SAND2016-10223C

Time-Resolved PIV and PSP for Measuring Transonic Cavity Resonance

Steven Beresh, Justin Wagner, Katya Casper, Ed DeMauro, John Henfling, and Rusty Spillers
Sandia National Laboratories
Albuquerque, NM, U.S.A.

STAI 126th Meeting
16-19 October, 2016
Melbourne, Australia

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.

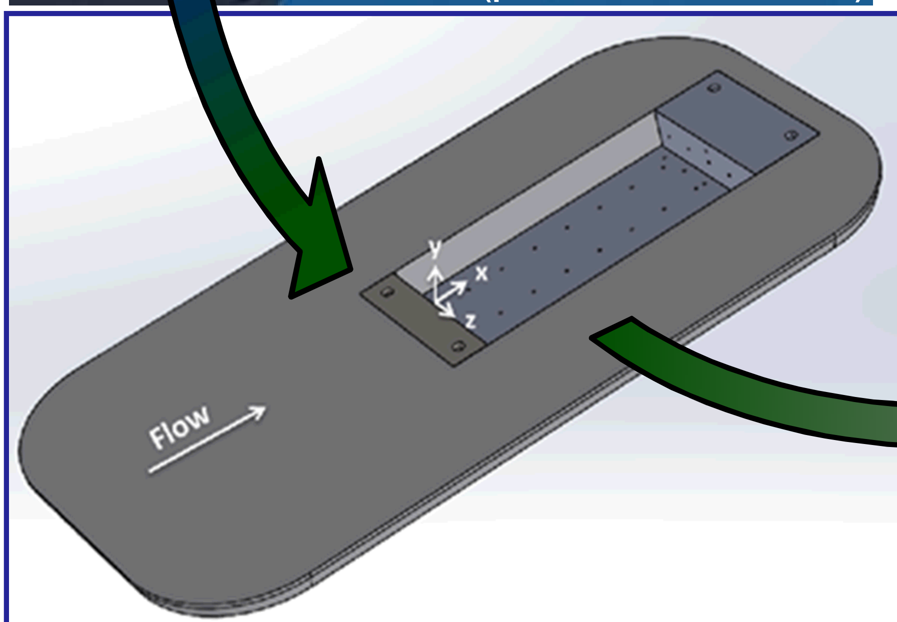
Sandia National Laboratories

What are the acoustics of an aircraft bay?

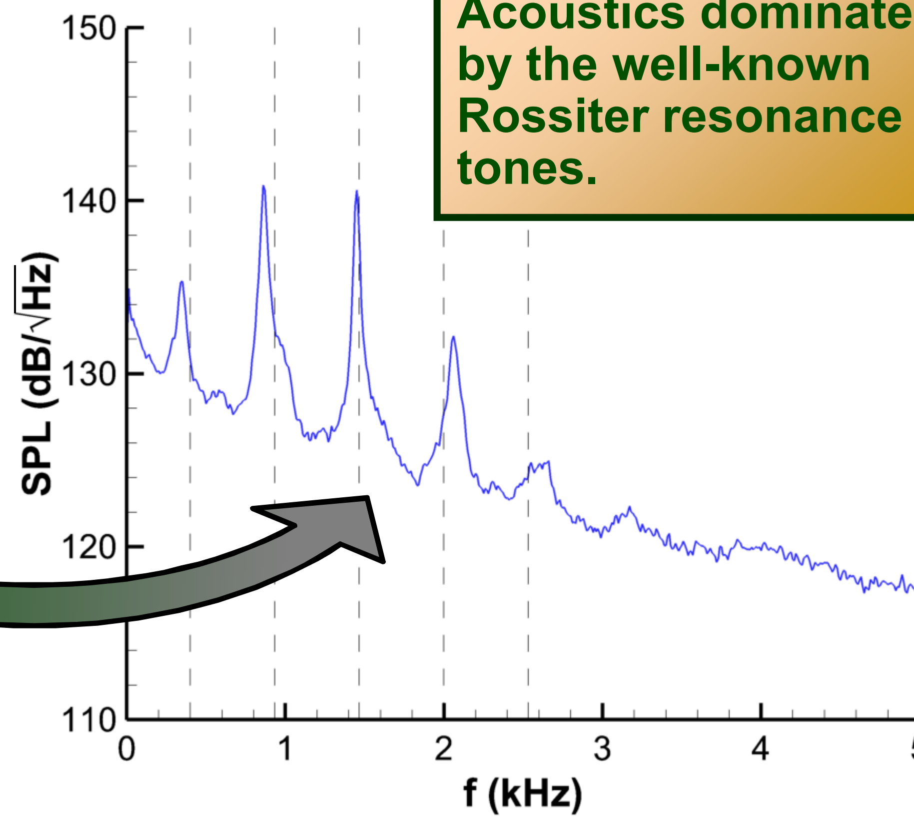
F-35 Weapons Bay
(photo: Lockheed Martin)

Most experiments represent an aircraft bay using a rectangular cavity.

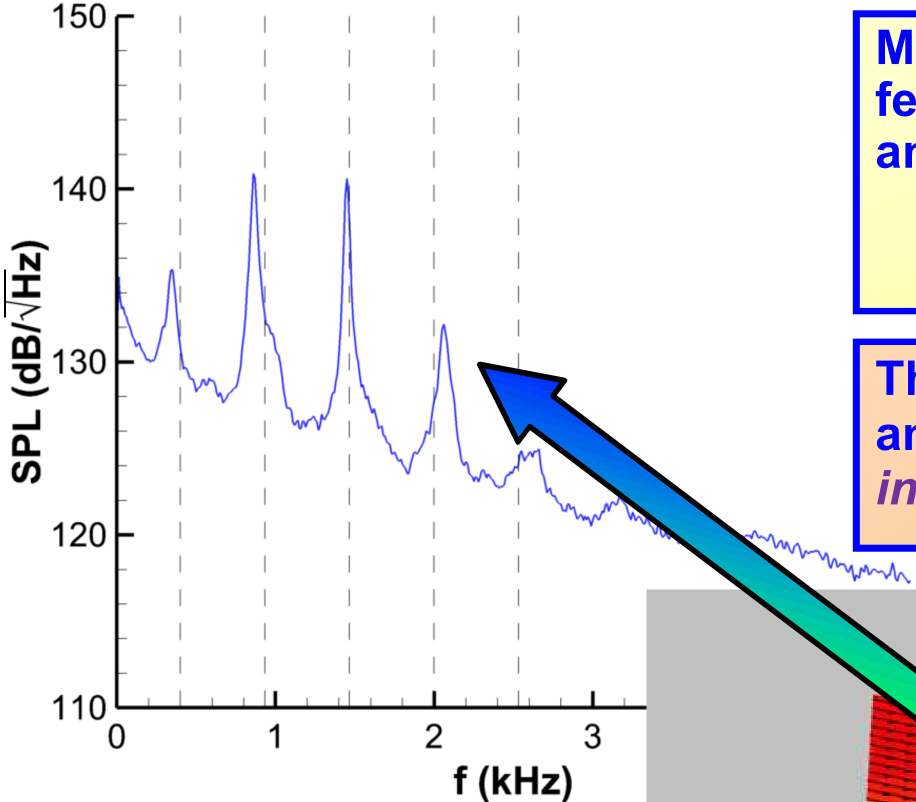
- Reproduces the fundamental physics of cavity flows.
- Influence of complex geometry is a separate topic.



Acoustics dominated by the well-known Rossiter resonance tones.



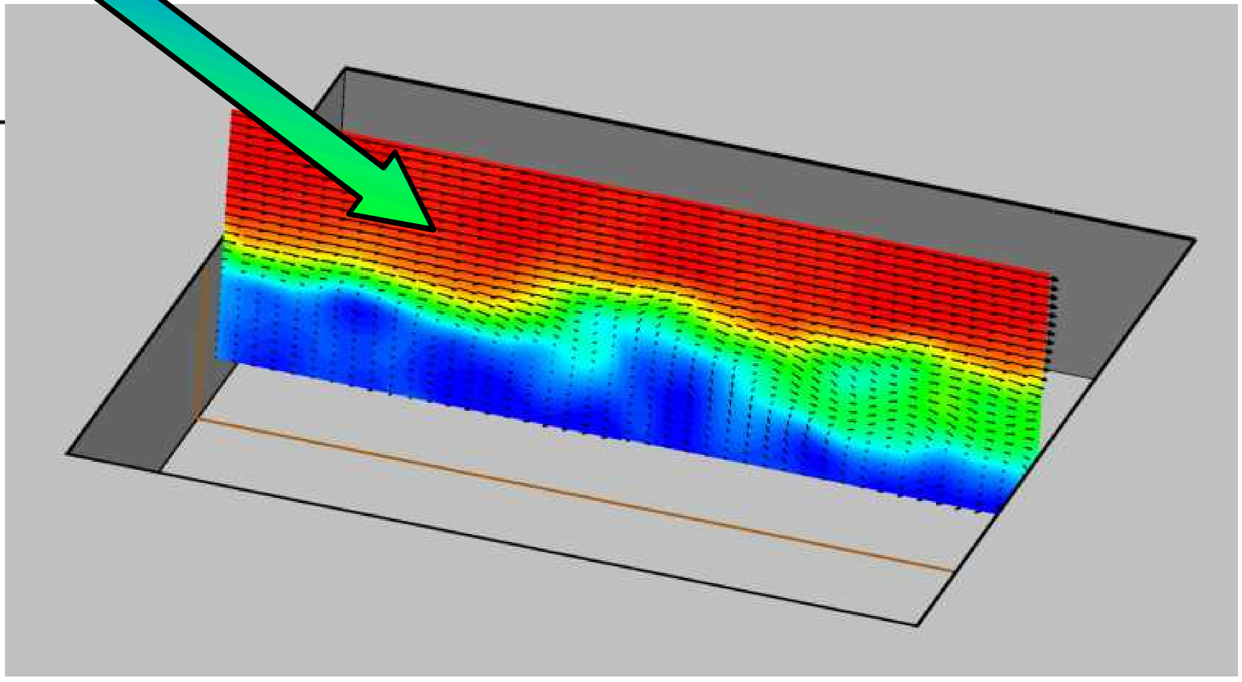
What causes the acoustic tones?



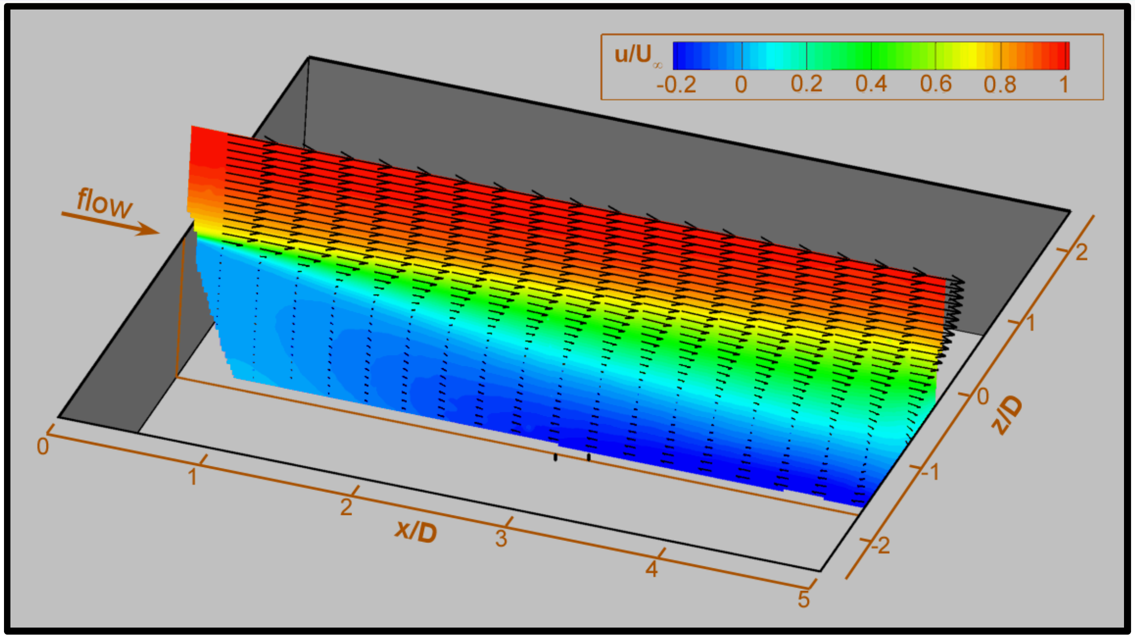
Multiple resonance modes occur due to a feedback loop between the acoustic field and the flow dynamics.

How do the shear layer and recirculation dynamics produce the acoustic field?

The spatial distribution of resonances is an important factor in *fluid/structure interaction* and vehicle vibration response.

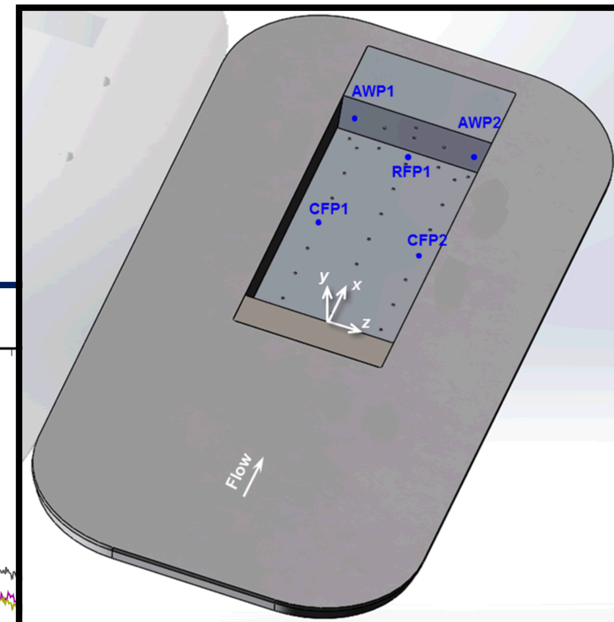


Conventional Measurement Technology



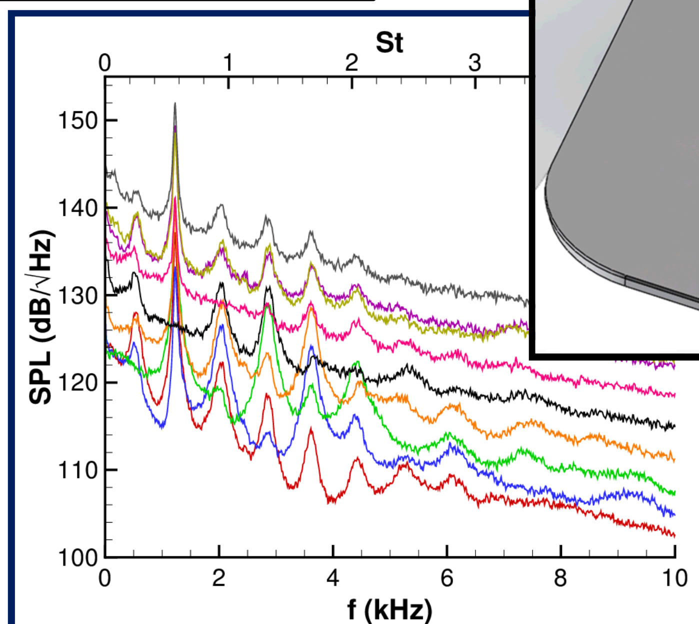
Conventional PIV gives us space but not time.

Conventional pressure sensors give us time but not space.



We want to study spatial distributions of the acoustic modes.

Therefore, what we really need are *velocity and pressure* data in both *time and space*.



Sandia National Laboratories

Time-Resolved PIV with a Pulse-Burst Laser

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

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

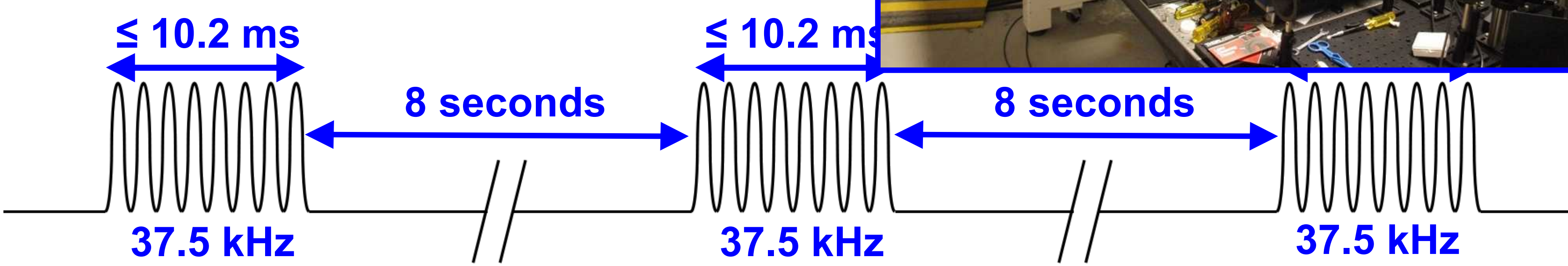
- **Faster repetition rates for briefer time scales.**
- **Higher energy required.**
  - **Scatter light off smaller particles**
  - **Expand laser sheet for larger field of view**

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

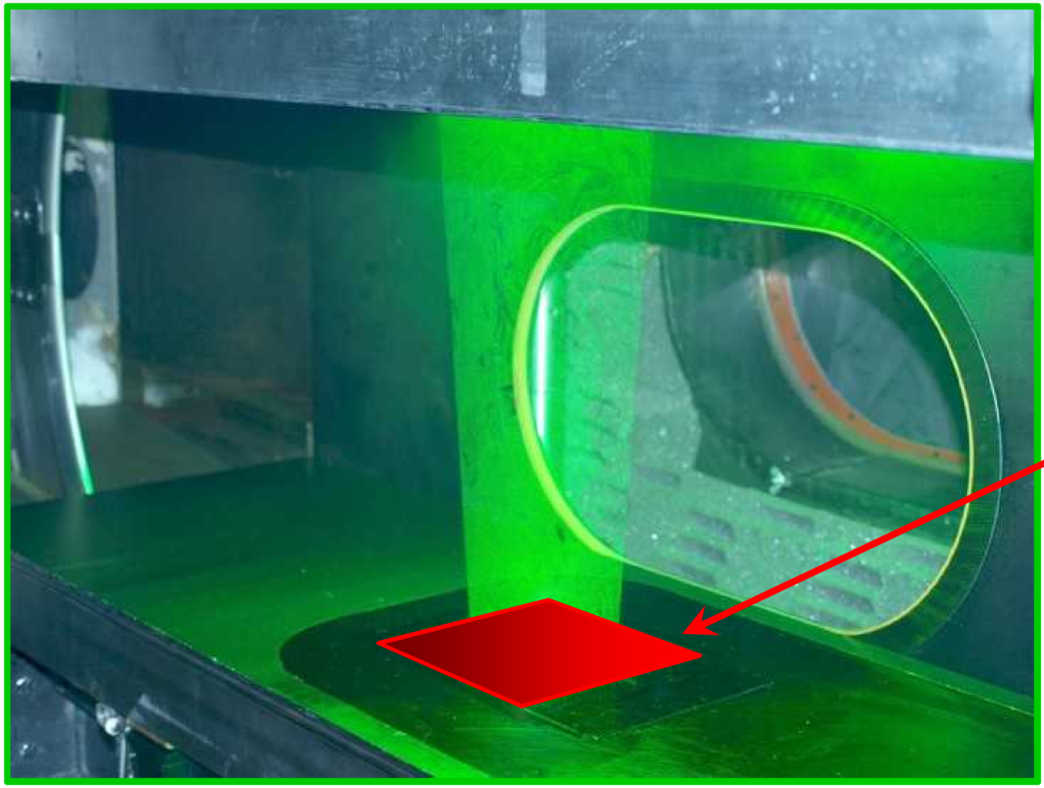
But a very low duty cycle.

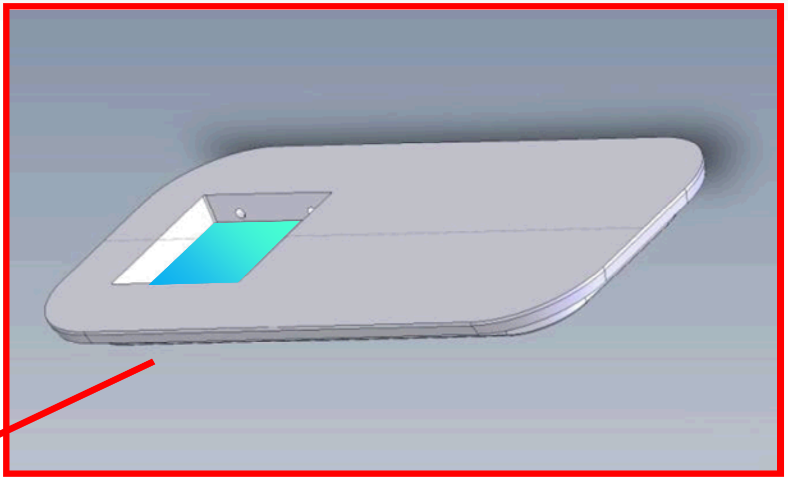
Pulse-Burst Laser:

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



Cavity Configuration





Build a cavity into the test section wall.

Floor is glass for laser access for PIV.

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

High-Speed Cameras for Pulse-Burst PIV

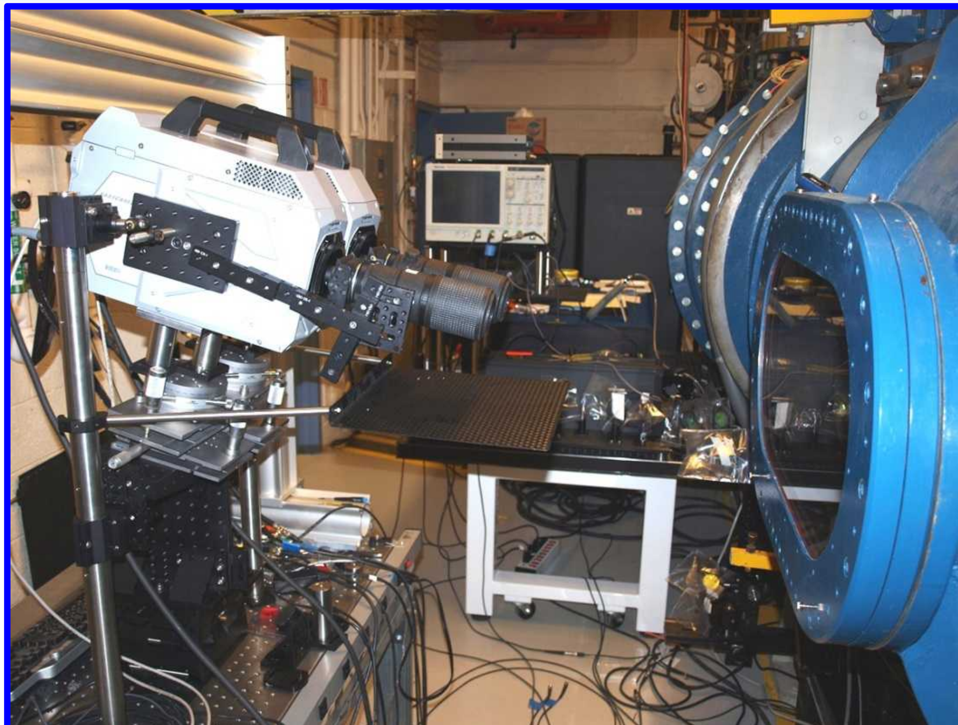
Two *Photron SA-Z's* placed adjacent for dual two-component PIV.

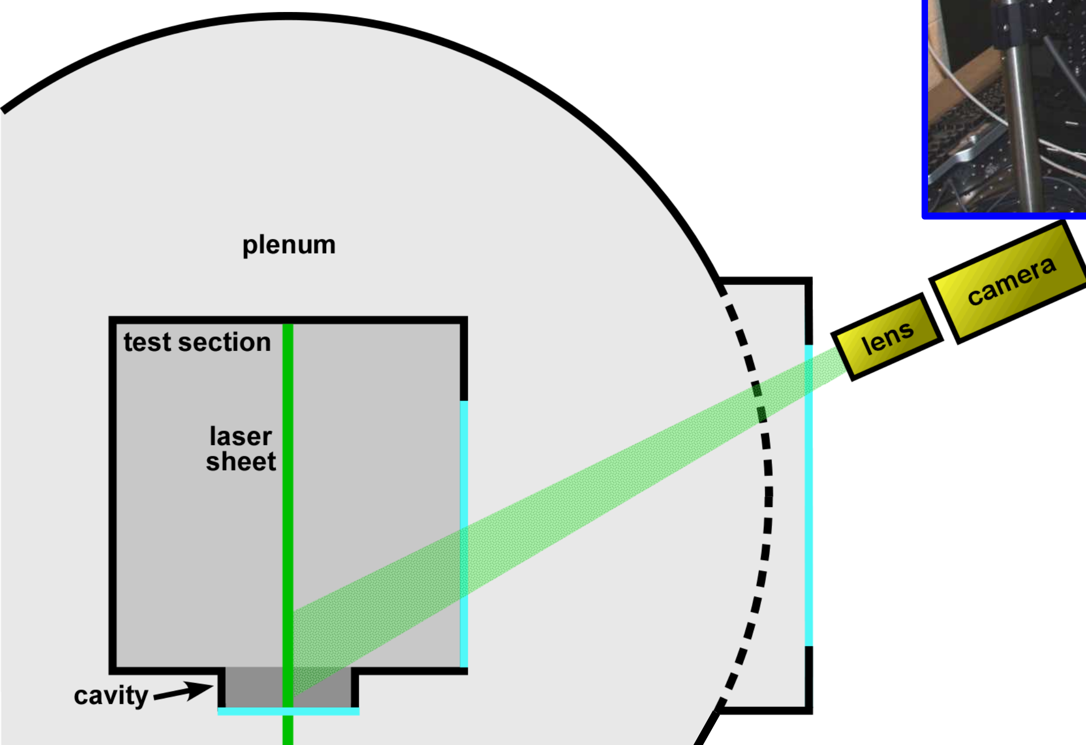
PIV framing rate is 37.5 kHz.

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

High-Speed Cameras for Pulse-Burst PIV

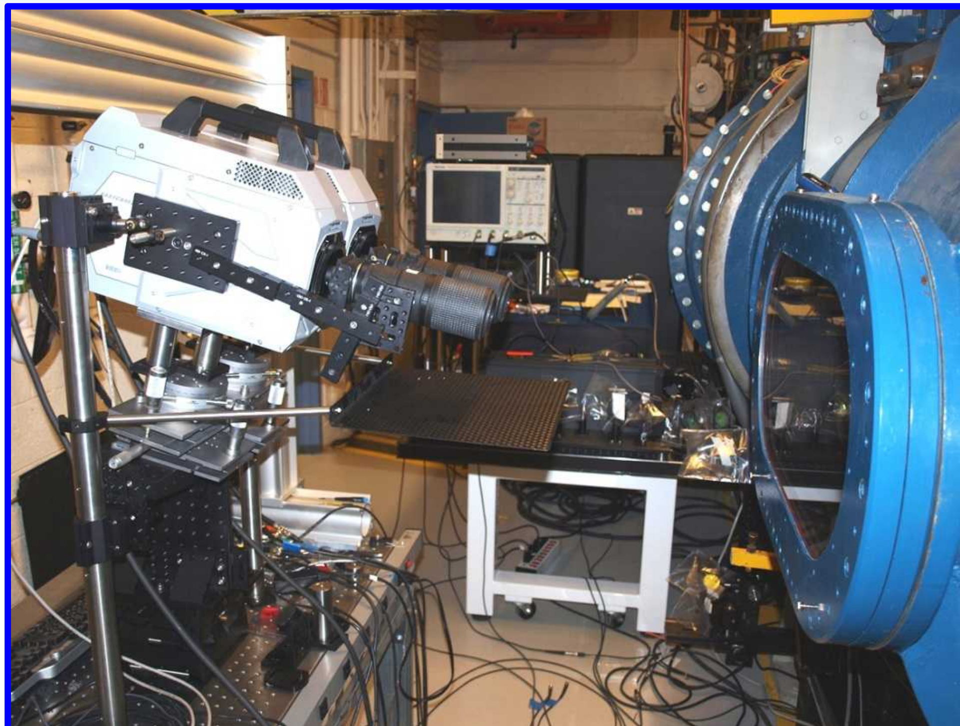
Two *Photron SA-Z's* placed adjacent for dual two-component PIV.

PIV framing rate is 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.



Camera settings:

- **640 × 360 pixels (×2)**
- **75 kHz framing rate**
- **Frame straddle pulse pairs**

Laser settings:

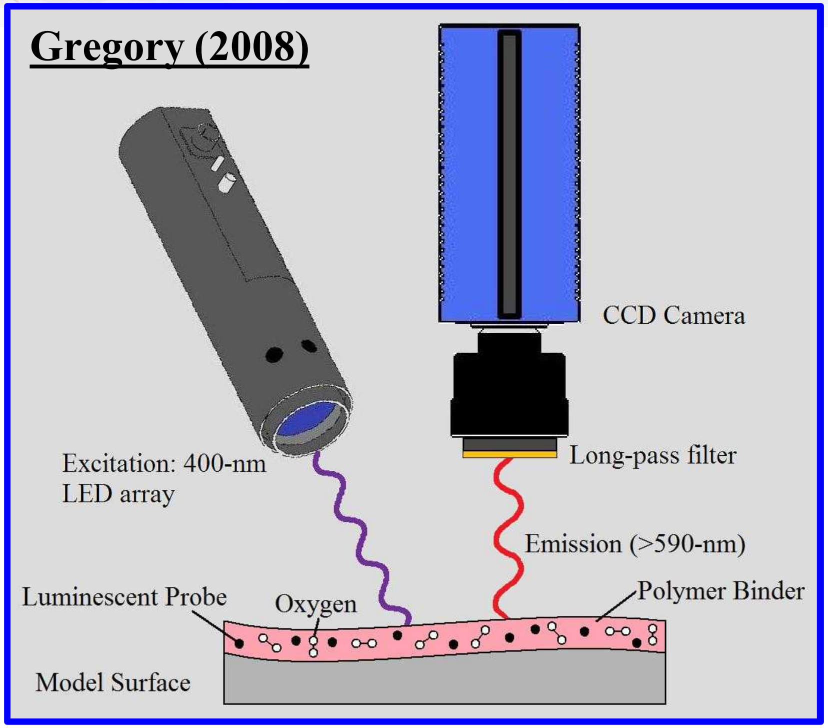
- **37.5 kHz of pulse pairs**
- **Δt = 3.40 μs**
- **10.2 ms burst, 27 mJ/pulse**

Acquire 250 - 300 bursts at each of three Mach numbers.

But we're just going to discuss Mach 0.8.

Sandia National Laboratories

Unsteady Pressure Sensitive Paint



Permeable binder allows fast response of luminophore (about *10 kHz*)

Cavity now installed on upper wall.

Floor painted with high frequency PSP from ISSI (PtTFPP in a porous binder).

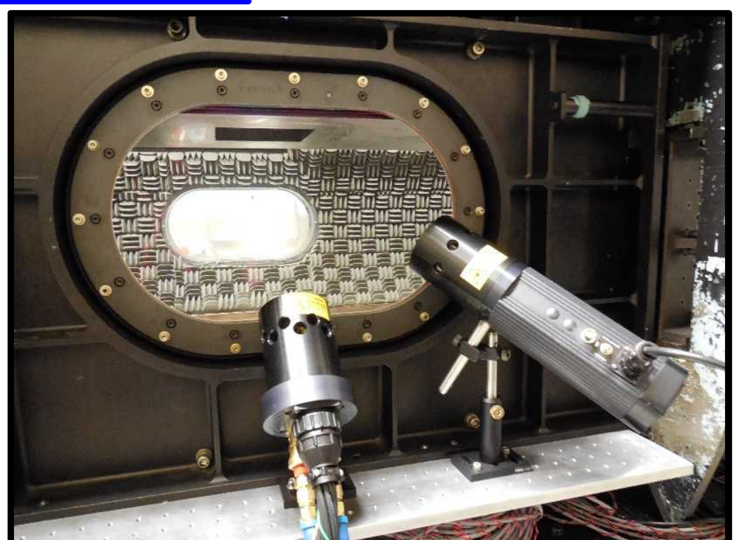
3 water cooled LED arrays at 400 nm.

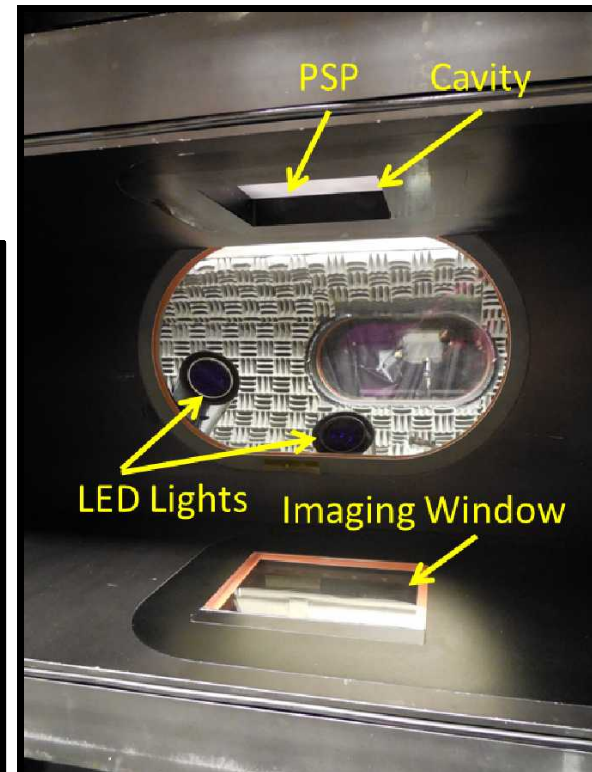
Photron SA-Z High-Speed Camera

(beneath tunnel)

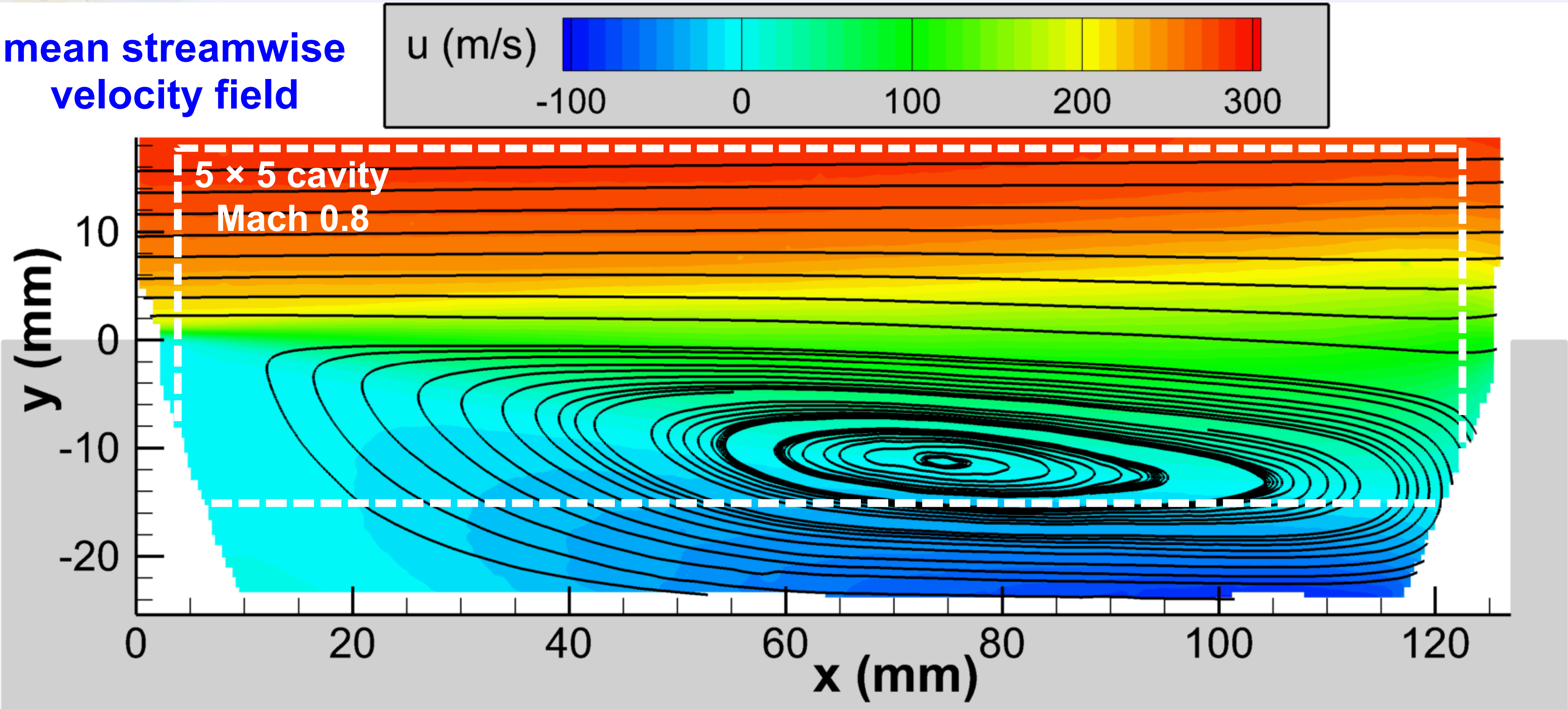
1 MP at 20 kHz.

590 nm long-pass filter removes excitation light.





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



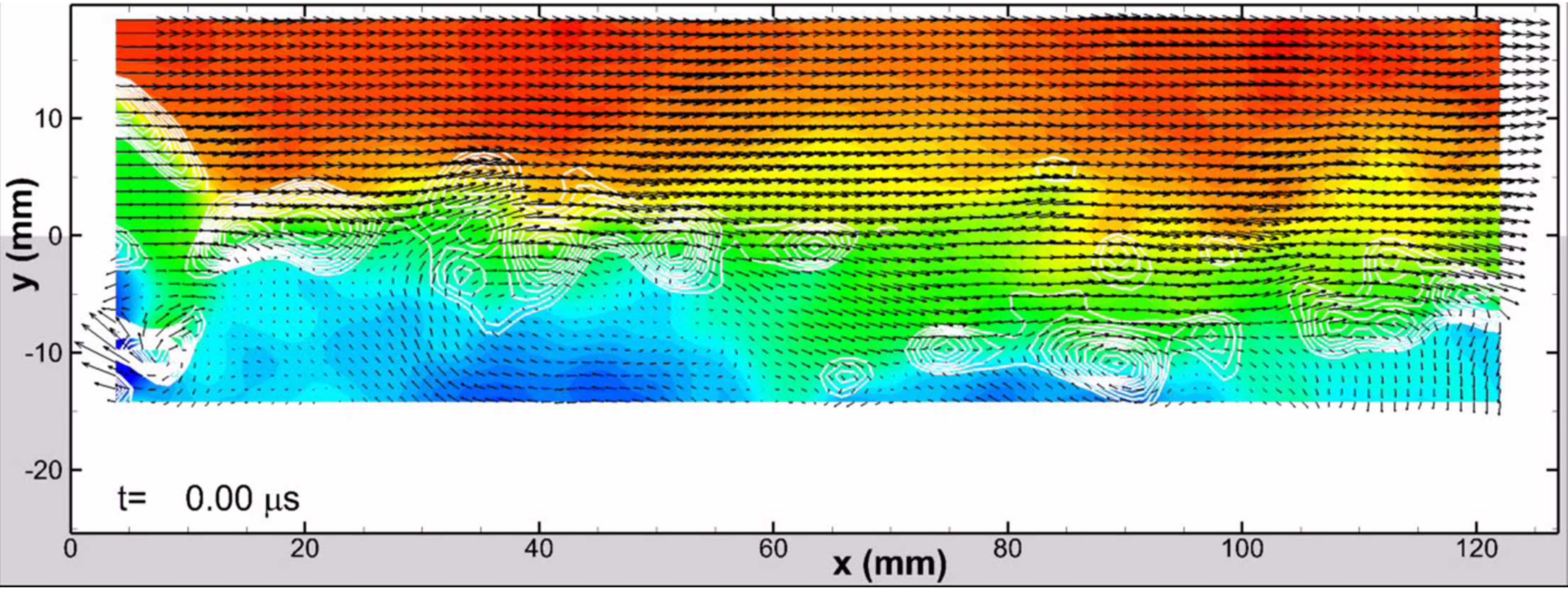
Streamlines clearly visualize the recirculation region and strong reverse velocities are evident.

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.



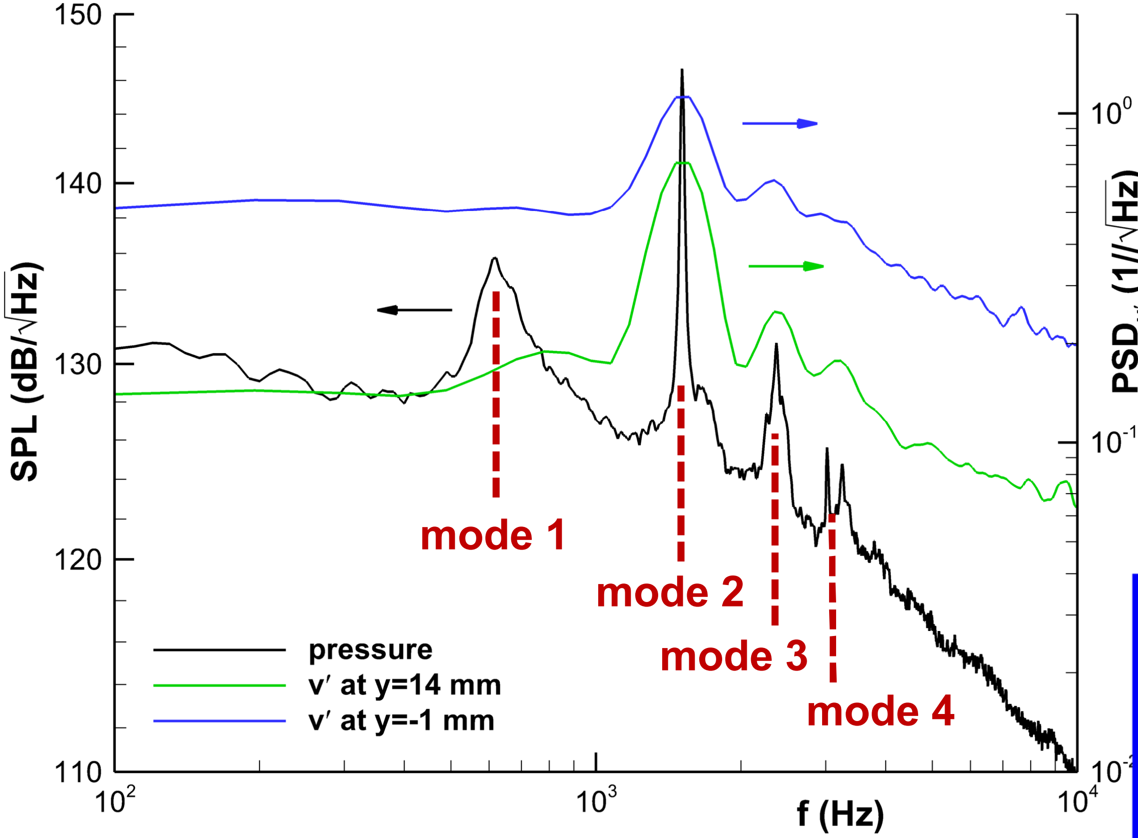
The pulse-burst PIV field of view visualizes most of the recirculation region including reverse velocities.

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

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.

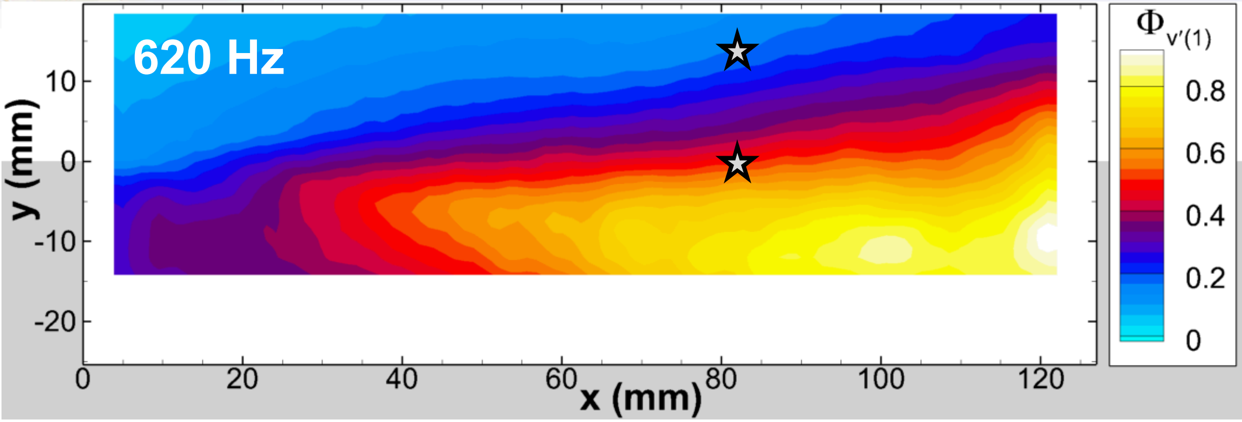
We can even see the bifurcated mode 4 peak in the shear layer velocity data.

Mode 1 is largely absent in the velocity data.

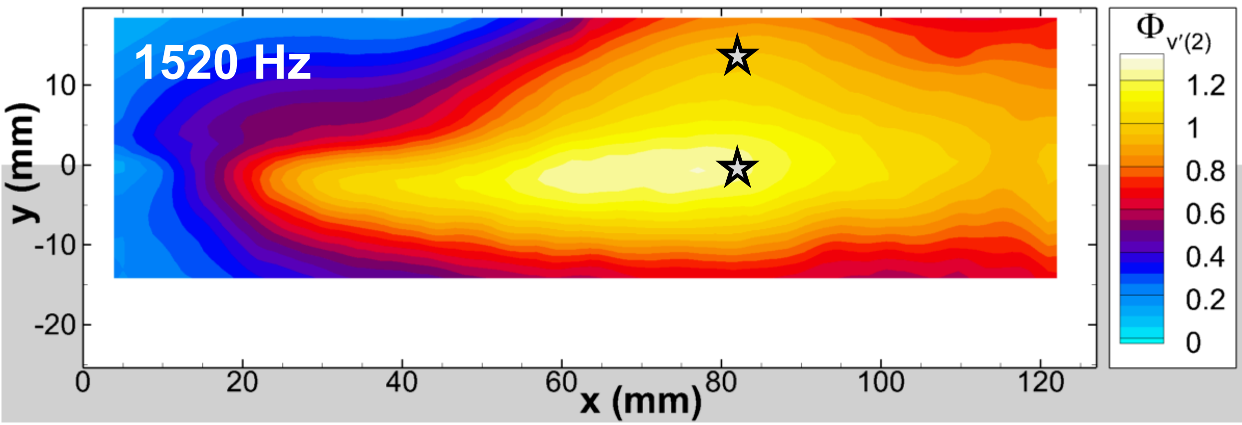
Pulse-burst PIV allows us to look at the *spatial distribution* of the resonance modes.

Sandia National Laboratories

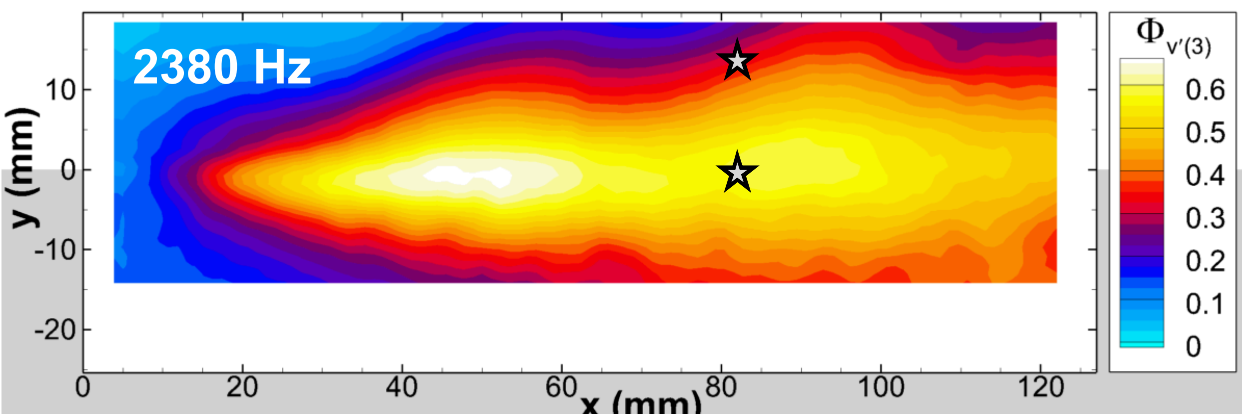
Spatial Distribution of Resonance Modes



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?

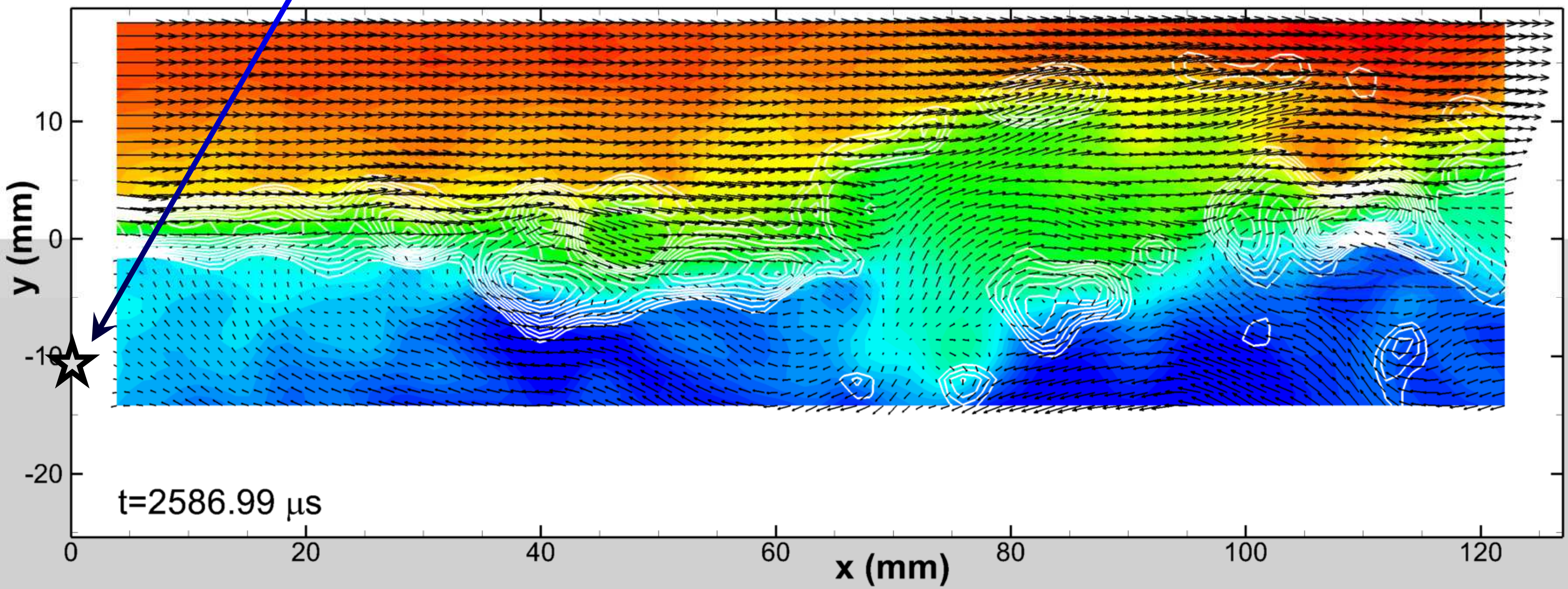
Spatio-temporal correlations

Correlate every vector in the velocity field with a *pressure sensor* in the forward wall.

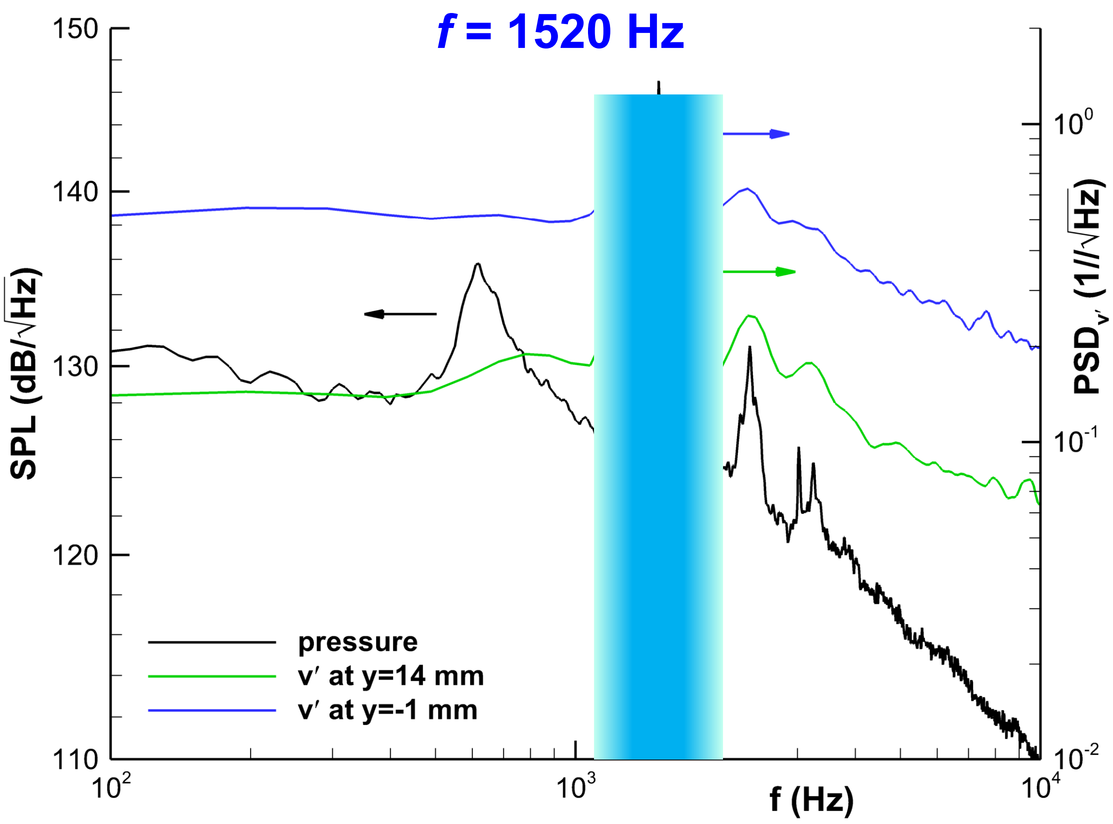
Track correlation fields through space and time.

Similar results when correlating with a pressure sensor placed elsewhere.

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.

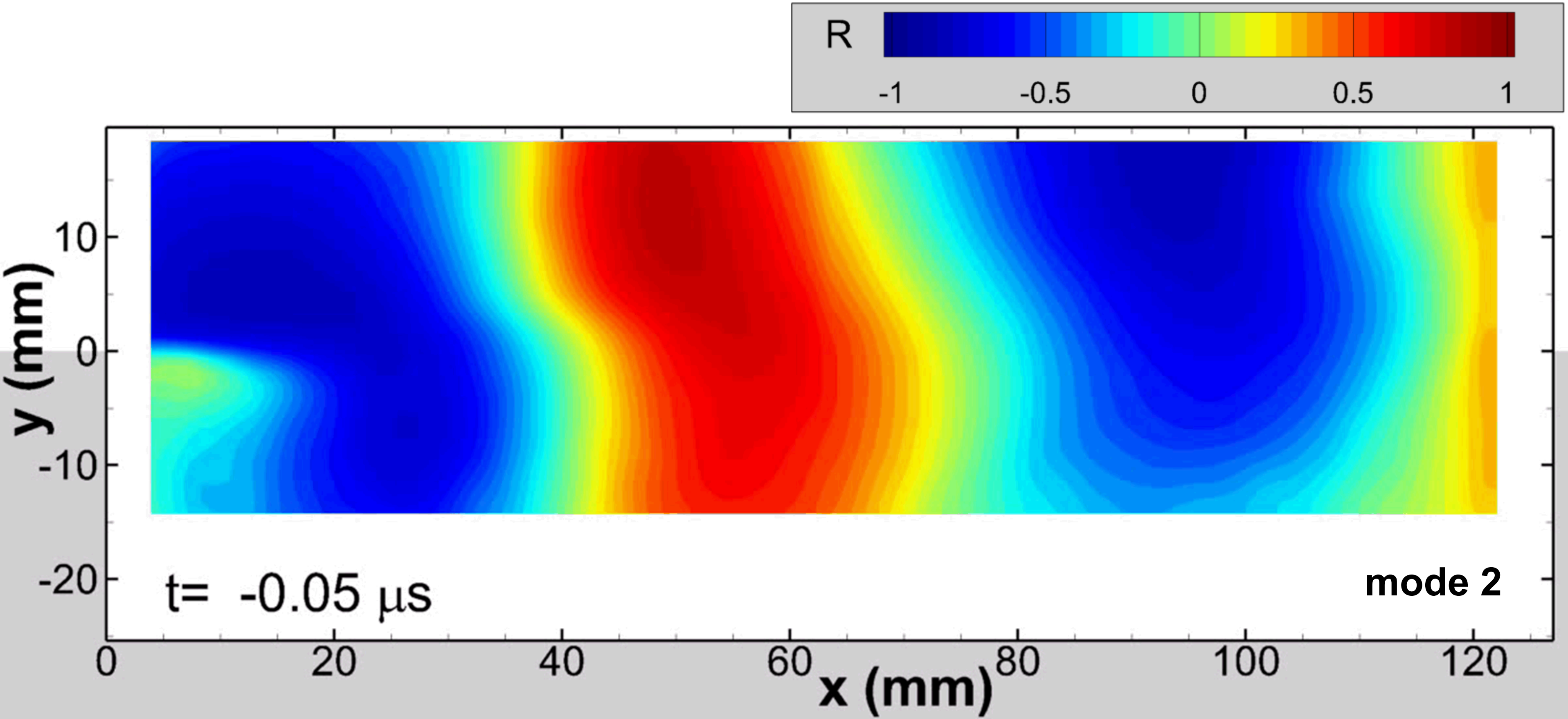
It turns out *mode 1* behaves differently than the rest, so let's start by discussing *mode 2*.

Sandia National Laboratories

Mode 2 Correlation Field

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

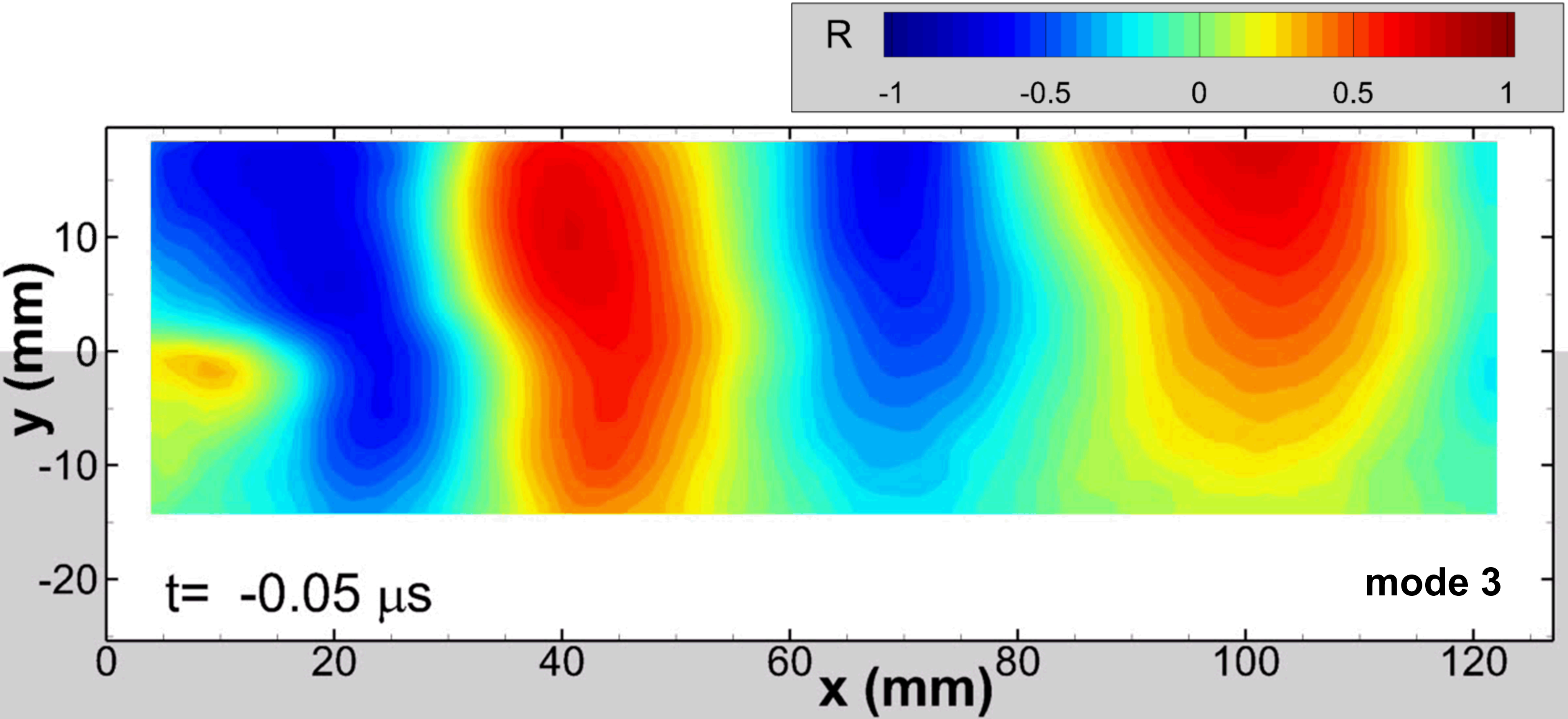
- **The spacing between the structures increases as they convect downstream.**
- **The structures tend to drift outward.**



Mode 3 Correlation Field

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

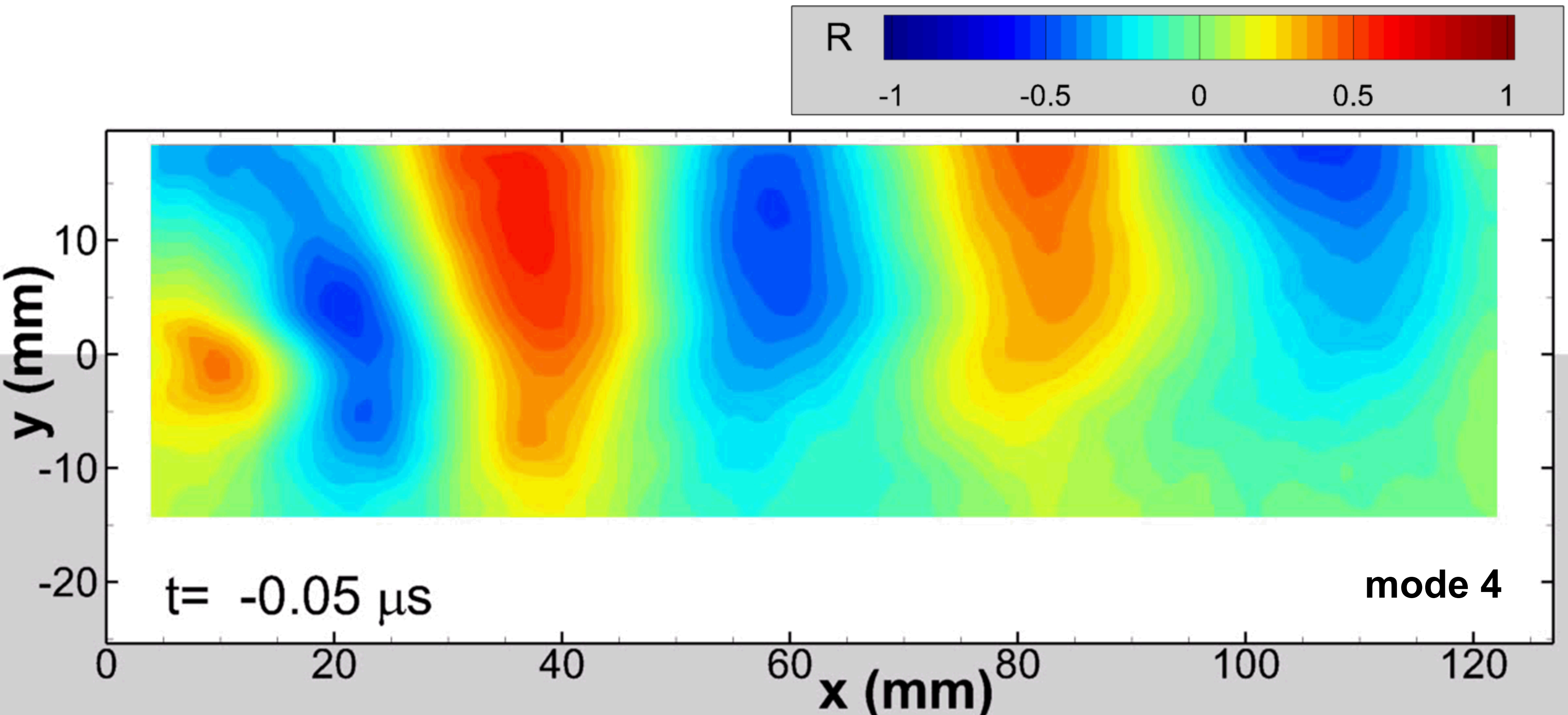
- **The spacing between the structures increases as they convect downstream.**
- **The structures tend to drift outward.**
- **The spatial scale of the coherent structures shortens as the mode increases.**



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.**



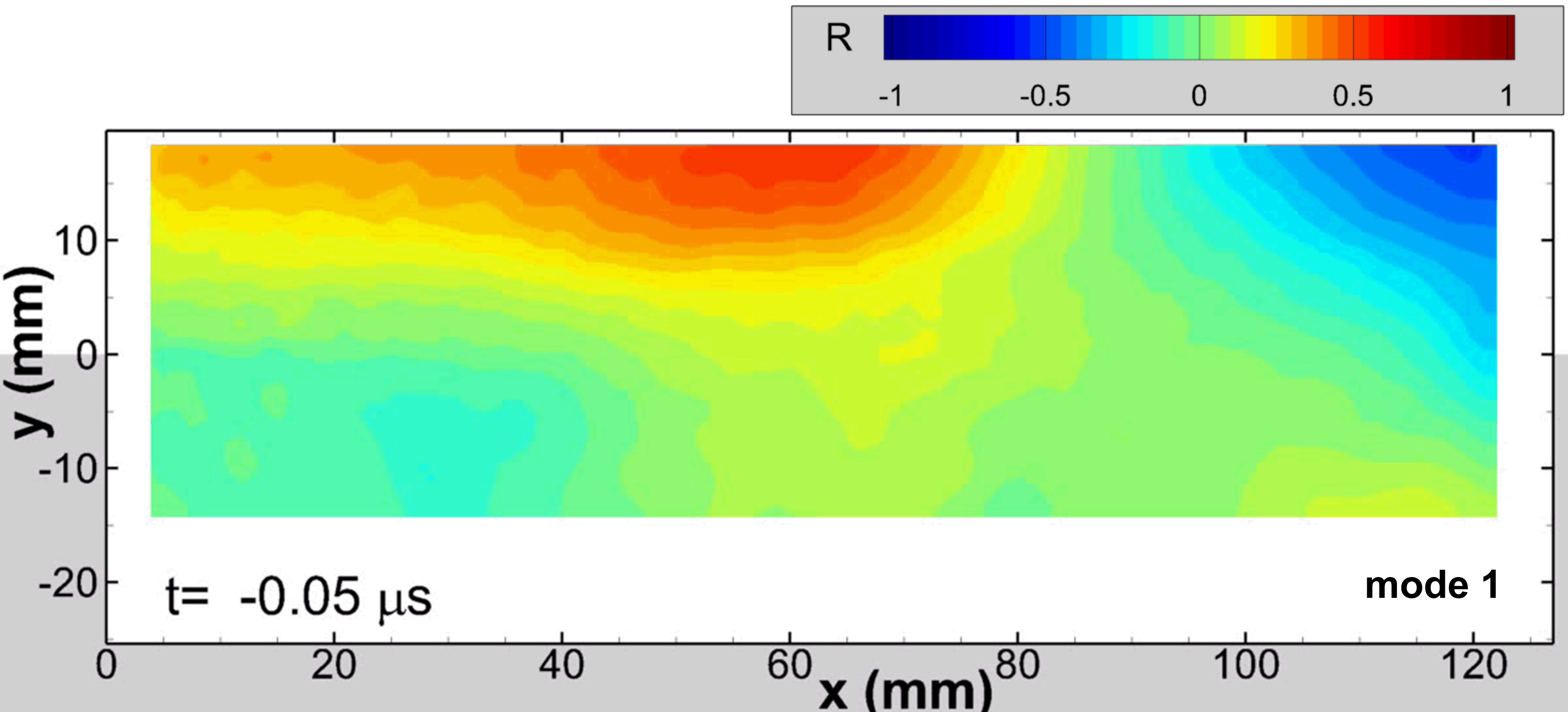
Mode 1 Correlation Field

Mode 1 shows little correlation within the cavity.

- **Acoustic radiation still emitted, but weakens sooner.**

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

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

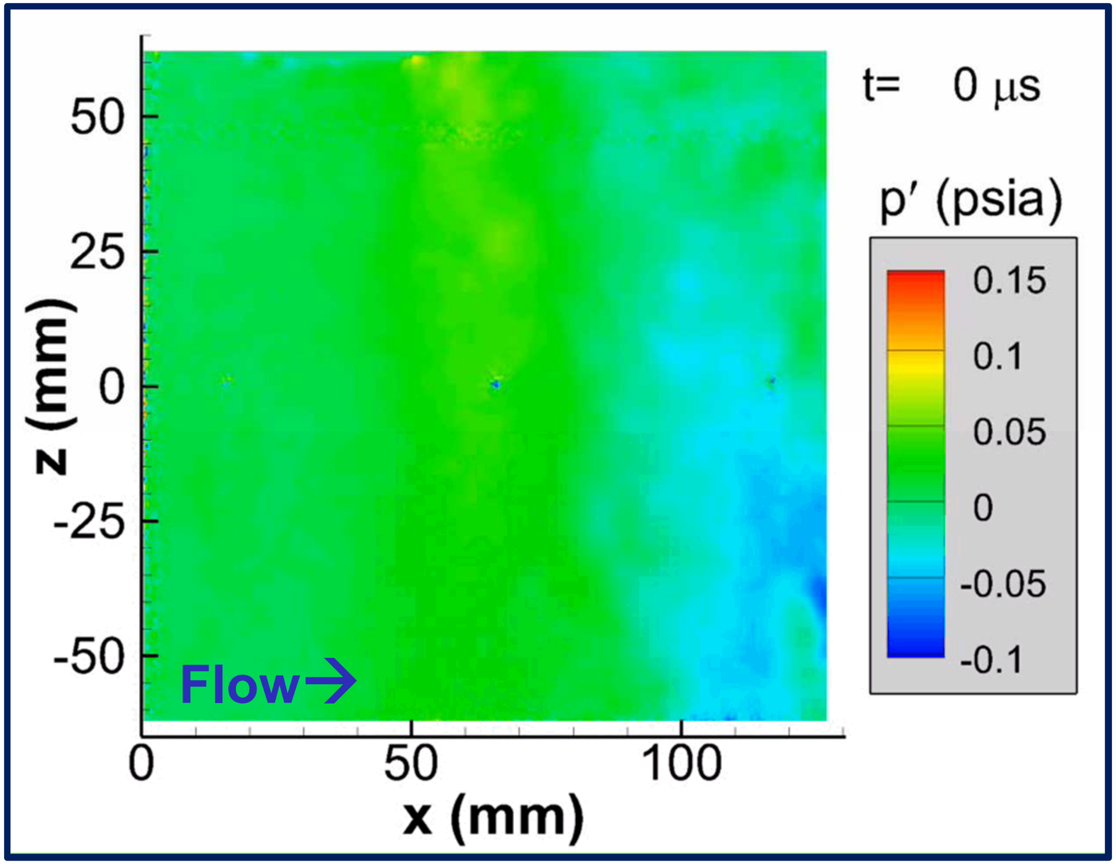


Pressure Sensitive Paint Results

PSP movies obtained on the floor of several cavity configurations.

Complex pressure field sets up in the cavity from a mixture of Rossiter modes and turbulence.

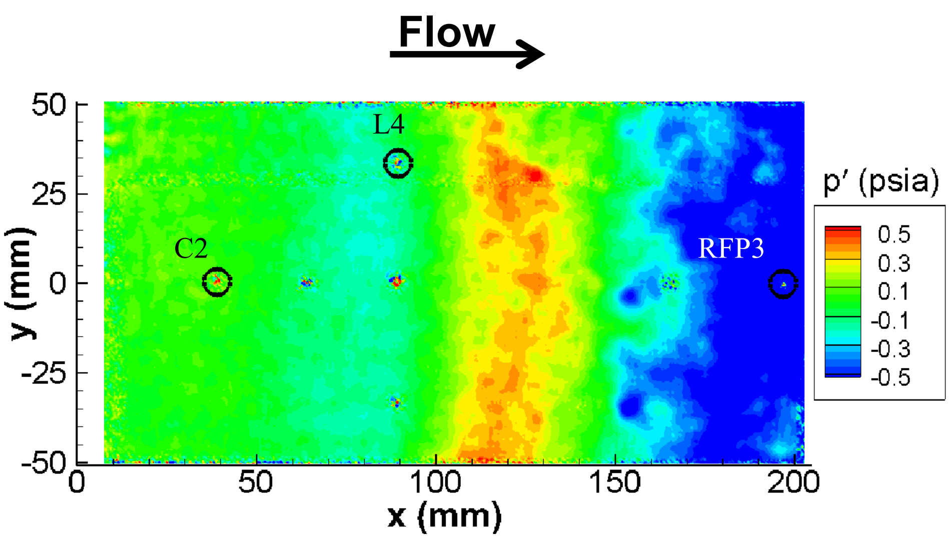
As in the pulse-burst PIV, we need additional data processing to visualize each cavity resonance mode.



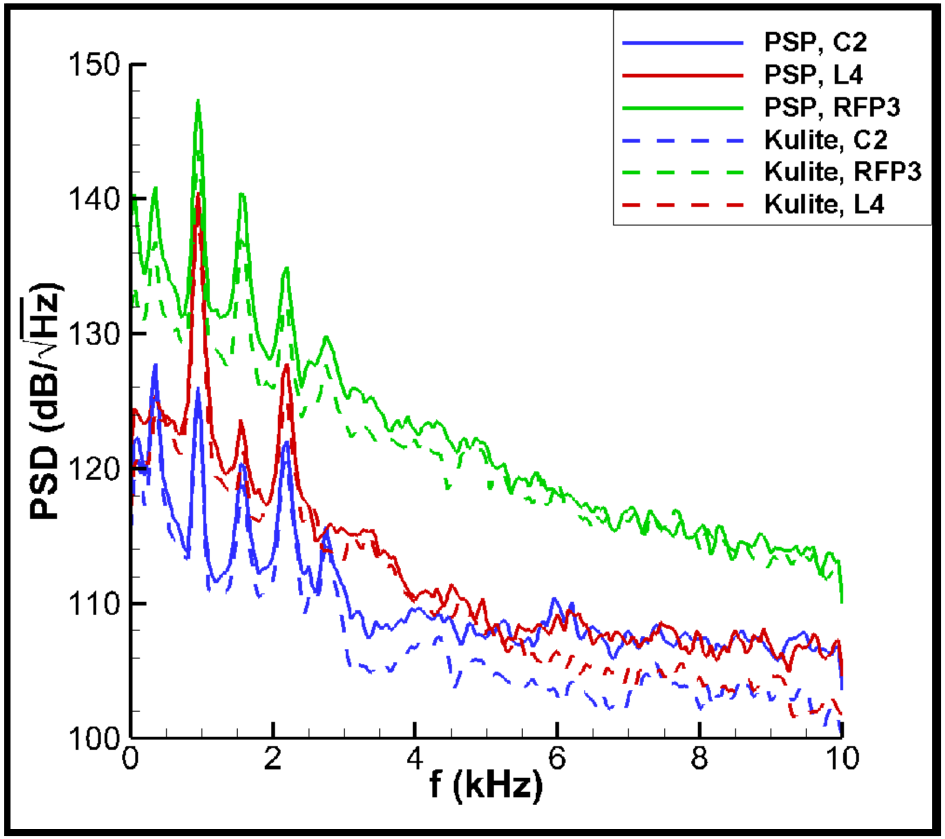
How accurate are the PSP data?

Results show reasonable comparison to Kulite pressure sensors throughout the cavity.

- Cavity resonance frequencies and amplitudes match well between pressure sensors and PSP.
- Noise floor of PSP is significantly higher.

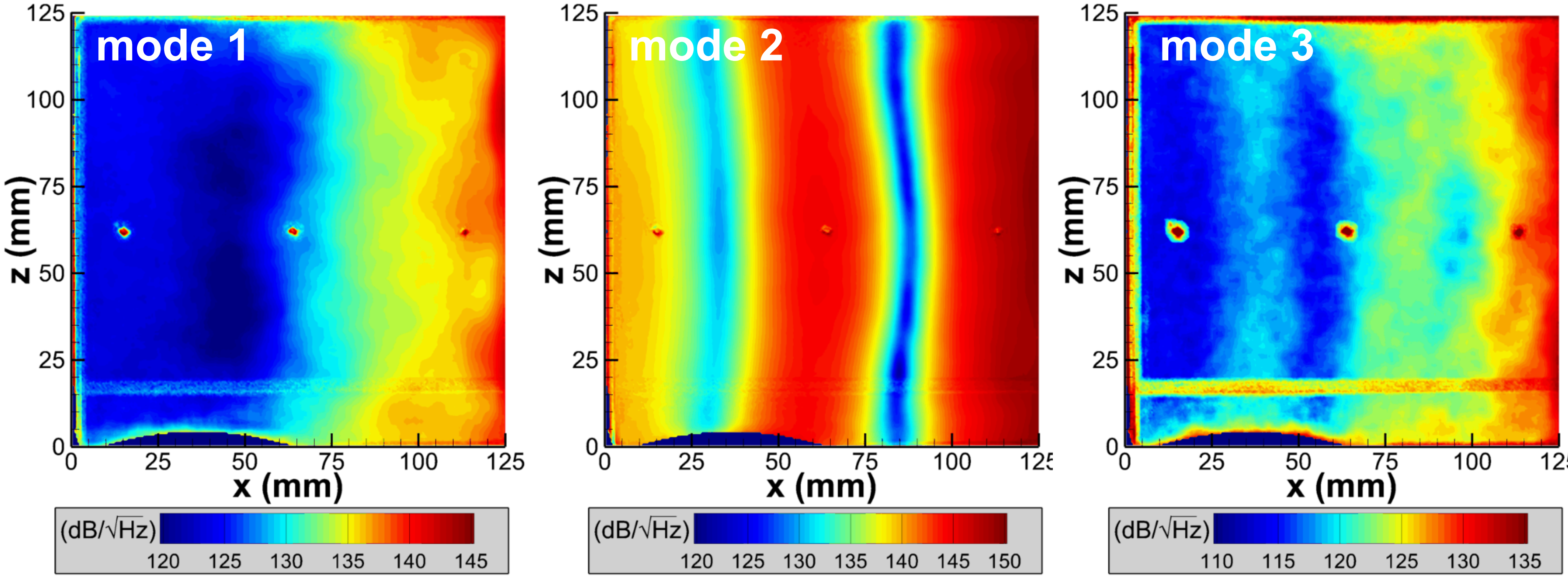


Snapshot of PSP movie



Pressure Power Spectra

Like pulse-burst PIV, we can look at spatial distributions of the power spectra amplitudes at each resonance frequency.



Resonant energy is largely two-dimensional with *substantial amplitude modulation in the streamwise direction*.

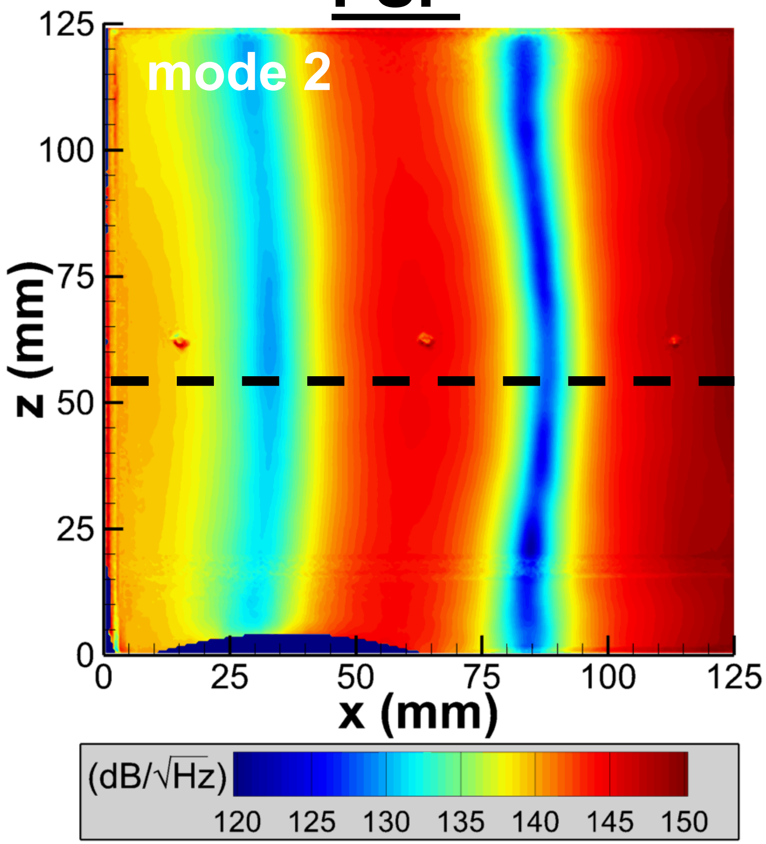
Additional maxima and minima as the mode number increases.

How does the PSP compare to the pulse-burst PIV?

Sandia National Laboratories

Compare PIV to PSP

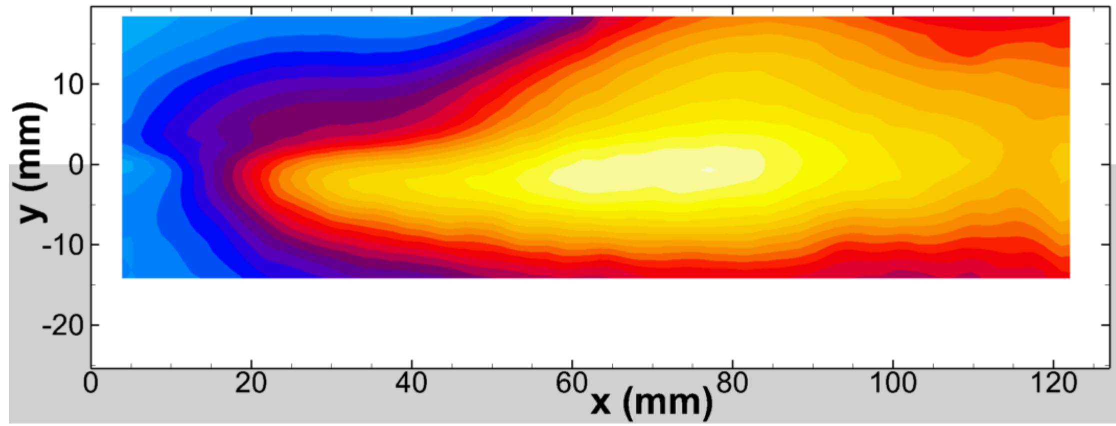
PSP



PSP spectra dominated by resonance.

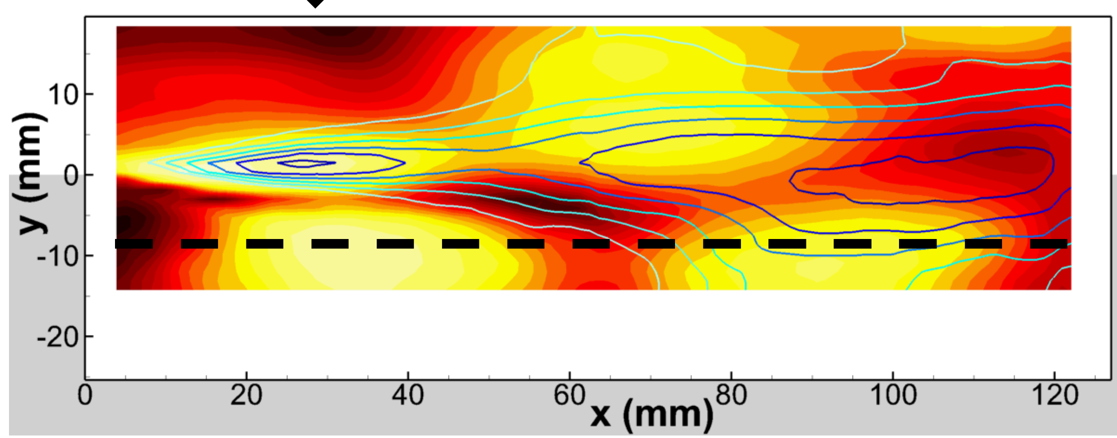
Turbulent pressure fluctuations are much smaller in magnitude.

PIV

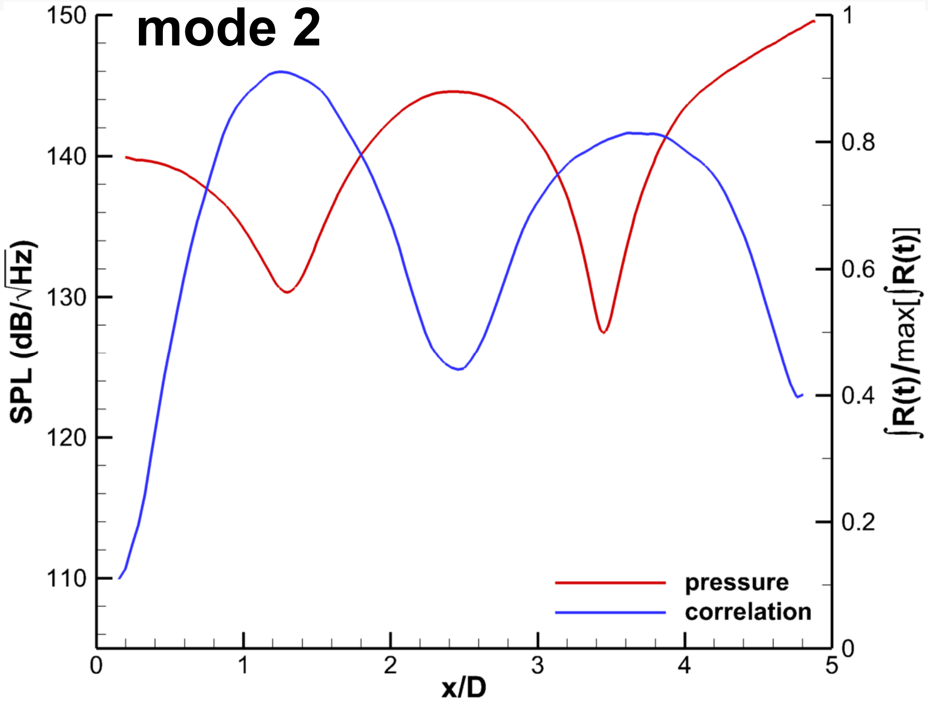


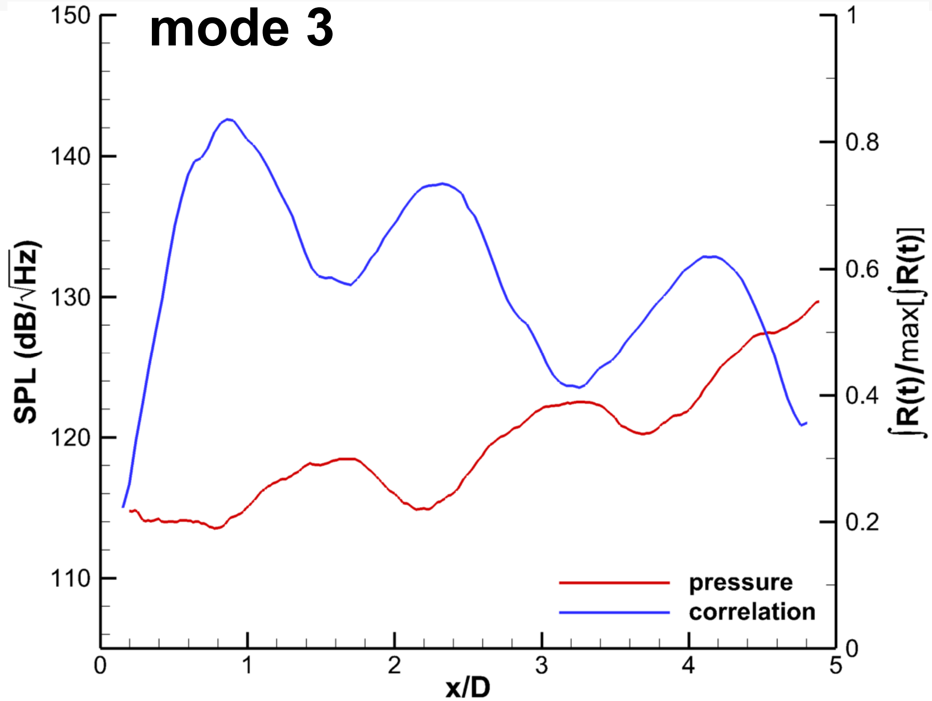
PIV spectra are a mixture of resonant energy and turbulent energy.

Some messy math separates the two.



Compare PIV to PSP





The pulse-burst PIV and the unsteady PSP show the same minima and maxima in the resonance amplitudes.

Some additional messy math shows that these are interference patterns from upstream- and downstream-traveling acoustic waves.

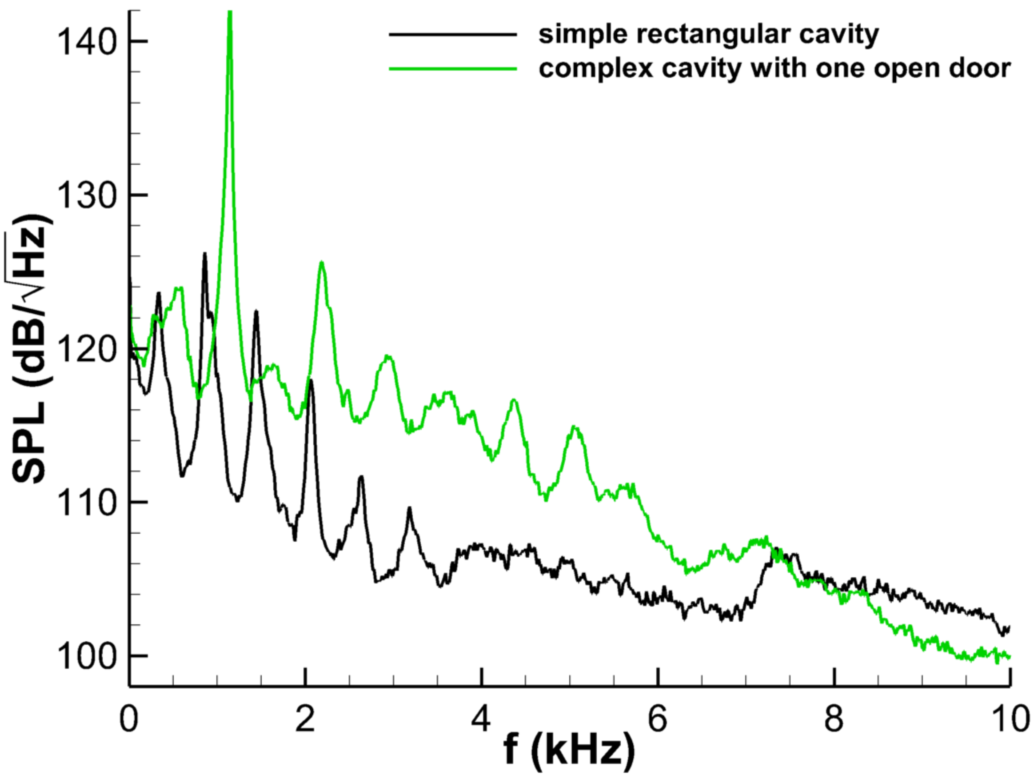
Sandia National Laboratories

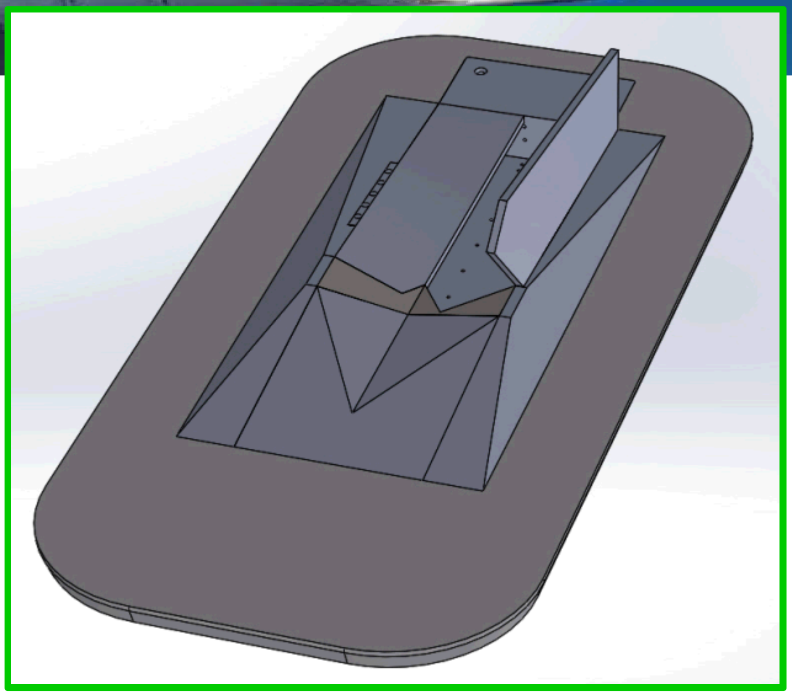
What Next?

Most existing work focuses on simple rectangular cavities.

- **Neglects important features that can modify cavity acoustics.**

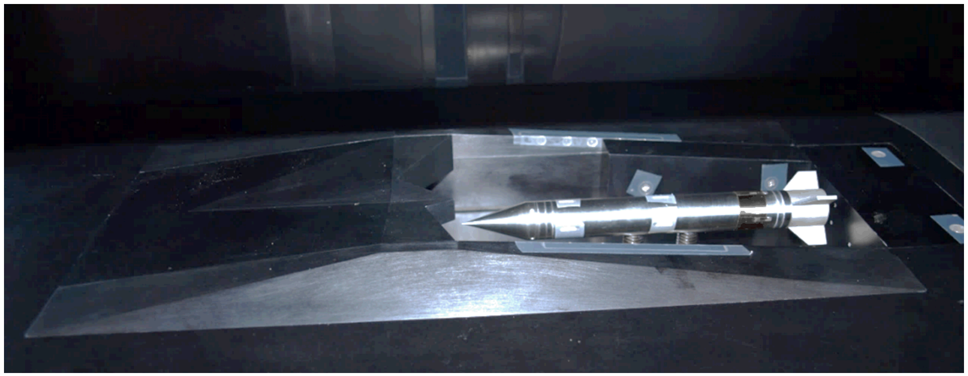
How do complex geometric changes to the bay affect flow structure and acoustic loading?

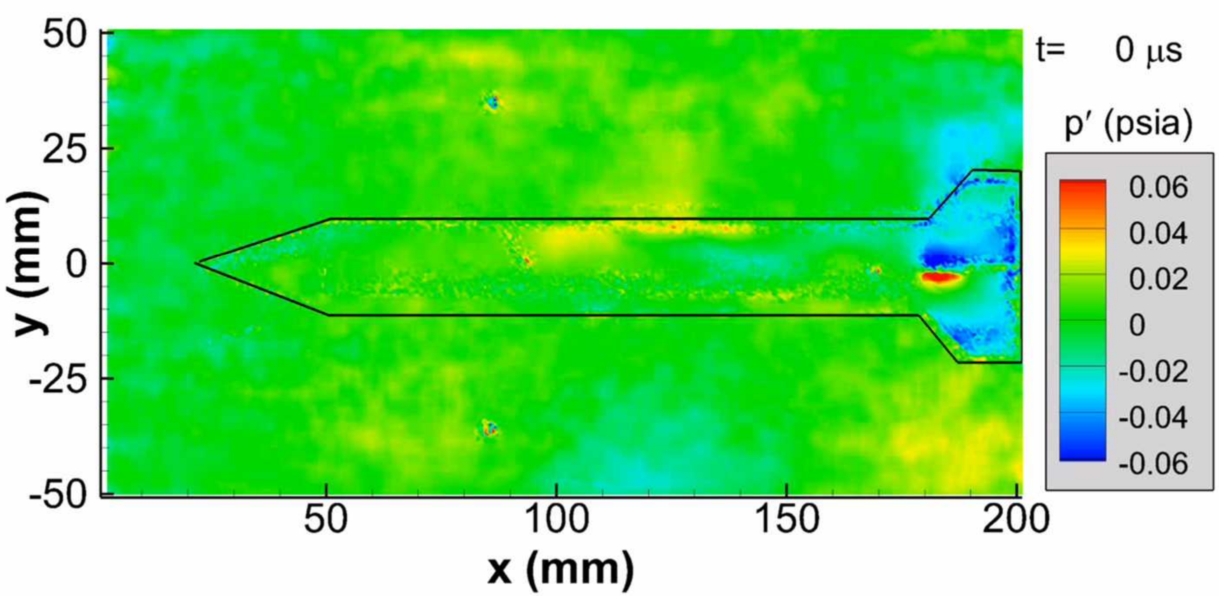




PSP and PIV of Complex Cavities

High-frequency PSP has been demonstrated in a complex cavity with a modeled store.





PSP shows coherent structures of pressure loading passing along the store.

How does this lead to store vibration?

We have some conventional PIV data in complex cavites.

Next, we will use pulse-burst PIV in complex cavities.

Sandia National Laboratories