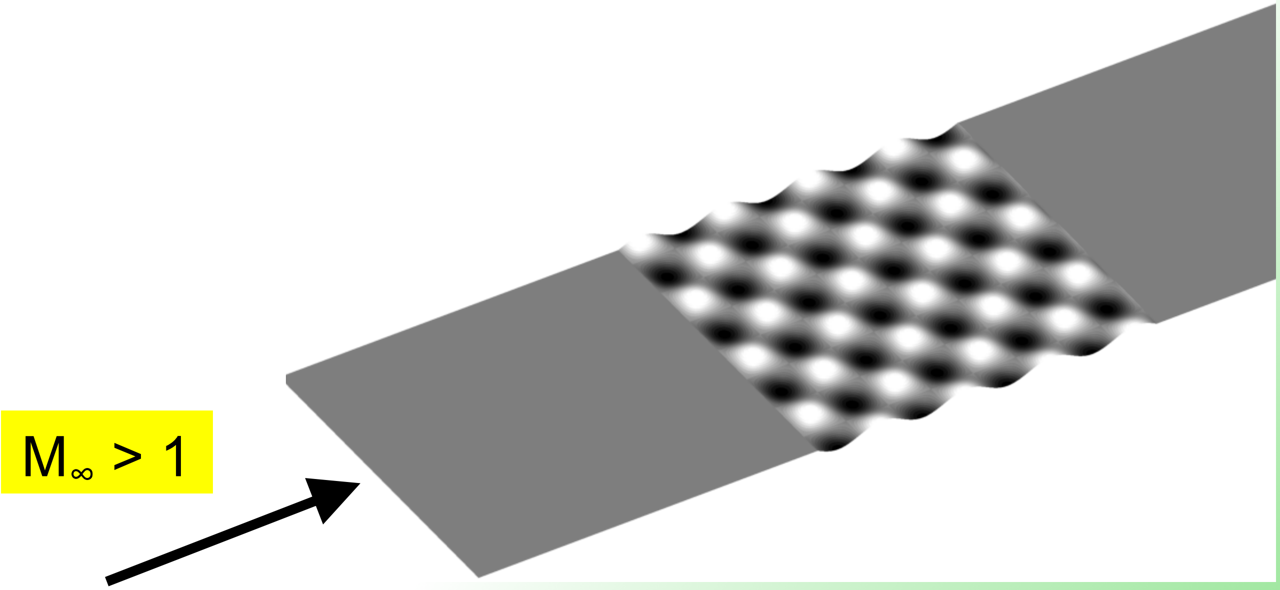
Effects of 3D roughness patch on transition in high-speed boundary layers



Meelan Choudhari, Fei Li, and Pedro Paredes*
NASA Langley Research Center, Hampton, VA
* National Institute of Aerospace
Lian Duan
Missouri University of Science and Technology

IUTAM Symposium on Laminar-Turbulent Transition
Sep. 2, 2019, 2:30 PM − 5:30 PM

Surface Roughness on High-Speed Vehicles

Discrete surface roughness

Hollis 2017

Distributed surface roughness

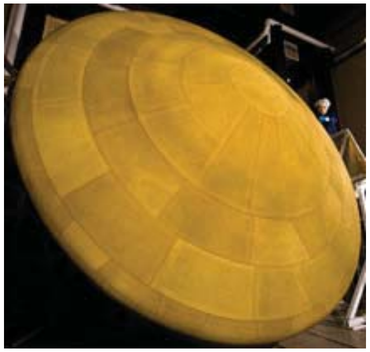
Cavities and protrusions

Attachment point cavities on Genesis heat shield

Physical damage

Damge to Shuttle Orbiter tiles

Tile patterns



TPS panels on Mars Science Laboratory heat shield

Honeycomb

Ablated TPS on Apollo heat shield

Sand-grain

Ablated TPS on Stardust heat shield

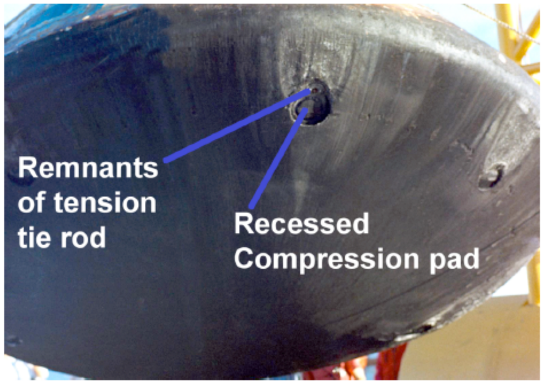
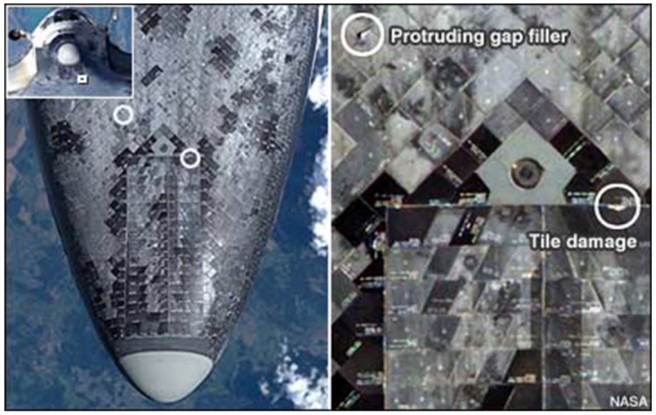
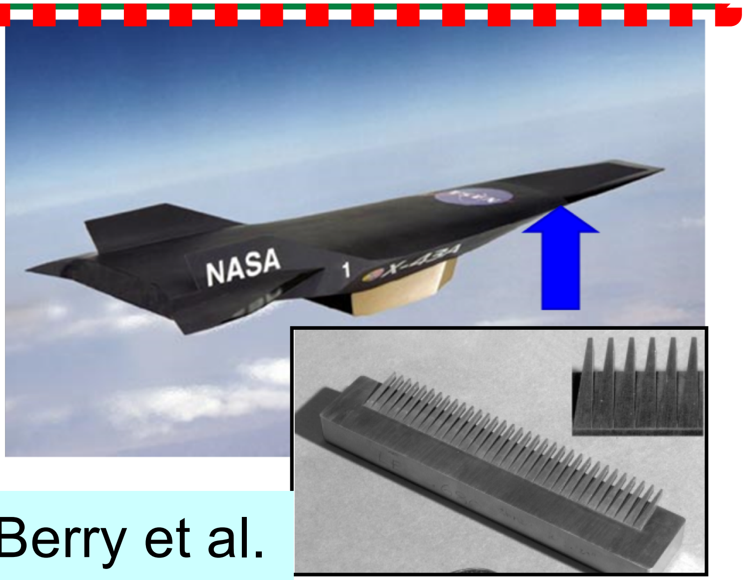


Figure 3. Effects of compression pad heating on Apollo Command Module heat-shield

Hollis 2008



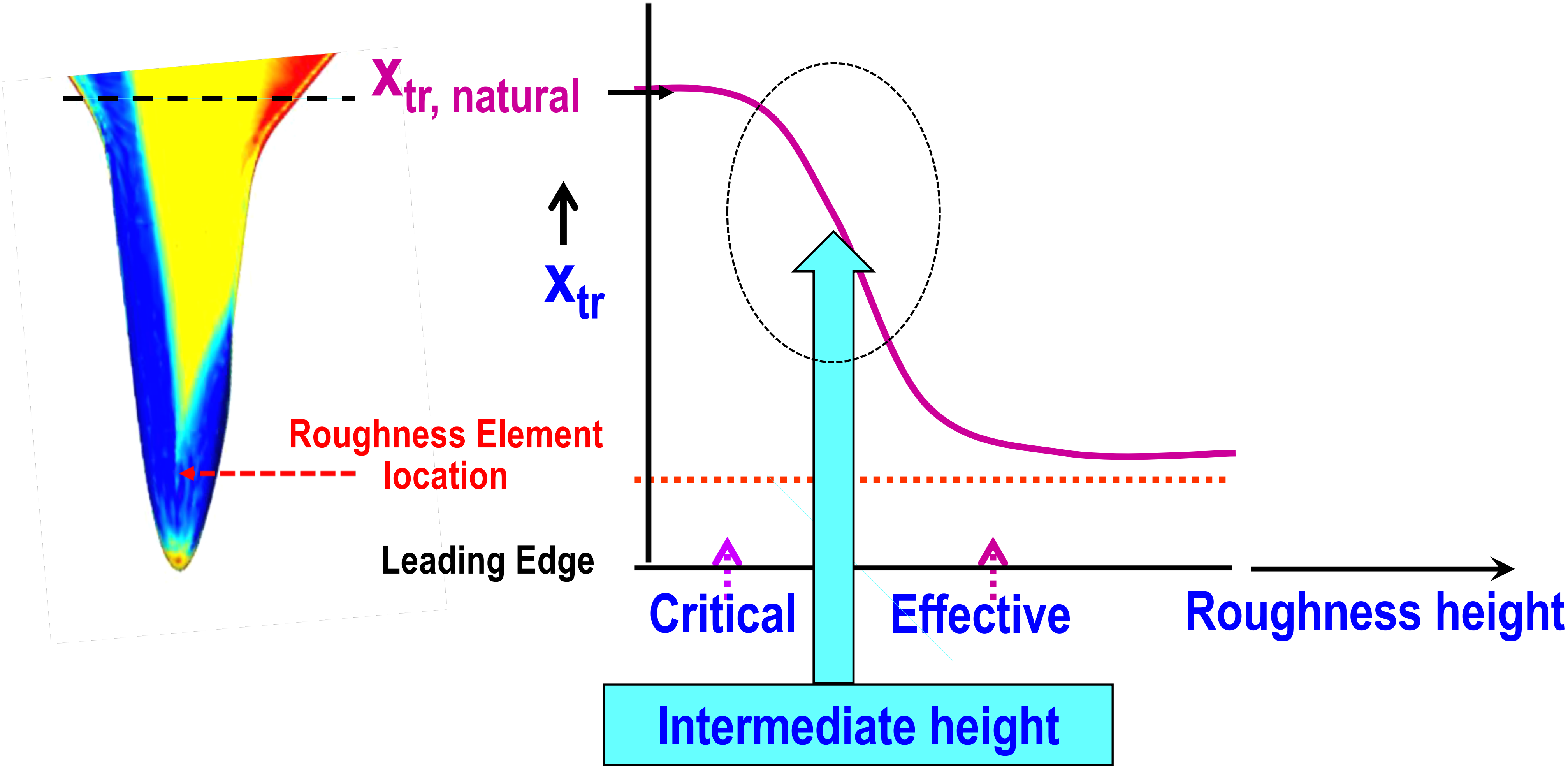


Berry et al. 2002

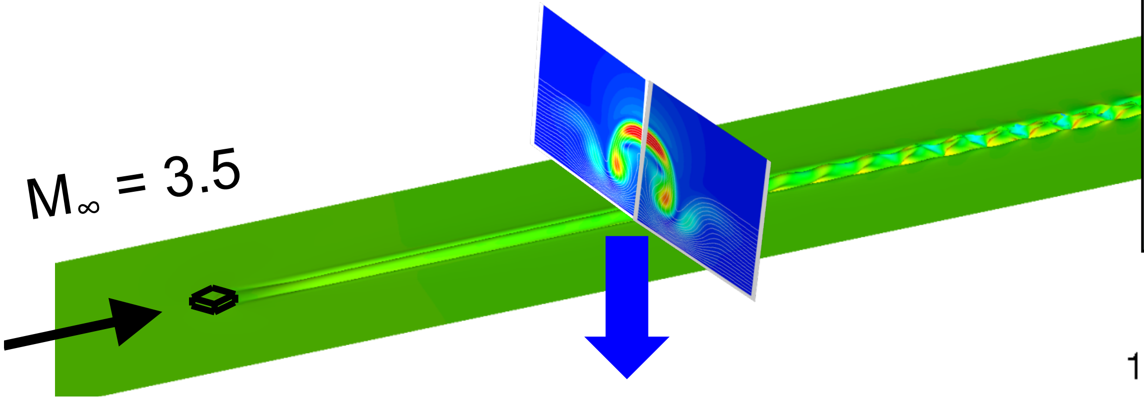
Transition due to Isolated Roughness Element:

Effect of Roughness Element Height on Transition Location

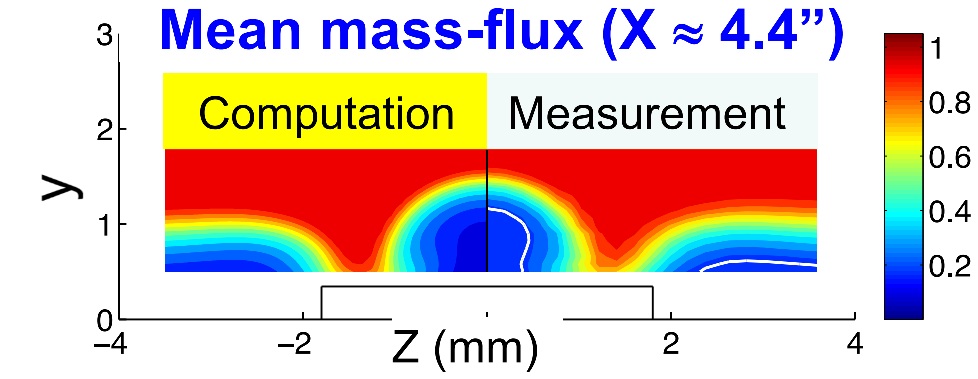
Van Driest and Blumer 1960, Wheaton and Schneider 2014

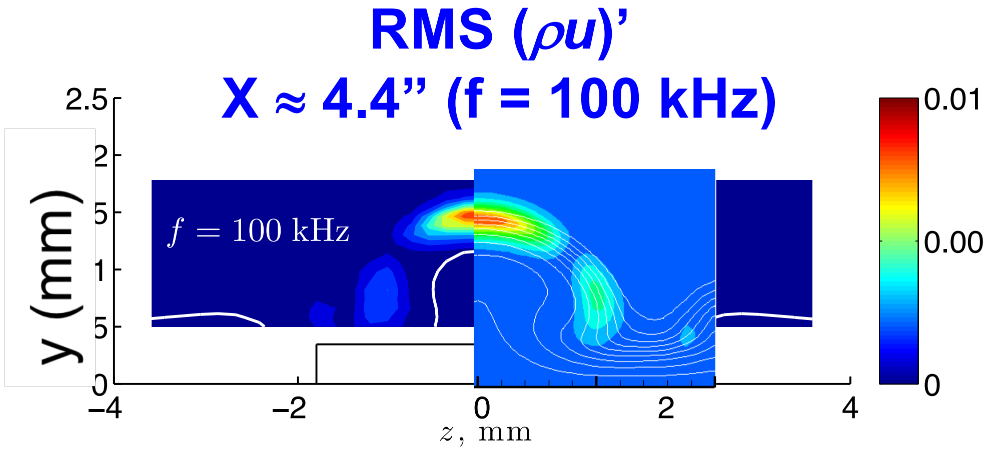


Transition due to Isolated Roughness Element: Validation of Streak Instability Theory

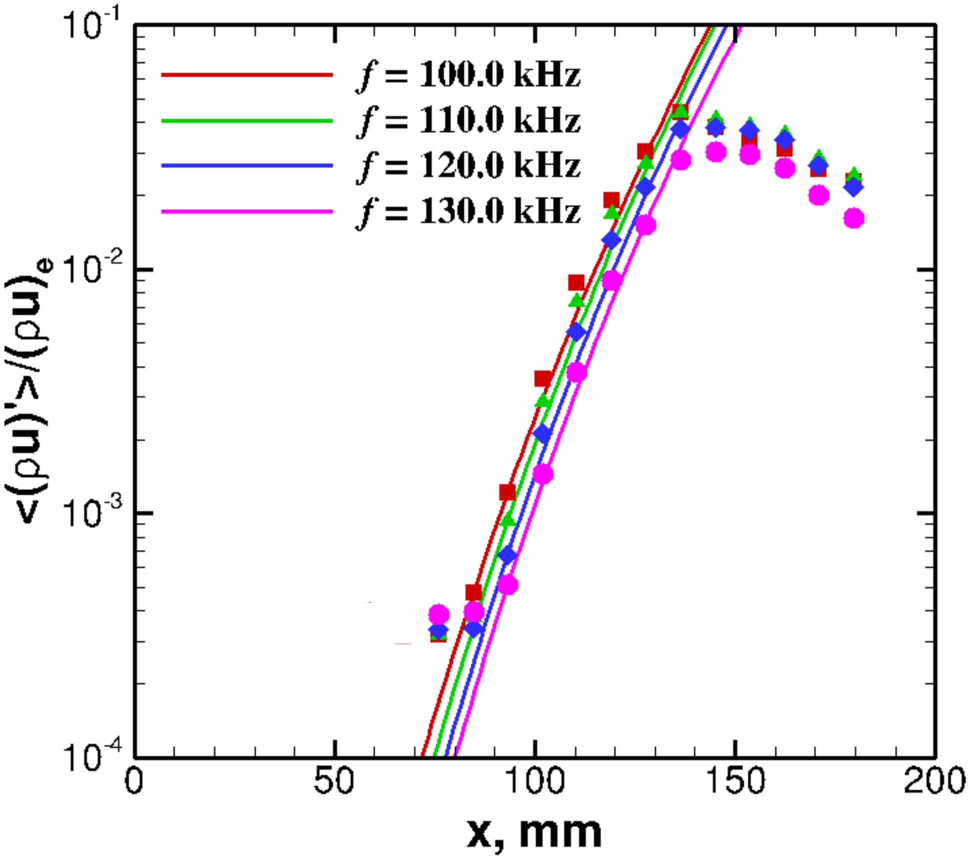


Theory: Choudhari et al. (2009,'10)
Validation: Kegerise et al. (2014)


Mean mass-flux (X ≈ 4.4")


RMS $(\rho u)'$
X ≈ 4.4" (f = 100 kHz)

Amplitude growth for selected *f*



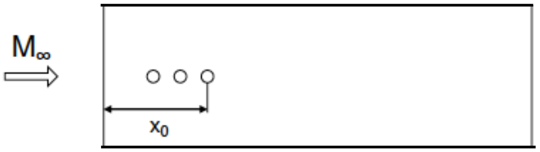
- **Excellent quantitative agreement between computation + measurement**

Distributed Roughness: More Dangerous, Myriad Geometries

$$\frac{Re_{kk,\mathrm{TR}}(\text{isolated})}{Re_{kk,\mathrm{TR}}(\text{distributed})} \cong \frac{800}{250} \cong \frac{3}{1}$$

(Reda et al. 2010)

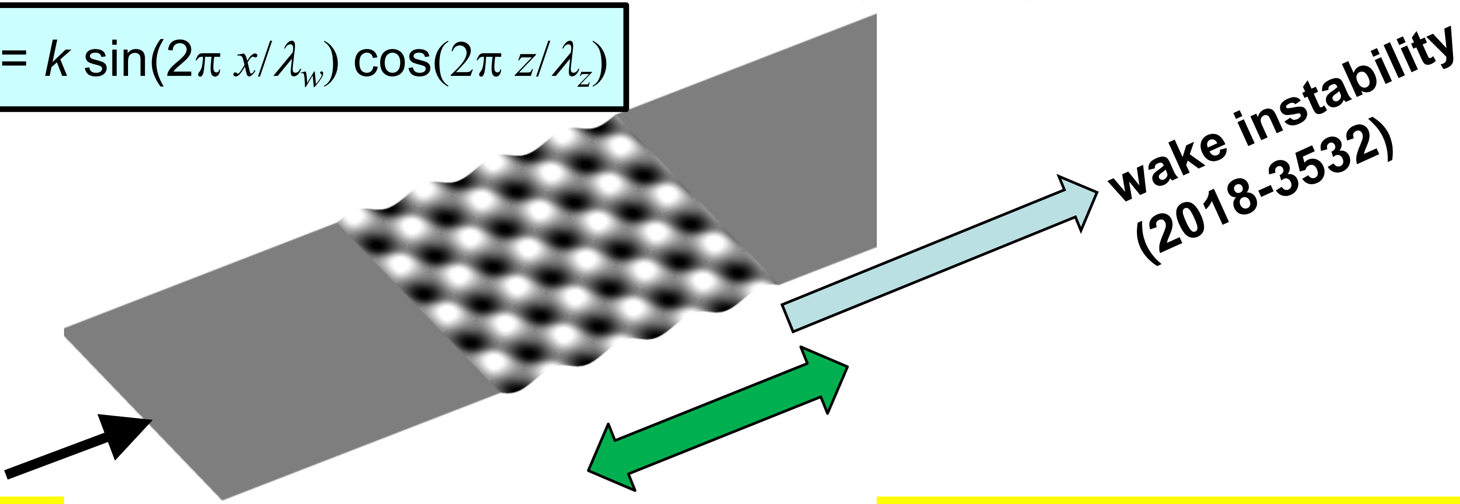
- **Simplest:** Multiple roughness elements (streamwise, spanwise proximity)



e.g., Choudhari et al. (2010), Chou et al. (2017, 2018)

- **Realistic: stochastic,** densely packed, heterogeneous planform scales, heights, and orientations, possibly combined with ablation-induced outgassing
  - Recent studies in low-speed flows
- **Intermediate complexity:** "Smooth" **patterned** height distribution over **finite length**, e.g., Muppidi et al. (2013)

$$h(x, z) = k \sin(2\pi\, x/\lambda_w) \cos(2\pi\, z/\lambda_z)$$



- **Objective: Investigate roughness patch effects on flow stability**
  - Extend previous work on wake instability (2018-3532) to disturbance evolution above roughness patch **(initial findings)**

Outline

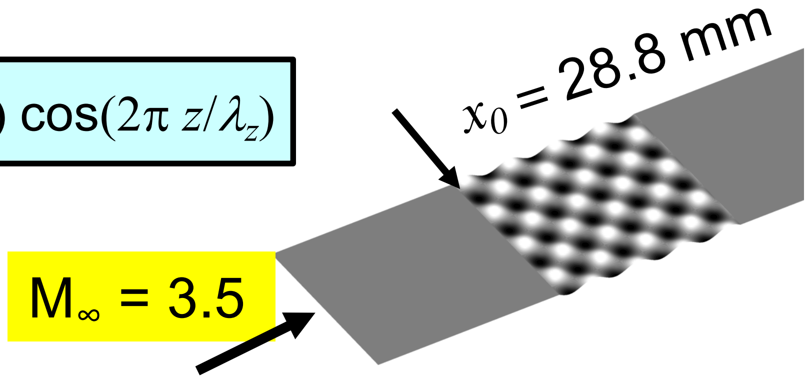
- Numerics (see paper for details)
- **Mach 3.5 flat plate configuration by Kegerise, Chou et al. in NASA Langley Supersonic Low Disturbance Tunnel (Laminar flow in the absence of roughness)**
  - Basic state
  - Stability analysis (other roles of roughness not considered)
    - Unperturbed boundary layer
    - Wake region (2018-3532: Aviation 2018)
    - Roughness patch region
- Summary

Outline

- $M_\infty = 3.5$, Re = 10.8×10^6/m
- $T_w/T_{ad} \approx 1.0$
- Plate length ≈ 0.4m → Modest 1st mode amplification

- Numerics (see paper for details)
- **Mach 3.5 flat plate configuration by Kegerise, Chou et al. in NASA Langley Supersonic Low Disturbance Tunnel (Laminar flow in the absence of roughness)**

$$h(x, z) = k \sin(2\pi\, x/\lambda_w) \cos(2\pi\, z/\lambda_z)$$



  - – Basic state
  - – Stability analysi
    - ➢ Unperturbed bou
    - ➢ Wake region (20
    - ➢ Roughness patc

Primary Configurations:

$\lambda_w = \lambda_z$ = 6.25 mm: $\lambda_w/\delta \approx 10.8$

k = 272 μm: $k/\delta \approx 0.45$

L_w/λ_w = **1, 4, 8**

Chou et al. (2017):

D = 3.58 mm

k = 280 μm: $k/\delta \approx 0.4$

- Summary

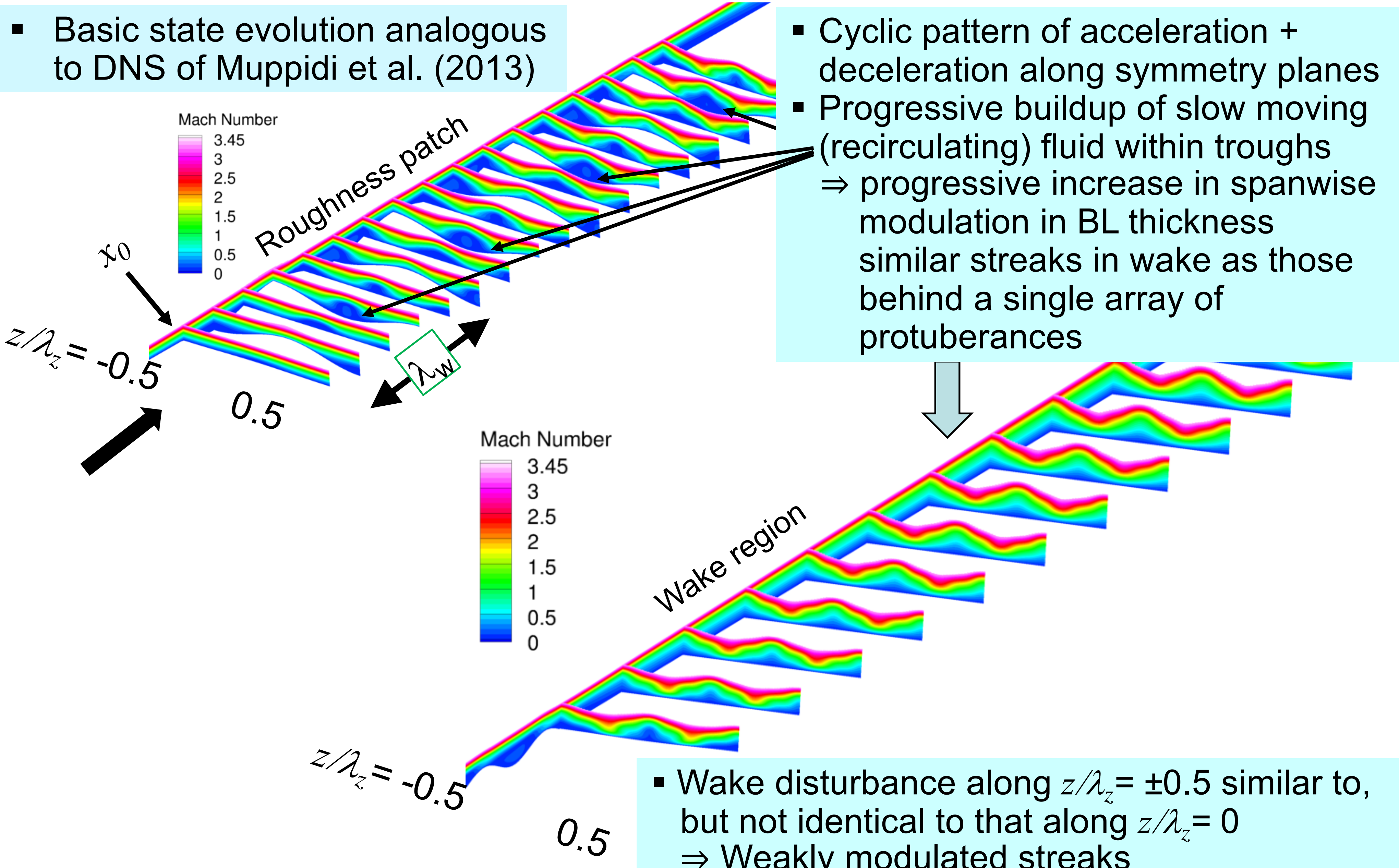
Outline

- **Numerics (see paper for details)**
- **Mach 3.5 flat plate configuration by Kegerise, Chou et al. in NASA Langley Supersonic Low Disturbance Tunnel (Laminar flow in the absence of roughness)**
  - ⇨ – Basic state
  - – Stability analysis (other roles of roughness not considered)
    - ➢ Unperturbed boundary layer
    - ➢ Wake region (2018-3532: Aviation 2018)
    - ➢ Roughness patch region
- Summary

Mean Flow Modification due to Roughness Patch

$x_r \in [28.8, 53]$ mm, $\lambda_w = \lambda_z = 6.25$ mm, $\lambda_w/\delta \approx 10.8$, $L_w/\lambda_w = 4$, $k/\delta \approx 0.45$

- Basic state evolution analogous to DNS of Muppidi et al. (2013)



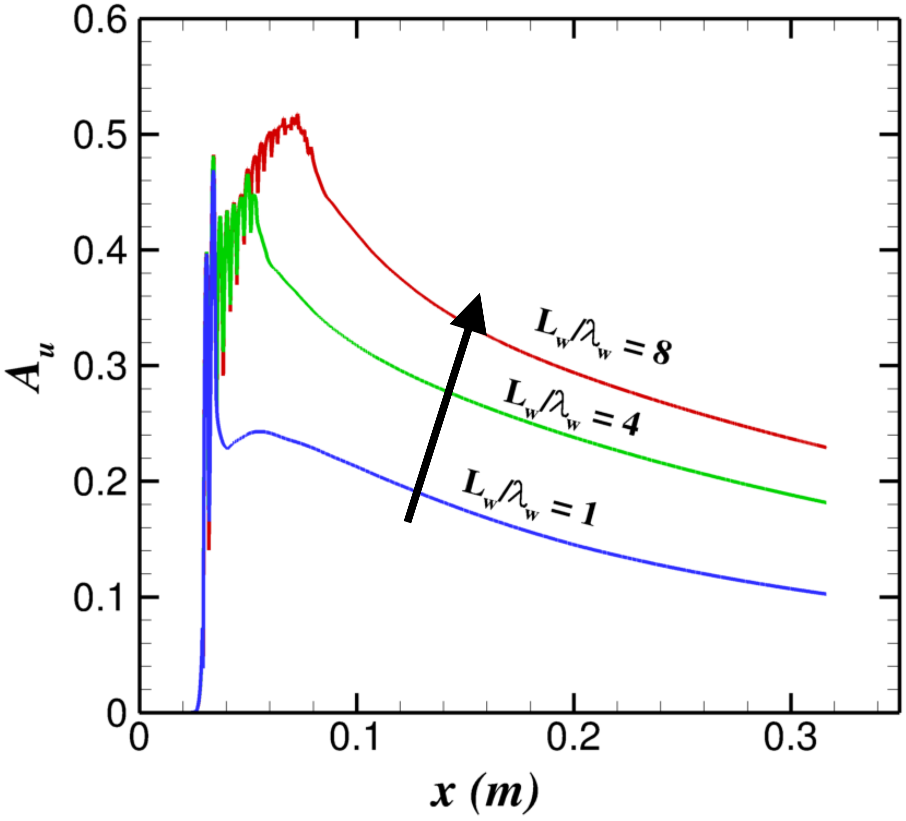
- Cyclic pattern of acceleration + deceleration along symmetry planes
- Progressive buildup of slow moving (recirculating) fluid within troughs
  ⇒ progressive increase in spanwise modulation in BL thickness
  similar streaks in wake as those behind a single array of protuberances

- Wake disturbance along $z/\lambda_z = \pm 0.5$ similar to, but not identical to that along $z/\lambda_z = 0$
  ⇒ Weakly modulated streaks

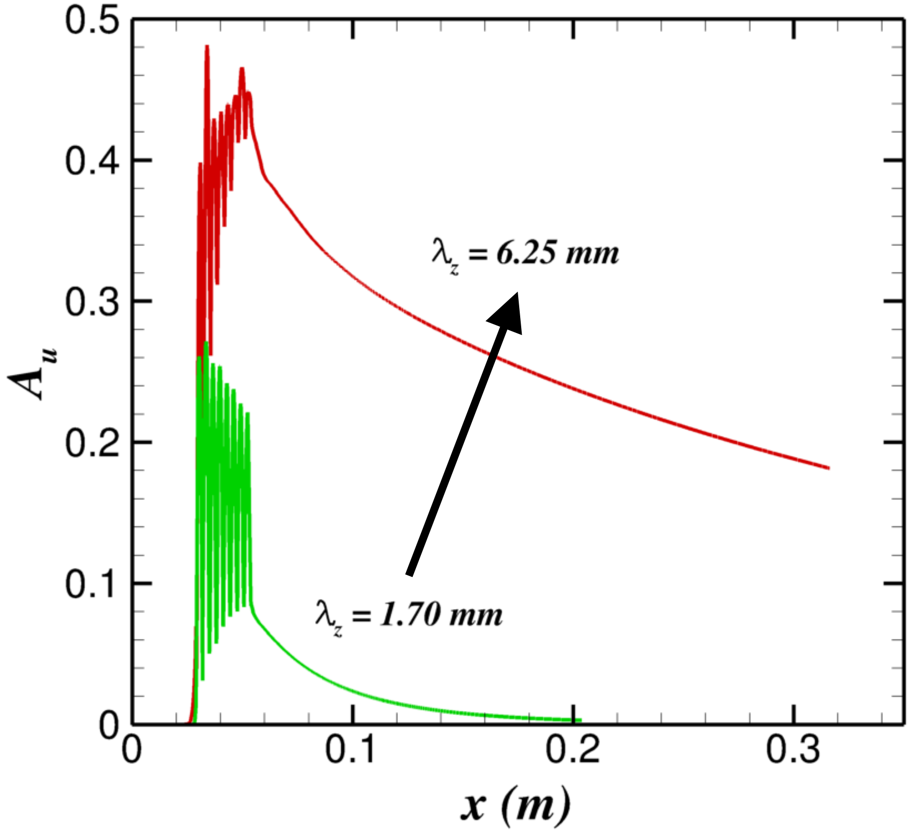
Streak Amplitude Evolution (*k* = 272 μm)

$A_u(x) = 0.5 * [max(\bar{u}'(x,y,z)) - min(\bar{u}'(x,y,z))]$ (Fransson et al. 2004)

Effect of Patch Length



Effect of Spanwise Wavelength

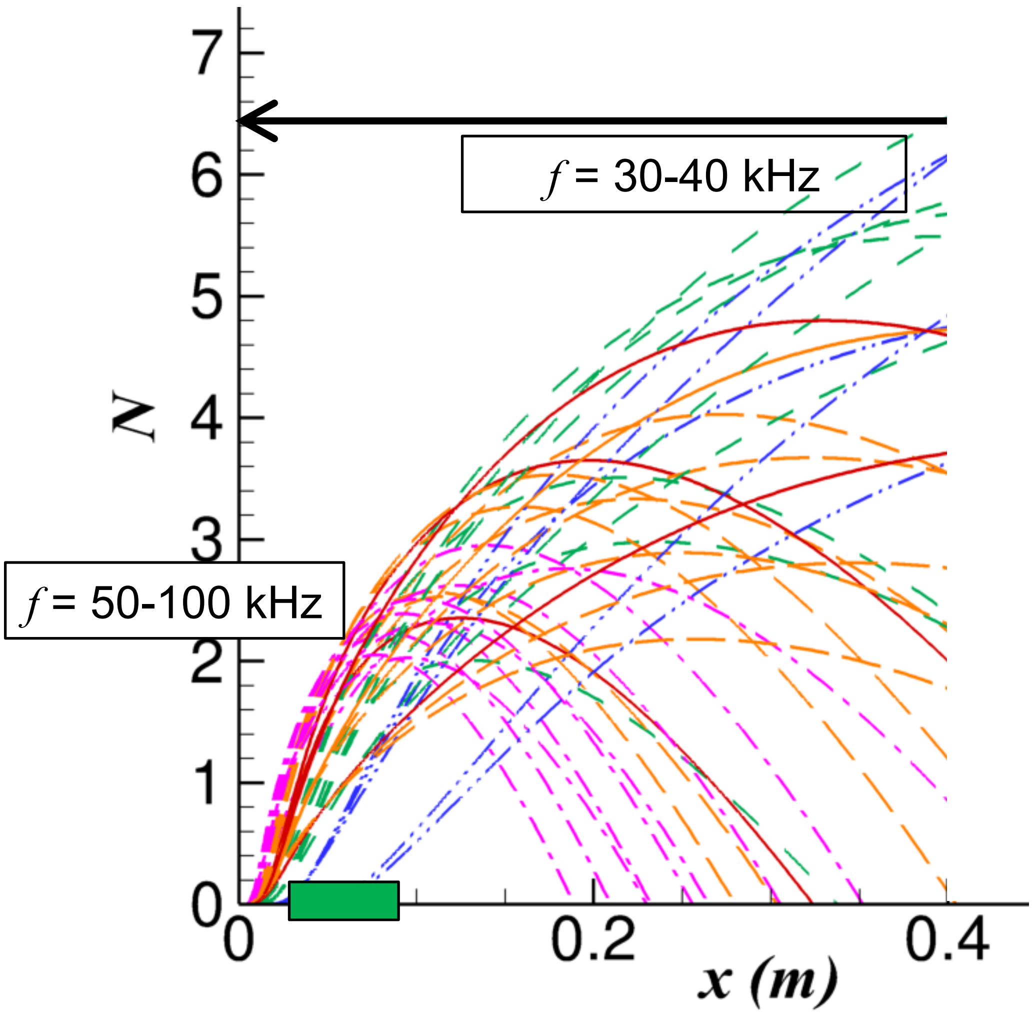


- Increasing roughness patch length ⇒ Higher peak amplitude, strong wake over longer region
  Diminishing increase in streak amplitude
- Smaller spanwise wavelength ⇒ substantially weaker streaks, rapid decay in wake

Outline

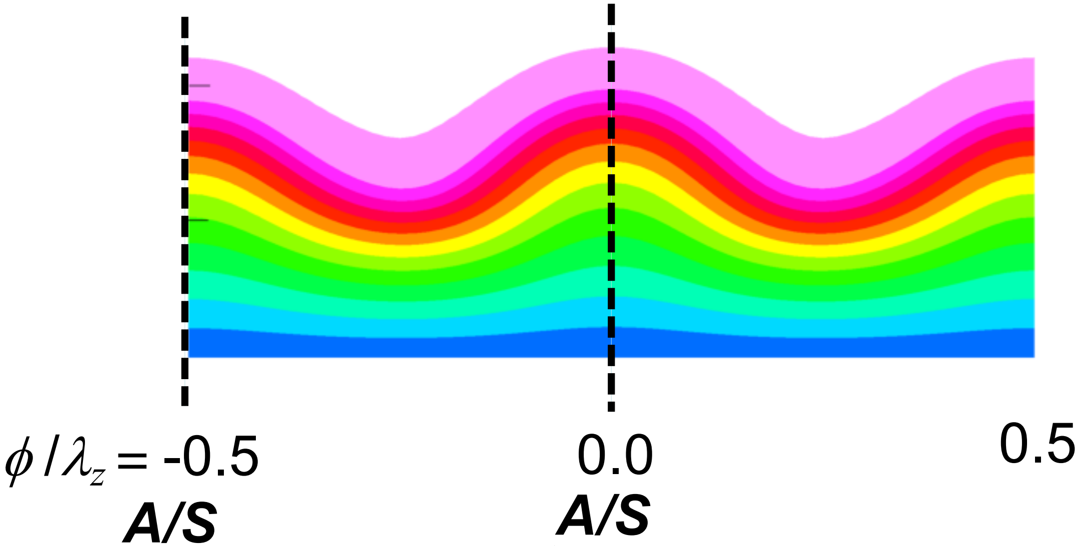
- **Numerics (see paper for details)**
- **Mach 3.5 flat plate configuration by Kegerise, Chou et al. in NASA Langley Supersonic Low Disturbance Tunnel (Laminar flow in the absence of roughness)**
  - Basic state
  - ➡ Stability analysis (other roles of roughness not considered)
    - ➢ Unperturbed boundary layer
    - ➢ Wake region (partly described in 2018-3532: Aviation 2018)
    - ➢ Roughness patch region
- Summary

N-factor Evolution of 1st Mode Instabilities Unperturbed Boundary Layer



- $N_{max} \approx 6.5 \Rightarrow$ No transition over smooth plate in quiet tunnel
- Most amplified 1st mode disturbances in roughness patch region: 50-60 kHz
  - N_{max} ($x_{r,\text{ begin}}$, f = 50 kHz) ≈ 1.4

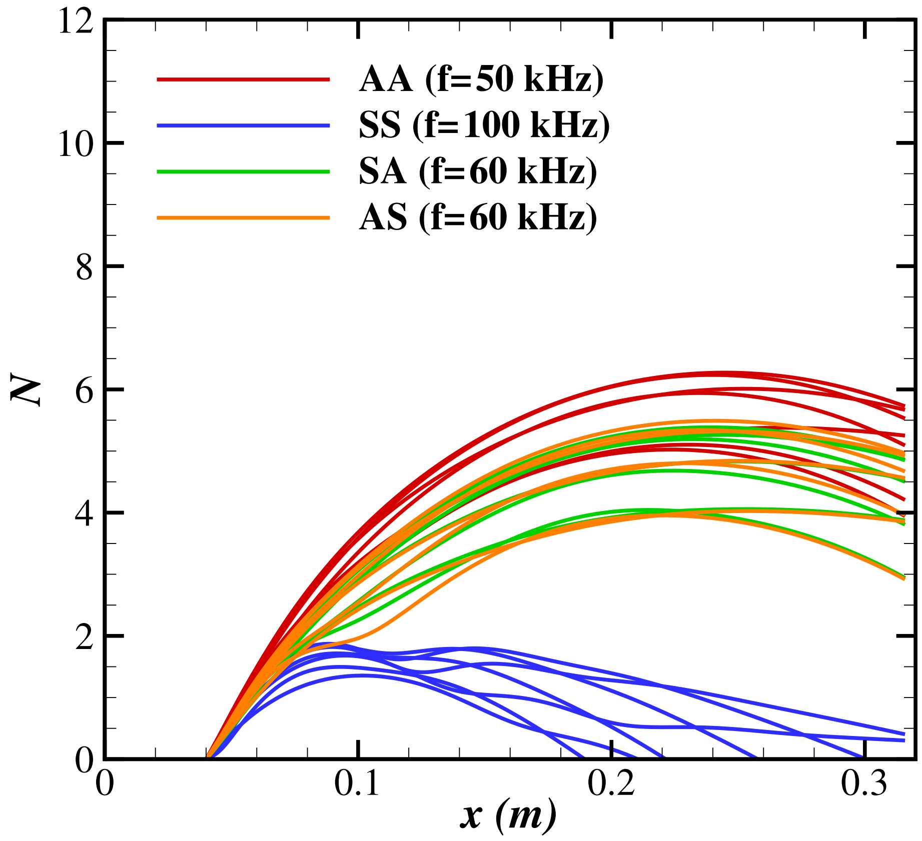
Instabilities in the Presence of Roughness Patch: Mode Classification

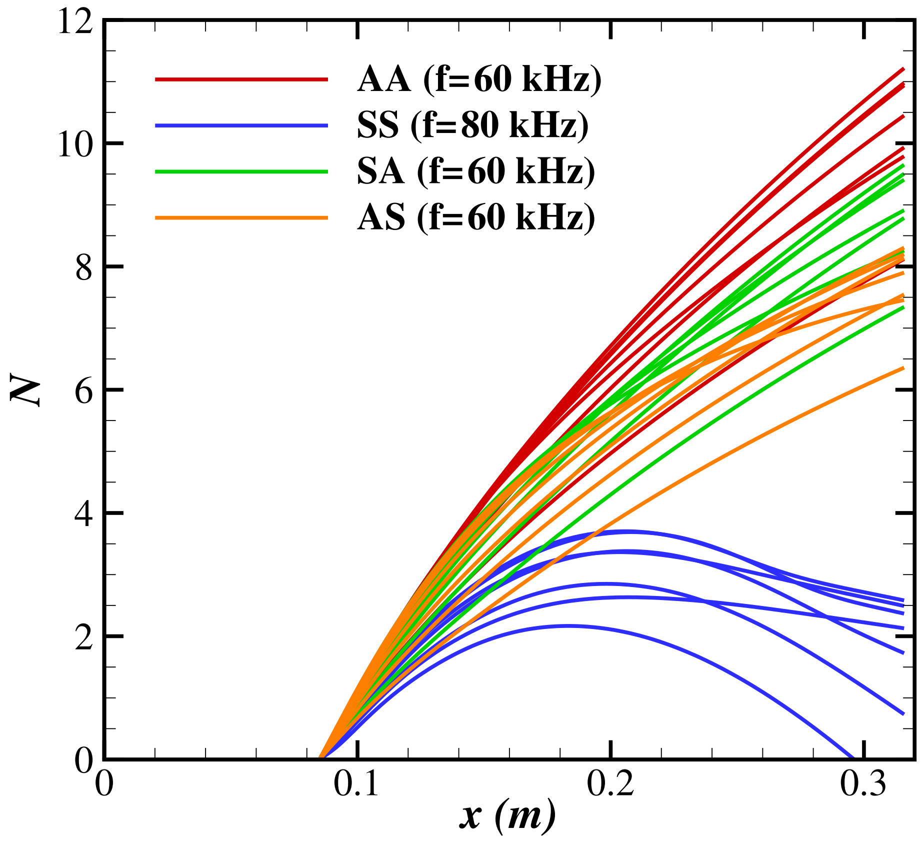


- Basic state has two symmetry planes across each λ_z :
  z/λ_z = -0.5, 0
- Unstable mode classification based on symmetry characteristics of perturbation field with respect to z/λ_z = -0.5, 0, respectively
  - AA, SS : λ_z/λ = n, n =1, 2, 3,…
  - SA, AS : λ_z/λ = n + 0.5
- Detuned modes not considered (see Paredes et al. 2016)

Wake Instabilities: Effect of Patch Length (k = 272 μm)

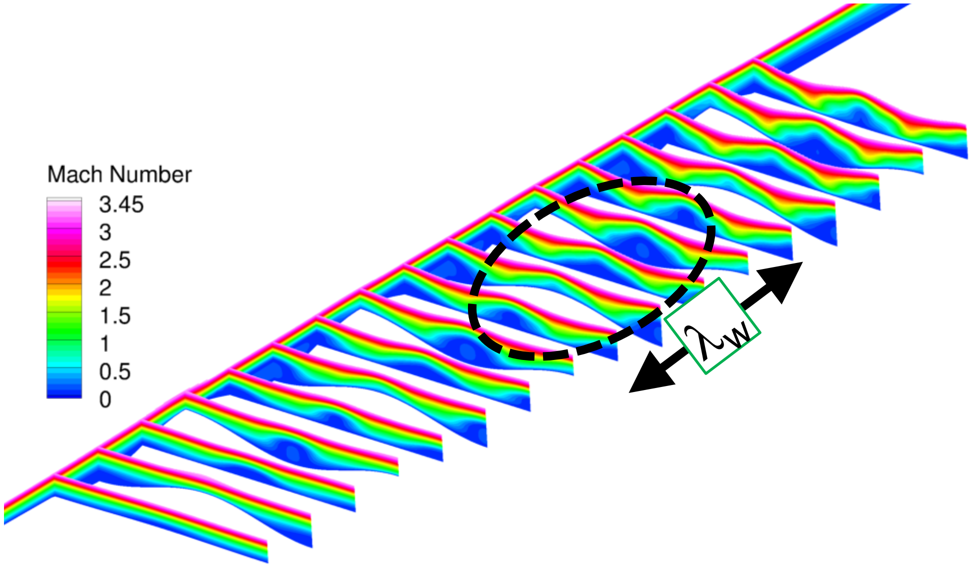
N-factor Evolution based on Plane Marching PSE


L_w/λ_w = **1.0**


L_w/λ_w = **8.0**

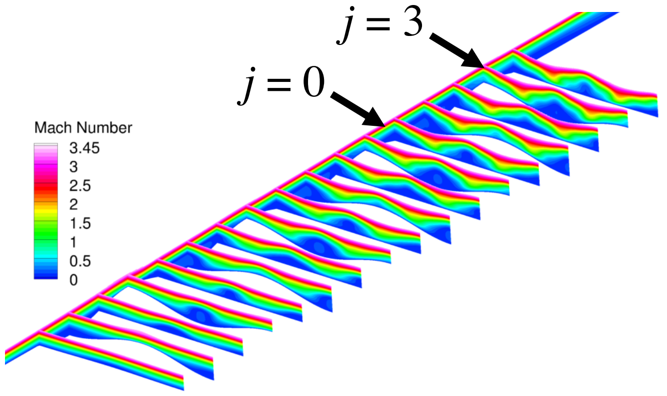
- Faster decay in wake amplitude for $L_w/\lambda_w = 1.0$ ➔ N_{max} ≈ 6, vs. N_{max} = 11+ for longer patch
- Modes AA and SA most amplified in both cases, f ≈ 50-60 kHz

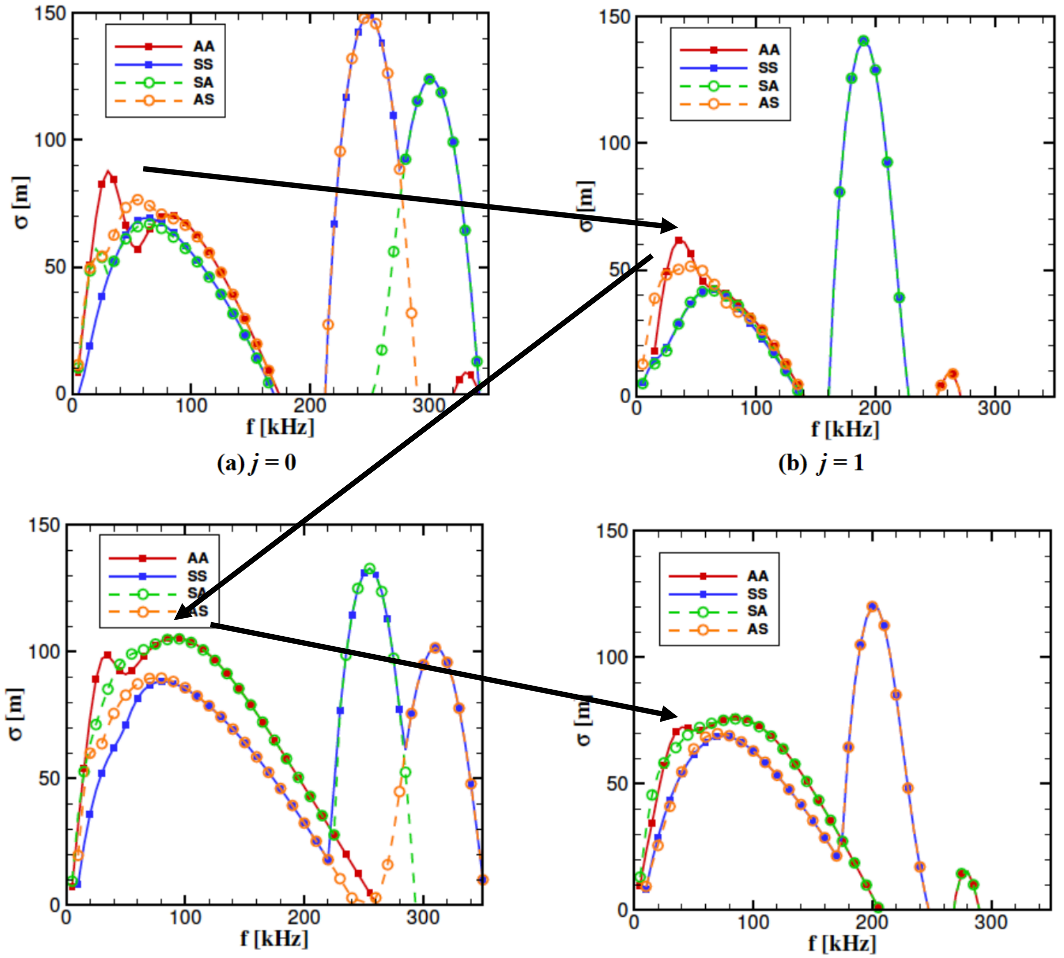
Stability Analysis Above Roughness Patch Region



- Cyclic, short-scale variations in basic state above roughness patch
  ⇒ can expect stronger non-parallel effects on disturbance growth
- However, cyclic variation mainly prominent in low-speed region
- Instabilities expected to be concentrated in high-shear region, which shows weaker streamwise variation
  ⇒ quasi-parallel stability analysis should provide a useful starting point
  - ☐ Other options: ✗ Floquet analysis of quasi-periodic basic state
    ✓ Direct numerical simulation (DNS)

Quasi-parallel Stability Analysis





(a) $j = 0$

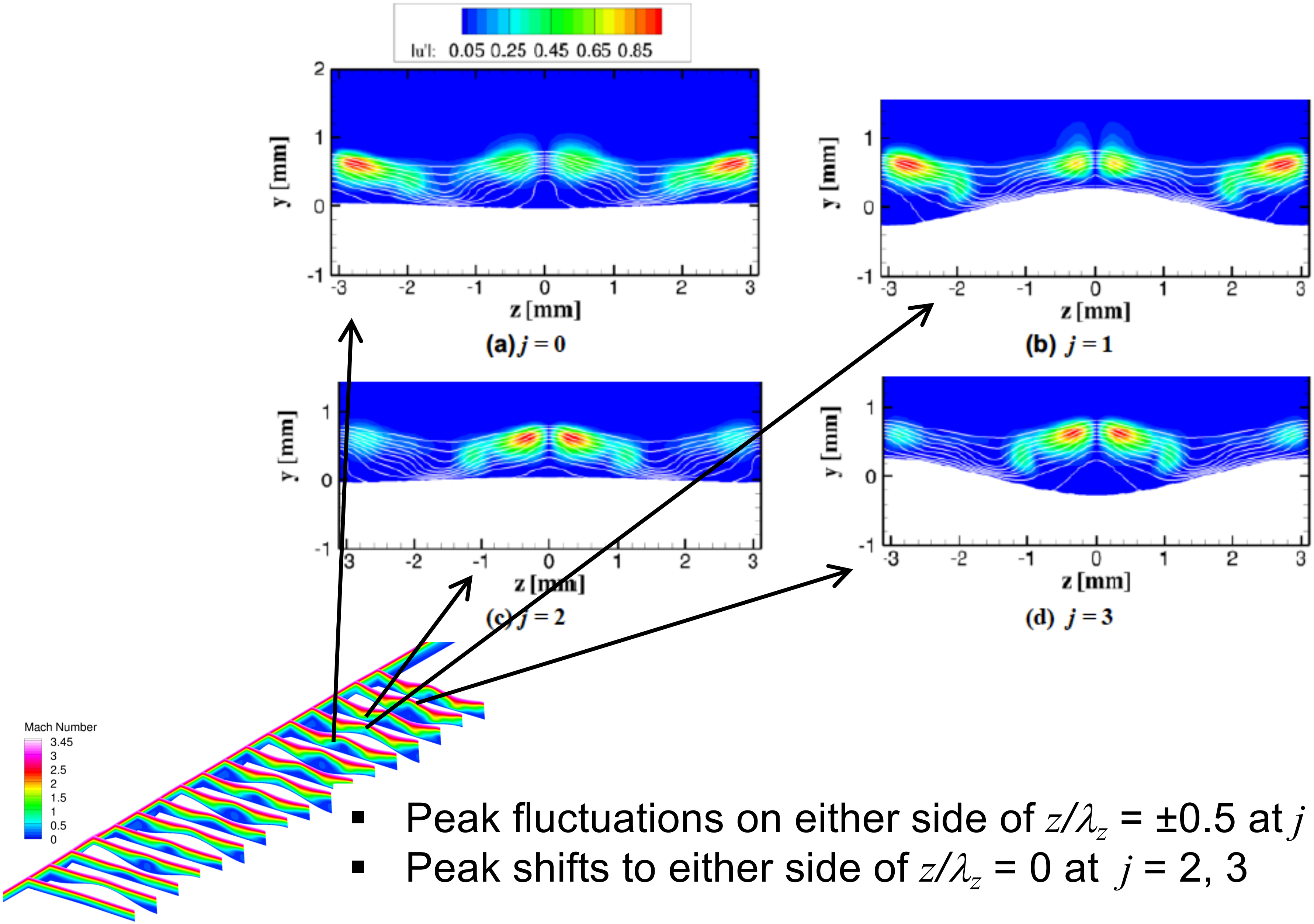
(b) $j = 1$

(c) $j = 2$

(d) $j = 3$

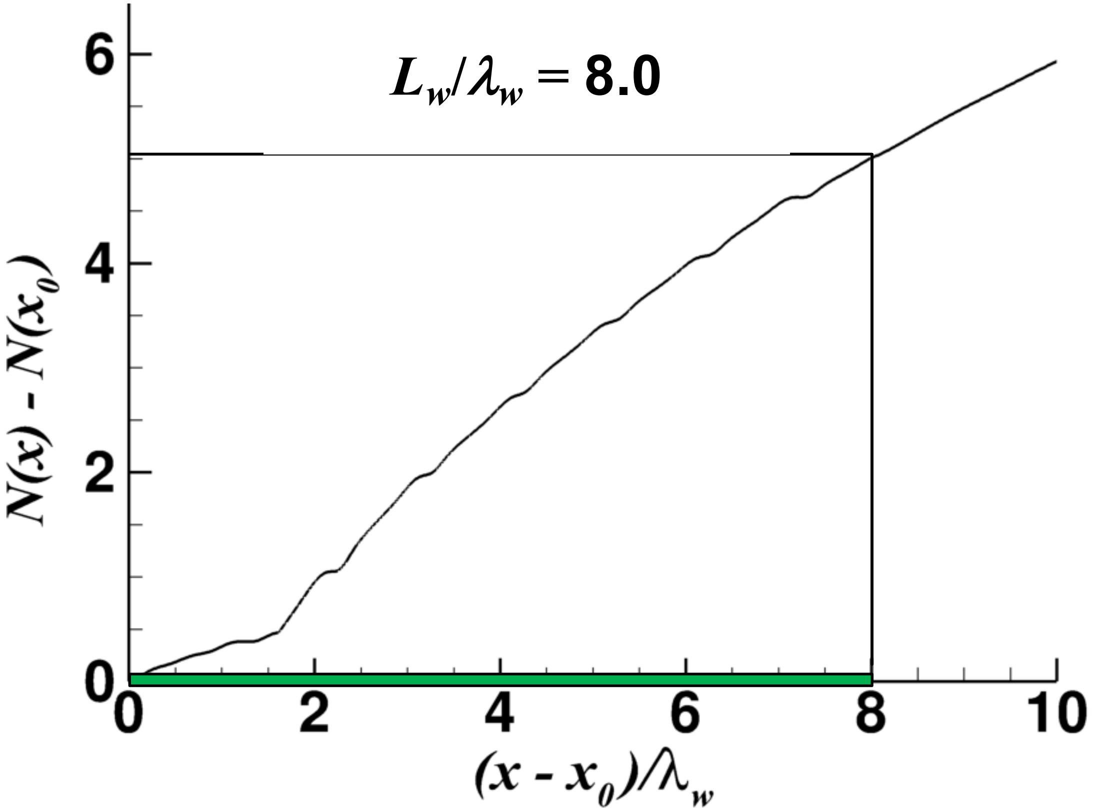
- ☐ Two types of disturbances
  - Low frequency modes: $f = O$(10-200) kHz, peak growth: O(50-100) kHz
    - Sustained growth across wavy patch, but with a cyclic component in growth rate
  - High-frequency modes: $f = O$(200-300) kHz
    - Shifting frequency band for given mode type
⇒ amplification confined to a part of the wavy-patch cycle?
    - Not connected to wake instability modes?

Quasi-parallel Stability Analysis: Mode Shapes
AA mode, *f* = 50 kHz



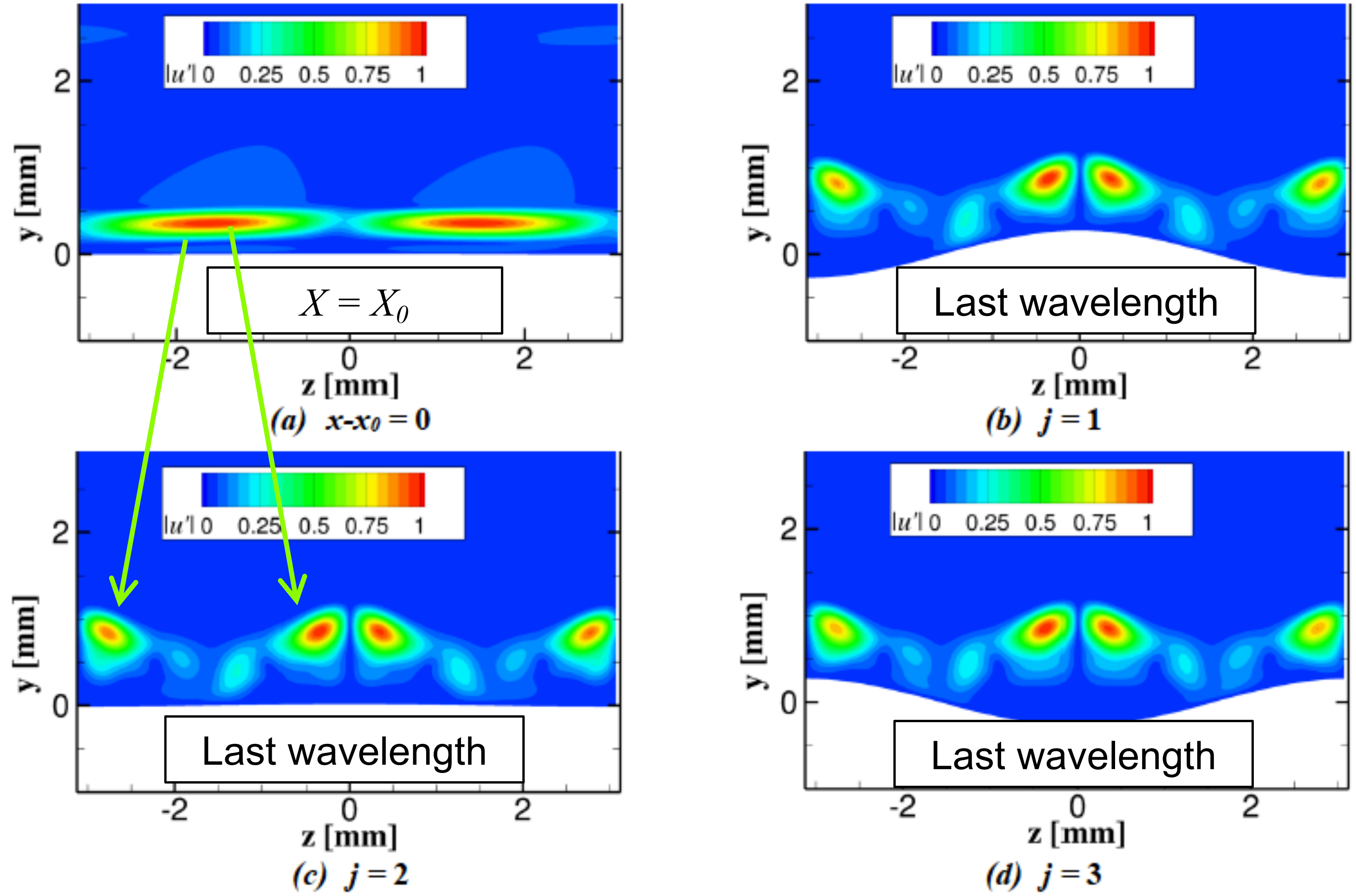
- Peak fluctuations on either side of $z/\lambda_z = \pm 0.5$ at $j = 0, 1$
- Peak shifts to either side of $z/\lambda_z = 0$ at $j = 2, 3$

DNS of Disturbance Growth above Roughness Patch N-factor Evolution (AA mode, f = 50 kHz)



- Appreciable, sustained disturbance amplification across roughness patch
  - N≈5 (vs. N≈1.4 over the same distance in the absence of roughness)
- Cyclic variation in slope
  ⇒ varying growth rates, analogous to quasi-parallel predictions
- Continued amplification within wake region
- Comparable growth for selected other frequencies, other mode types

DNS of Disturbance Evolution: Mode Shapes



(a) $x\text{-}x_0 = 0$ (b) $j = 1$

(c) $j = 2$ (d) $j = 3$

- Initial, nearly sinusoidal mode shape gets progressively distorted over roughness patch
- Mode shapes resemble those from quasi-parallel analysis, but some difference in relative amplitudes of peaks near z/λ_z = -0.5, 0

Summary

- Patterned roughness patches with sinusoidal height distribution

  M = 3.5 flat plate BL at Chou et al. quiet tunnel conditions:
  $k/\delta \approx 0.45$, $\lambda_w/\delta \approx 10.8$, $L_w/\lambda_w = 1.0, 4.0, 8.0$

  – Suitable planform length scale ($\lambda_z = \lambda_w >> \delta$) can lead to strong mean flow distortion both above the roughness patch and within patch wake

➡ Flow above roughness appears to support two types of instability waves

  – Low freq. modes with sustained amplification; continued growth within wake;

  – High freq. modes that amplify only within a part of each roughness wavelength

➡ Disturbance growth over roughness patch: N > 5 for $L_w/\lambda_w = 8.0$

  ⇒ instability growth within wake region alone not adequate for transition correlation for longer roughness patches

- Ongoing work
  - Nonlinear evolution + potential breakdown within roughness region
  - Better understanding of high-frequency modes

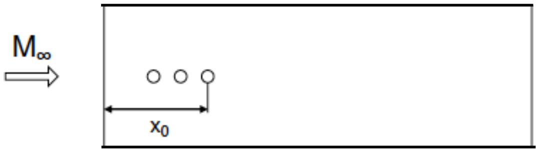
Extra Charts

Distributed Roughness: More Dangerous, Myriad Geometries

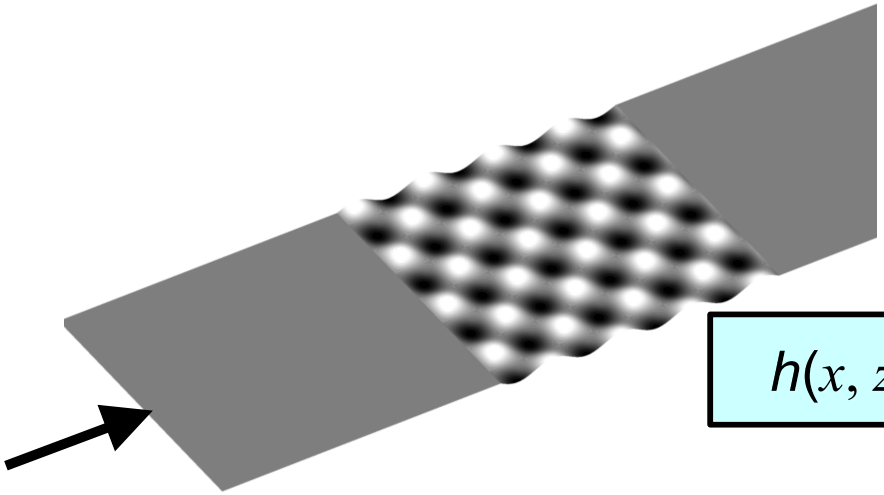
$$\frac{Re_{kk,\mathrm{TR}}(\text{isolated})}{Re_{kk,\mathrm{TR}}(\text{distributed})} \cong \frac{800}{250} \cong \frac{3}{1}$$

(Reda et al. 2010)

- **Simplest:** Multiple roughness elements (streamwise, spanwise proximity) e.g., Choudhari et al. (2010), Chou et al. (2017, 2018)



- **Realistic: stochastic,** densely packed, heterogeneous planform scales, heights, and orientations, possibly combined with ablation-induced outgassing)
  - Recent studies in low-speed flows
- **Intermediate complexity:** “Smooth” **patterned** height distribution over **finite length**, e.g., Muppidi et al. (2013)



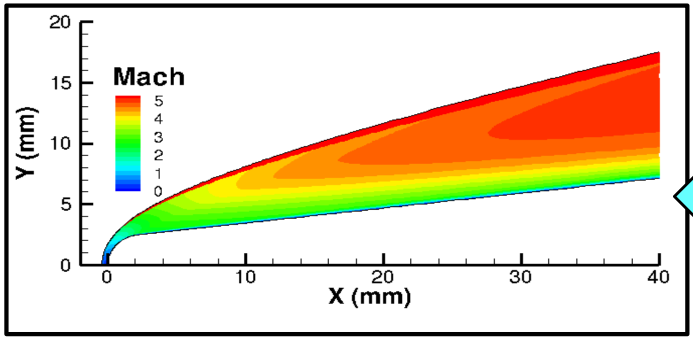
$$h(x, z) = k \sin(2\pi\, x/\lambda_w) \cos(2\pi\, z/\lambda_z)$$

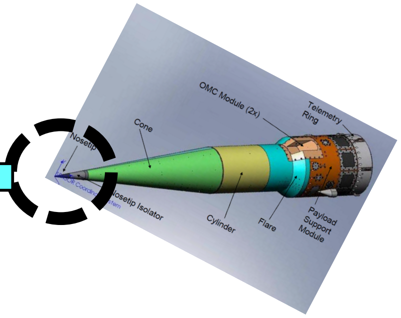
- **Objective: Investigate roughness patch effects on flow stability**
  - Not investigated during M = 2.9 DNS of Muppidi et al. (2013)

Outline

- Numerics (see paper for details)
- **HIFiRE-1 7-deg half angle cone (Mack mode dominated)**
  - Basic state
  - Stability analysis (other roles of roughness not considered)
    - Frequency range
    - Mode shapes
    - Growth factors
- **Mach 3.5 flat plate (weakly 1st mode unstable) (Kegerise et al., Chou et al. configuration for NASA Langley Supersonic Low Disturbance Tunnel)**
  - Basic state parameter study to guide future measurements
  - Stability analysis for single selected case
- Summary

Outline





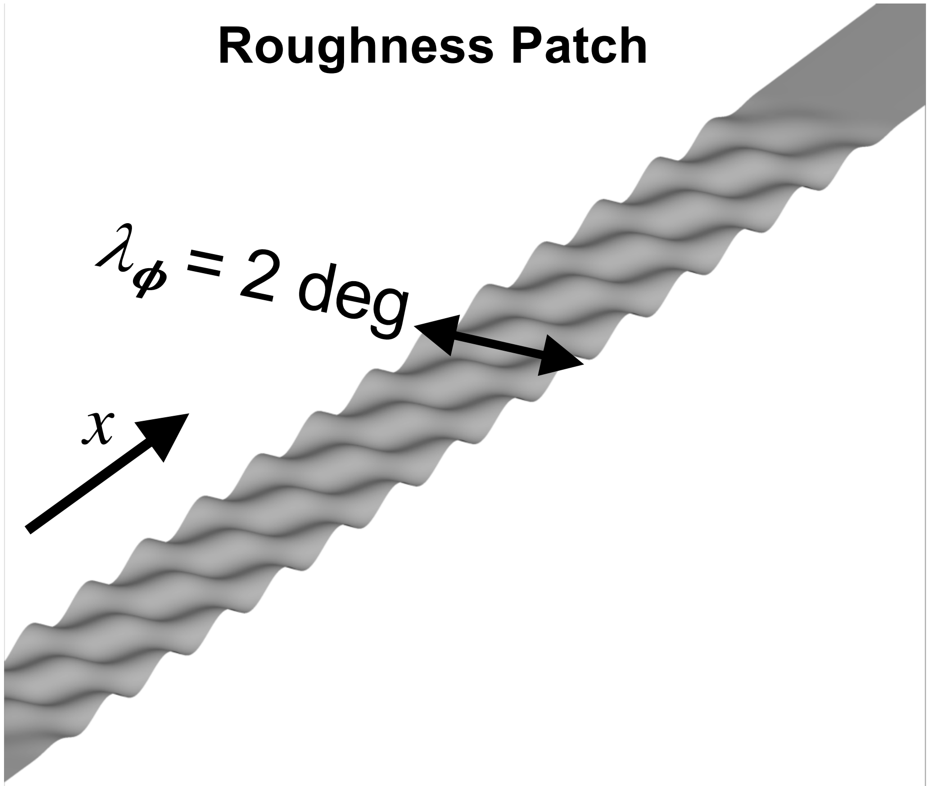
- Numerics
- **HIFiRE-1 7-deg half angle cone (ascent phase: *t* = 21.5 s)**
  - – Basic state
  - – Stability analysis
    - ➢ Frequency range
    - ➢ Mode shapes
    - ➢ Growth factors

- H = 18.9 km, **M_∞ = 5.3**, Re = 13.4×10^6/m
- **$T_w/T_{ad} \approx 0.35$**
- **$x_{tr} \approx$ 0.85 m ⇒ *N* = 14.7 (Li et al. 2015)**

- **Mach 3.5 flat plate boundary layer (Kegerise et al., Chou et al. configuration for NASA Langley Supersonic Low Disturbance Tunnel)**
  - –Basic state parameter study
  - –Stability analysis for selected case
- Summary

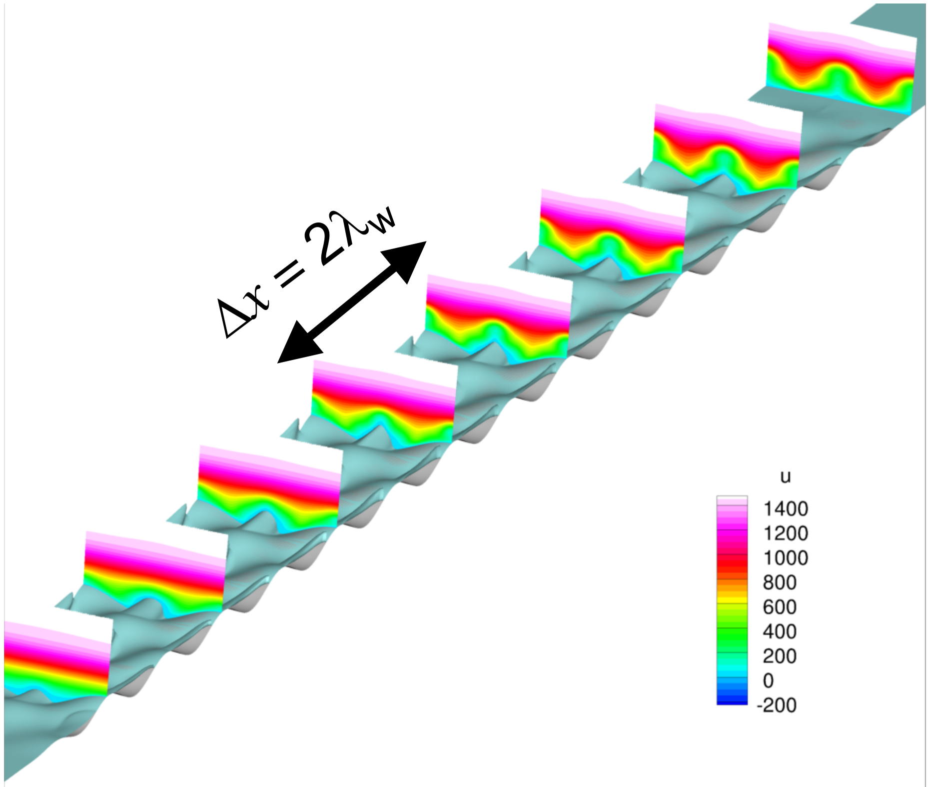
Mean Flow Modification Near Roughness Patch

$x_r \in [0.49, 0.52]$ m, $\lambda_w/\delta \approx 2.6$, $\lambda_z/\lambda_w = 1$, $L_w/\lambda_w = 12$, $k/\delta \approx 0.2$



Roughness Patch

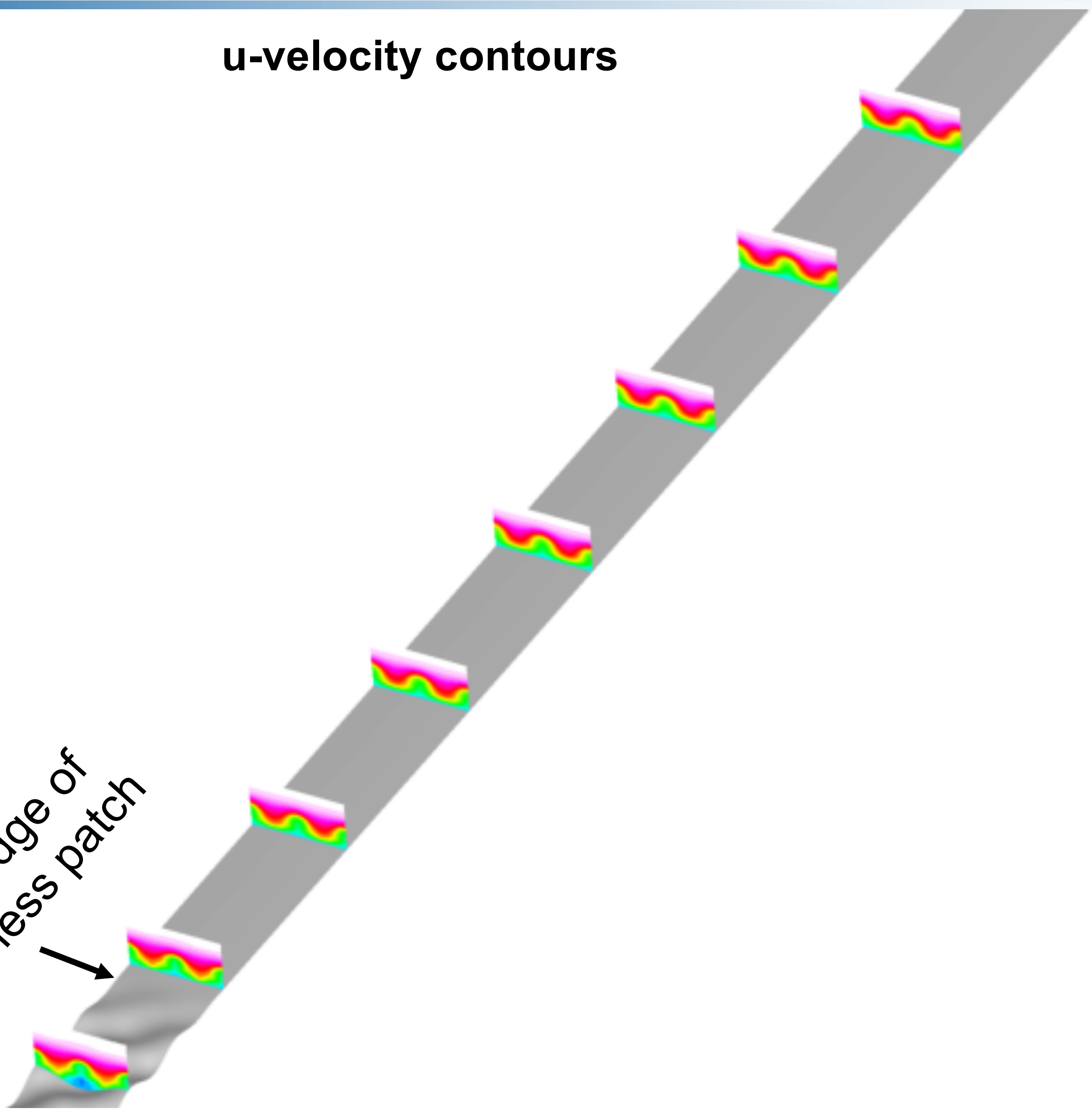
Boundary of recirculating region and u-velocity contours



- Recirculating region = narrow, finite-length ridges that are aligned with azimuthal symmetry planes (crests of roughness height distribution)
- Spanwise modulation gets progressively stronger across roughness patch length, yielding a wake structure that resembles the wake of a single array of roughness elements (Choudhari et al. 2009)

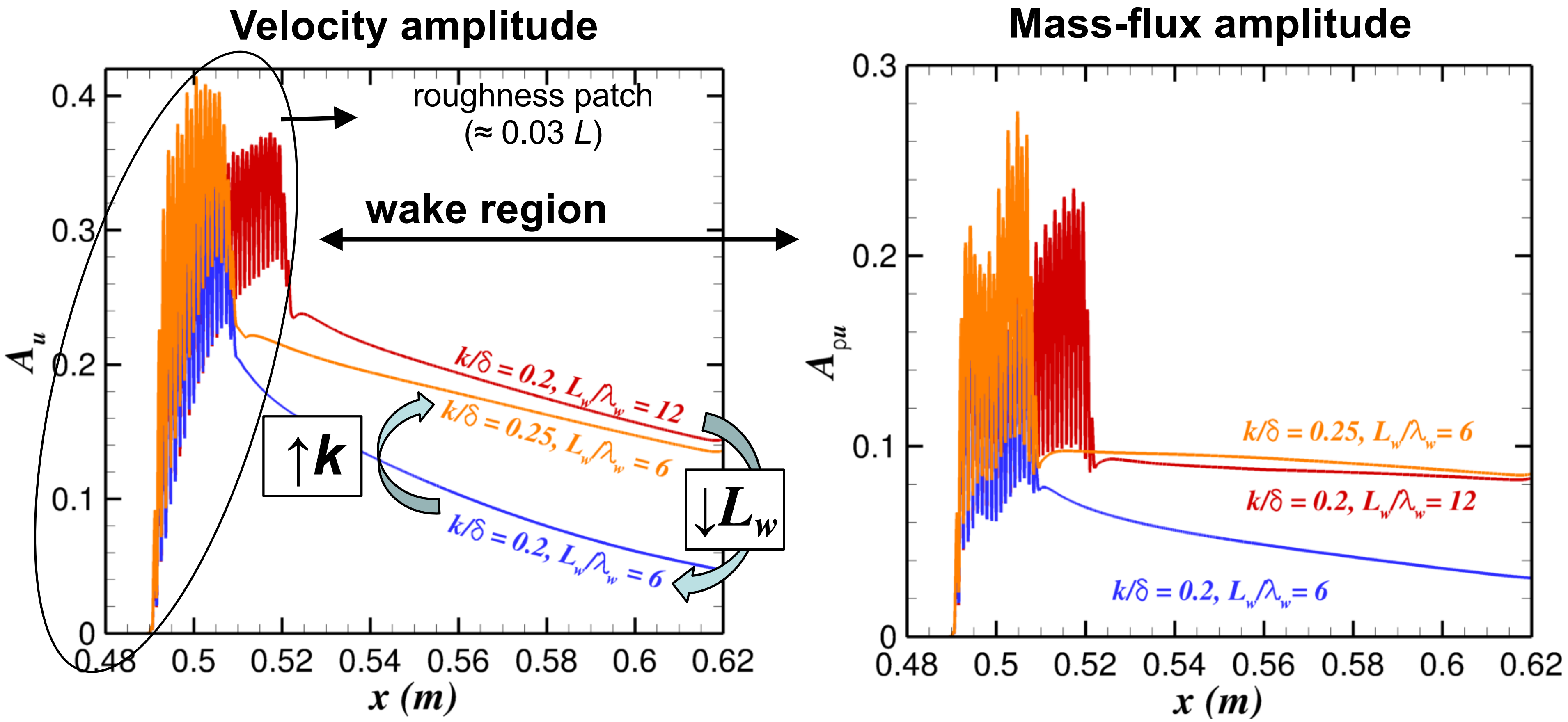
Mean Flow Modification Behind Roughness Patch

u-velocity contours



Trailing edge of roughness patch

Streamwise Evolution of Streak Amplitude in Wake: Effect of Roughness height k and Patch Length L_w



Velocity amplitude

Mass-flux amplitude

roughness patch (≈ 0.03 *L*)

wake region

0.5*[*max*(*u*') - *min*(*u*')]
Fransson et al. (2004)

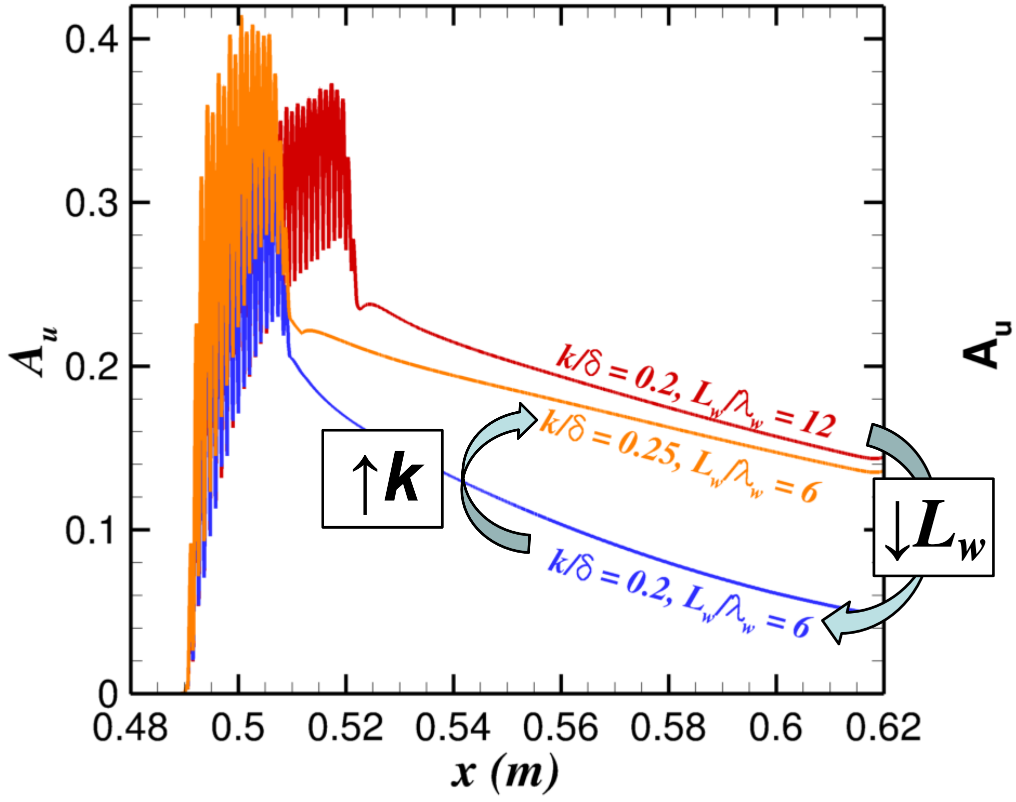
- A_u decreases significantly with x, but decrease in $A_{\rho u}$ is significantly slower
- Highly nonlinear dependence of $A_{\rho u}$ and A_u on patch length & roughness height

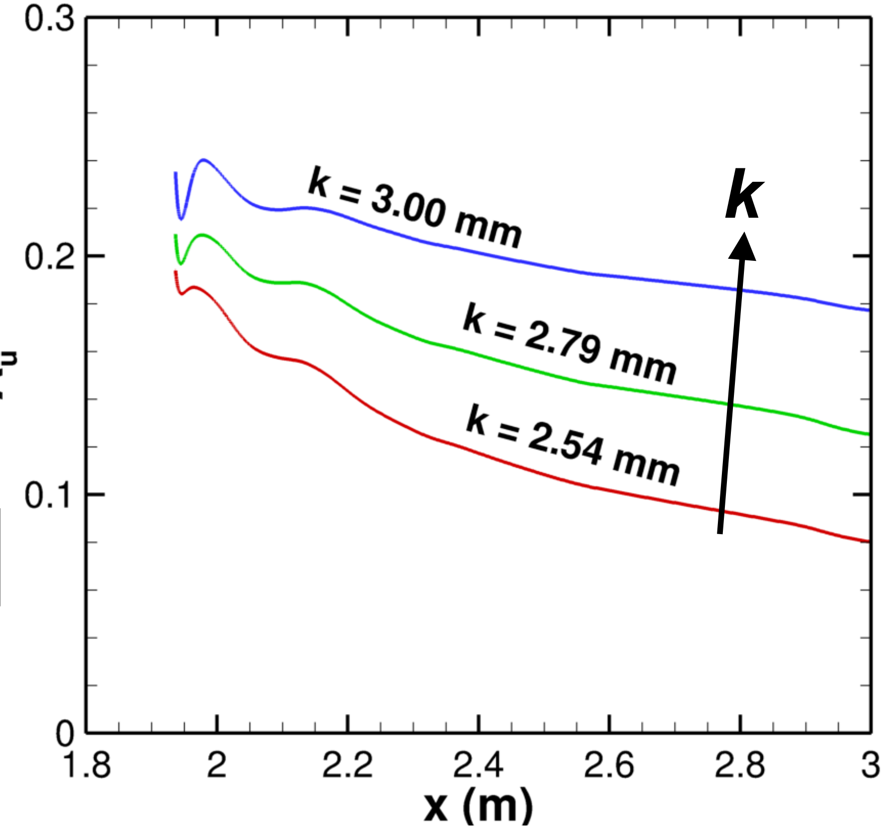
Streamwise Evolution of Streak Amplitude: Roughness Patch vs. Isolated Roughness Element

Isolated cylindrical roughness element: Wheaton and Schneider (2014) experiment

(Choudhari et al. 2015)

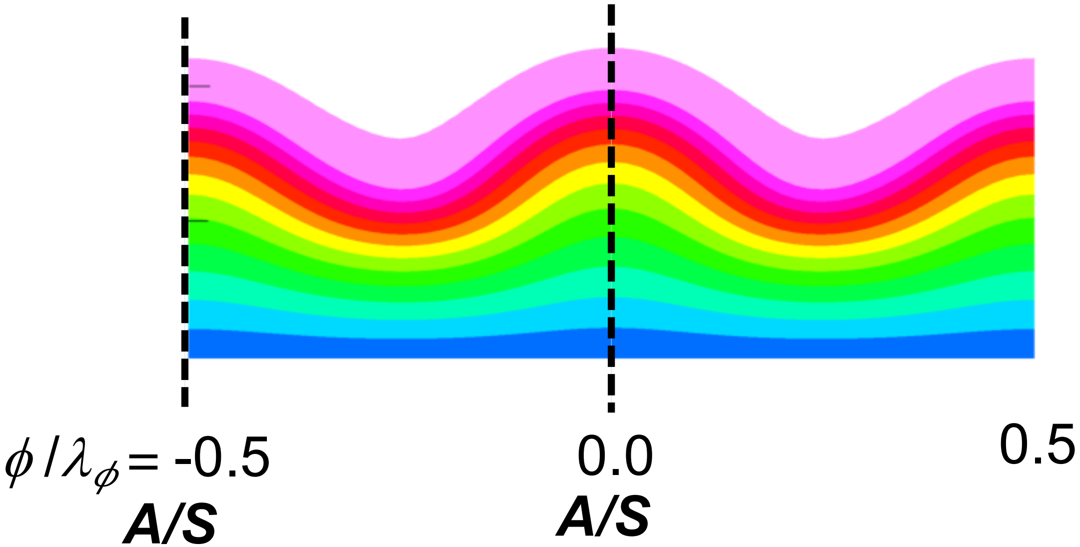
Distributed roughness patch





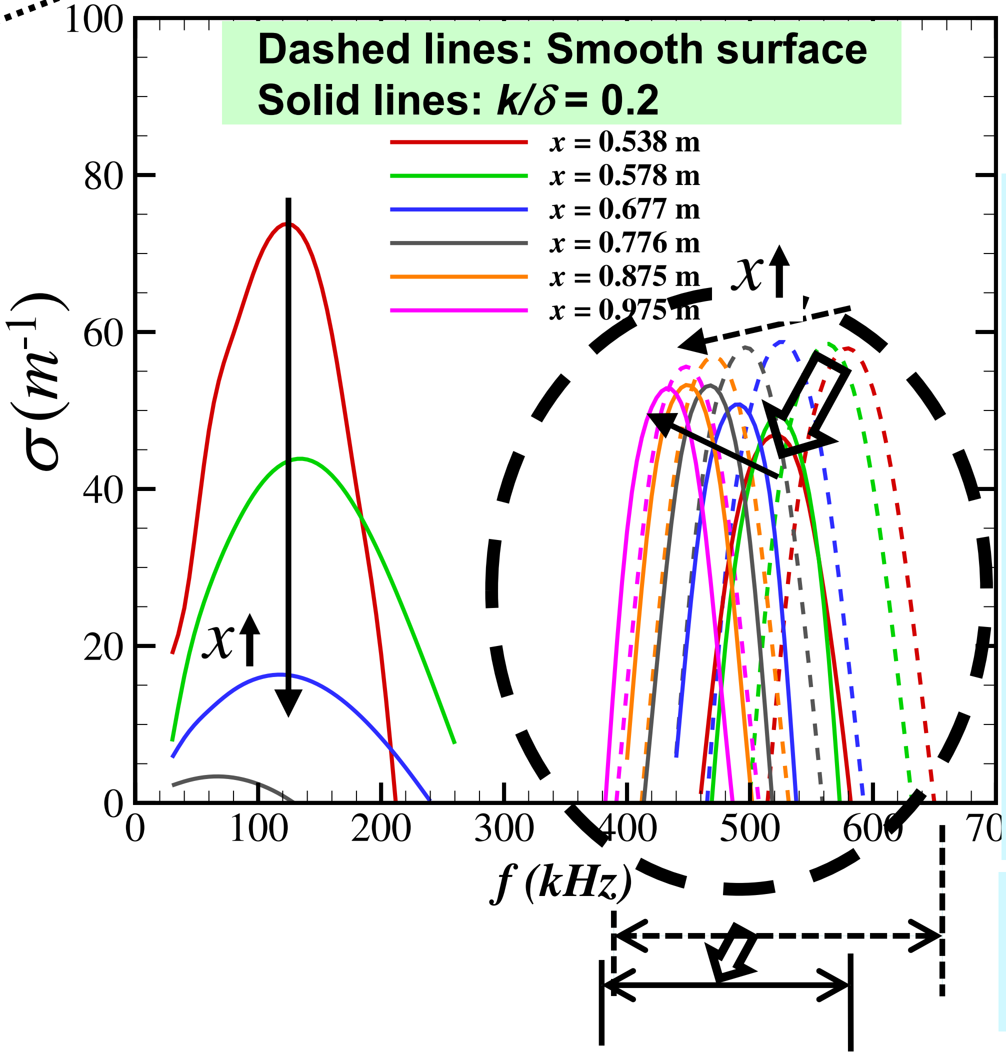
- Larger *k* or Larger initial amplitude ⇒ slower decay in disturbance amplitude A_u

Wake Instabilities: Mode Classification



- Basic state has two symmetry planes across each λ_ϕ:
  ϕ/λ_ϕ = -0.5, 0
- Unstable mode classification based on symmetry characteristics of perturbation field with respect to ϕ/λ_ϕ = -0.5, 0, respectively
  - AA, SS : Fundamental
  - SA, AS : 1st Subharmonic
- Detuned modes, higher subharmonics not considered (see Paredes et al. 2016)

Growth Rate Spectra (Plane Marching PSE) Selected, Dominant Families of Wake Instabilities



Streak Instabilities AA Type

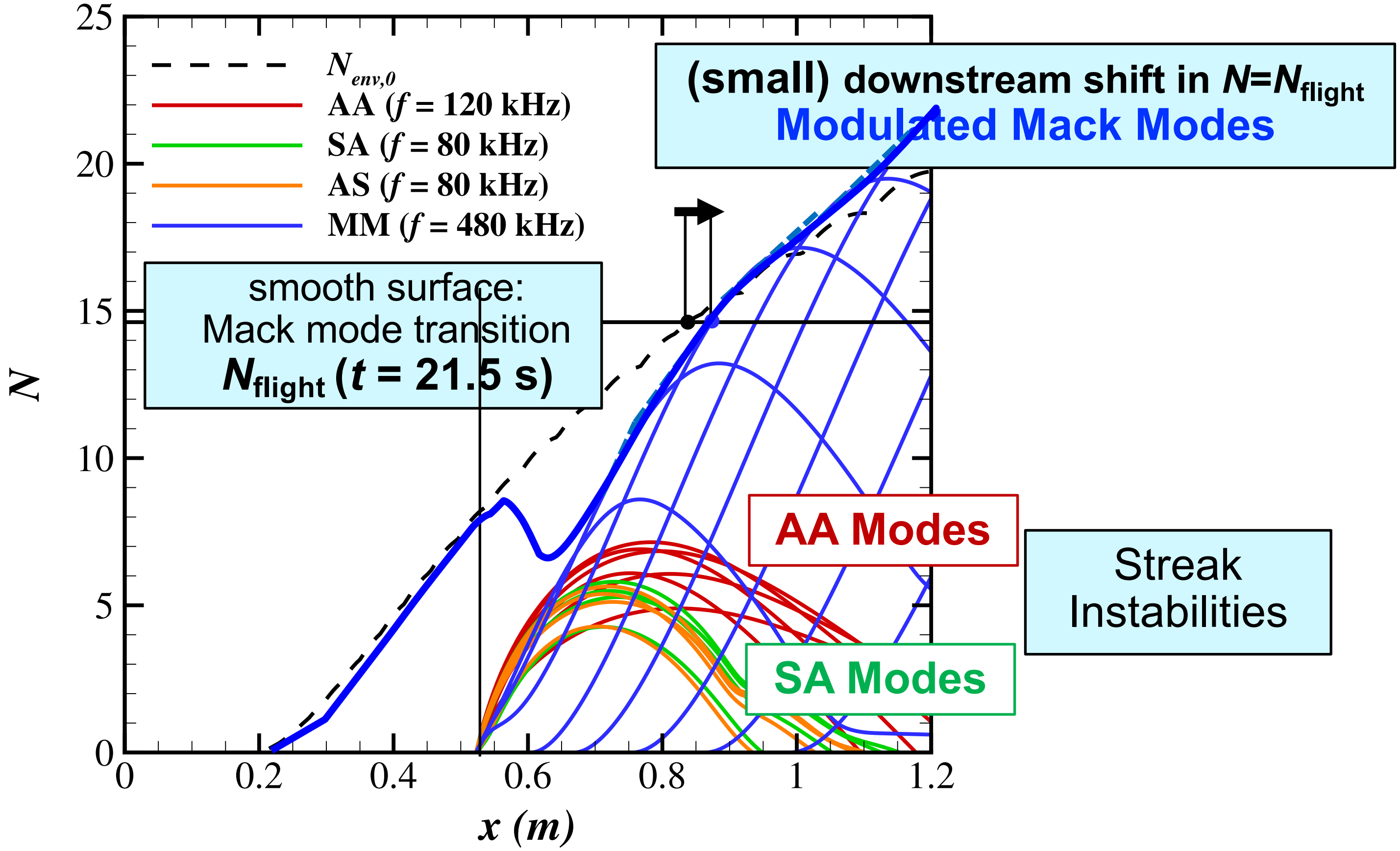
- **Absent in baseline case**
- Peak growth: $f \approx 120$ kHz
- Peak growth rate higher than Mack modes, but decreases rapidly with x (similar to $A_u(x)$)

Modulated Mack modes (SS Type)

Dominant Instability

- Lower peak growth rate frequencies (520-430 kHz) than baseline case (600-450 kHz)
- Peak growth rate lowest just behind the roughness patch and increases along cone (different trend from the baseline case) **(Recall: Paredes et al. 2018)**
- Lower frequency bandwidth in the presence of roughness patch

N-factor Evolution of Wake Instabilities



(small) downstream shift in N=N_{flight}

Modulated Mack Modes

smooth surface:
Mack mode transition
N_{flight} (t = 21.5 s)

AA Modes

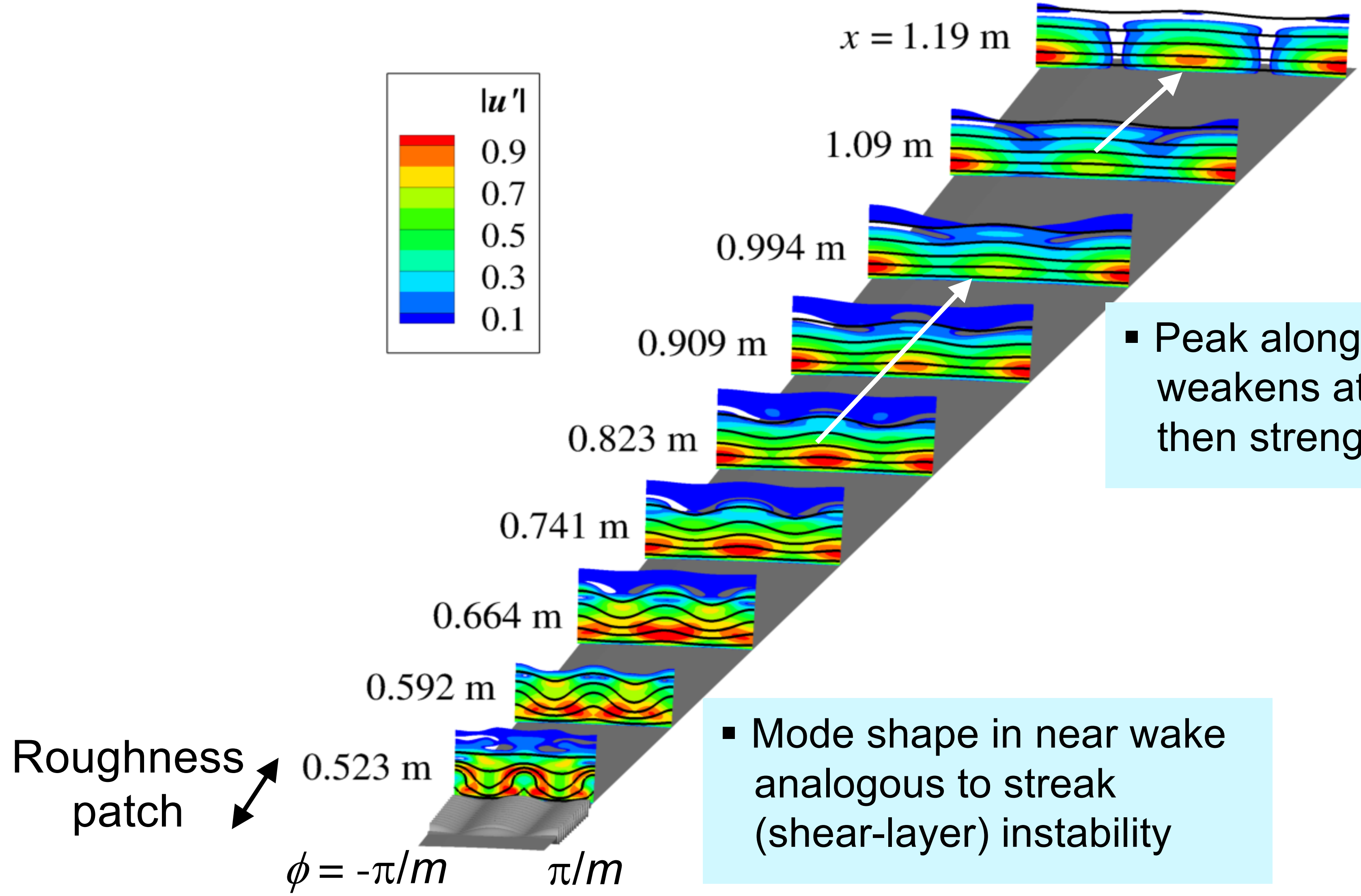
SA Modes

Streak Instabilities

- Stronger reduction in Mack mode amplification possible via suitably designed vortex generators: addressed by Paredes et al. during session FD-19, Stability and Transition IV: High-Speed II, on June 26.

Mode Shapes of Modulated Mack Modes (SS type, f = 480 kHz)

- Beyond near wake, peak *u*’ fluctuations occur within inner part of boundary layer
  - Spanwise locations aligned with crests of roughness height distribution
  - Contrasting evolution to secondary instability of crossflow vortices (Li et al. 2016, Choudhari et al. 2017)

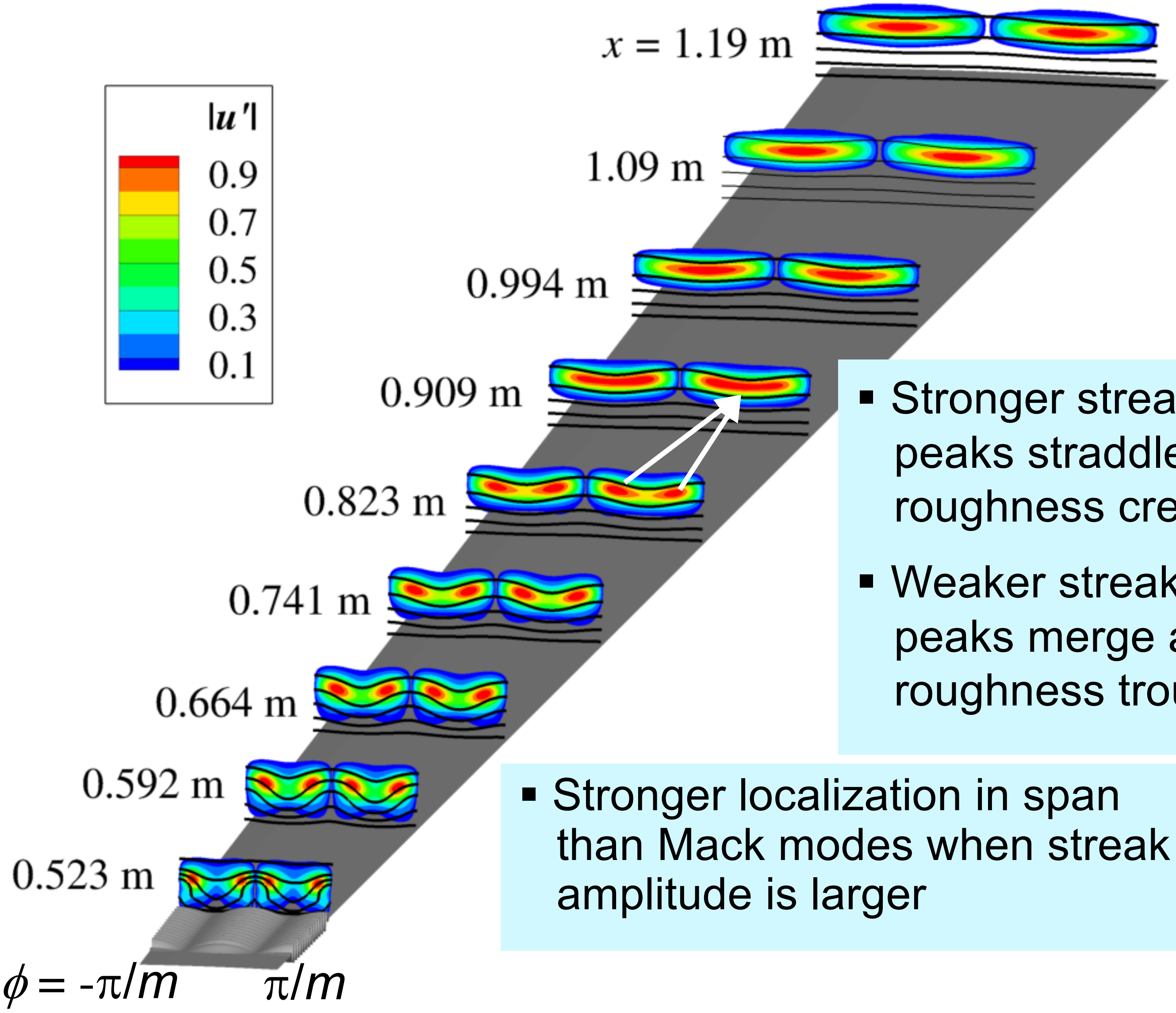


- Peak along centerplane weakens at first, then strengthens again

- Mode shape in near wake analogous to streak (shear-layer) instability

Mode Shapes of Streak Instabilities (AA modes, f = 120 KHz)

- Peak *u*’ fluctuations always in high shear region within outer part of boundary layer
  - Spanwise nodes at crests of roughness height distribution



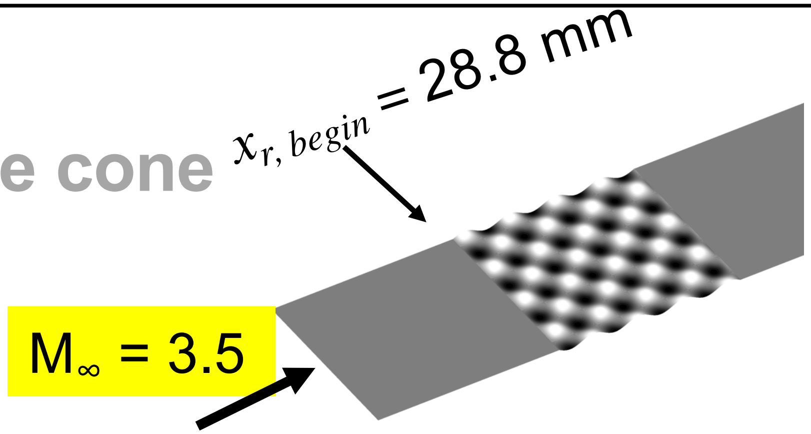
- Stronger streaks upstream: peaks straddle the roughness crests
- Weaker streaks downstream: peaks merge at the roughness trough planes

- Stronger localization in span than Mack modes when streak amplitude is larger

Outline

- $M_\infty = 3.5$, $Re = 10.8\times10^6/\mathrm{m}$
- $T_w/T_{ad} \approx 1.0$
- Weak 1st mode amplification

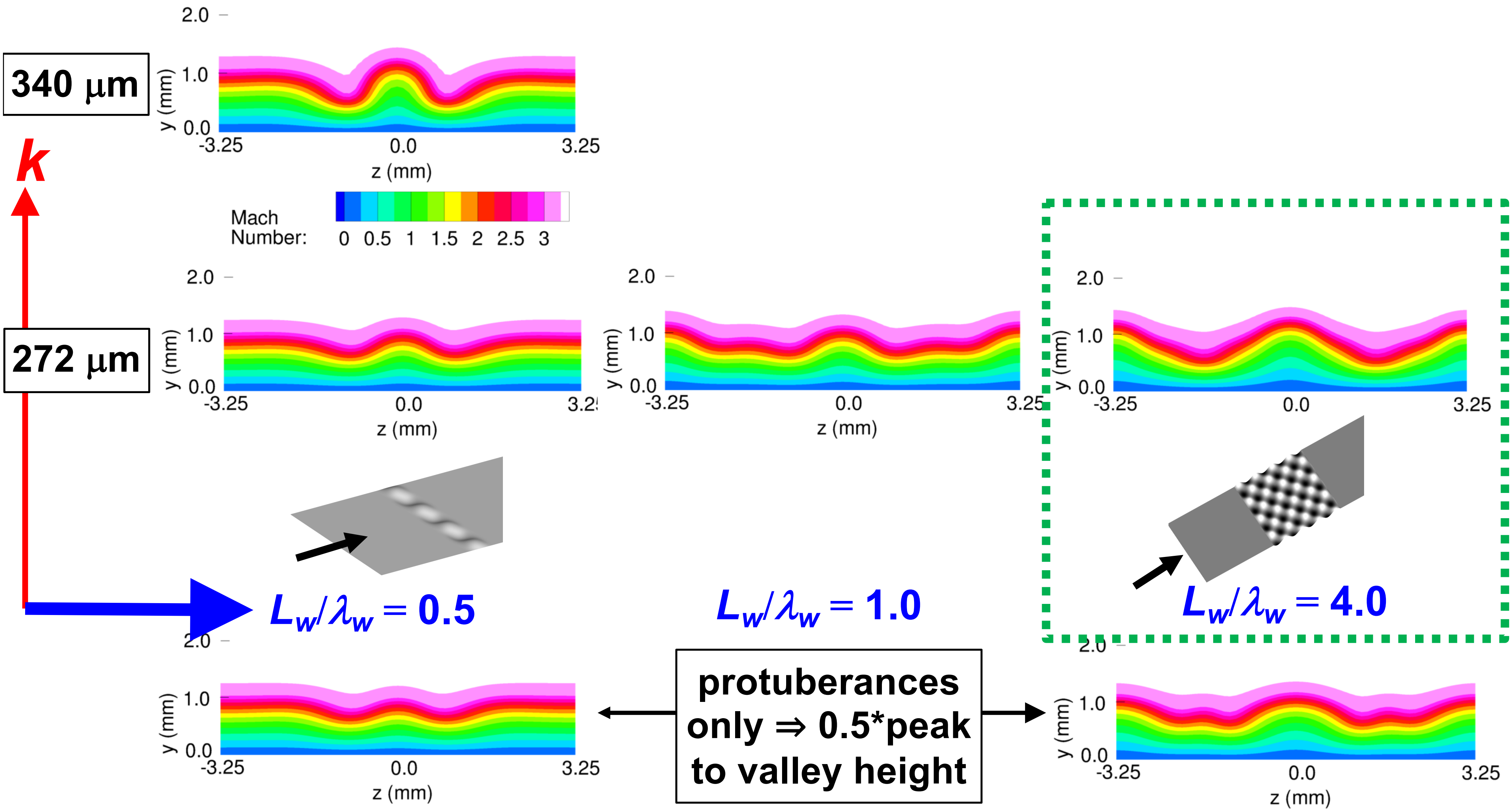
- Numerics
- HIFiRE-1 7-deg half angle cone
  - Basic state
  - Stability analysis
    - Frequency range
    - Mode shapes
    - Growth factors



Primary Configuration:
$x_r \in [28.8, 53.8]$ mm, $\lambda_w = \lambda_z = 6.25$ mm: $\lambda_w/\delta \approx 10.8$, $L_w/\lambda_w = 4$, $k/\delta \approx 0.45$

- **Mach 3.5 flat plate boundary layer (Kegerise et al., Chou et al. configuration for NASA Langley Supersonic Low Disturbance Tunnel)**
  - Basic state parameter study
  - Stability analysis for selected case
- Summary

Effect of Selected Roughness Patch Parameters on Wake Distortion
Mean Mach Number Contours at x = 120 mm ($x_{r,\ begin}$ = 28.8 mm)



340 μm

k

272 μm

L_w/λ_w = 0.5

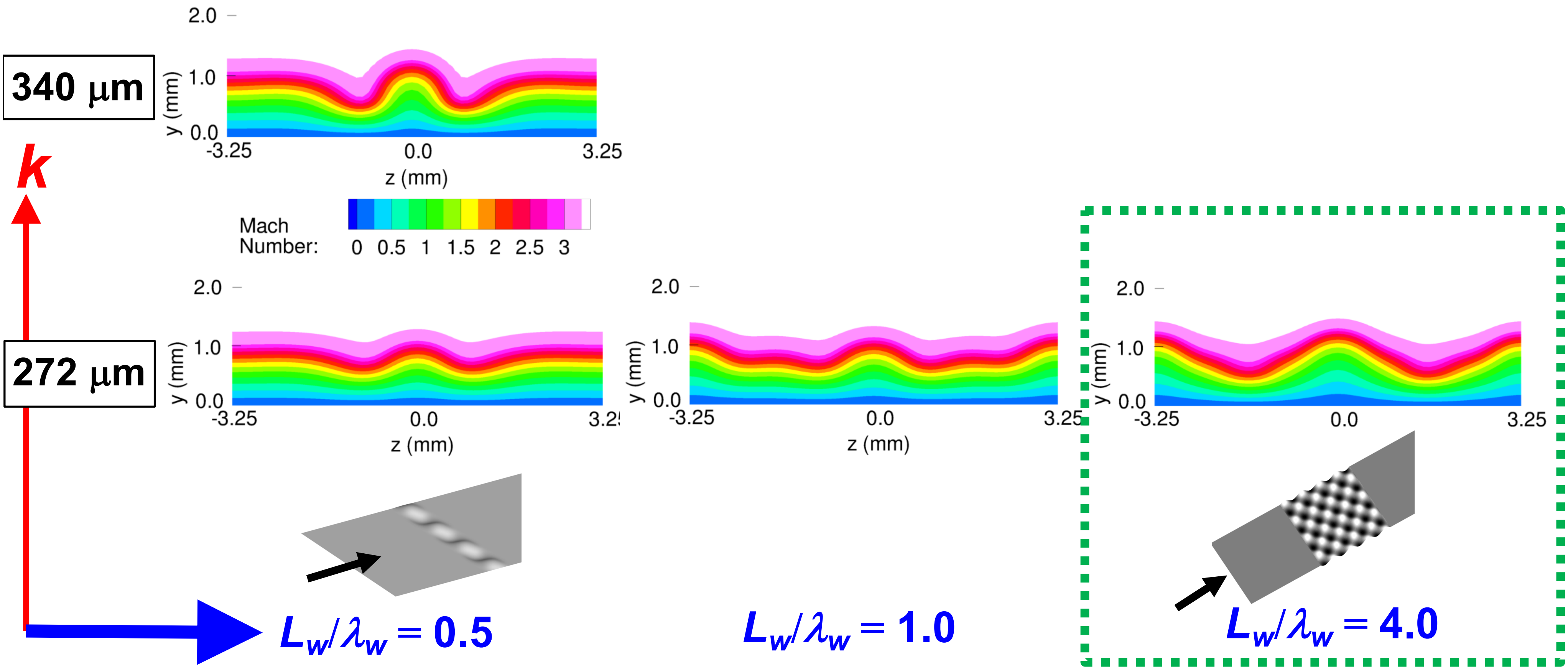
L_w/λ_w = 1.0

L_w/λ_w = 4.0

protuberances only ⇒ 0.5*peak to valley height

- Surface dimples have less effect than protuberances (agrees with Chang et al. 2011)
  - Peak to valley height less meaningful than protuberance height?
- Increasing patch length ⇒ increasing wake distortion

Effect of Selected Roughness Patch Parameters on Wake Distortion
Mean Mach Number Contours at x = 120 mm (x_0 = 28.8 mm)



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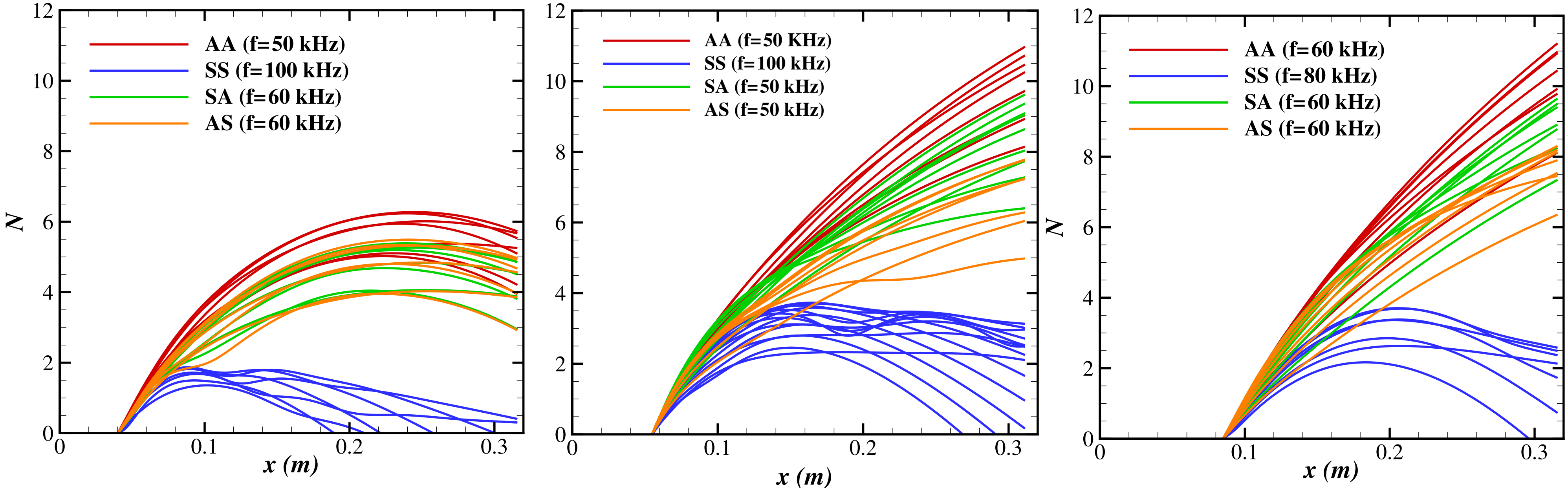
- Surface dimples have less effect than protuberances (agrees with Chang et al. 2011)
  - Peak to valley height less meaningful than protuberance height?
- **Increasing patch length ⇒ increasing wake distortion**

N-factor Evolution of Wake Instabilities (k = 272 μm)

Effect of Patch Length

L_w/λ_w = 1.0 | L_w/λ_w = 4.0 | L_w/λ_w = 8.0



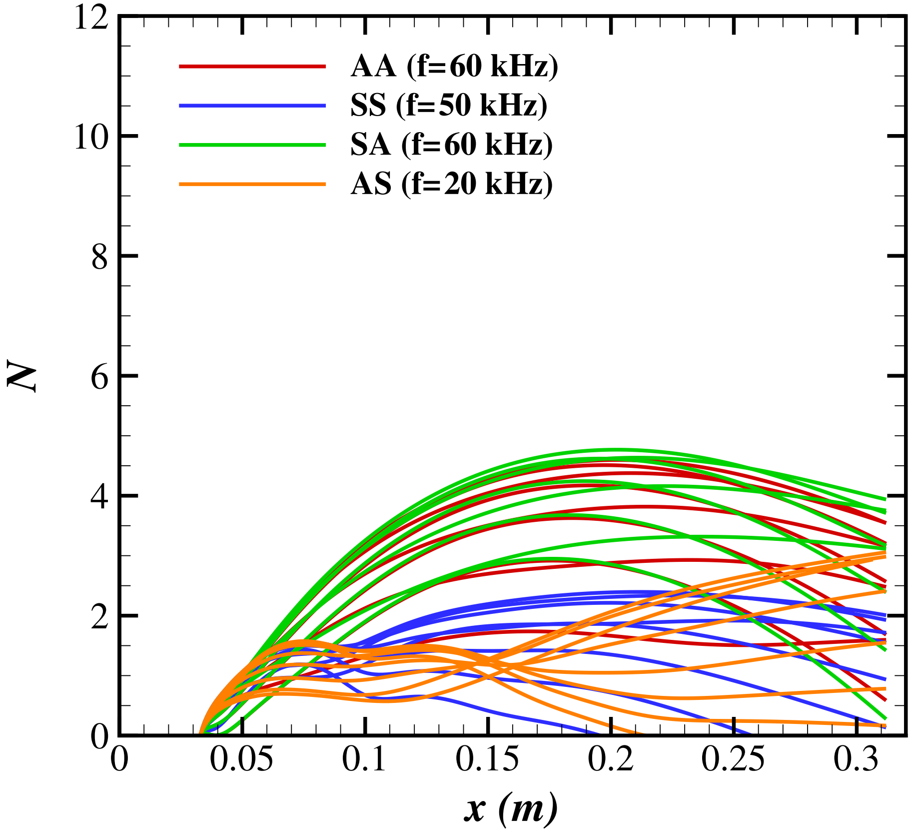
- Faster decay in wake amplitude for $L_w/\lambda_w = 0.5$ → $N_{max} < 5$, vs. $N_{max} = 11$ for longest patch
- Modes AA and SA most amplified in all cases

N-factor Evolution of Wake Instabilities (*k* = 272 μm)

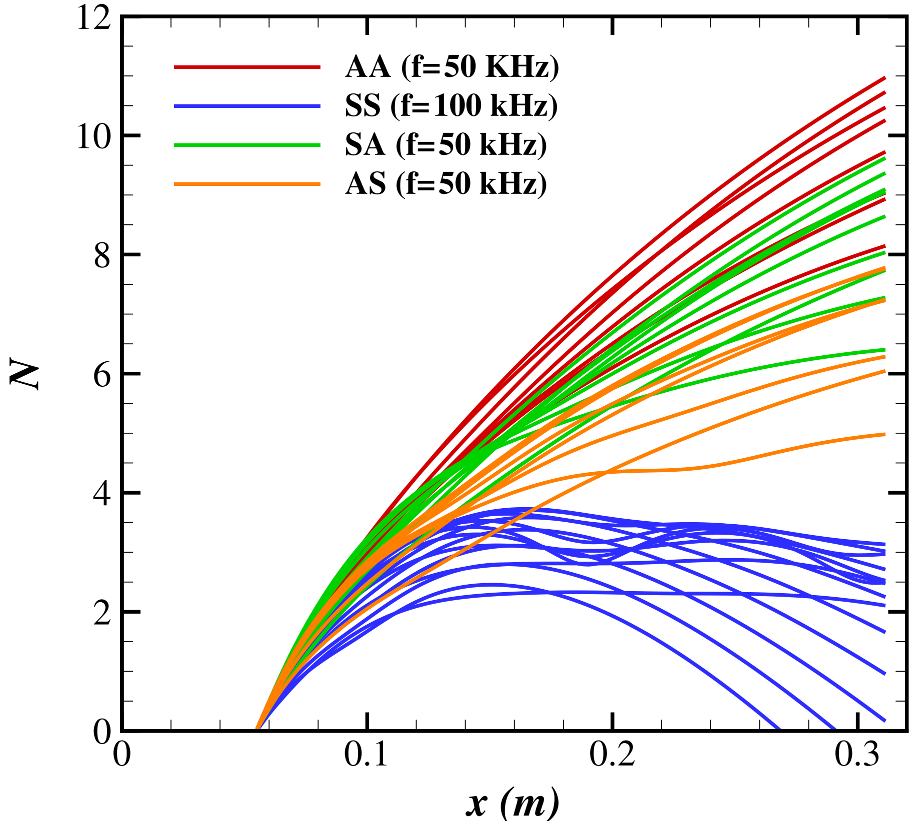
Effect of Patch Length

L_w/λ_w = 0.5

(single spanwise periodic array of protuberances & dimples)



L_w/λ_w = 4.0



- Faster decay in wake amplitude for $L_w/\lambda_w = 0.5$ → $N_{max} < 5$, vs. $N_{max} = 11$ for longer patch
- $L_w/\lambda_w = 0.5$ patch unlikely to yield transition within $x < 0.3$, but $L_w/\lambda_w = 4.0$ patch should!
- Modes AA and SA most amplified in both cases

Summary-2

- Patterned roughness patches with sinusoidal height distribution
  - **Suitable planform length scale can substantially increase mean flow distortion within roughness patch wake**
  - Protuberance portion of roughness patch more important than dimples

- **Roughness patch can have mixed effect on wake flow stability**

- M = 5.3 HIFiRE-1 cone: $k/\delta \approx 0.20$, $L_w/\lambda_w = 12.0$, $\lambda_w/\delta \approx 2.6$
  - Streak instabilities less important than modulated Mack modes
  - Roughness patch ⇒ slightly reduced N-factors

- M = 3.5 flat plate BL at Chou et al. quiet tunnel conditions: $k/\delta \approx 0.45$, $L_w/\lambda_w = 4.0$, $\lambda_w/\delta \approx 10.8$
  - Roughness patch likely to yield transition via streak instabilities, whereas a single array ($L_w/\lambda_w = 0.5$) will not

- Non-uniform effects of roughness resemble measurements by Holloway and Sterrett (1964) for array of roughness elements at $M_e = 4.8$ vs. 6

- Ongoing work: disturbance evolution within roughness region