

Separation and Transition on the ROTEX-T Cone-Flare

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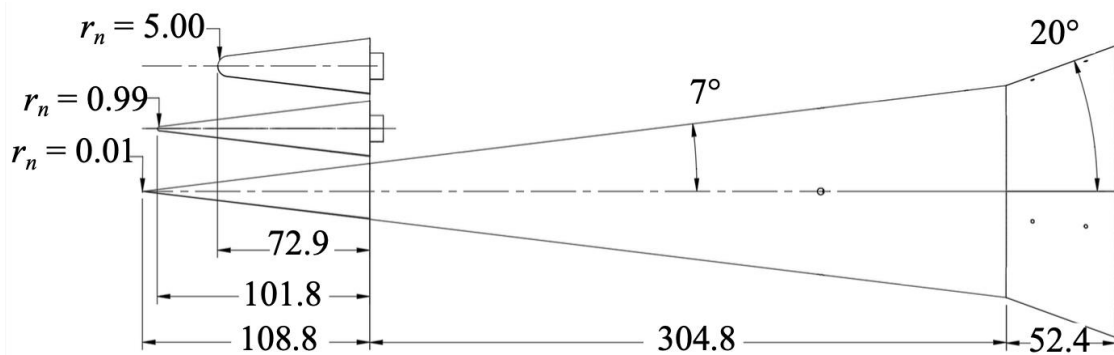
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AIAA SciTech 2024, FD-15, NATO AVT-346:
Instability and Transition in Hypersonic Separated Flows
January 8, 2024, 4:30 pm EST



ROcket Technology EXperiment-Transition (ROTEX-T)^[2]

[3]

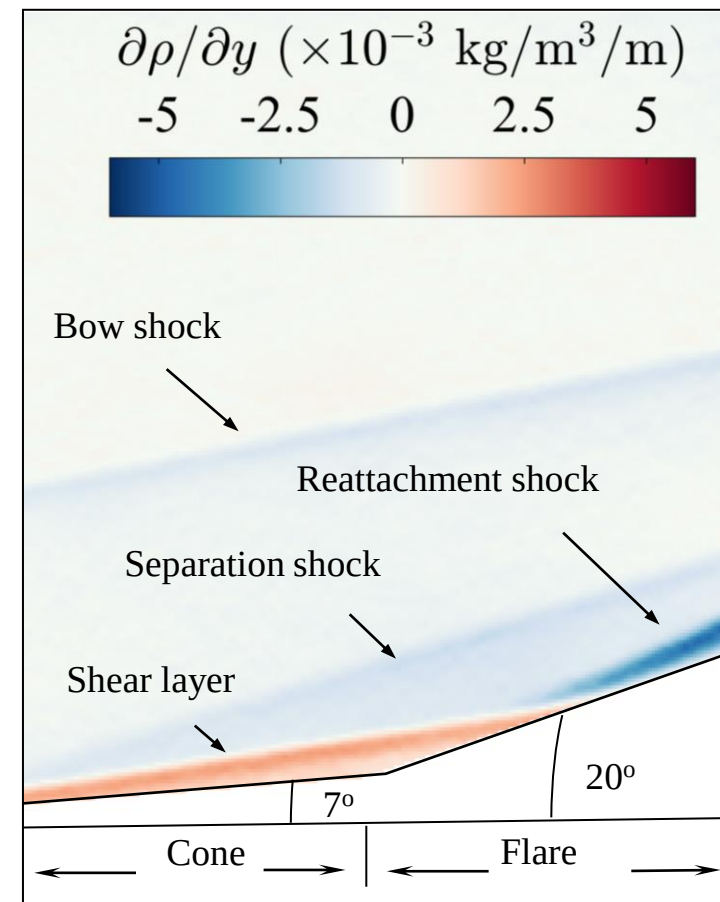


AFOSR Notre Dame Large Mach-6 Quiet Tunnel

- Noisy flow ($M_\infty = 5.7$, $p'/\bar{p} \approx 2.5\%$)
- $Re_\infty = 5.8 - 12.2 \times 10^6 \text{ m}^{-1}$
- $P_0 = 490 - 1022 \text{ kPa}$ and $T_0 = 435 \text{ K}$
- Nominally zero AoA

AFRL Mach 6 Ludweig Tube (with Elizabeth Benitez)

- Noisy flow ($M_\infty = 6.14$, $p'/\bar{p} \approx 3\%$)
- $Re_\infty = 2.2 - 24.7 \times 10^6 \text{ m}^{-1}$
- $P_0 = 252 - 2673 \text{ kPa}$ and $T_0 = 460 \text{ K}$
- Nominally zero AoA

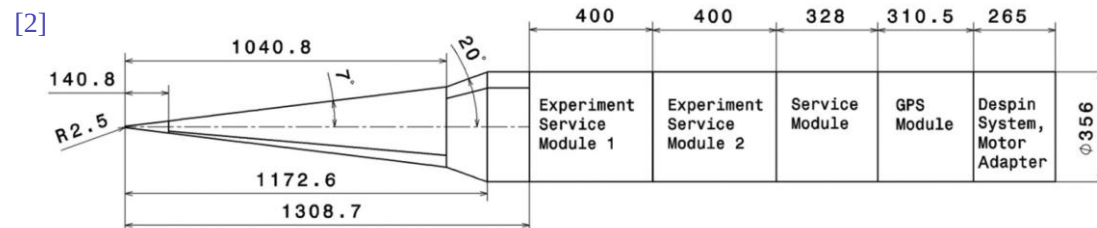
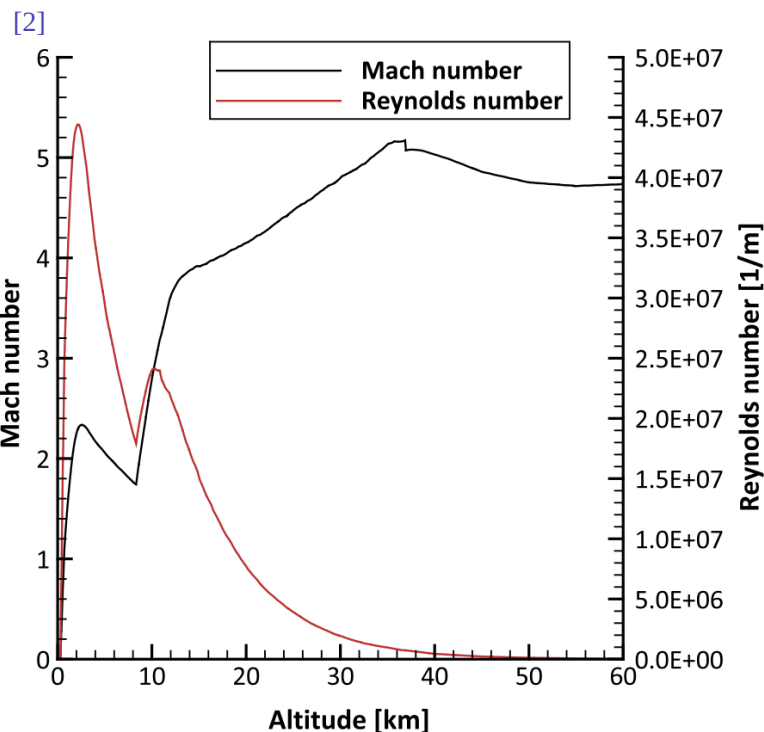


^[1] Davami, Juliano, Paredes, Scholten. "Hypersonic Shock-Wave/Boundary-Layer Interactions on the ROTEX-T Cone/Flare." (2023-1436).

^[2] Thiele, T., Gulhan, A., & Oliver, H., "Instrumentation and Aerothermal Postflight Analysis of the Rocket Technology Flight Experiment ROTEX-T," (2018)

Rocket Technology Experiment–Transition (ROTEX-T)

- Two-stage sounding rocket flight test
- Surface pressure transducers, heat flux microsensors (HFM), coaxial thermocouples (TC)
- Comparisons were focused on ascent, $M_\infty = 4.4$ to 5.1
- Laminar boundary layer at separation



[2] Thiele, T., Gulhan, A., & Oliver, H., "Instrumentation and Aerothermal Postflight Analysis of the Rocket Technology Flight Experiment ROTEX-T," (2018)

ANDLM6QT

AFRL M6LT

High resolution BOS

- Canon EOS RP
- 3840×2160 pixels
- 24-105 mm lens
- $f_{\text{samp}} = 24 \text{ Hz}$

IR Thermography

- MWIR camera
- 512×640 pixels
- 25 mm lens
- $f_{\text{samp}} = 355 \text{ Hz (ND)}$
- $f_{\text{samp}} = 720 \text{ Hz (AFRL)}$

4 PCB 132B38

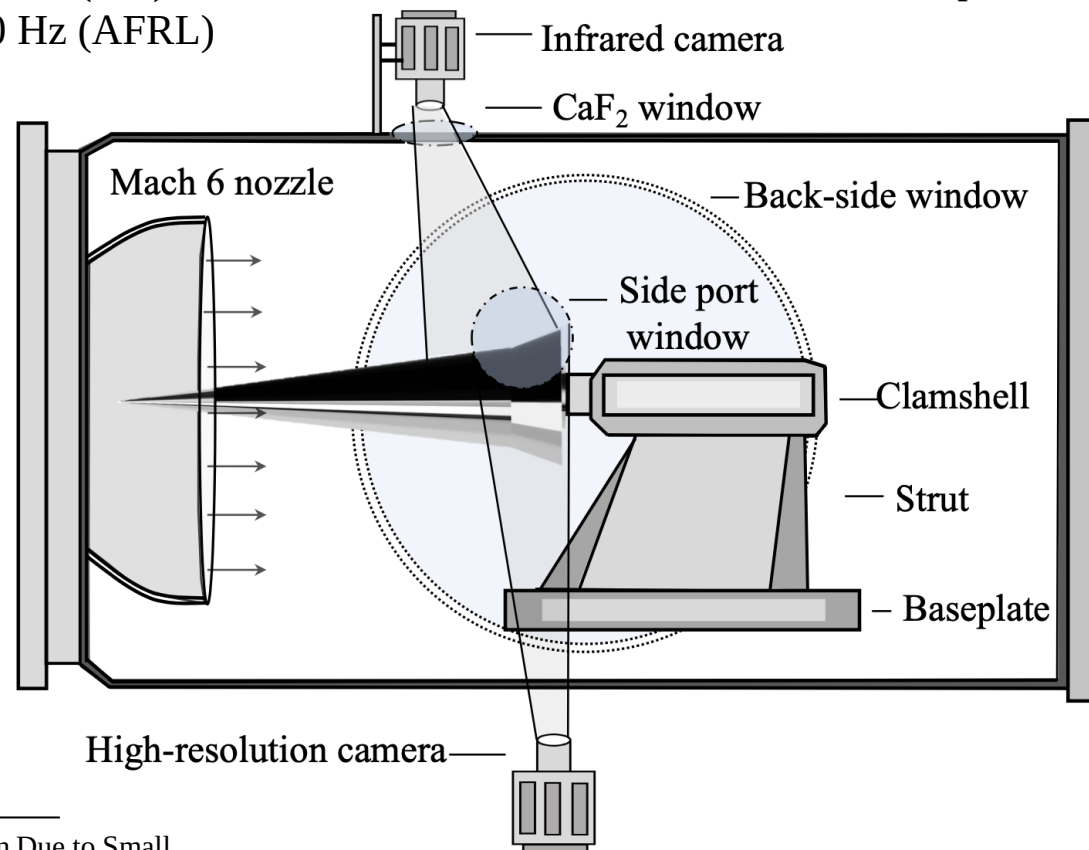
- $f_{\text{samp}} = 2 \text{ MHz}$
- Alignment^[6]

SAFS

- Photron Fastcam
- $f_{\text{samp}} = 630 \text{ kHz}$

LA-FLDI

- Thorlabs BC106N-VIS
- CCD beam profiler



^[3] Benitez, Jewell, & Schneider “Separation Bubble Variation Due to Small Angles of Attack for an Axisymmetric Model at Mach 6.” (2021-0245).

Transient 1D heat conduction [4,5]

➤ Assumptions:

1. Homogenous material properties
2. Uniform initial temperature
3. Front-face BC
4. Adiabatic back-face BC [3]
5. Neglect radiation
6. Cylindrical

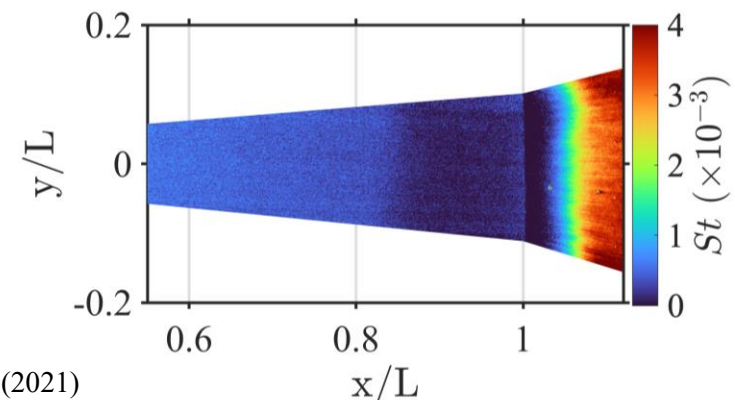
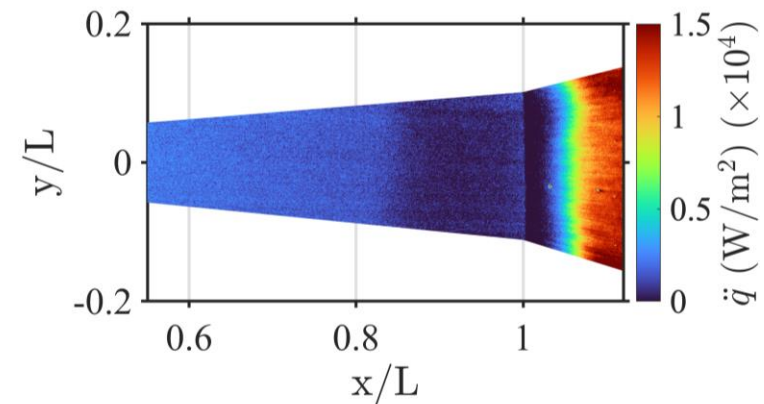
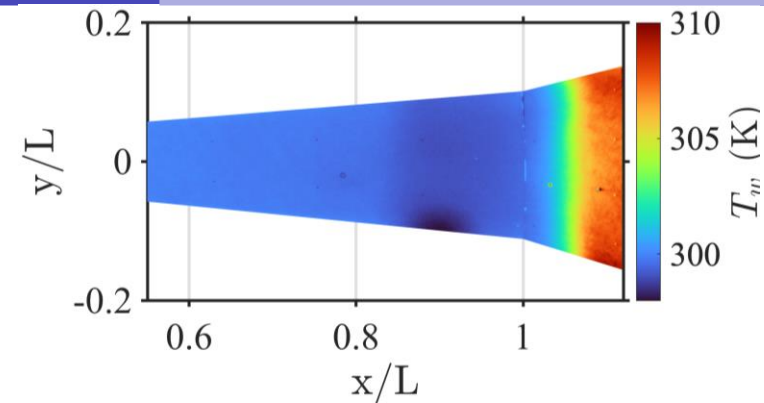
➤ Modified Stanton number: $St = \frac{\dot{q}''}{\rho_{\infty} u_{\infty} c_p (T_0 - T)}$

ANDLM6QT:

- Spatial resolution: 0.1 mm
- Temporally filtered 0.03 s (10 frames)

AFRL M6LT:

- Spatial resolution: 0.8 mm
- Temporally filtered 0.03 s (20 frames)

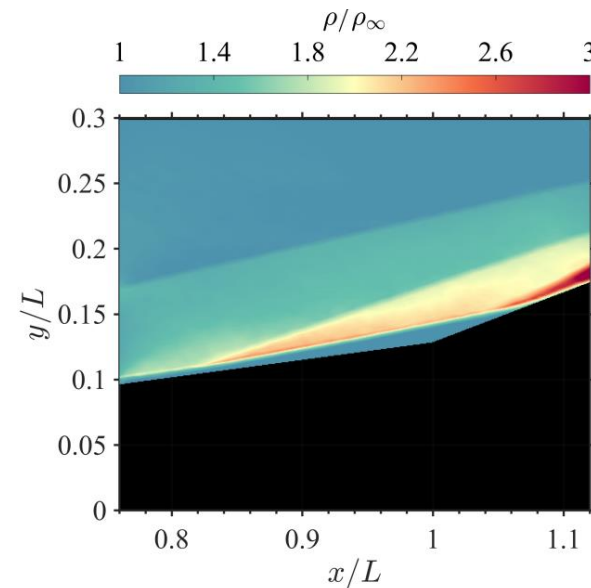
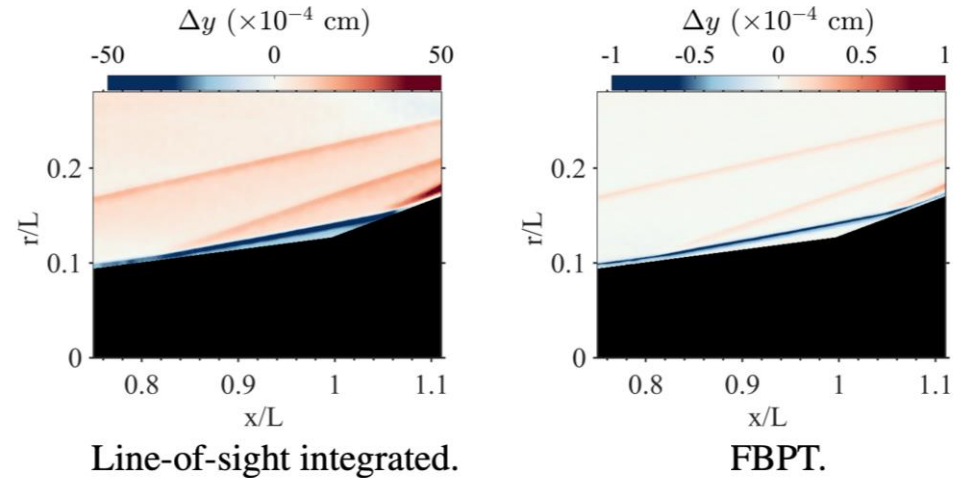
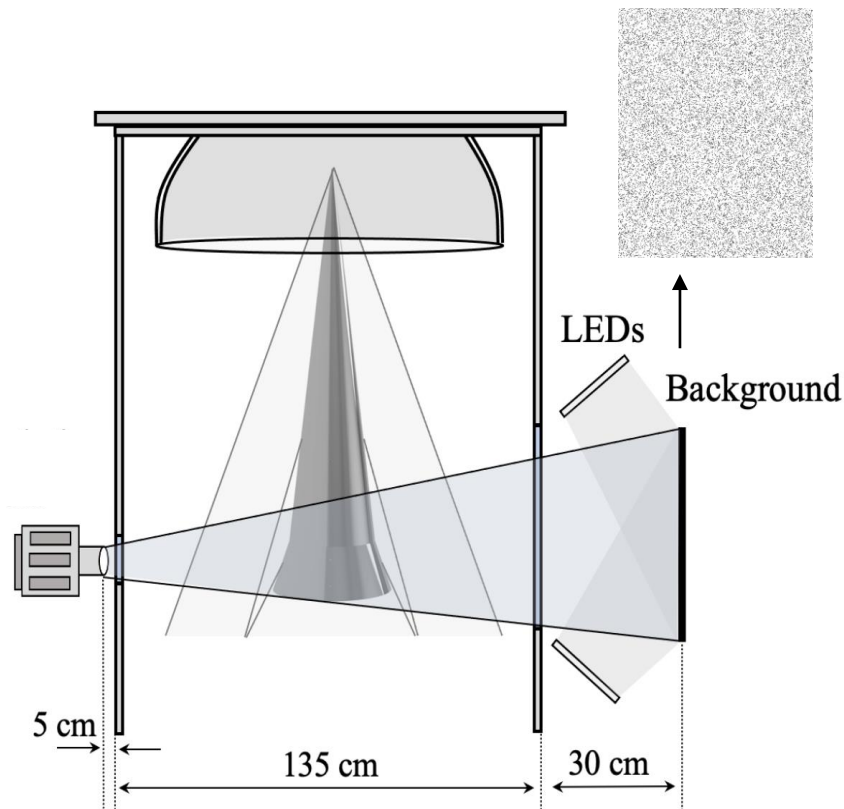


[4] Juliano et al. "HIFiRE-5 Flight Test." (2015).

[5] Rataczak et al. "Verification of quantitative infrared thermography heat-flux measurements." (2021)

[6] Running, C. L et al. "A wrap-film technique for infrared thermography heat-transfer measurements in high-speed wind tunnels," (2022)

- Displacements fields from cross-correlation of wind-off and -on images
- Filtered back projection to compute center plane displacement field of the axisymmetric flow^[4]
- Temporally filtered 0.13 s (3 frames) with a spatial resolution of 0.3 mm



^[7] Venkatakrishnan & Meier "Density Measurements using the Background Oriented Schlieren Technique." (2004).

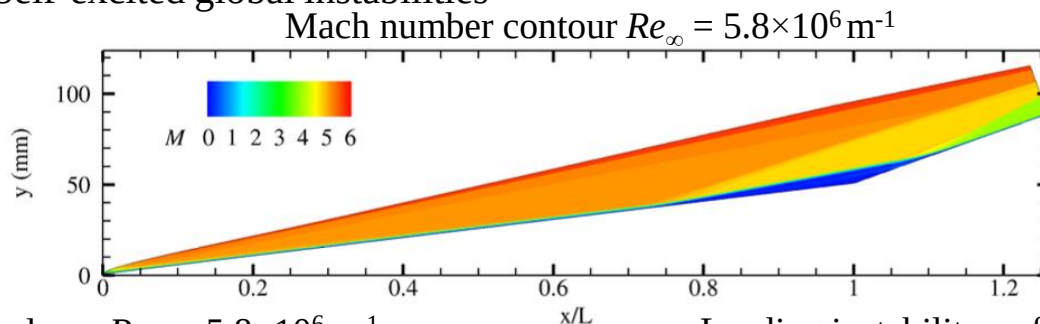
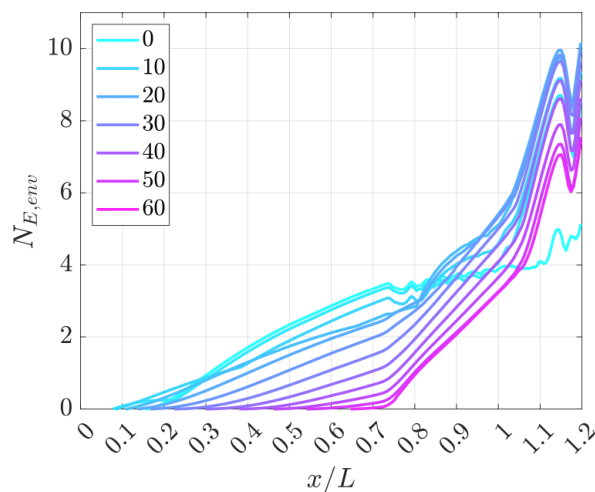
^[8] Davami, Juliano, Moreto, Liu, "Reconstructing a Hypersonic Shock-Wave/Boundary-Layer Interaction using Parallel-Ray Omni-Directional Integration." (2023)

Axisymmetric solution from VULCAN-CFD and SU2 solvers

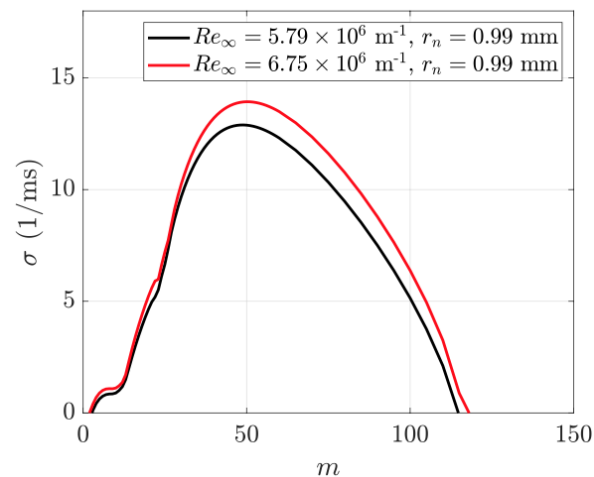
- VULCAN-CFD: shock-capturing, 2nd-order finite-volume NS solver
- Shock-adapted grid with 1601×601 points

Stability analysis

- PSE, HLNSE: Convective disturbances
- Global EVP: Self-excited global instabilities

N-factor envelope $Re_\infty = 5.8 \times 10^6 \text{ m}^{-1}$ 

Leading instability as function of wavenumber



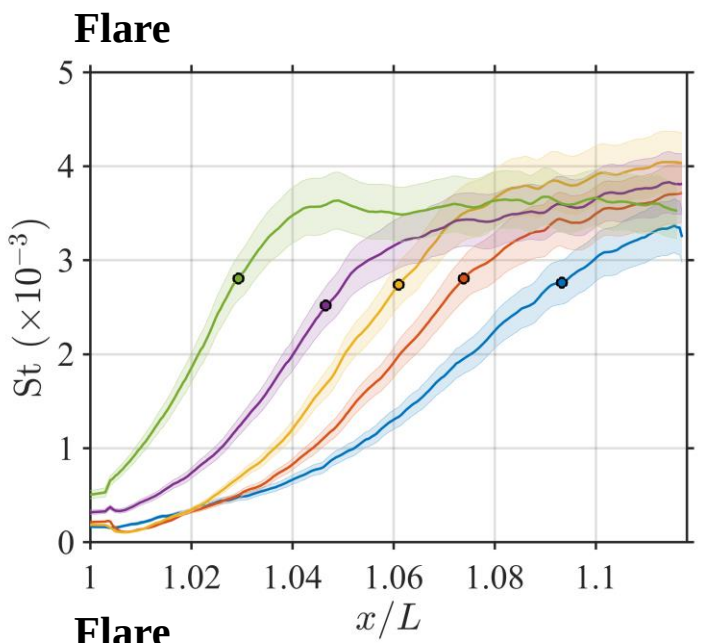
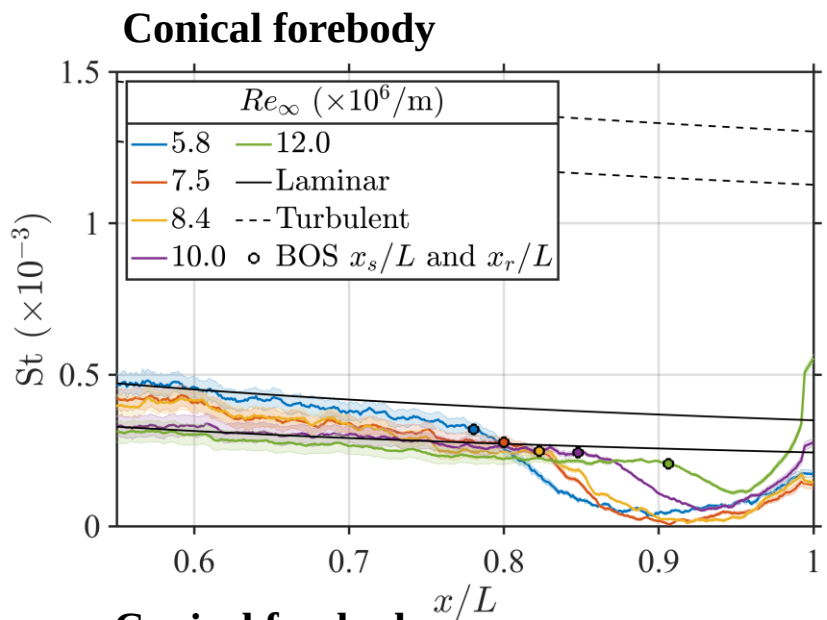
[9] Scholten et al. “Automatic Boundary-Layer Adaptation of Structured Grids in VULCAN-CFD.” (2022)

[10] Paredes et al. “Nosetip Bluntness Effects on Transition at Hypersonic Speeds: Experimental and Numerical Analysis.” (2019)

[11] Theofilis, et al. “On the origins of unsteadiness and three-dimensionality in a laminar separation bubble,” (2000)

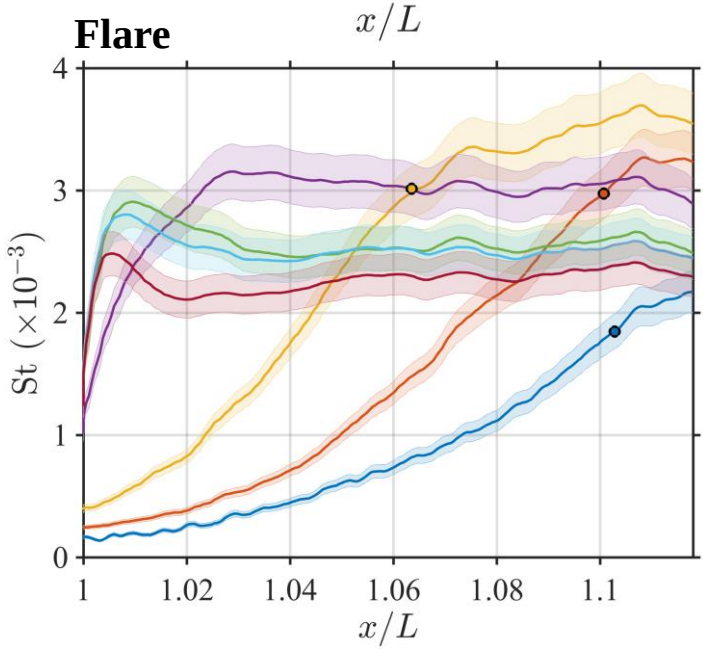
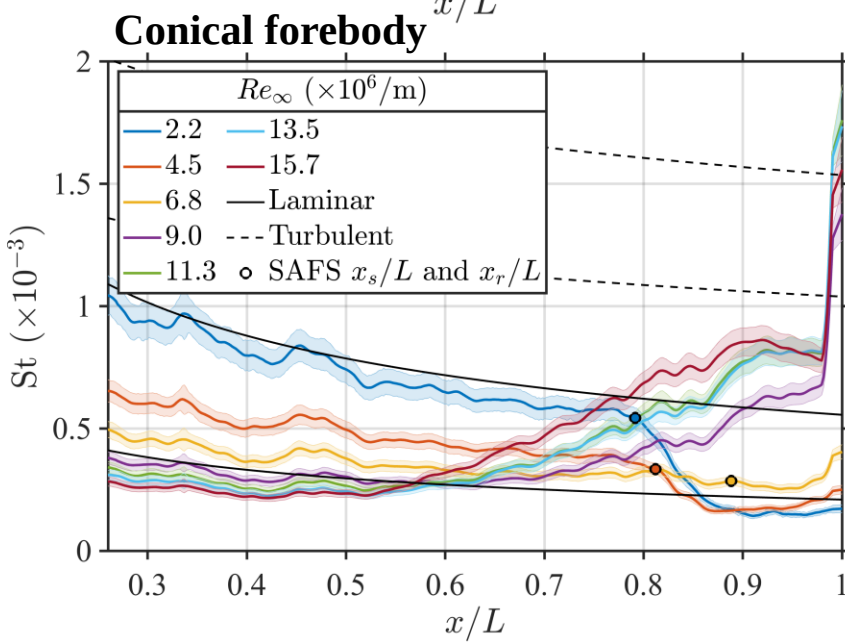
ANDLM6QT

$M_\infty = 5.7$
Noise: 2.5%



AFRL M6LT

$M_\infty = 6.14$
Noise: 3%

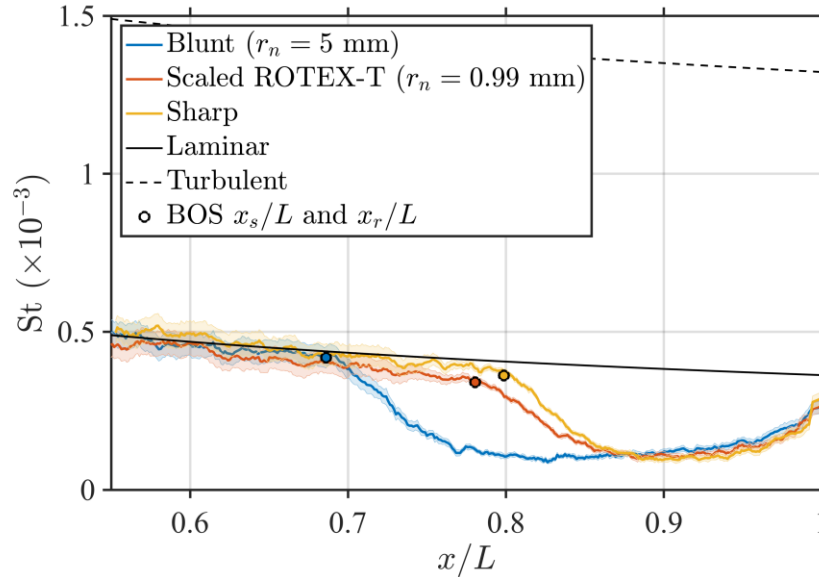


ANDLM6QT

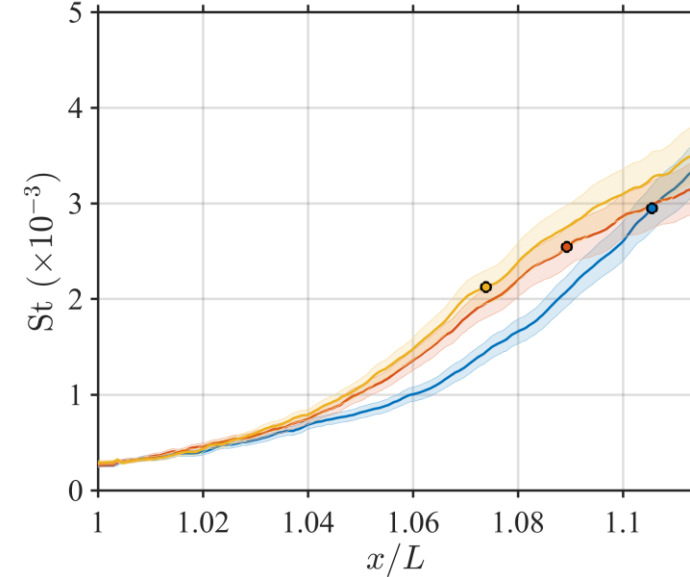
$$M_\infty = 5.7$$

$$\text{Re}_\infty = 5.8 \times 10^6 / \text{m}$$

Conical forebody



Flare



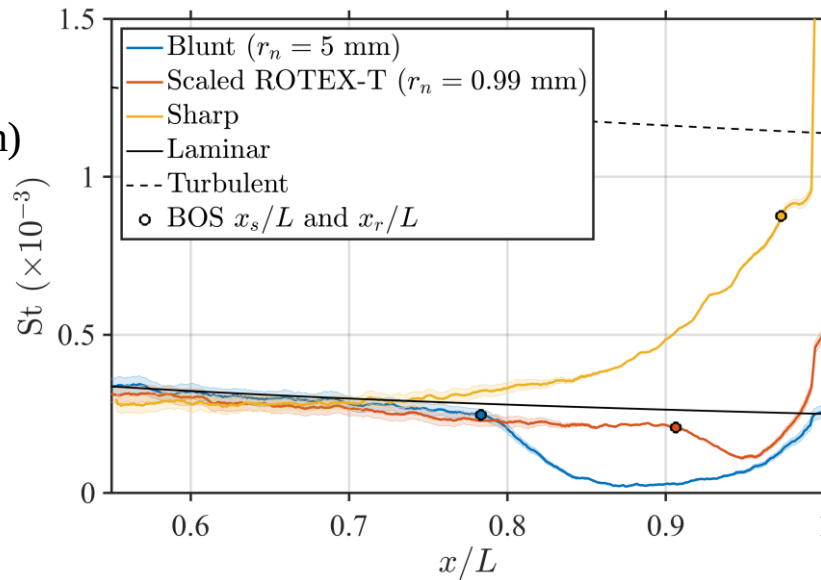
ANDLM6QT

$$M_\infty = 5.7$$

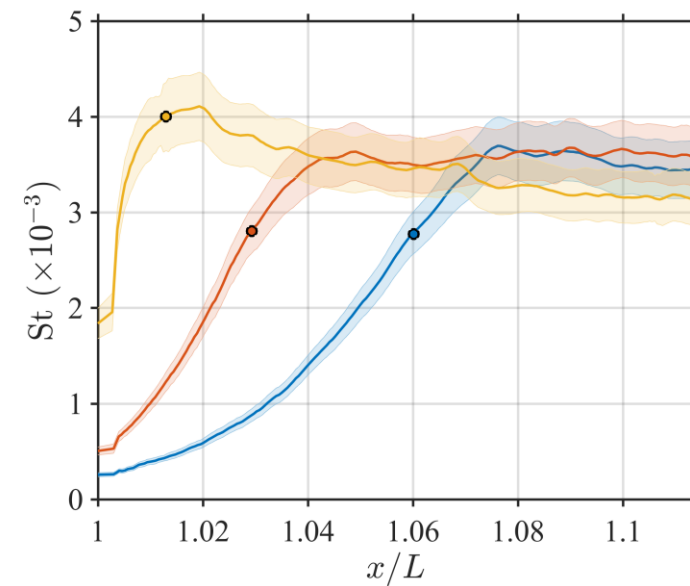
$$\text{Re}_\infty = 12.0 \times 10^6 / \text{m}$$

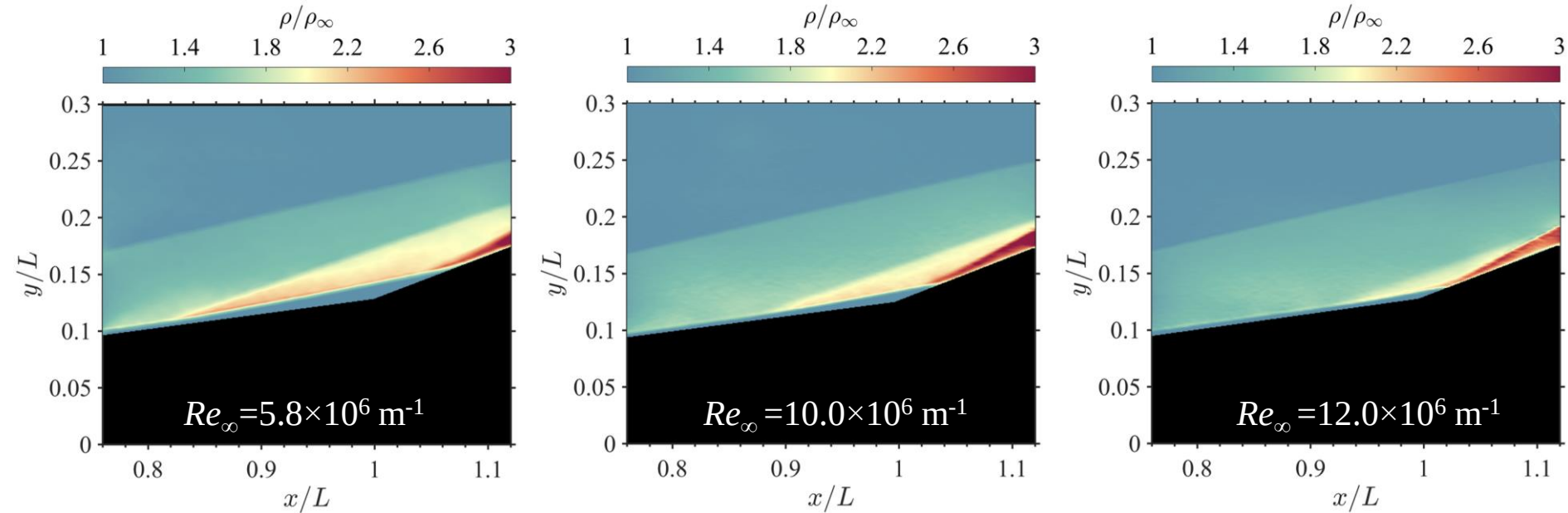
(Sharp: $12.2 \times 10^6 / \text{m}$)

Conical forebody

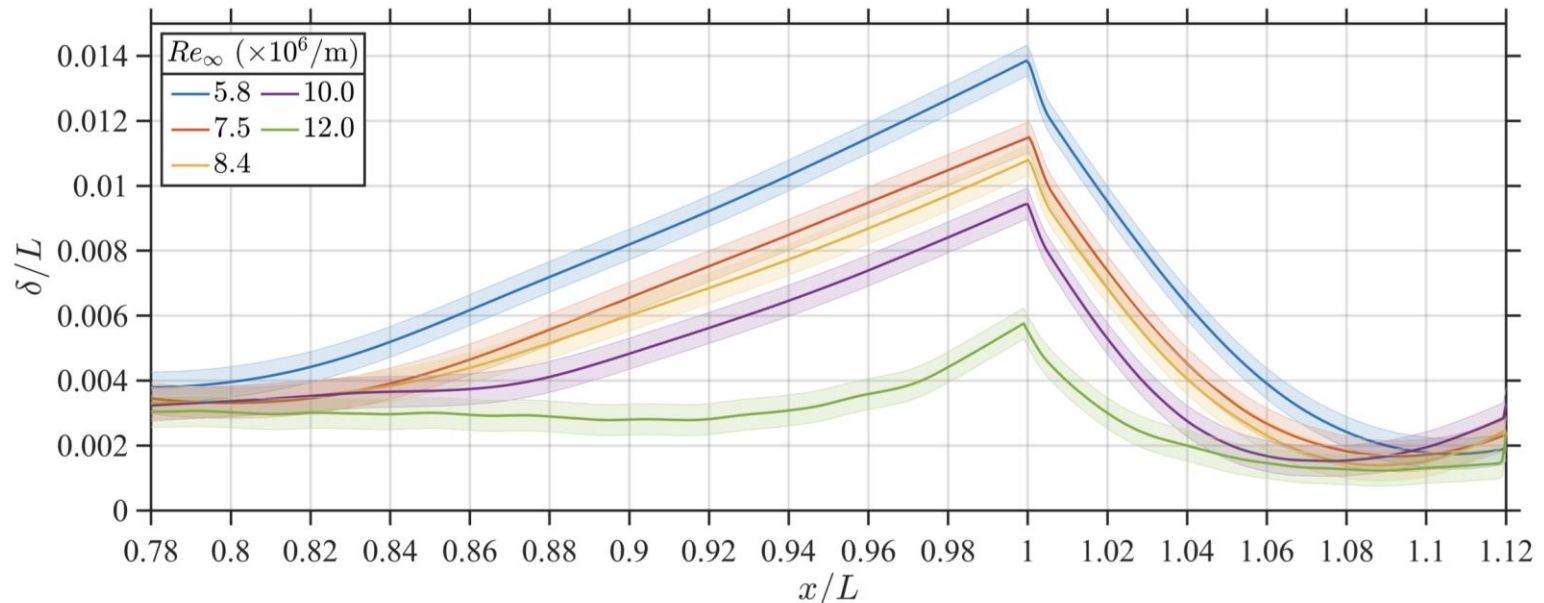


Flare

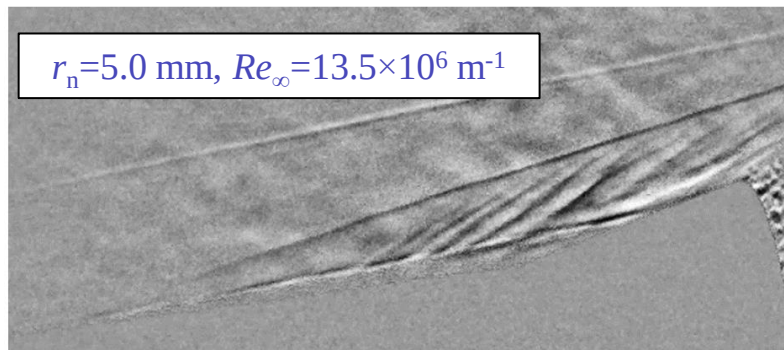
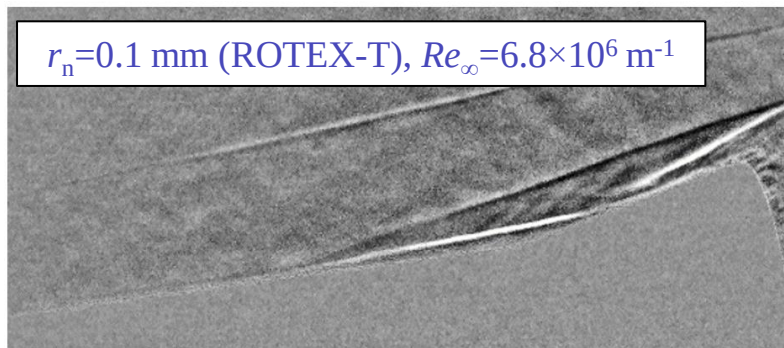
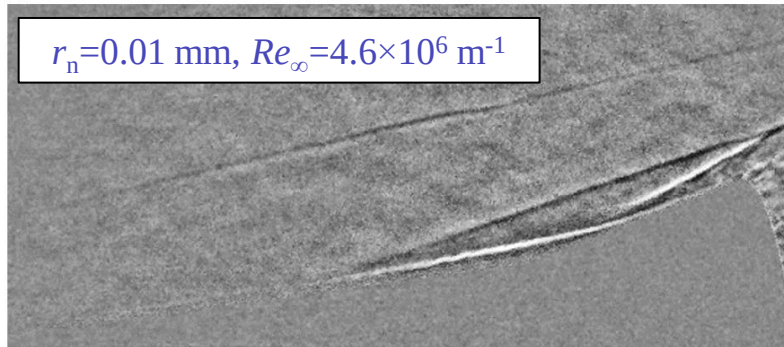




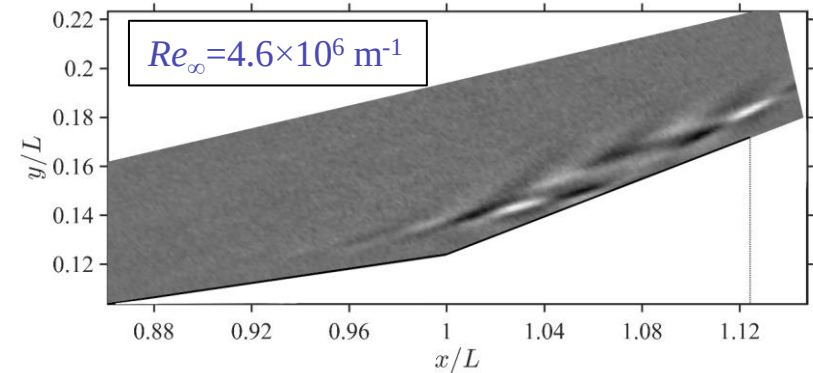
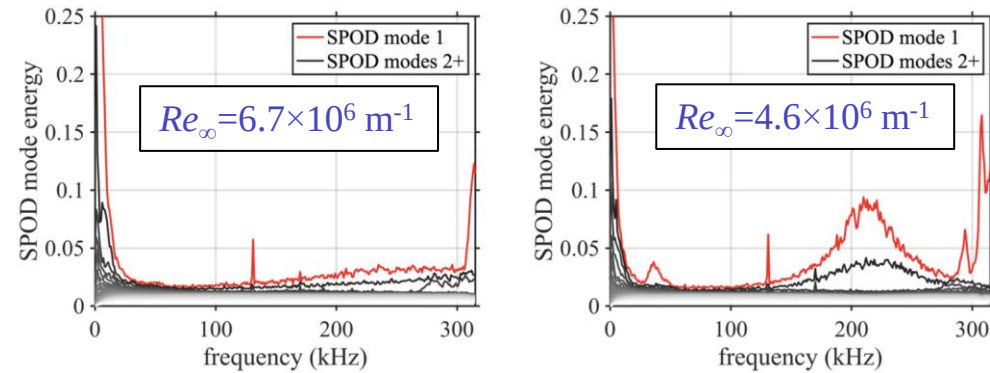
Boundary-layer thickness: wall-normal distance at which $\partial\rho/\partial y$ peaks (δ)



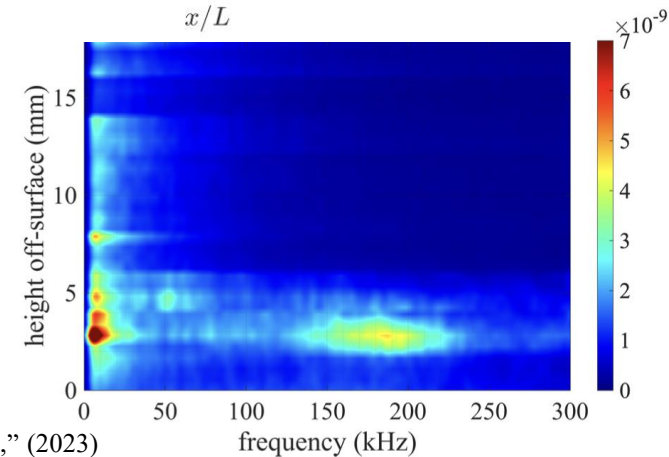
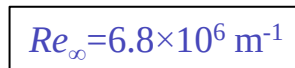
Instantaneous SAFS



SPOD Analysis, ROTEX-T

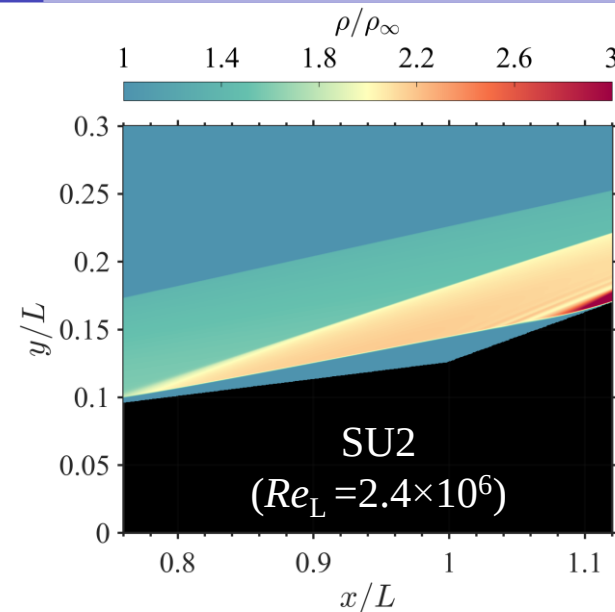
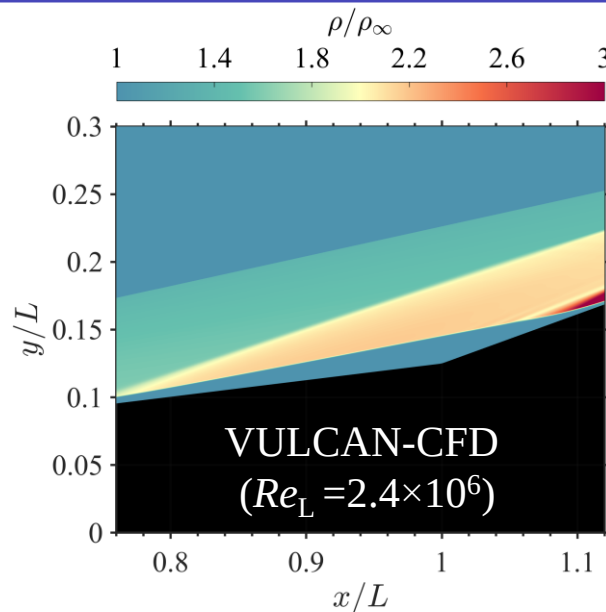
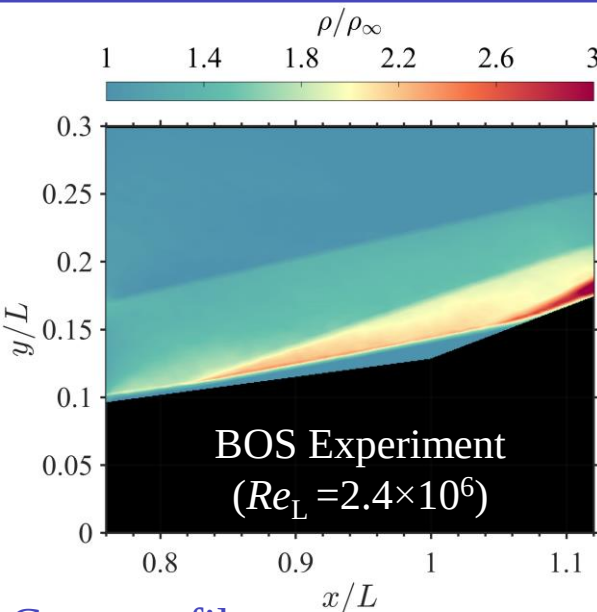


LA-FLDI

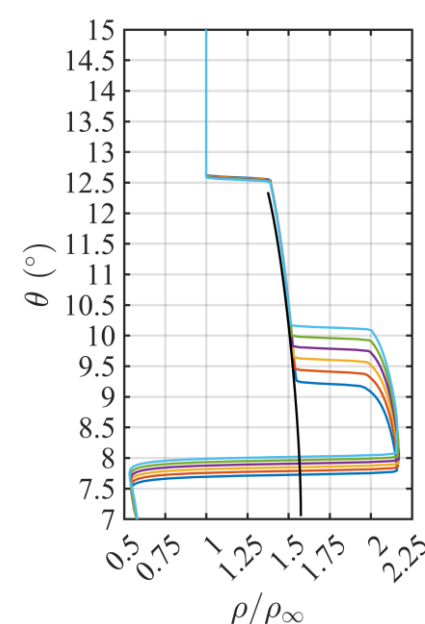
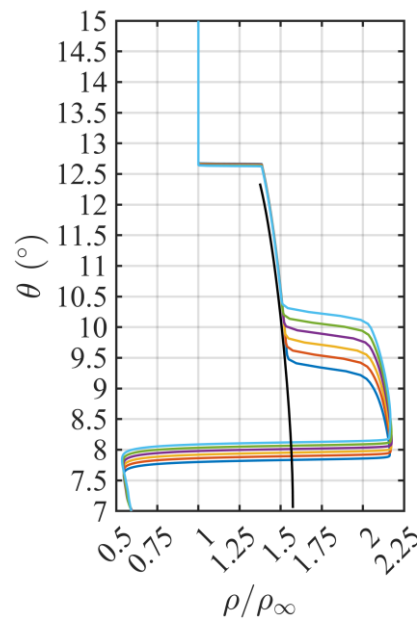
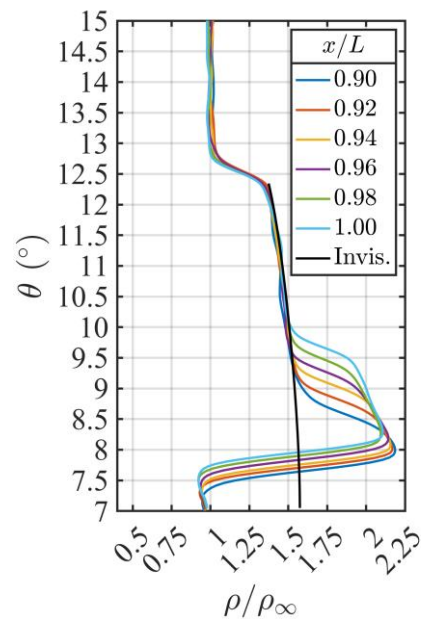


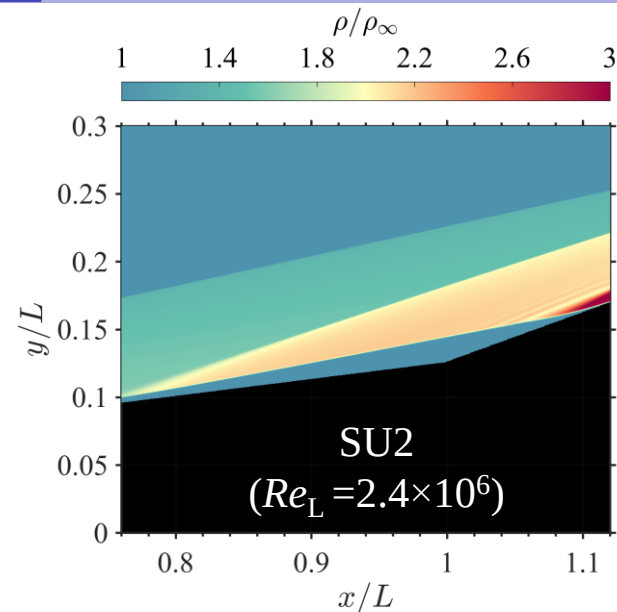
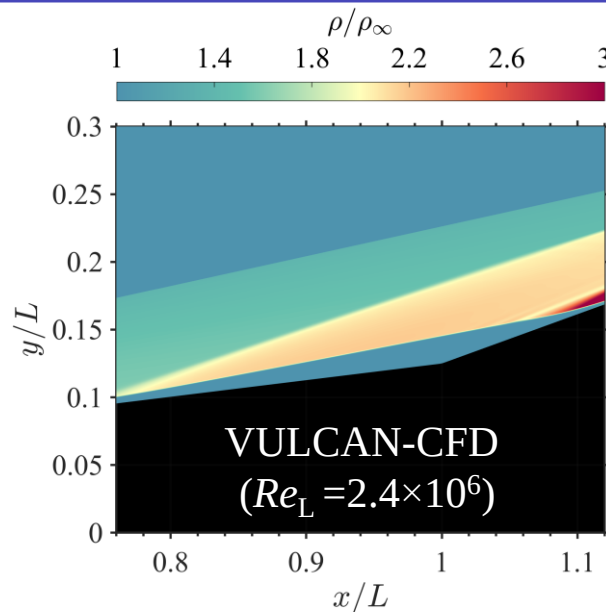
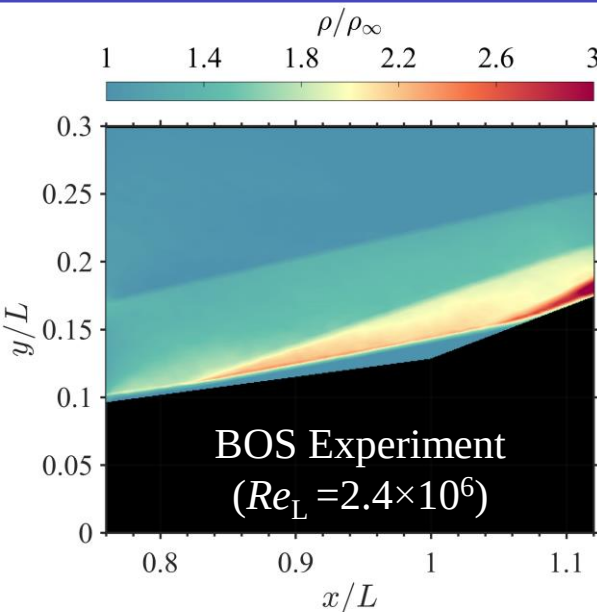
^[12]Hill et al. "Implementation of Self-Aligned Focusing Schlieren for Hypersonic Boundary Layer Measurements," (2023)

^[13]Benitez et al. "Hypersonic Transitional Boundary-Layer Profile using a Linear-Array FLDI," (2023)

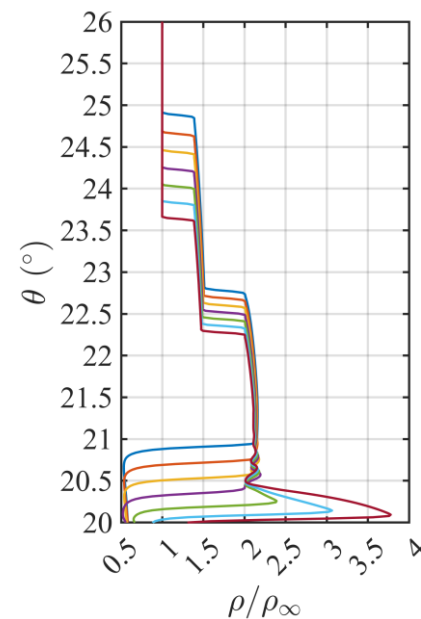
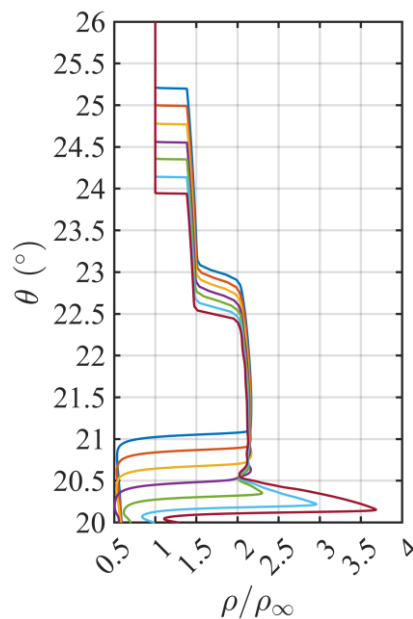
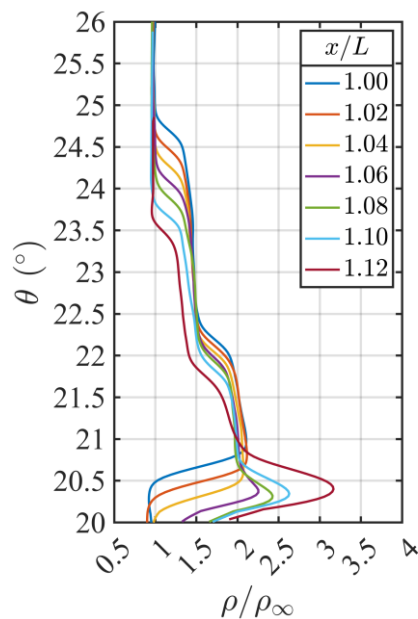


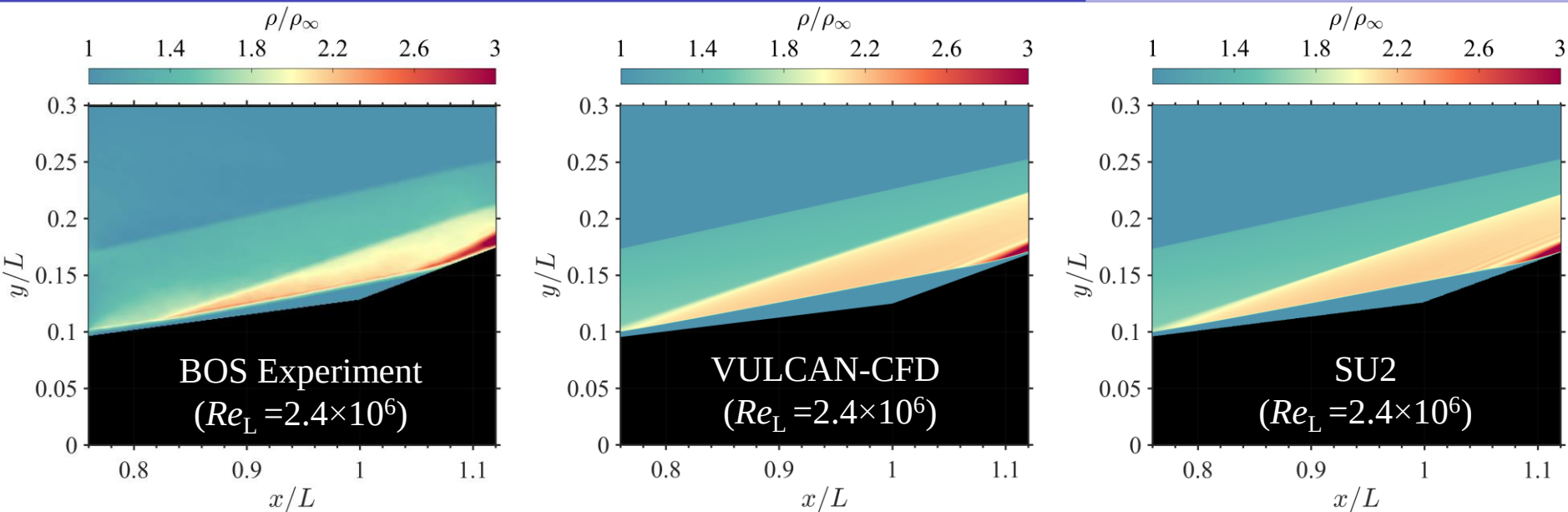
Cone profiles:



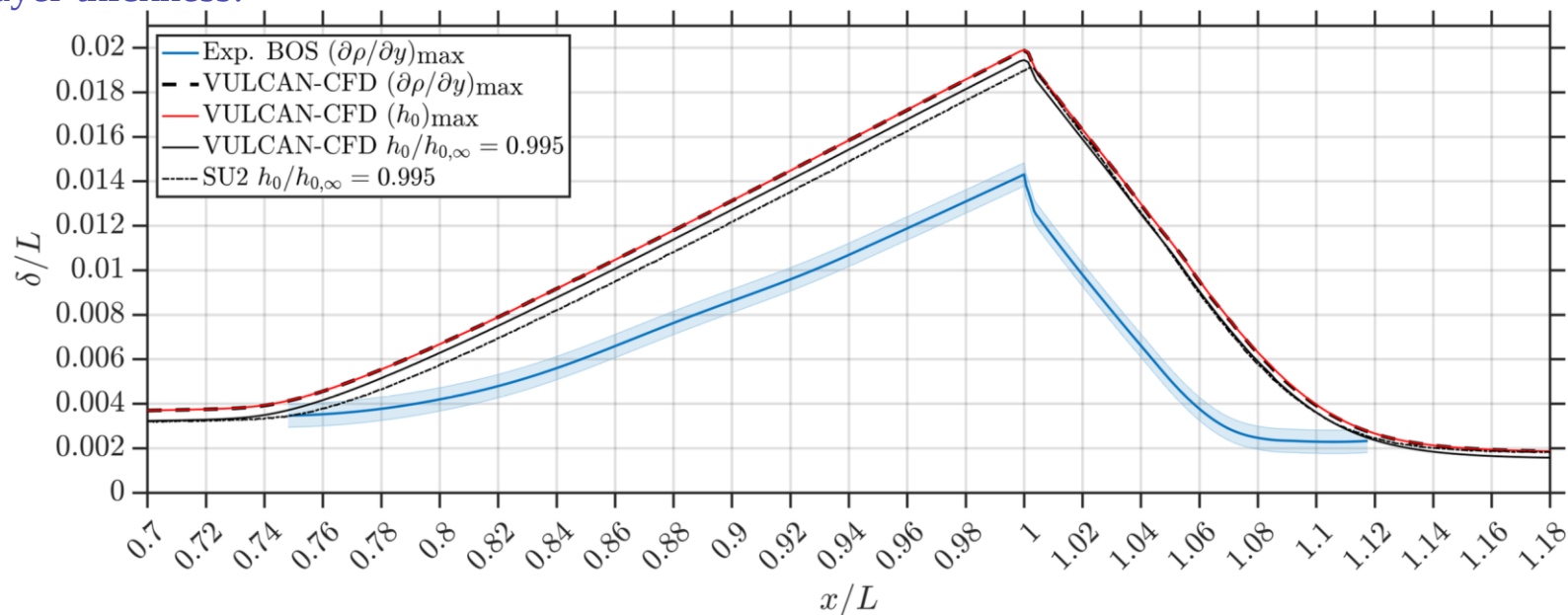


Flare profiles:

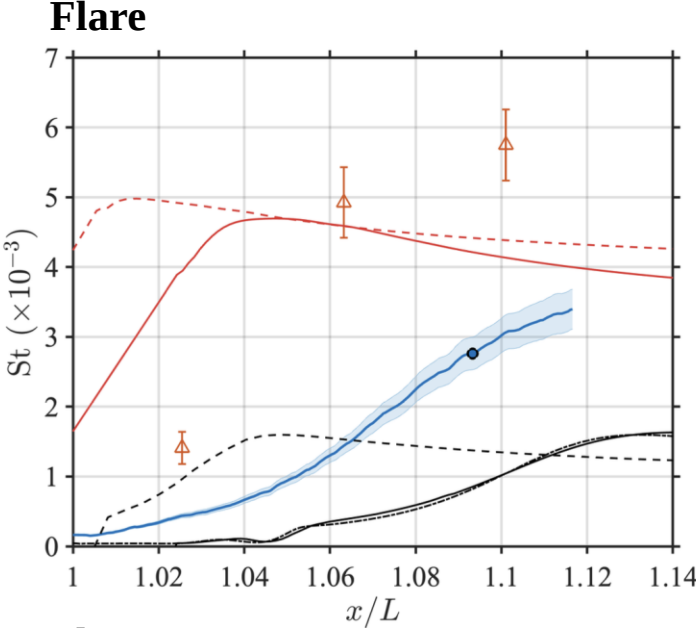
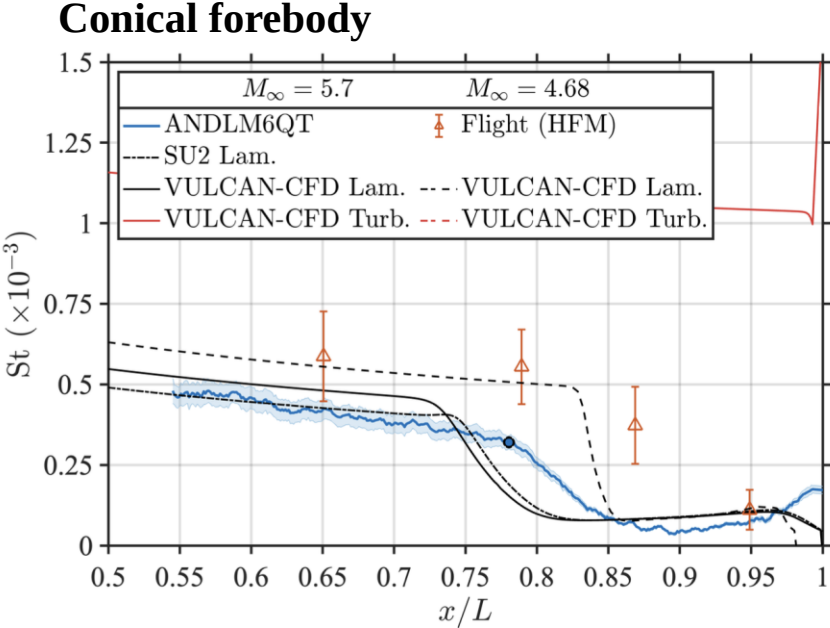




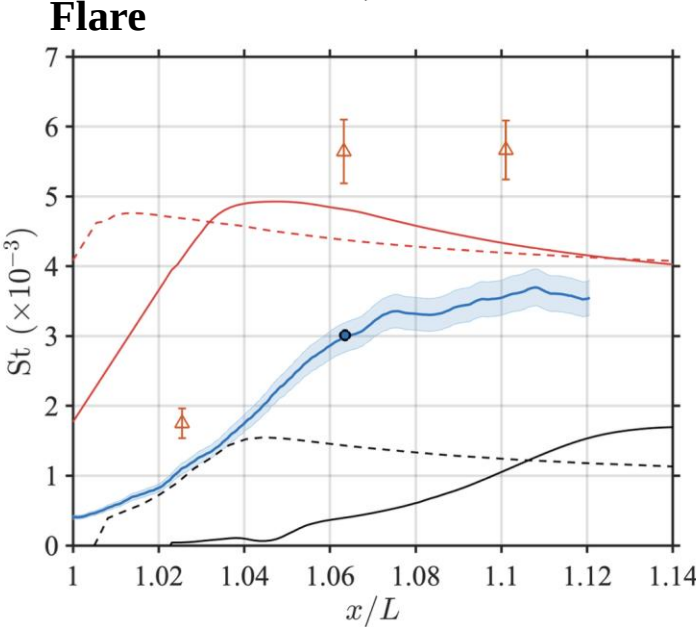
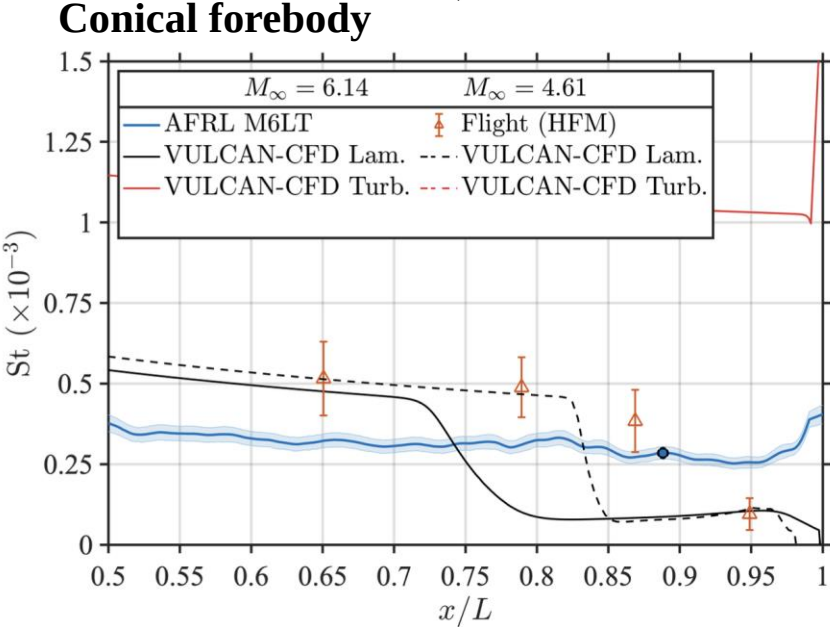
Boundary-layer thickness:

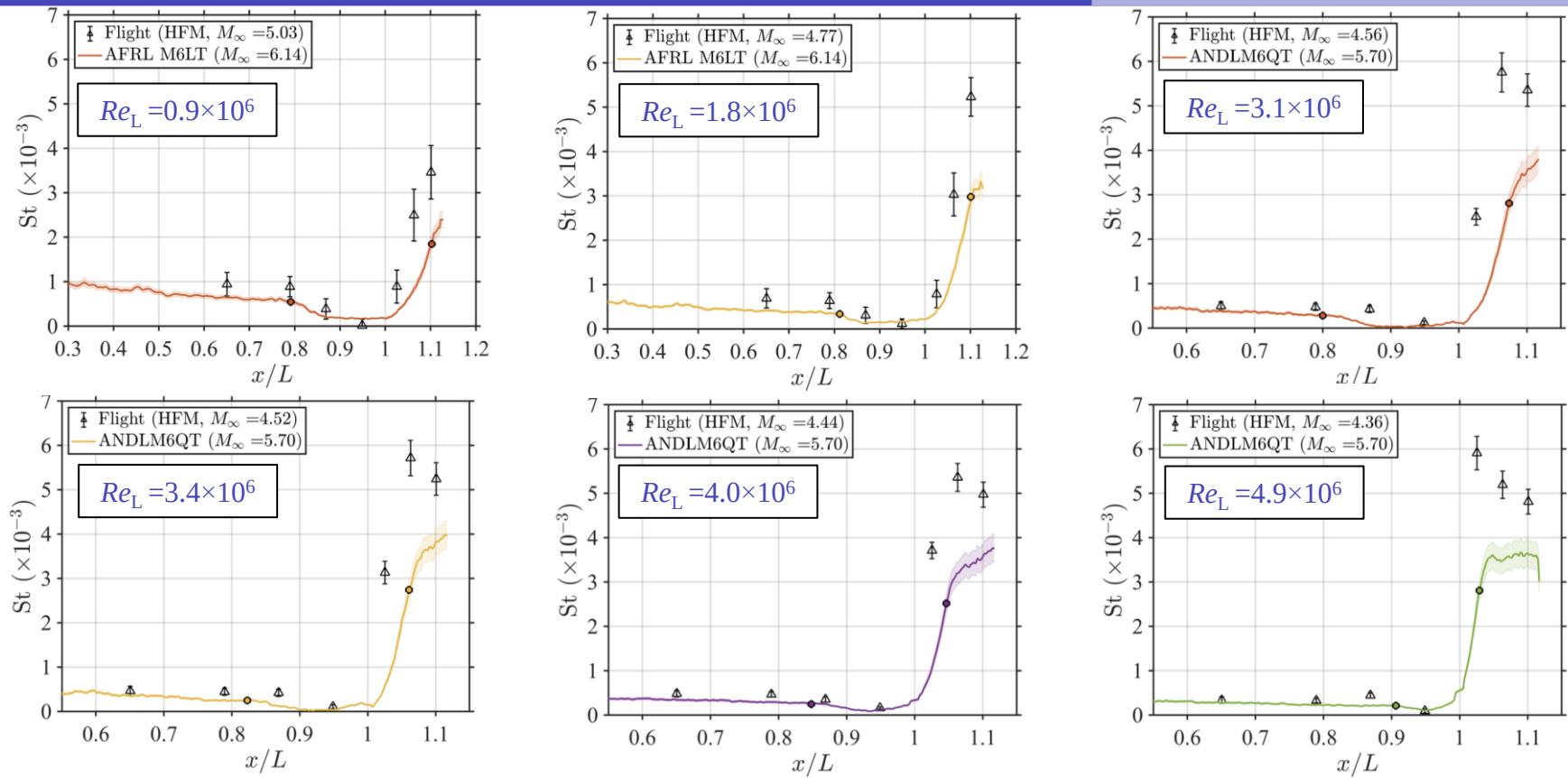


ANDLM6QT
Comparison



AFRL M6LT
Comparison





Source	M_∞	Flare Boundary-Layer State	x_s/L	x_r/L
ANDLM6QT	5.7	Transitional	0.78	1.09
SU2 (ground)	5.7	Laminar	0.7587	1.1180
VULCAN-CFD (ground)	5.7	Laminar	0.7479	1.1261
Flight	4.68	Transitional	0.79–0.95	–
VULCAN-CFD (flight)	4.68	Laminar	0.8718	1.0572
AFRL M6LT	6.14	Transitional	0.89	1.06
VULCAN-CFD (ground)	6.14	Laminar	0.7404	1.1264
Flight	4.61	Transitional	0.79–0.95	–
VULCAN-CFD (flight)	4.61	Laminar	0.8481	1.0572

Summary

- Excellent quantitative heat flux and density measurements
- Evolution of boundary-layer thickness was determined from experiments
- BOS-density fields match closely with laminar VULCAN and SU2 computations
- Boundary-layer thickness was similar to computations
- Heating comparisons between flight, experiment, and ground-tests agreed on conical forebody, less so on the flare (heating behavior was similar for flight and ground-tests)
- Insights gained from the coordinated, on- and off-wall ground-test measurements allowed for assessment of reattaching flow during flight

Future Work

- Test at lower freestream unit Reynolds numbers in the ANDLM6QT
- Design and test longer flare petals to observe the full evolution of the boundary layer
- Study effect of angle of attack and yaw on the SWBLI
- Pressure sensitive paint on a smaller model and on the flare petals of this model
- Experiments at Mach 3.5 in NASA SLDT and NASA 20-in. Mach 6 Tunnel
- Direct Numerical Simulation

- Dr. Elizabeth Benitez, Dr. Matthew Borg, and Luke Hill, for allowing Jonny to help setup and test ROTEX-T at AFRL
- Andrew Leidy, for helping proof-read the conference paper
- Jonathan Davami is supported by a University of Notre Dame Dean's Fellowship.
- Anton Scholten and Pedro Paredes are supported by the U. S. Office of Naval Research under award numbers N00014-20-1-2261 and N00014-23-1-2456.
- Pedro Paredes is also partially supported by the Hypersonic Technology Project (HTP) under the NASA Aeronautics Research Mission Directorate (ARMD) and by the Air Force office of Scientific Research under award number FA9550-20-1-0023. The computational resources supporting this work were provided by the DoD High Performance Computing Modernization Program and the NASA LaRC K Cluster at the Langley Research Center.
- The work of Kamil Dylewicz, Wojtech Pezlar and Vassilis Theofilis is supported by the Air Force Office of Scientific Research under award number FA8655-23-1-7031 “Linear modal and non-modal instability analyses of high-speed laminar separated flow over complex geometries. Part II: The HIFiRE-1, ROTEX-T and Oberkampf vehicles” with Dr. Douglas Smith as Program Officer.

- [1] Davami, J., Juliano, T. J., Scholten, A., and Paredes, P., “Hypersonic Shock-Wave/Boundary-Layer Interactions on the ROTEX-T Cone/Flare,” AIAA Paper 2023-1436, January 2023.
- [2] Thiele, T., Gulhan, A., and Oliver, H., “Instrumentation and Aerothermal Postflight Analysis of the Rocket Technology Flight Experiment ROTEX-T,” AIAA Journal of Spacecraft and Rockets, Vol. 55, No. 5, 2018
- [3] Benitez, K. E., J. S. Jewell., and Schneider, P. S., “Separation Bubble Variation Due to Small Angles of Attack for an Axisymmetric Model at Mach 6.” (2021). AIAA SciTech 2021-0245.
- [4] Juliano, T. J., Adamczak, D., and Kimmel, R. L., “HIFiRE-5 Flight Test Results,” *Journal of Spacecraft and Rockets*, Vol.52, No. 3, 2015, pp. 650–663.
- [5] J. A. Rataczak and C. L. Running and T. J. Juliano., “Verification of quantitative infrared thermography heat-flux measurements,” *Experimental Thermal and Fluid Science*, Vol. 37, 2004, p. 237–247.
- [6] Running, C. L., Rataczak, J. A., Zaccara, M., Cardone, G., and Juliano, T. J., “A wrap-film technique for infrared thermography heat-transfer measurements in high-speed wind tunnels,” *Experimental Thermal and Fluid Science*, Vol. 135, No. 110604, 2022, pp. 1–8.
- [7] Venkatakrisnan, L., and Meier, G. E. A., “Density Measurements using the Background Oriented Schlieren Technique,” *Experiments in Fluids Paper*, Vol. 121, 2021, p. 1-8.
- [8] Davami, J., Juliano, T. J., Moreto, J. R., and Liu, X., “Reconstructing a Hypersonic Shock-Wave/Boundary-Layer Interaction using Parallel-Ray Omni-Directional Integration,” ISPIV, 2023.
- [9] Scholten, A., Paredes, P., Li, F., White, J., Baurle, R., and Choudhari, M., “Automatic Boundary-Layer Adaptation of Structured Grids in VULCAN-CFD,” ICCFD11 Paper 2022-1304, 2022.
- [10] Paredes, P., Choudhari, M., Li, F., Jewell, J., Kimmel, R., Marineau, E., and Grossir, G., “Nosetip bluntness effects on transition at hypersonic speeds: experimental and numerical analysis,” *Journal of Spacecraft Rockets*, Vol. 56, No. 2, 2019.
- [11] Theofilis, V., Hein, S., and Dallmann, U., “On the origins of unsteadiness and three-dimensionality in a laminar separation bubble,” *Phil. Trans. R. Soc. Lond. A*, Vol. 358, 2000, pp. 3229–3246.
- [12] Hill, J., Borg, M., Benitez, E., Running, C., and Reeder, M., “Implementation of Self-Aligned Focusing Schlieren for Hypersonic Boundary Layer Measurements,” AIAA Paper 2023-2438, 2023.
- [13] Benitez et al. “Hypersonic Transitional Boundary-Layer Profile using a Linear-Array FLDI,” (2023)

Extra Slides