Possible Secondary Instability of Stationary Crossflow Vortices on an Inclined Cone at Mach 6

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Plus some of Joshua Edelman's data, not yet published

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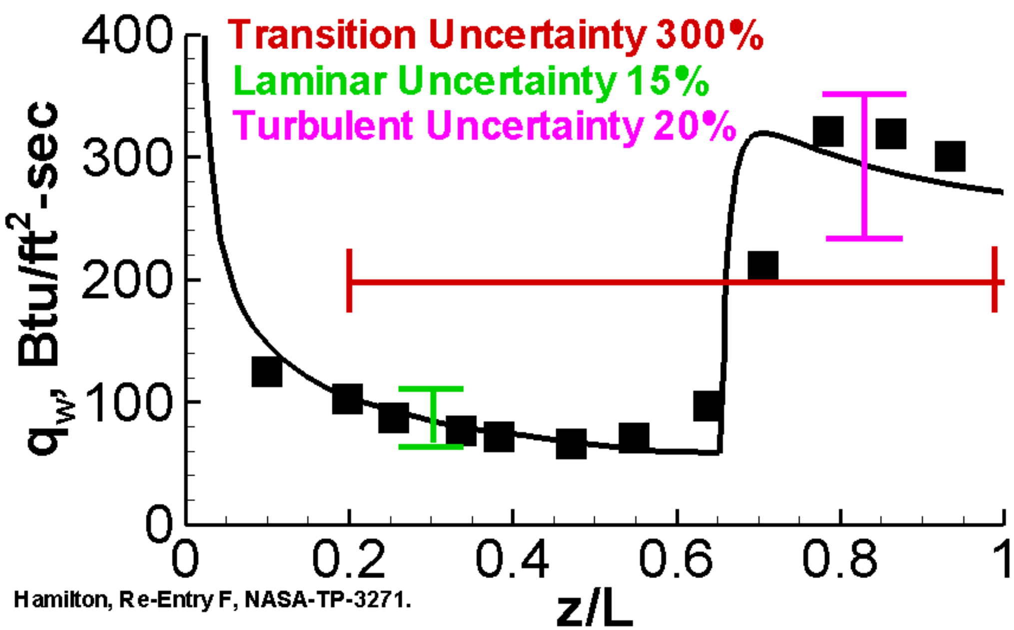
Hypersonic Boundary-Layer Transition

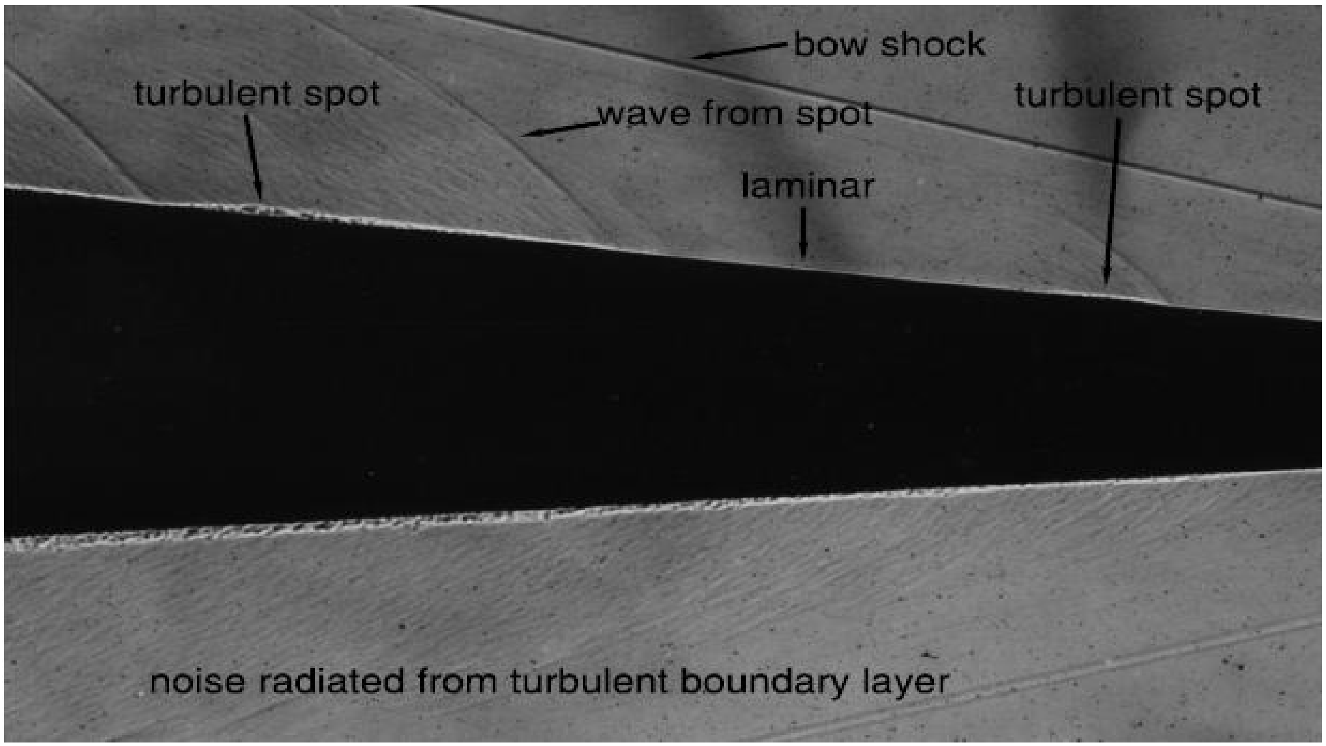
13-foot Beryllium Cone at Mach 20 in Reentry
CFD predicts heating well --ONLY IF--
transition location picked to match flight



Hamilton, Re-Entry F, NASA-TP-3271.

- **Boundary-layer transition is a complicated and poorly understood process.**
- **State of boundary layer affects heat transfer, skin friction and separation.**
- **Prediction of transition is inexact, and can dramatically affect the design of flight vehicles (especially hypersonic vehicles).**
- **Empirical and semi-empirical methods are used to predict transition**
- **Better understanding of the flow physics that causes transition will aid development of better methods.**

Freestream Disturbances in Hypersonic Tunnels



Shadowgraph of 5 degree sharp cone at M=4.31, $\alpha = 0$, Re = $31.9*10^6$/foot, Naval Ordnance Lab Ballistics Range

- **Nozzle-wall turbulent boundary layer radiates high levels of noise (acoustic fluctuations)**
- **Conventional tunnels have noise levels an order of magnitude larger than quiet tunnels with laminar nozzle-wall boundary layers**
- **Tunnel noise moves transition upstream and can change the mechanism and the parametric trends.**

Crossflow Instability

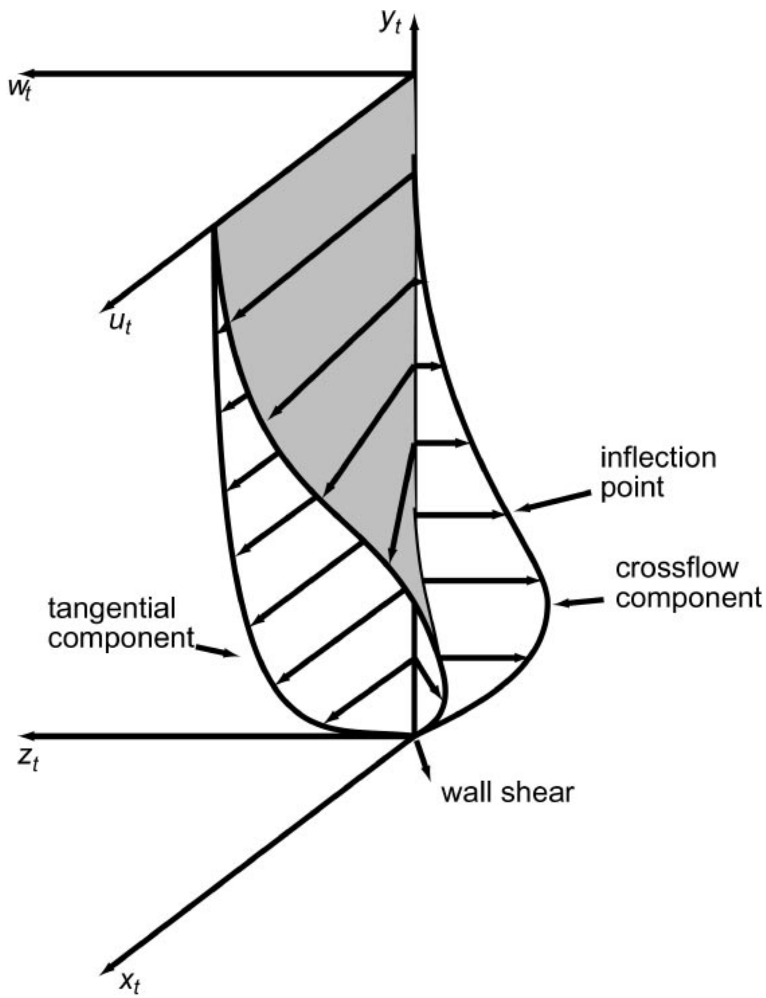
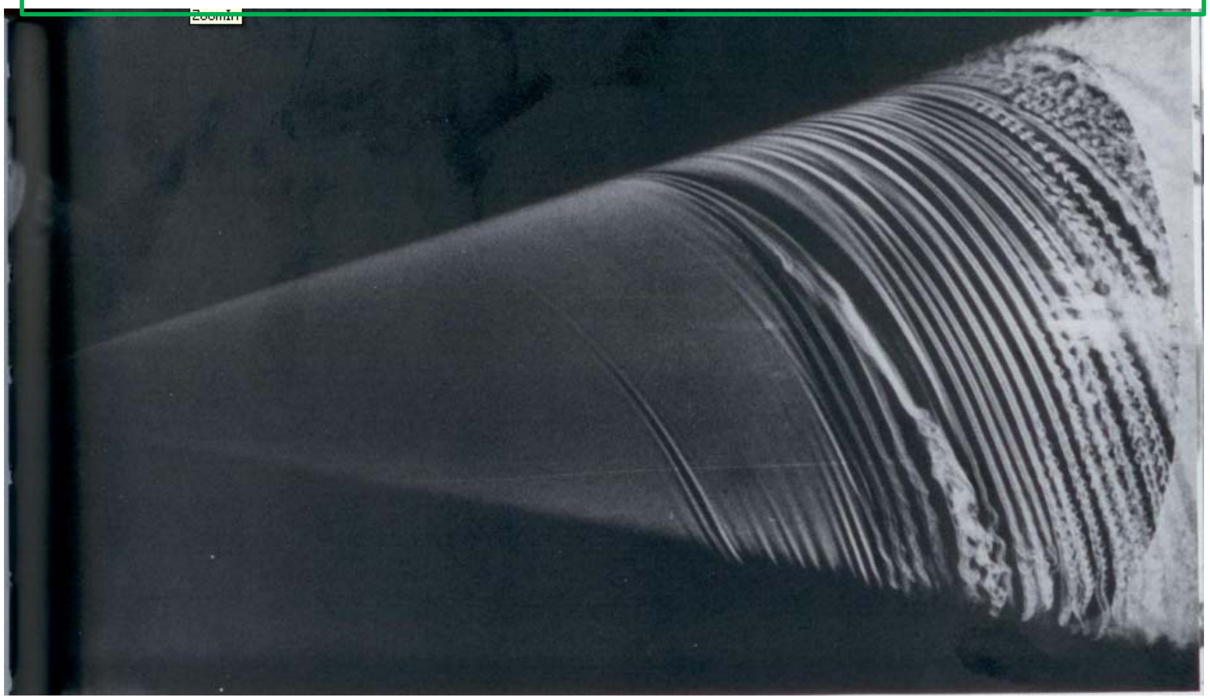


Image from Saric et al. *Annual Review of Fluid Mechanics*, 2003.

- **Inflection point in crossflow velocity is a source of an inviscid instability.**
- **Primary instability shows up as co-rotating vortices in the boundary layer.**
- **The crossflow vortices can be travelling or stationary with respect to the surface.**
- **Low speed experiments show that the travelling vortices dominate transition in high-disturbance environments, while stationary vortices dominate transition in low-disturbance environments.**

Secondary Instability of the Stationary Vortices

Does this occur at High Speed also? In this paper, more preliminary evidence from the Mach-6 quiet tunnel.

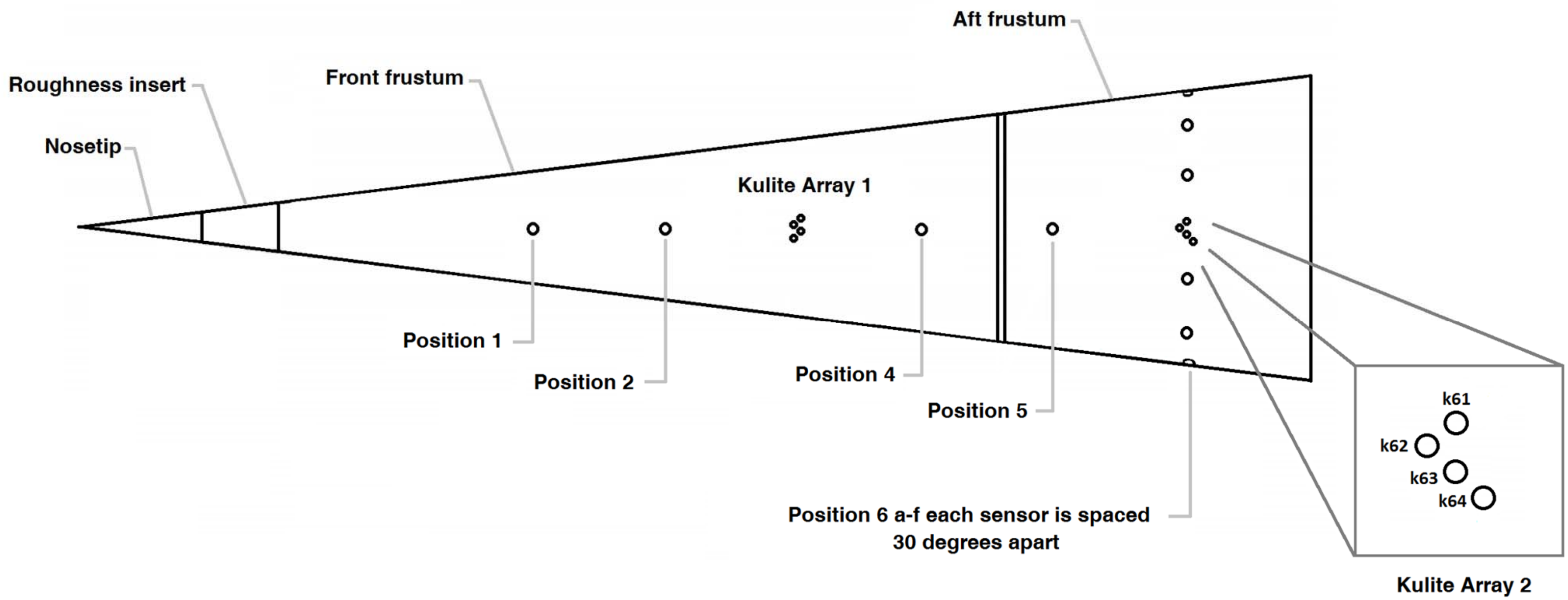


15° half angle cone at 0° AoA rotating in an air stream of 2.9 m/s

Image from "An Album of Fluid Motion", Van Dyke, Parabolic Press, 1982.

- **When stationary vortices saturate, secondary instabilities appear, at least at low speeds.**
- **Secondary instabilities travel along the stationary vortices at frequencies higher than the primary travelling instability.**
- **These secondary instabilities are believed to cause break down of the stationary vortices to turbulence. See Malik and many others**
- **Crossflow-induced transition occurs along a jagged transition front.**

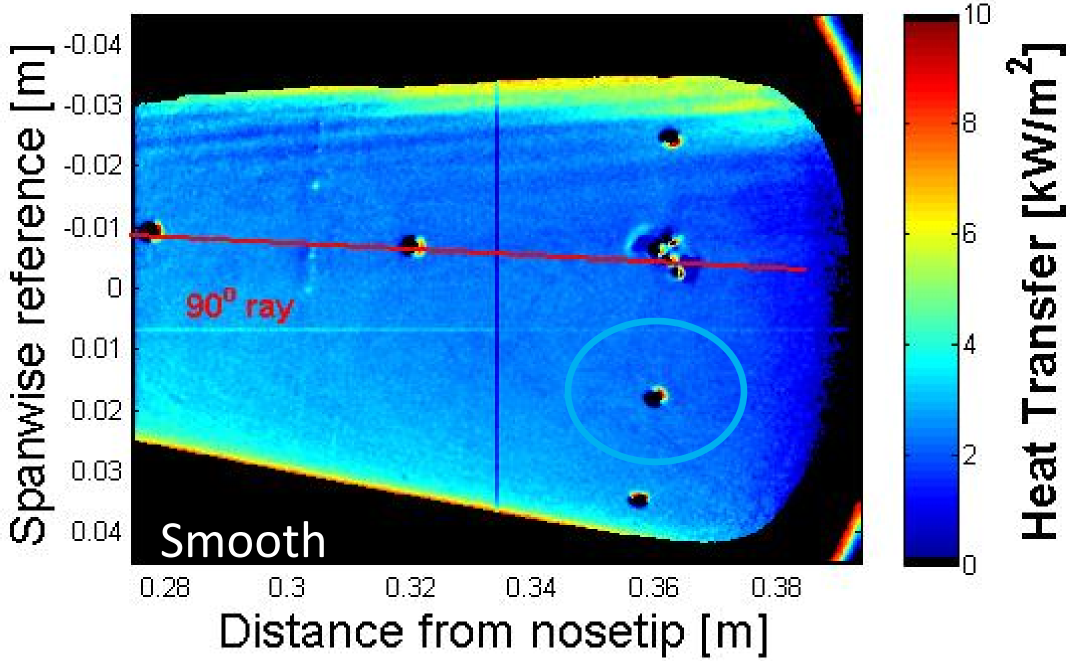
Generic Sharp-Cone Model for Crossflow Studies

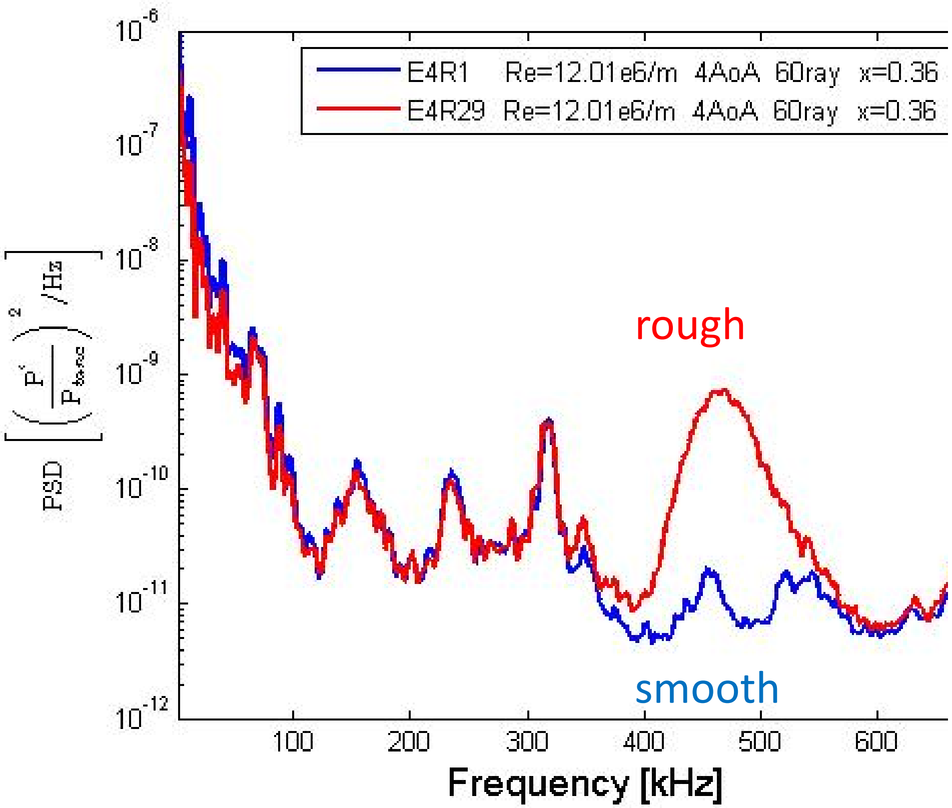


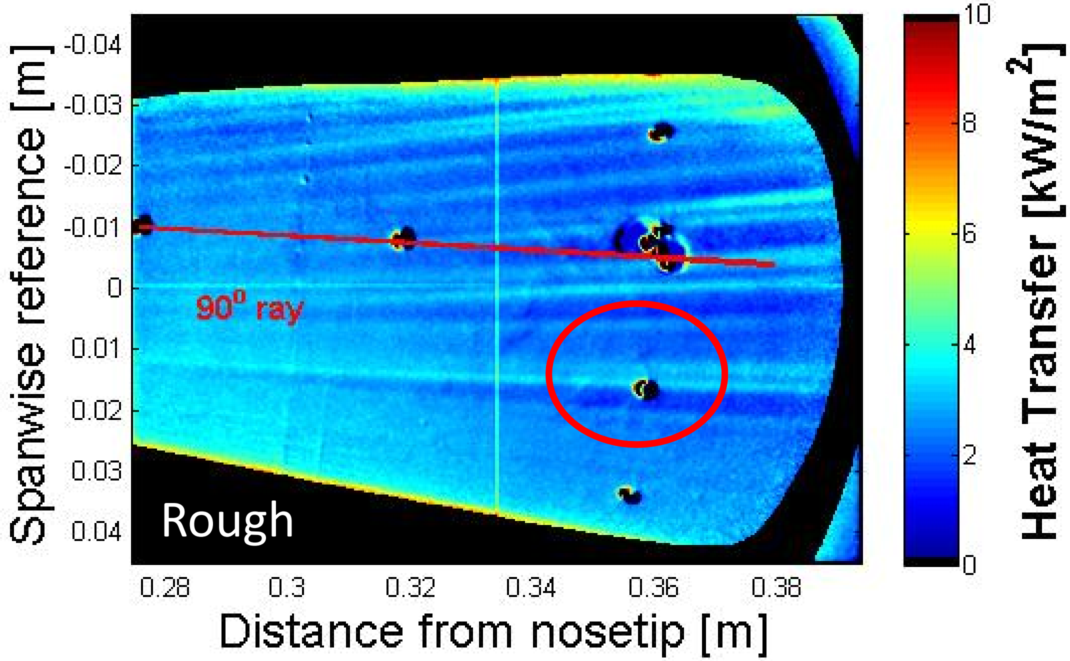
- **Sharp 7-deg half-angle cone, 3-6° angle of attack.**
- **Test under quiet flow with either smooth or rough insert.**
- **Roughness elements 0.05 m from the nosetip, near the neutral point of the most amplified stationary waves (Li et al. AIAA Paper 2010-4643)**
- **50 roughness elements placed around the azimuth.**
- **Crater roughness element has an approximate depth of 30 μm, diameter of 300 μm and a height of 10 μm (after Corke and Schuele).**

Possible Secondary Instability, Case 1

- **4° AoA, Re = 12.01e6/m**
  - **Top: Smooth surface**
  - **Bottom: Nail-polish ring**
- **PCB shows a disturbance near 475 kHz, only in rough case where crossflow streak is visible near sensor**

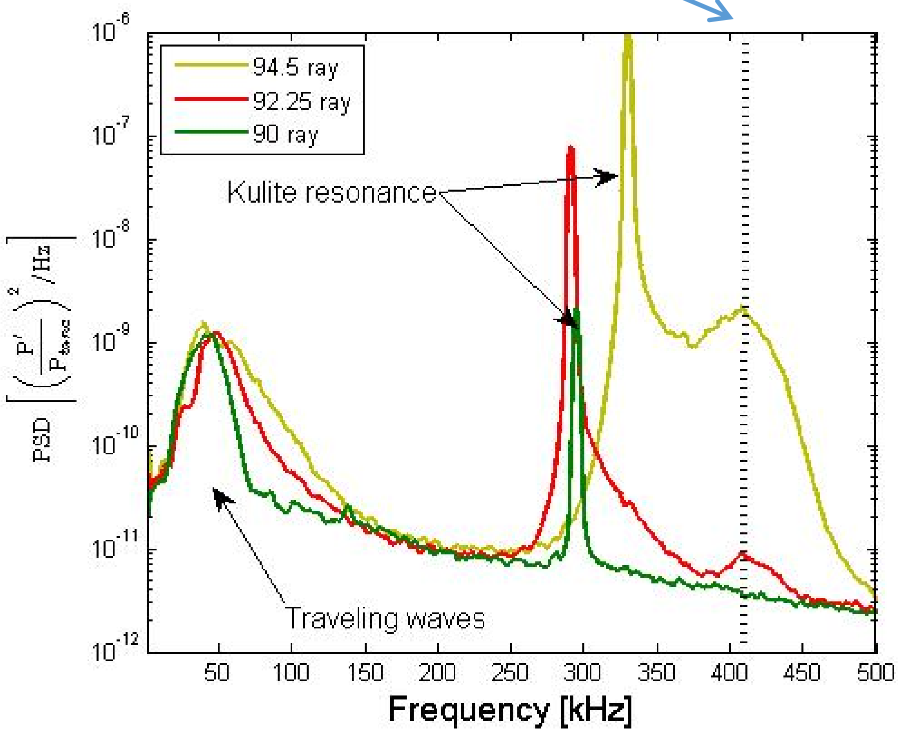


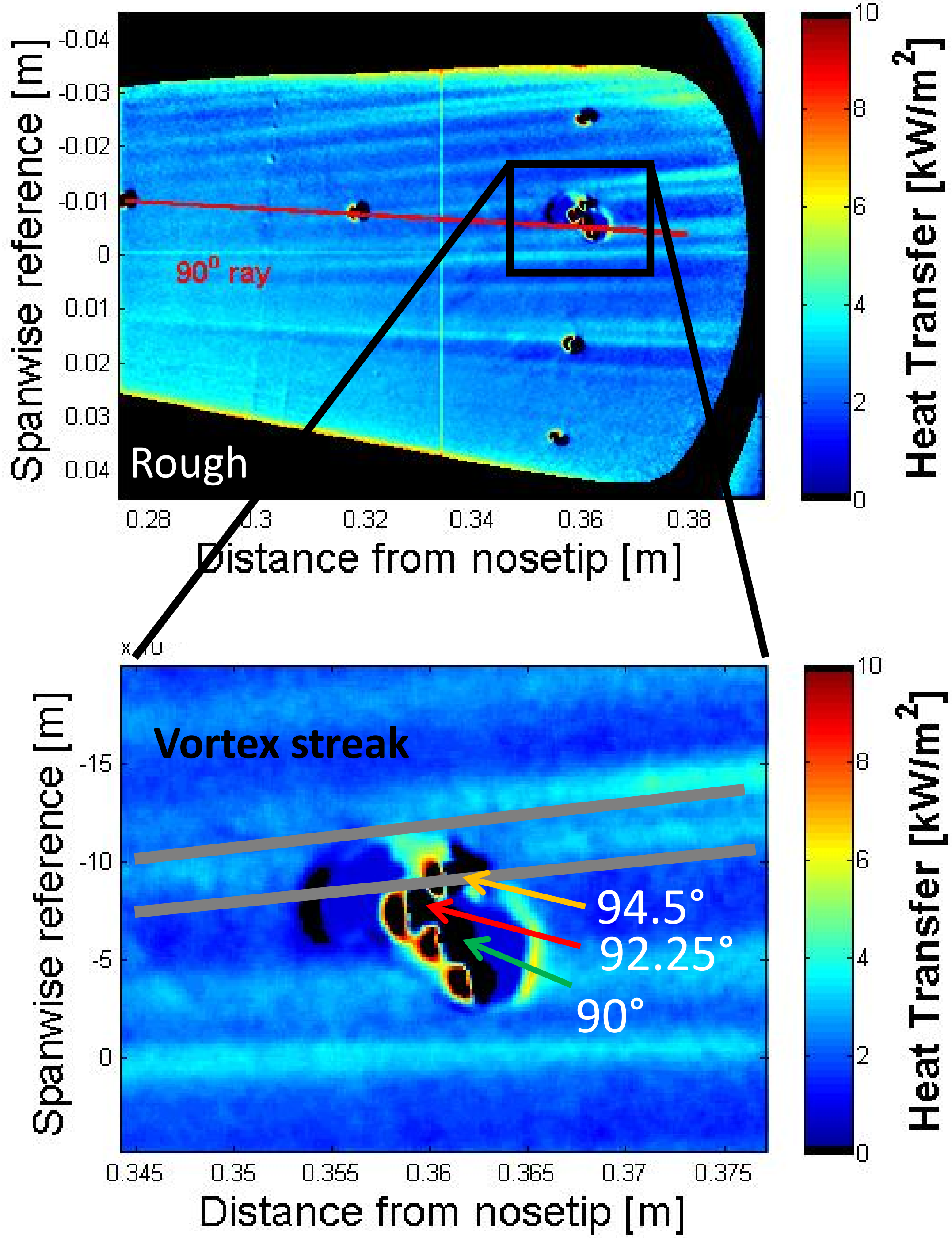




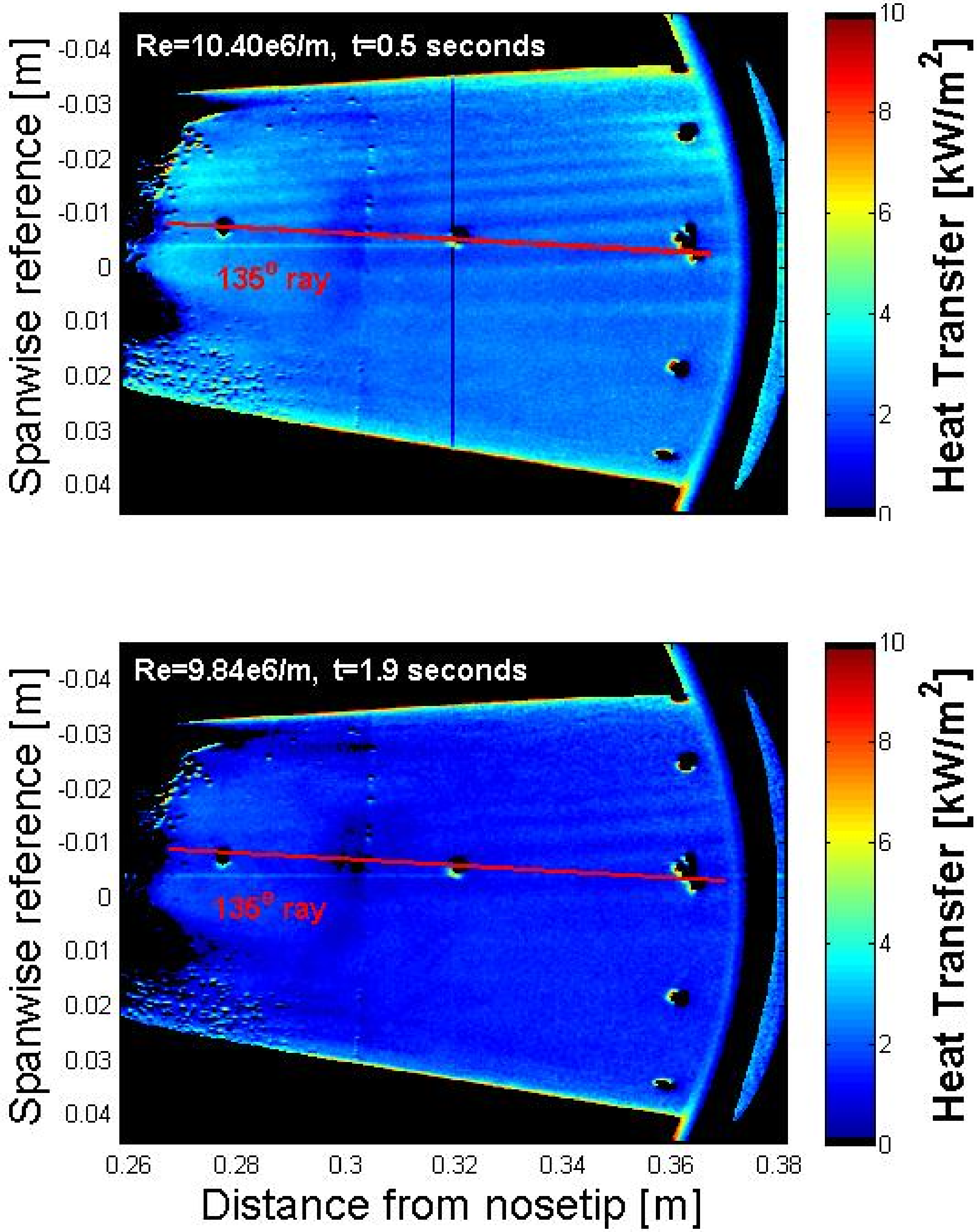
Possible Secondary Instability, Case 2

- **Vortex streak crosses Kulite at the 94.5° ray. A large disturbance is observed at 410 kHz.**
- **Kulite at the 92.25° ray shows a smaller disturbance at the same frequency.**





Reynolds number effects on apparent secondary instability



- **3° AoA**
- **Re = 10.40-9.84e6/m**

- **During a single run, Reynolds number will decrease as the expansion fan in the driver tube reflects between the upstream end and the contraction.**

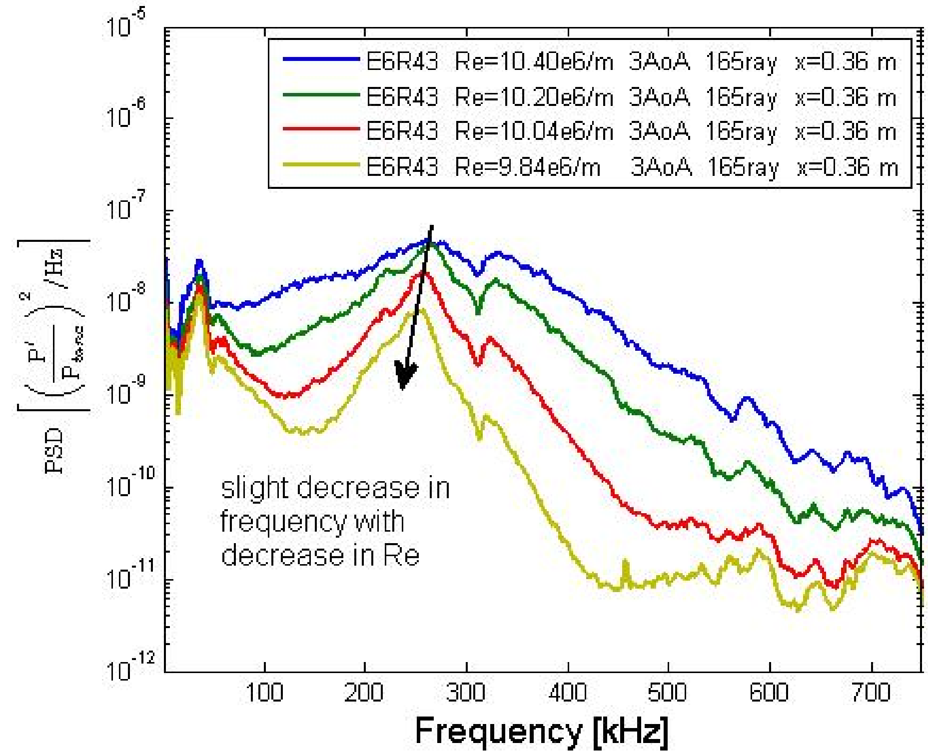
- **As Re decreases, stationary-wave amplitudes also decrease, as seen by a decrease in heat transfer in the TSP images.**

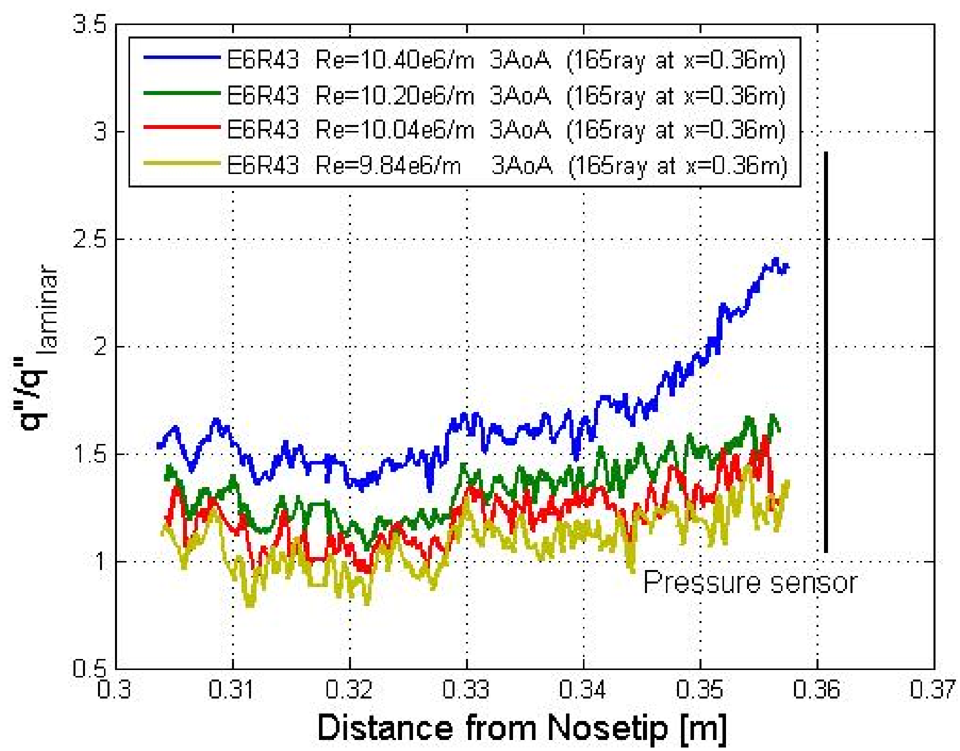
Reynolds number effects on apparent secondary instability

- **3° AoA**
- **Re = 10.40-9.84e6/m**

- **A disturbance near 260 kHz is found. The PCB frequency decreases with Reynolds number, along with the mean heat flux from the TSP.**

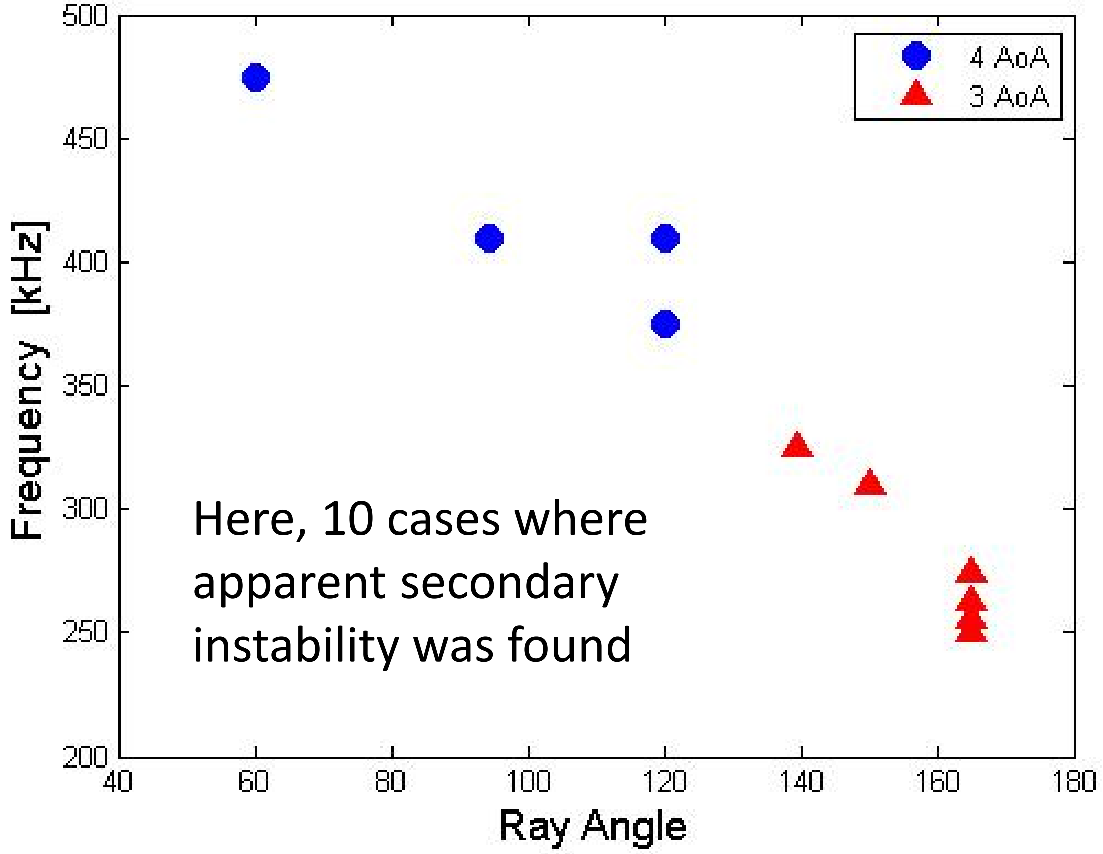
- **From heat flux profiles, vortex that crosses over the sensor is on its initial growth region, not in a saturation region, unlike at low speeds. How does all this really work, at hypersonic speeds?**





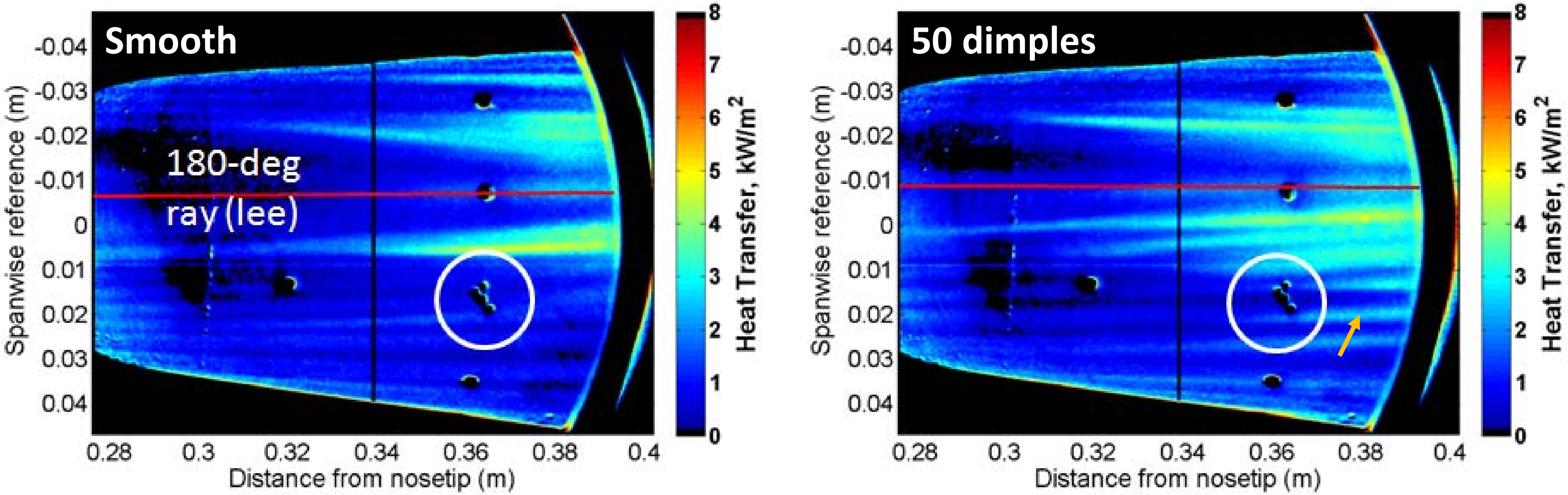
Effect of Azimuthal Angle on Possible Secondary Instability

- **The frequency consistently decreases when the instability is found closer to the lee ray**
- **The boundary layer on the cone is thicker towards the lee ray (180-deg).**
- **The frequency of the secondary instability appears to be a function of boundary-layer thickness, as might be expected**



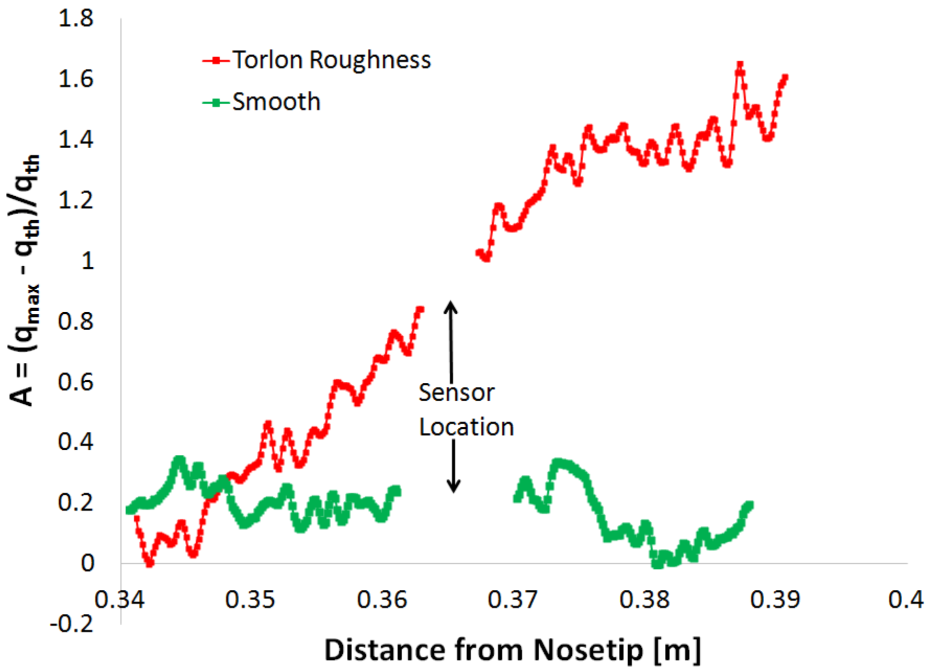
High-Frequency Instability Appears When Stationary Modes Grow Large (TSP data)

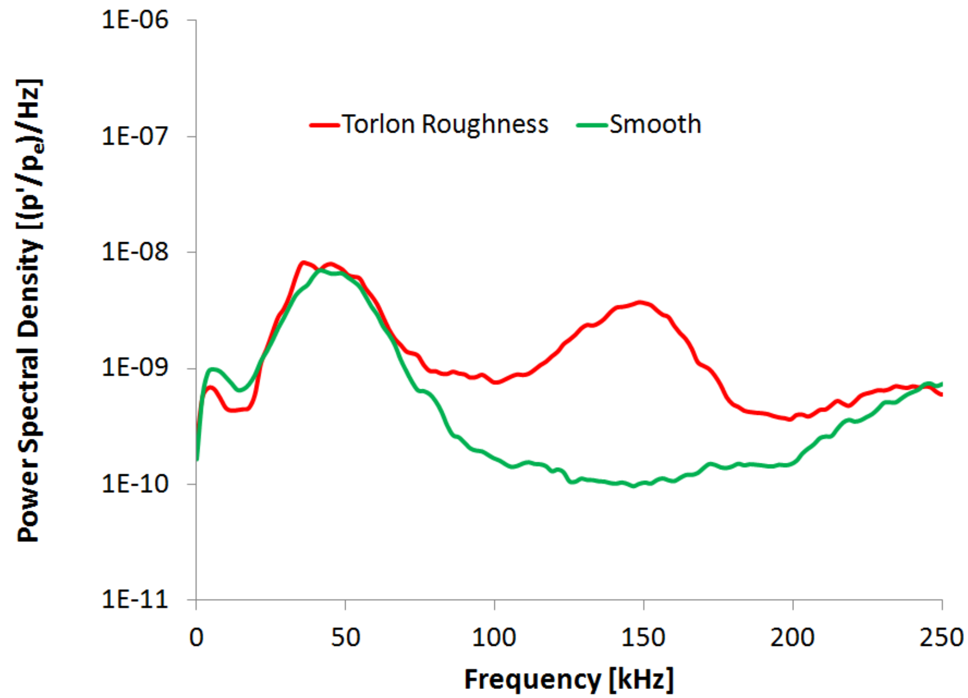
6-deg AoA, Lee side, quiet flow, Re – 9.3x10^{6} /m



- **Kulite sensor among 4 circled in the images (150° ray).**
- **When the roughness is added, several stationary vortices grow large near the Kulite array, and may be breaking down to turbulence.**

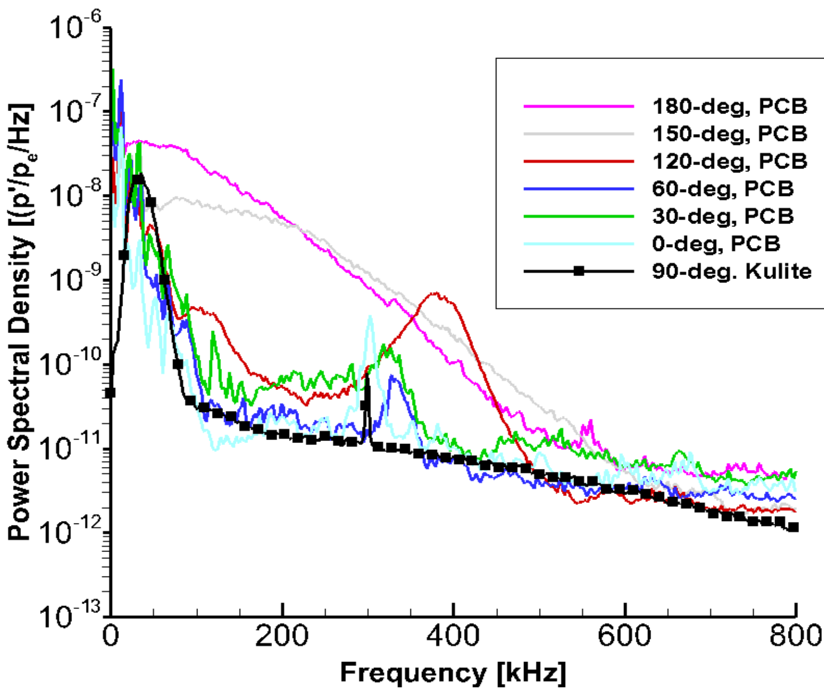
High-Frequency Instability Appears When Stationary Modes Grow Large (PCB data)

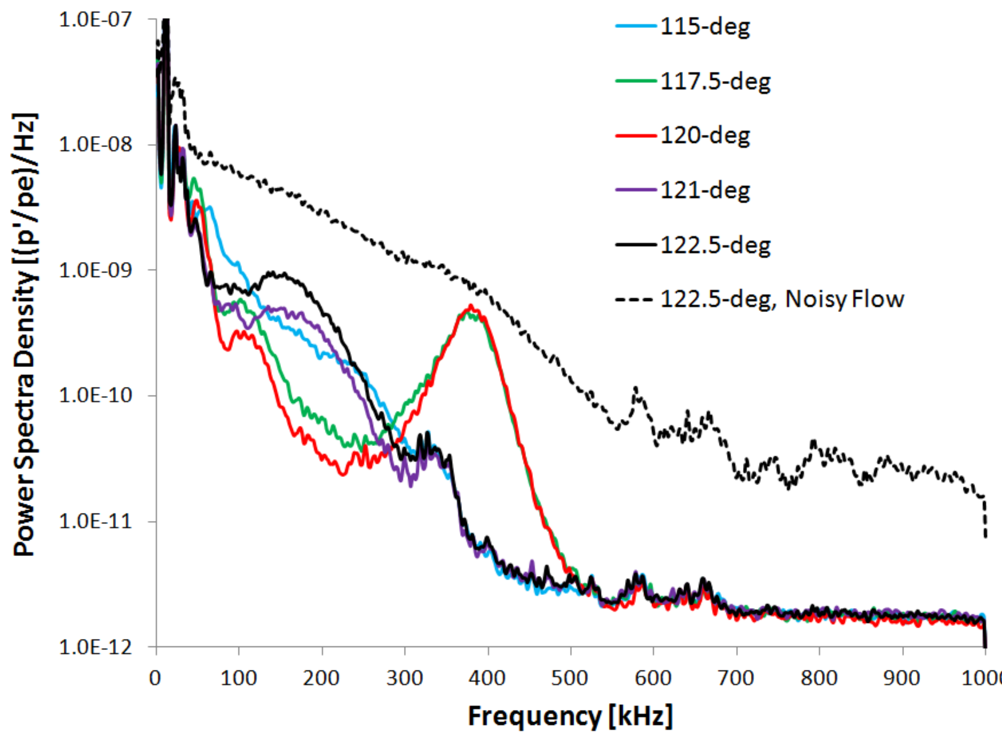




- Amplitude of stationary vortex near the sensor array shows saturation near the sensor location.
- The spectra show the primary travelling instability is visible near 40 kHz.
- When the stationary wave grows large and possibly begins to break down to turbulence, a secondary peak at 150 kHz appears in the PSD.
- Is this 150 kHz peak due to a secondary instability?

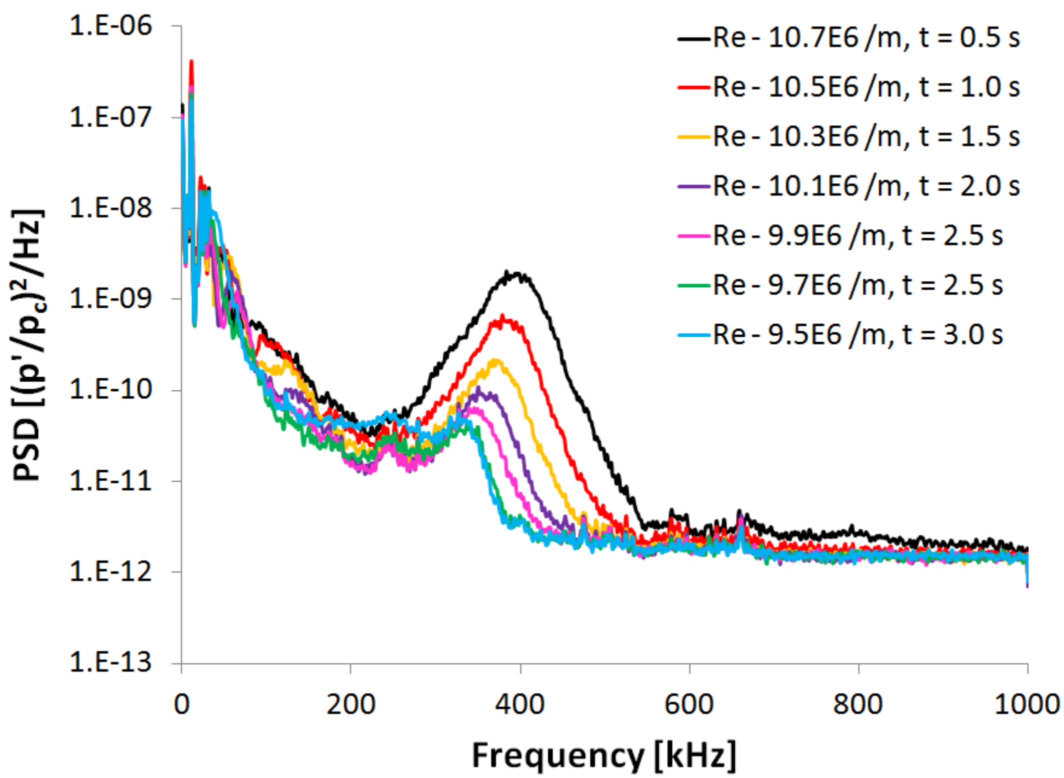
Instability Sensitive to Small Changes in Azimuthal Angle





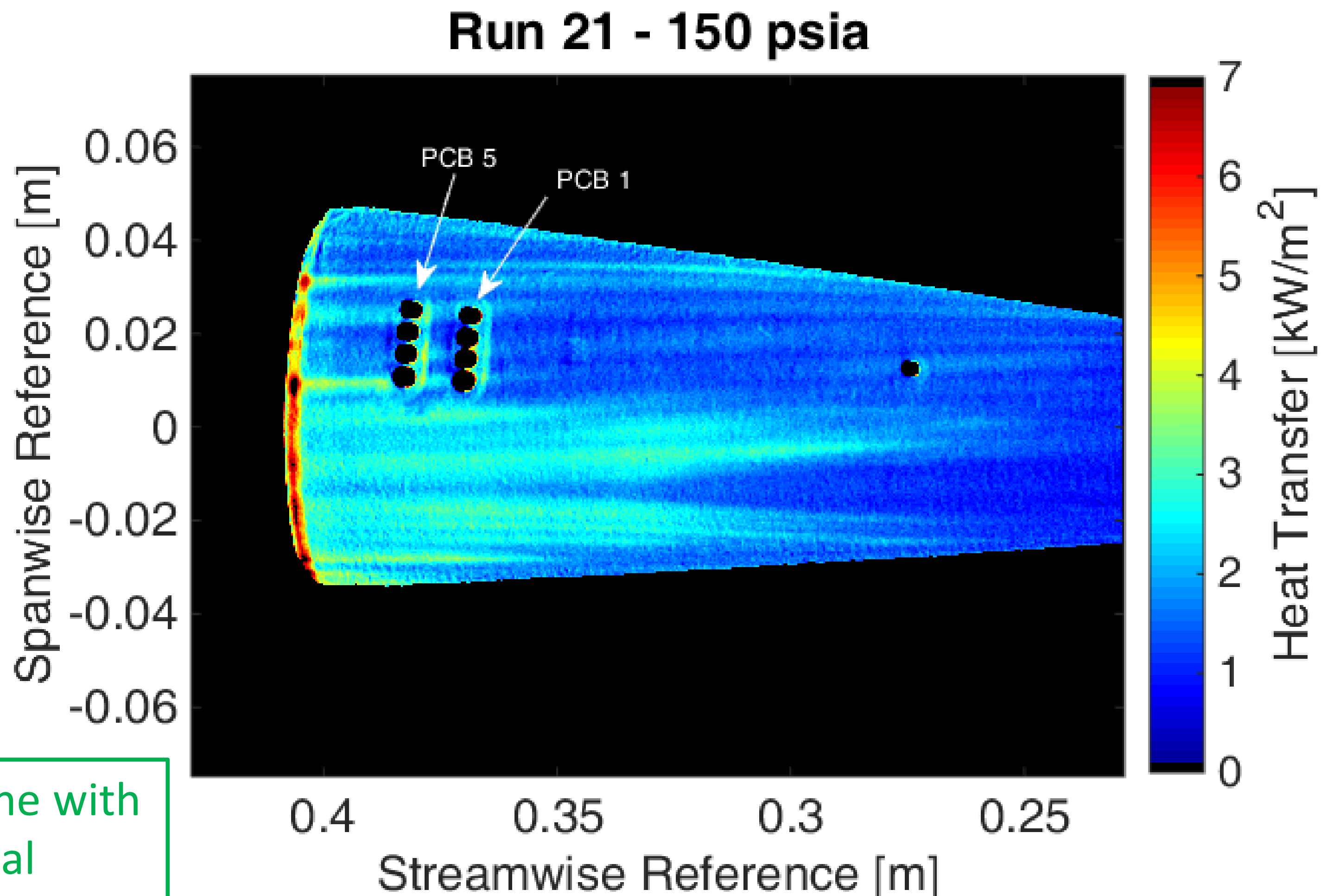
- 6-deg AoA, Re – 10.8 x 10^6 /m, roughness insert installed (no TSP available).
- PCB sensor 120-deg from windward ray shows large peak at 400 kHz.
  - Evidence of the secondary instability?
- Peak disappears when sensors rotated several degrees.
- Second peak visible near 200 kHz.
  - Also related to the secondary instability?

Peak Amplitude and Frequency Decrease with Decreasing Reynolds Number



- **Data from a PCB sensor 0.36 m from the nosetip on the 120° ray at different times during a single run.**
- **As the Reynolds number decreases, the amplitude and the frequency of the peak decreases.**
- **This could be caused by the movement of the transition location or the thickening of the boundary layer with decreasing Reynolds number.**

Another Possible Secondary Instability on Stationary Crossflow Wave



Modified Cone with Two azimuthal arrays of PCB-132 sensors

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Data included for PCBs 1 and 5, shown above with streak passing through.

Run Table

Run	P_0 (psia)
20	168
21	150
22	160
23	140
24	133

- PCB 1,5 at 132° from windward ray
- 6° AoA
- Roughness insert, 50 dimples, 0.004” depth

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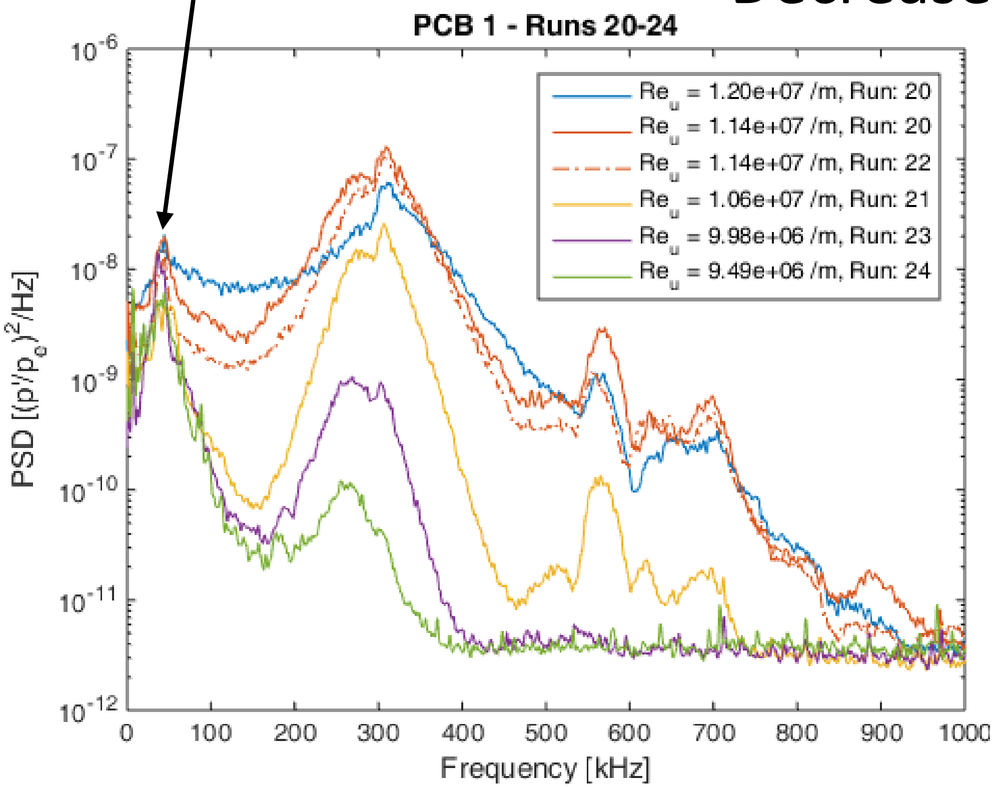
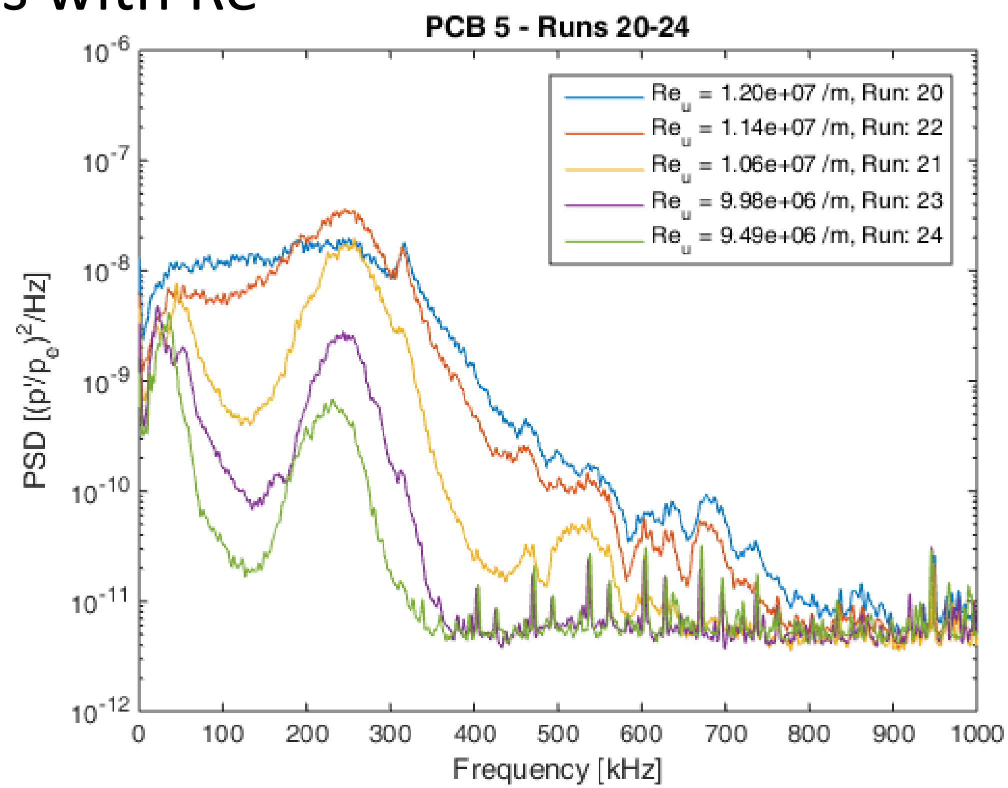
Spectra: PCBs 1 (Upstream) and 5 (Downstream)

Travelling crossflow wave

Secondary Instability Near 250kHz?
Decreases with Re





PSDs from Welch's method, frequency resolution of 2 kHz. PCB 5 is downstream of PCB 1.

Normalized by edge pressure for cone at zero angle of attack (Taylor-Maccoll).

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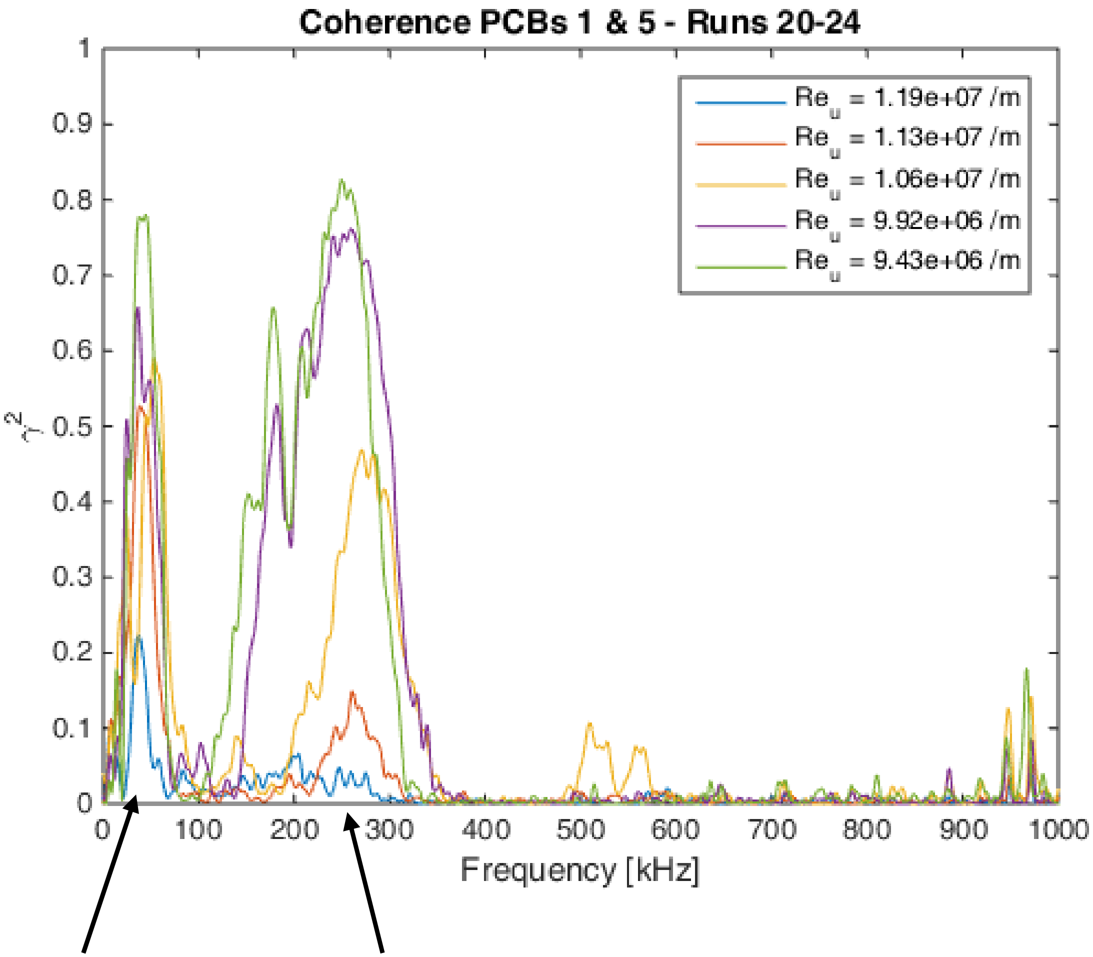
High Value of the Magnitude Squared Coherence for PCBs 1 & 5 (when not turb.)



Travelling crossflow wave

Potential secondary instability

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Summary

- A high frequency instability was frequently measured near the break down of stationary crossflow waves, with a frequency between 150 and 500 kHz.
- The frequency of the disturbance appeared to decrease with increasing azimuthal angle and increasing boundary layer thickness (as expected).
- The instability was sensitive to small changes in azimuthal angle.
- The instability was also sensitive to the amplitude of the stationary wave.
- Based on the experiments, it appears that the instability is the secondary instability of the stationary crossflow.
- **However, we seek computational comparisons**
- Further measurements will be part of Edelman’s MS thesis