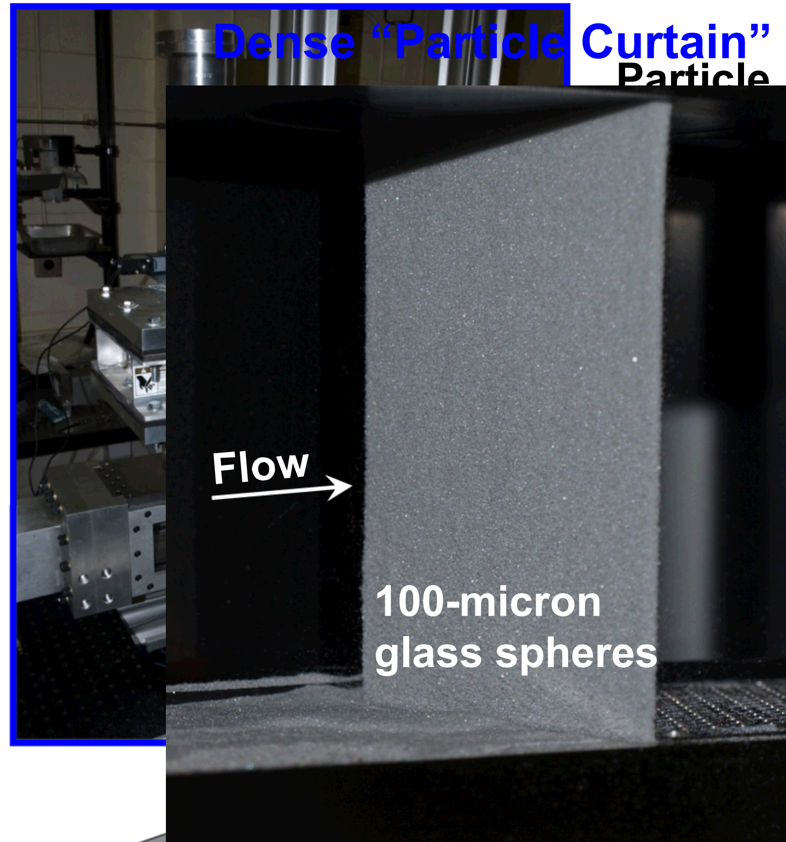
Particle Curtain Experiments in MST

Multiphase shock tube facility

MST built to study
shock / particle interactions
in dense gas-solid flows.

Dense “Particle Curtain”

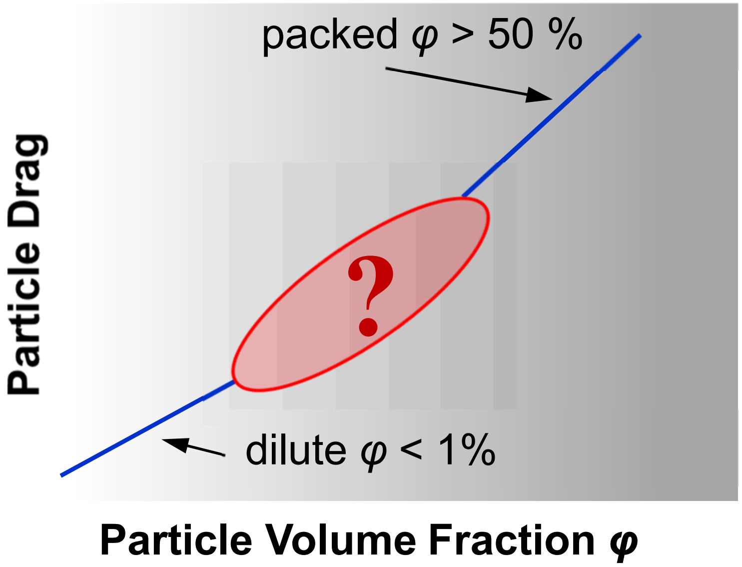
Particle



Particle volume fraction ≈ 20%

Sandia National Laboratories

Why do we care about a particle curtain?



Explosive Particle Dispersal

Dynamics of densely packed particles influence explosive processes.

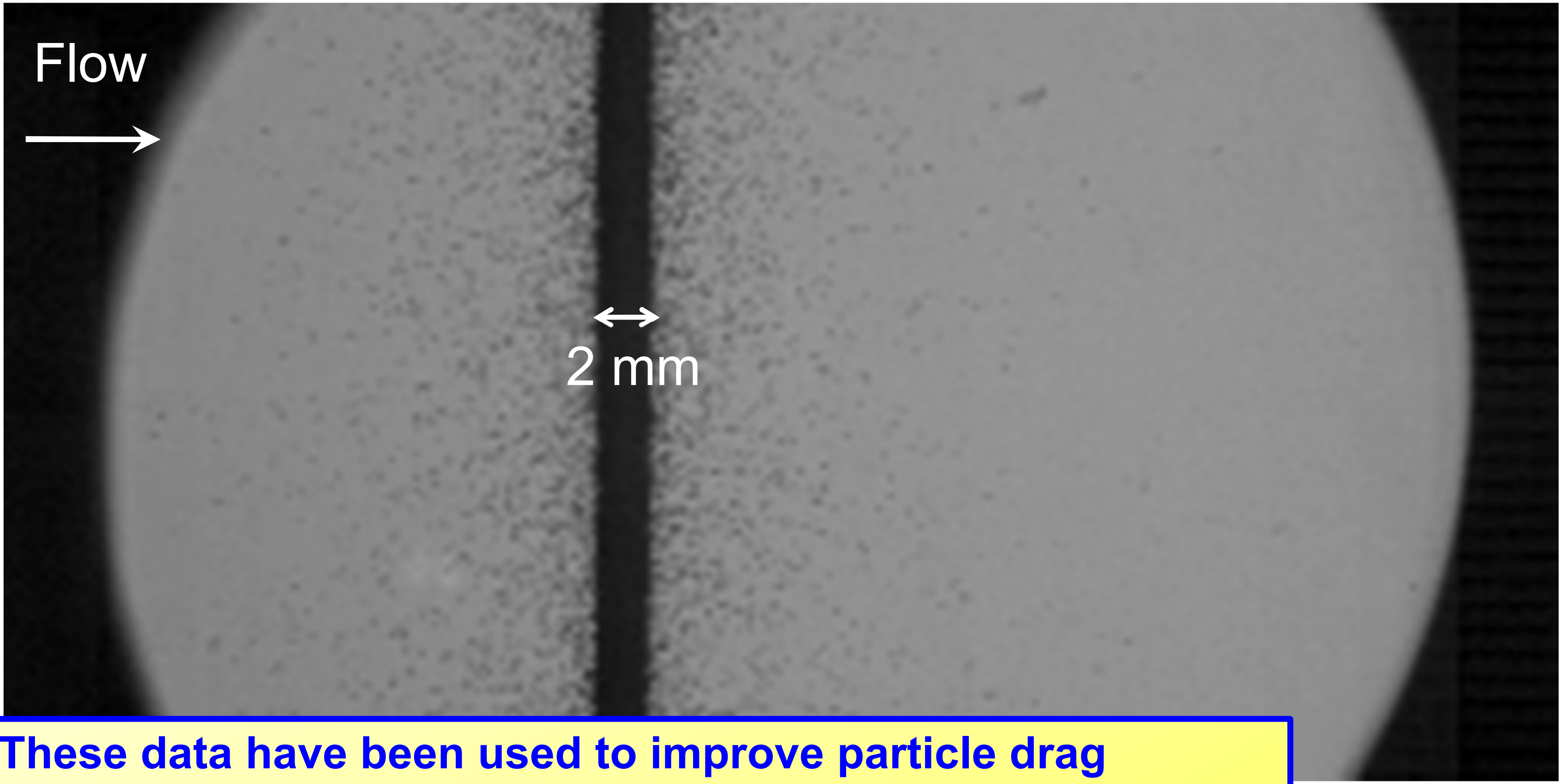
Particle Dynamics

- Dynamics governed by volume fraction φ
- Very little data in "dense" regime (1% < φ < 50%)

Sandia National Laboratories

High-Speed Schlieren (130 kHz)

Interaction at shock Mach number = 1.67



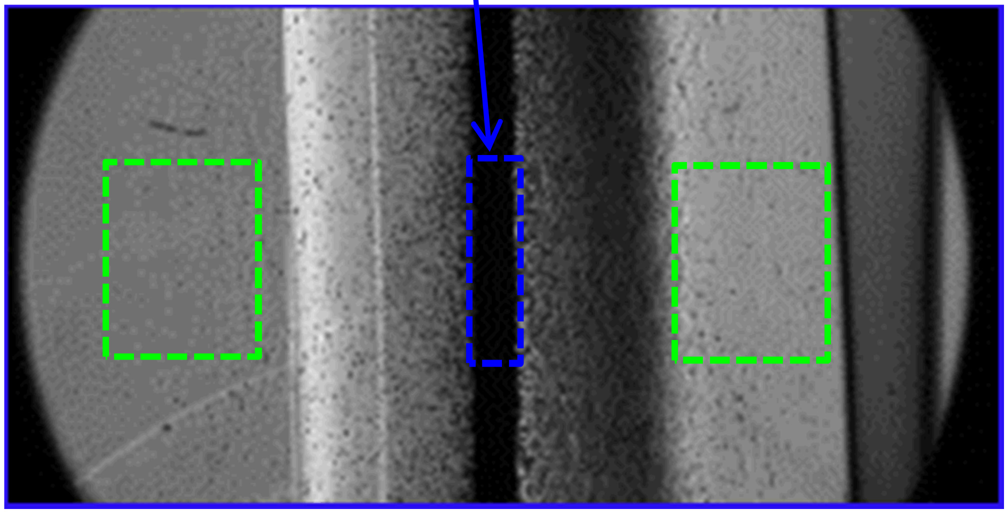
These data have been used to improve particle drag models for prediction of explosive processes.

But we need *gas-phase velocities* to accurately provide drag coefficients.

Sandia National Laboratories

Pulse-Burst PIV can probe much deeper physics.

We've previously focused on the solid particles.



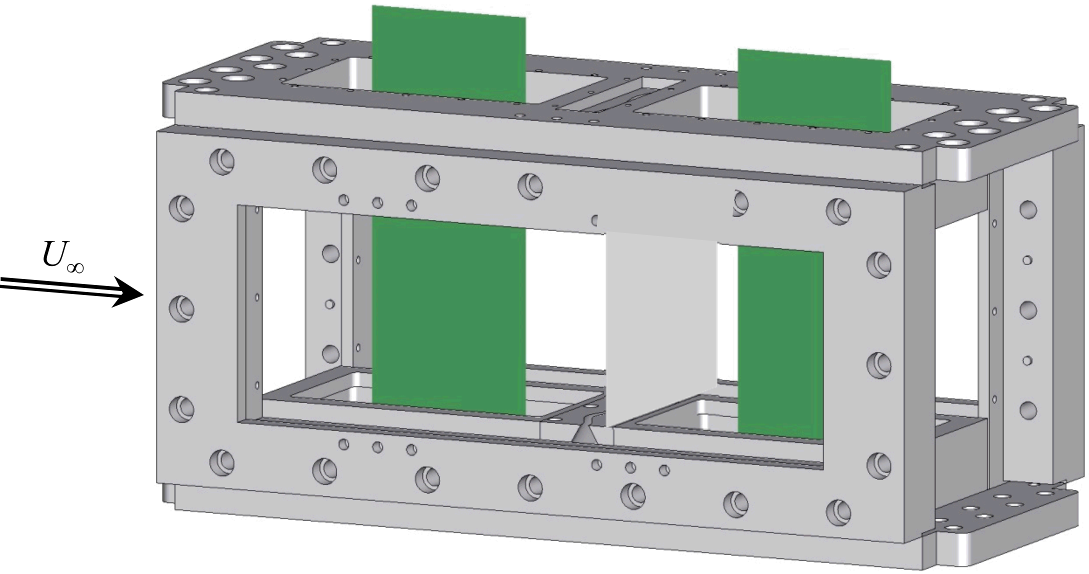
A conventional PIV system allows only one realization in the millisecond test times of a shock tube.

Time-resolved gas phase data can measure:

- **Interaction Unsteadiness**
- **Interphase Momentum Transfer**
- **Particle-Induced Turbulence**

Sandia National Laboratories

Particle Curtain Pulse-Burst PIV



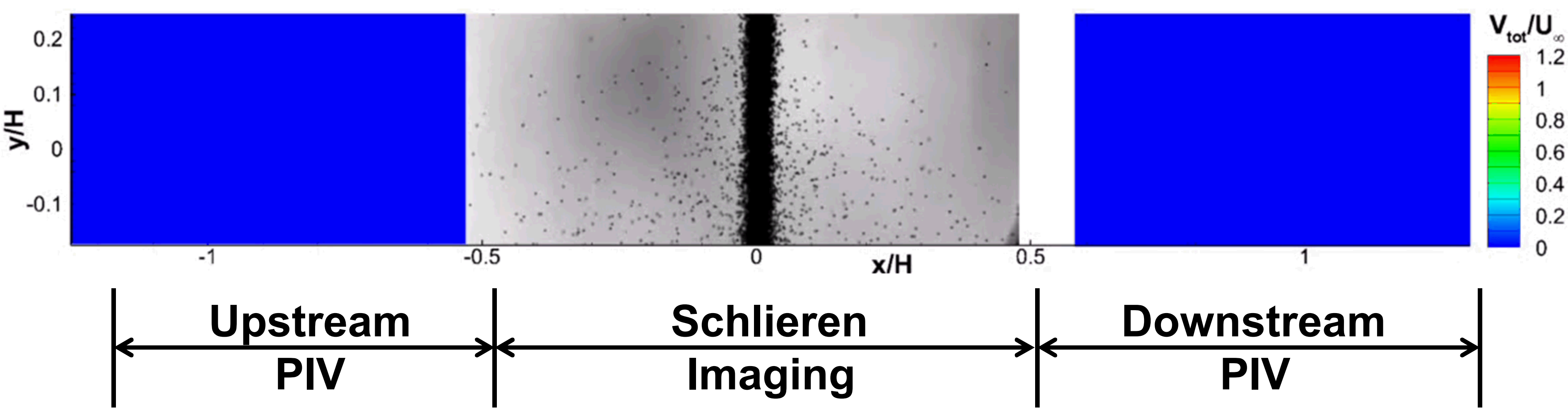
Split the laser into upstream and downstream sheets.

Image each using synchronized cameras.

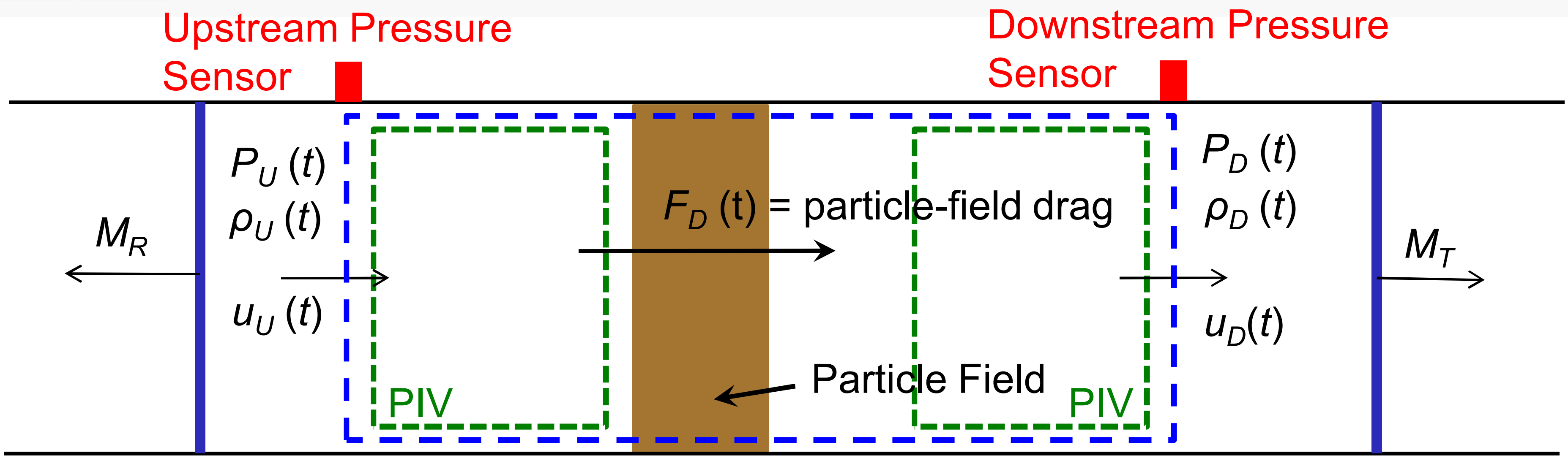
Data capture gas jetting through the curtain and angled shock waves.

Control volume analysis to determine the particle drag.

Mach 1.4, *U*=200 m/s



Calculating the Particle Drag

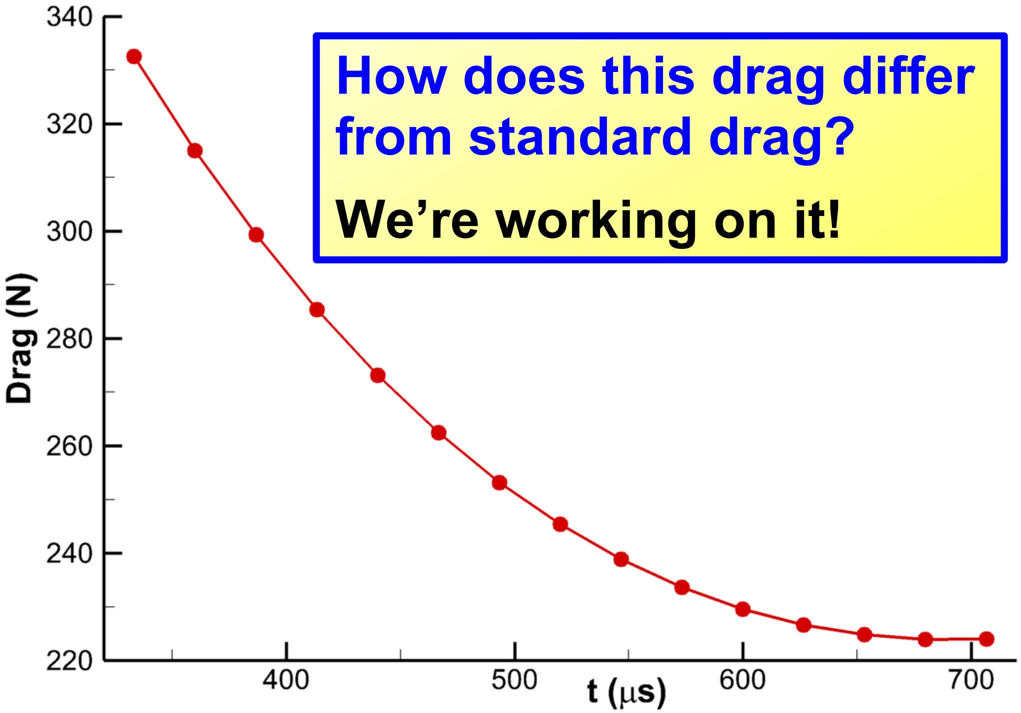


Control volume balance of momentum conservation

Get pressure $P_U(t)$ and $P_D(t)$ from pressure sensors.

Get density $\rho(x,y)$ from shock equations.

Get velocity $u(x,y,t)$ from pulse-burst PIV.



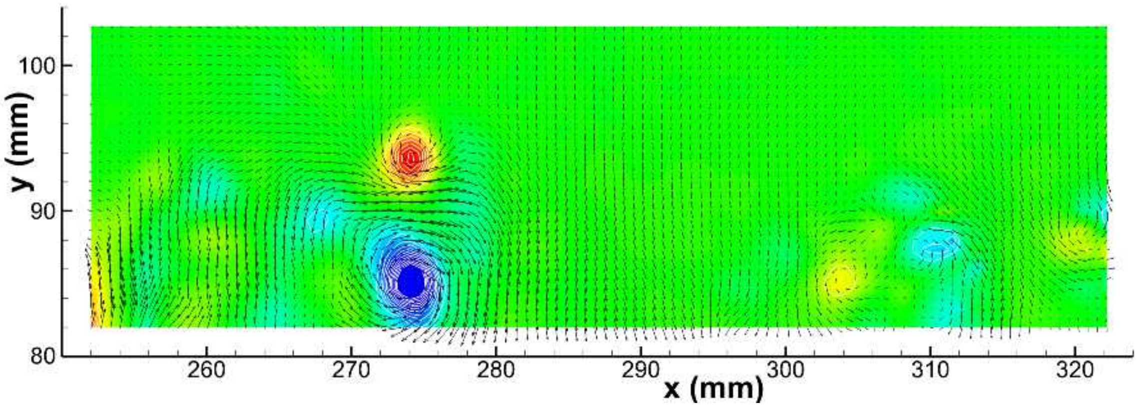
How does this drag differ from standard drag?

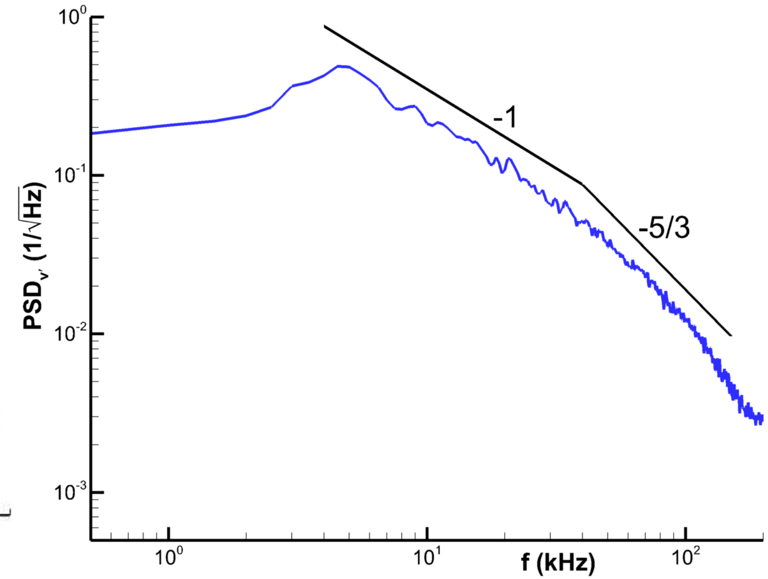
We're working on it!

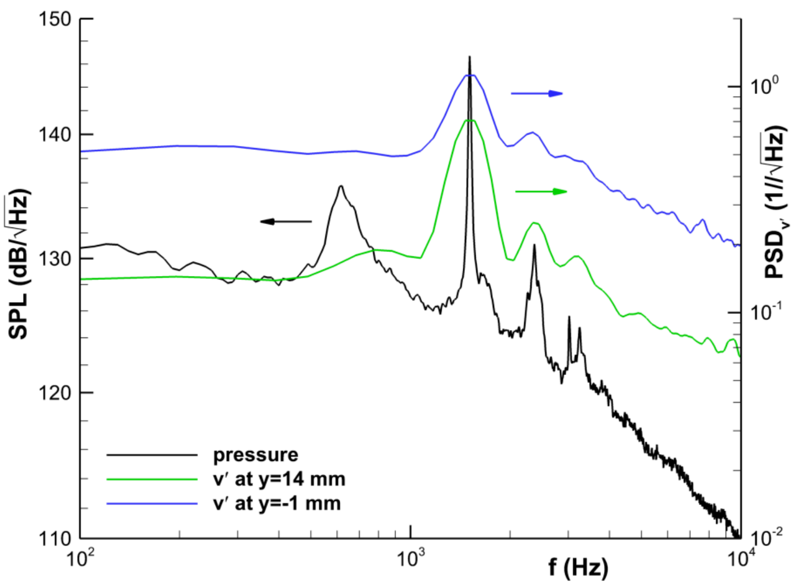
Pulse-burst lasers make TR-PIV feasible for high-speed flows.

This is the first application of Pulse-Burst PIV to a ground test facility.

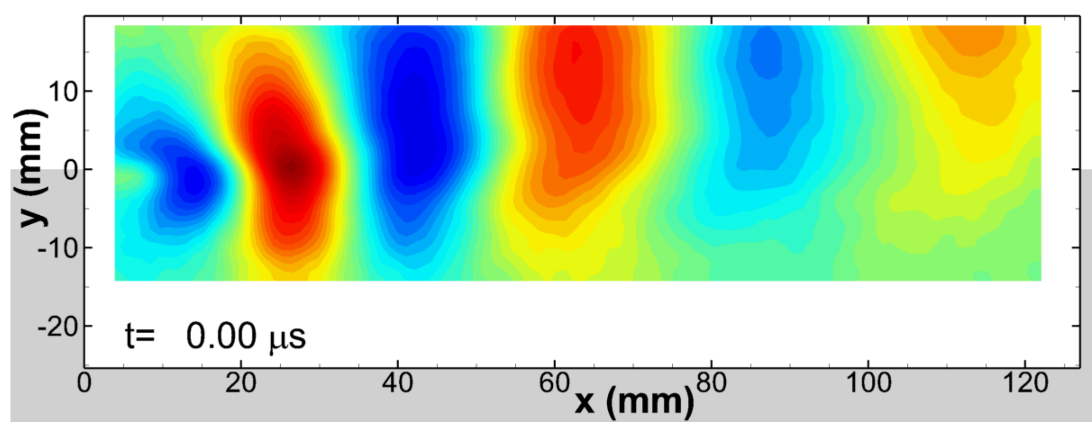
Supersampling of jet-in-crossflow data has revealed turbulent scaling laws.





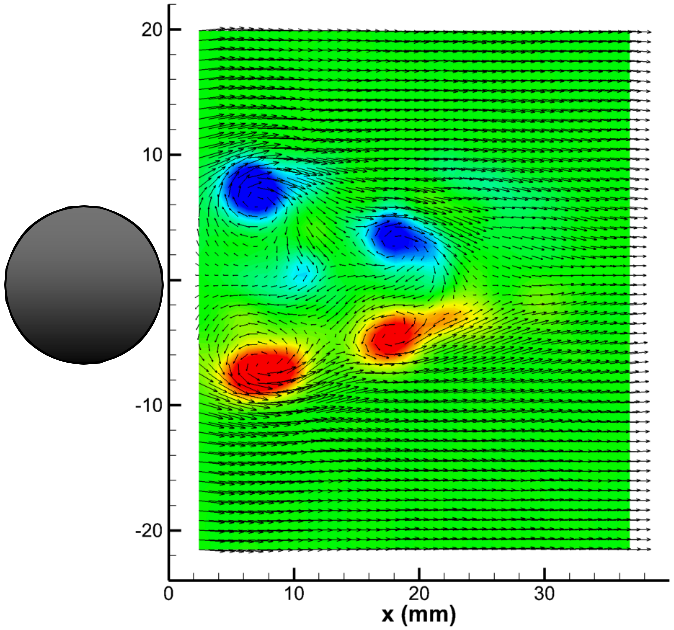


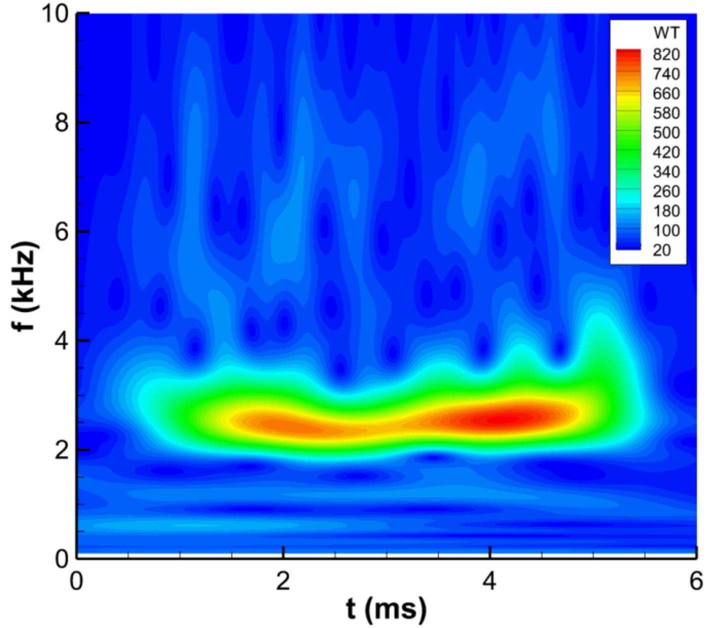
Cavity data show flow structures that create aeroacoustic resonances.



Pulse-burst lasers make TR-PIV feasible for high-speed flows.

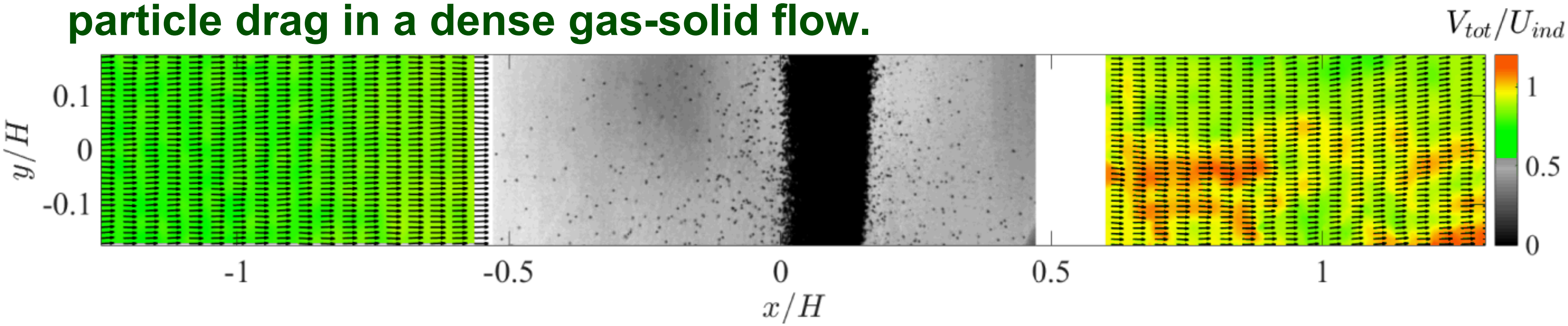
This is the first application of Pulse-Burst PIV to a ground test facility.





Shock tube data reveal the transient start of cylinder vortex shedding.

Shock-particle interaction data can be used to determine particle drag in a dense gas-solid flow.



More physics to be revealed as we continue to analyze these data sets!