# Measurements of Boundary-Layer Instability and Transition in the Mach-6 Quiet Tunnel
## (funded by AFOSR & various partners)

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(for further detail, see AIAA Papers 2012-0281, 2012-0282, 2012-3147, 2012-3148, Letterman, Casper & Luersen theses)

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# Talk is a Brief Summary from Several Projects

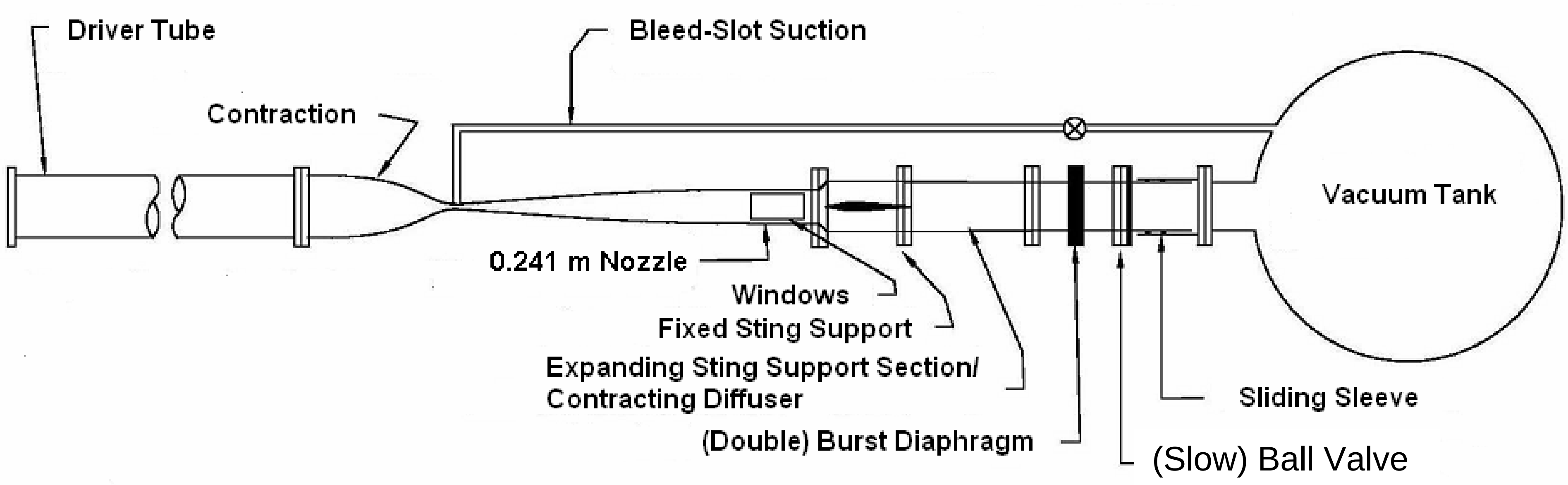
Several Projects are Jointly Funded with Other Sponsors

- Second-mode packets and turbulent spots (Casper) (NDSEG, SNL and AFOSR) (continued by Abney, SNL+AFOSR)
- Roughness-induced instabilities at Mach 6 (Wheaton)(NASA+AF)
- Developing laser perturber for Mach-6 tunnel (Chou)(AFOSR+ NASA Langley)
- Crossflow instability on cone at AoA (Ward)
- Calibrating PCB sensors for quantitative second-mode measurements (Berridge) (NASA Langley & AFOSR)
- Nonlinear breakdown of $2^{nd}$-mode waves under quiet flow using small discrete roughness on a flared cone (Luersen)
- First-mode waves to be measured with pressure sensors on a specially designed cone-cylinder-flare (Maj. Greenwood)(USAF)
- DLR meas. with UAC surfaces on 3-deg. cone (Willems-Ward)
- Summary/Conclusions

# Overall Strategy: Cooperatively Develop Mechanism-Based Prediction and Control Methods

- No single tunnel can simulate all aspects of hypersonic flight
- Quiet tunnels are critical to evaluating noise effects, but existing hypersonic quiet tunnels are limited to cold flow at moderate Reynolds numbers and Mach 6
- No simulation can fully account for all aspects of transition in flight, all must make assumptions
- Conventional tunnels will continue to be used for development and test of hypersonic vehicles
- Semi-empirical mechanism-based simulations must be cp. to existing flights and then used in support of new flights
- Cooperatively develop best combination of ground experiments, simulations and flight tests
- Try to focus on the particular mechanisms that appear most relevant to prospective vehicles of current interest.
- Iterate strategies for how the research can improve designs

# Boeing/AFOSR Mach-6 Quiet Tunnel (BAM6QT)




- Larger of two operational hypersonic quiet tunnels in the world
- Ludwieg Tube Design provides low operating costs, 3-10 sec. run
- Good optical access, last nozzle section permits various inserts
- Capable of running quiet or noisy

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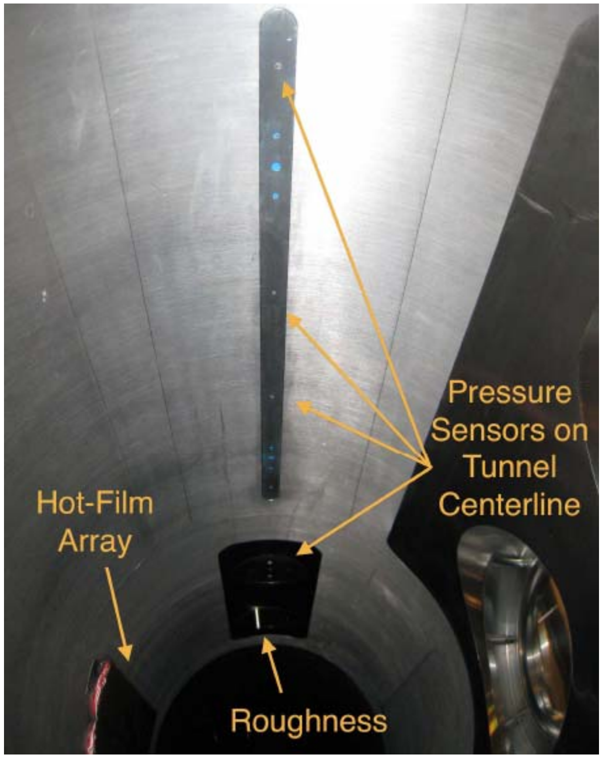
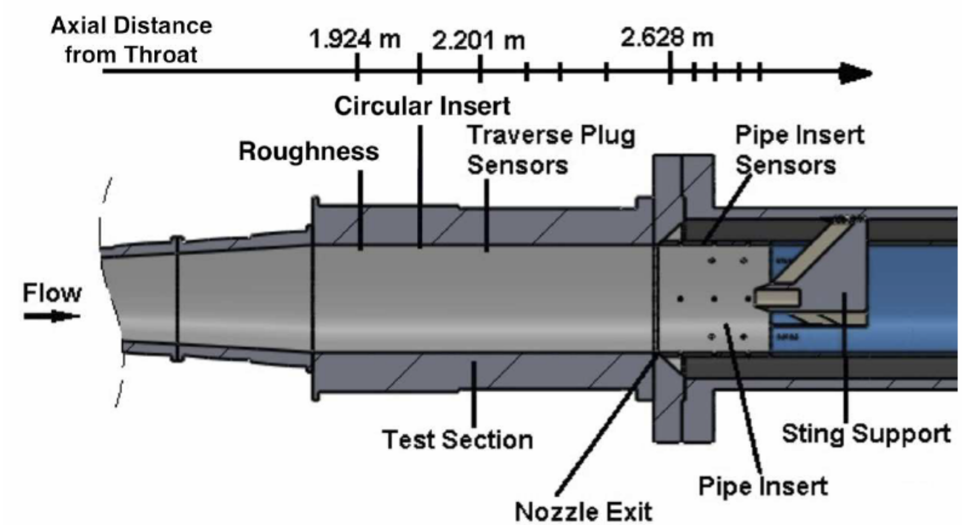
# FY12 Quiet-Flow Tunnel Performance

- Since Sept. 2010, max quiet pressure has remained higher than before, about 165-170 psia or $3.8 \times 10^6$/ft. Have not opened throat.
- Nozzle-wall boundary layer is laminar **well past the nozzle exit** at these pressures, so model sees fully quiet flow (although this still needs to be confirmed with direct model-mounted pitot measurements)
- Running 45-50 weeks per year, ~20 runs/week
- Over Long Term, Need to Develop Spare Nozzle Throat
  - Driver-tube seals will need to be replaced, risking particle introduction
  - Throat finish degrades over time, repolishing will fail eventually
  - Identified a new vendor & process. However, no funds to build test pieces in FY12
- Replaced first-stage 60HP compressor 7/2012 for reliability

# Surface-Pressure Measurements with Roughness

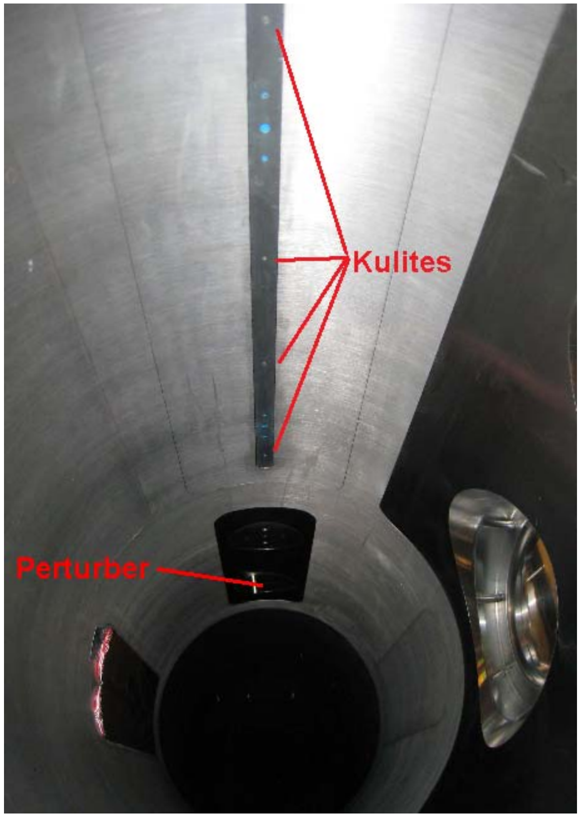



- Roughness and sensors in laminar Mach-6 boundary layer on upper wall
- Flush-mounted fast pressure sensors used to measure instabilities
- Kulite XCQ-062-15A (dynamic response flat to 90-120 kHz)
- Limited to measurements at surface and at particular locations
- Can non-intrusively acquire data simultaneously using many sensors
- Second apparatus allows use of pitot or hot-wire probes

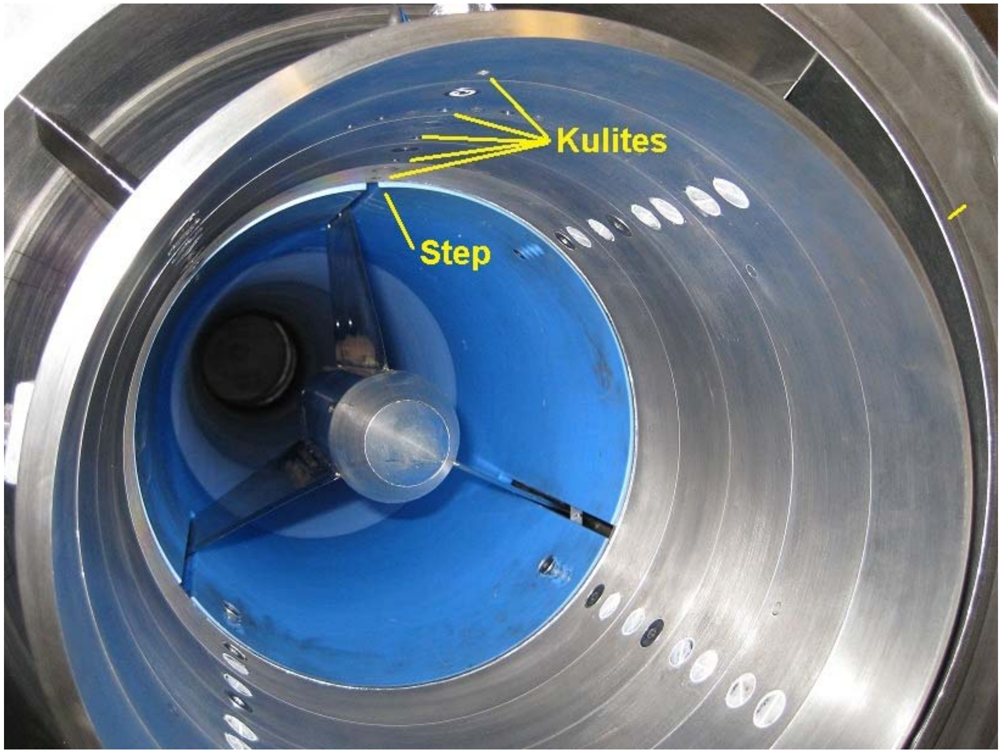


# Instrumentation: Kulite Pressure Transducers (XCQ-062-15A)

- •Resonant frequency near 300 kHz.
- •A-screen used for frequency measurements up to ~90 kHz.
- •Higher frequency measurements will have some attenuation.



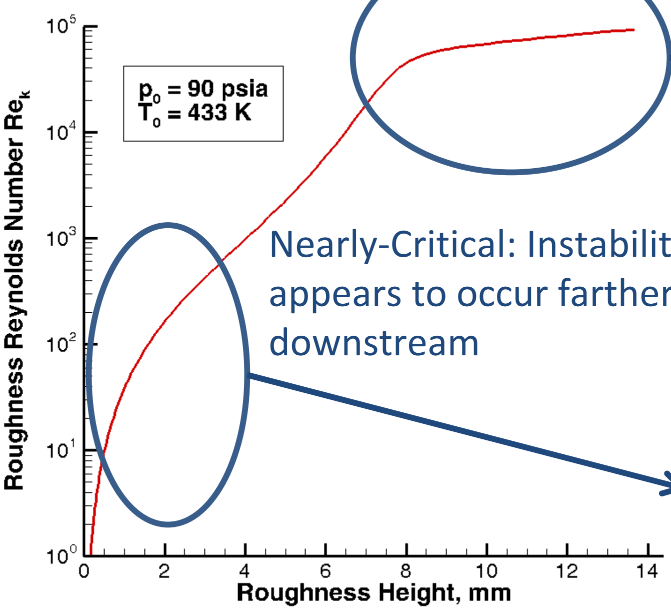

**Sensors installed in traverse plug (looking upstream).**



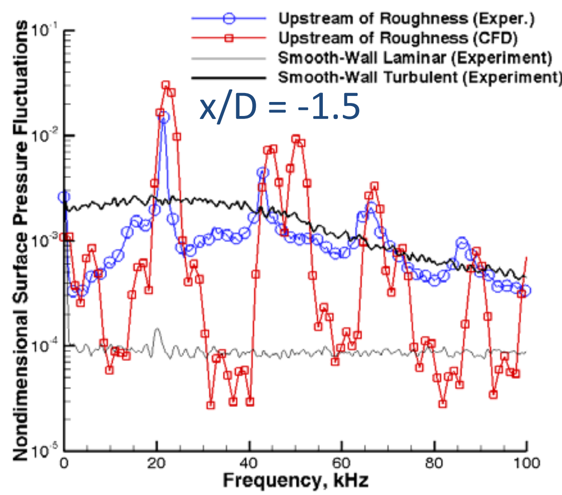

**Sensors installed in pipe insert (looking downstream).**

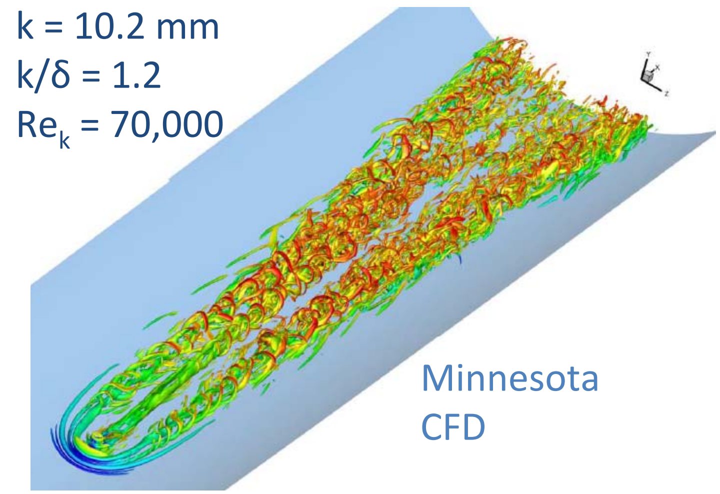
# Improved Understanding of the Change in Mechanisms for Transition due to Roughness

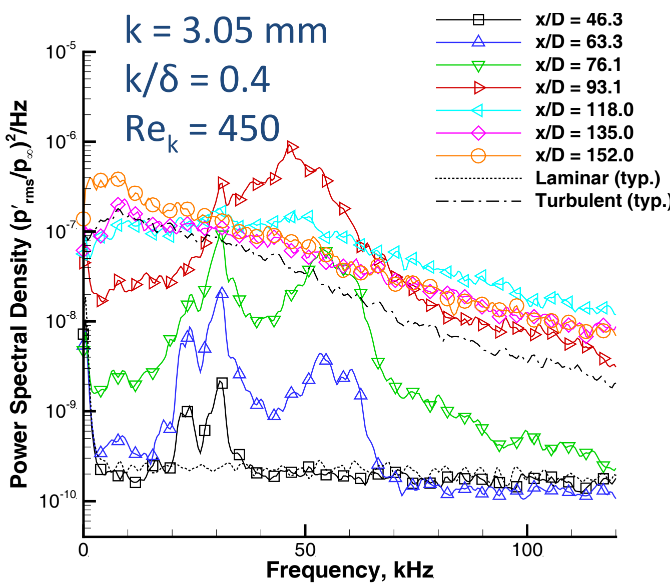
Nearly-Effective: Periodic instability originates in separation region with large amplitude, transition close to roughness

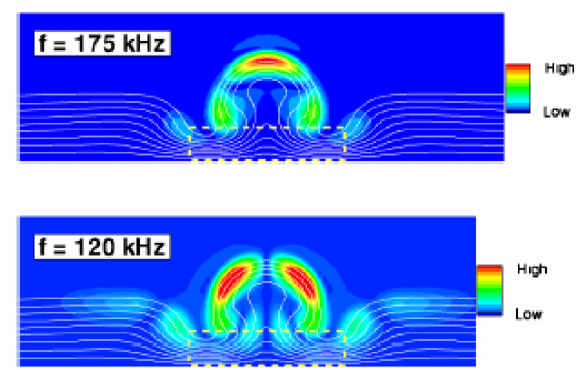



Nearly-Critical: Instability appears to occur farther downstream



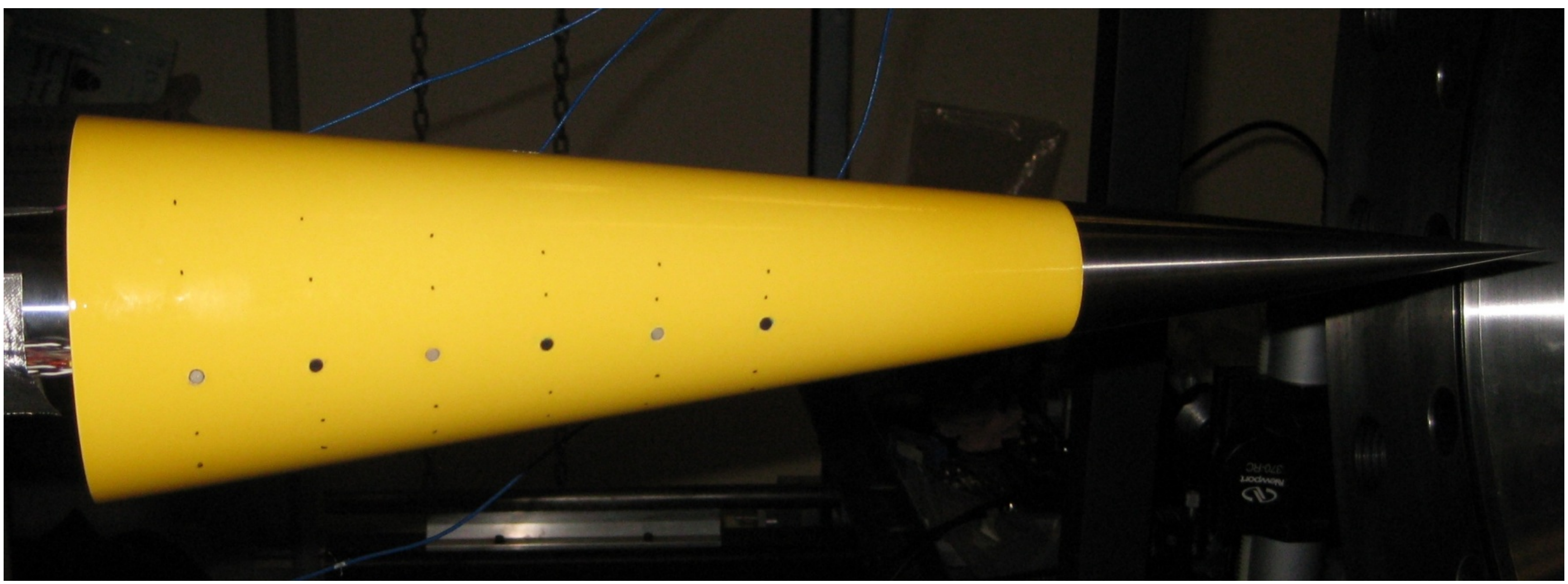

Roughness Reynolds number $Re_k$ increases by several orders of magnitude with roughness height.

Suspect mechanism for small roughness similar to predictions by Choudhari et al. (above, AIAA 2010-1575). Computations currently in progress for this case.

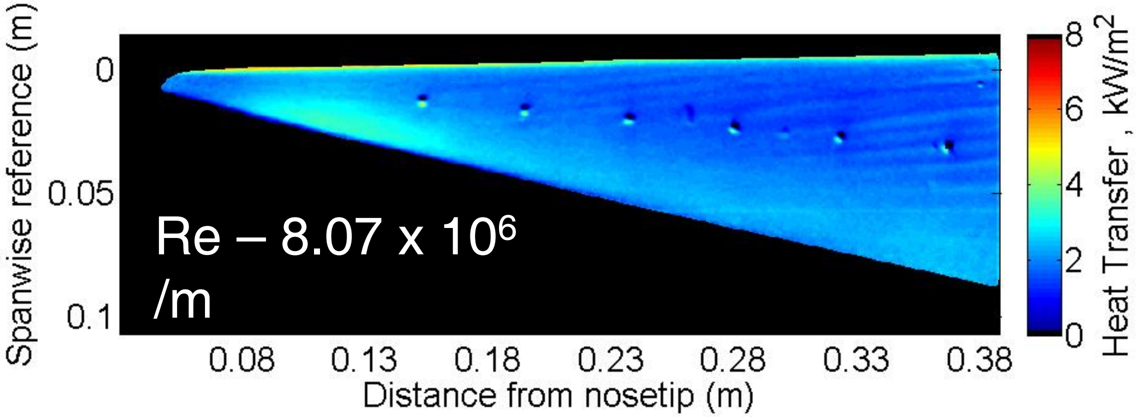
Wheaton/Schneider (Purdue University)
Bartkowicz/Subbareddy/Candler (University of Minnesota)

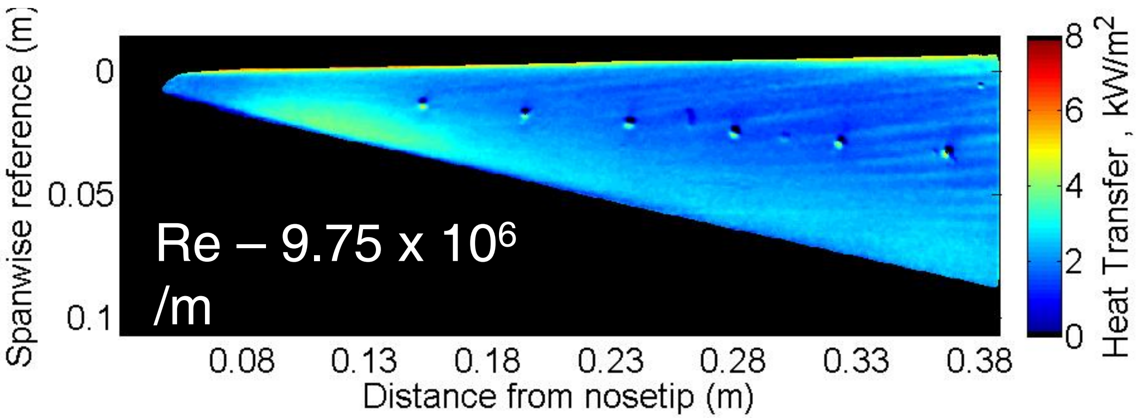
# Crossflow Instability on a Cone at AoA

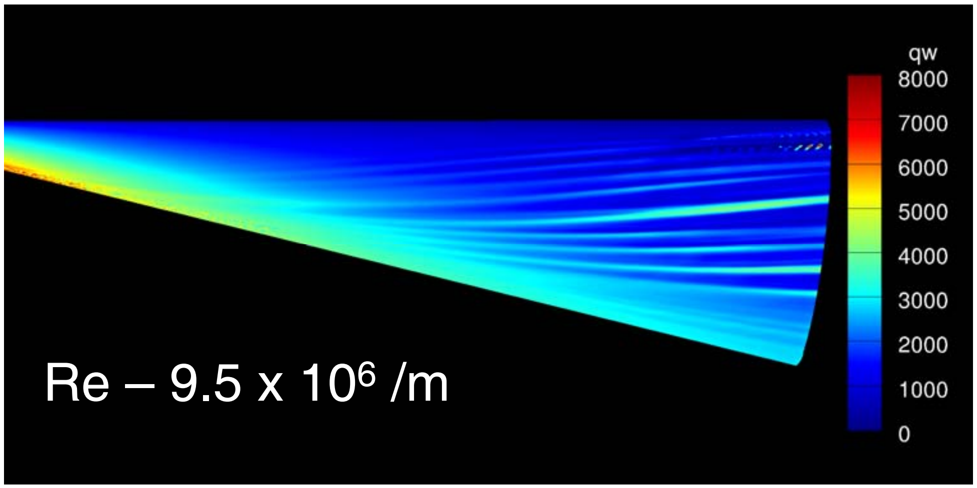
- 7° half-angle cone at 6° angle of attack with nominally-sharp nosetip
- TSP now carefully feathered at leading edge
- Model equipped with temperature-sensitive paint, 4 Schmidt-Boelter heat transfer gauges and 2 PCB pressure transducers.



# Yaw Side Results

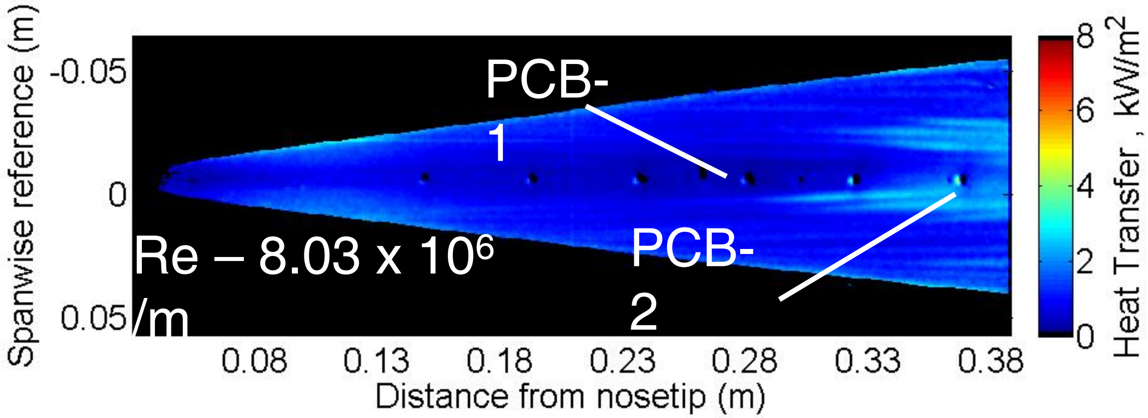


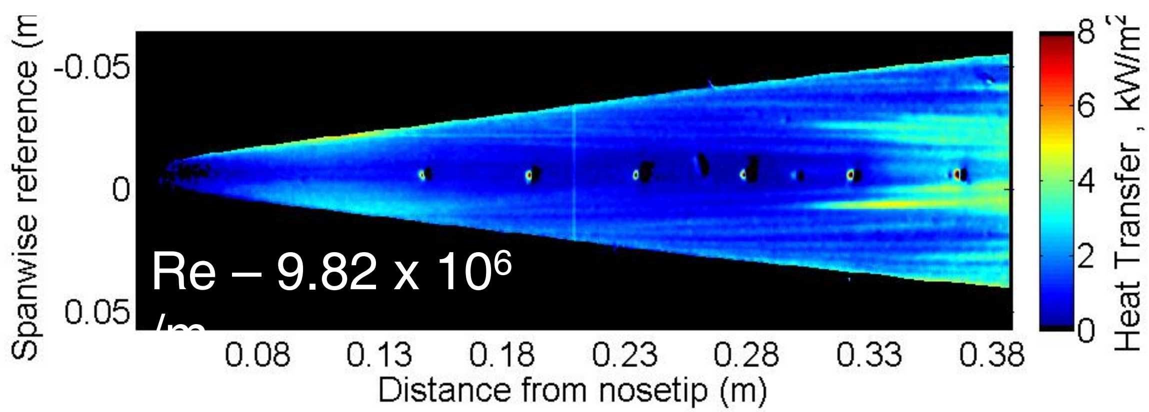



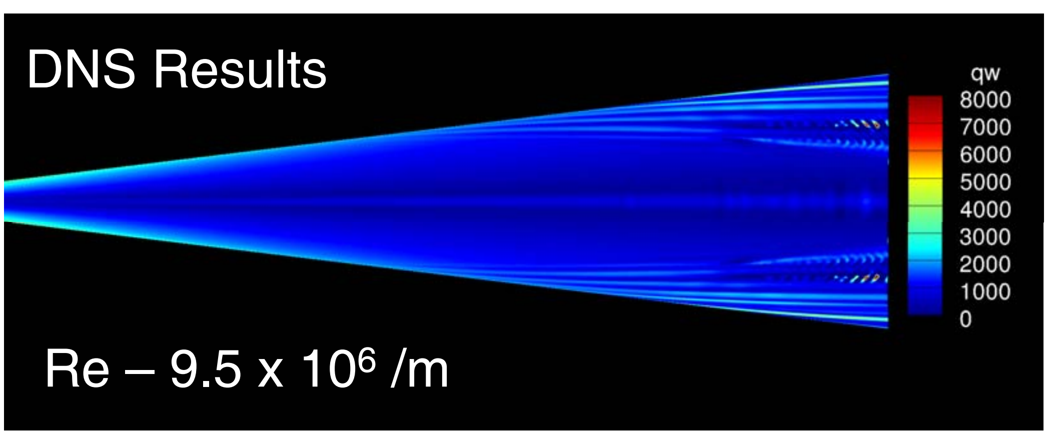




- The stationary vortices are visible on the yaw side, but do not break down to turbulence
- DNS results by Minnesota qualitatively agree with the experiments
- The PCB gauges were not able to measure any instabilities on the yaw side (e.g. the travelling crossflow waves)

# Lee Side Results

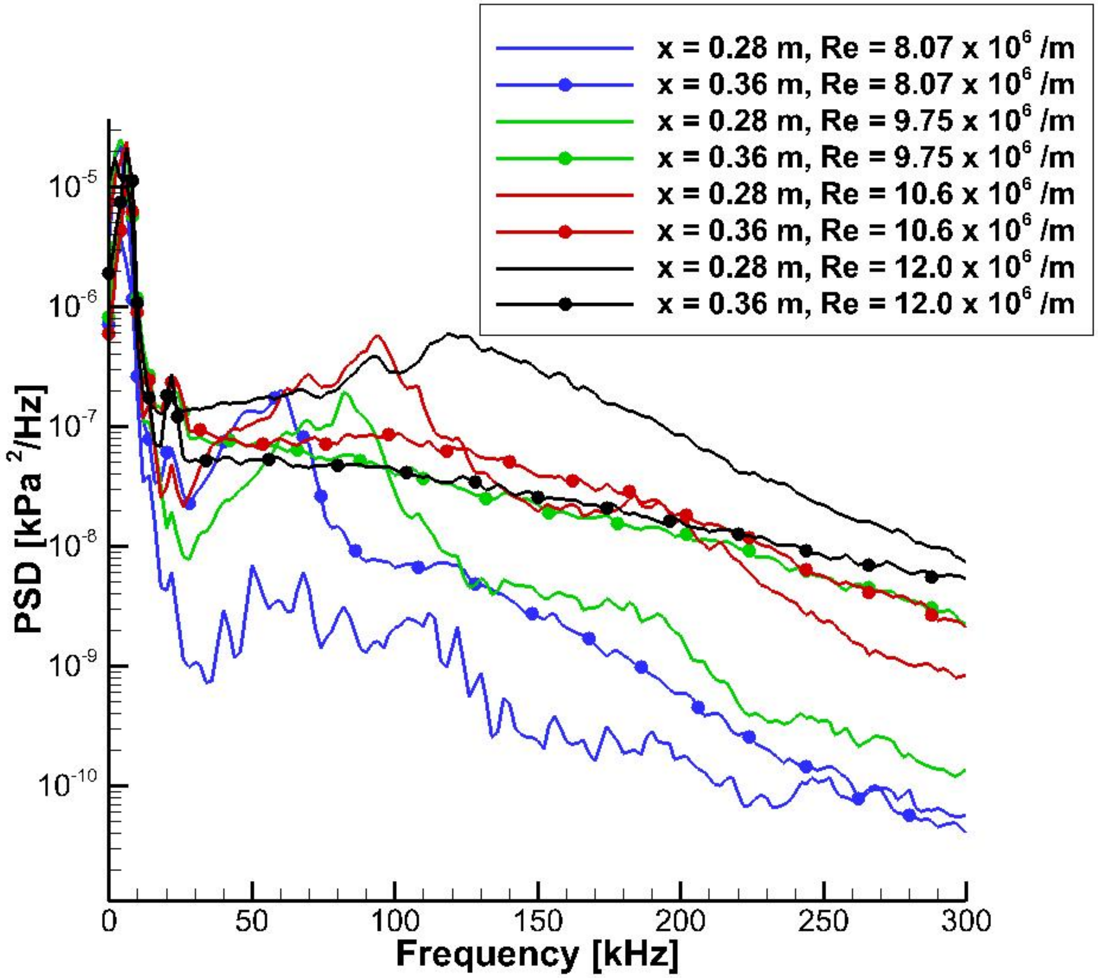


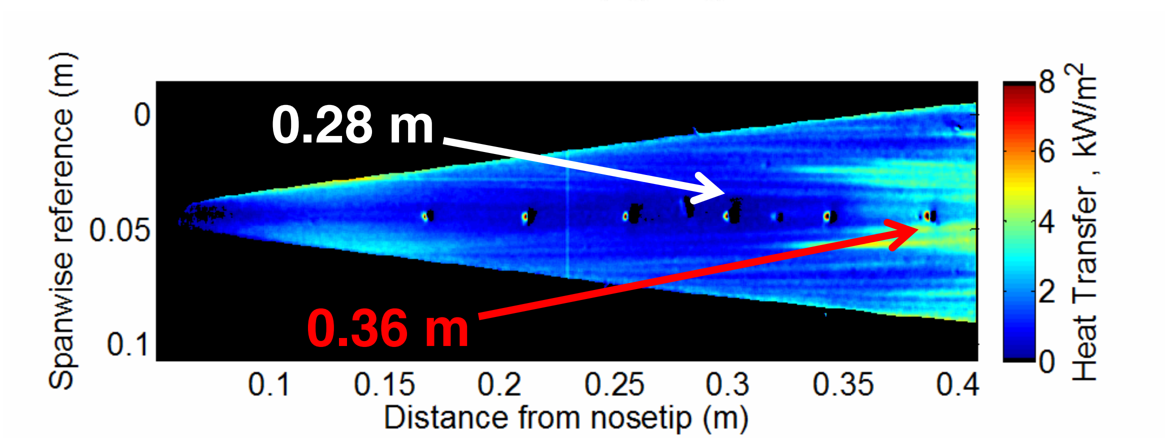




- At lowest Reynolds number, stationary vortices are visible but do not appear to break down to turbulence
- At higher Reynolds number, stationary vortices appear to break down to turbulence, but TSP not conclusive
- DNS results (Joel Gronvall, Univ. of Minnesota) at similar Reynolds number agree qualitatively with experiments
- DNS with no freestream disturbances, randomly distributed roughness patch near nose along windward ray

# Lee-Side PCB Spectra



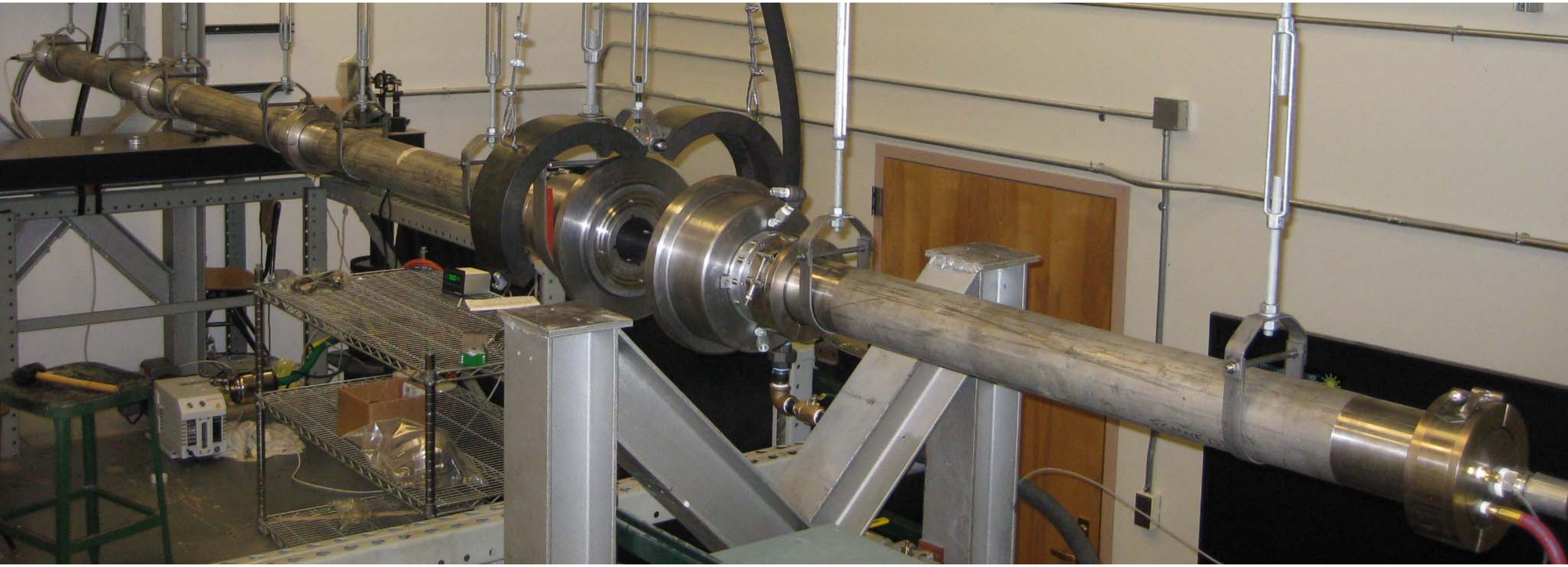




- Power spectra computed with two PCB gauges 0.28 and 0.36 m from the nosetip.
- Instability present near 0.28 m
- At the three highest unit Reynolds numbers, it appears that transition occurs near the downstream gauge. Appears that this occurs **under fully quiet flow.**

# Redevelopment of Laser Perturber System

- Hot spot from laser-induced breakdown as controlled perturbation for receptivity studies
- Study receptivity on flared cone at zero AoA in cooperation with computations by Zhong, Fasel, Tumin et al.
- System resurrected after nearly a decade
- Now running in BAM6QT with flat window
- Perturber being tested using forward-facing cavity model
- Developing improved procedures for aligning the tunnel and optics to put the hot spot directly upstream of the model
- Amanda Chou is now a NASA grad coop student. She will spend the fall of 2012 at Langley measuring hot-spot properties in the Mach-3 calibration jet, using same optics at same density (with Wilkinson, McGinley, Danehy, etc.)

# New 3-inch Shock Tube for Calibrating PCB’s



- To create cleanest possible thin weak shocks (static pressure rise on the order of 10 Pa), as planar as possible
- 3.5” I.D., honed stainless pipe, 4-ft sections for easy machining of many varieties of sensor ports, about 17 feet long
- Vacuum in driven section demonstrated to 1.4 millitorr
- 2 psid diaphragm-break pressures using aluminum foil
- Half-scale version of successful GALCIT 6” shock tube from 1950’s.

# Summary

- Quiet flow performance was steady in FY12. Did not open the throat. Stray particulate remains a critical issue.
- Measurements of instability that originates well behind isolated roughness in laminar hypersonic boundary layer. To be compared to Langley simulations. This work ends Dec. ’12.
- Continued measurements of crossflow instability on cone at AoA. With feathered paint, surprising breakdown to turbulence near lee ray, apparently under fully quiet flow.
- Laser perturber now working in Mach-6 tunnel with flat windows. Getting results with forward-facing cavity. Flared cone is next.
- Built a small shock tube to calibrate PCB’s.
- Trying to control nonlinear breakdown of $2^{nd}$ mode waves on flared cone, under fully quiet flow. Necessary roughness is 0.0005 in. $< k <$ 0.020 in. Still need to find a good way to build the roughness.

# Outstanding Research Issues and Challenges

- How well can we maintain quiet flow and low operating costs?
- Can we manipulate the crossflow waves using some kind of controlled roughness?
- Can we manipulate the nonlinear breakdown streaks on the flared cone using some kind of controlled roughness?
- Can we get good calibrated PCB measurements of waves?
- Can we measure first-mode waves? traveling crossflow?
- Will the laser perturber generate a useful and measurable effect on the flared-cone flow?
- Can we develop a better perturber to make turbulent spots farther upstream, so we can watch them grow and merge, using the available space and sensors?
- etc.