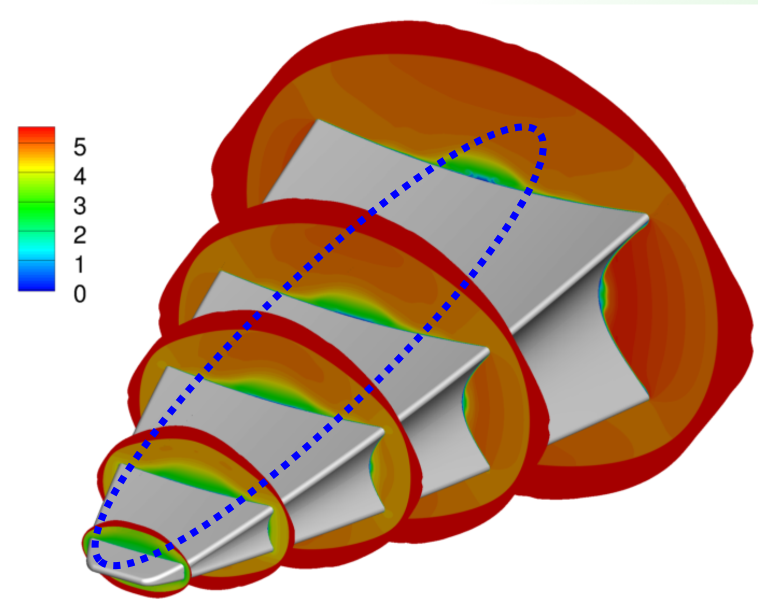
A Computational Analysis of Boundary Layer Instability over the BOLT Configuration

(Effect of Nonzero AoA and Yaw)



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Session FD-39, Transition Control in High-Speed Flows

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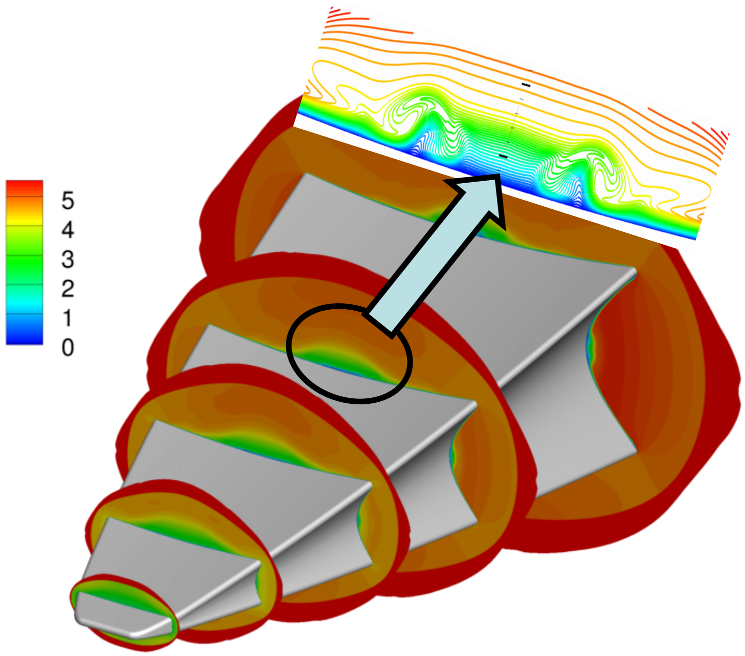
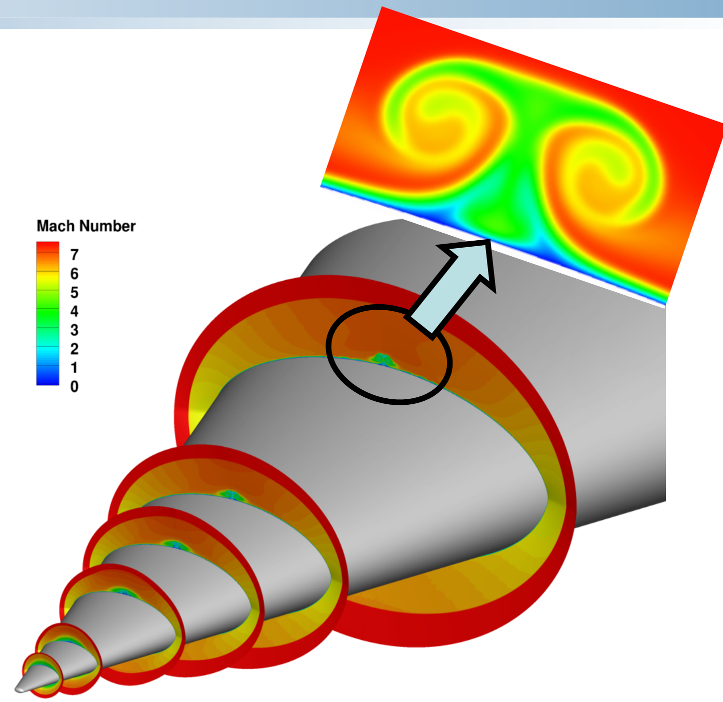
BOLT Geometry vs. HIFiRE-5b





BOLT

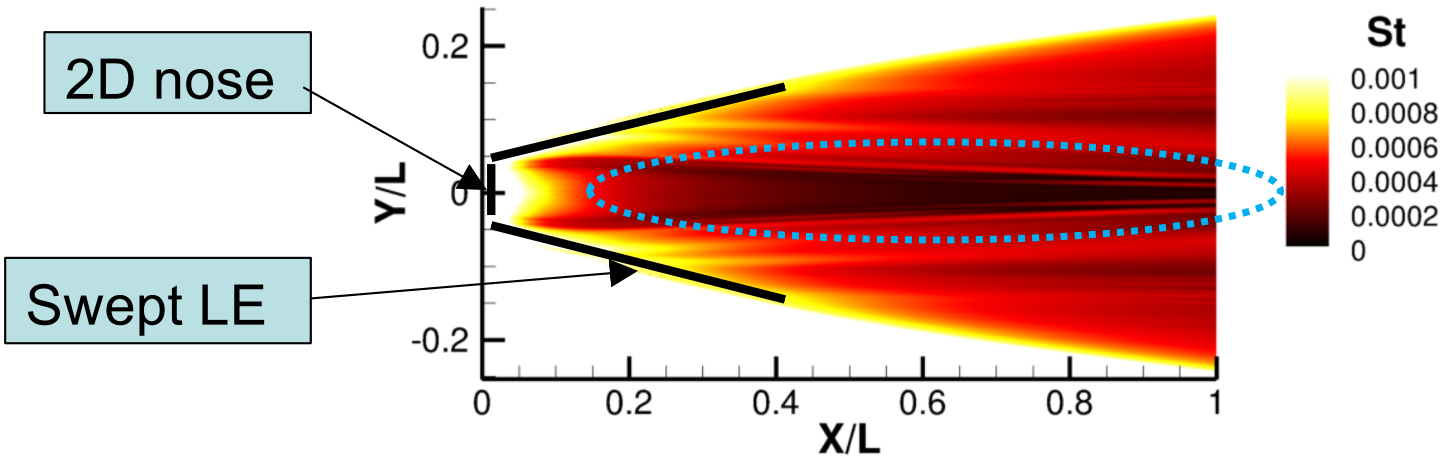
HIFiRE-5b
Elliptic Cone

- 2D nose tip, twice the nose radius relative to HIFiRE-5b
- 4 swept leading edges joined by 4 laterally concave surfaces

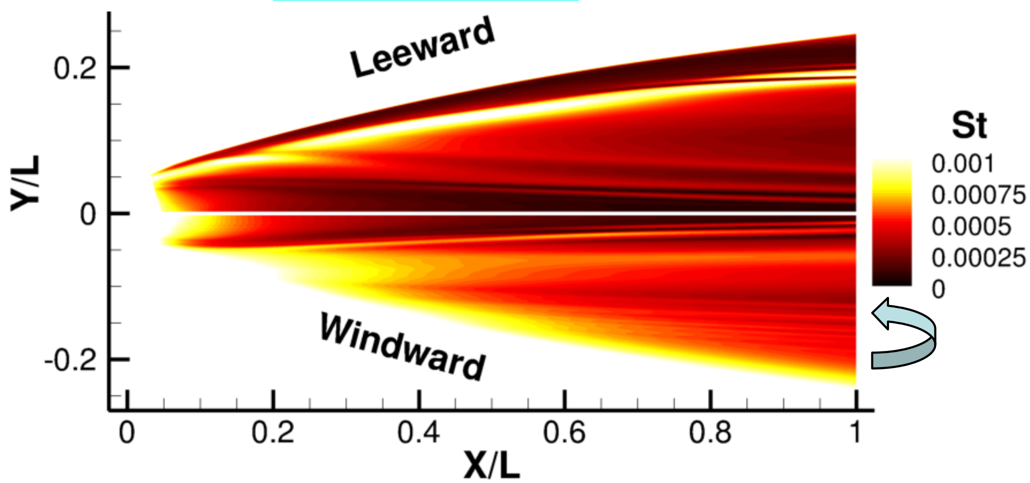
Ascent Condition from Flight Trajectory

t = 28.88 sec, M_∞ = 5.53, and $Re_L = 4.25\times10^6$

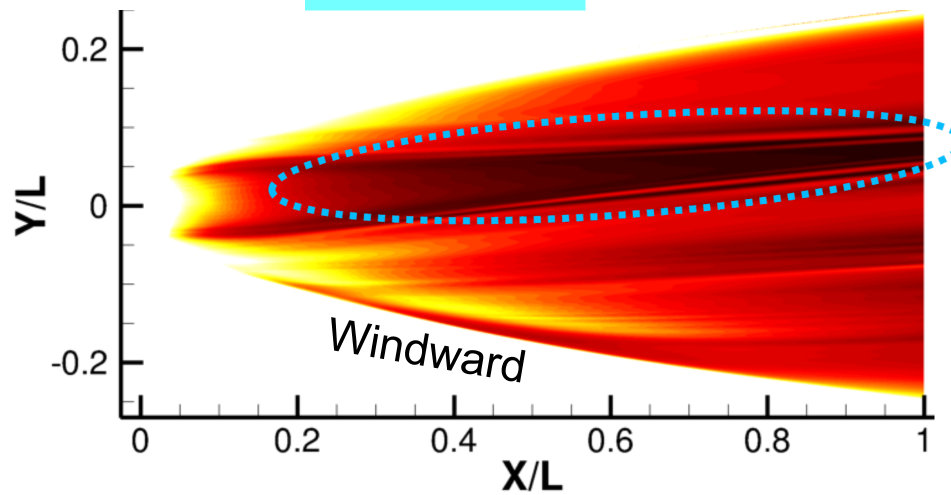
$\alpha = \beta = 0$ deg



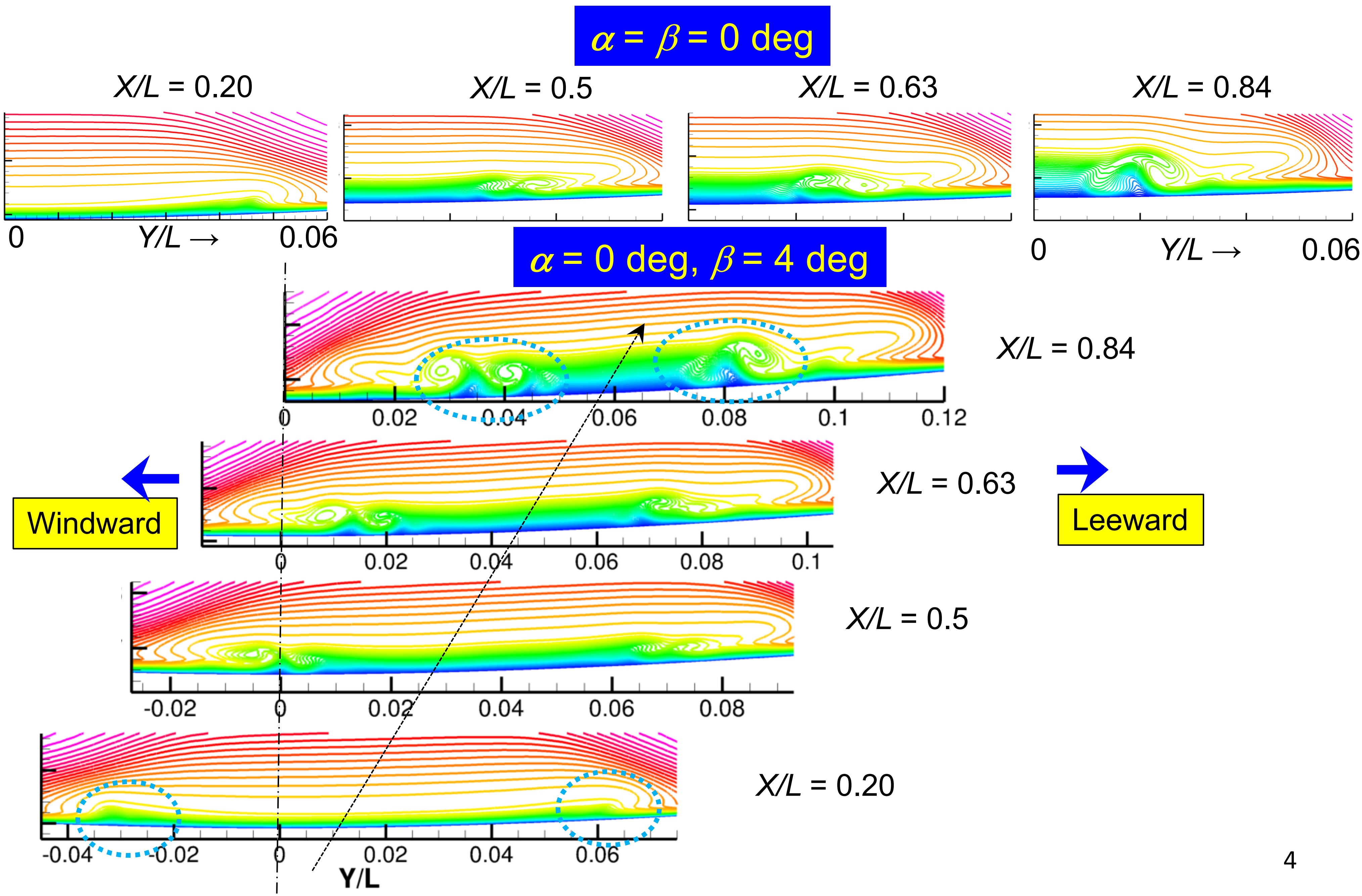
$\alpha = 4$ deg



$\beta = 4$ deg



Mach number contours: 0 to 5 ($\Delta M = 0.25$)

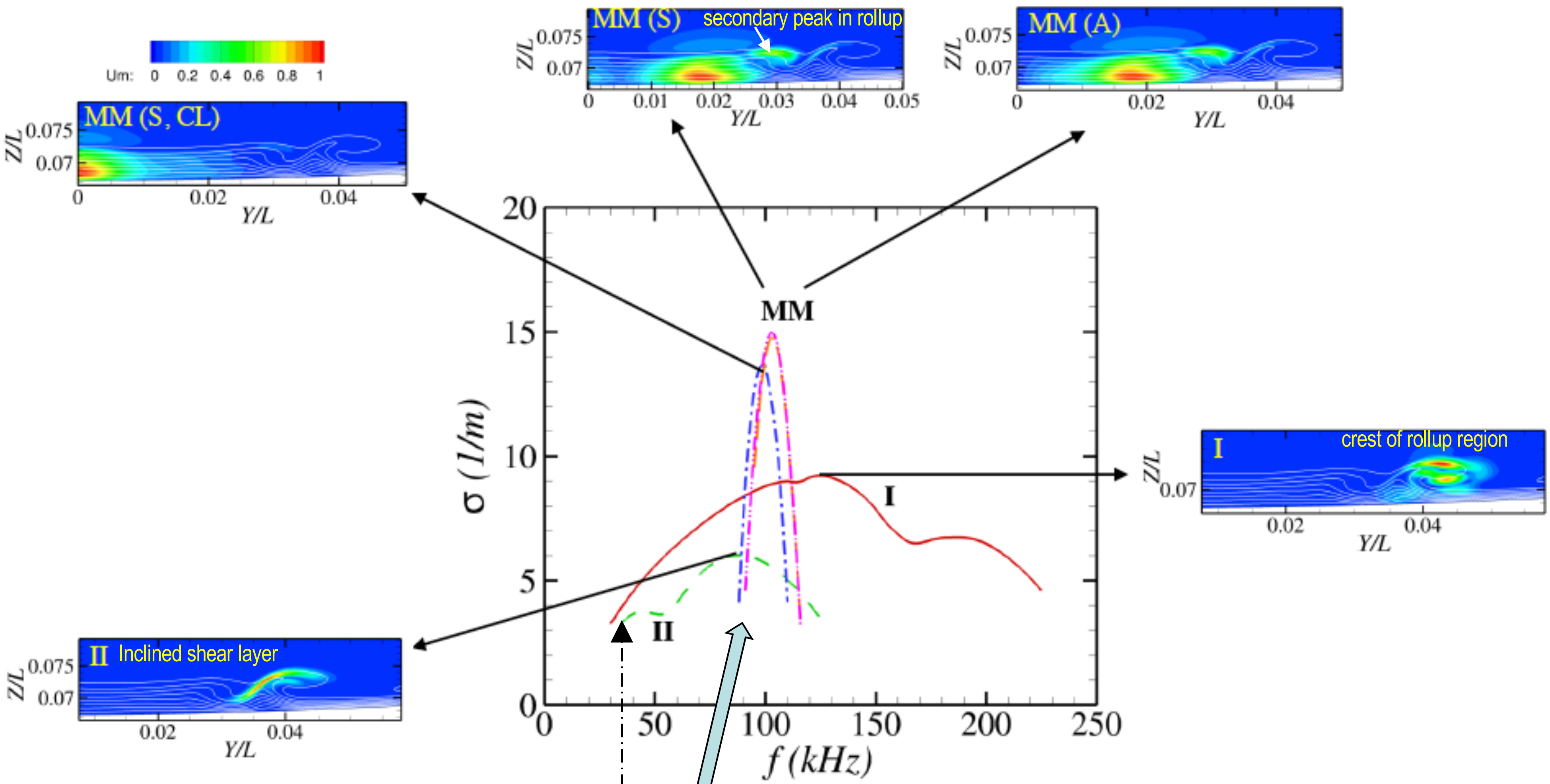


Stability Characteristics Near Centerline

- Local growth rate spectra
- N-factor evolution
- Mode shape evolution

Local Instability Characteristics: α = 4 deg (Leeward)

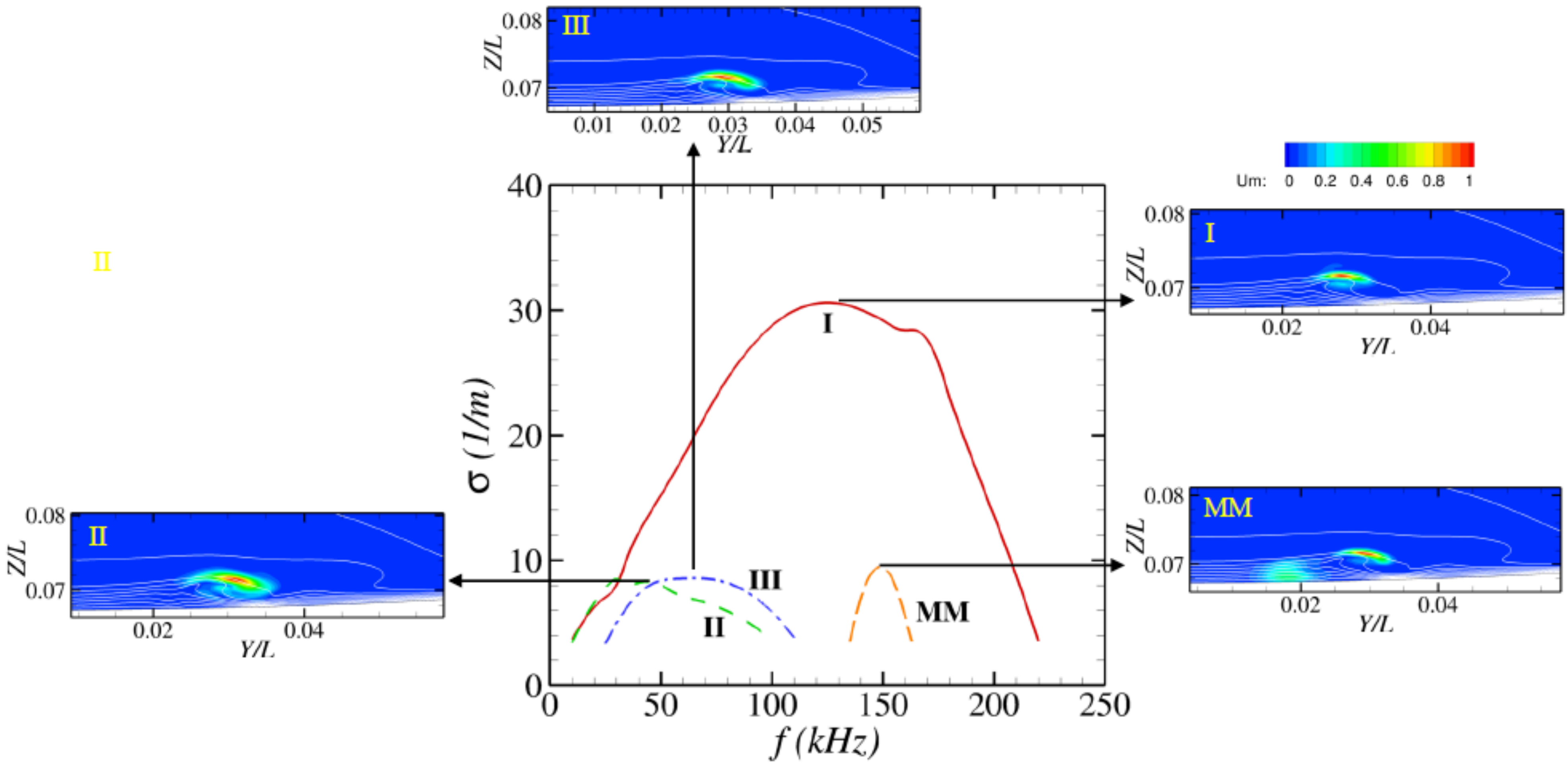
Growth rate spectra at X/L = 0.515



- Two major mode types:
  - a) **Mack modes:** narrow bandwidth, near-wall peak fluctuations, dominant planar, trapped acoustic modes confined in wall-normal & azimuthal directions
  - b) **Shear layer modes (streak instabilities)**: concentrated away from the wall, large frequency bandwidth

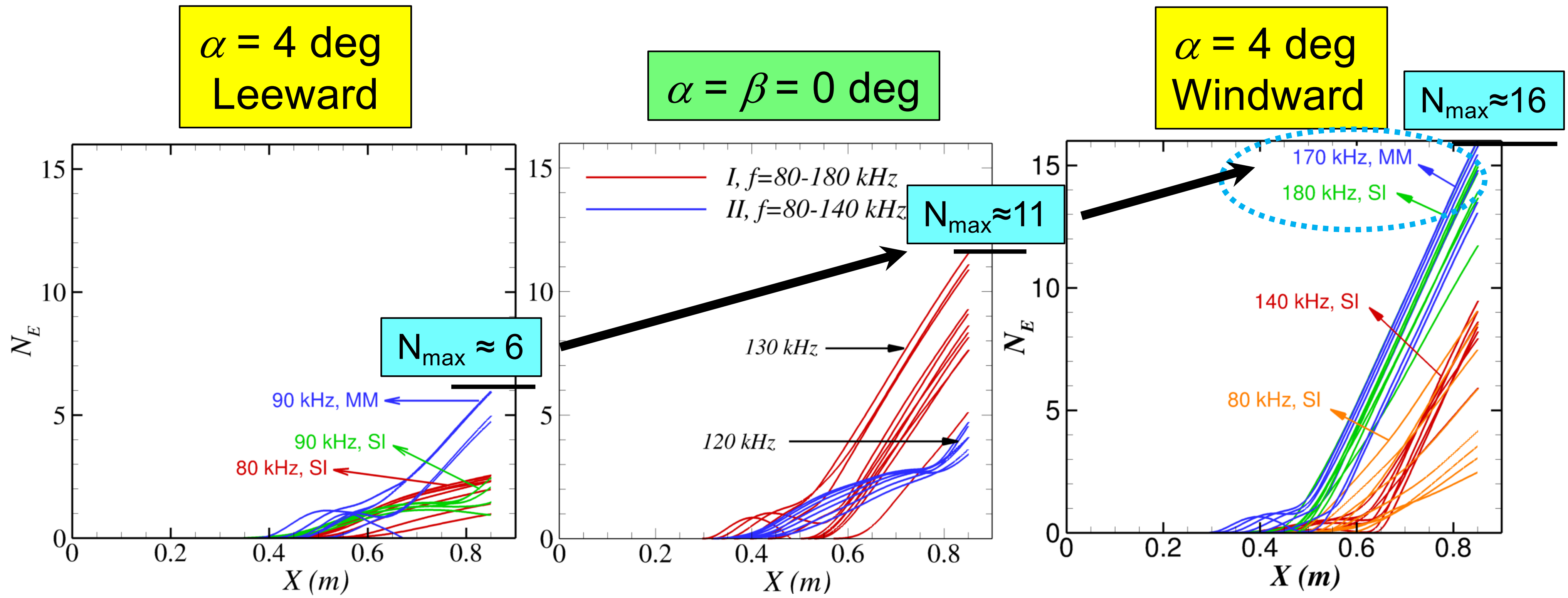
Local Instability Characteristics: α = 4 deg (Windward)

Growth rate spectra at *X/L* = 0.515



- Mack mode growth rates moderately lower than those on leeward side
- Substantially higher peak growth rate for shear layer mode #1

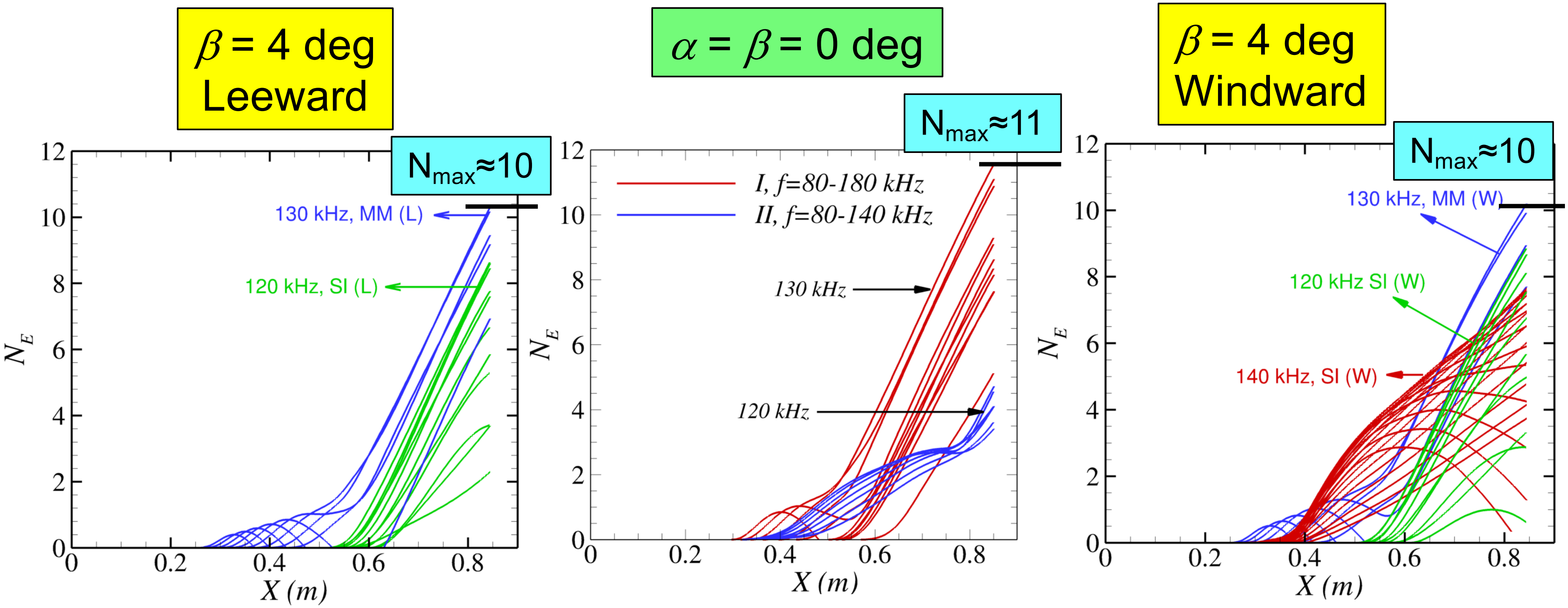
N-Factor Evolution Based on Plane Marching PSE : FAL$_\alpha$



- In all cases, the most amplified modes originate as Mack modes that subsequently morph into streak instabilities that amplify more rapidly, although purely streak instabilities can achieve comparable growth on the windward side
- Strong reduction in peak N-factors on leeward side and substantially higher N-factors on windward side

  ⇒ Transition near centerline is unlikely on leeward side, but very likely on windward side

N-Factor Evolution : FAL_β

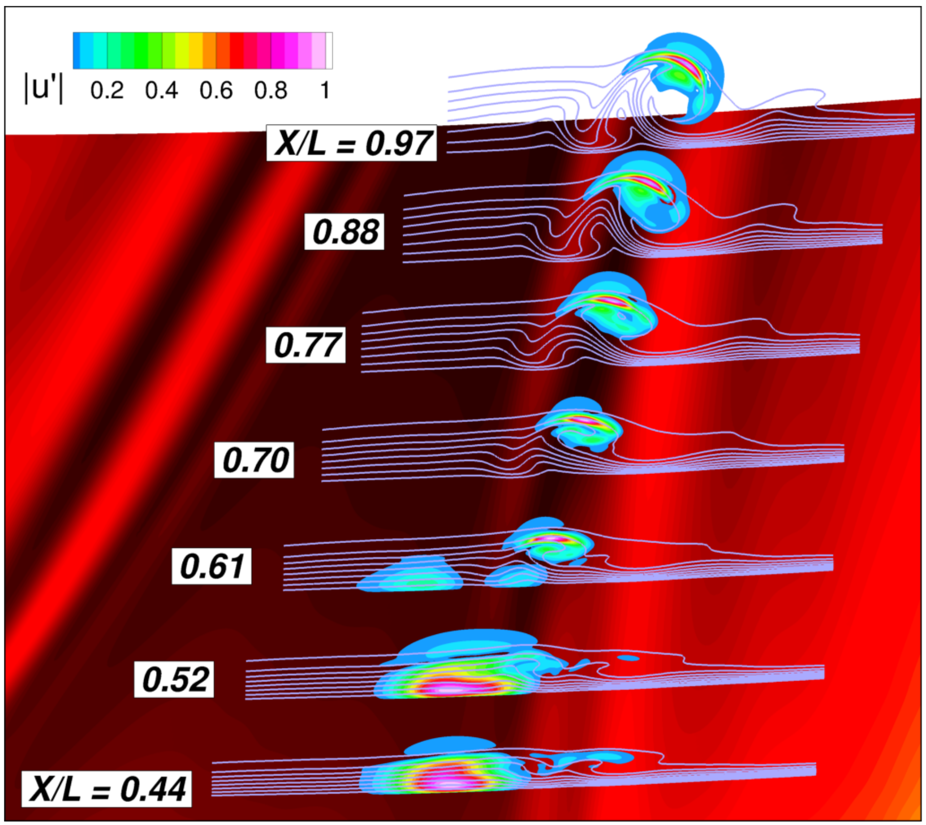


- Comparable peak N-factor of 10-11 in all cases
- Achieved by Mack modes that evolve into shear-layer modes

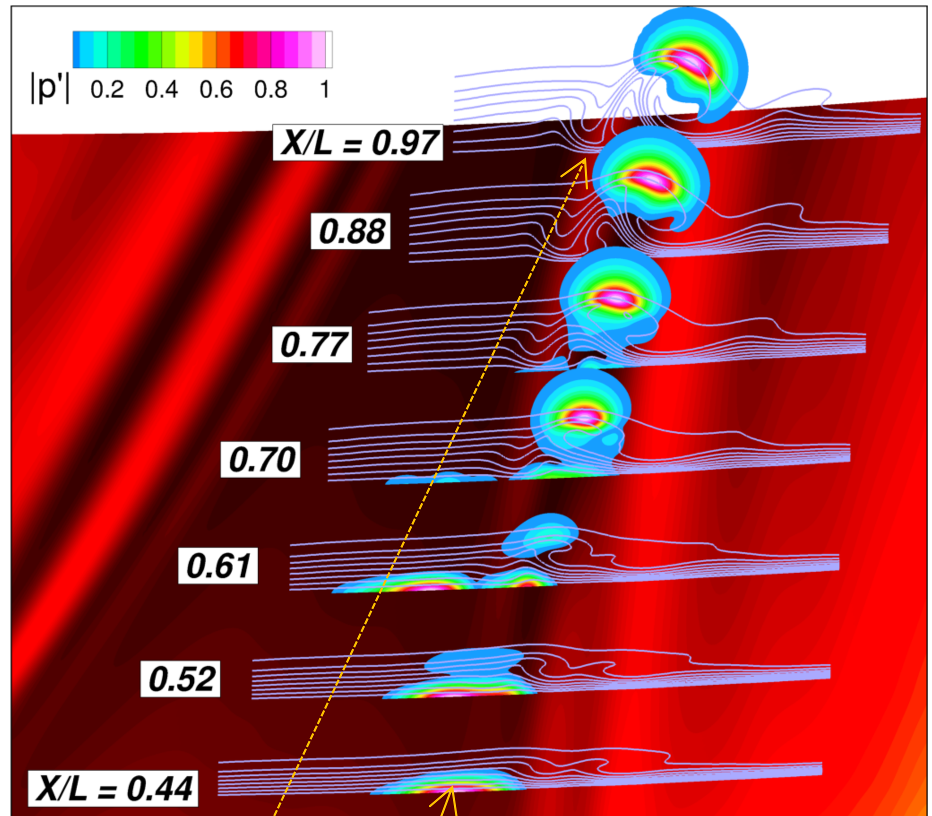
Mode Shape Evolution : FAL$_\beta$ (Leeward)

f = 130 kHz, MM

|*u'*|



|*p'*|

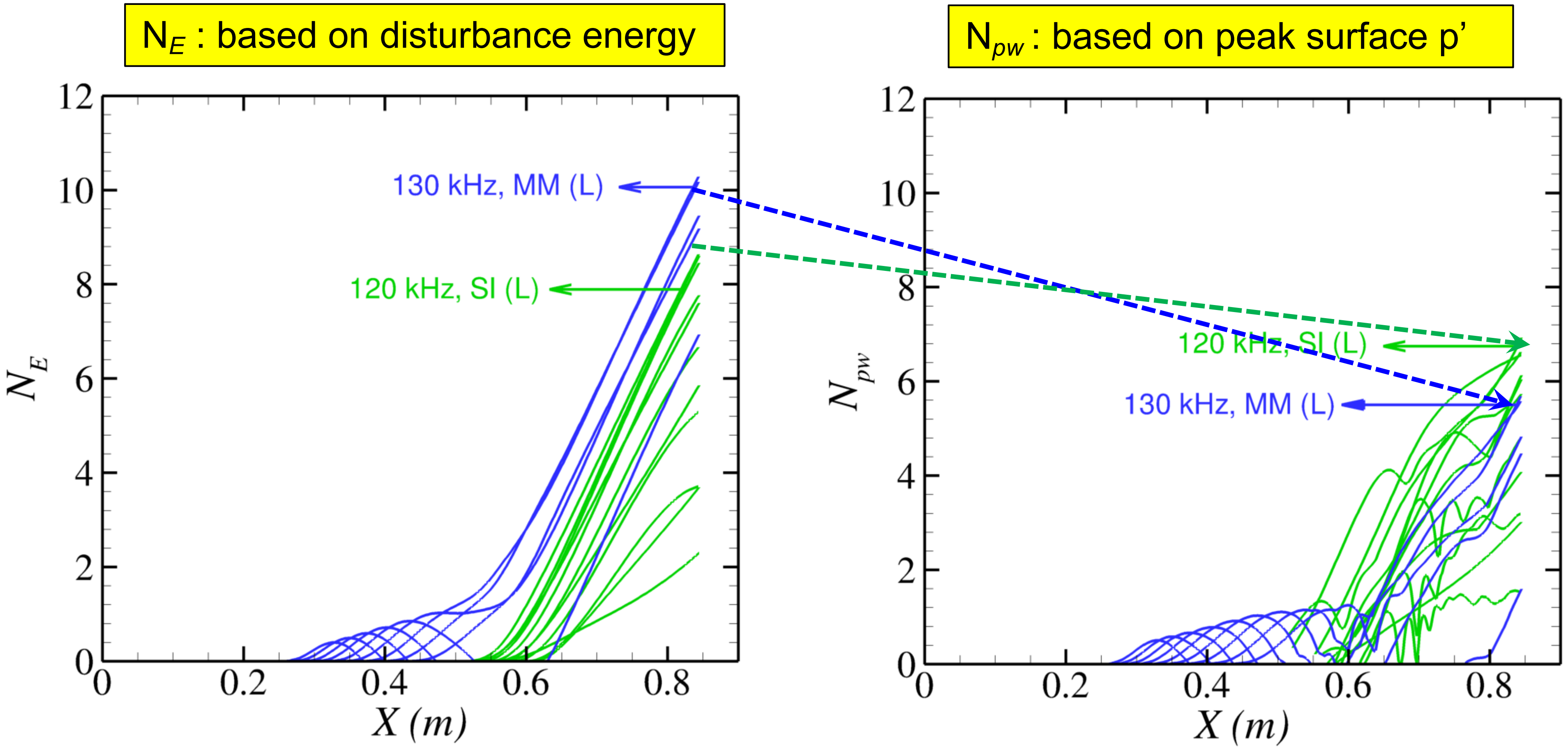


Upstream: strong p' signature

Downstream: weak p' signature

N-Factor Evolution : FAL_β (Leeward)

β = 4 deg



Summary

At the ascent condition of interest ($t = 28.88$ sec, $M_\infty = 5.53$, and $Re_L = 3.68\times10^6$),

- **4 deg yaw ➔ No major change in N-factors** of streak instabilities near the middle of the test surface
- **4 deg AoA ➔ Earlier transition on windward side**
  No transition on leeward side
- Surface pressure sensors may not provide meaningful characterization of modal growth of hybrid modes that originate as Mack modes and morph into shear-layer modes

Extra Charts

Outline

- **Motivation**
- **BOLT vehicle geometry**
- **Numerics (see paper for details)**
- **Effects of nonzero AoA and yaw at flight conditions**
  - Basic state
  - Stability analysis
    - Local stability characteristics
    - Non-parallel spatial evolution
- Summary

Motivation

- Modeling of boundary layer transition an important part of predicting the aerothermal loads on hypersonic vehicles
  - In-flight measurements critical to calibration of predictive models

- BOLT flight experiment
  - Extends previous flight data for cones with circular (HIFiRE-1) and elliptic (HIFiRE-5b) cross sections to more complex shape (Wheaton et al. 2018-2892, 2020-1041)
  - Rich transition physics
    - Multiple, potentially interacting instability mechanisms (Mack modes, crossflow instability, dominance of streak instabilities)
    - Entropy layer effects
  - Few studies of streak instability near the centerline of test surface (Thome et al. 2018 − DNS, Li et al. 2020 − Modal Analysis), **and none at off-design conditions**

Flight Condition of Interest

- **Flight, Ascent (Case FAL from Li et al. 2020)**
  - M = 5.53, Re = 4.24M/m, Re_L= 3.68M
  - P = 2380.2 Pa, T = 222.0 K, T_w = 400 K, t = 28.8767 s
- **Target attitude for flight experiment (Wheaton et al. 2018)**
  - Combined AoA + yaw < 5 deg (threshold), < 2 deg (objective)
  - Quiet tunnel tests for α, β = 4 deg (Berridge et al. 2018)
  - Conventional tunnel measurements (Berridge et al. 2018)
- **Nonzero AoA Case (FAL_α)**
  - Nonzero AoA Case (FAL_α) : α = 4 deg, β = 0 deg
  - Nonzero yaw Case (FAL_β) : α = 0 deg, β = 4 deg
- **Complements numerical study by Mullen & Reed (2020)**
  - $\alpha, \beta = \pm 1$ deg, acreage region away from prominent streaks

Analysis Codes

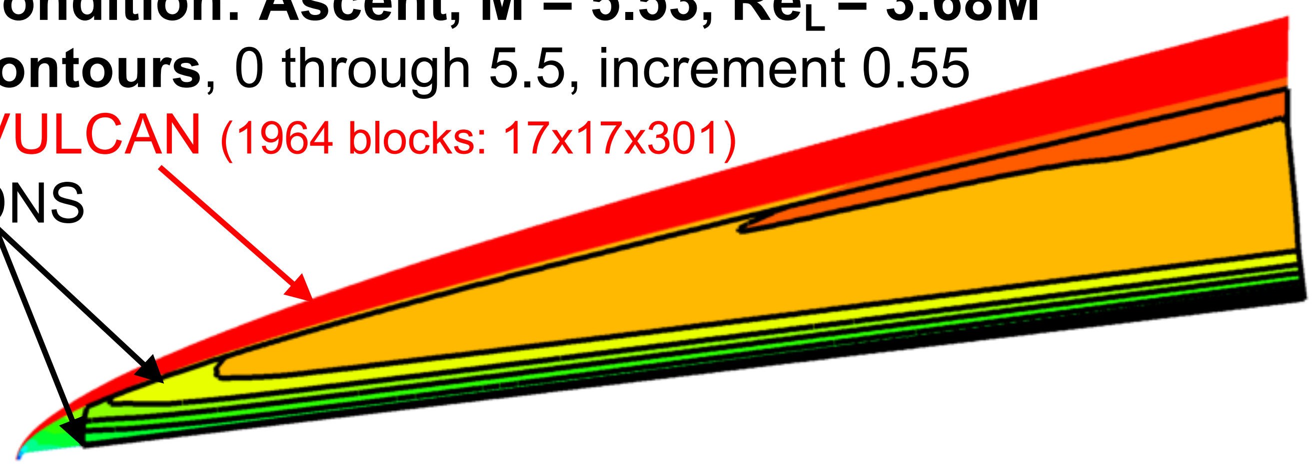
- VULCAN: 2^{nd}-order NS code for initial laminar base flow
- DNS Code: 7^{th}-order finite difference (based on Martin et al., *J. Comp. Phys*. 2006) for more accurate base flow
- MAFIA: LST, PNP (Partially Nonparallel) Analysis and Plane-marching PSE for streak instability computations.

Strategy for Basic State Computation for Stability Analysis

- **DNS domain**
  - Begins a short distance behind the leading edge
  - Confined to the region just below the shock

- **VULCAN solution provides inflow conditions + BCs along outer boundary of DNS domain**
  - Evolution of complex flow features downstream of the leading edge computed using higher order code

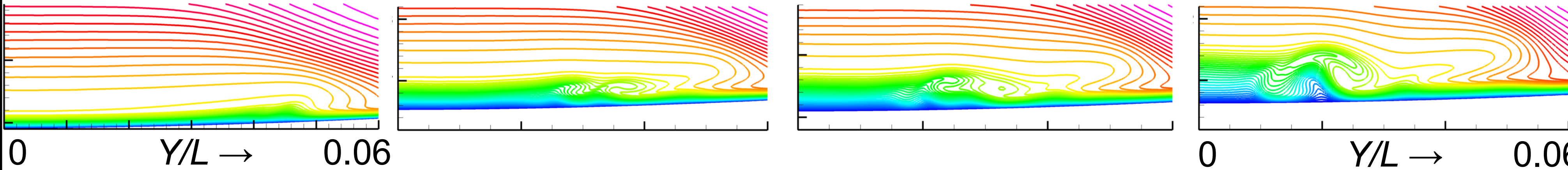
Flight condition: Ascent, M = 5.53, Re_L = 3.68M
Mach contours, 0 through 5.5, increment 0.55
Flood: VULCAN (1964 blocks: 17x17x301)
Lines: DNS



Mach number contours: 0 to 5 ($\Delta M = 0.25$)

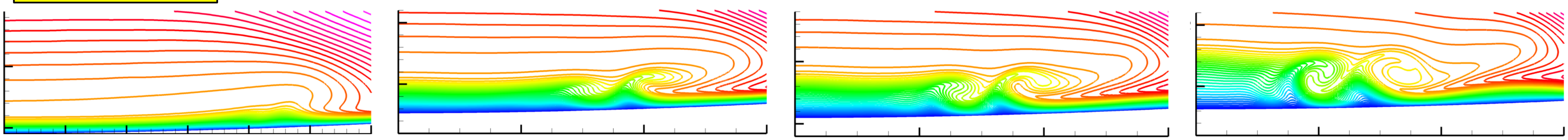
$\alpha = \beta = 0$ deg

$X/L = 0.20$ | $X/L = 0.5$ | $X/L = 0.63$ | $X/L = 0.84$

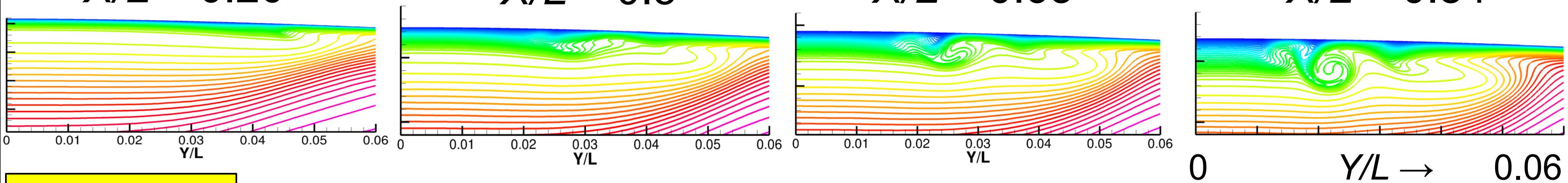


$\alpha = 4$ deg, $\beta = 0$ deg

Leeward



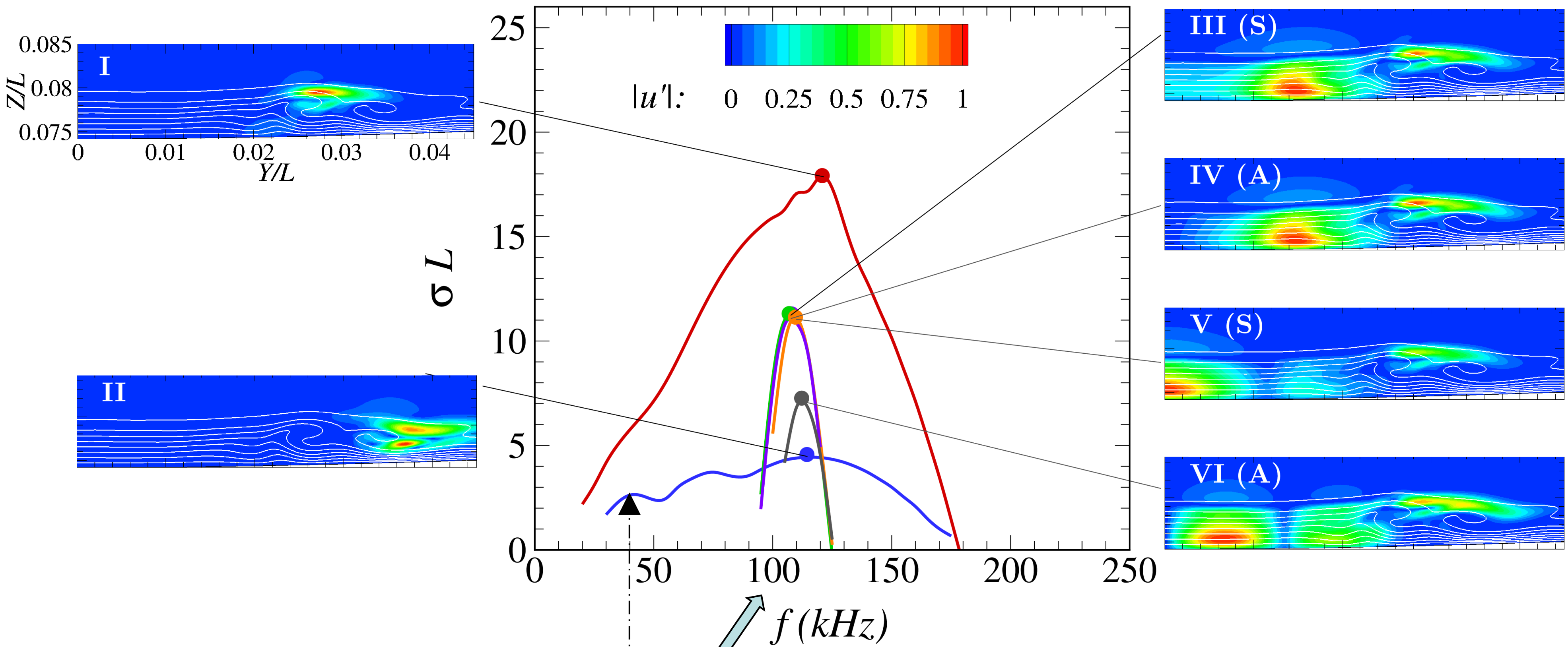
$X/L = 0.20$ | $X/L = 0.5$ | $X/L = 0.63$ | $X/L = 0.84$



Windward

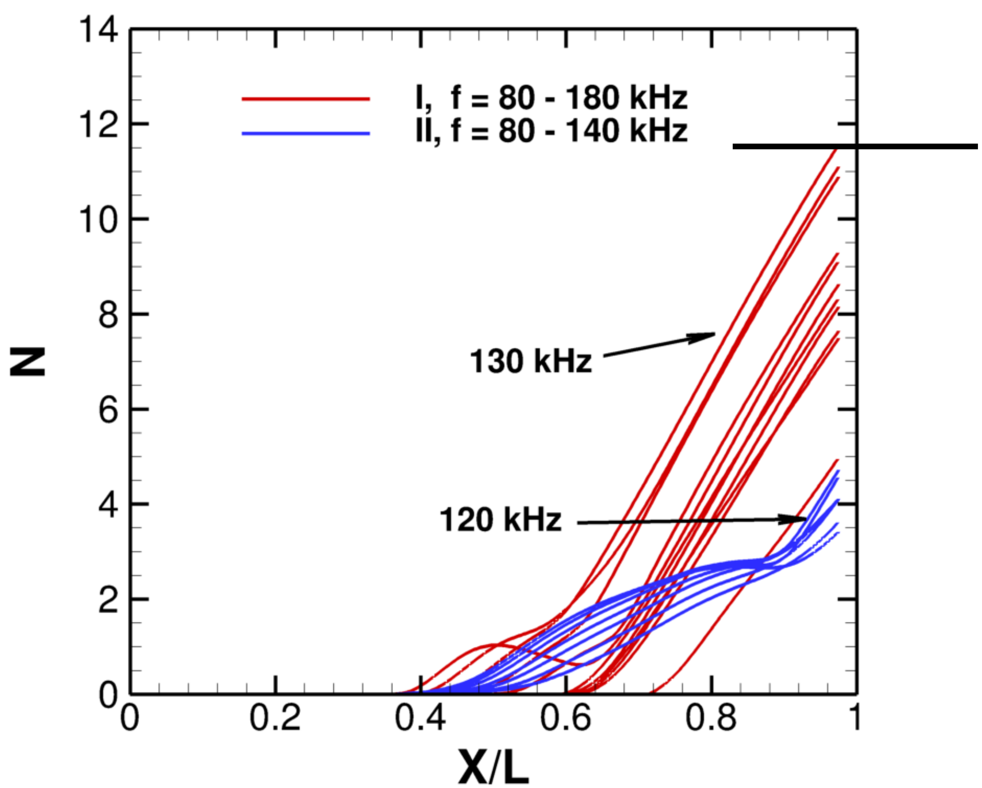
Local Instability Characteristics: $\alpha = \beta = 0$ deg

Growth rate spectra at X/L = 0.573

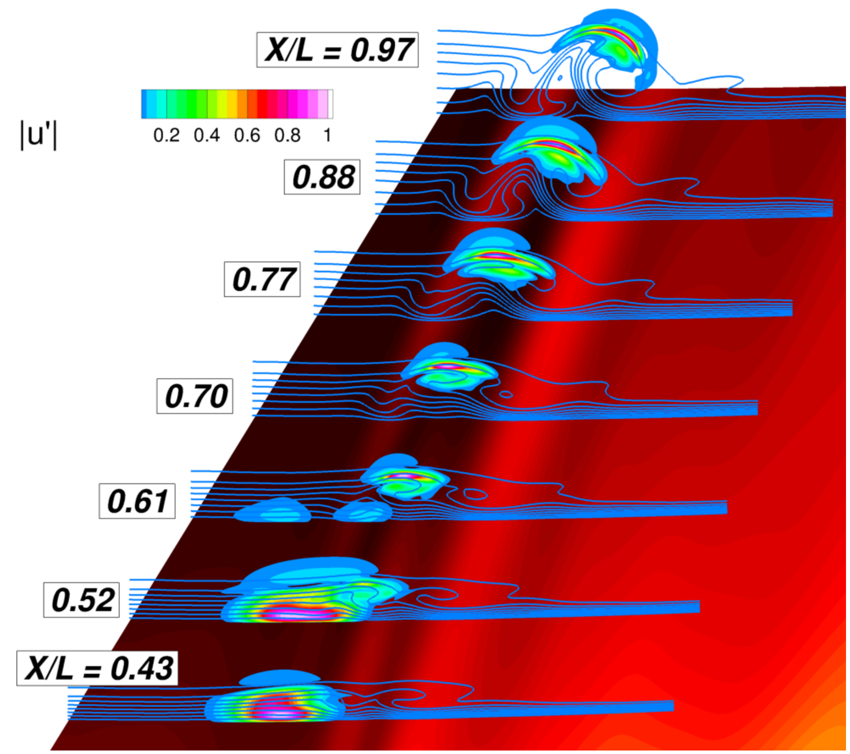


- Two major mode types:
  - **I. Mack modes:** narrow bandwidth, near-wall peak fluctuations, dominant planar + weaker oblique, trapped acoustic modes confined in wall-normal & azimuthal directions
  - **II. Shear layer modes (streak instabilities)**: concentrated away from the wall, large frequency bandwidth, higher peak growth rates

Streak Instability Characteristics: FAL



N-factors

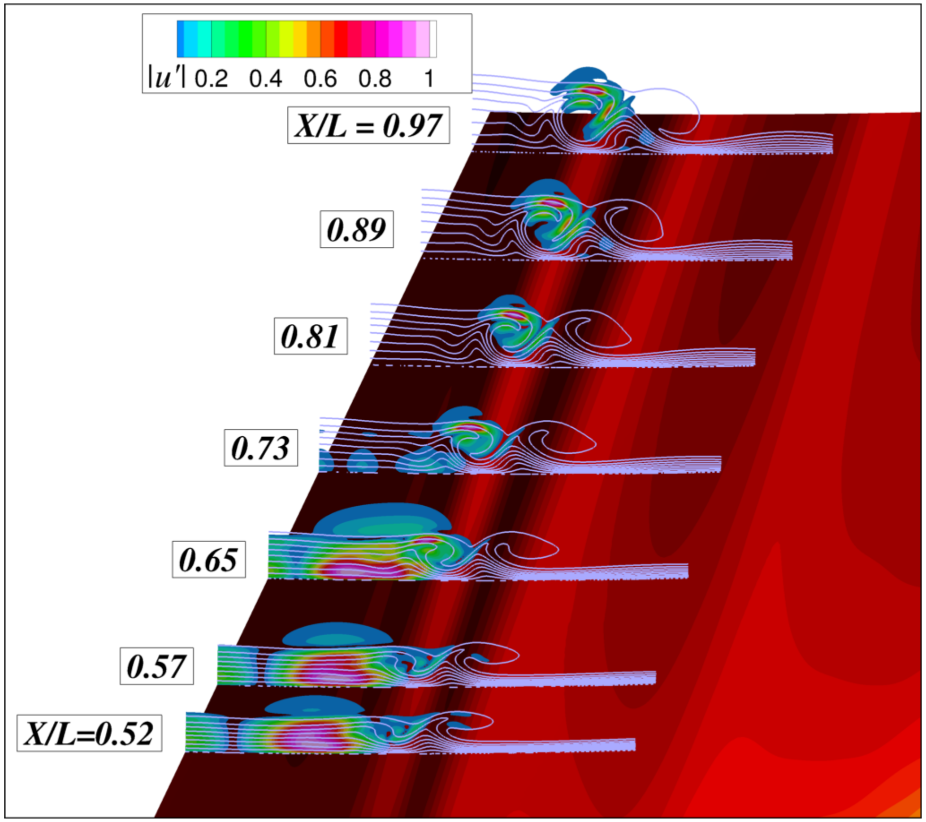


Mode shape evolution of Mode I
f = 130 kHz

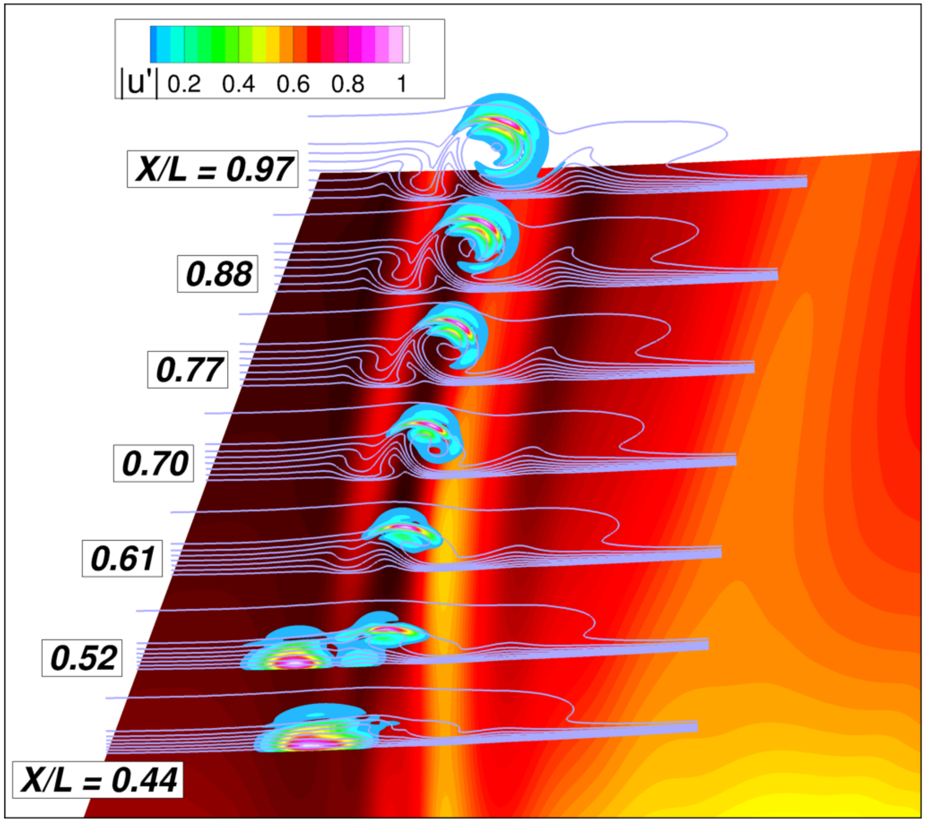
Mode Shape Evolution : FAL$_\alpha$

$|u'|$

Leeward



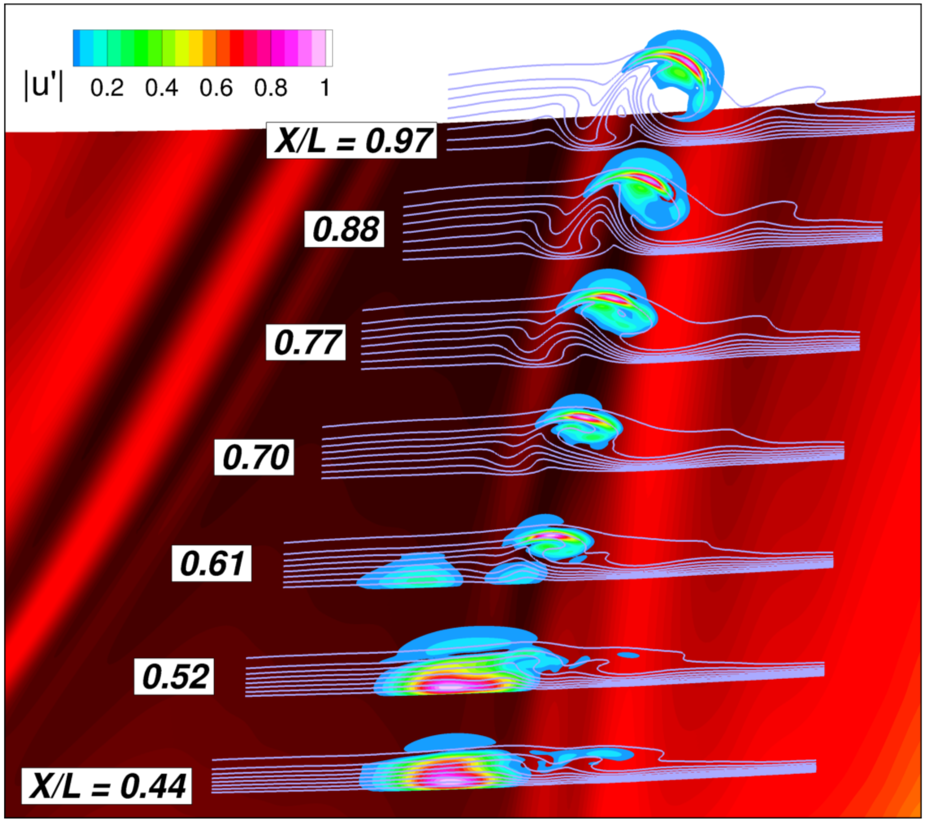
Windward



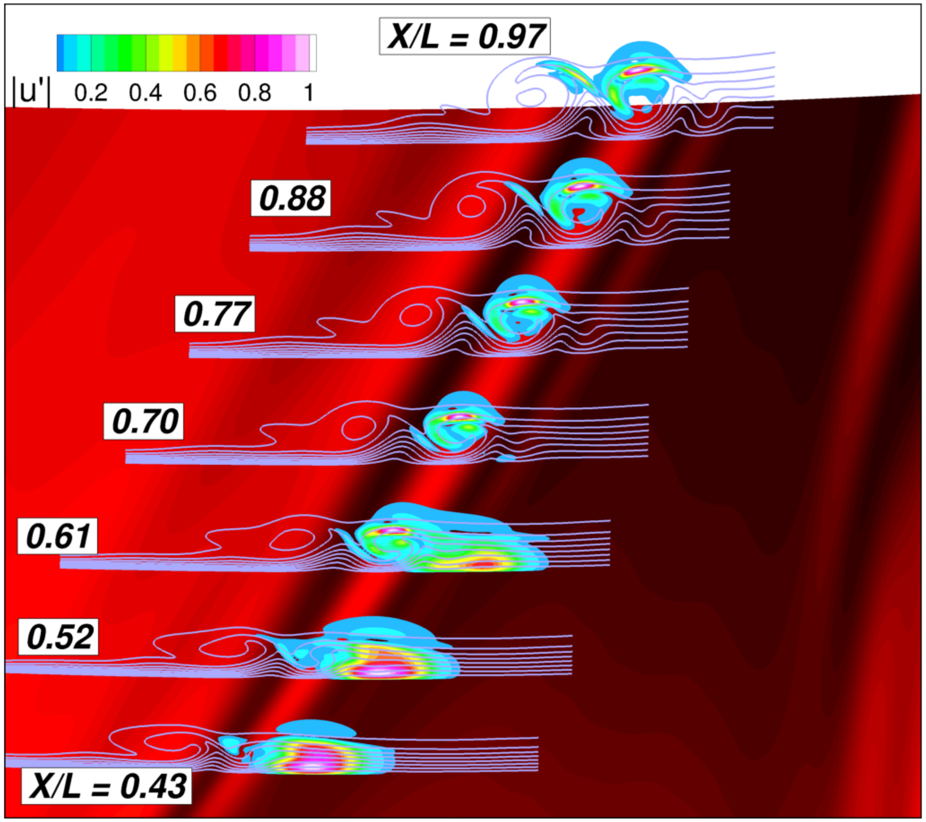
Mode Shape Evolution : FAL$_\beta$

$|u'|$

Leeward

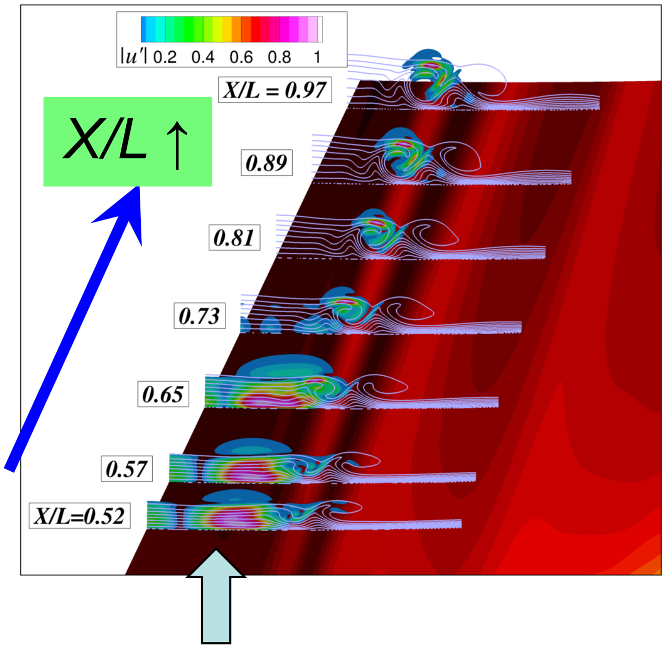


Windward

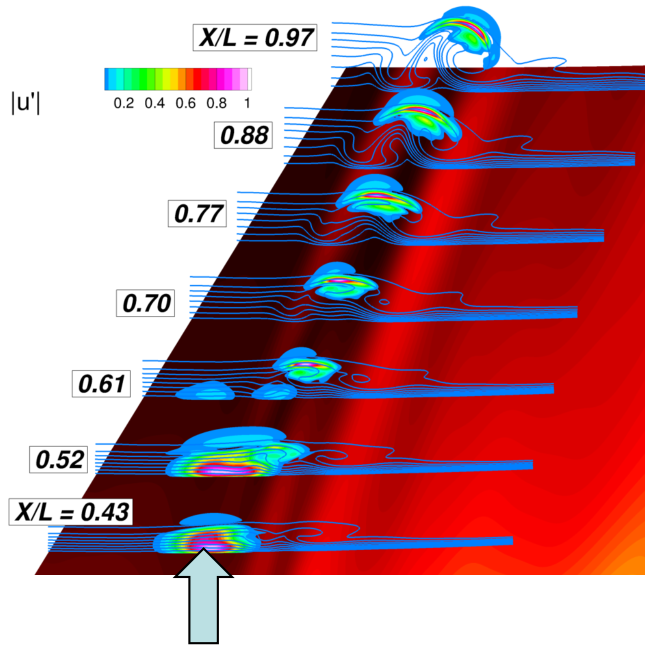


$|u'|$ Mode Shape Evolution : FAL_{α}

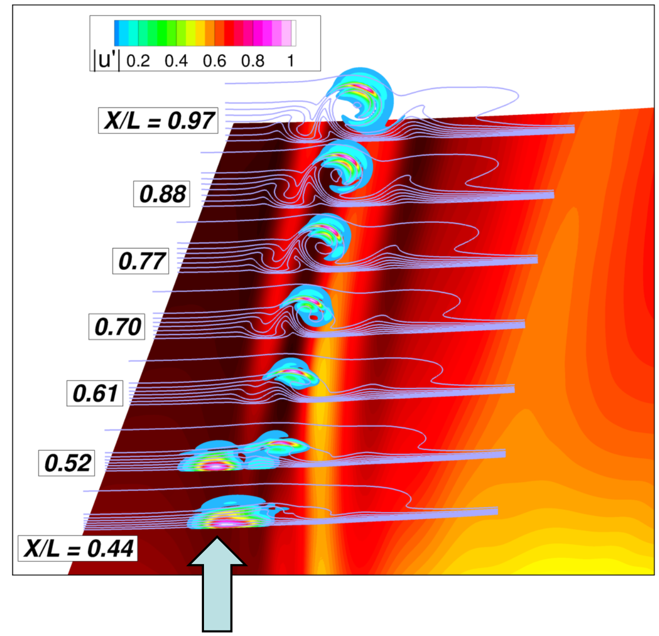
Leeward
f = 90 kHz, MM-SI



$\alpha = \beta = 0$ deg
f = 130 kHz, MM-SI
(Li et al. 2020)



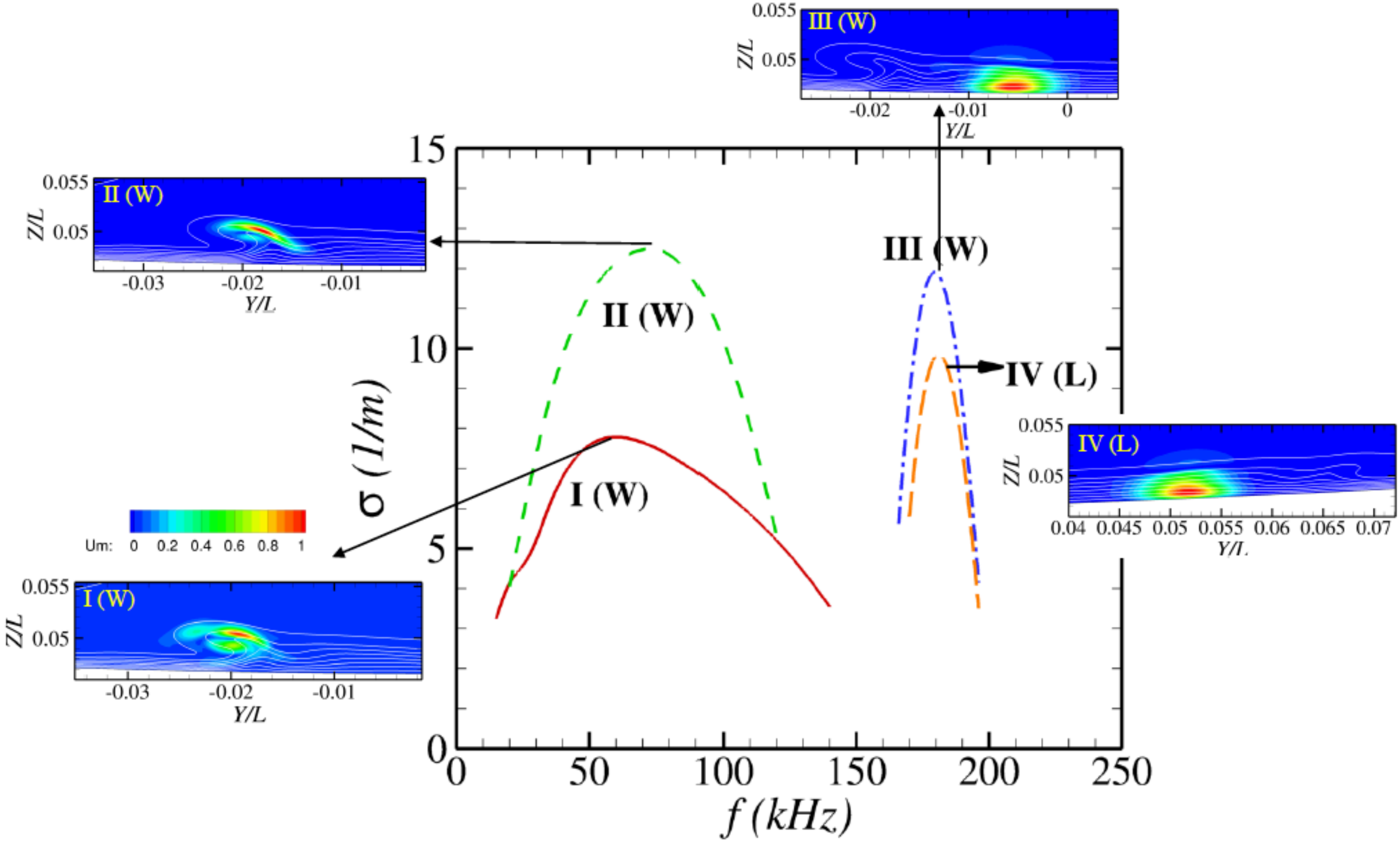
Windward
f = 170 kHz, MM-SI



- Mode shape initially resembles Mack modes with a near-wall peak in wall-normal direction, but soon evolves into a shear-layer mode that peaks along the crest of rollup − referred to as hybrid Mack Mode−Streak Instability (MM-SI) modes

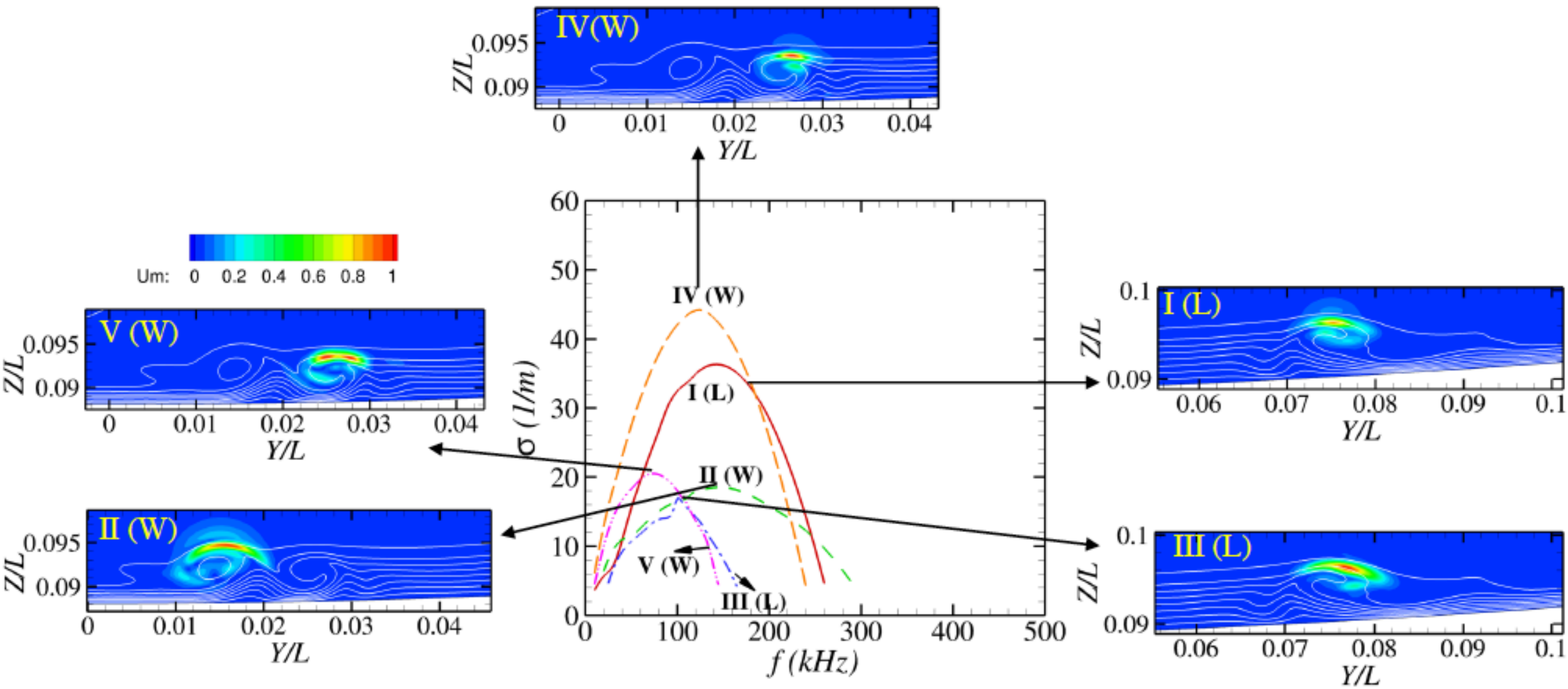
Local Instability Characteristics: β = 4 deg

Growth rate spectra at *X/L* = 0.343



Local Instability Characteristics: β = 4 deg

Growth rate spectra at X/L = 0.687



N-Factor Evolution : FAL_β

Leeward
f = 130 kHz, MM

$\alpha = \beta = 0$ deg
f = 130 kHz, MM

Windward
f = 130 kHz, MM