Preliminary Measurements on the BOLT Geometry in the Supersonic Low Disturbance Tunnel

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Session: Instability and Transition II, Tuesday 1:00 PM to 3:00 PM

Introduction

- Goal of the BOLT program: Improve high-speed boundary layer transition models (Wheaton et al., 2018)
  - Multiple transition mechanisms
  - Computations, Ground tests, Flight test
- A common model was tested in multiple facilities (Berridge et al., 2019; Kostak et al., 2019)
- BOLT-II was tested at CUBRC prior to flight (Dufrene et al., 2023)
- A third flight test is upcoming
- Modifications have been made to ground test models (Wernz, 2023; Hill et al., 2023)

Wheaton, B. M., Berridge, D. C., Wolf, T. D., Stevens, R. T., and McGrath, B. E., "Boundary Layer Transition (BOLT) Flight Experiment Overview," AIAA Paper 2018-2892, June 2018
Berridge, D. C., Kostak, H. E., McKiernan, G. R., King, R. A., Wason, M. P., Wheaton, B. M, Wolf, T. D., and Schneider, S. P., "Hypersonic Ground Tests With High-Frequency Instrumentation In Support of the Boundary Layer Transition (BOLT) Flight Experiment," AIAA Paper 2019-0090, January 2019
Kostak, H. E., Bowersox, R. D. W., McKiernan, G. R., Thome, J., Candler, G. V., and King, R. A., "Freestream Disturbance Effects on Boundary Layer Instability and Transition on the AFOSR BOLT Geometry," AIAA Paper 2019-0088, January 2019
Dufrene, A. T., Portoni, P., Wadhams, T. P., Kostak-Teplicek, H. E., and Bowersox, R. D. W., "Boundary Layer Turbulence Flight Experiment in Memory of Mike Holden: Vehicle Design, Instrumentation, and Ground Test Results," AIAA Paper 2023-0478, January 2023
Wernz, S., "Flat-BOLT Surrogates for Investigating Second-Mode and Crossflow Instabilities," AIAA Paper 2023-3442, June 2023
Hill, J. L., Borg, M. P., Tufts, M. W., Benitez, E. K., and Reeder, M. F., "Leading-Edge Curvature Influence on Hypersonic Boundary Layer Transition," AIAA Paper 2023-0098, January 2023

Motivation for supersonic testing

- The BOLT-1A flight reached a maximum Mach of 3.9 (Butler et al., 2022)
- A vehicle must pass through supersonic flow to reach hypersonic flow
- Quiet tunnel data is desirable for computational comparisons

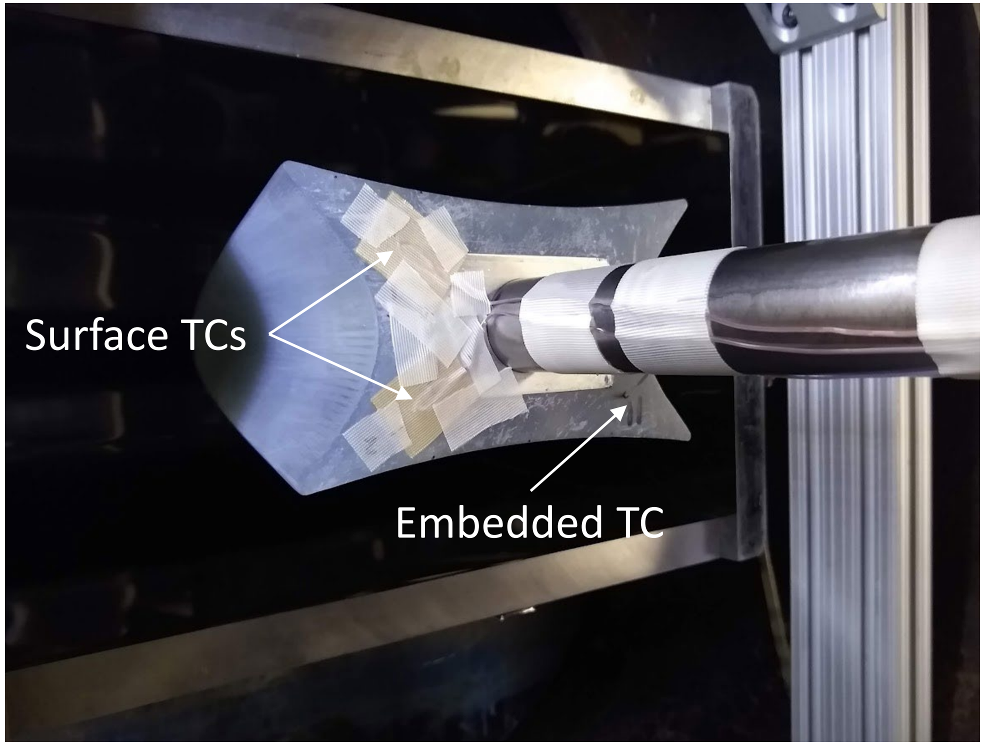
Butler, C. S., Araya, D. B., McKiernan, G. R., and Wheaton, B. M., "Supersonic Transition Measurements During the BOLT Flight Experiment Descent Phase," AIAA Paper 2022-4099, June-July 2022

Supersonic Low Disturbance Tunnel (SLDT)

- Mach 3.5 quiet tunnel (Beckwith et al., 1983)
- 2-D planar rapid expansion nozzle
- Infrastructure allows for running for hours at a time

Nominal Testing Conditions

	M	T_0 (K)	P_{01} (kPa)	$Re \times 10^{-6}$ (/m)
Surface	3.5	299.8	82.7 – 276	4.75 – 15.8
Freestream	3.5	299.8	138, 207, 276	7.92, 11.9, 15.8
Off-body	3.5	299.8	138	7.92

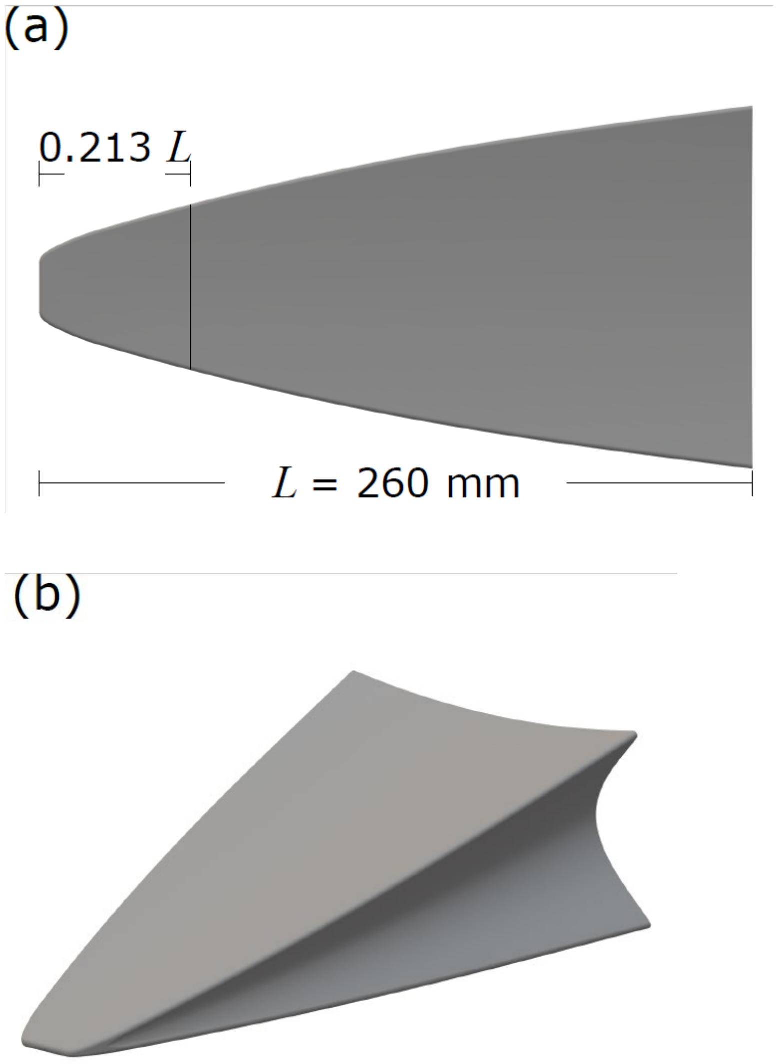


BOLT model in SLDT

Beckwith, I. E., Creel, T. R., Chen, F. J., and Kendall, J. M., "Free-Stream Noise and Transition Measurements on a Cone in a Mach 3.5 Pilot Low-Disturbance Tunnel," NASA TP 2180, September 1983

BOLT model

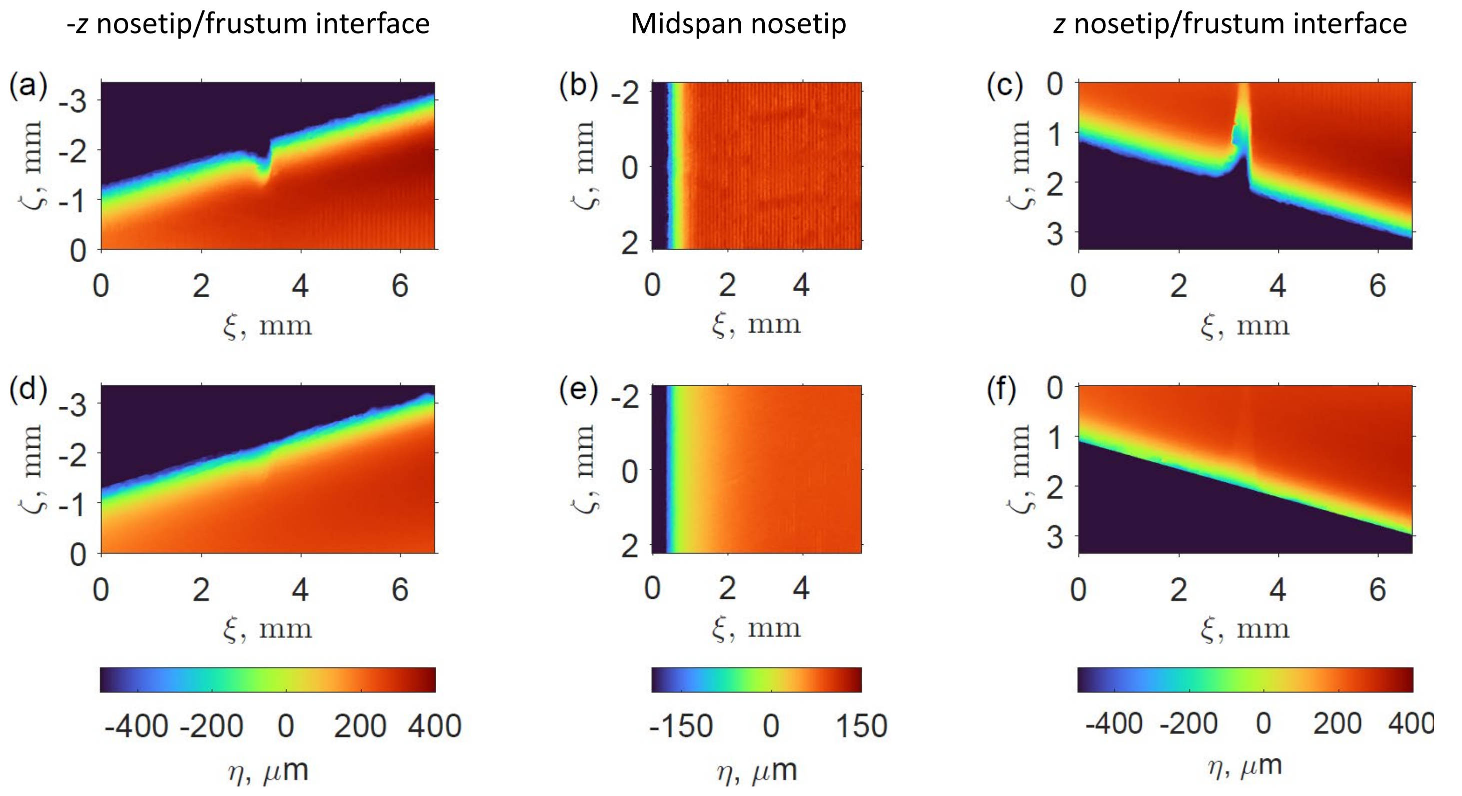
- Model is 30% scale of the flight geometry
- 3-D printed of polycarbonate
- Nosetip and frustum pieces aligned with pins and bonded with epoxy
- Model was tested in two entries
    - As printed
    - After improvements



BOLT model: (a) Top view, (b) Isometric view

BOLT optical scans

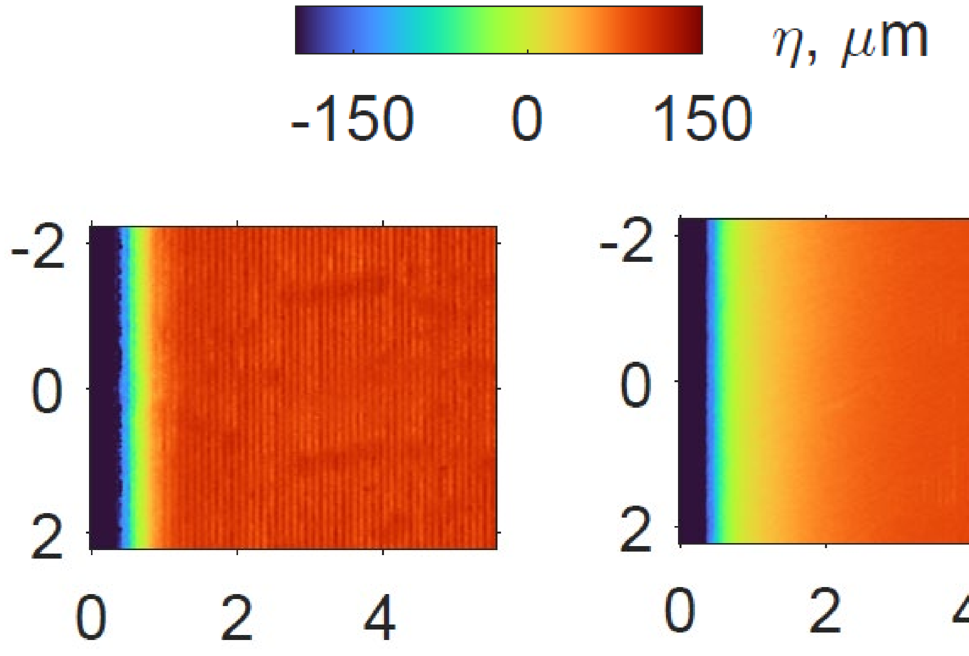
- The as-printed and improved versions of the model were scanned using a 3-D optical profilometer
- Leading-edge gaps and surface roughness were initially present due to printing



BOLT model Side A scans.
Top row: as-printed model
Bottom row: model after improvements

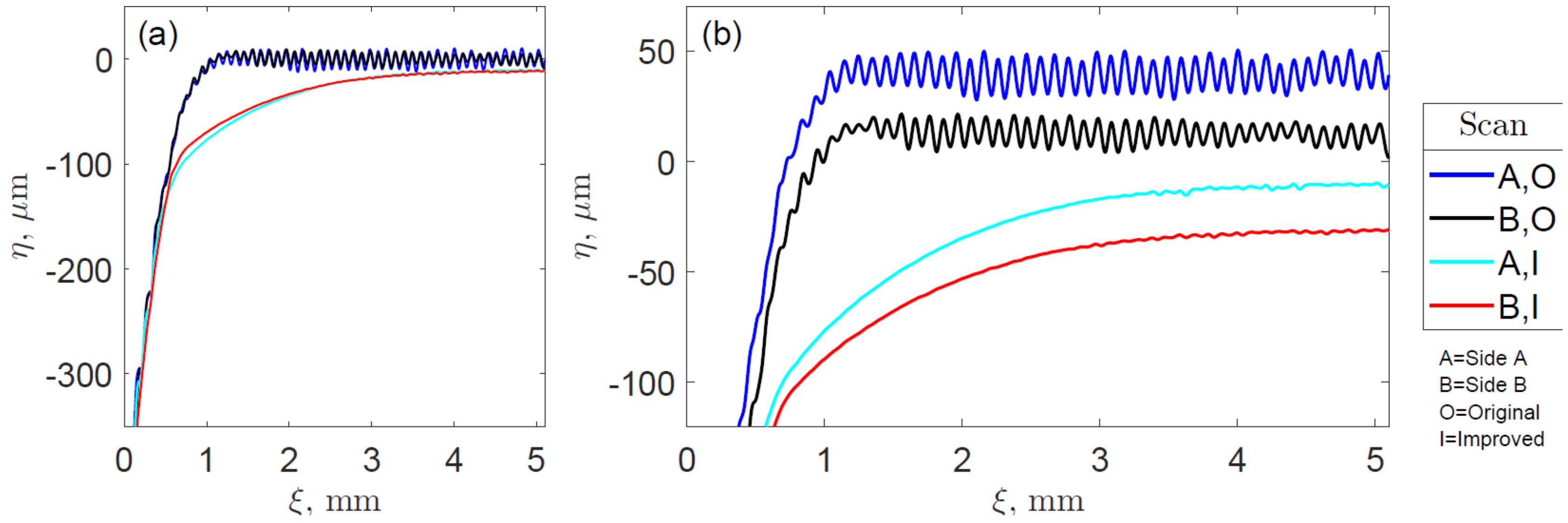
BOLT optical scans

- Nosetip roughness is spanwise oriented and periodic
- Improving the model changed the curvature at the tip



Midspan nosetip scans: (left) as-printed and (right) after improvements

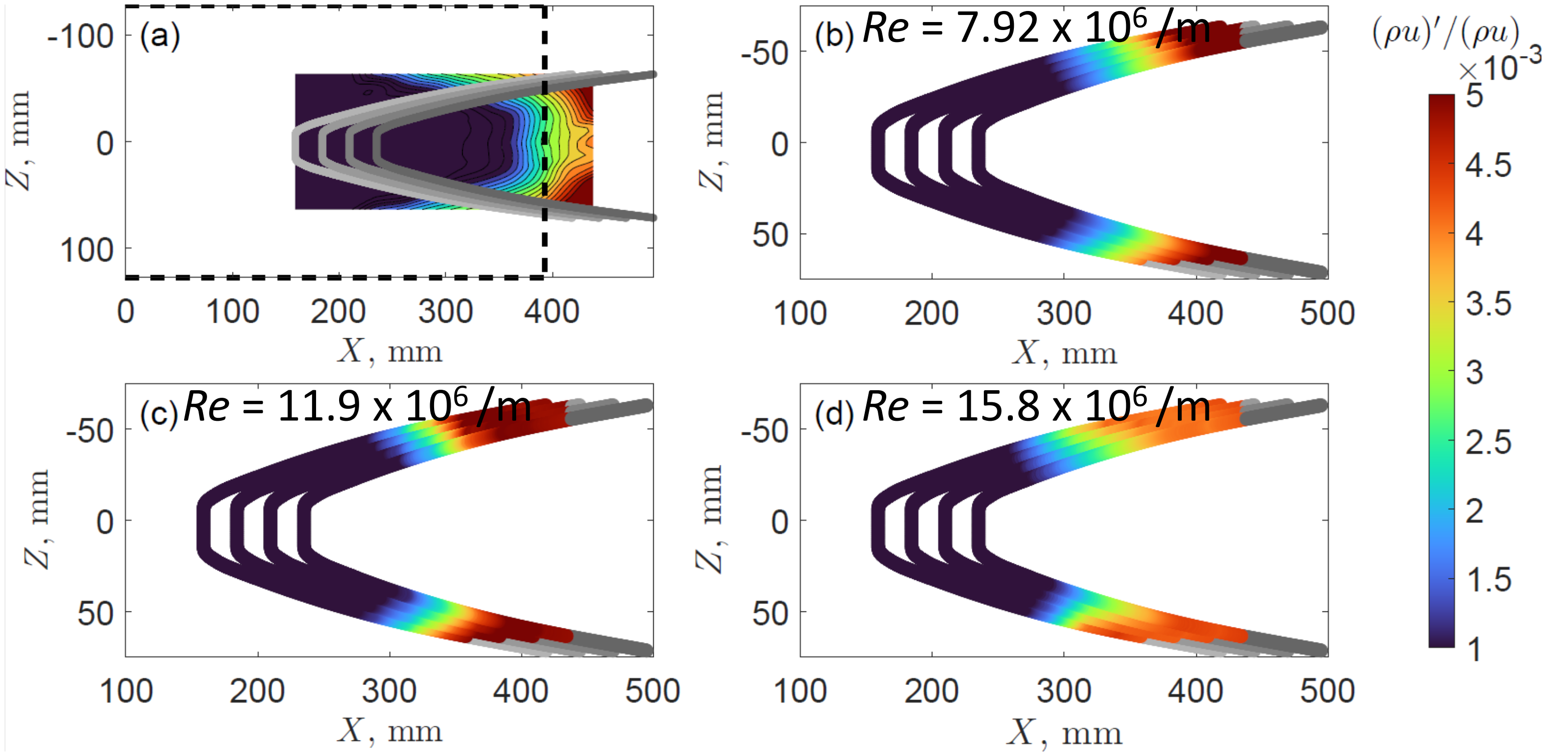
- Geometry is consistent on both sides of the model
- Improving the model reduced R_q from 6.98 to 1.18 μm



Relative height averaged across the span to highlight: (a) differences in curvature, (b) surface roughness

Quiet flow: Freestream hot-wire surveys

- Surveys were made using a dual-wire hot-wire probe
- Mass flux was measured for 3 different *Re*
- Quiet core, *(ρu)'/(ρu)* <0.1%, shown as dark violet
- Fluctuations are projected on to the positions of the model tested during the campaign



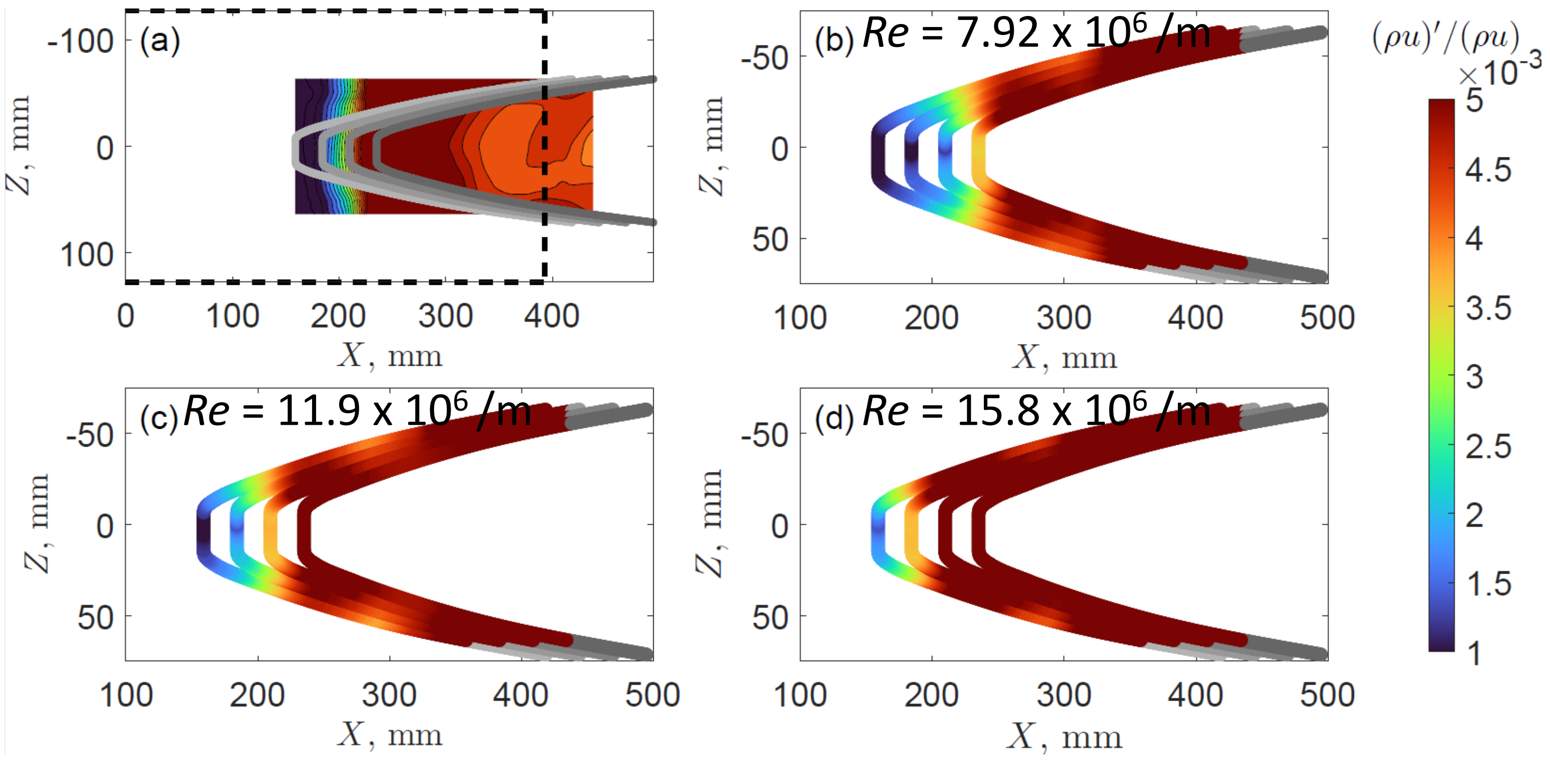
Freestream mass-flux fluctuations in quiet flow

(a) at Y=0 for Re = 11.9 x 10^6 /m

Projected fluctuations on model leading edge for:
(b) Re = 7.92 x 10^6 /m , (c) Re = 11.9 x 10^6 /m , (d) Re = 15.8 x 10^6 /m

Noisy flow: Freestream hot-wire surveys

- Quiet flow is minimal and upstream of the model for most testing positions
- Projected fluctuations on most of the leading edge > 0.5%



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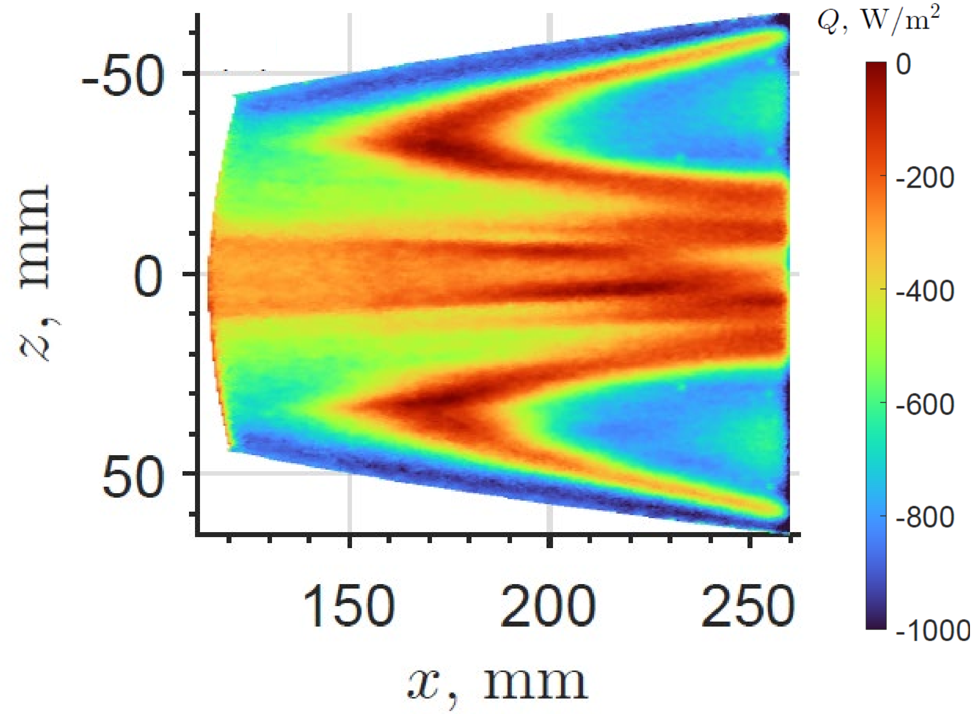
IR results: Preliminary considerations

- Tunnel runs involved *Re* sweeps and lasted ~5 minutes
- Heat flux results from Side A are shown herein
- Values are generally negative since $T_{aw} < T_w$
- Not reduced to Stanton number
  - Would add additional uncertainty from $(T_0 – T_w)$ term
  - Further amplifies some minima due to nature of *Re* sweep
- Larger heat-flux values generally indicate boundary-layer transition

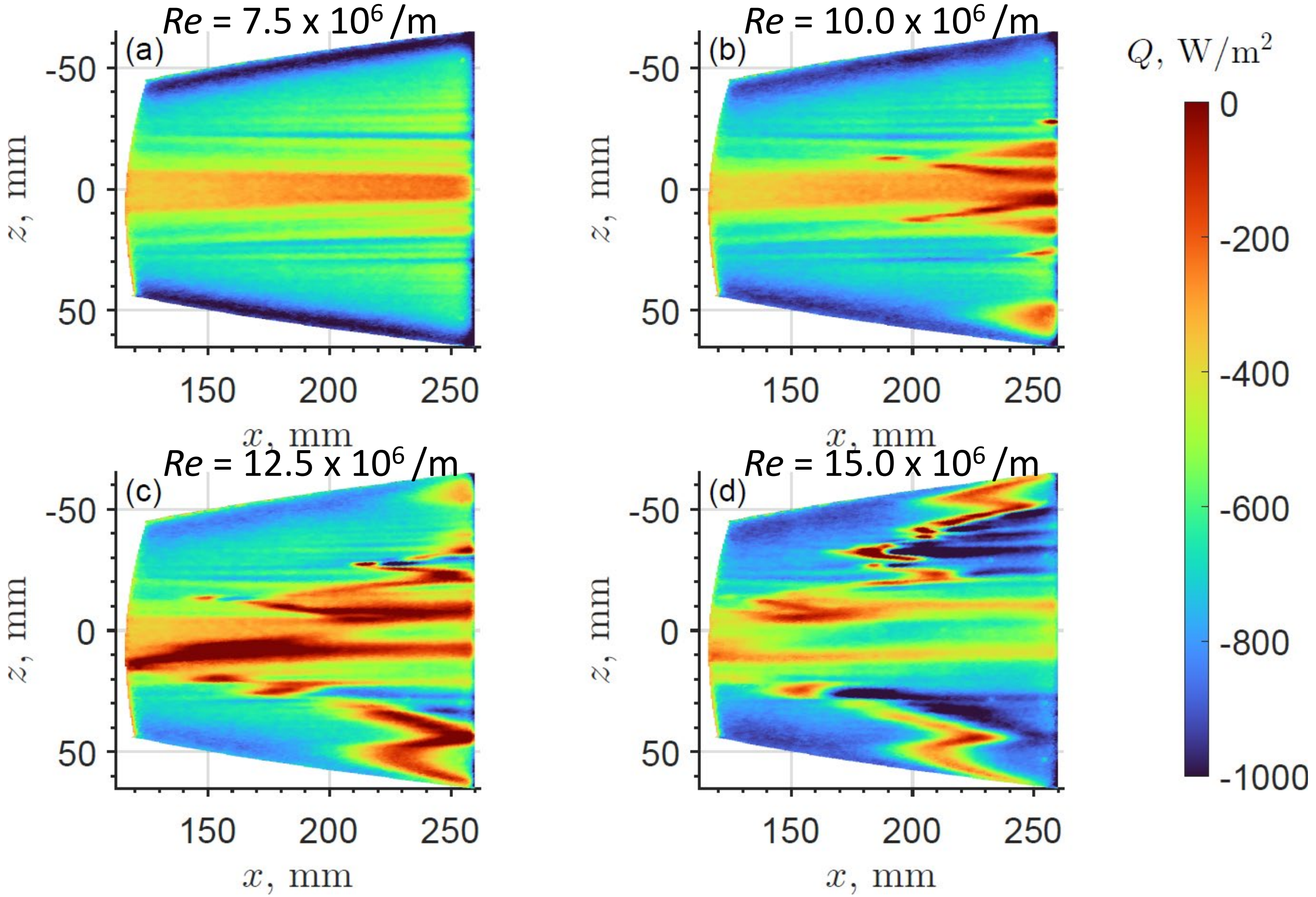


Sample heat-flux map from a noisy flow run

$$St = \frac{Q}{\rho_\infty u_\infty c_p (T_0 - T_w)}$$

Quiet flow: As-printed model

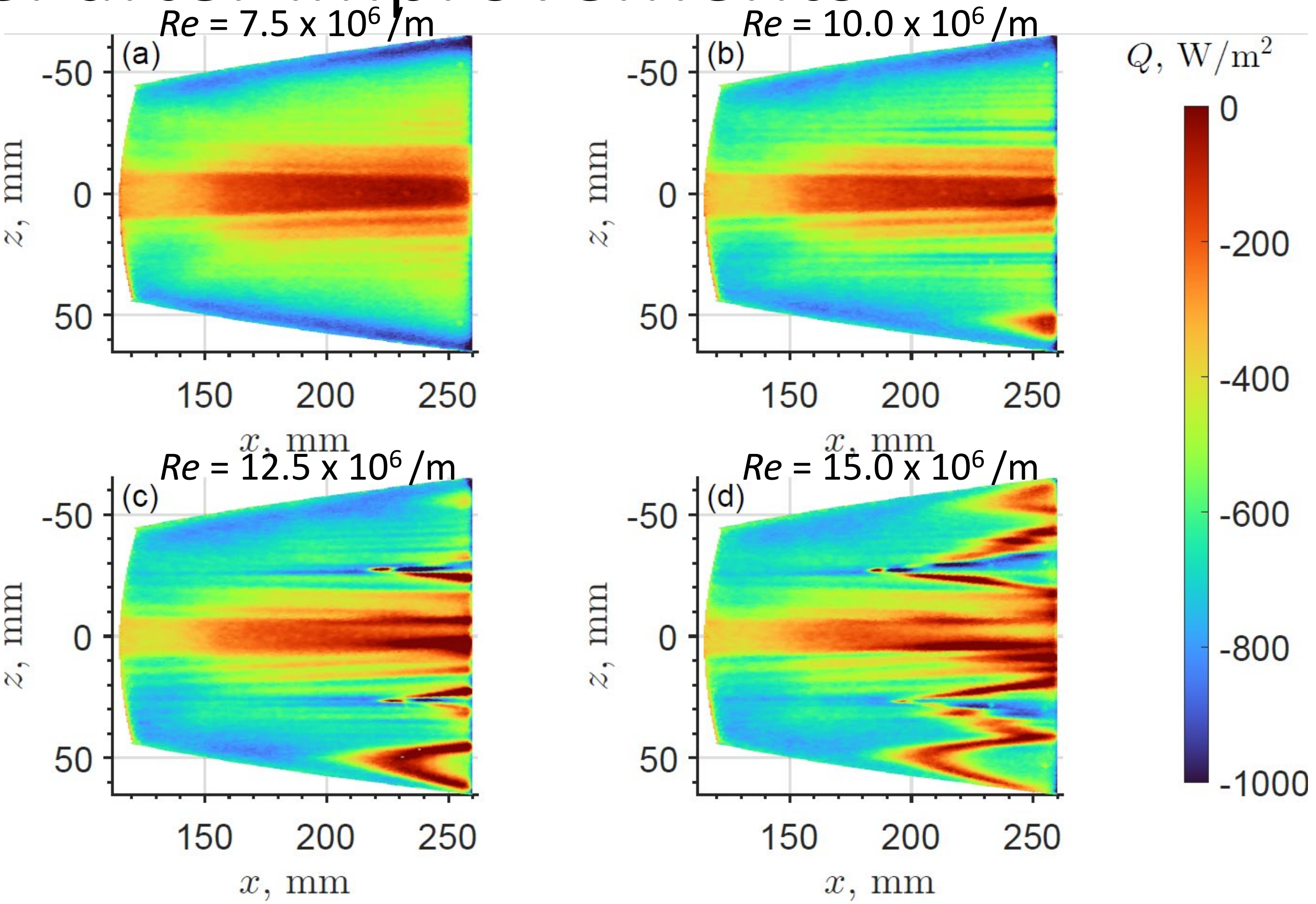
- Symmetric, laminar streaks at low *Re*
- Heating wedge on +*z* shoulder starting at *Re* = 10.0 x 10^6 /m
- Transition front is farther advanced on +*z* side for high *Re*
- Transition front has a jagged wedge shape on the -*z* side for high *Re*



Heat-flux maps for the as-printed model in quiet flow
(a) Re = 7.5 x 10^6 /m , (b) Re = 10.0 x 10^6 /m ,
(c) Re = 12.5 x 10^6 /m , (d) Re = 15.0 x 10^6 /m

Quiet flow: Model after improvements

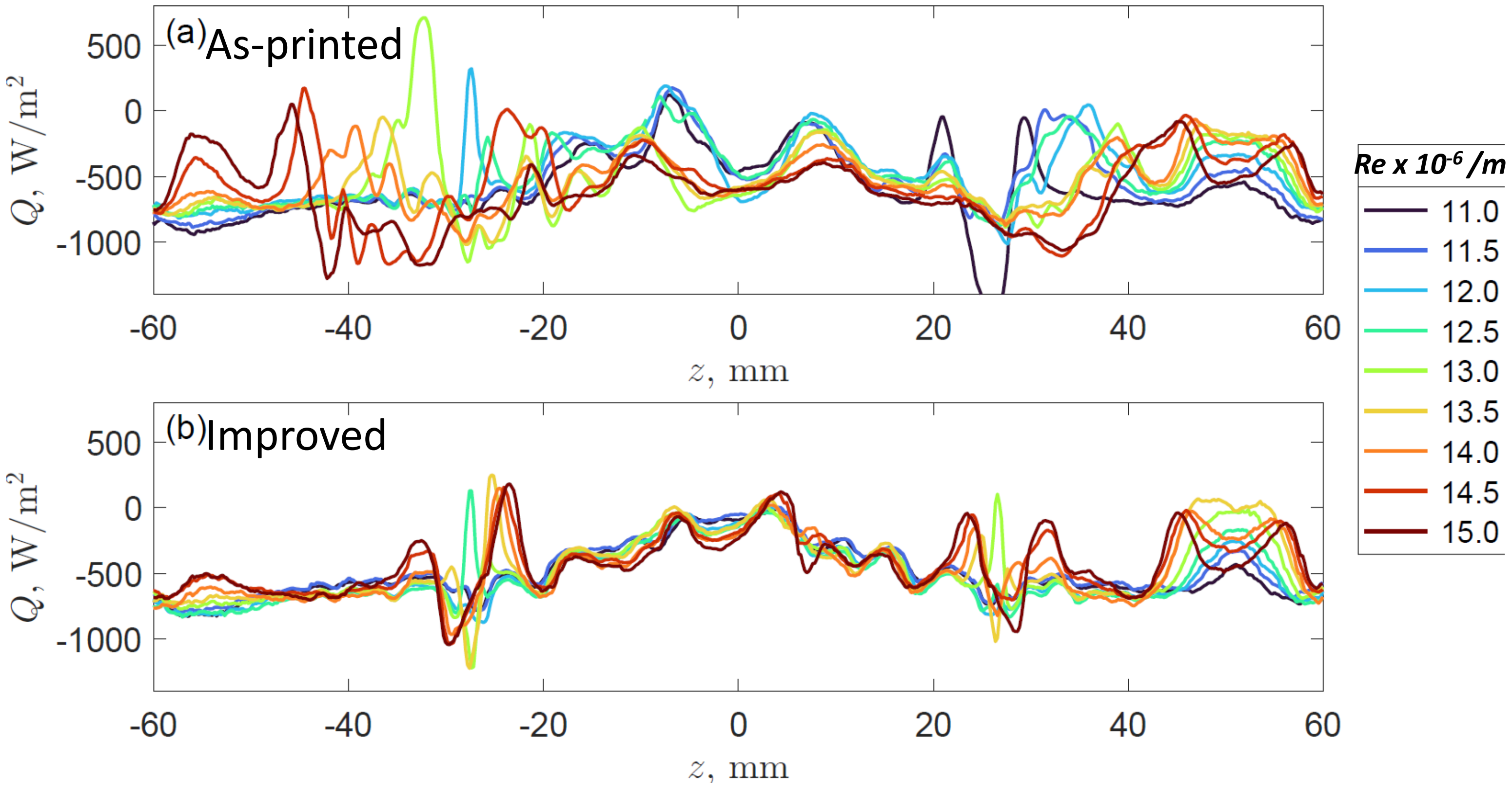
- Laminar heating streaks develop at slightly higher *Re*
- Heating wedge on +*z* shoulder looks the same at *Re* = 10.0 x 10^6 /m
- Transition front is much farther downstream
- Transition front is more symmetric



Heat-flux maps for the improved model in quiet flow
(a) Re = 7.5 x 10^6 /m , (b) Re = 10.0 x 10^6 /m ,
(c) Re = 12.5 x 10^6 /m , (d) Re = 15.0 x 10^6 /m

Quiet flow: Heat flux across span

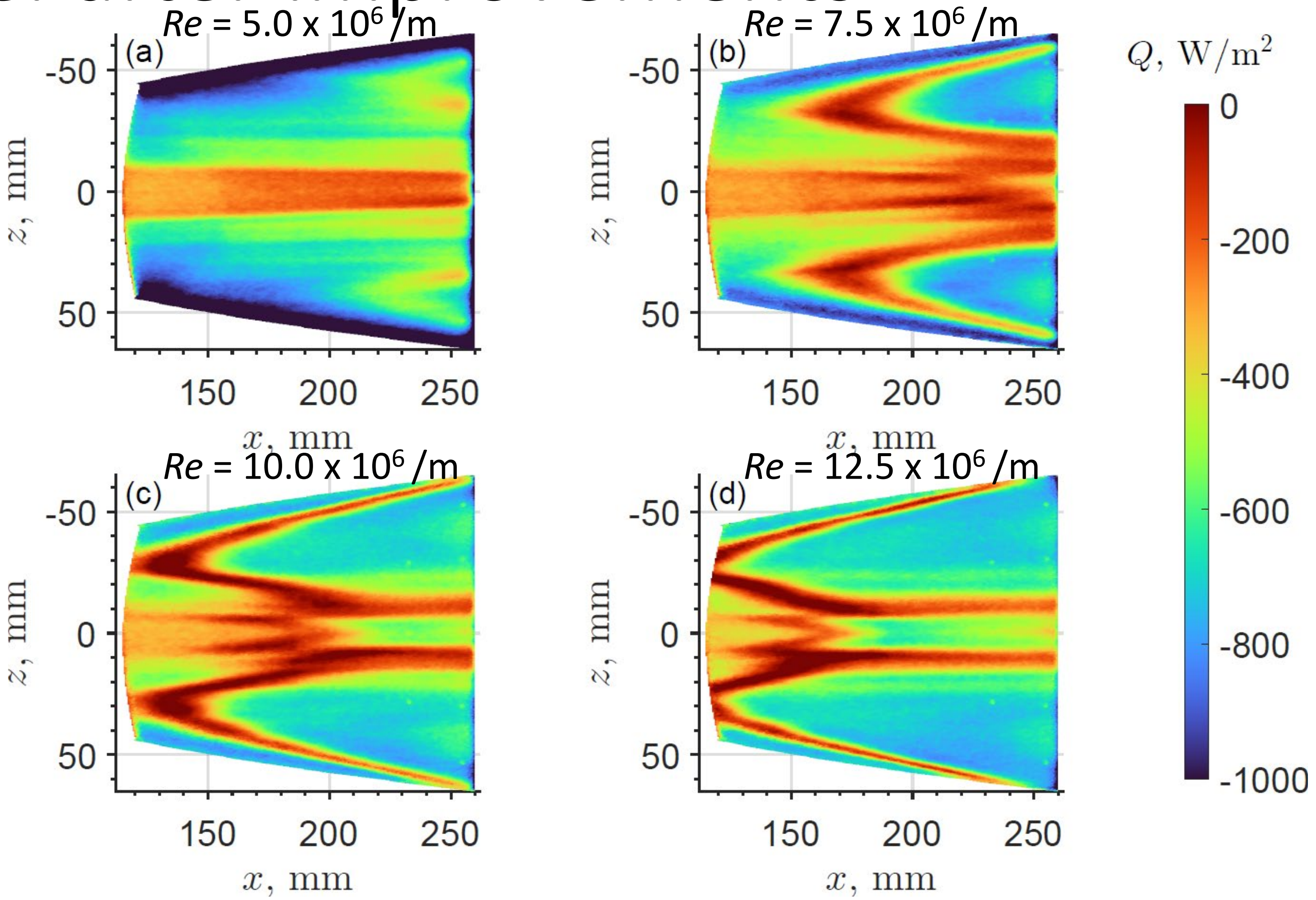
- Heat-flux values across the span are plotted for the higher *Re* conditions
- Transition rapidly evolves for the as-printed model
- Local maxima are often followed by local minima at subsequent *Re* from the passing transition front



Heat-flux values across the span at x=220 mm (x/L = 0.85) for 11.0 ≤ Re x 10^{-6} /m ≤ 15.0 in quiet flow for the (a) as-printed model and (b) improved model

Noisy flow: Model after improvements

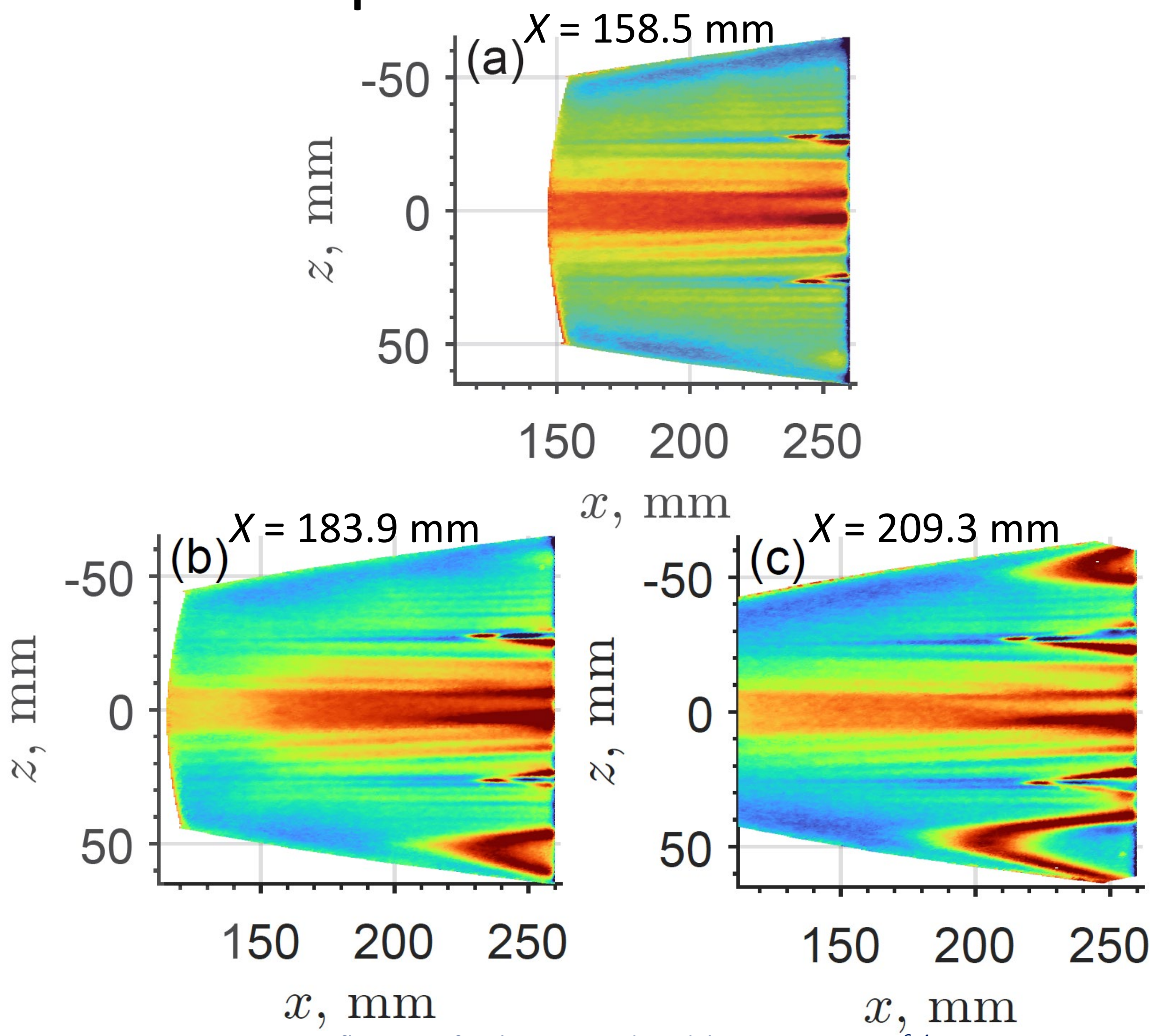
- Transition is already observed at *Re* = 5.0 x 10^6 /m
- Outboard wedges are the dominant feature
- Transition streaks appear near the midspan
- The transition front appears defined across the midspan for *Re* = 10.0 x 10^6 /m



Heat-flux maps for the improved model in noisy flow
(a) Re = 5.0 x 10^6 /m , (b) Re = 7.5 x 10^6 /m ,
(c) Re = 10.0 x 10^6 /m , (d) Re = 12.5 x 10^6 /m

Quiet flow: Model streamwise position

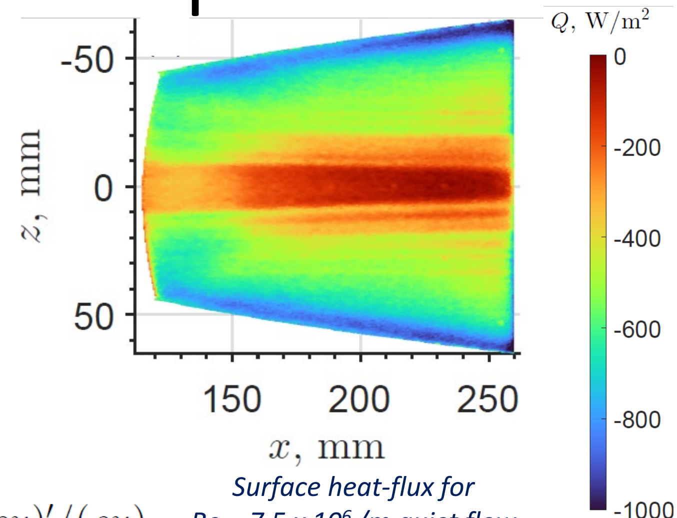
- Transition is minimal with model positioned farthest upstream
- Transitional streaks near the midspan and wedges midway to shoulder advance slightly as the model is shifted downstream
- The wedges on the shoulder see the most growth from the model shifts
- Asymmetry in shoulder transition due to model position off nozzle centerline



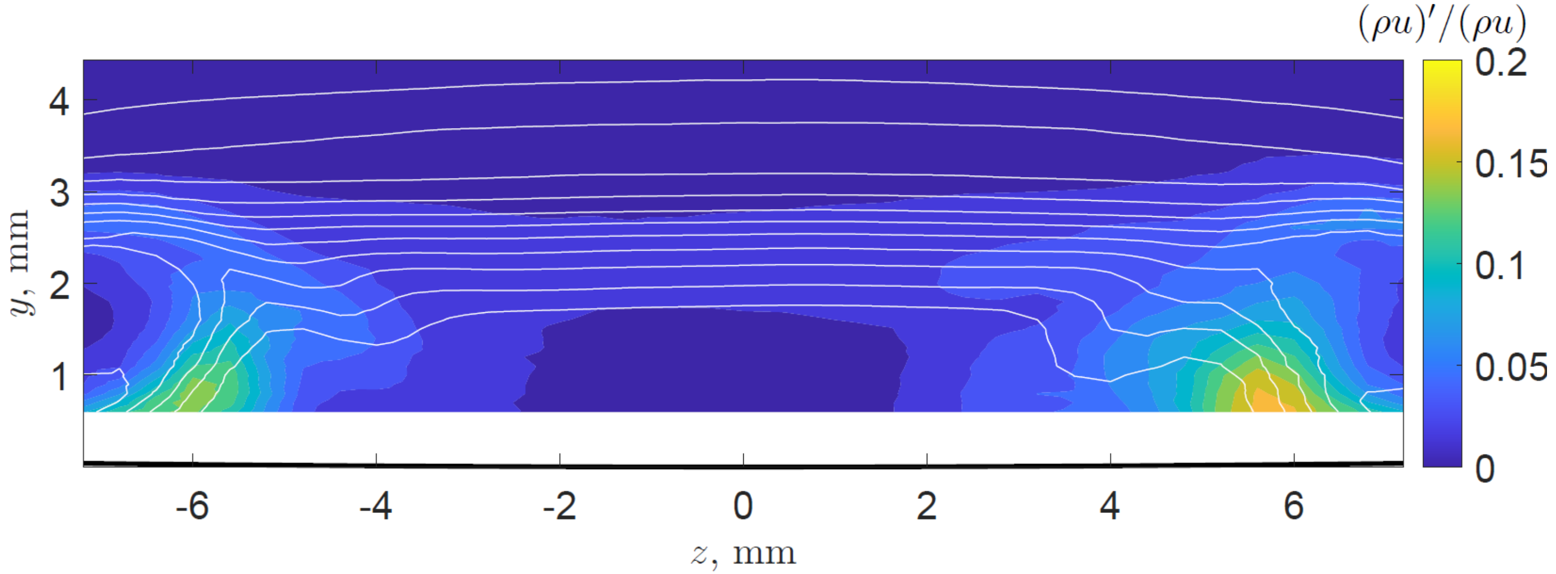
Heat-flux maps for the improved model at Re = 11.9 x 10^6 /m
(a) X = 158.5 mm (b) X = 183.9 mm (c) X = 209.3 mm

Quiet flow: Hot-wire survey across midspan

- Upwelling of low-momentum flow near midspan
- Vortices bound the midspan
- Fluctuations are <1.5% for much of the midspan, indicating laminar flow



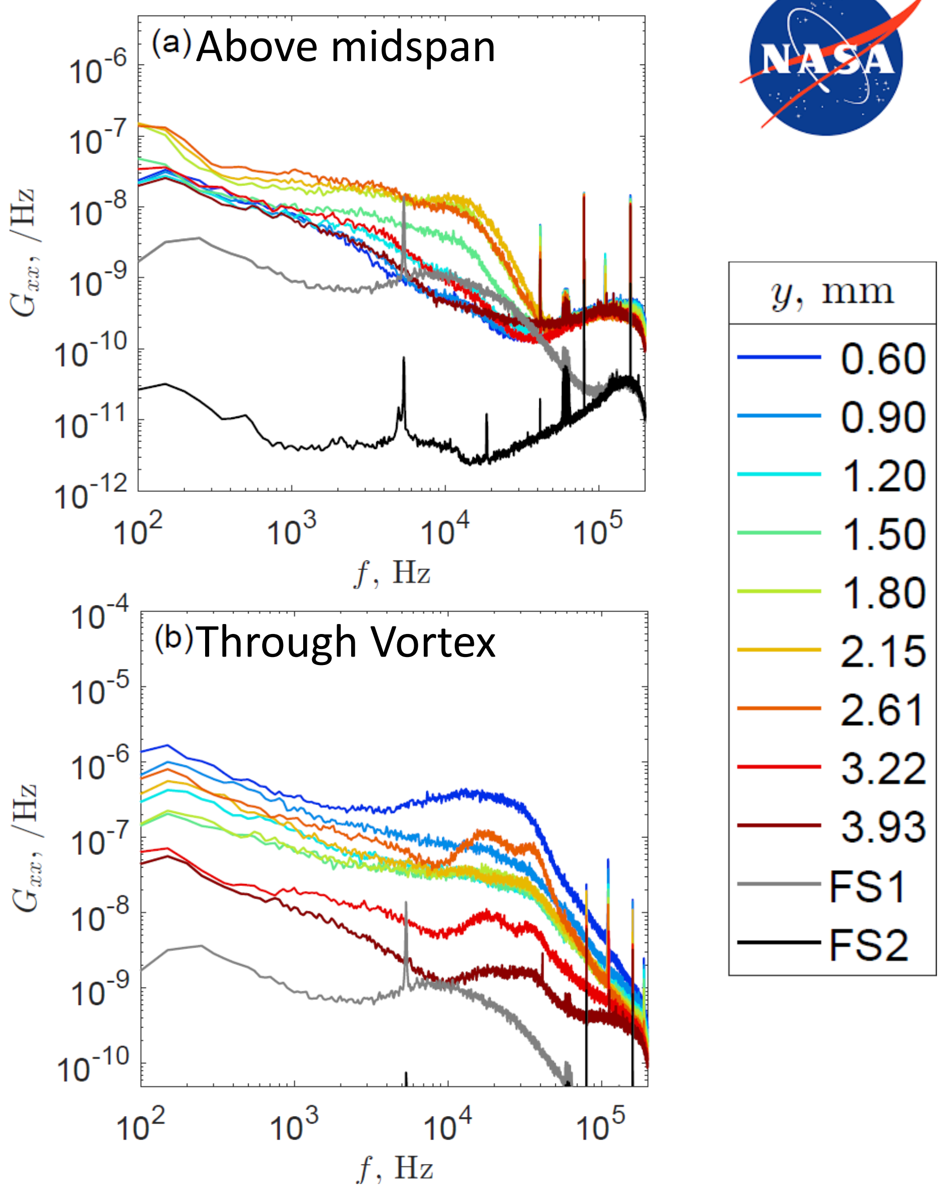
Surface heat-flux for Re = 7.5 x 10⁶ /m quiet flow



Contour maps of mean mass flux (white lines) and rms fluctuations (filled).
Survey was conducted at x = 257 mm (x/L = 0.99) for Re = 7.92 x 10⁶ /m quiet flow

Spectra from hot-wire survey

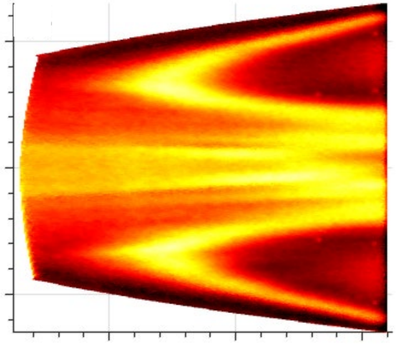
- Power spectral density (PSD) plots were generated for points above the midspan and through a vortex
- Black and gray spectra are from the freestream survey for comparison
- Above midspan: PSD amplitudes and bandwidth reach a maximum around *y* = 2.15 mm
- Above vortex: PSD amplitudes tend to decrease farther from the wall. A double peak (17 and 34 kHz) emerges for heights near the vortex crest



PSD plots of normalized mass-flux fluctuations
(a) Above the midspan (z=0)
(b) Through a vortex (z=5.60 mm)

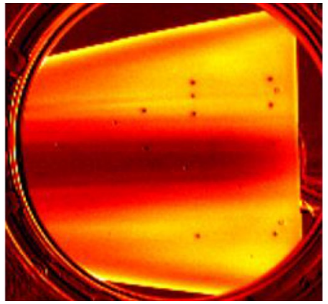
BOLT experimental comparison

- SLDT noisy flow heat-flux maps are qualitatively similar to Mach 3.5 results in PCT (Davami et al., 2023)
- More differences are observed in comparison to higher Mach heating results
    - Turbulent lobes are mostly uniform
    - Midspan heating features are absent
- SLDT quiet flow results are consistent with BOLT flight data (Butler et al., 2022)
    - *Re* was not high enough in SLDT to see transition on the centerline
    - The centerline transitions at higher *Re* than the outboard regions

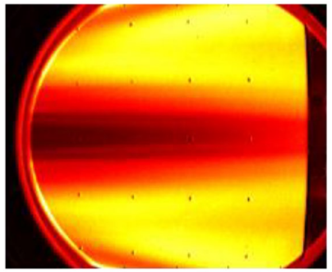


SLDT (noisy) Mach 3.5
Re = 7.5 x 10^6 /m

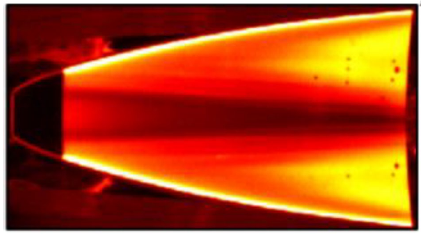
Mach 6 APL model (Kostak et al., 2019)



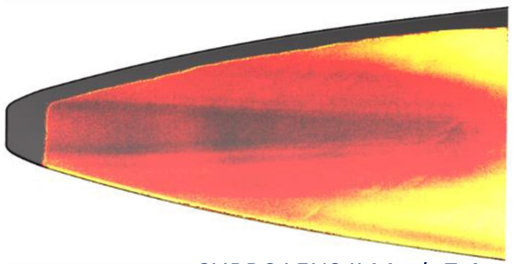
TAMU ACE



Purdue BAM6QT (noisy)



LARC 20"M6



CUBRC LENS II Mach 7.4

Davami, J., Juliano, T. J., Chou, A., and Leidy, A. N., "Effect of Roughness on Transition on the BOLT-1a Geometry in Supersonic Flow," AIAA Paper 2023-3441, June 2023
Butler, C. S., Araya, D. B., McKiernan, G. R., and Wheaton, B. M., "Supersonic Transition Measurements During the BOLT Flight Experiment Descent Phase," AIAA Paper 2022-4099, June-July 2022
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Concluding remarks

- Measurements were made on a 3-D printed 30% scale BOLT model in the NASA Langley Mach 3.5 SLDT
    - Quiet and noisy flow
    - Varied streamwise model positioning
    - As-printed and improved model surfaces
- Hot-wire measurements were made to characterize the freestream
- IR thermography was used to compute the surface heat-flux
- Off-body measurements were made across the midspan

Concluding remarks

- Freestream environment and model surface quality had significant impacts on the transition front
- Hot-wire measurements helped explain relatively higher midspan heating
- The noisy flow heating features differed from those in Mach 6 tests
- The SLDT results are consistent with those from flight, but comparisons are limited

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