SAND2016-6247C

Applications of Temporal Supersampling in Pulse-Burst PIV

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

"The Lisbon Meeting"
4-7 July, 2016
Lisbon, Portugal

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

Time-Resolved PIV with a Pulse-Burst Laser

Current TR-PIV capability isn't enough for a high-speed wind tunnel.

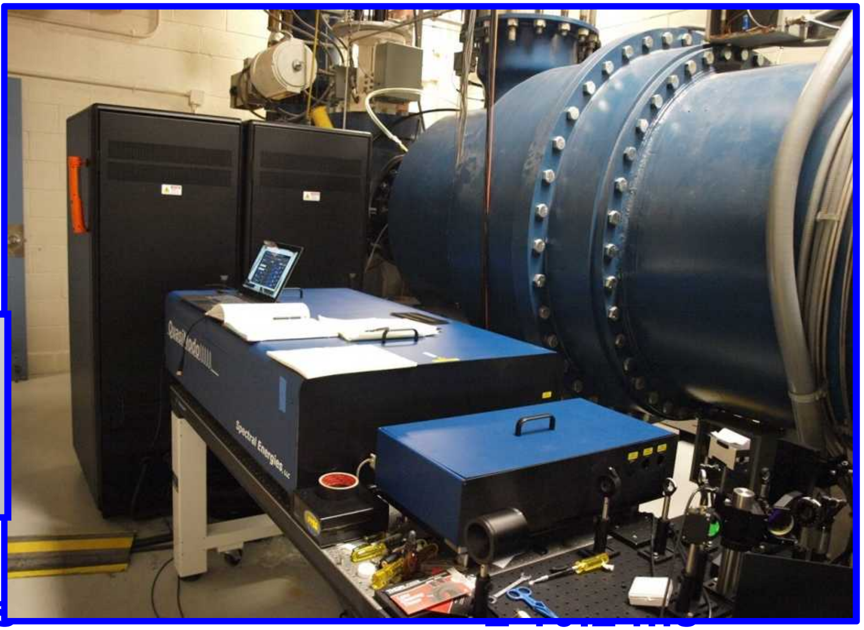
- **Faster repetition rates for briefer time scales.**
- **Higher energy required.**
  - **Scatter light off smaller particles**
  - **Expand laser sheet for larger field of view**

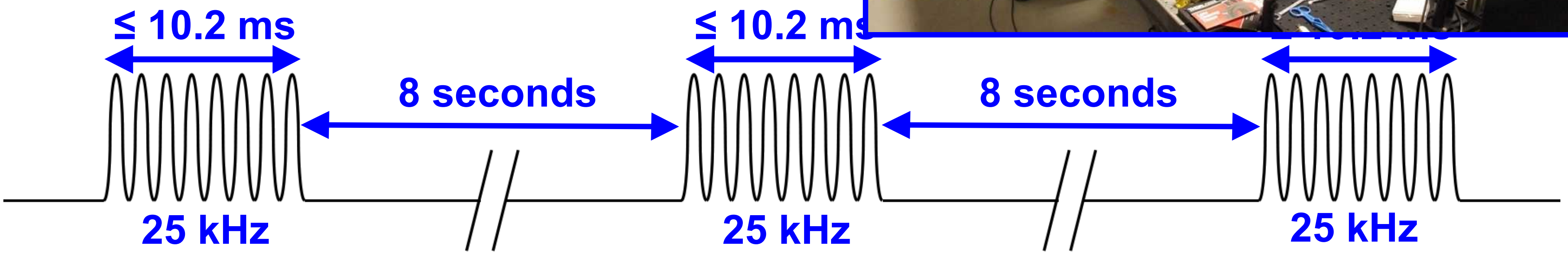
A *pulse-burst laser* allows high energy and high repetition rates.

But a very low duty cycle.

Pulse-Burst Laser:

- **Manufactured by Spectral Energies, LLC**
- **Up to 500 kHz of pulse pairs, 20-500 mJ**

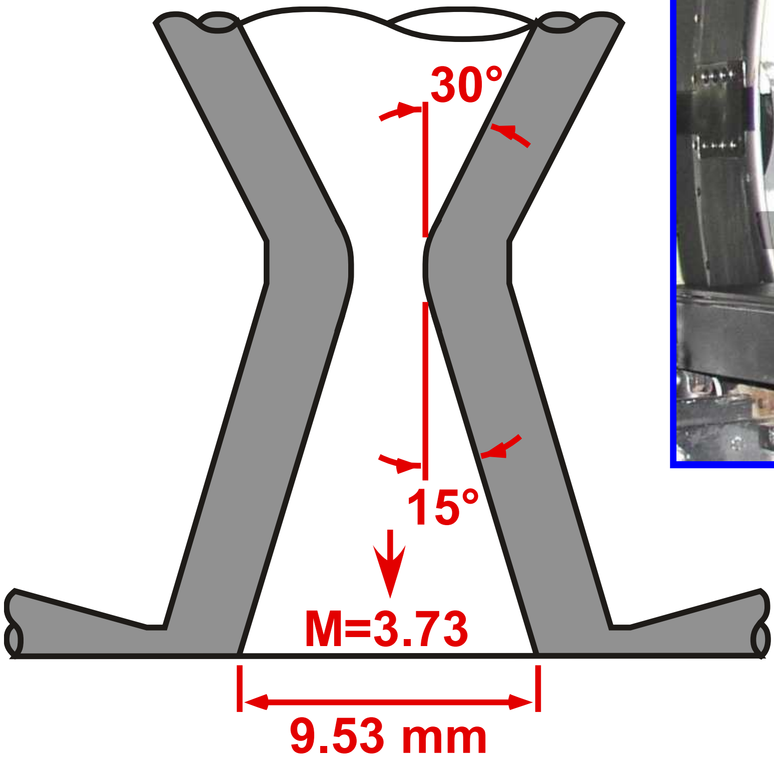


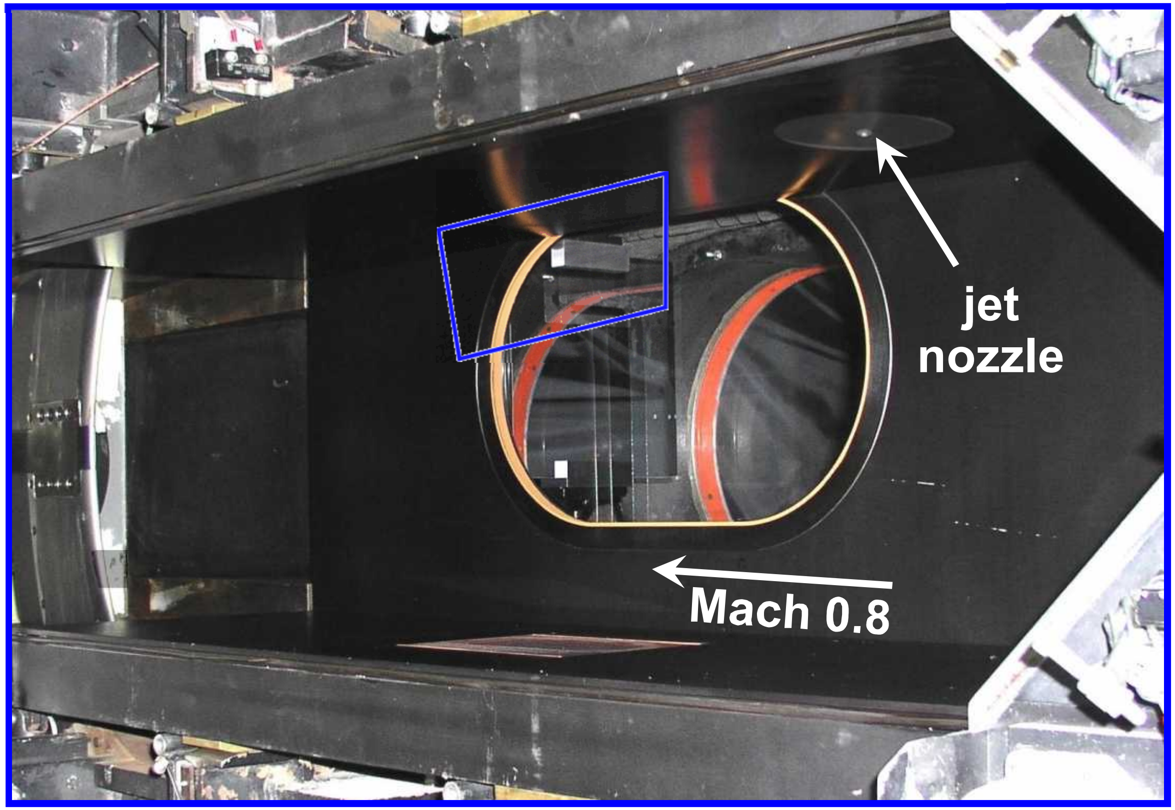


Our First Test Application

Supersonic Jet in Transonic Crossflow

Installed in Sandia's Trisonic Wind Tunnel





A jet nozzle mounts on top wall of TWT, driven by high-pressure air.

View the far-field of the interaction.

Sandia National Laboratories

High-Speed Cameras

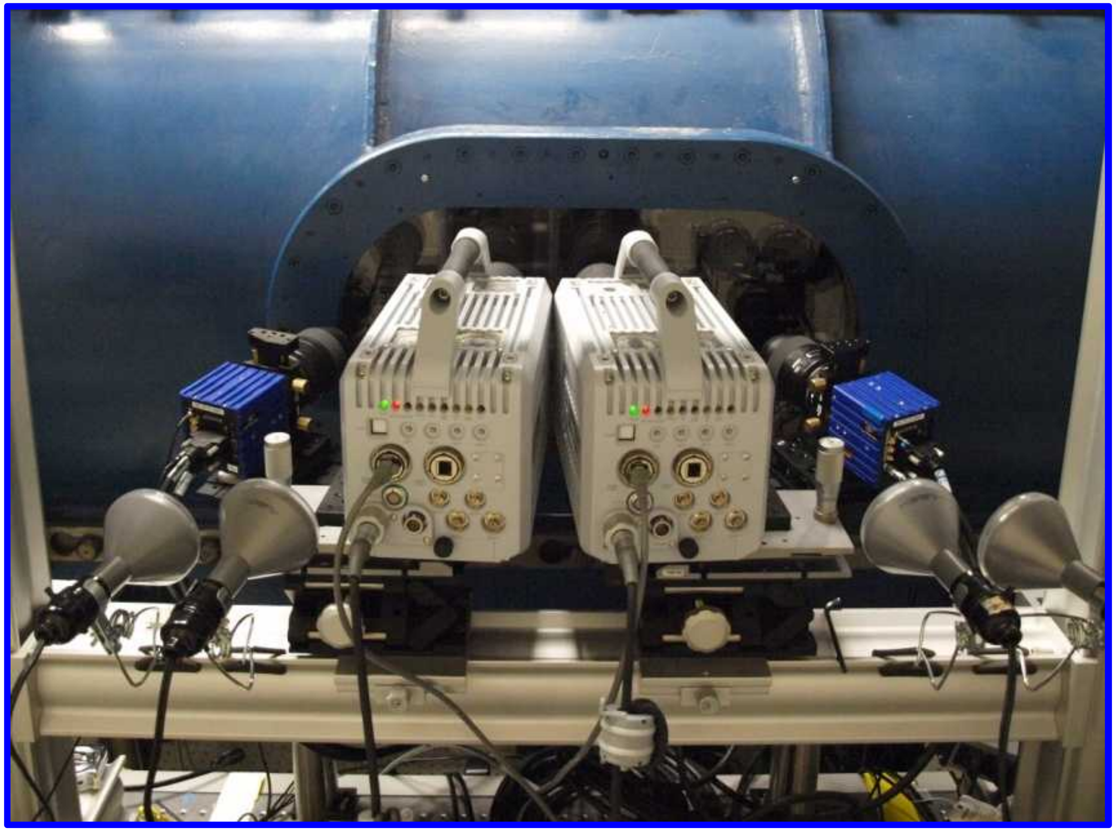
Photron SA-X2 cameras

- Two side-by-side for wider field of view
- Combined 1280 × 384 pix
- Two-component PIV

Cameras at 50 kHz.

Frame straddle laser pulse pairs at 25 kHz.

- Δt = 2.00 μs
- 2.5 ms burst, 175 mJ/pulse



Field of View

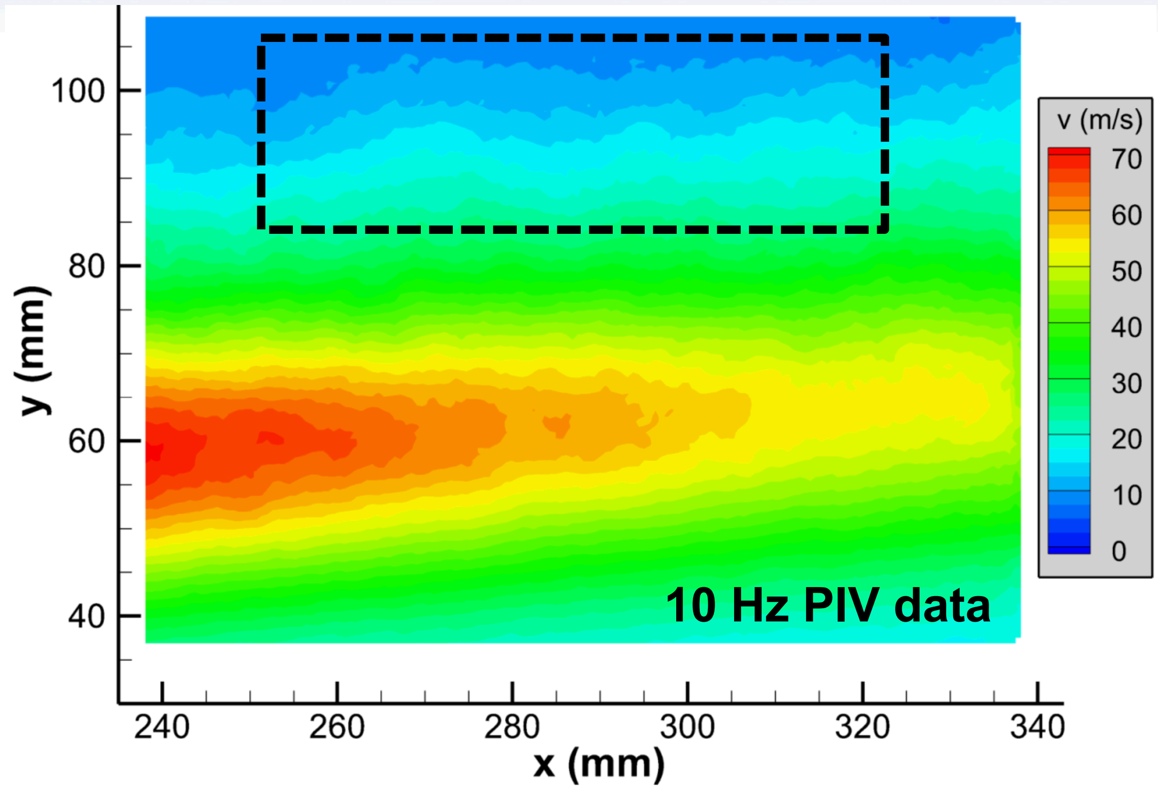
Combined field of view:

Image turbulent eddies at the outward mixing layer.

Today's data at J=8.1

Far from jet core and sparser turbulent eddies.

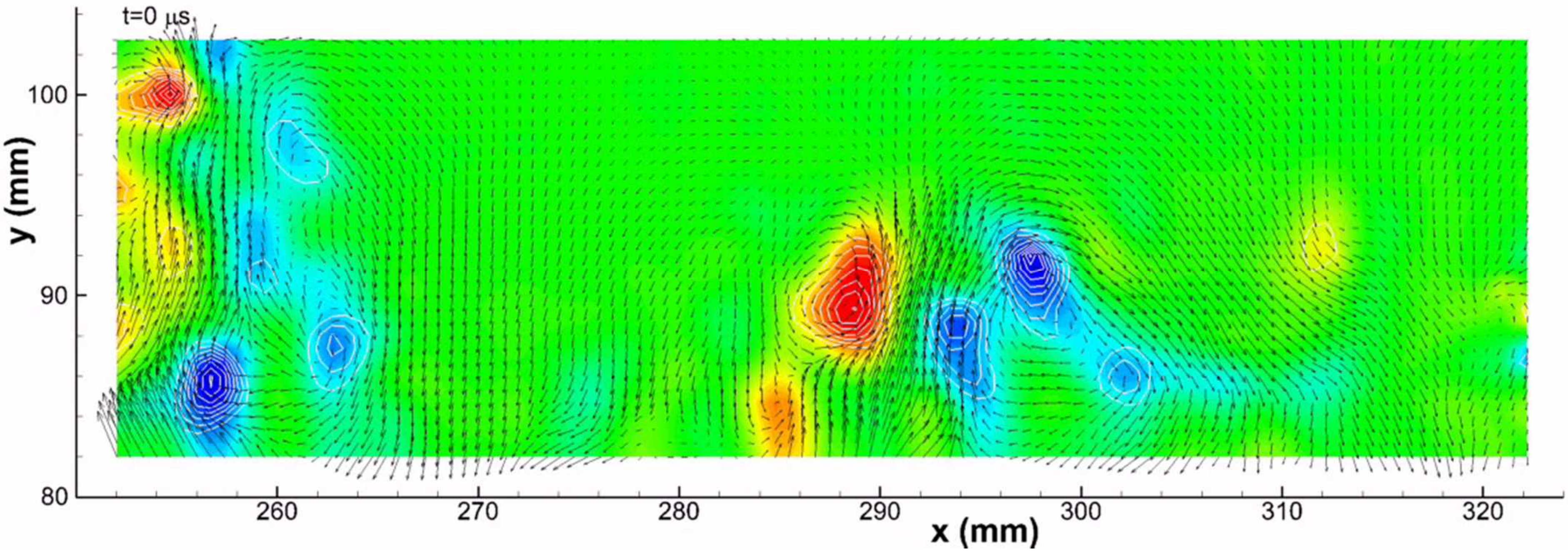
Makes data more visually interpretable.



jet exit

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.

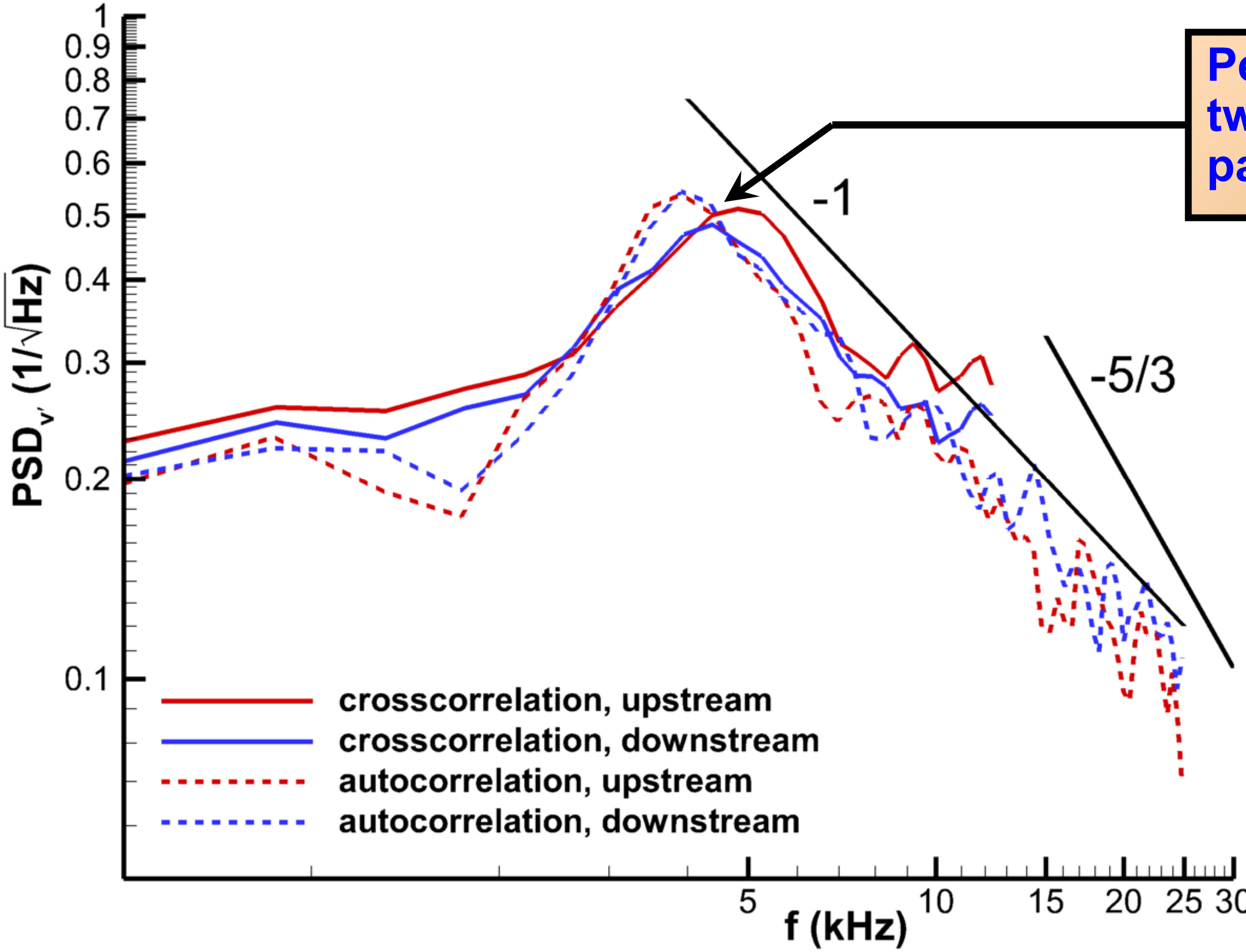
Final pass uses 24 × 24 pixel interrogation windows.

Counter-rotating eddies convect past, typically in pairs.

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

What frequency content do we find in 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?**

We need higher frequency response…

Sandia National Laboratories

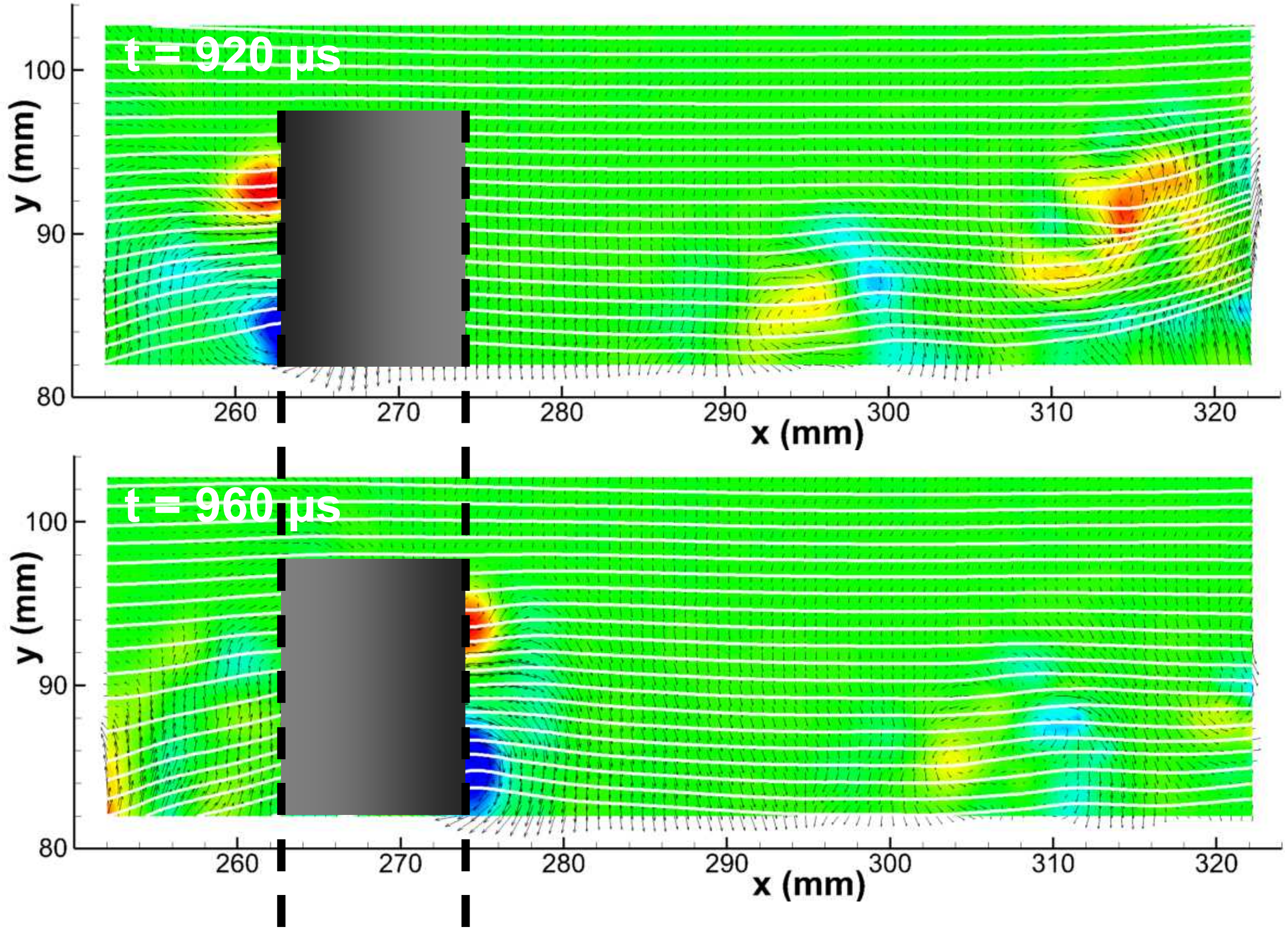
Velocity Supersampling

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.



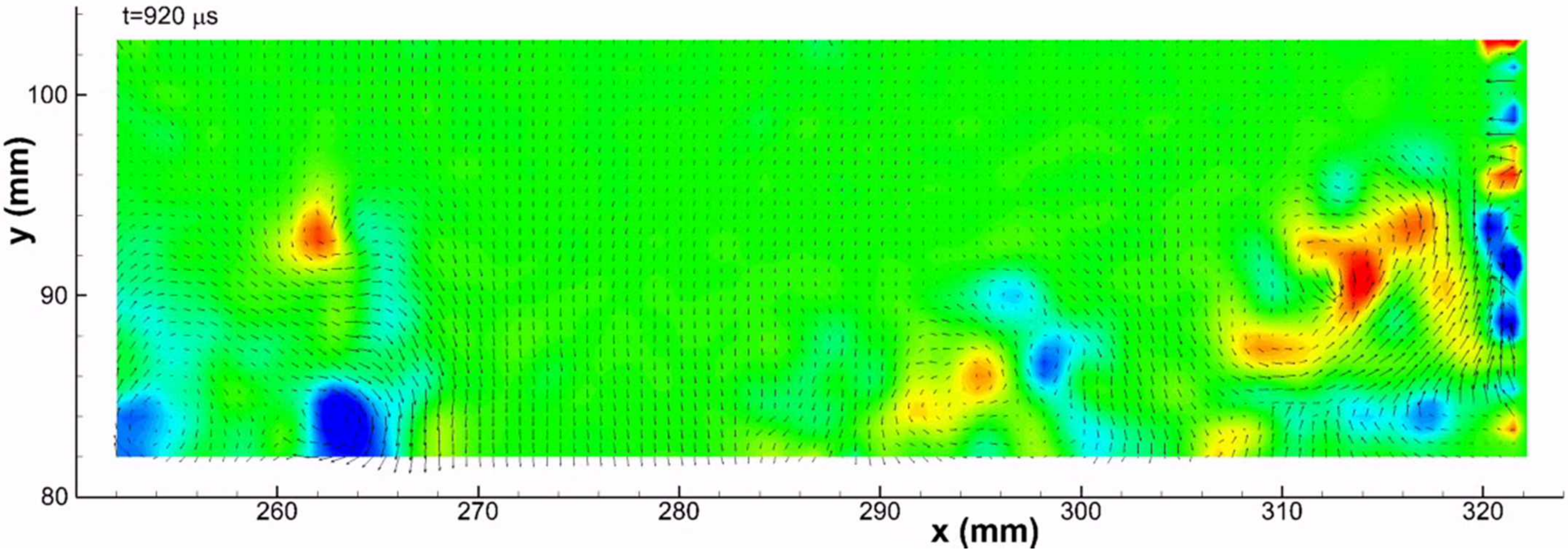
Follow the local streamlines

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?

Velocity Supersampling Power Spectrum

This will extend the power spectrum to much higher frequencies.

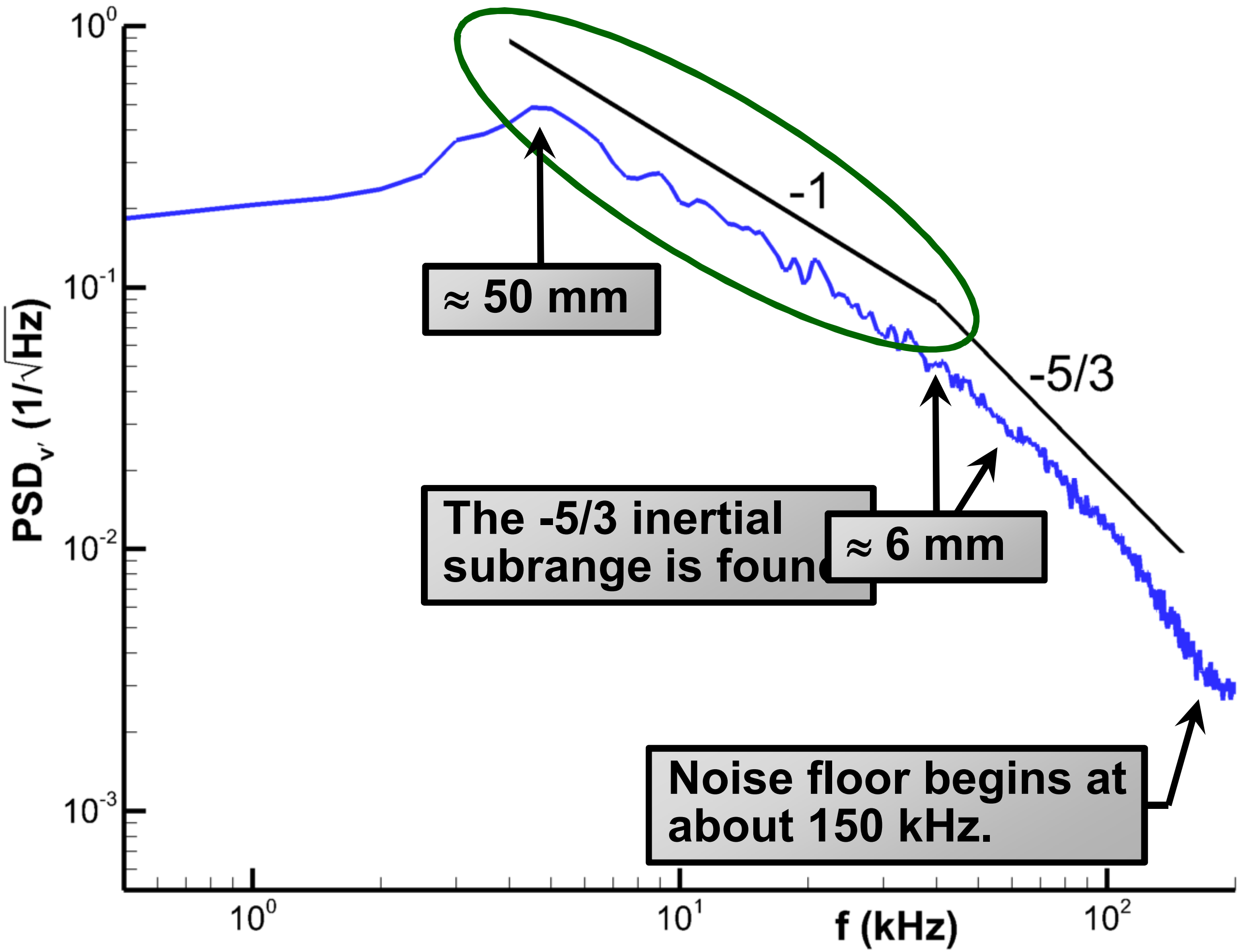
The -1 region is substantiated.

- 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.

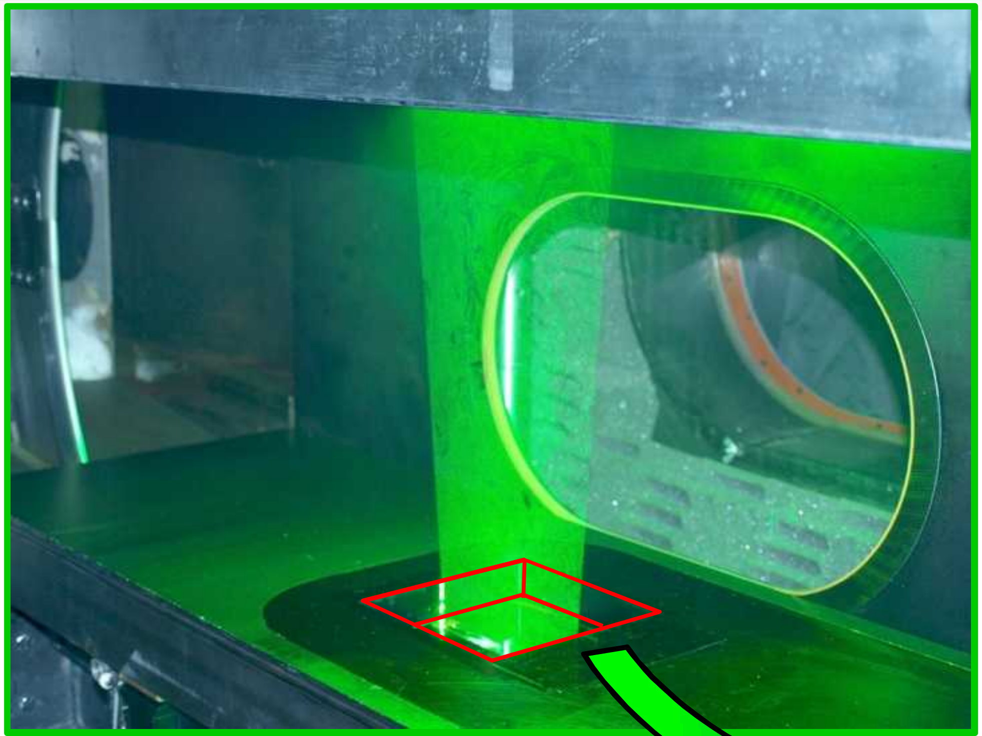
Corresponds to the dominant turbulent eddies measured by PIV.



This provides spectral content for LES/DES model development.

Sandia National Laboratories

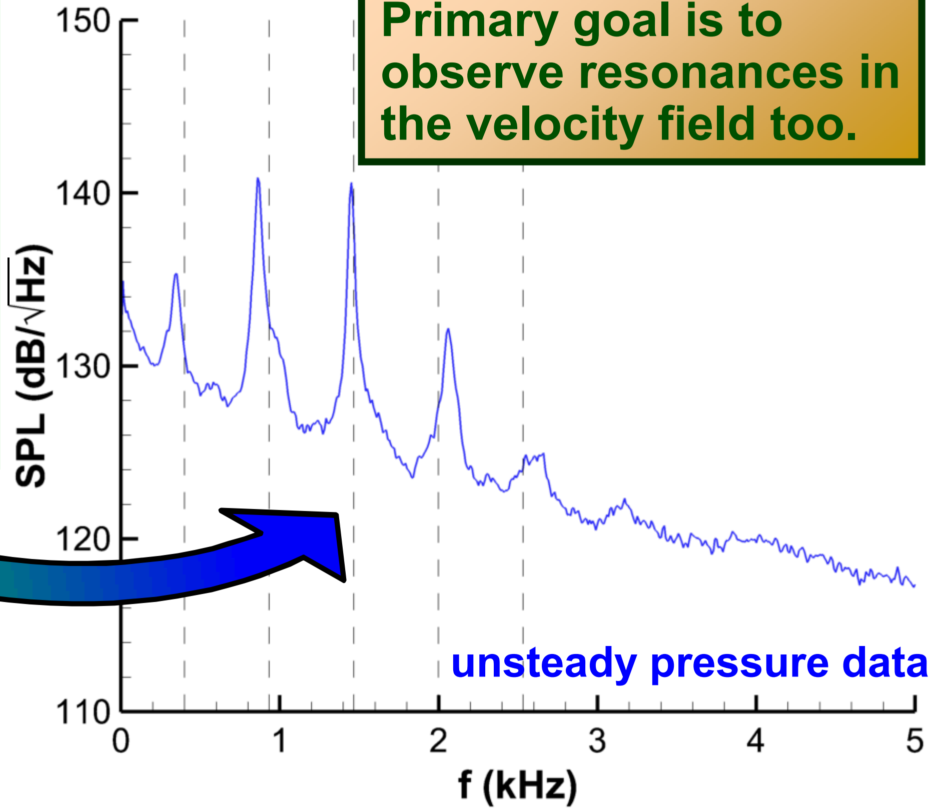
Second Application: Cavity Flow



Flow over a cavity creates a harsh aeroacoustic environment.

Multiple strong resonance tones.

Primary goal is to observe resonances in the velocity field too.



Our cavity is a rectangular cutout built into the test section floor:

- 5″ long × 5″ wide × 1″ deep
- Cavity floor is glass for laser access

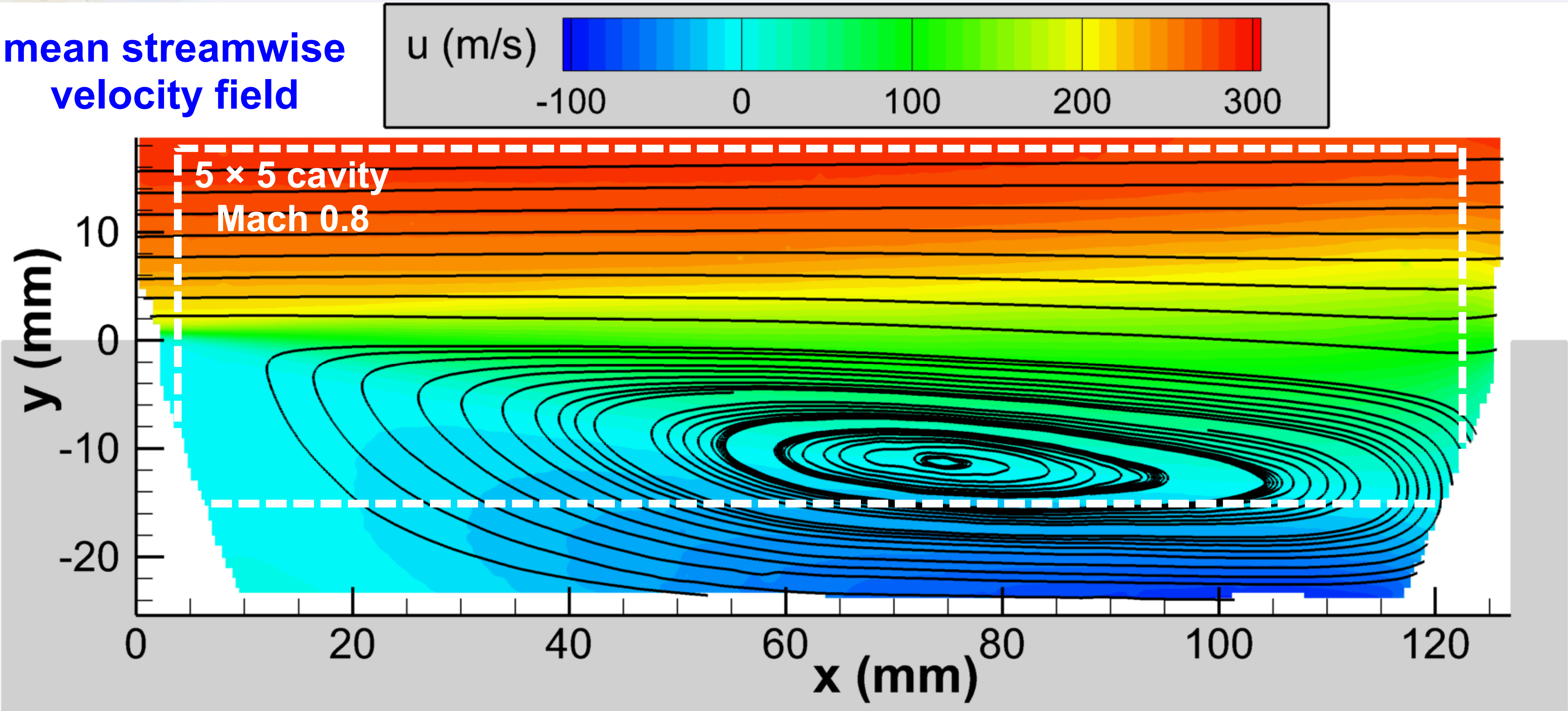
Tested at Mach 0.6, 0.8, and 0.94.

Upgrade cameras to *Photron SA-Z's*.

PIV framing rate now 37.5 kHz.

Sandia National Laboratories

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



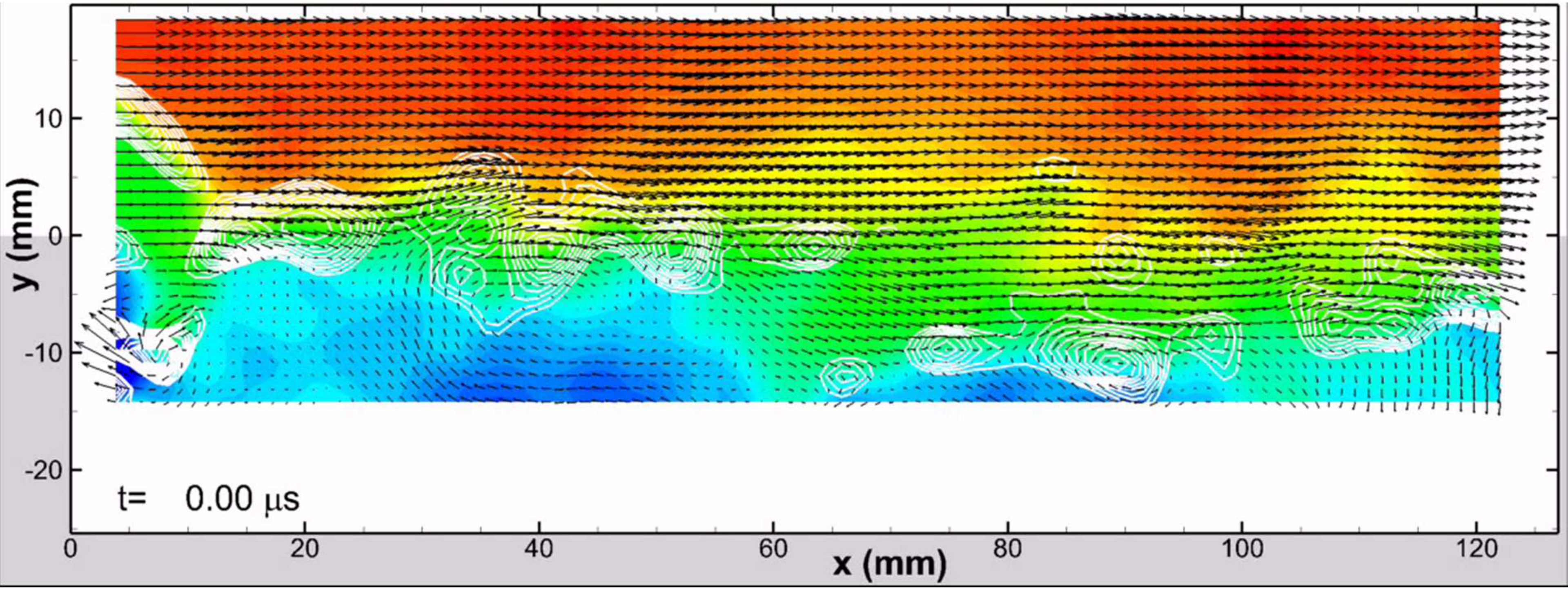
Streamlines clearly visualize the recirculation region and strong reverse velocities are evident.

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.

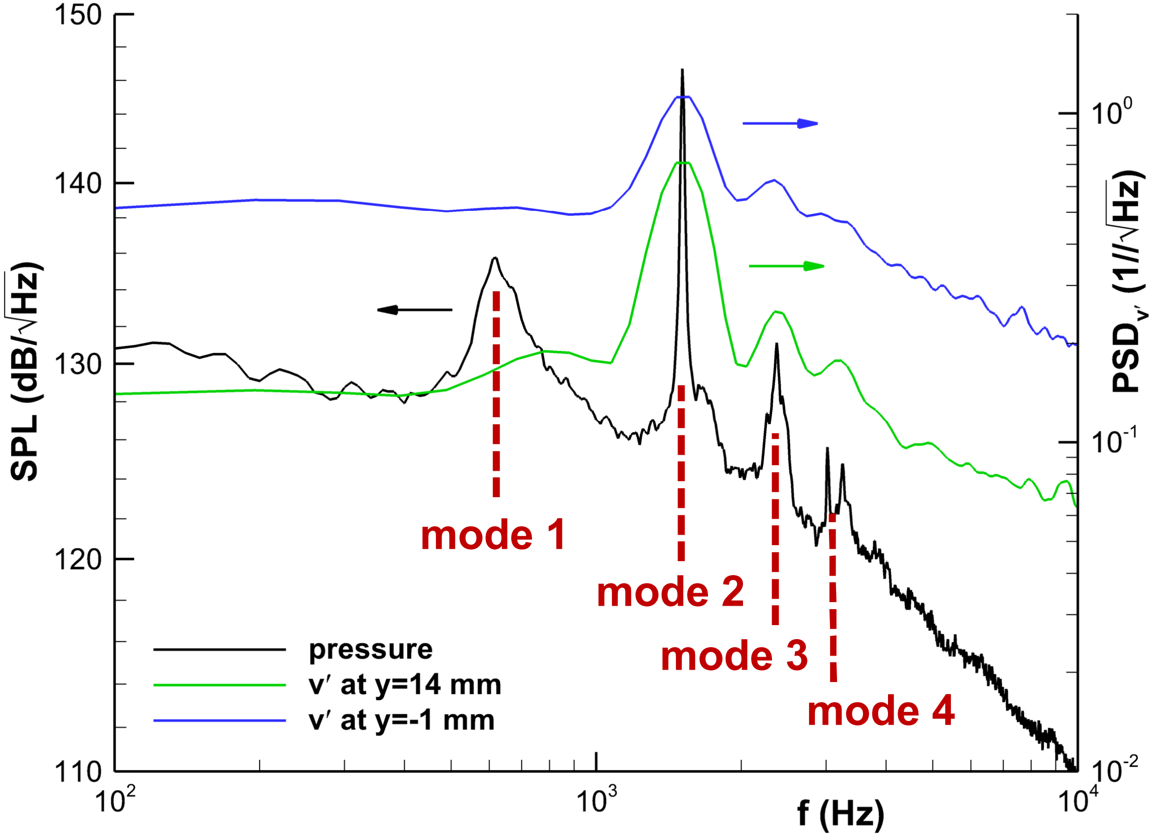


The pulse-burst PIV field of view visualizes most of the recirculation region including reverse velocities.

The flowfield is a combination of multiple acoustic resonances and turbulent activity in the shear layer and recirculation region.

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

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



We find resonances in the velocity field matching those from pressure sensors.

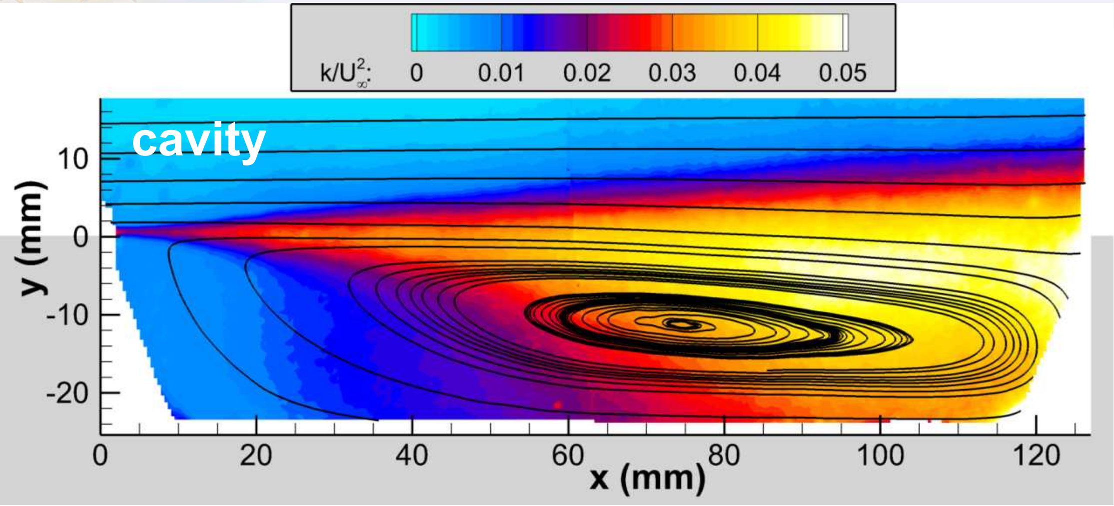
Modes 2 – 4 match very well.

Mode 1 is trickier to locate in the velocity data.

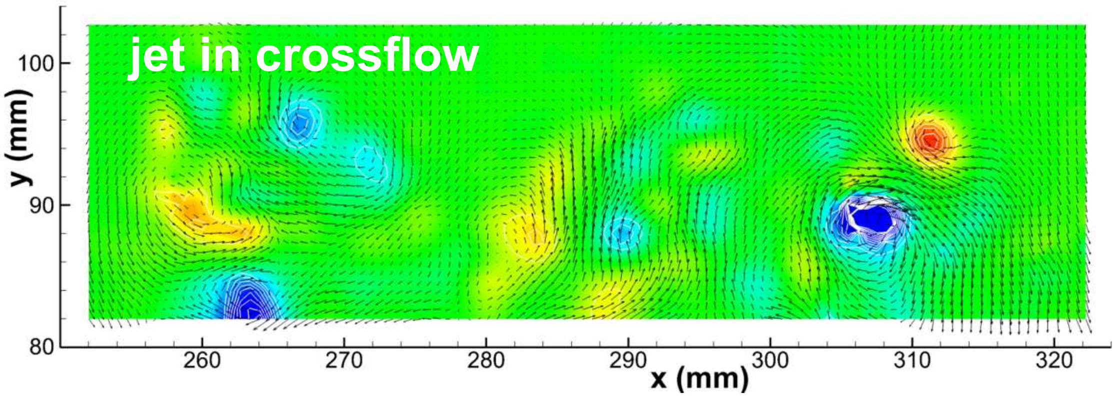
But to guide LES/DES model development, we need to measure much higher turbulent frequencies.

Sandia National Laboratories

Velocity Supersampling for the Cavity Flow



127 mm



70 mm

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:

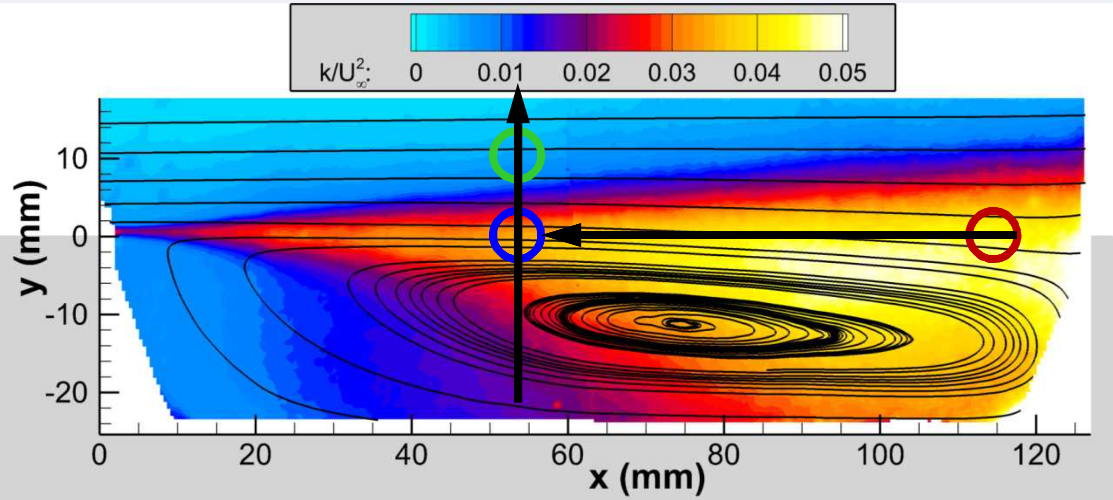
$$f = U_c / dI$$

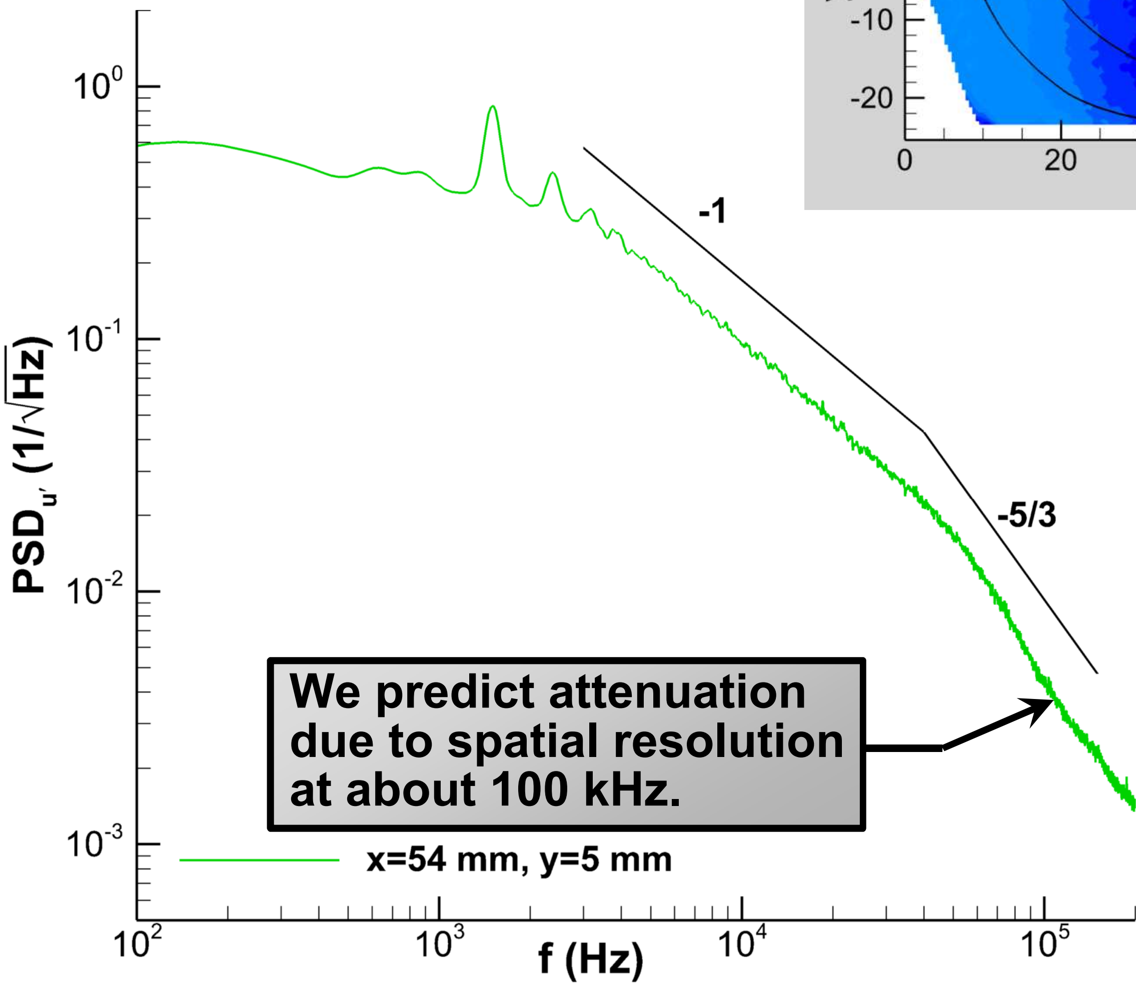
The spatial resolution (dI) of the cavity data is twice that of the jet in crossflow.

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

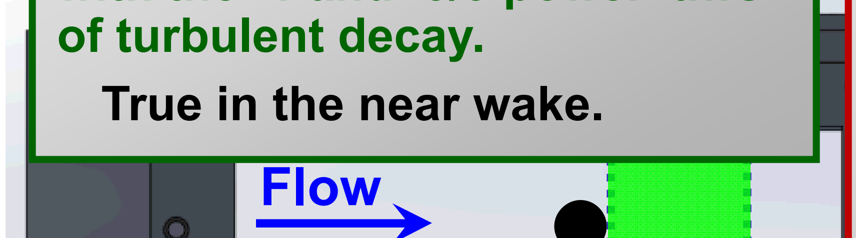
Can we measure turbulent spectra in our shock tube?

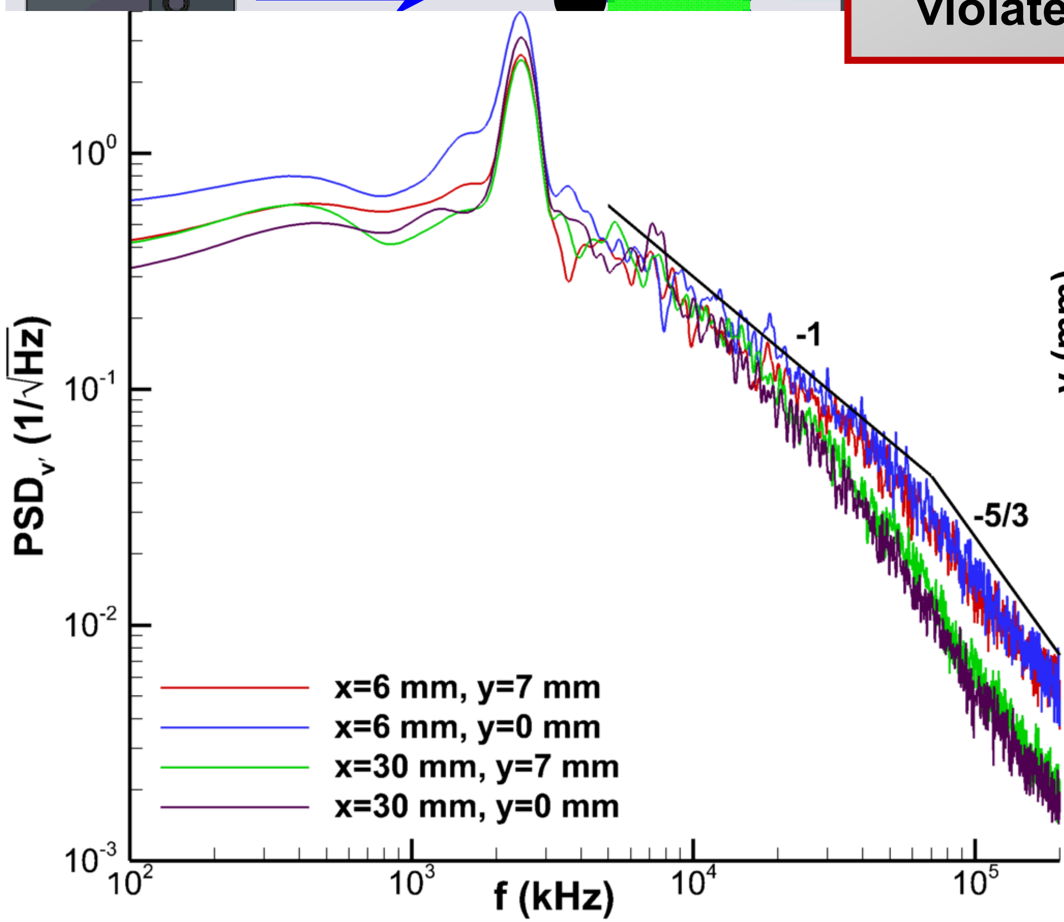
We see reasonable agreement with the -1 and -5/3 power laws of turbulent decay.

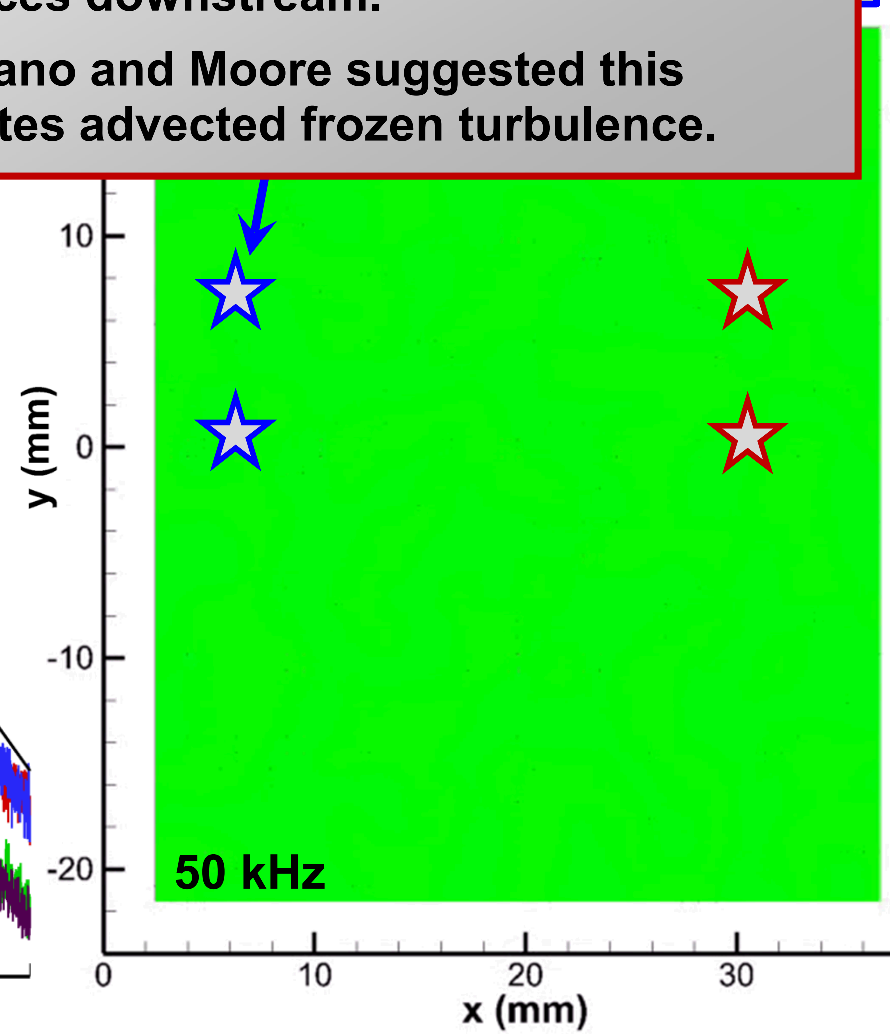
- True in the near wake.

Further downstream, we find poorer agreement with turbulent scaling laws.

- Possibly due to an interaction of large vortices downstream.
- Scarano and Moore suggested this violates advected frozen turbulence.

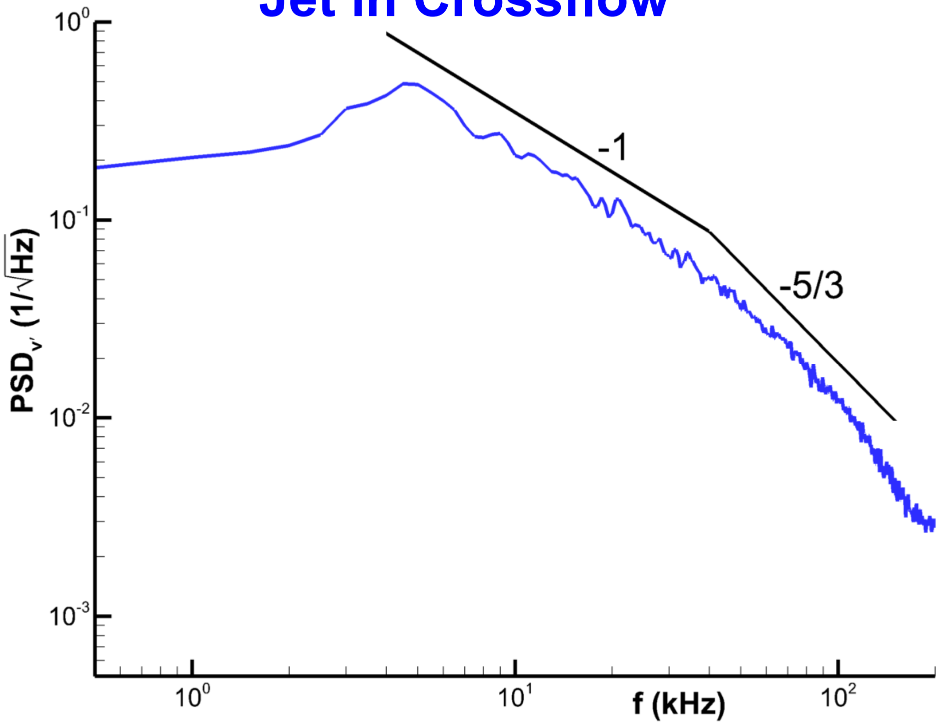




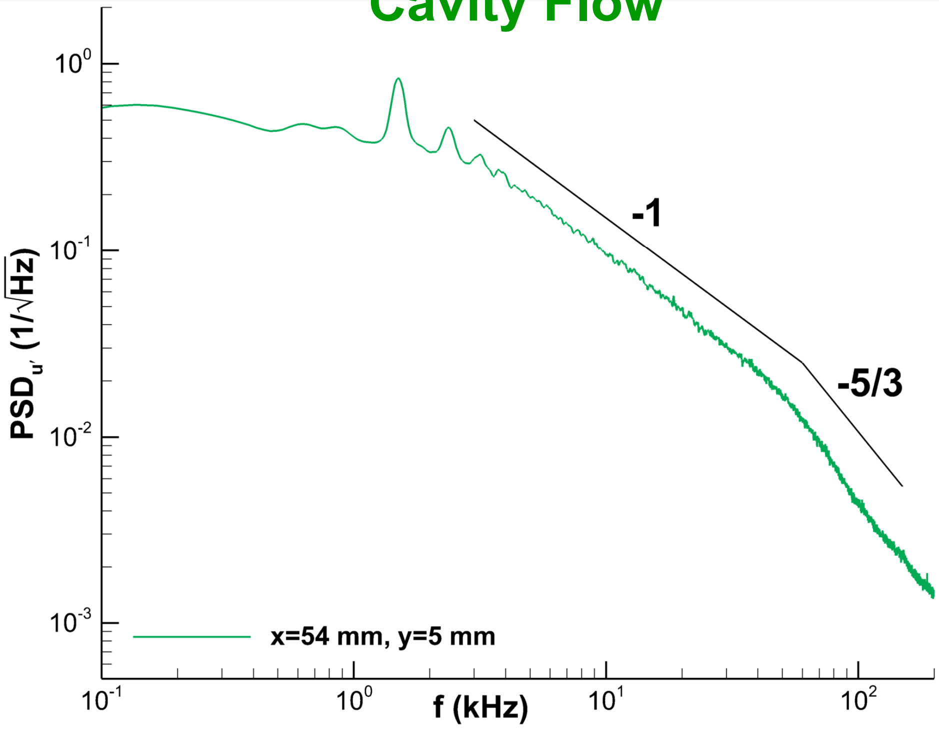


Turbulence Decay Laws

Jet in Crossflow



Cavity Flow



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.

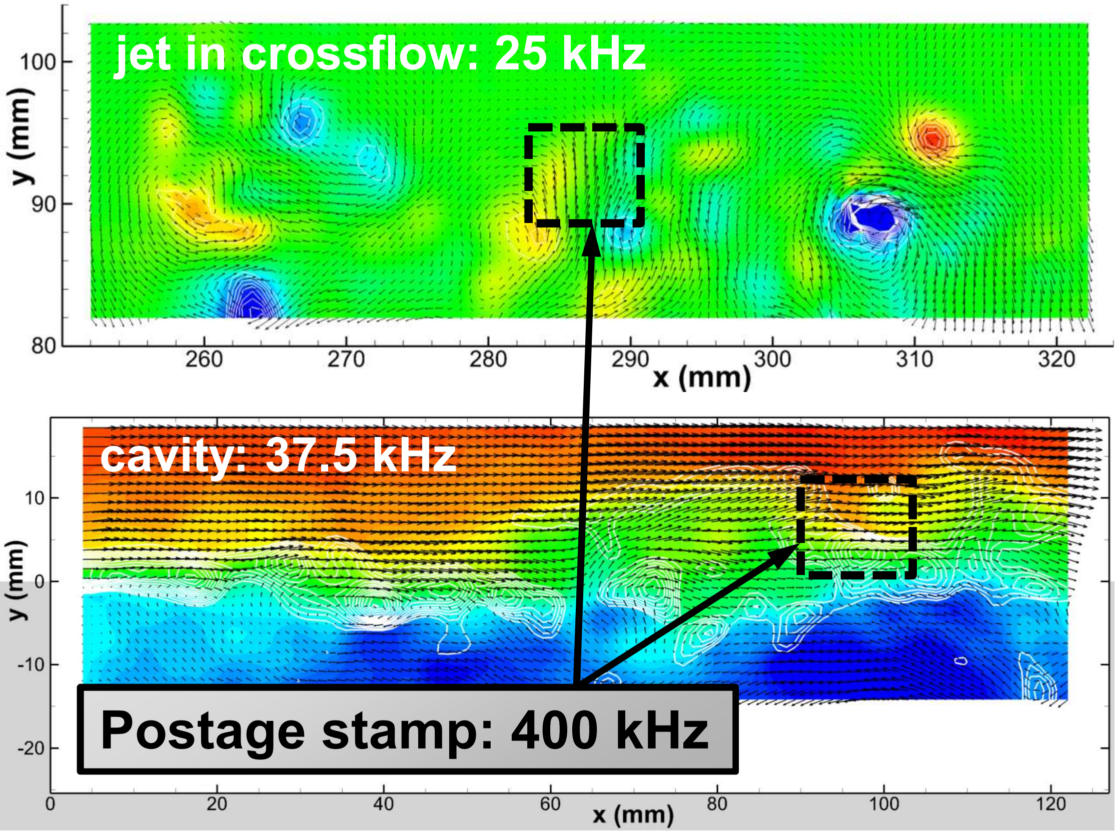
It is not known for free shear flows.

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!

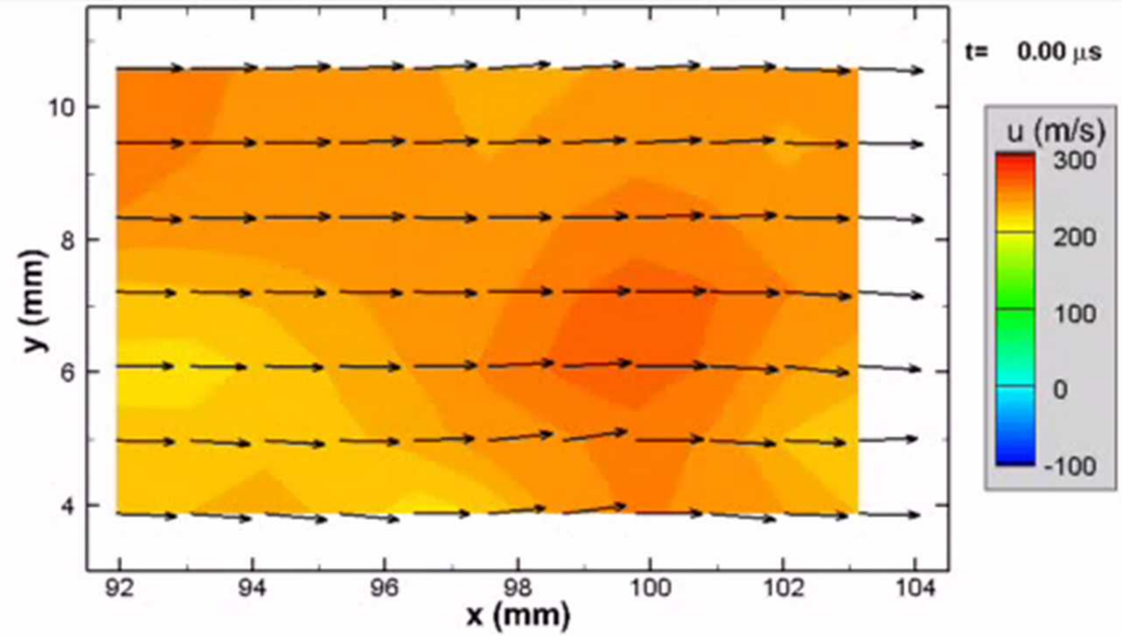
…if we use a very small field of view.

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

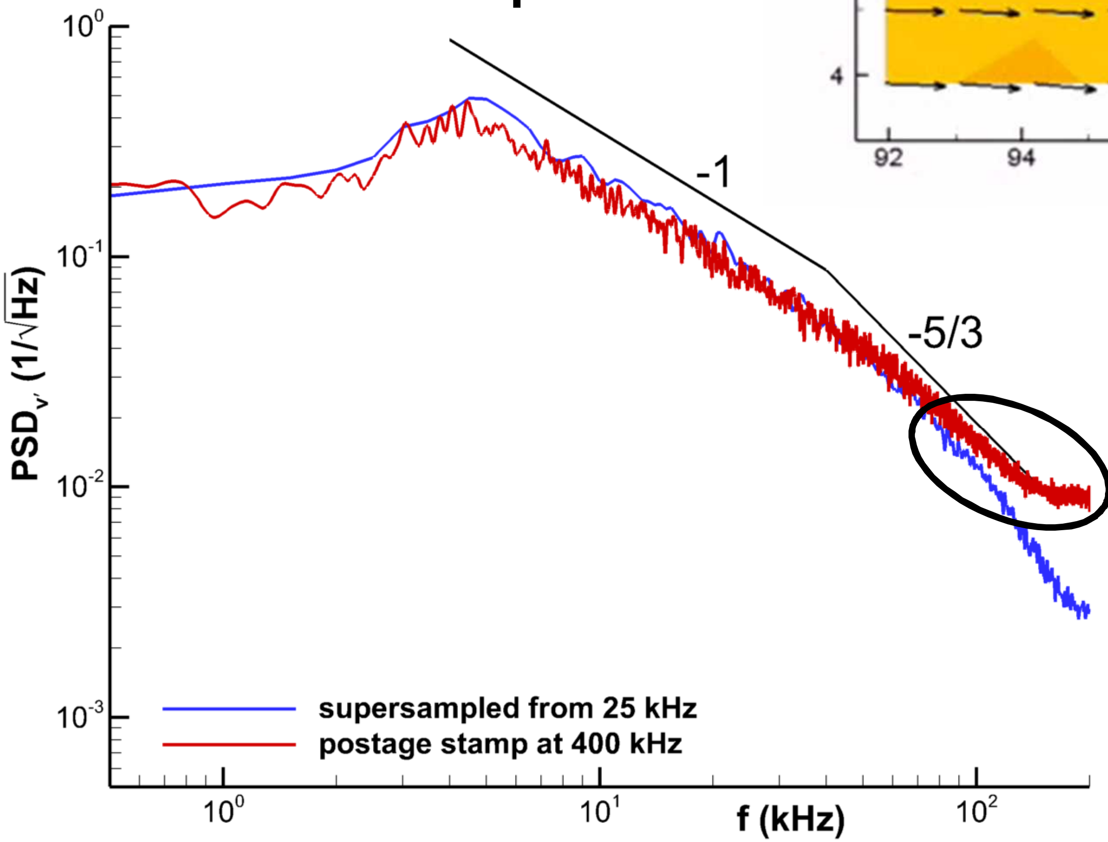
Sandia National Laboratories

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

Conclusions

Supersampling has proven effective increasing the frequency response of pulse-burst PIV.

But, supersampling has limitations:

- **The assumption of convected frozen turbulence breaks down when large-scale vortices interact.**
- **When out-of-plane motion is large, the correct turbulent fluctuations cannot be found.**
- **The finite spatial resolution of a velocity vector attenuates higher frequencies.**

Data at points not subject to these limitations appear to reveal a previously unremarked turbulent scaling law.

High-speed free-shear flows show a -1 power-law dependence for a frequency range corresponding to energetic eddies.

Sandia National Laboratories