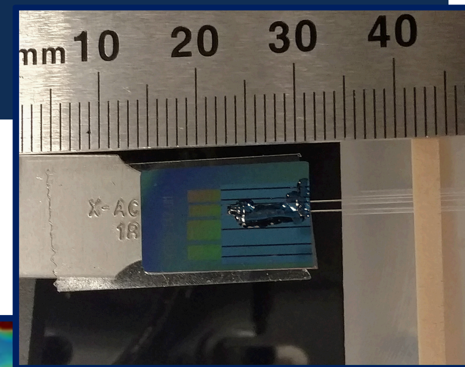
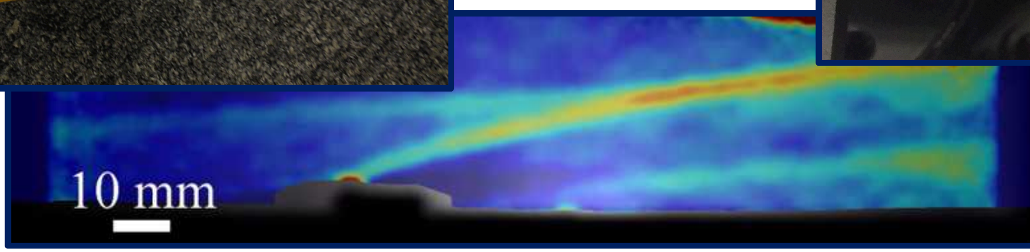
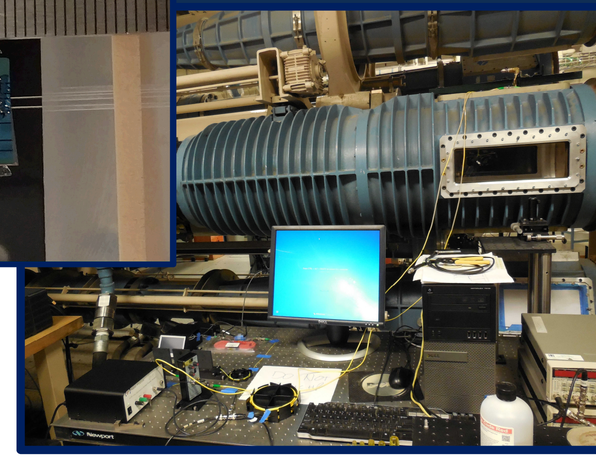
SAND2017-10818C







Diagnostic Development for the Sandia Hypersonic Wind Tunnel

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Sandia National Labs

STAI Conference, Tallahasee, FL

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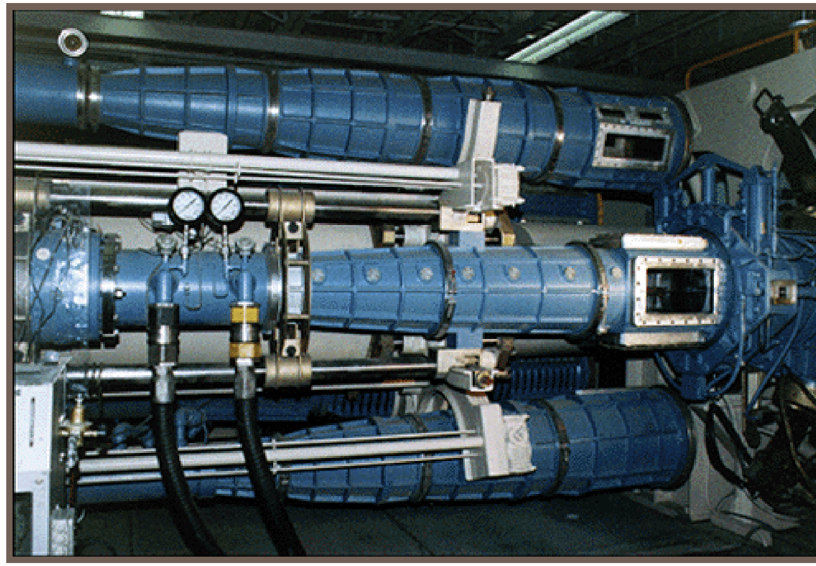
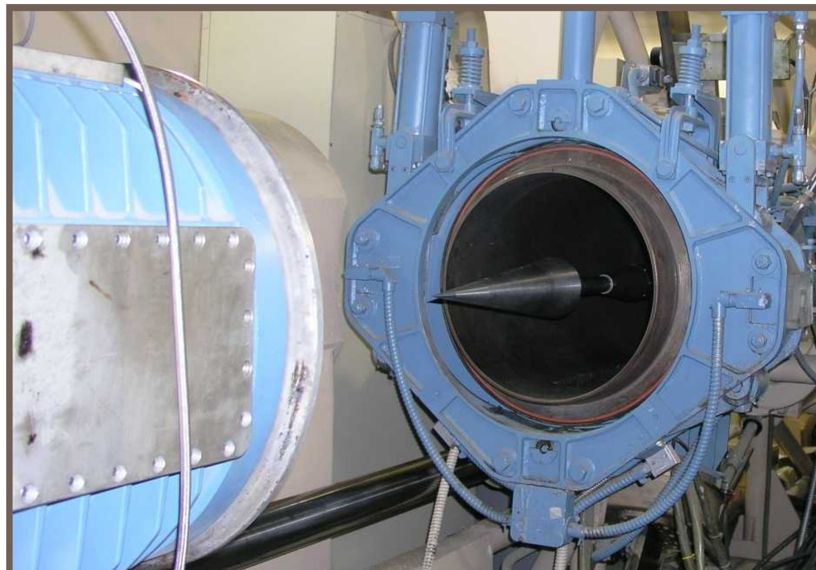
Sandia Hypersonic Wind Tunnel (HWT)

Technical Characteristics

- Blowdown to vacuum
- M = 5, 8, 14
- Re = 0.2 - 10 x 10^6 /ft
- Run times: ~45 sec at 45 minute intervals
- Gases:
  - air at Mach 5
  - N_2 at Mach 8 and 14
- 18 inch diameter test section
- 4 – 5 inch maximum diameter model size
- Stagnation temperature to 2500° R (1400 K)

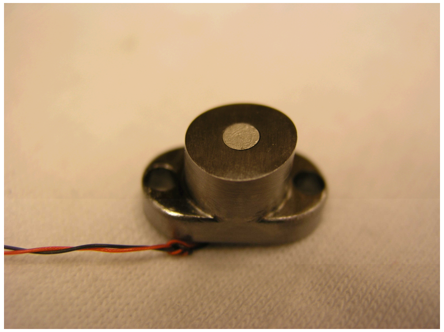




Traditional Sensors

- High frequency pressure measurements
  - Kulite XCQ-062 sensors (up to ~30 kHz)
  - PCB132 pressure sensors (11 kHz – 1 MHz)

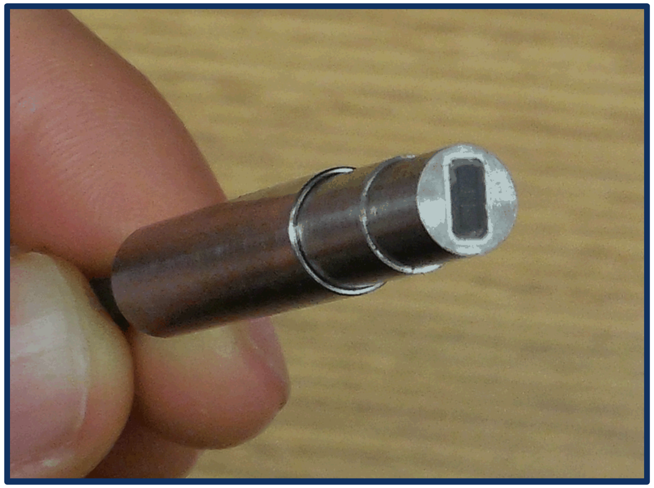
- Temperature and heat-transfer measurements
  - Schmidt-Boelter/Thermocouples
- Structural response
  - Endevco and PCB accelerometers (up to 10 kHz)



What we are lacking

- Shear stress sensors.
- High-frequency accelerometers.
- Spatially resolved surface measurements.

New Shear Stress Sensors



- **Shear Stress Sensor Type CS-D50**
  - from Interdisciplinary Consulting Corp (IC2)
  - Optical floating element-based direct sensor
- **Specifications**
  - Maximum shear stress 100 Pa
  - Bandwidth (3 dB) DC – 1.8 kHz
  - Mean (DC) sensitivity 45.2 ± 0.8 mV/Pa
  - Dynamic sensitivity @ 1 kHz 49.6 ± 0.9 mV/P
  - Minimum resolution @ 1 kHz 0.2 mPa
  - Sensing element dimensions 1 mm x 0.7 mm
  - Operating temperature range 0 – 425° C (32 – 800° F)
- **Will be testing on the nozzle wall of HWT-8 soon**

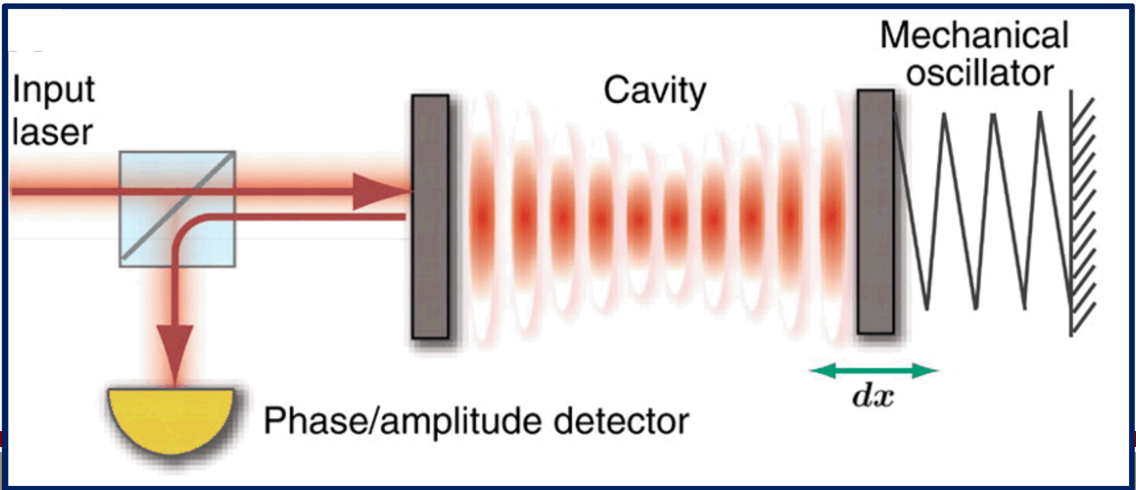
High-Frequency Miniature Accelerometer Development at Sandia

Sandia National Laboratories

Current high-sensitivity accelerometers are limited to about 10 kHz.

New sensors will leverage NOMS (nano optomechanical systems) technology.

- State-of-the-art optical resonators that are exquisitely sensitive to motion
- Displacement sensor is 1-2 orders of magnitude better than the displacement sensors used in current MEMS accelerometer technologies
- This means we can make our accelerometer based on this 1-2 orders of magnitude stiffer than state-of-the-art accelerometers while retaining the same resolution

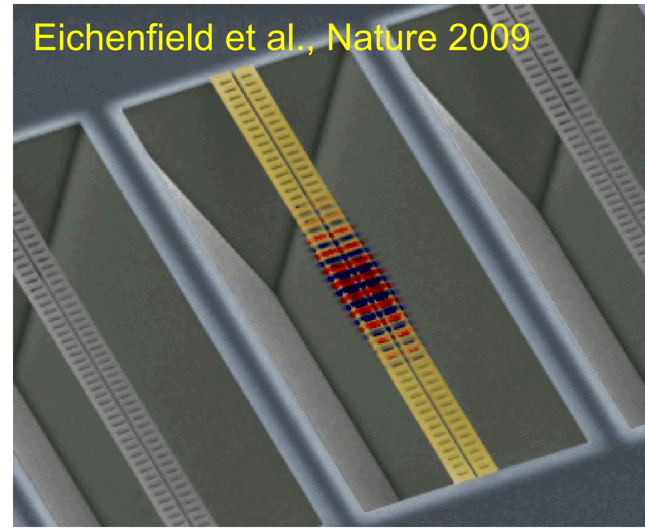


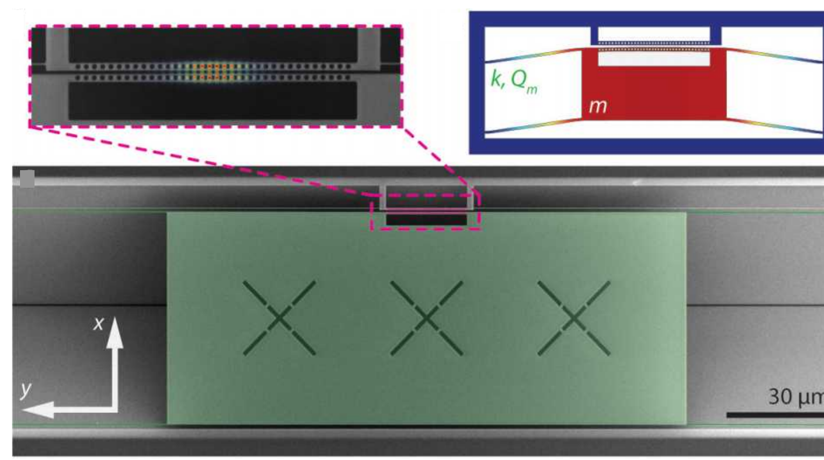
NOMS Accelerometers

Current displacement sensors: two identical SiNx nanobeam photonic crystal defect cavity resonators separated by a nanoscale gap ("zipper").

- Optical modes couple and the resulting modes are very sensitive to the gap between the individual resonators.
- A change in spacing between the two halves causes a change in the optical resonant frequency, which results in a change of intensity for transmitted light

To form an accelerometer, one side is attached to a mechanical proof mass.



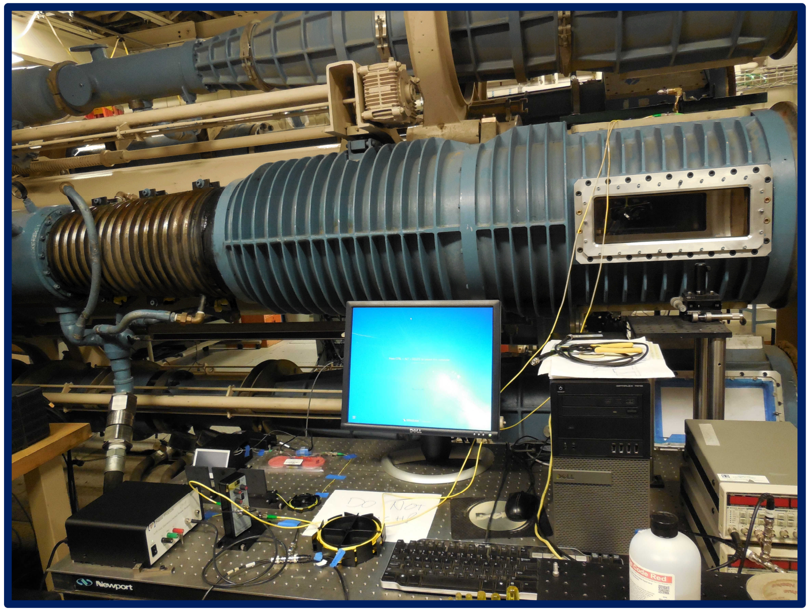


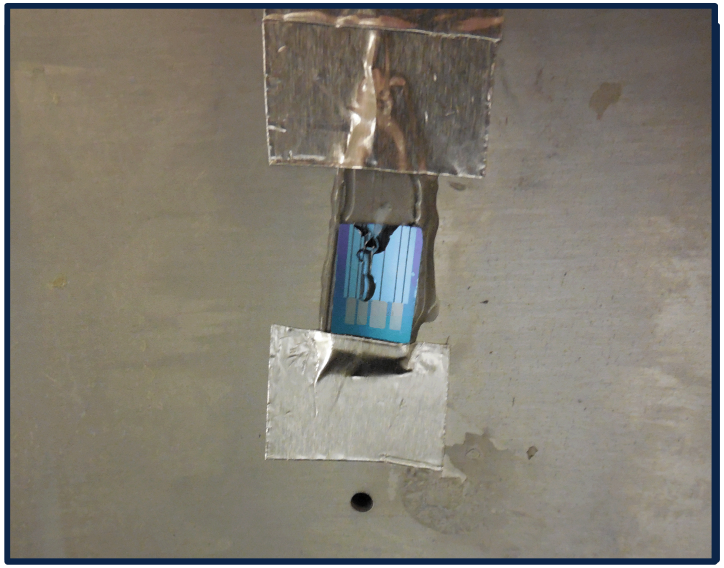
Krause et al., Nature Photonics 2012

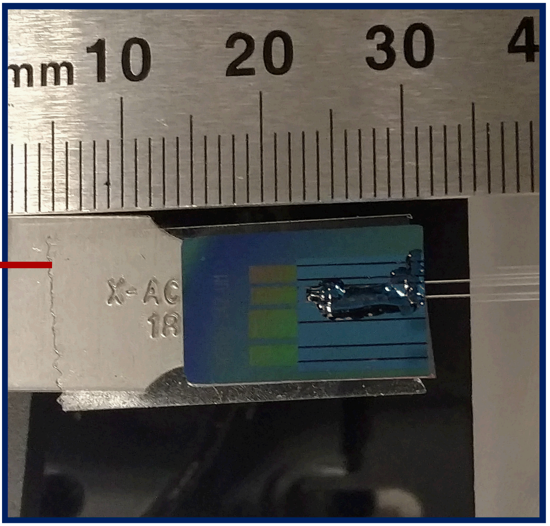
Current Progress

Testing stability and robustness of some early devices.

- MEMS team is learning about wind-tunnel testing environments.
- Wind-tunnel team has learned about handling fiberoptic MEMS devices.







Temperature-Sensitive Paint (TSP)

Sandia National Laboratories

Spatially resolved measurement of temperature (heat-transfer).

- Nonintrusive diagnostic.
- Alternative to instrumenting model with many thermocouples.
  - Single heat-transfer gage still used to anchor TSP.
- Paint is durable, photodegrades slowly (1% per hour).

Typical Specifications (Rubpy in Clear Cote):

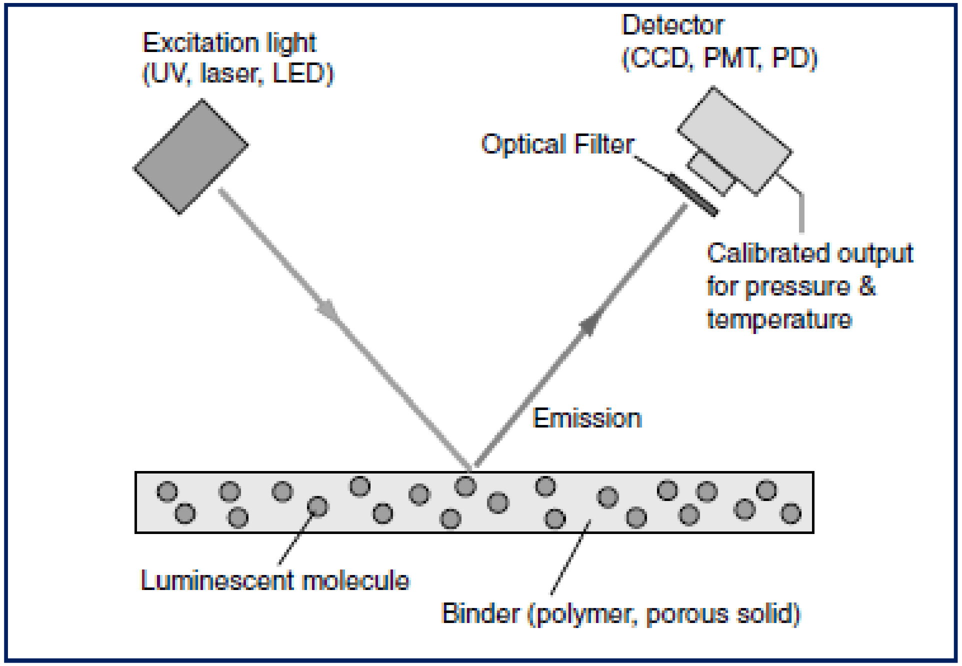
- Temperature range: 10-80 C
  - Nonlinear outside this range.
- Response time: 750 ms,
- Frequency response of ~ 2Hz
- Sensitivity: 0.9% per C

Model painted with TSP

Temperature-Sensitive Paint (TSP)

Typical setup:

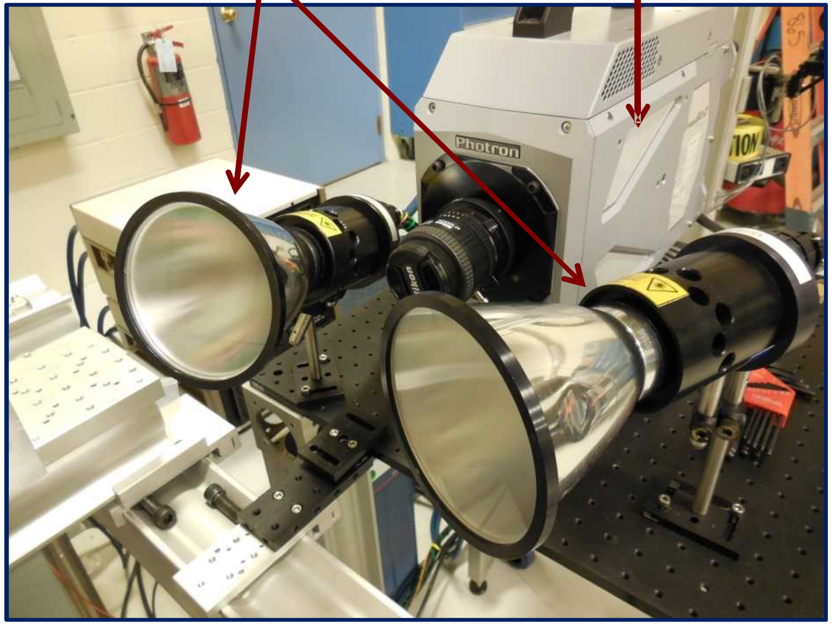
- Paint model with insulating base layer, topped with TSP
- Excite paint with 460 nm LED excitation lights.
- Camera detects paint emission as a function of temperature.



From Liu (2005)

Camera

Excitation lights



Typical TSP setup

Crossflow-Dominated Transition

Pressure gradient transverse to streamlines causes "crossflow" within boundary layer

- Cones at angle of attack
- Non-axisymmetric
- Swept wings

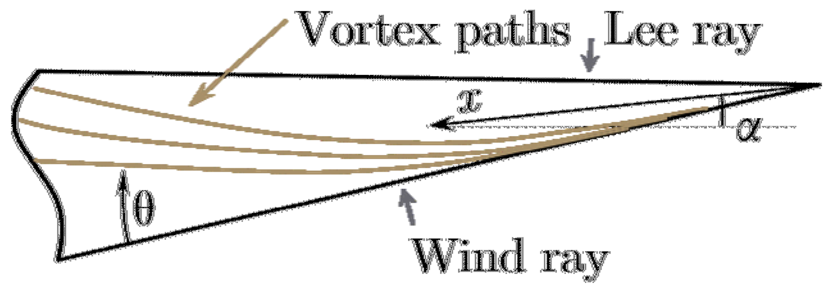
Crossflow profile is unstable

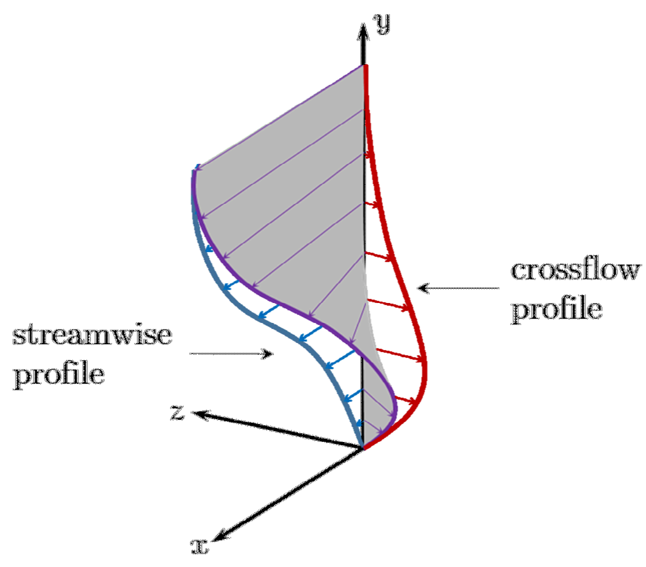
Instability manifests as

- Stationary, co-rotating vortices
- Travelling vortices

Second-mode acoustic instability occurs at same time as crossflow.

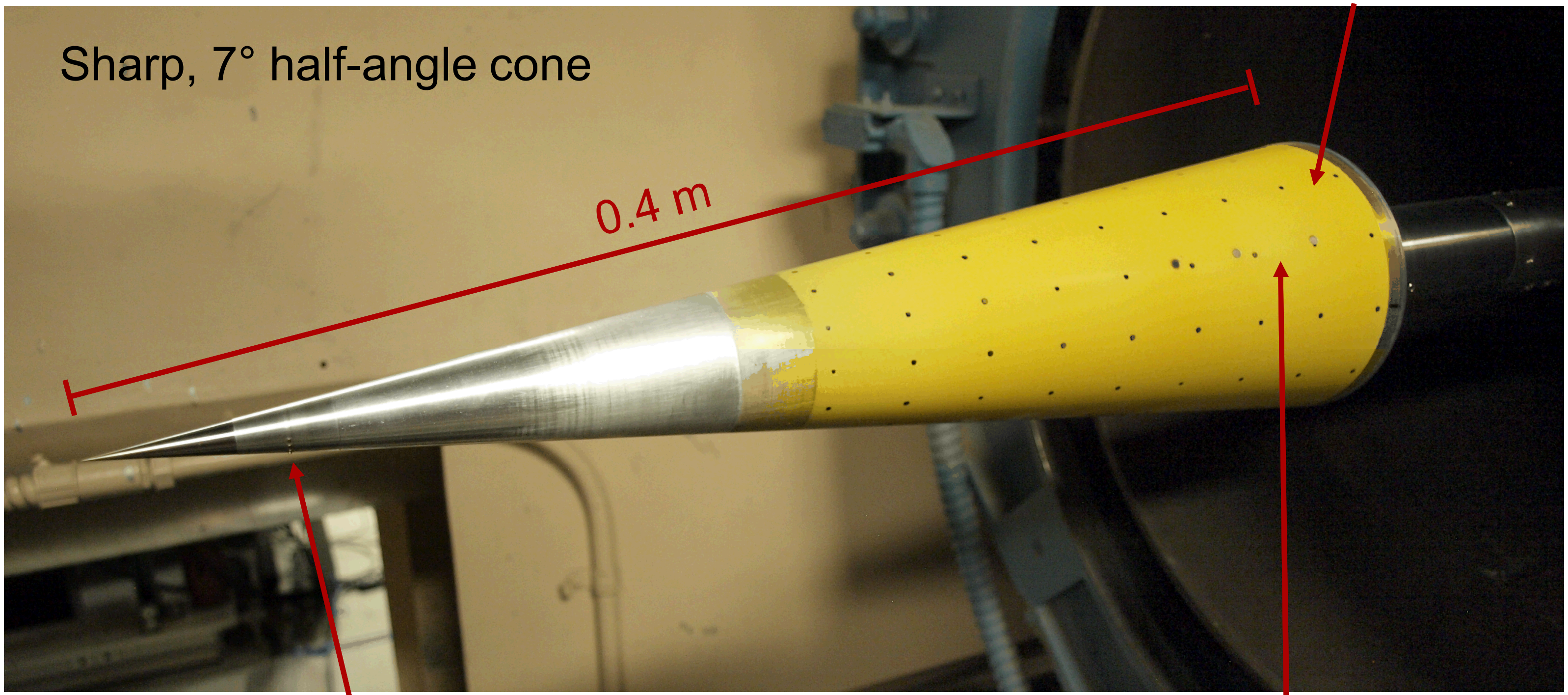
- Can become trapped/looks similar to a secondary instability of the crossflow waves.





Model Overview

Temperature-sensitive paint



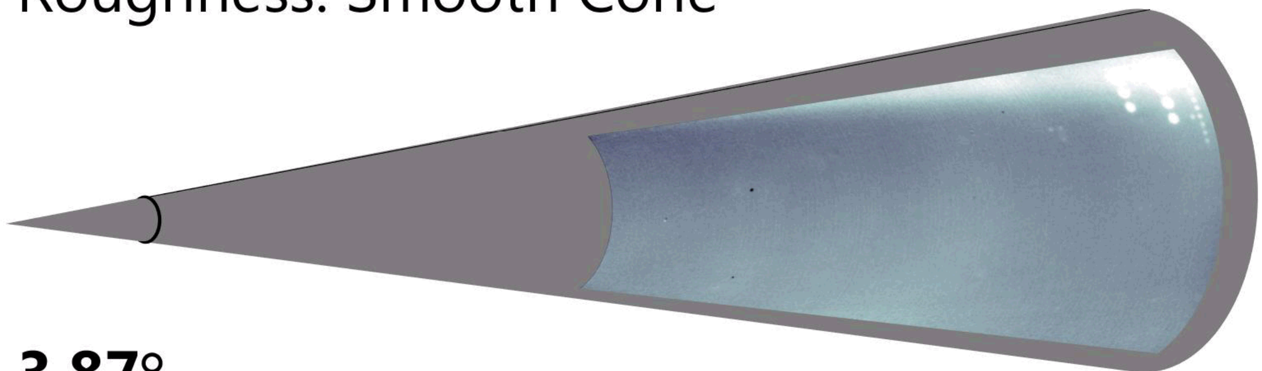
Interchangeable, discrete roughness elements near nose

Space for 9x PCB pressure sensors, 11x Kulite Pressure Sensors

Mach 5 & 8, Smooth Cone

Re = 6.3e6 /m, M = 5

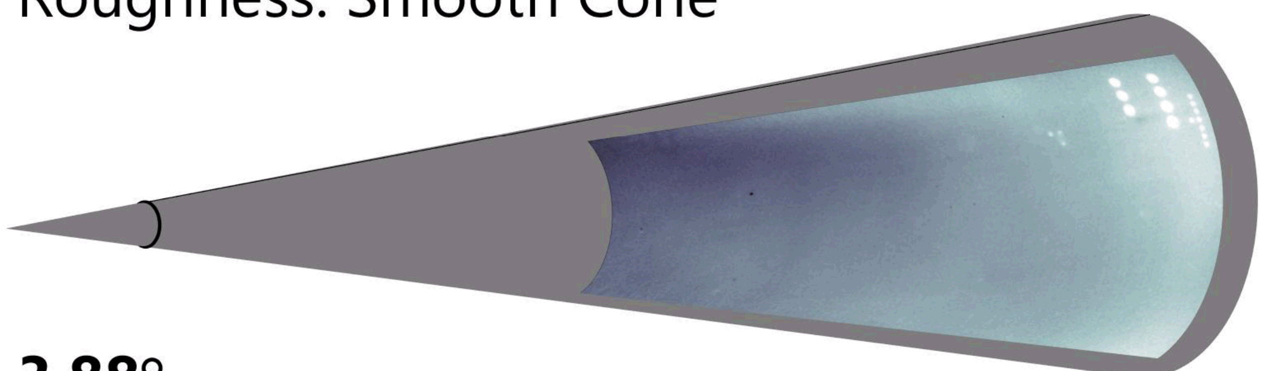
Roughness: Smooth Cone



3.87°

Re = 11.3e6 /m, M = 8

Roughness: Smooth Cone

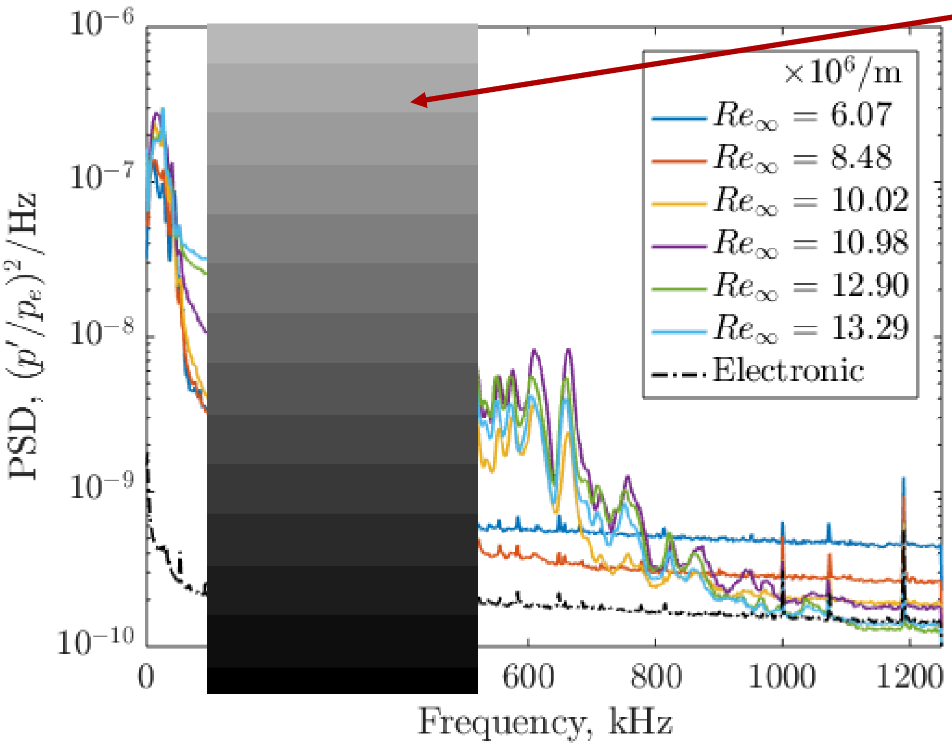


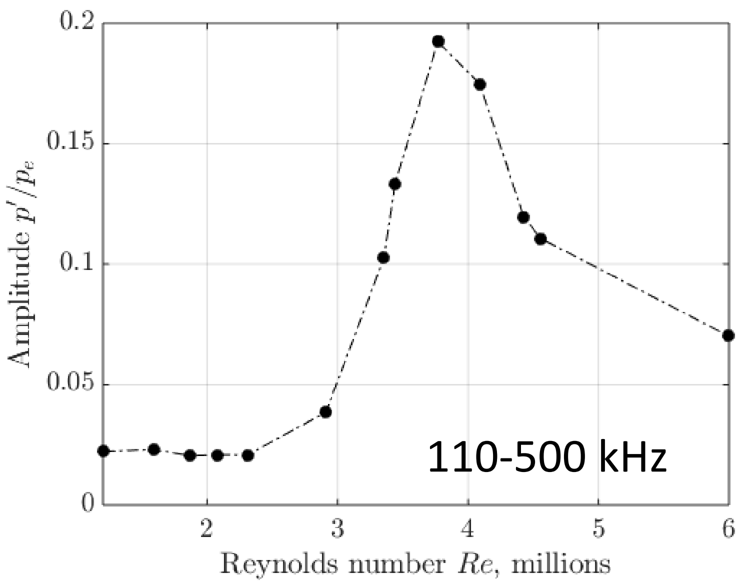
3.88°

Pressure Sensor Results, Smooth Cone, Mach 8

- Pressure sensor is in crossflow region
- Measured instability amplitude rises from noise floor around Re = 3 million
- Peak fluctuation amplitude of 20% edge pressure

Integration band:
110-500 kHz



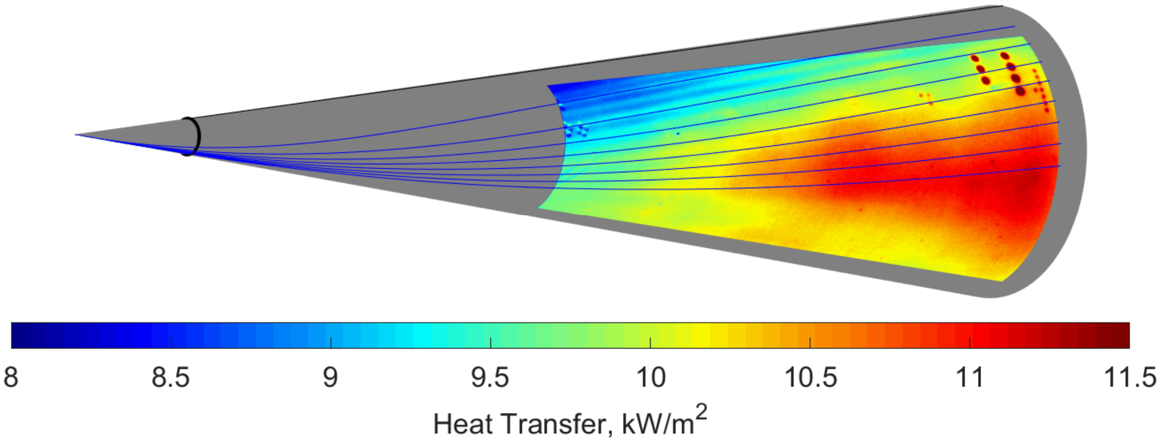


Next Steps

TSP provides valuable validation case for stability computations, and will help to understand Mach number effects on crossflow instability.

- Crossflow instability a major factor in boundary-layer transition on cones at angle of attack, swept-wings and non-axisymmetric vehicles.
- This breakdown process has not been measured in detail before in conventional wind tunnels.

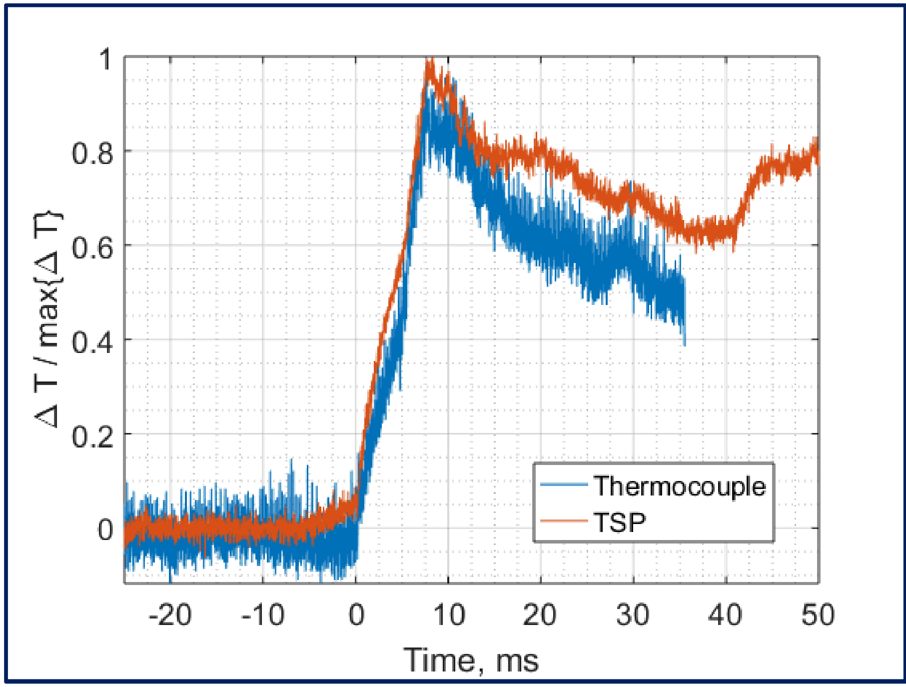
Need computations to verify unstable wavelength, results, etc. Verify a breakdown correlation.



Other Surface Diagnostics

Fast Temperature Sensitive Paint

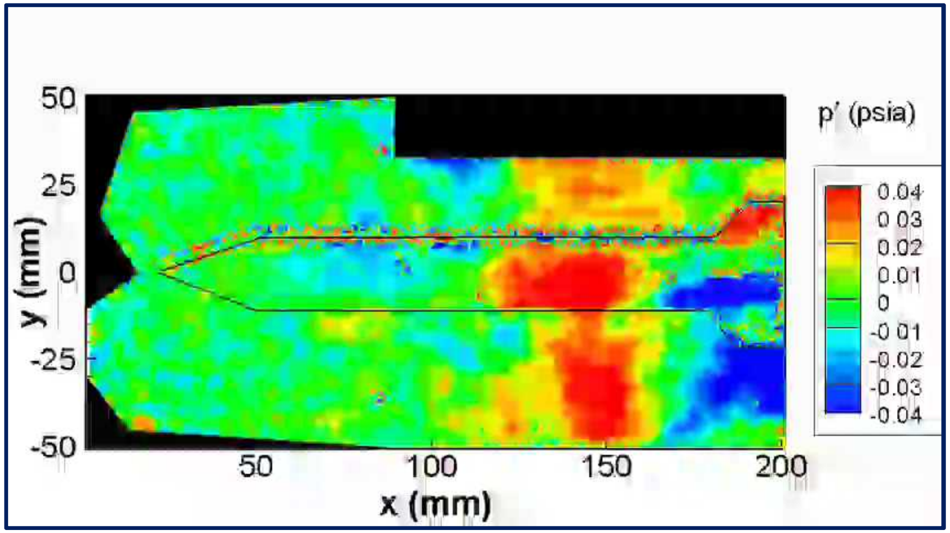
- Has the potential to respond much faster – up to 10 kHz.
- The downside of the high speed formulation is less sensitivity.
  - Has been demonstrated in the multiphase shock tube and in high enthalpy shock tunnels.
  - Not enough sensitivity in HWT yet.



Other Surface Diagnostics

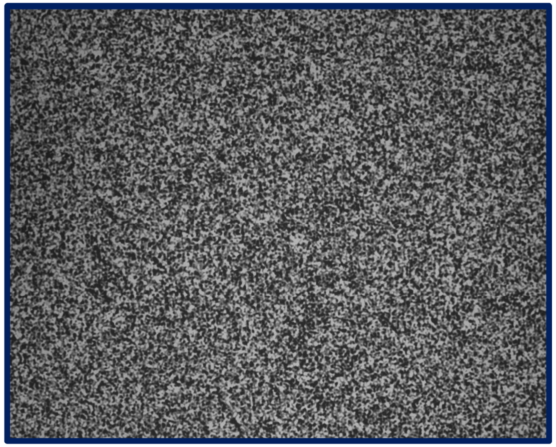
Fast Pressure Sensitive Paint

- Measurements up to 10 kHz in the Sandia Trisonic Wind Tunnel.
- Need to demonstrate in low pressure environment of hypersonic wind tunnel.



Digital Image Correlation

- Would provide spatially resolved structural response.
- How do boundary-layer density gradients affect the measurements?

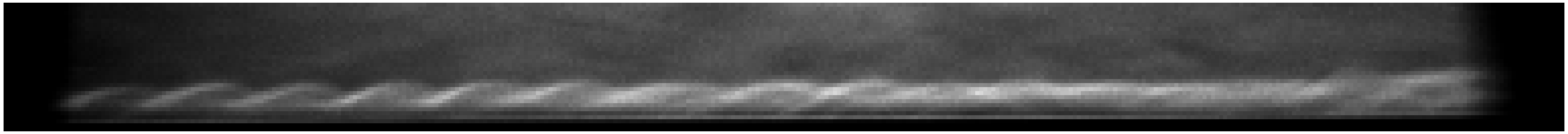


Traditional Flowfield Measurements

High Speed Schlieren

- Movies of boundary layer disturbances at several 100 kHz.
- Integrates across the line of sight, and therefore cannot resolve three-dimensionality of disturbances.

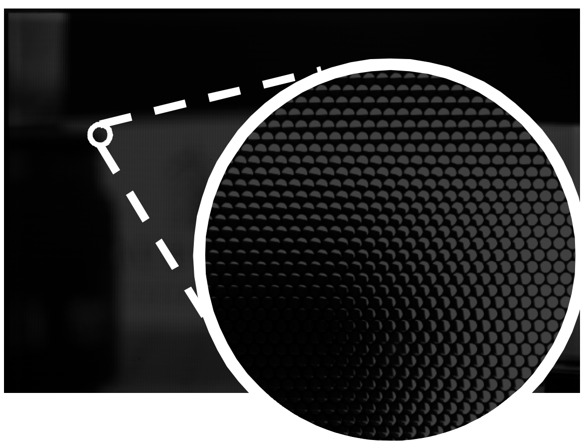
Mach 5, Turbulent Spot Development

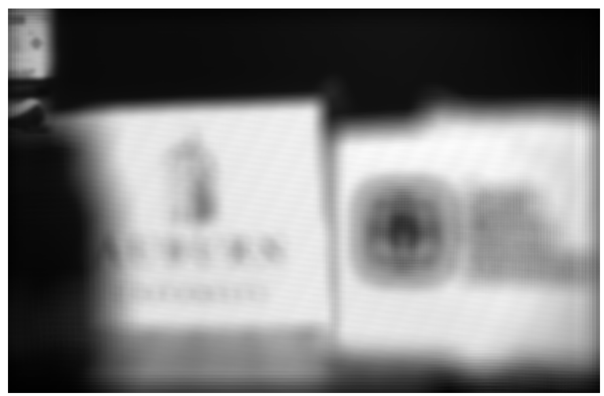


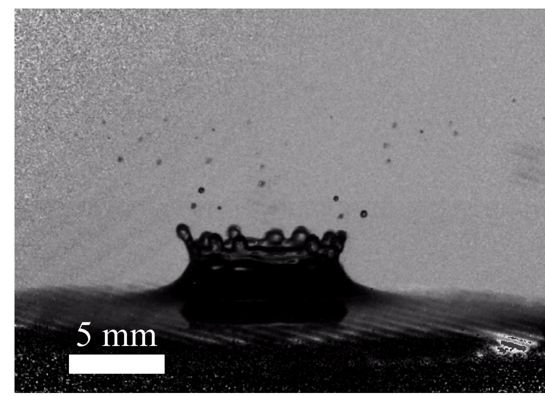
Mach 8, Second-Mode Instability Wave Packets

Plenoptic Background Oriented Schlieren

- Leverage plenoptic camera technology.
  - Microlens array resolves angular information
- ***Technical goal:* Dramatically improve the spatial resolution of plenoptic BOS to enable 3D measurement of the hypersonic boundary layer (d ~ 3 mm)**



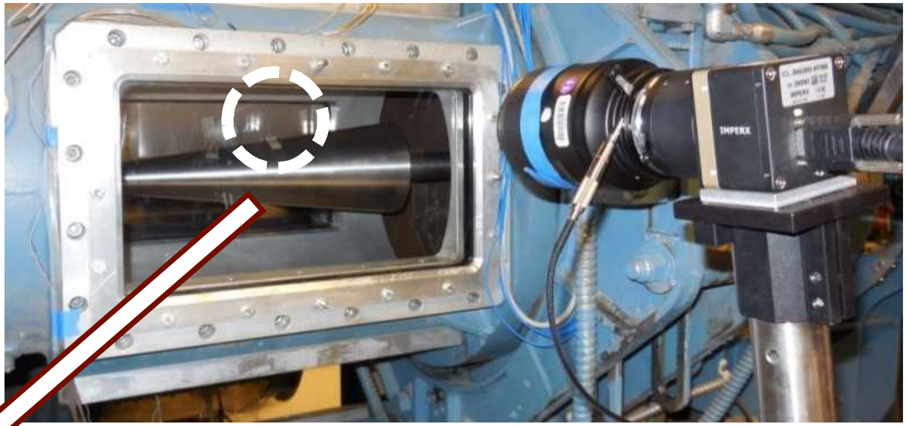


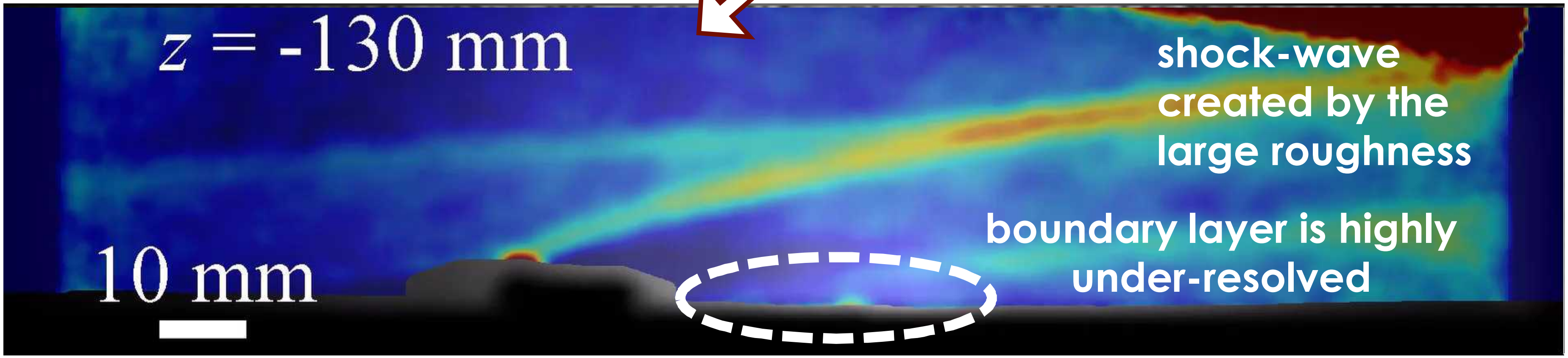


Plenoptic BOS, Round 1

Initial test:

- Backlit speckle pattern.
- Plenoptic camera with standard optics.
- Visualized the shock created by a square roughness element.



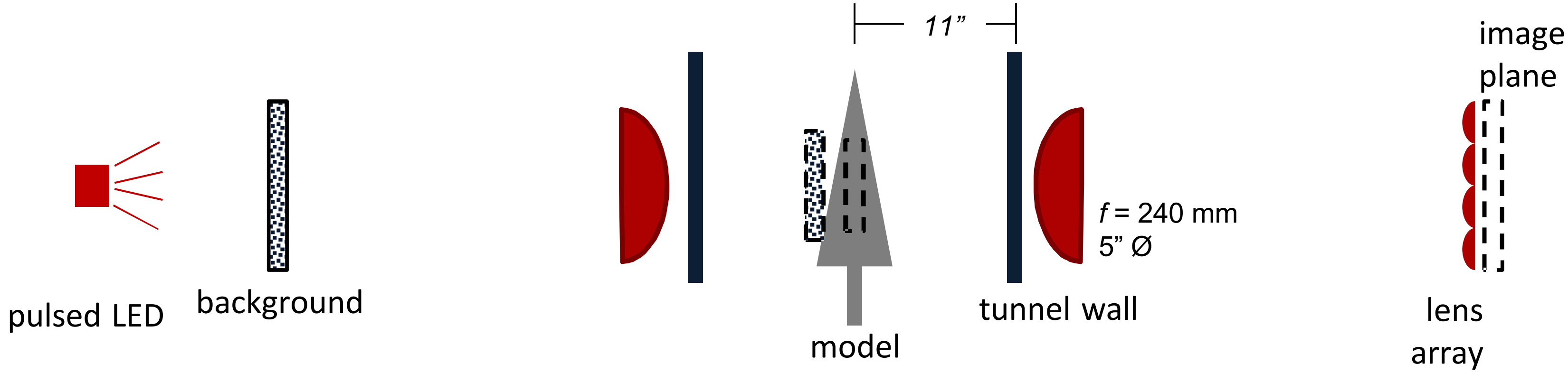


Plenoptic BOS, Round 2

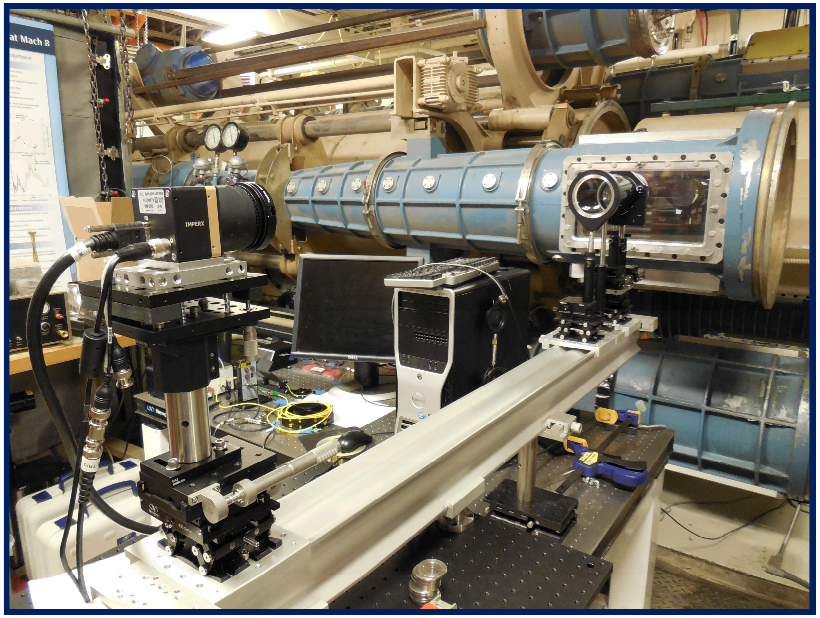
High-magnification, high-standoff optics required to obtain adequate sensitivity to resolve boundary layer disturbances.

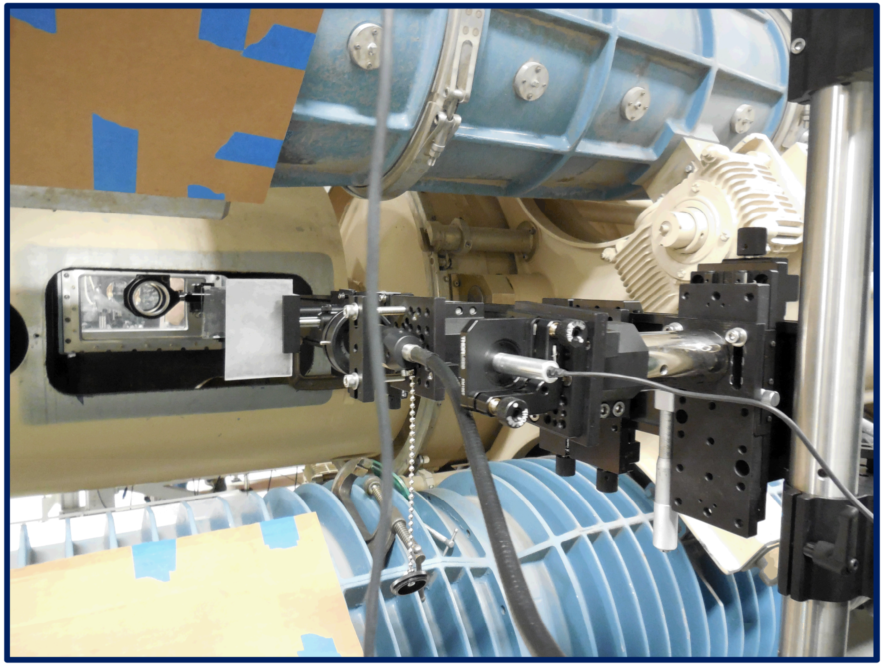
- New custom lens
- Relay image speckle pattern into the tunnel

Predicted performance
Δx = 25 μm
Δz = 160 μm
DOF = 3.5 mm
Standoff, l_o = 280 mm



Plenoptic BOS, Round 2



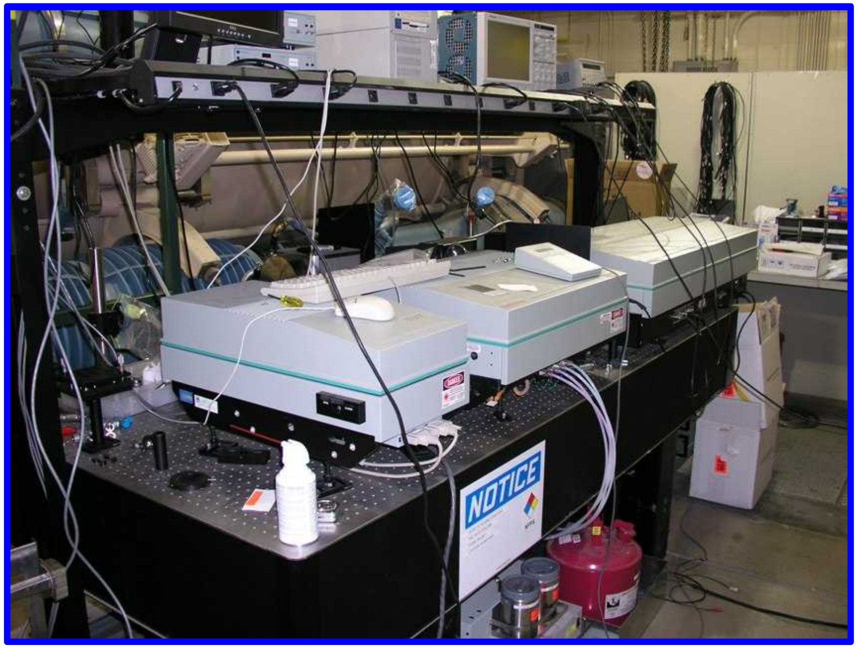


Plentoptic BOS setup in HWT

- Testing completed in September 2017.
- New plenoptic BOS system does resolve boundary layer disturbances, though the signal to noise ratio is low.
- Data processing and improvements to the design are underway.

Laser Diagnostics

- We are now working to develop quantitative velocity flowfield measurements.
  - Rayleigh Scattering
  - Planar Laser Induced Fluorescence (Kr-PLIF)
  - FLEET
- Stay tuned….



Adjustable Sting Design

- **With new flowfield diagnostics, need to be able to precisely place/change field of view.**
  - Need an adjustable sting design to provide.
    - Simple, mechanical design for axial/rotational placement.
  - Complex design, actuated sting.
- **Any suggestions?**

Questions?

Backup Slides

Temperature-Sensitive Paint (TSP)

Can use alternate paints for different temperature ranges.
- -180 C to 150 C

Need thermal phosphors for higher temperature ranges.
- 0 – 1300 C

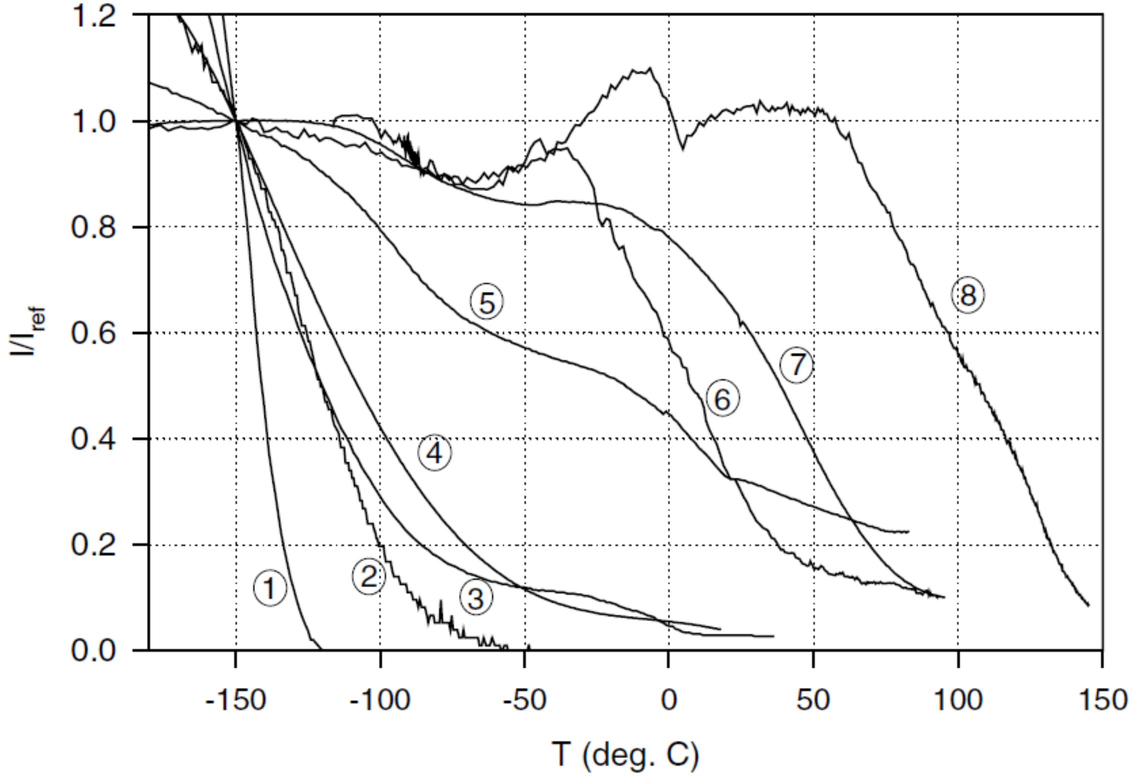
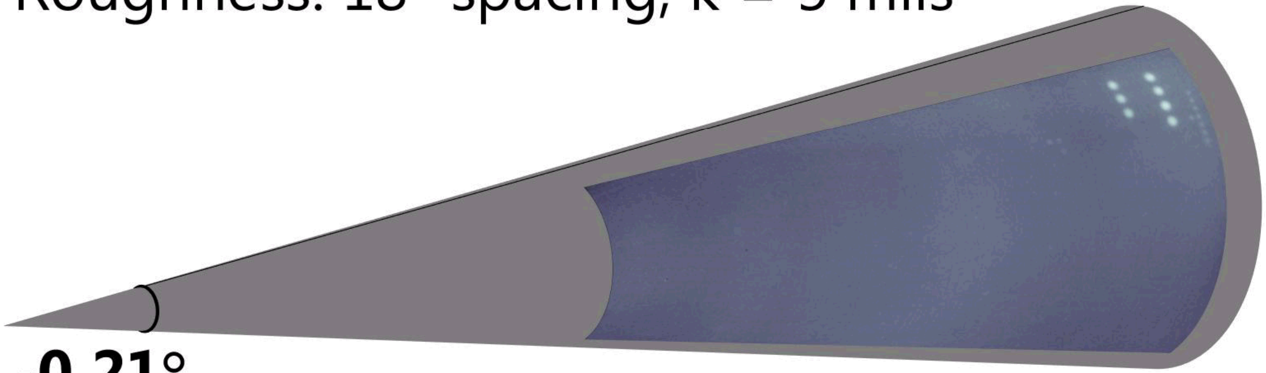


Fig. 3.13. Temperature dependencies of the luminescence intensity for TSP formulations: (1) Ru(trpy) in Ethanol/Methanol, (2) Ru(trpy)(phtrpy) in GP-197, (3) Ru(VH127) in GP-197, (4) Ru(trpy) in DuPont ChromaClear, (5) Ru(trpy)/Zeolite in GP-197, (6) EuTTA in dope, (7) Ru(bpy) in DuPont ChromaClear, (8) Perylenedicarboximide in Sucrose Octaacetate. (T_{ref} = -150°C). From Liu et al. (1997b)

Mach 5 & 8, Roughness

Re = 5.3e6 /m, M = 5

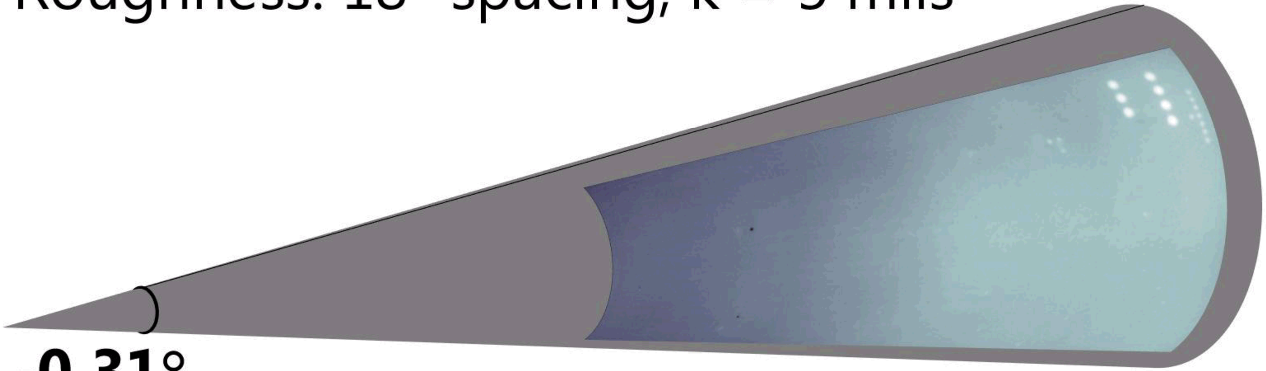
Roughness: 18° spacing, k = 5 mils



-0.21°

Re = 10.7e6 /m, M = 8

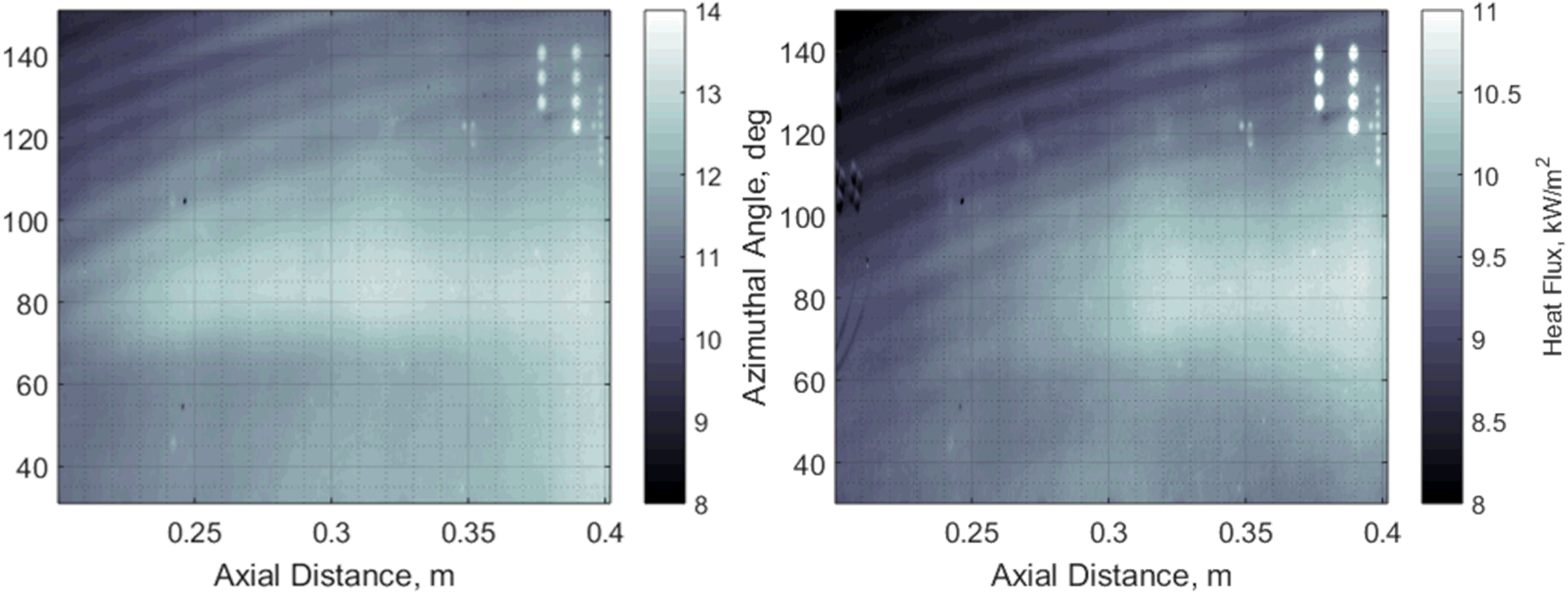
Roughness: 18° spacing, k = 5 mils



-0.31°

Roughness Effect on Wavelength

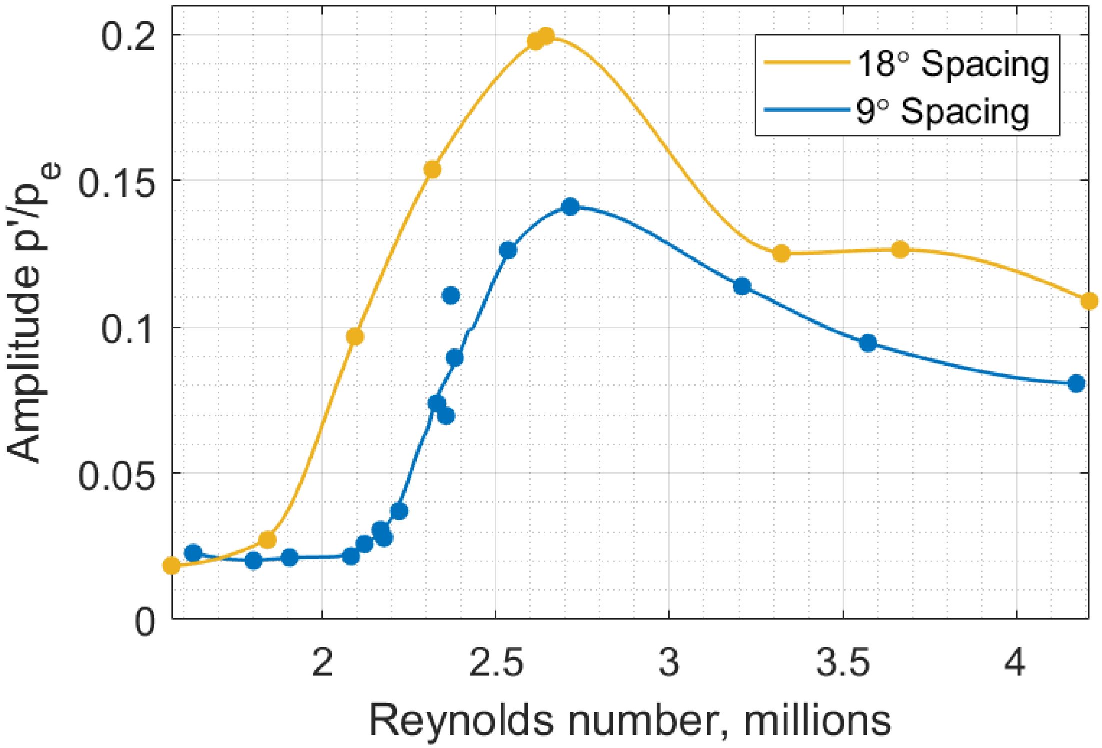
18 deg. Spacing, Mach 8 AoA = 6° 9 deg. Spacing, Mach 8



For both roughness spacings, stationary wavelength is about 9 deg at 0.35 m
(The smooth case is 7-8 deg)

Roughness Effect on Growth of Second-Mode/Secondary Instability

- Even though the freestream conditions for these cases are the same, and the heating pattern from the crossflow is the same, different growth and breakdown of second-mode/secondary instability.
- Implies a difference in the initial growth of the instability near the roughness.



Pressure-Sensitive Paint (PSP)

Spatially resolved measurement of pressure on the model.

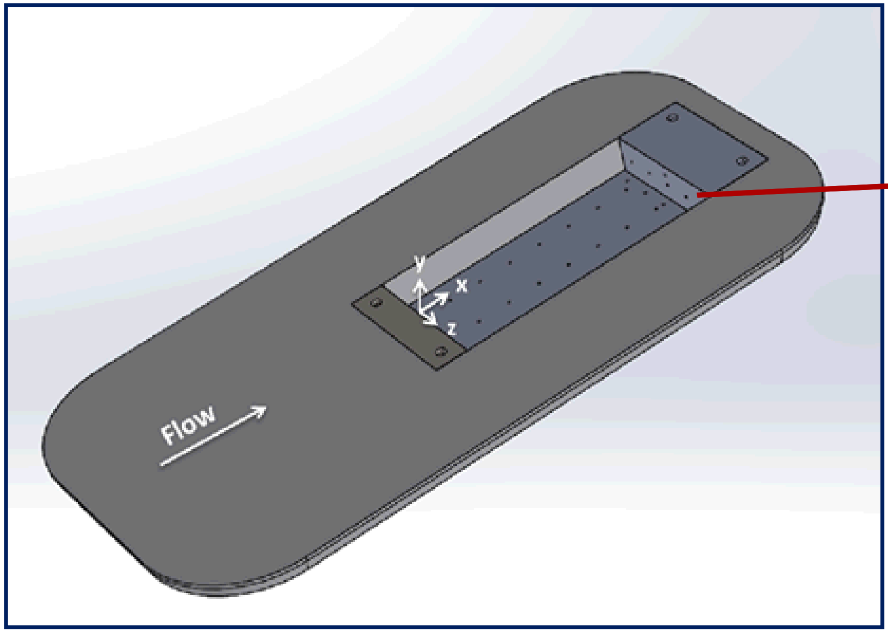
- Nonintrusive diagnostic.
- Alternative to instrumenting model with many pressure sensors.
- Single pressure sensors are still used for validation.

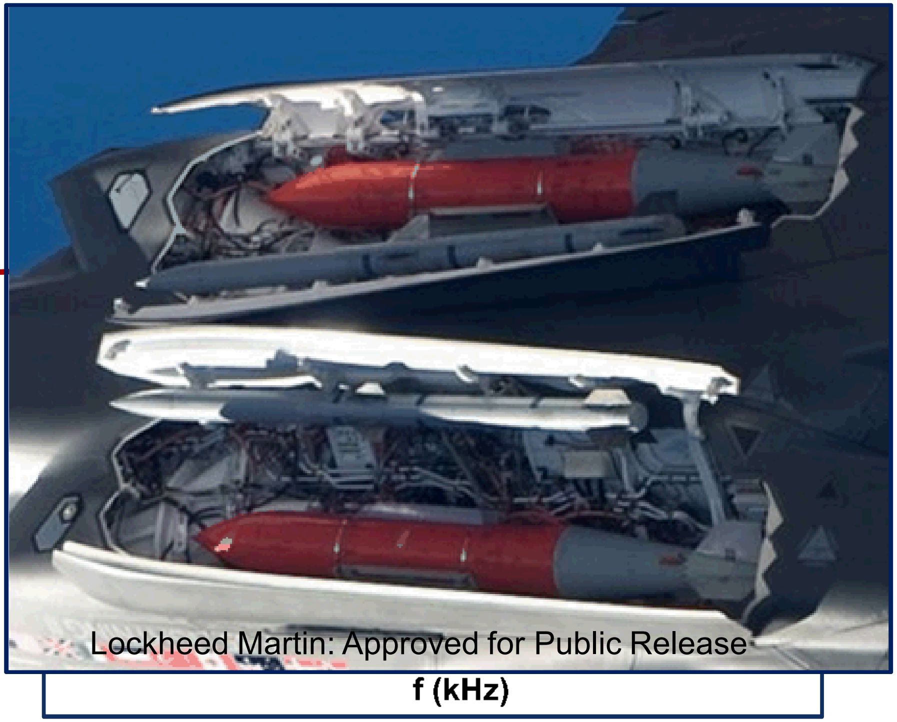
Two formulations:

- **Low-frequency version**
  - 3 Hz or 1 kHz versions
  - Paint has low temperature sensitivity.
  - Photodegrades slowly (1% per hour).
- **High-frequency version**
  - Higher frequency resolution (up to ~10 kHz)
  - Faster photo degradation, more temperature sensitivity.

Motivation: Cavity Flows

- Interaction of free shear layer and cavity walls produces resonant tones with high Sound Pressure Levels (*SPL).*
- Resonant tones can have high SPL up to 170 dB in some cases.
- Fluctuations provide a driver for potential large vibrations of internal stores in weapons bays.





Motivation

Most existing work focuses on simple rectangular cavities.

- Simple cavities neglect important geometric parameters that can modify cavity acoustics.

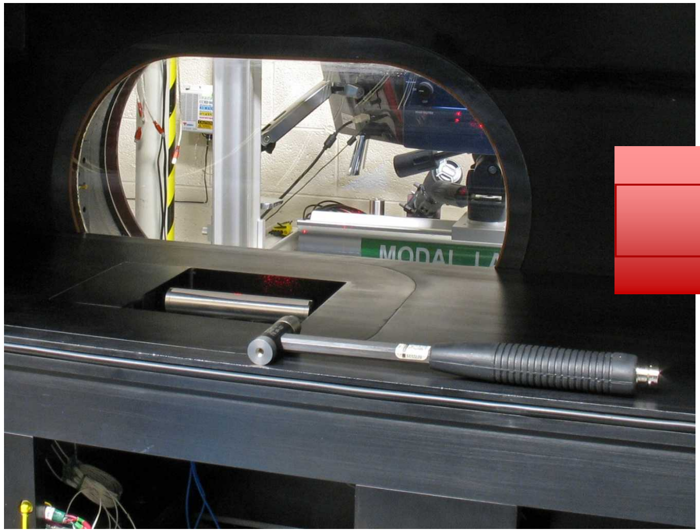
How do complex geometric changes to the bay affect pressure loading and the store response?

- Asymmetric inflows.
- Complex leading edge geometry.
- Varying internal geometry.
- Doors.

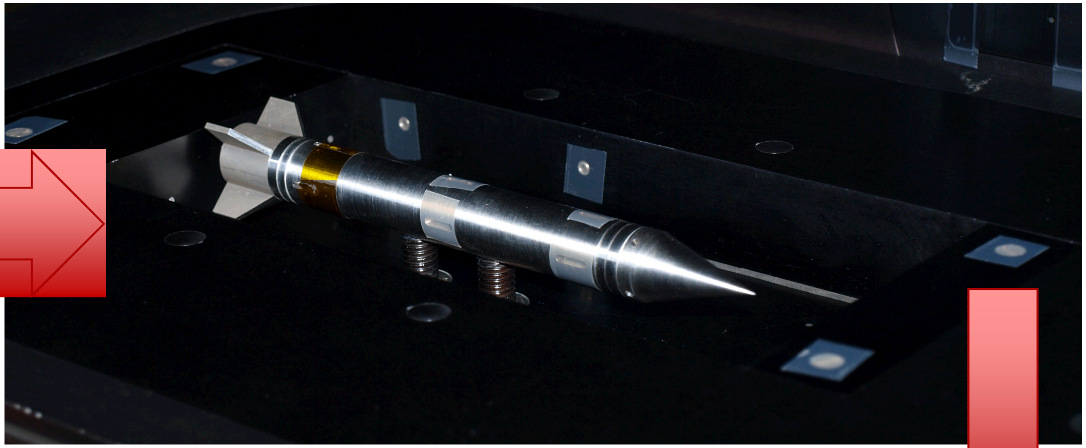

Lockheed Martin: Approved for Public Release

Experimental Approach

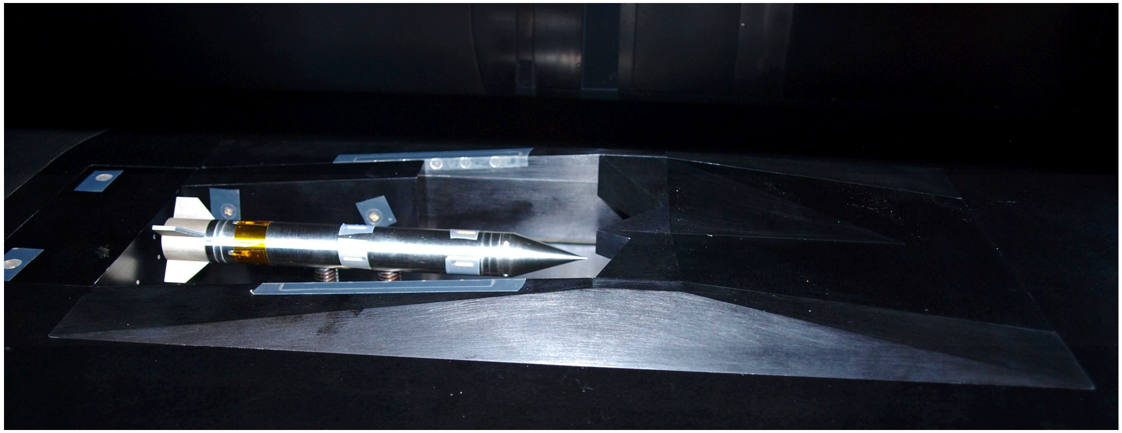
1) Simple Store in Simple Cavity



2) Complex Store in Simple Cavity



3) Complex Store in Complex Cavity



- Wagner, et. Al., Physics of Fluids, 2015
- Wagner, et al., AIAA Journal, 2016

Pressure Sensitive Paint (PSP) Setup

Floor and store painted with high frequency PSP from ISSI.

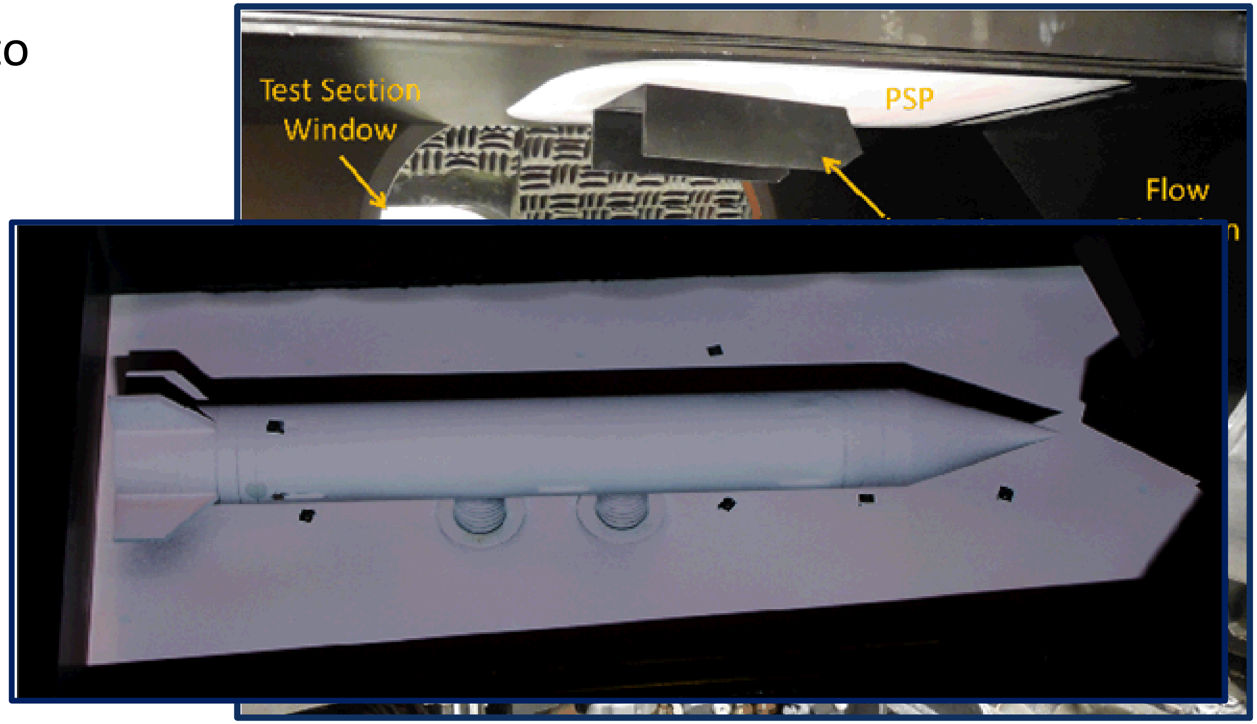
- PtTFPP in a porous binder

3 water cooled ISSI LM4X LED arrays

- 400 nm wavelength excites PSP.

Photron SA-Z High-Speed Camera

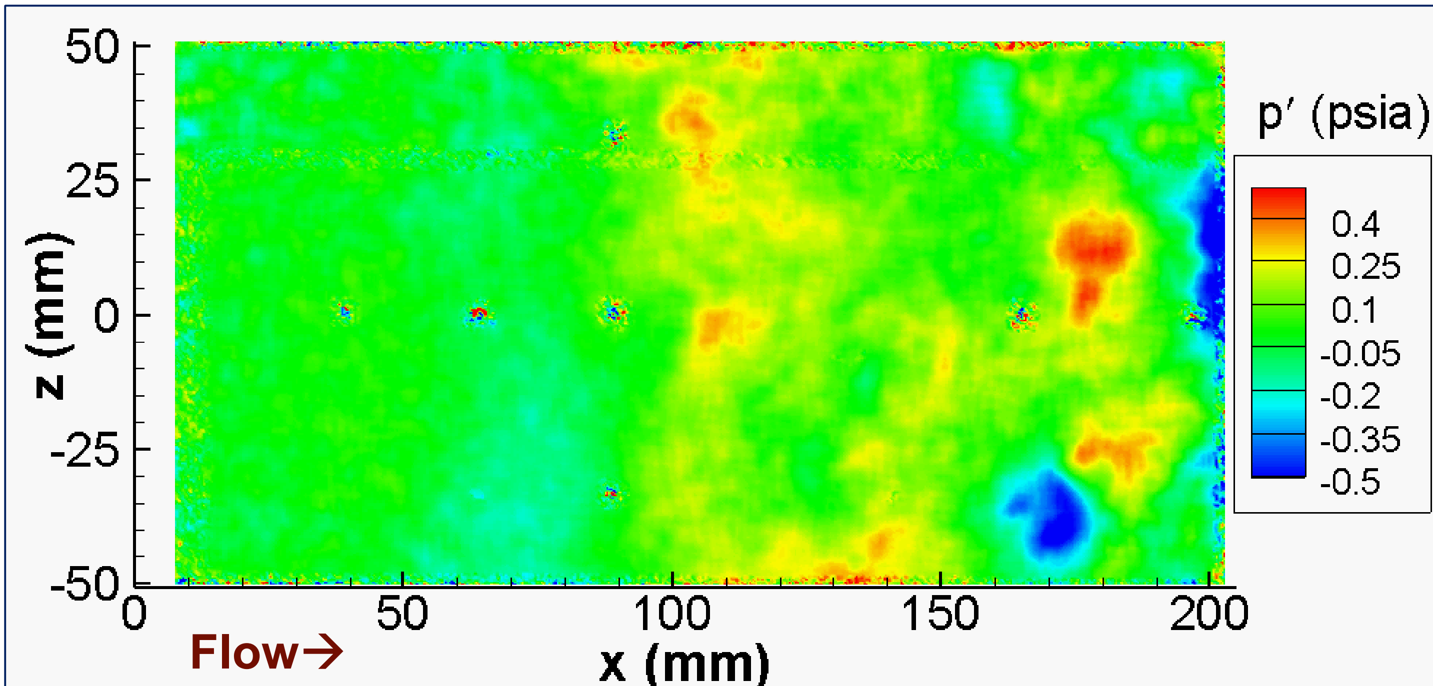
- 590 nm long-pass filter to remove excitation light.
- Framing rate of 20 kHz.

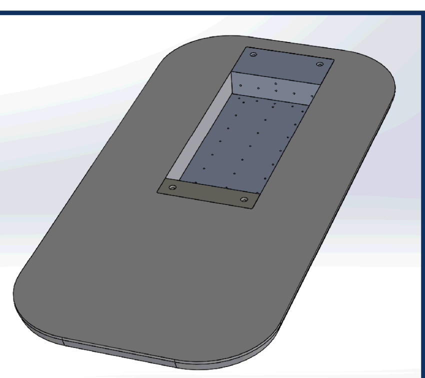


PSP Movies – Simple Rectangular Cavity

PSP movies obtained on the floor of all complex configurations.

- Complex pressure field sets up in the cavity from a mixture of Rossiter modes and turbulence.
  - More coherent structures upstream.
  - More turbulent structures downstream.
- Both upstream and downstream propagating disturbances are observed.

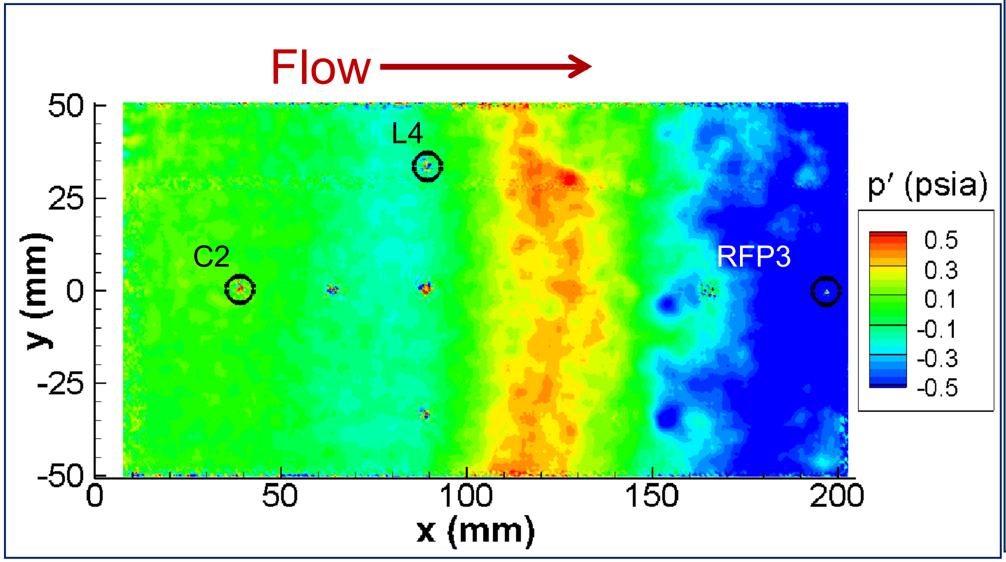




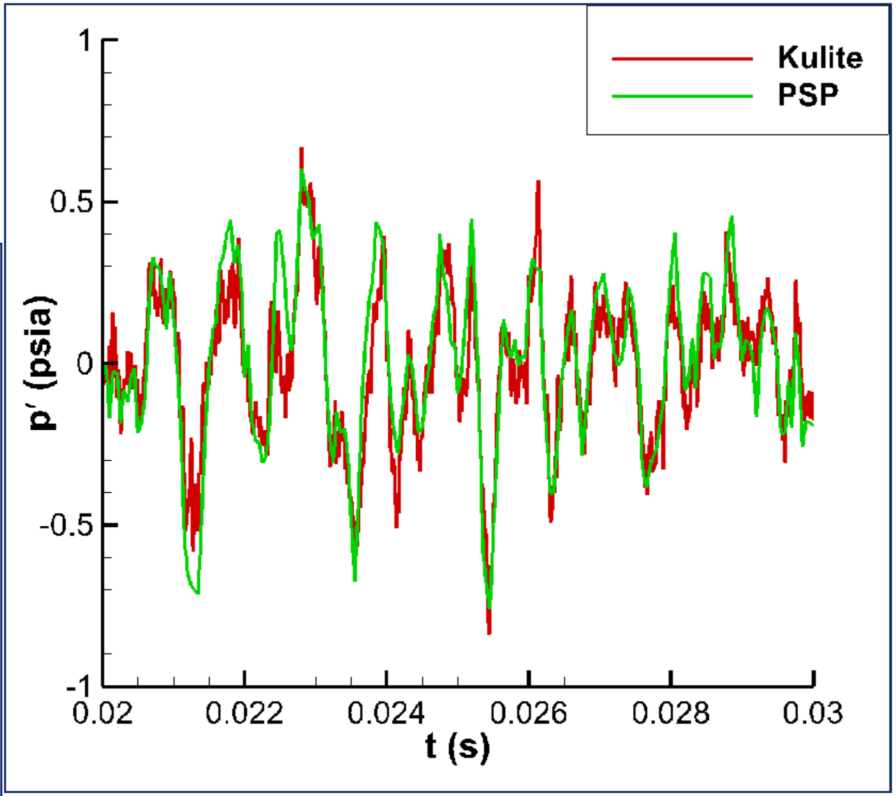
Comparison of PSP and Kulite Pressure Data

PSP results compare well to Kulite pressure sensors throughout the cavity.

- Cavity resonance frequencies and amplitudes match well.
- Noise floor of PSP allows resolution of fluctuations as low as 106 dB/√Hz.
- A higher signal-to-noise ratio is still desired, because the signal falls below the PSP noise floor at the front of the cavity.



PSP movie snapshot.



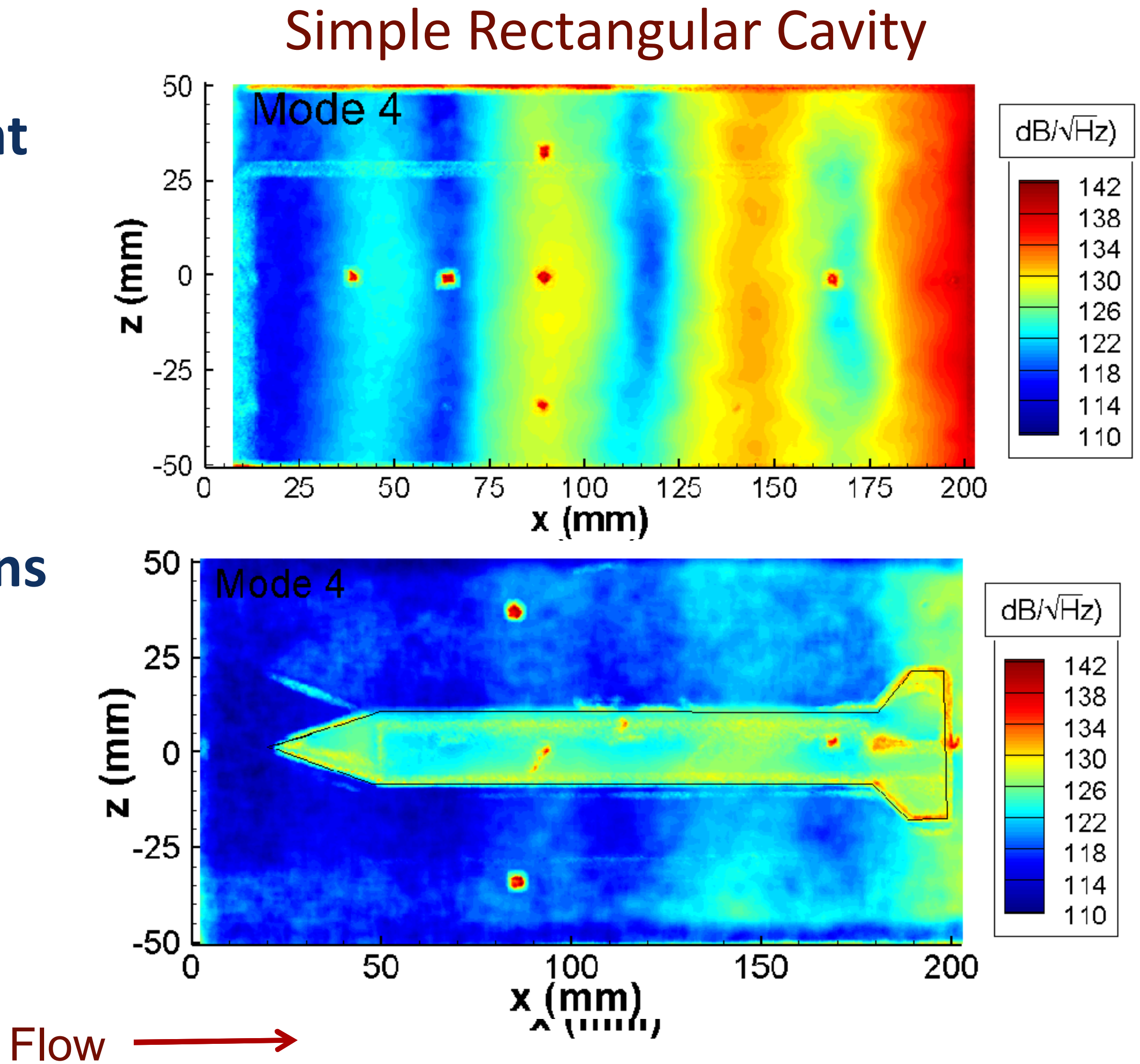
Comparison of Kulites and PSP.

Simple Rectangular Cavity Spatial PSD’s

Simple cavity pressure field is relatively constant across the span.

- Some variations near the edges of the cavity, likely related to spillage vortices.

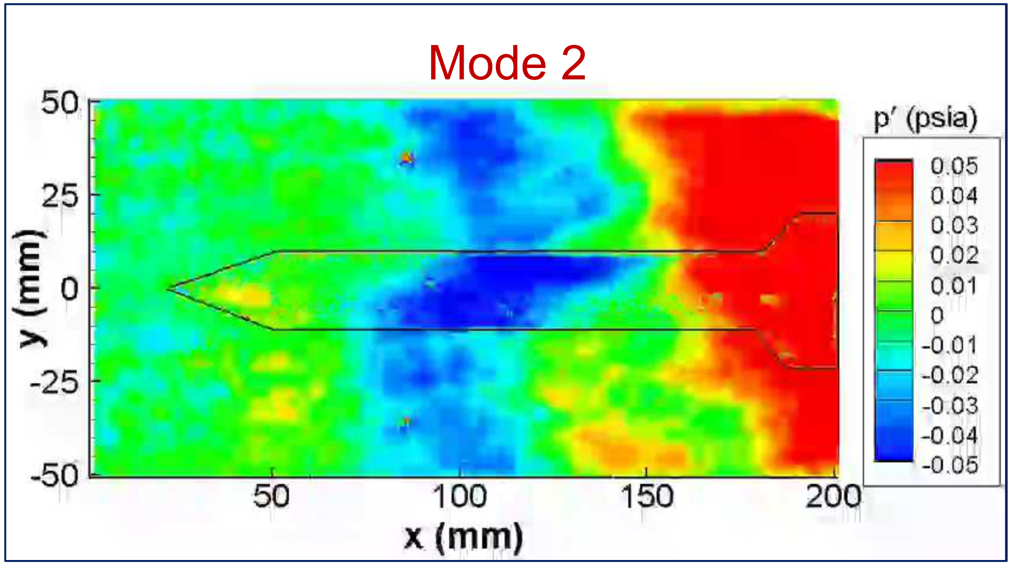
Store tends to suppress amplitudes of fluctuations on floor.

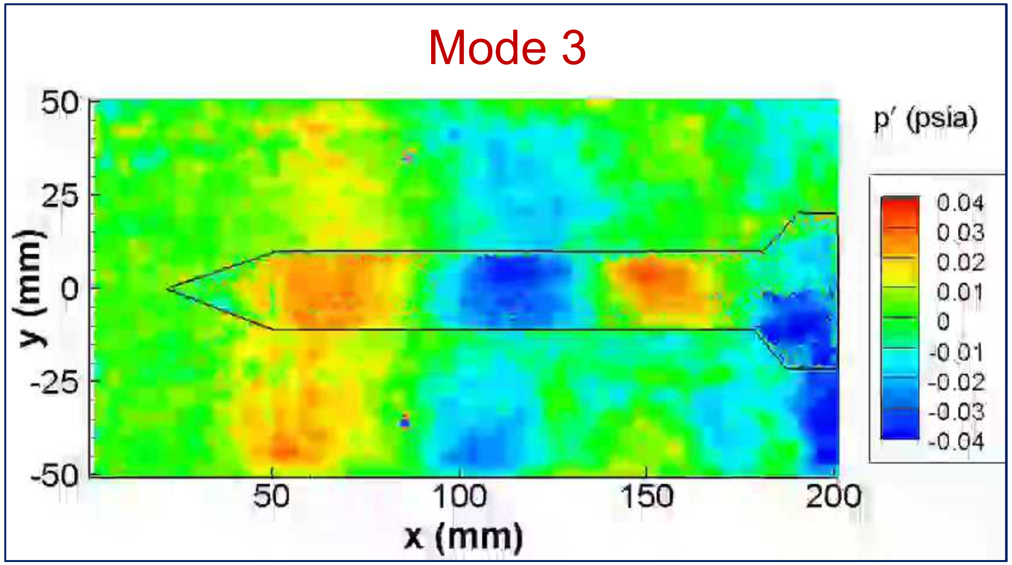


Bandpass Filtered Movies

Movies show the dynamic behavior of the modes.

- Dominated by downstream propagation.
- Resonant tones tend to be in phase across the store.
- Some asymmetries, but mostly uniform across the span (in pressure).

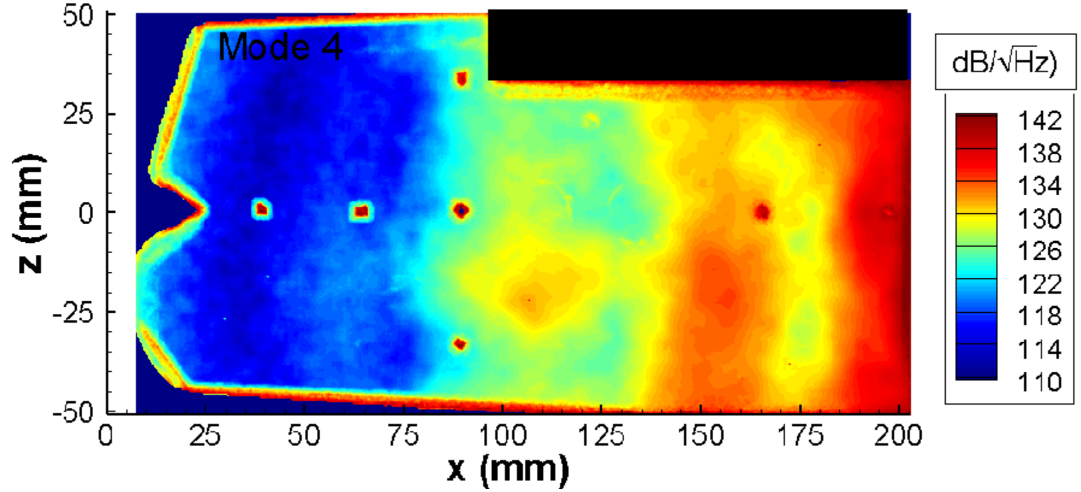


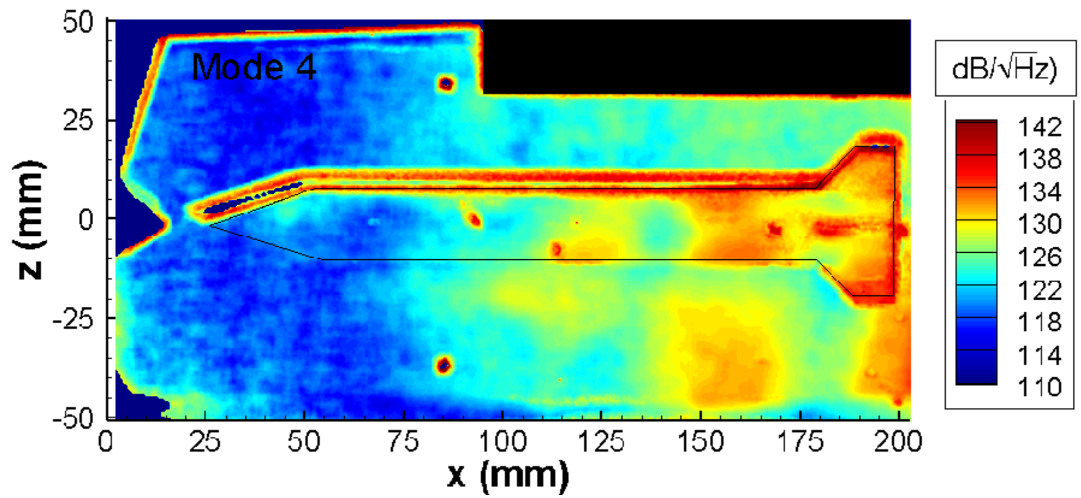


Complex Cavity Spatial PSD's

Complex cavity generates more complicated pressure field on cavity floor.

- Higher pressure region downstream of tooth configuration.
- Higher pressure biased away from side insert at cavity rear.



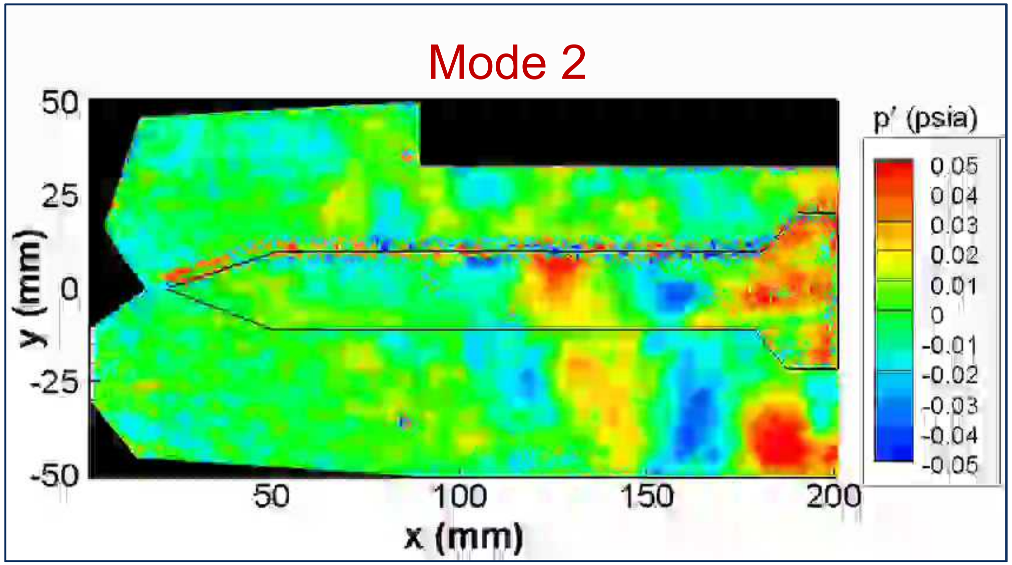


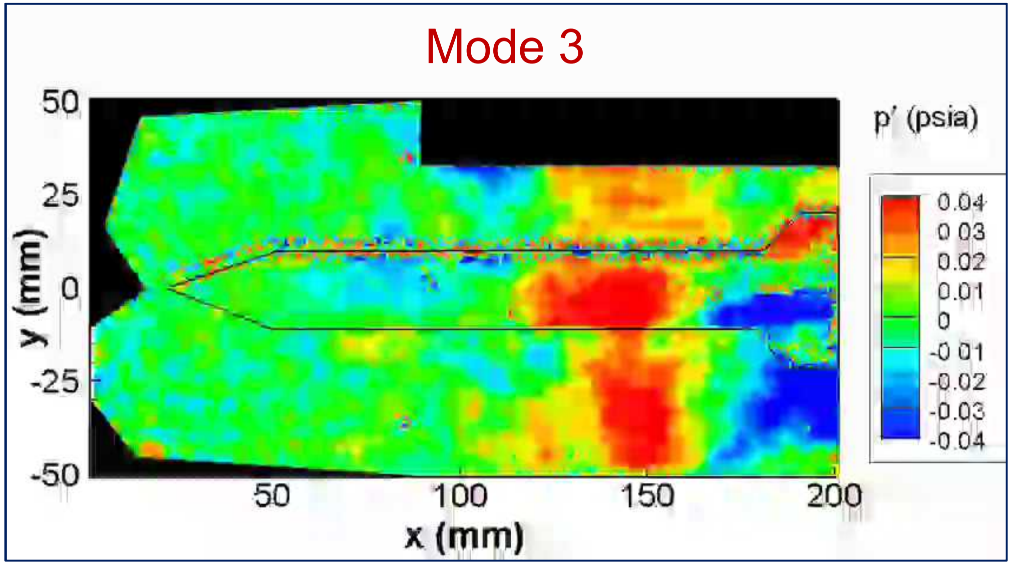
Flow →

Bandpass Filtered Pressure Movies

Bandpass filtered movies more clearly show assymmetries.

- Fluctuations tend to be out of phase across the store.
- Very unsteady pressure field.





Mode Matching in the Complex Cavity

Mode matching in the complex cavity creates an elevated response in all three directions.

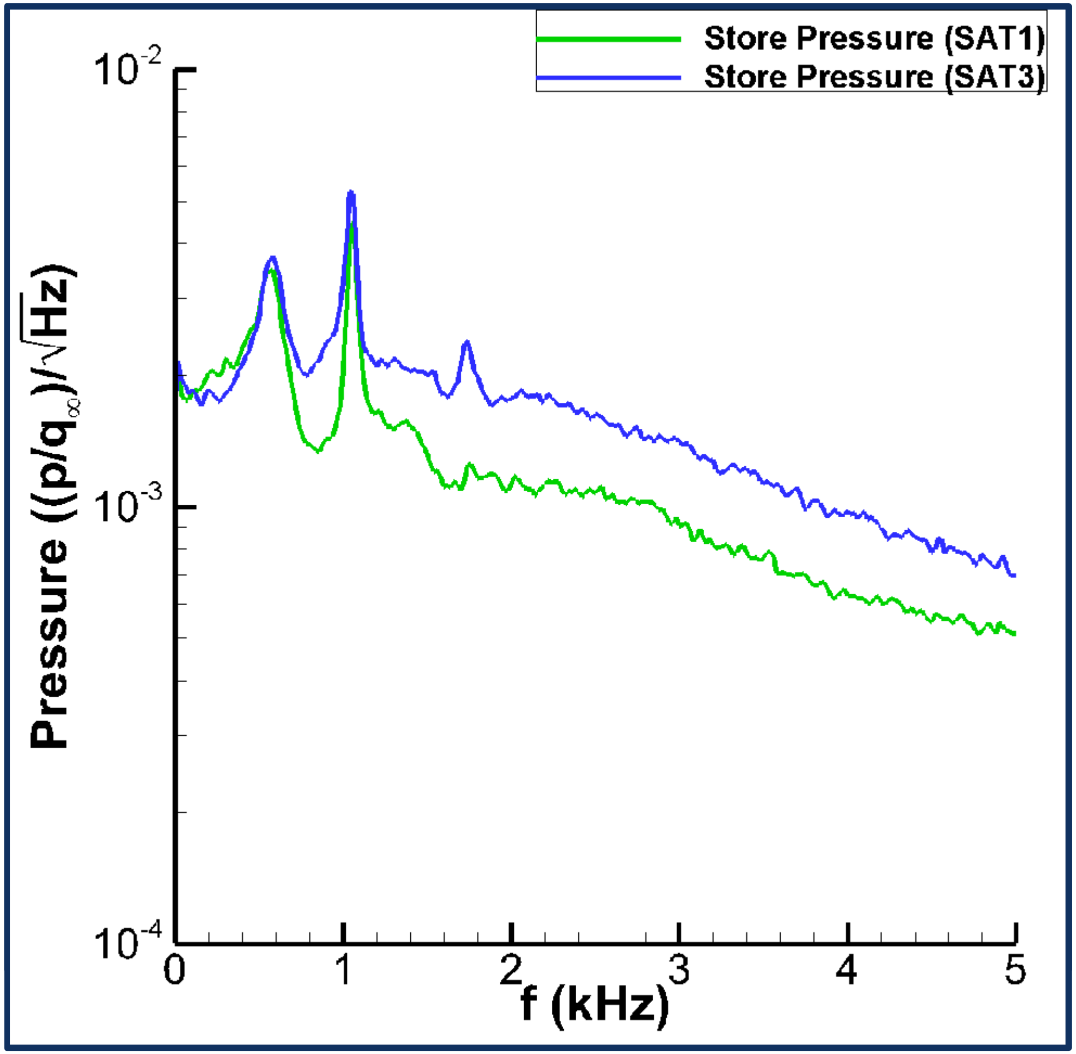
- Spanwise response to the cavity tones was not observed in the simple rectangular cavity.

Pressure spectra on either side of the store show different loading levels across the span of the store.

- Pressure fluctuations are also often out of phase across the span of the store.

Differing response shows importance of conducting FSI studies in similar flowfields to flight.

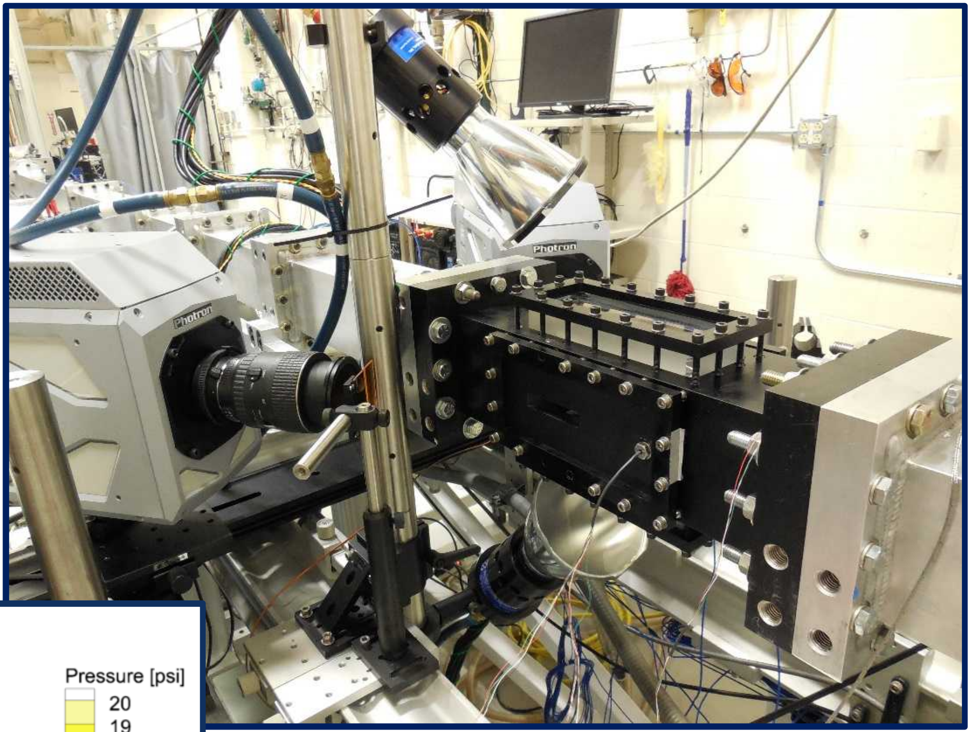
Pressure Spectra on Either Side of Store

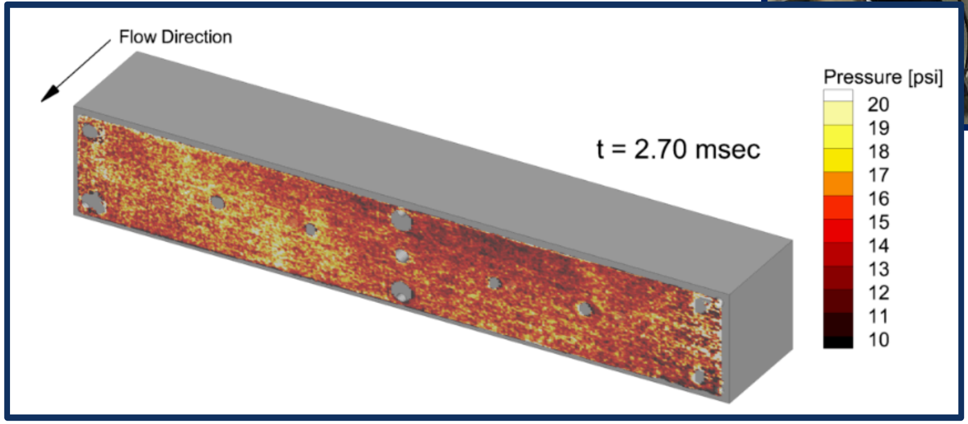


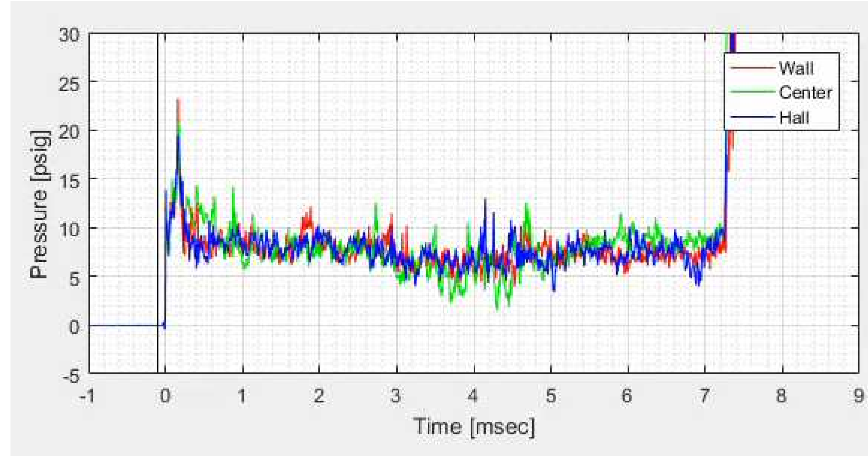
Shock-Tube Application of PSP

Non-linear joints LDRD (PI: Justin Wagner)

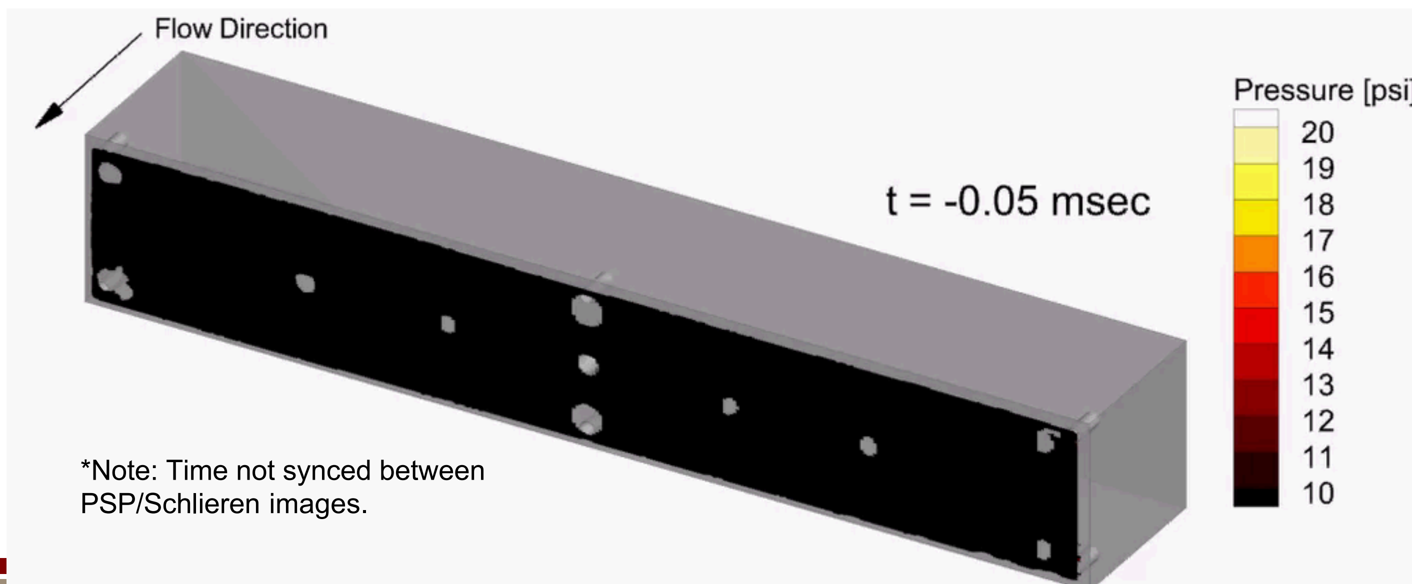
- Studying shock loading on solid beam and various nonlinear joints, to improve modeling capabilities.

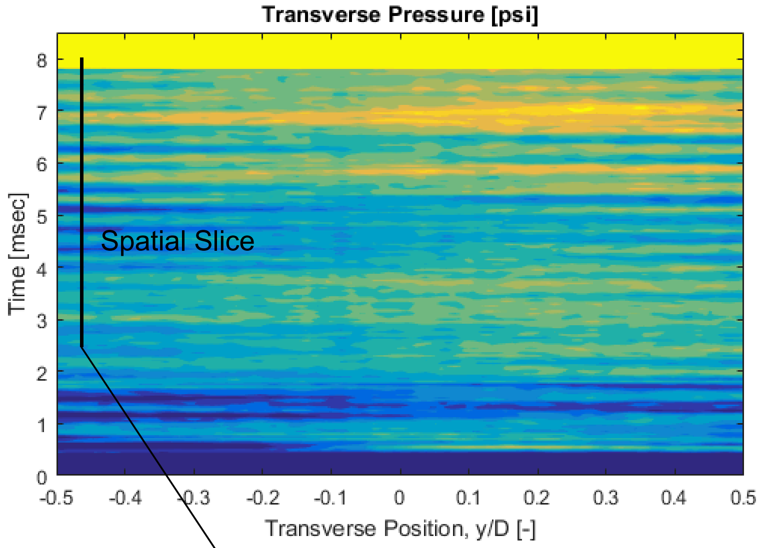




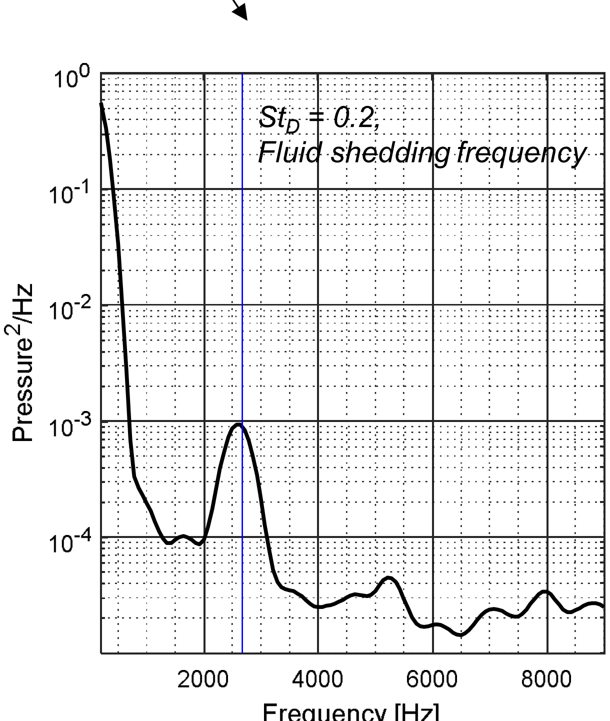


Flow separation and periodic vortex shedding behavior leads to an unsteady transverse beam loading captured with PSP

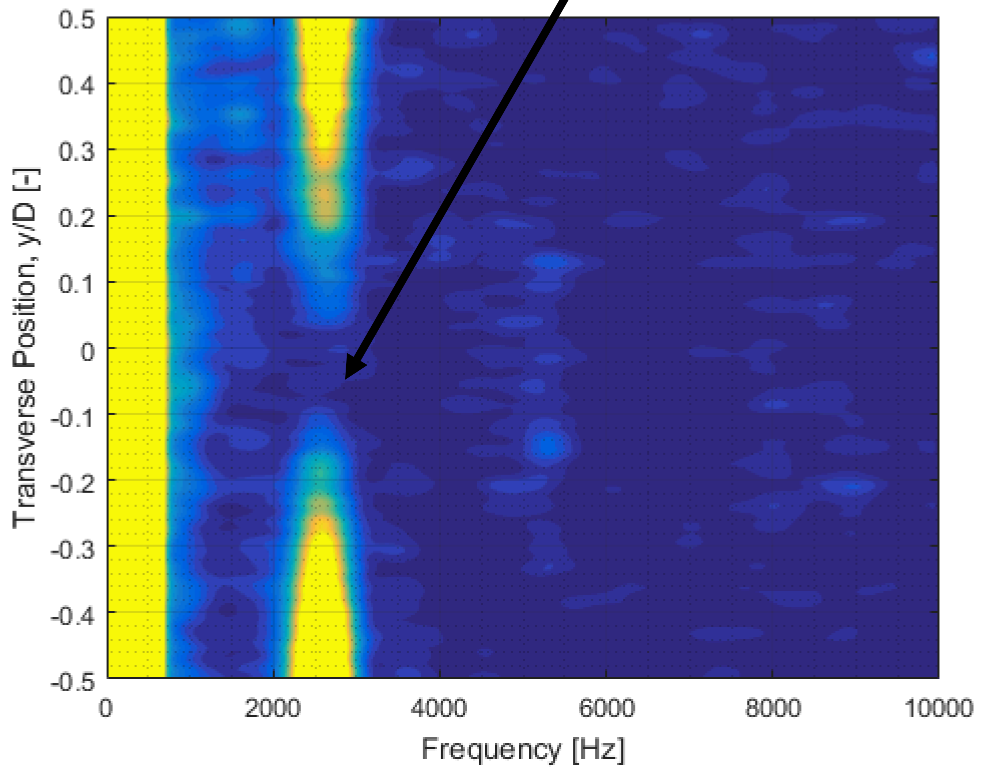




PSP allows us to characterize the unsteady fluid forcing, as well as its distribution along the beam.



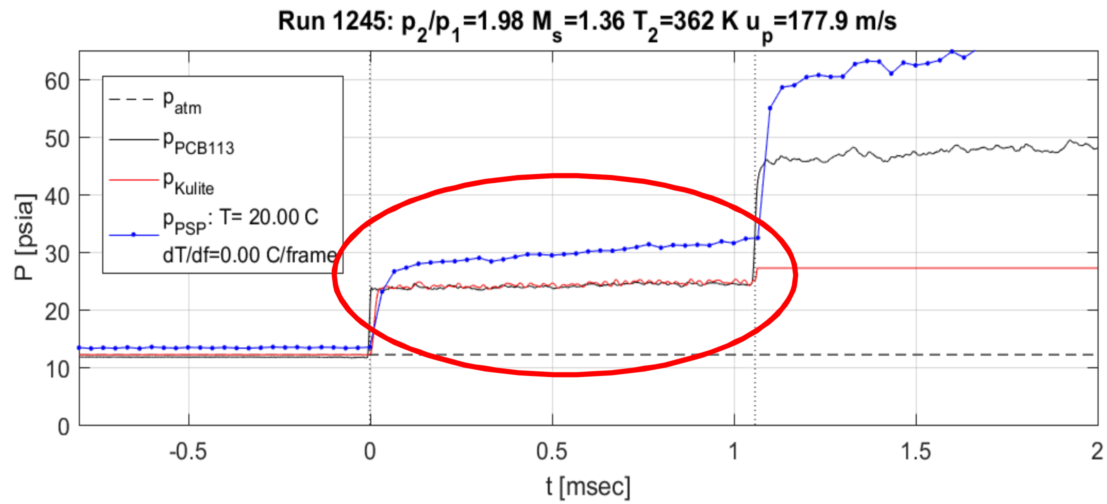
Transverse fluctuations active at edges of beam, inactive at center



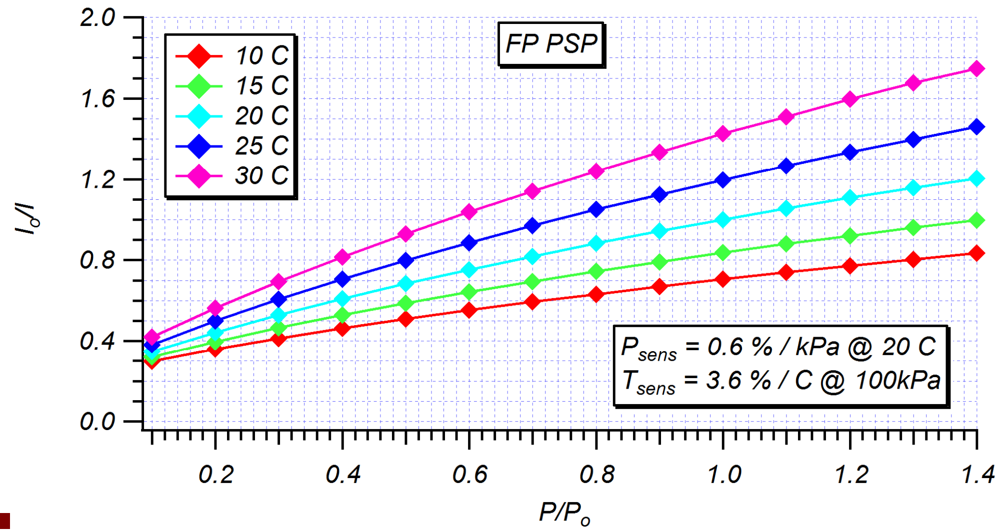
Temperature Correction of TR-PSP

Shock tube calibration of TR-PSP was completed in Summer 2017.

- Subsequent data analysis shows *absolute* pressure values subject to a significant drift compared to wall-mounted transducers.
- Literature suggests that shock-tube walls can heat up by 3-4 K during msec runtime.



Calibration data from ISSI shows paint luminosity has *strong* temperature dependence

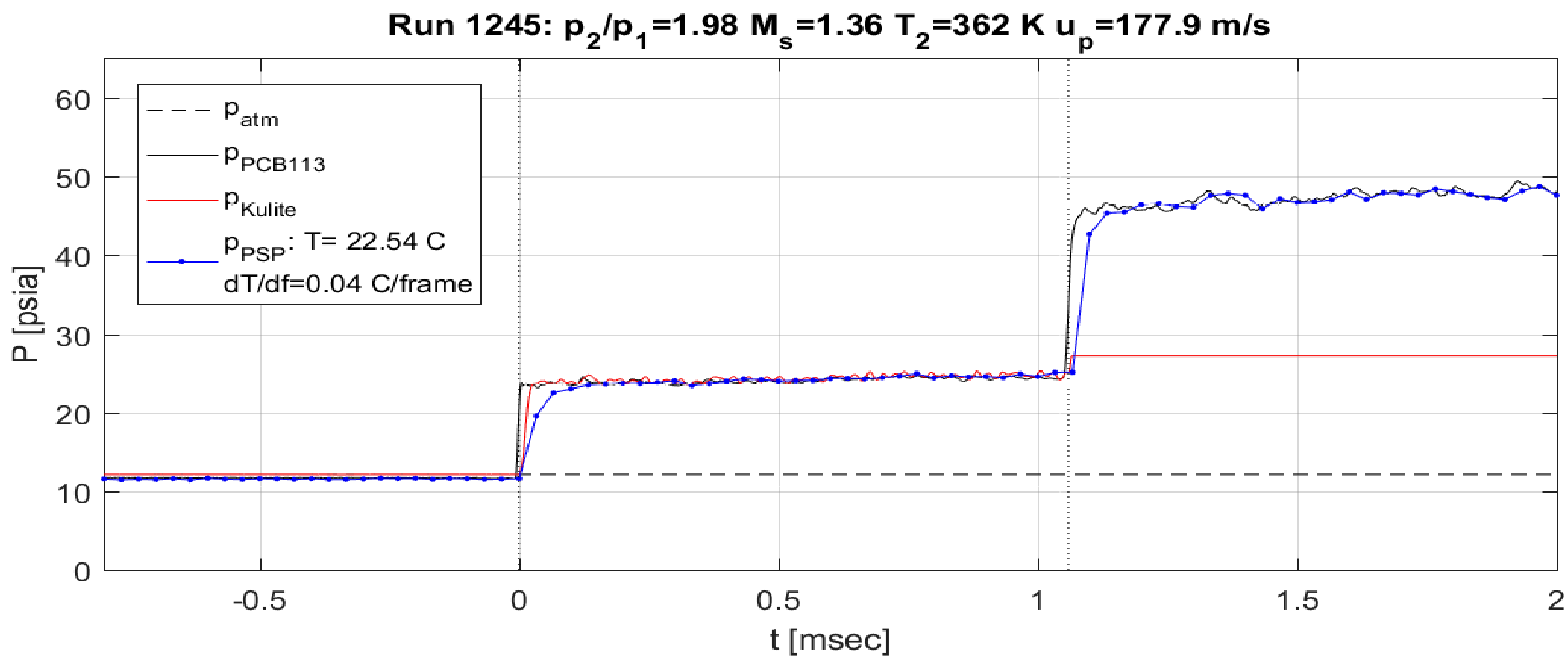


Temperature Correction of TR-PSP

Correction: Impose a time-varying temperature during run.

- Excellent match now observed for a number of runs.

Corrected
Uncorrected

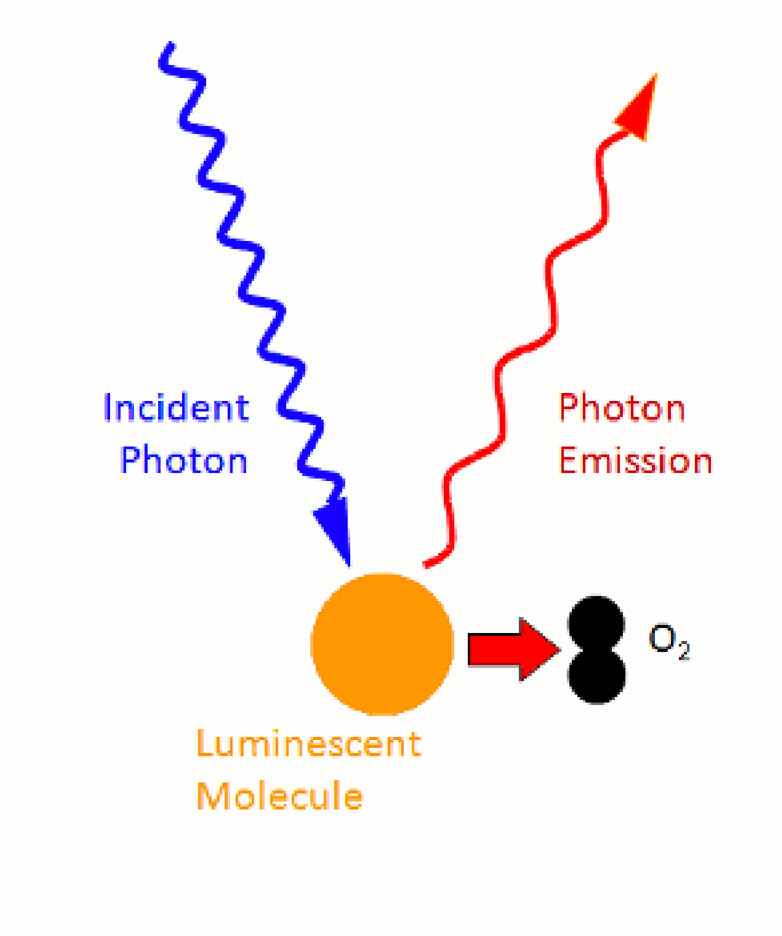


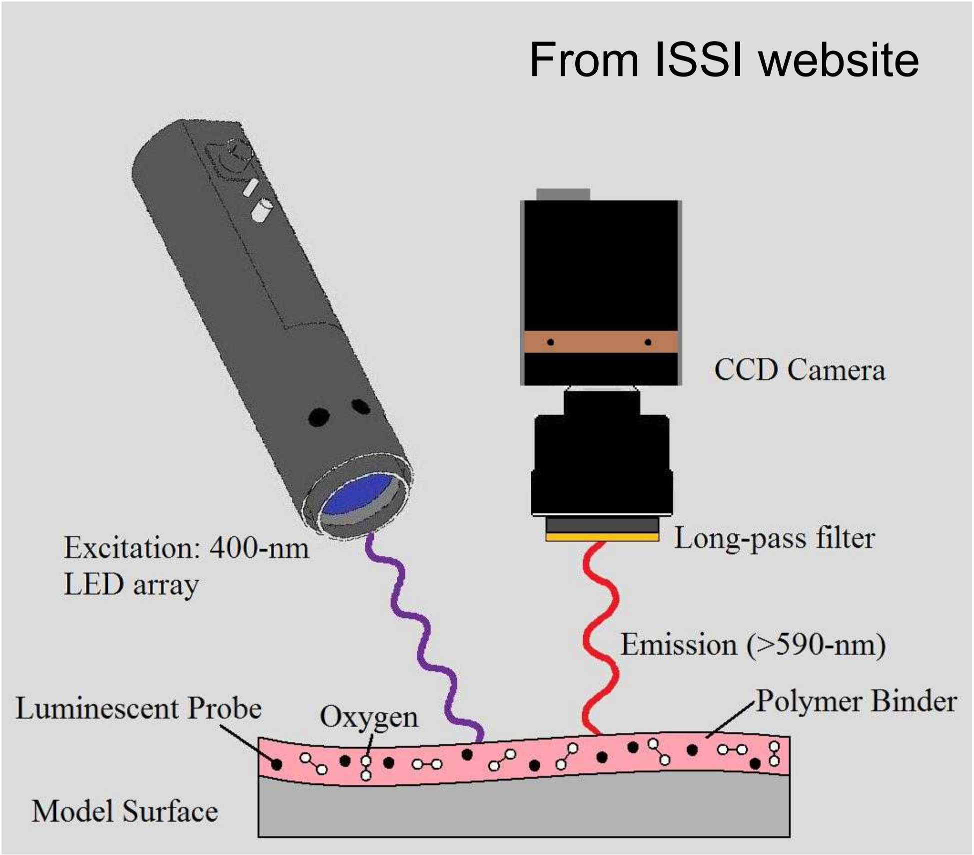
PSP Specifications

Paint Type:	BinaryFIB™	TurboFIB™	Porous Fast Response
Pressure sensitivity	0.6% per kPa	0.8% per kPa	0.6% per kPa
Pressure range	0-kPa to 200-kPa	0-kPa to 200-kPa	0-kPa to 200-kPa
Temperature sensitivity	0.03% per °C	0.4% per °C	3.6% per °C
Temperature range	0°C to 50°C	0°C to 50°C	0°C to 80°C
Response time	**300-ms**	**< 1-ms**	**< 100-µs**
Photo-degradation rate	1% per hour	1% per hour	1% per minute

PSP operation

Fast PSP uses a porous binder to increase surface area exposed to oxygen.

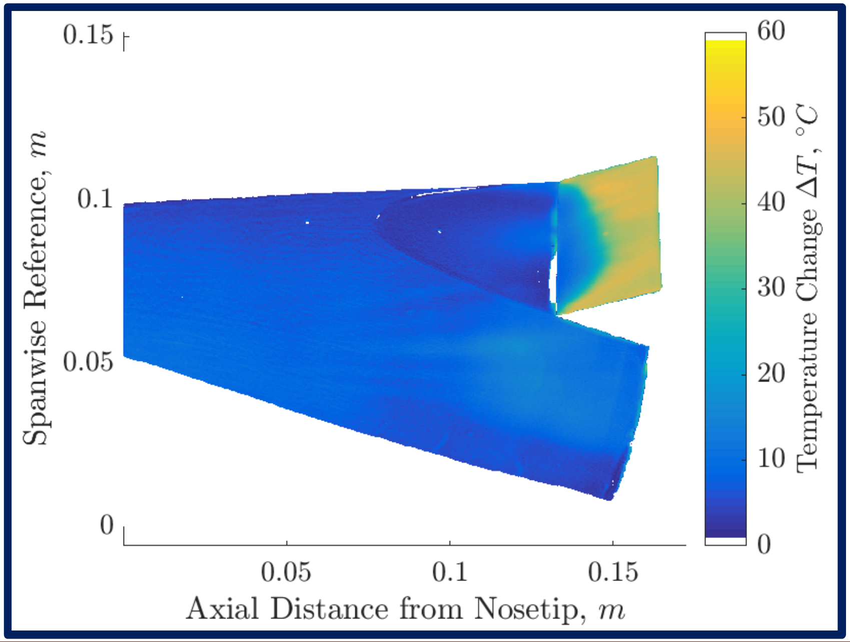




Hypersonic Fluid/Structure Interactions using TSP

We are studying in fluid-structure interactions of hypersonic surfaces.

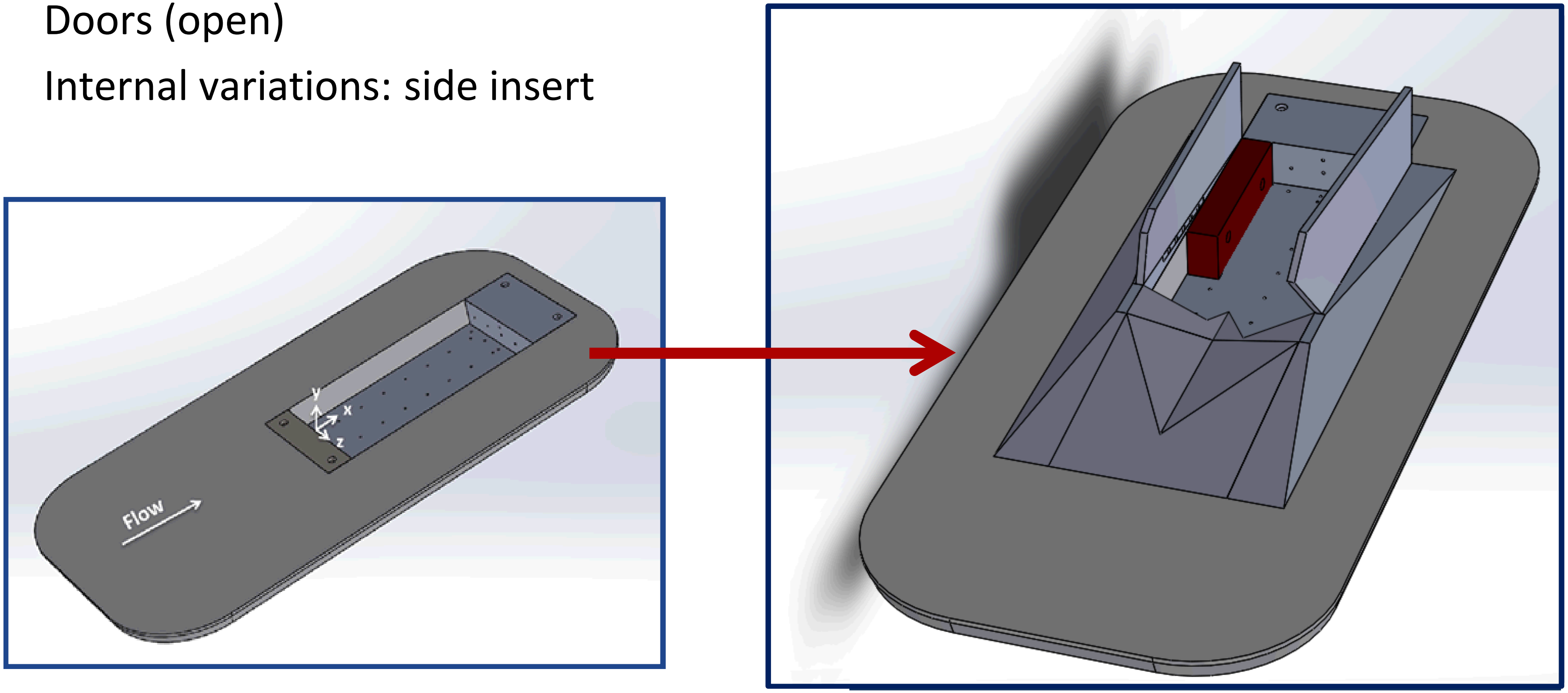
- Can study response to laminar/transitional/turbulent separation regions.
- *TSP marks the separation region and shock locations that are a principal driver of vibration loading.*



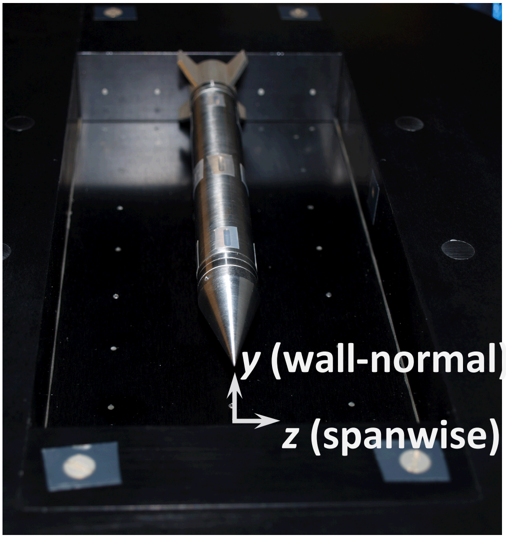
Complex Cavity Geometries

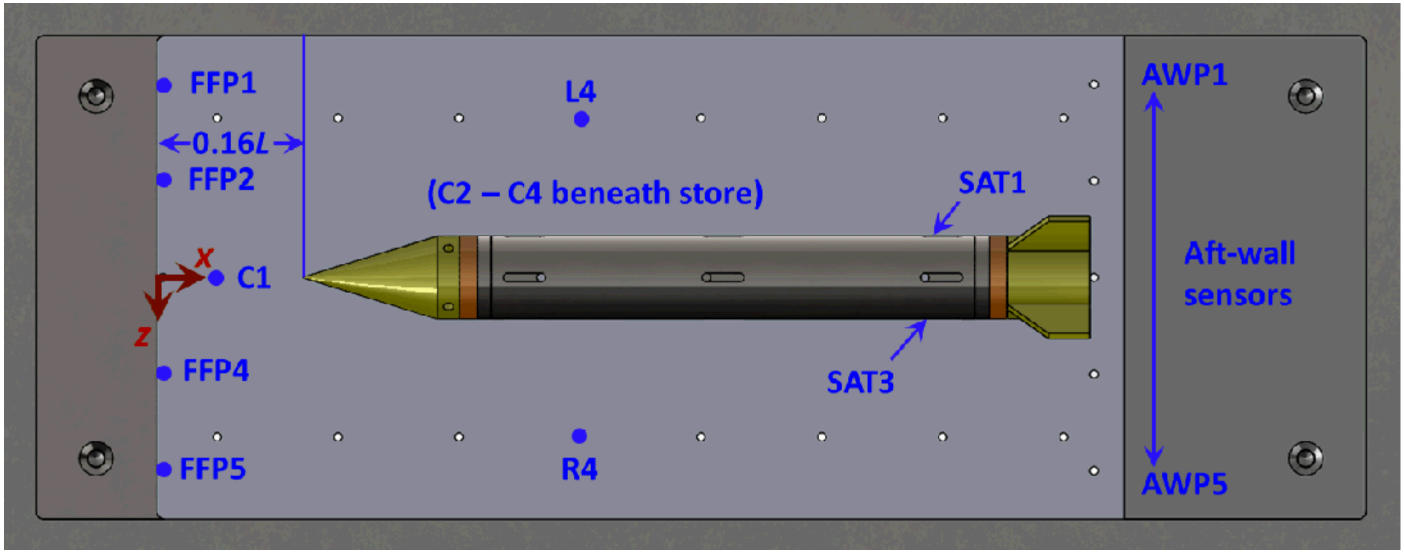
Use a building block approach to introduce complex geometric features one at a time into a simple rectangular cavity.

- Baseline configuration: side and front ramps
- Inlet geometry: center scoop and tooth
- Doors (open)
- Internal variations: side insert



Experimental Setup





Test Conditions

- **Mach 0.6-0.9, Re ≈ 10^7 / m**
- Incoming turbulent boundary layer
- ***L/D* = 7,** *L/W* = 2, ***δ* ≈ 0.5*D***
- Top of store cylinder flush with floor

Pressure Instrumentation

- **Cavity Surfaces:** Kulite XCQ-062-30A
- **Store Surface:** Kulite LQ-062-25A
- Flat frequency response to ≈ 50 kHz

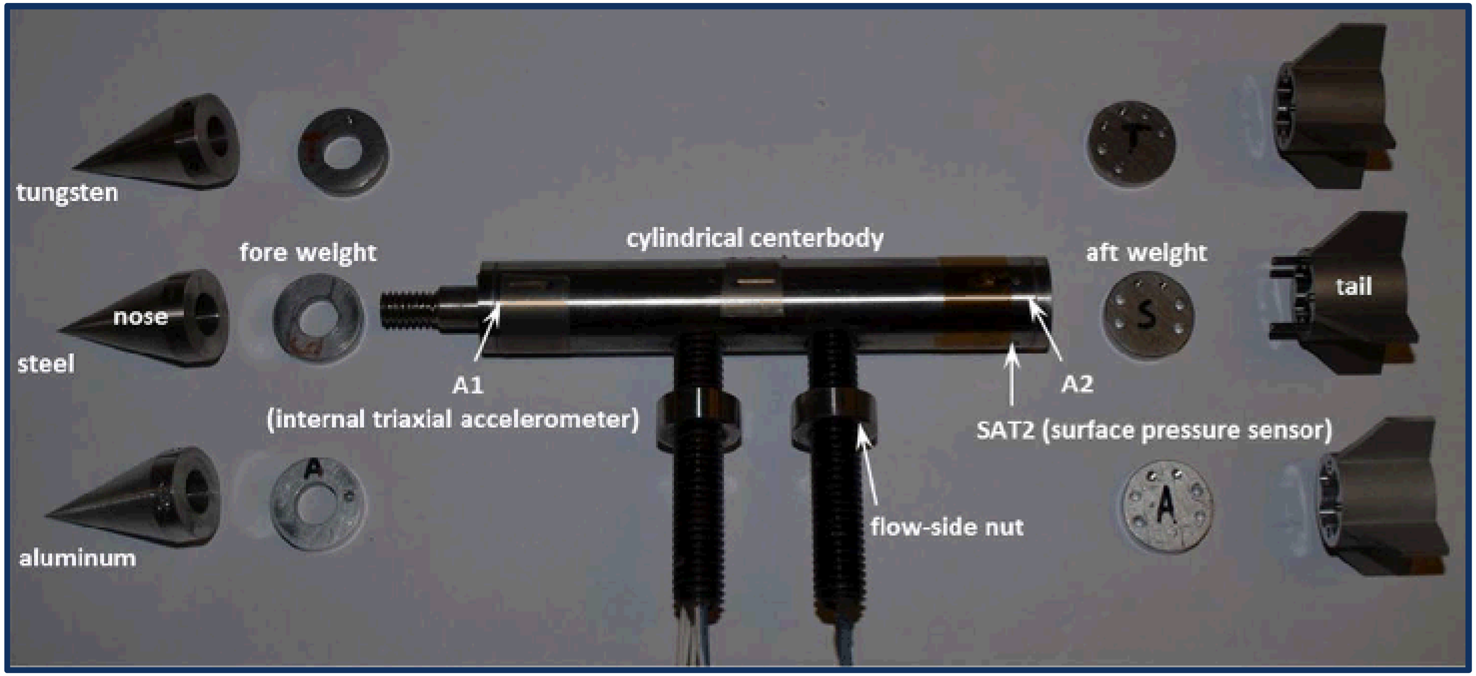
Acceleration Instrumentation

- Triaxial accelerometers at front and rear of store

Tunable Store Design

Nine different structural configurations were tested along with a steel centerbody.

- Varied nosetip and tail material between tungsten, steel, and aluminum.
- Each change varied structural natural frequencies between 100-300 Hz.
- Finer adjustment of 10-30 Hz were obtained by changing fore and aft weights.

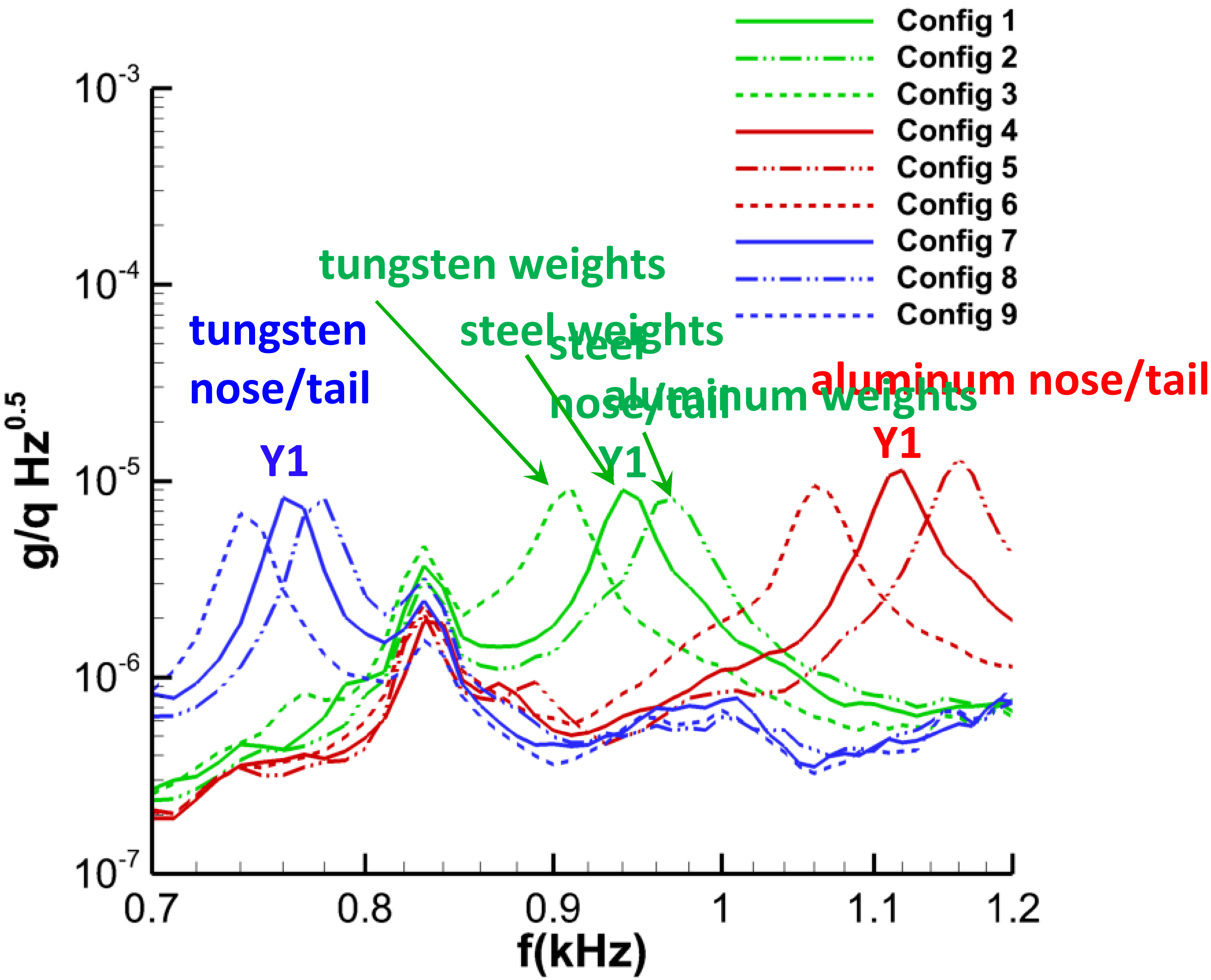


Variation of Structural Natural Frequencies

Changing nose and tail results in large natural frequency variations.

Smaller variations can be achieved through weight changes.

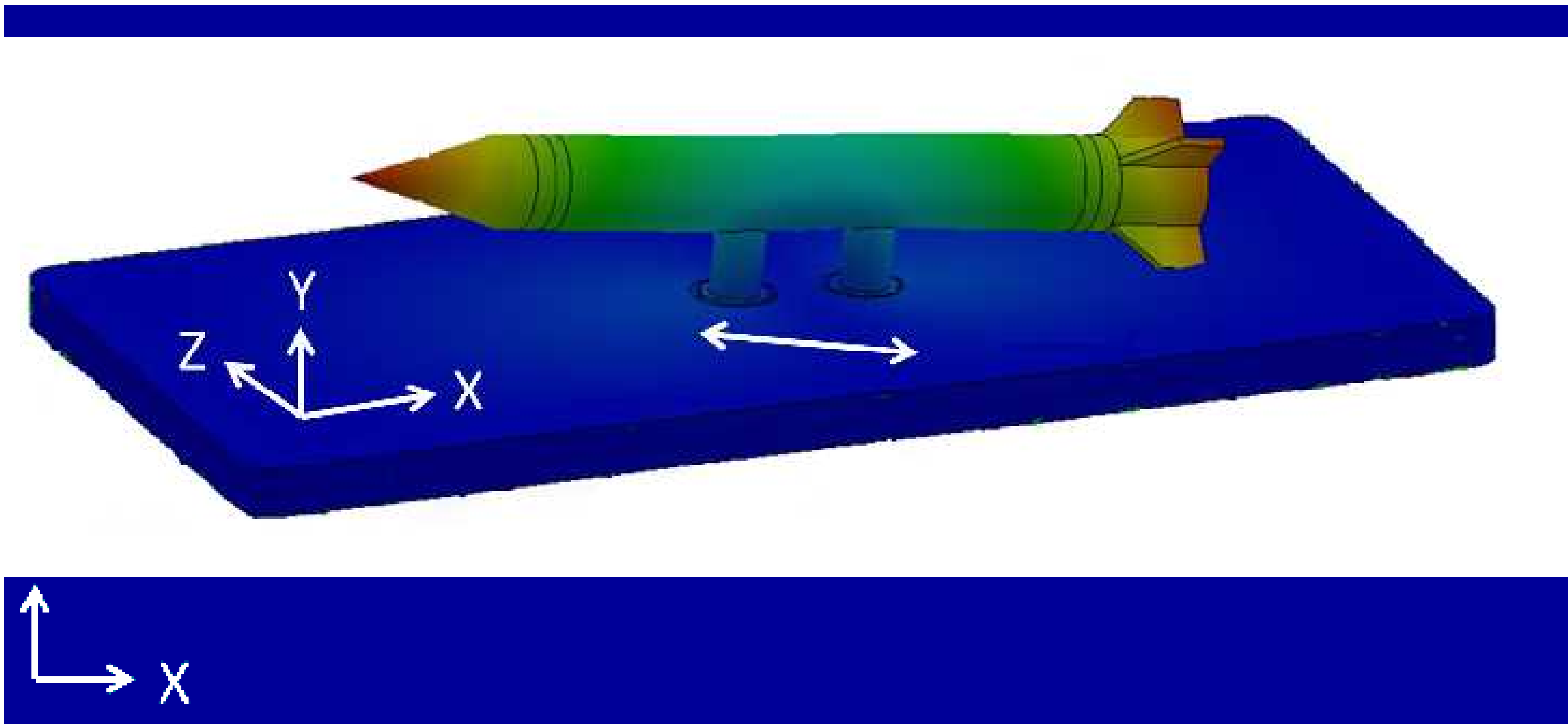
Streamwise Accelerations in Mach 0.8 Cavity Flow



Structural Mode Shapes

Hammer test conducted to identify dominant mode shapes and frequencies for each configuration.

Y Z1X Spanwise Fore Aft Rocking



Simple Rectangular Cavity Pressure Spectra

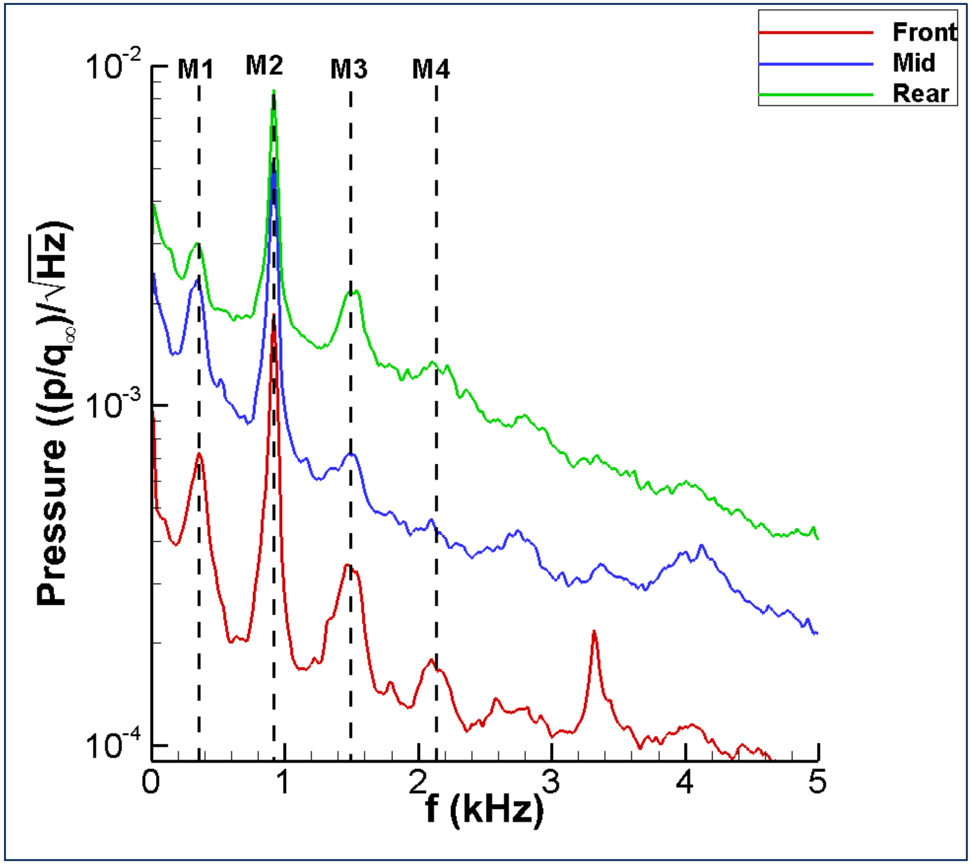
Pressure spectra along floor of cavity show expected behavior.

- Resonant tone corresponding to the Rossiter modes.
- Higher amplitude turbulent fluctuations at the rear of the cavity.

Get a more complete picture by doing this at every point in the cavity using PSP.

- Plot modal amplitudes to give us a spatial picture of the cavity mode behavior.

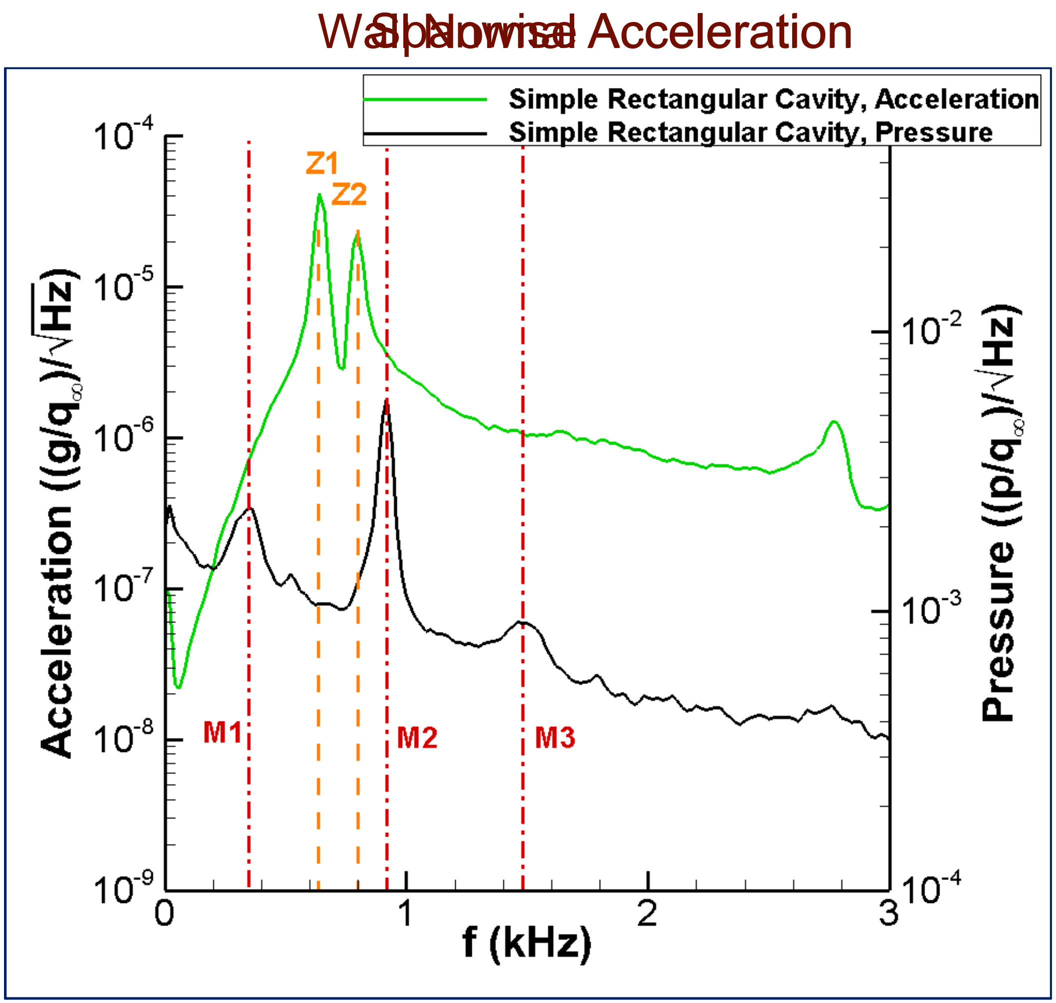
Pressure Spectra



How does this loading relate to the store response?

See response at dominant structural natural frequencies in each direction.

- What happens when a cavity tone matches a structural natural frequency?
- Use all 9 structural configurations to shift natural frequencies in and out of mode matching with the cavity tone.



Previous Results: Mode Matching in the Simple Rectangular Cavity

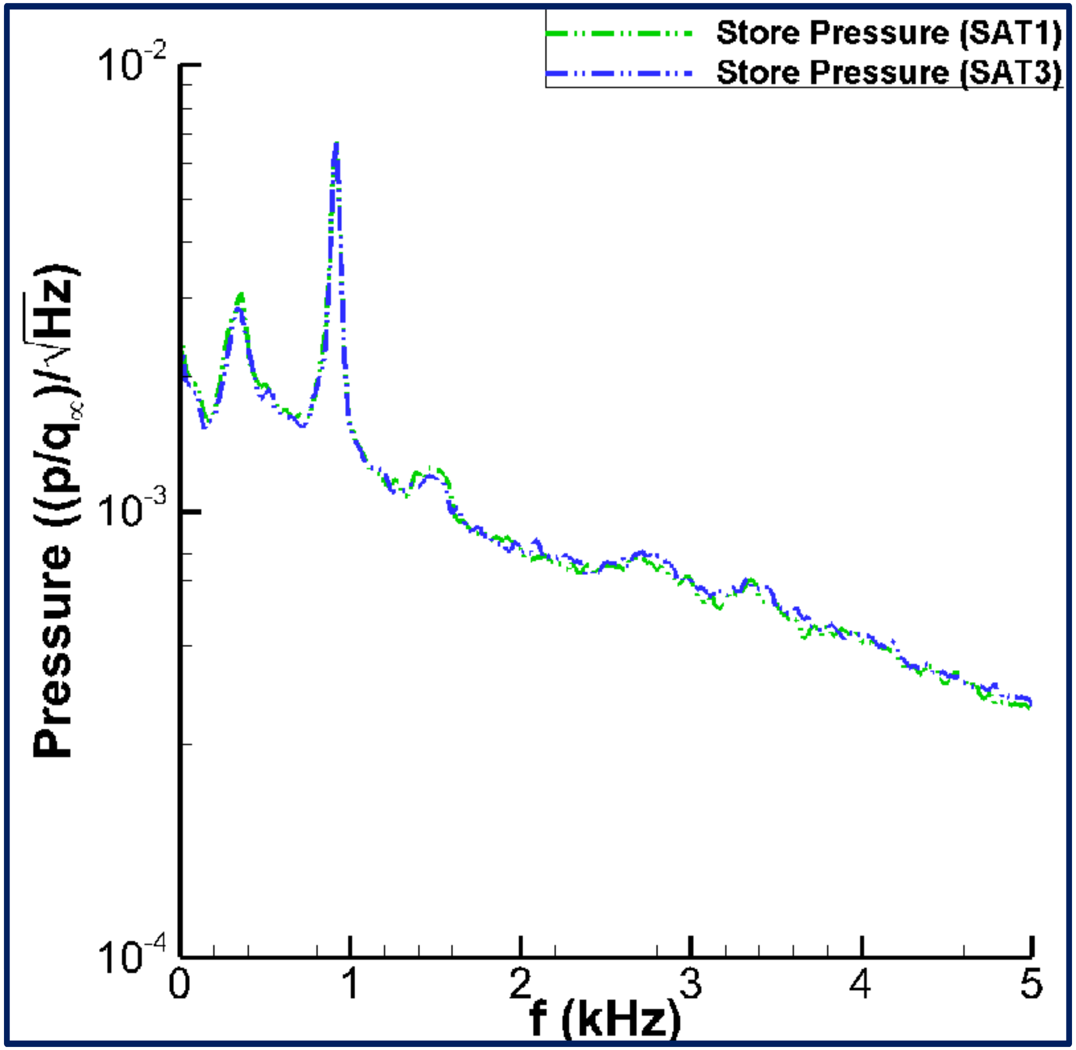
Previous studies in the simple rectangular cavity show:

- Mode matching a structural natural frequency to a cavity tone frequency creates an elevated response in the streamwise and wall normal directions.
- An elevated response is not seen in the spanwise direction.

Pressure spectra on either side of the store are similar.

Pressure fluctuations due to cavity resonance are in phase.

Pressure Spectra on Either Side of Store



Complex Cavity Pressure and Acceleration Spectra

Complex cavity changes the cavity pressure spectra.

- Shifts cavity tones to higher frequencies.
- Elevated resonant fluctuations as well as broadband turbulent fluctuations.

Generally measure higher amplitudes in complex cavity where the pressure loading is higher.

Streamwise Acceleration