



Secondary Instability of Crossflow Disturbances in Hypersonic Boundary Layers

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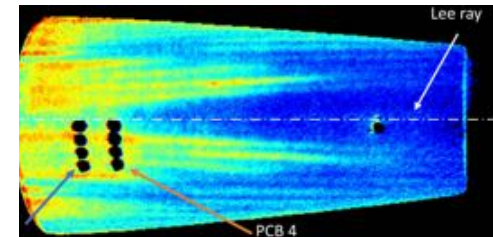
NATO STO AVT-240 & RTG-082 Working Group Meeting
Hypersonic Boundary-Layer Transition Prediction
Tullahoma, TN, April 10-11, 2017



Measurements on 7° Cone, AoA $\approx 6^\circ$

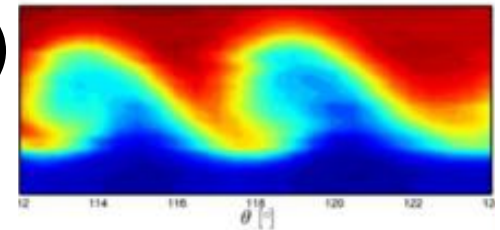
- **Purdue BAMQT data** (Schneider, Ward, Edelman,...)

- Multiple peaks: 100 kHz to 400+ kHz
- Secondary instability of stationary crossflow?



- **TAMU measurements** (Craig & Saric)

- Two bands:
 - 15 kHz-60 kHz (traveling crossflow?)
 - 80 kHz-130 kHz (spanwise-shear mode of secondary instability?)



- **TU Braunschweig measurements** (Munoz et al.)

- Two bands:
 - 20 kHz-50 kHz : 60 to 70 deg propagation angle (traveling crossflow?)
 - 300 kHz-350 kHz (second mode disturbances?)



Measurements on 7° Cone at AoA $\approx 6^\circ$ and HIFiRE-5

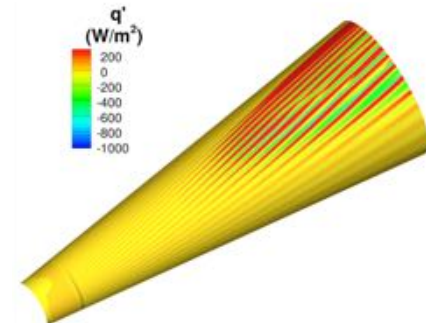
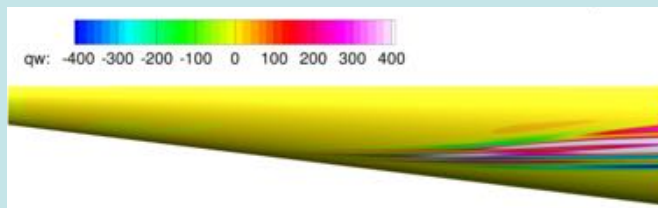
■ Objectives

- Help reconcile measurements and guide follow-on experiments by using DNS and secondary instability theory
- Use computational data to guide the application of primary and secondary instability theory for transition prediction over 3D bodies

■ Strategy

- Use relatively simple controlled forcing in DNS to excite stationary crossflow pattern that resembles naturally occurring crossflow disturbances in wind tunnel experiments in terms of azimuthal length scale and range of amplitudes
 - Previous work: Azimuthally periodic, axially localized, non-compact “bracelet” source

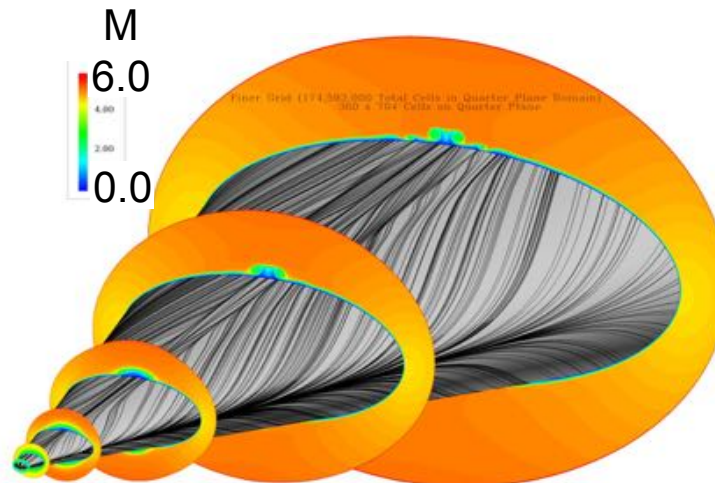
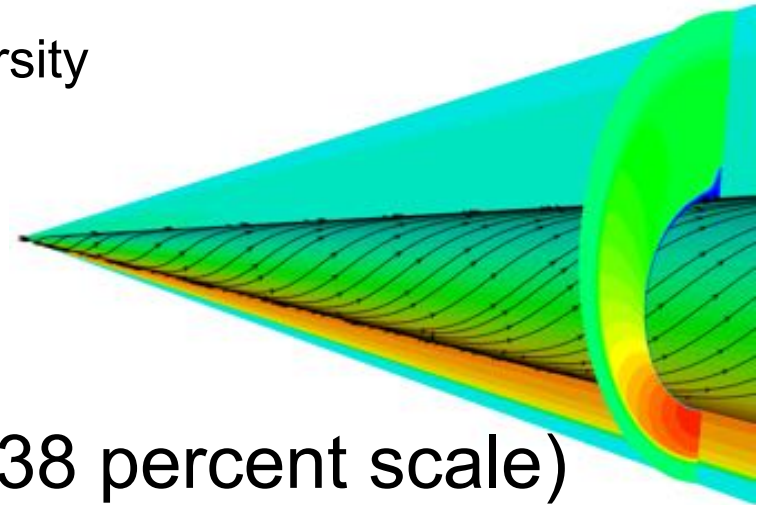
- **Current work: Azimuthally compact source**





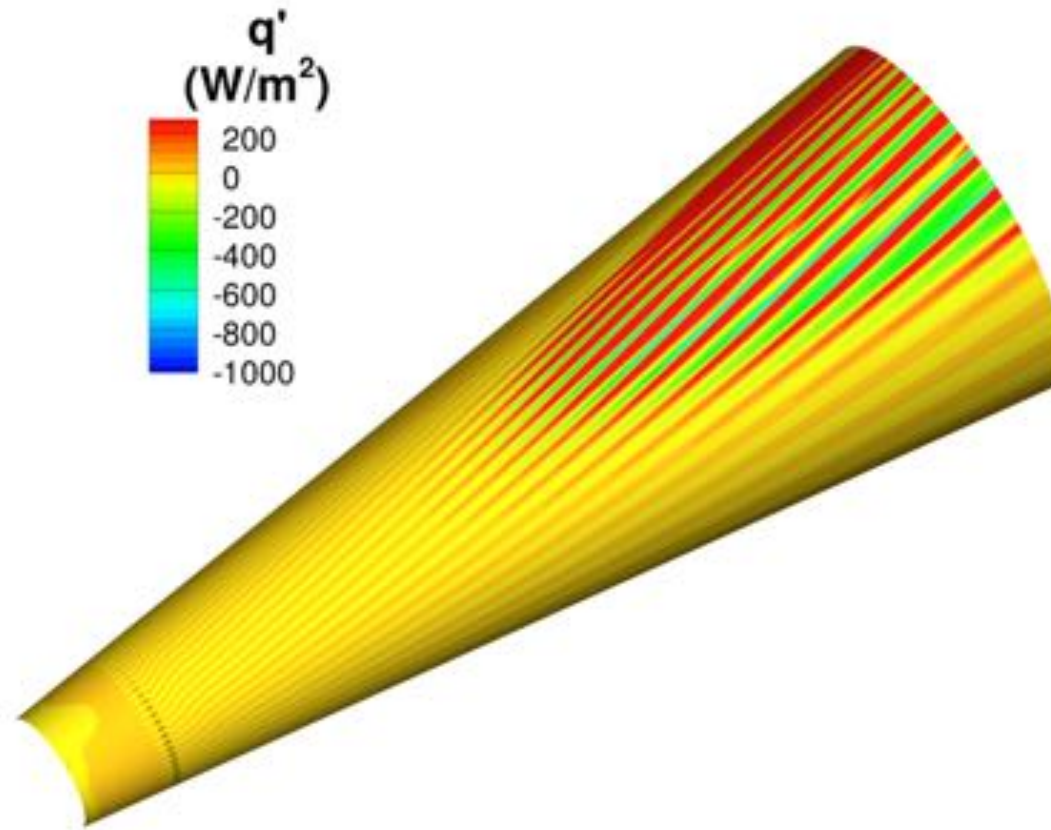
Flow Configurations

- 7° Circular Cone at 6° AoA
 - Mach 6 quiet tunnel at Purdue University
 - $Re = 3 \times 10^6/ft$
- HiFIRE5 wind tunnel model (38 percent scale)
 - AFRL experiments in Mach 6 quiet tunnel at Purdue University,
 $Re = 2.5 \times 10^6/ft$





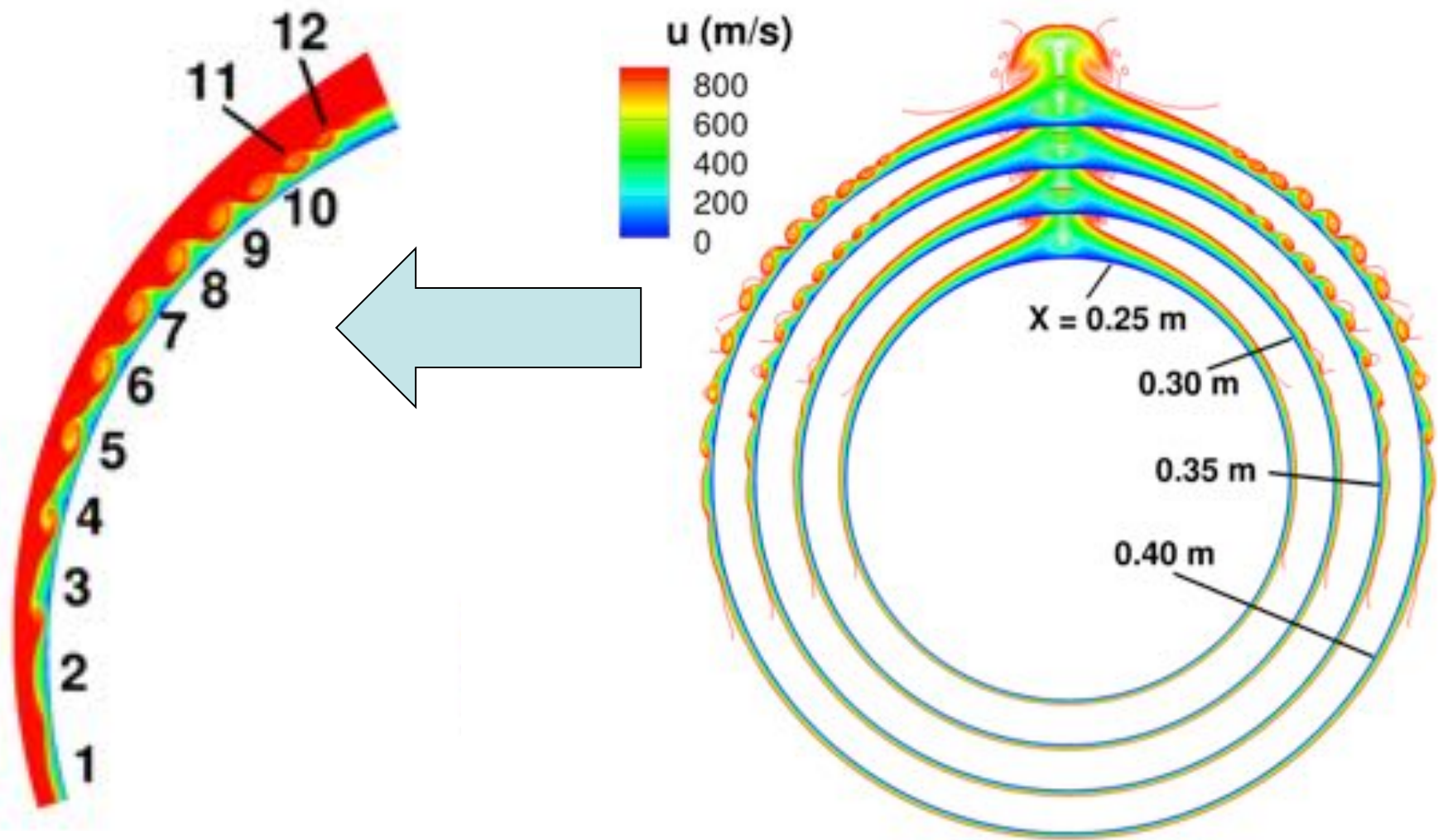
Evolution of Vortex Pattern: Periodic Source



- Li, F., Choudhari, M., and Paredes, P., "Nonlinear Evolution and Secondary Instability of Crossflow Disturbances in Hypersonic Boundary Layer over a Cone," NATO-STO AVT-240 & RTG-082 Meeting on Hypersonic Boundary Layer Transition, Prague, Czech Republic, Oct. 15- 16, 2015.
- Li, F., Choudhari, M., Paredes, P., and Duan, L., "Secondary Instability of Stationary Crossflow Vortices in Mach 6 Boundary Layer over a Circular Cone," NASA/TM-2015-218997, Dec. 2015.
- Li, F., Choudhari, M., Paredes, P., and Duan, L., "High-Frequency Instabilities of Stationary Crossflow Vortices in a Hypersonic Boundary Layer," Phys. Rev. Fluids, 1, 083601.

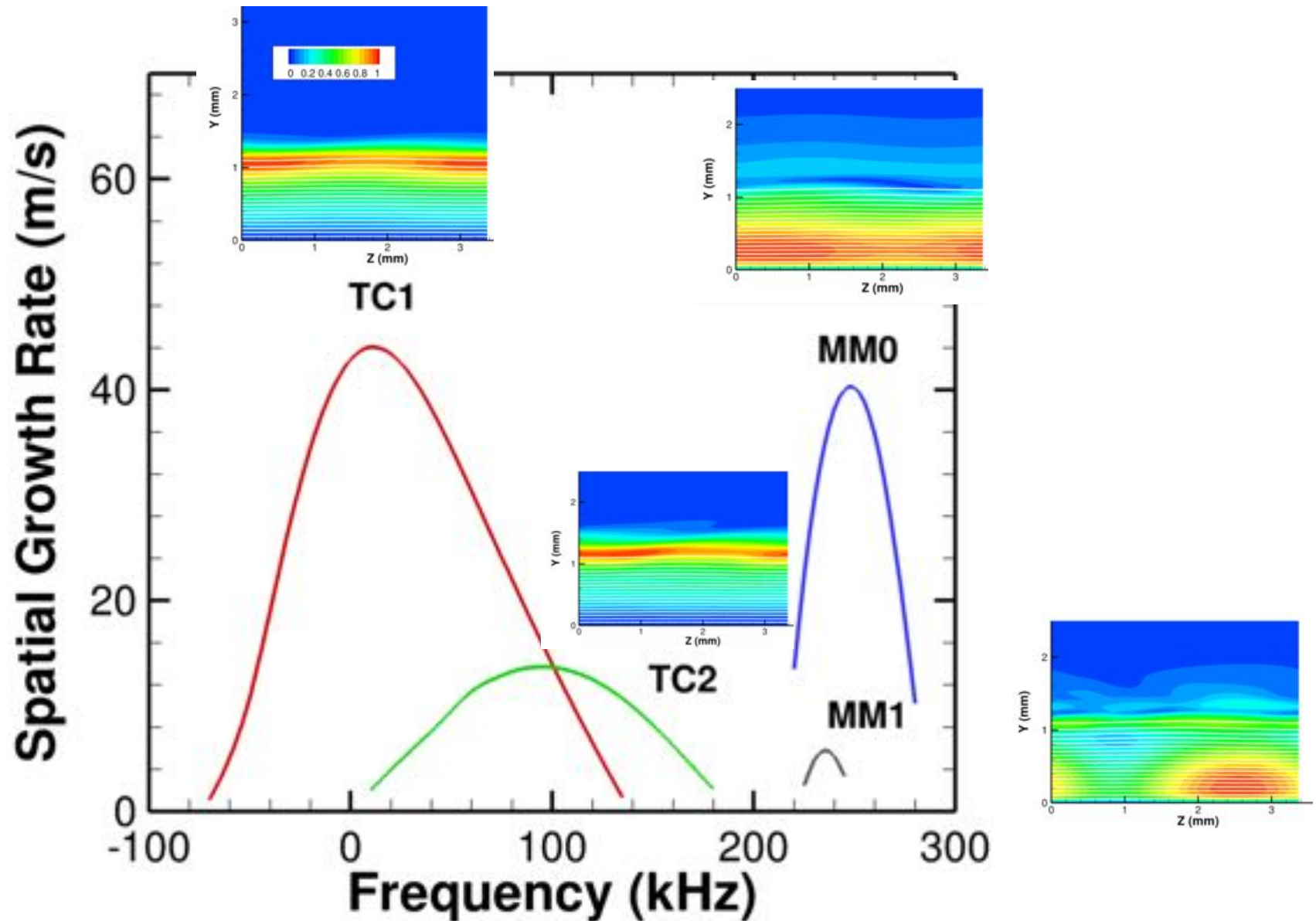


Axial Velocity Contours





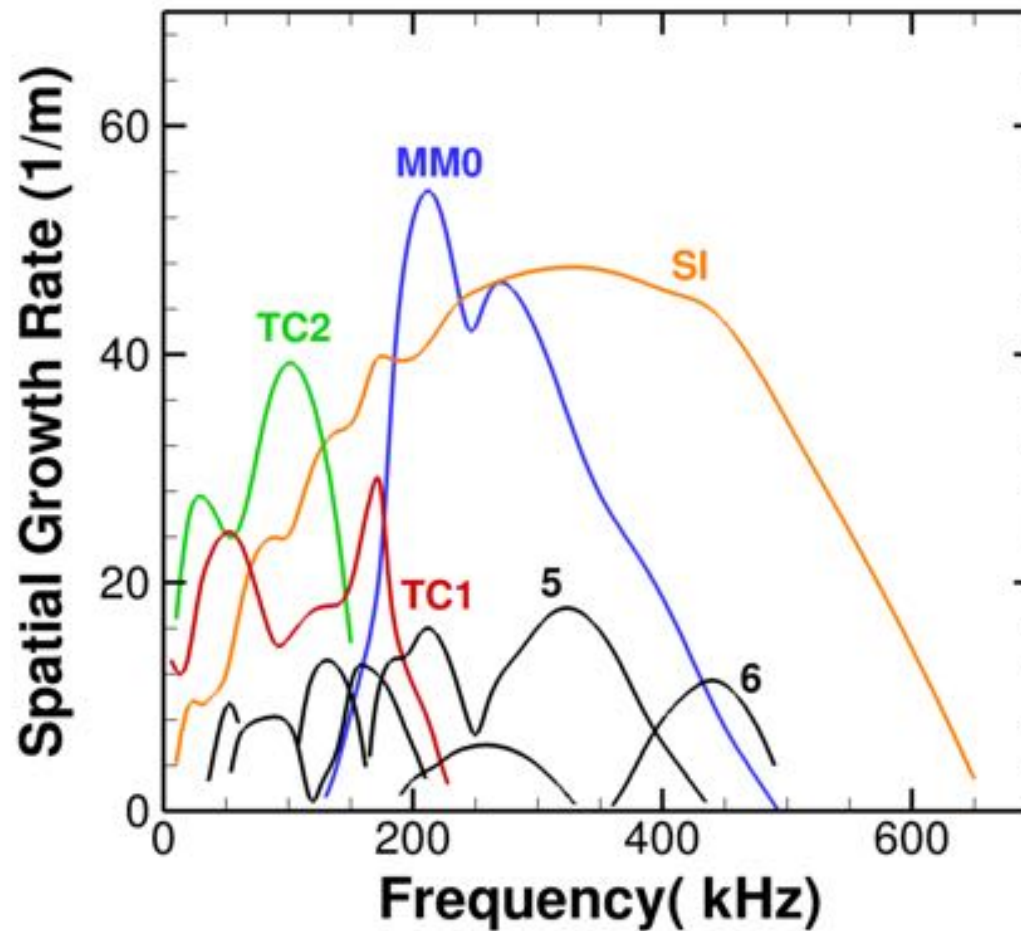
Local Growth Rates (V10, X = 0.25 m)





Local Growth Rates: Downstream Locations

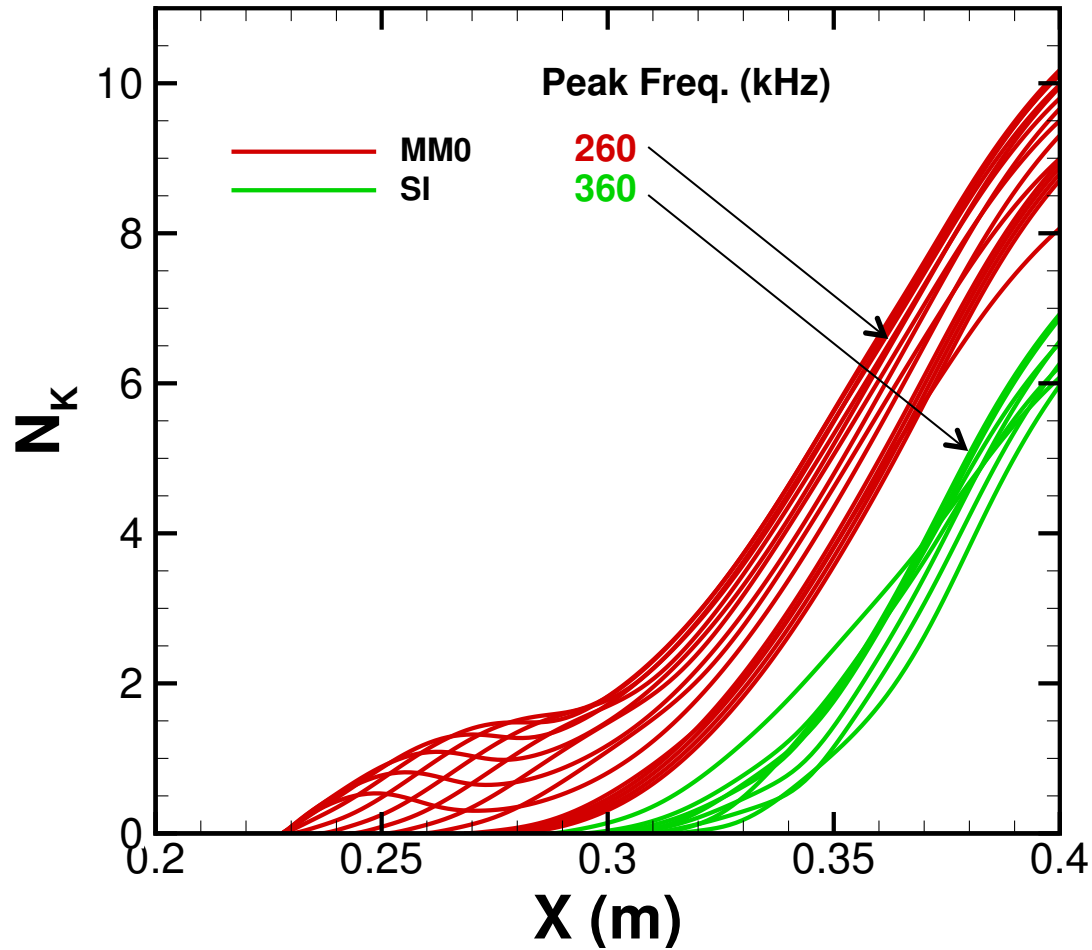
$X = 0.33 \text{ m}$





PSE Predictions: N-Factor Evolution

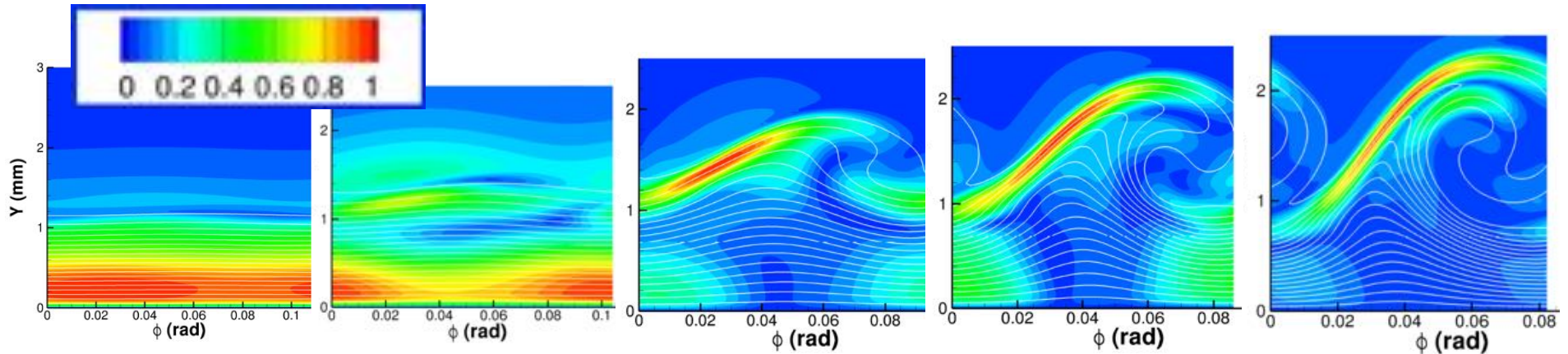
V10





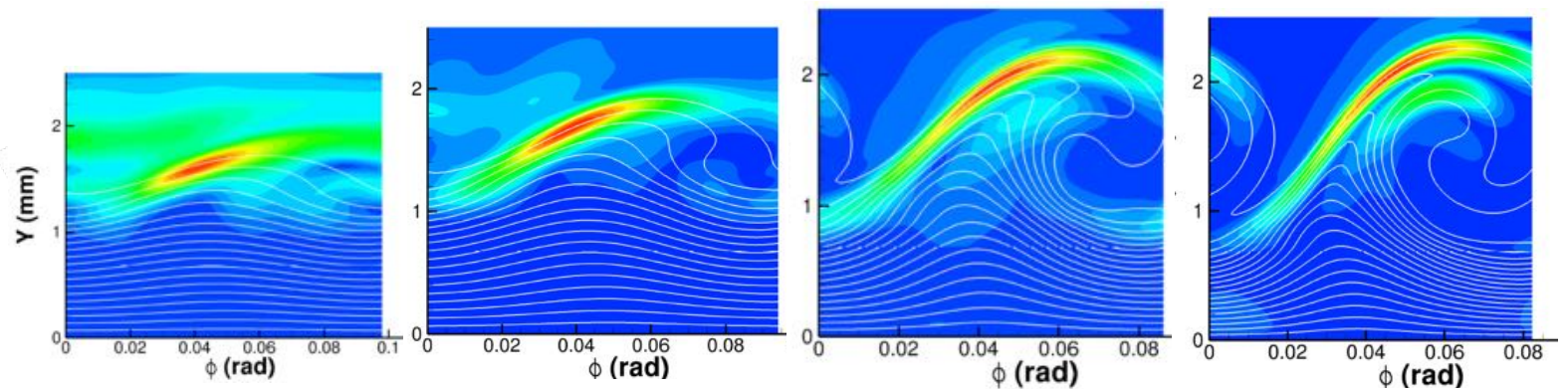
$|u'|$ Mode Shape Evolution for V10 (PSE)

Mode MM0 (260 kHz)

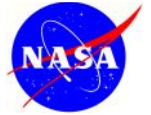


X →

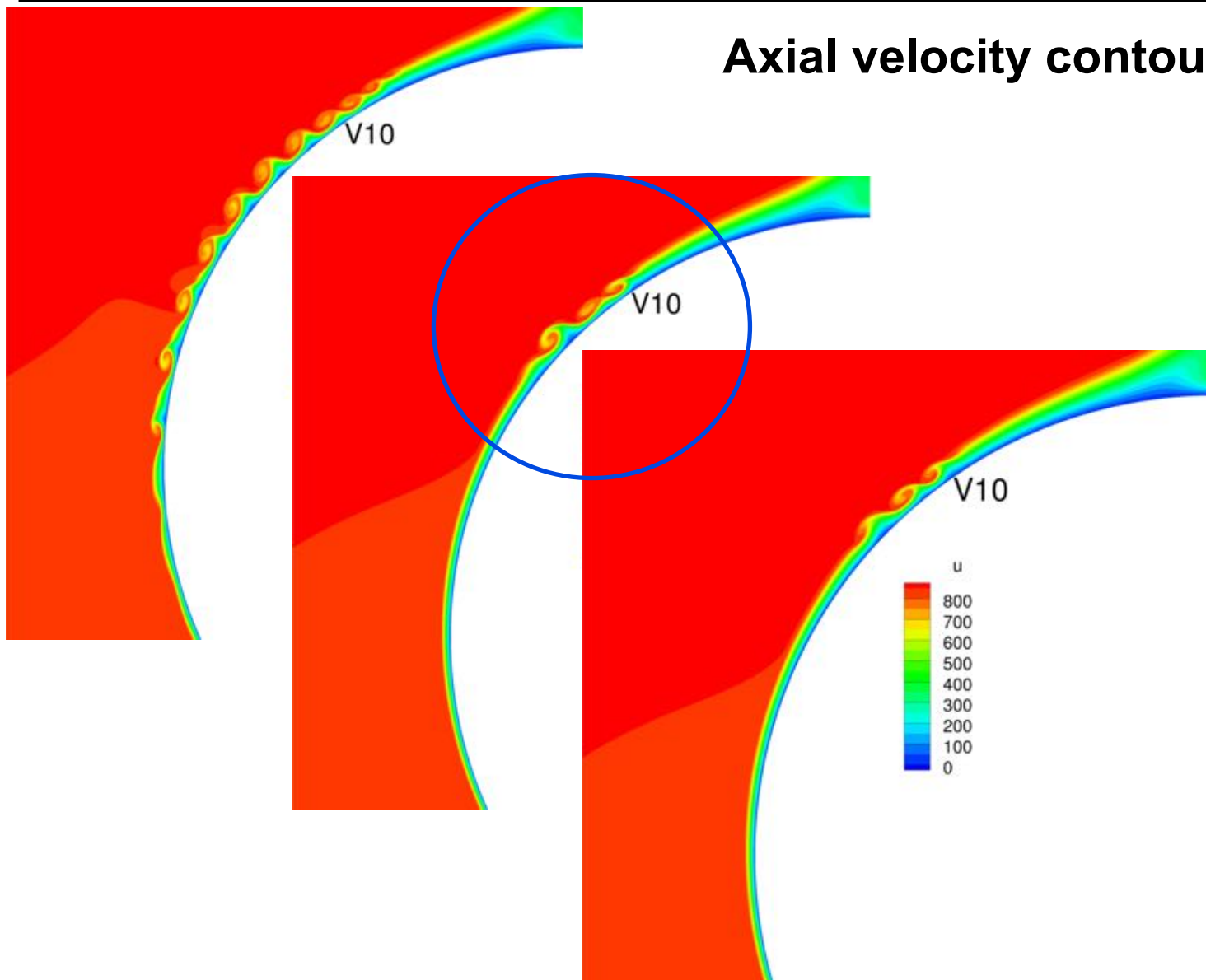
Mode SI (360 kHz)



Effect of Azimuthal Extent of Source

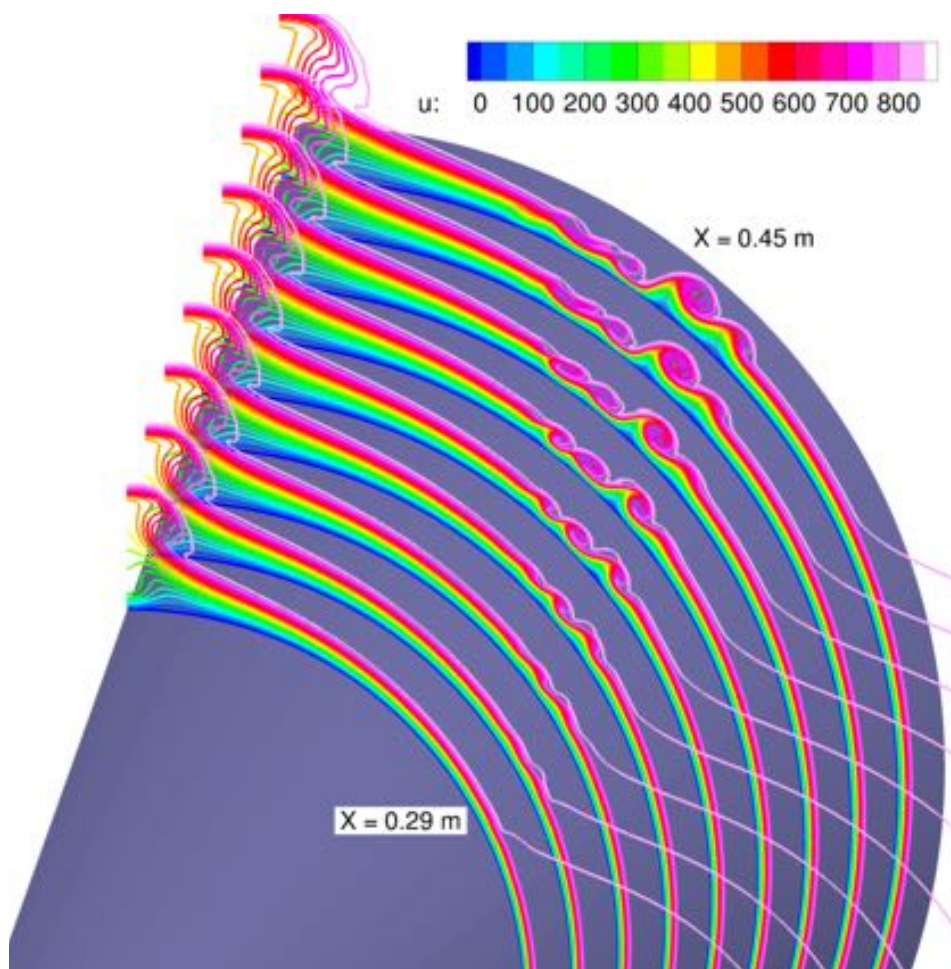


Axial velocity contours at $X = 0.4$ m

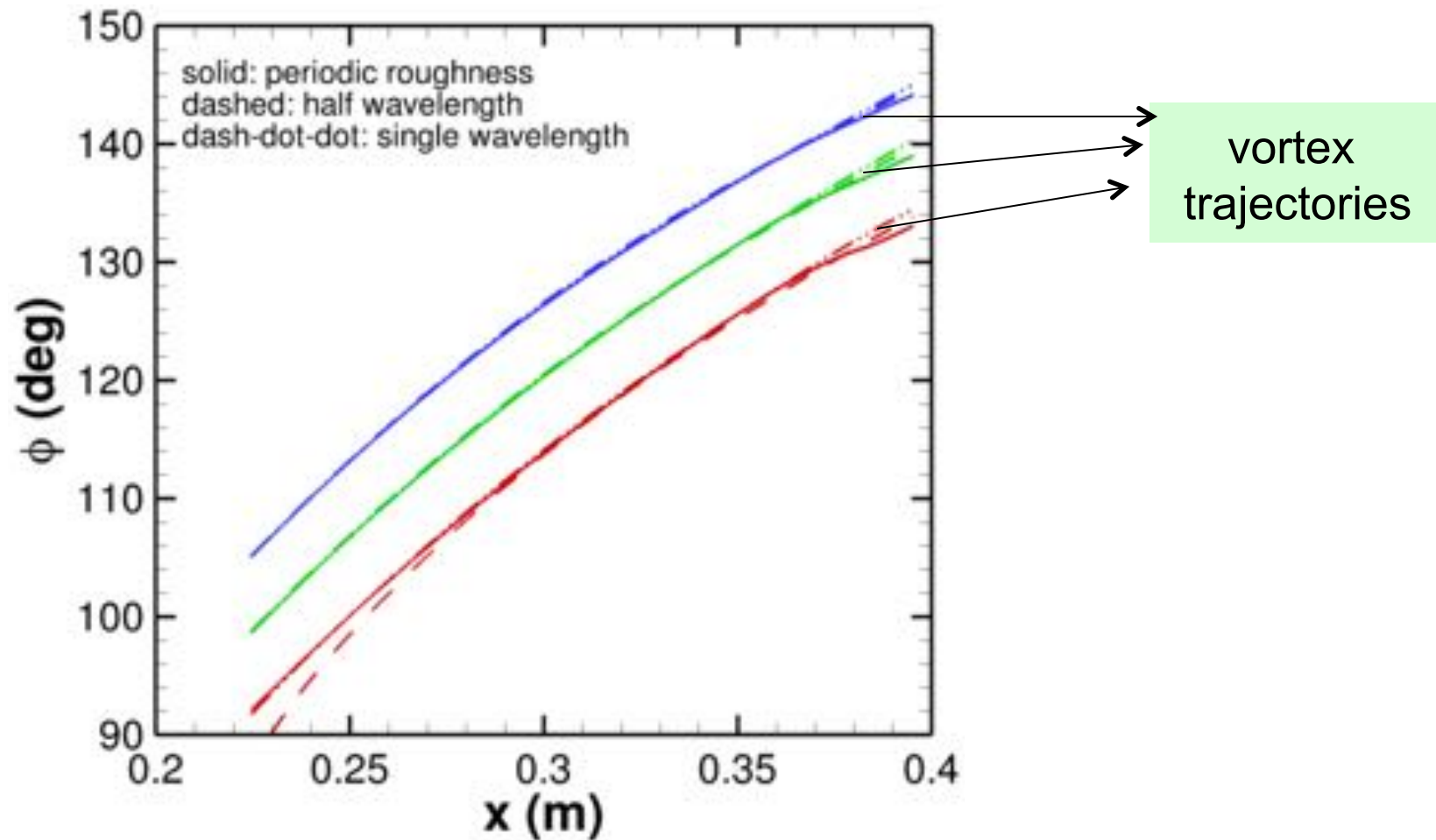
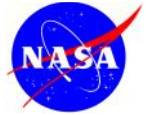


Localized Source

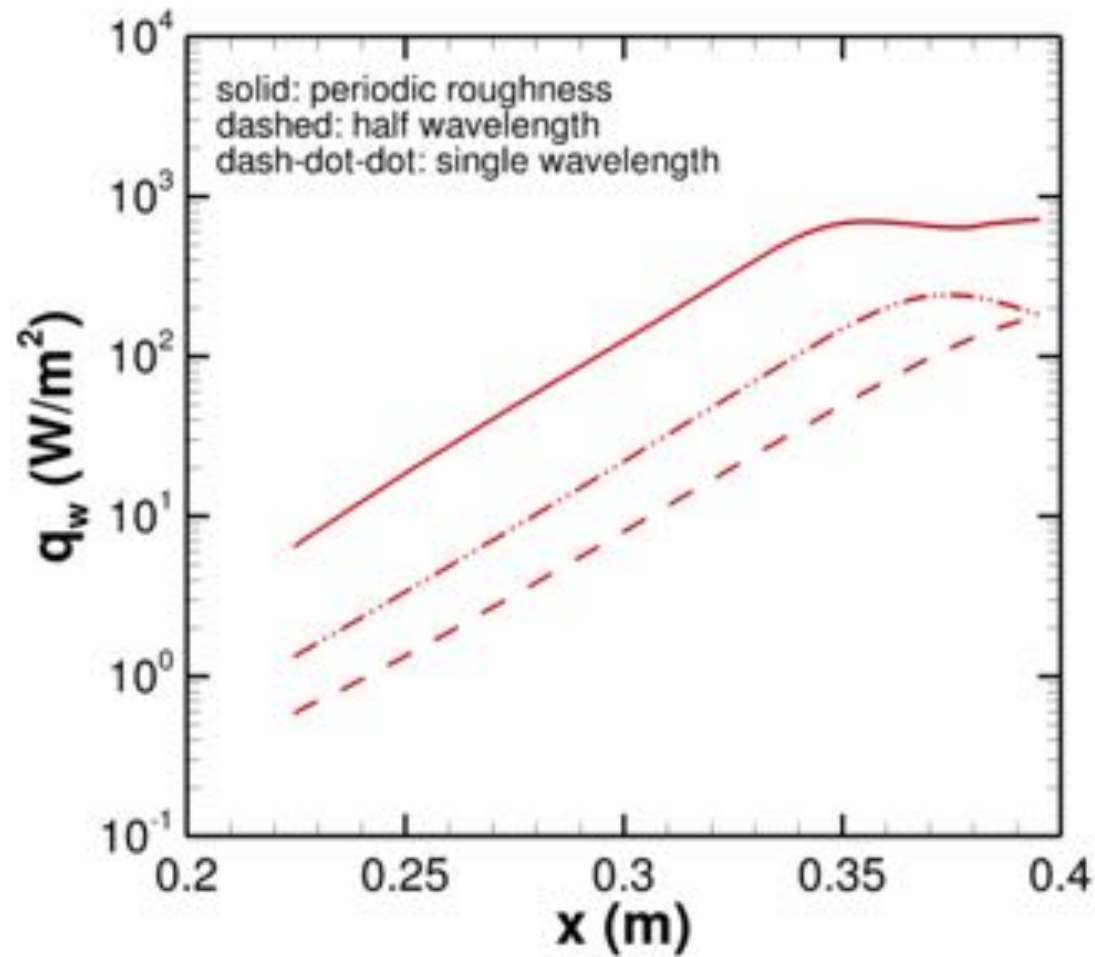
Axial velocity contours



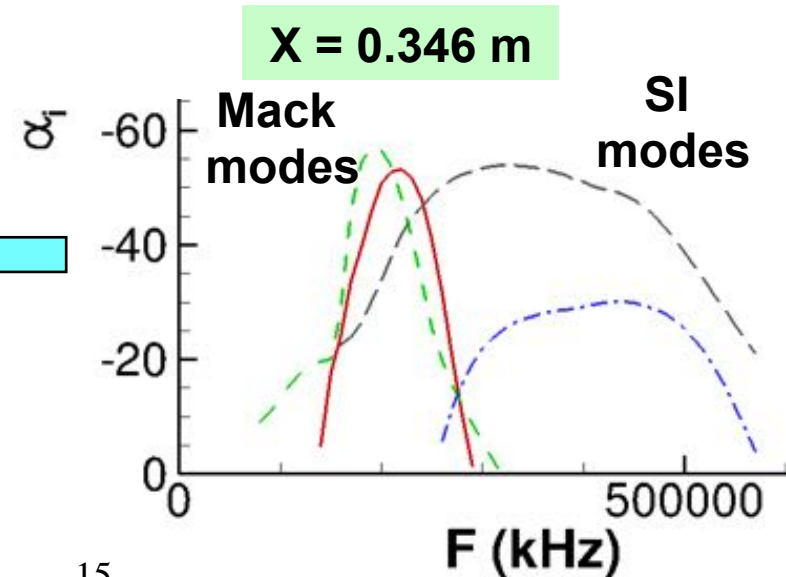
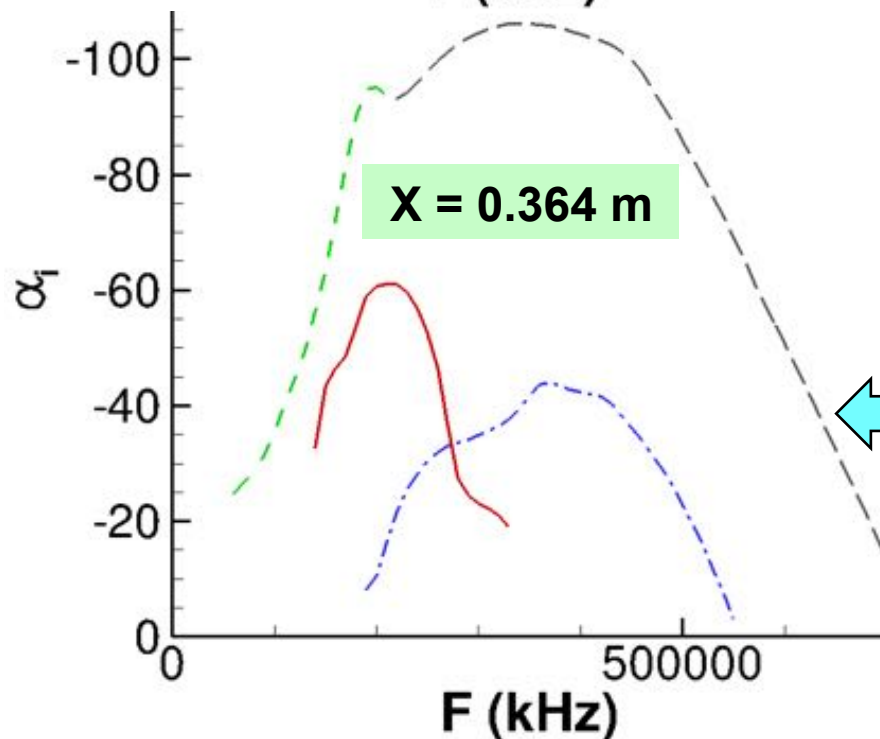
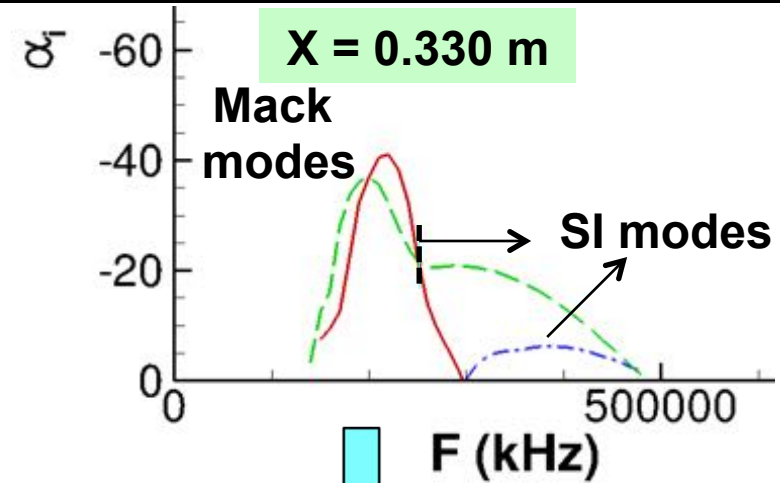
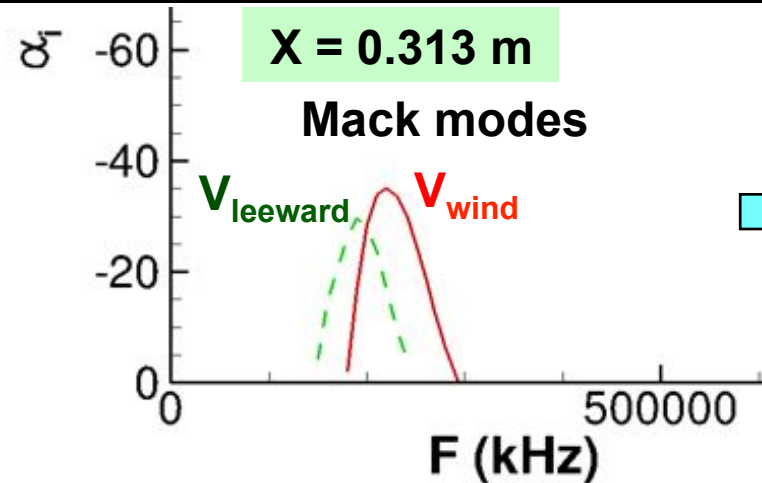
Vortex Trajectories: Effect of Azimuthal Source Distribution



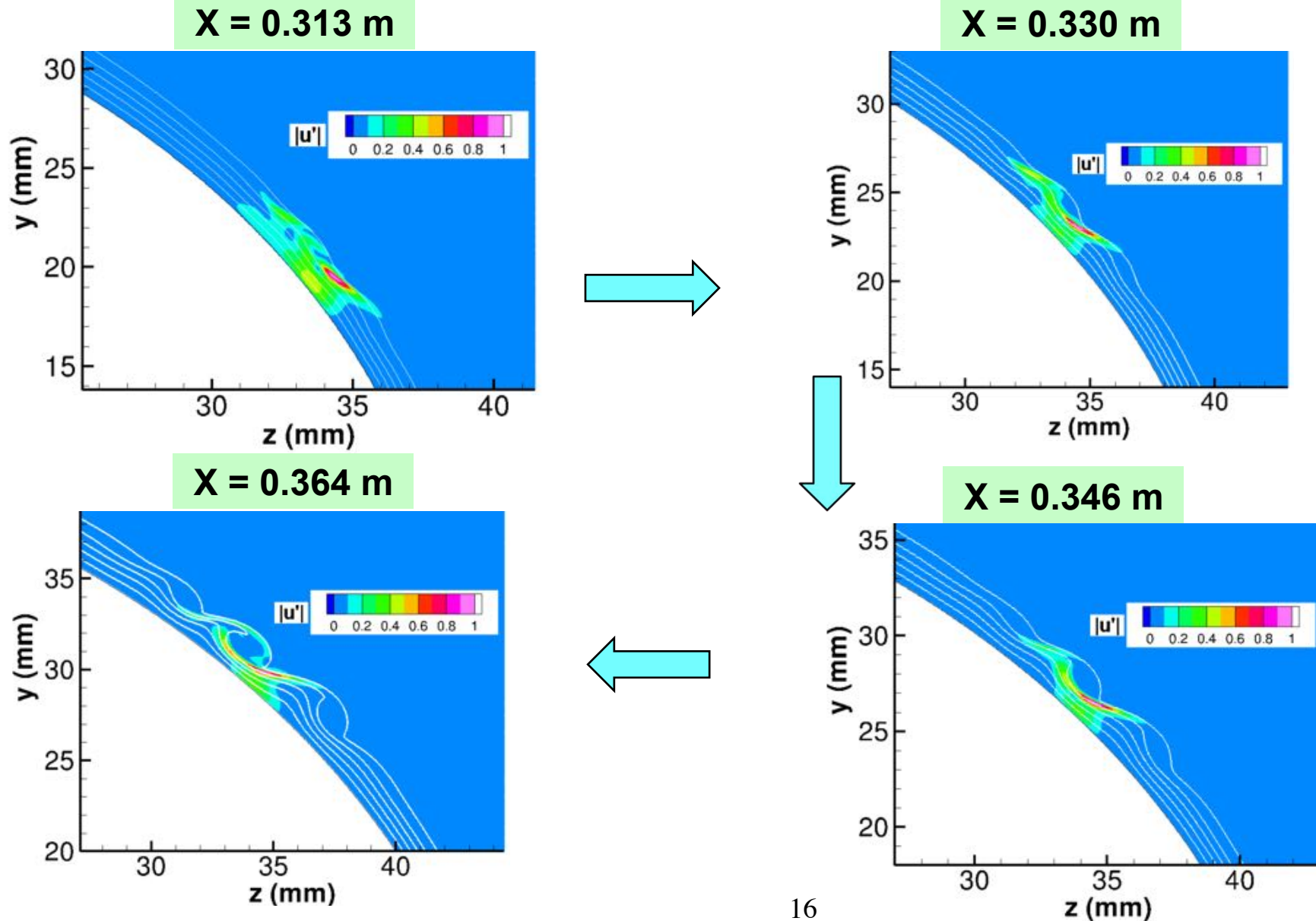
Vortex Amplitudes: Effect of Azimuthal Source Distribution



Growth Rate Spectra at Selected Stations



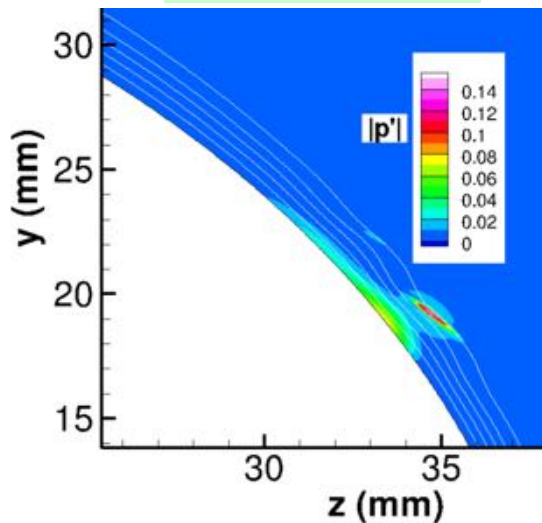
$|u'|$ Mode Shapes for Windward Vortex: Mack Mode



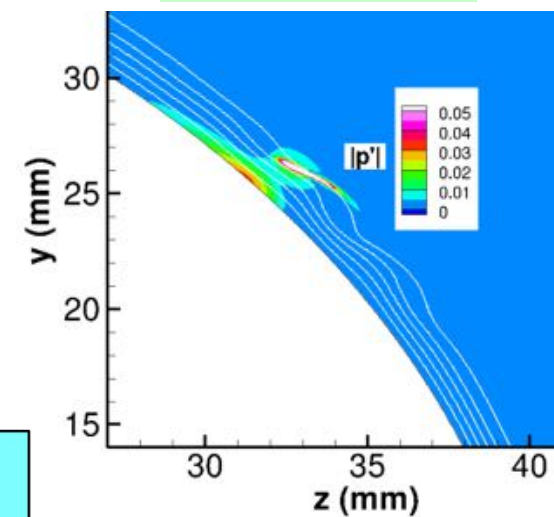
$|p'|$ Mode Shapes for Windward Vortex: Mack Mode



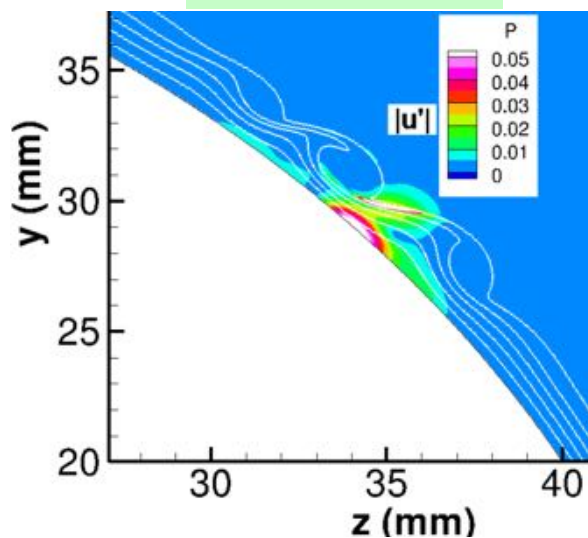
$X = 0.313 \text{ m}$



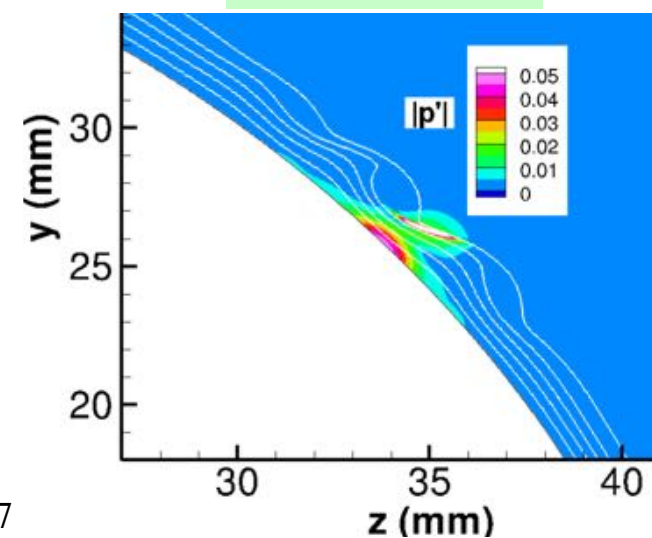
$X = 0.330 \text{ m}$



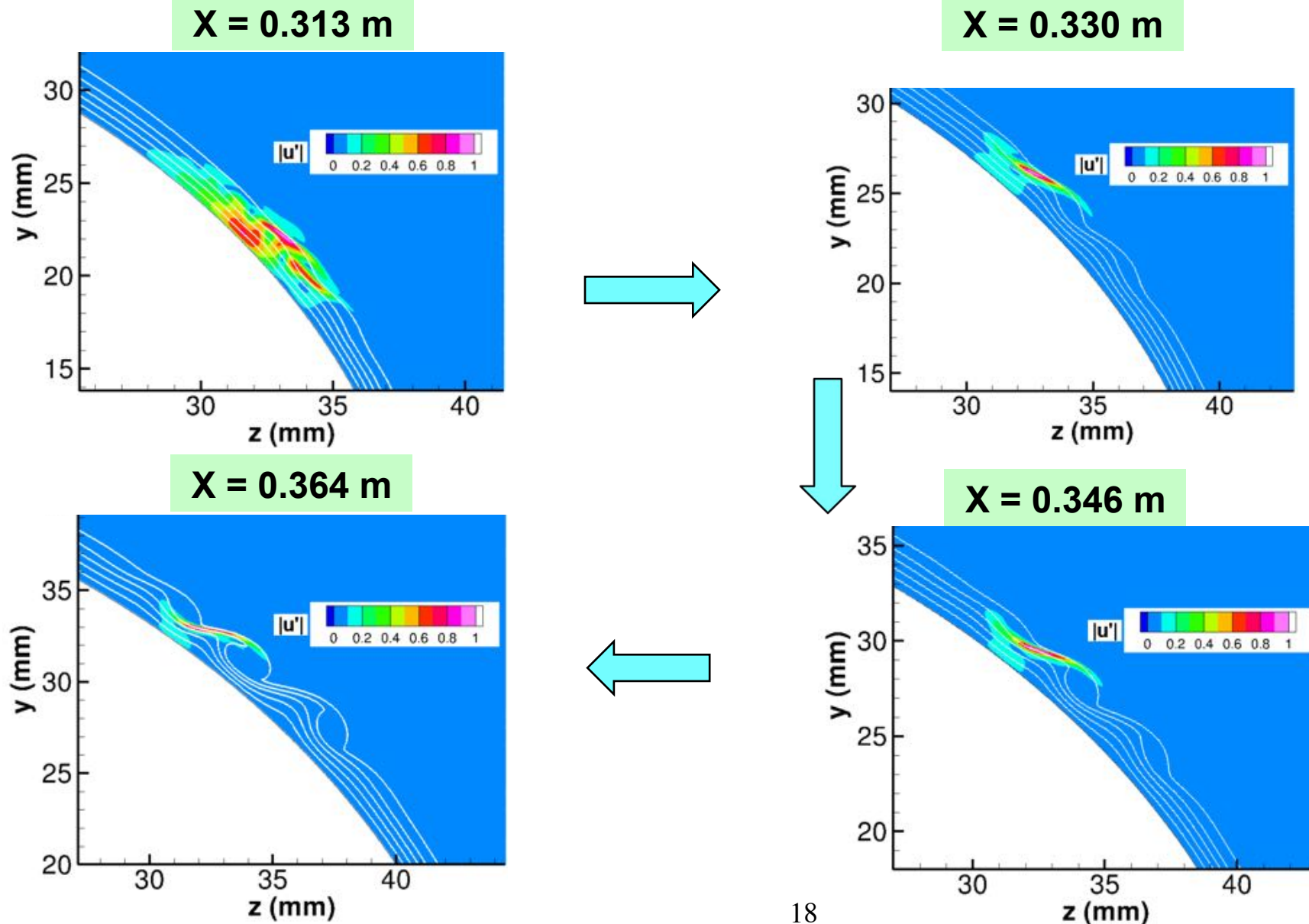
$X = 0.364 \text{ m}$



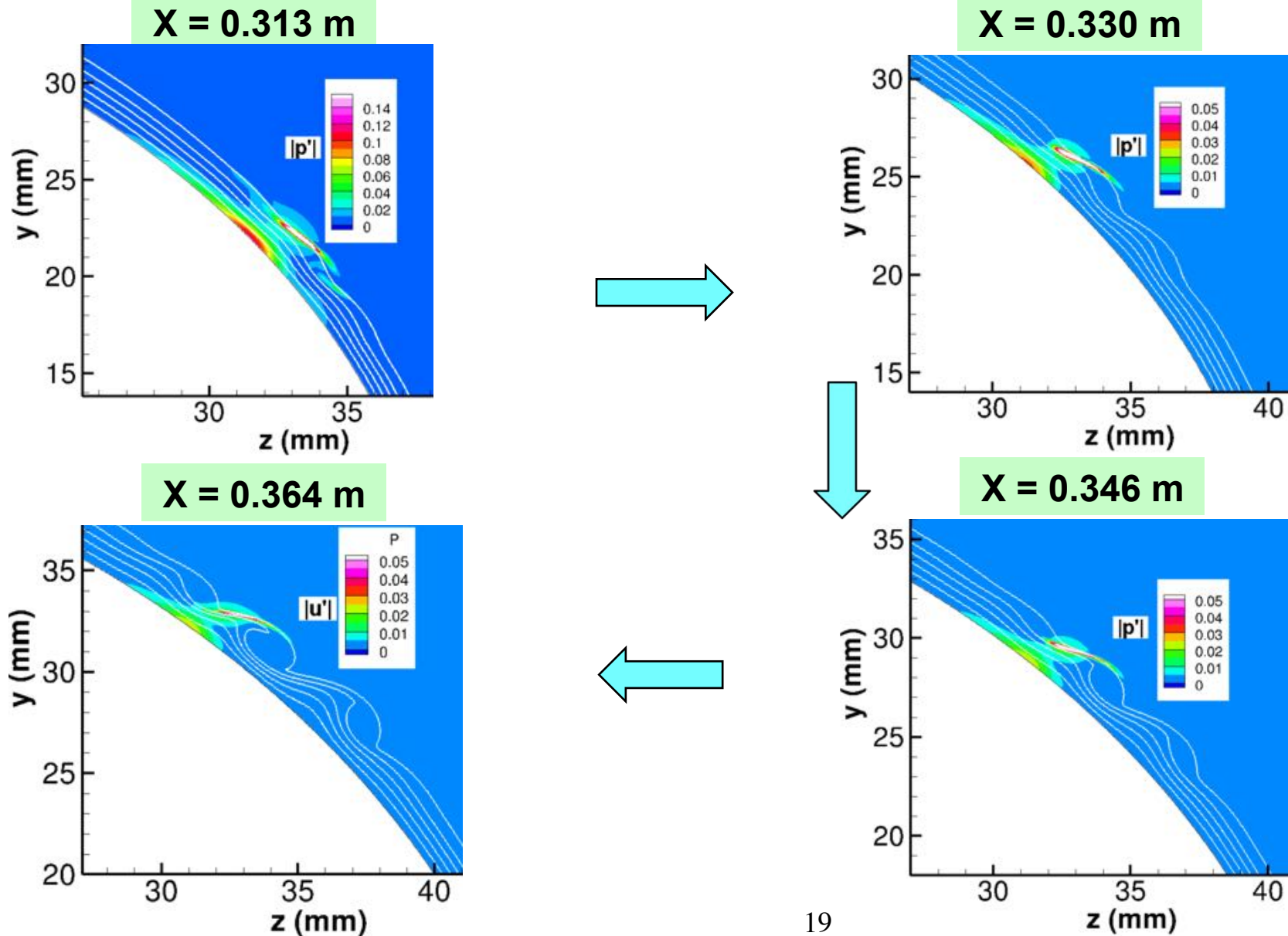
$X = 0.346 \text{ m}$



$|u'|$ Mode Shapes for Leeward Vortex: Mack Mode

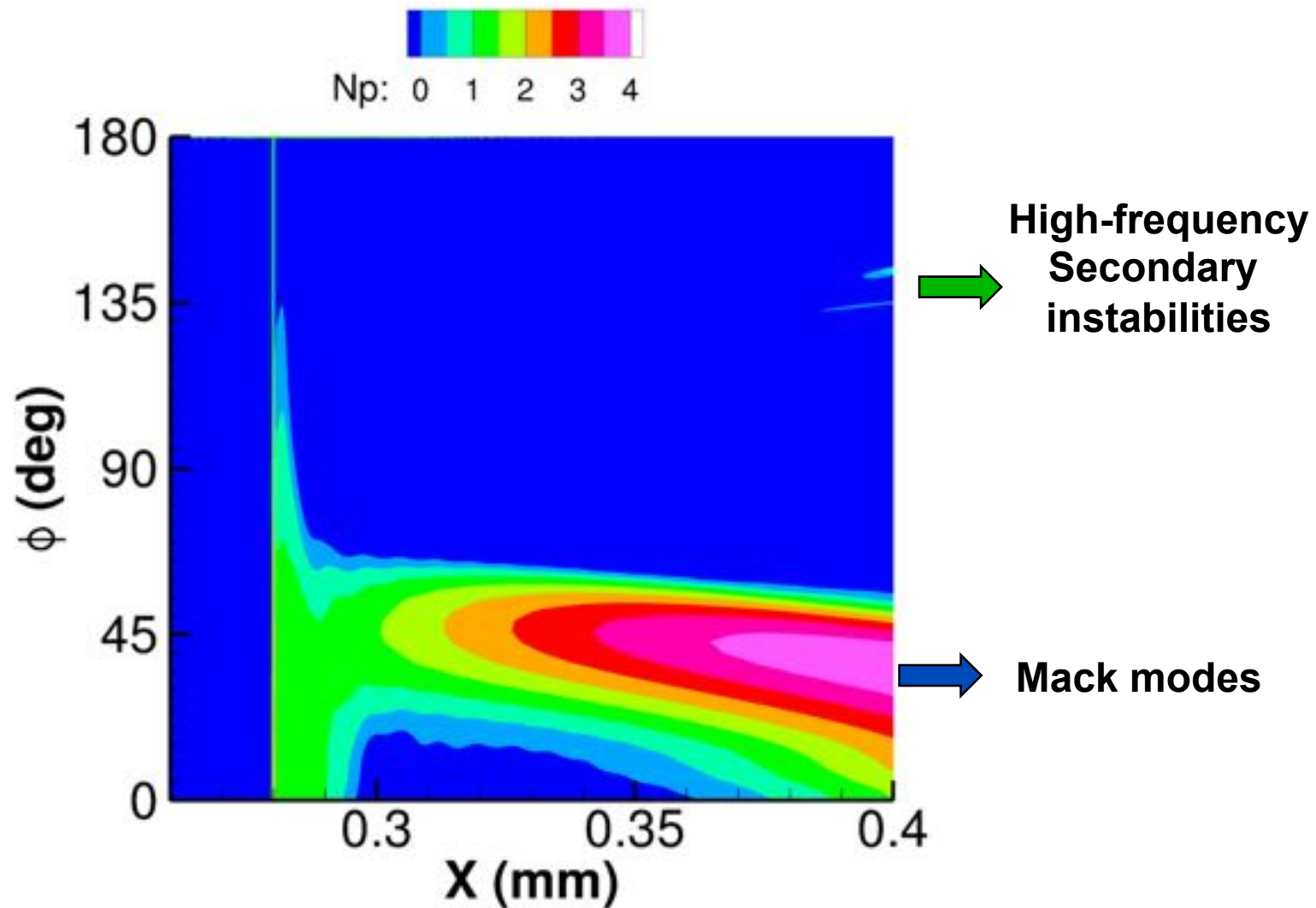


$|p'|$ Mode Shapes for Leeward Vortex: Mack Mode

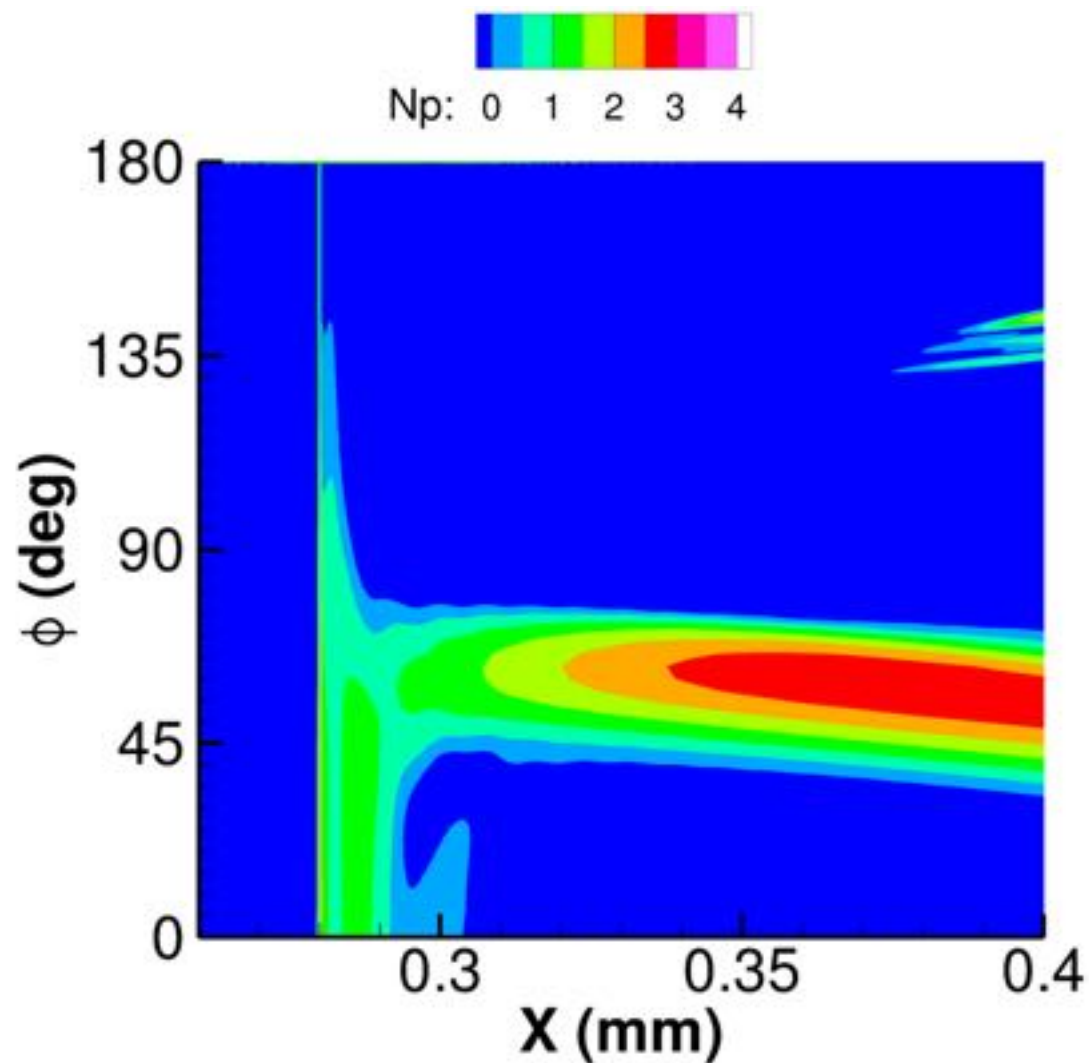


DNS Data

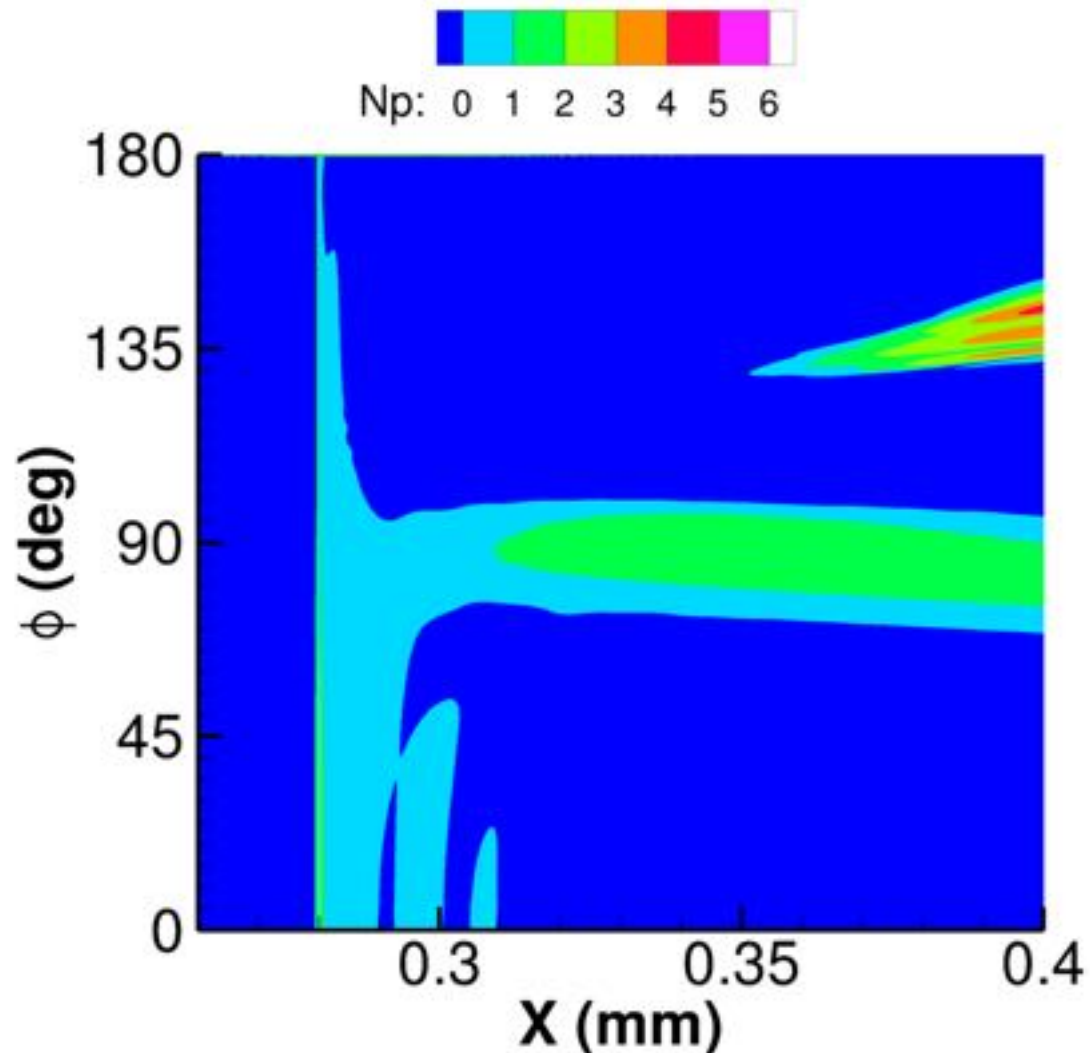
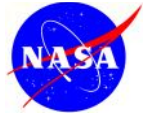
N-Factor Distribution: 440 kHz



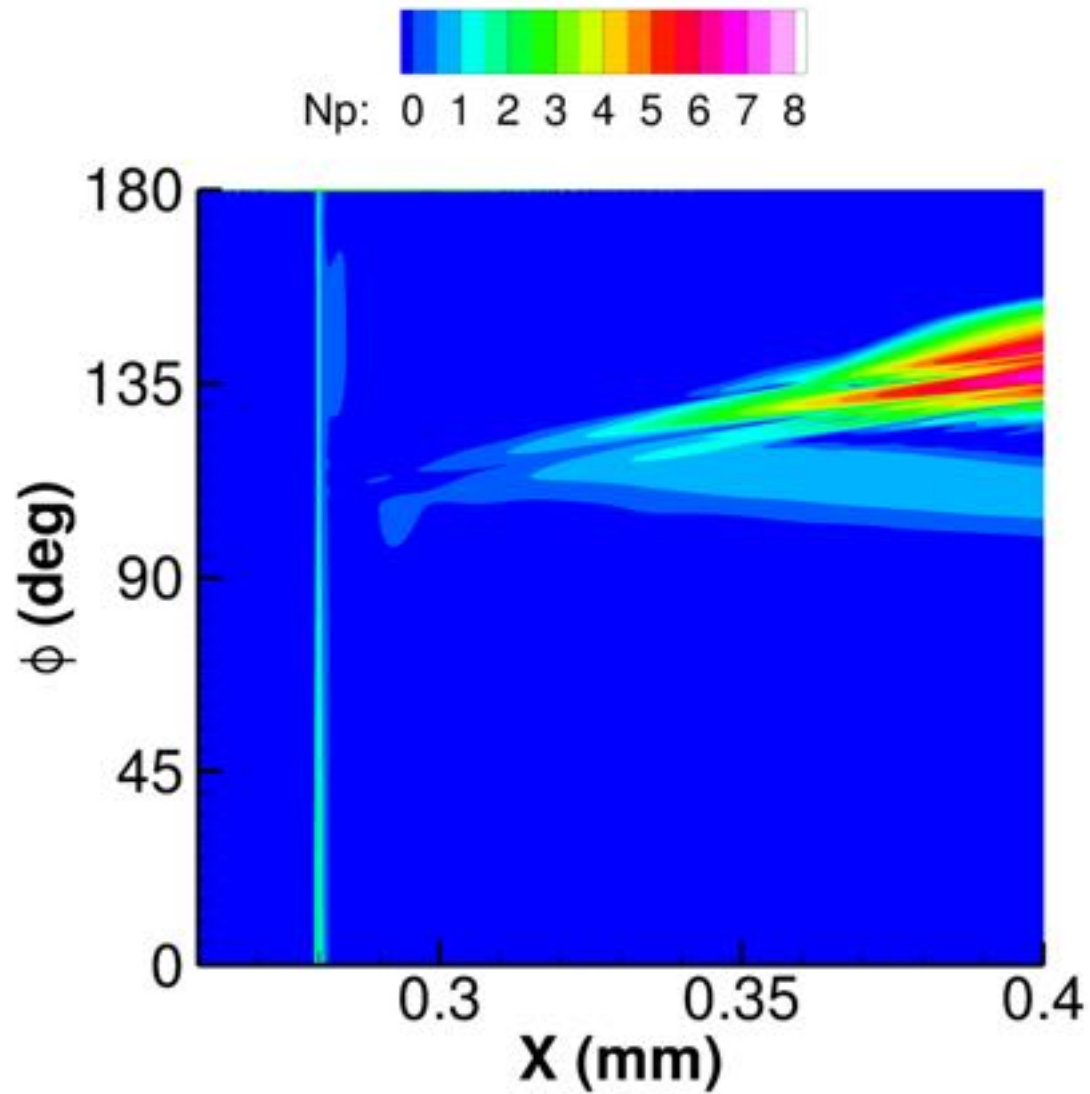
N-Factor Distribution: 400 kHz



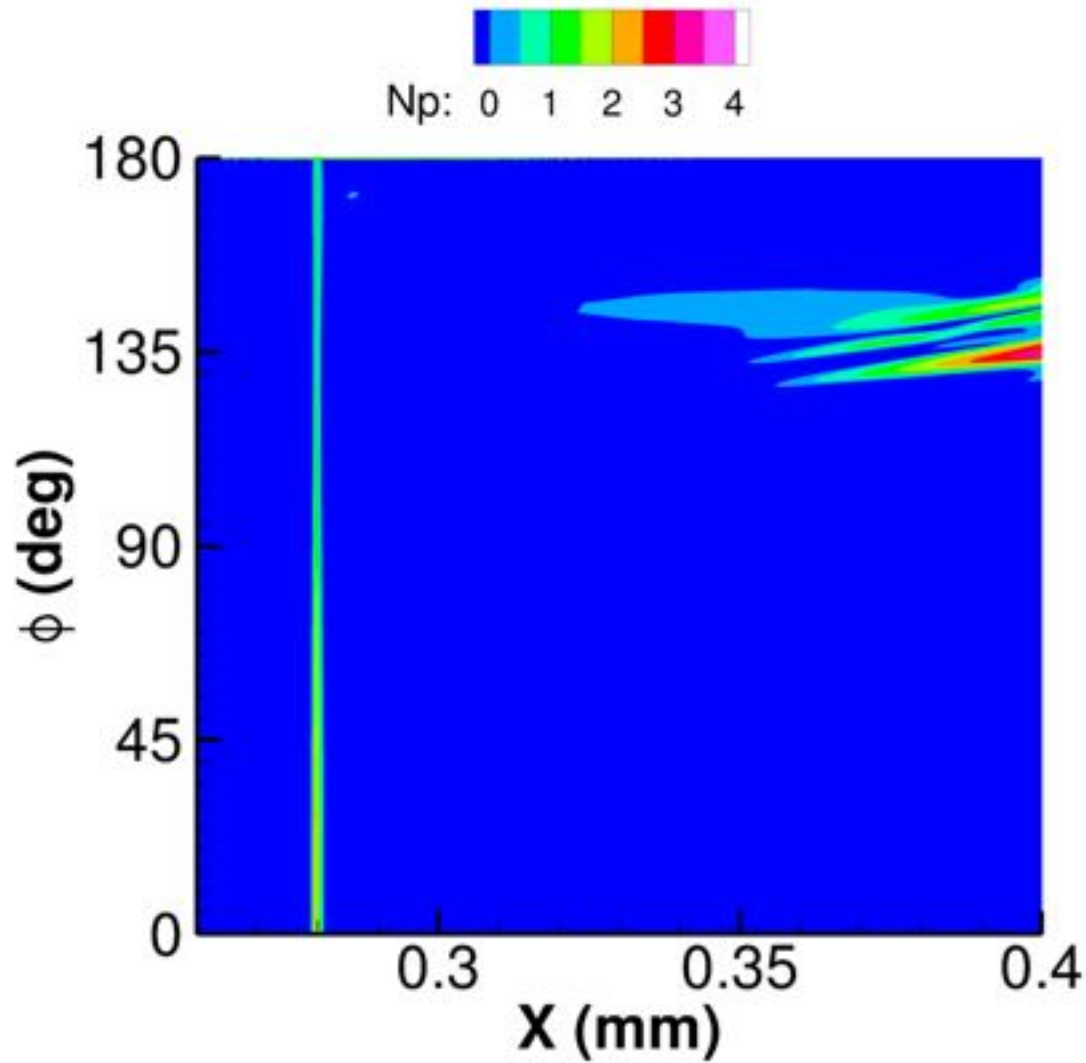
N-Factor Distribution: 320 kHz



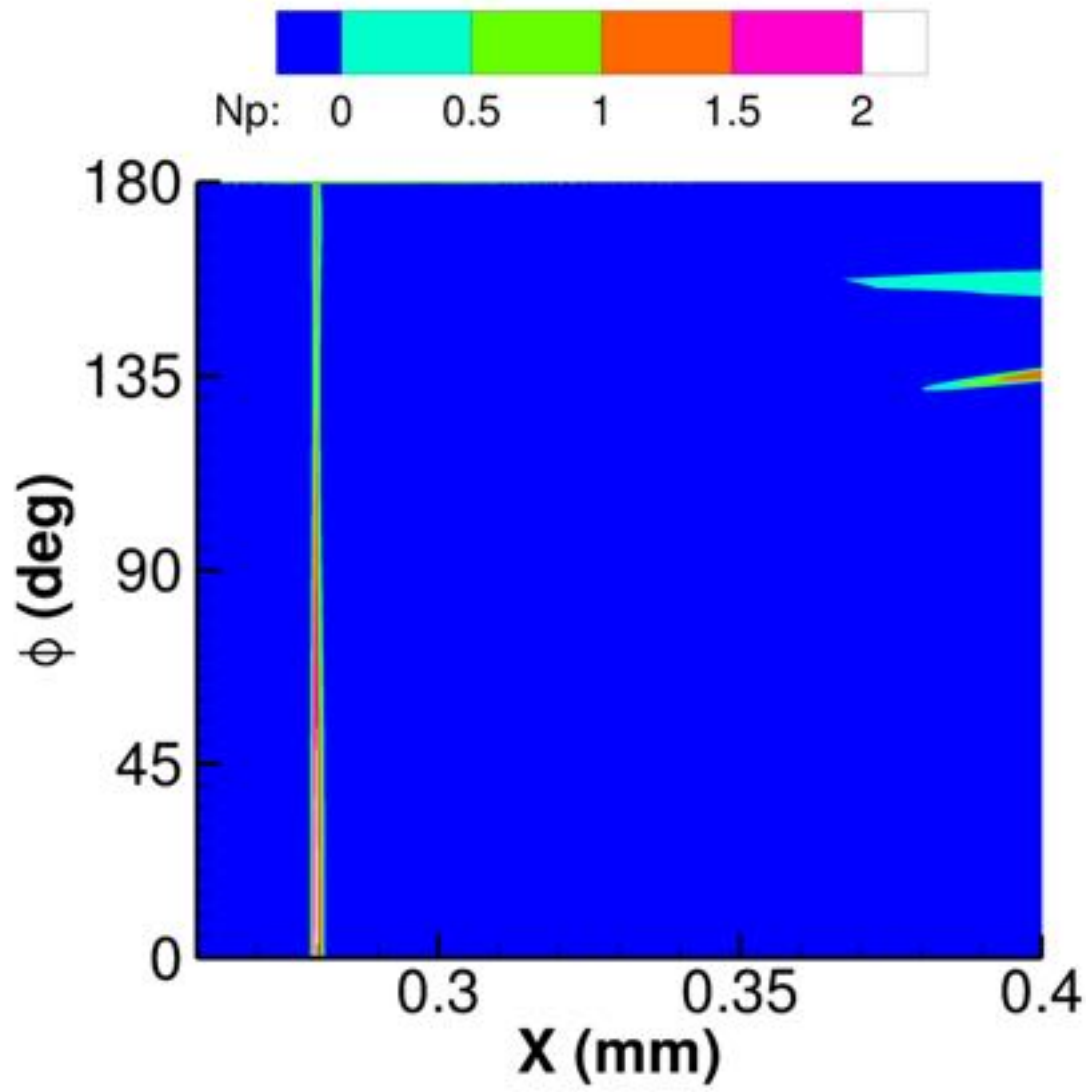
N-Factor Distribution: 240 kHz



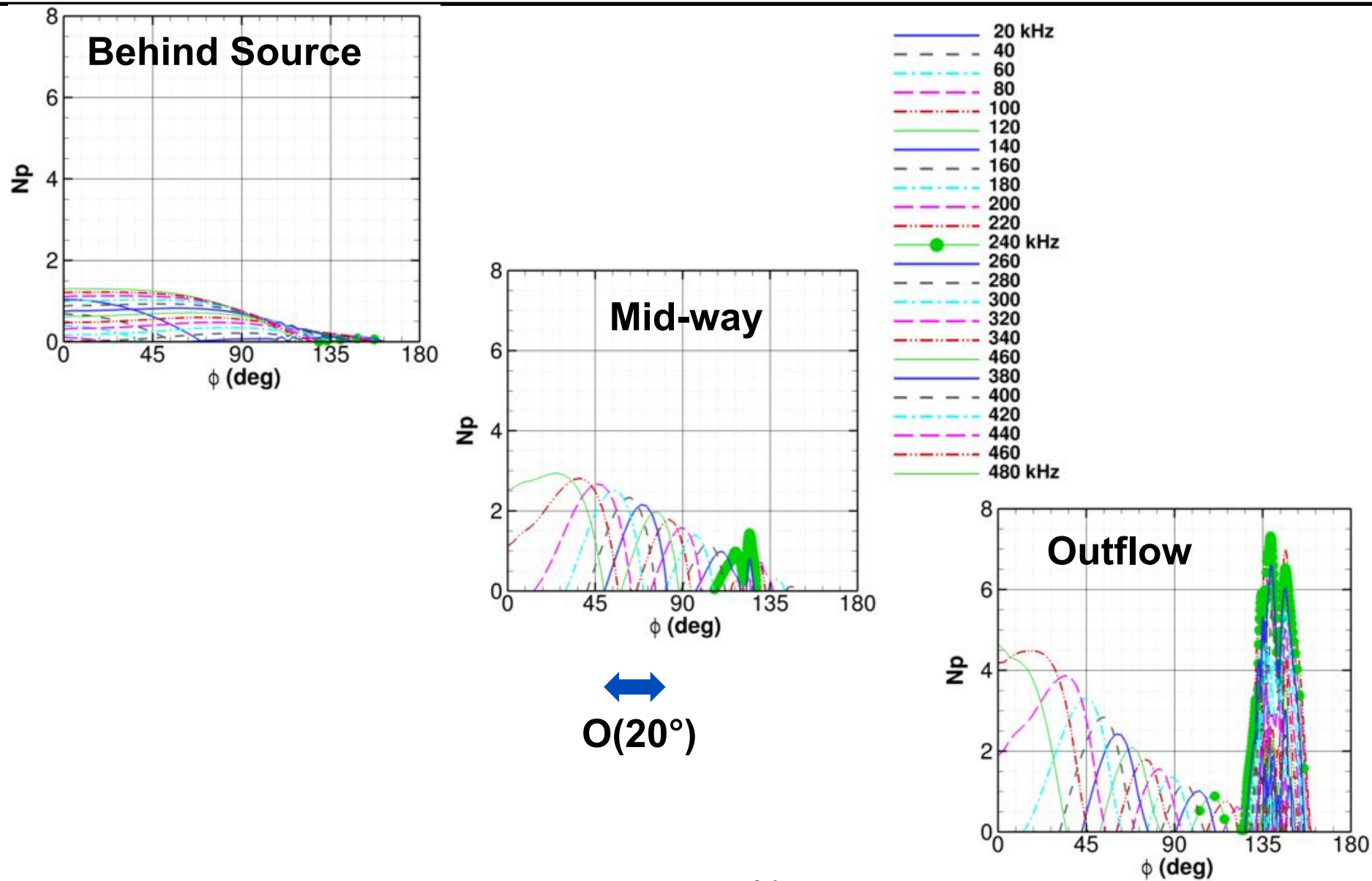
N-Factor Distribution: 160 kHz



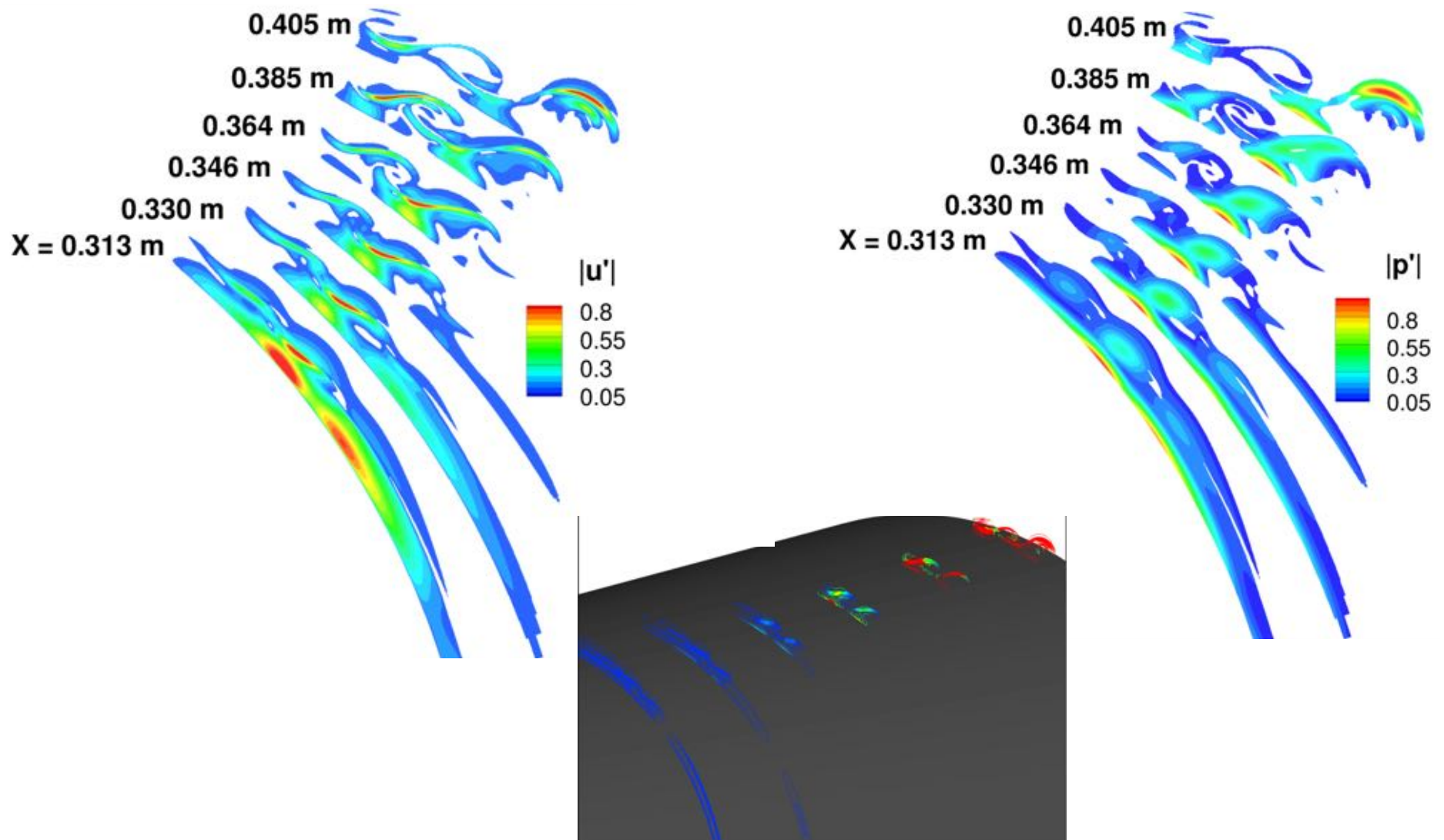
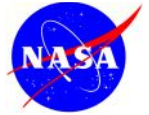
N-Factor Distribution: 120 kHz



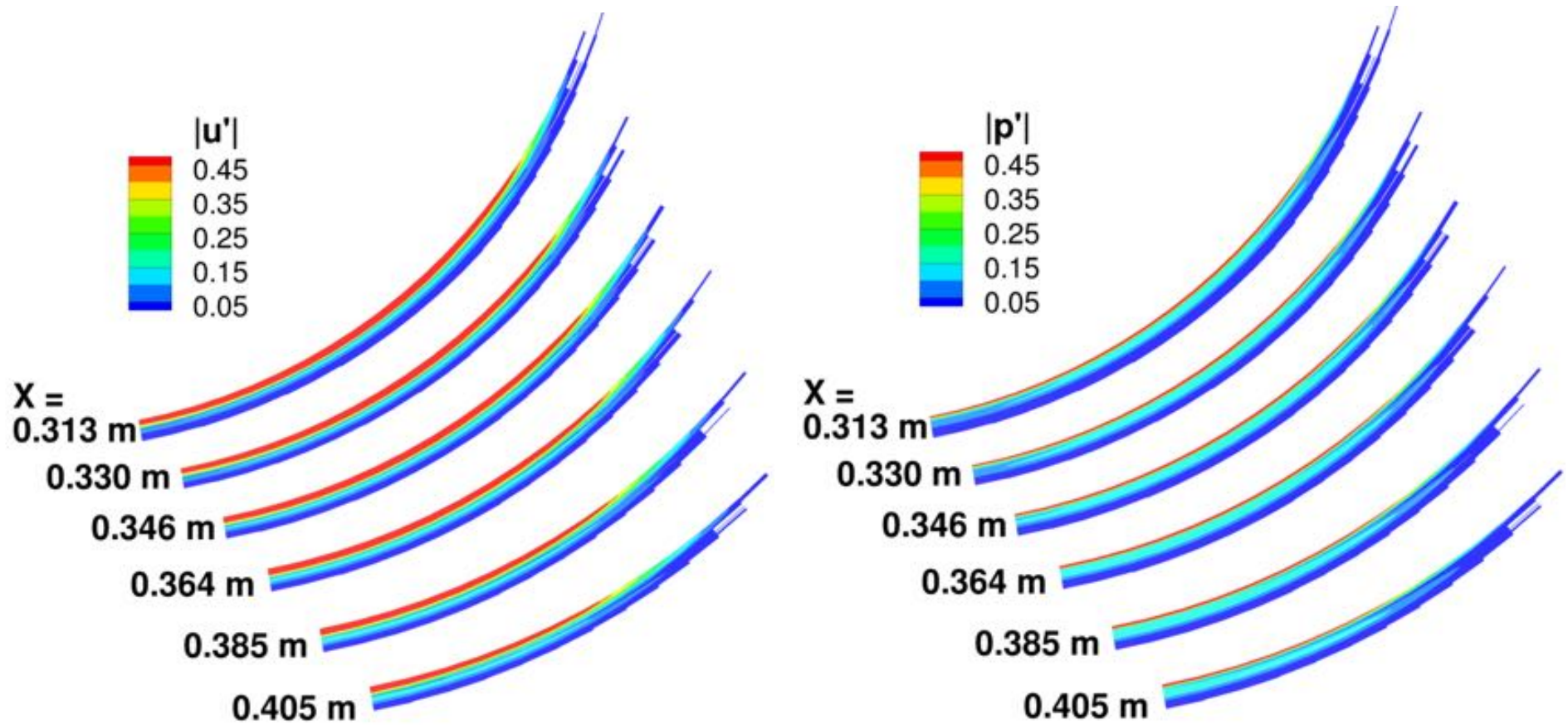
N-Factor Evolution



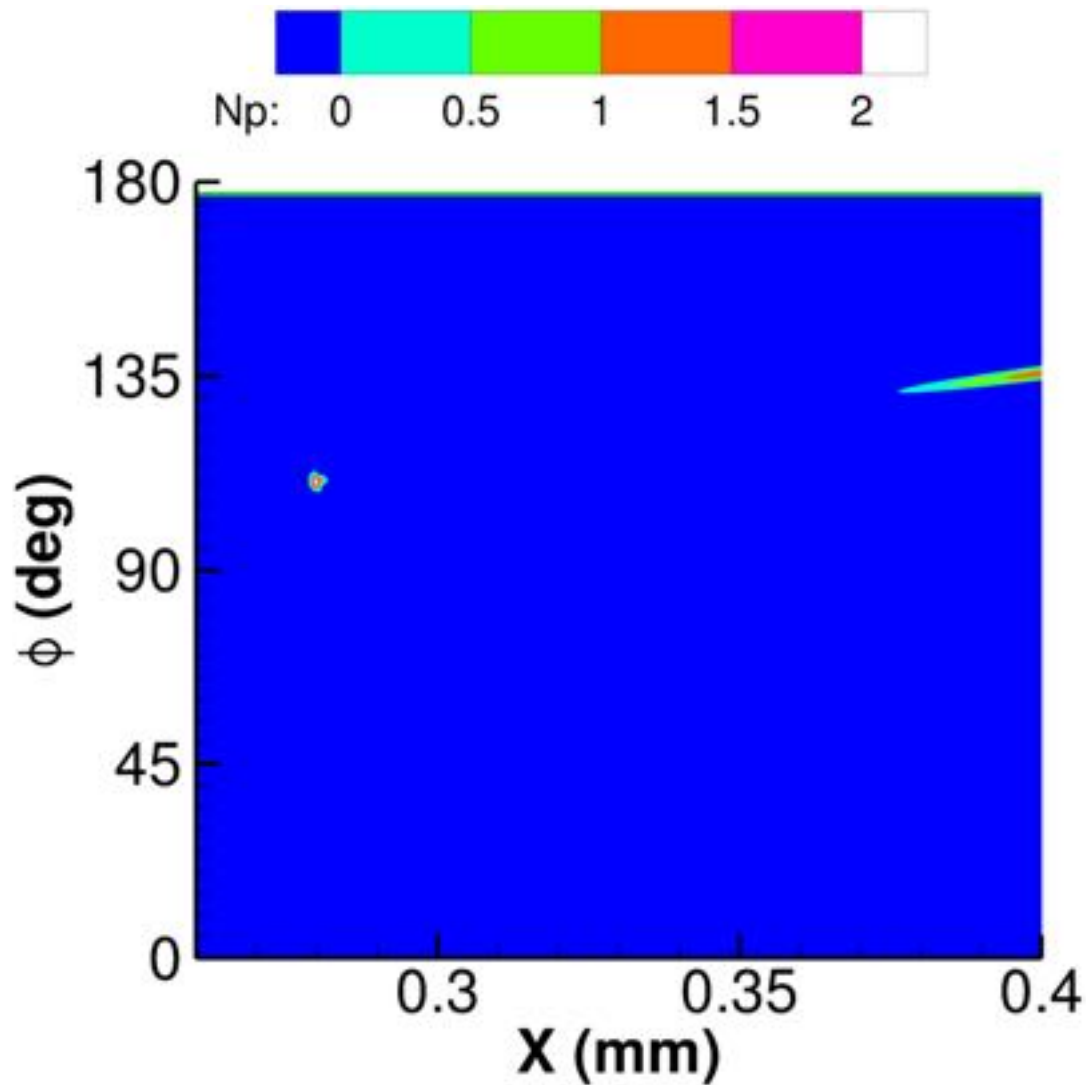
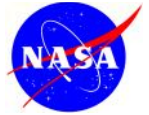
Mode Shape Evolution: 240 kHz



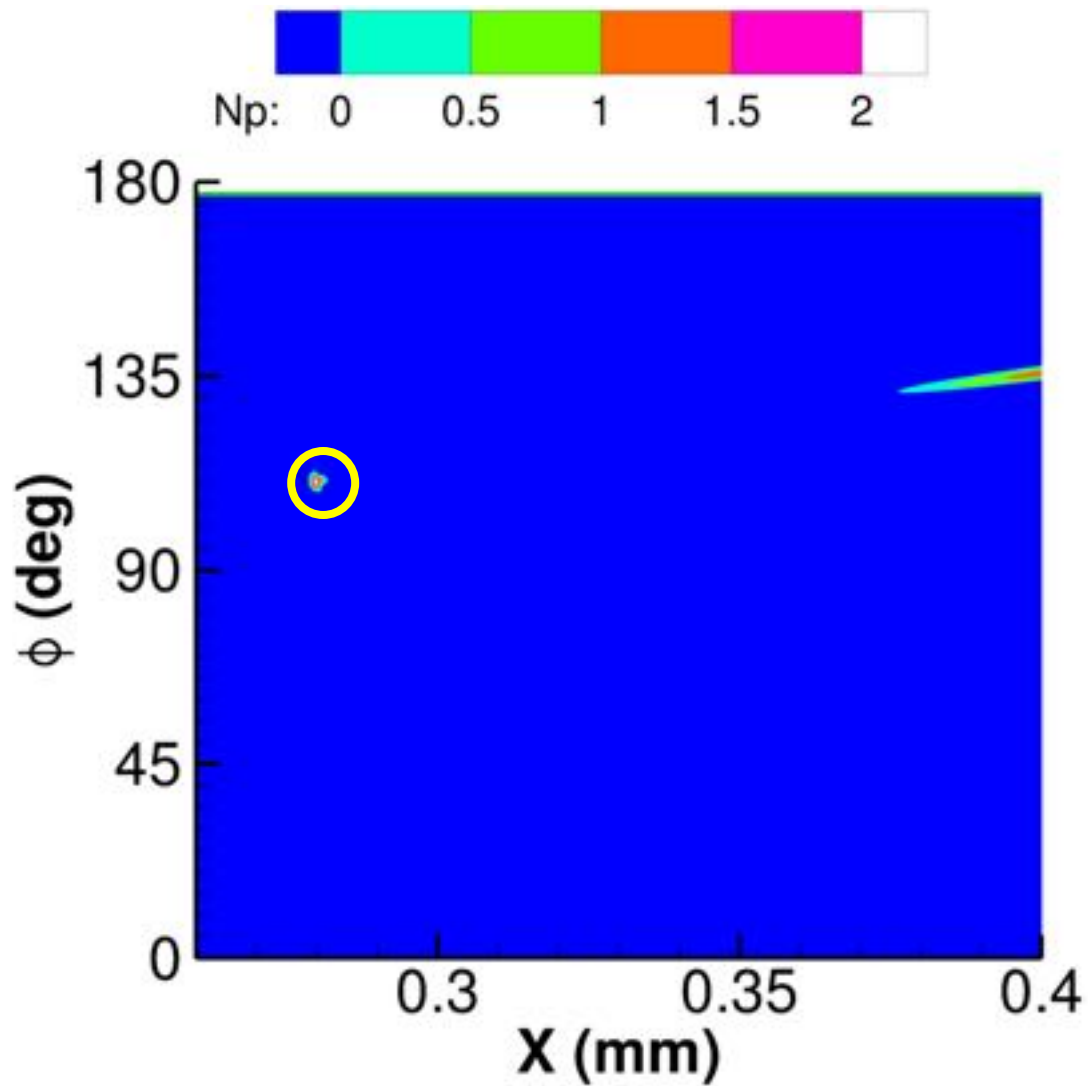
Mode Shape Evolution: 440 kHz



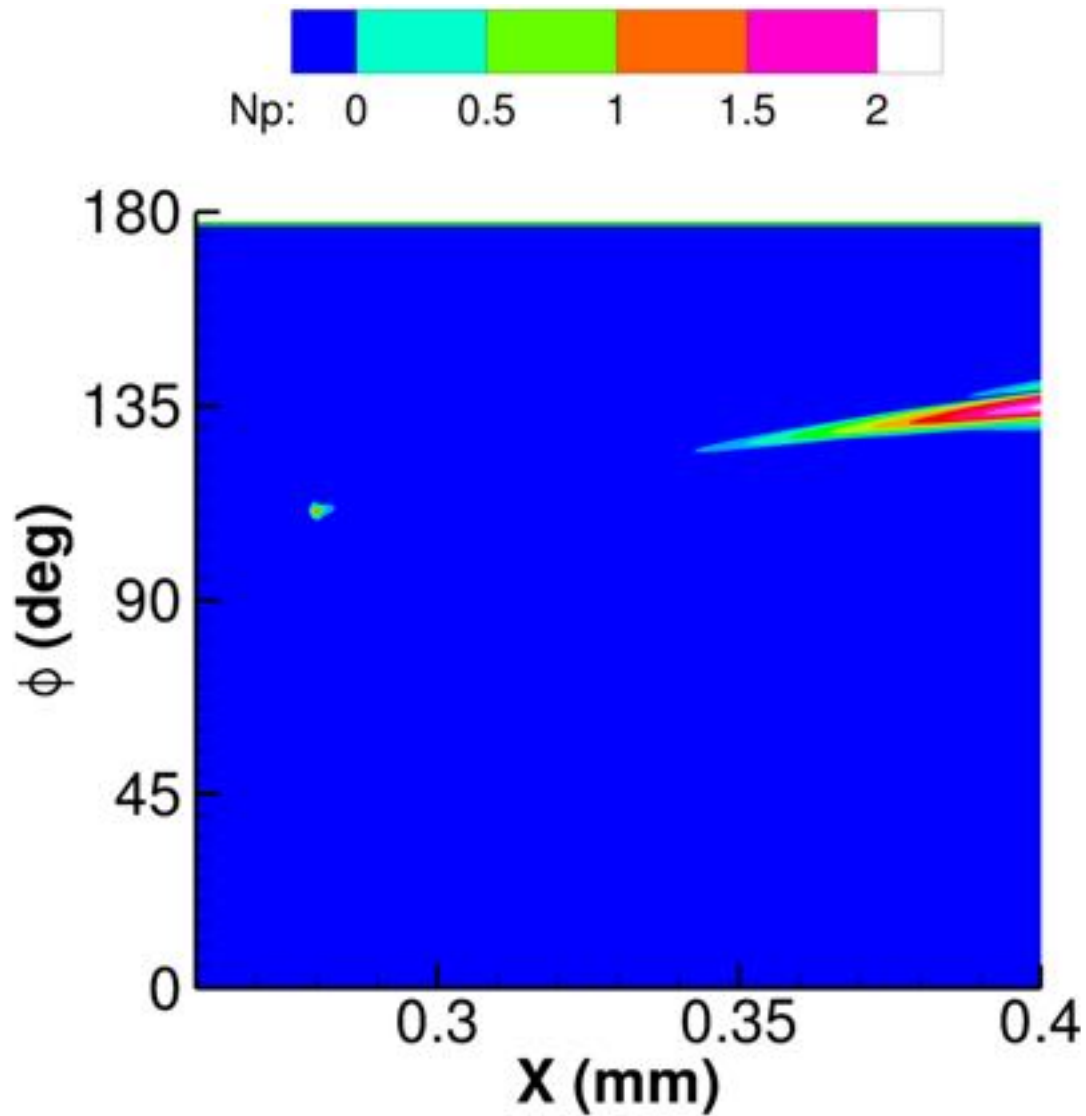
Localized Unsteady Forcing N-Factor Contours: 100 kHz



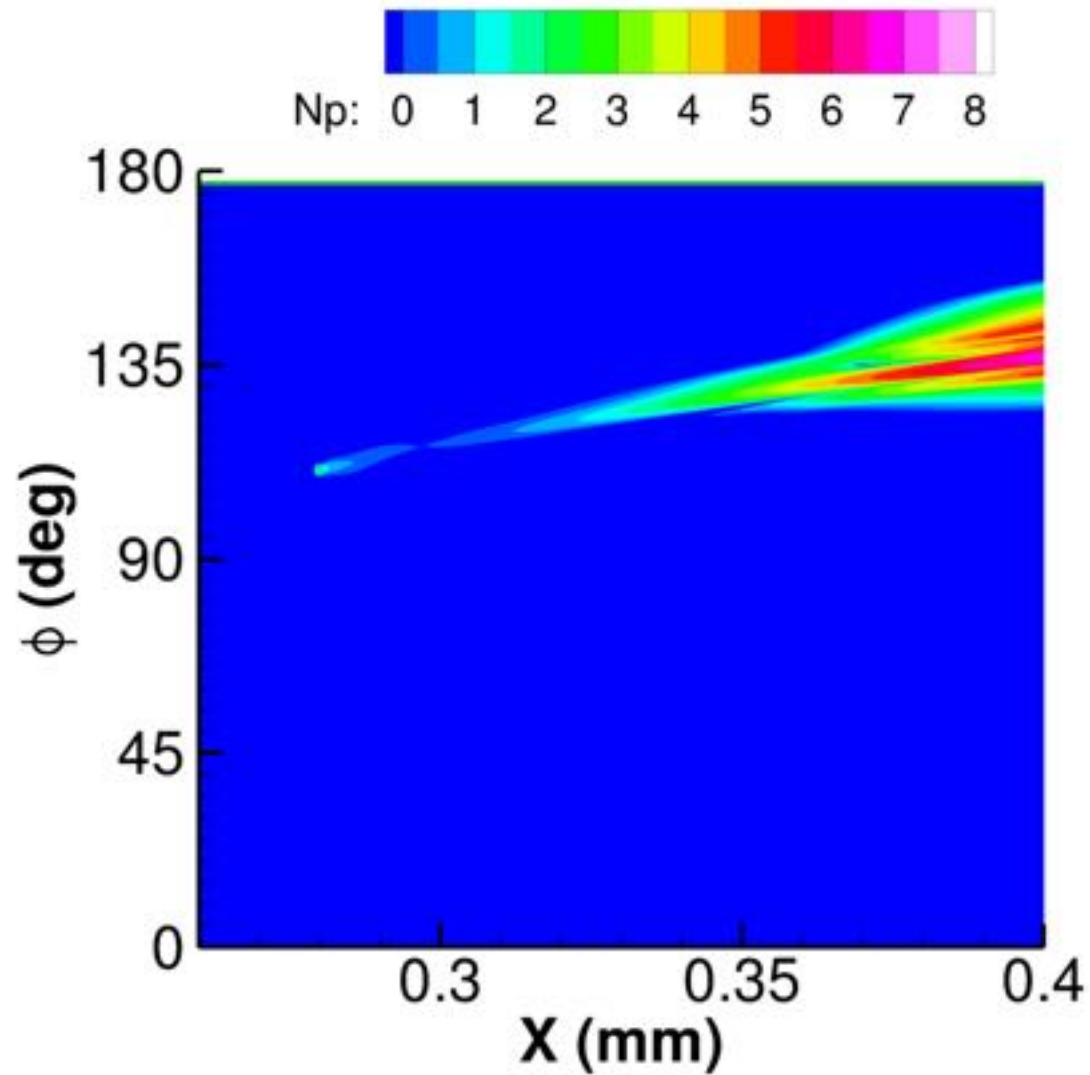
N-Factor Contours: 100 kHz



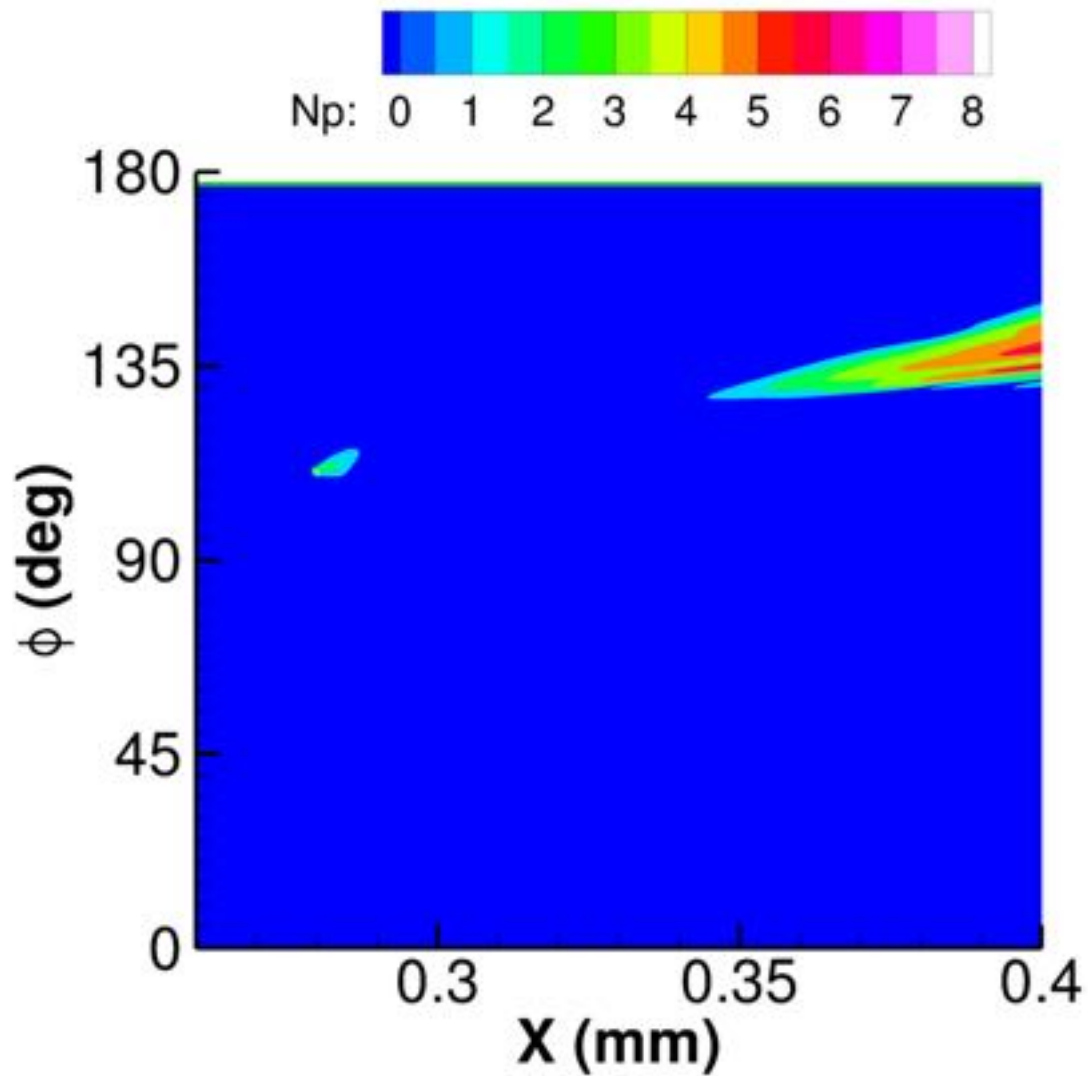
N-Factor Contours: 160 kHz



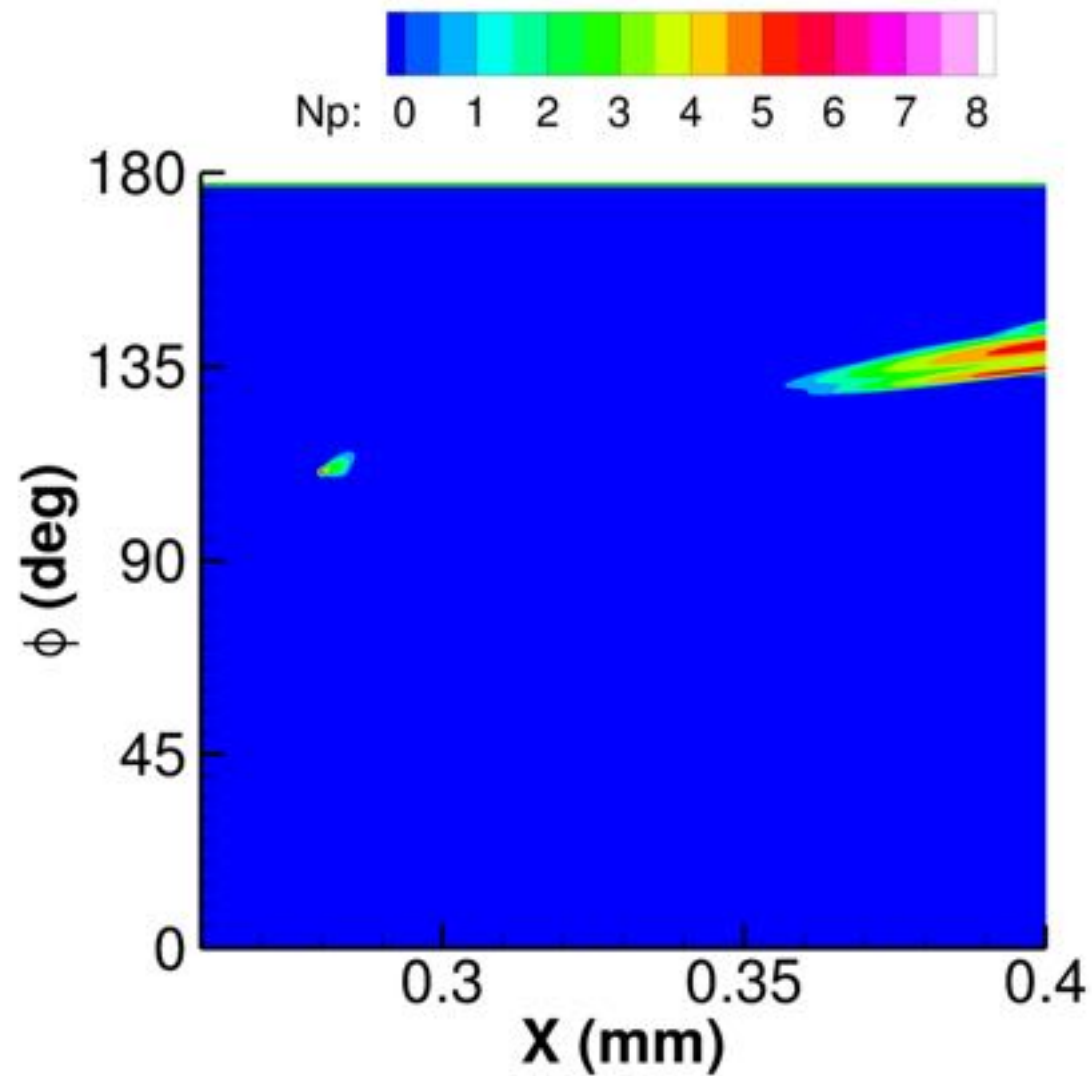
N-Factor Contours: 240 kHz



N-Factor Contours: 320 kHz

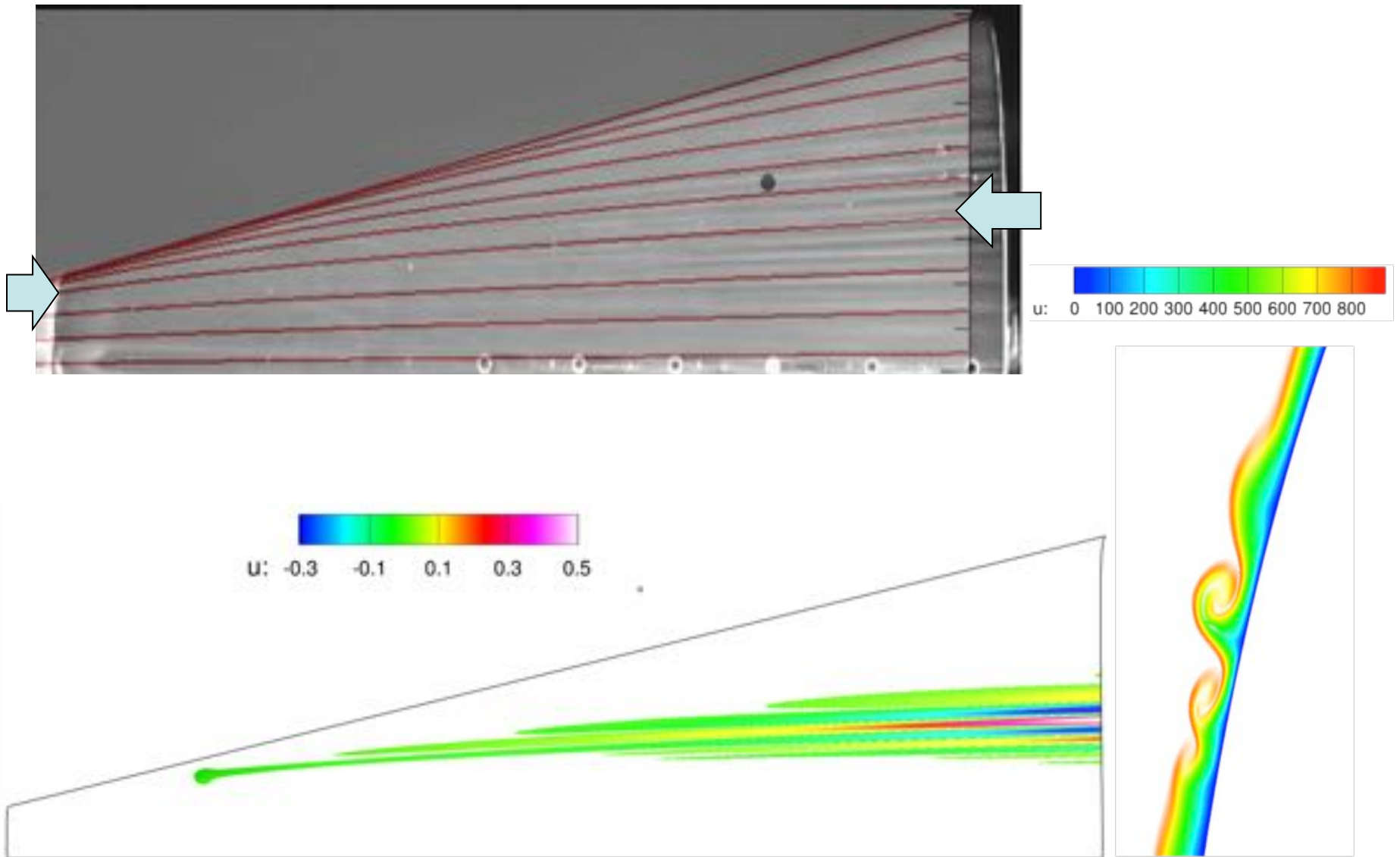


N-Factor Contours: 360 kHz

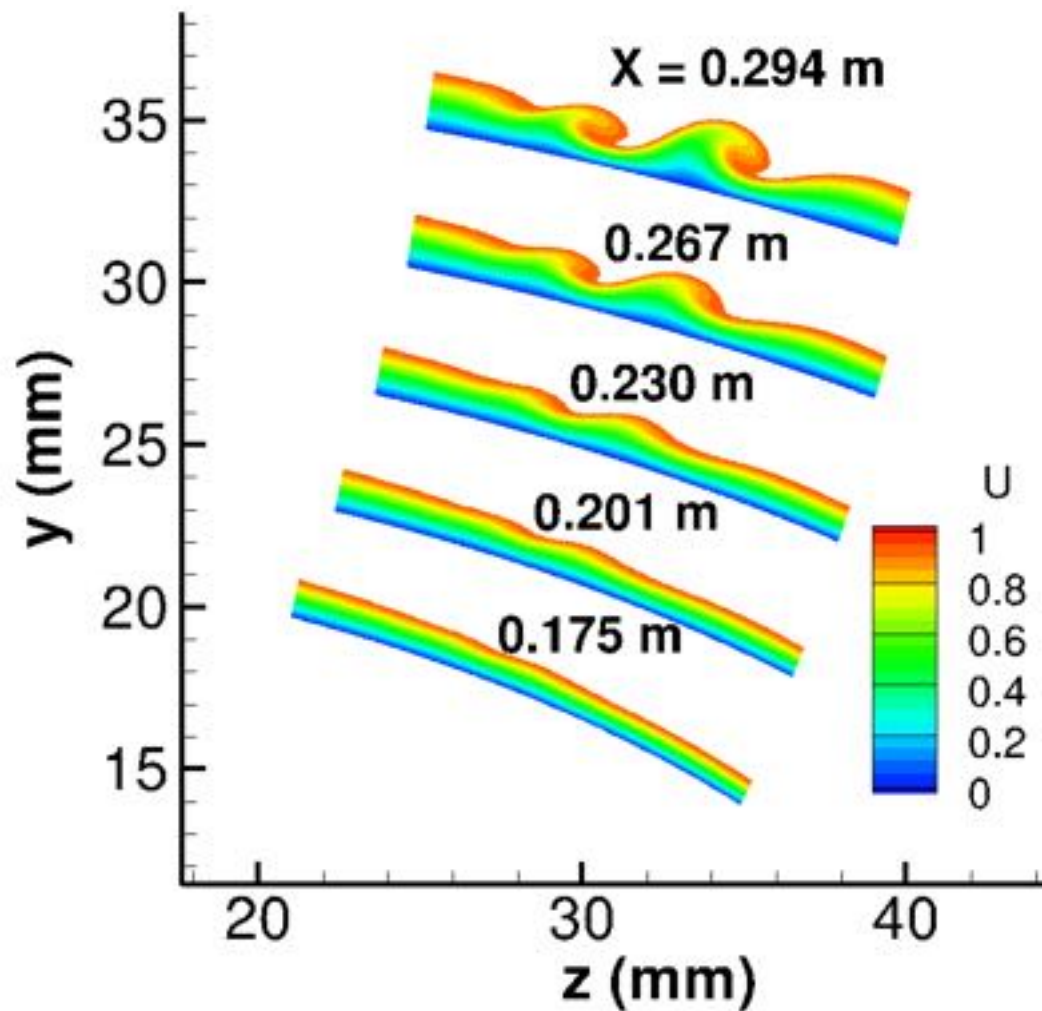




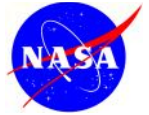
Pattern of Stationary Crossflow Vortices Due To Point Source



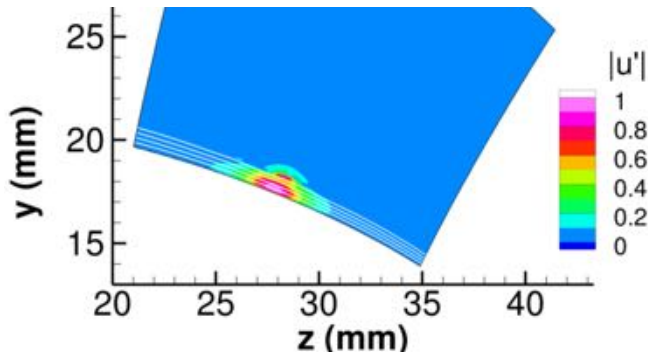
HIFiRE-5 Localized Source: Axial Velocity Contours



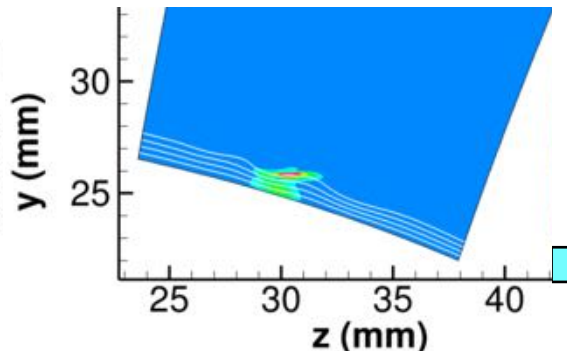
$|u'|$ Mode Shapes: Mack Mode



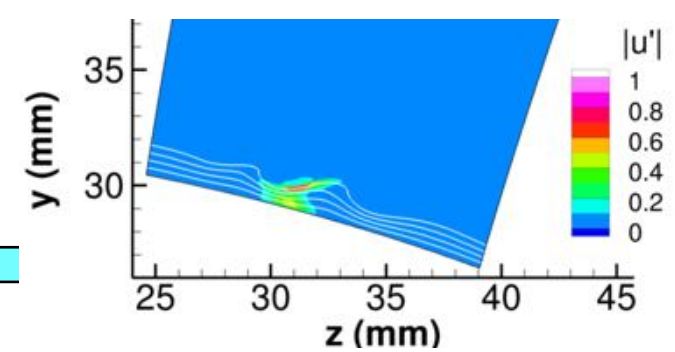
X = 0.175 m (310 kHz)



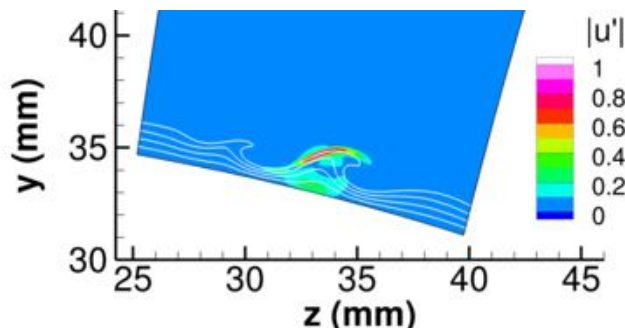
X = 0.230 m (280 kHz)



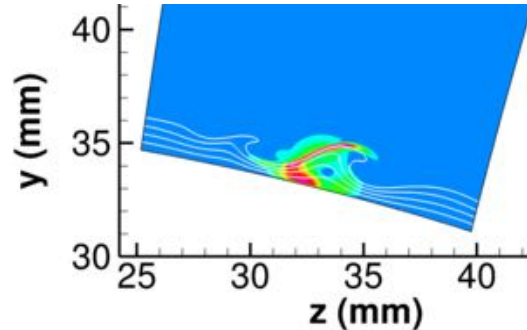
X = 0.267 m (290 kHz)



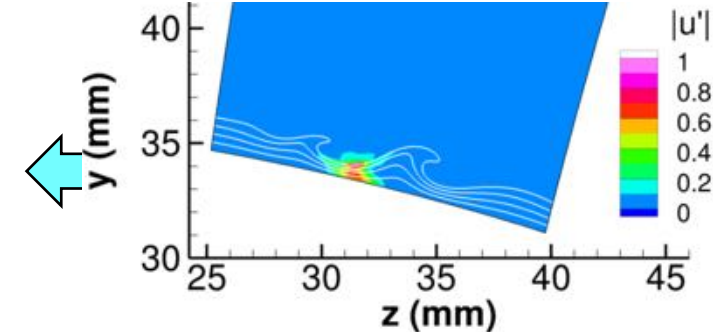
X = 0.294 m (200 kHz)



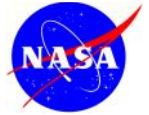
X = 0.294 m (260 kHz)



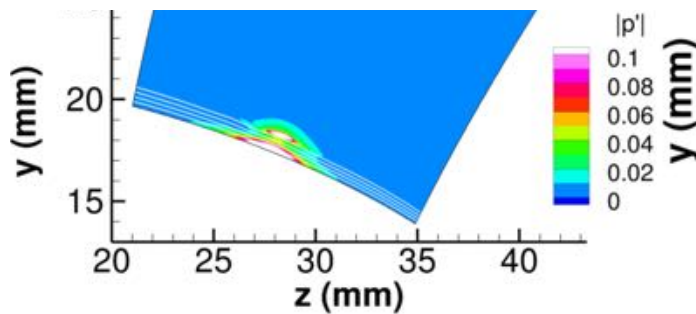
X = 0.294 m (350 kHz)



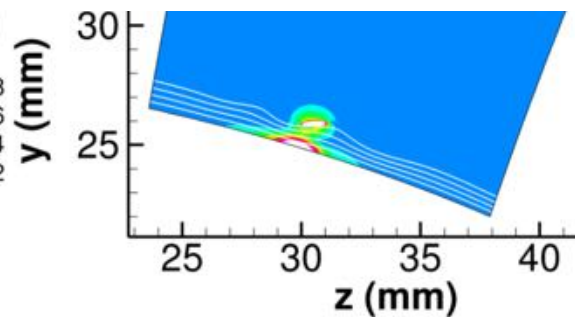
$|p'|$ Mode Shapes: Mack Mode



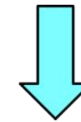
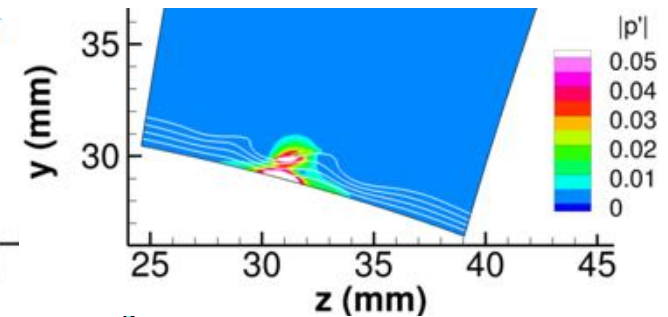
X = 0.175 m (310 kHz)



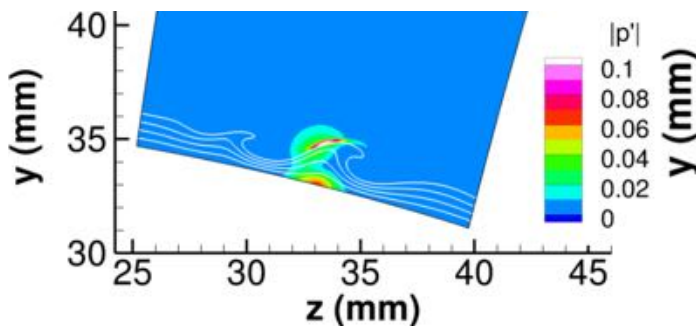
X = 0.230 m (280 kHz)



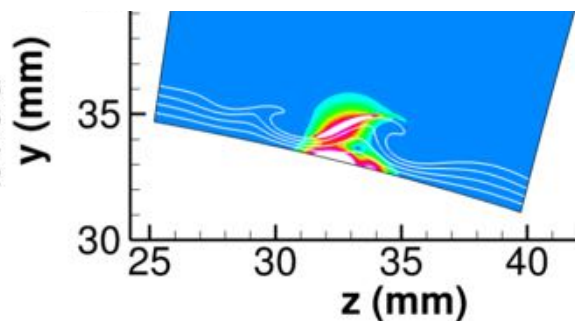
X = 0.267 m (290 kHz)



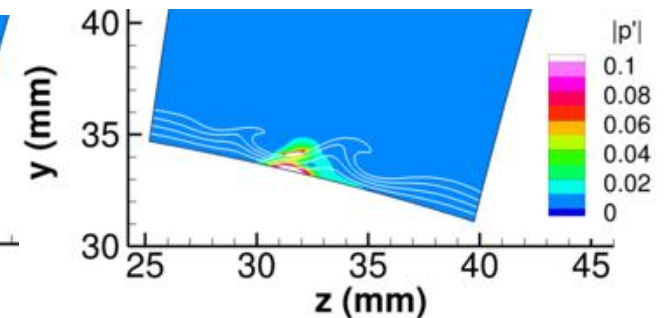
X = 0.294 m (200 kHz)



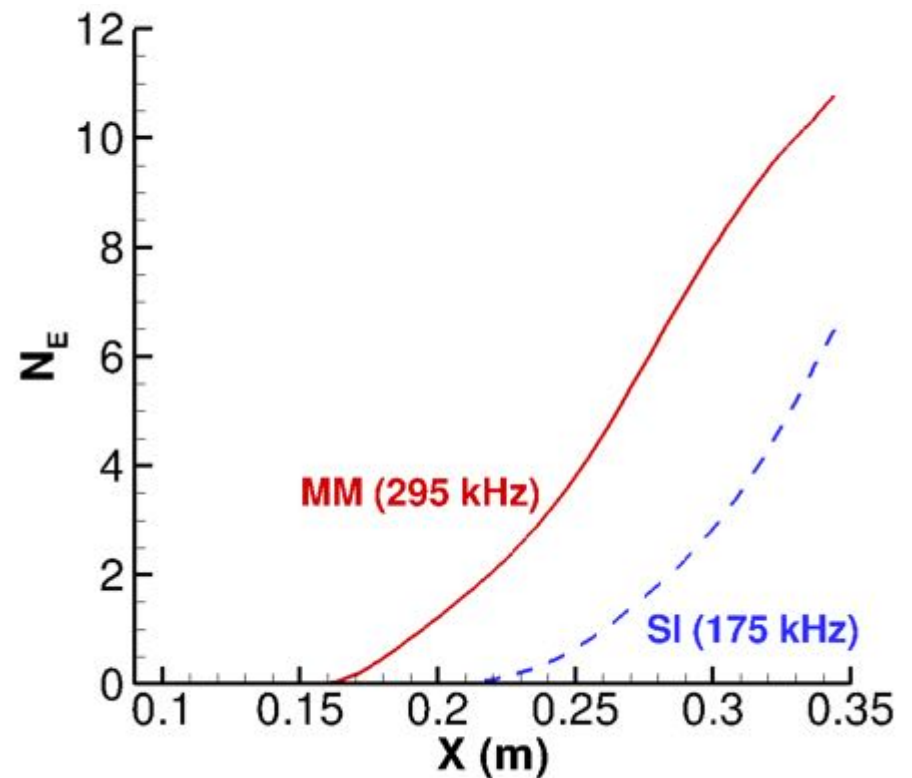
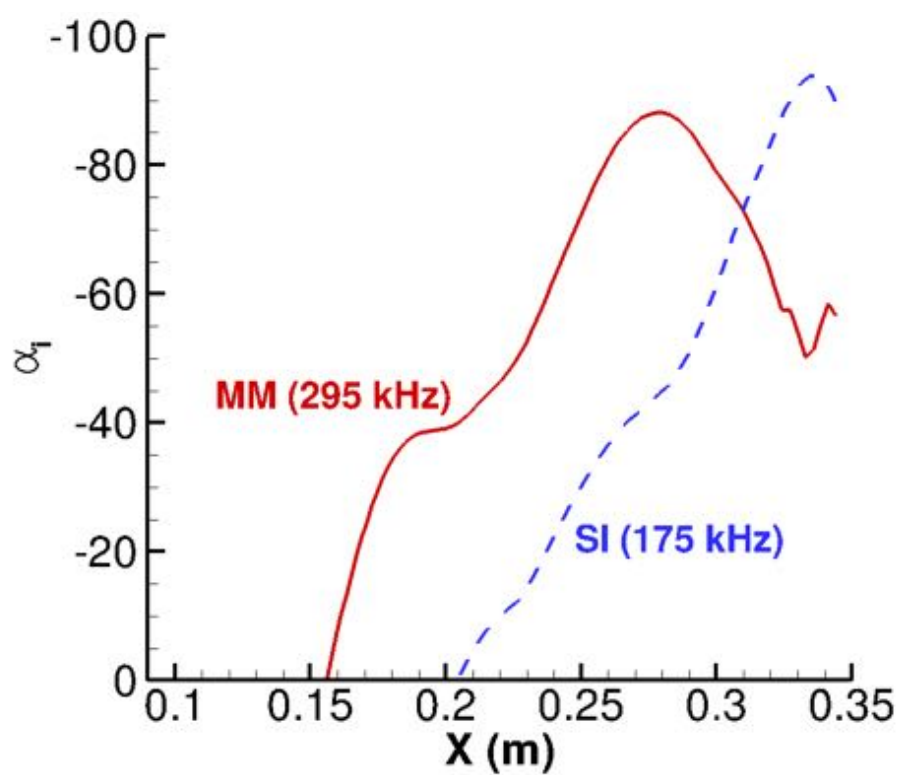
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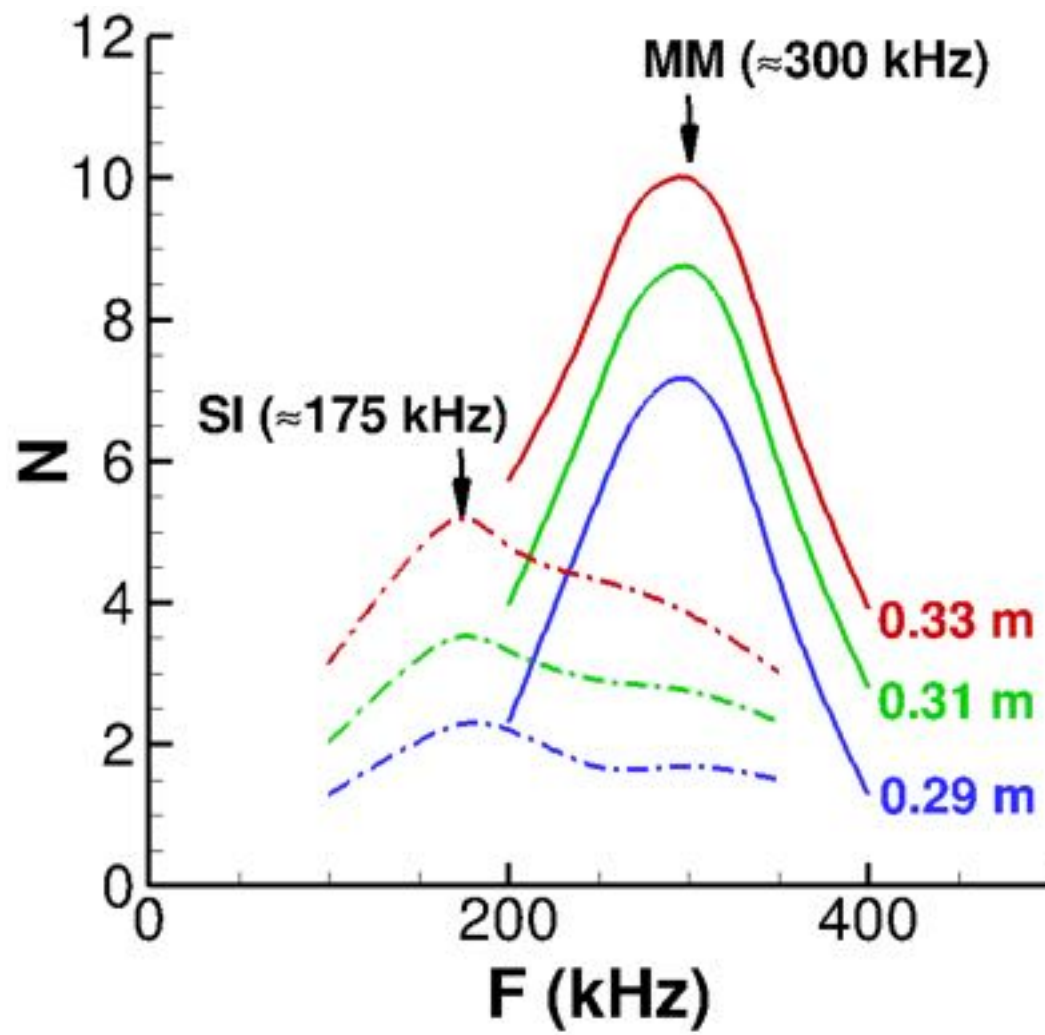
X = 0.294 m (350 kHz)



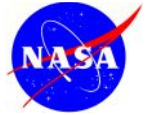
HIFiRE-5: Spatial Evolution



HIFiRE-5: N-factor Spectra

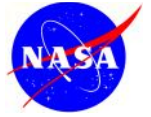


Summary



- DNS + secondary instability analysis for nonlinear evolution of crossflow disturbances over cones
 - Azimuthally compact vortex patterns over circular cone and HIFIRE5 model in BAMQT
- Simulated vortex structures resemble those from quasi-periodic vortex pattern
 - Provides conceptually easier path to interpret results from planar eigenvalue + PSE analysis for entire vortex pattern
- Secondary instability of compact crossflow vortex pattern
 - Mode shapes of dominant modes concentrated in individual vortices
 - Intricate modal structure with concentration of peak fluctuations along inclined shear layer ("Z" modes) and b.l. edge in region of downwelling
 - Modes along the top of the rolled up vortex generally subdominant
 - Broad range of frequencies with similar range as Purdue BAMQT measurements
- Disturbance evolution from DNS resembles predictions of secondary instability theory
 - Need to perform quantitative comparisons

Extra Charts : Circular Cone



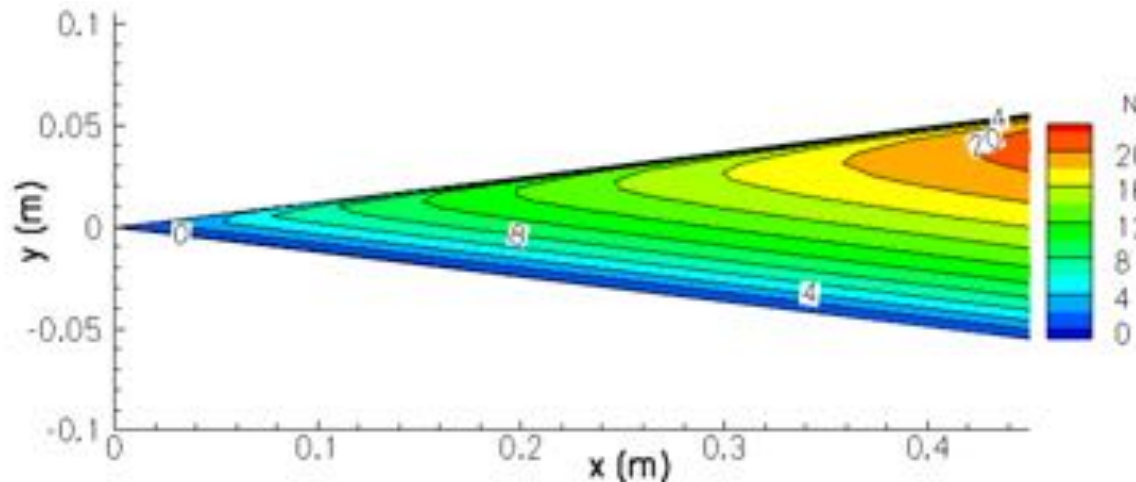


Stationary Crossflow Instability

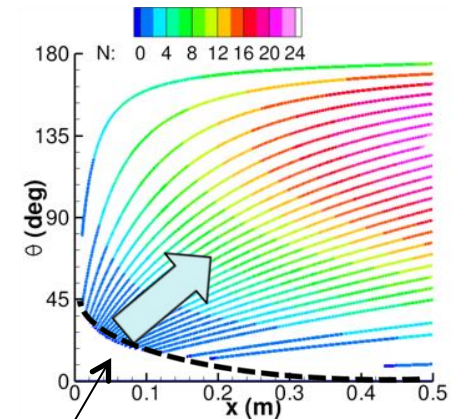
Li et al. (2010)

6 degree angle of attack

N-factor values over cone surface



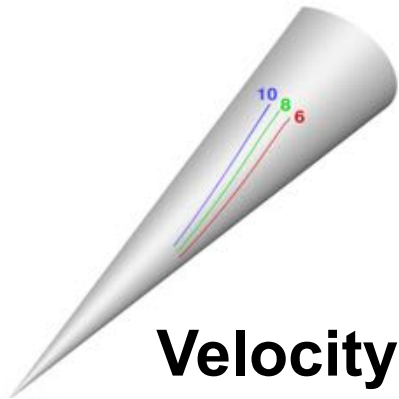
N-factor contours in x - θ plane
i.e., “**NSP**”



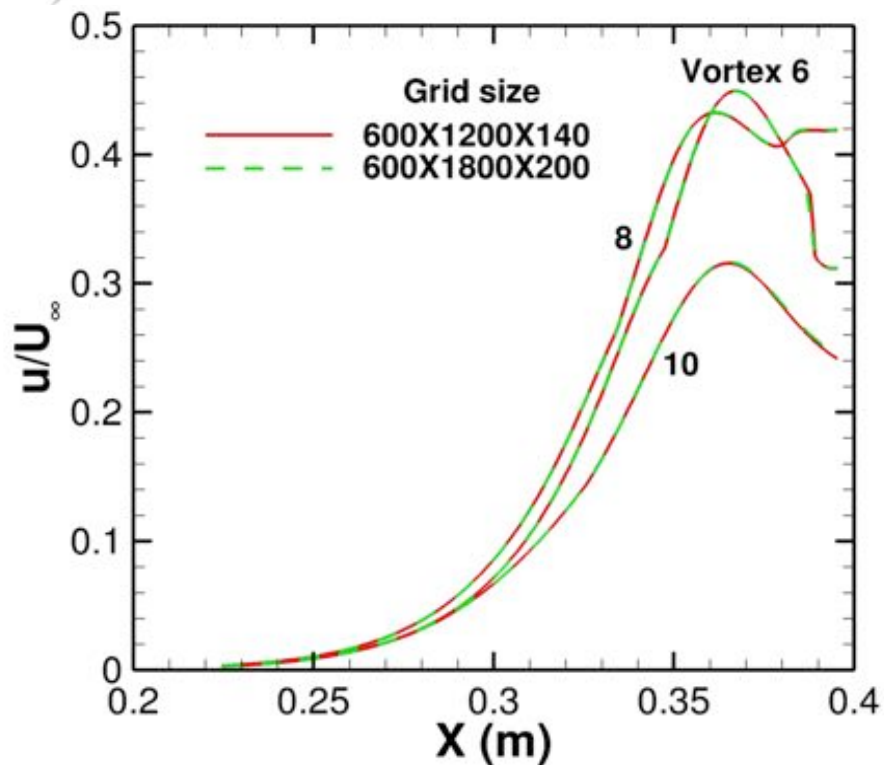
- Stationary crossflow modes are stable
- Roughness induced excitation likely to be less effective



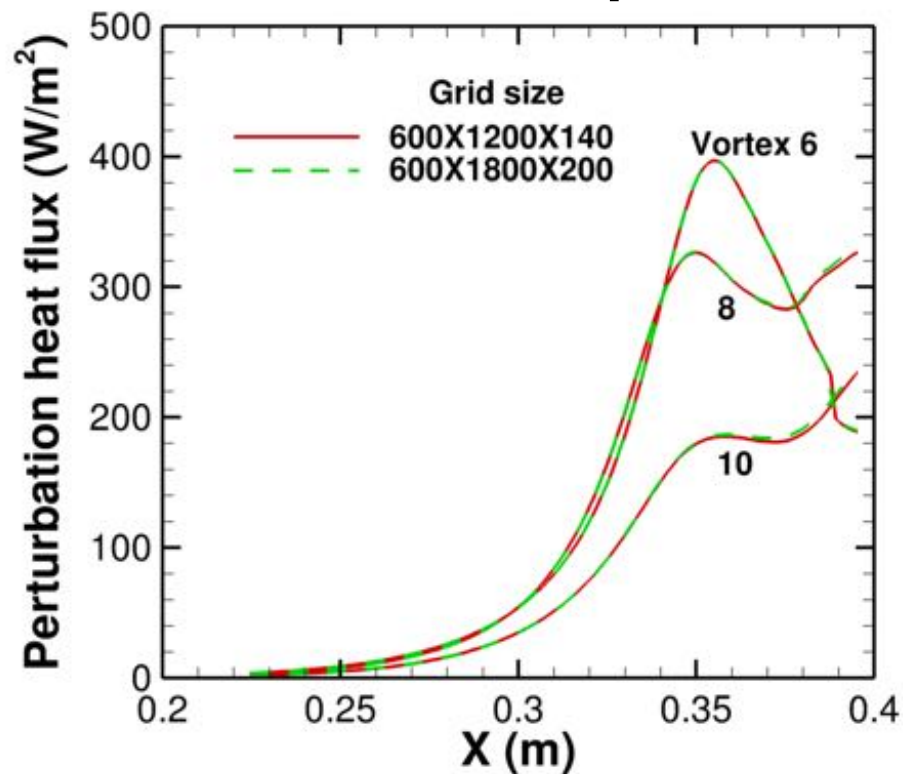
Evolution of Vortex Amplitudes



Velocity Amplitude

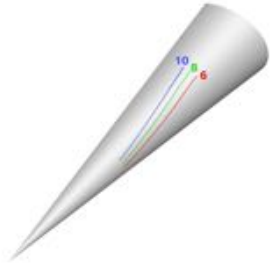


Heat-Flux Amplitude



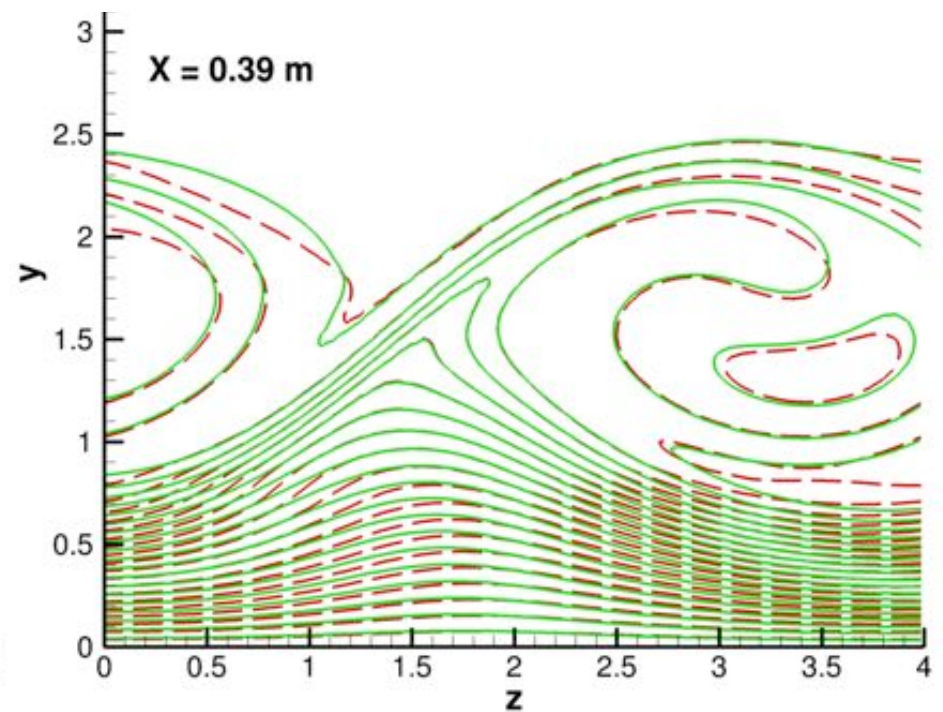
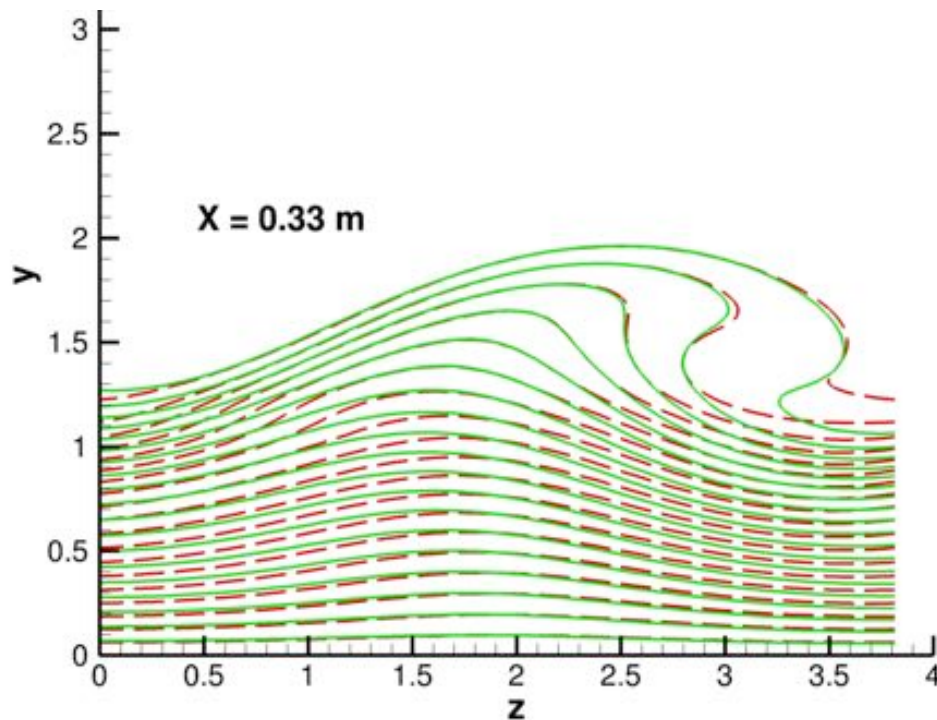


Quasi-periodic Approximation (V10)



Green, solid: actual basic state

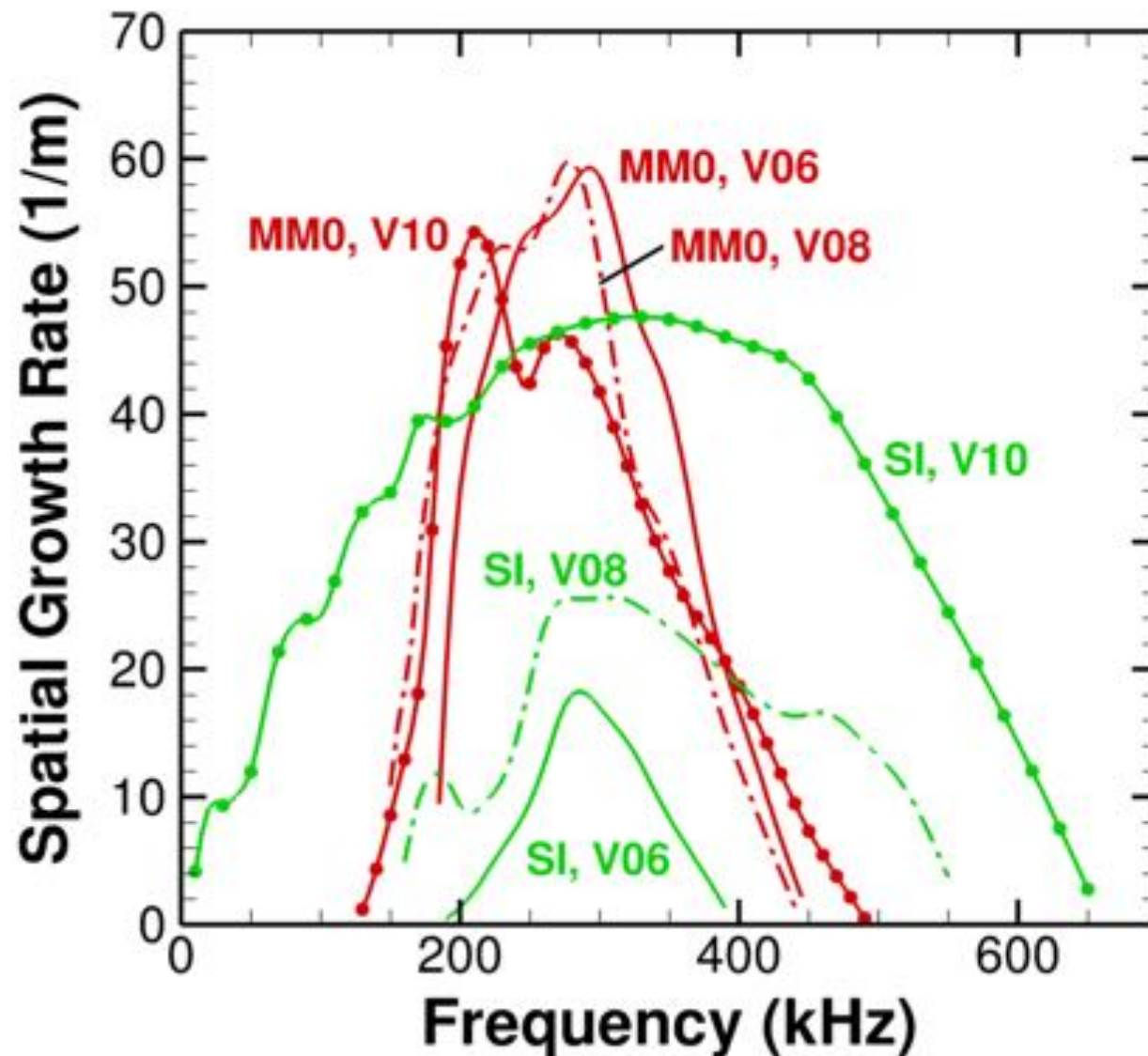
Red, dashed: quasi-periodic approximation





Azimuthal Variation of Growth Rate Spectra

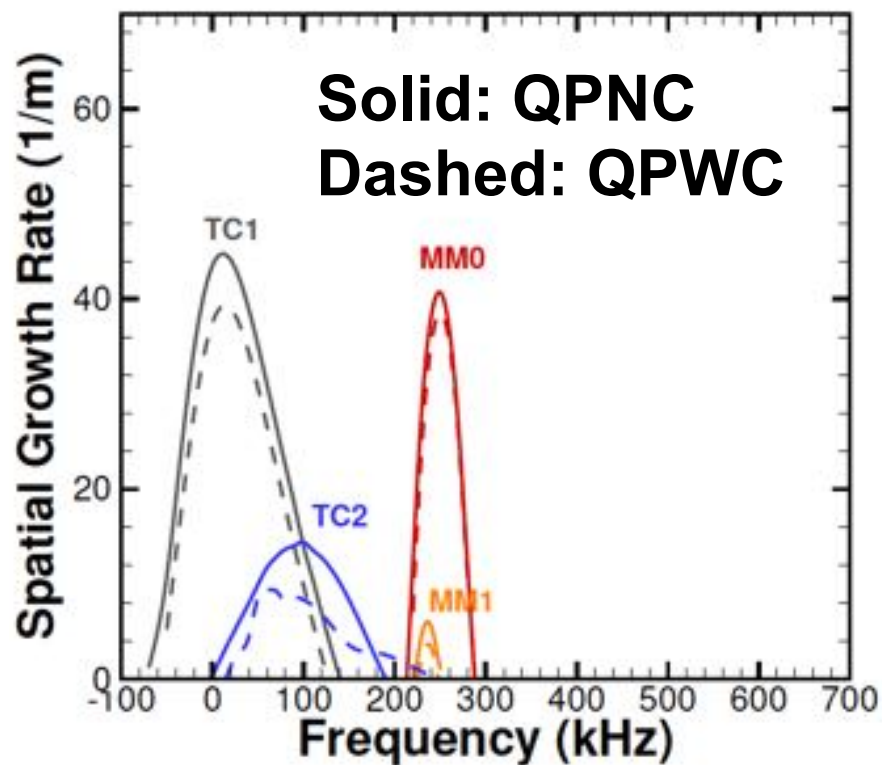
$X = 0.33$ m



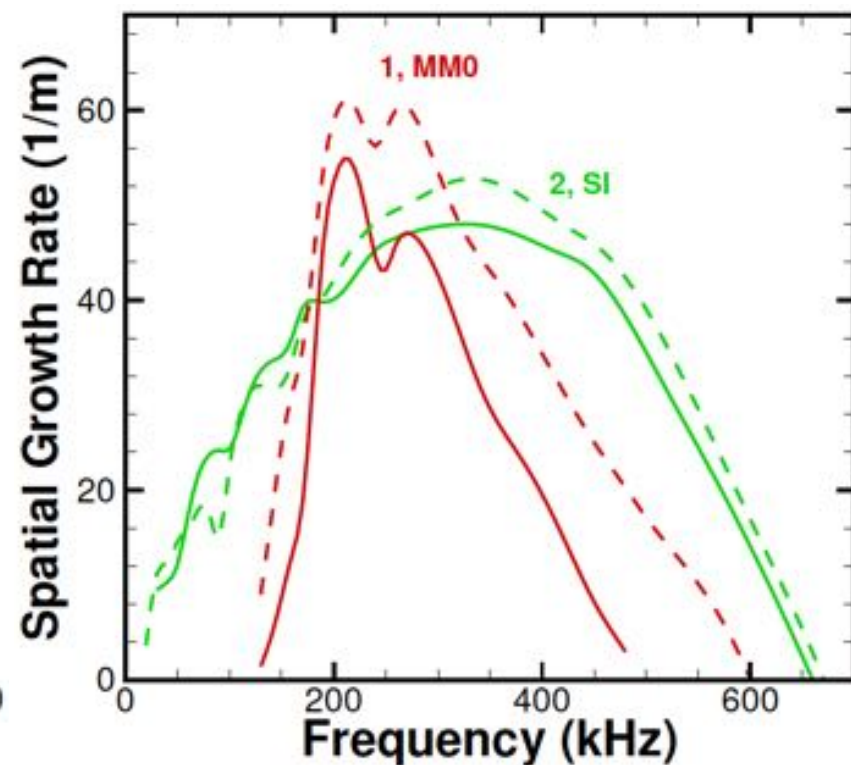


Effect of Transverse Curvature: Growth Rate Spectra

$X = 0.25$ m



$X = 0.33$ m



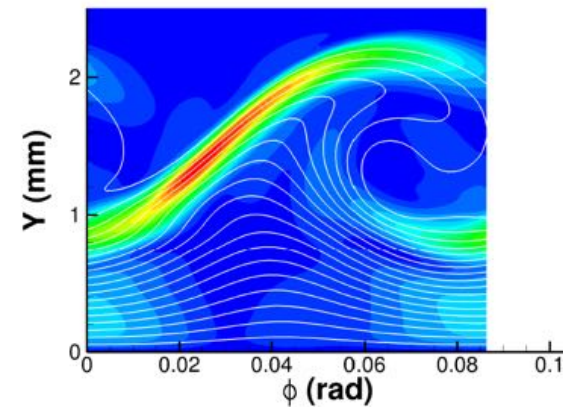
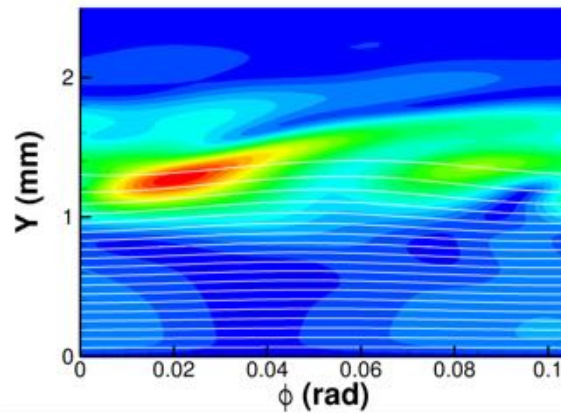


Effect of Transverse Curvature: MM0 Mode Shapes for $|u'|$

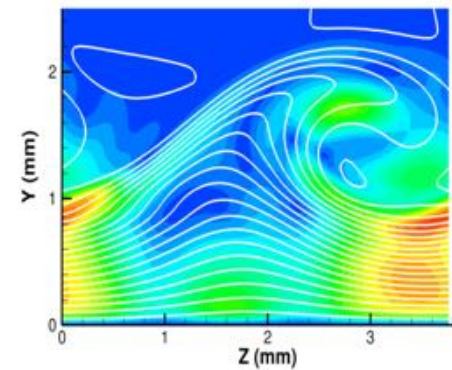
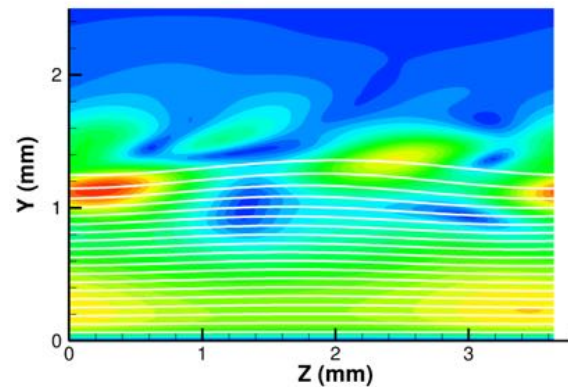
$X = 0.28$ m

$X = 0.35$ m

**QPWC
(260 kHz)**



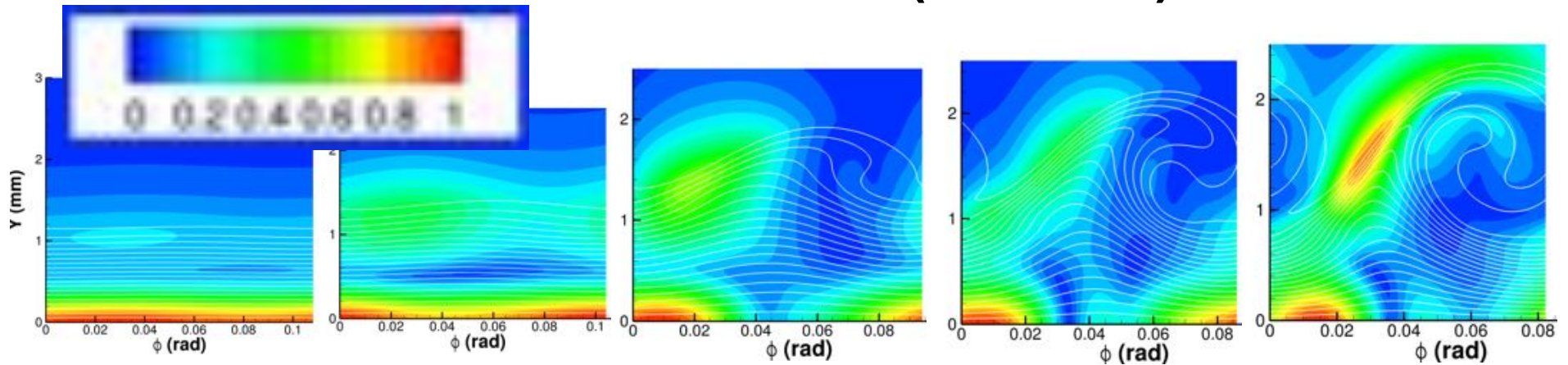
**QPNC
(235 kHz)**





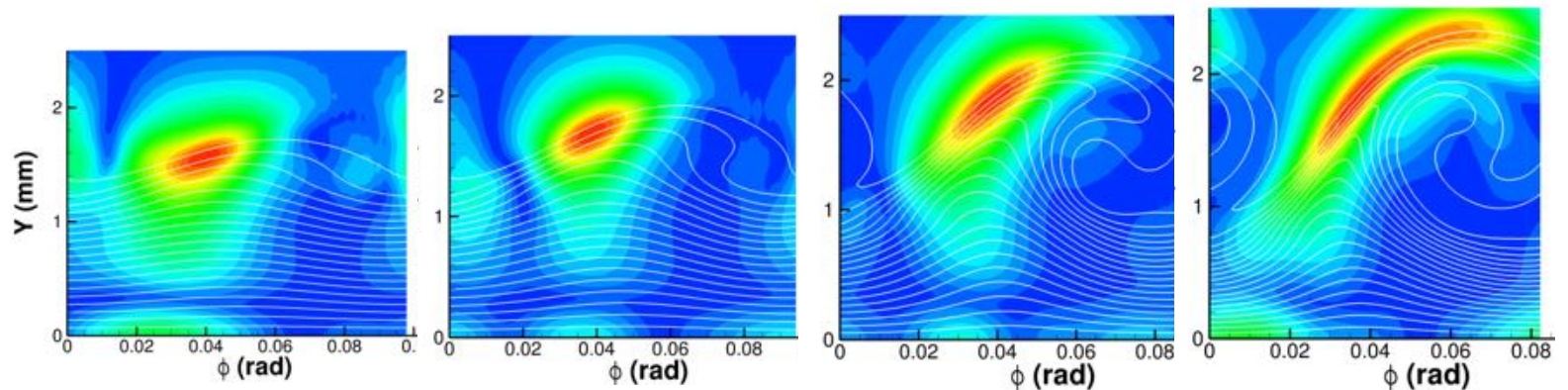
$|p'|$ Mode Shape Evolution (PSE)

Mode MM0 (260 kHz)



X →

Mode SI (360 kHz)

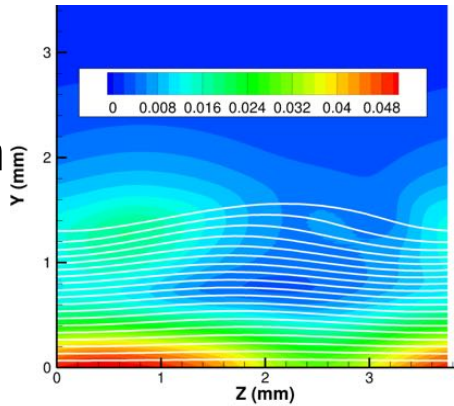




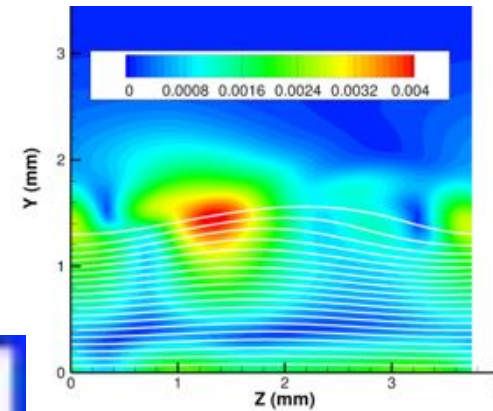
$|p'|$ Mode Shapes

MM0 (200 kHz)

$X = 0.30$ m

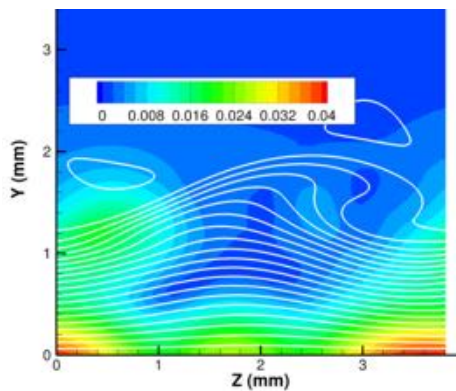


SI (218 kHz)

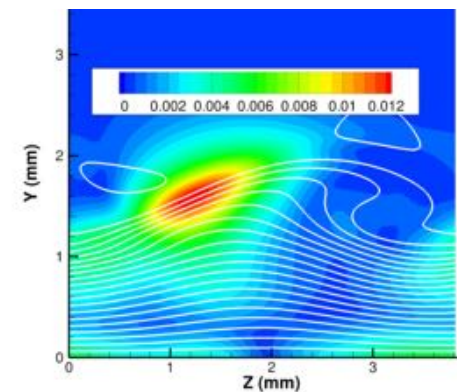


MM0 (213 kHz)

$X = 0.33$ m



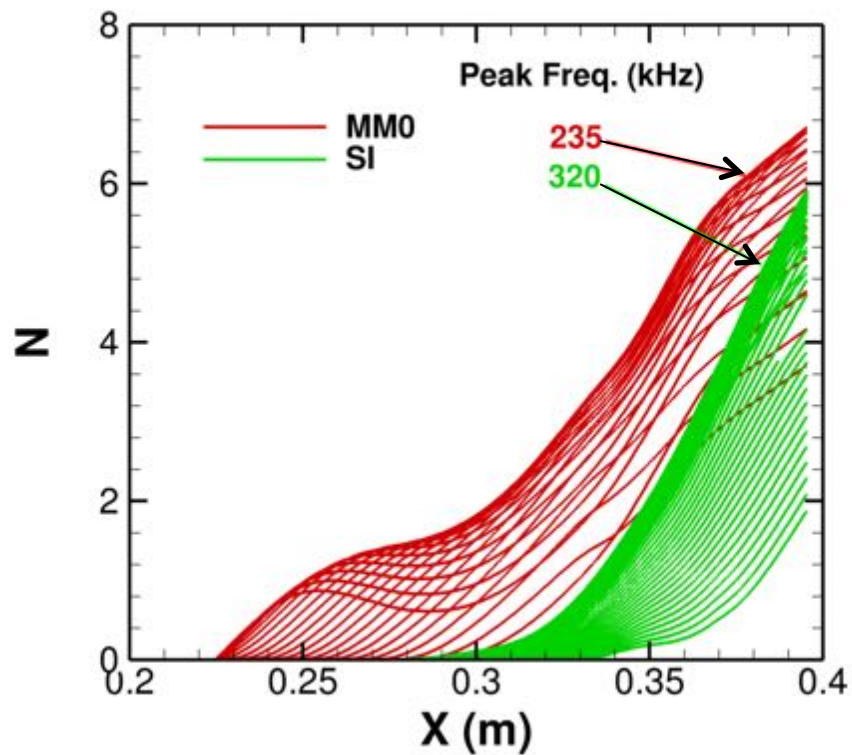
SI (340 kHz)



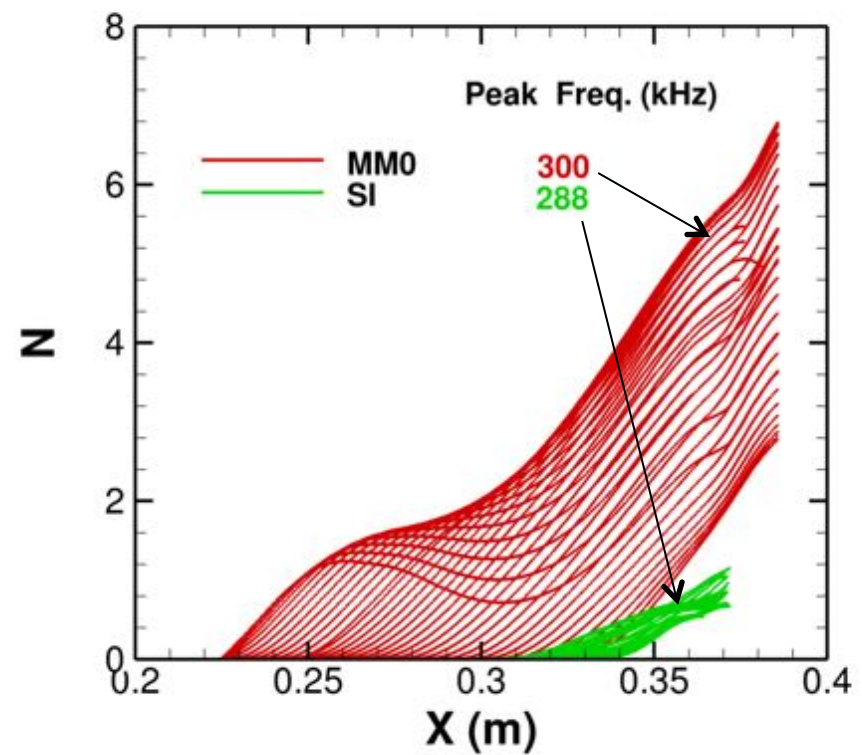


N-Factor Evolution (QPNC)

V10



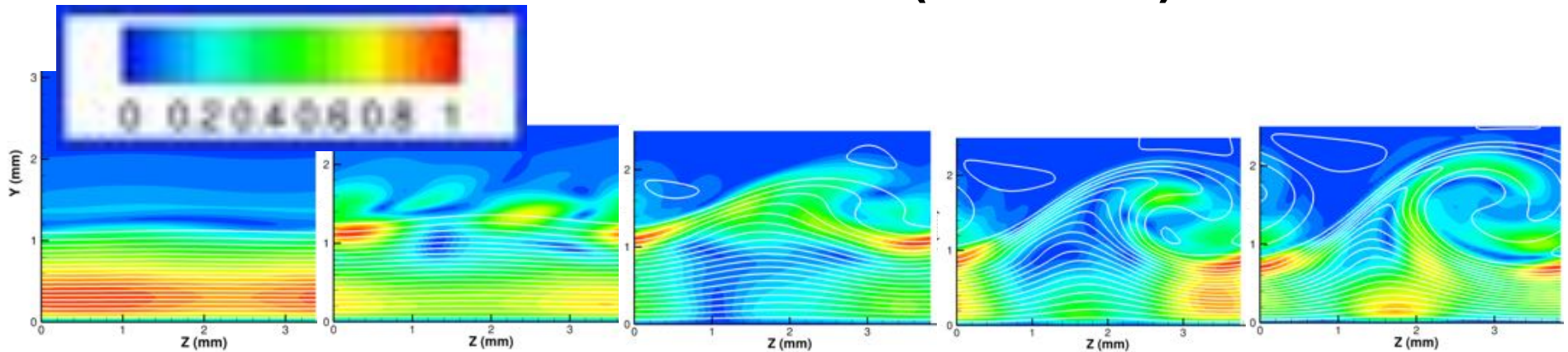
V06





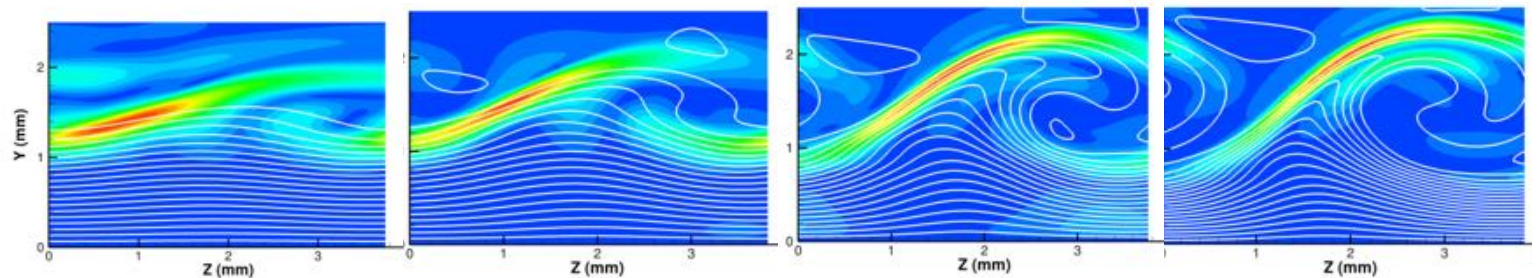
$|\mathbf{u}'|$ Mode Shape Evolution (QPNC)

Mode MM0 (235 kHz)



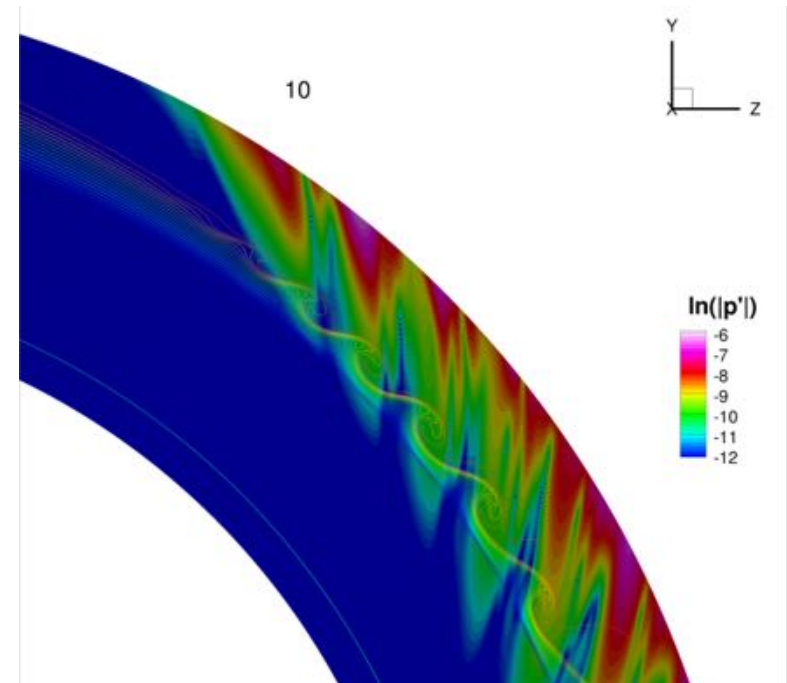
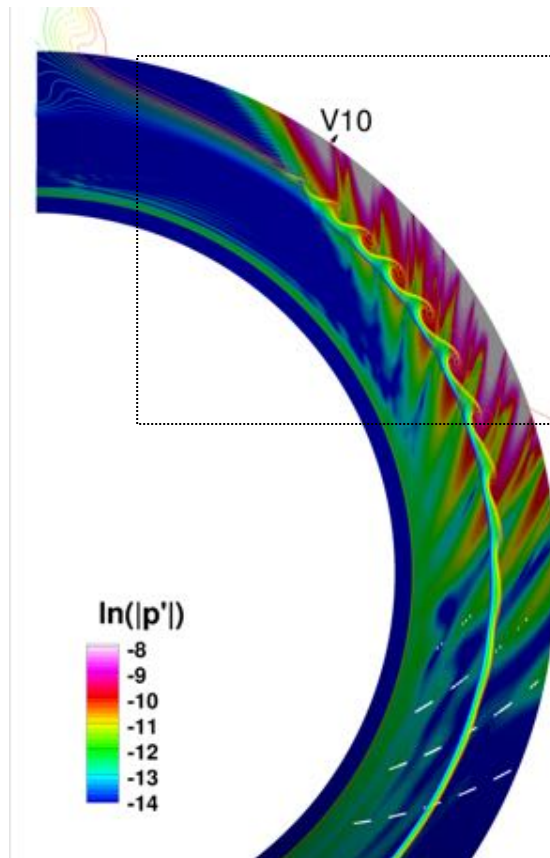
X →

Mode SI (320 kHz)





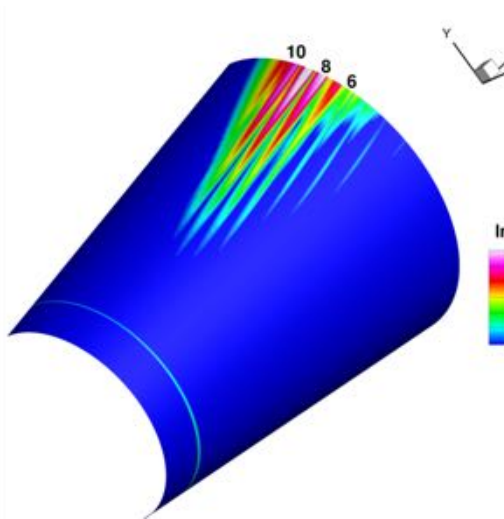
DNS of Secondary Instability: $|p'|$ Evolution at $f = 280$ kHz



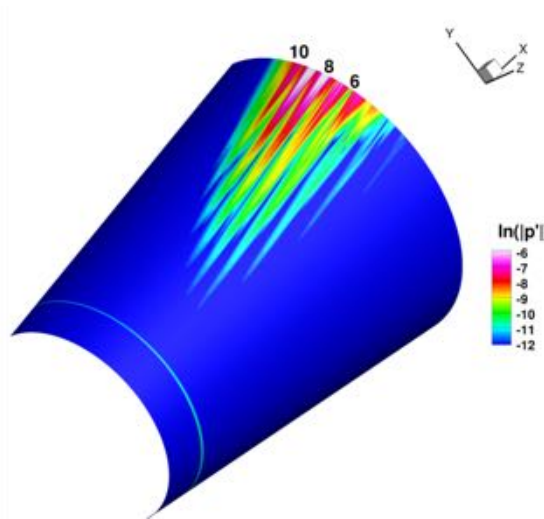


DNS of Secondary Instability: $|p'|$ Evolution at Selected Frequencies

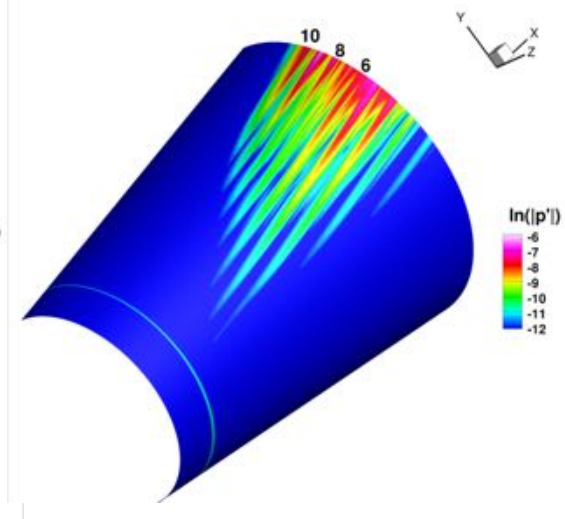
$f = 200$ kHz



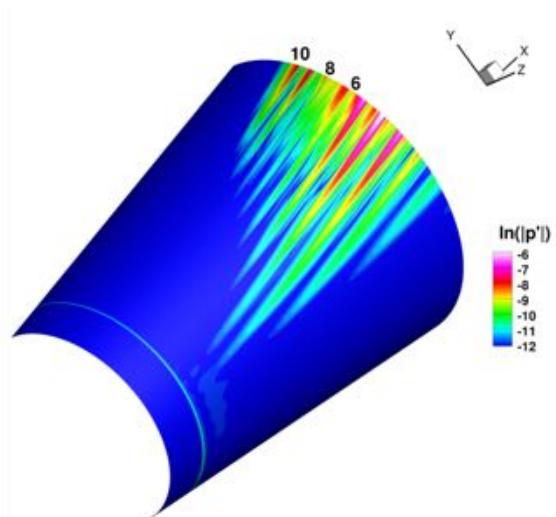
240 kHz



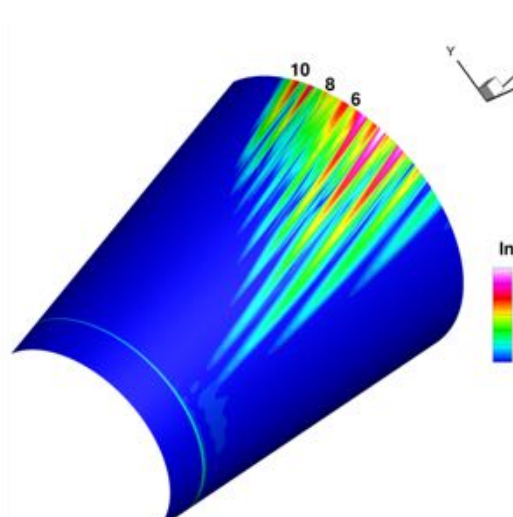
280 kHz



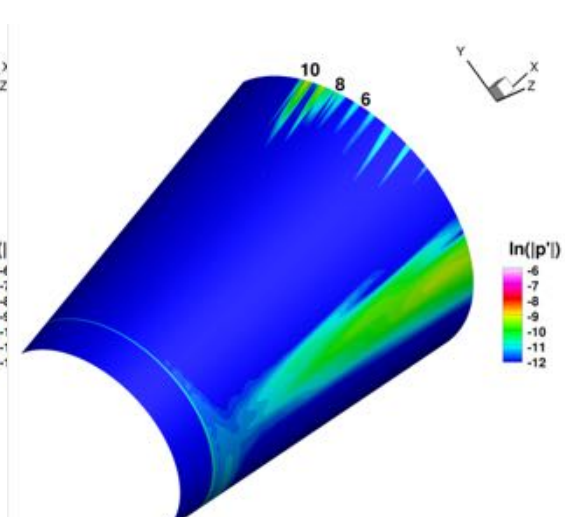
$f = 320$ kHz



360 kHz



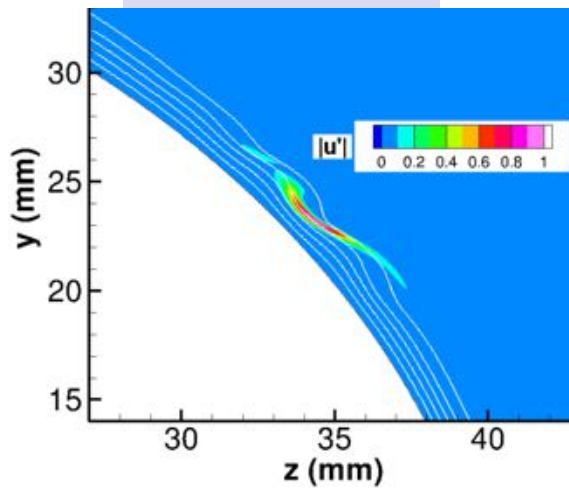
400 kHz



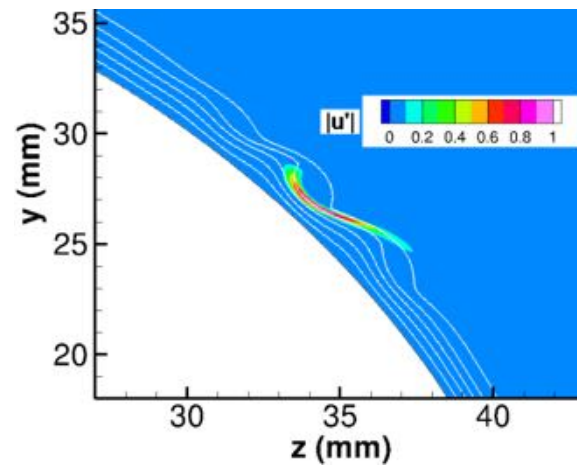


SI Mode Shapes for Windward Vortex:

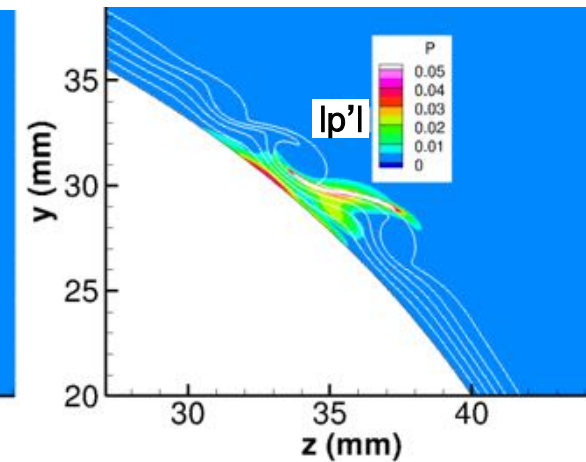
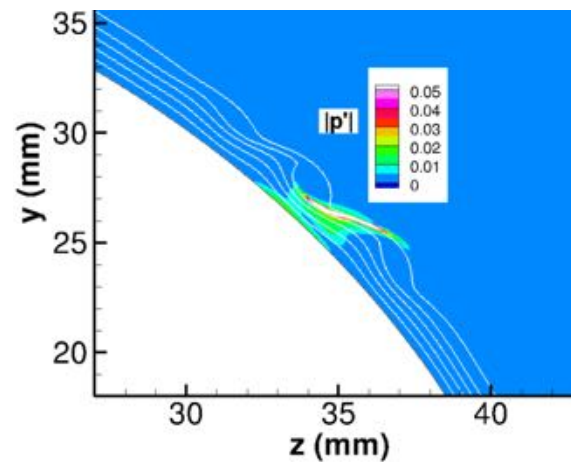
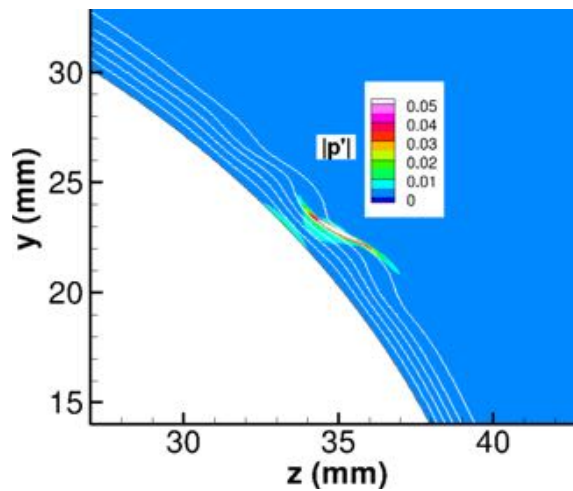
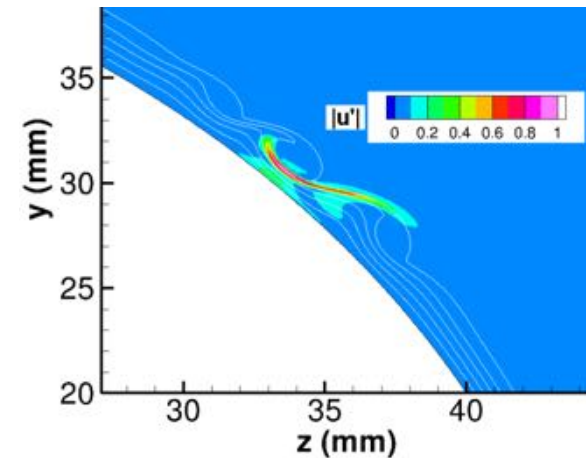
$X = 0.330 \text{ m}$



$X = 0.346 \text{ m}$



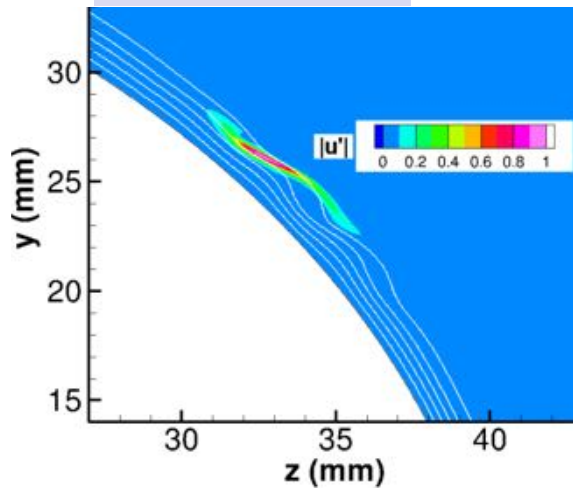
$X = 0.364 \text{ m}$



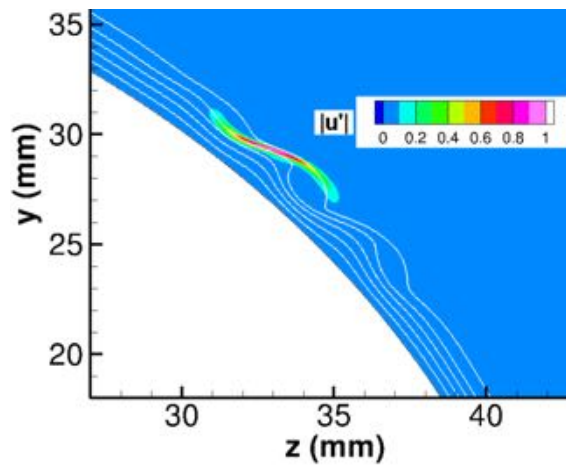


$|u'|$ Mode Shapes for Leeward Vortex: SI Mode

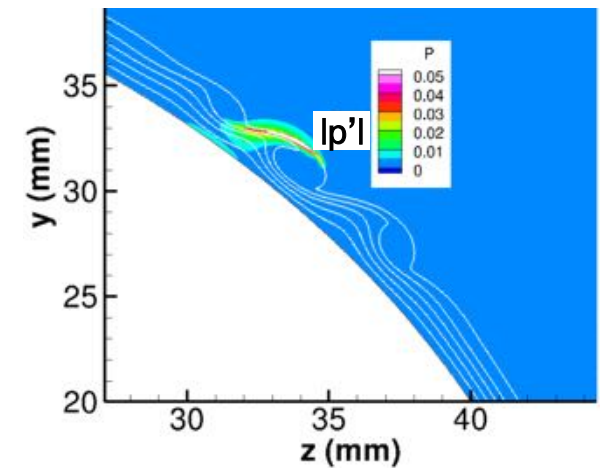
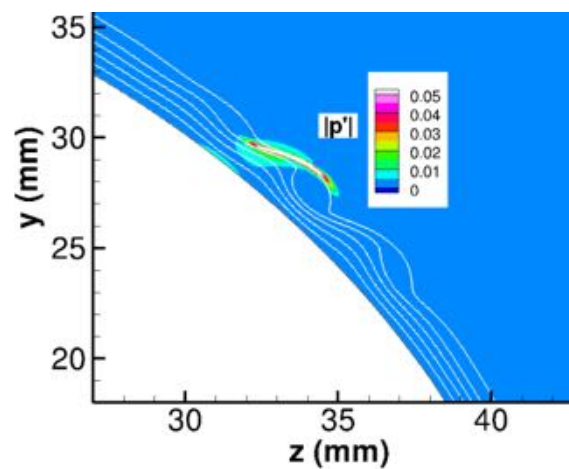
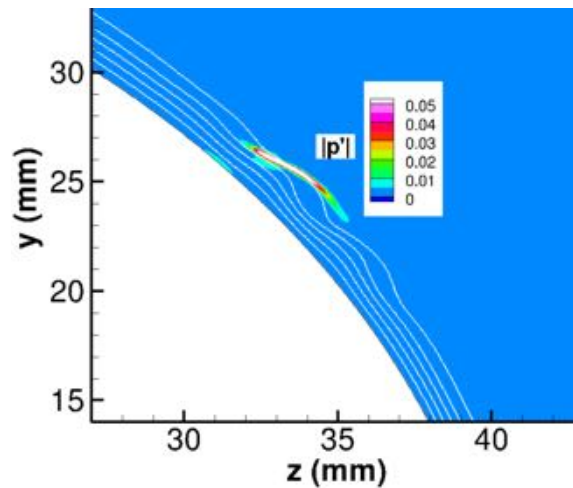
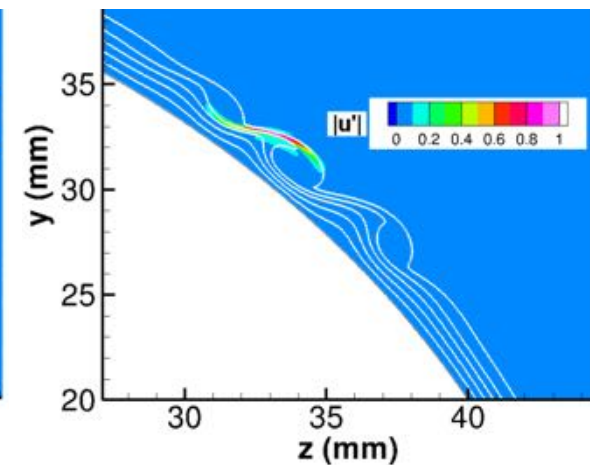
$X = 0.330$ m



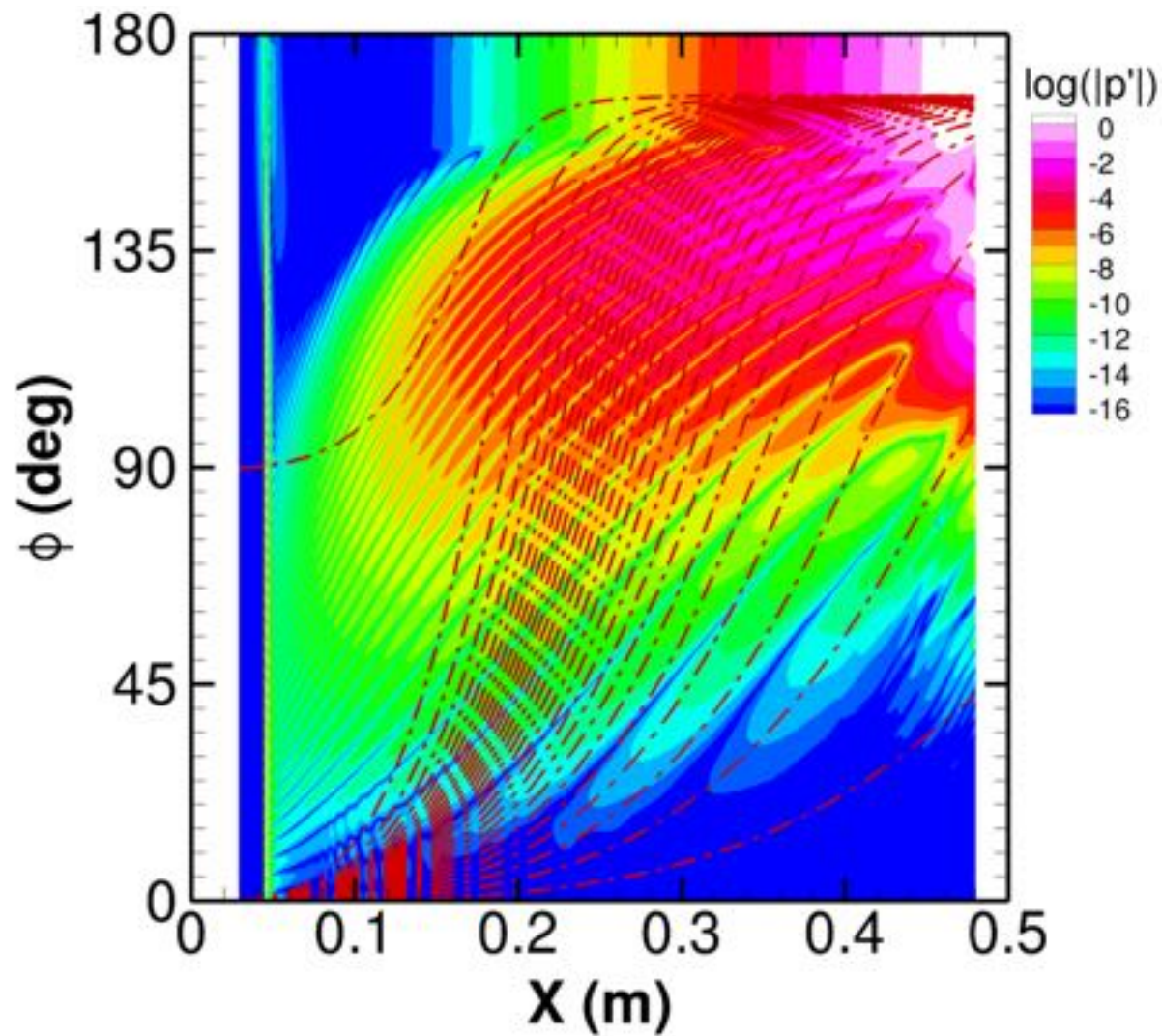
$X = 0.346$ m



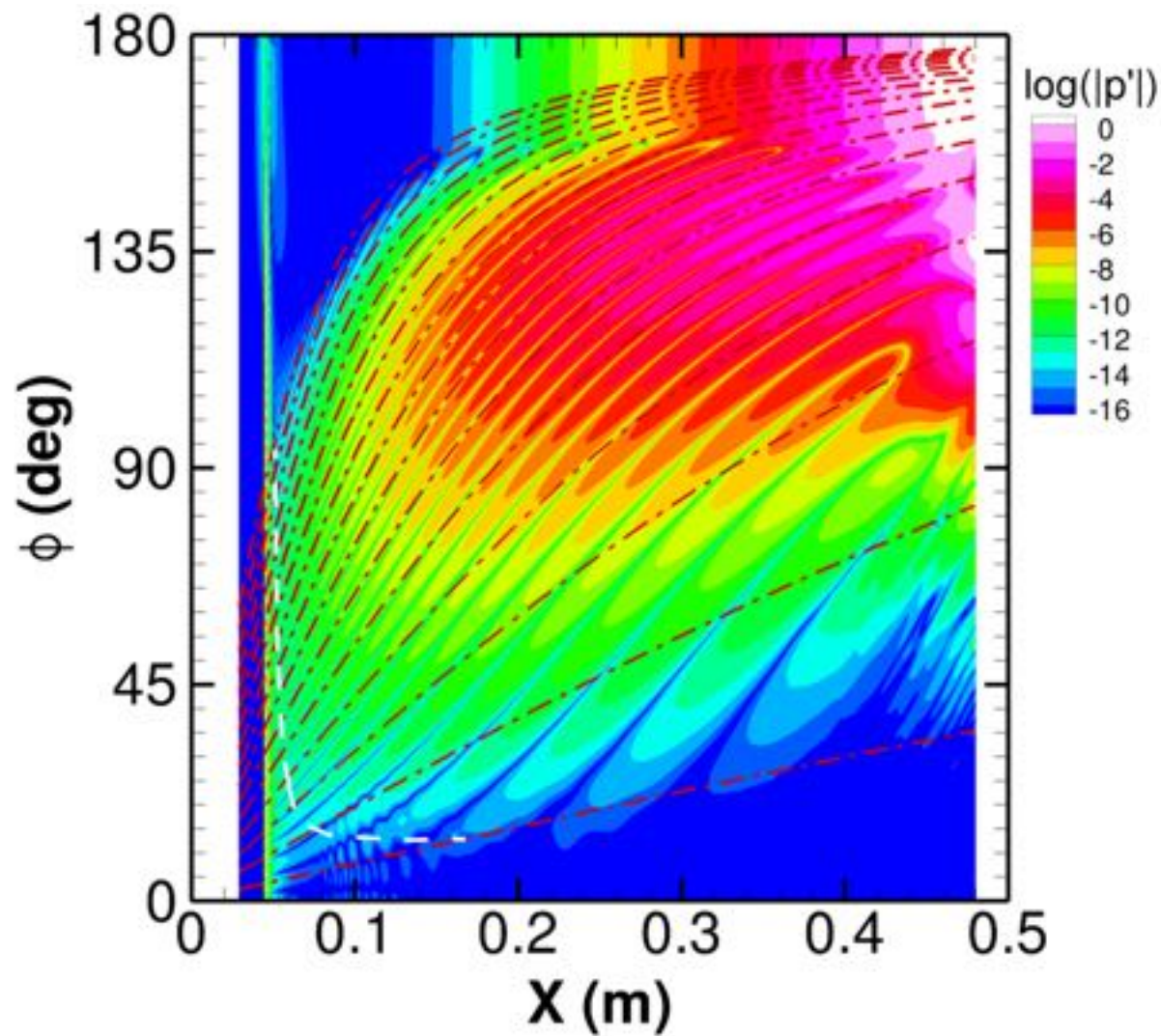
$X = 0.364$ m



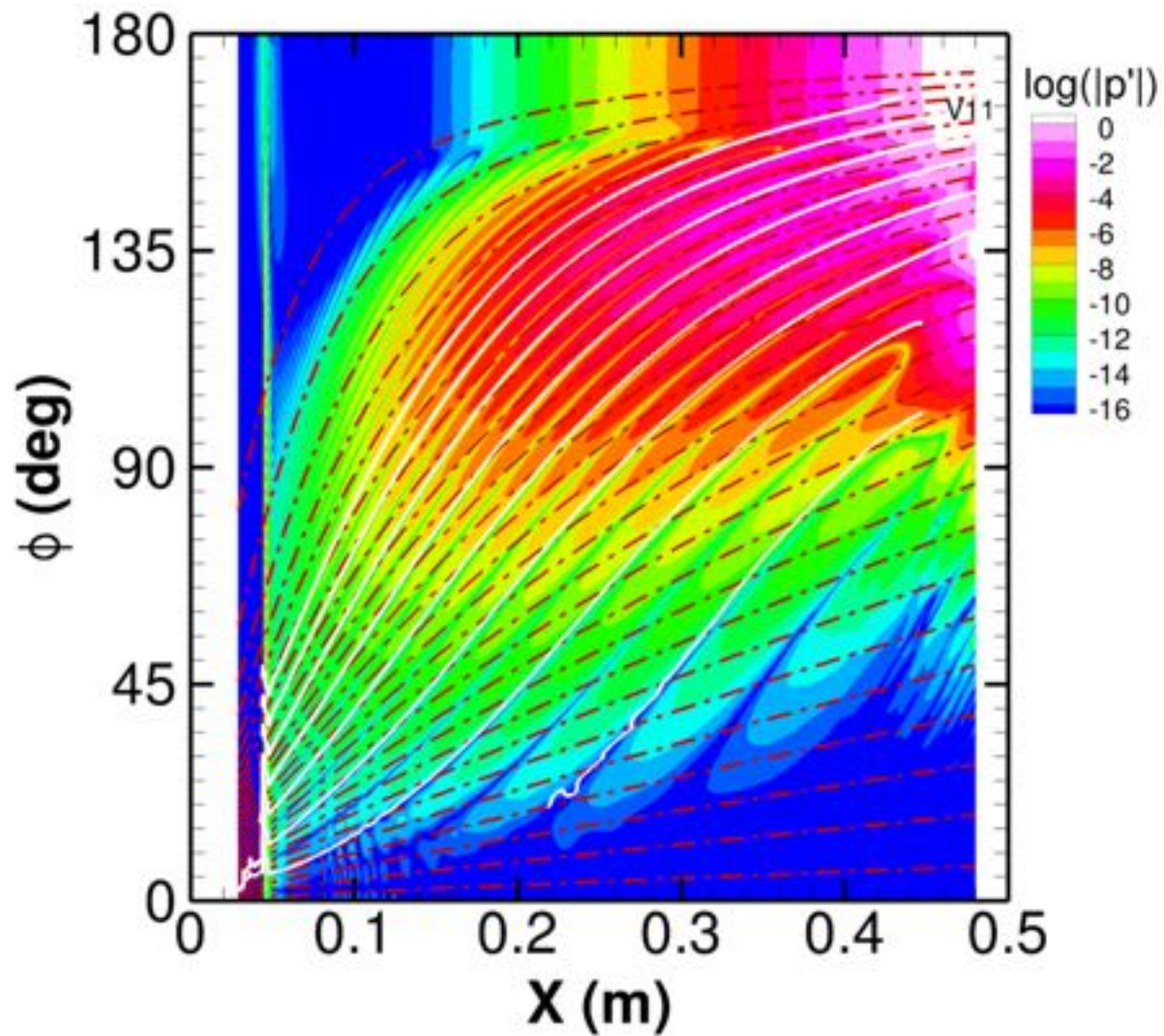
Vortex Trajectories vs. Friction Lines



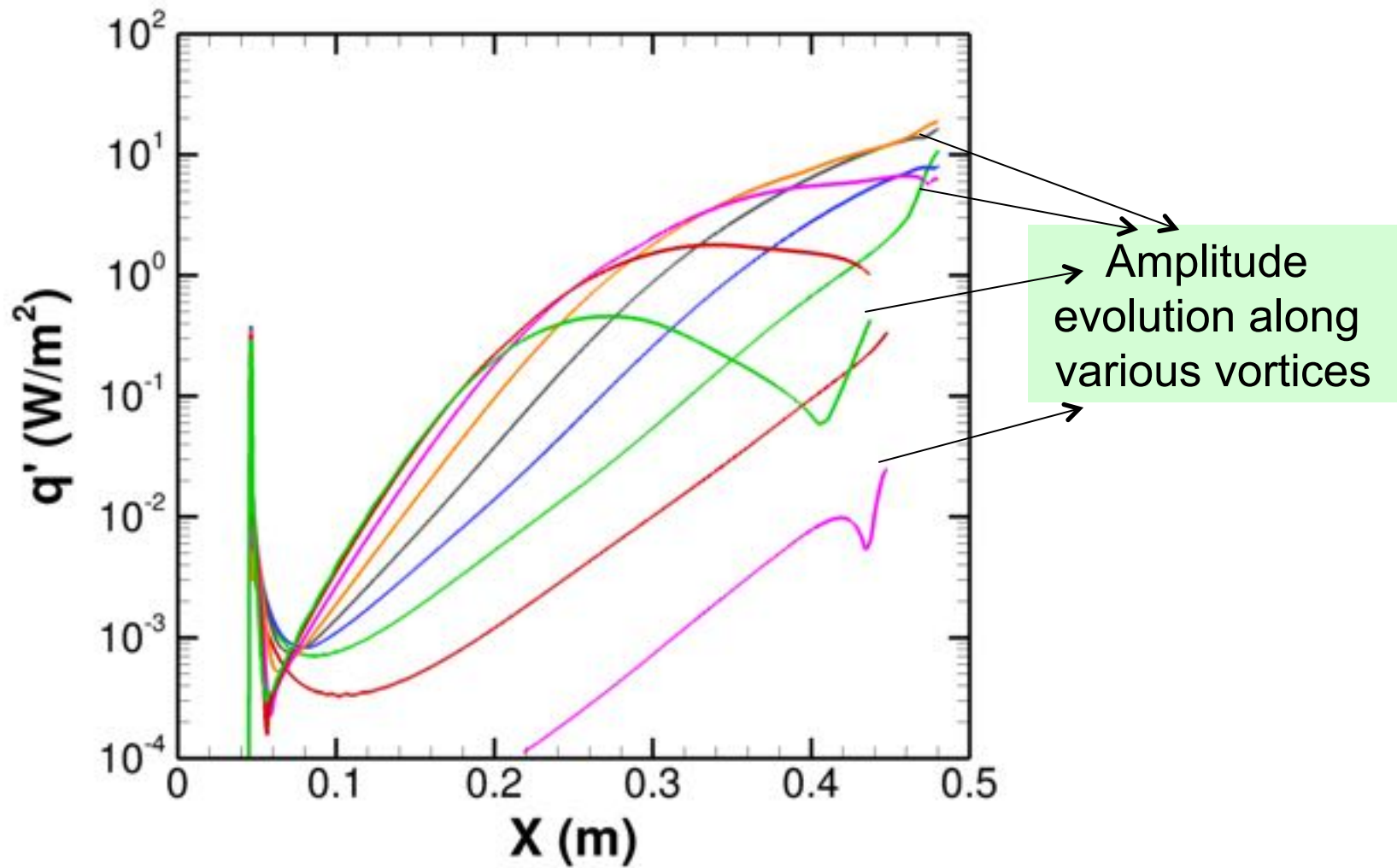
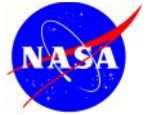
Vortex Trajectories vs. Inflection Lines



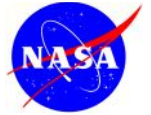
Vortex Trajectories vs. Streamlines



Vortex Amplitude Evolution



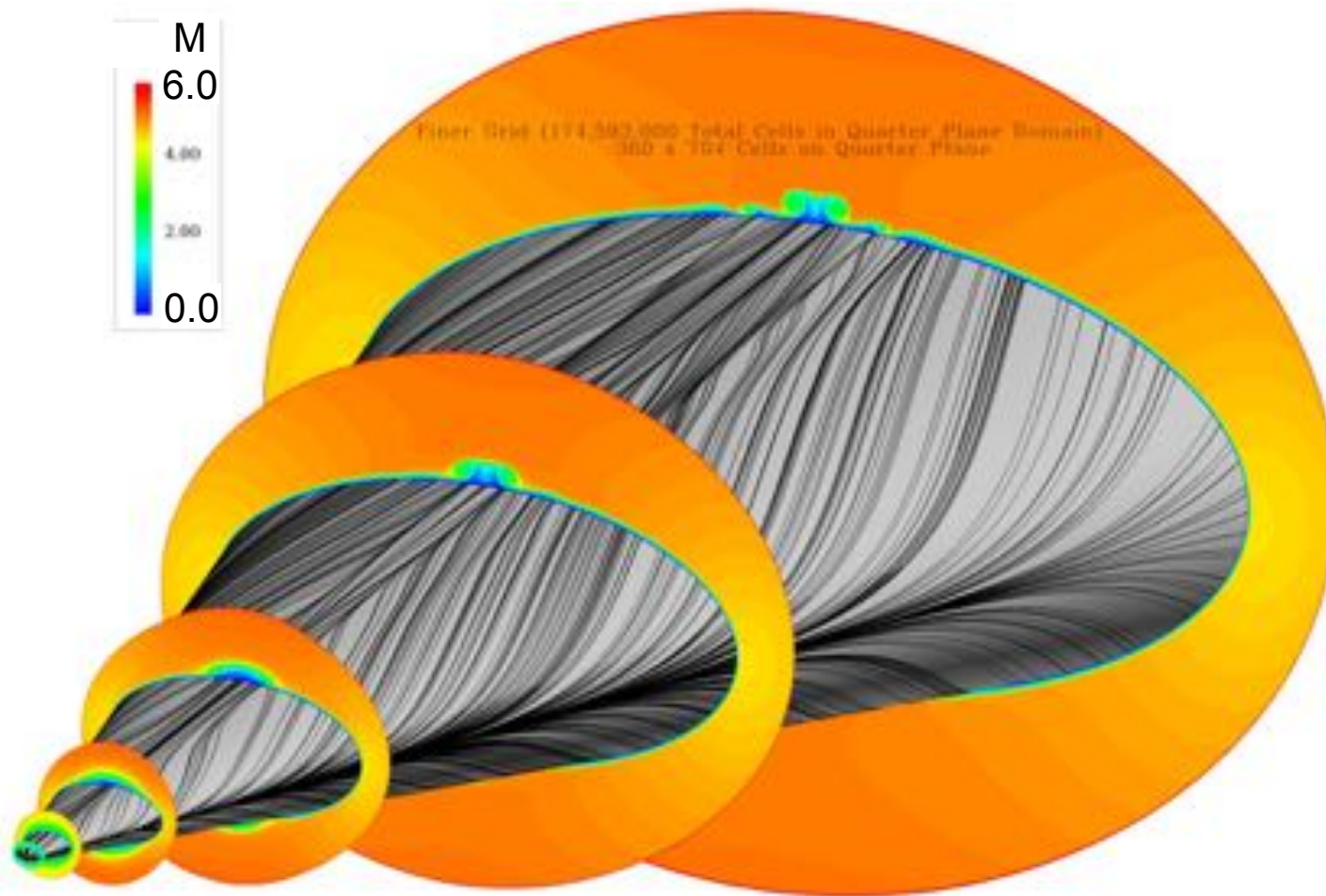
Extra Charts : HIFiRE-5 Cone





HiFIRE5

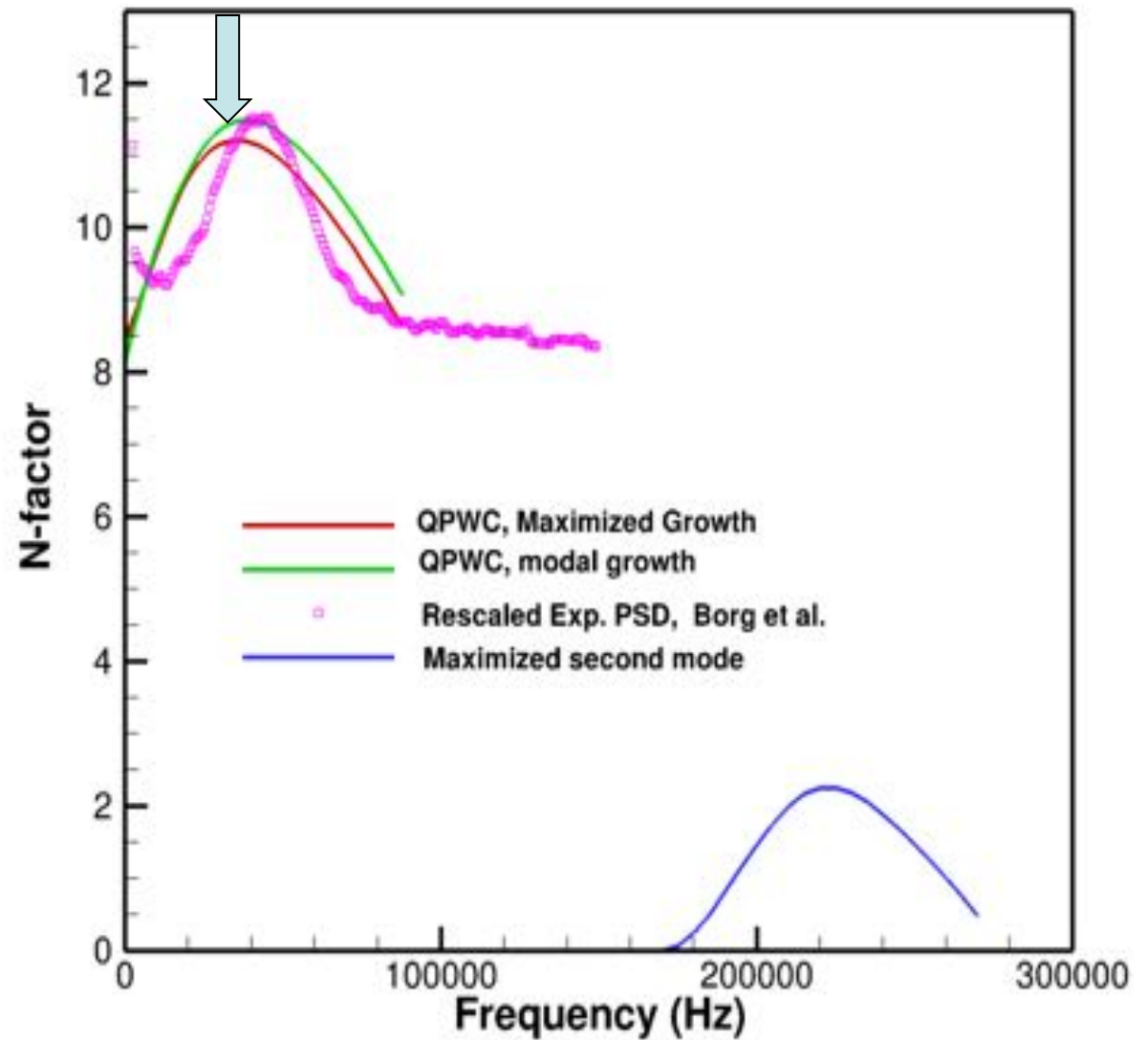
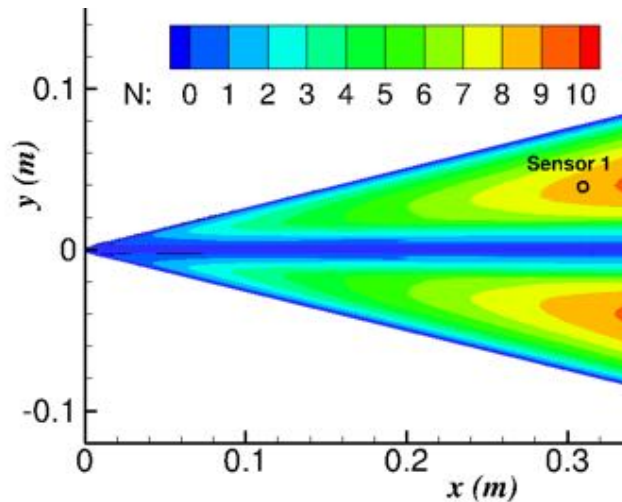
Li et al. (2012)





Traveling Crossflow: Frequency Spectrum

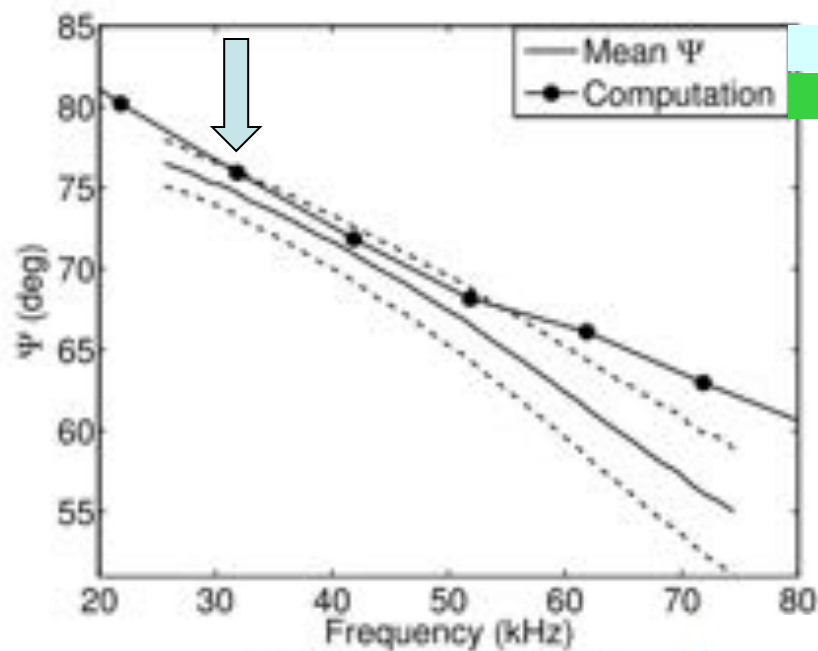
Li et al. (2012)



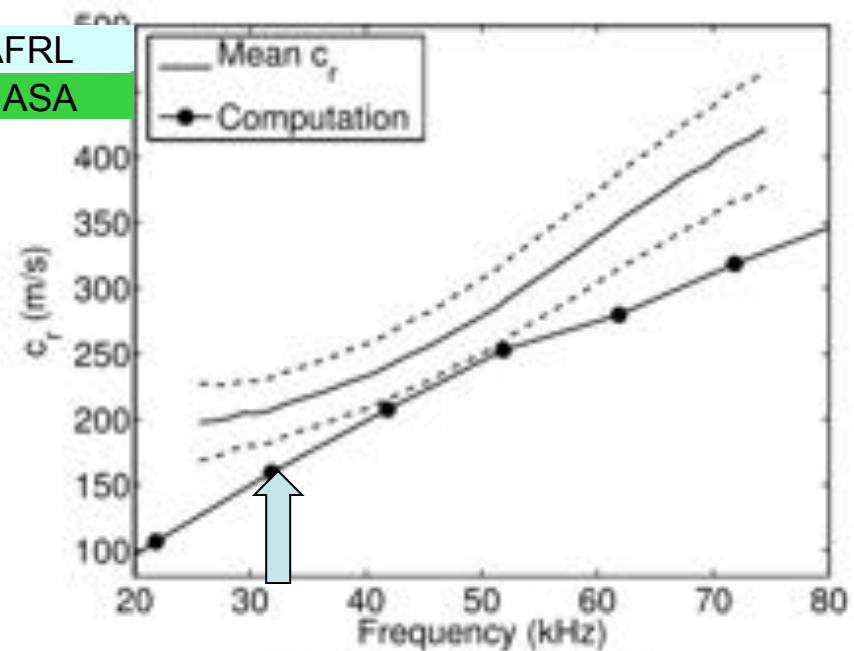


Traveling Crossflow: Wave Angles and Phase Speeds

Comparison with measurements by AFRL (Borg et al. 2014)



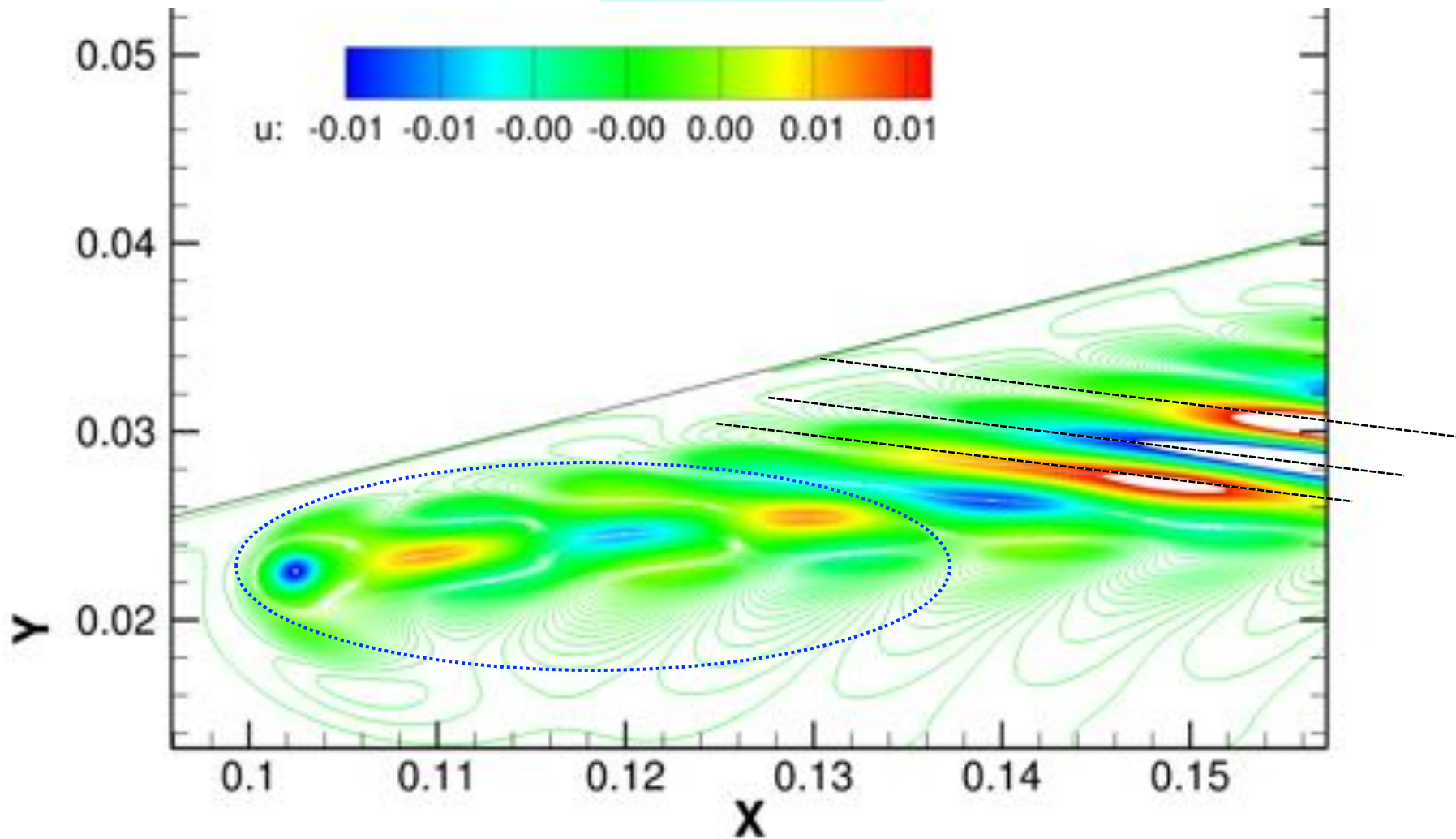
AFRL
NASA





DNS of Traveling Crossflow Waves Due To Point Source ($f = 32$ kHz)

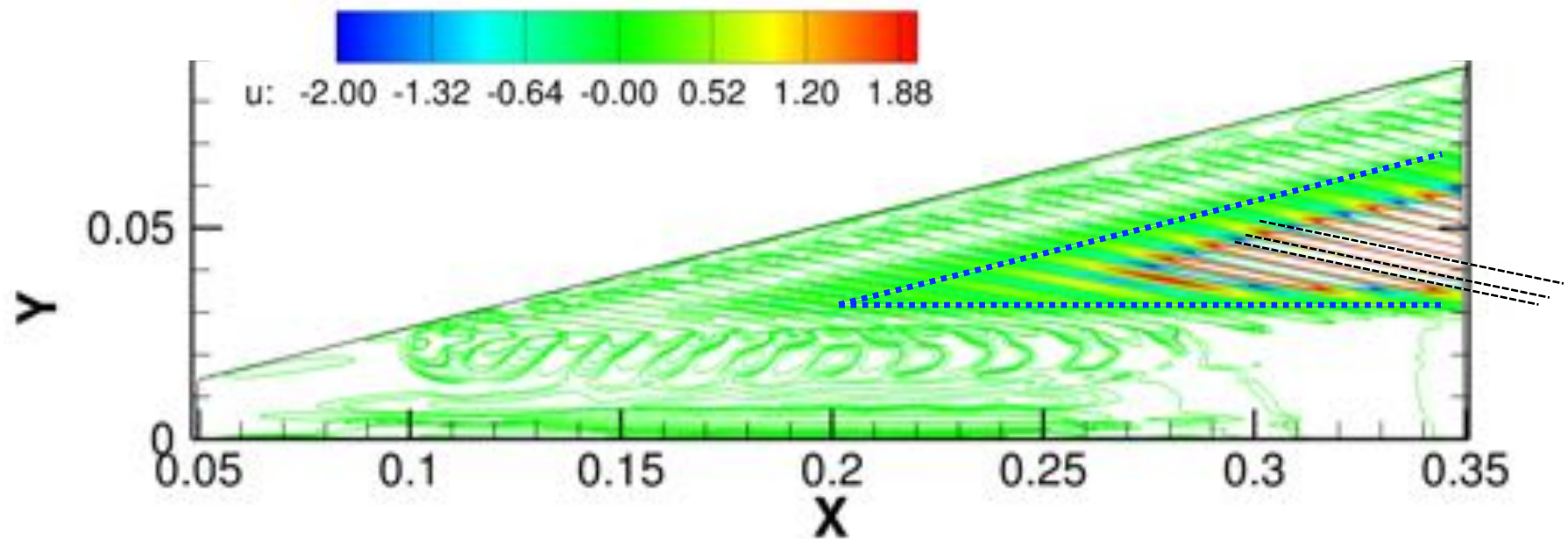
Near Field





Pattern of Traveling Crossflow Waves from Point Source (HiFIRE5 in BAMQT)

Far Field

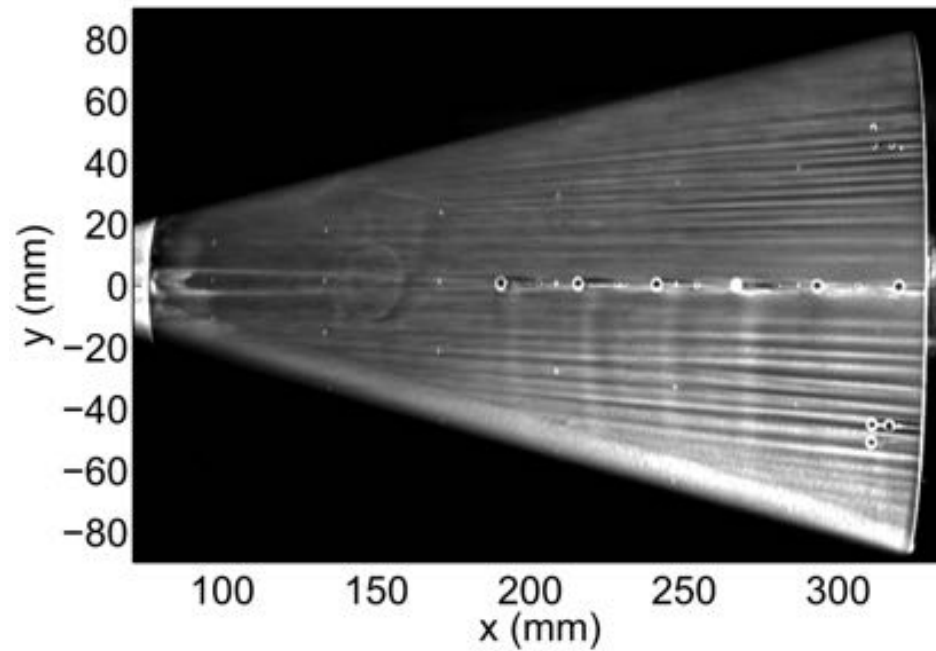




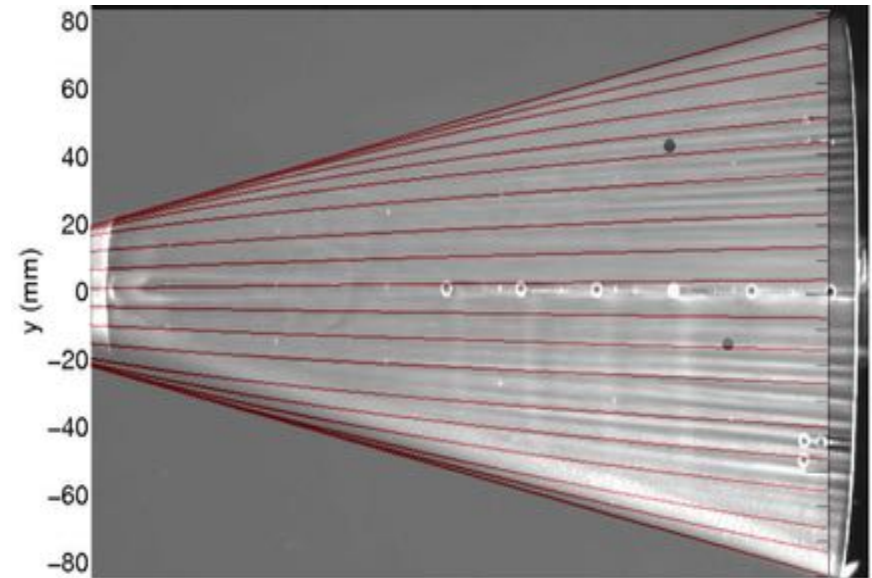
Stationary Crossflow

Borg et al. (2014)

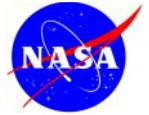
Oil Flow



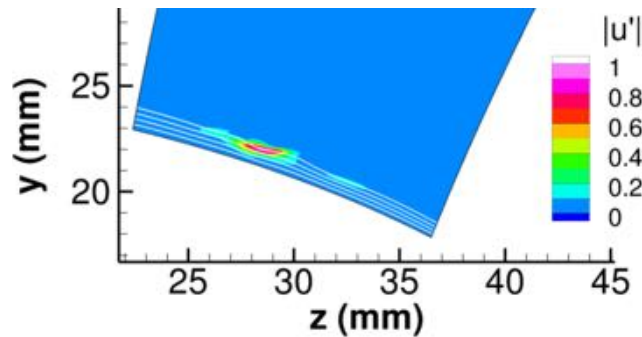
+ inviscid streamlines



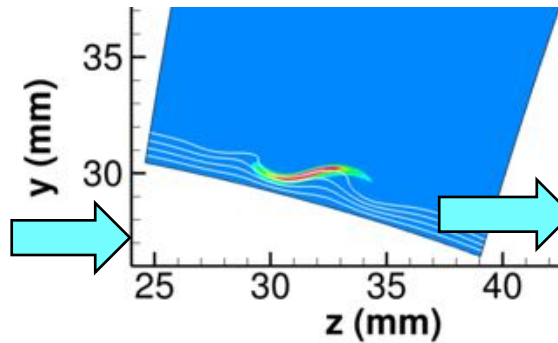
$|u'|$ Mode Shapes: SI Mode



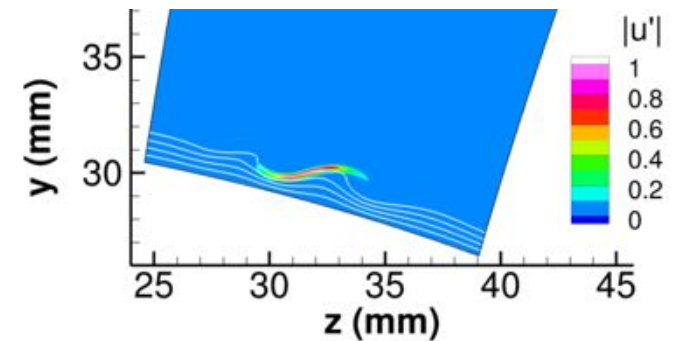
X = 0.201 m (100 kHz)



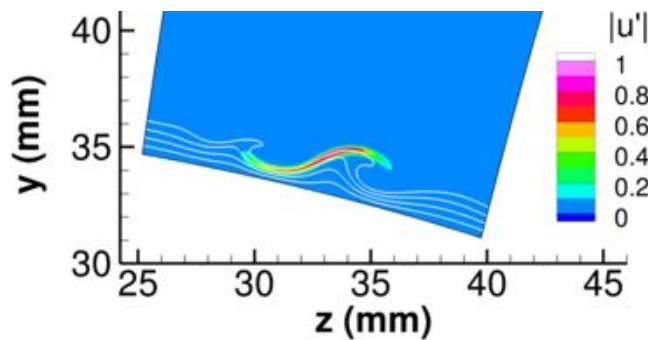
X = 0.267 m (190 kHz)



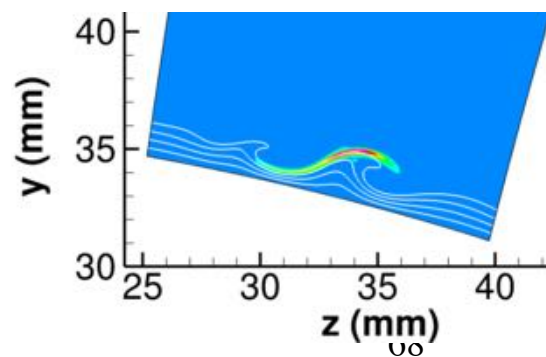
X = 0.267 m (310 kHz)



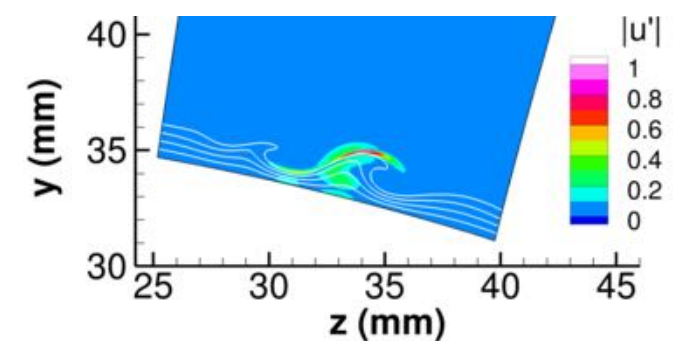
X = 0.294 m (170 kHz)



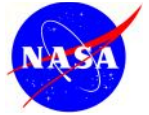
X = 0.294 m (250 kHz)



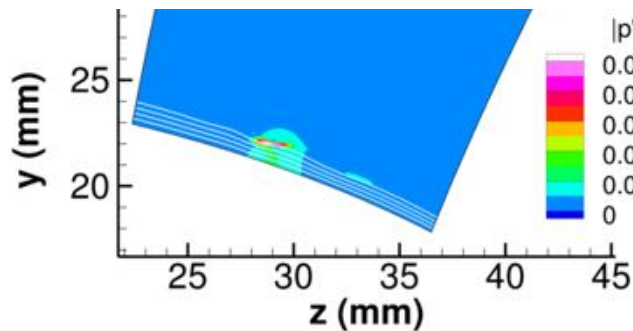
X = 0.294 m (440 kHz)



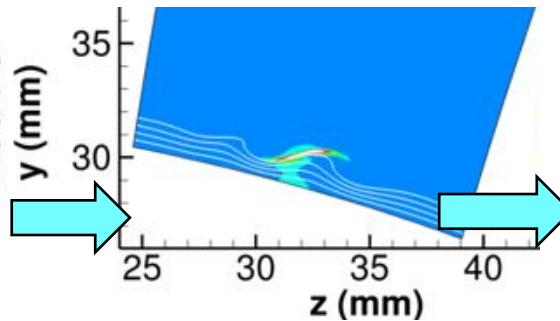
$|p'|$ Mode Shapes: SI Mode



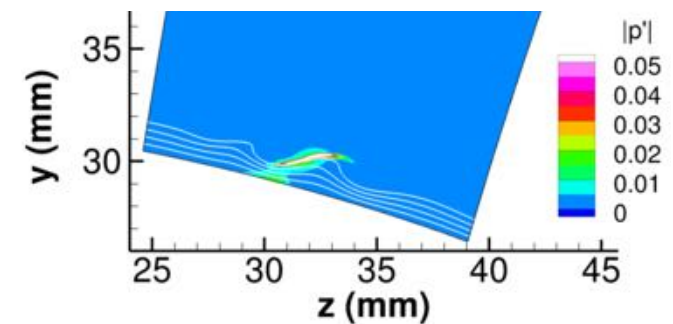
X = 0.201 m (100 kHz)



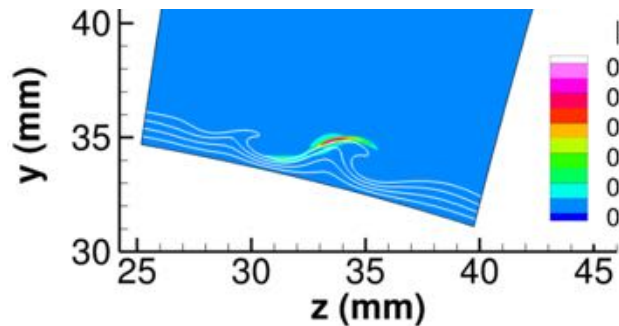
X = 0.267 m (190 kHz)



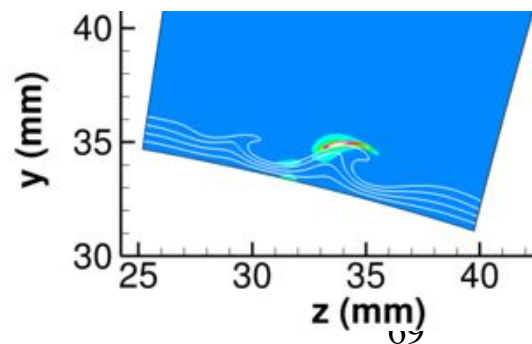
X = 0.267 m (310) kHz)



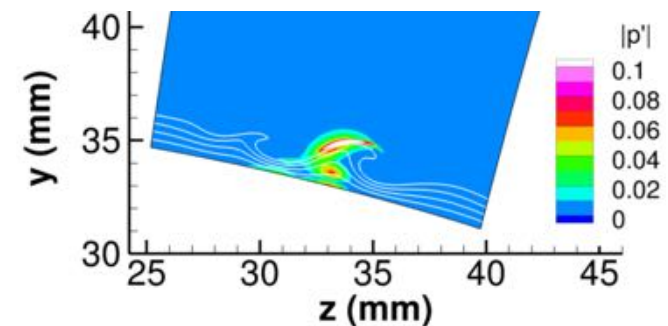
X = 0.294 m (170 kHz)



X = 0.294 m (250 kHz)



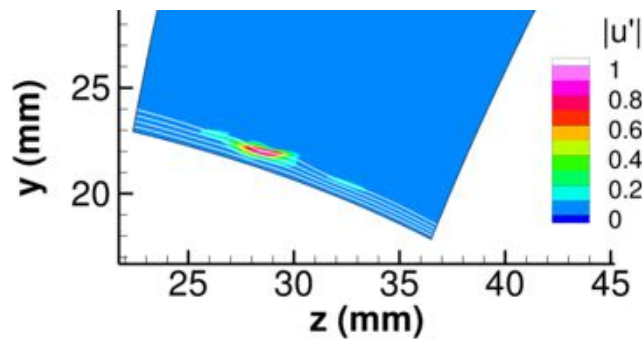
X = 0.294 m (440 kHz)



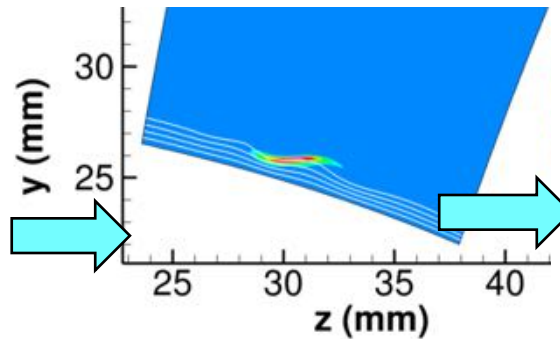
HIFiRE5 $|u'|$ Mode Shapes: SI Mode



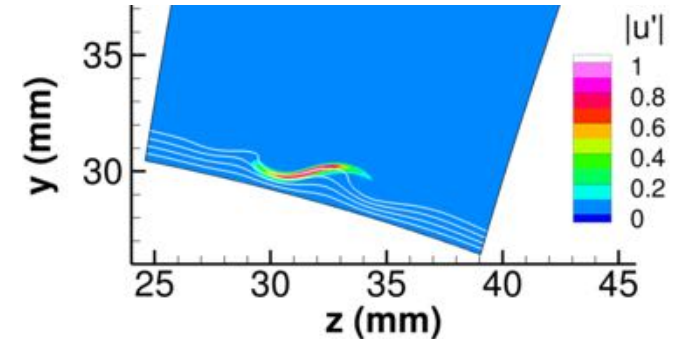
X = 0.201 m (100 kHz)



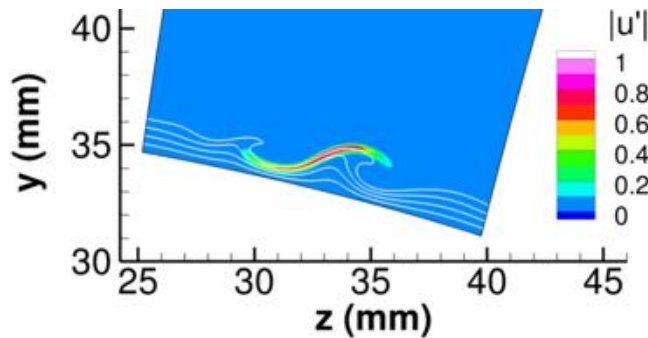
X = 0.230 m (210 kHz)



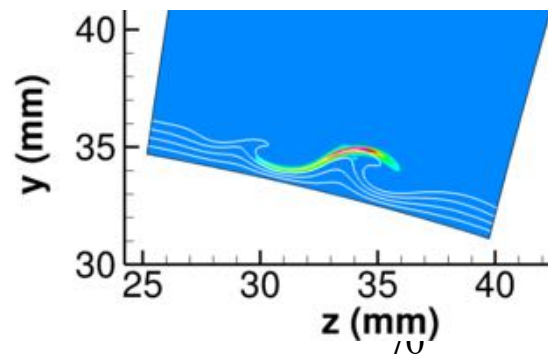
X = 0.267 m (190 kHz)



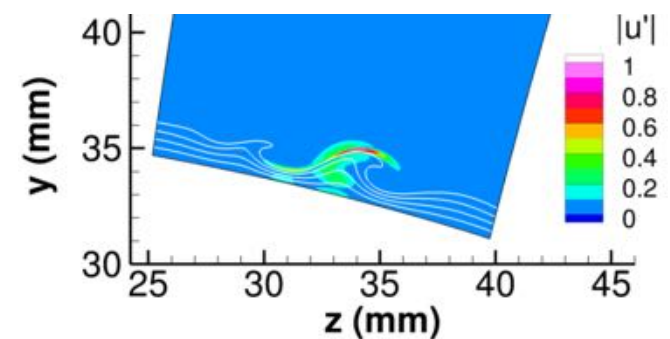
X = 0.294 m (170 kHz)



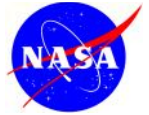
X = 0.294 m (250 kHz)



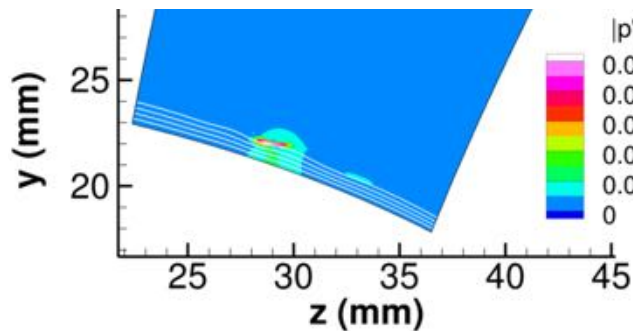
X = 0.294 m (440 kHz)



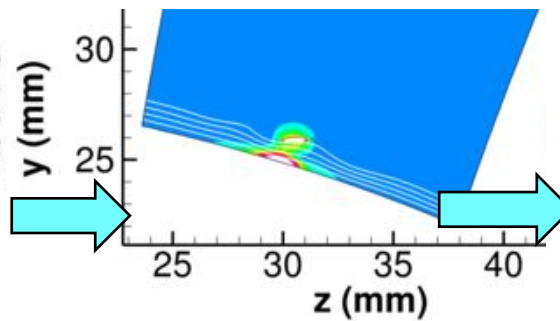
$|p'|$ Mode Shapes: SI Mode



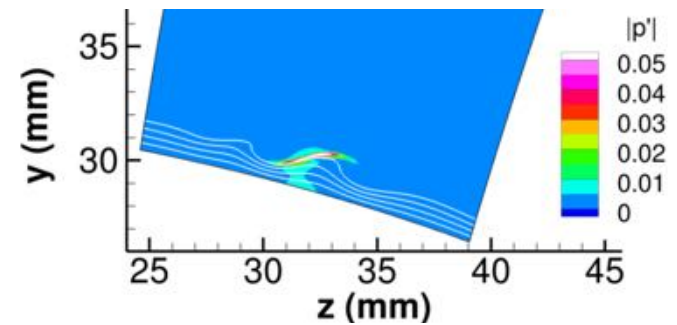
X = 0.201 m (100 kHz)



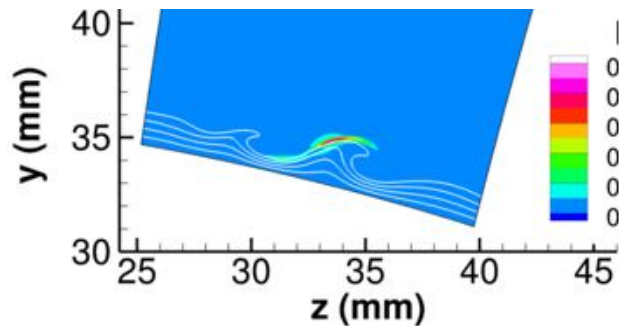
X = 0.230 m (210 kHz)



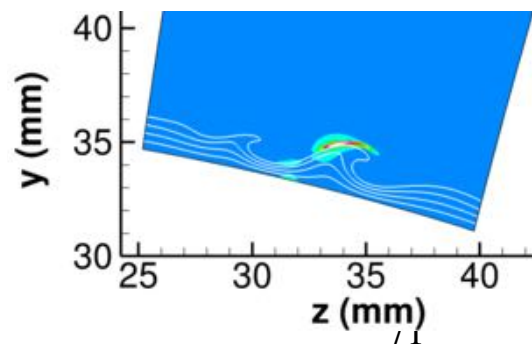
X = 0.267 m (190 kHz)



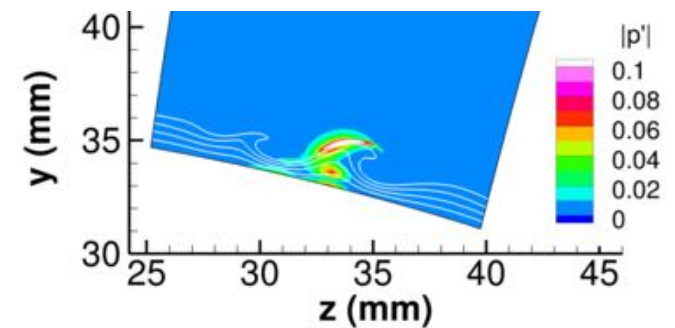
X = 0.294 m (170 kHz)



X = 0.294 m (250 kHz)



X = 0.294 m (440 kHz)



HIFiRE-5: Growth Rate Spectra

