Self-Aligned Focusing Schlieren at the 0.3-M Transonic Cryogenic Tunnel and the National Transonic Facility

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NASA Langley Research Center

AIAA 2024 SciTech Forum

January 2024

Overview of Testing at 0.3-M and NTF

- Why test in cryogenic facilities like 0.3-M and NTF?
  - Highest transonic Reynolds numbers testing to duplicate flight conditions
- Measurements already available?
  - Force/moment, static/dynamic pressure, strain, accelerometers, model deformation and wing twist, PSP/TSP

Off-body flow visualization in these facilities remains challenging
- Limited optical access and difficult working environment

0.3-M Transonic Cryogenic Tunnel
- Risk-reduction testing for SAFS system prior to installation at NTF
- Testing three models to evaluate best option for steady shock positioning for upcoming PTV testing

National Transonic Facility (NTF)
- Tail cone thruster (TCT) sting-mounted model
- First demonstration of SAFS at NTF, and first FS effort since 2000

0.3-M

Capabilities
Speed: Mach 0.1 to 0.9
Reynolds number: 1 to 100×10^6 per ft
Pressure: 14.7 to 88 psia
Temperature: -320 to 130 °F
Test gas: Nitrogen or air
Test section size: 13" H x 13" W
Type: Closed circuit

NTF

Capabilities
Speed: Mach 0.1 to 1.2
Reynolds number: 4 to 145 x 10^6 per ft
Pressure: 15 to 130 psia
Temperature: -250 to -150 °F
Test gas: Nitrogen or dry air
Test section size: 8.2' H x 8.2' W x 25' L
Drive power: 135,000 hp
Type: Closed Circuit

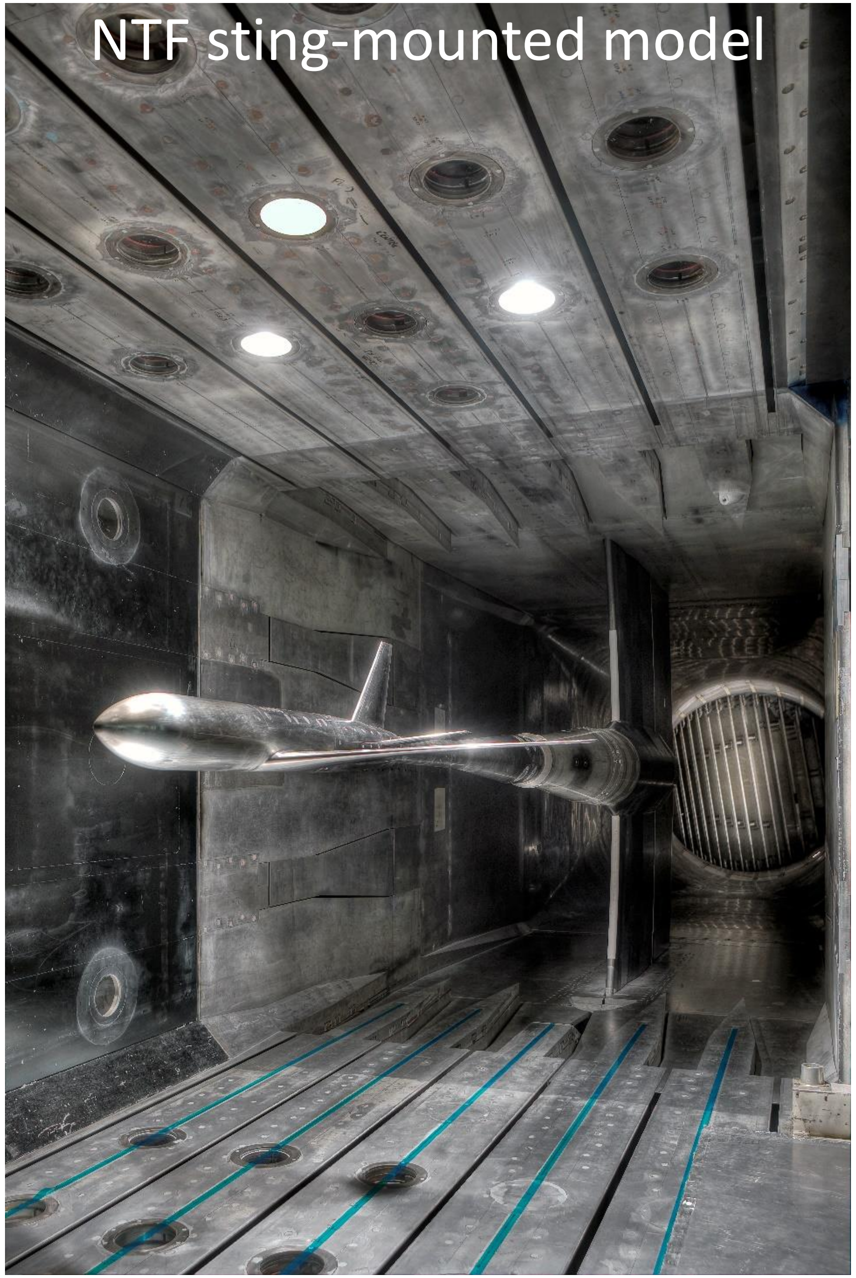
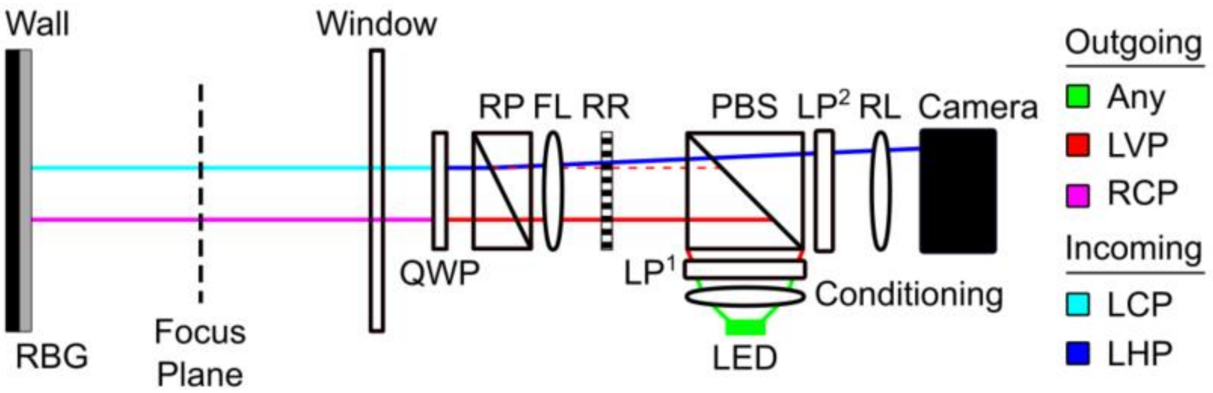
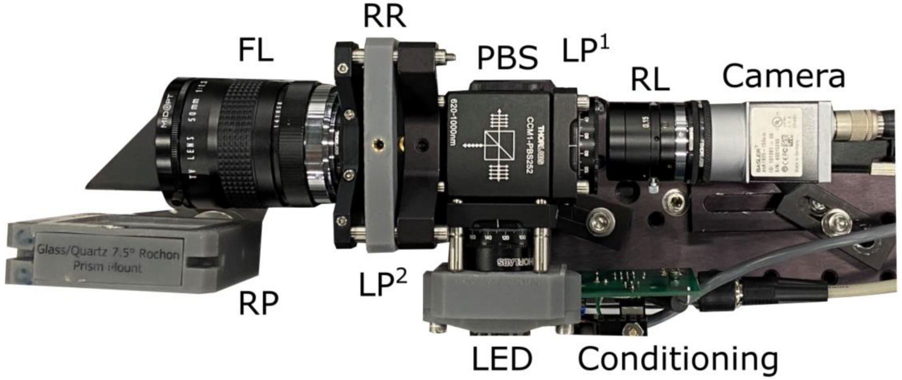


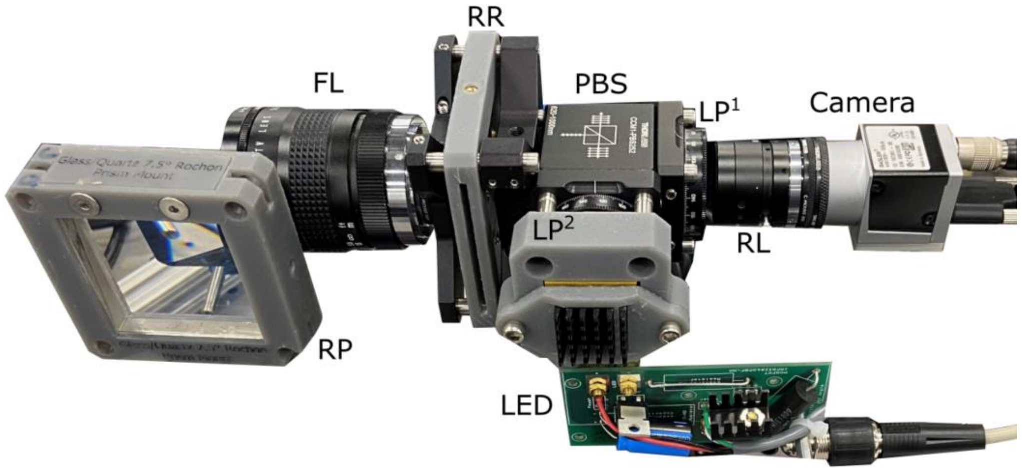
Image credit: NASA Image and Video Library

Self-Aligned Focusing Schlieren (SAFS)

- Single-sided optical access
- Inherently self-aligned due to retroreflective background
- Insensitive to vibration
- Can be made to be compact
- Simple adjustment of sensitivity
  - Ronchi ruling (RR) focus on retroreflective background (RBG)
  - Translation/rotation of Rochon prism (RP)
- Simple adjustment of focus plane
  - Translation of camera or adjustment of relay lens (RL) focus
- Realignment of system is quick (on the order of minutes)

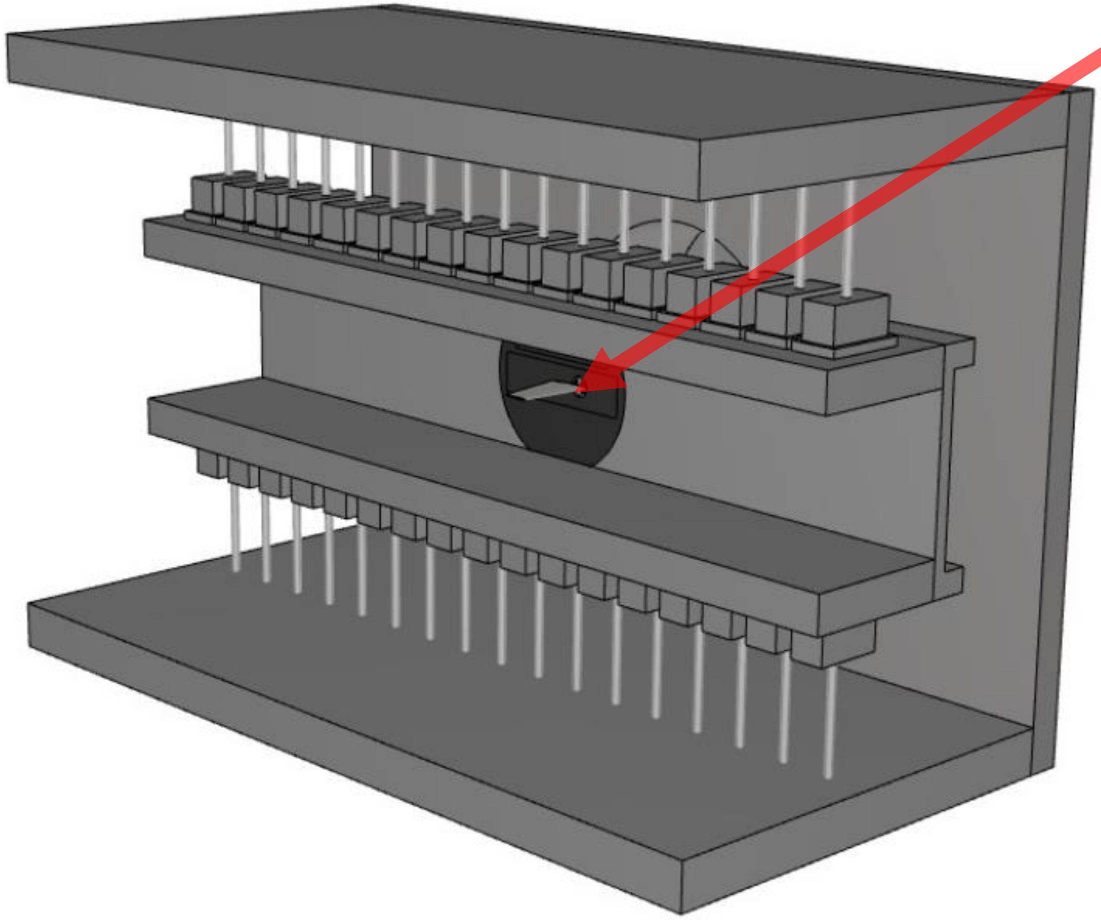


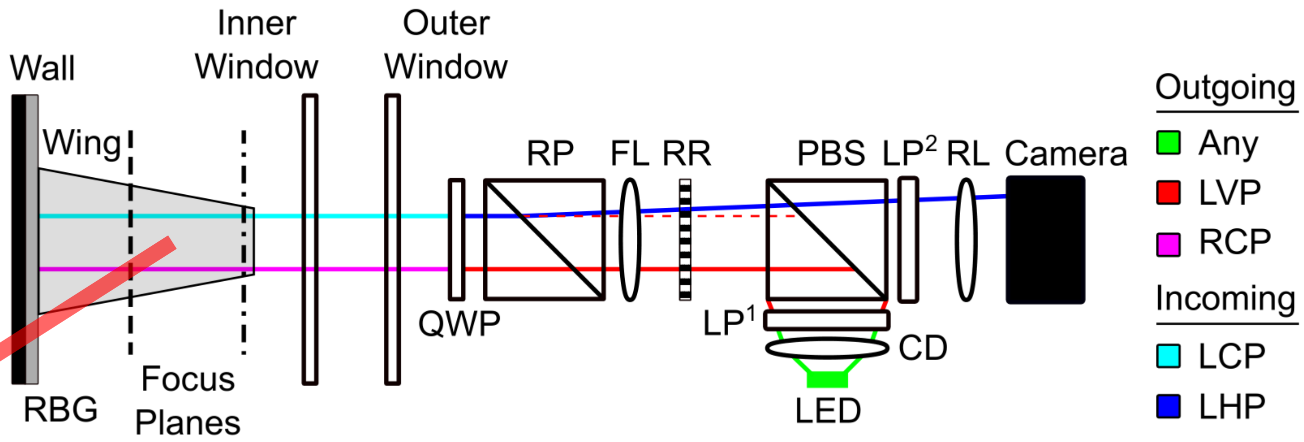


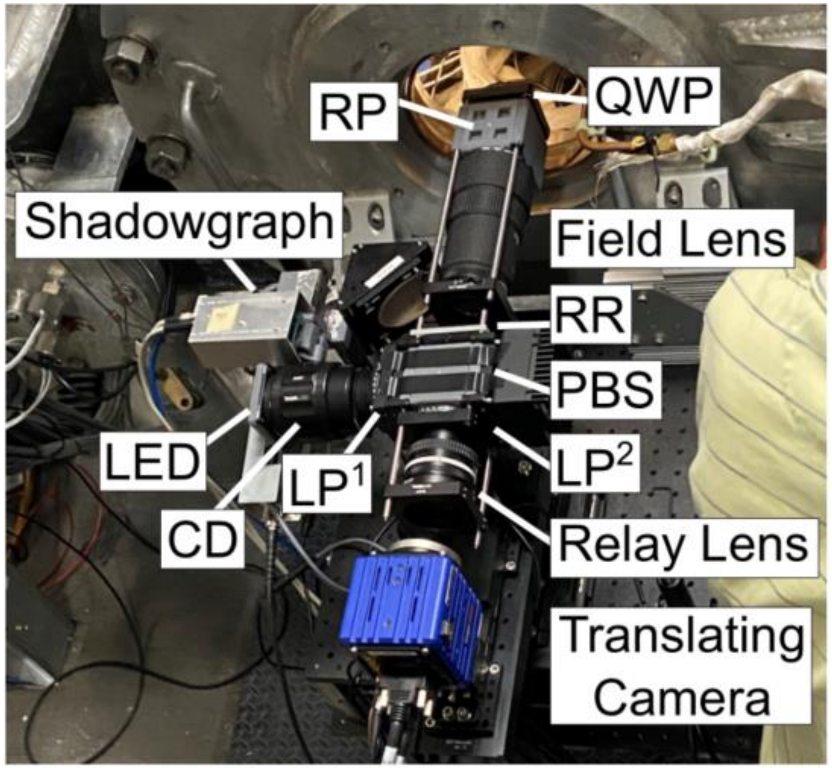


0.3-M // System Installation and Retroreflective Material

- System installed on breadboard mounted to outer plenum door
  - Shadowgraph system installed next to SAFS







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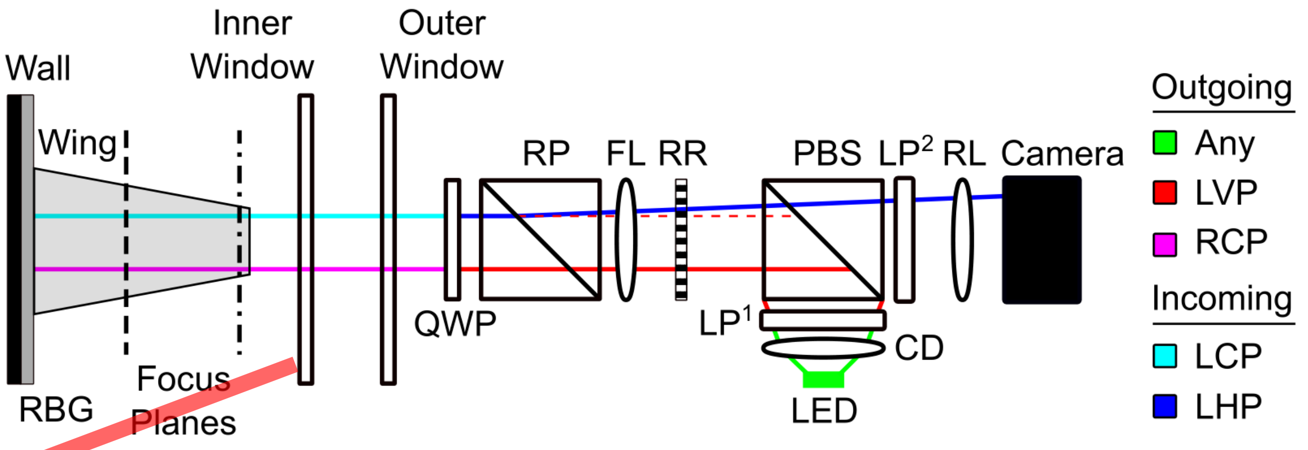

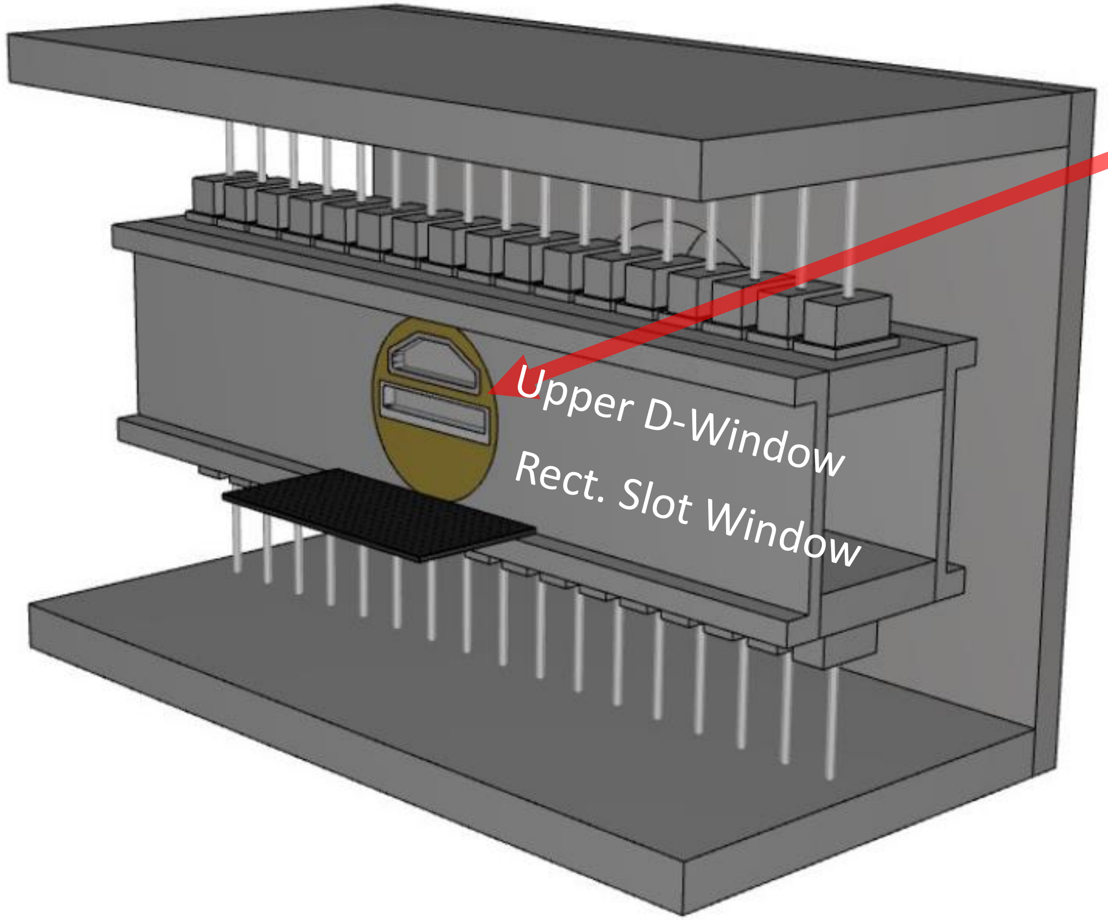

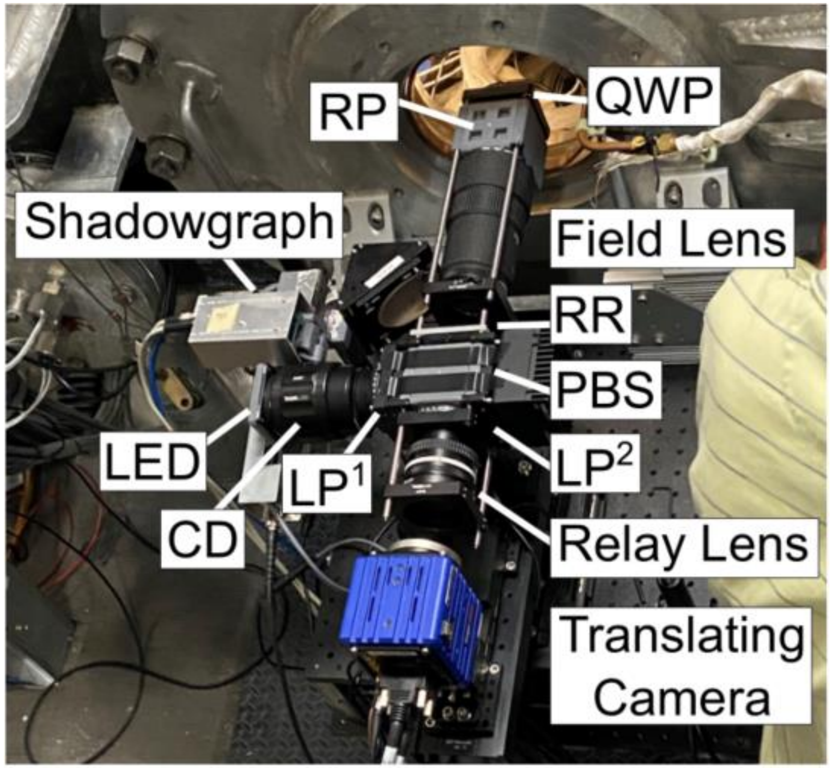

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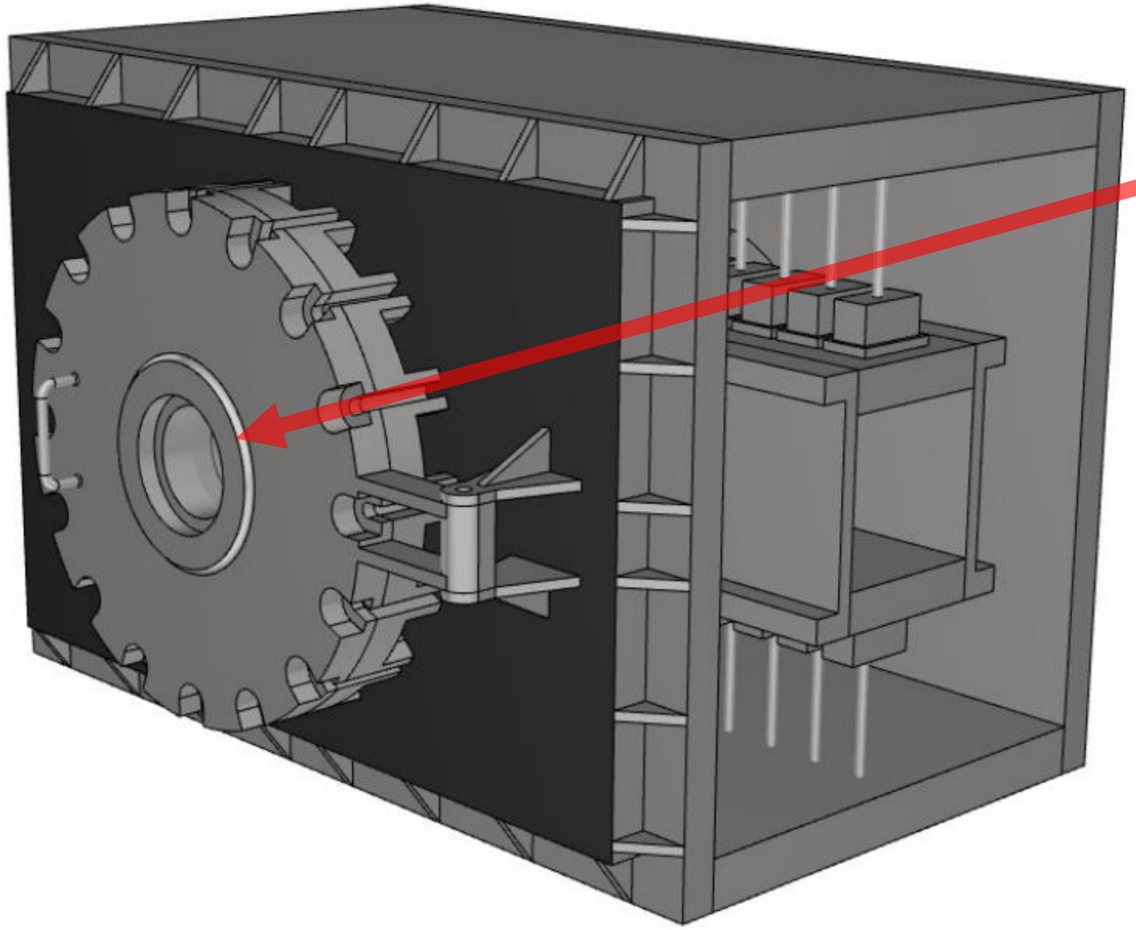
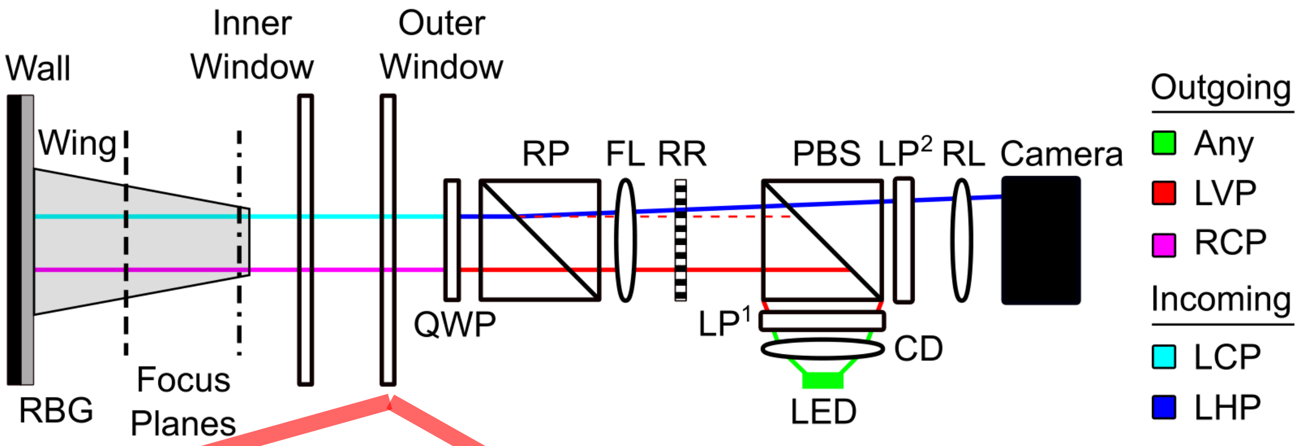
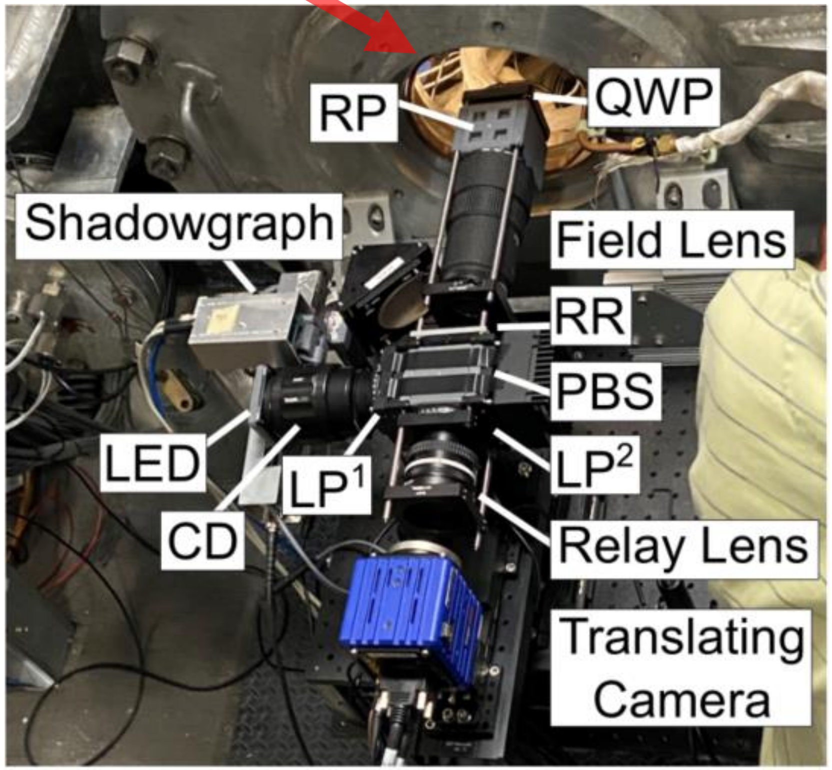
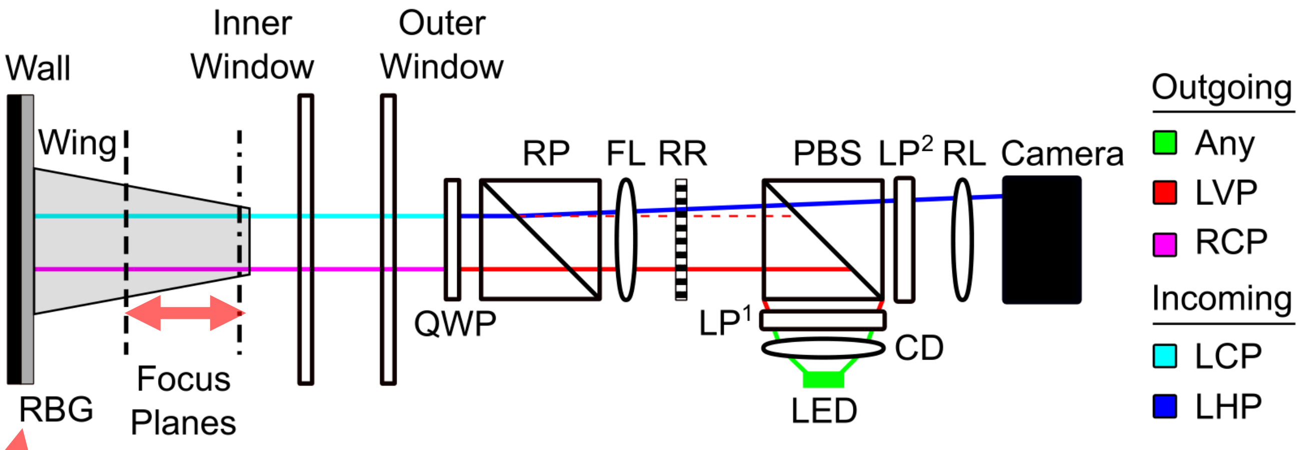


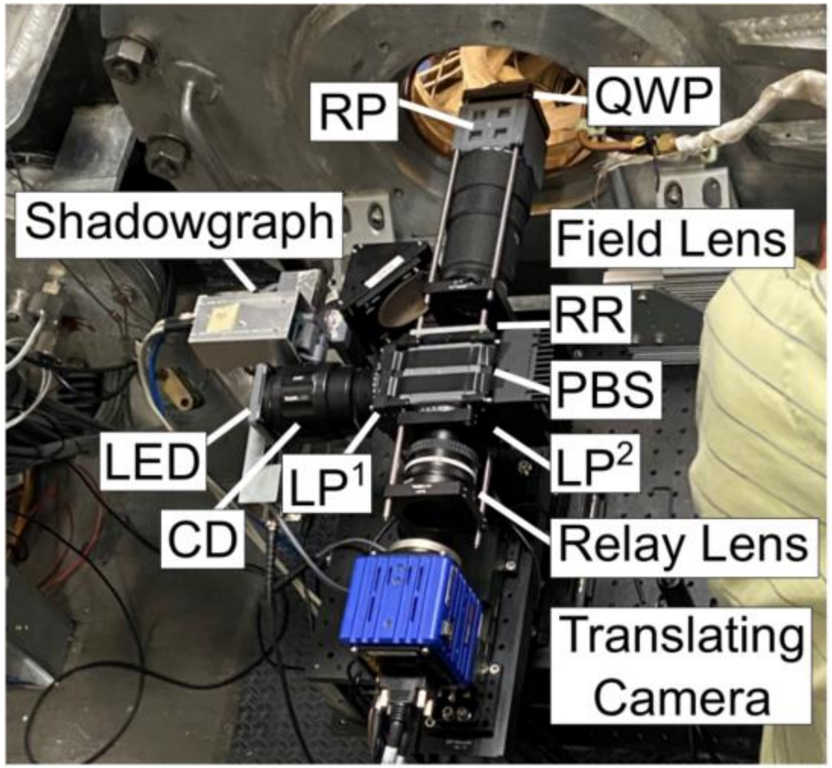


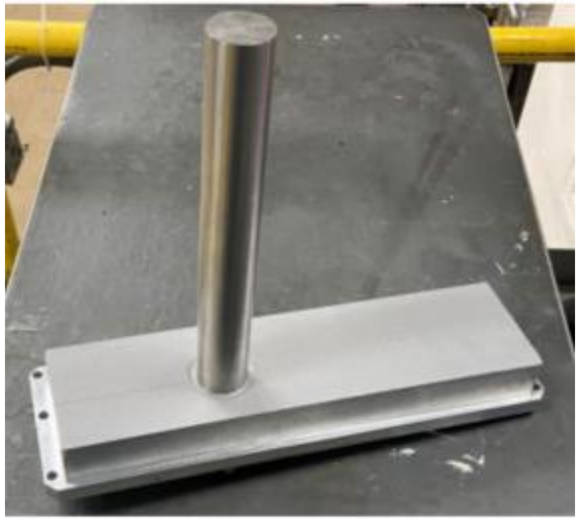


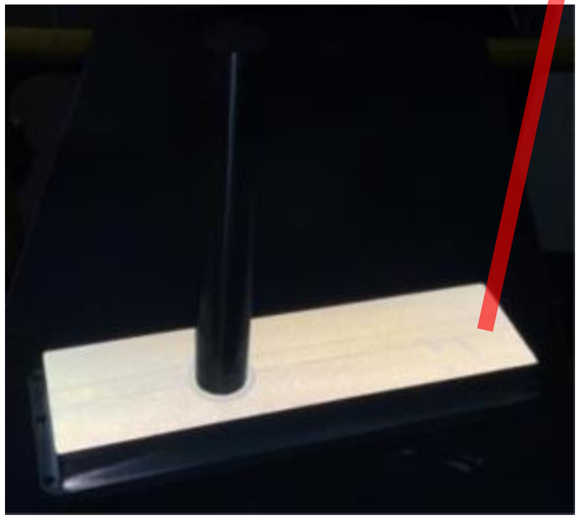
0.3-M // System Installation and Retroreflective Material

- System installed on breadboard mounted to outer plenum door
  - Shadowgraph system installed next to SAFS
- Camera on translation stage for precise focus plane adjustment during testing
- Retroreflective material applied to the model inserts on opposite wall
  - Strips of 3M Scotchlite 7610 material adhered directly to metal insert

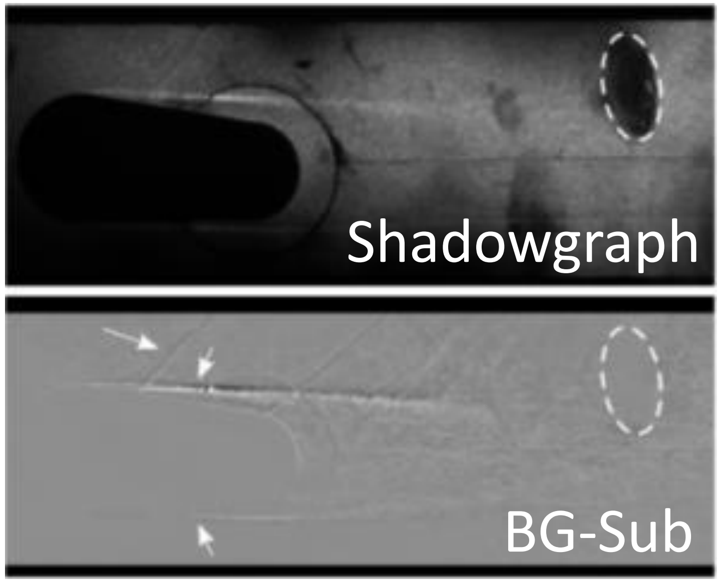


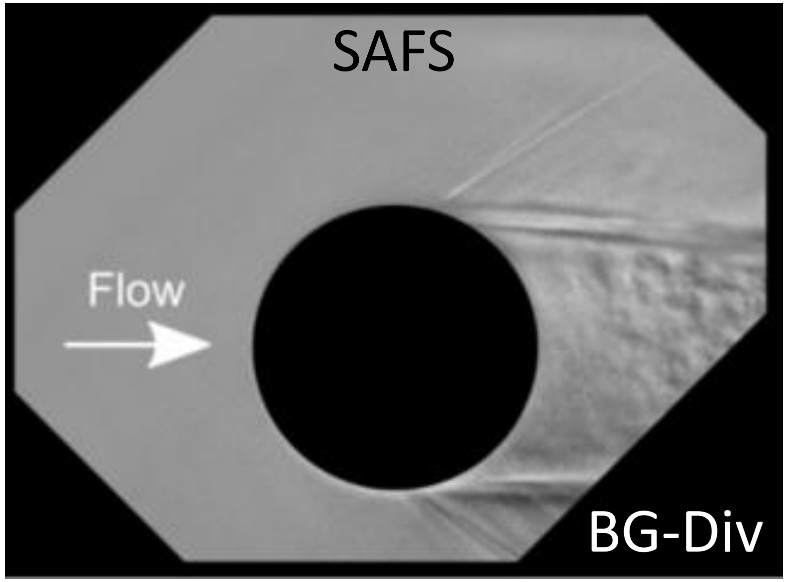



Without Flash

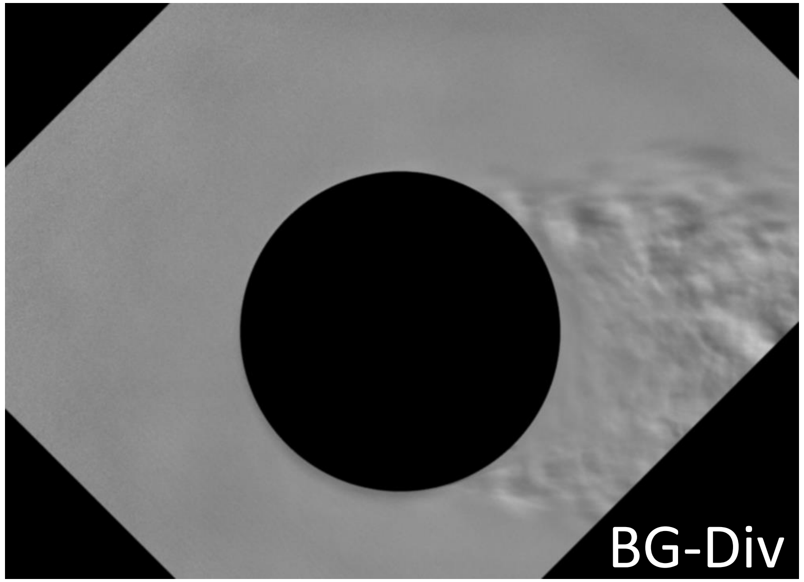

With Flash

- Mach 0.25: Wake behind cylinder visible
- Mach 0.69: Unsteady shock waves visible on upper and lower surface of cylinder
- Shocks never steady, so cylinder not a good option for PTV measurement
- Shadowgraph system shows sensitivity to shocks and shear flow (arrows), but not wake flow
  - More sensitive to imperfections in RBG material (white dashed)

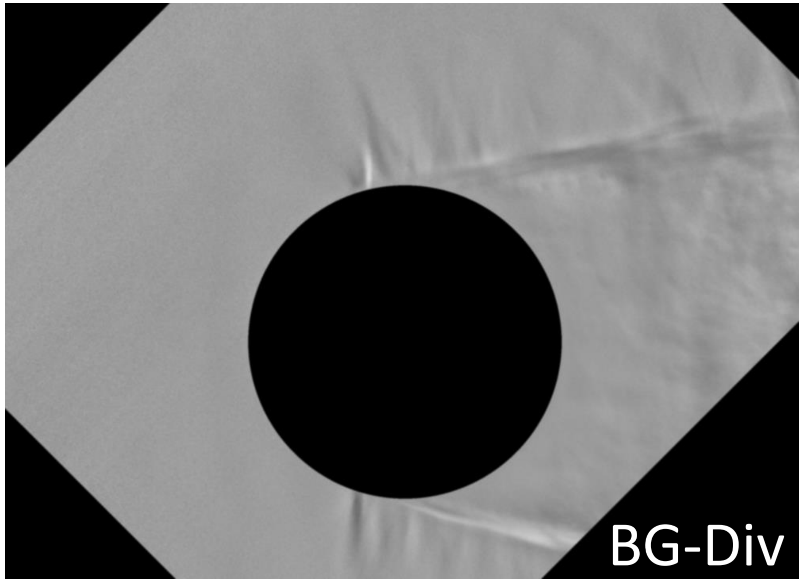




M = 0.25, P_0 = 79 psia, T_0 = 279 K

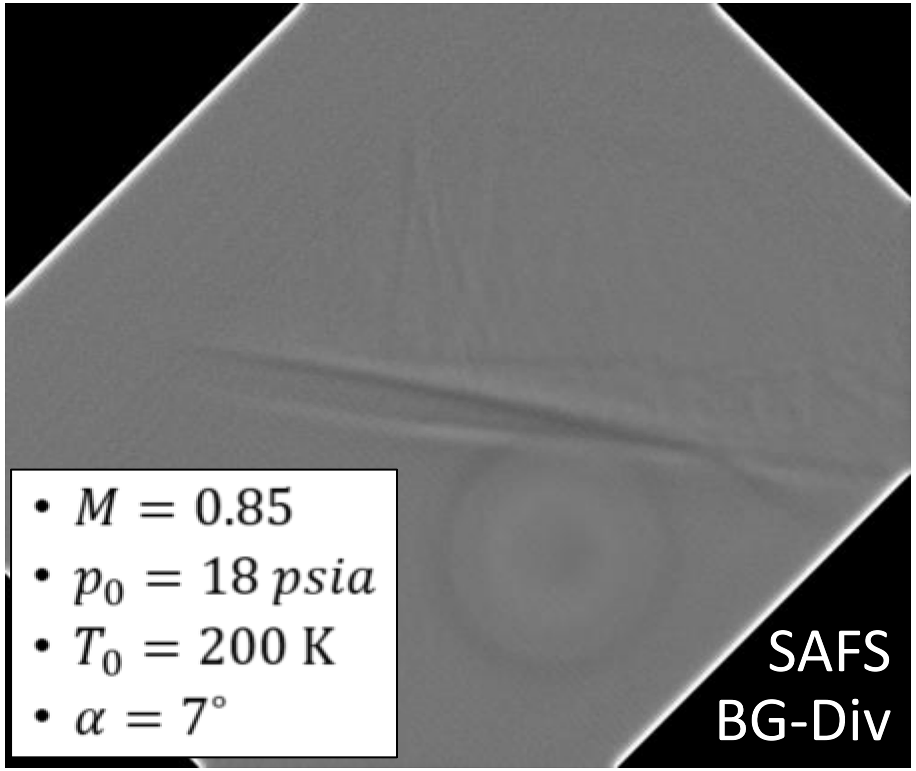


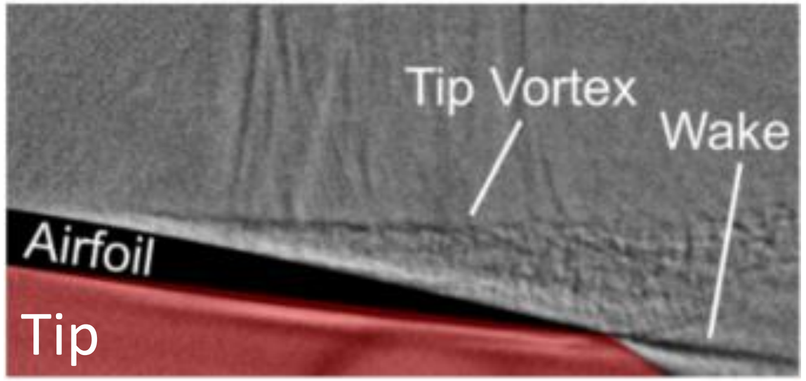
M = 0.69, P_0 = 18 psia, T_0 = 276 K

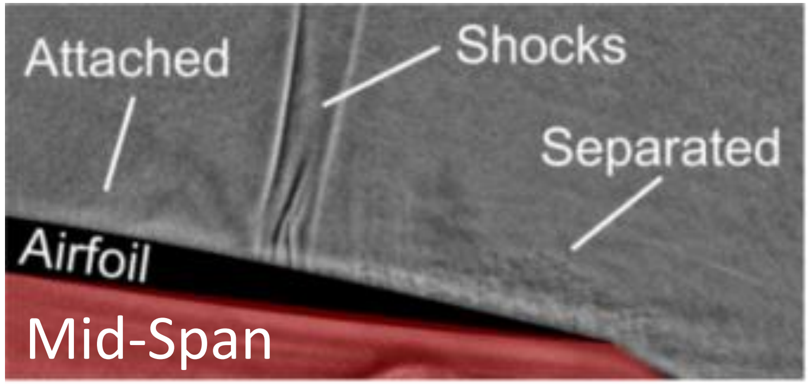


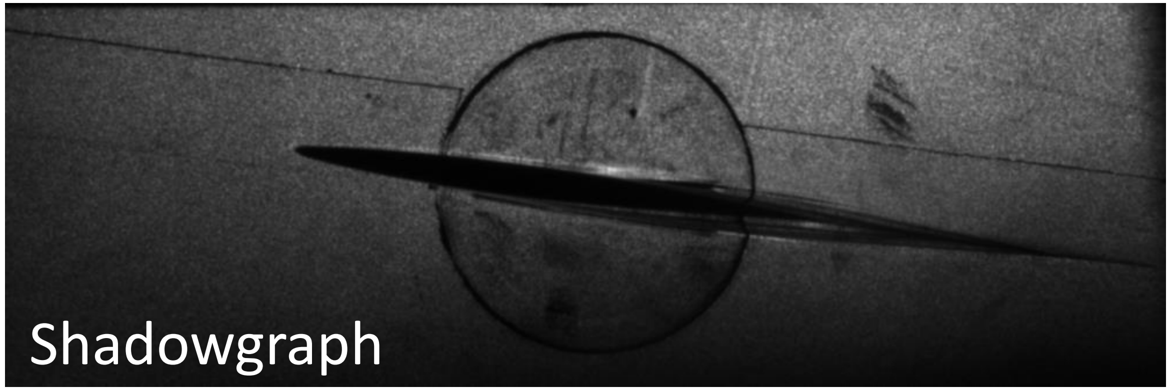
0.3-M // Cylinder – Semi-Span Airfoil – Full-Span Airfoil

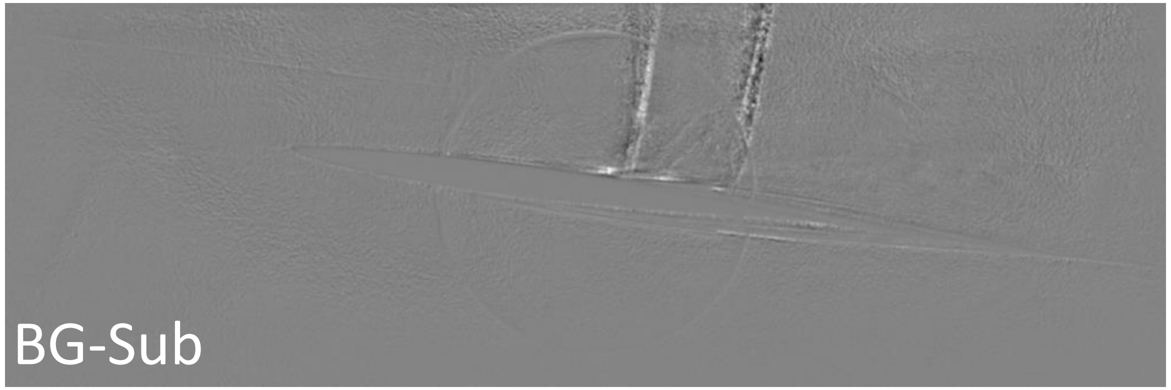
- Temperatures down to 200 K
  - Limitation of rectangular slot window
- Translating camera to adjust focus plane from airfoil tip to root
- Isolate tip flow and shocks/separated flow
- Shocks visible in shadowgraph, but lateral position on airfoil unknown





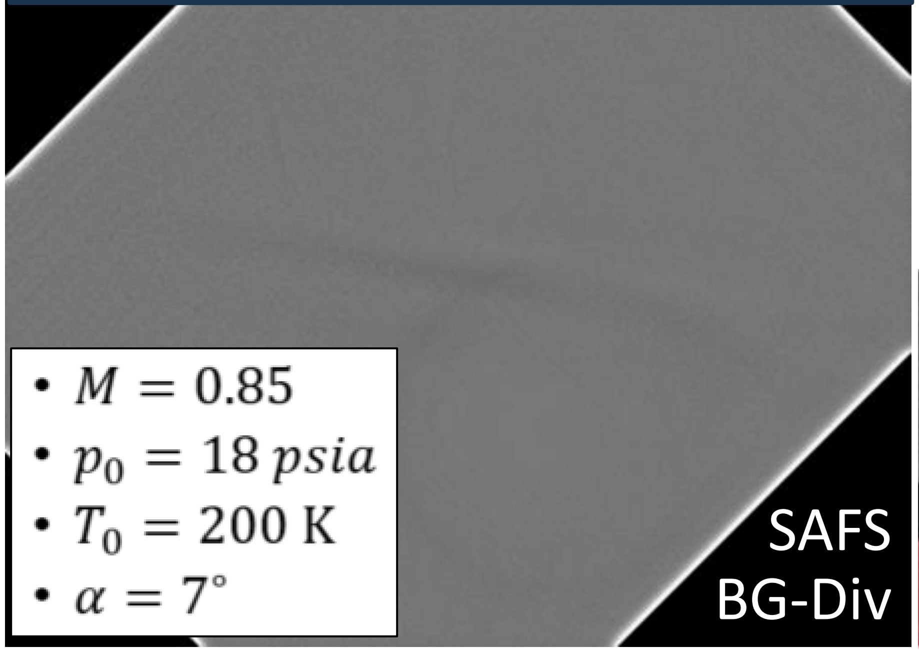




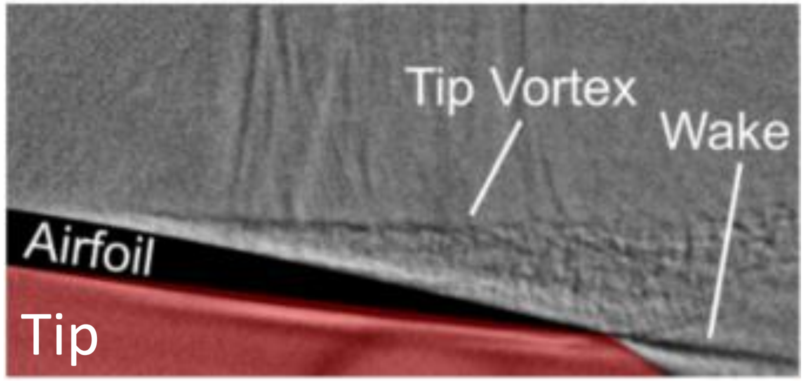


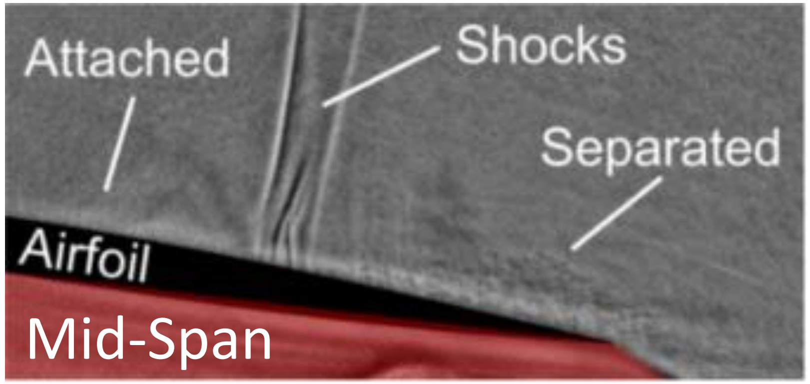
- Temperatures down to 200 K
  - Limitation of rectangular slot window
- Translating camera to adjust focus plane from airfoil tip to root
- Isolate tip flow and shocks/separated flow
- Shocks visible in shadowgraph, but lateral position on airfoil unknown

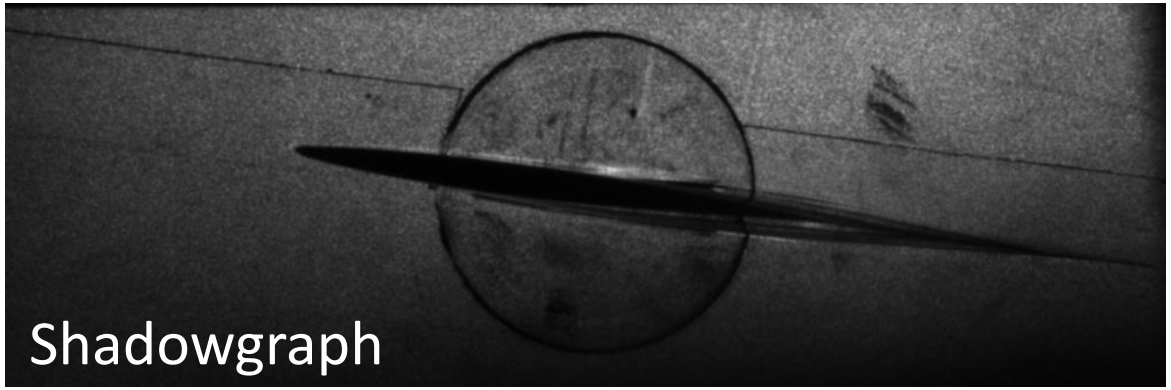
Freestream shocks between airfoil tip and window

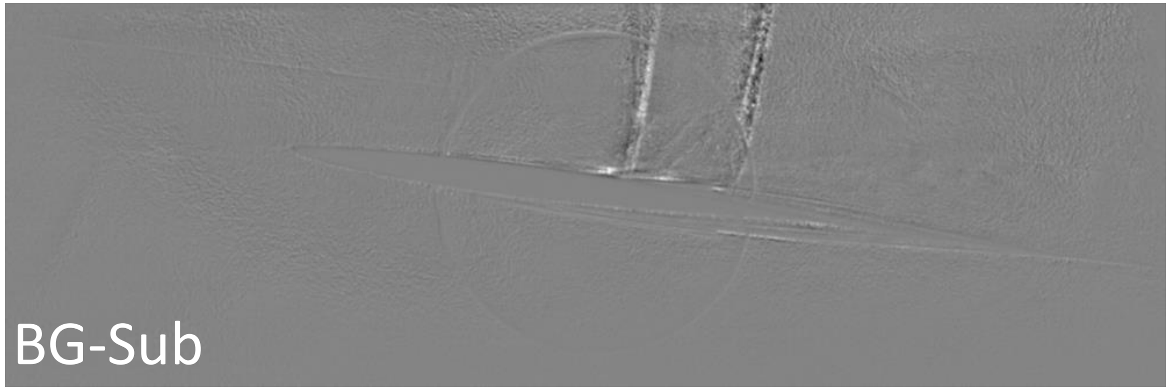


- $M = 0.85$
- $p_0 = 18\,psia$
- $T_0 = 200$ K
- $\alpha = 7°$

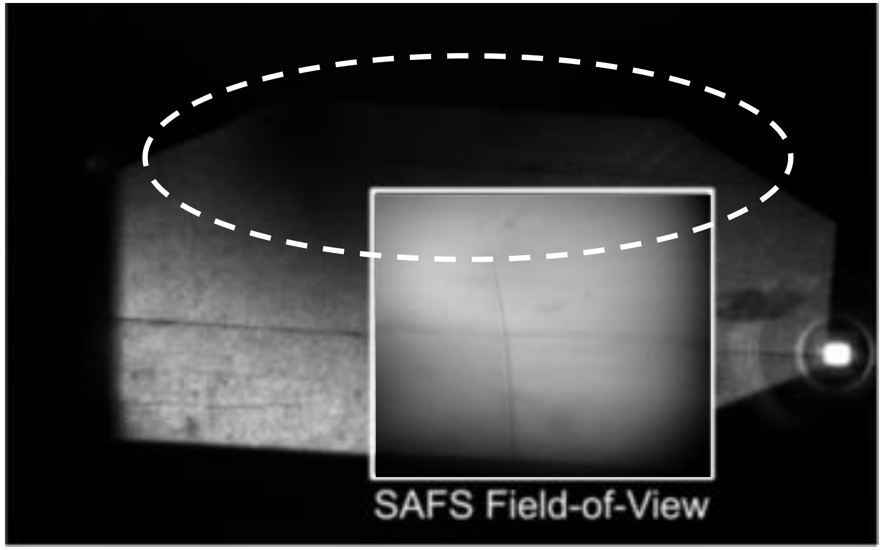


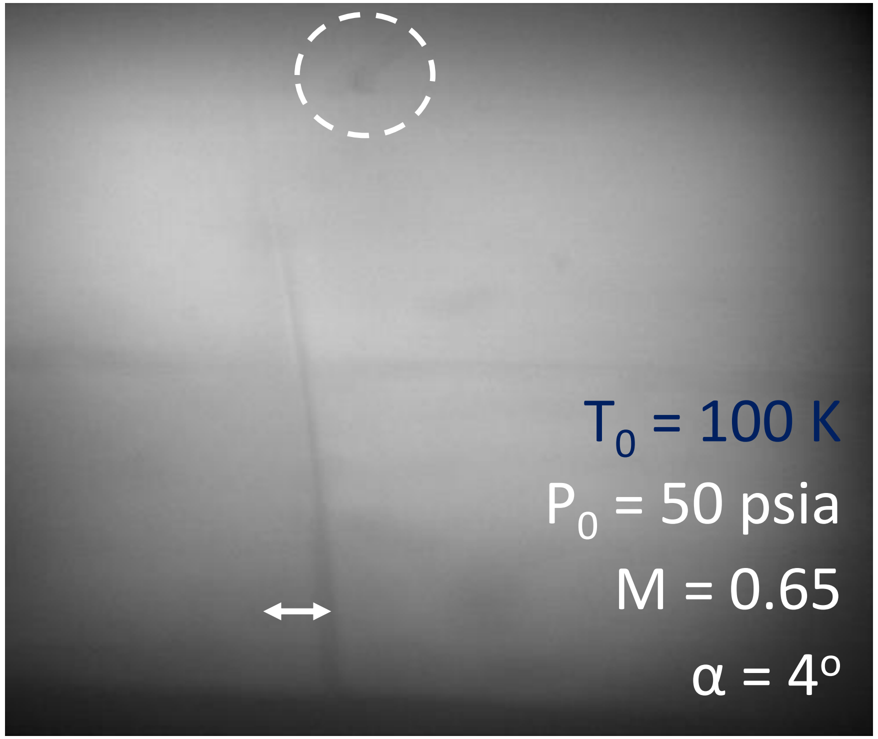


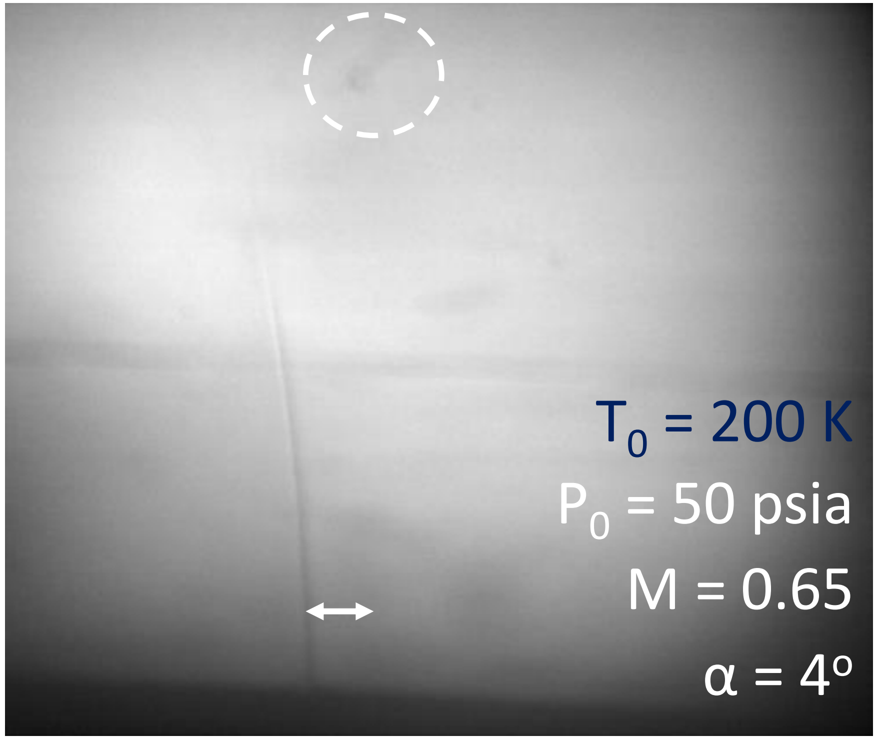




- Required use of upper D-window instead of rectangular slot window
- Smaller field-of-view for SAFS system than shadowgraph
- Relatively steady shock structure on airfoil at $\alpha < 5^{o}$
- Darkening of shadowgraph from polarization altering window stresses seen at top of the window
  - Replacement of glass/quartz RP with quartz/quartz RP to avoid stress-induced birefringence

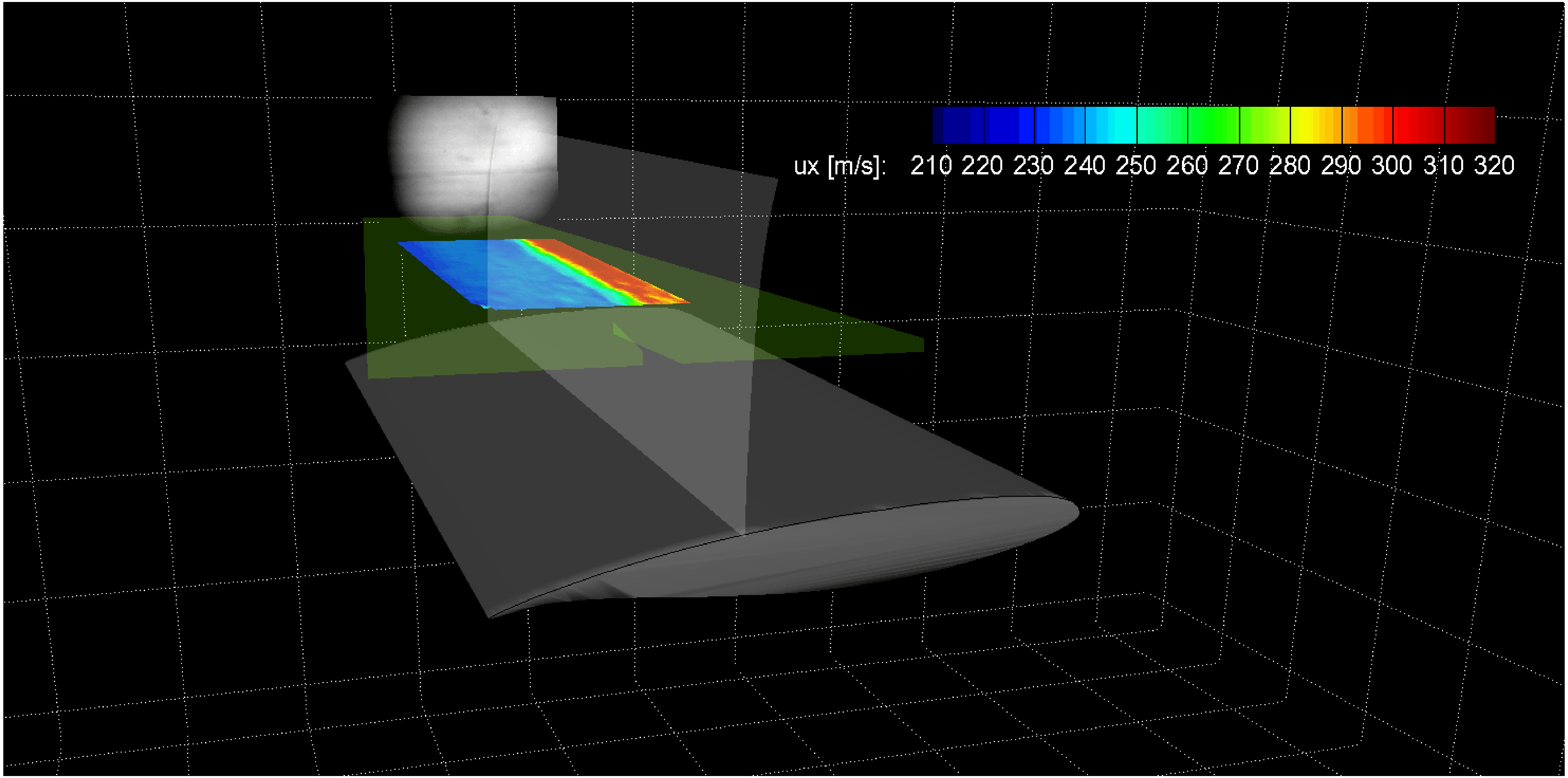






0.3-M // Cylinder – Semi-Span Airfoil – Full-Span Airfoil

Burns, Gao, and Danehy, “Characterization of naturally occurring particles in the NASA Langley 0.3-m Transonic Cryogenic Tunnel using PTV,” AIAA SciTech 2024.

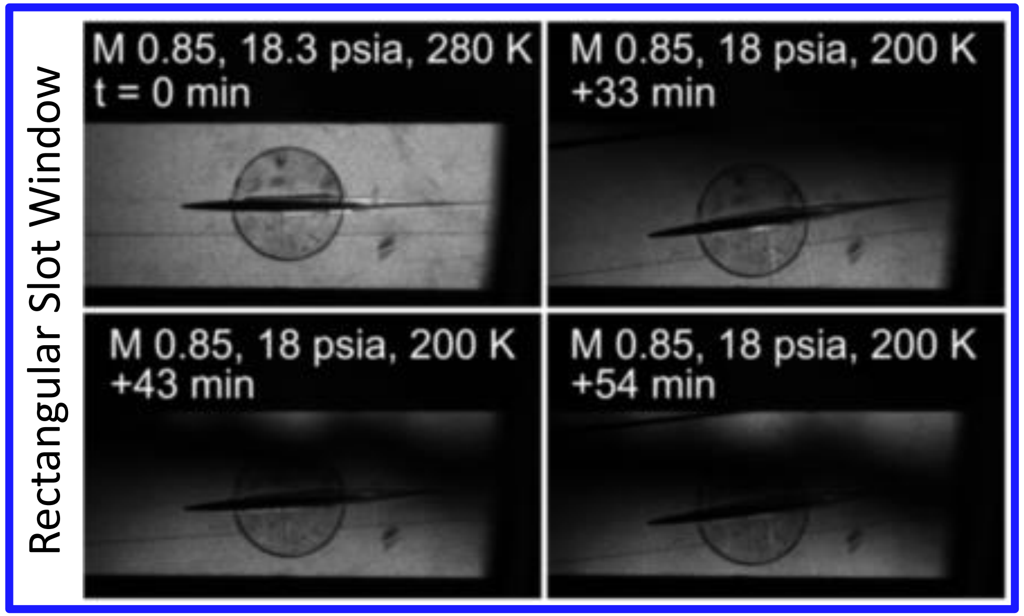


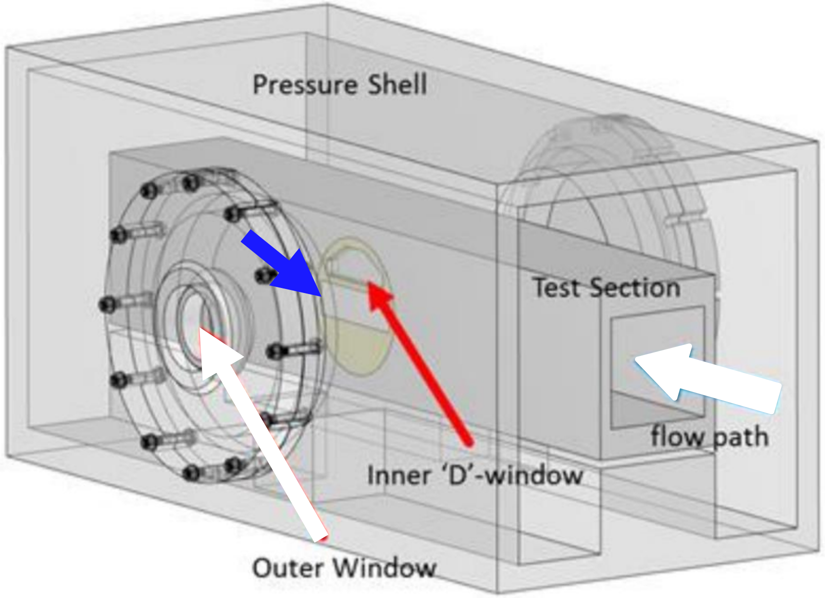
0.3-M // Stress-Induced Window Birefringence

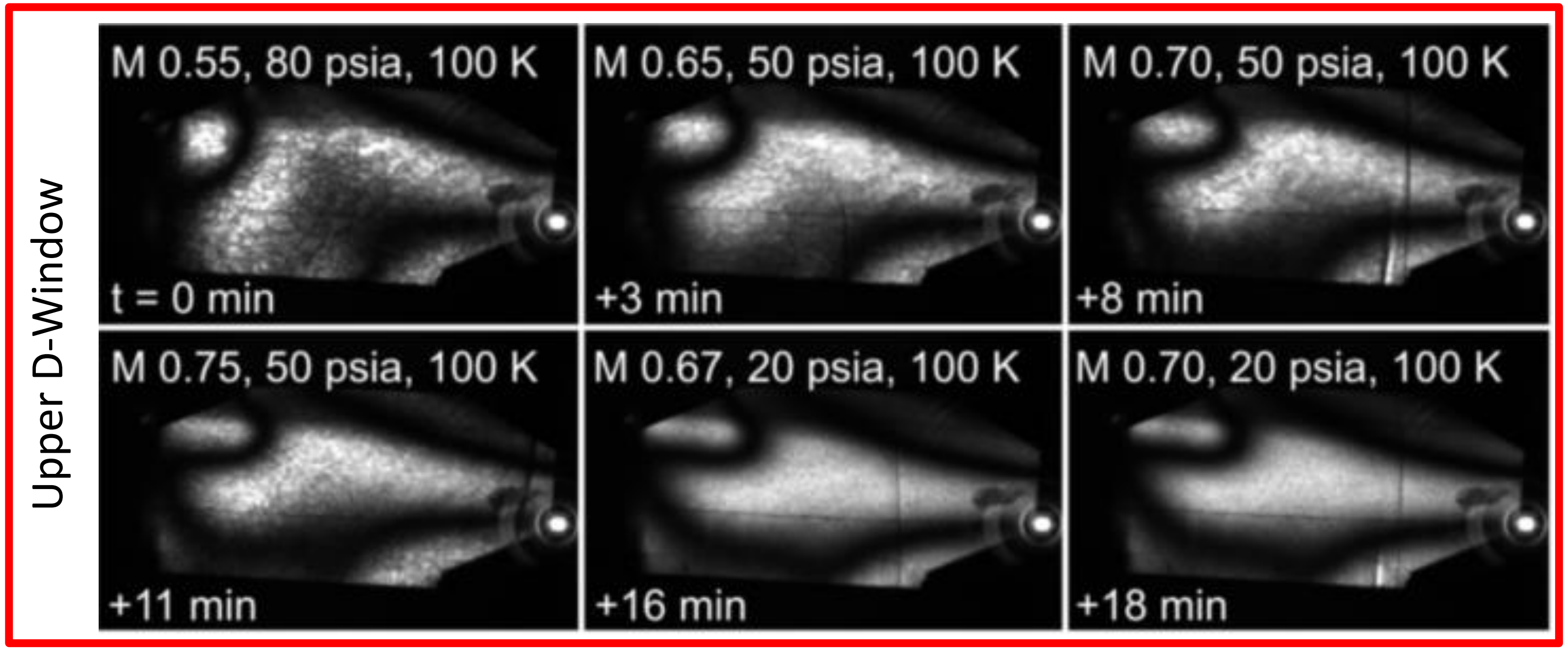
- Lowering temperature causes stress-induced window birefringence
  - Alters polarization of light transmitted through window

- Middle rectangular slot window for temperatures down to 200 K

- Upper D-window for temperatures down to 100 K



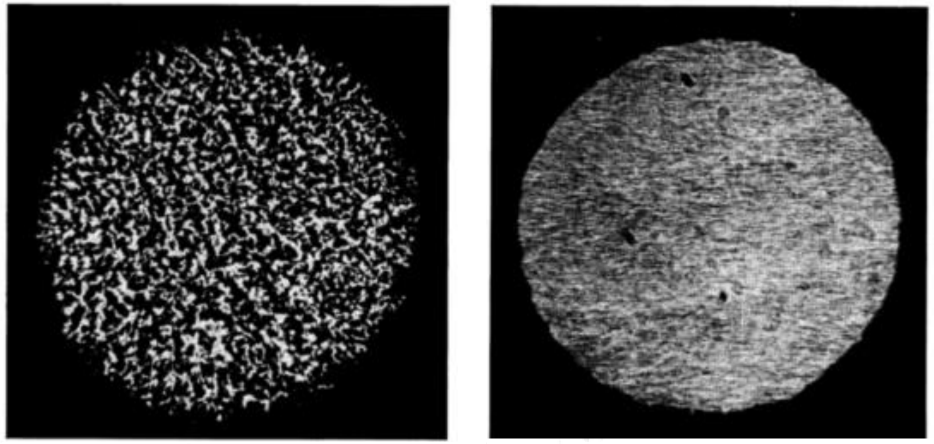




Burns et al., "Multiparameter Flowfield Measurements in High-Pressure, Cryogenic Environments Using Femtosecond Lasers," AIAA 2016-3246.

0.3-M // SAFS vs. Shadowgraph at High Pressure

- Benefit of SAFS over shadowgraph at higher pressures
- Cell-like structure of plenum flow filtered out in SAFS images



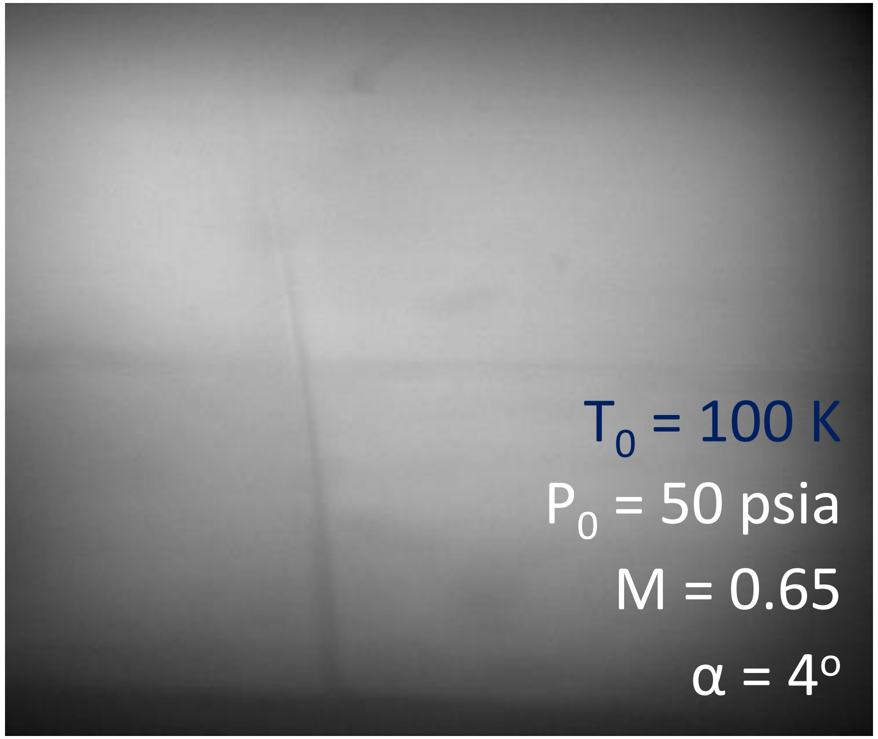
Test section + plenum   Test section only

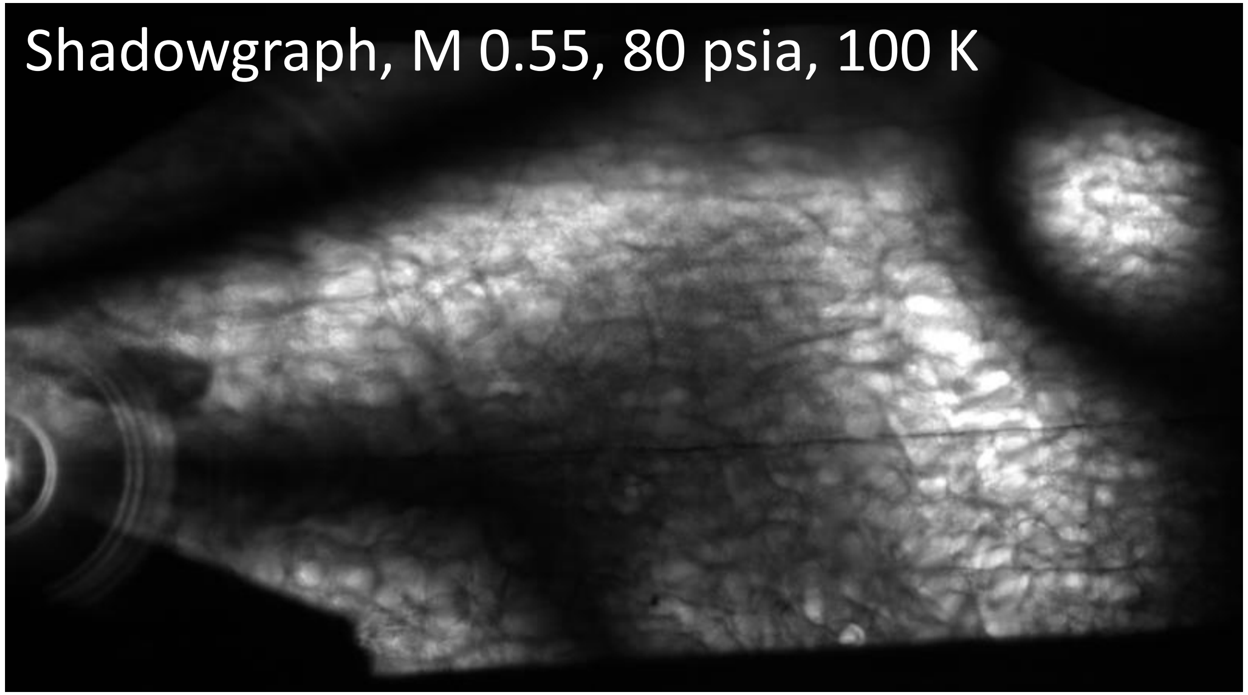
NASA Technical Memorandum 87730

Improvement in the Quality of Flow Visualization in the Langley 0.3-Meter Transonic Cryogenic Tunnel

Walter L. Snow, Alpheus W. Burner, and William K. Goad

AUGUST 1986

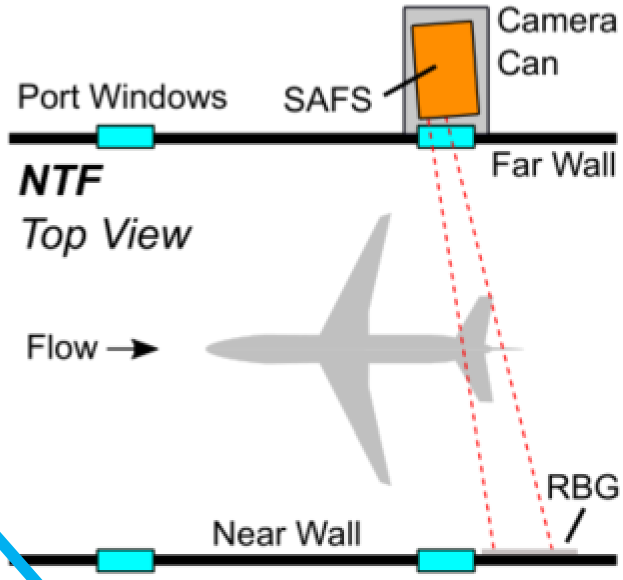


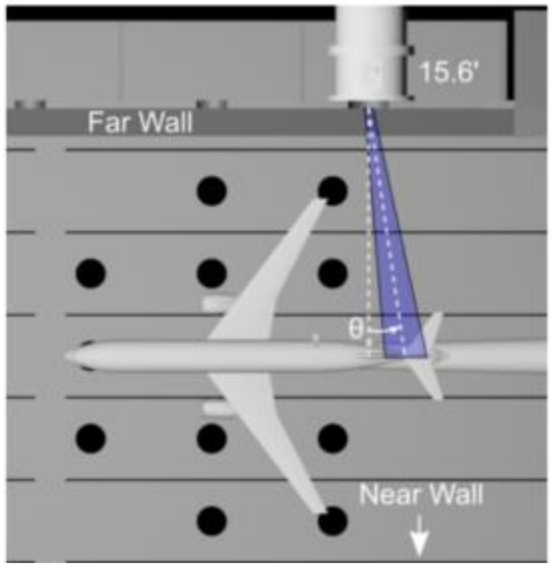


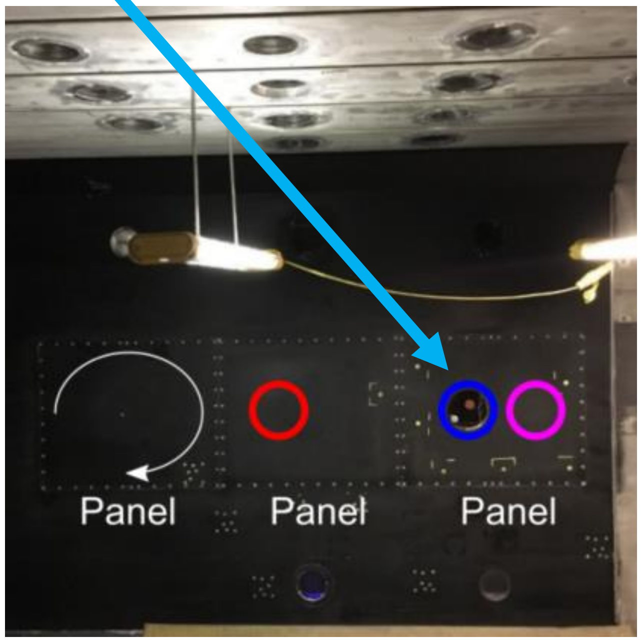
NTF // CAD Rendering for System Design

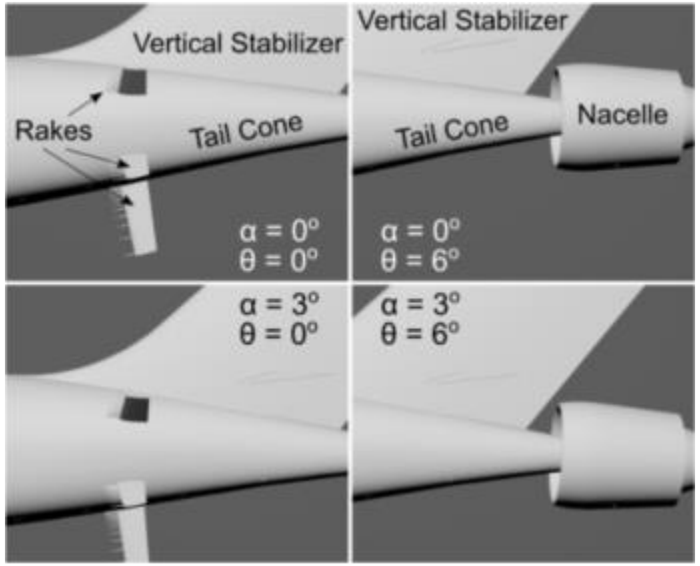
- CAD renders of tunnel/model used to:

1. Select camera can position on far wall
   - Camera can shifted downstream to 15.6’ wall position
2. SAFS system angling downstream for optimum FOV
   - Angled downstream by approximately 6 degrees
   - View tail cone and inlet of thruster nacelle
3. Location and size of retroreflective material on near wall
   - Approximately double the size of the centerline FOV







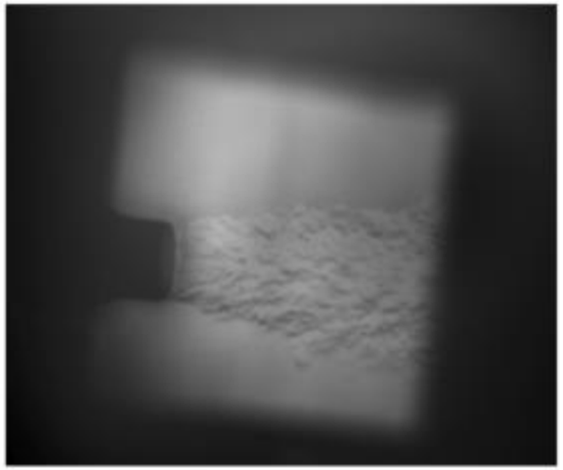


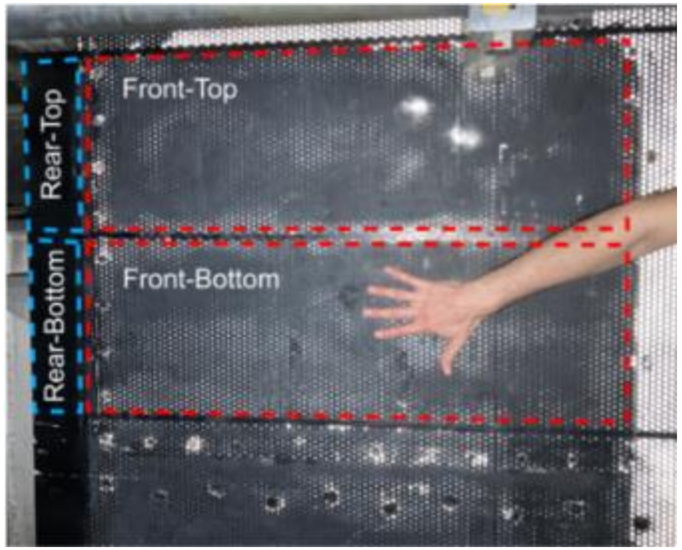
NTF // Retroreflective Material Installation

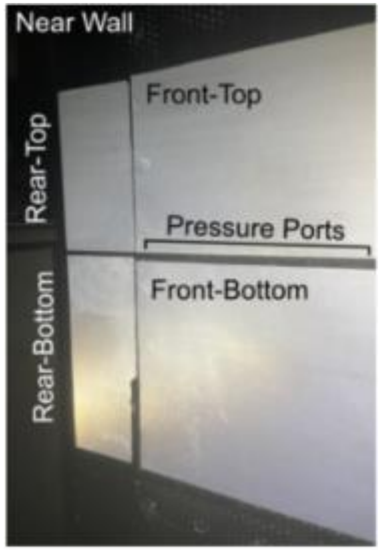
- Existing retroreflective dots on entire near wall from previous focusing schlieren tests in early 2000s
  - Insufficient intensity return to use these dots

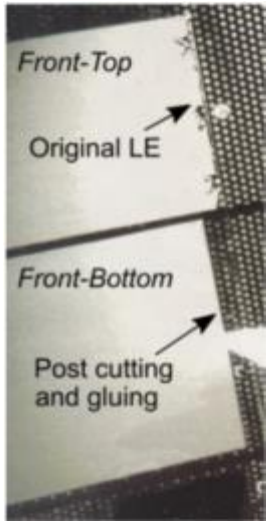
- Sanded existing retro dots and applied 3M Scotchlite 7610 retroreflective film
  - Four separate regions applied due to row of pressure ports and wall seam

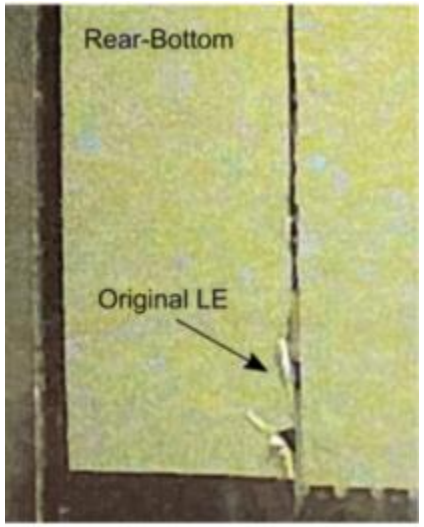
- After some running, leading edge (LE) tearing slightly
  - Cut off tearing LE and super glued new LE
  - No further tearing visible for remainder of testing

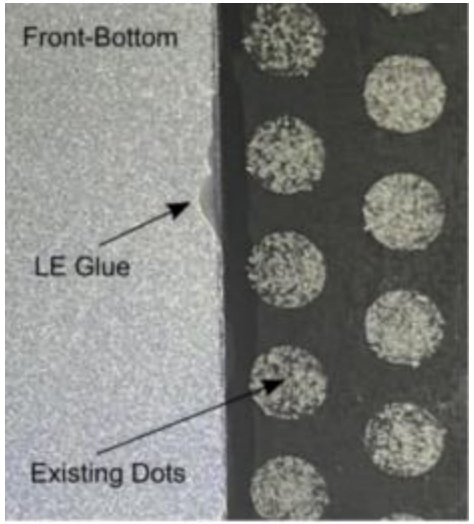






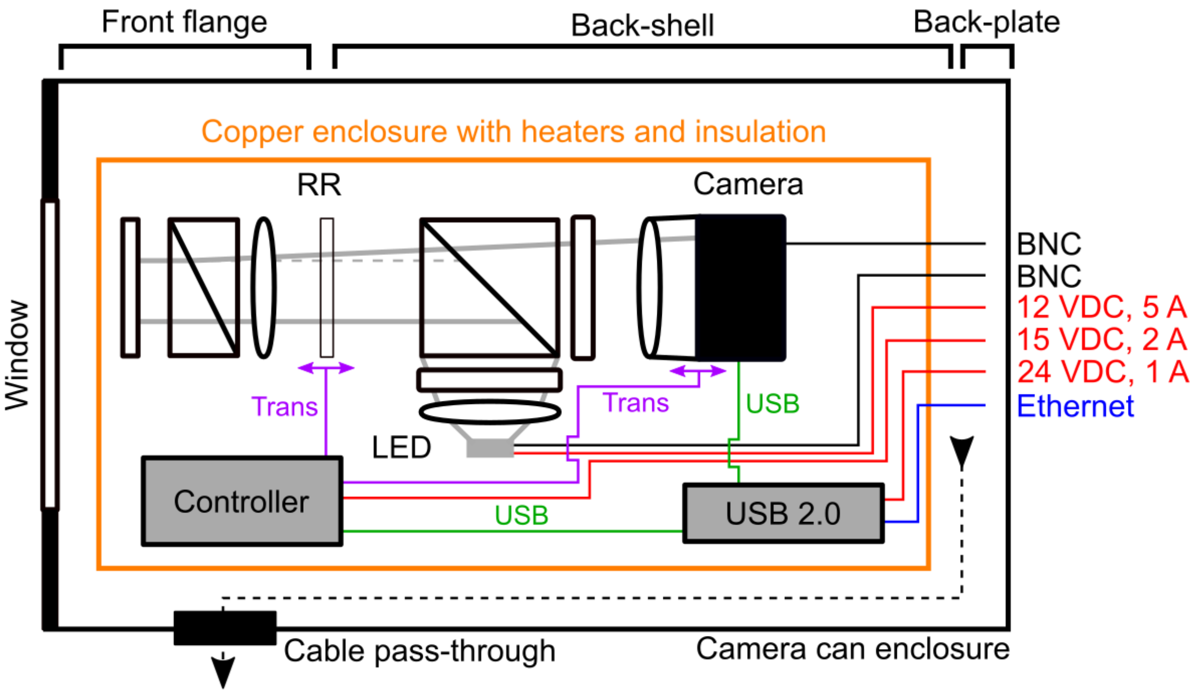


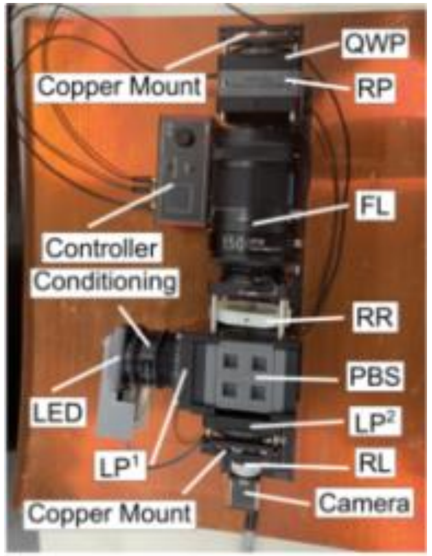


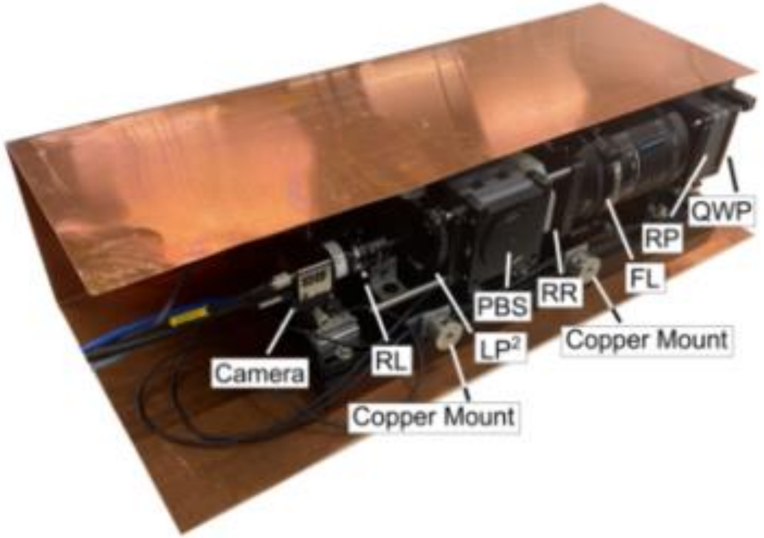


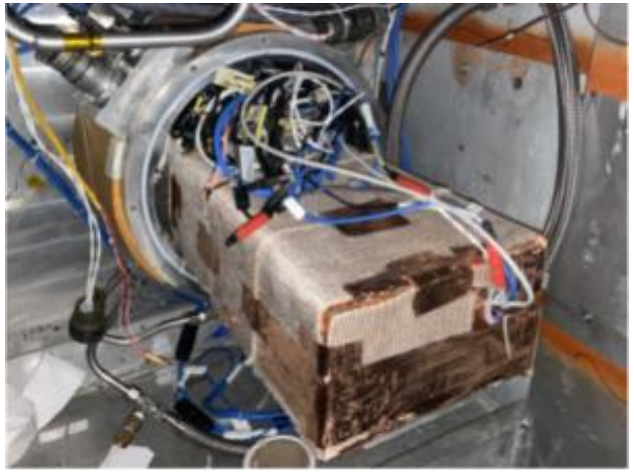
NTF // System Design and Installation

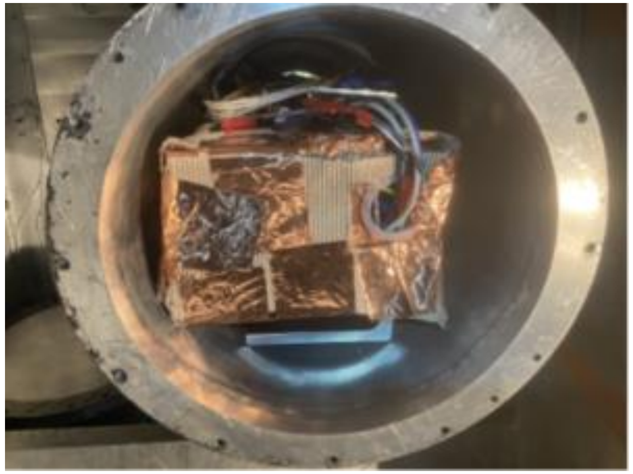
- System assembled as compactly as possible given required imaging distances
- Enclosed in copper panels to better conduct heat from resistance heaters
- Using existing cables in pass-through port (power, ethernet, BNC)
- Slides on existing optical rail, angled downstream before tightening set screws





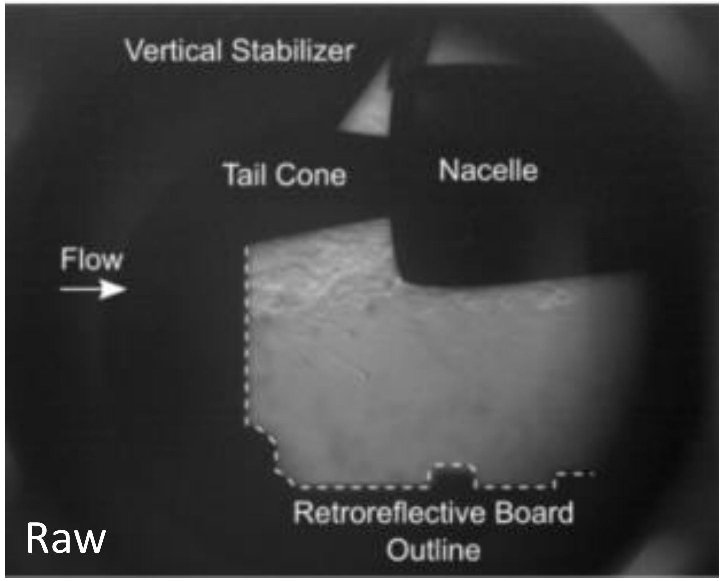


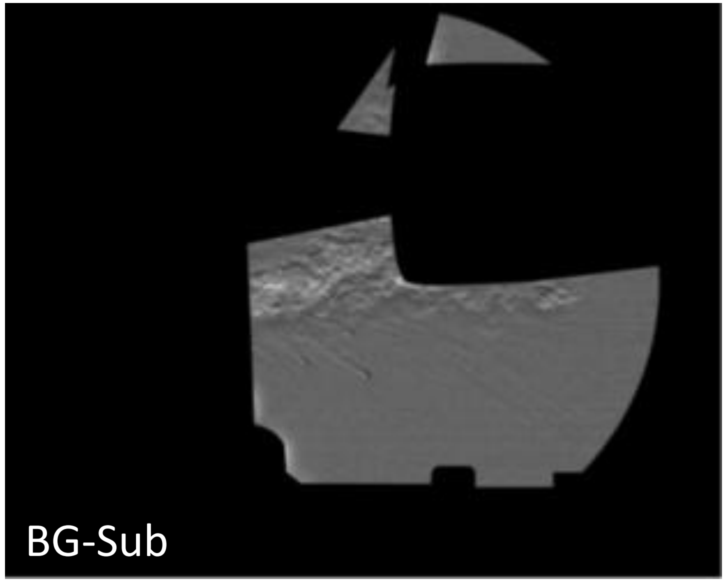


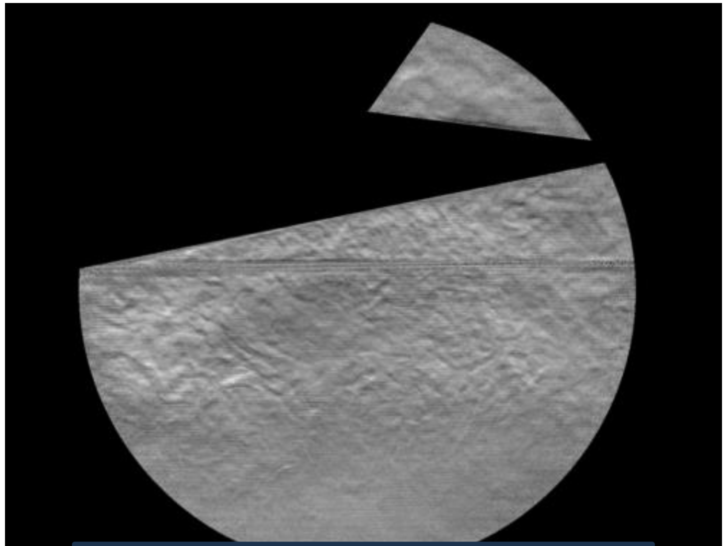


NTF // Tunnel-Off Sensitivity

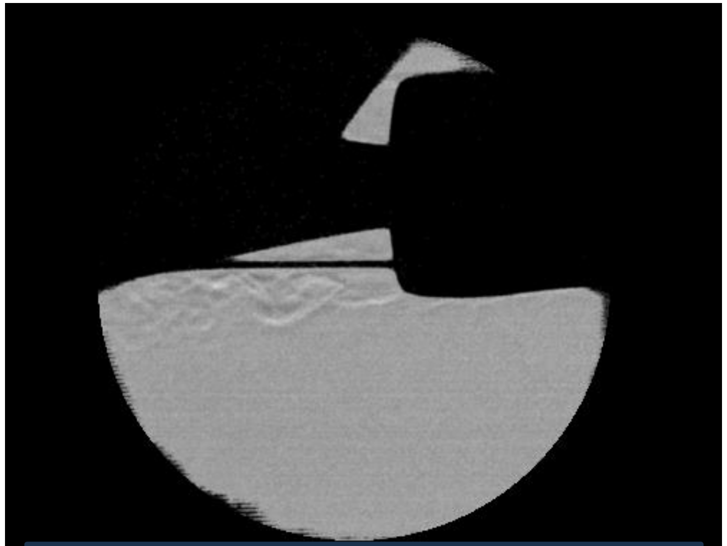
- Top images:
  - Intensity return of LED lighting sufficient
  - Good sensitivity to density gradients (canned air duster)
  - High-quality imaging even near view-obstructing tail cone and nacelle
- Bottom left:
  - Wafting of gas in the test section after tunnel was turned off
- Bottom right:
  - Difference in temperature between ambient flow and model nacelle
- These are slow-moving flows, unlike flow-on conditions







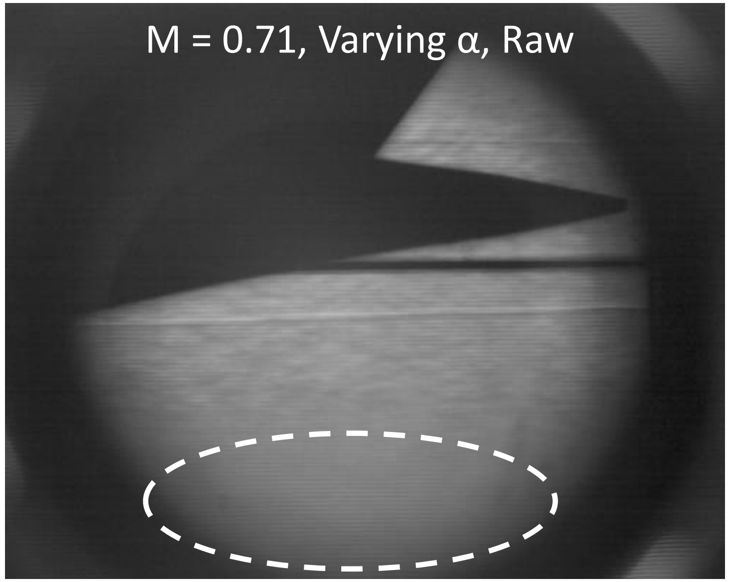
Sensitive over entire FOV

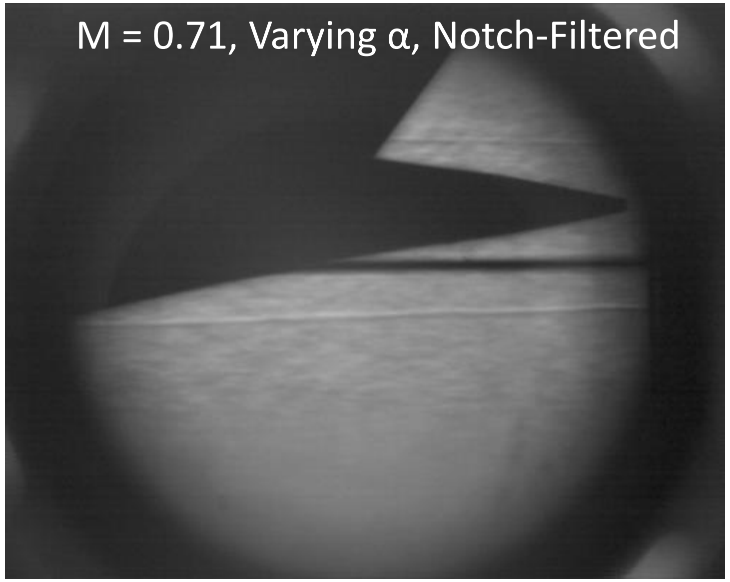


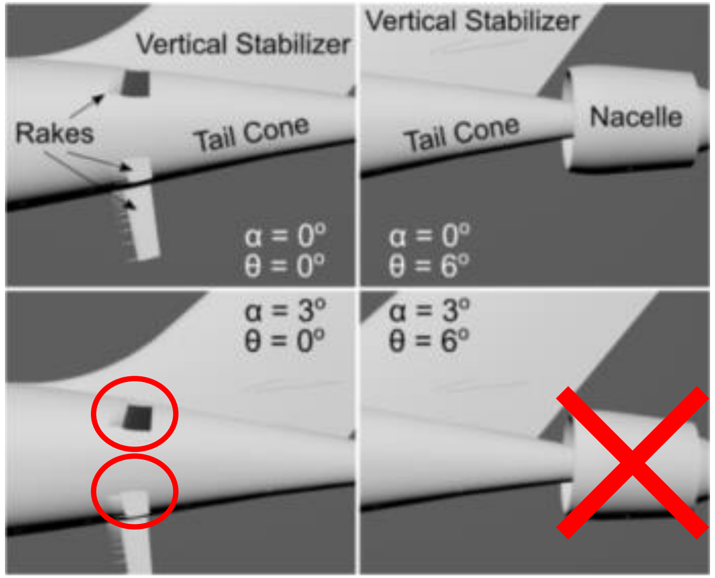
Sensitive to boundary layer flow

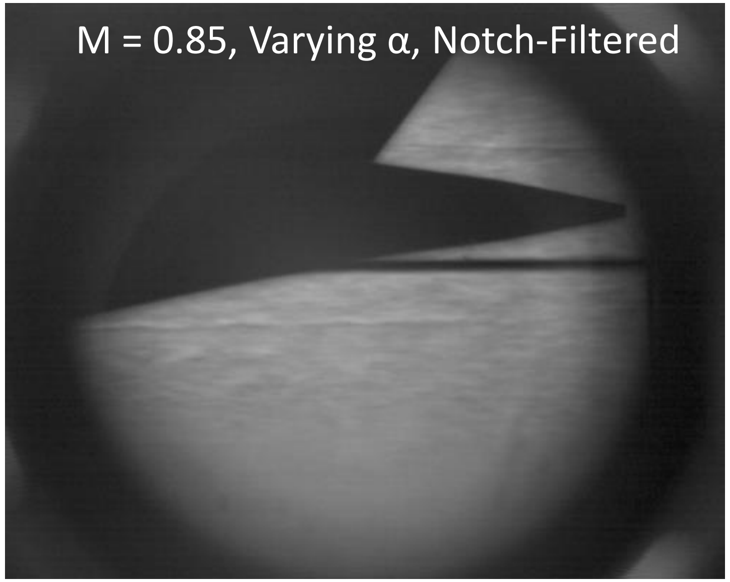
NTF // Flow Results, No Nacelle, Cryogenic Running

- Model configuration:
  - Tail cone thruster nacelle not installed
  - Boundary layer rakes installed upstream of FOV
- Ronchi ruling grid lines faintly visible in some raw images
  - Notch-filtering removes these lines
- Mach 0.71, α-sweep (top right)
  - Low α, upper and lower rake tip vortices visible
  - Higher α, upper rake tip vortex becomes fainter
  - Boundary between aircraft wake and freestream clear
- Mach 0.85, α-sweep (bottom right)
  - Rake tip vortices less steady than lower Mach numbers
  - Boundary between aircraft wake and freestream clear
- Tail cone boundary layer flow not visible



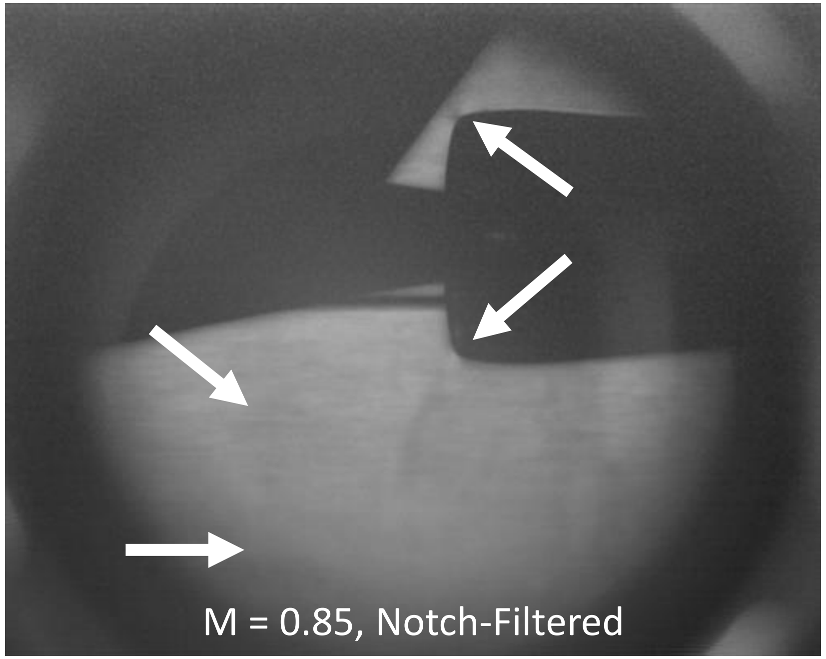


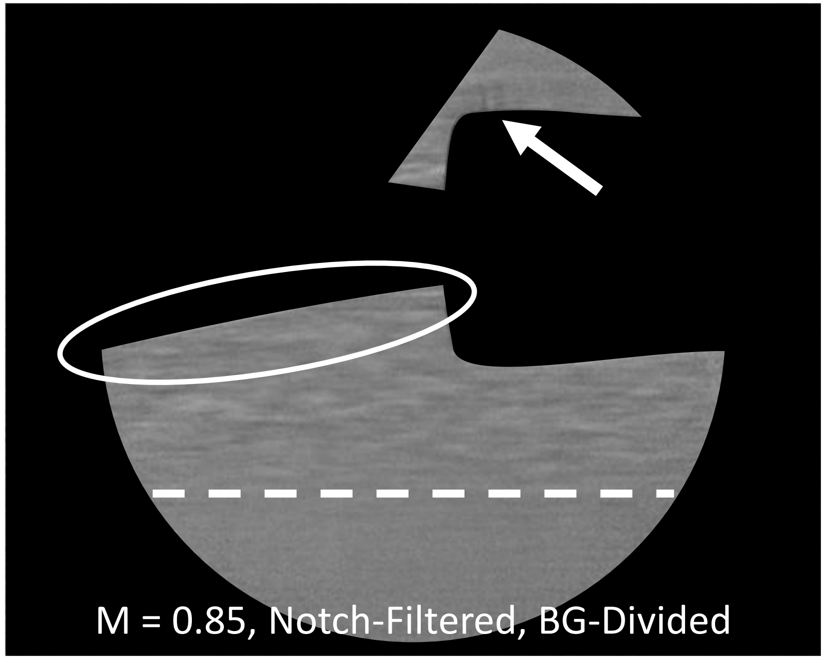




NTF // Flow Results, With Nacelle, Air Running

- Model configuration:
  - Tail cone thruster nacelle installed
  - Limited to air mode operation with nacelle
  - Boundary layer rakes not installed
- Raw images:
  - Nacelle inlet pressure gradient on bottom and top
  - Aircraft wake flow and freestream
- Background-divided images:
  - Aircraft wake flow and freestream boundary better visible
  - Shock structure on upper surface of nacelle
- Tail cone boundary layer flow not visible





Conclusions and Future Work

- Implementation at 0.3-M was successful
  - –Can image through slot window or D-window
  - –For lower temperatures, use quartz-quartz Rochon prism to mitigate influence of stress-induced window birefringence
- Implementation at NTF was generally successful
  - –Capable of high-quality imaging
  - –Quick setup time (no influence on main test objectives)
  - –Low-cost
  - –Boundary layer measurement not successful
- Future improvements
  - –Laser for lower pulse widths and higher intensity
  - –High-speed camera for time-resolved imaging
  - –Translation/rotation stages for sensitivity and focus plane adjustment