Sandia National Laboratories

Exceptional service in the national interest

Ground Testing of Unsteady Aerodynamic Environments in Hypersonic Flight

Steven Beresh

NASA / AFRL Workshop
on High-Speed Test Techniques

November 30 and December 1, 2022

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U.S. DEPARTMENT OF ENERGY

NNSA

Who is working this program?

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Marie DeZetter
Brian Denk

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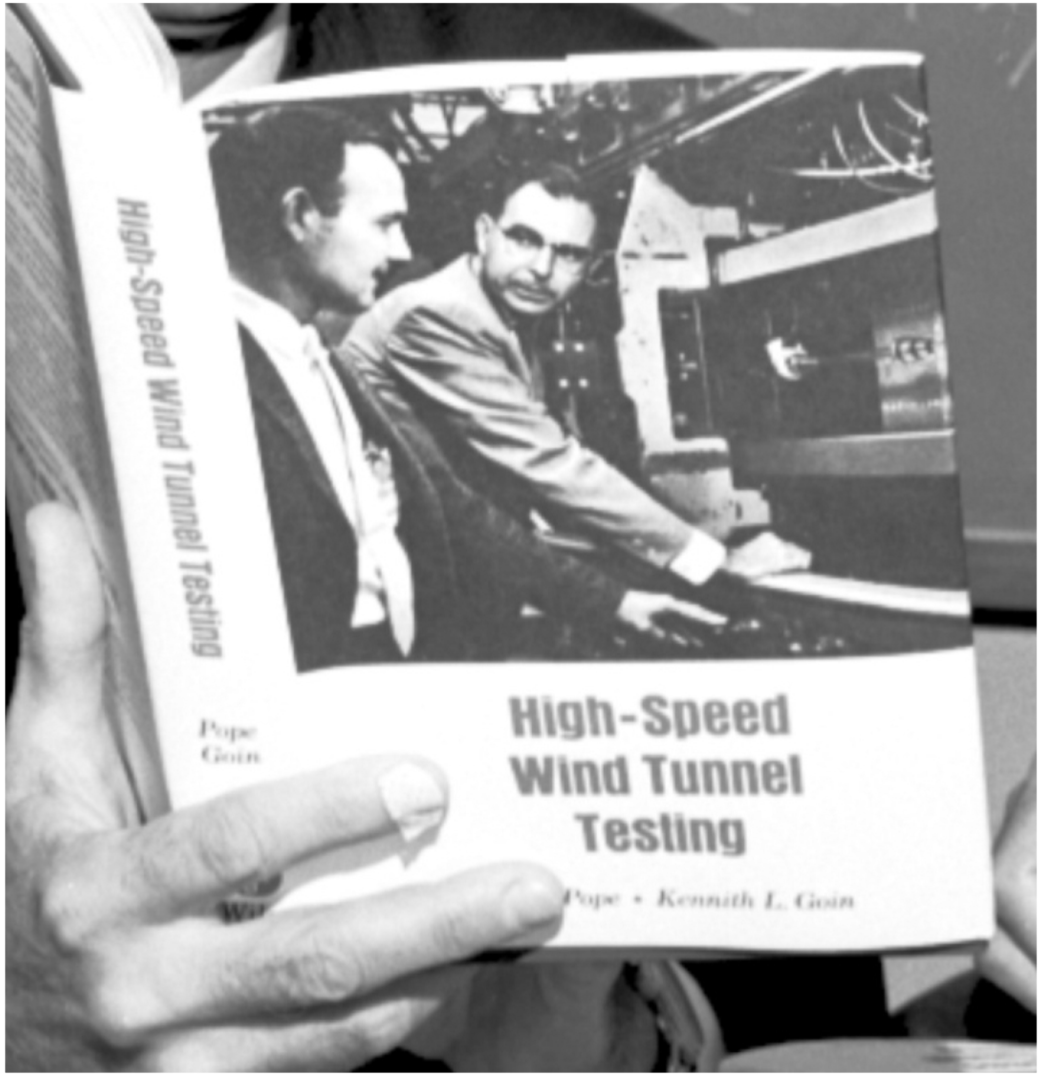
Daniel Richardson
Elijah Jans

Shock Tunnel: Justin Wagner
Kyle Lynch
Kyle Daniel
Josh Hargis
CJ Downing

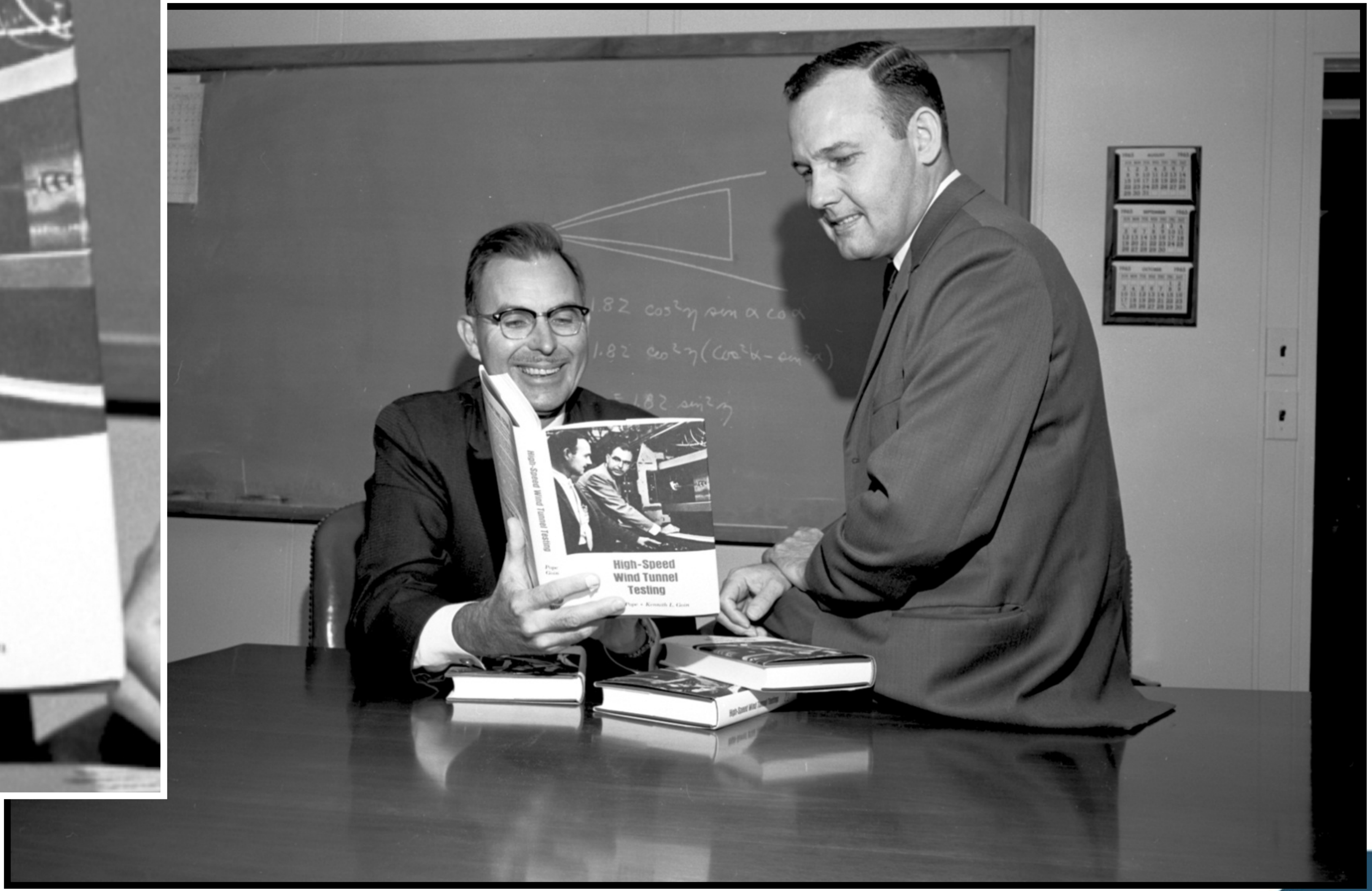
Centrifuge: Rich Jepsen
Greg Tipton

PI: Steve Beresh
(undeservingly takes credit for everything)

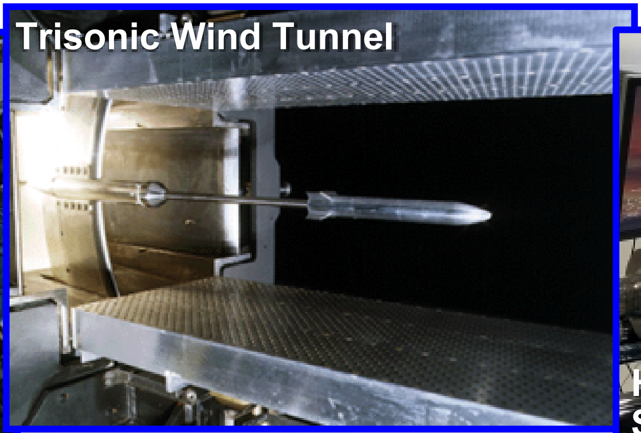
Sandians literally wrote the book on high-speed wind tunnel testing.

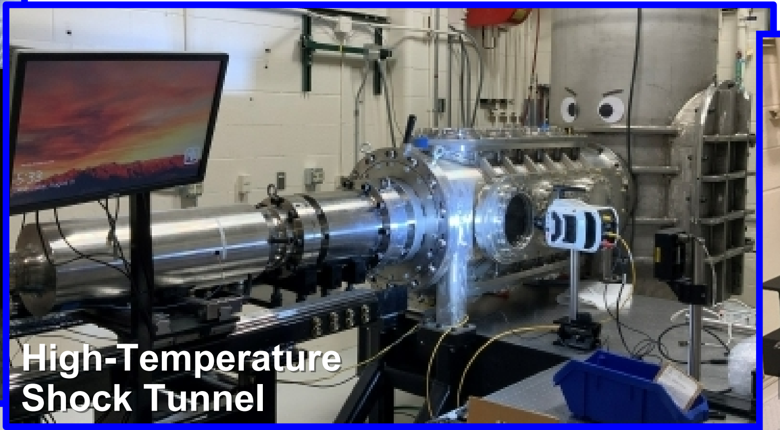


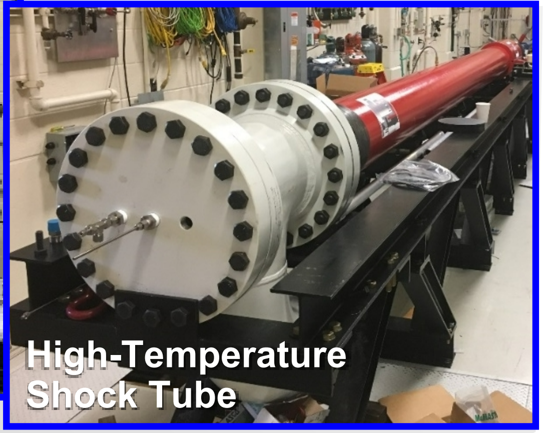
Alan Pope and Ken Goin, 1965

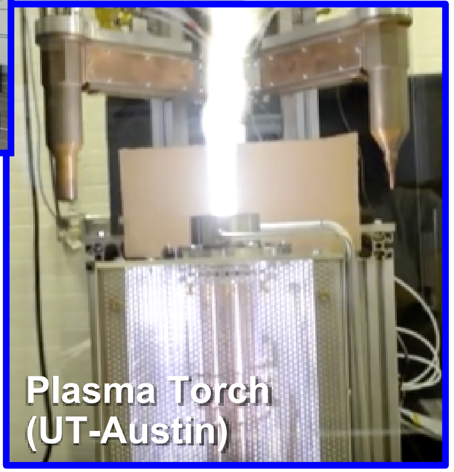


Hypersonic Ground Test Facilities to Characterize Aero Environments



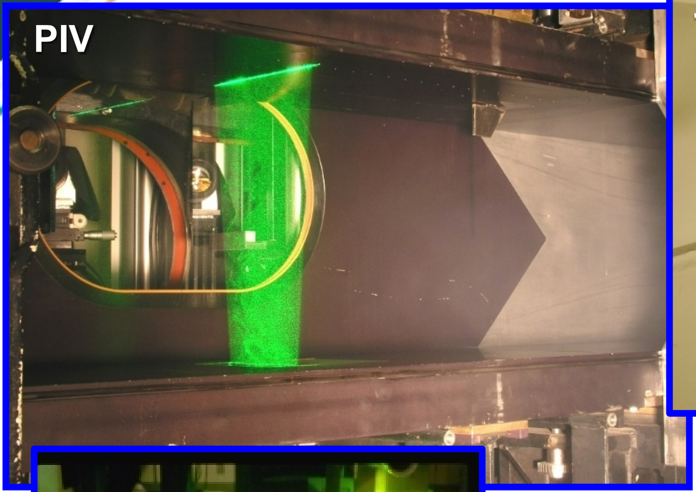






Fundamental physics discovered from a foundation of scientific infrastructure.

Advanced Diagnostics to Characterize Aero Environments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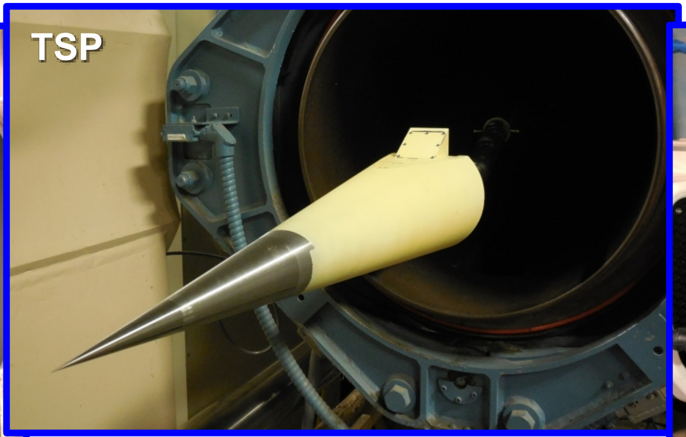
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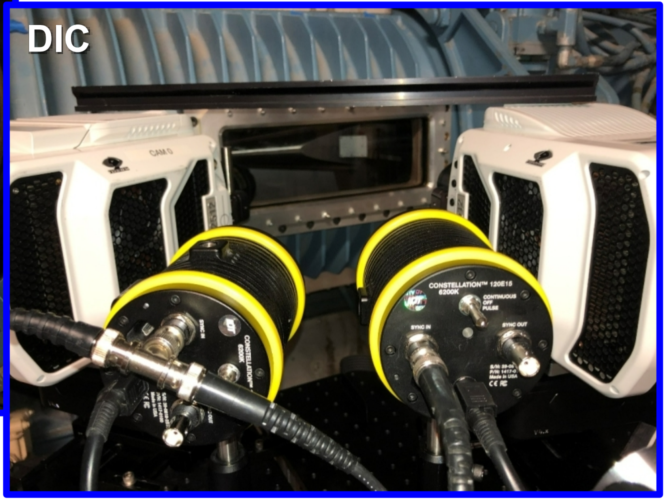
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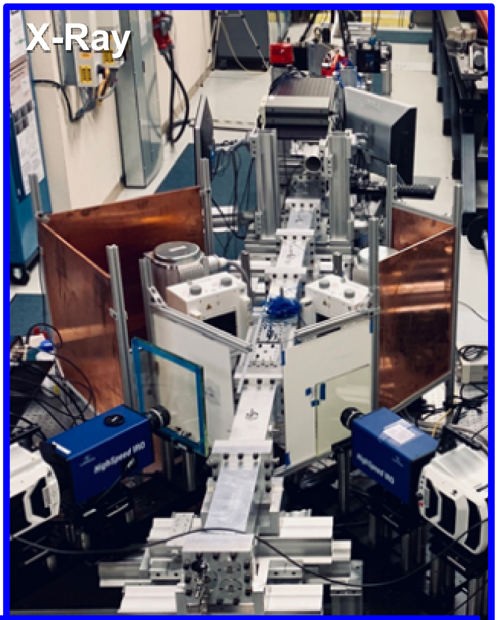
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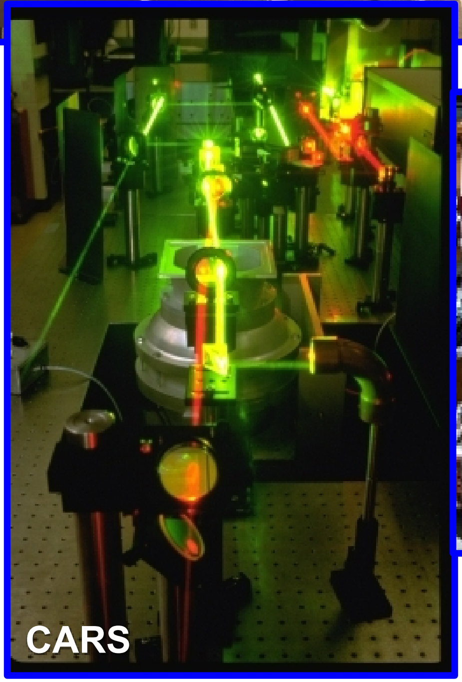
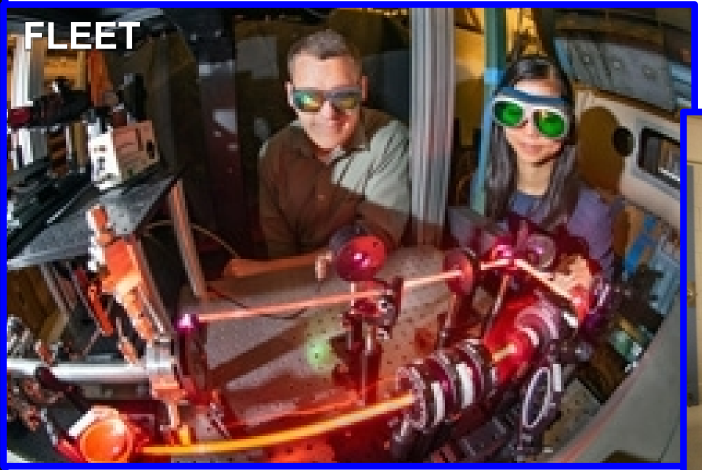
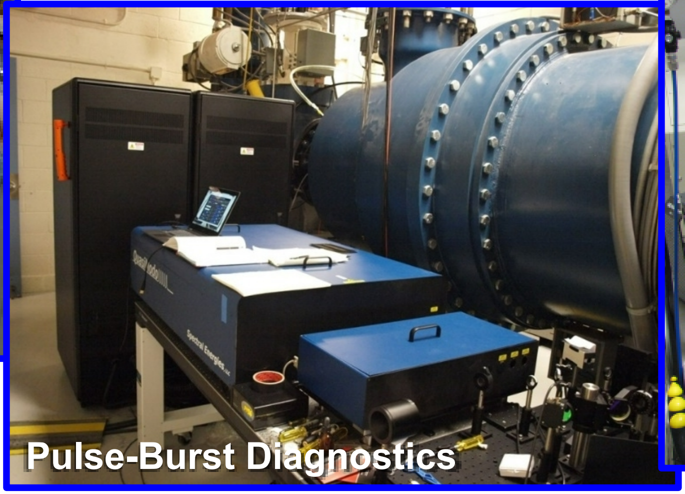
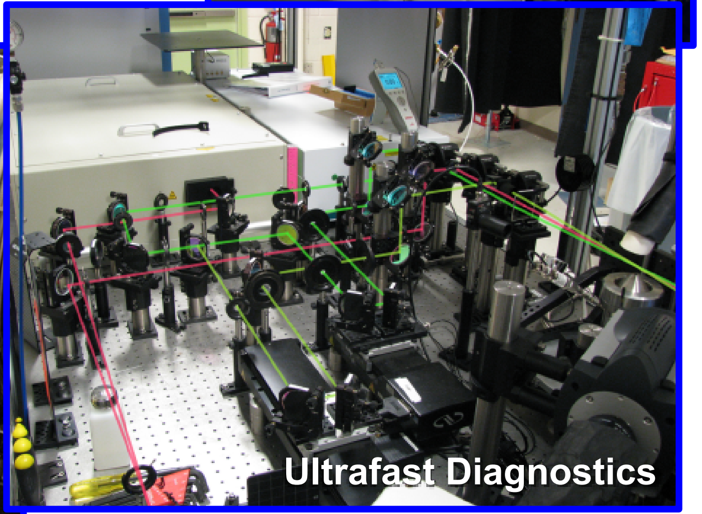

CARS


FLEET

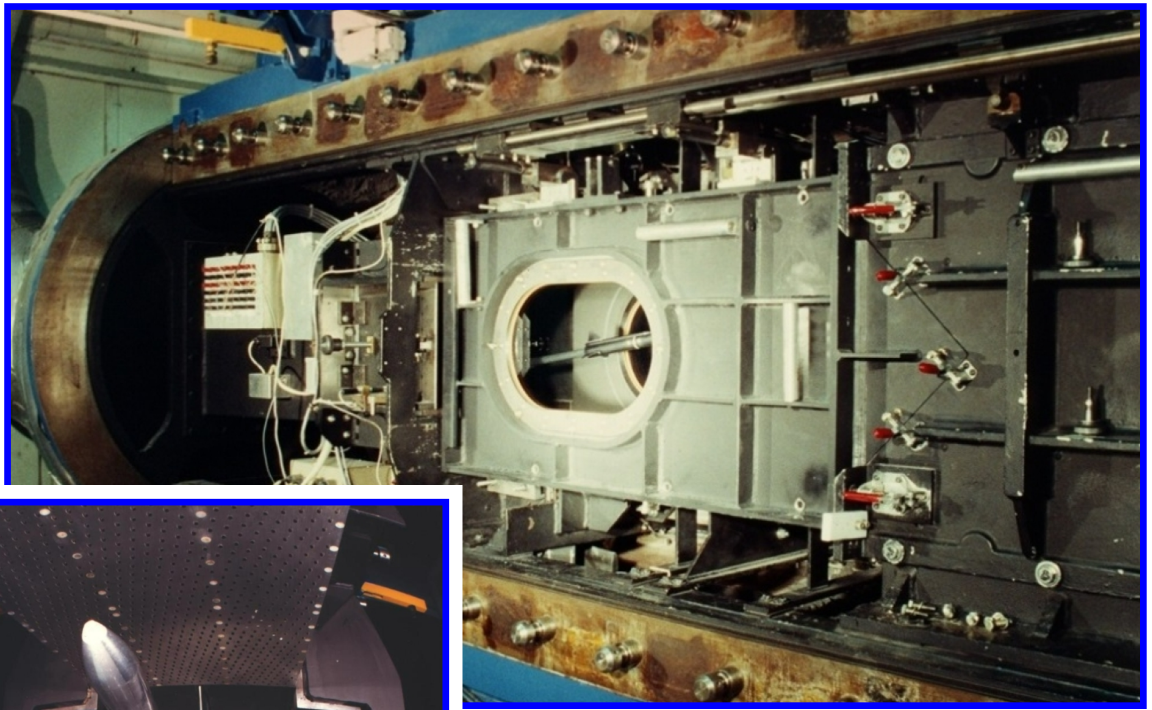

Pulse-Burst Diagnostics

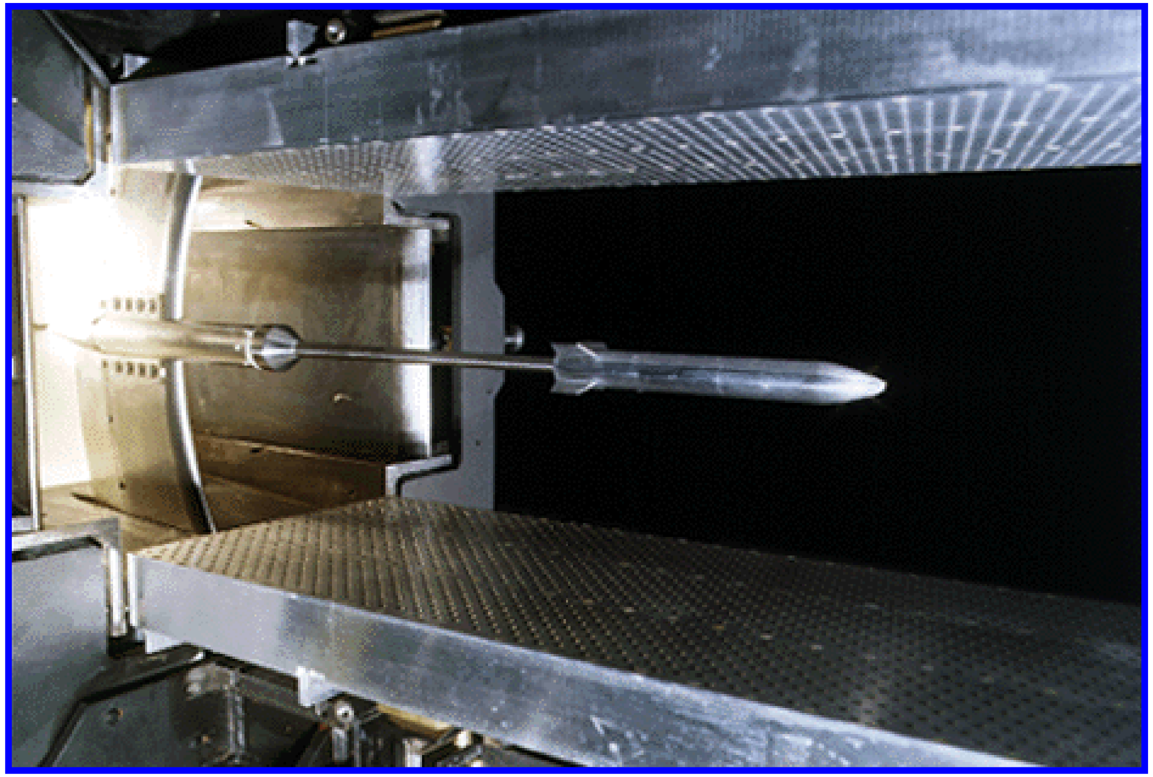

Ultrafast Diagnostics

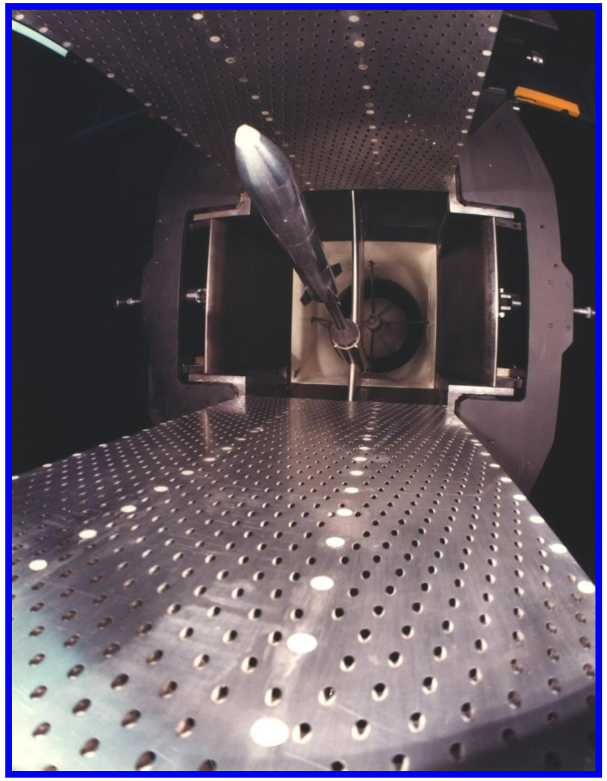
High-fidelity measurements to discover the physics our codes must model.

Trisonic Wind Tunnel (TWT)

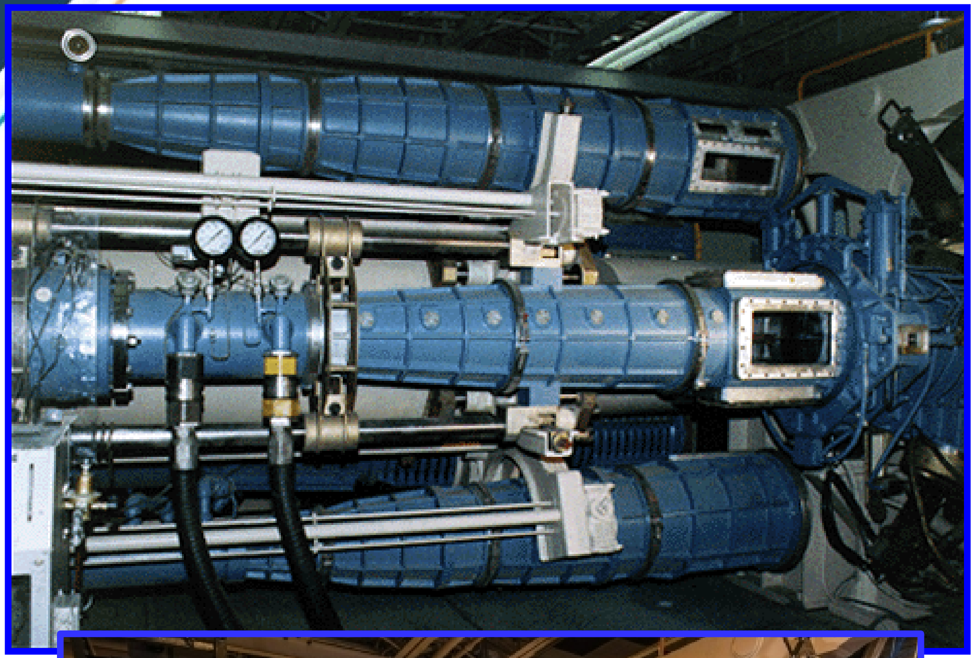
- Blowdown to atmosphere
- M_∞ = 0.5 - 1.3, 1.5, 2.0, 2.5, 3.0
- Re = 3 - 20 × 10^6 /ft
- Run times: 20 - 120 seconds at 20 - 30 minute intervals
- 12" × 12" test section

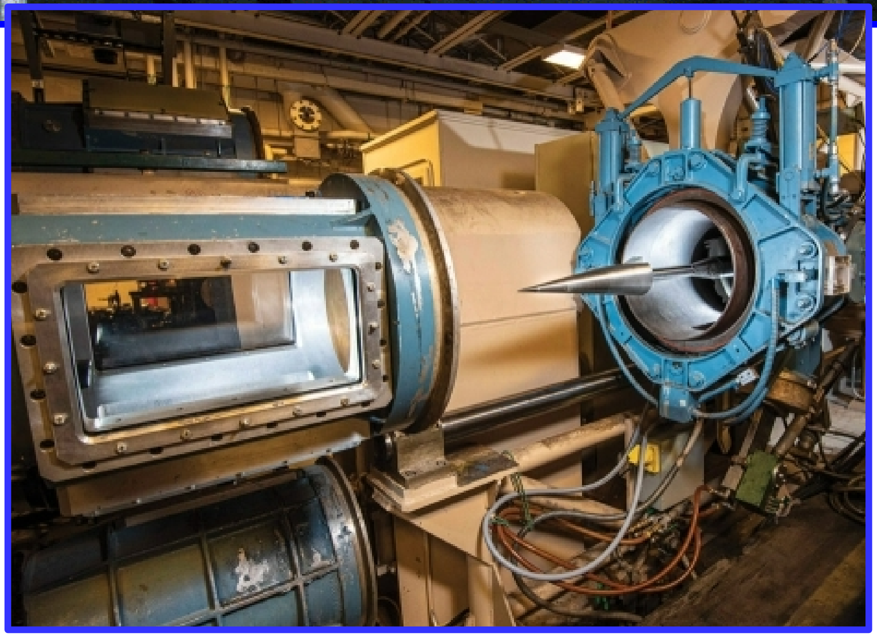






Hypersonic Wind Tunnel (HWT)





- **Blowdown to vacuum**
- **Mach 5, 8, and 14**
  - air at Mach 5
  - N_2 at Mach 8 and 14
- **Re = 0.2 - 10 x 10^6 /ft**
- **Run times: ~45 sec at 60 minute intervals**
- **18" diameter test section**
- **T_0 to 2500°R (1400 K)**

Sandia recently has invested considerable funds modernizing our tunnel infrastructure.

- **High-pressure air tanks**
- **Compressors, dryers, and filters**
- **Refurbished vacuum tanks**
- **Data acquisition electronics**
- **Refurbished flow heaters**
- **Electrical service for heaters**
- **Valves for gas handling**
- **Control console**
- **Pitching strut motor**
- **New vacuum pumps (in progress)**
- **Nozzle contour refurbishment (in progress)**

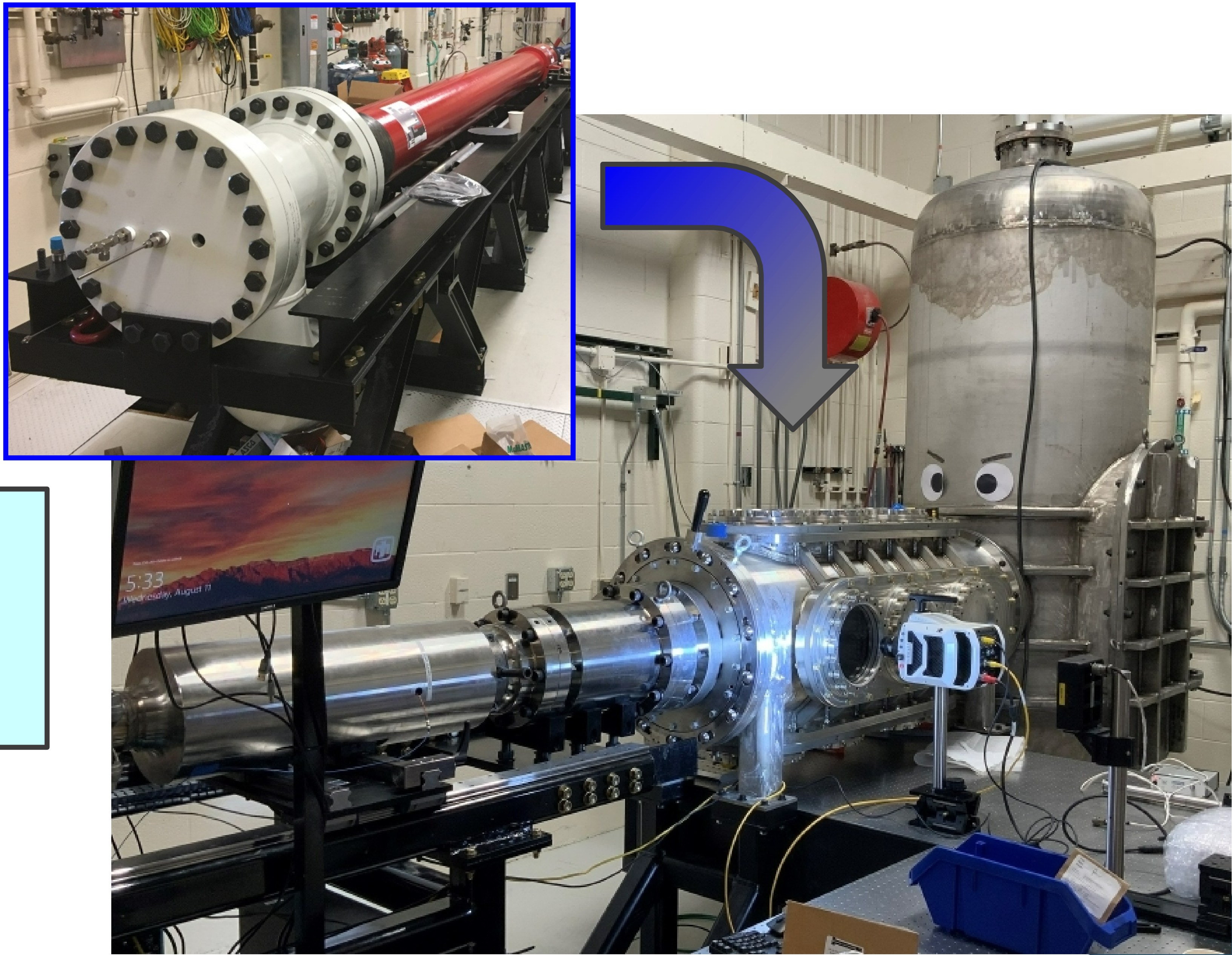
…and much more!

Goal to increase runs per day by 50%.

High-Temperature Shock Tube/Tunnel (HST)

High-Temperature Shock Tube commissioned in 2018.

- *For ignition of combustible particles and explosives research*
- Temperature to 12000°F (7000 K)
- Pressure to ≈ 3500 psi (24 MPa)
- High-enthalpy real gas effects



Now the Mach 8 Shock Tunnel

- ***For high-enthalpy gas chemistry in hypersonic flight***
- **14-inch test section diameter**
- **Enthalpy to ≈ 14 MJ/kg**

First shot on August 10th 2021!

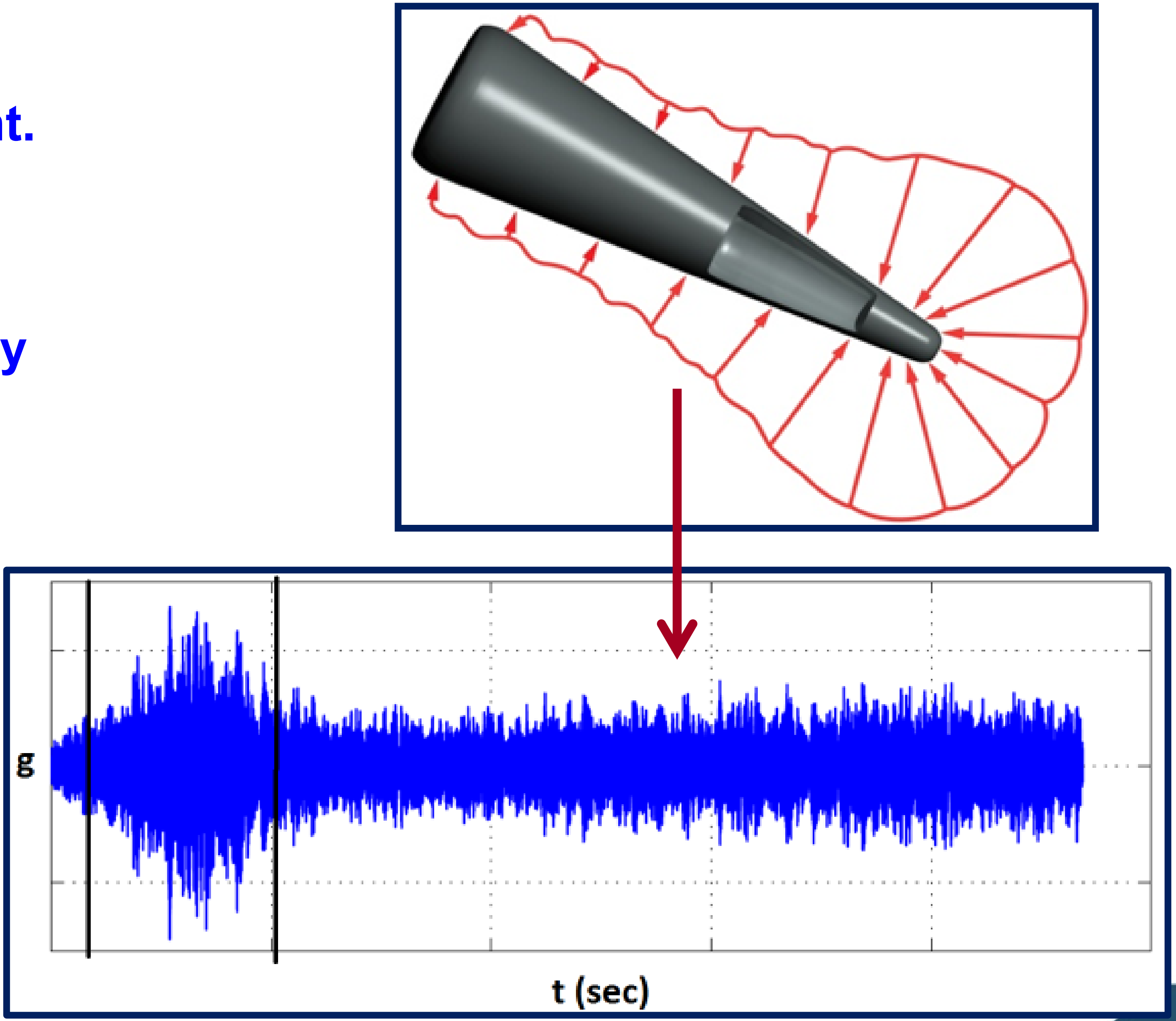
Our focus is on characterization of the hypersonic aerodynamic environment.

Vehicle vibration results from the strenuous hypersonic environment.

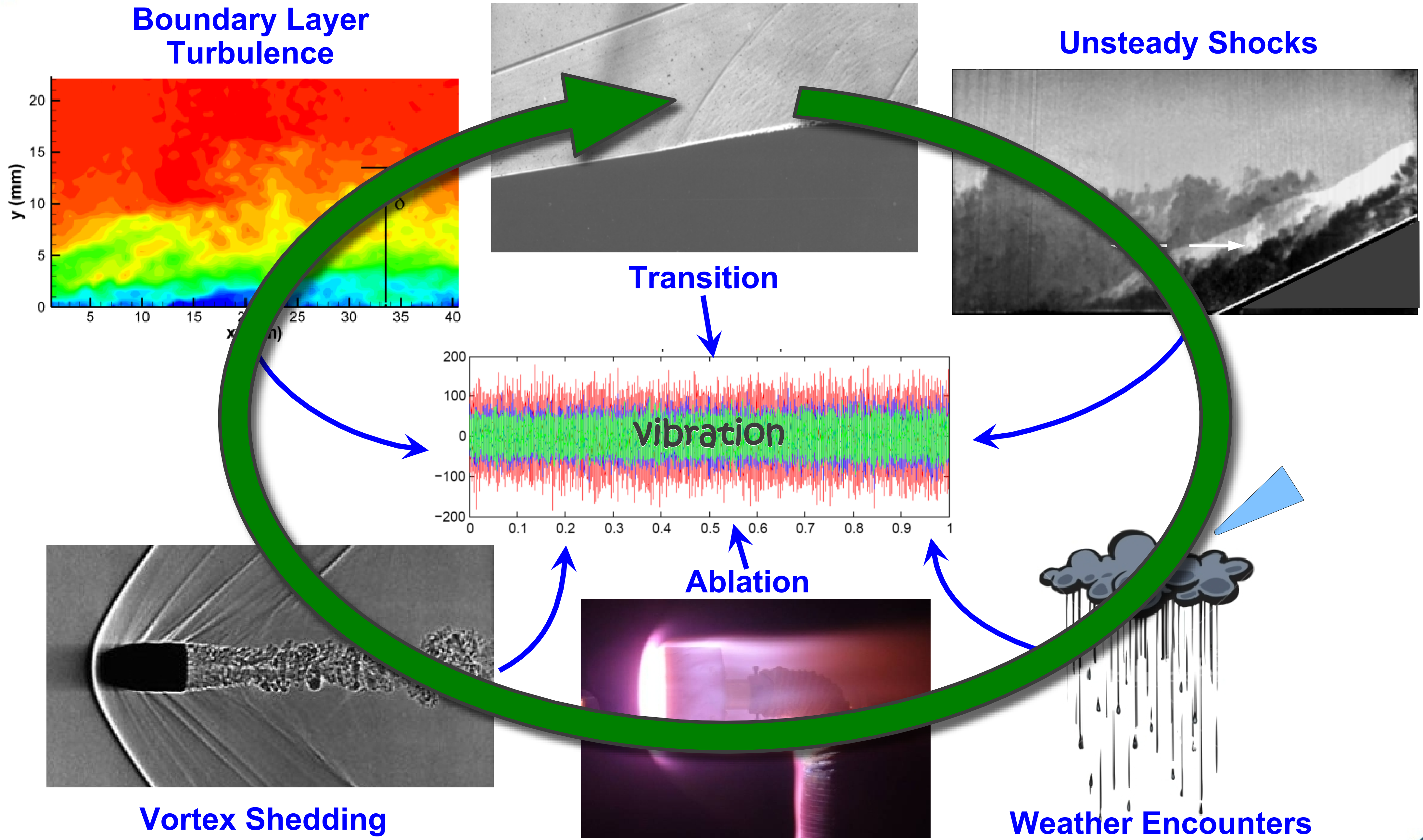
May create adverse internal component response.

We need to determine the unsteady loading environment responsible for *fluid/structure interactions*.

Wind tunnel data underly mod/sim efforts to define the environment and predict component response.

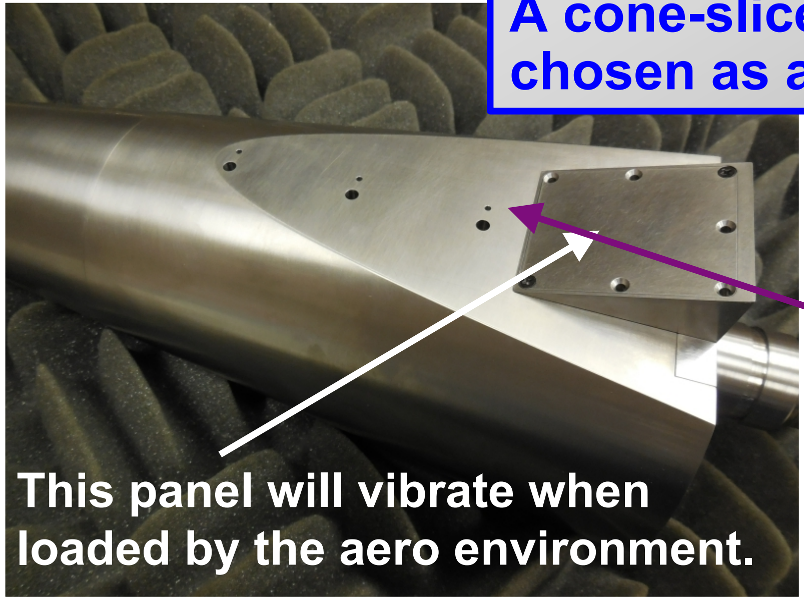


Sources of Unsteady Aero Environments



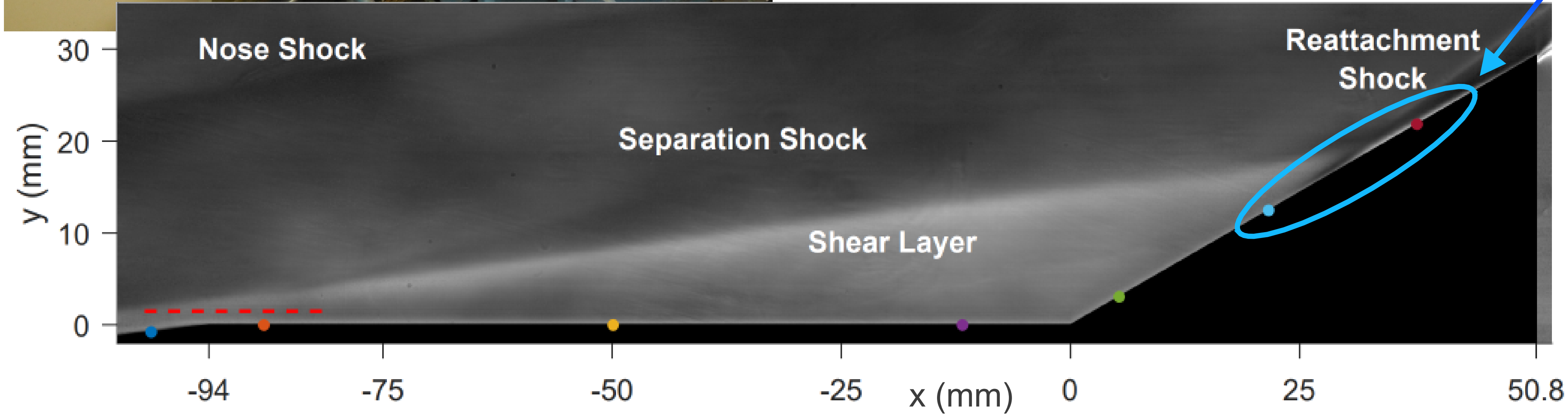
Example: Shock/Boundary Layer Interactions as a source of unsteady pressure loading.

A cone-slice-ramp geometry has been chosen as a representative design.



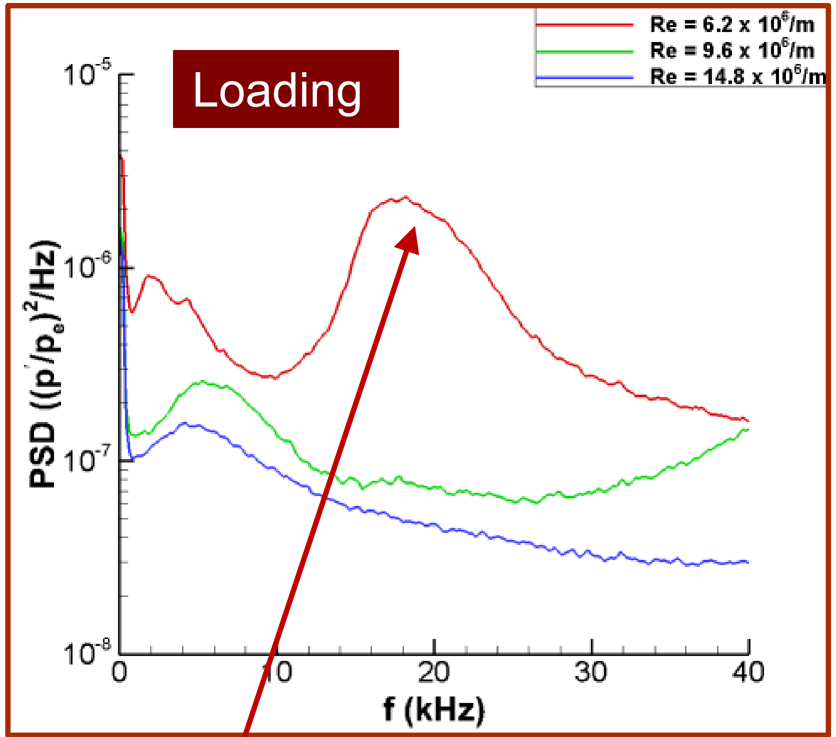
Pressure measurements from these sensors.

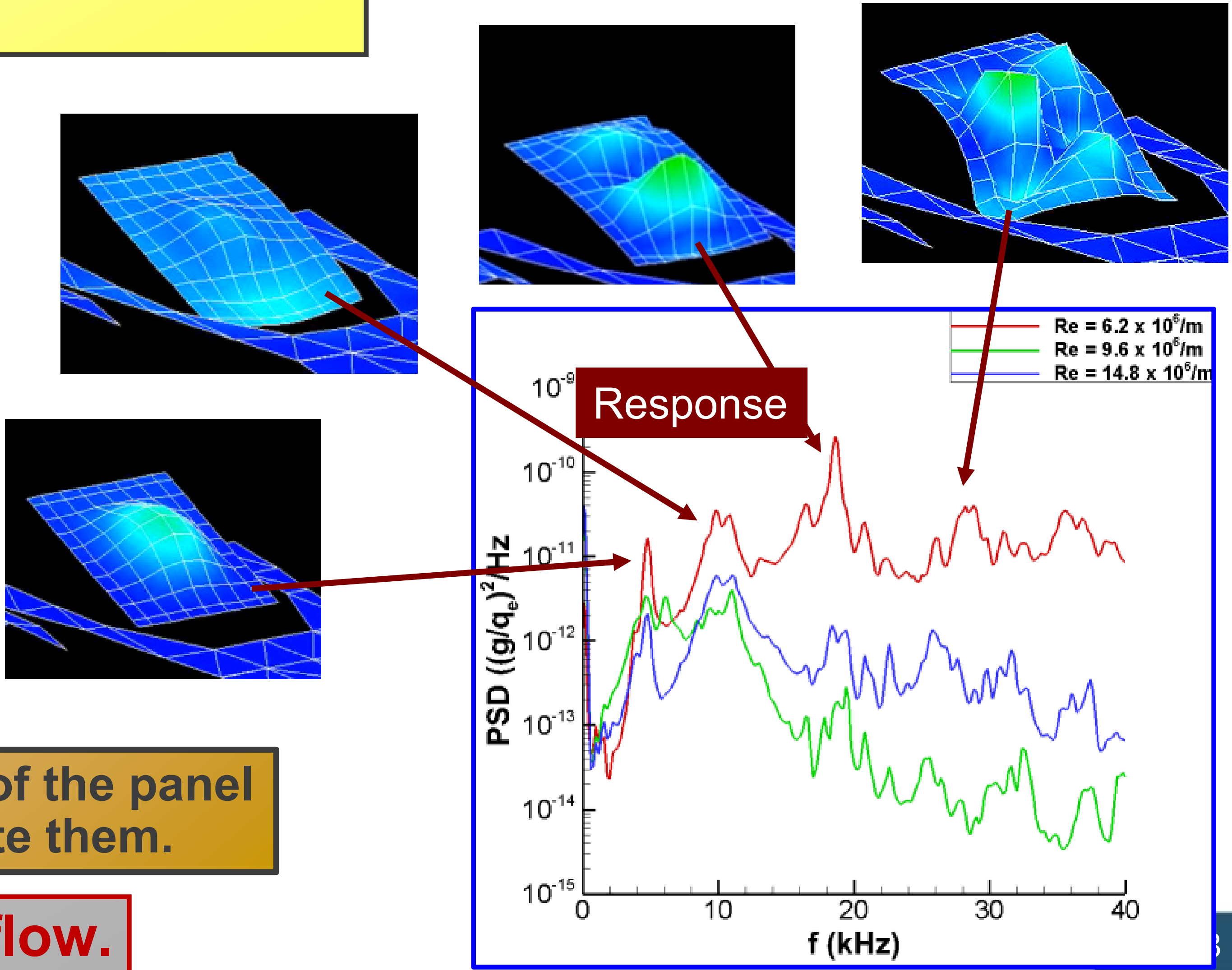
The shear layer flaps against a panel in the ramp.



Structural Response in the Panel

We measure in the wind tunnel the pressure loading and the resulting panel vibration.



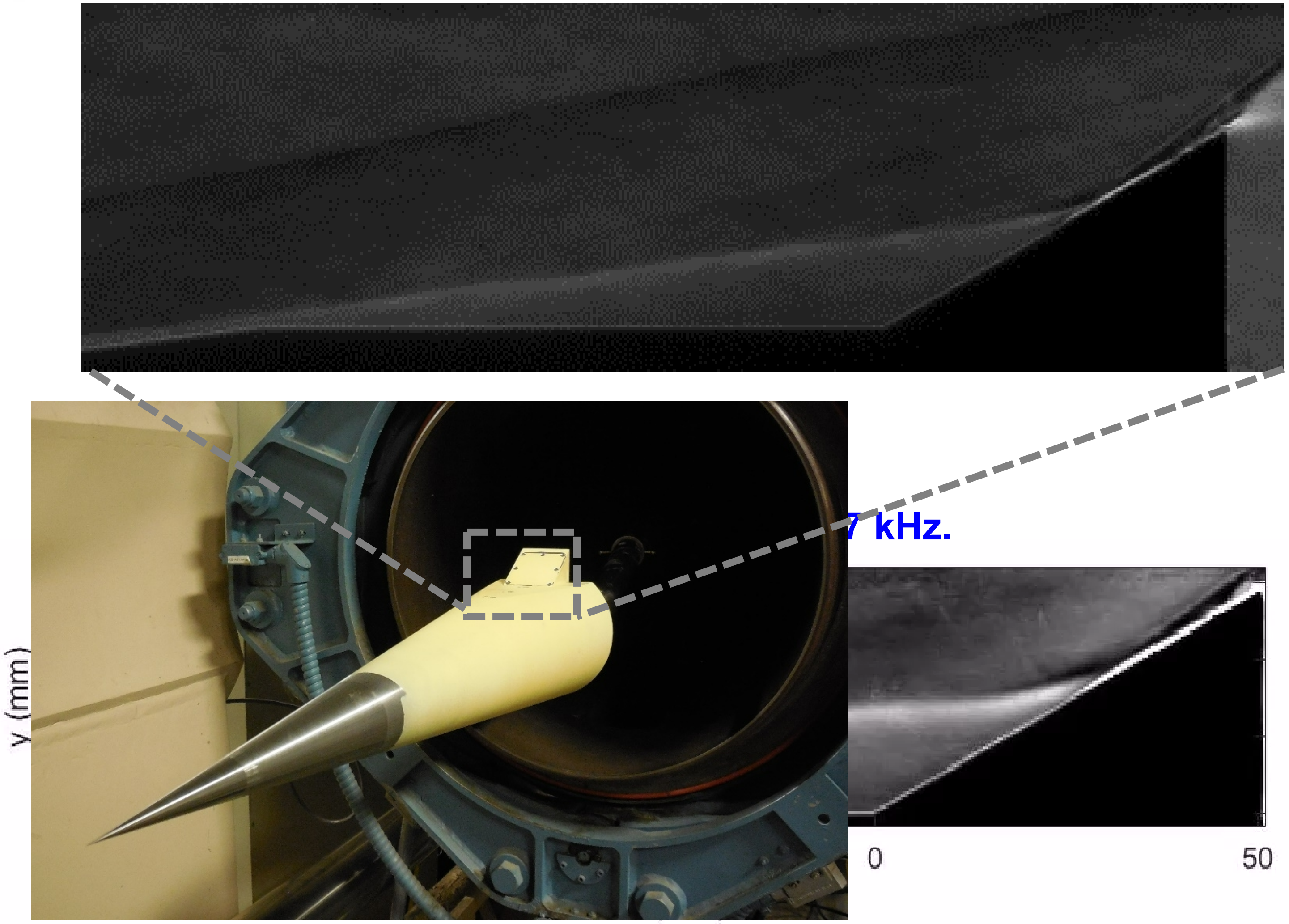


This captures the structural mode shapes of the panel response and the flow conditions that excite them.

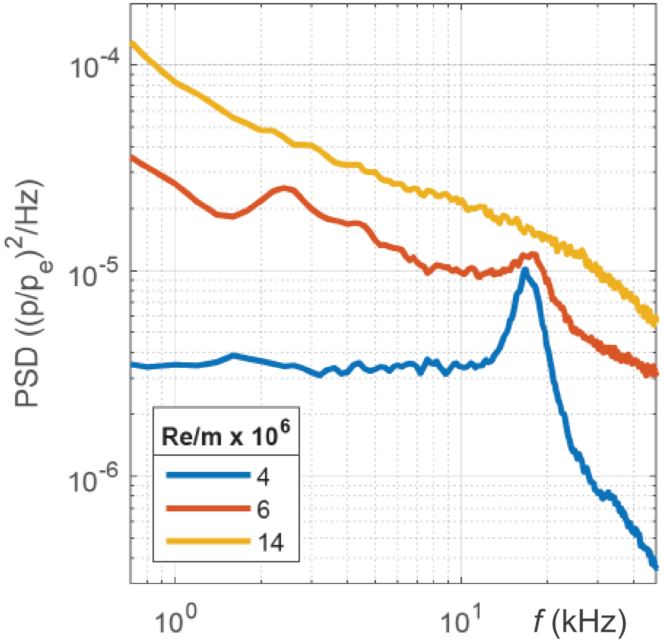
Shear layer flapping under laminar flow.

But the shock/boundary layer interaction adds to the response.

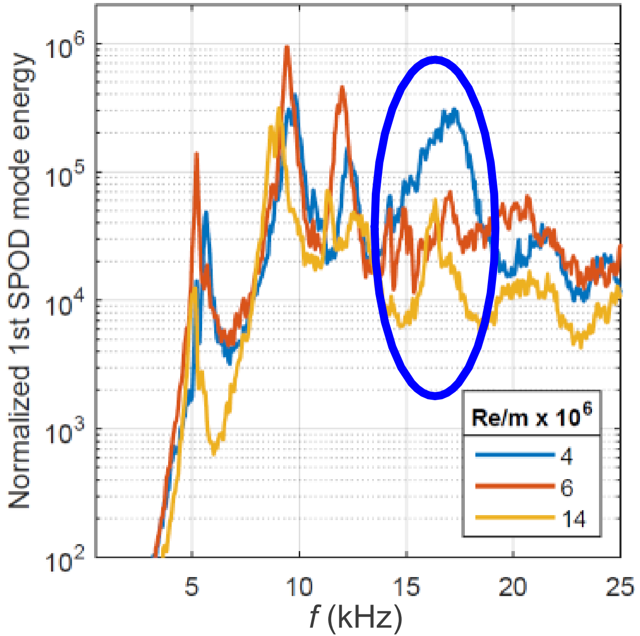
Schlieren movie of shock-induced separation flapping and impinging on the panel at laminar Reynolds Number.



Pressure sensors show a flapping mode at 17 kHz.



This 17 kHz mode emerges in the panel response at matching Reynolds Numbers.



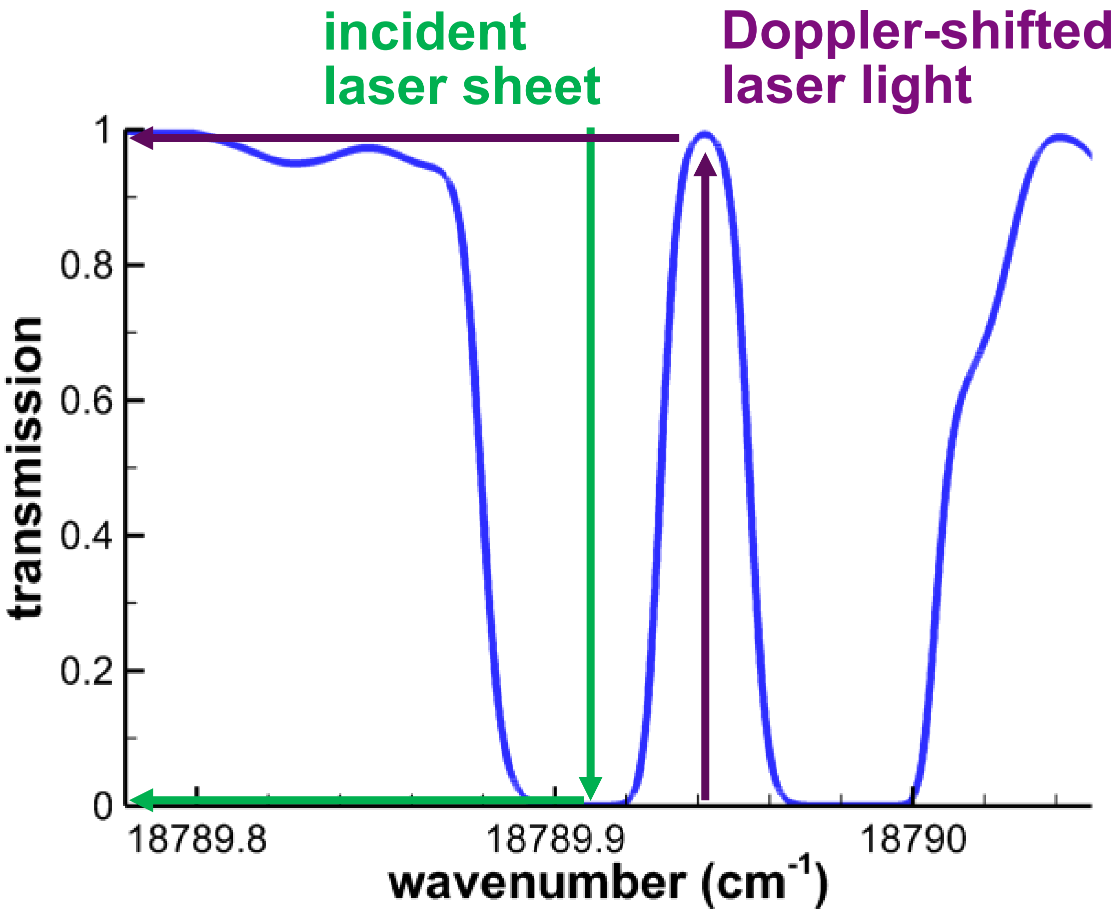
Filtered Rayleigh Scattering (FRS) for Flow Visualization

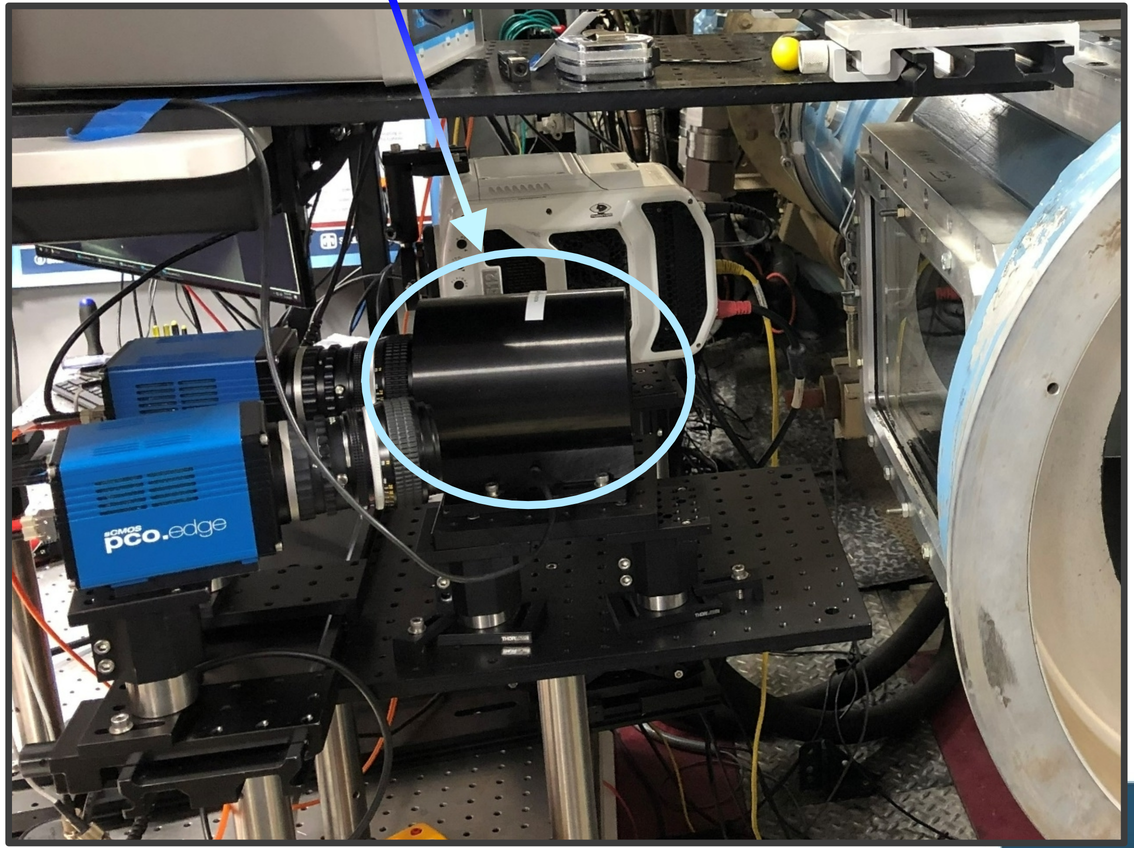
- **A planar laser imaging technique whereas schlieren integrates volumetrically.**
- **Yields much better definition of the fluid dynamic structures.**

Narrow linewidth laser is Doppler shifted when it scatters from particles in motion.

No Doppler shift when laser scatters from stationary background.

Filter images through an iodine vapor cell to suppress background interference and improve the signal-to-noise ratio.



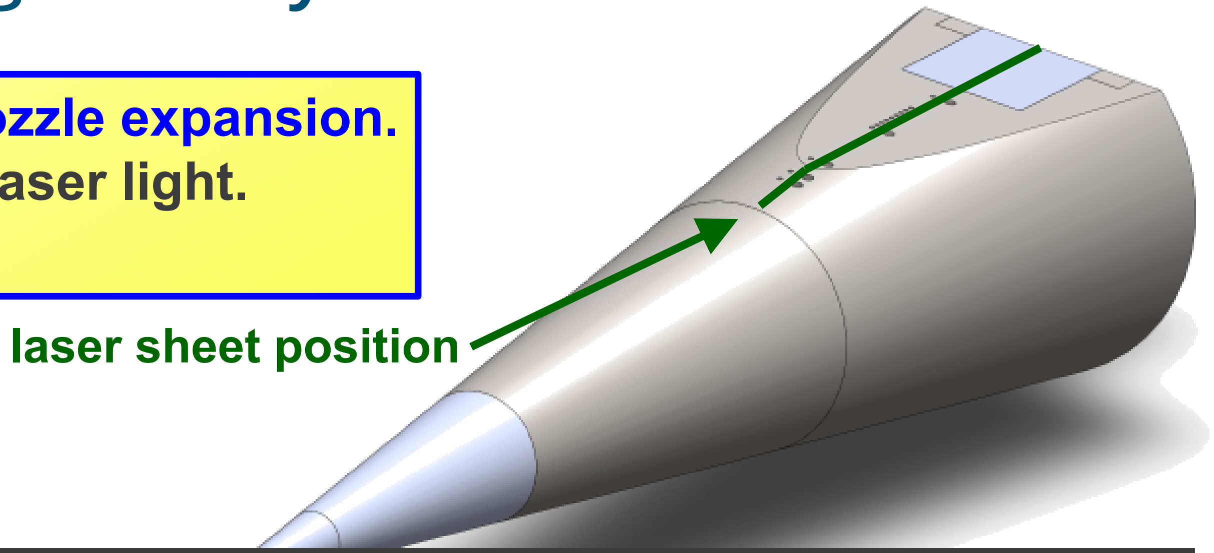


FRS on the cone-slice-~~ramp~~ geometry

CO_2 added to the gas flow will condense during nozzle expansion.

- Forms fog of tiny particles (<50 nm) that scatter laser light.
- Fog evaporates in warm boundary layer.

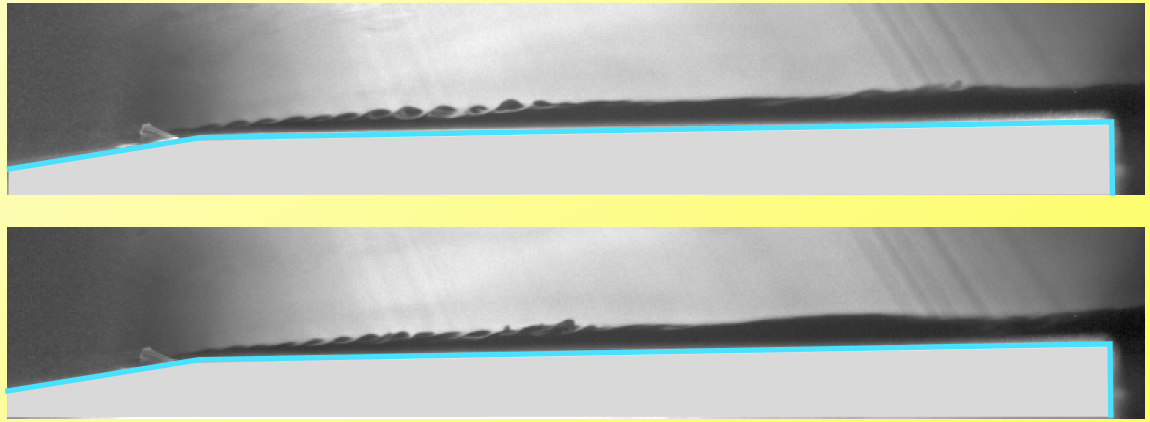
FRS is used here to detect the boundary layer interface after it passes an expansion corner.



Some cases show evidence of relaminarization.

This observation is supported by previous unsteady wall pressure measurements.

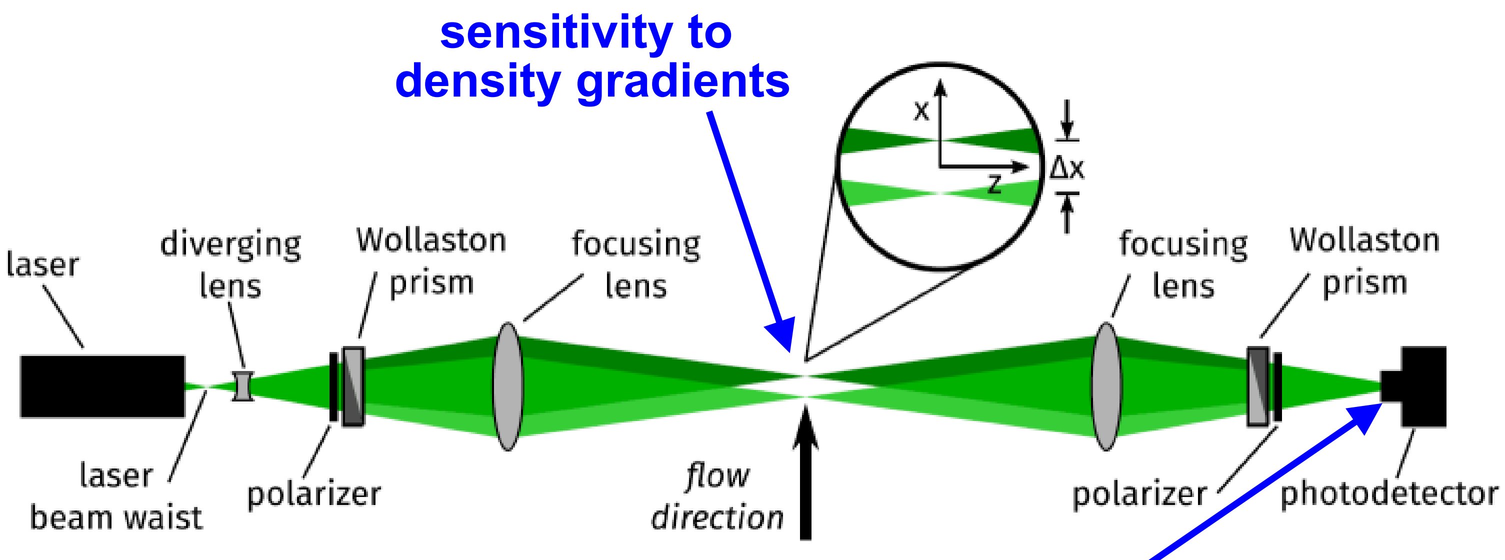
This will alter the boundary layer characteristics that drive separation at the ramp.



Focused Laser Differential Interferometry (FLDI)

FLDI can measure flow frequency content at MHz rates.

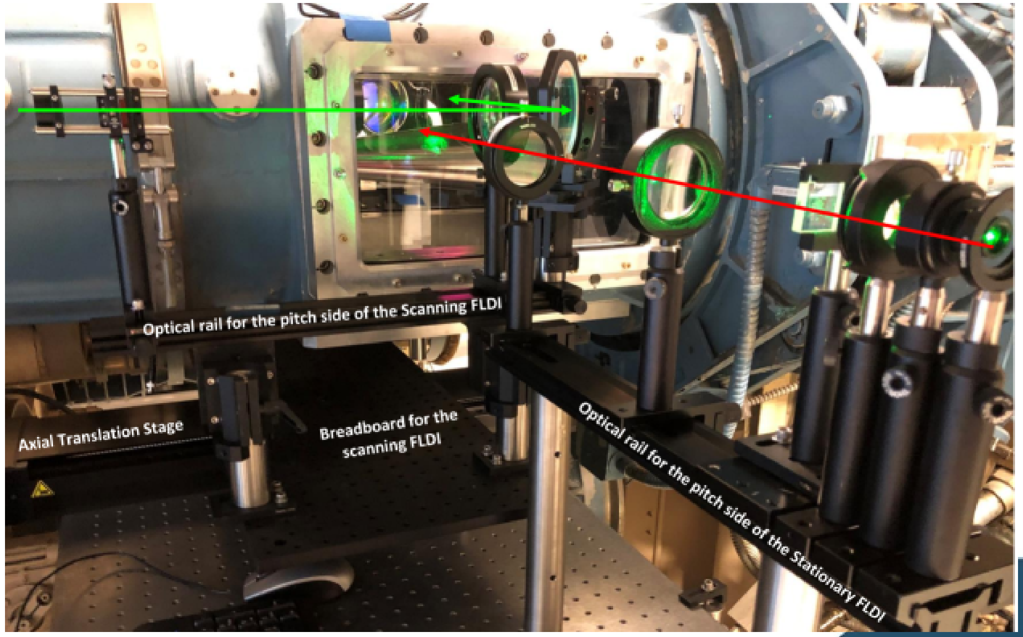
This reveals flow instabilities and coherent motion relevant to unsteady loading and structural response.



Lawson *et al* (2020)

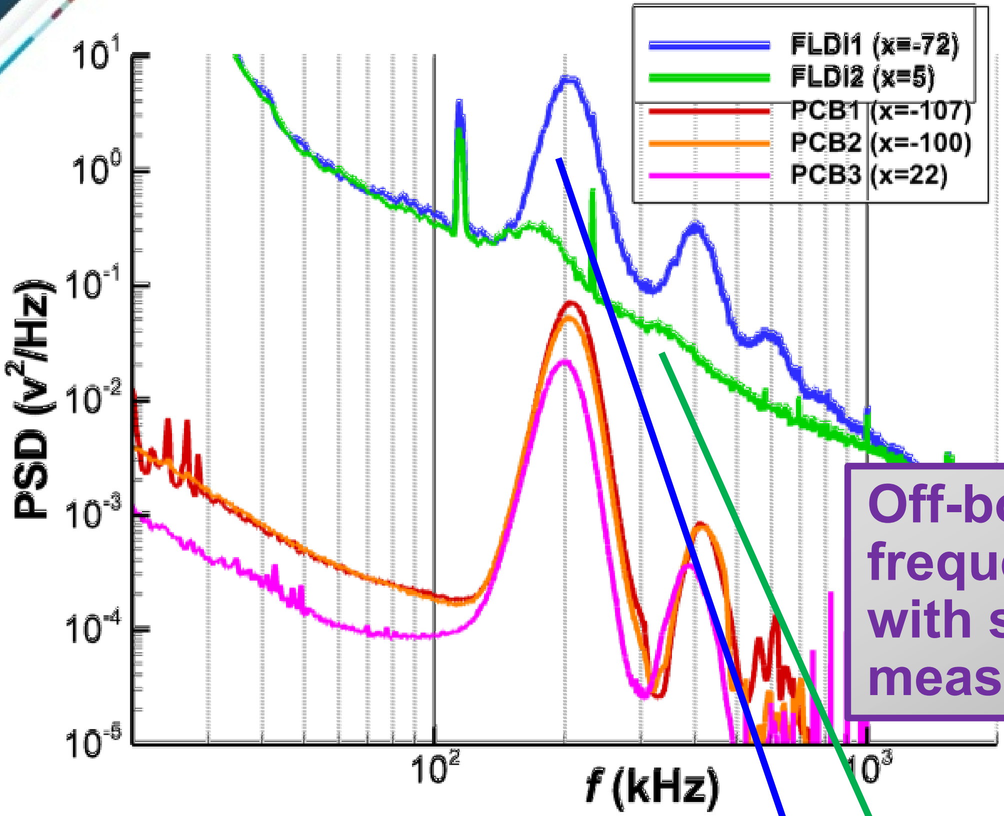
heterodyne for interference signal

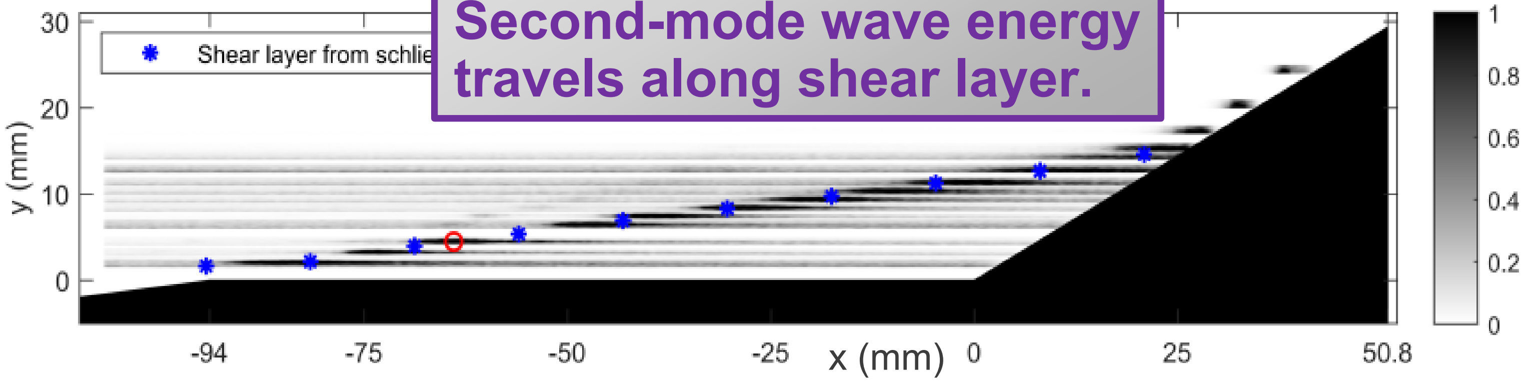
FLDI installed into HWT



FLDI in the shock/boundary layer interaction

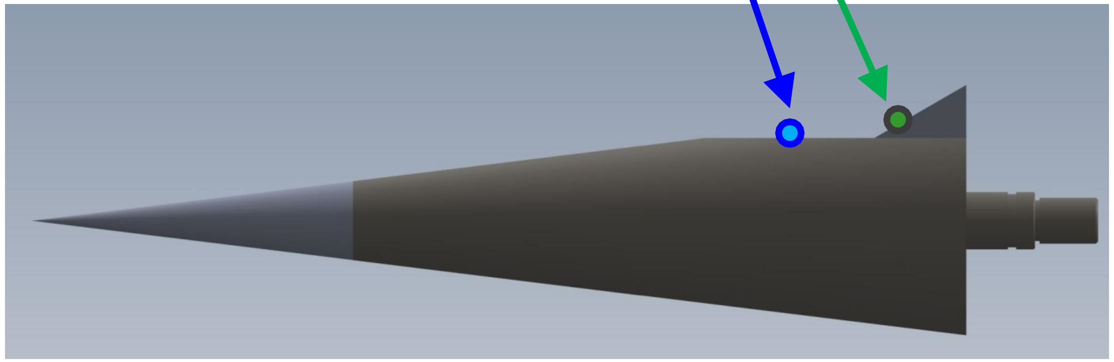
Scan the FLDI probe through the separation shear layer.

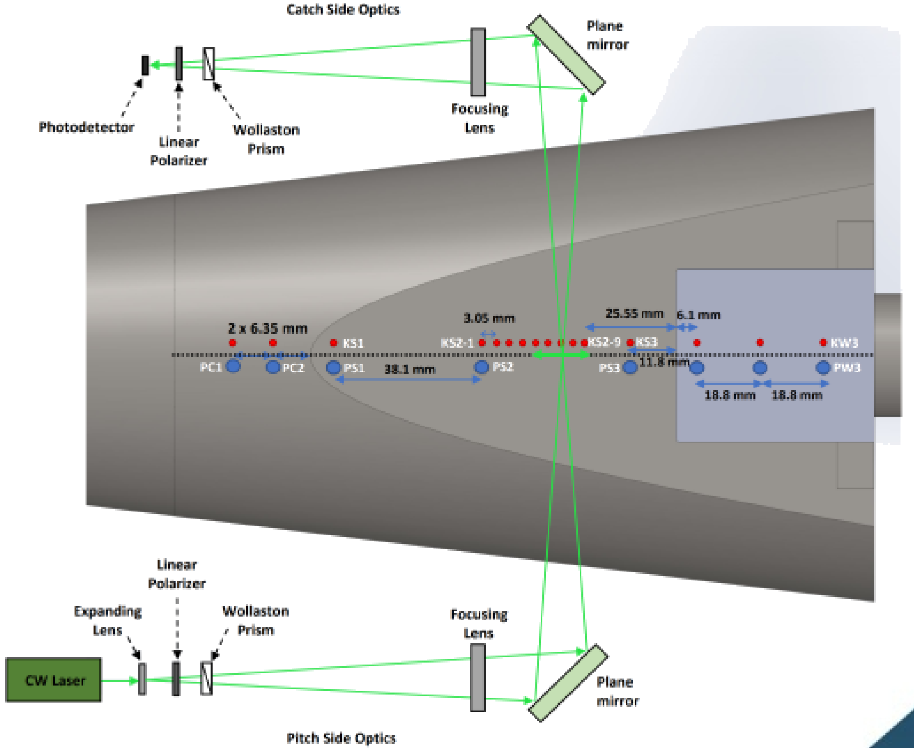




Second-mode wave energy travels along shear layer.

Off-body instability frequencies match well with surface pressure measurements.

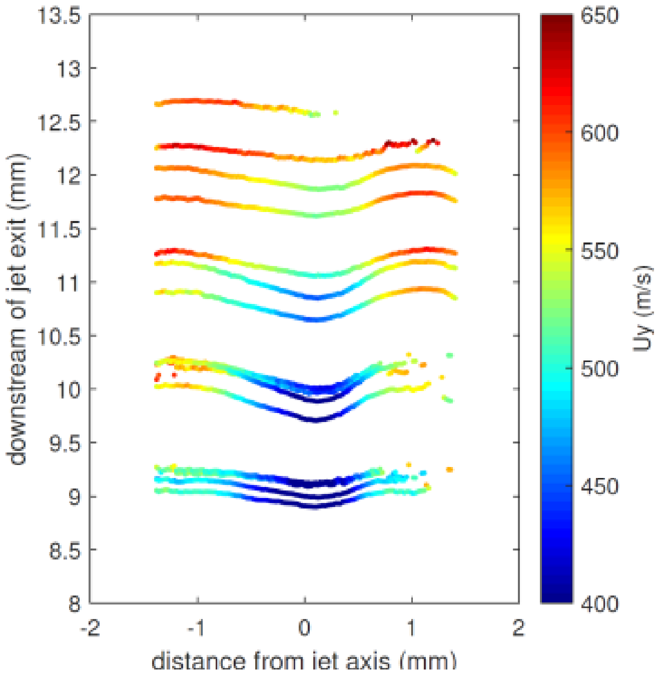




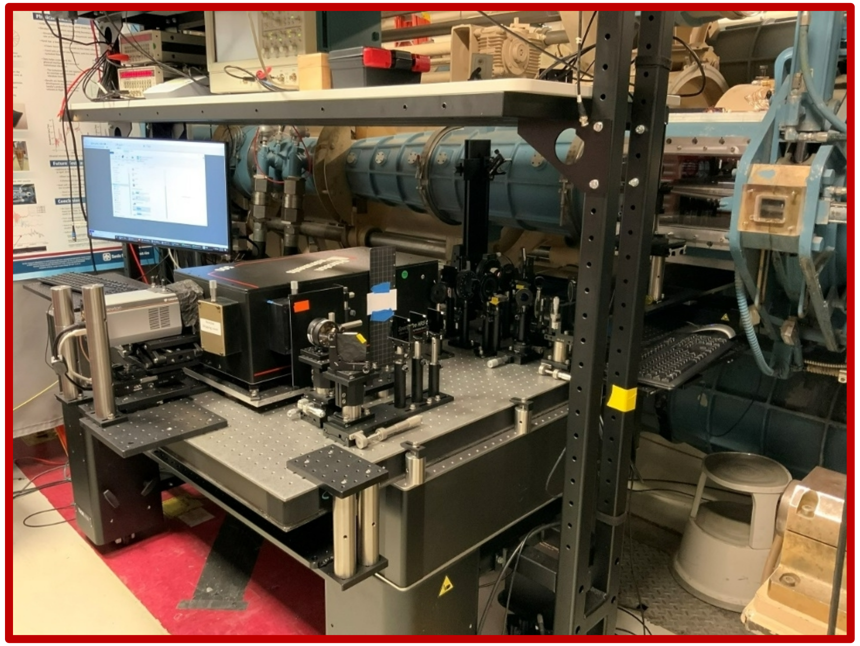
Other diagnostics under development for HWT

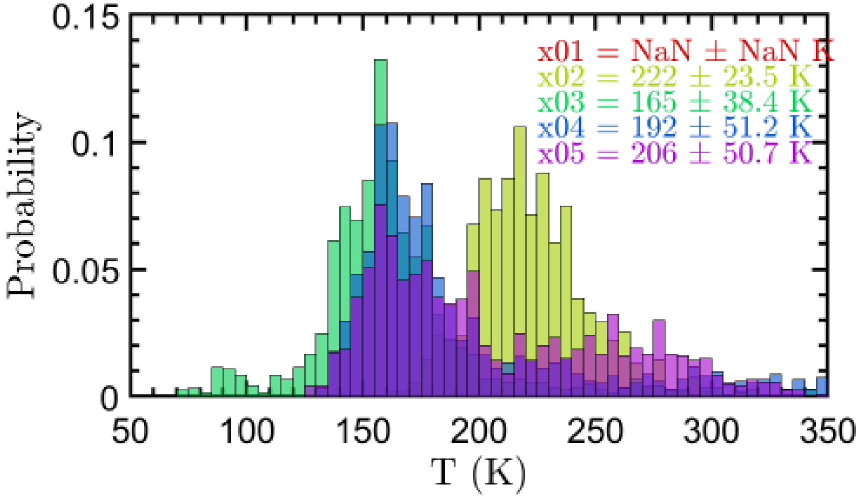
FLEET for velocimetry

Soon to move into HWT



CARS for fluctuating temperatures in the wake of a cone

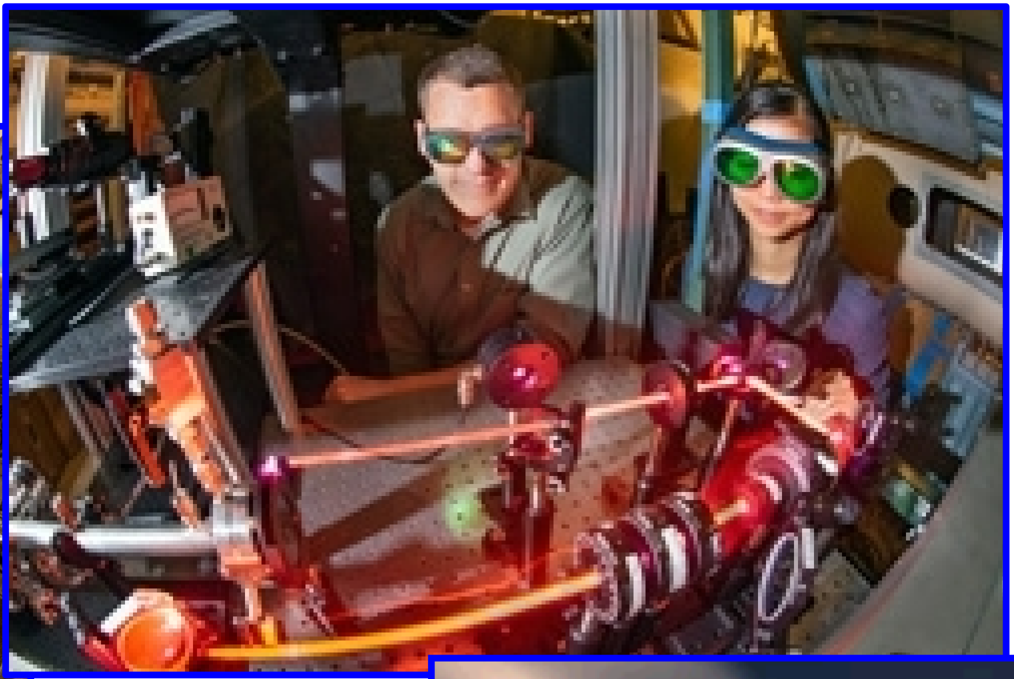




Also:

- **Doppler Global Velocimetry (DGV)**
- **IR thermography**
- **Digital Image Correlation (DIC)**

Sandia's Experimental Aerosciences Facility



- **Fundamental physics discovered from a foundation of scientific infrastructure.**
- **High-fidelity measurements to discover the physics our codes must model.**
- **Support for the national hypersonics mission for both DOE and DoD customers**