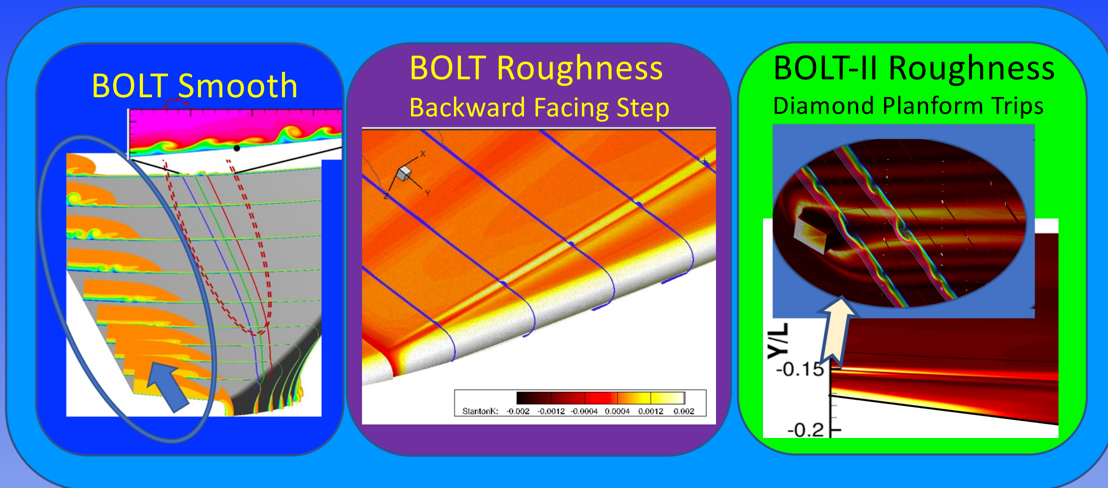
Basic State Computations and Stability Analysis for Selected BOLT-II Flight Conditions



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FD-14, BOLT-II Flight Experiment II

January 23, 2023, from 2:00 PM to 3:40 PM Eastern Time.

Introduction

- The ability to predict boundary-layer transition and flow separation is a crucial issue according to CFD Vision 2030 (Slotnick et al., NASA/CR-2014-218178, 2014)
  - Insufficient validation of BLT predictions for hypersonic configurations
  - Inadequacy of classical stability theory in many instances due to increased complexity of hypersonic transition (bluntness effects, streaks, shock-BL interactions, roughness effects on prevalent TPS)
  - CFD predictions especially critical due to limitations of ground facilities and challenges in detailed, high-frequency measurements
- Computational tool development under NASA's Hypersonic Technologies Project (HTP): Next generation predictive capability for complex hypersonic configurations, with the goal of augmenting the currently empirical prediction tools with advanced, higher fidelity methods that are anchored in BLT physics
  - BOLT/BOLT-II flight campaigns provide unprecedented opportunity to explore transition physics for complex configurations and to calibrate the predictive tools against quality flight data
- **Objectives of present work**
  - Extend previous instability analyses to flight conditions at higher Re
  - Wake evolution behind discrete trips and comparison with preliminary flight data
  - Preliminary characterization of step-excrescence effects

Outline

- ❑ Introduction
- ❑ Numerical details and previous results
  - ➢ See Li et al. 2020-3028, 2021-2905, 2022-1063, Choudhari et al. 2021-1207
- ❑ Basic State Features for Smooth Surface and Effect of Reynolds Number
  - ➢ Near centerline
  - ➢ Acreage region (will be impacted by surface roughness on real-world surface!)
- ❑ Stability Characteristics ($\alpha = \beta = 0$ deg)
  - ➢ Mack's second modes (MM) and crossflow instabilities (CF) in quasi-homogeneous regions
  - ➢ Streak instabilities near centerline
  - ➢ Streak instabilities in acreage region
- ❑ Effect of Step Excrescence
- ❑ Secondary Side Experiment: Effect of Discrete Trips
  - Wake evolution and disturbance growth
  - Wake evolution and comparison with preliminary data from BOLT-II flight
- ❑ Concluding Remarks

Flow Conditions: Smooth Surface BOLT (Preflight) Configuration

($\alpha = \beta = 0$ deg)

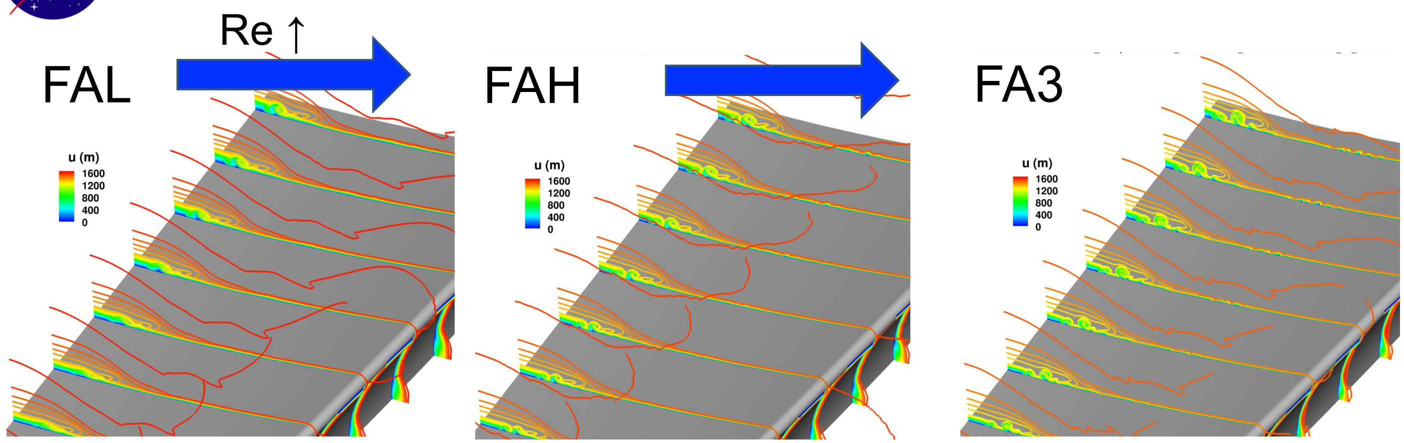
	M	Re (10^6/m)	P (Pa)	T (K)	T_w (K)
FAL: Flight Ascent, Low Re	5.53	4.25	2.379e3	221.90	400
FAH: Flight, Ascent, High Re	5.37	6.60	3.735e3	219.09	400
FA3: Flight, Ascent, Higher Re	5.25	9.98	5.690e3	216.65	400
FD3: Flight, Descent, Higher Re	7.36	9.98	4.108e3	218.48	400
FD4: Flight, Descent, Highest Re	7.36	11.53	4.717e3	217.76	400

Flow Conditions: Smooth Surface BOLT-II (Preflight) Configuration

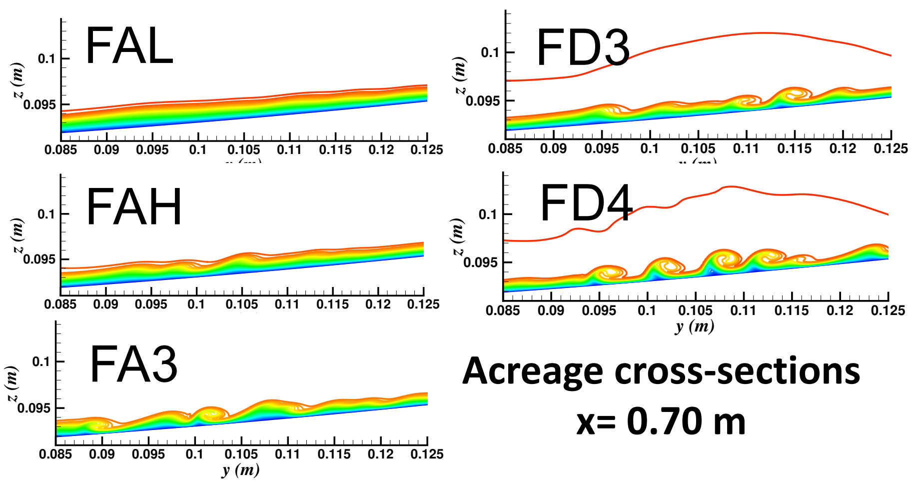
	M	Re (10^6/m)	P (Pa)	T (K)	T_w (K)
BOLT-II Preliminary Trajectory Flight Ascent, t = 27.8 sec	5.53	4.25	2.379e3	221.90	400

Will be covered during conference presentation

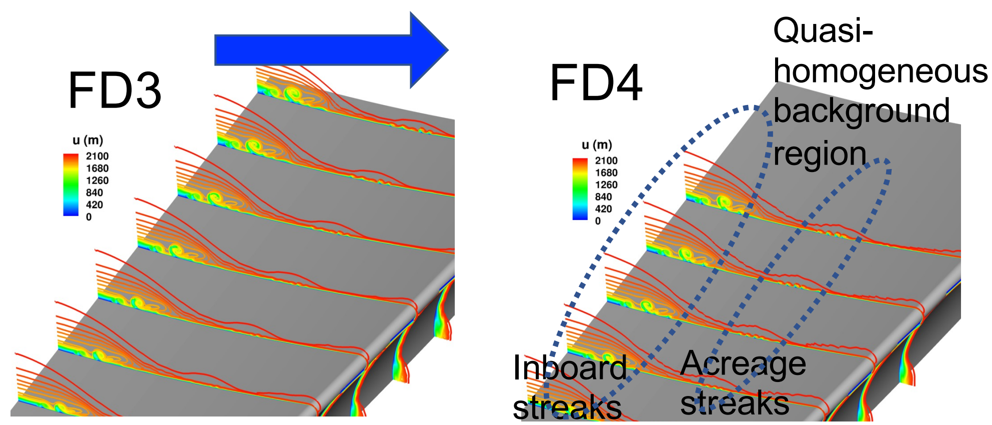
Basic State Features: Reynolds-Number Effect



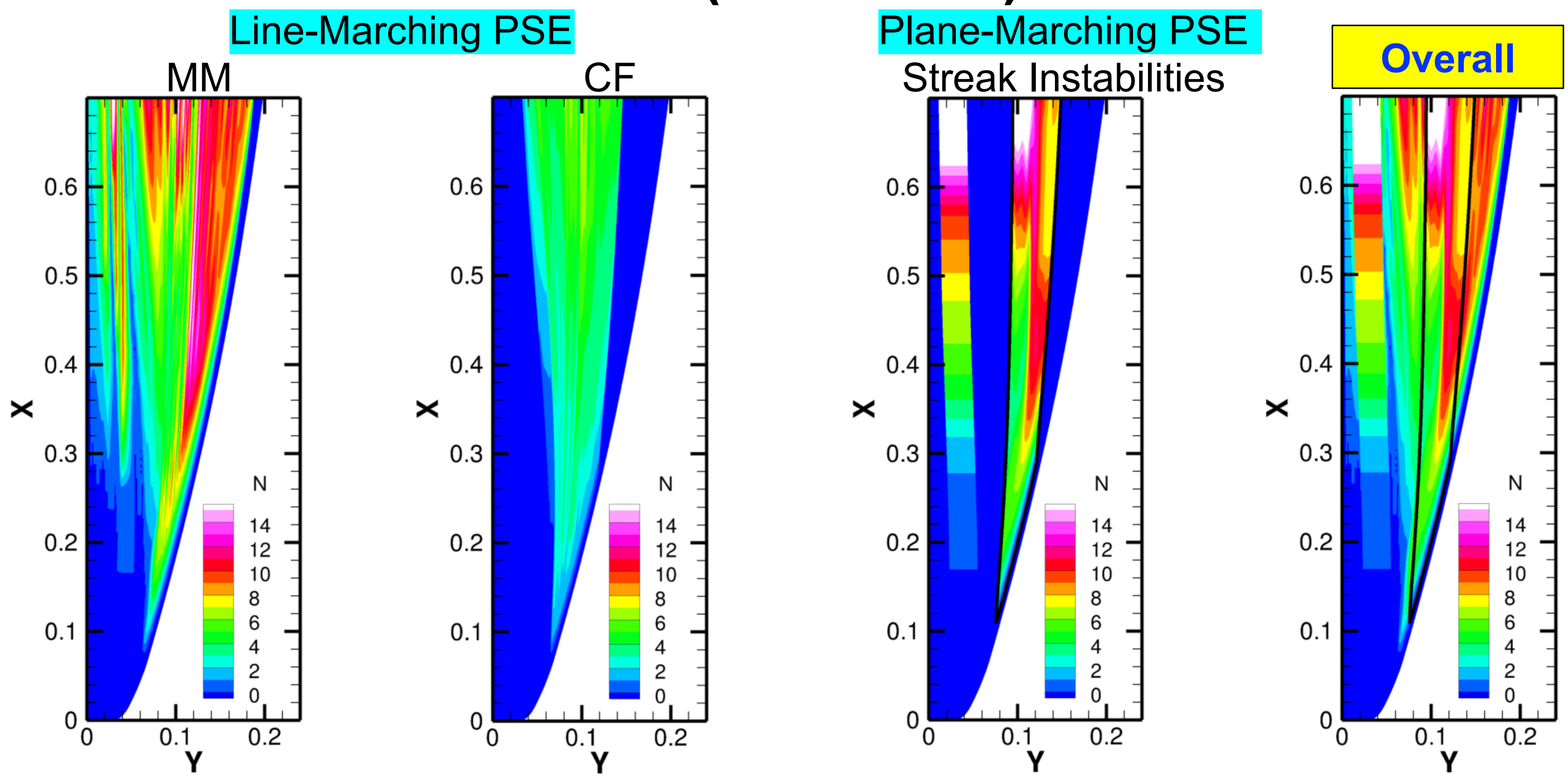
- Increasing Re → stronger streaks



Acreage cross-sections
x= 0.70 m



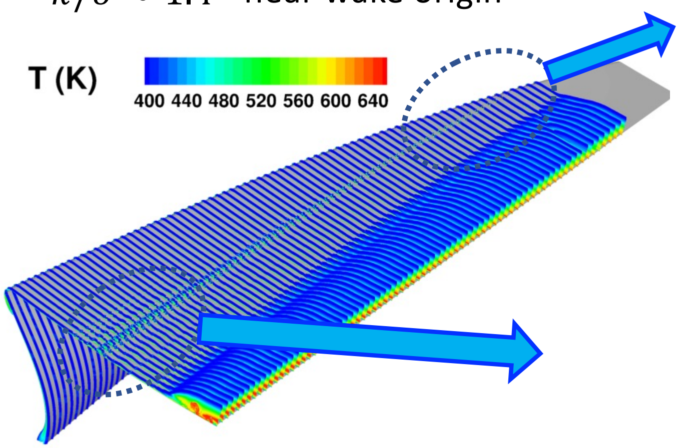
Overall N-Factor Envelope over Primary Test Surface (Case FD4)

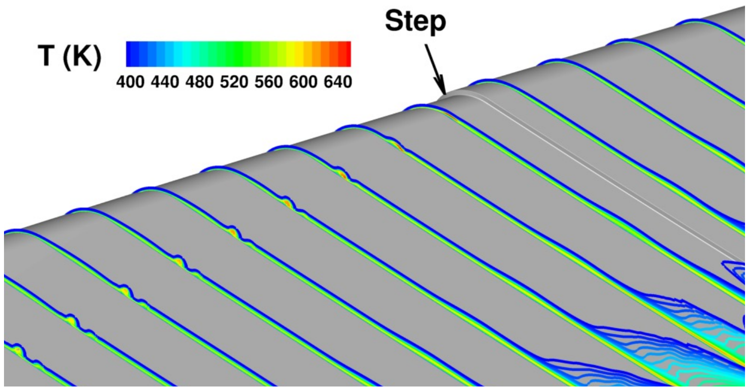


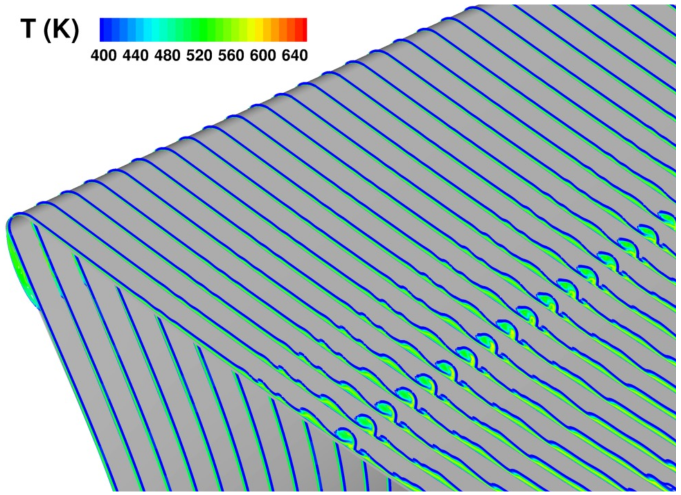
Caution:
- Critical N-factor likely to vary with type of instability!
- Surface roughness effects (neglected herein) likely to be significant for CF and sideline streaks

Effect of Backward Facing Step

M = 5.25, Re = 9.98M/m
Step location: x =0.18415 m
k = 0.533 mm
$k/\delta \approx 1.4$ near wake origin

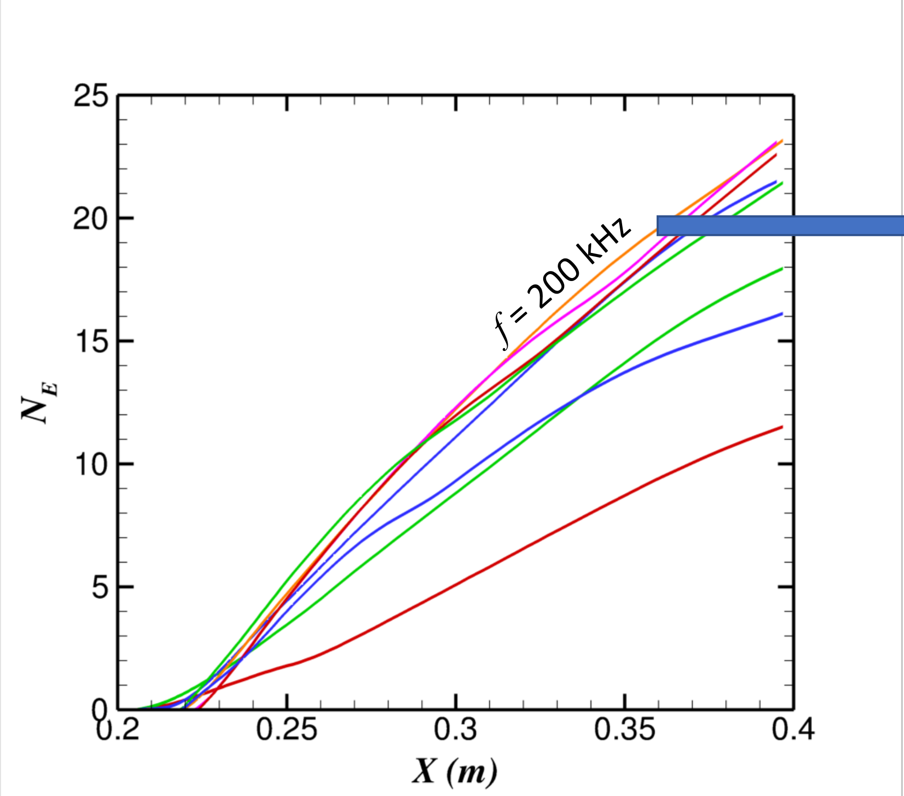


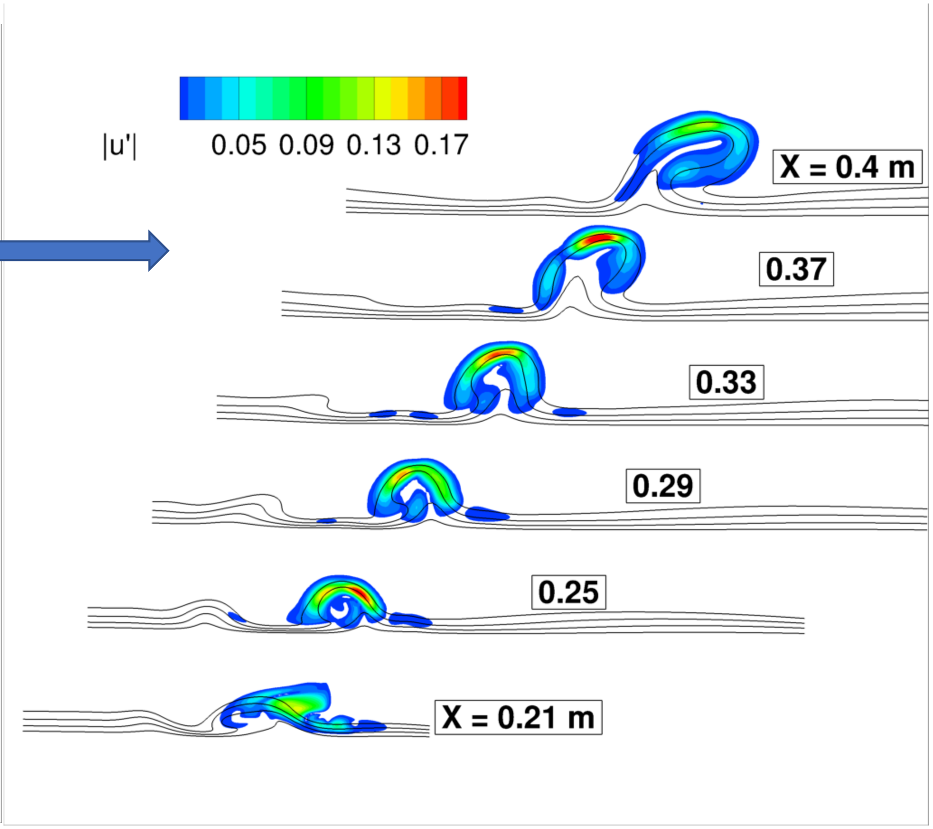




- Backward facing step leads to emergence of streak from the corner near the intersection with the LE
  - Will induce streak instabilities analogous to those due to naturally occurring streaks within acreage region
- Ongoing computations for additional step parameters

Streak Instability Characteristics of Step Vortex

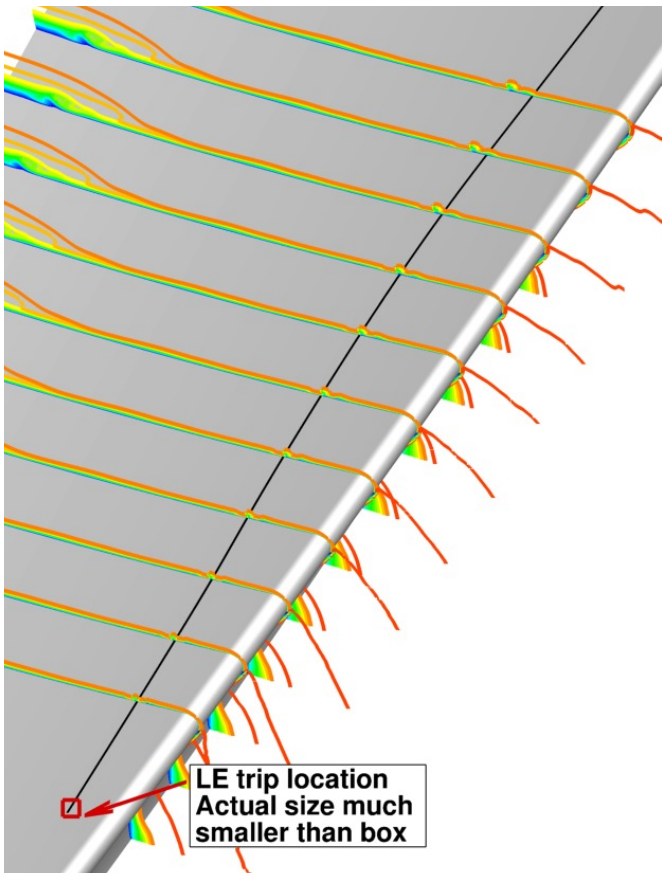


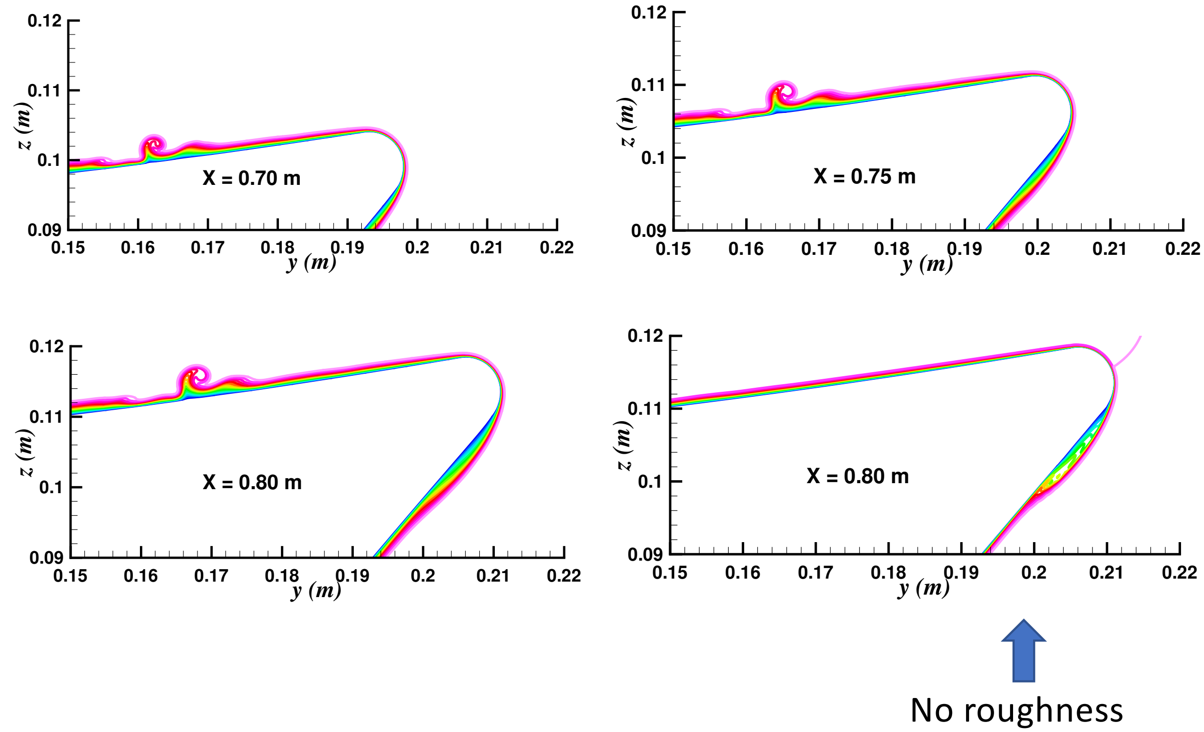


Flow Conditions: Secondary Surface BOLT-II Flight Configuration

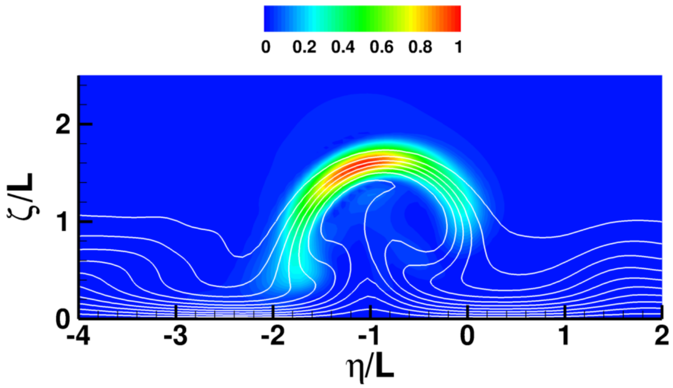
	M	Re (10^6/m)	P (Pa)	T (K)	T_w (K)
Descent (preflight), D1.5	5.44	2.50	1.638e3	225.50	400
Ascent, t = 28 sec	6.23	7.55	3.547e3	212.80	400
Ascent, t = 29 sec	6.17	5.63	2.682e3	213.48	400
Ascent, t = 30 sec	6.11	4.20	2.034e3	214.4	400

Wake Flow Behind Leading Edge Trip





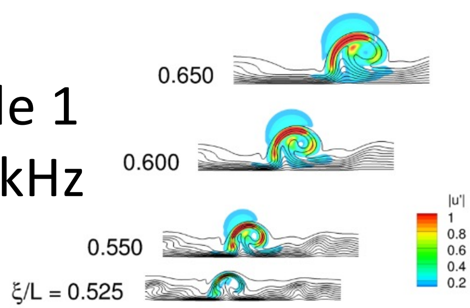
Wake Instability Analysis: Leading Edge Trip



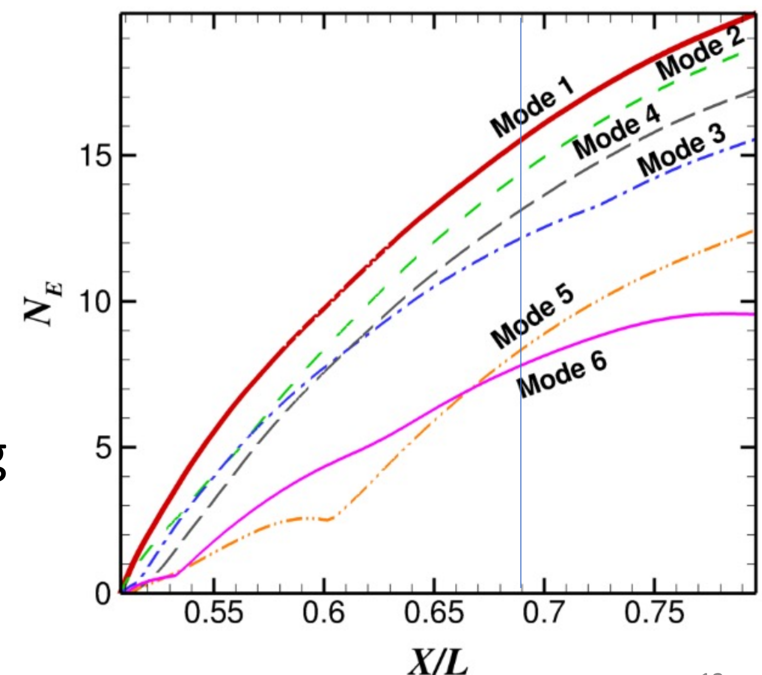
PNP

X/L = 0.525

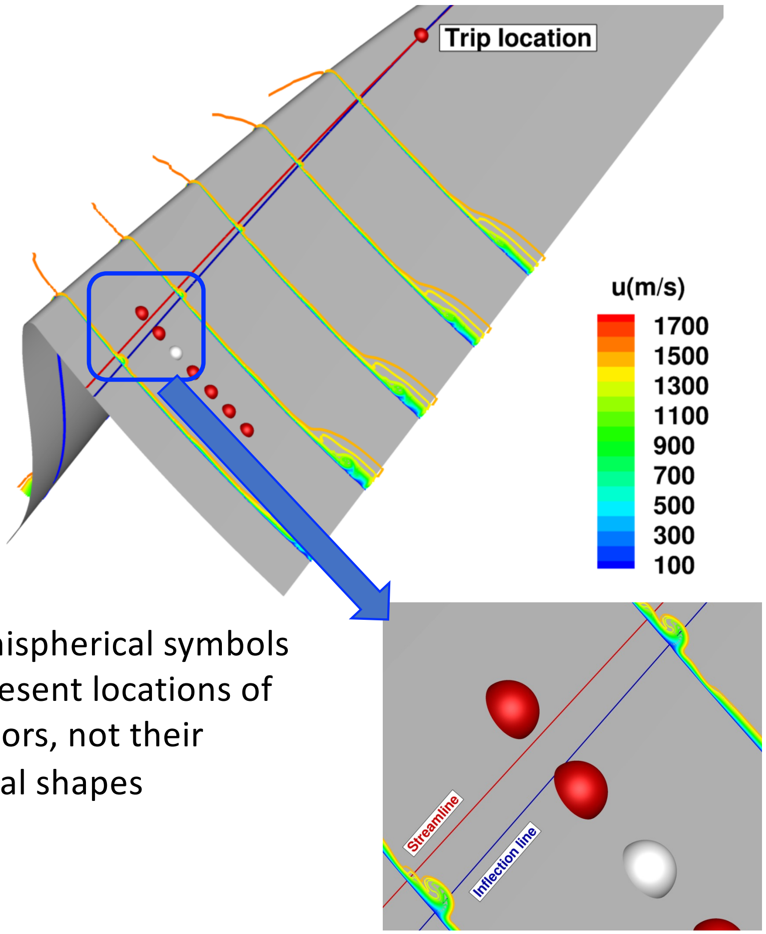
Mode 1
240 kHz



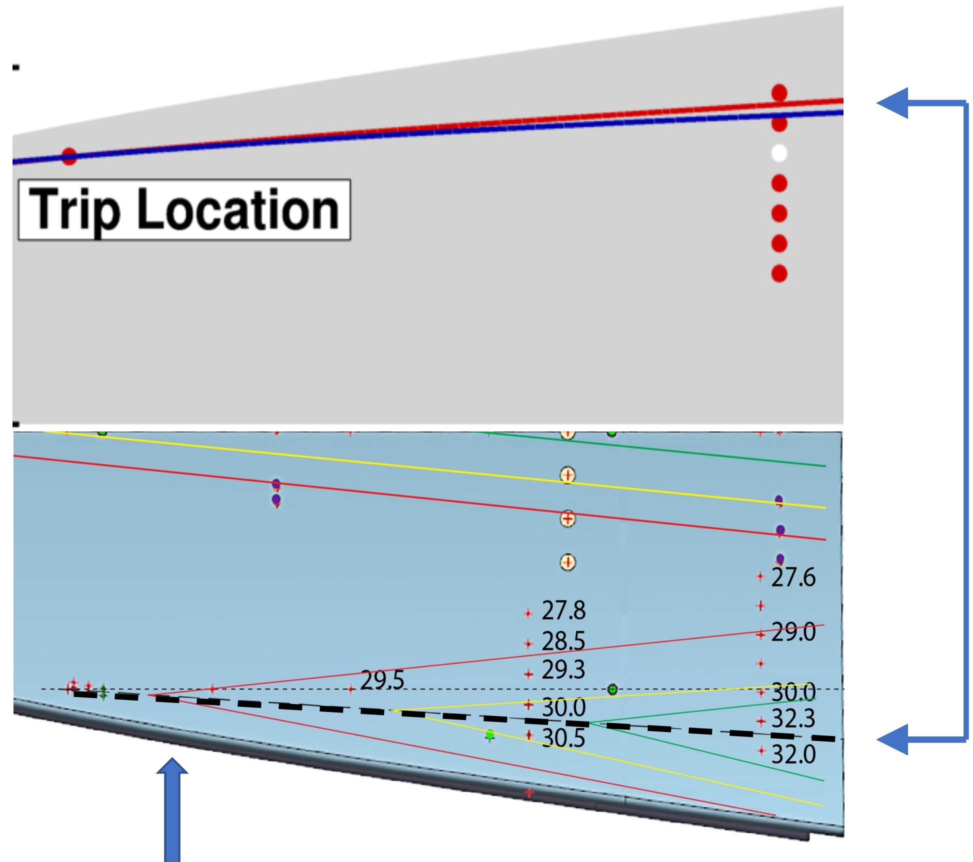
Plane Marching
PSE



Predicted Trip-Wake Trajectories Consistent with Flight Data



Hemispherical symbols represent locations of sensors, not their actual shapes

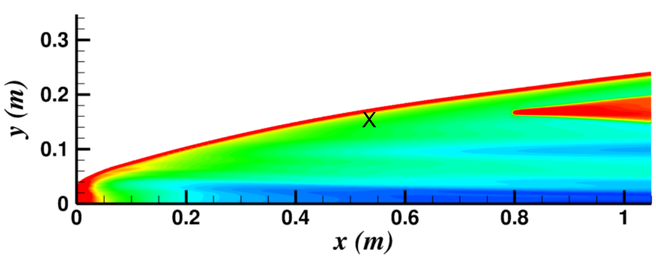


Preliminary Analysis of Flight Data by Scott Berry

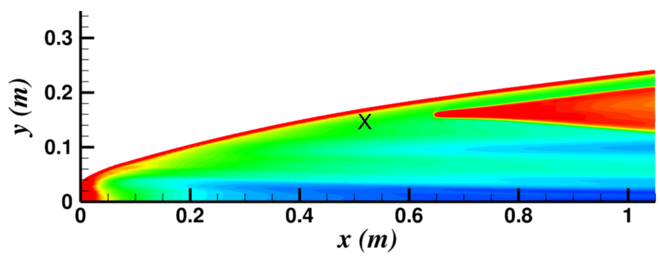
Turbulent Wedges Downstream of Wake Transition Behind Leading-Edge Trip (marked by “x”)

- RANS CFD with localized onset of transition within trip wake

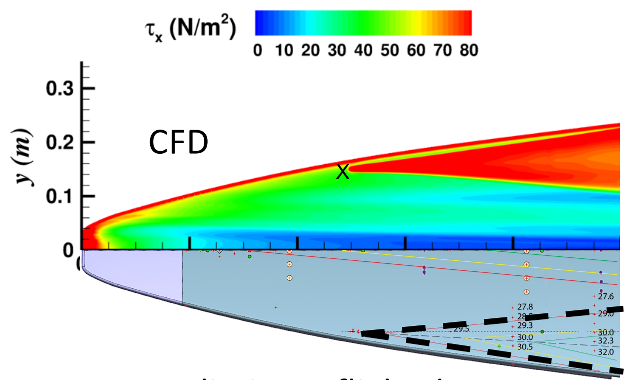
X_{tr} = 0.80 m (incipient)



X_{tr} = 0.65 m (critical)



X_{tr} = 0.50 m (Effective trip)



Preliminary flight data (Berry)

Summary

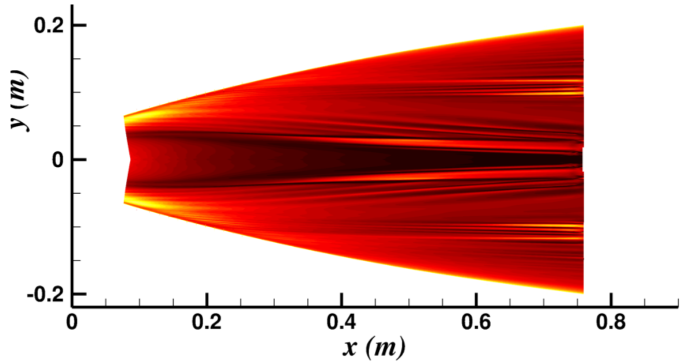
- State of the art tools for computational analysis of BOLT/BOLT-II flight configurations
- Various base flow features and instabilities on (smooth) primary side
  - Streaks become stronger with increasing flight Re and are likely to dominate transition process both in the vicinity of centerline and near the middle of the acreage region
    - Multitude of streak instability modes – hybrid MM/SI and pure SI
    - For BOLT descent case FD4, peak centerline N reaches 14 at x = 0.62 m and acreage streaks achieve N=14 also near x = 0.62 m. Base Flow Features and Instabilities for Secondary Side
  - Step excrescence effect: Preliminary computations for a single step height (k = 0.533 mm) indicate the emergence of a prominent streak aligned with inviscid streamline originating from the intersection of step with the LE. Peak N-factor reaches 14 at x = 0.32 m.
  - Discrete trips on BOLT-II model: Predicted wake trajectory behind LE trip consistent with preliminary flight data
- Need (much) further analysis to improve predictive tools using flight measurements

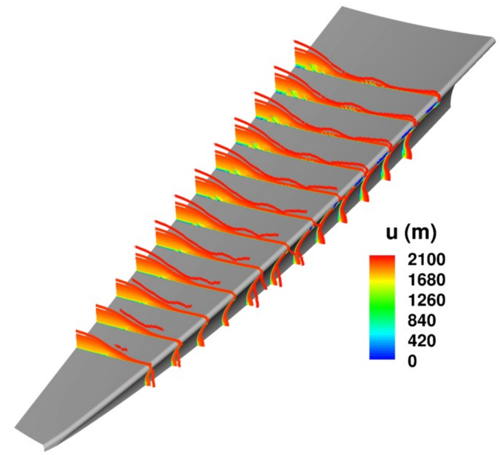
Acknowledgements

- Supported by NASA Hypersonic Technology Project
- Air Force Office of Scientific Research (Paredes)
- NASA Advanced Supercomputing (NAS)
- People
  - Dr. Frank Greene, NASA Langley, for sharing a basic state grid and solutions based on LAURA.
  - Dr. Robert Baurle and Mr. Jeffery White, NASA Langley, for help with VULCAN code
  - Dr. Daniel Rodriguez for help with grid generation for trips

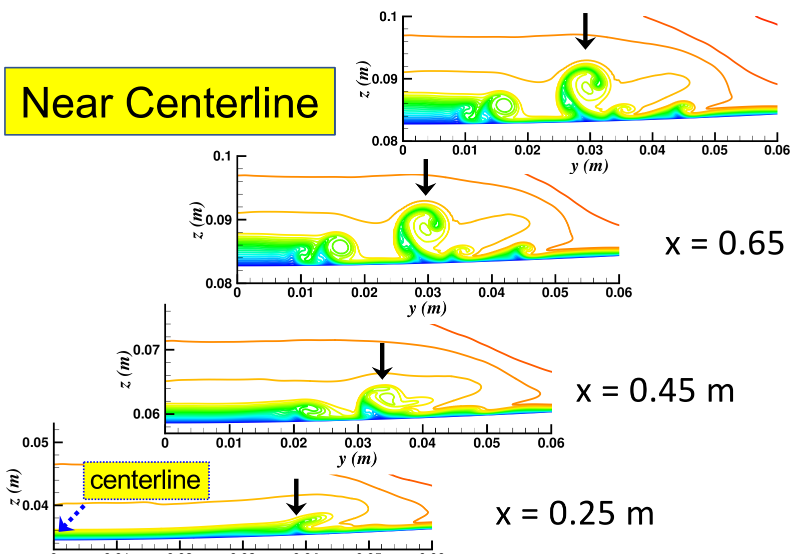
Extra Charts

Basic State Features: Case FD4 ($\alpha = \beta = 0$ deg)





Near Centerline



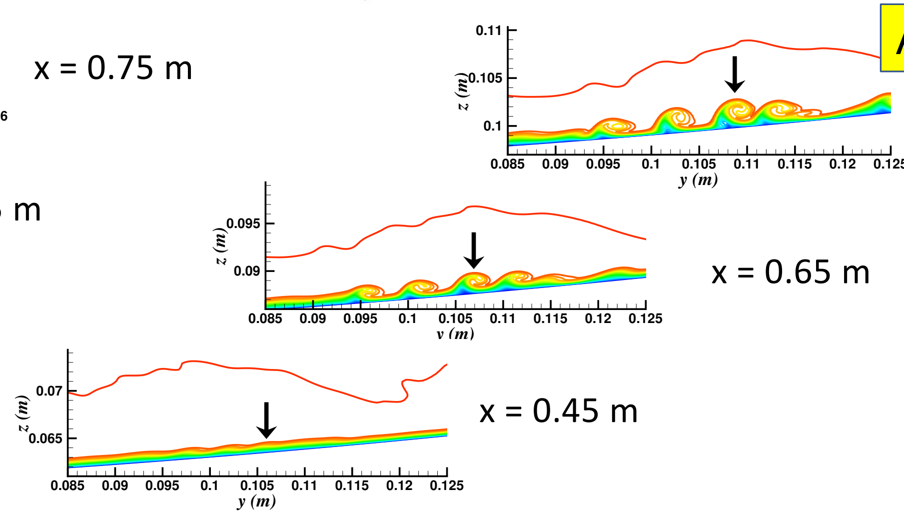
x = 0.75 m

x = 0.65 m

x = 0.45 m

x = 0.25 m

Acreage Region

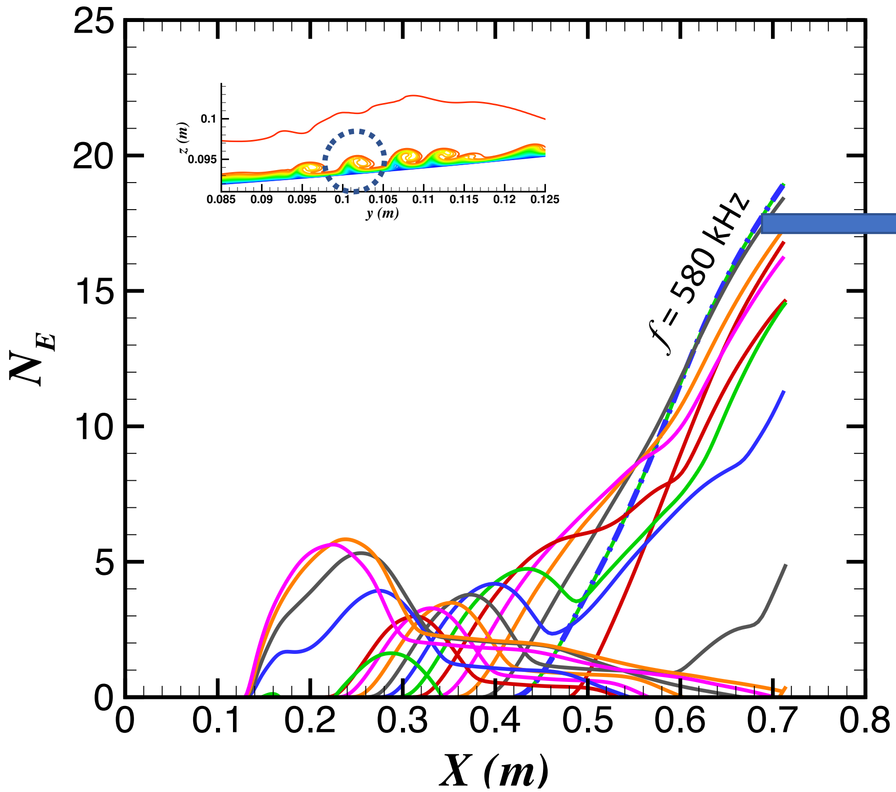


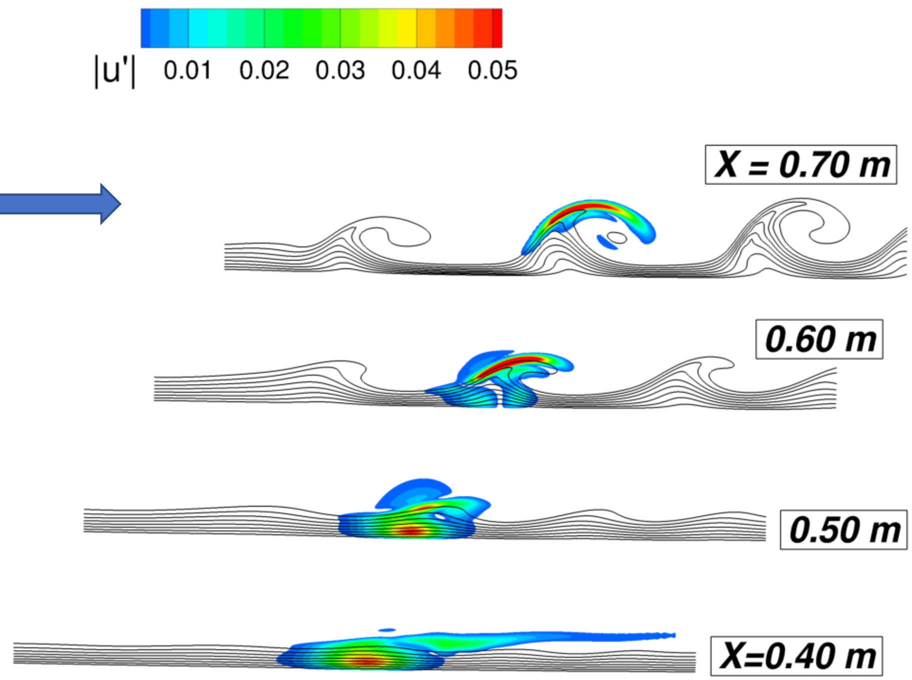
x= 0.75 m

x = 0.65 m

x = 0.45 m

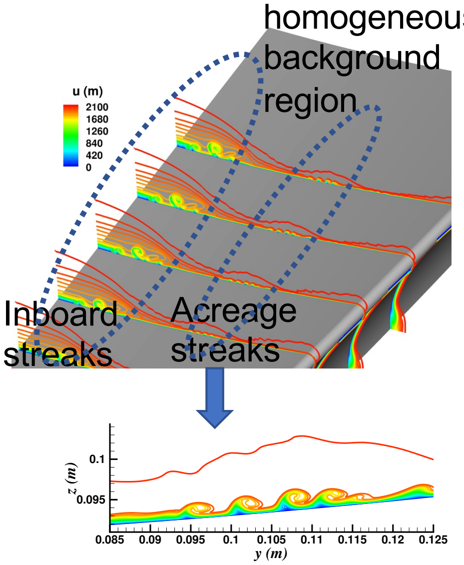
Streak Instability Characteristics in Acreage Region (continued)



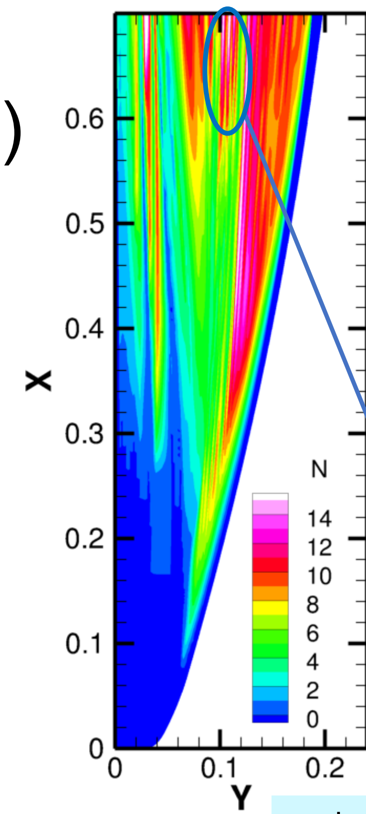


Case FD4:
Growth Characteristics Based on Line-Marching PSE Computations

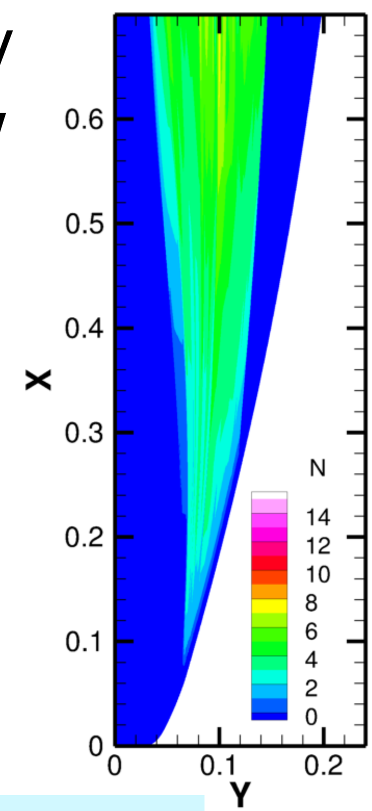
FD4



Mack's 2nd Modes (MM)

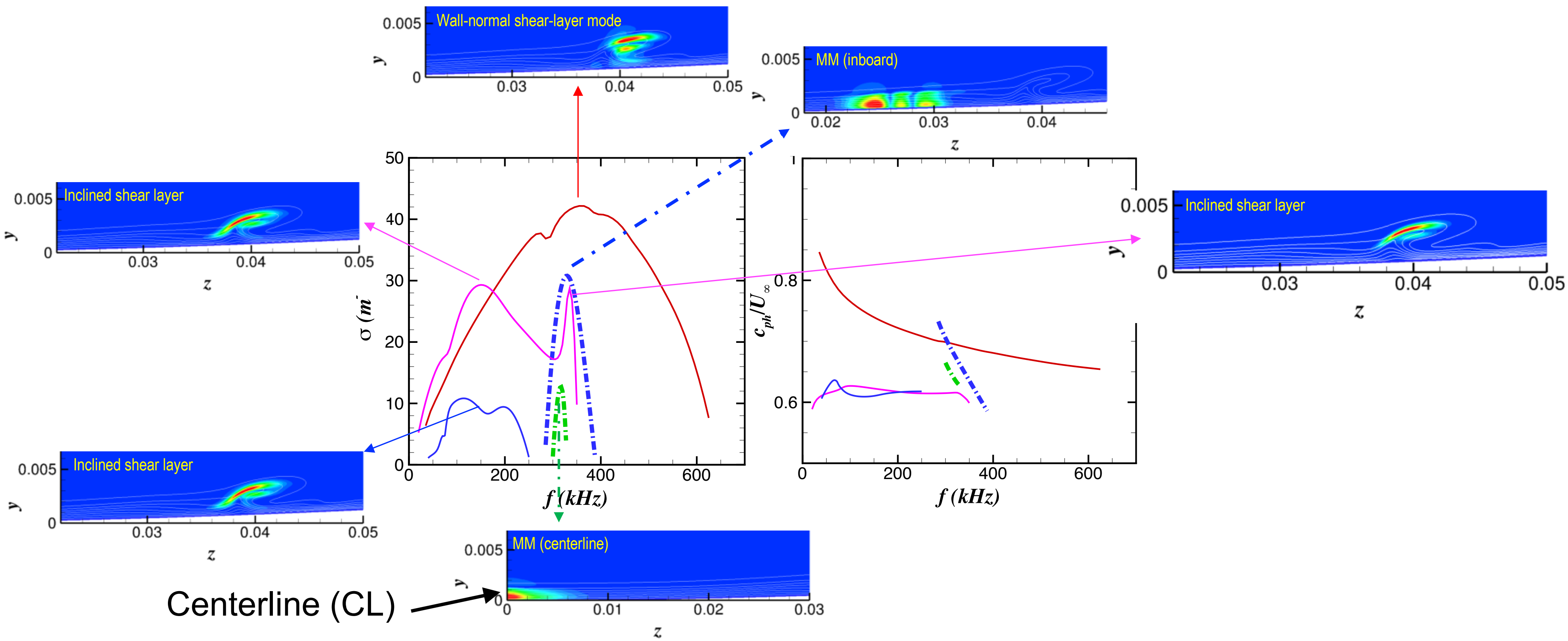


Stationary Crossflow (CF)



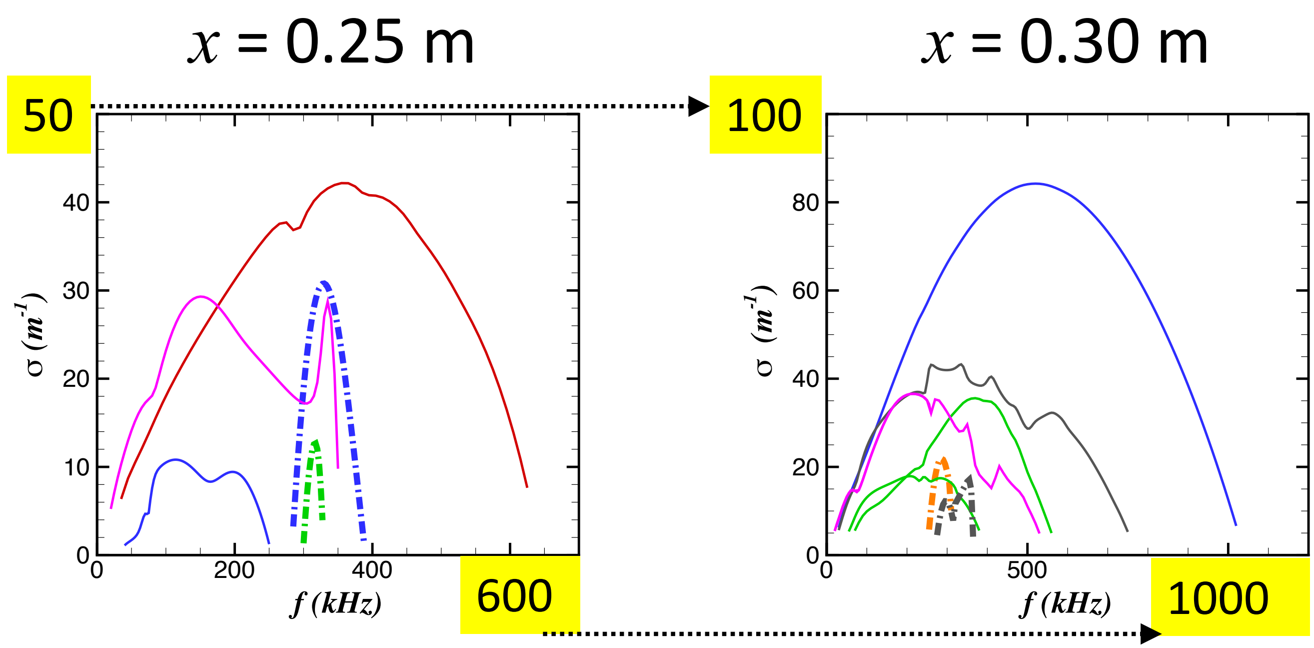
- Large N-factor locations coincide with streaks in acreage region!
- However, spanwise gradients are ignored by line-marching PSE!

Inboard Stability Characteristics Based on Plane Marching PSE
Local Frequency Spectra at x = 0.25 m



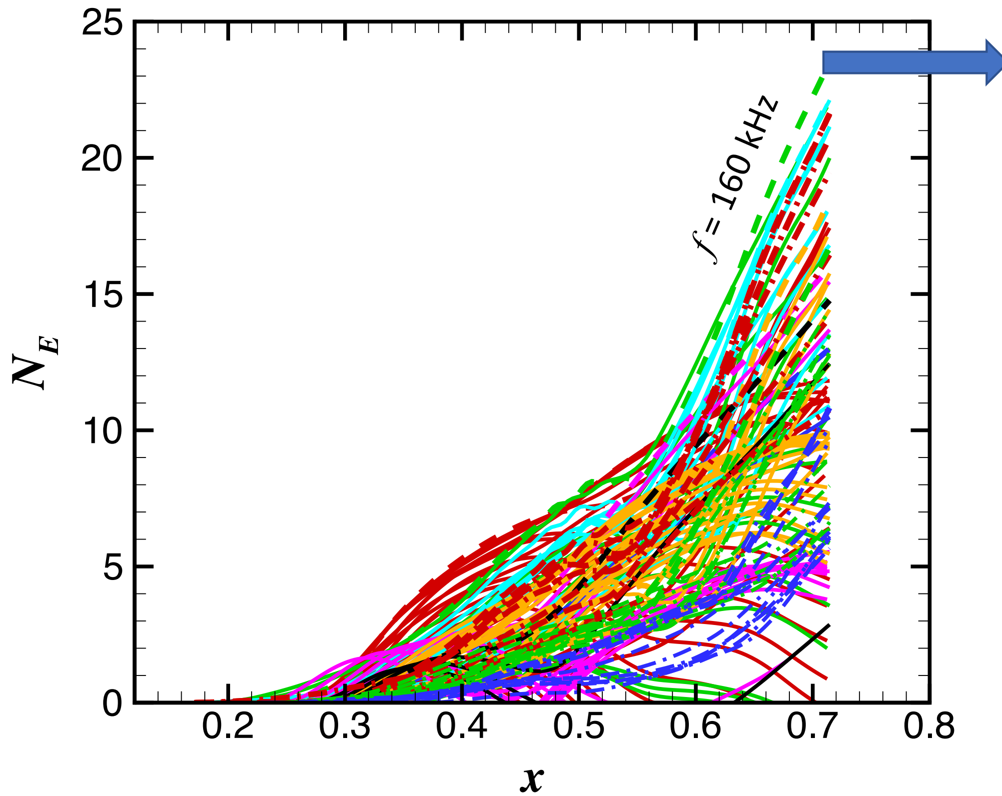
- Two major mode types for instabilities near centerline (CL)
  - **a) Mack modes:** narrow bandwidth, near-wall peak fluctuations, trapped acoustic modes
  - **b) Shear layer modes (streak instabilities)**: concentrated away from the wall, large frequency bandwidth

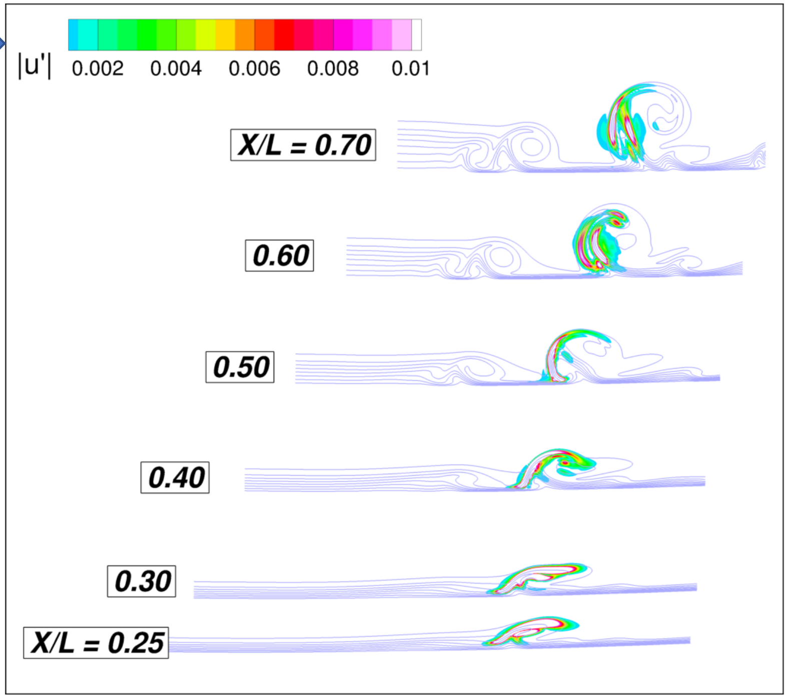
Evolution of Growth Rate Spectra with Increasing x



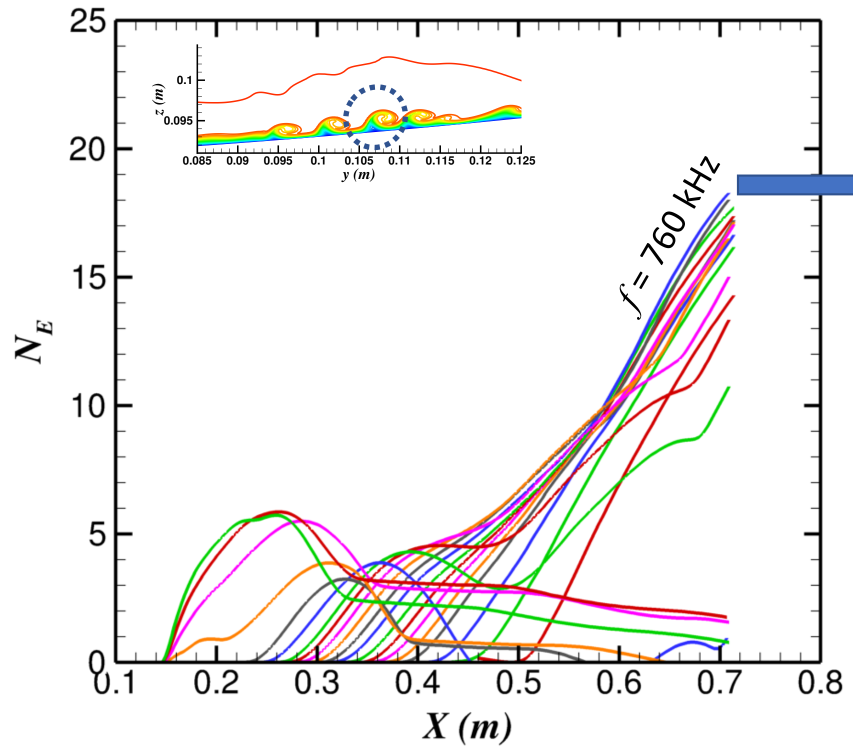
- Peak growth rates of Mack modes decrease downstream, peak growth rates of shear-layer instabilities increase downstream (as streaks become stronger)
- Substantially higher peak growth rate for shear layer modes

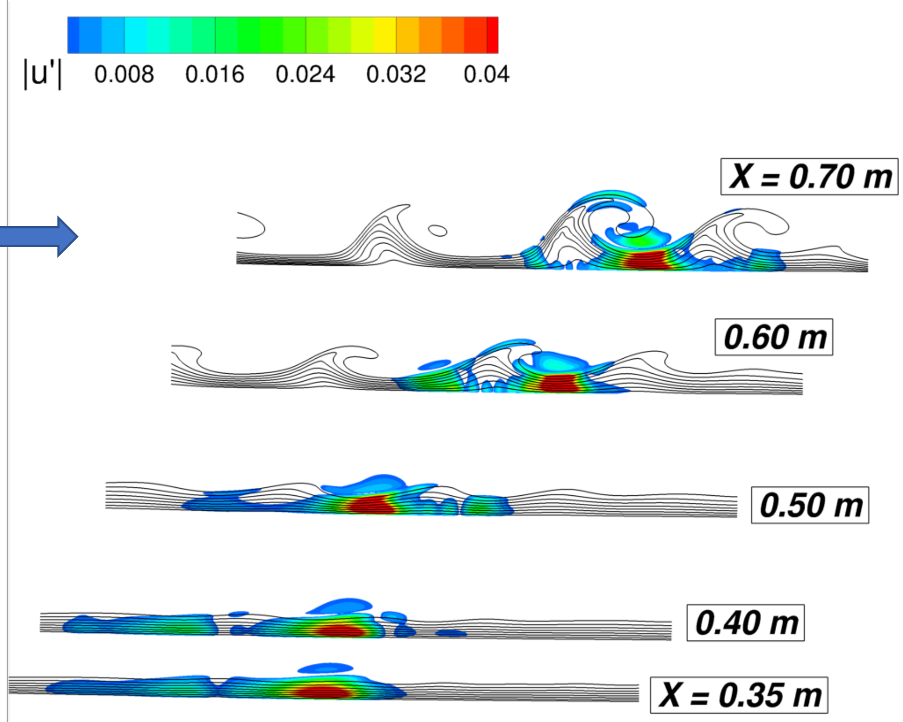
N-Factor Evolution for Streak Instabilities near Centerline





Streak Instability Characteristics in Acreage Region





BOLT-II Secondary Side
Transition Patterns Behind Discrete Trips

(Preliminary Analysis of Flight Data by Scott Berry)