SAND2016-4592C

Obtaining High-Frequency Content from Pulse-Burst PIV for Turbulence Model Development

Steven Beresh, Justin Wagner,
John Henfling, and Rusty Spillers
Sandia National Laboratories
Albuquerque, NM

STAI 125th Meeting
May 15-18, 2016
Riverhead, NY, U.S.A.

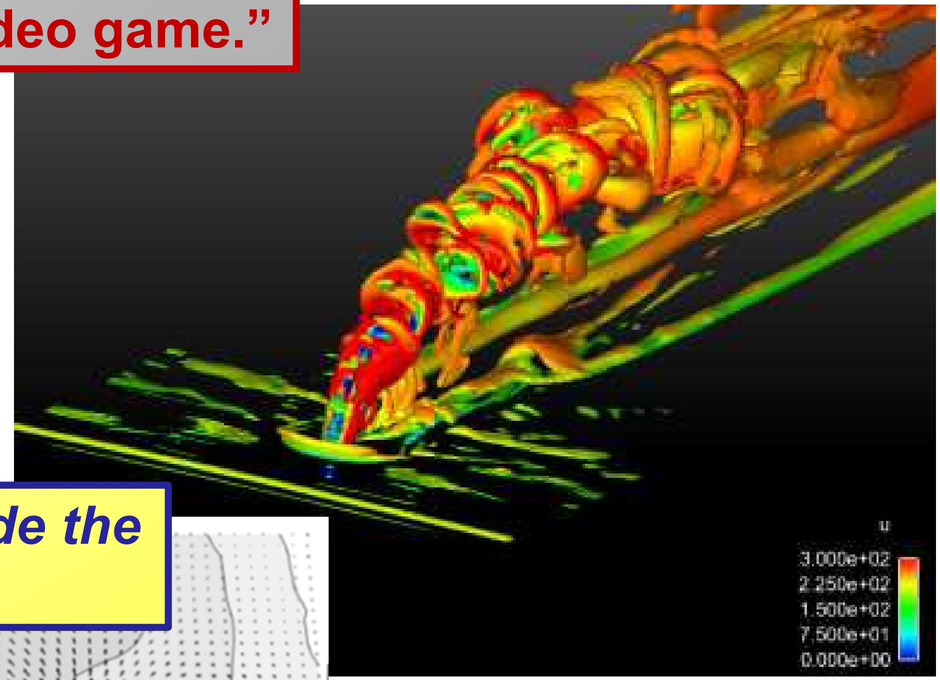
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

PIV Data for CFD Validation

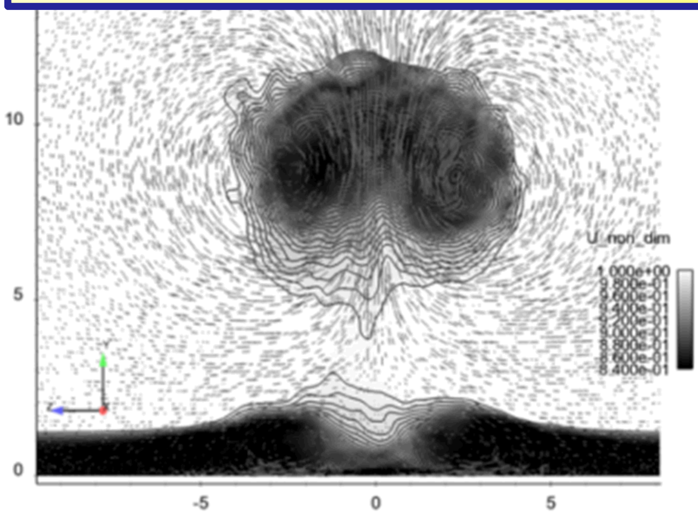
"Without validation, CFD is just a video game."

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

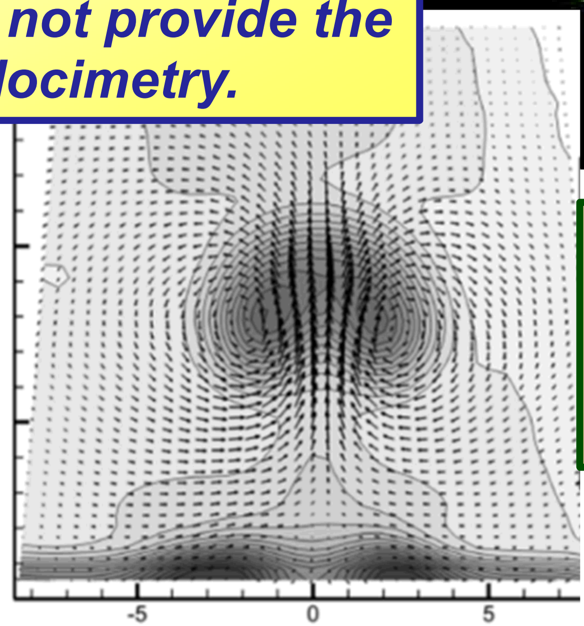
Our PIV experiments provide key validation data.



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



Hybrid RANS-LES / DES of Jet-in-Crossflow



PIV data of Jet-in-Crossflow

Recent applications require development of models of unsteady behavior.

Sandia National Laboratories

Evolving our use of CFD

Most of our CFD has been *RANS* (Reynolds-Averaged Navier Stokes)

- Low computational cost, simulate many cases.
- Results have been disappointing while demands for accuracy are rising.

More use of *LES/DES* (Large-Eddy Simulation / Detached-Eddy Simulation)

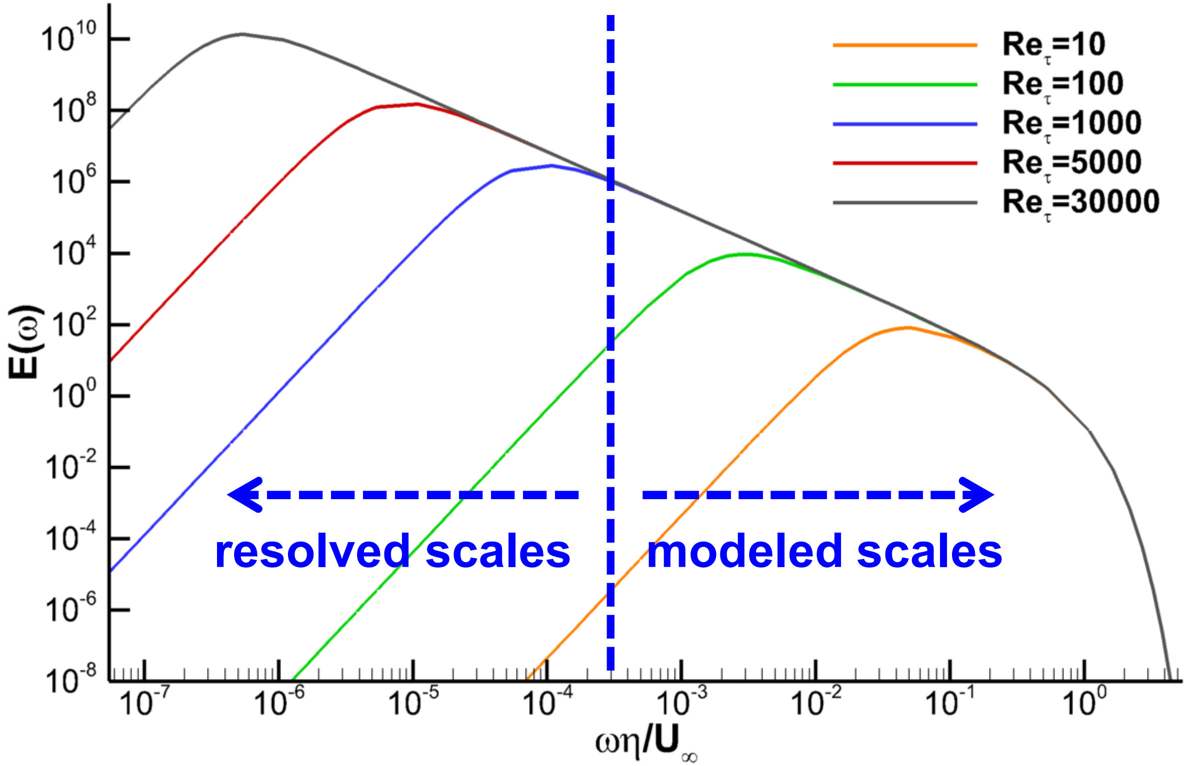
- Much more computationally expensive.
- Poses different needs for validation – ***temporal flowfield data***.

A spectral form for turbulent fluctuations is assumed.

Are these spectra an accurate description of the flow?

For computational efficiency, only simulate large scales.

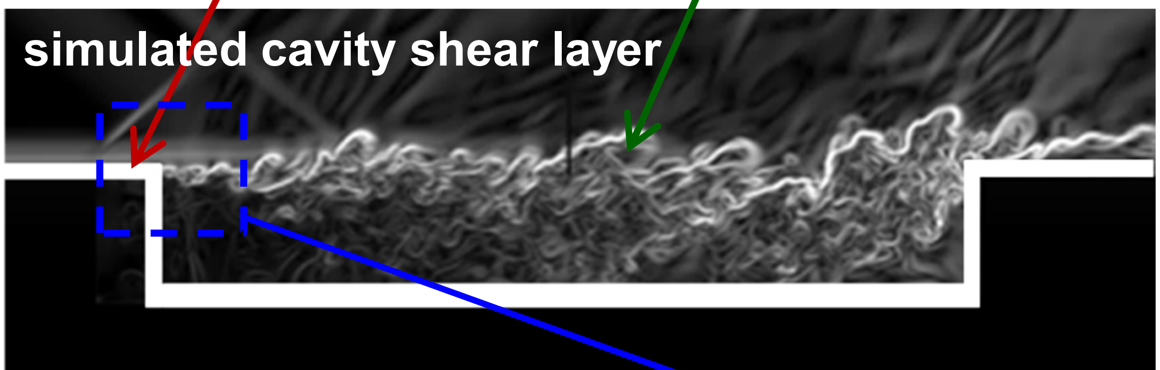
What is the cutoff frequency between large eddies and a subgrid model?



Hybrid RANS/LES Modeling

LES model applied away from walls

RANS model applied in the near-wall region



Where should the boundary between RANS/LES reside?

Is the assumed spectral content of turbulence accurate?

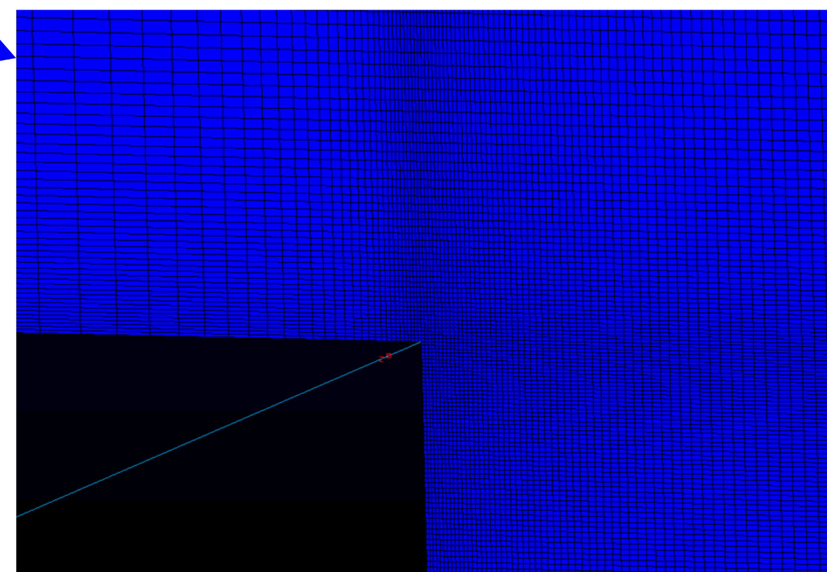
We need experimental data to validate these simulations!

Expand our PIV capability to provide the time component.

Grid determined by computational size or geometrical complexity.

Grid enforces a cutoff frequency.

This may apply the subgrid model on inappropriate scales.



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**

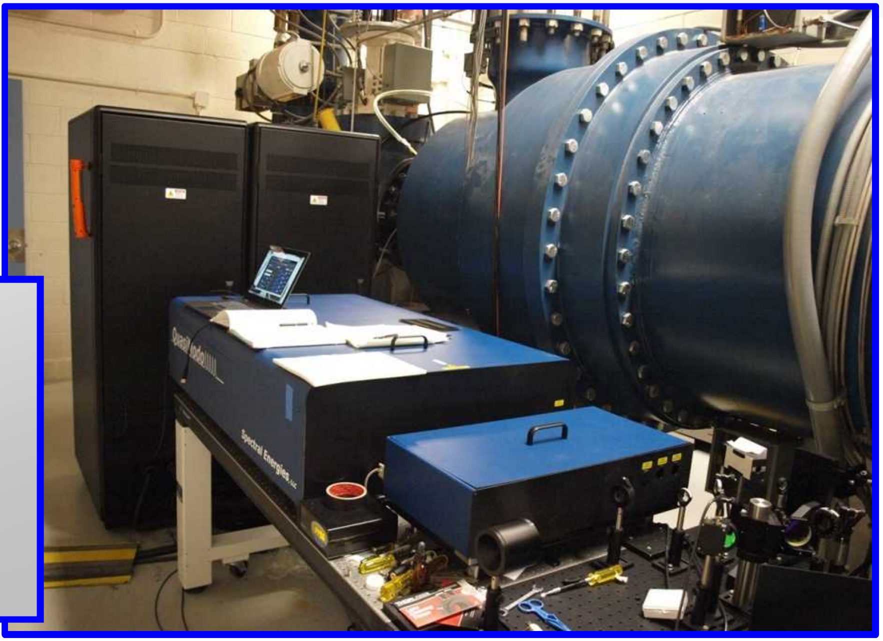
A pulse-burst laser is necessary.

Sandia National Laboratories

Pulse-Burst Laser

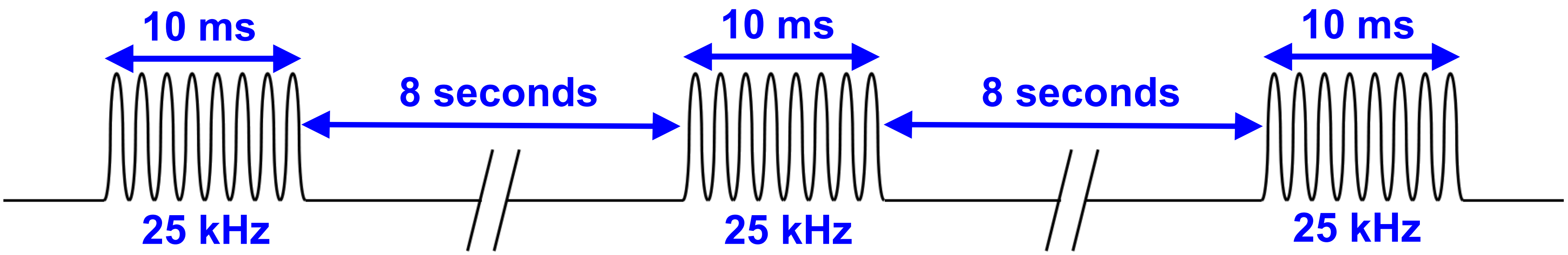
A pulse-burst laser allows high energy and high repetition rates.

But a very low duty cycle.



Pulse-Burst Laser:

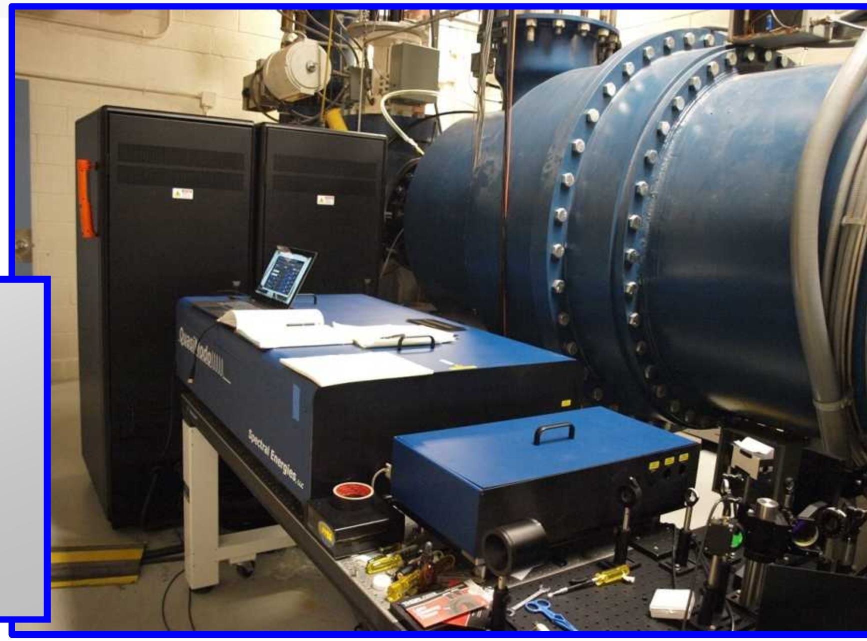
- Manufactured by Spectral Energies, LLC
- Bursts of pulses for 10.2 ms
- Up to 500 kHz of pulse pairs, 20-500 mJ
- But only one burst every 8 sec



Pulse-Burst Laser

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

But a very low duty cycle.

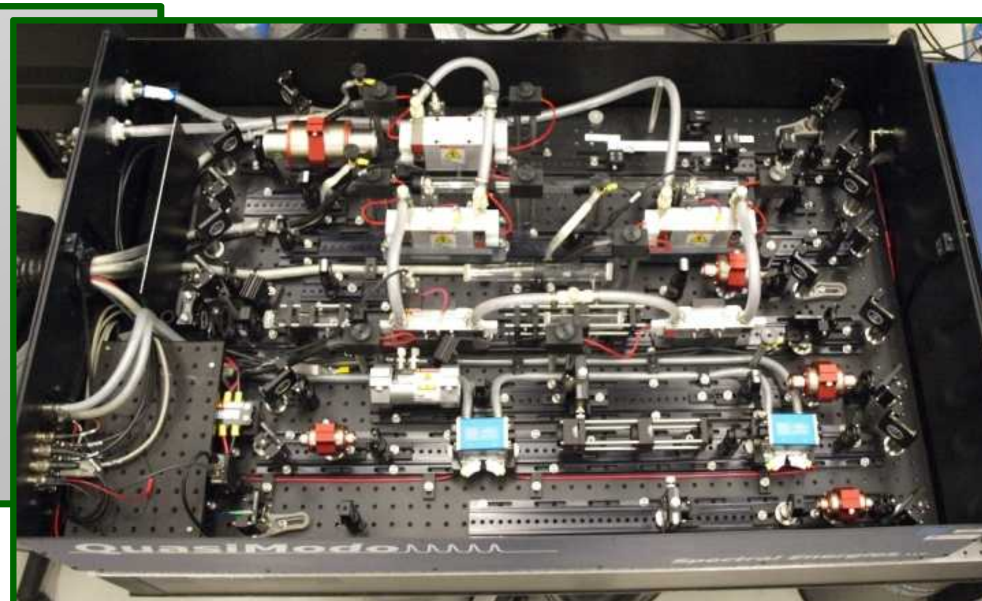


Pulse-Burst Laser:

- **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**



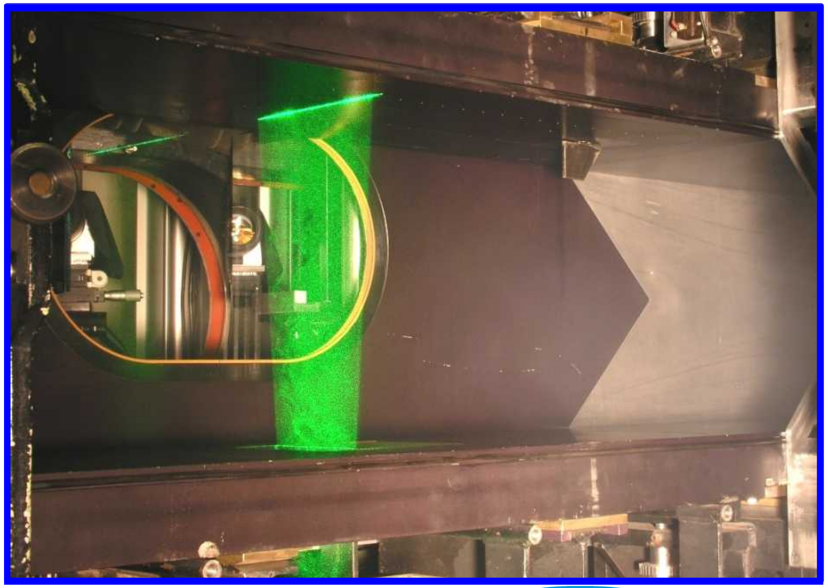
Trisonic Wind Tunnel (TWT)

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

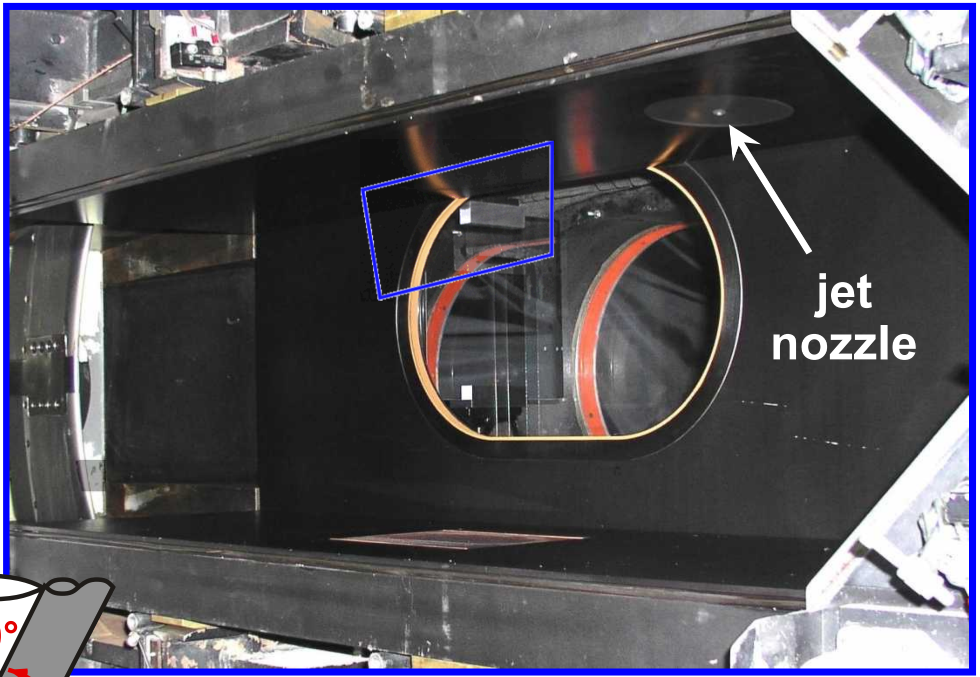
- Multiple configurations
  - 4 porous walls
  - 3 porous & 1 solid wall (half-body models)
  - 2 porous walls, 2 solid walls (imaging)
  - 4 solid walls   **Typical PIV Configuration**
- Test section enclosed in pressurized plenum



Sandia National Laboratories

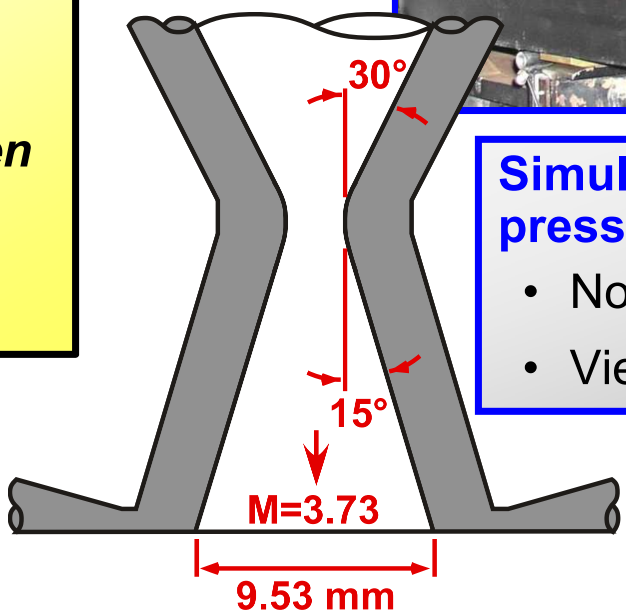
Our First Test Application

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.

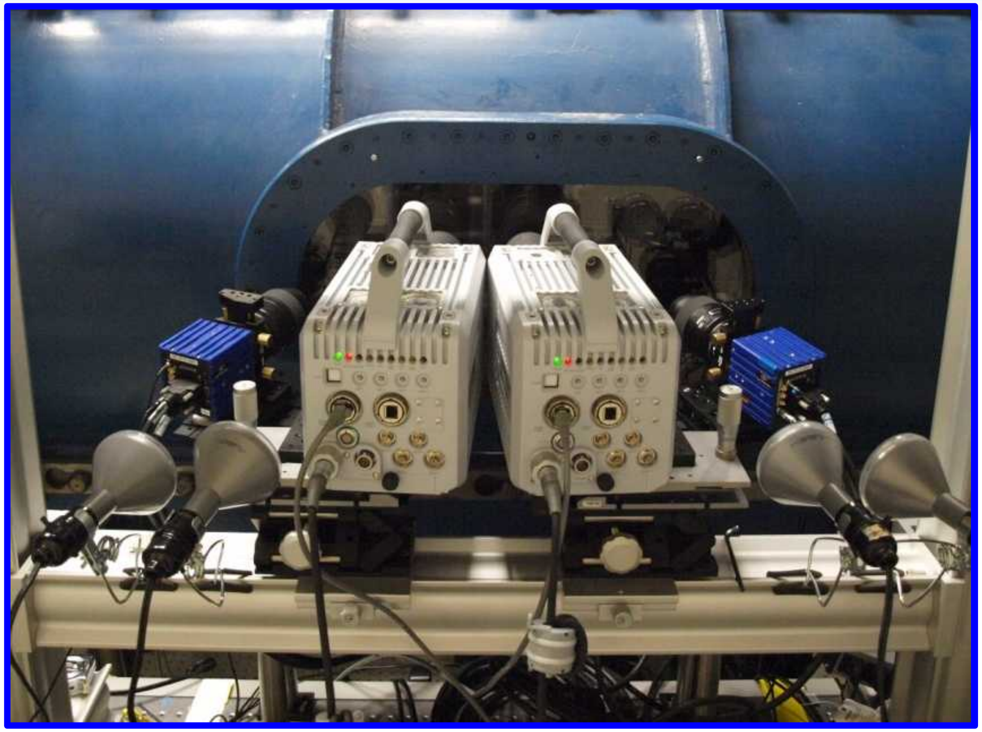
- Nozzle mounts on top wall of TWT.
- View the far-field of the interaction.

Sandia National Laboratories

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

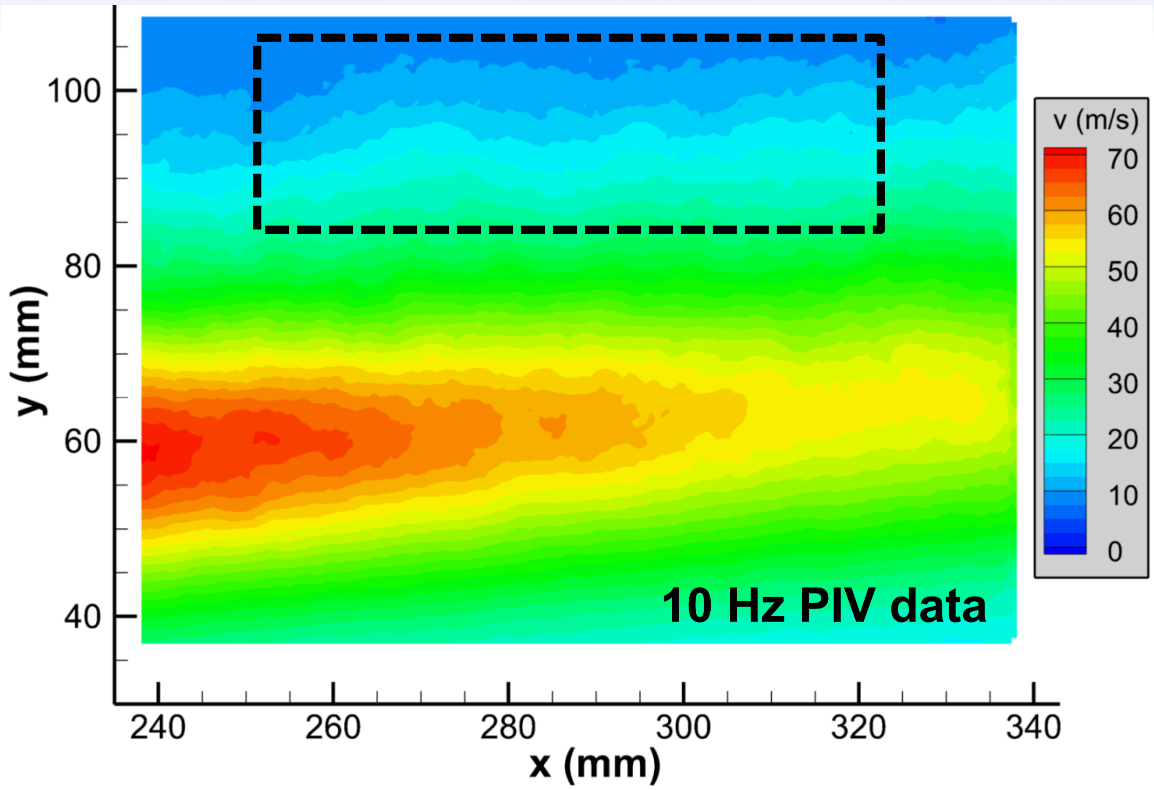
Combined field of view:

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.

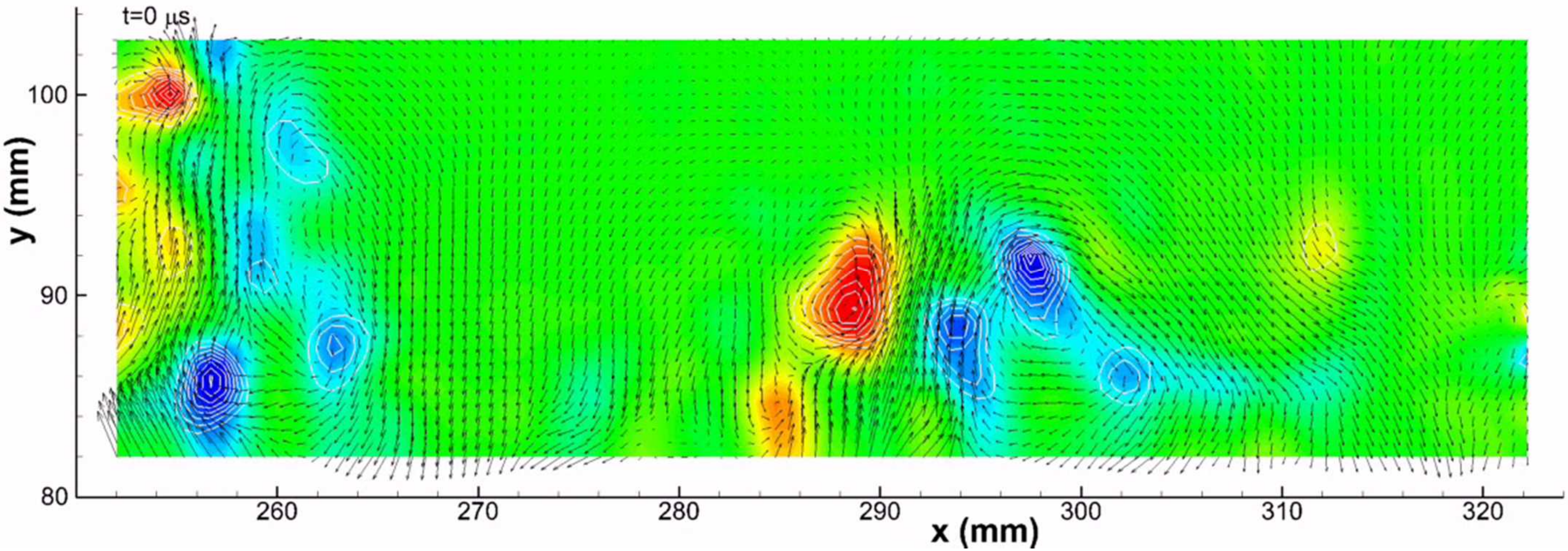


jet exit

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.

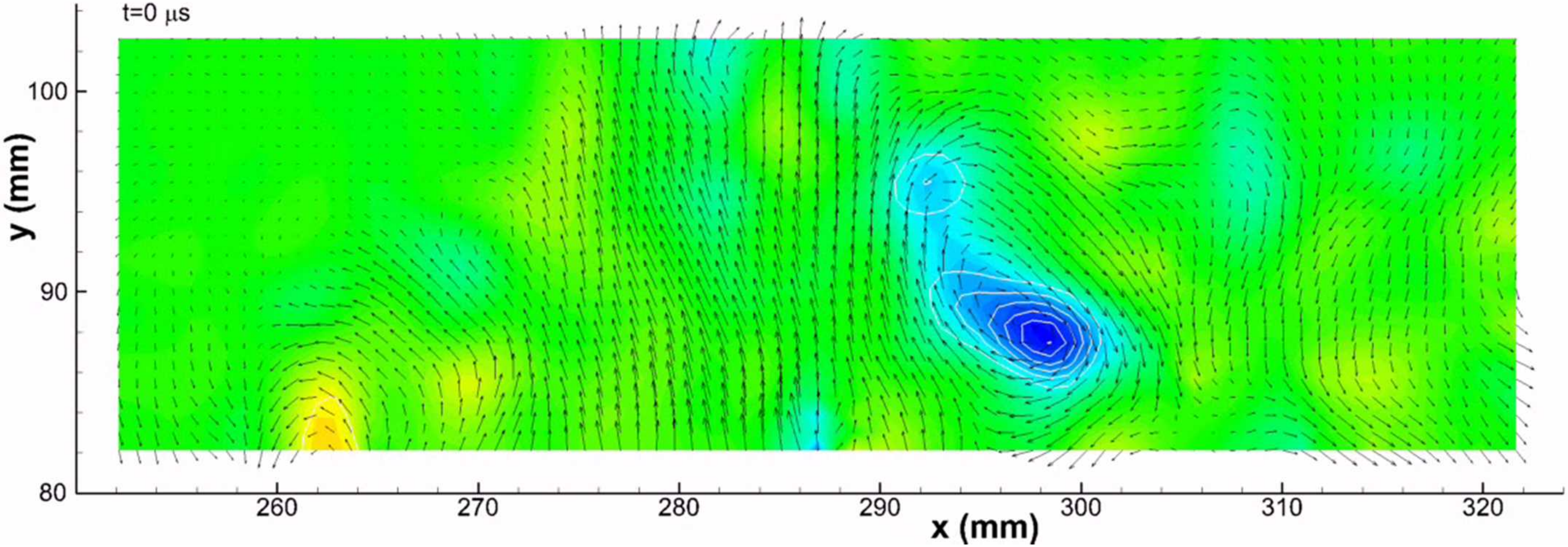
Counter-rotating eddies convect past, typically in pairs.

- **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.

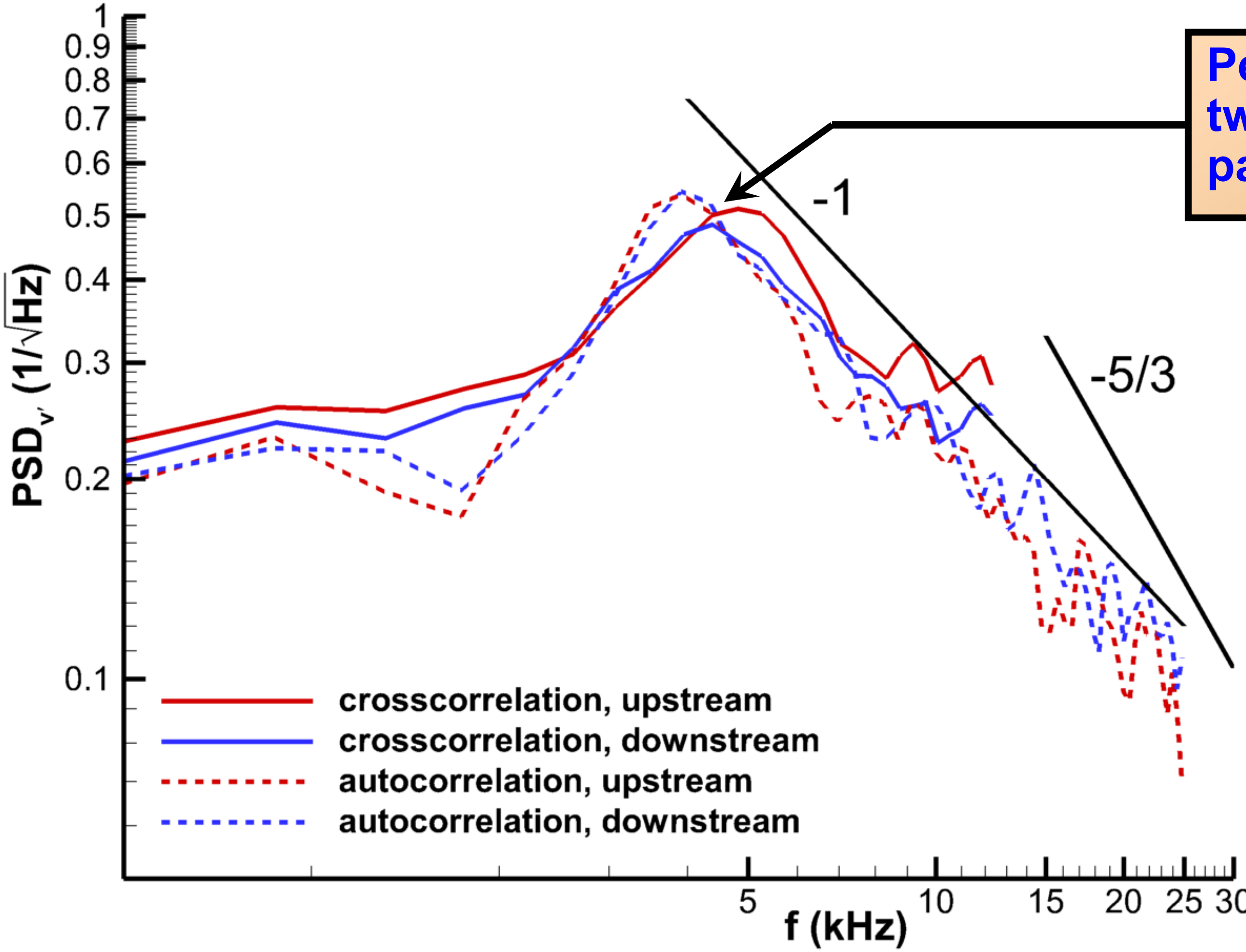
Final pass is 32 × 32 pixel due to increased noise.

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

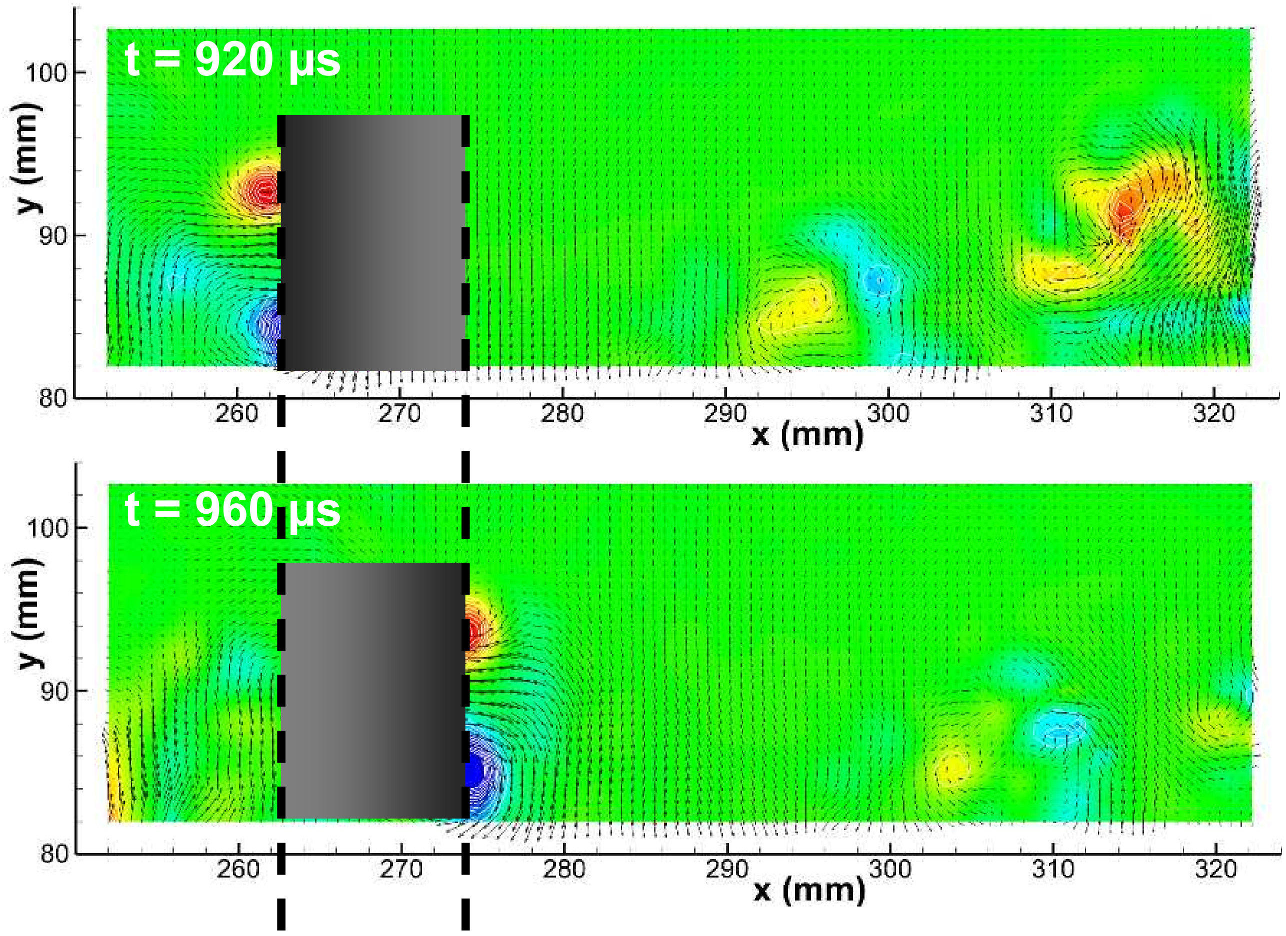
Velocity Supersampling

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.



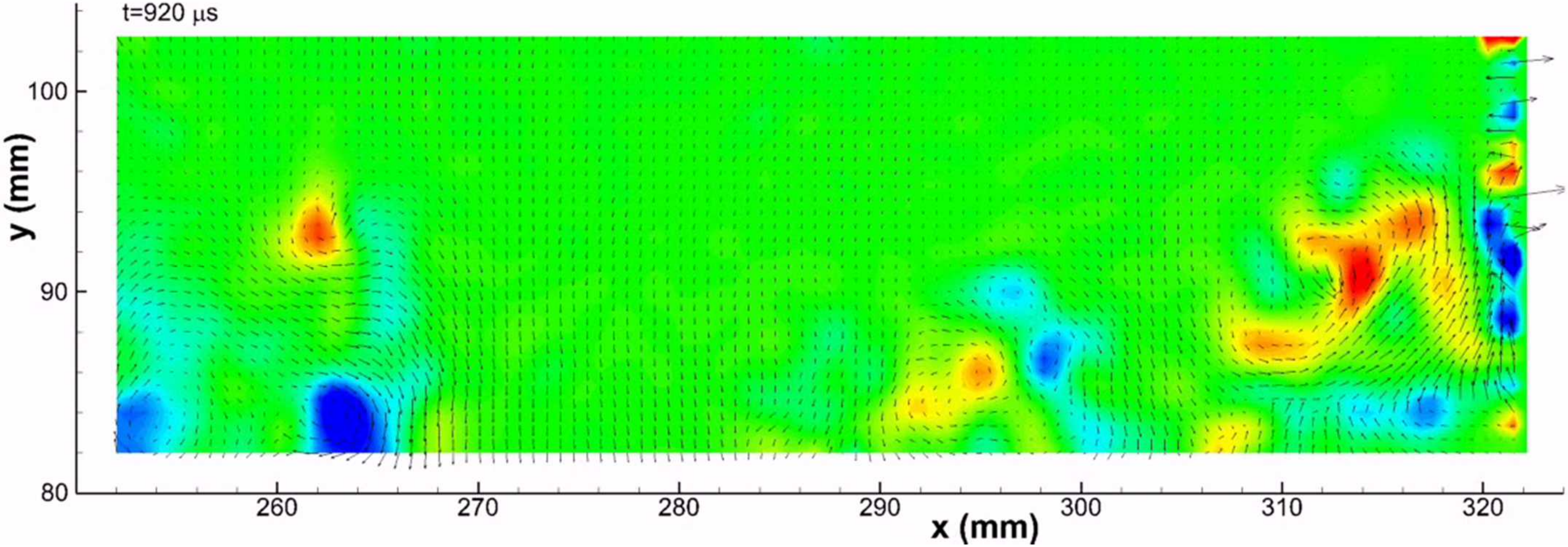
Follow the local streamlines

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.

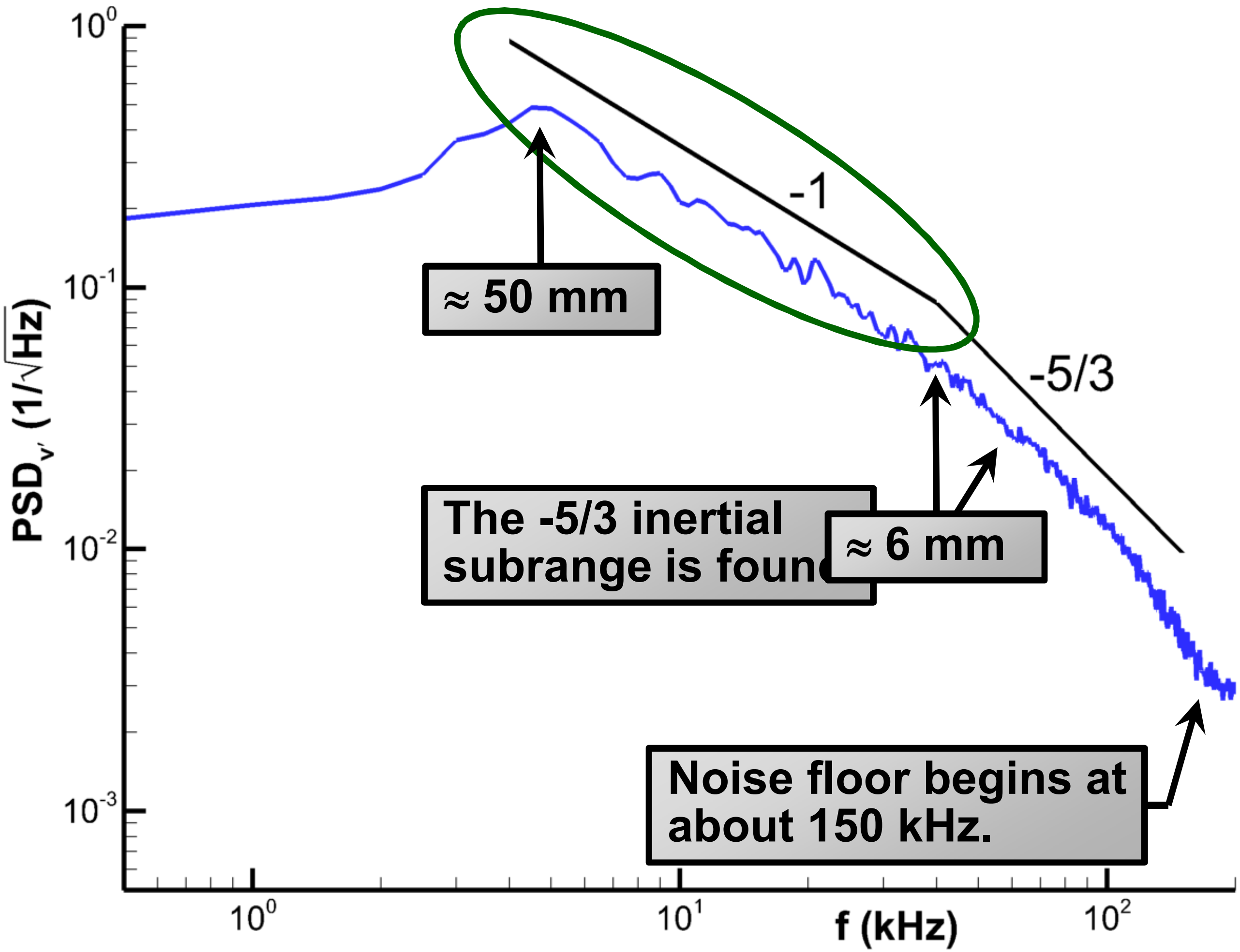
The -1 region is substantiated.

- 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.



This provides spectral content for LES/DES model development.

Sandia National Laboratories

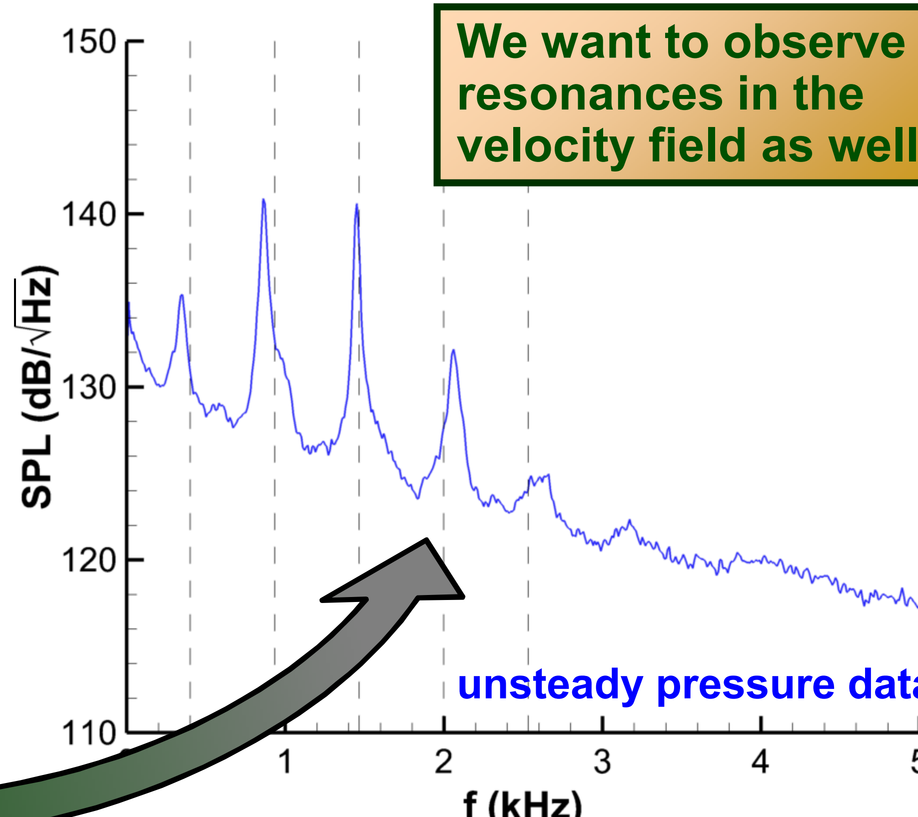
Next Application: The Acoustics of an Aircraft Bay

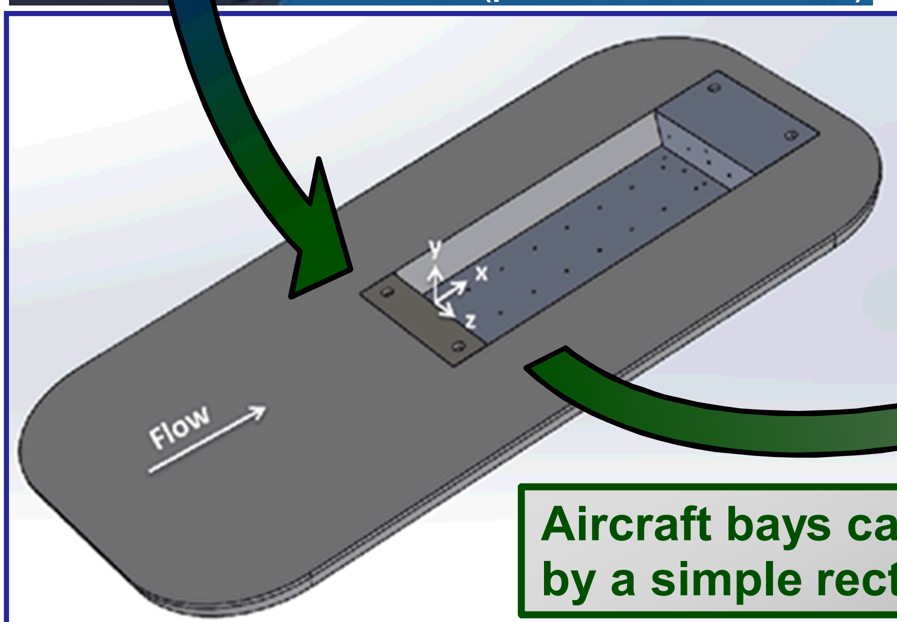
F-35 Weapons Bay
(photo: Lockheed Martin)

Flow over an aircraft bay creates a harsh aeroacoustic environment.

Multiple strong resonance tones.

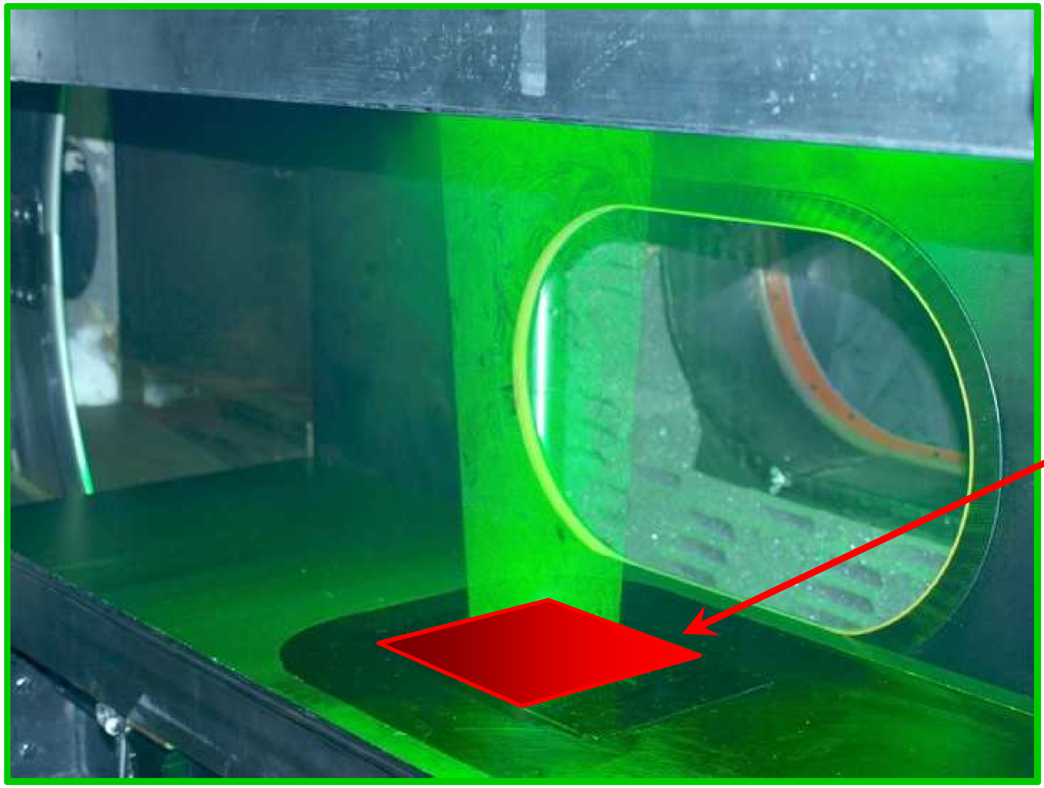
We want to observe resonances in the velocity field as well.

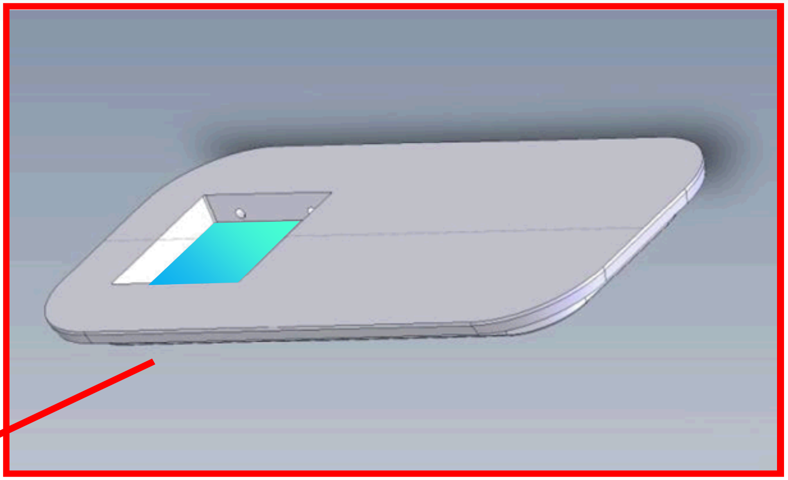




Aircraft bays can be well represented by a simple rectangular cavity.

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.

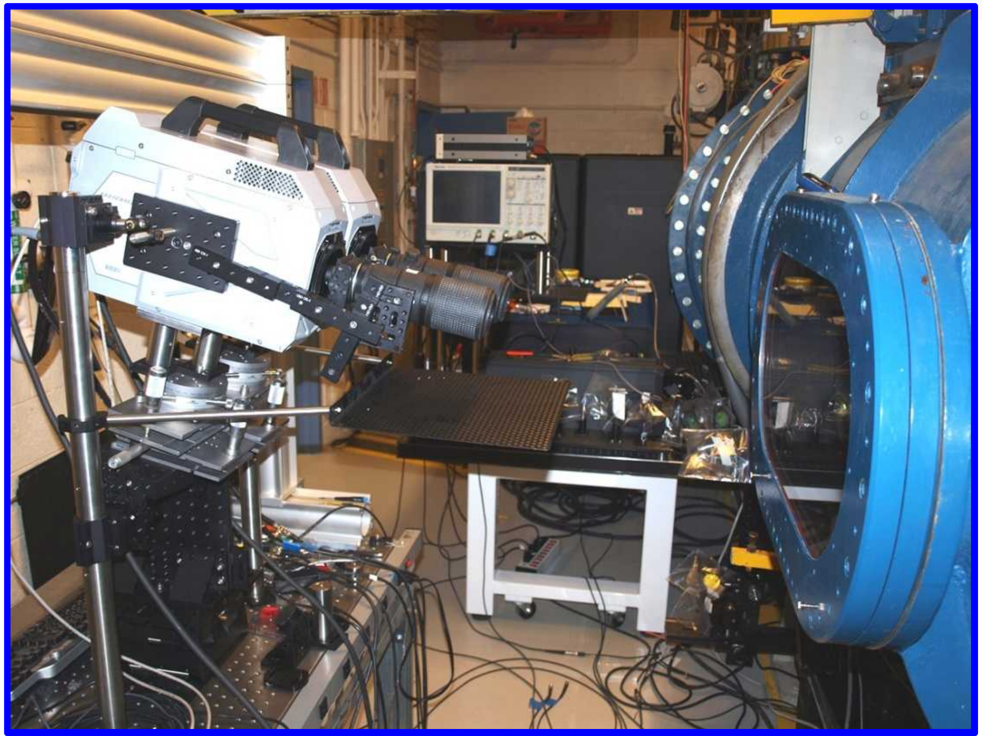
New High-Speed Cameras

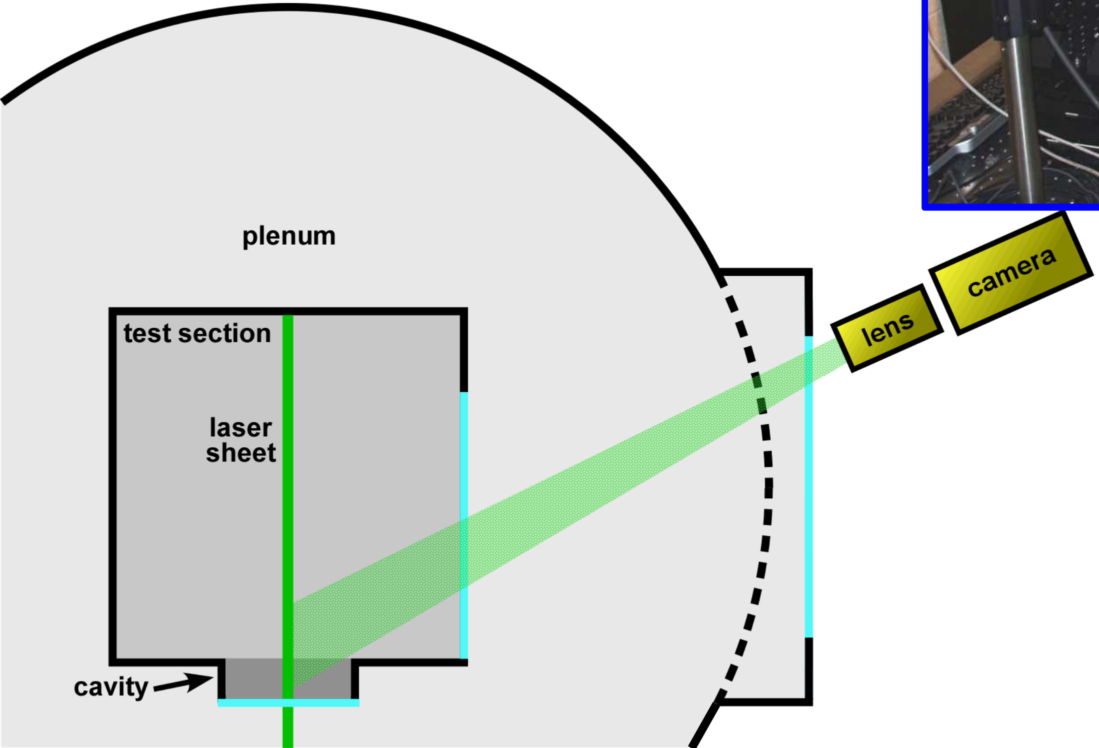
Two *Photron SA-Z's* placed adjacent for dual two-component PIV.

- 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.



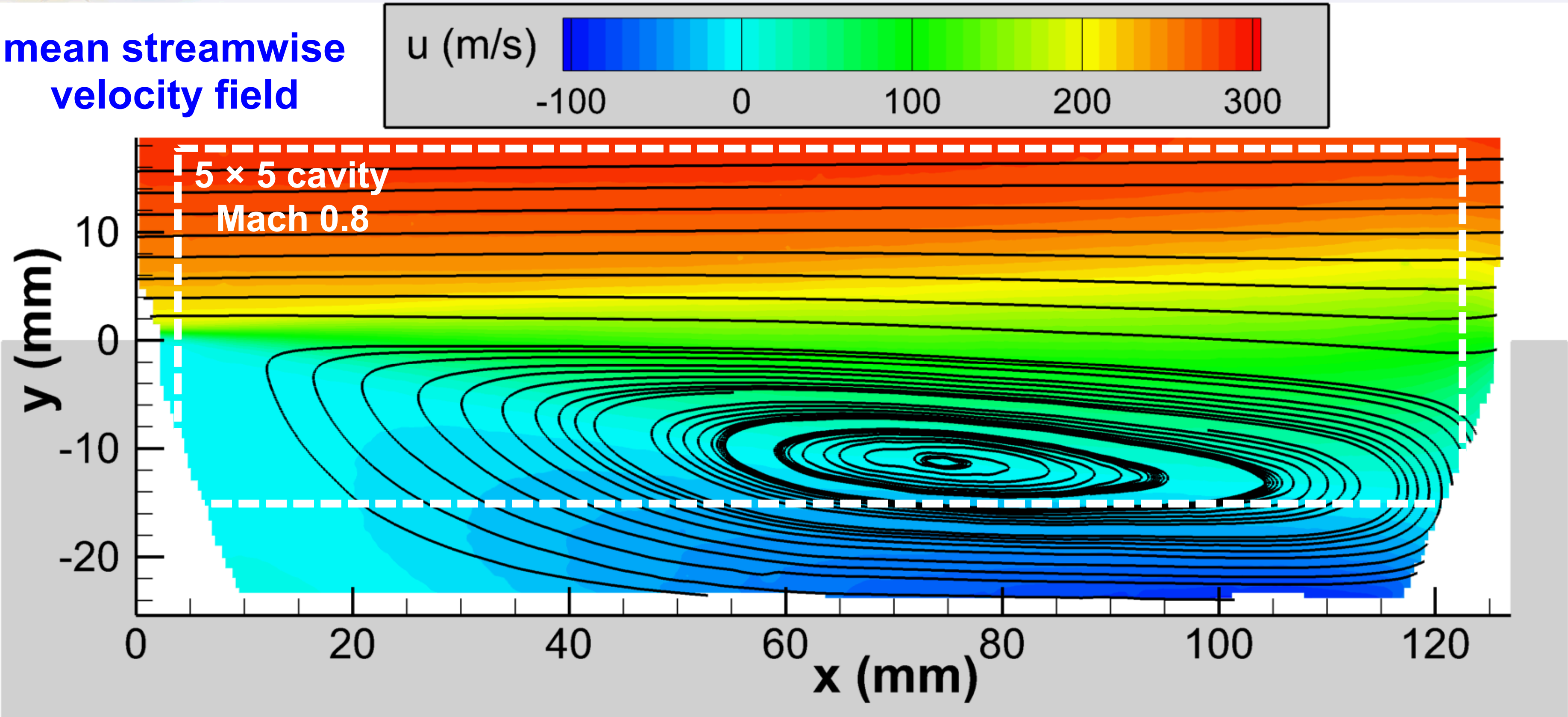


Previous 10-Hz PIV data were acquired similarly.

- 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.



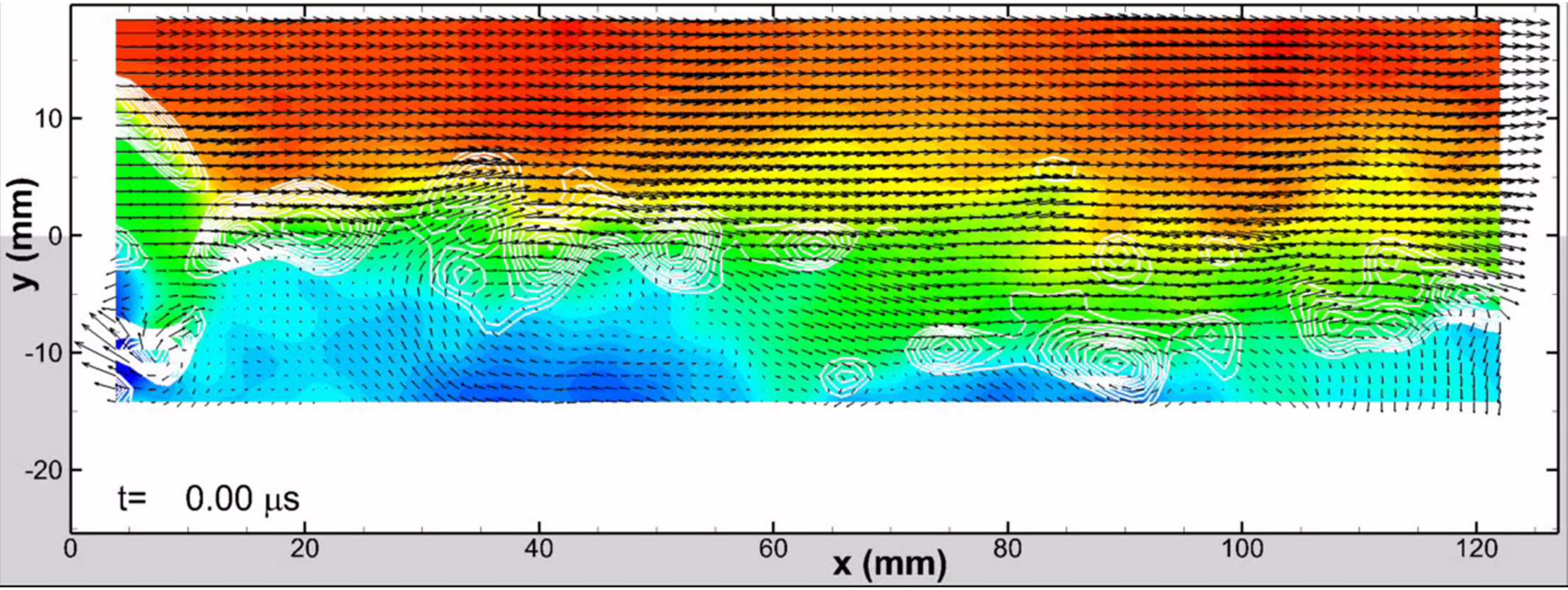
Streamlines clearly visualize the recirculation region and strong reverse velocities are evident.

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.



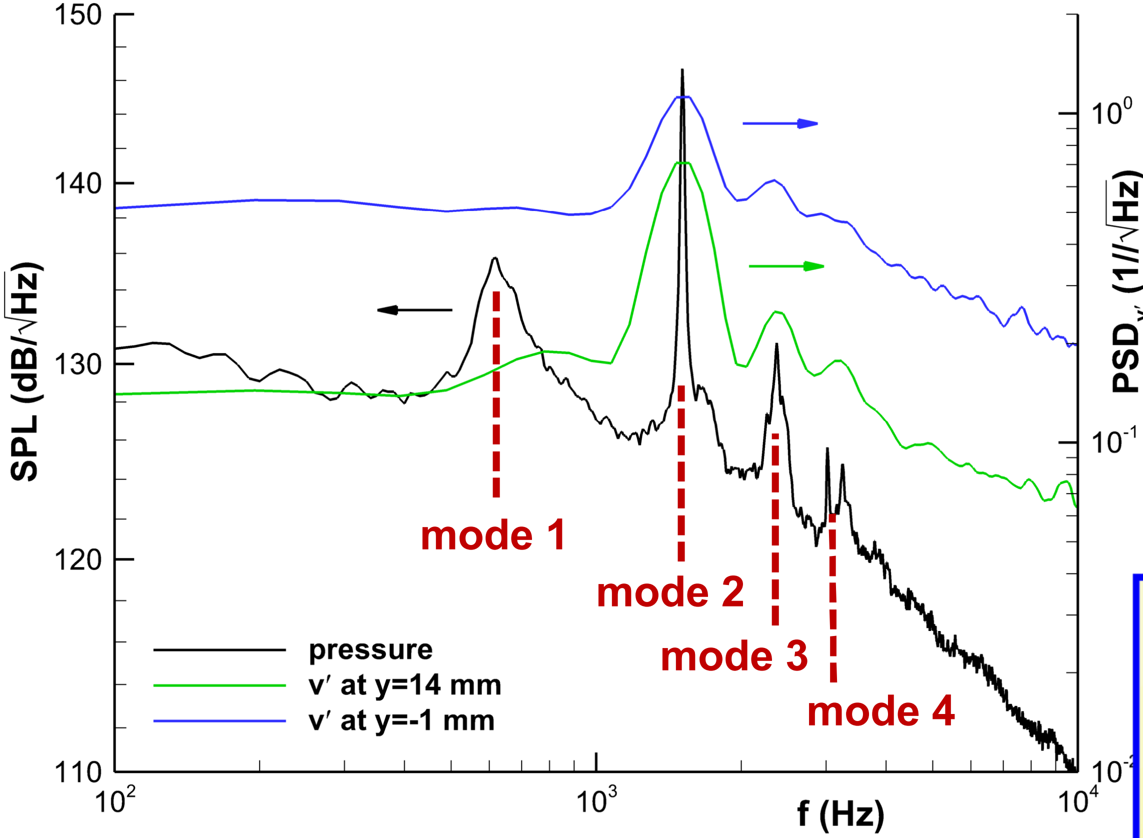
We can visualize:

- 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.

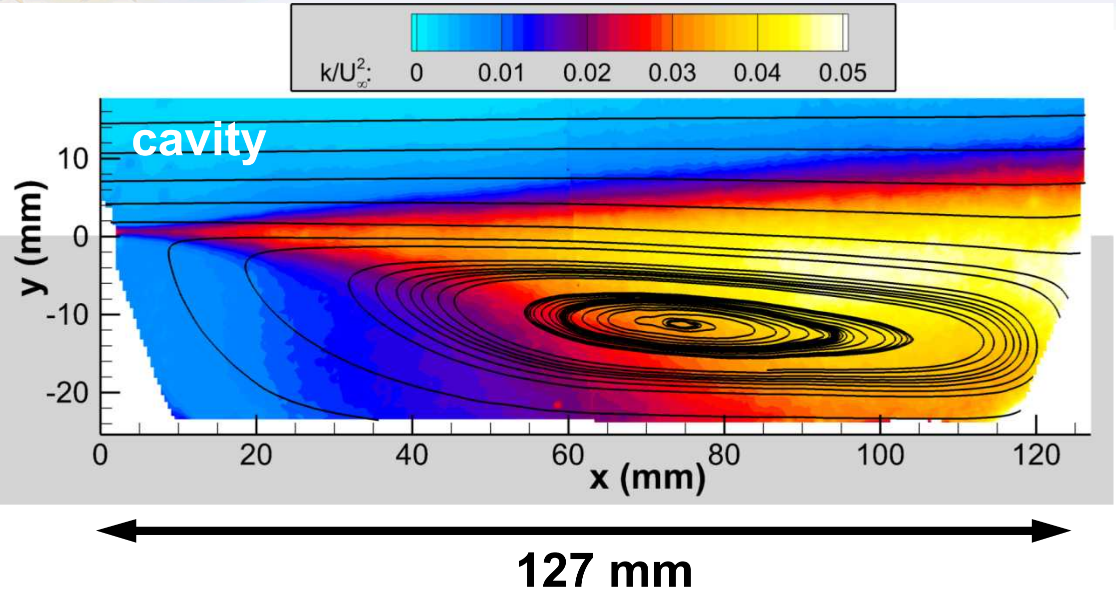
We can even see the bifurcated mode 4 peak in the shear layer velocity data.

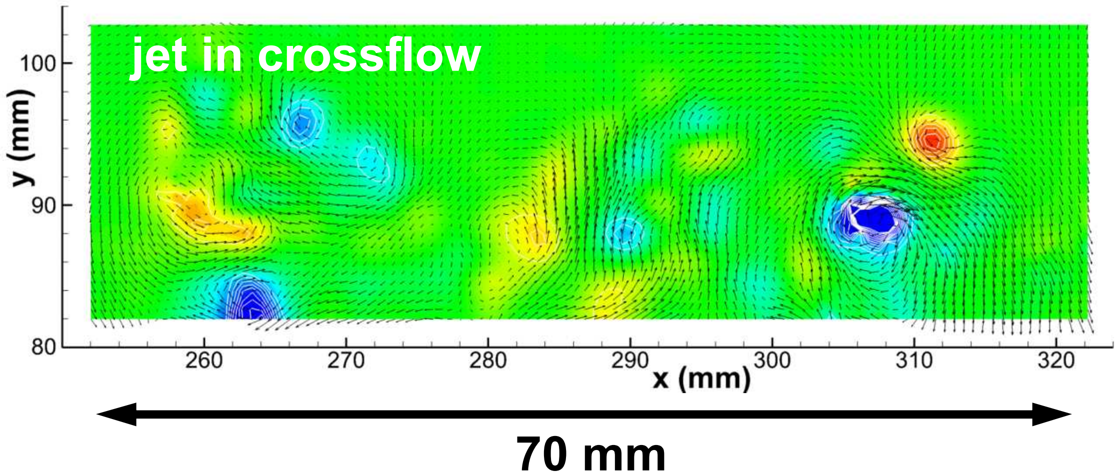
Mode 1 is trickier to locate in the velocity data.

But to guide LES/DES model development, we need to measure much higher turbulent frequencies.

Sandia National Laboratories

Velocity Supersampling for the Cavity Flow





The cavity flow will challenge the limits of supersampling more than the jet in crossflow.

This is a planar measurement, so supersampling cannot track out-of-plane motion.

The cavity out-of-plane motion is 3 times larger than the jet in crossflow.

The spatial resolution of a vector imposes a frequency response:

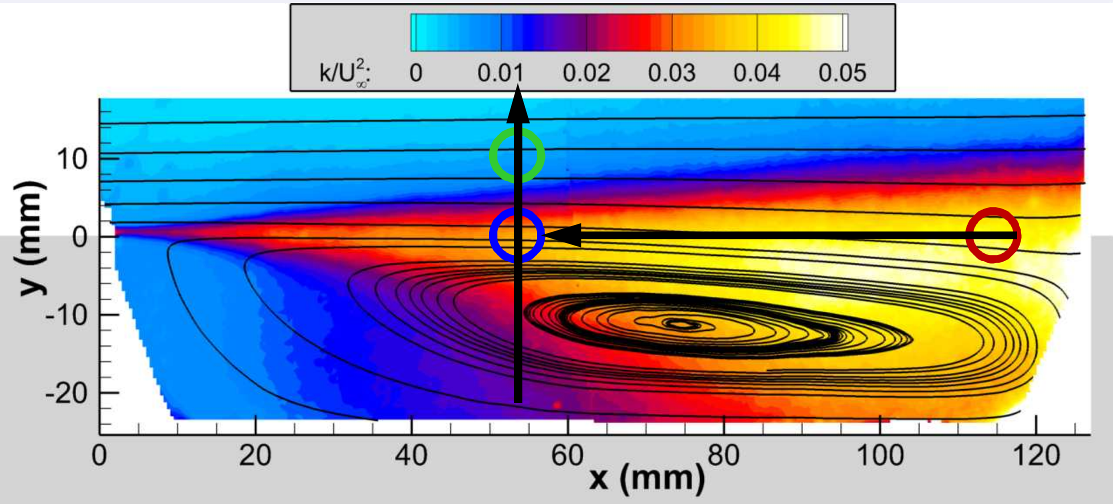
$$f = U_c / dI$$

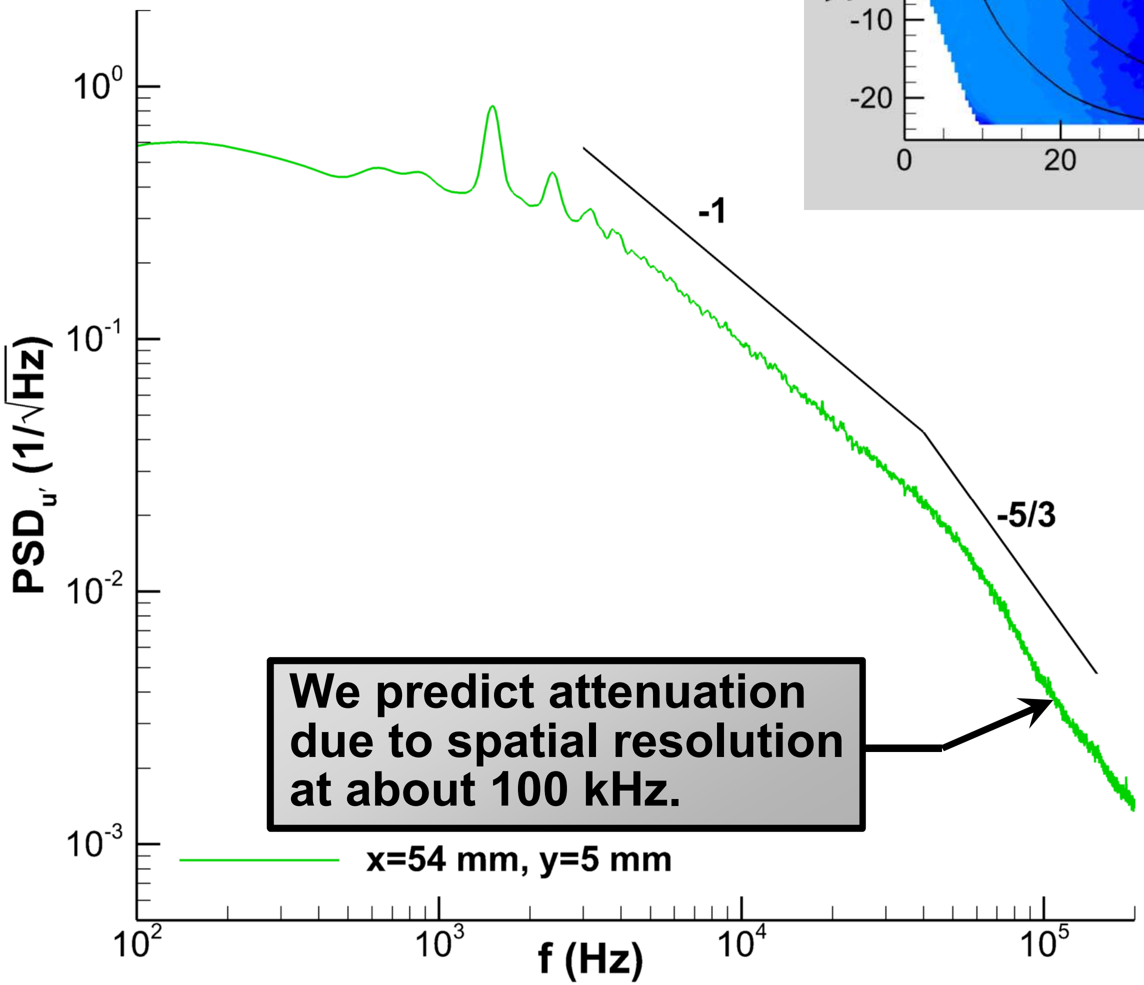
The spatial resolution (dI) of the cavity data is twice that of the jet in crossflow.

And, the local convection velocity (U_c) can be much smaller.

Supersampled Power Spectra

Where the frequency response is sufficient, we see good agreement with the -1 and -5/3 power laws of turbulent decay.





We predict attenuation due to spatial resolution at about 100 kHz.

Out-of-plane motion is larger downstream.

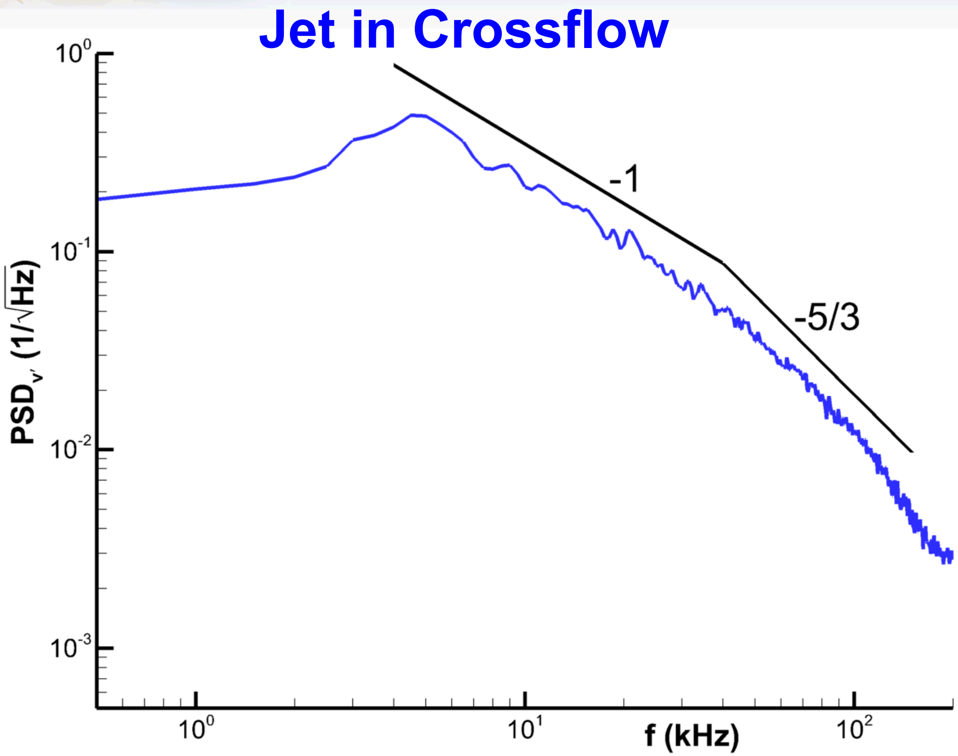
Better frequency response upstream.

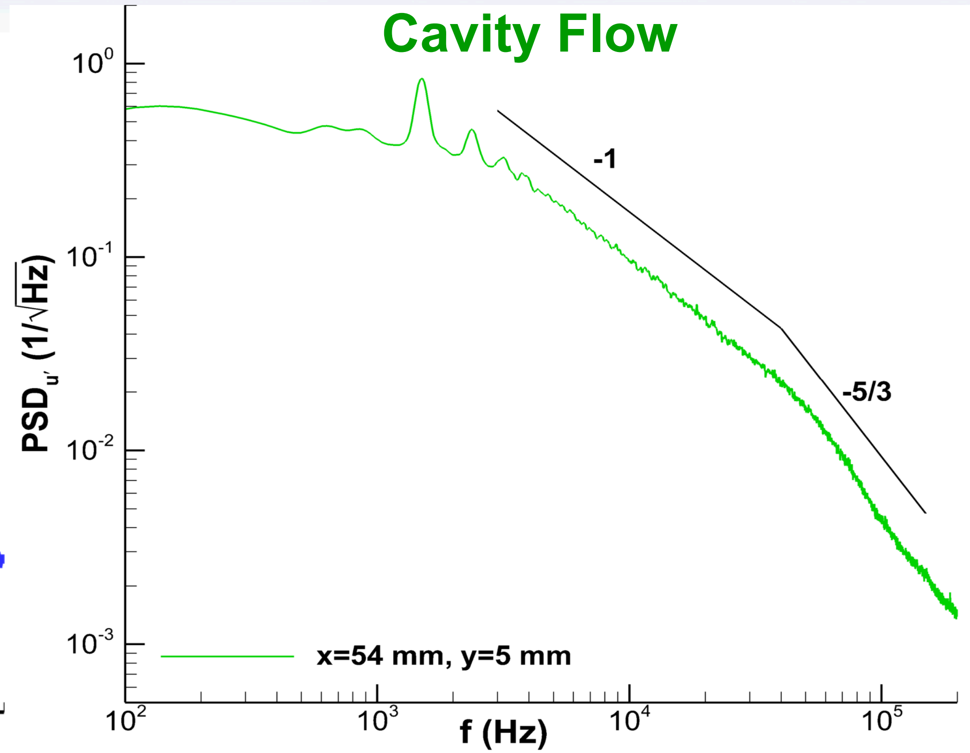
Local convection velocity is smaller deeper in the cavity.

Better frequency response higher in the shear layer.

Sandia National Laboratories

Turbulence Decay Laws





The -5/3 power law is well known and theoretically predicted for all flows.

It has been found previously by careful, well-planned experiments.

The -1 power law is predicted for wall-bounded turbulence.

It has been measured in high-Reynolds-number experiments.

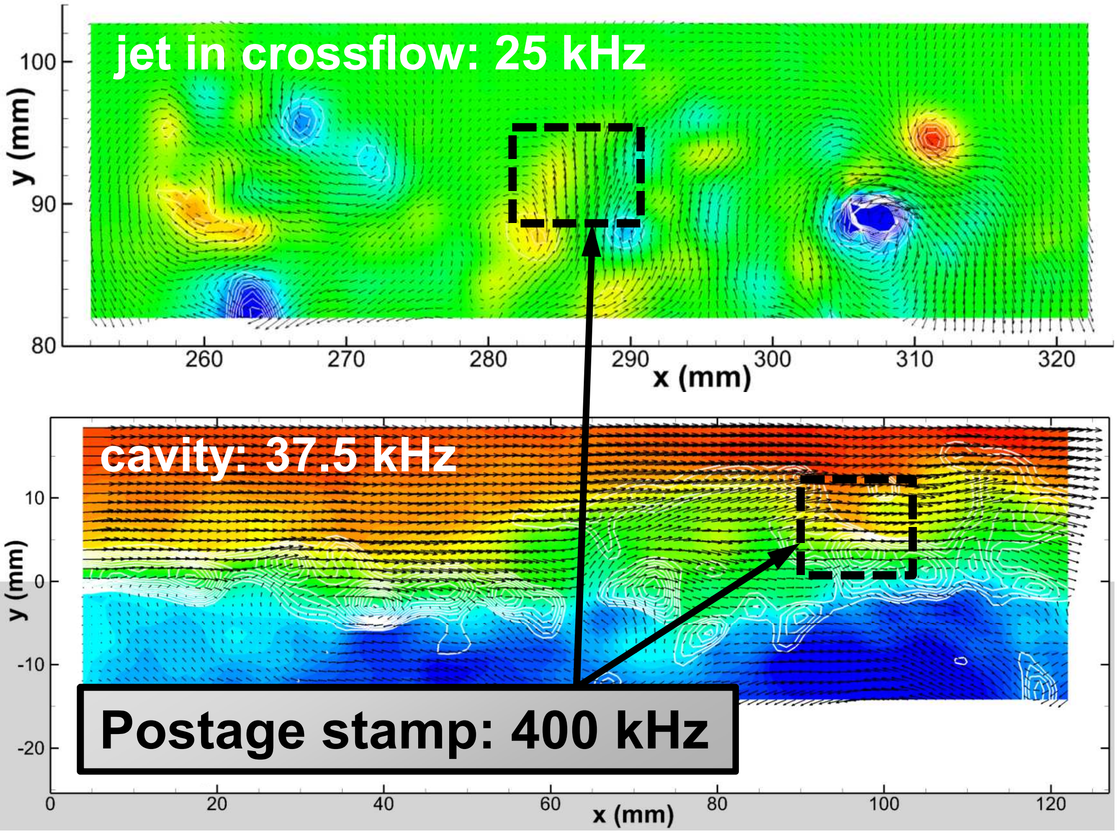
It is not known for free shear flows.

Have we found something new?

Sandia National Laboratories

We know supersampling has limitations, so we better validate our results.

Introducing: "Postage-Stamp PIV"



If we use a very small field of view, the cameras can run much faster.

If we accept much less energy per laser pulse, the laser can run much faster.

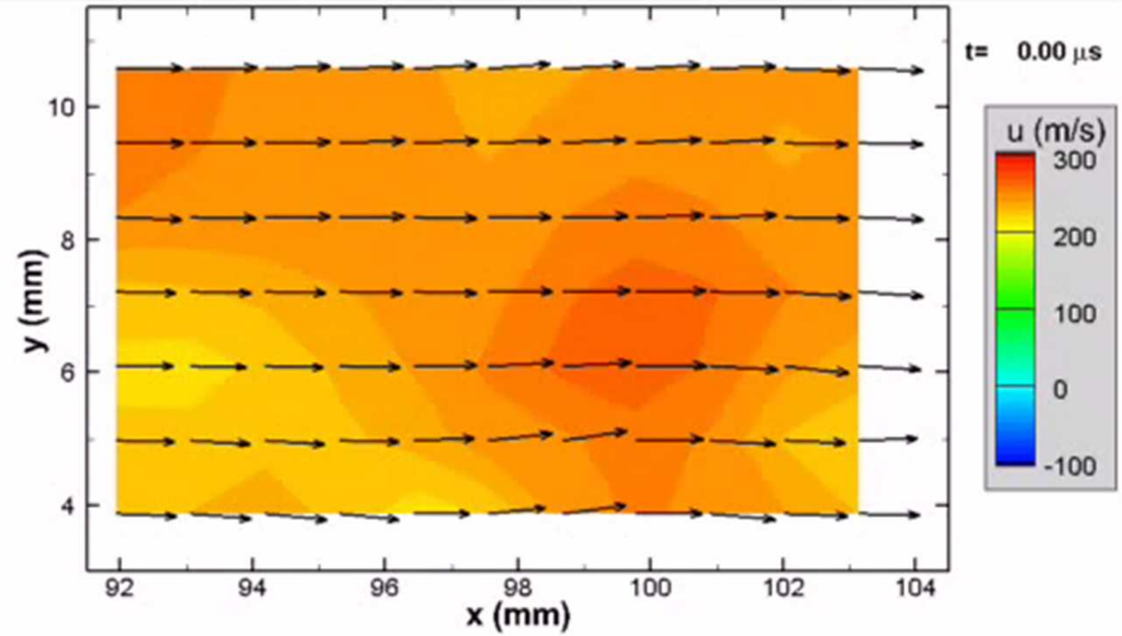
We can acquire PIV data at 400 kHz!

…if we use a very small field of view.

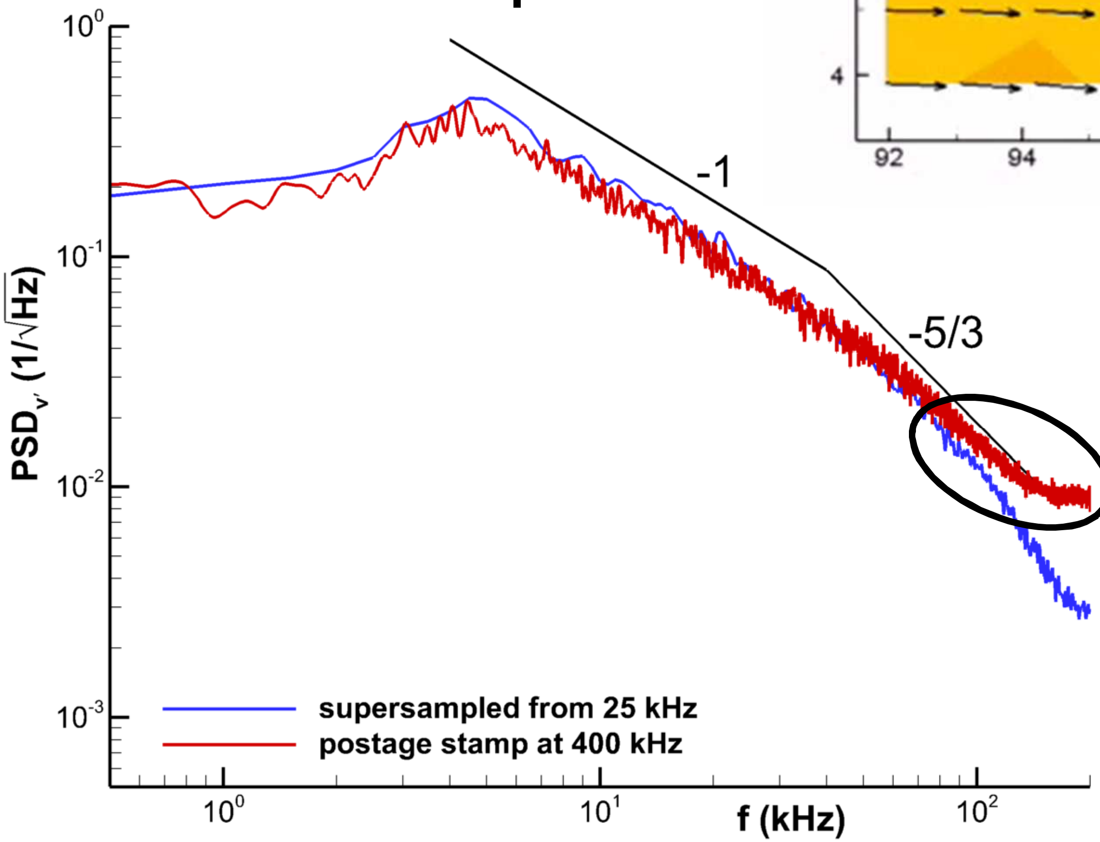
This isn't much use for describing the flow…
…but it is *great* for measuring spectra!

Preliminary Results from Postage-Stamp PIV

Sample movie from the cavity flow.



Jet in Crossflow Spectra



Data at 400 kHz confirm the -1 power-law regime!

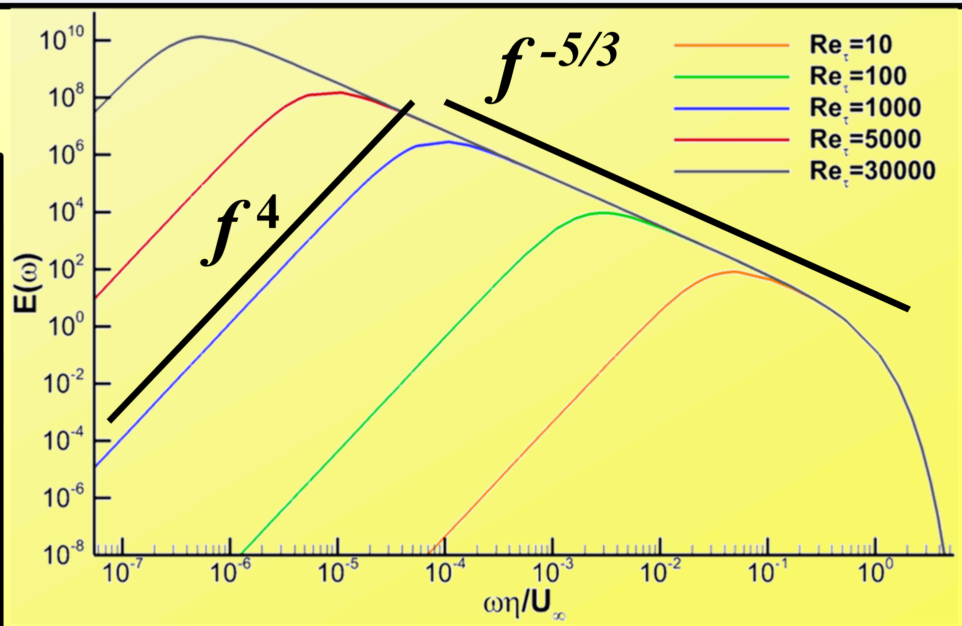
High noise floor in preliminary data analysis.

Advanced algorithms can improve this.

Sandia National Laboratories

How does this benefit model development?

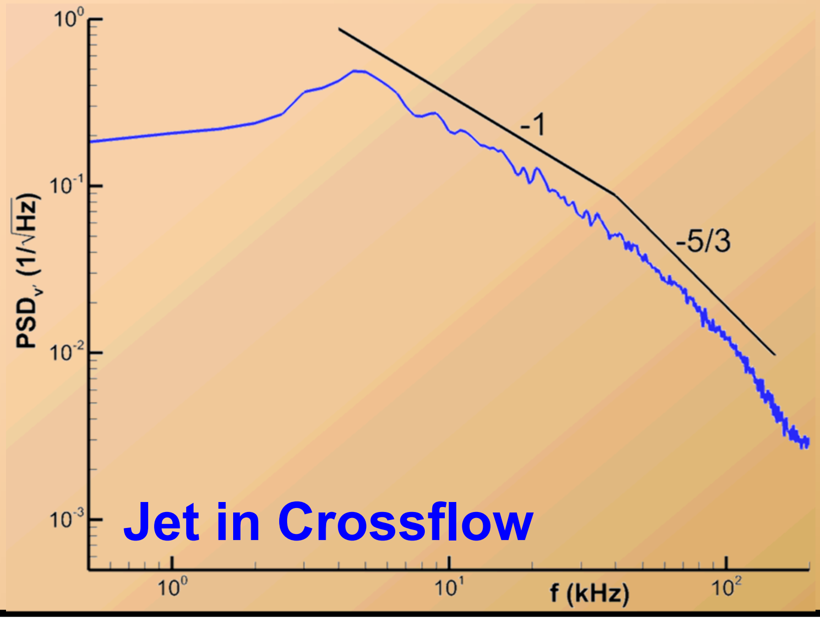
These are assumed spectra in computational models.

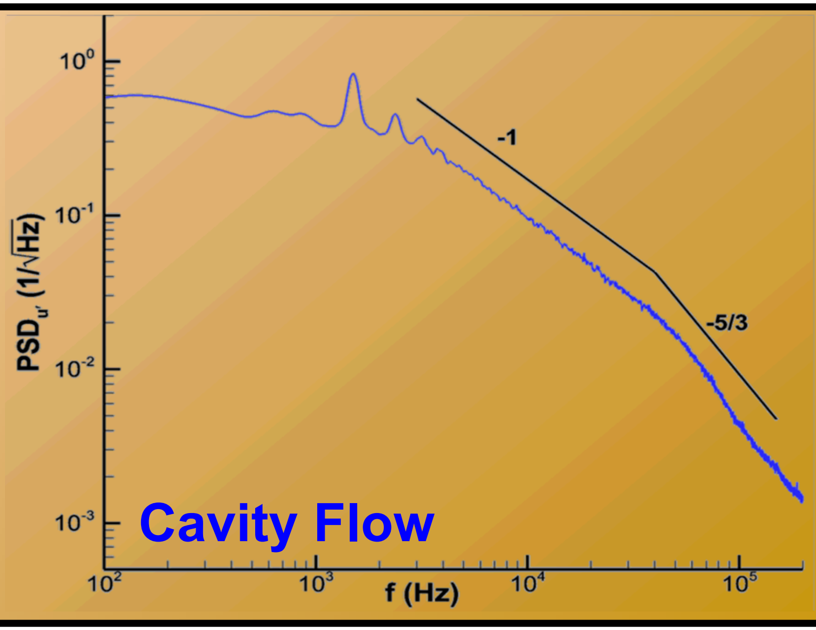


We will incorporate these spectra into our LES/DES subgrid models.

Experimental data are needed to accurately describe the flow.

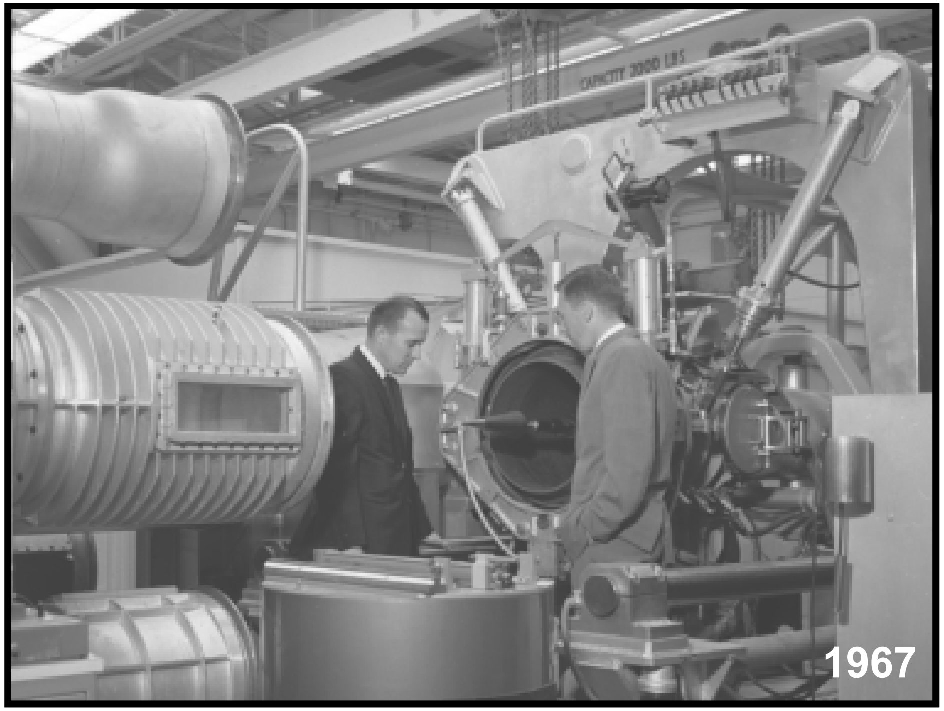
These are wind tunnel spectra measured using pulse-burst PIV.





One Final Comment…

Computational simulation is built on a foundation of experimental data!



This is an example of how wind tunnels are integral to the development of modeling and simulation.

To increase the fidelity and accuracy of models, they need to be developed with real data, not assumed models.

New experimental technologies allow us to do things we never could have imagined a generation ago.