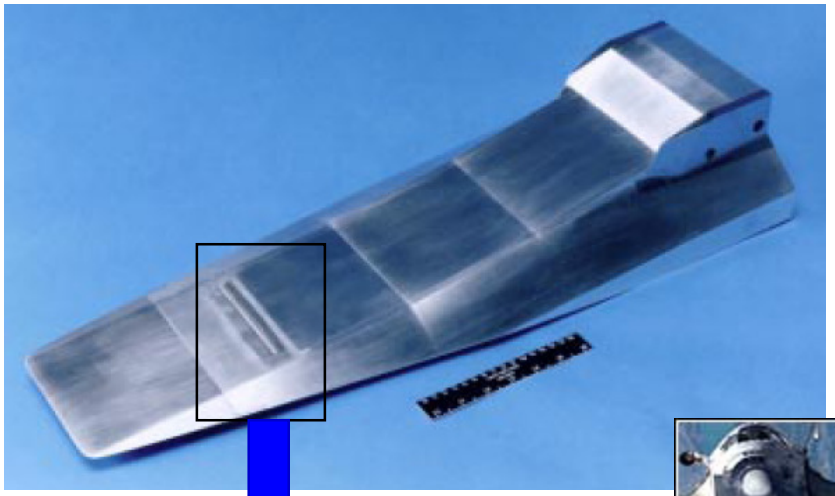
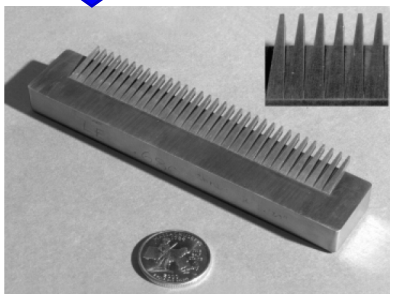
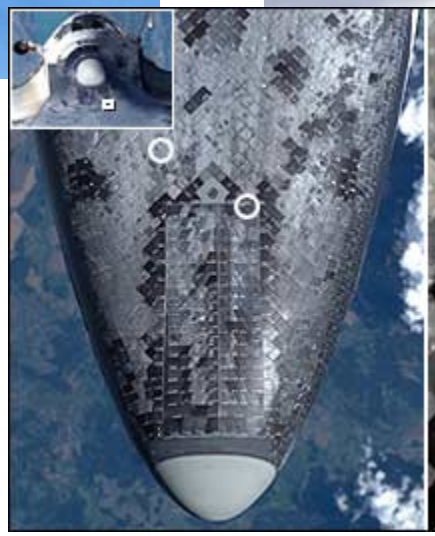
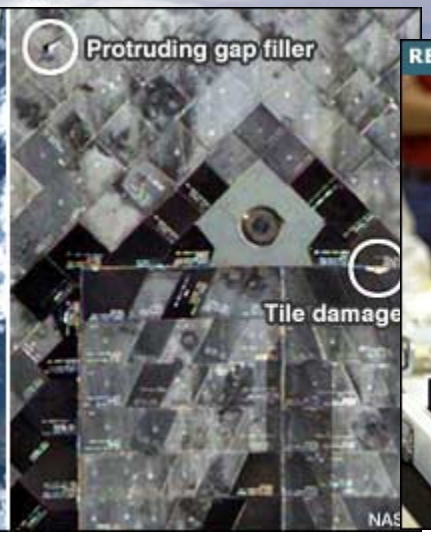
Transition in High-Speed Boundary Layers due to Discrete Roughness Elements

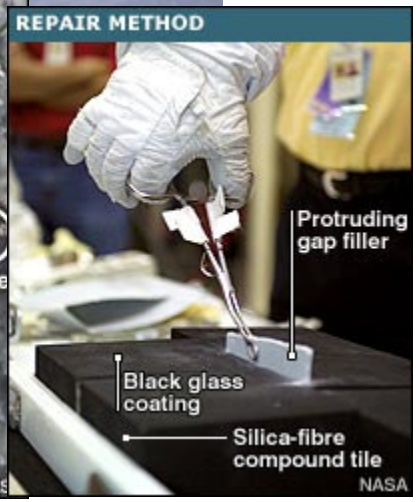












Meelan Choudhari
NASA Langley Research Center

Acknolwedgments: F. Li, C.-L. Chang, M. Wu, J.R. Edwards, A. Norris, M. Kegerise



Outline

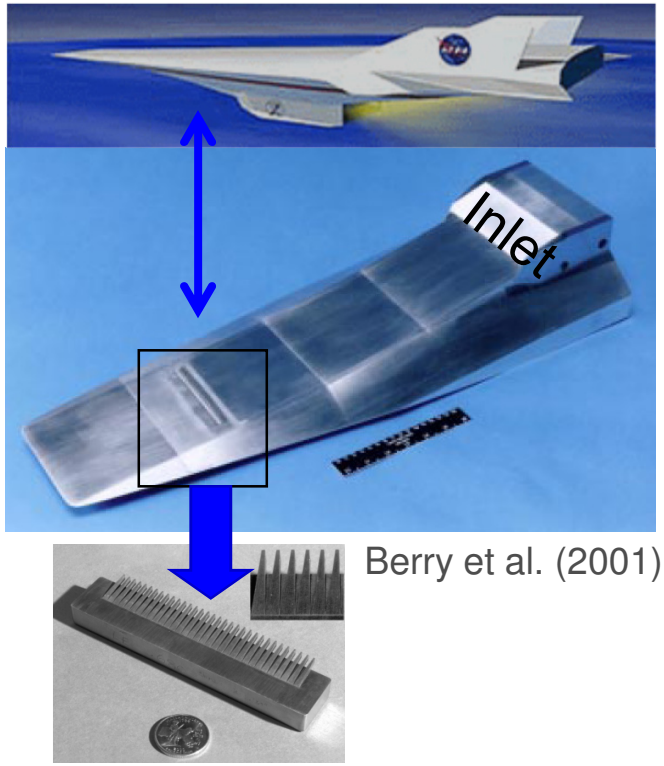
- Motivation
- Periodic Array of Trip Elements on Hyper-X
  - Trip/Roughness Modified B.L.: Basic State
  - Stability Analysis
- Isolated Roughness Element on a Flat Plate: M=3.5
  - Validation of Theory via Experiment
  - Bridging the Gaps in Physical Understanding
- Isolated Roughness Element on a Flat Plate: M=6
- Summary and Remarks



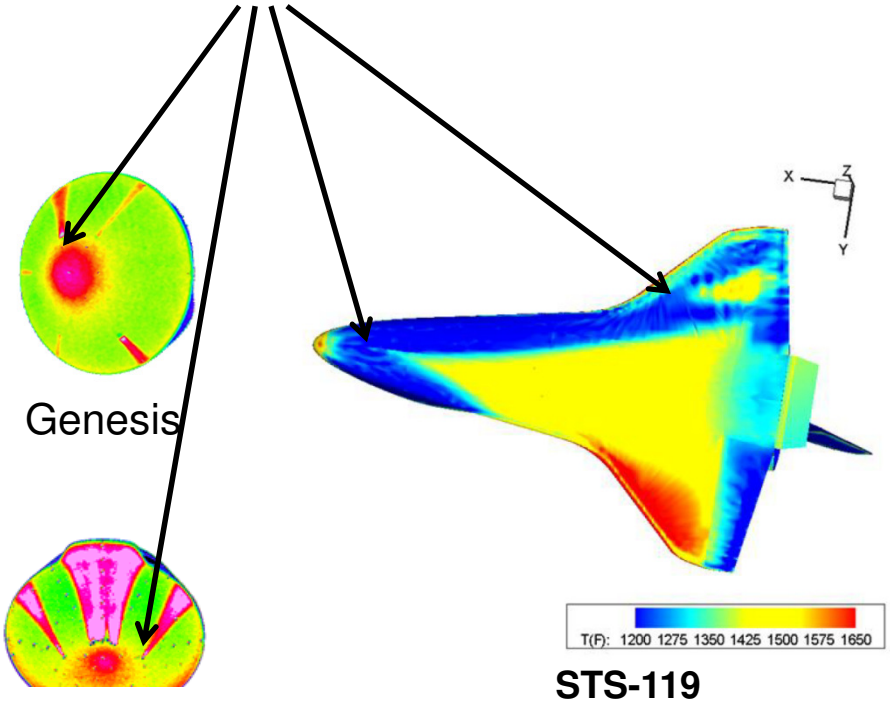
Motivation
Boundary Layer Transition & Roughness Effects

- **BLT prediction important aspect of hypersonic vehicle design**
  - Impact on TPS selection, vehicle trajectory, cross-range
  - BLT prediction critical for scramjet cruise vehicles and extended glide vehicles.
- **Transition on re-entry vehicles is roughness dominated**
  - Protuberances/cavities/distributed roughness inevitable on shuttle, planetary probes, etc.
  - Trips essential to ensure efficient mixing in scramjet inlets
- **Underlying physical mechanisms remain unknown**
  - Current modeling based on **purely empirical correlations**
  - Recently proposed **transient-growth based model** successfully correlates an established database for subcritical transition due to nose-tip roughness

"Bypass" Transition in Supersonic/Hypersonic B.L.s due to Discrete Roughness Elements



Berry et al. (2001)

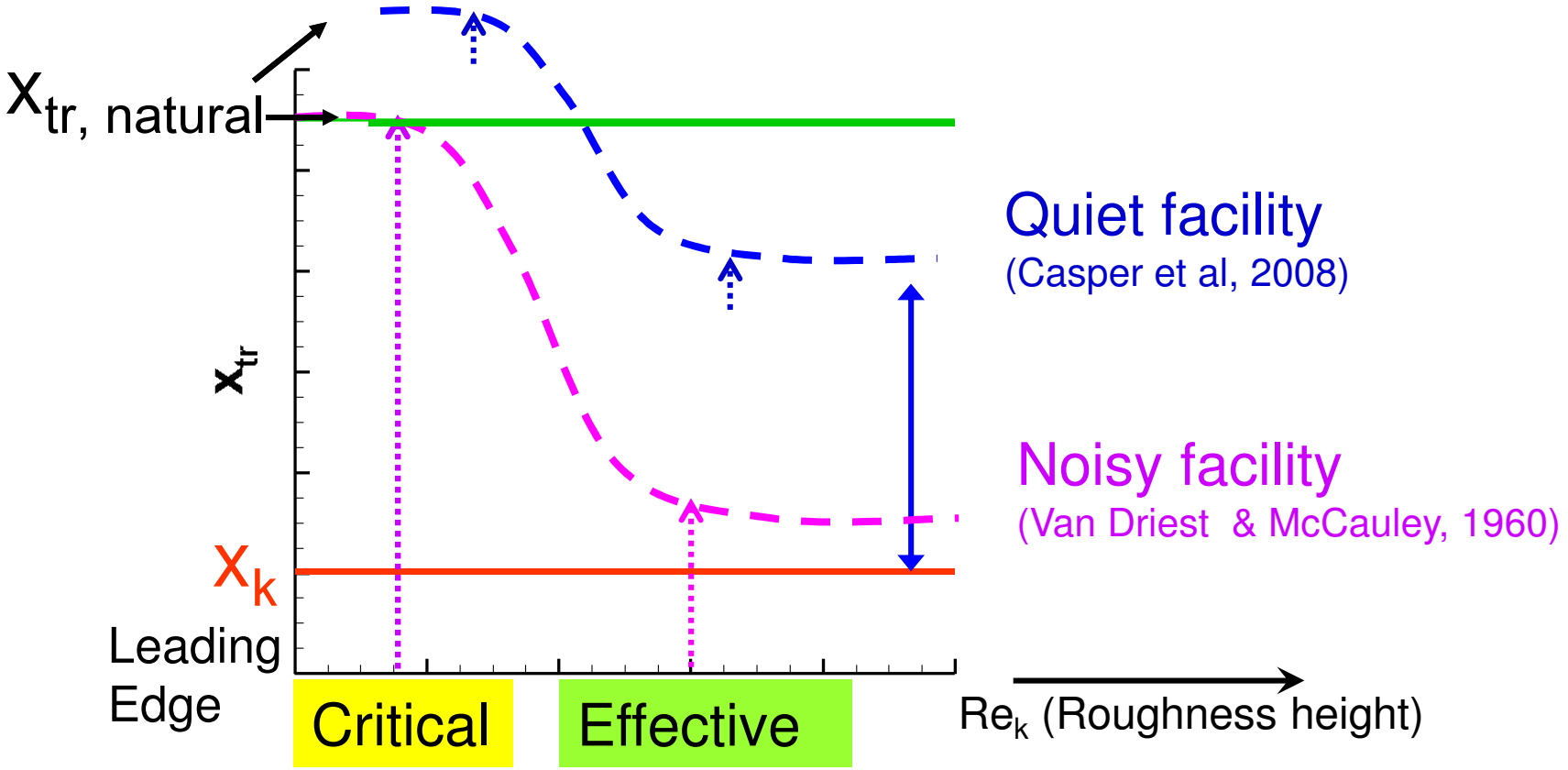


STS-119
courtesy: T. Horvath

- Transition occurs even though underlying boundary layer is stable
  - Transition ***bypasses*** usual route (and established paradigm)

Effect of Roughness Height on Transition at M >> 1

- **M >> 1 => 3D trips more effective**
- **Effect of 3D trip height at a fixed set of flow conditions:**



Roughness Induced Tripping
'Potential' Physical Mechanisms

In general:

- **Accelerated growth of existing instability modes**
- **New class of instabilities in trip modified flow**

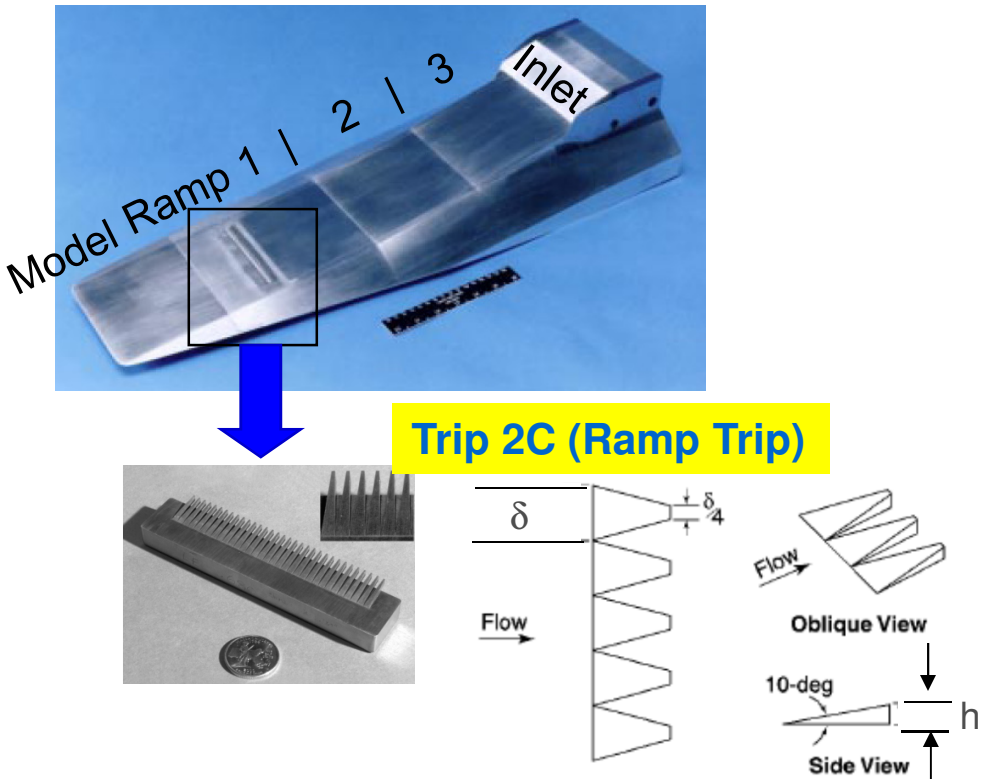
→ – **convective modes** (Recall substantial impact of facility on x_{tr})

  – **absolute/global instabilities of separated flow (vortex shedding, etc.)**

- **Provide environment for strong transient growth**
  - via seeding of appropriate disturbances
  - via enhanced algebraic growth of incoming disturbances
- **Something else? (Receptivity agent, etc.)**

Hyper-X wind tunnel experiment (Berry et al., JSR 2001)

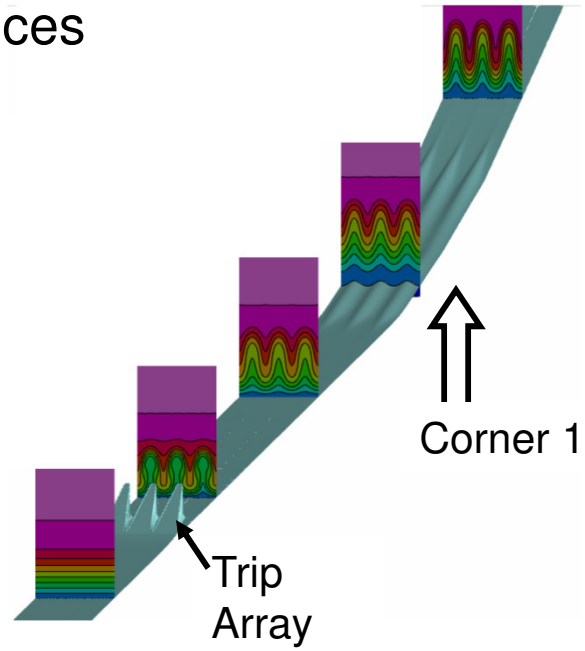
1/3 scale model, tested at Mach 6, 7.3, and 10

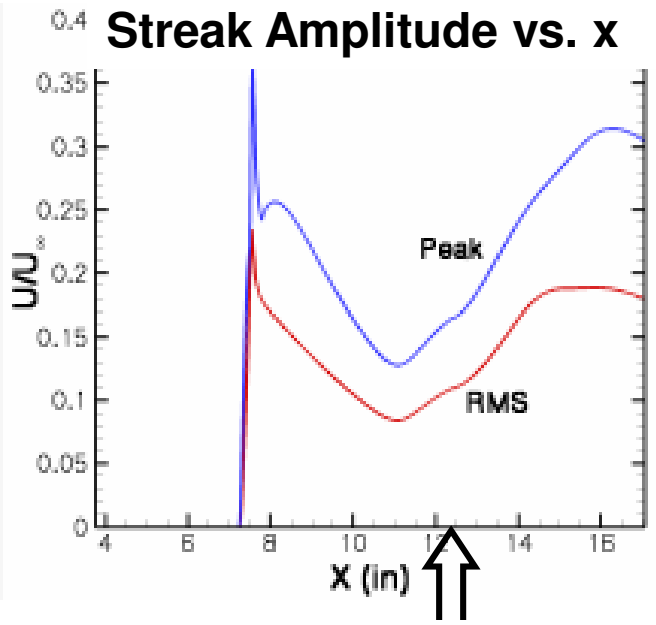


- **h = 0.060” ⇒ Transition onset over ramp 1**

Laminar Mean Flow

- Computations by Jack Edwards (NCSU) under AFOSR support
  - Immersed boundary method
- Flow settles into steady state; short separated region near trip array
- **Wake flow dominated by streamwise streaks** that persist for long distances



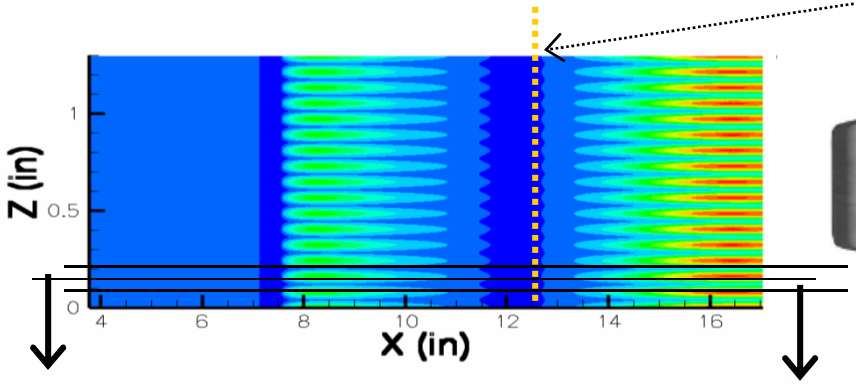


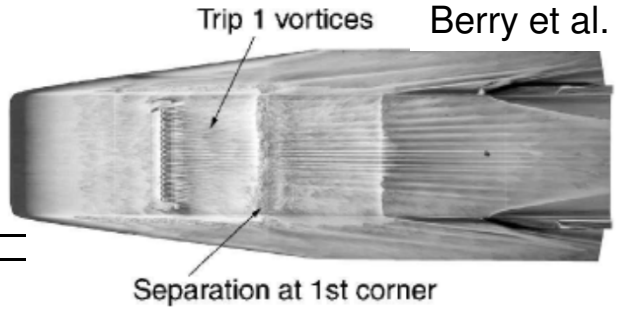
- Energized B.L. more resistant to separation

→ substantially weakened 3D separation bubble near 1st compression corner

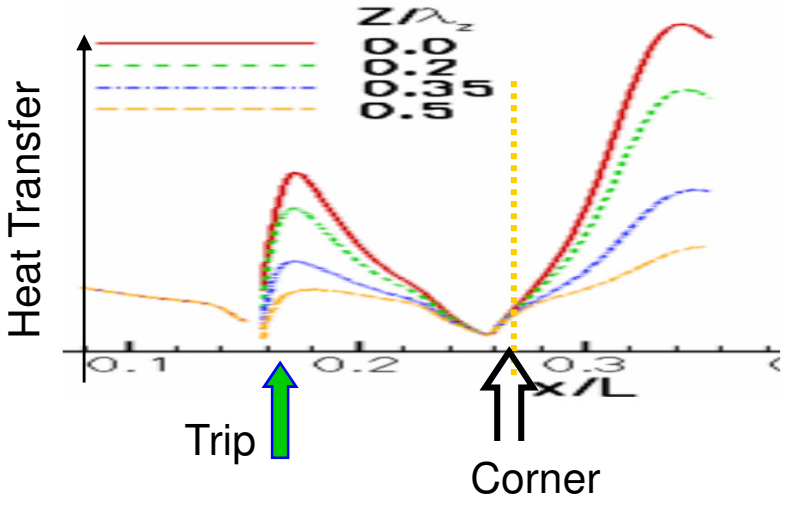
Streak Characteristics

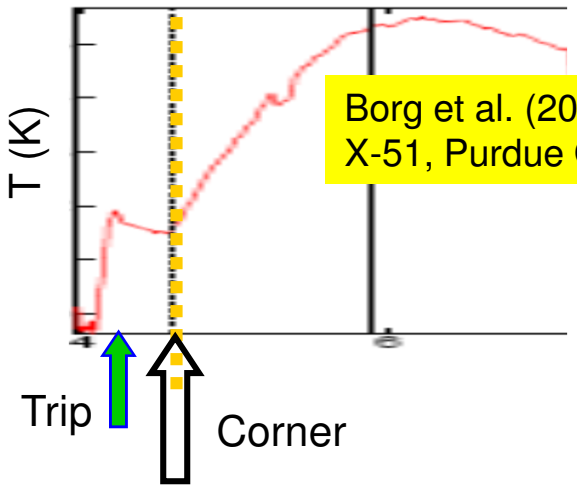
- Streaks are amplified across the corner and substantially increase the surface heat transfer, consistent with measurements in Purdue quiet tunnel.





Berry et al. (2001): Hyper-X





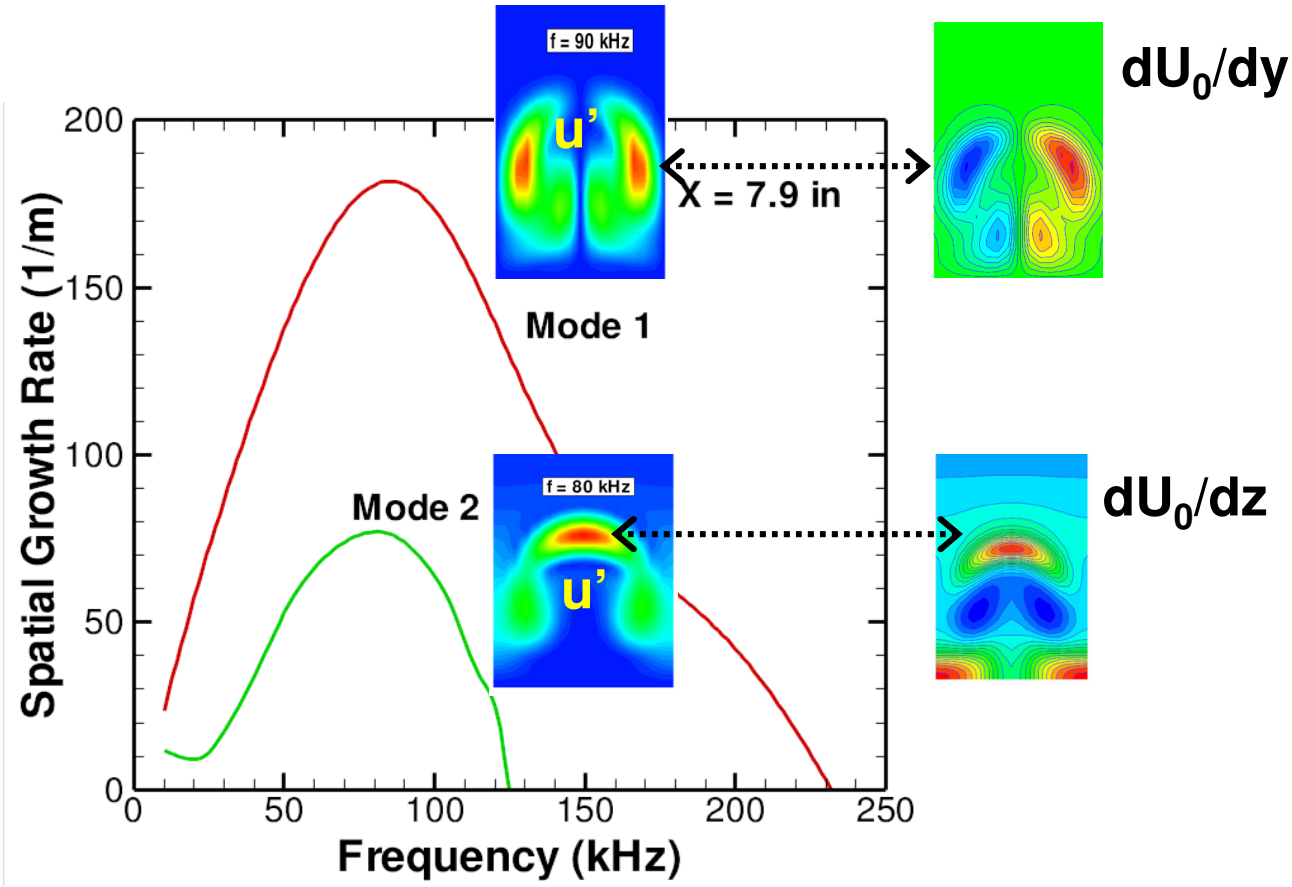
Borg et al. (2008)
X-51, Purdue Quiet Tunnel

- Modest growth in spanwise Fourier harmonics:
  Combination of concave streamline curvature and transient growth?

Instabilities of Trip Array Wake

- Streaks have comparable length scale in wall-normal and spanwise directions

=> PDE based eigen analysis necessary to infer instability characteristics behind trip array

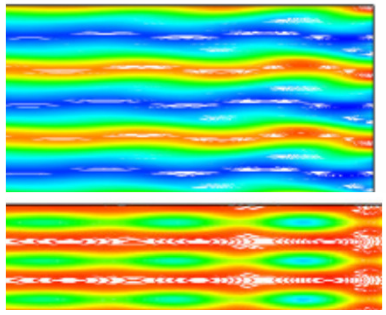


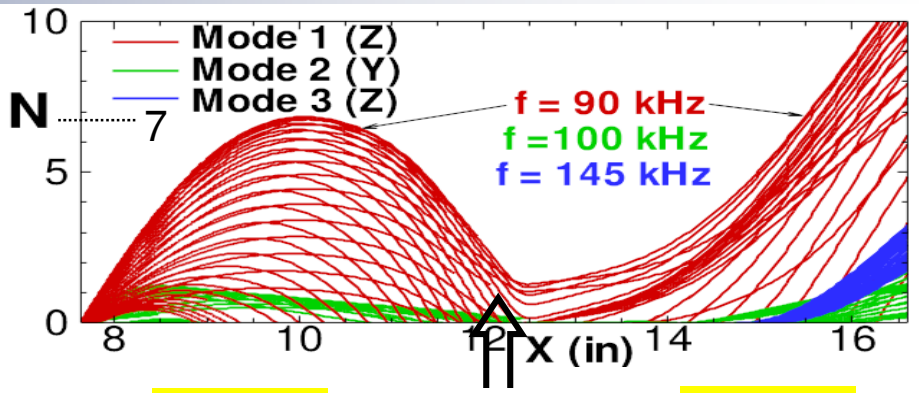
Integrated Amplification of Streak Instabilities (N factors)

Mode 1 = odd/sinuous

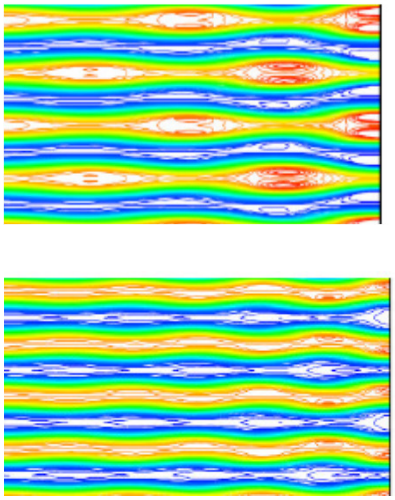
Fundamental Modes

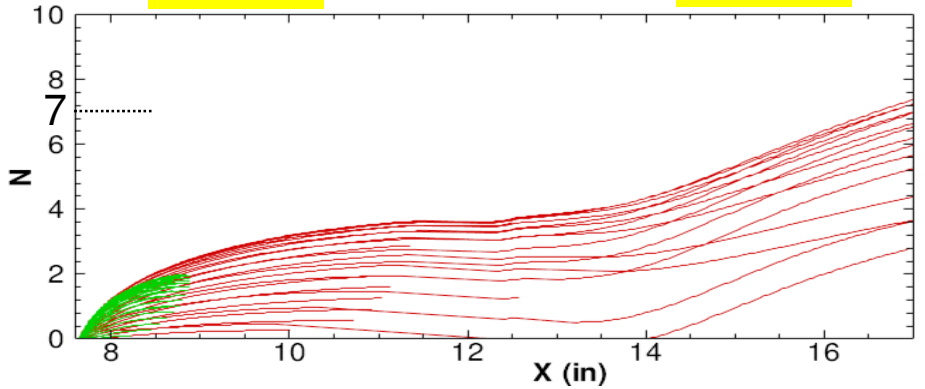
Mode 2 = even/varicose





Subharmonic Modes



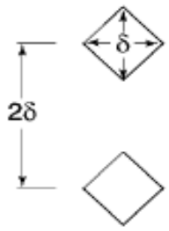


- Relatively stable region near the corner between ramps 1 and 2 =>
  - N < 7 → transition onset within Δx/L = 0.05 from the trip*
  - N > 7 → transition may jump past the middle of ramp 2

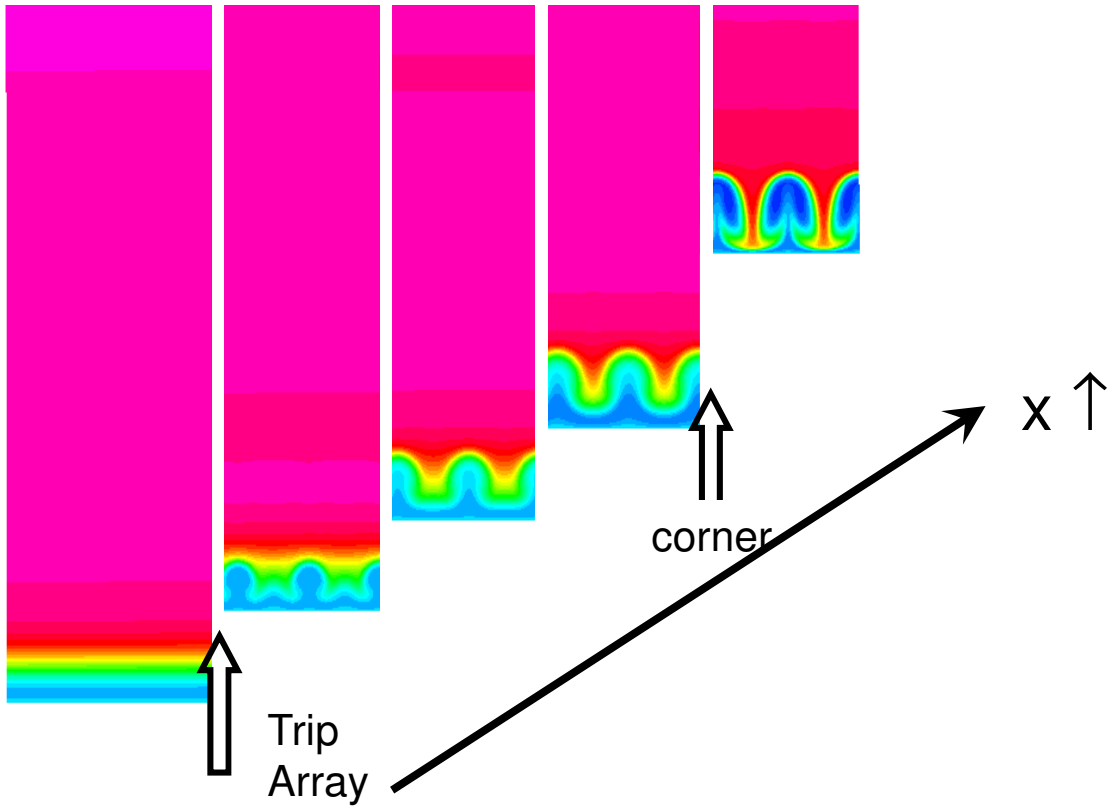
  * Not considering the role of immediate vicinity of the trip here!

Other Trip Configurations

- Effect of array spacing δ
- Effect of trip shape: diamond trips



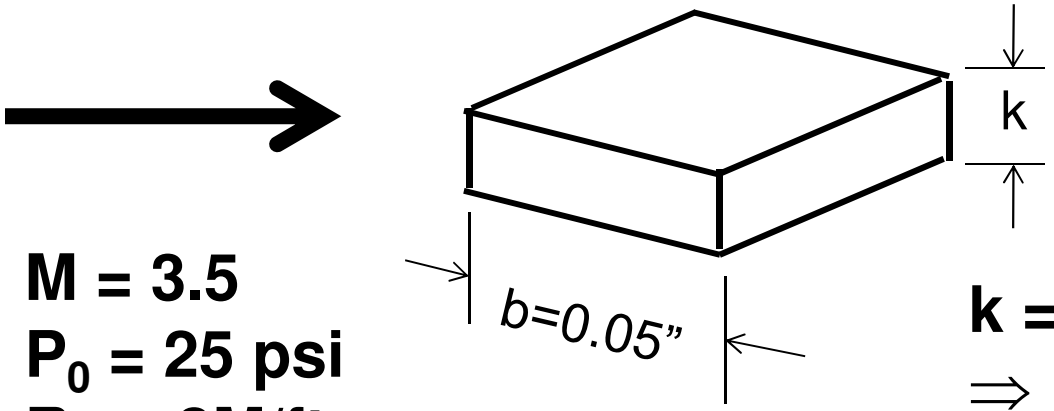
Similar findings,
Stronger streaks



Isolated Roughness on Flat Plate
NASA Quiet Tunnel Experiment (Kegerise et al.)

Diamond Trip Located at X ≅ 1.6”

(plate length = 16”)



M = 3.5
P_0 = 25 psi
Re ≈ 3M/ft
$\delta_{0.995} \approx$ 0.027”

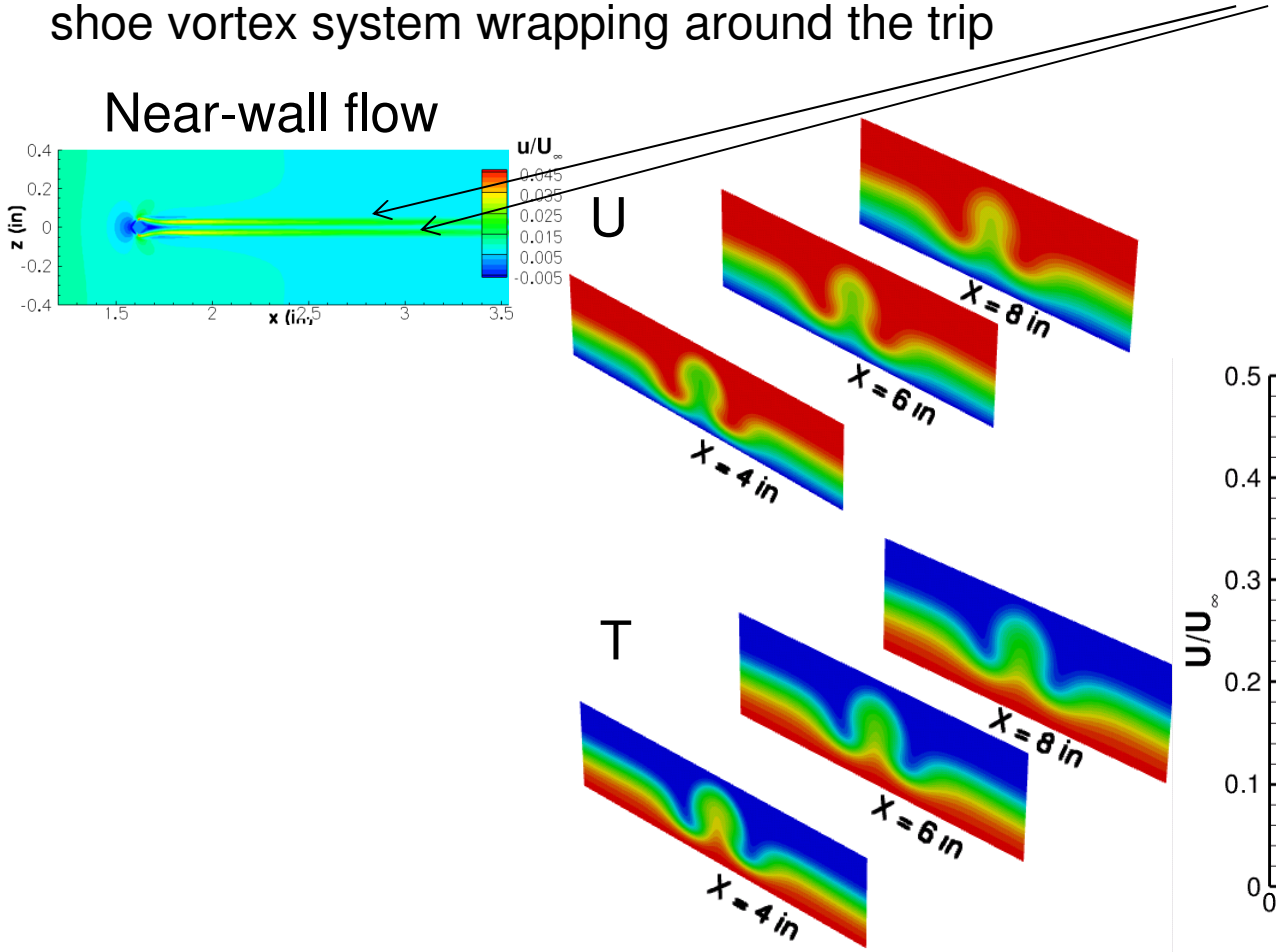
k = 0.015”
$\Rightarrow Re_{kk} \approx 550$

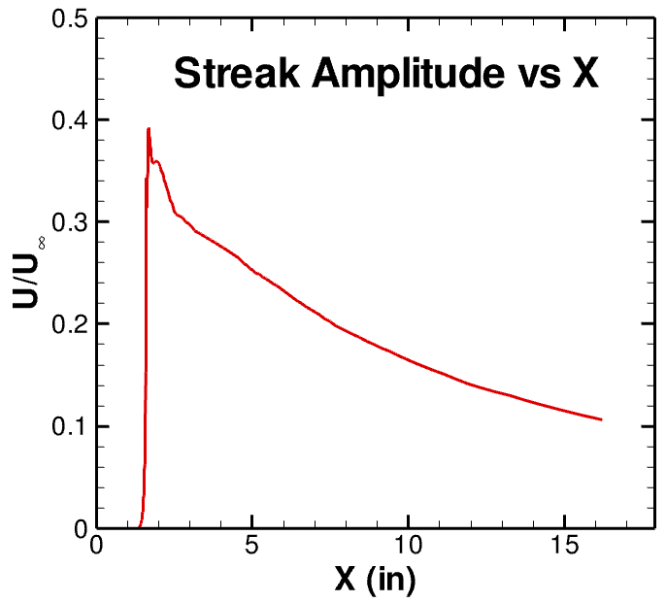
$$\frac{Re_\theta}{M_e}\frac{k}{\delta_{0.995}} \approx 66$$

- x_{tr}(N=9) ≈ 48”; x_{tr}(N=5) ≈ 18”, i.e., no transition over smooth plate
- Most amplified first mode instabilities over plate length
  - f = 20-25 kHz, spanwise wavelength >> b

Laminar Mean Flow Behind Roughness

- Navier-Stokes computations using immersed boundary method by Choi et al. (‘08)
- Long range wake signature includes a prominent centerline streak with increased boundary layer thickness, surrounded by higher-speed streaks associated with horse-shoe vortex system wrapping around the trip

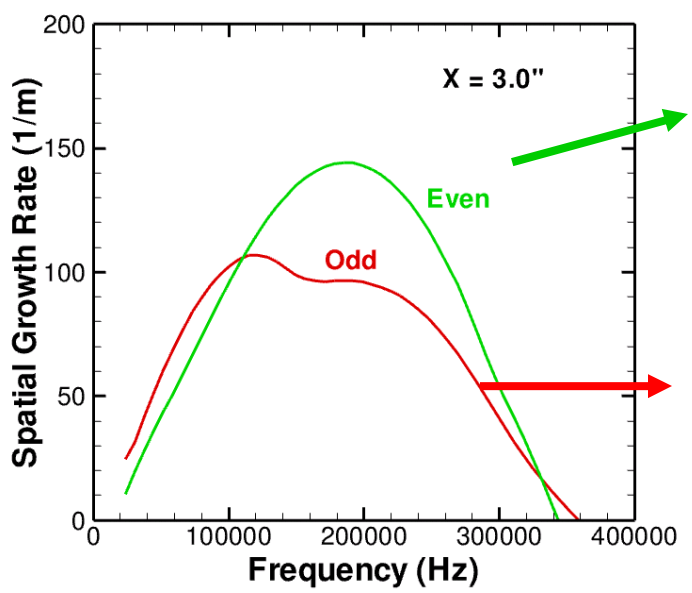


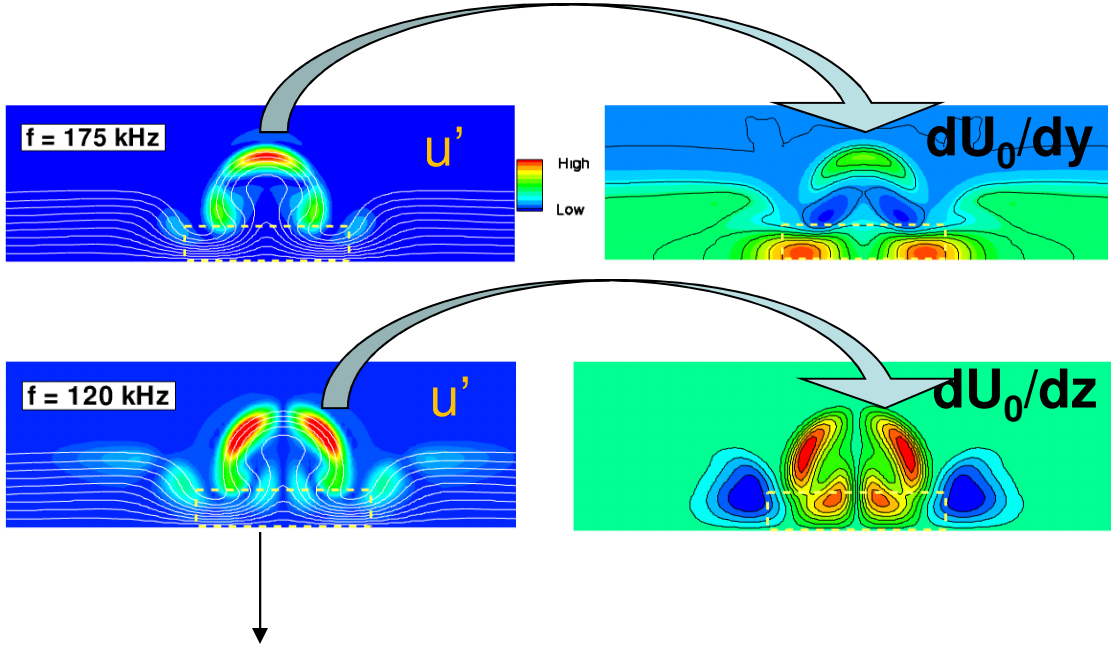


Instabilities of Isolated Roughness Wake

- Streak has comparable length scale in wall-normal and spanwise directions

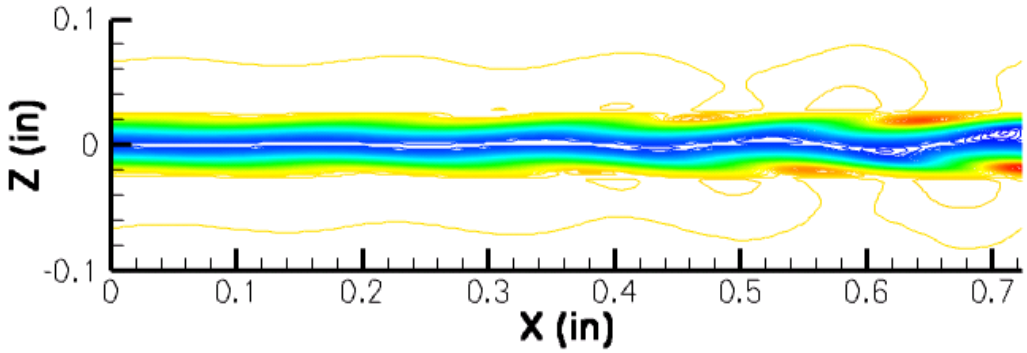
=> PDE based eigen analysis necessary to infer instability characteristics behind trip array



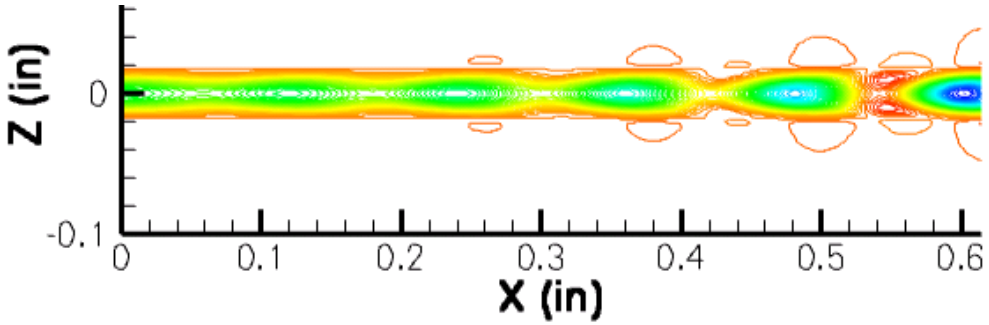


(yellow) dashed line:
cross-section of trip

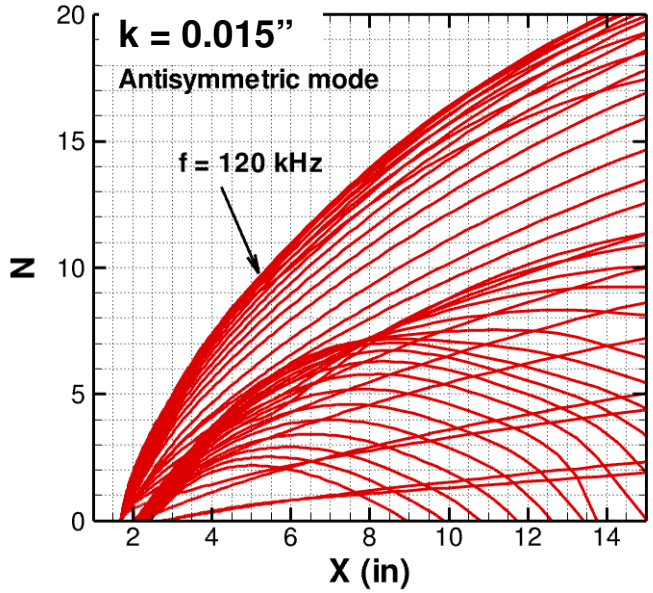
Integrated Amplification of Streak Instabilities (N factors)

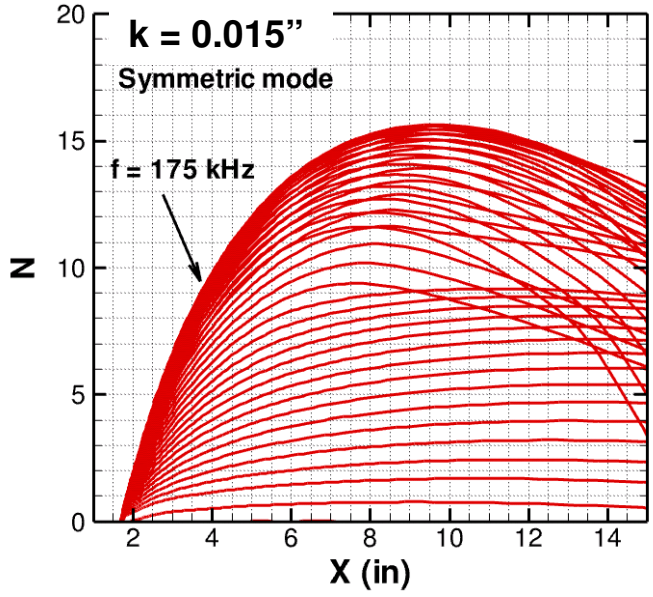


Mode 1: odd / sinuous
f = 120 kHz, X = 0.0766 m



Mode 2: even / varicose
f = 175 kHz, X = 0.0766 m

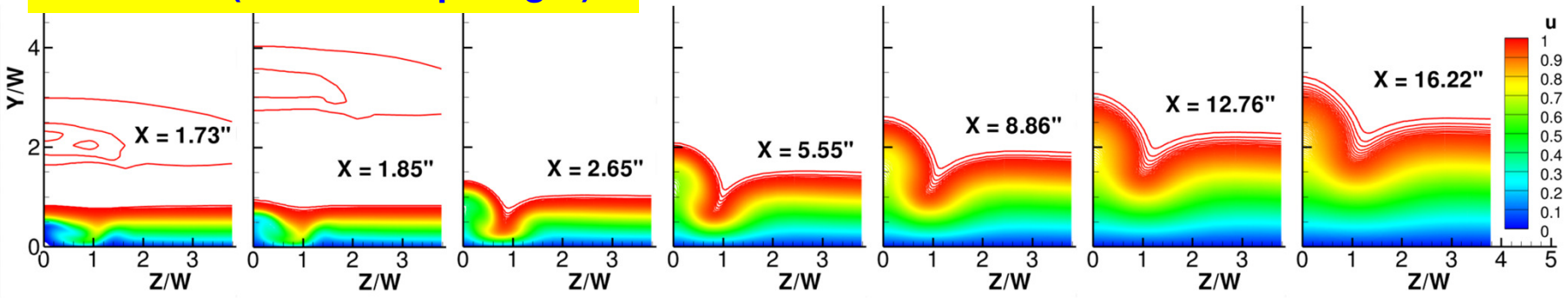




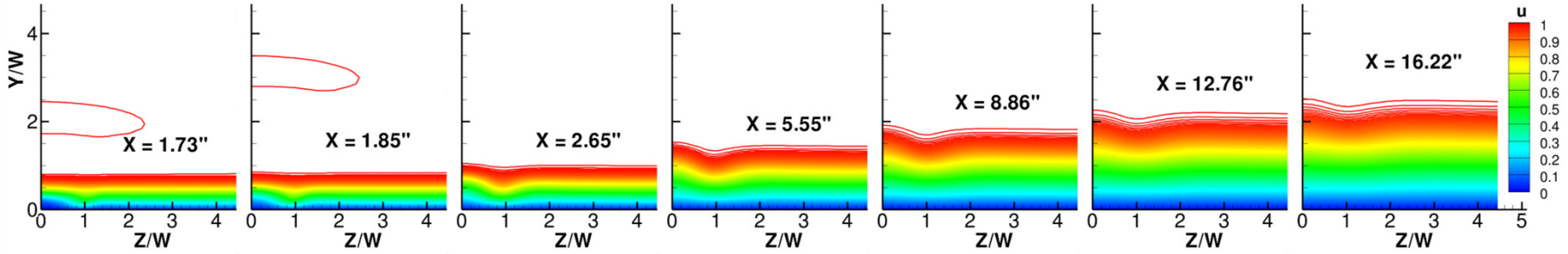
Isolated Diamond Trip Over Flat Plate

Evolution of Streamwise Velocity Contours

k = 0.015” (baseline trip height)



k = 0.0075”

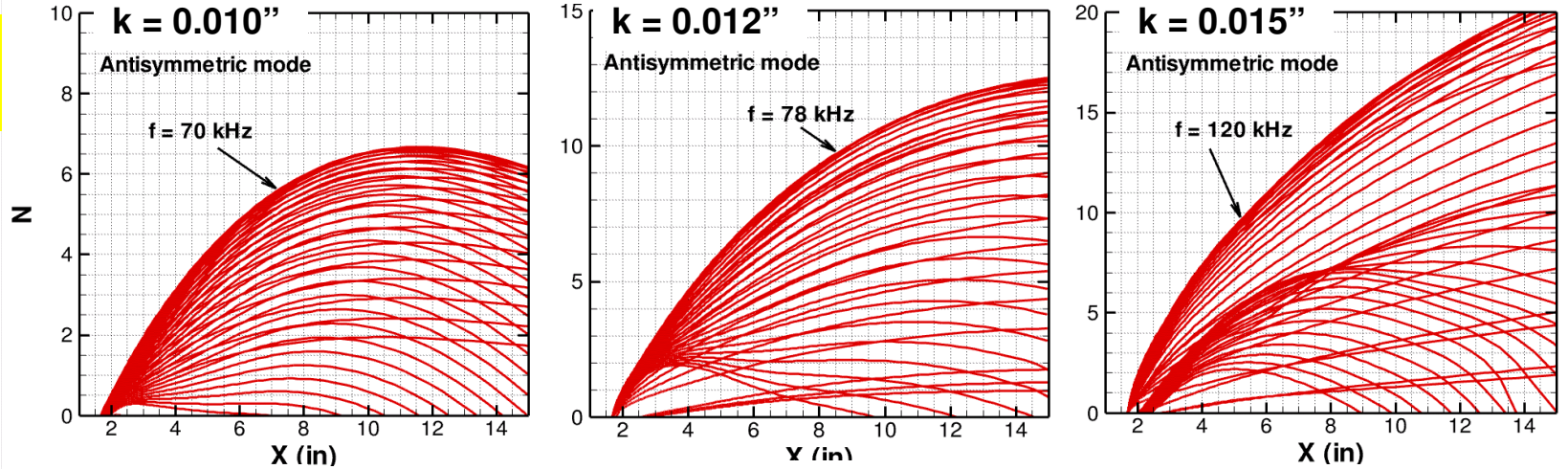


- k = 0.0075” ⇒ weak wake signature (⇒ weaker wake instabilities)
  - Nonlinear dependence of streak amplitude on roughness height

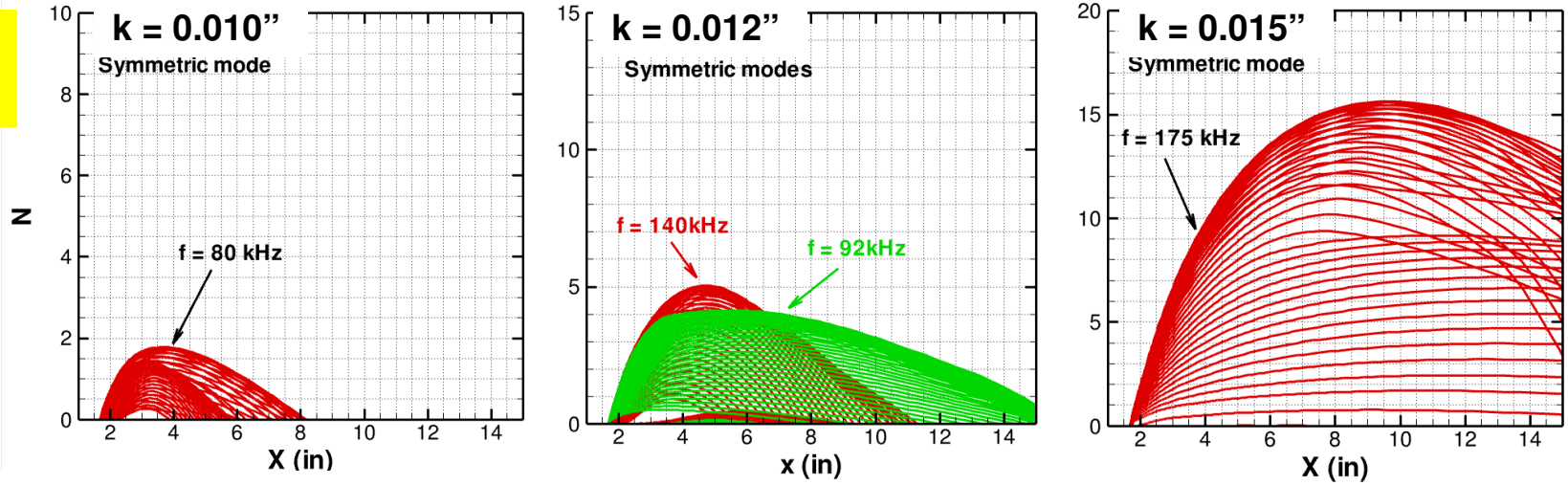
Isolated Diamond Trip Over Flat Plate
Effect of Trip Height on Growth of Streak Instabilities

- Heights large enough to ensure N > 5: k = 0.010”, 0.012”, and 0.015”

Odd Mode



Even Mode

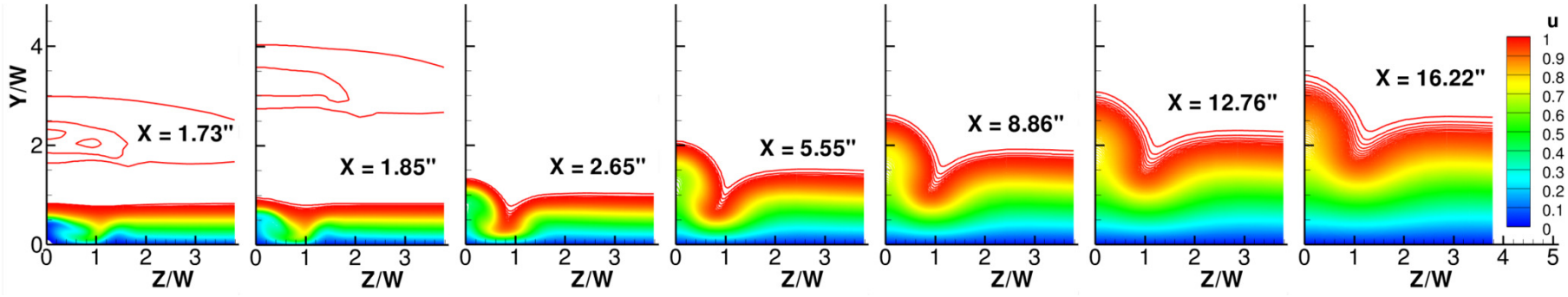


- Post “critical” heights: odd mode significantly stronger
- k ≥ 0.015”: even mode reaches N=5 and N=9 first

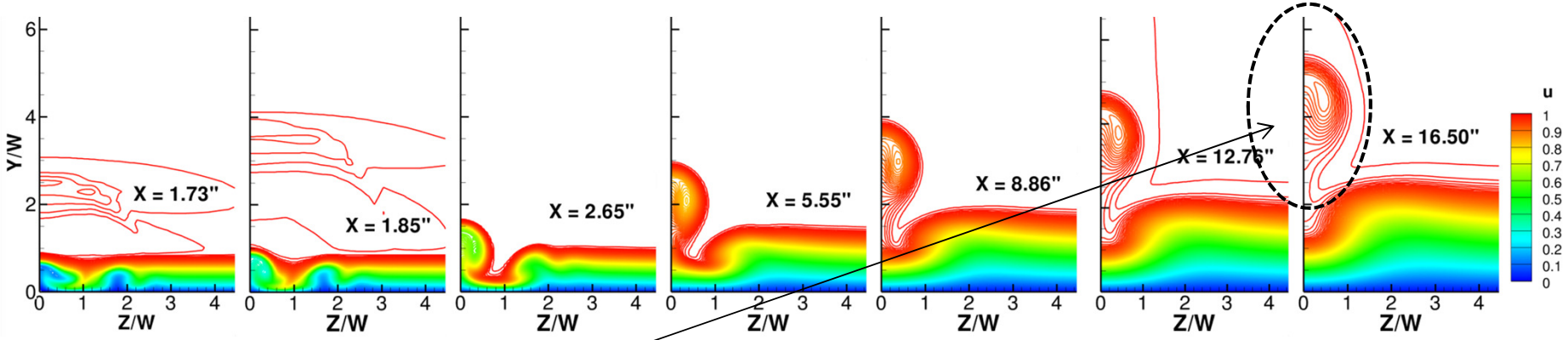
Evolution of Streamwise Velocity Contours at Larger Height

k = 0.015”

X →

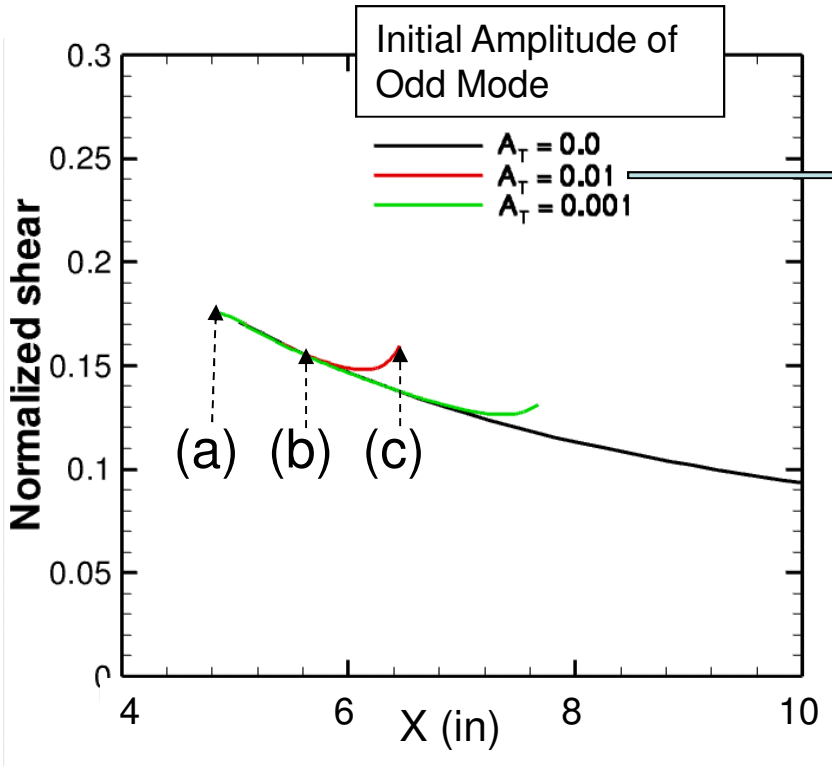


k = 0.020”



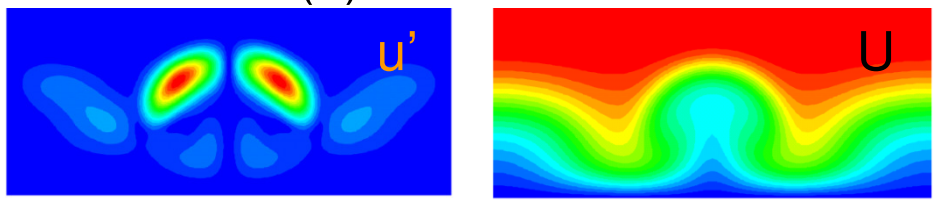
- Vorticity structure pinching off at large heights (k≥0.02”)

Can wake modes with large enough N-factor cause transition? Nonlinear PSE Computations for Odd Mode Evolution

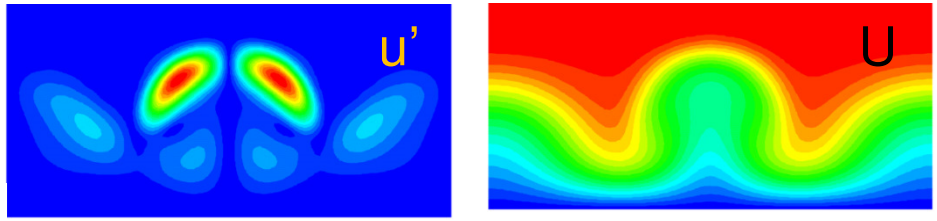


A_T = 0.01

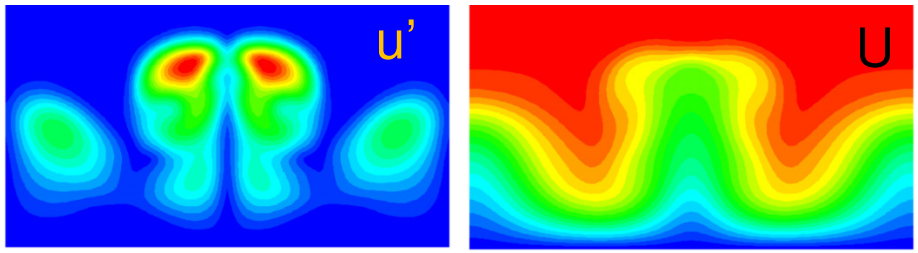
(a) X=0.121 m



(b) X = 0.141 m

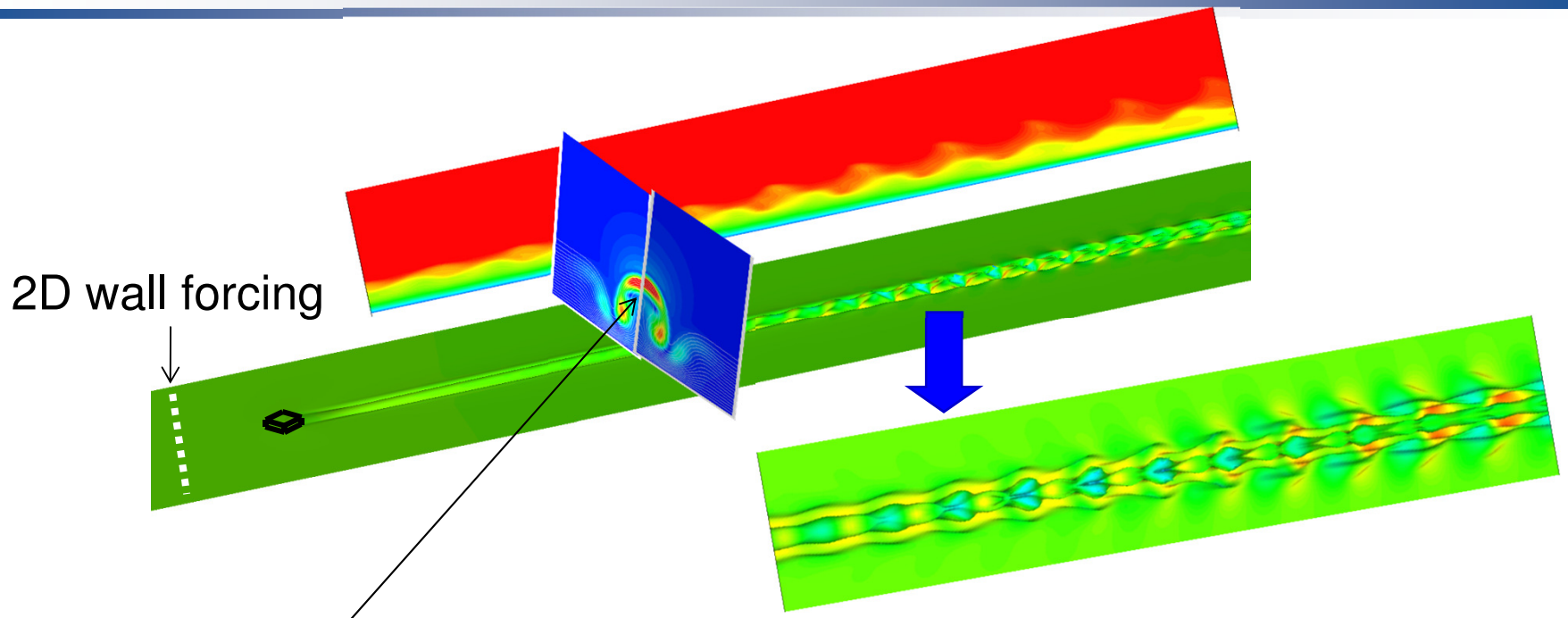


(c) X = 0.161 m



- Initial disturbance amplitudes (i.e., disturbance environment) can impact streak induced transition
- "Amplitude" criterion for transition onset, provided initial amplitudes (i.e., excitation mechanisms) are known

Excitation of wake instability via interaction between upstream disturbances and roughness nearfield

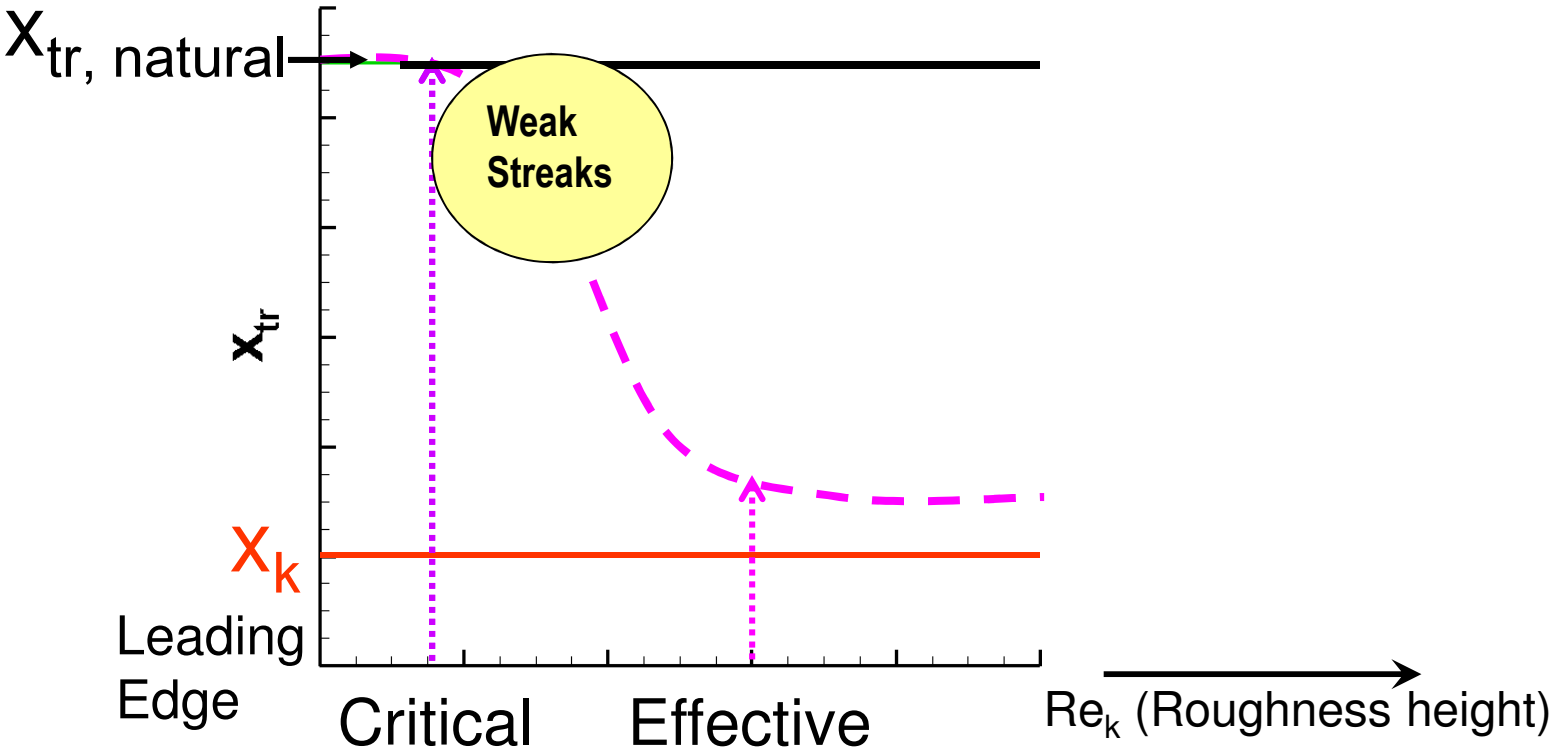


- Roughness nearfield scatters upstream 2D disturbances into wake instability modes
  i.e., no special ingredients necessary to induce receptivity!
- Signs of transition onset seen within downstream portion of simulation



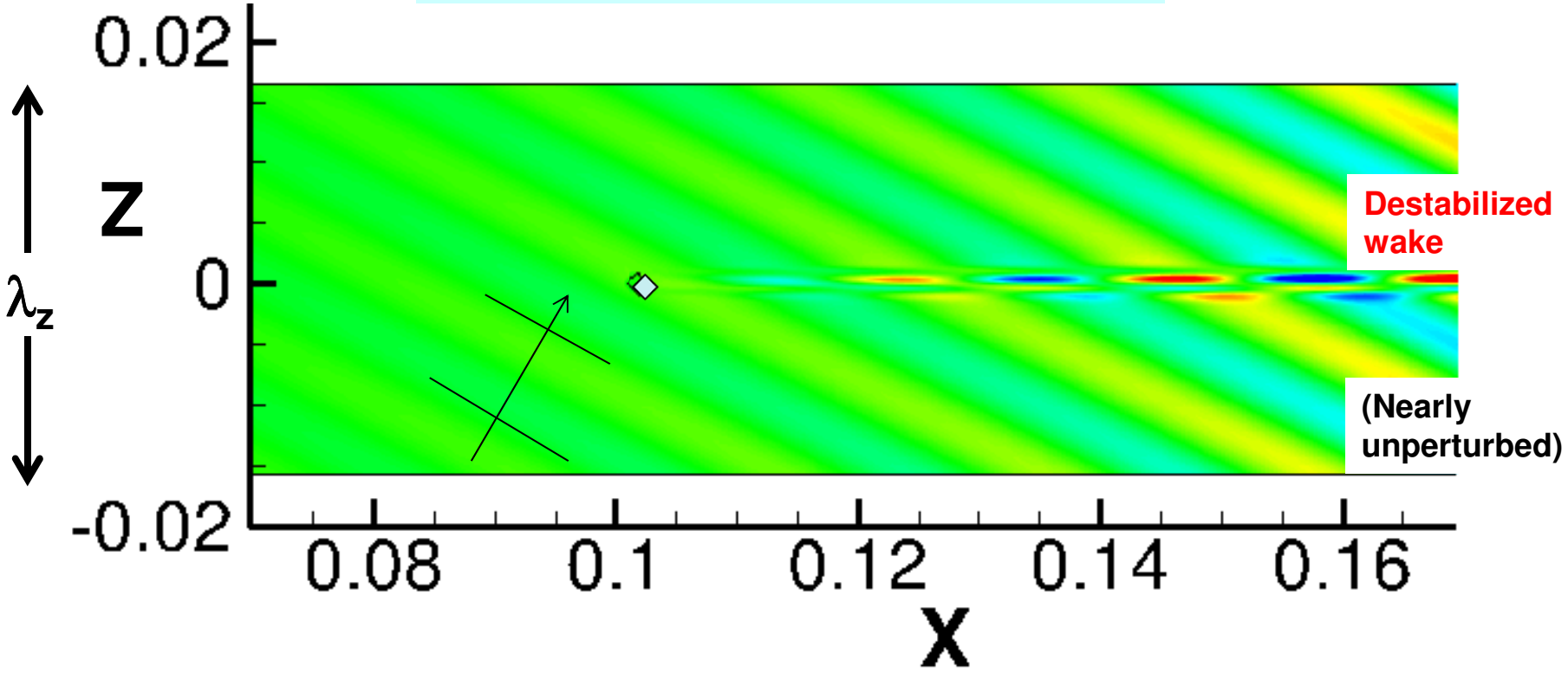
Wake interaction with instability modes in approaching boundary layer

Effect of trip height



Effect of "Smaller" Height Roughness on 1st Mode Growth

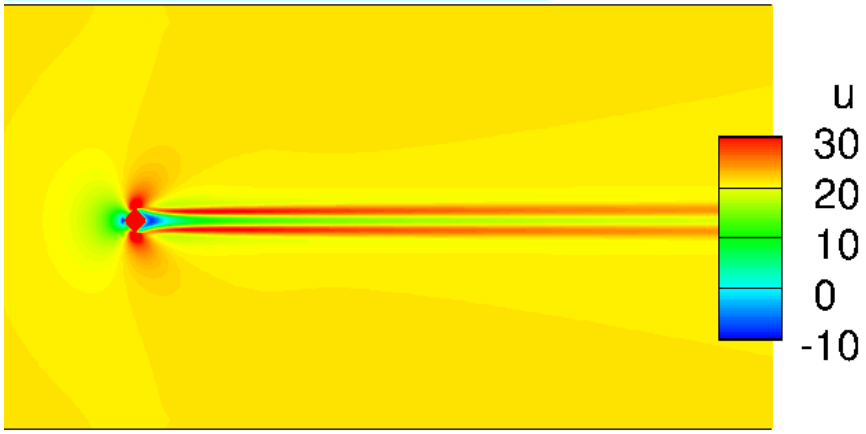
u' contours near height of max |u'|



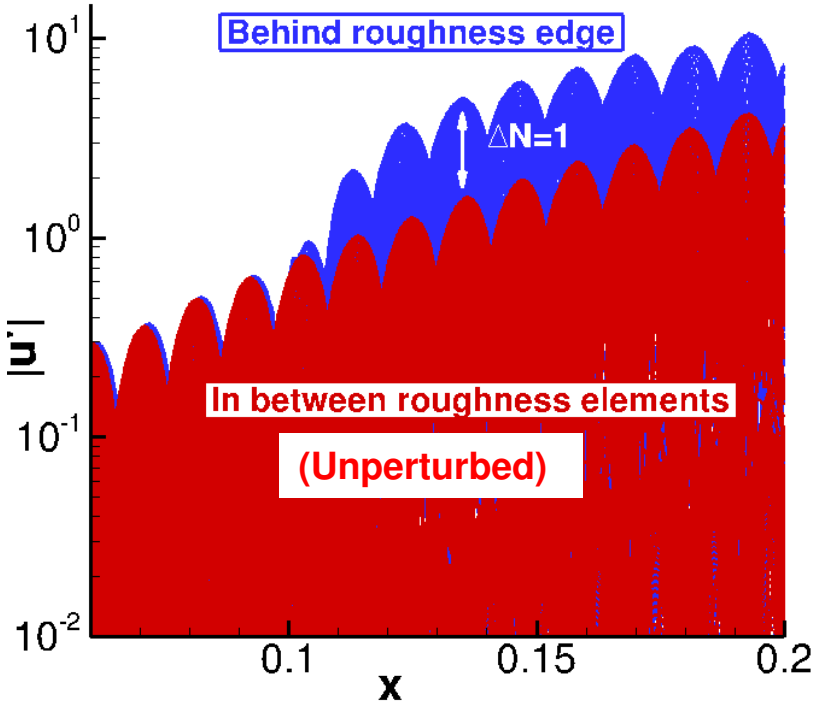
- Higher 1st mode growth within near wake

Effect of "Smaller" Height Roughness on 1st Mode Growth

Near wall u contours

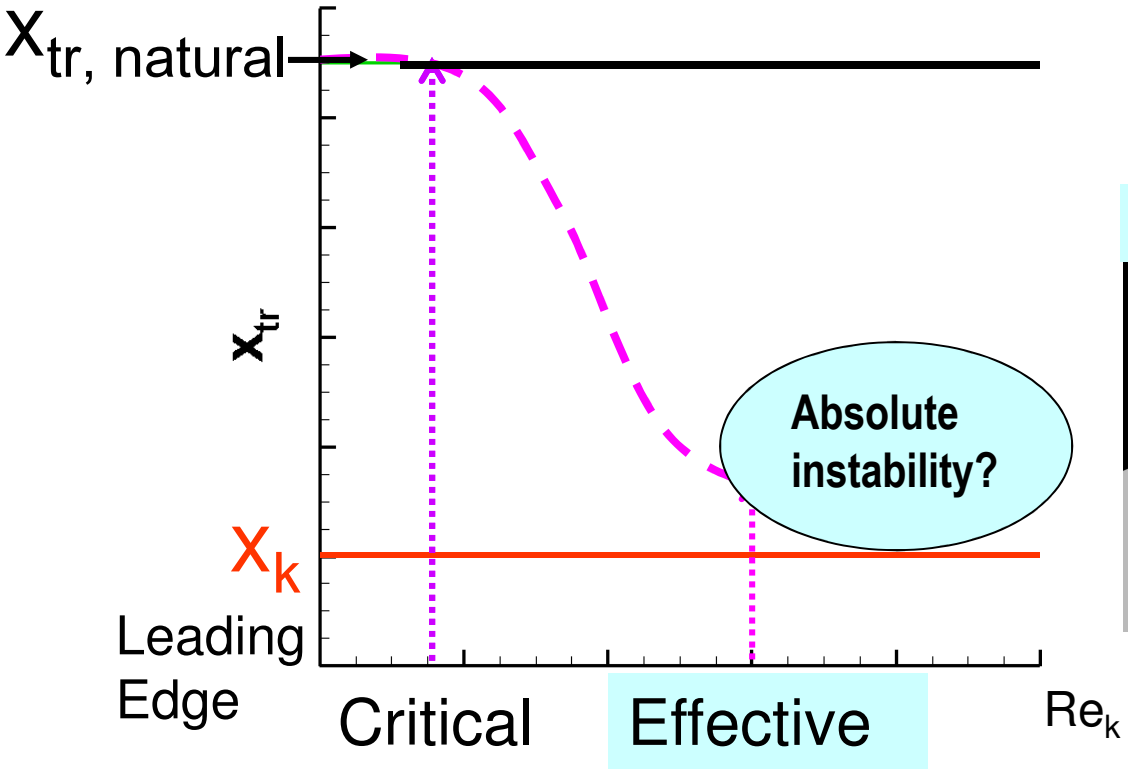


u' evolution with and w/o roughness

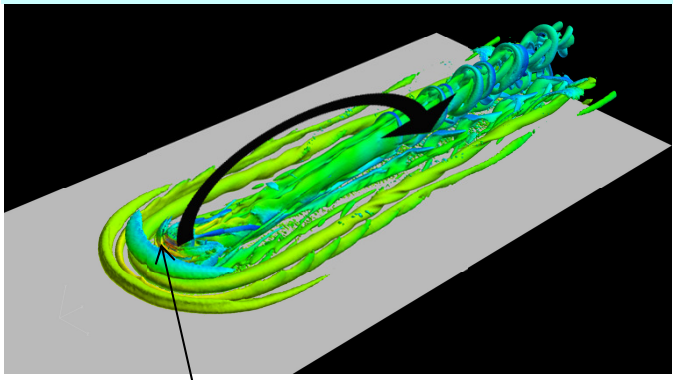


- Moderately higher growth in near to intermediate wake
- Effect analogous to backward facing step

Effect of trip height



"Large" roughness in hypersonic b.l.

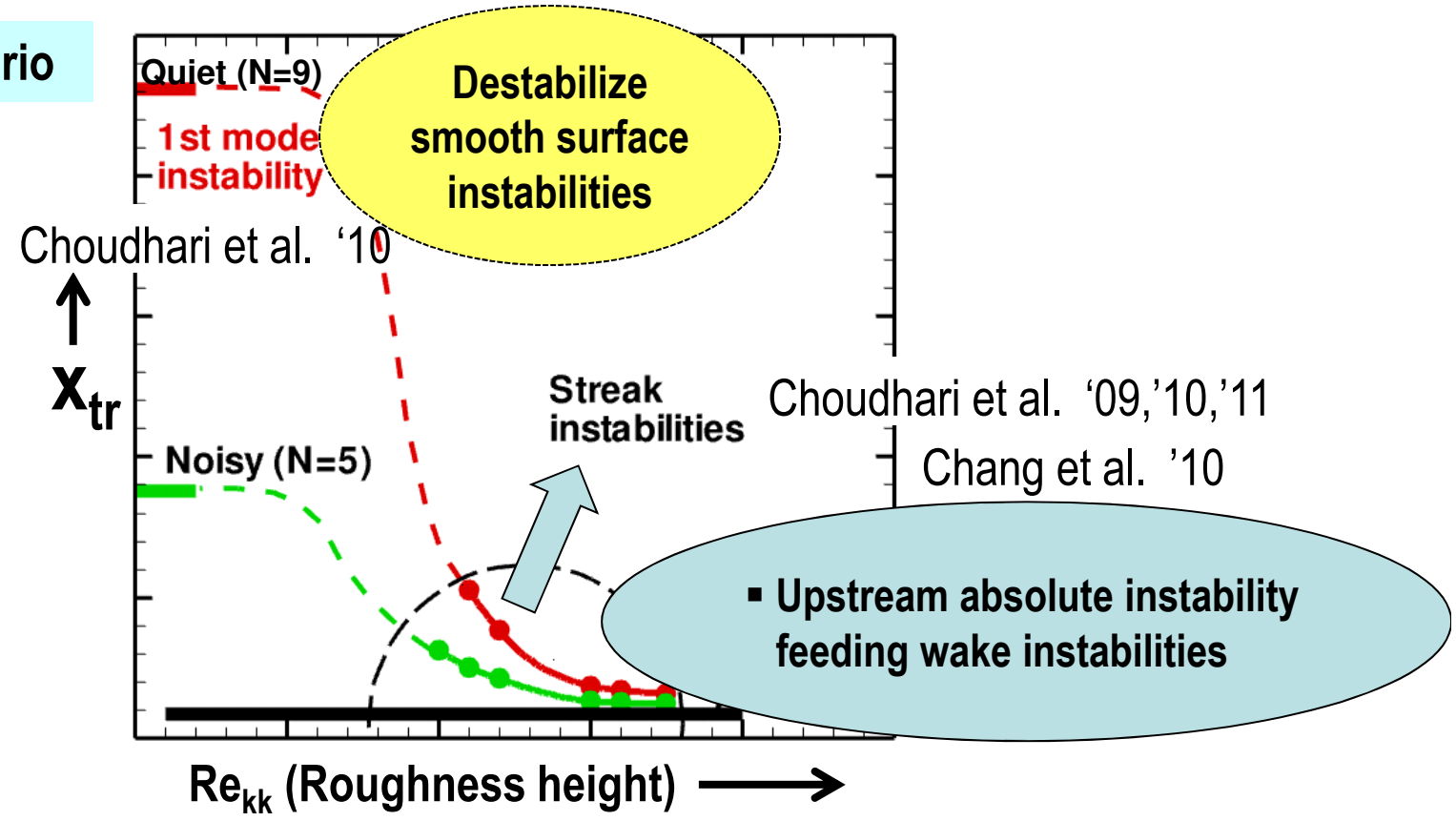


Chang et al. (2009-0173)

- **Instability originates in front separation region**
- **Feeds into wake amplifier**

Transition Prediction via Amplification Ratio (N-factor) Criterion: Effect of Roughness Height

Possible scenario



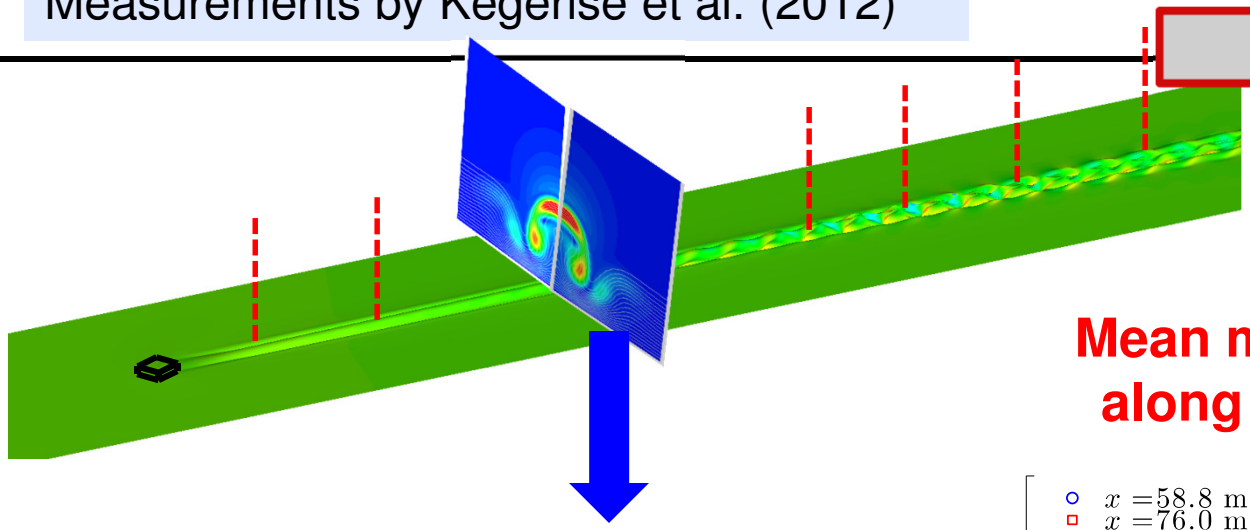
- Variation in transition location similar to existing measurements in conventional and quiet facilities



Validation of Streak Instability Theory

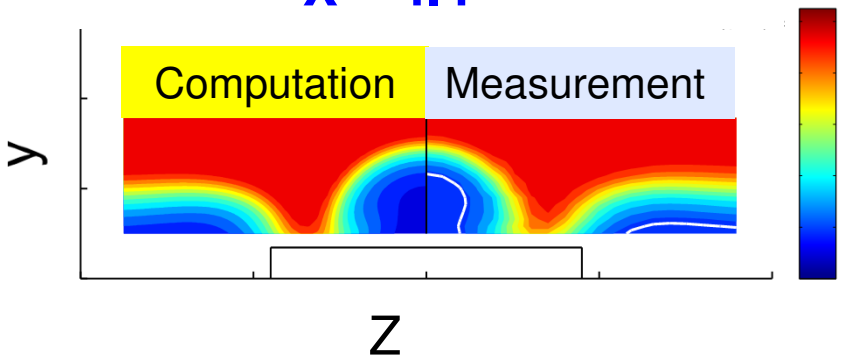
Computation vs. Experiment : Steady Flow

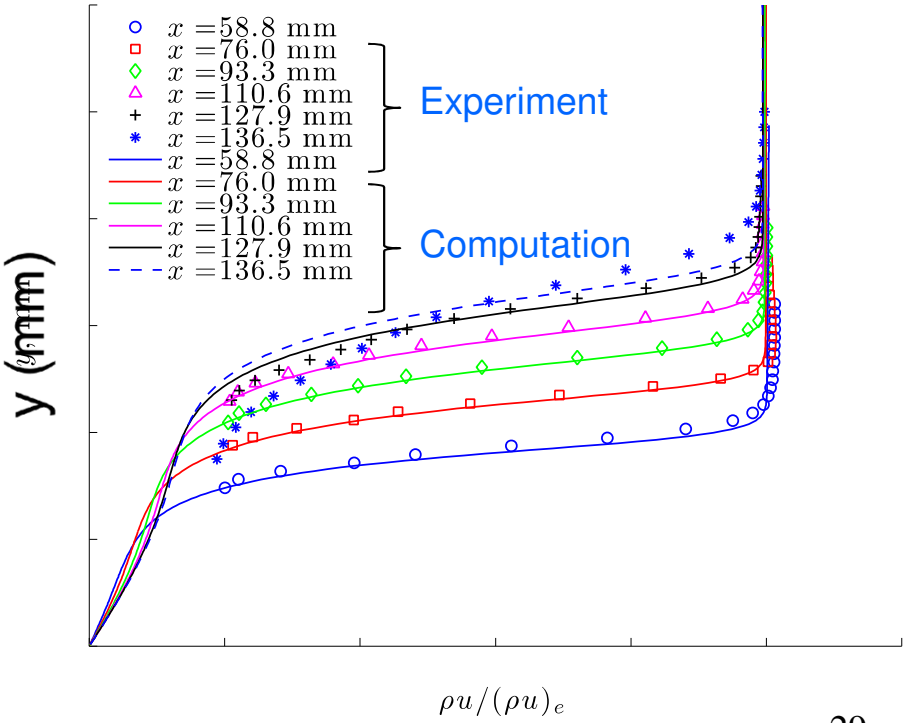
Measurements by Kegerise et al. (2012)



Mean mass-flux profiles along wake centerline

Mean mass-flux distribution
X ≈ 4.4”

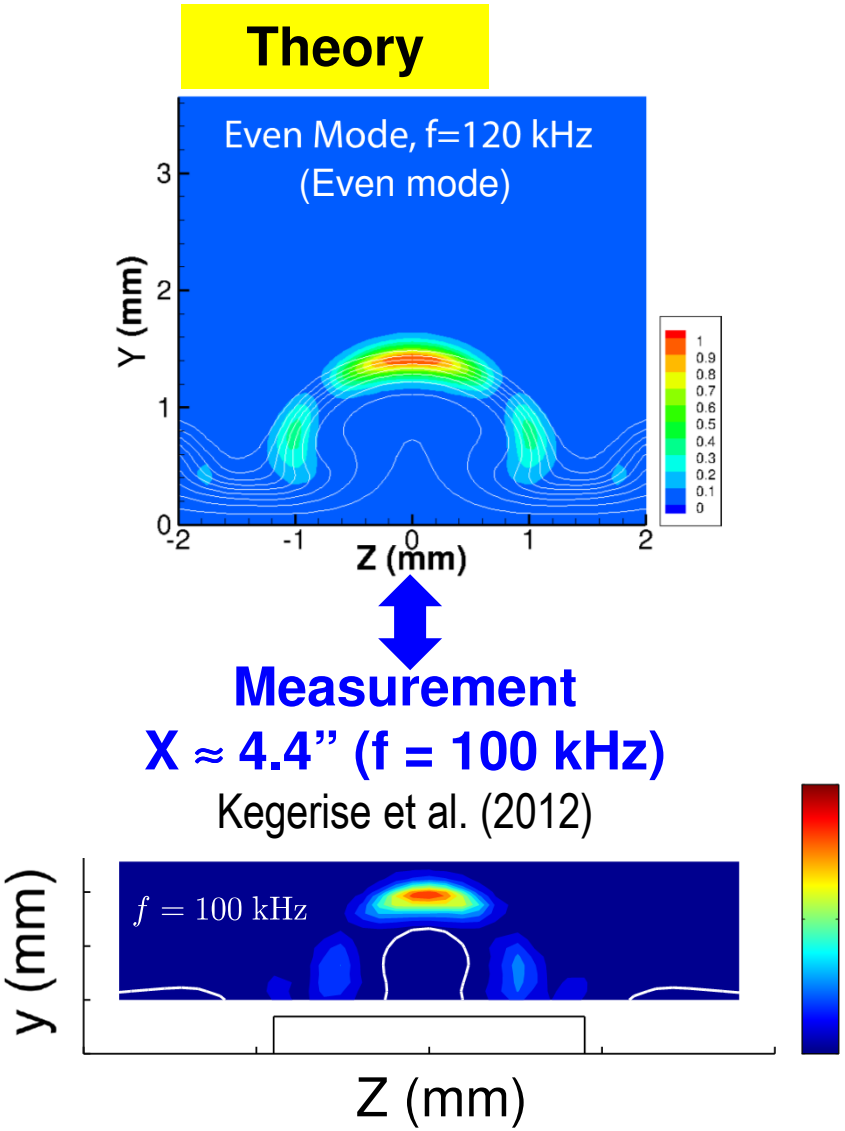




- **Excellent quantitative agreement between computation + measurement**

Unsteady Fluctuations

Mass Flux Distribution over Streak Cross-Section

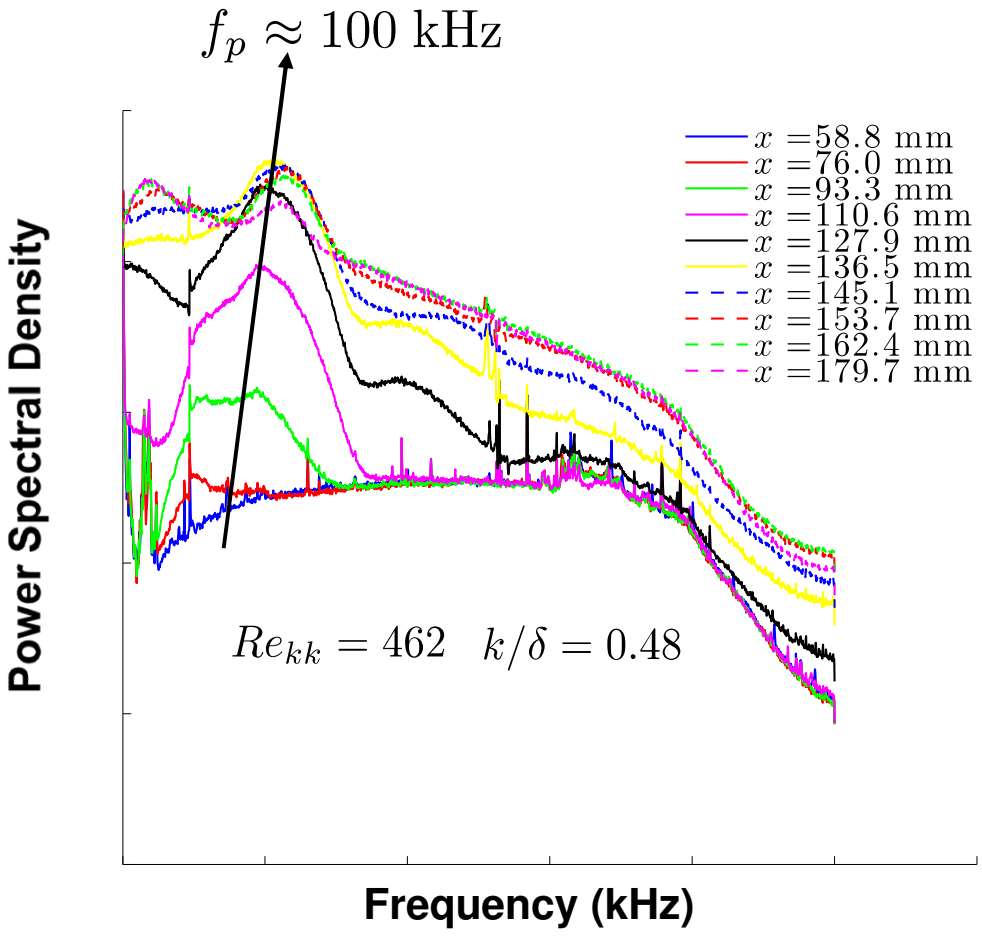


- **Same fluctuation mode shapes in computation and measurement**

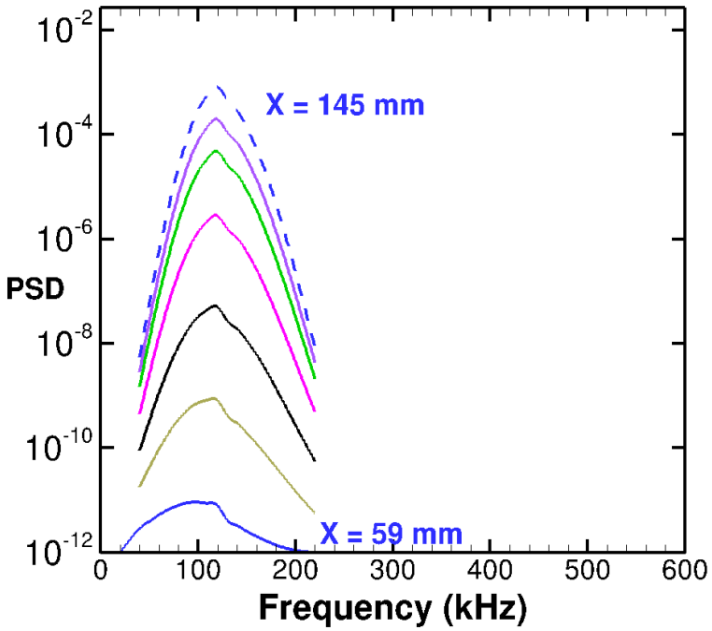
Mass-Flux Spectra in Roughness Wake

Measured mass-flux spectra
(selected stations along wake centerline)

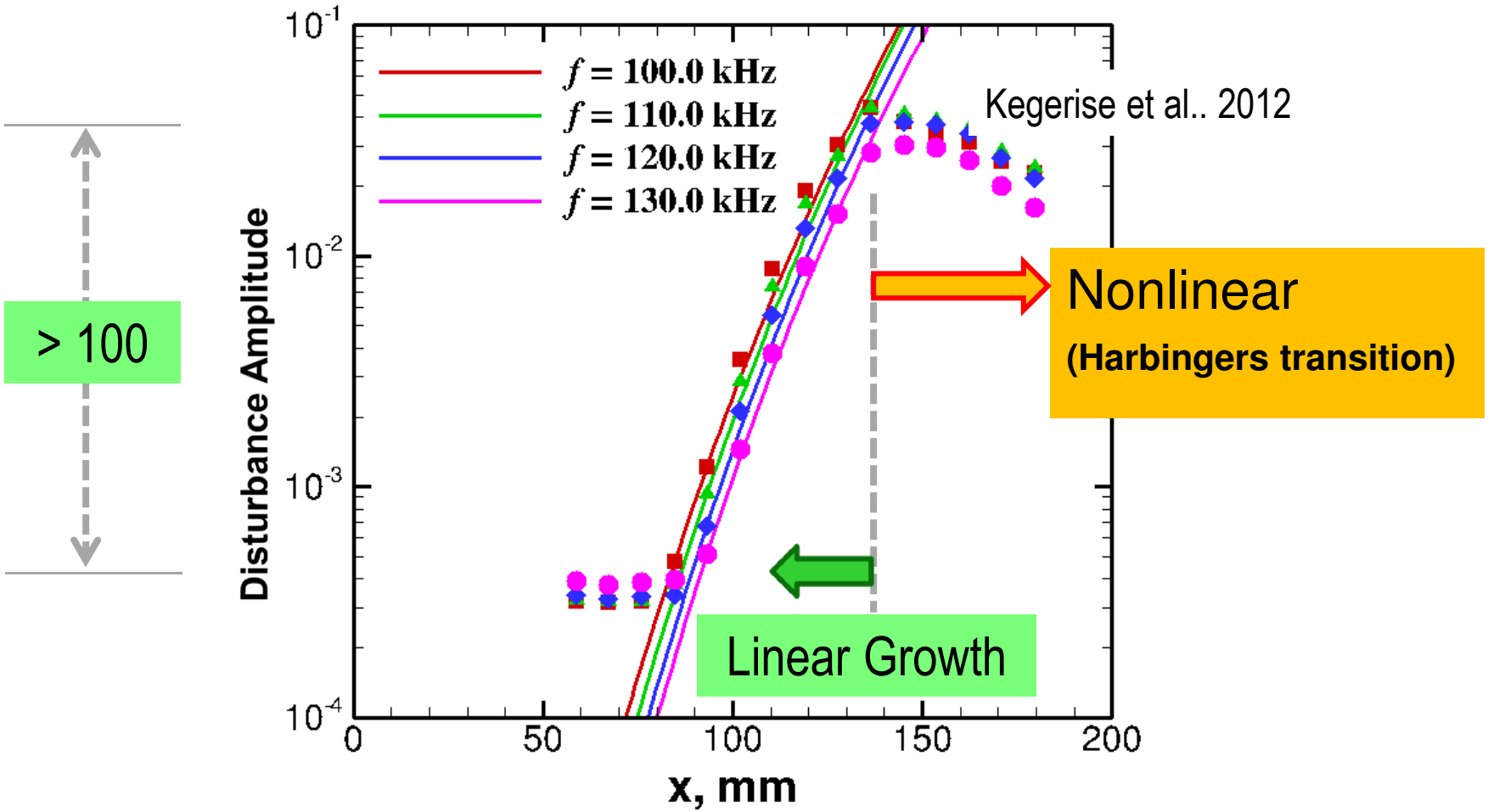
Kegerise et al.. 2012



Predicted spectra
(even mode)



Amplitude Growth of Dominant Fluctuations



- **In depth comparison with quiet tunnel measurements**

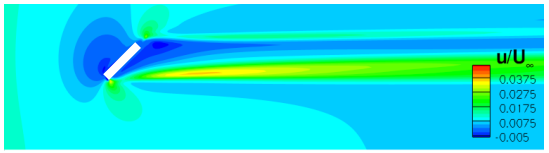
  ⇒ *Whodunit verdict:*

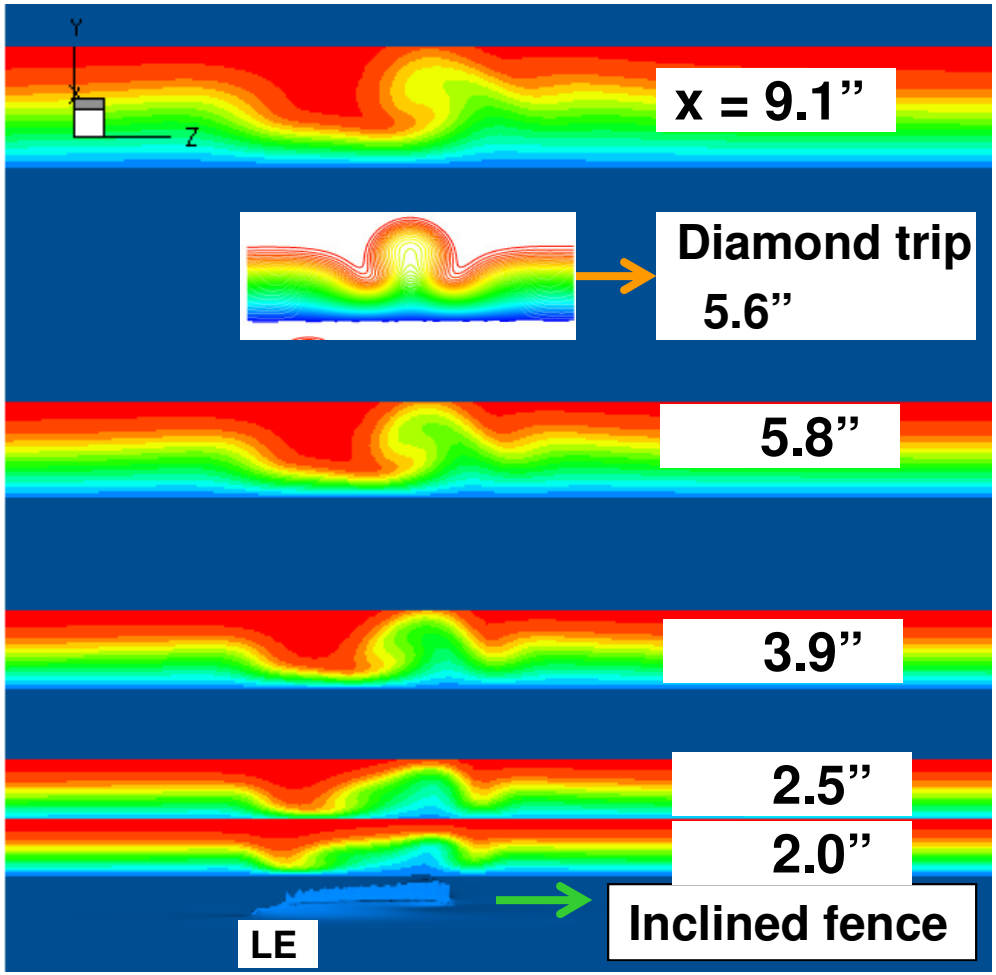
  Ms. Streak in far wake using (new class of) instabilities

Effects of Roughness Asymmetry: Wake of Rectangular Fence Inclined at 45 deg

(Aspect Ratio Similar to Orbiter Experiment)

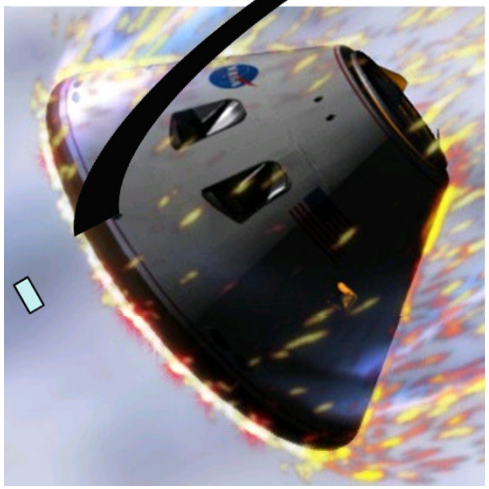
Near surface u contours



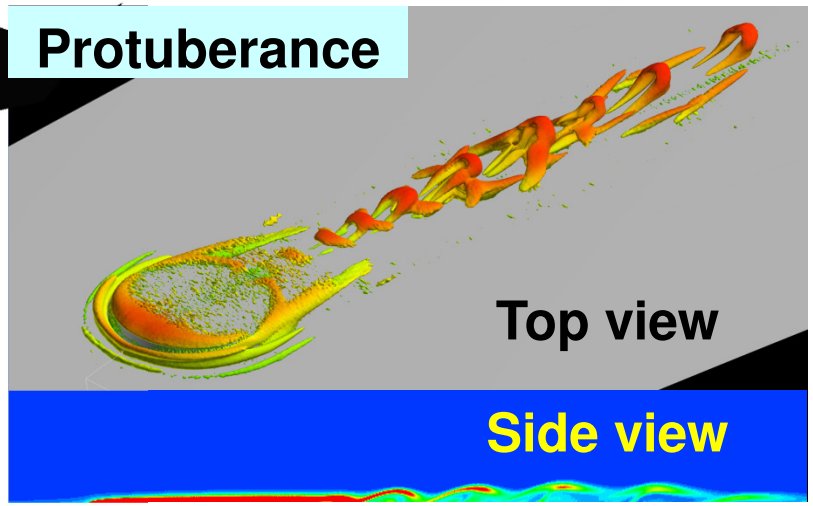


- Stronger low-speed streak behind downstream end of inclined fence
- Instability characteristics of asymmetric streak remain to be investigated

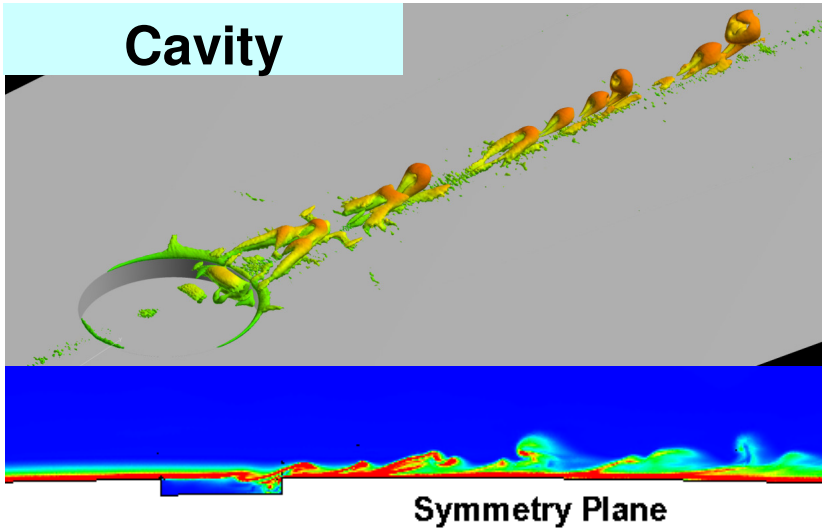
Trip Element on a Blunt Capsule



Often designed for fully turbulent heat loads



Chang et al. (2011)





Isolated Roughness Element in Mach 6 Boundary Layer

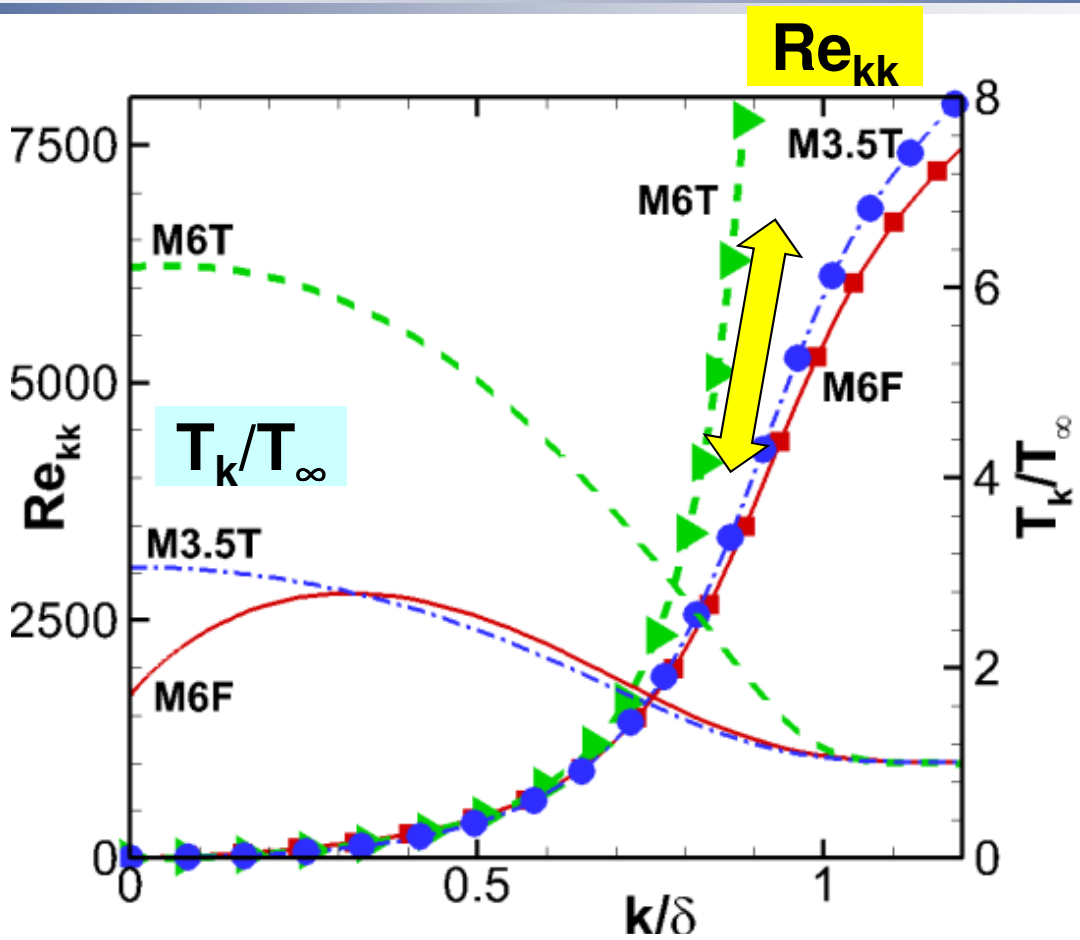
Roughness Element in M ≈ 6 B.L.

- **M = 3.5 vs. M ≈ 6**
  - ⇒ Change in instability mechanism in unperturbed/approaching flow
    (1st mode → 2nd mode ⇒ reduced gap between roughness and instability length scales)
  - ⇒ Change in B.L. profile
  - ⇒ Streak instability characteristics may change as well
- **Maintain partial dynamic similarity**
  - $k/\delta \approx 0.55$, $b/k \approx 3.33$, $Re_{kk} \approx 550$
  - Just one way of posing the comparison, useful precursor to study of Purdue exp.

Summary of Flow Configurations

Case	M_∞	$Re_u\,(m^{-1})$	$T_\infty\,(K)$	$x_r\,(m)$	T_{wall}/T_{ad}	Re_δ	$Re_\theta/M_e\;k/\delta$
M3.5T	3.5	9.89×10^6	87.0	0.0411	1.00	6.7×10^3	66
M6T	5.91	9.84×10^6	54.2	0.3853	0.90	36.9×10^3	119
M6F	5.91	2.07×10^6	226.9	0.1985	0.25	6.3×10^3	35

Re_{kk}, T_k/T_∞ vs. k/δ



- Re_{kk} and T_k/T_∞ variation in M6F case rather similar to M3.5T, despite differences in Mach number
- Steep variation in Re_{kk} for $k/\delta > 0.7$: Is it accompanied by abrupt change in flow physics?

(vs. linear variation in $Re_\theta/M_e\ k/\delta_{0.995}$)

Instability Amplification (M6T)

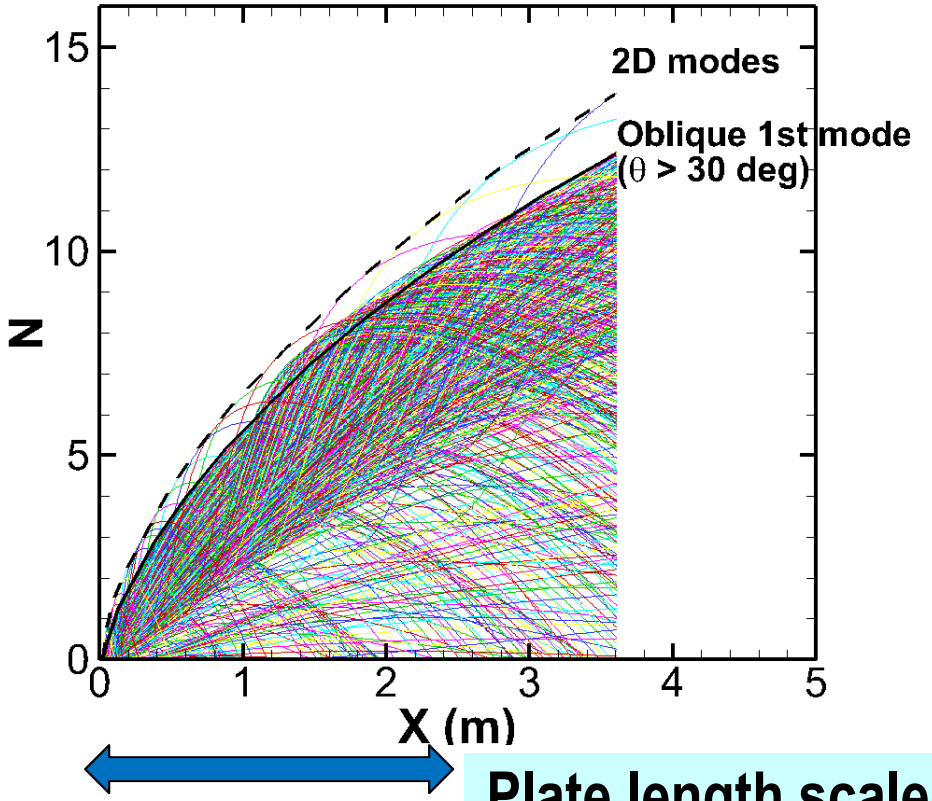
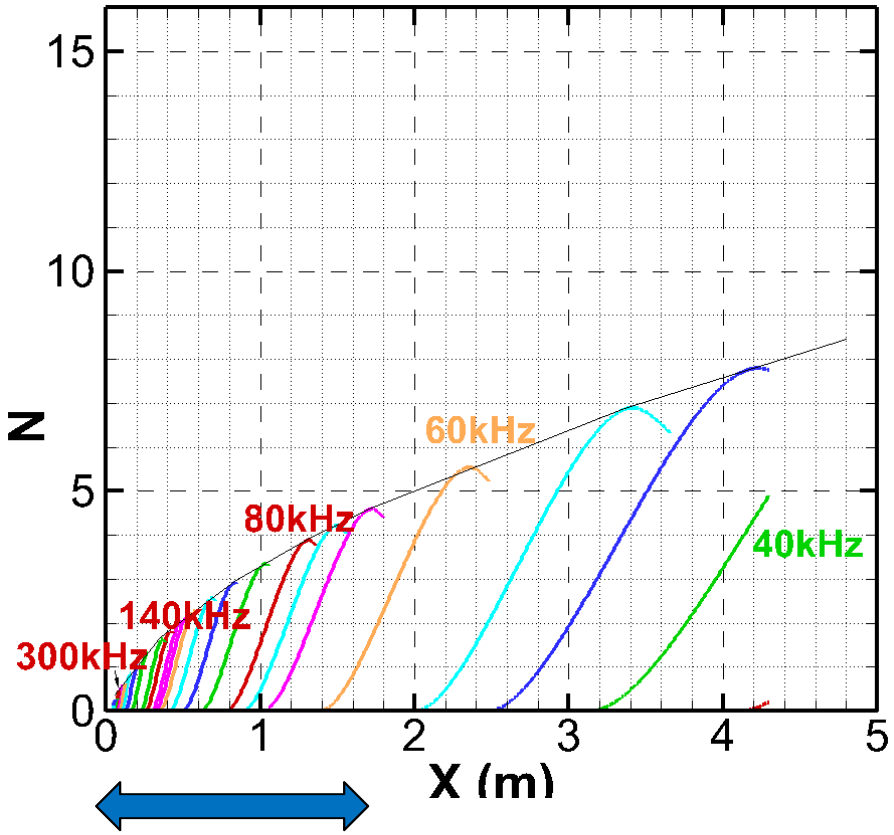


Plate length scaled from M3.5T

- No roughness case: N=10 at x=2.2m
- Nearly comparable N factors for 2nd mode and oblique first mode waves
- Faster growth of streak instabilities than 1st and 2nd mode waves

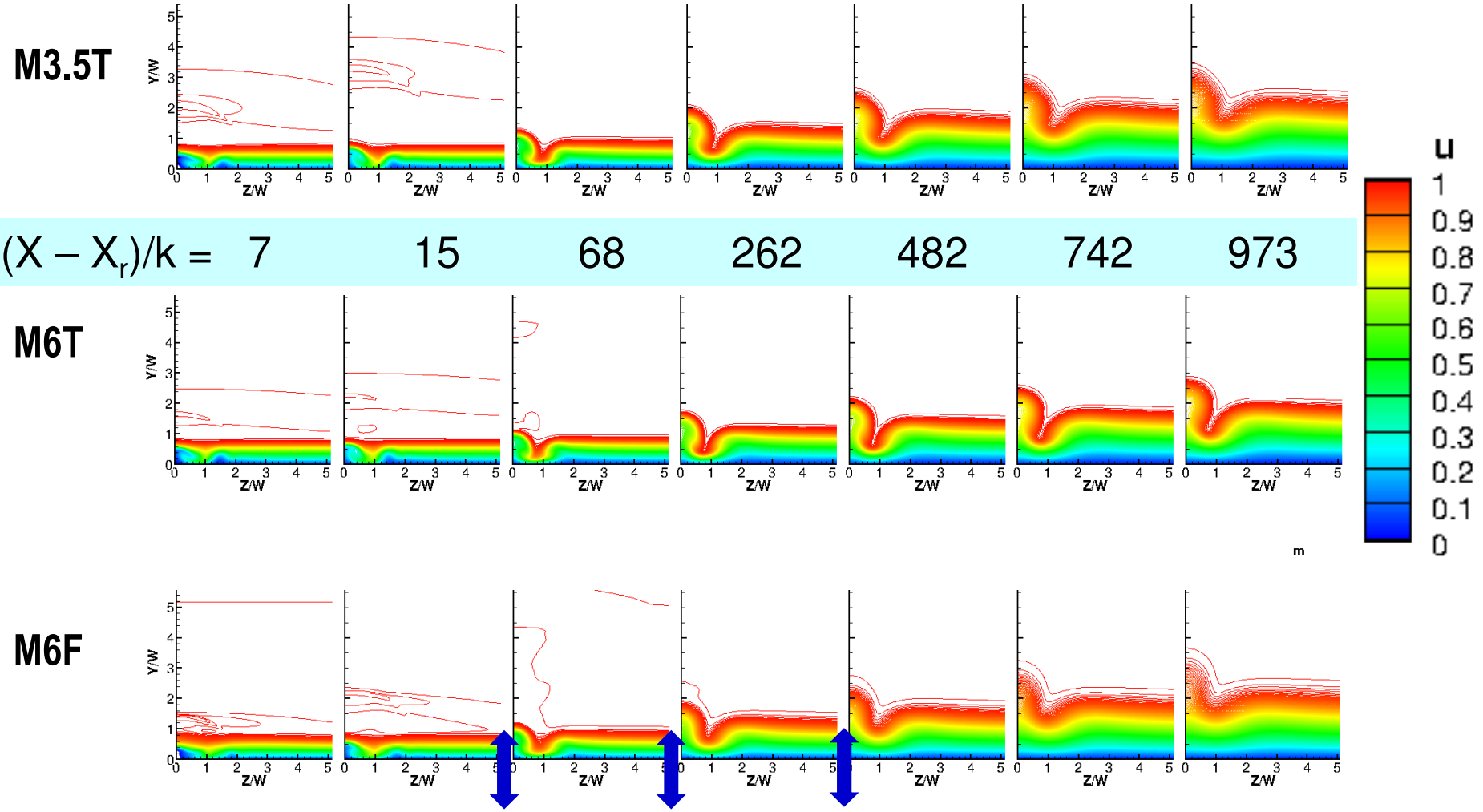
Instability Amplification (M6F)



- M6F: cold wall case ⇒ 2nd mode waves dominate in no-roughness case
- N<10 for X<5m
- Streak instabilities achieve higher amplification than 2nd mode waves

u-Contours within Wake

- Same values of $(X - X_r)/k$ in all cases



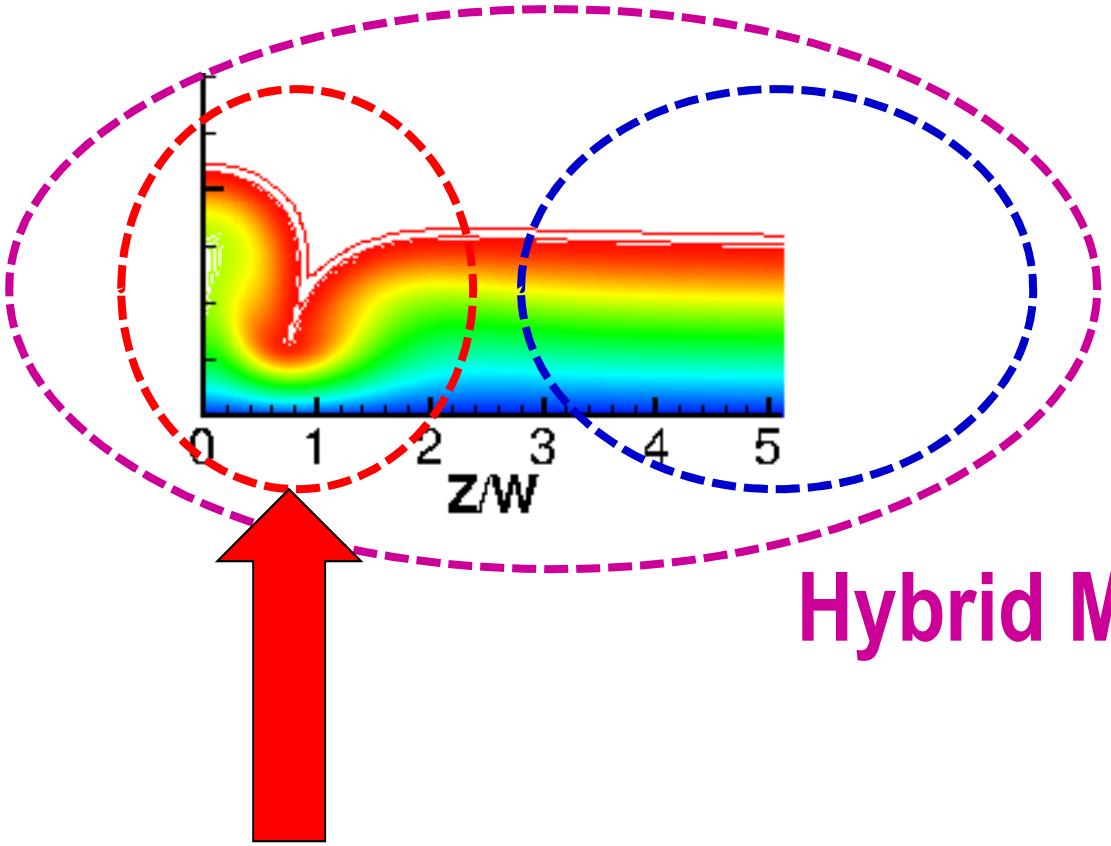
$(X - X_r)/k$ = 7 15 68 262 482 742 973

- u-contours in Mach 6 cases similar to M3.5T case

M6T: u' Mode Shapes

Wake Modes

B.L. Mode(s)

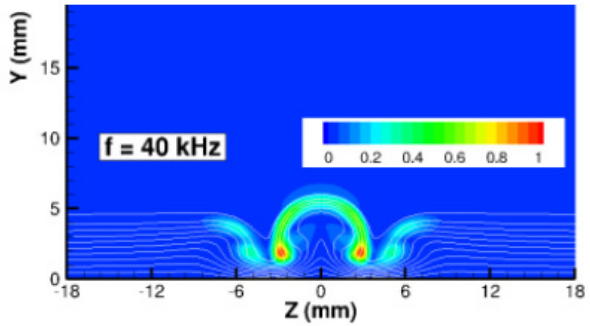


Hybrid Mode(s)

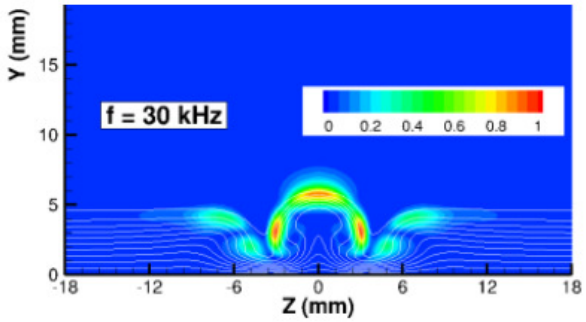
M6T: u' Mode Shapes for Wake Modes

$(x-x_r)/k \approx 92$

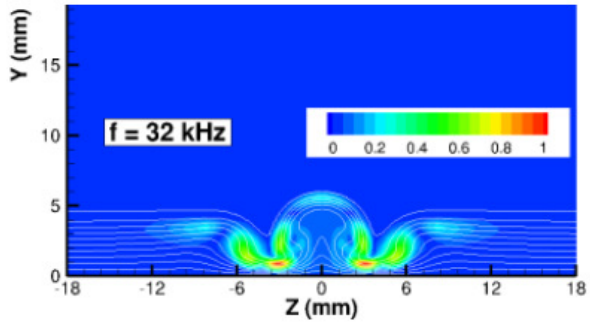
Even Modes



(a) Mode S

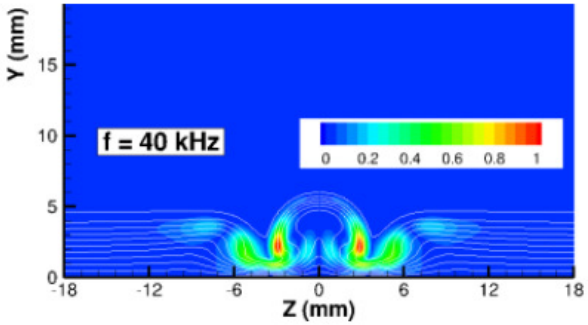


(b) Mode CS

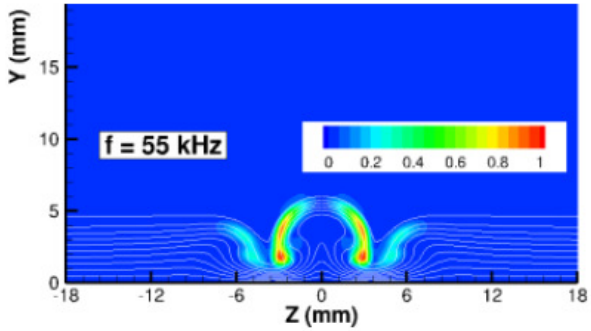


(c) Mode SI

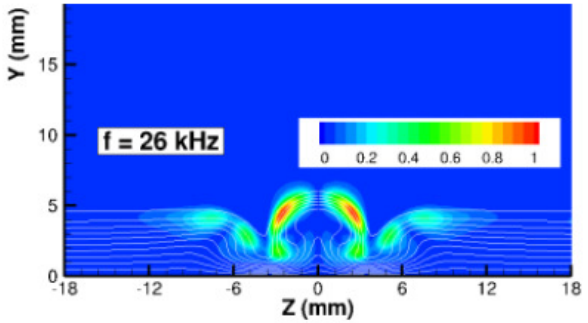
Odd Modes



(a) Mode SI



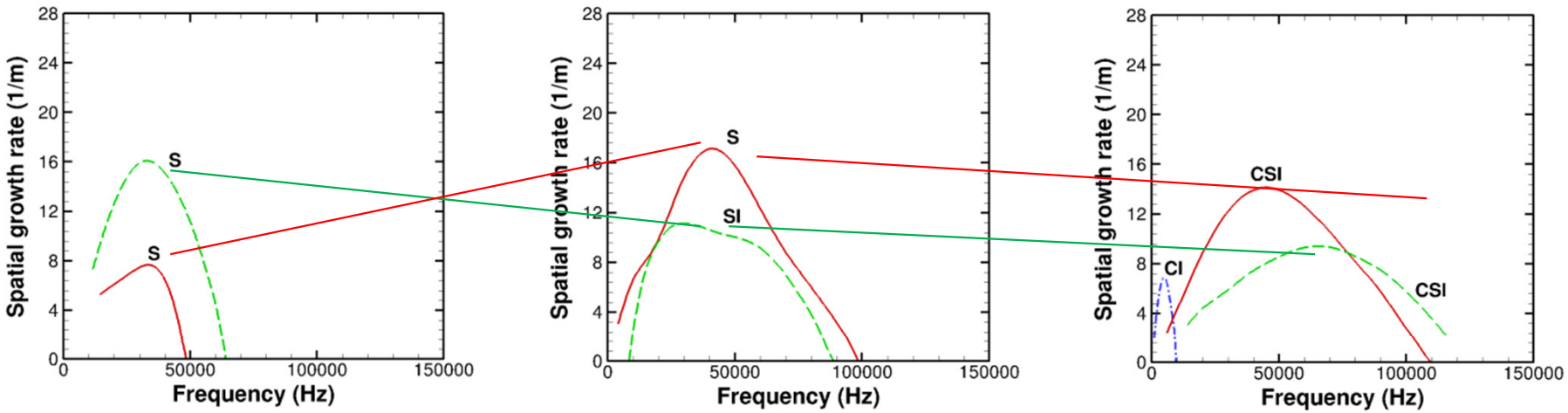
(b) Mode S



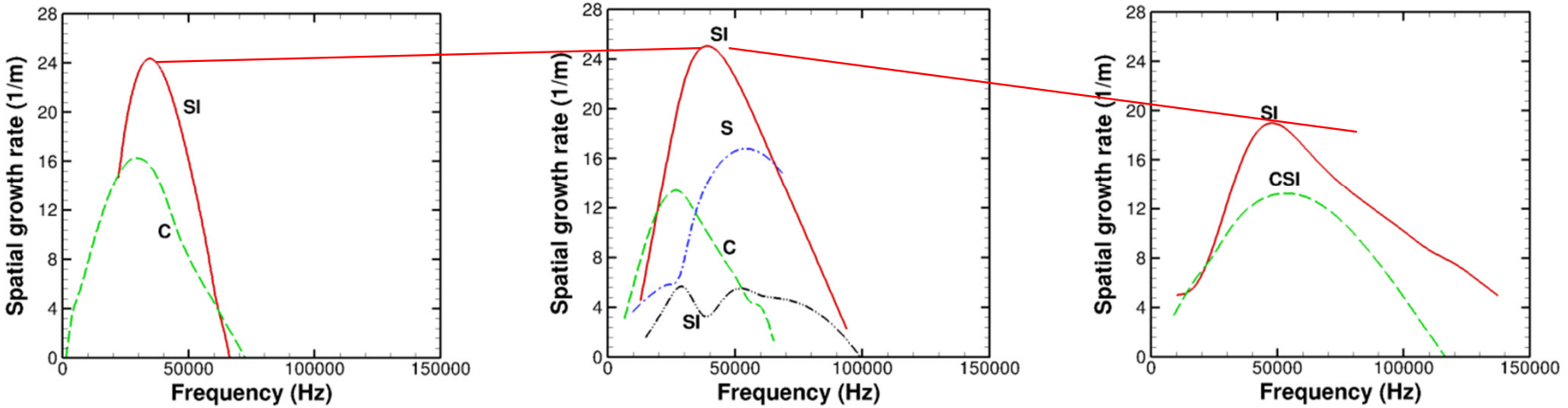
(c) Mode C

M6T: Local Growth Rate vs. Frequency

$(x-x_r)/k \approx 47$ 92 399



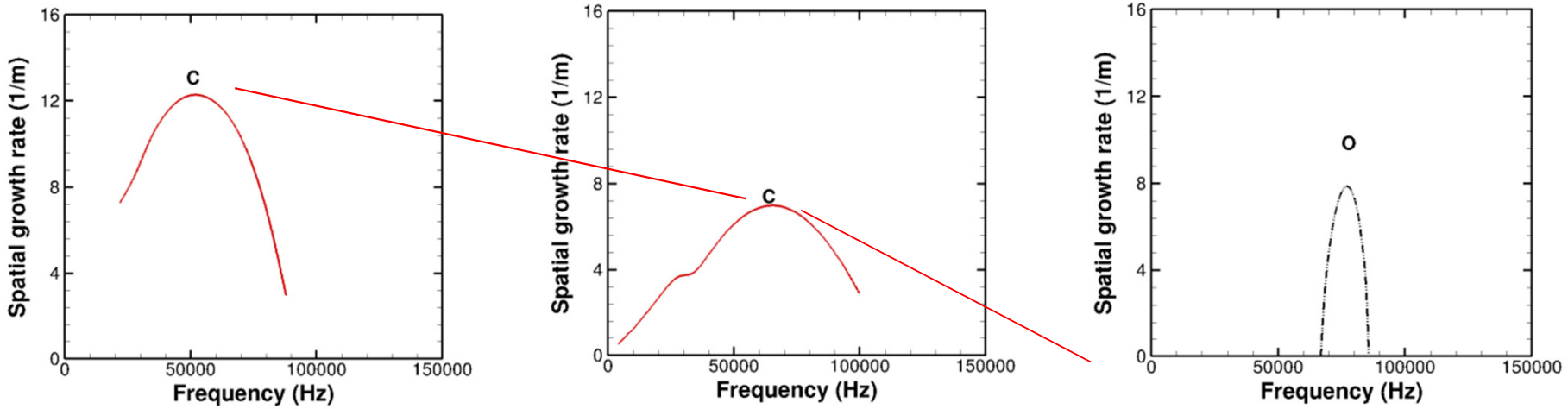
Even (i.e., symmetric) modes.



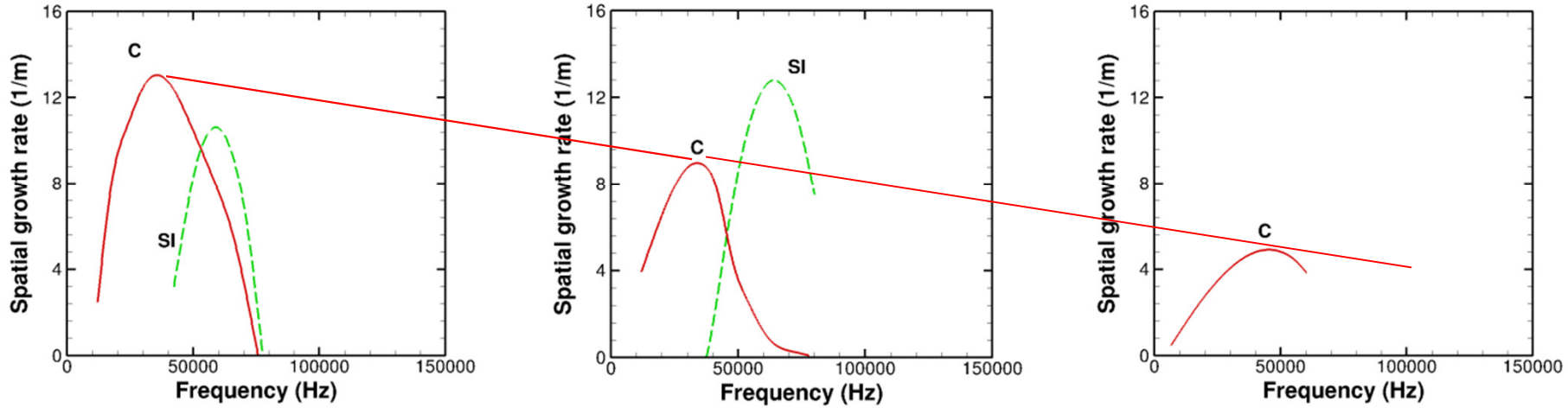
Odd (i.e., antisymmetric) modes.

M6F: Local Growth Rate vs. Frequency

$(x-x_r)/k \approx 47$ 92 399



Even (symmetric) modes.



Odd (antisymmetric) modes.

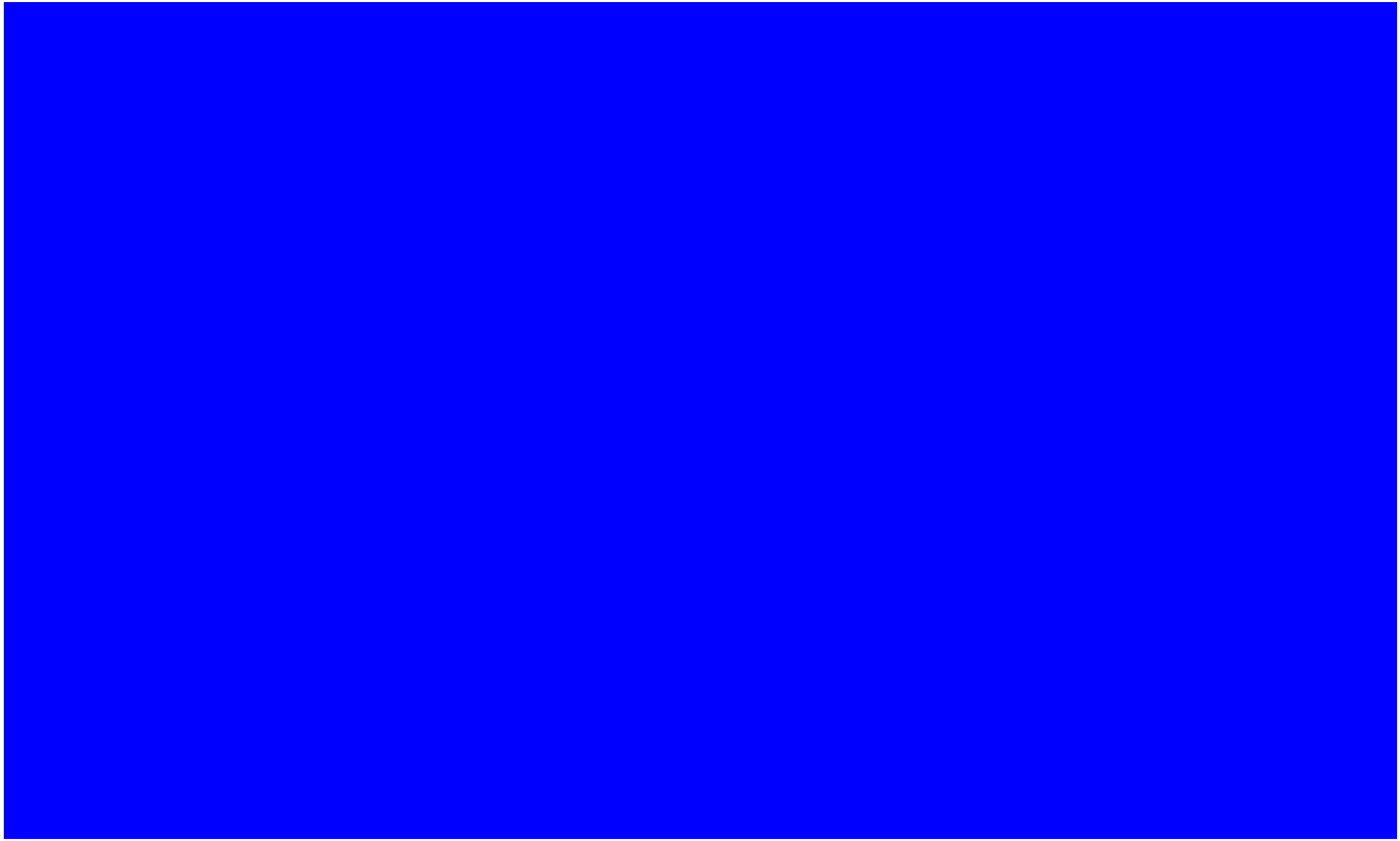


Summary

- 3D discrete roughness element with “intermediate” height
  - Earlier transition due to streak instabilities
  - Increased richness to modal structure at hypersonic speeds
- Understanding of other physical regimes via numerical simulations
- With sustained effort, it is possible to translate the outcomes into improved predictive capability for future hypersonic vehicles
  - Broader parameter study + comparison with additional measurements
  - Modeling enhancements

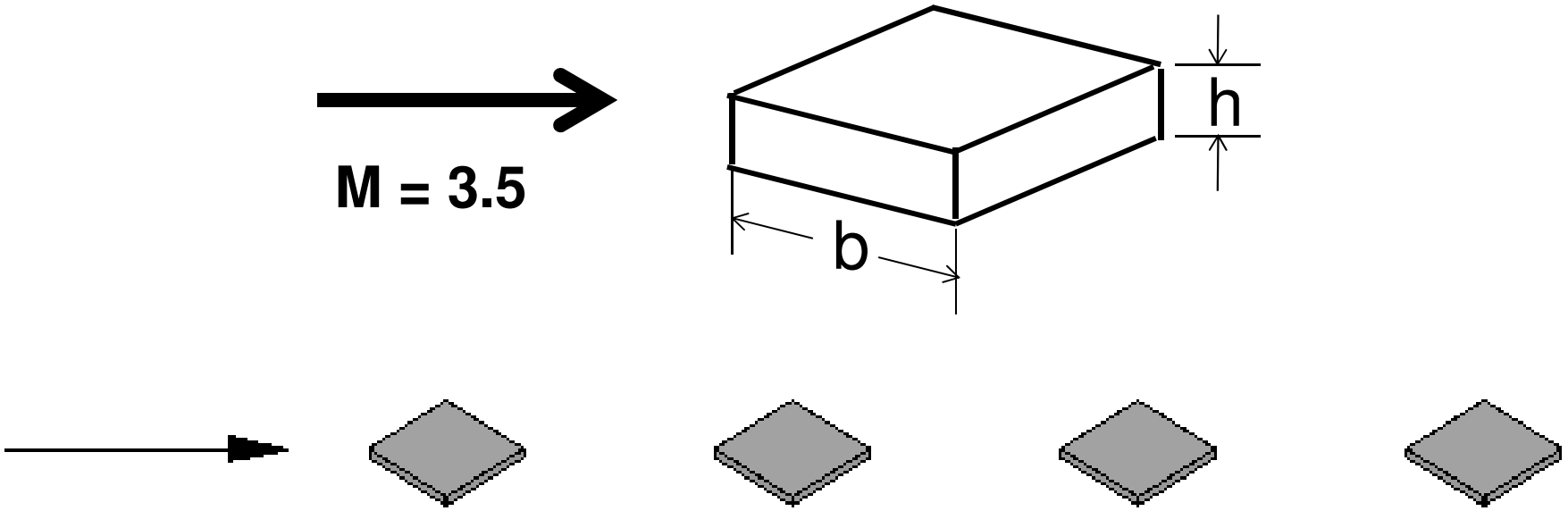
→ Reduced risk/conservatism in TPS design for new vehicles

Extra Charts



NASA Quiet Tunnel Experiment: Isolated Roughness on Flat Plate

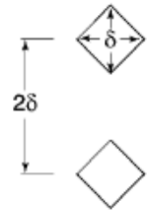
Diamond Trip



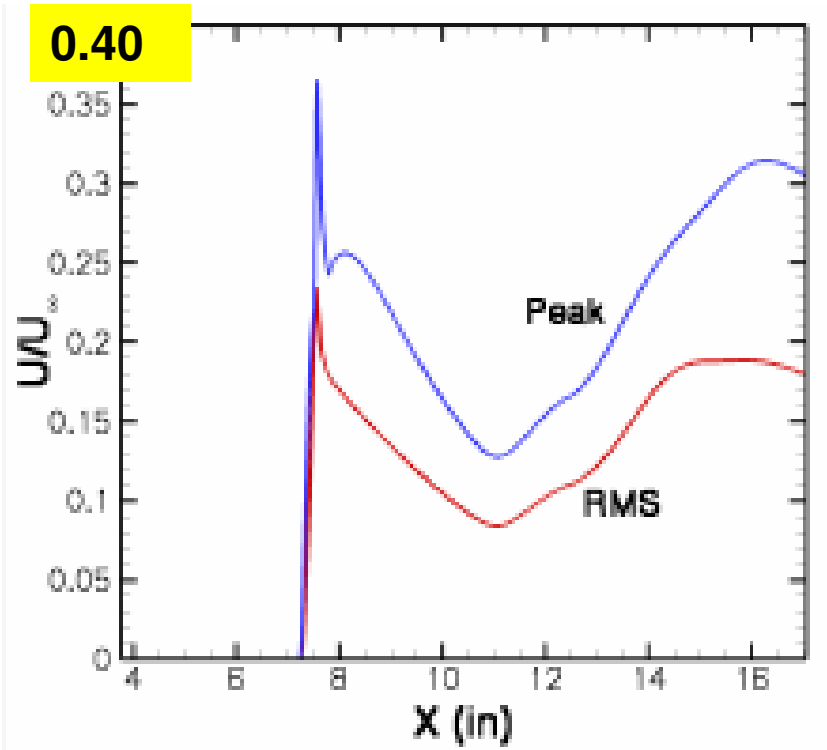
Diamond vs. Ramp Trips: Streak Amplitudes

h=0.060”, δ = 0.081”

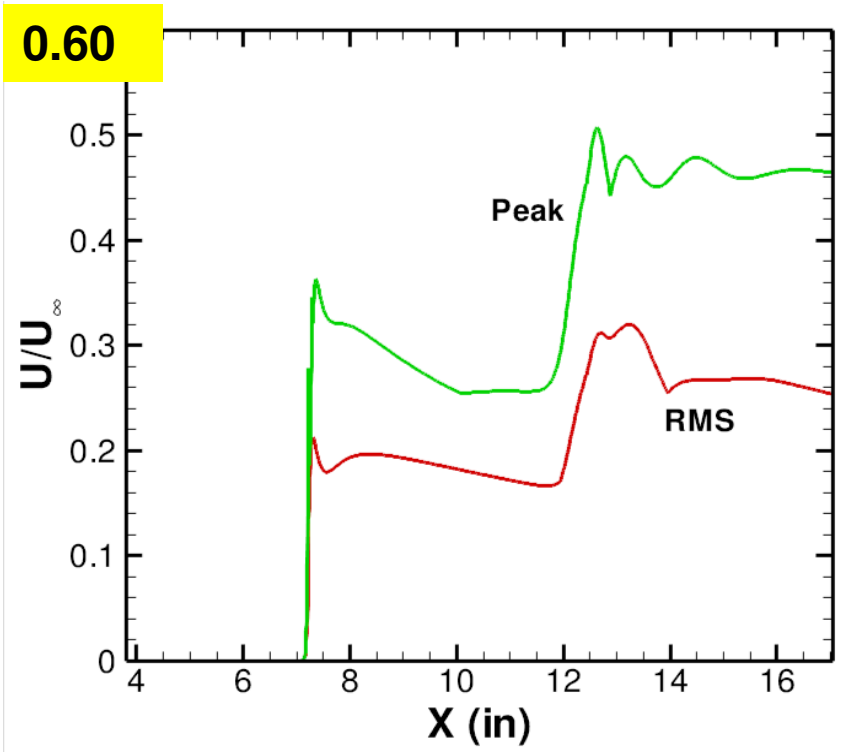
- Diamond trips: Analogous streaks as ramp trips, but stronger
  Streaks decay slowly, amplify rapidly
  => Much stronger flow distortion, similar to expt.



Ramp, h=0.060”



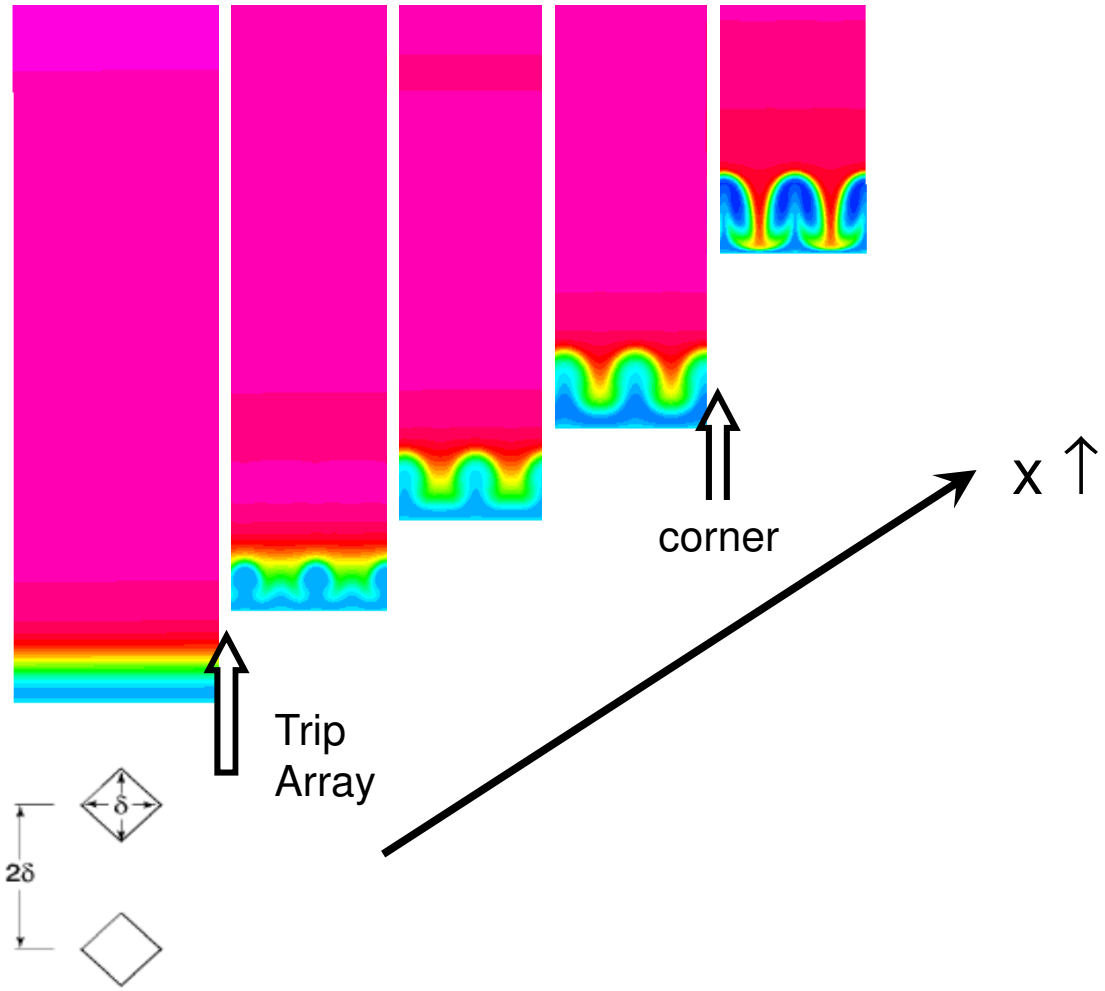
Diamond, h=0.060”



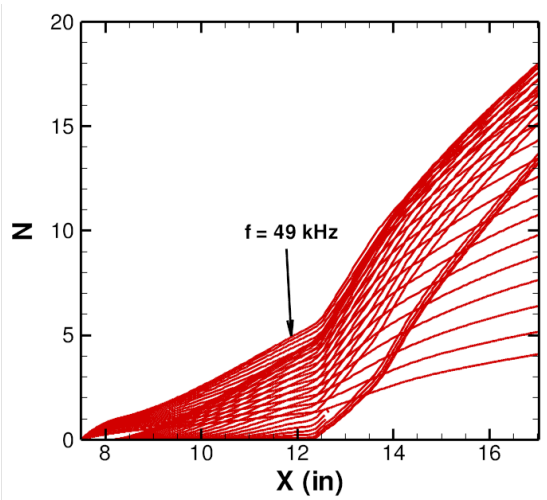
Effect of Roughness Shape: Diamond Trips

h=0.060”, δ = 0.081”

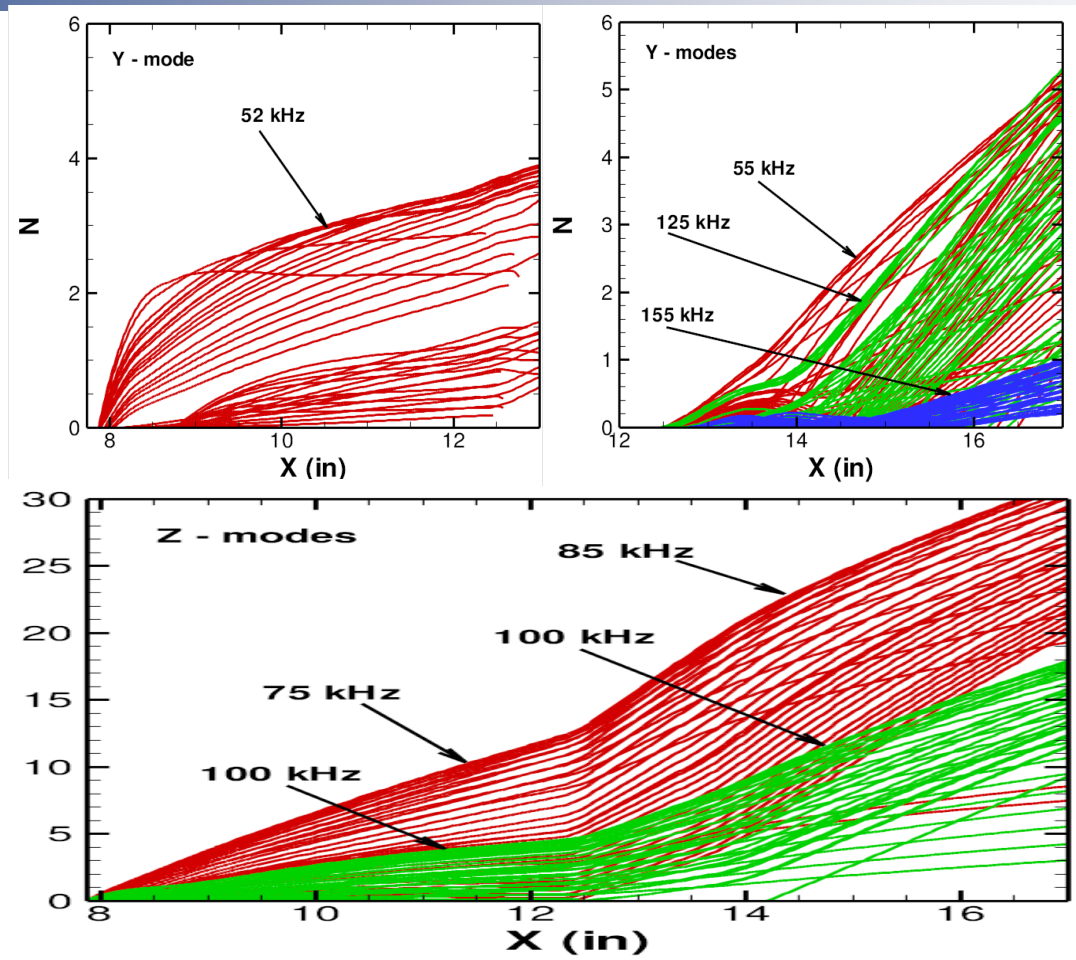
- Strong mushroom shaped structures in crossflow plane



N-factors for *z*-modes



Effect of Array Spacing δ: Ramp Trips

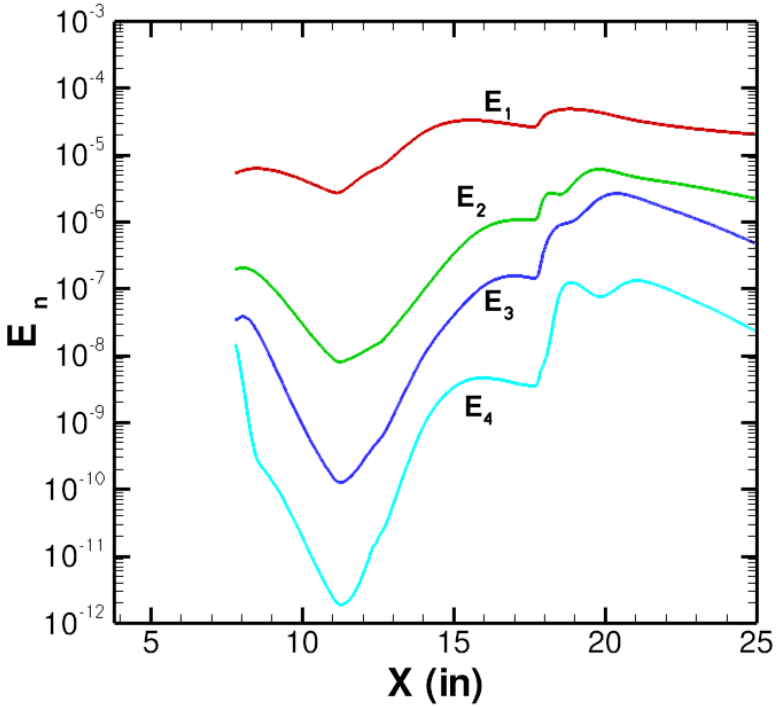


- **δ = 0.12" => *z*-modes still dominant**
  - N>10 over ramp 1 → very likely transition onset over ramp 1, perhaps regardless of noisy or quiet disturbance environment
  - Sustained growth across the compression corner

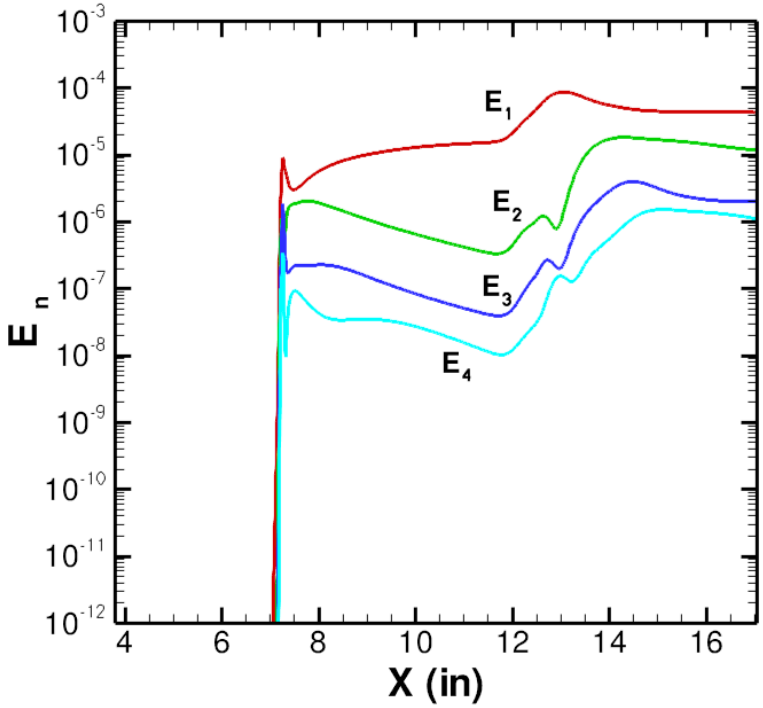
Modal Energy Evolution

- Modest logarithmic energy growth, details dependent on trip geometry
  (Similar to low-speed observations: White & Ergin 2003, Choudhari & Fischer 2005)
- Higher harmonics slaves to self-interaction of fundamental?
- Transient growth and/or curvature effects?

Ramp Trip, h=0.060”

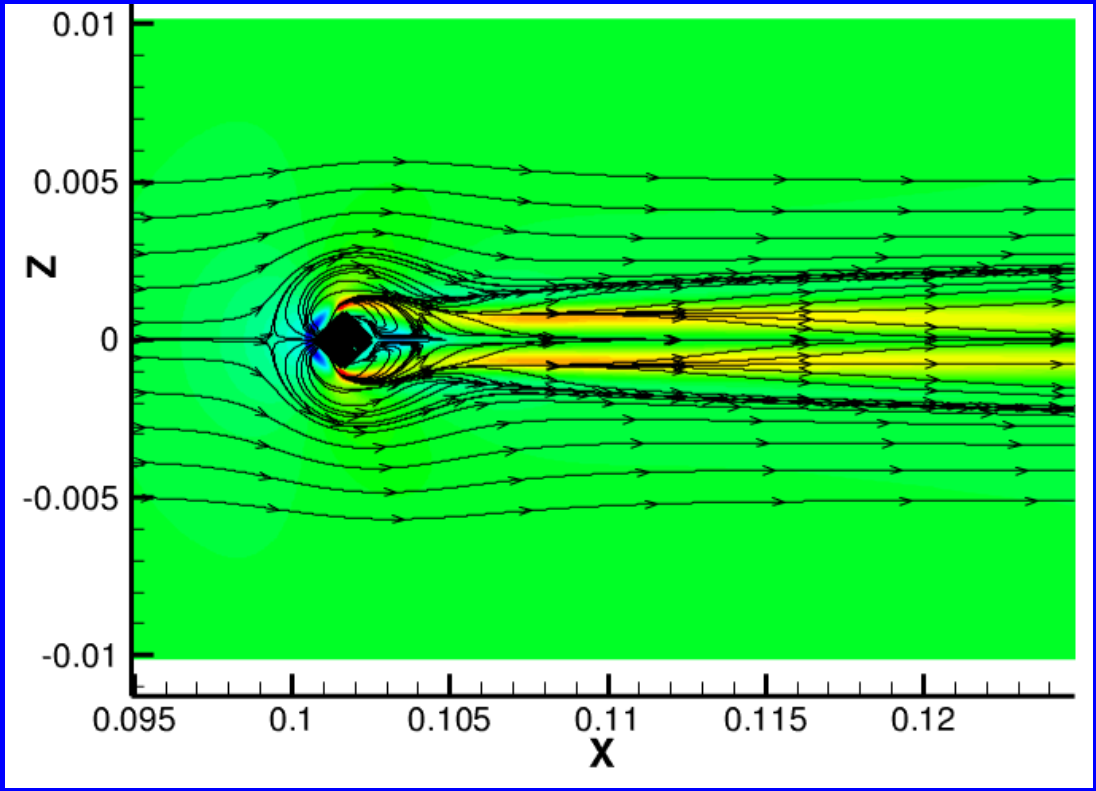


Diamond Trip, h=0.060”

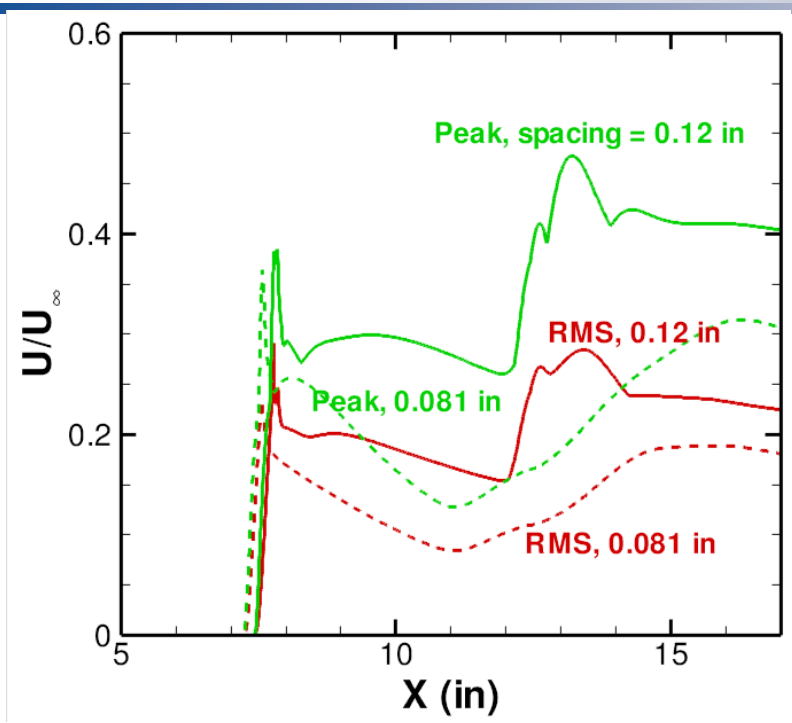


Oil Flow Visualization for Diamond Trip

Streamlines along j=2 surface superposed on u-velocity contours



Effect of Array Spacing δ: Ramp Trips

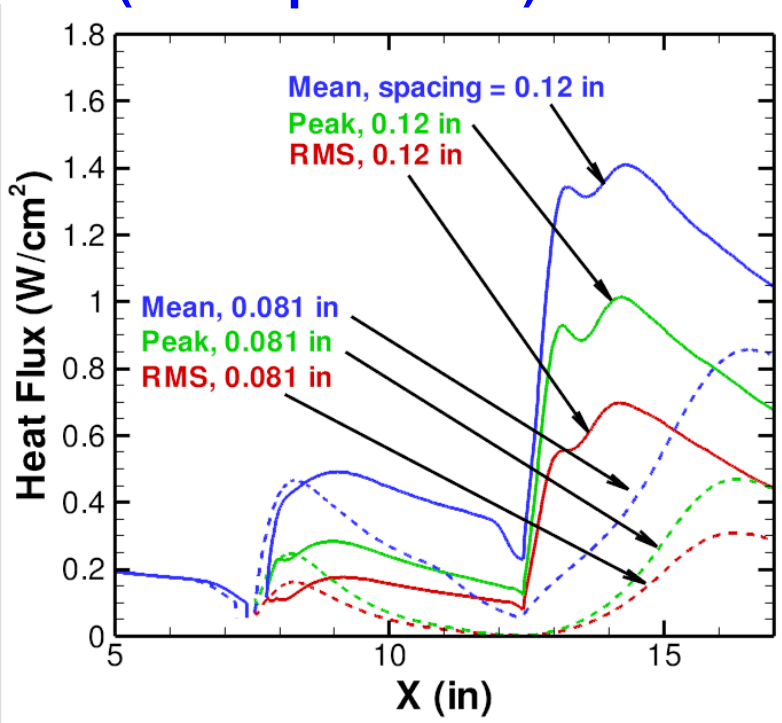


δ = 0.12" => larger streak amplitudes

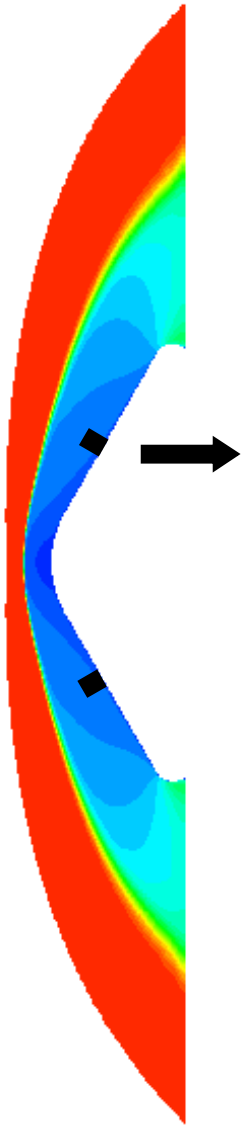
δ = 0.081"

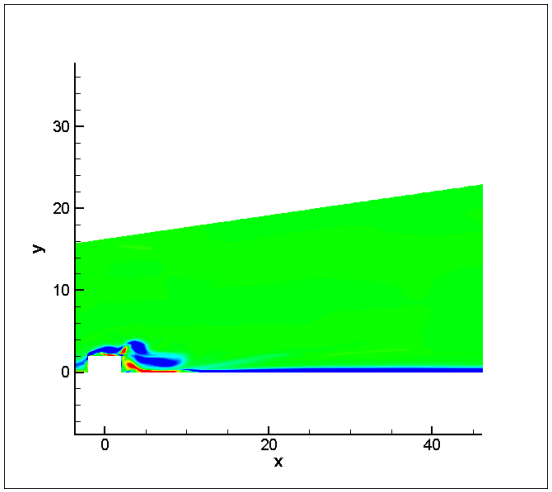
and

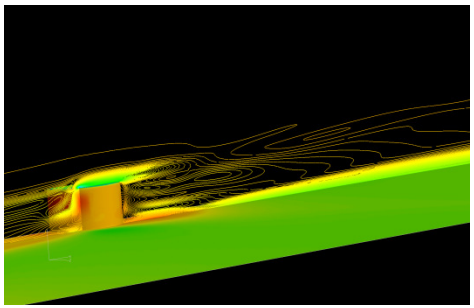
heat transfer (mean/peak/rms)



Isolated Roughness Elements
Blunt Body Flow



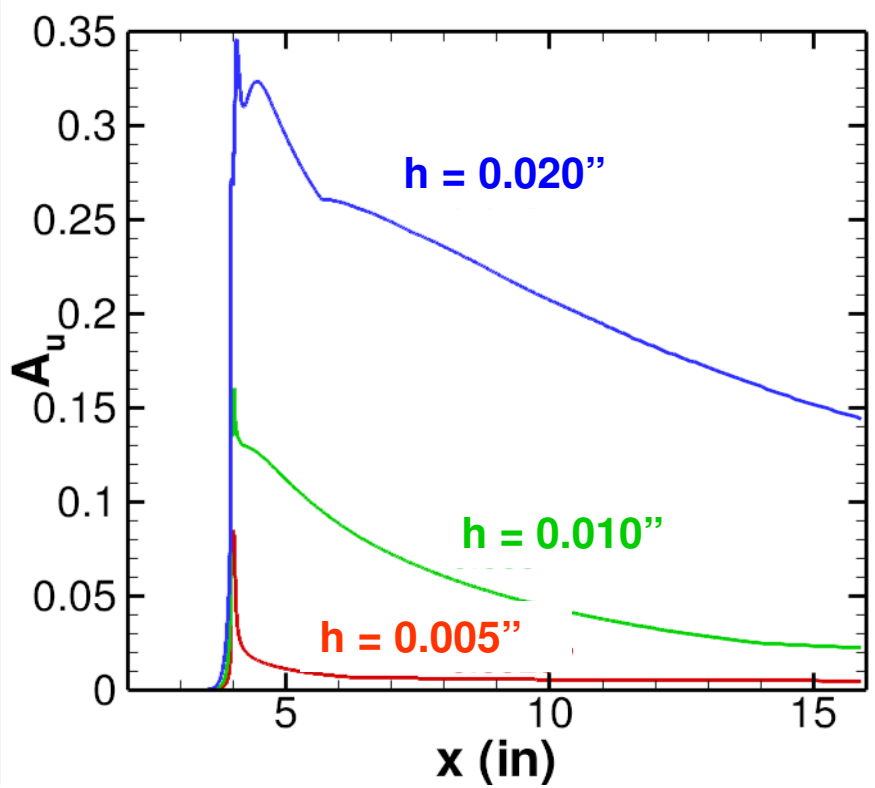


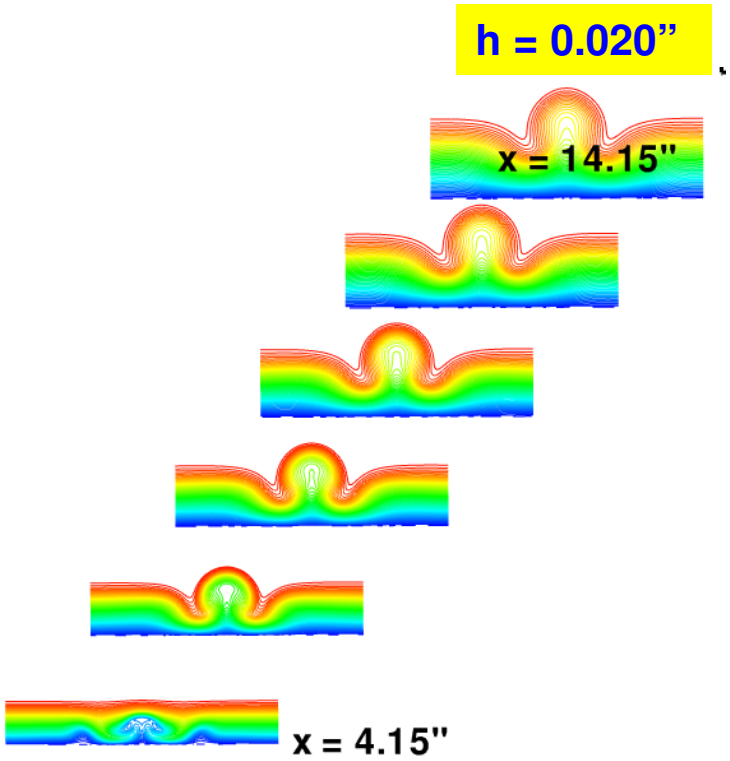


- Preliminary simulation indicates spontaneous vortex shedding for a model configuration

Isolated Diamond Trip Over Flat Plate

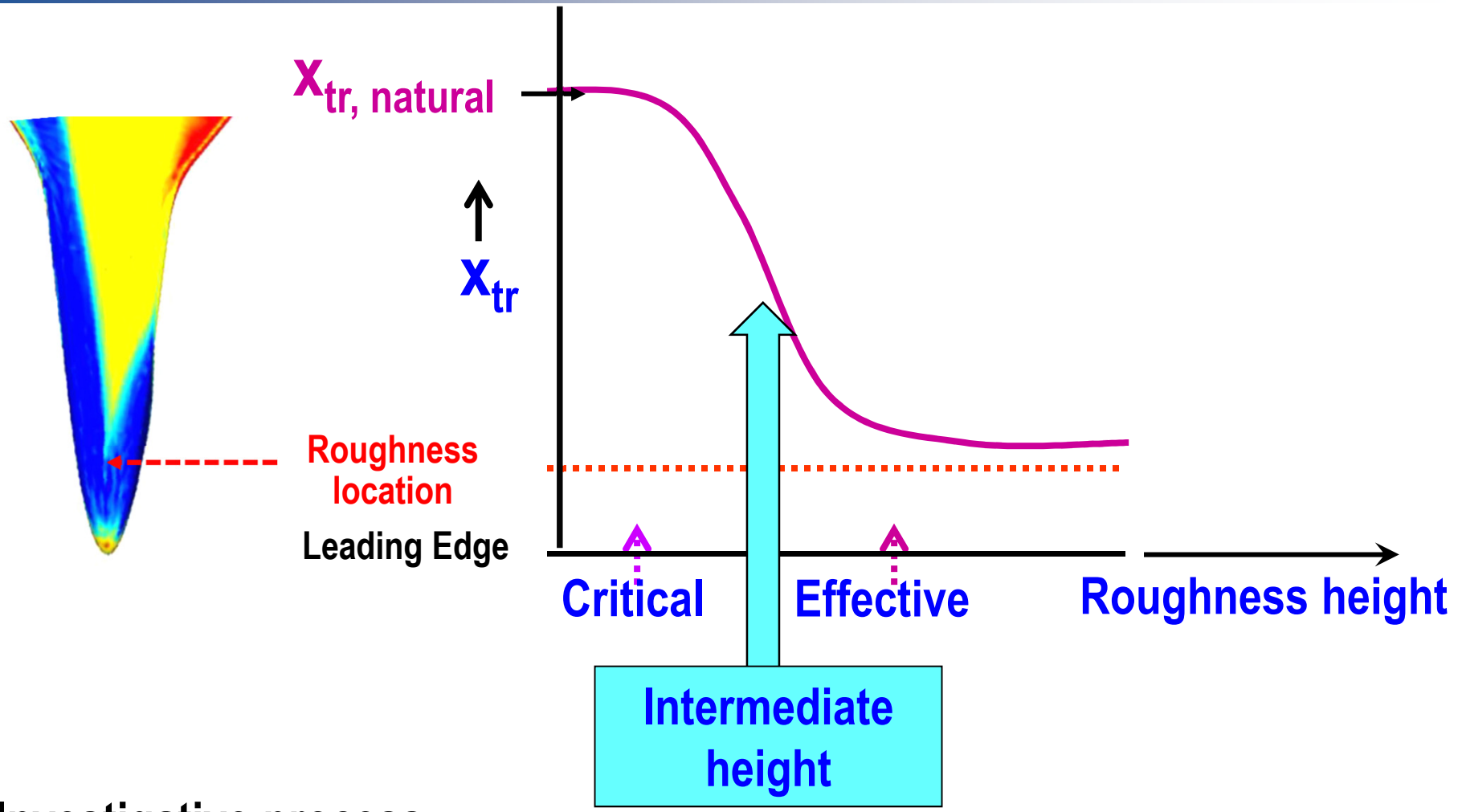
- Mach 3.5 Flat Plate Experiment in SLDT, NASA LaRC (M. Kegerise)





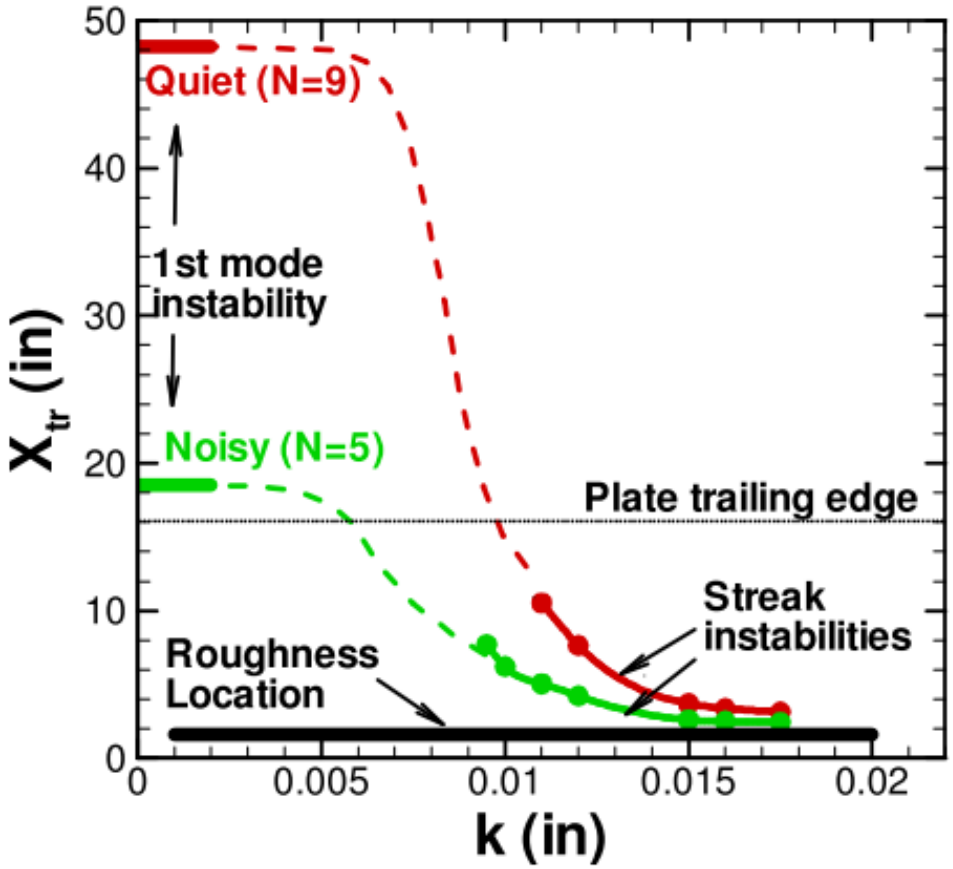
- Peak variation decays nearly monotonically
- Streak amplitude is nonlinear function of trip height

Effect of Roughness Height on Transition Location
(The Evidence)



- **Investigative process**
  - Empirical evidence + previous record → help identify suspects
  - Modeling + simulation → verify alibis, establish modus operandi
  - Experiment → Set up sting operation to confirm "theory"

Transition Prediction via Amplification Ratio (N-factor) Criterion: Effect of Roughness Height



- Variation in transition location similar to existing measurements in conventional and quiet facilities – detailed comparisons after the completion of planned experiment at NASA LaRC