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Pulse-Burst PIV: Velocimetry Movies in a High-Speed Wind Tunnel

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Albuquerque, NM

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National Nuclear Security Administration

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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 MP
- 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.

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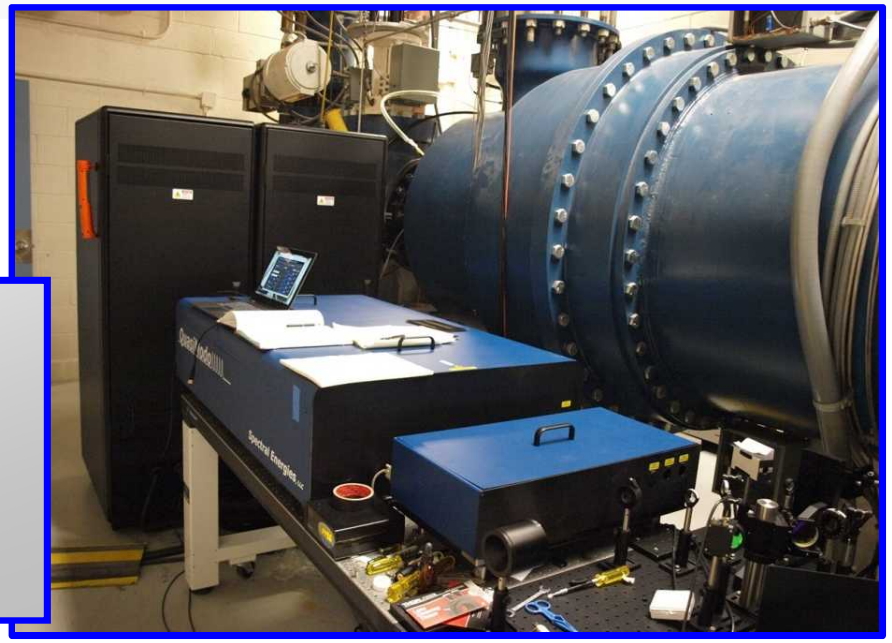
Pulse-Burst Laser

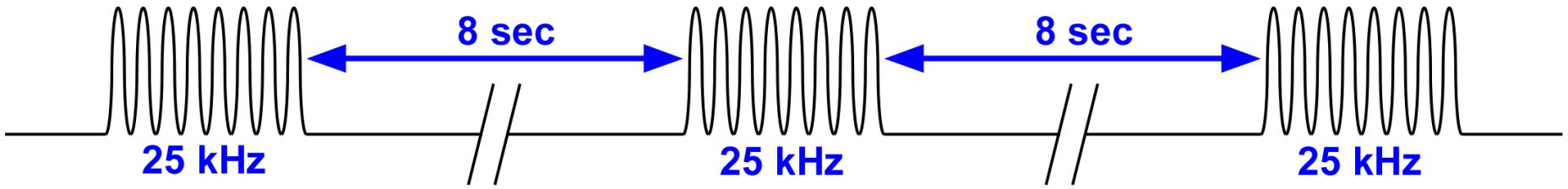
A pulse-burst laser allows high energy and high repetition rates.

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



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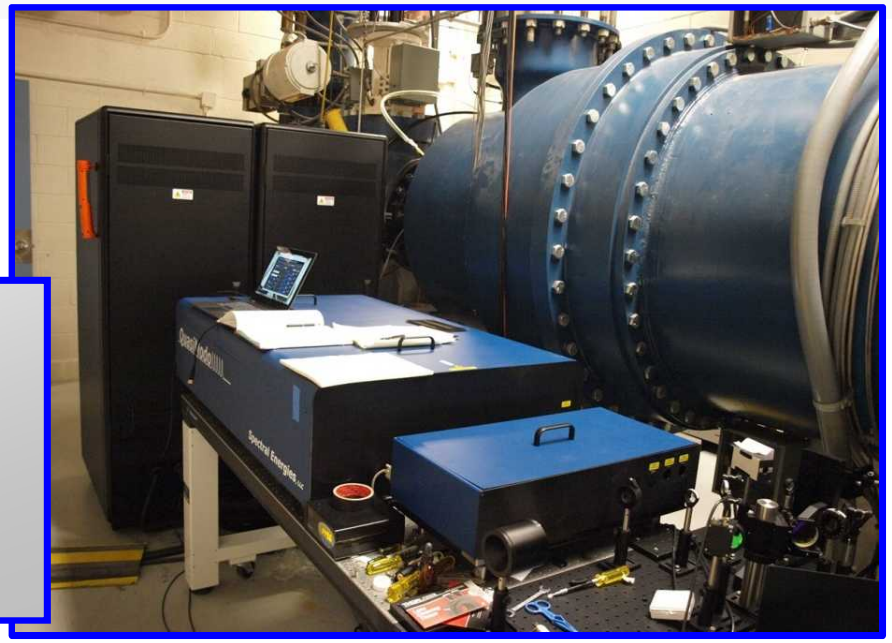

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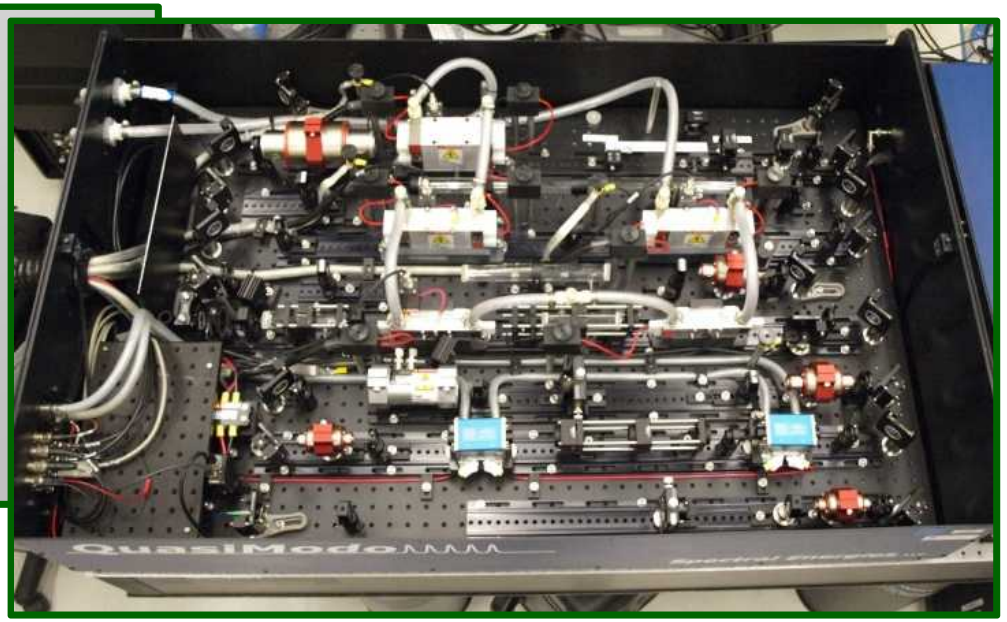
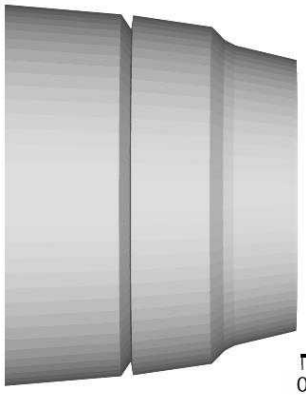
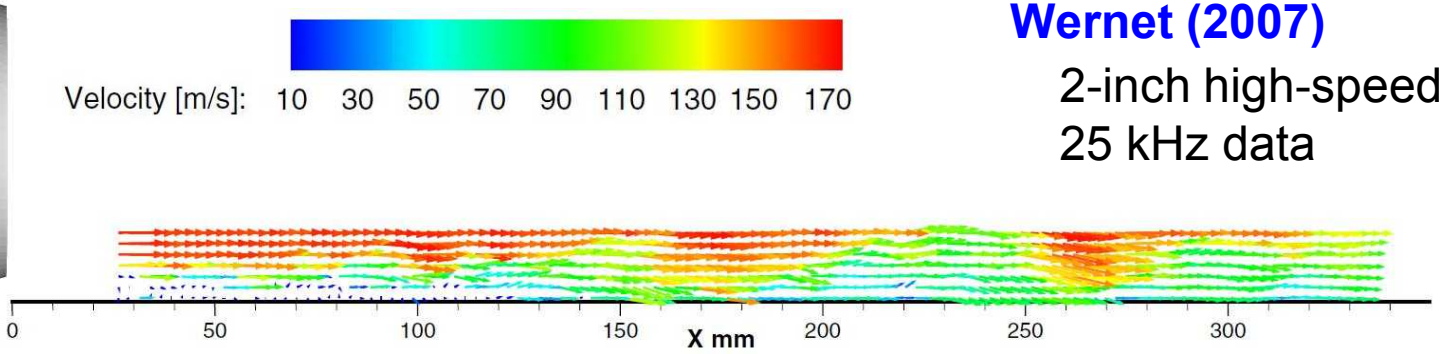
Laser Design:

- 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



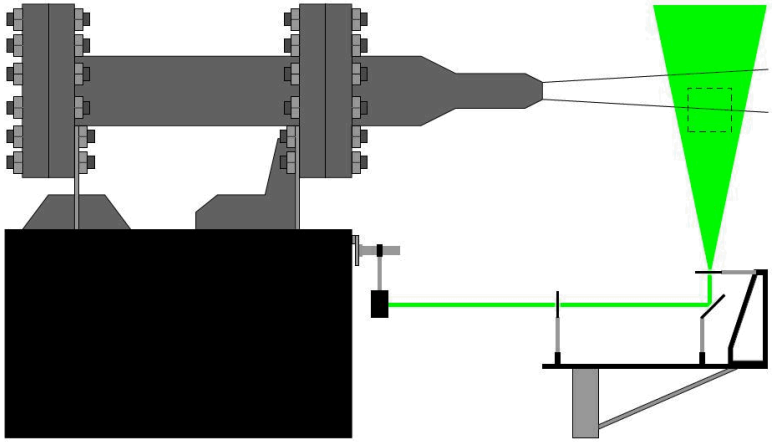


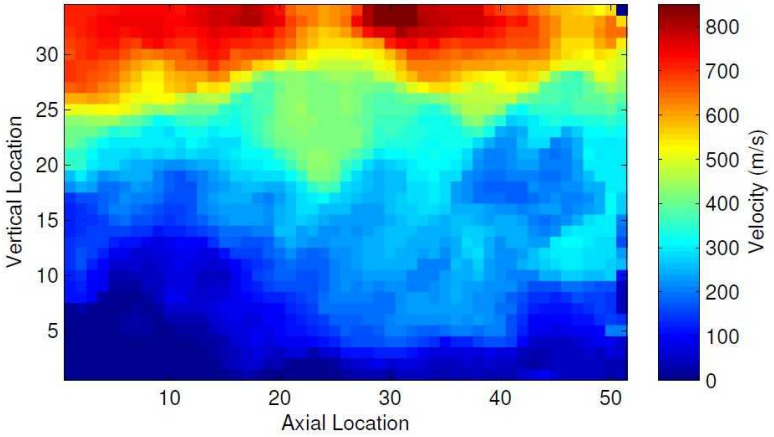
Wernet (2007)

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





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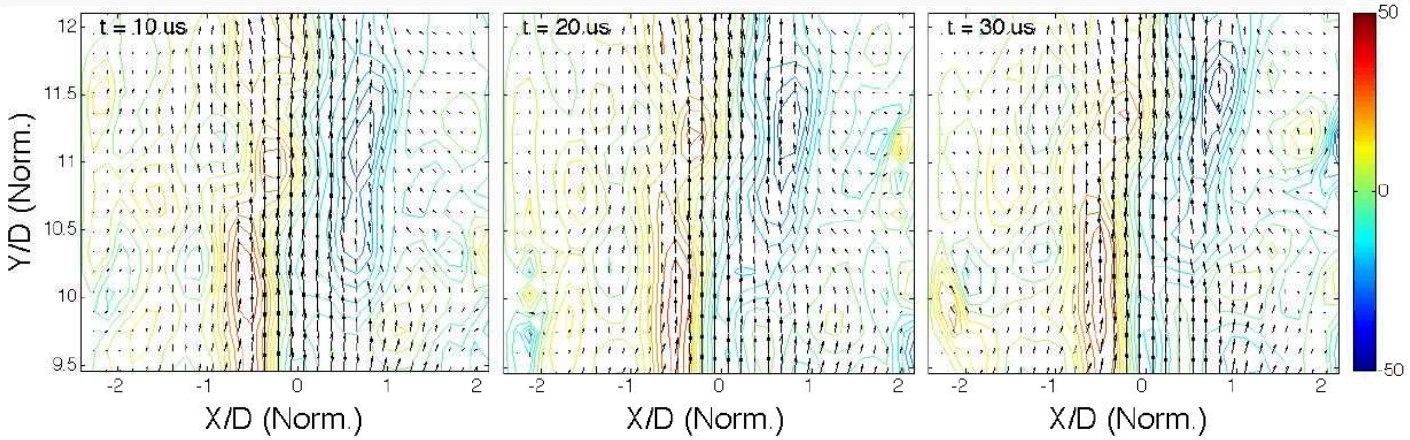
A Brief History of Pulse-Burst PIV



Miller et al (2013, 14)

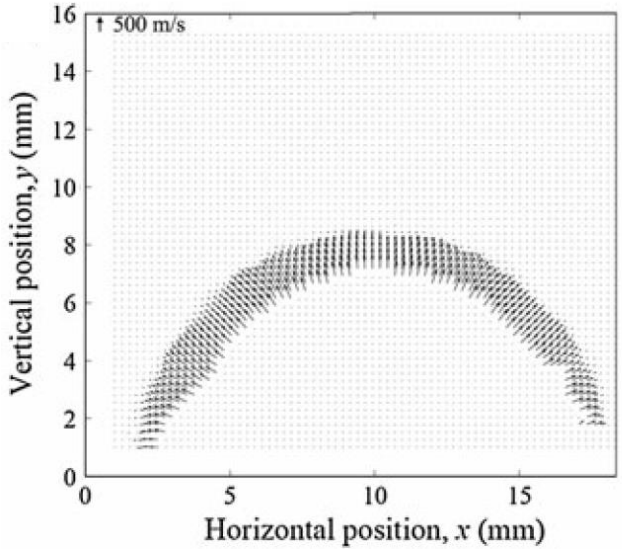
First at 10 kHz, then 100 kHz

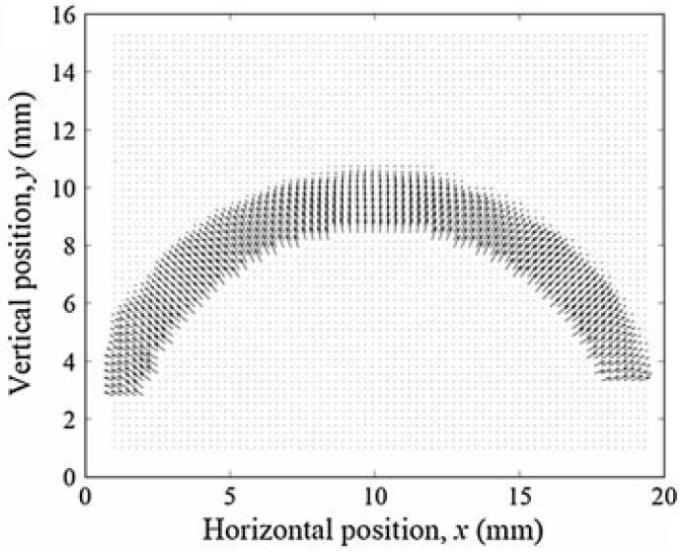
4.6 mm jet at Mach 0.3

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.

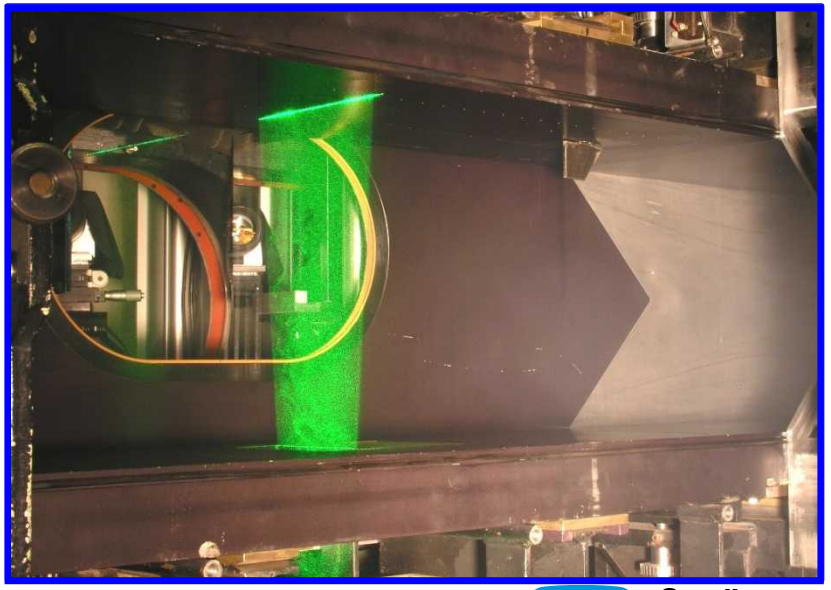
Trisonic Wind Tunnel (TWT)

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



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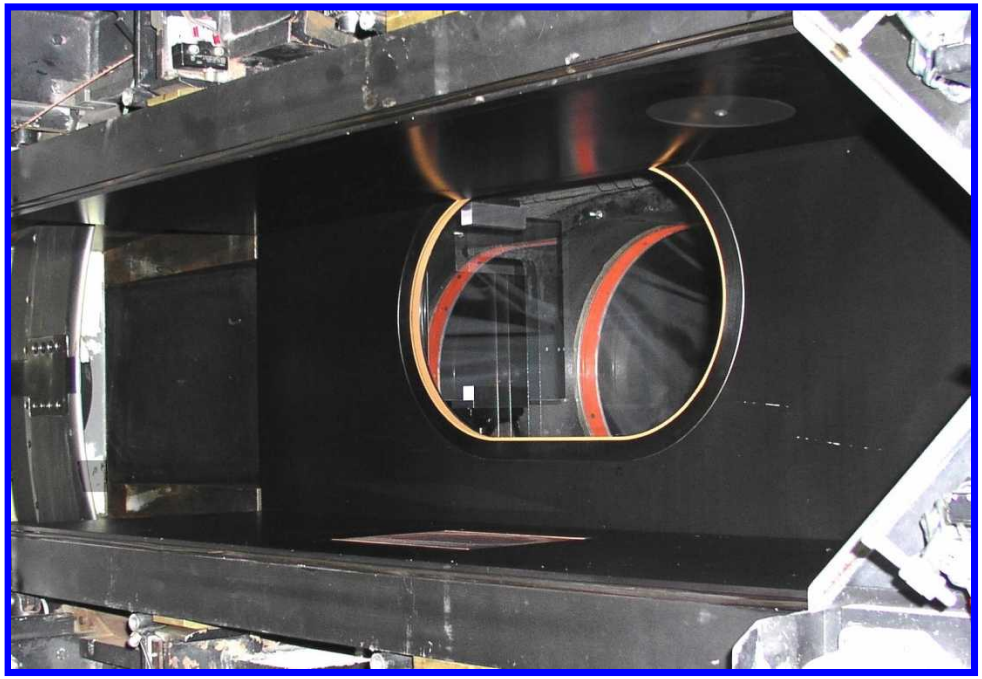
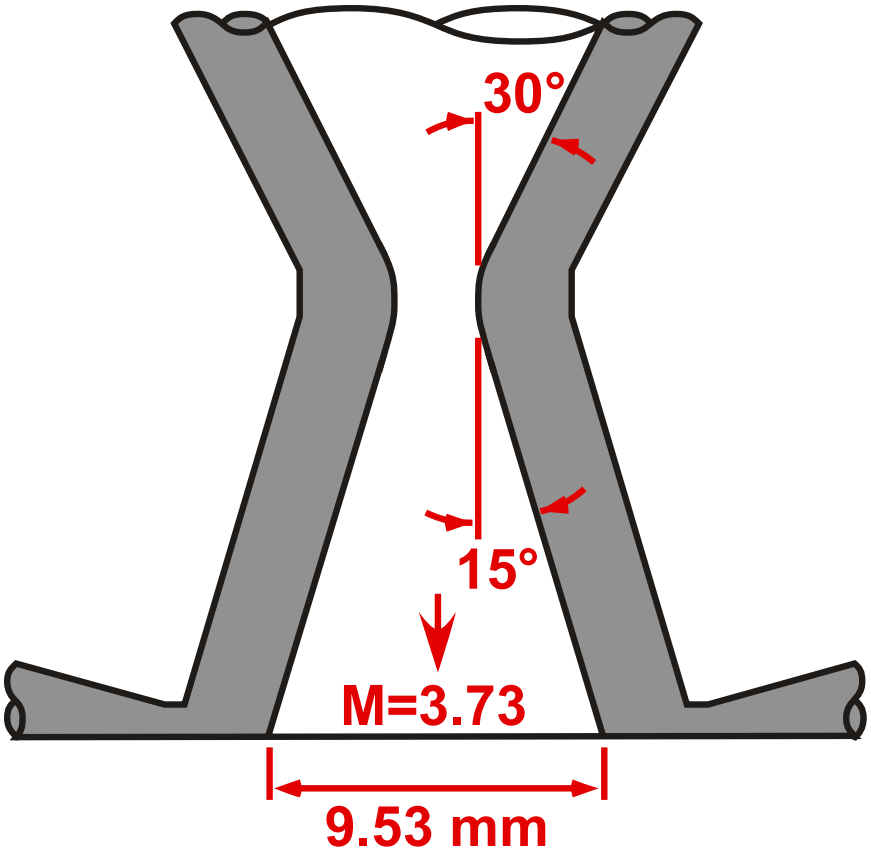
Two Test Applications

Jet in Crossflow
and
Cavity Flow
both at Mach 0.8

Supersonic Jet in Transonic Crossflow





Jet Nozzle Installation

- Mounts on top wall of TWT
- View the far-field of the interaction

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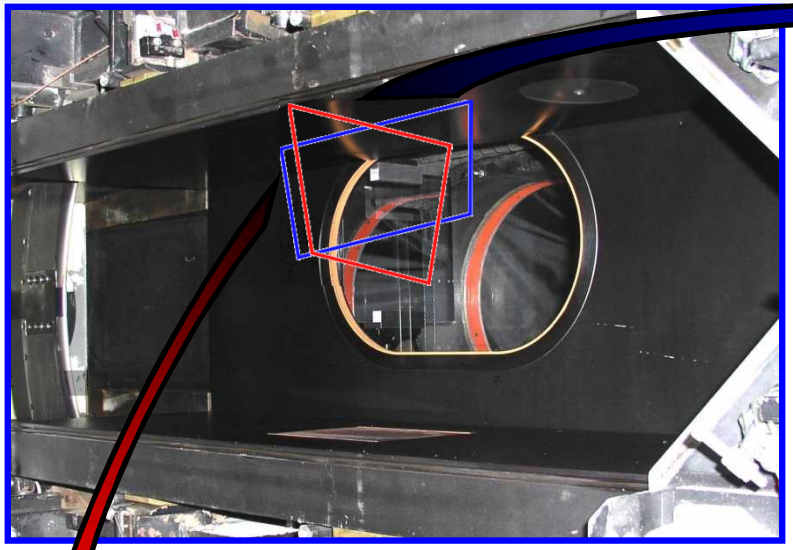
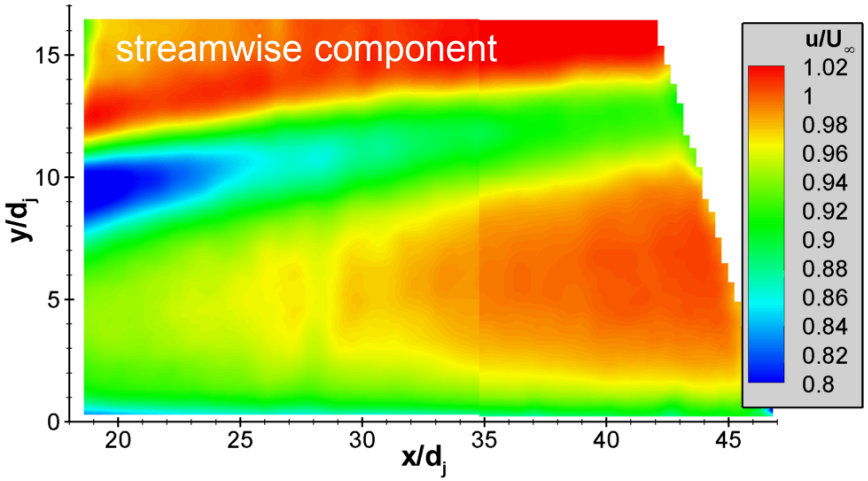
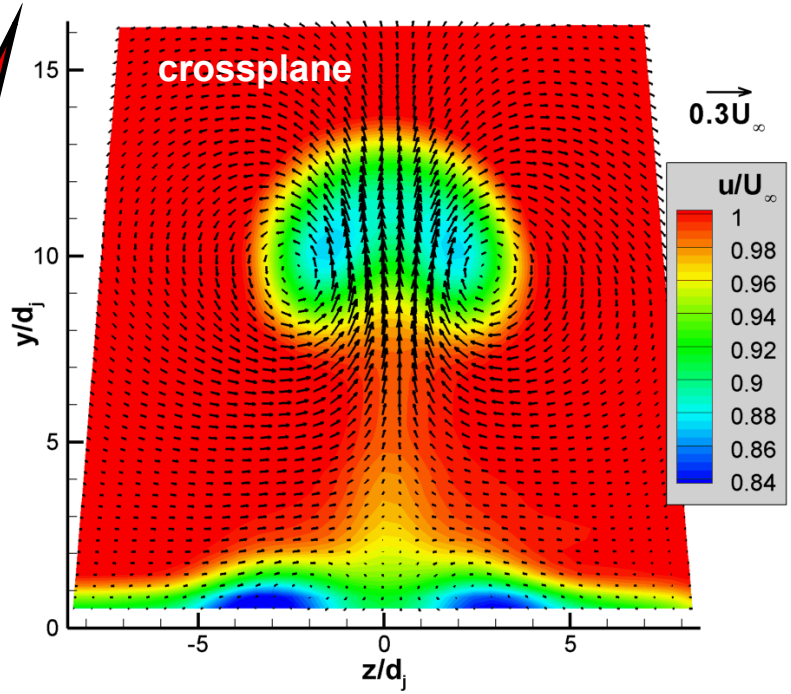
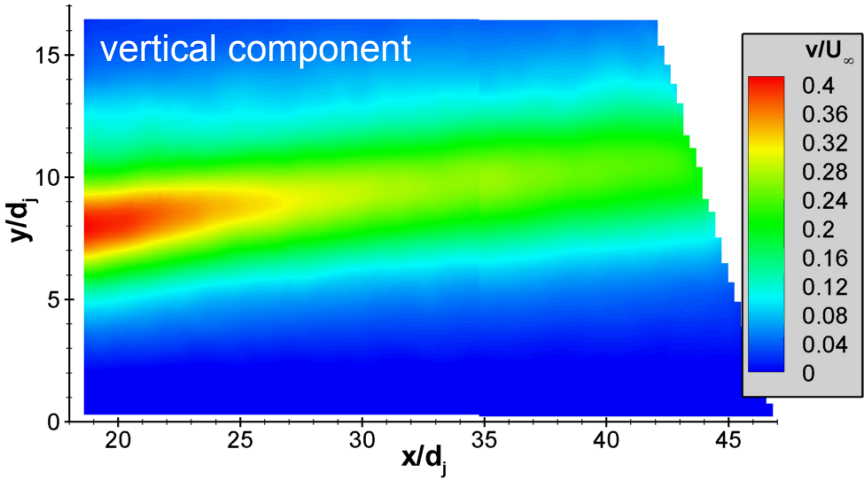
We have a lot of previous data on this configuration.



streamwise plane







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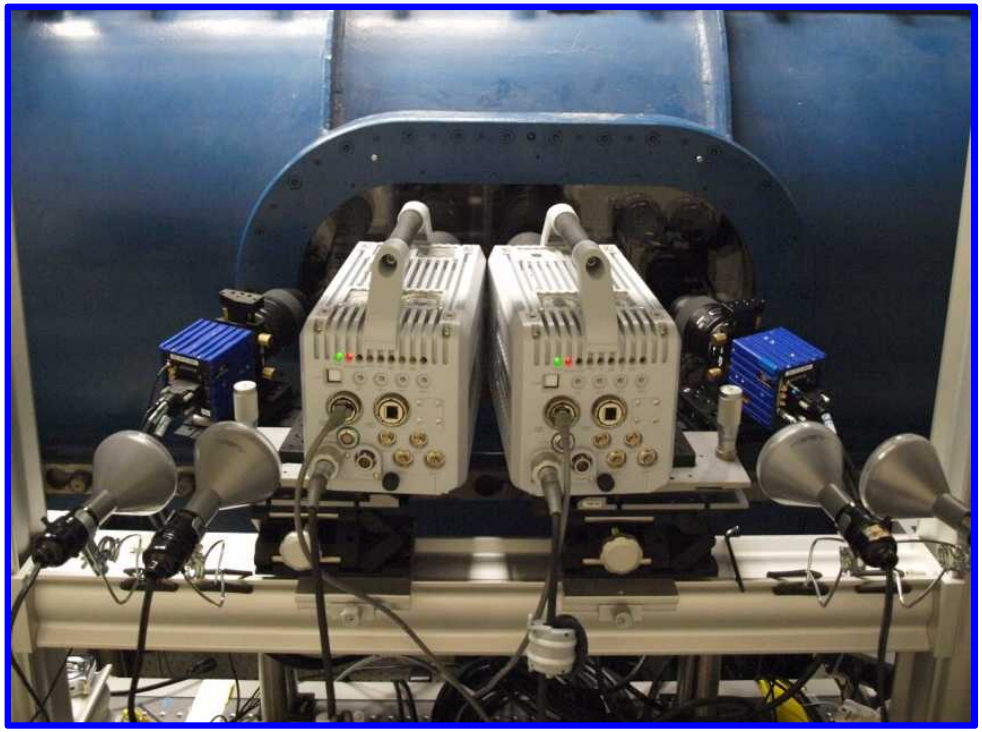
High-Speed Cameras

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

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Field of View

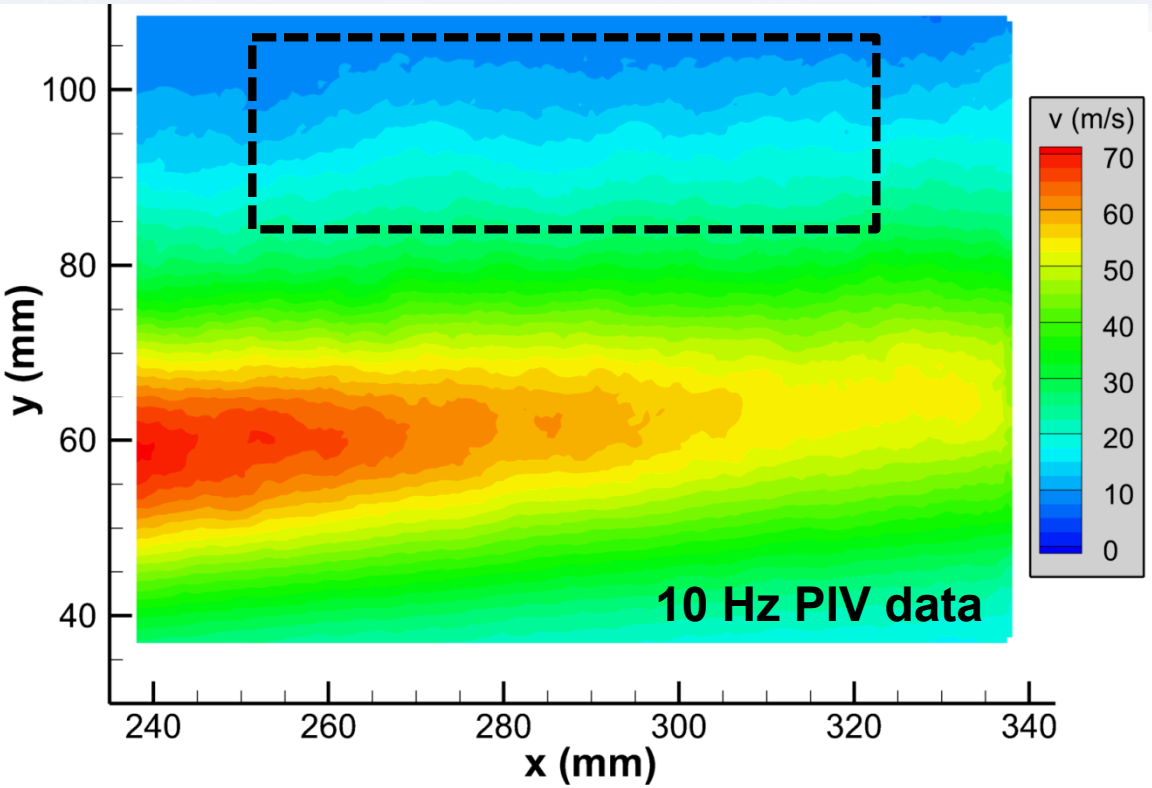
Combined field of view:

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.



jet exit

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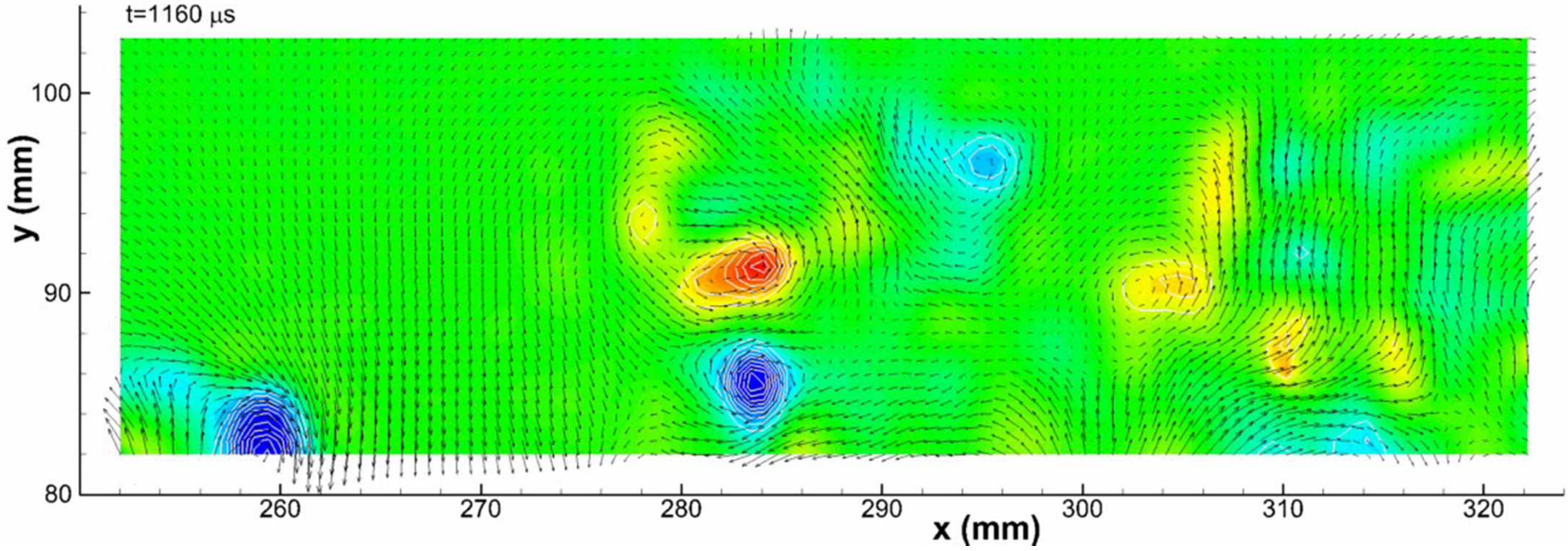
A Sample Pulse-Burst PIV Movie

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.

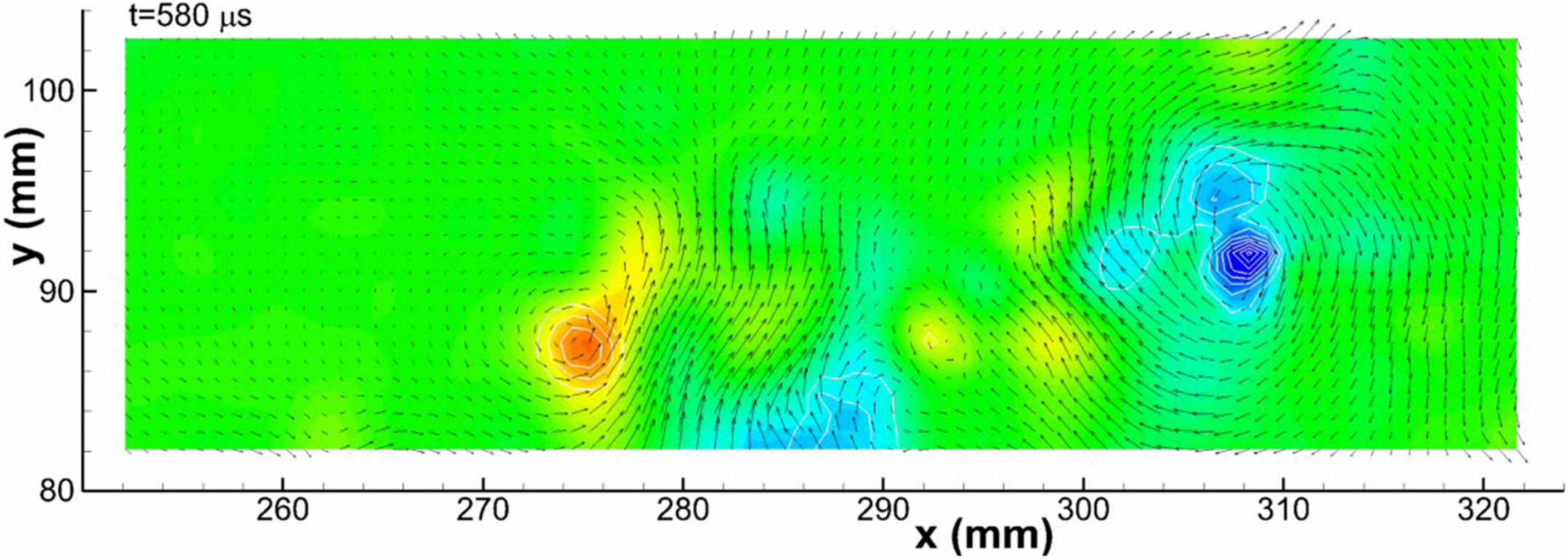
Counter-rotating eddies convect past, typically in pairs.

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

Data used for developing turbulence models and Large Eddy Simulations.

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.

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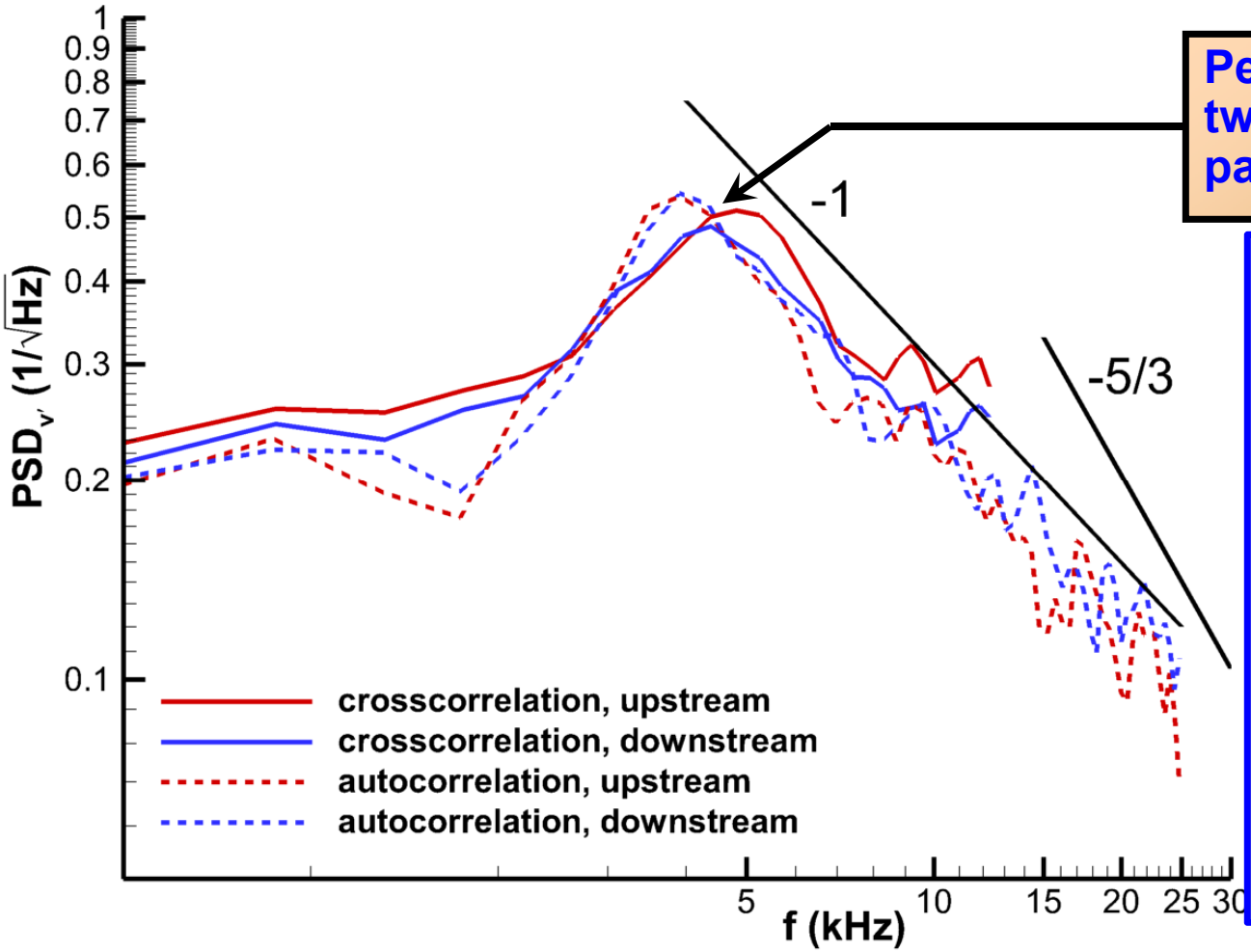
What else can we do with Pulse-Burst PIV?

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.**
- **May be a measurement artifact here.**

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

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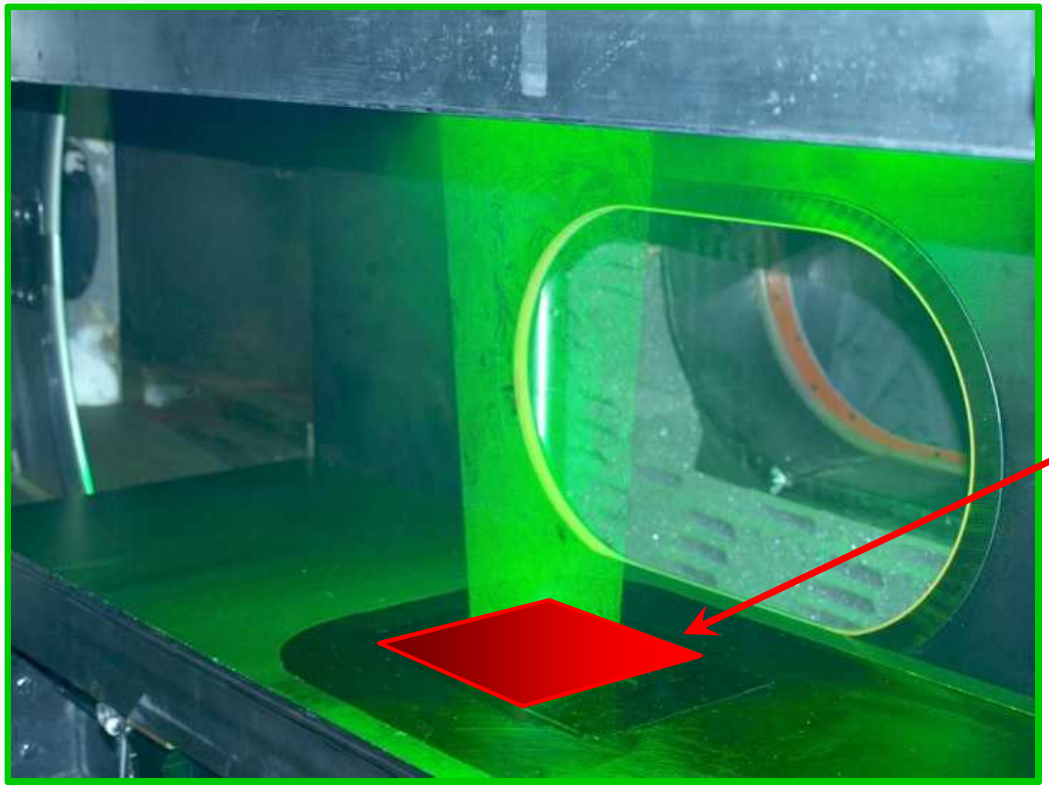
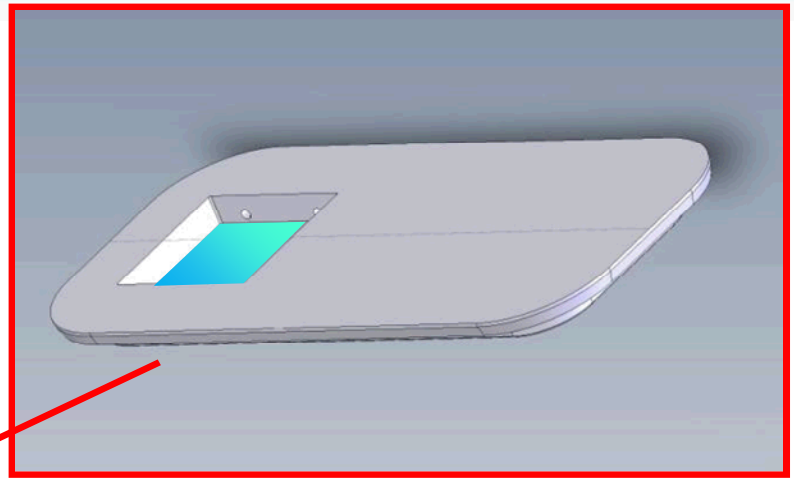
Cavity Flow





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 0.8.

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

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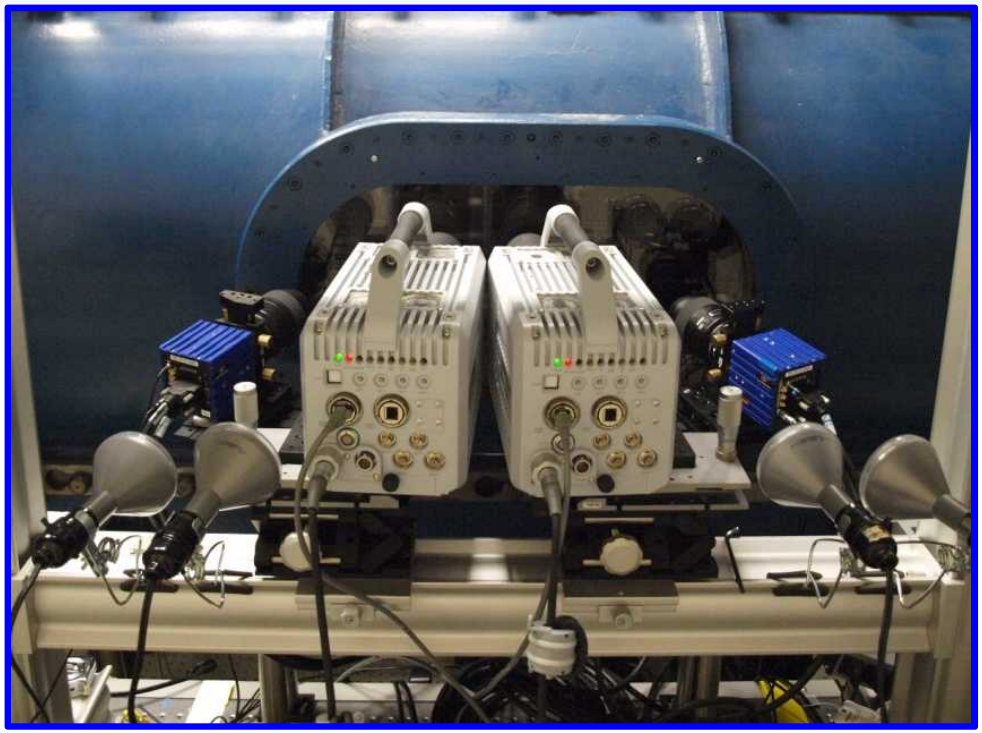
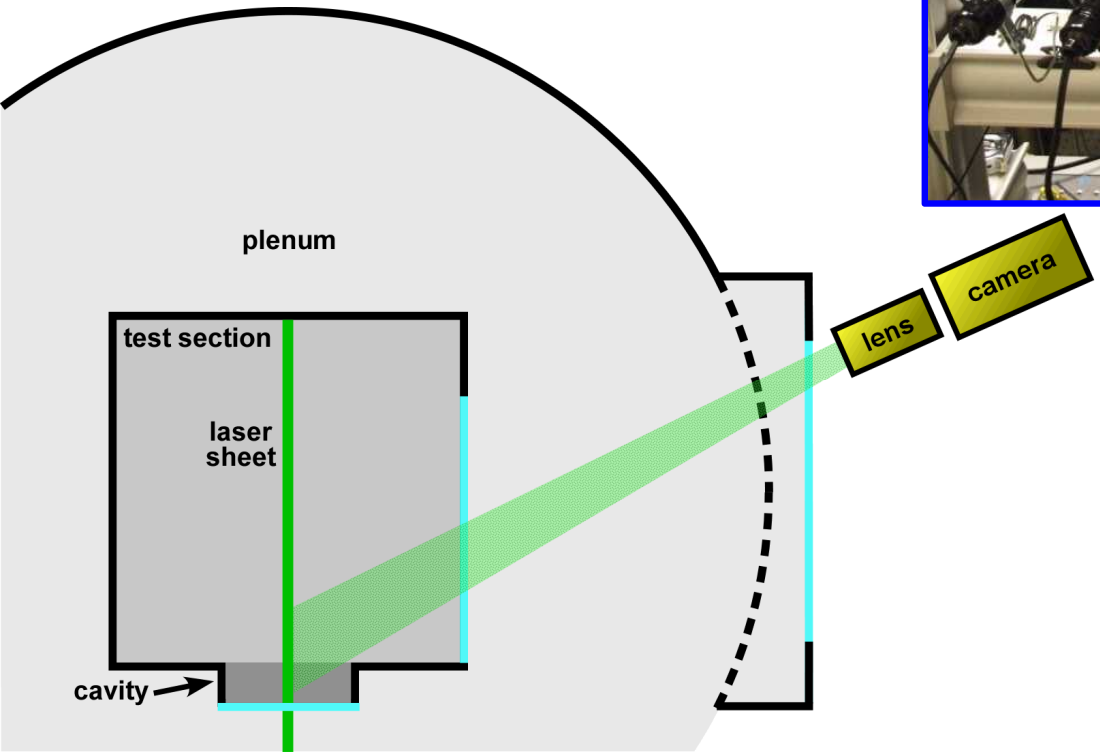
Adjust the Camera Position

Move the cameras back to increase the field of view.

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

- Can reach about 55% depth.
- Maximum of 20% 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.

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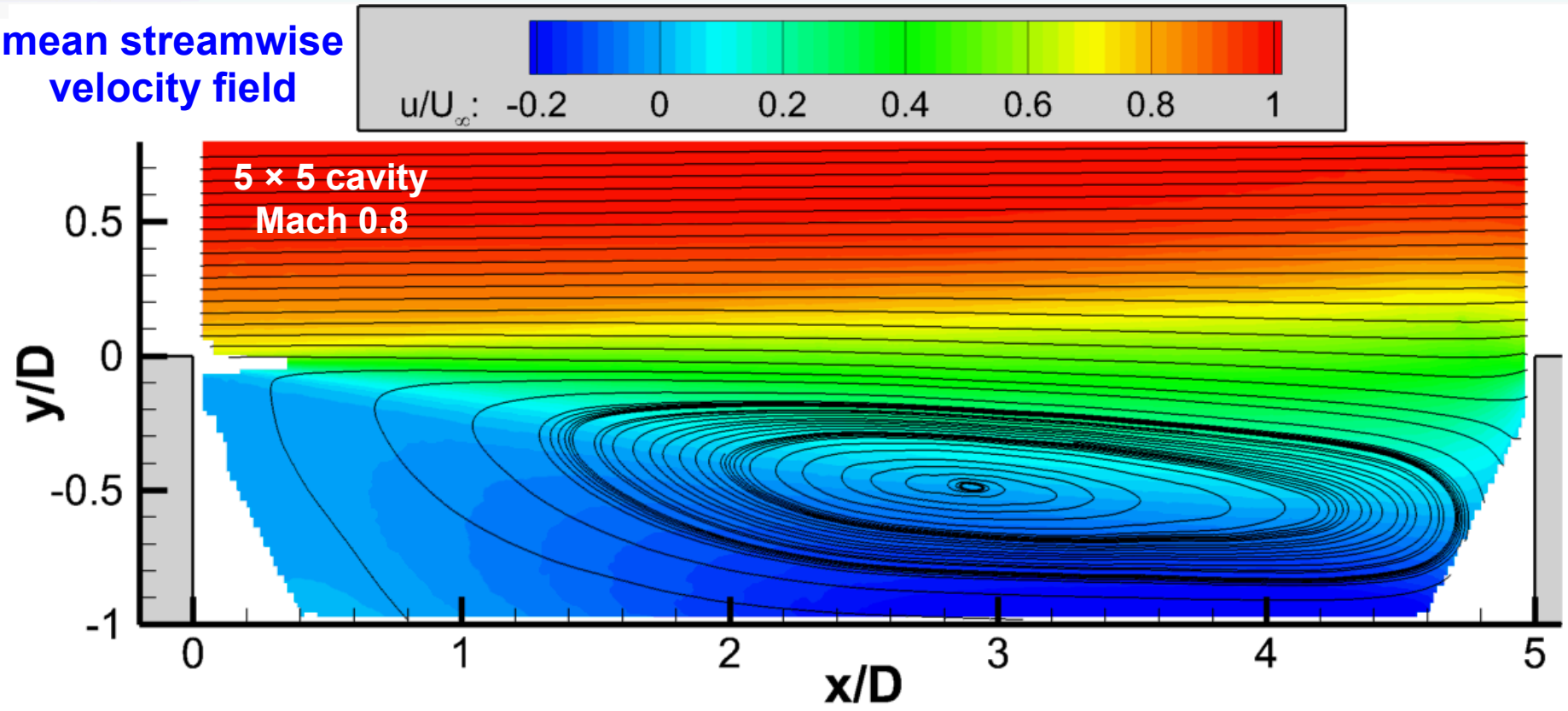
We have a lot of data on this flow as well.

mean streamwise velocity field



A dual stereo PIV setup imaged nearly the entire depth of the cavity despite the optical access restrictions of a finite-width cavity.

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

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

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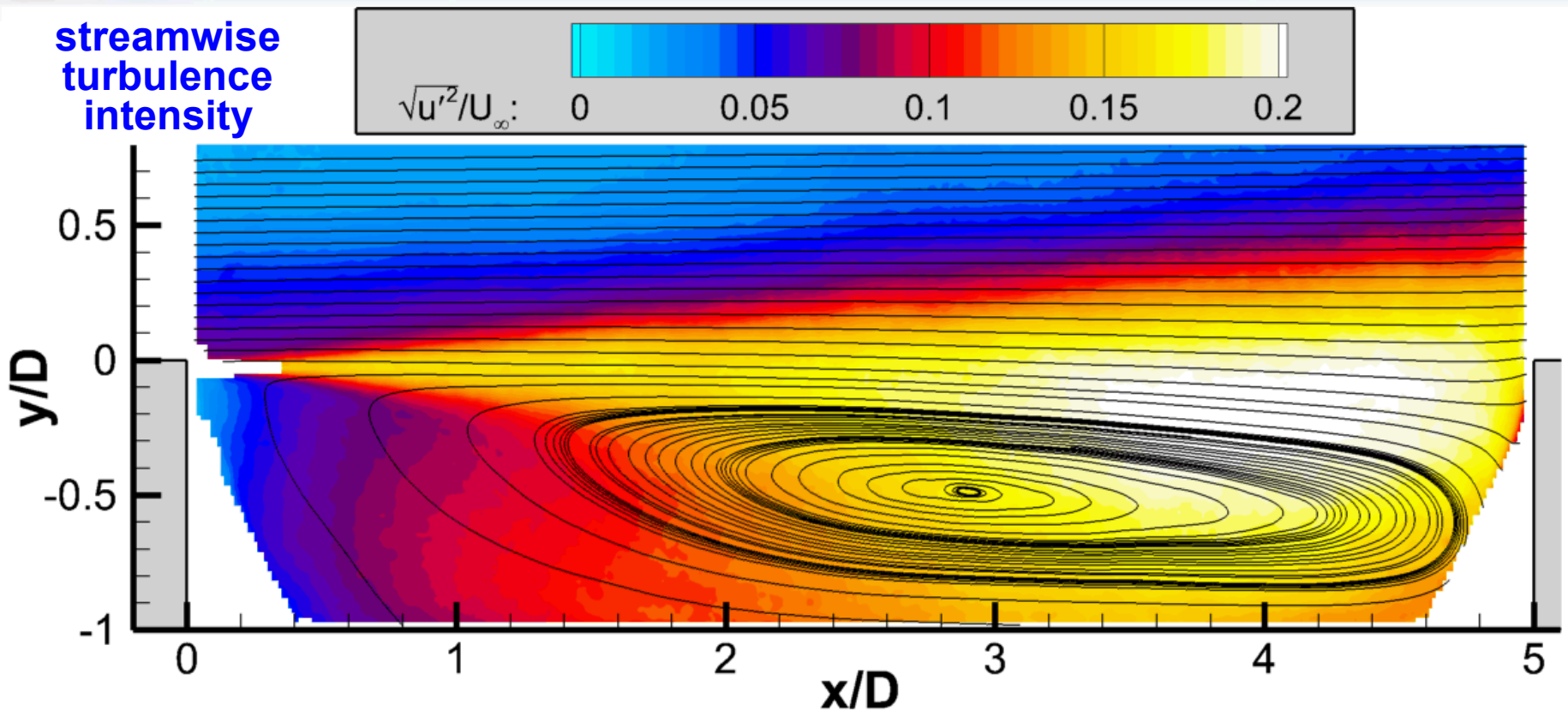

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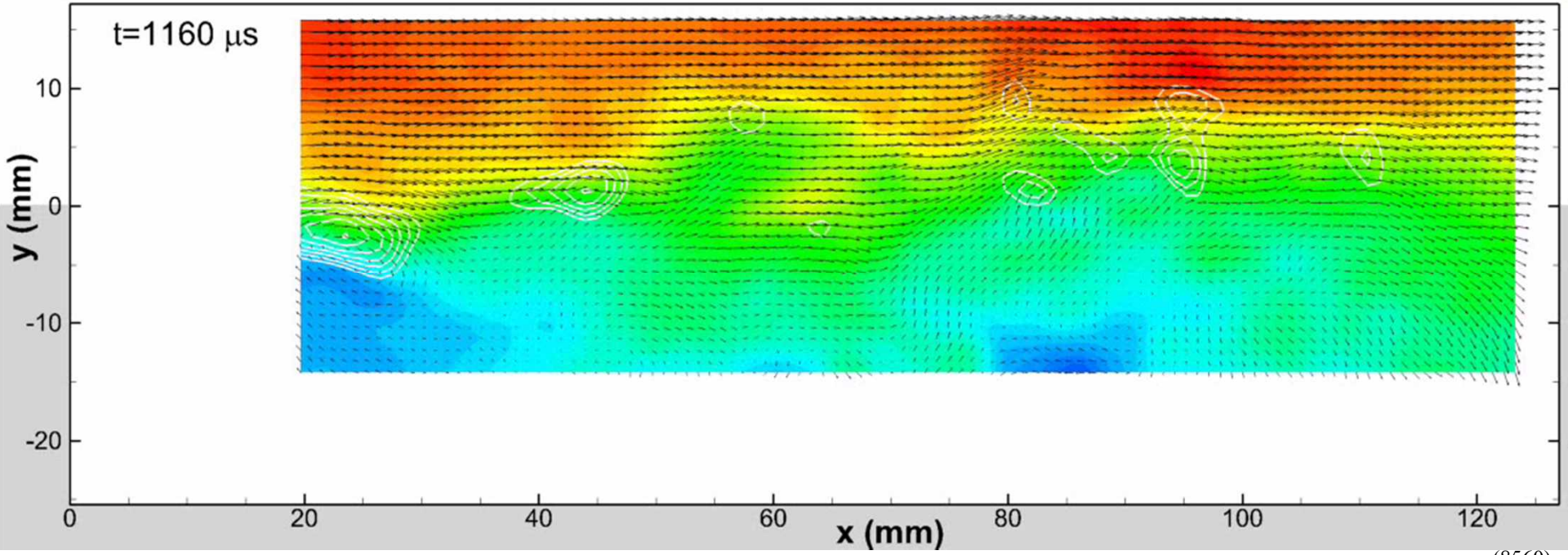
Sample Pulse-Burst PIV Movies

This is a 10.2 ms movie with 256 vector fields acquired at 25 kHz.



(8560)

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.

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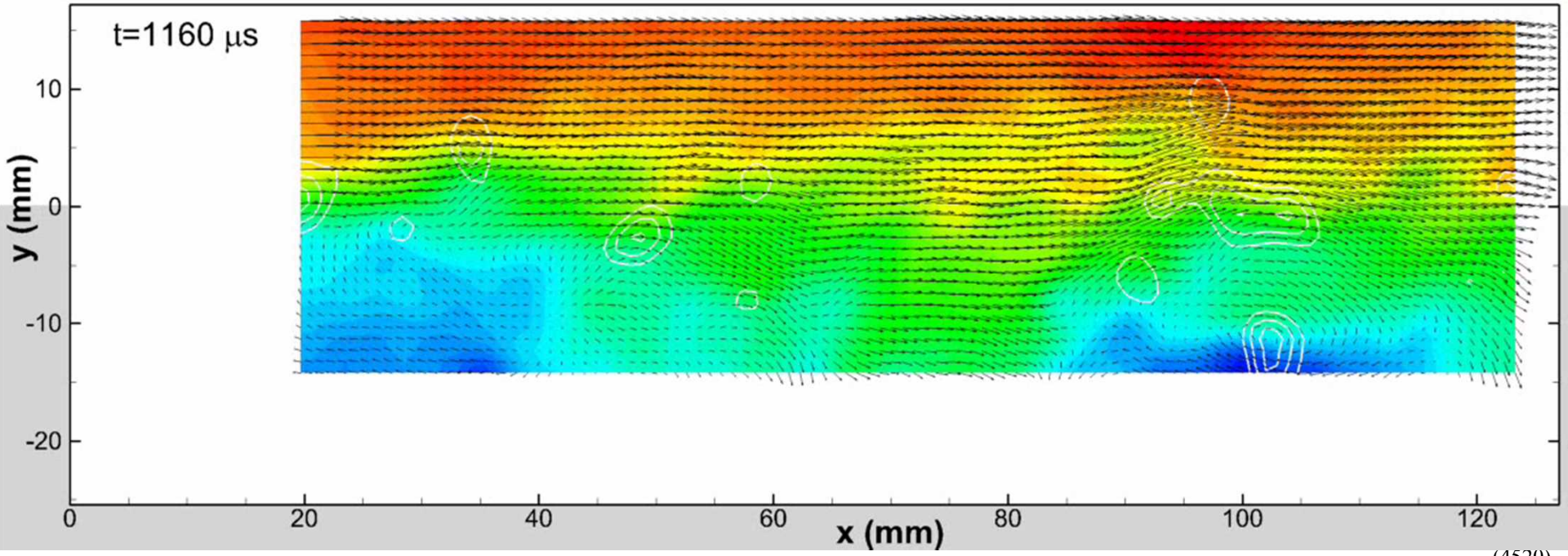

(4520)

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.

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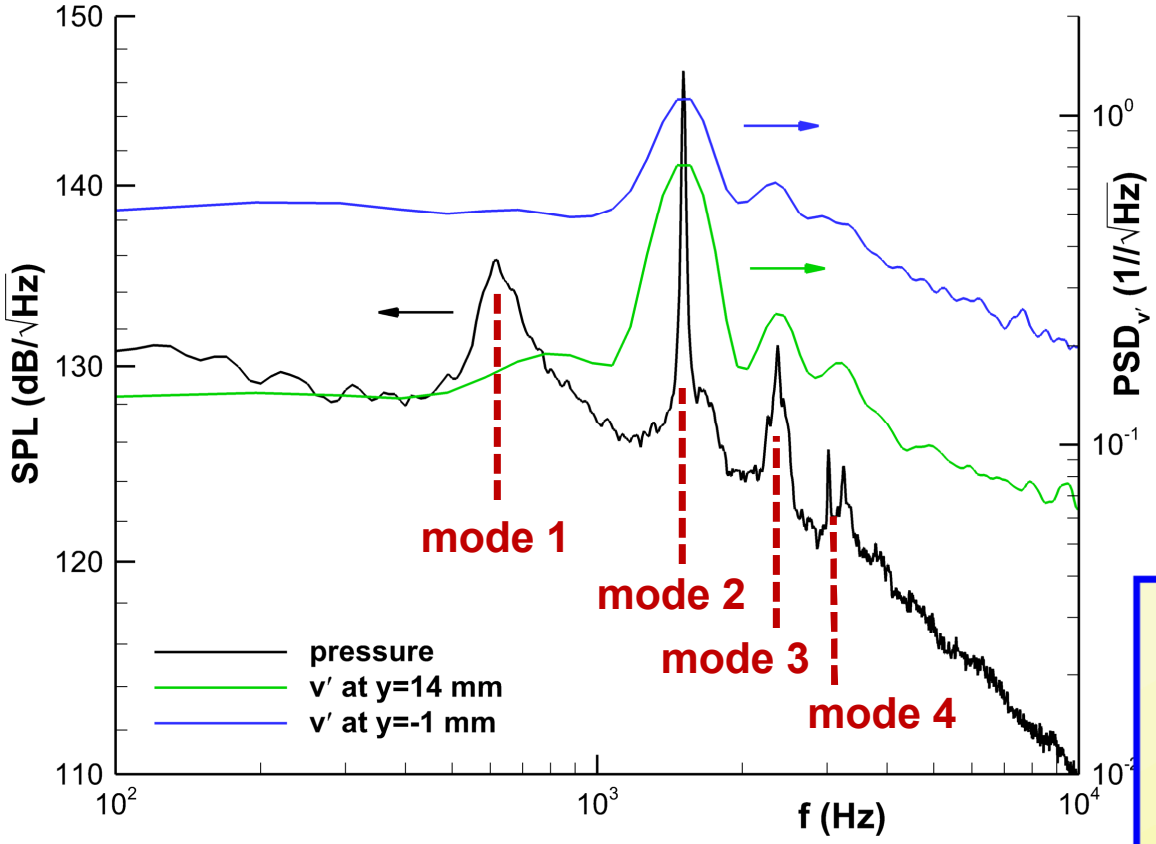
Can we identify the cavity resonances using Pulse-Burst PIV?

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.

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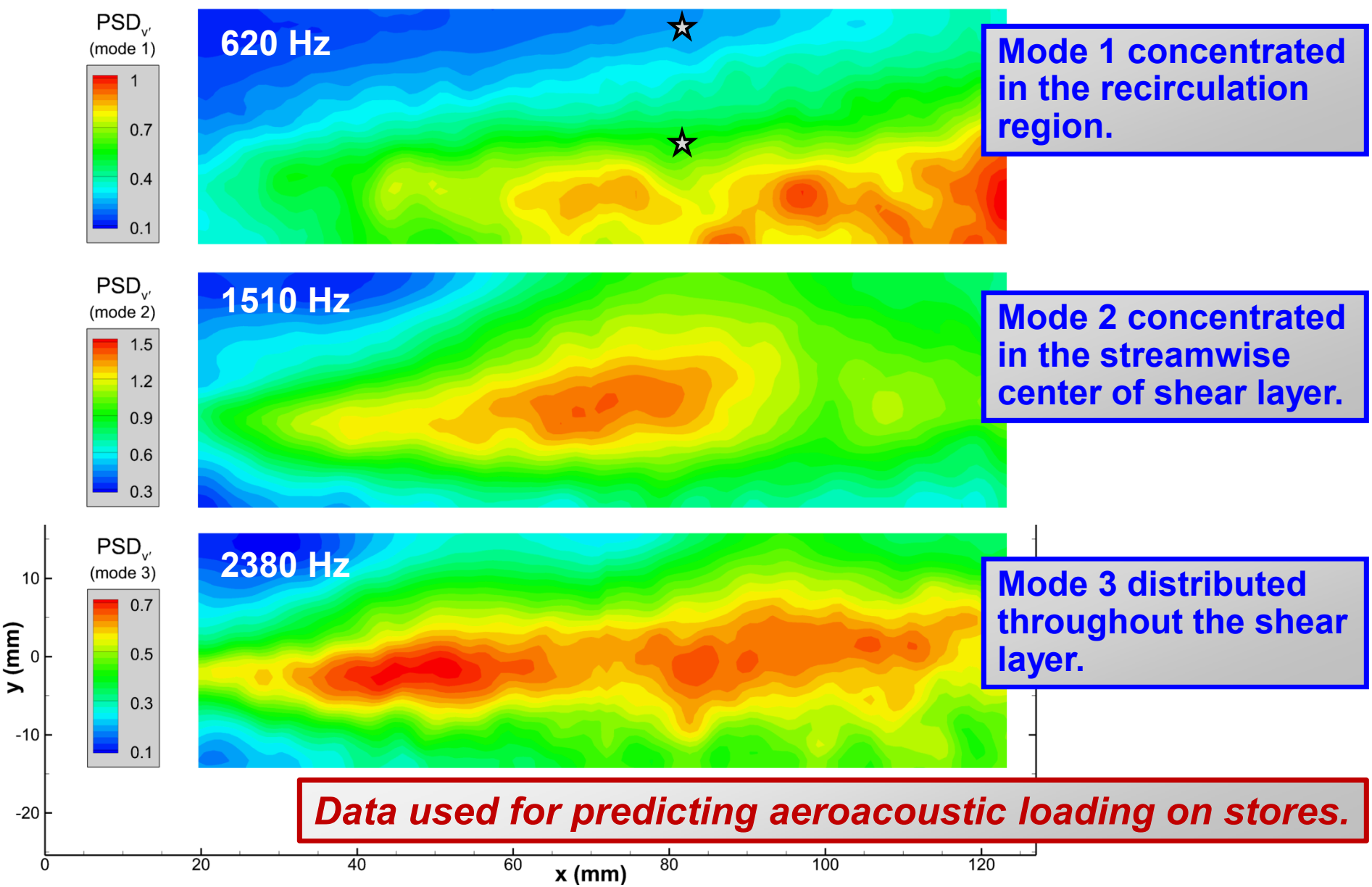
Spatial Distribution of Resonance Modes



Data used for predicting aeroacoustic loading on stores.

What's Next?

Data up to Mach 2.5.

- Started working on this a few weeks ago.

Add more cameras!

- Boost the framing rate without sacrificing spatial resolution.
- More cameras will allow us to further tile the field of view.

Data analysis possibilities seem nearly endless:

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

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.

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