



Summary of Shock Wave Turbulent Boundary Layer Interaction Experiments in a Circular Test Section

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Agenda



- Background
- Facility
- Test Configurations
- Instrumentation
- Sample Results
- Conclusions and Recommendations

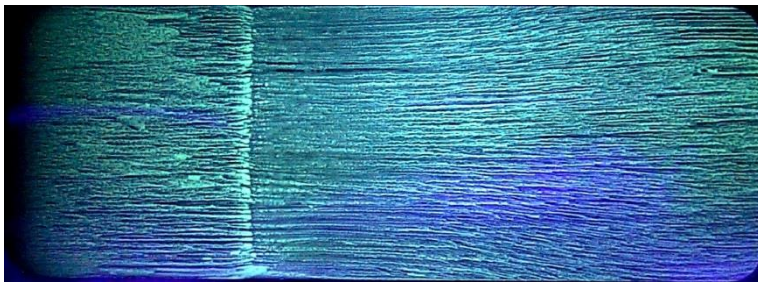
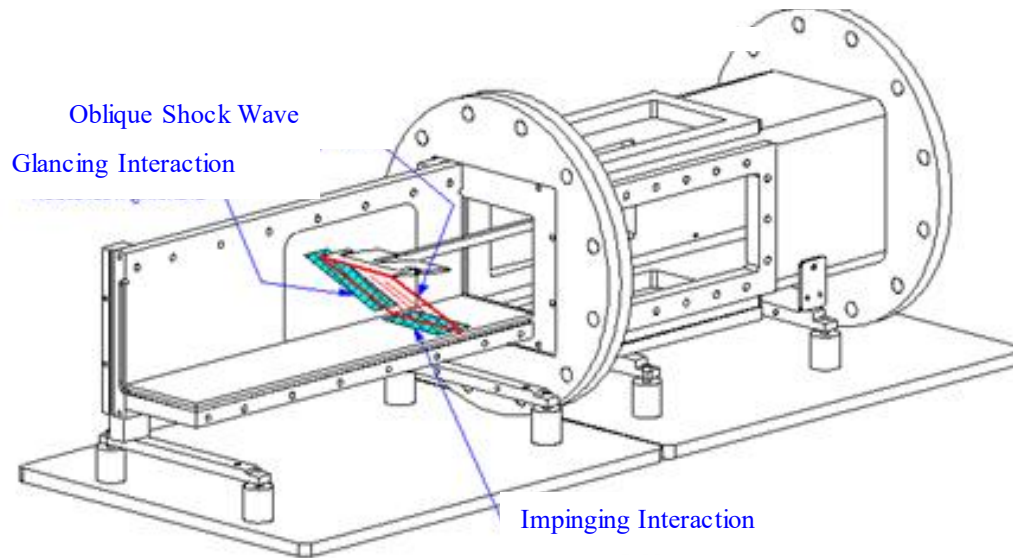


Background

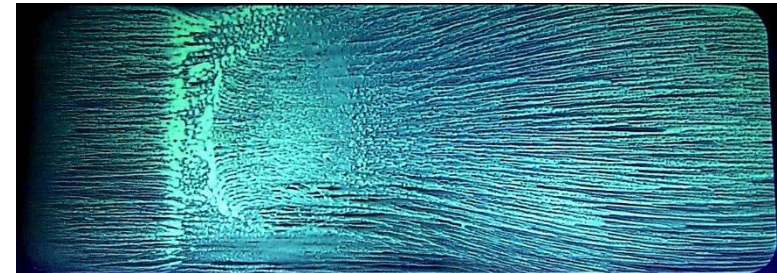


- The Transformational Tools & Technologies (TTT) Project under NASA's Transformative Aeronautics Concepts Program (TACP) is tasked, in part, with providing quality computable experiments, both subsonic and supersonic, for the purpose of validating CFD codes and turbulence models.
- A Mach 2.5 SWBLI has been identified as one of the test cases desired.
- Goal - Provide a benchmark quality experimental database to support inlet and nozzle CFD validation efforts.

- In SWBLI CFD validation experiments performed in non-circular wind tunnels pressure gradients induced by the SWBLI turn a nominally two-dimensional flowfield into a three-dimensional flowfield.



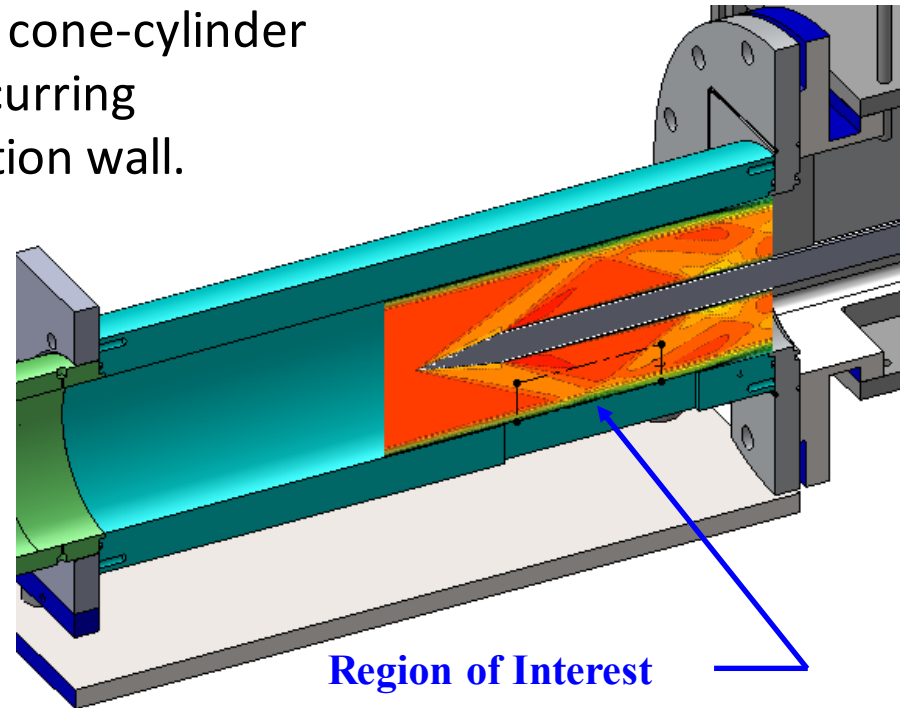
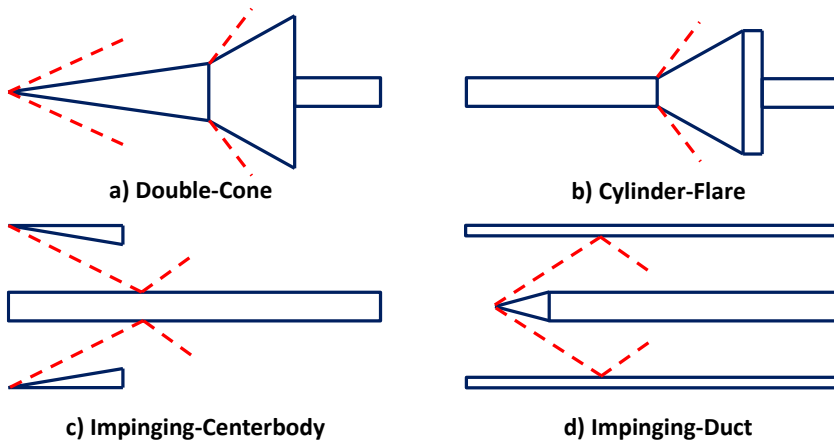
$\alpha = 7.5^\circ$



$\alpha = 9.5^\circ$

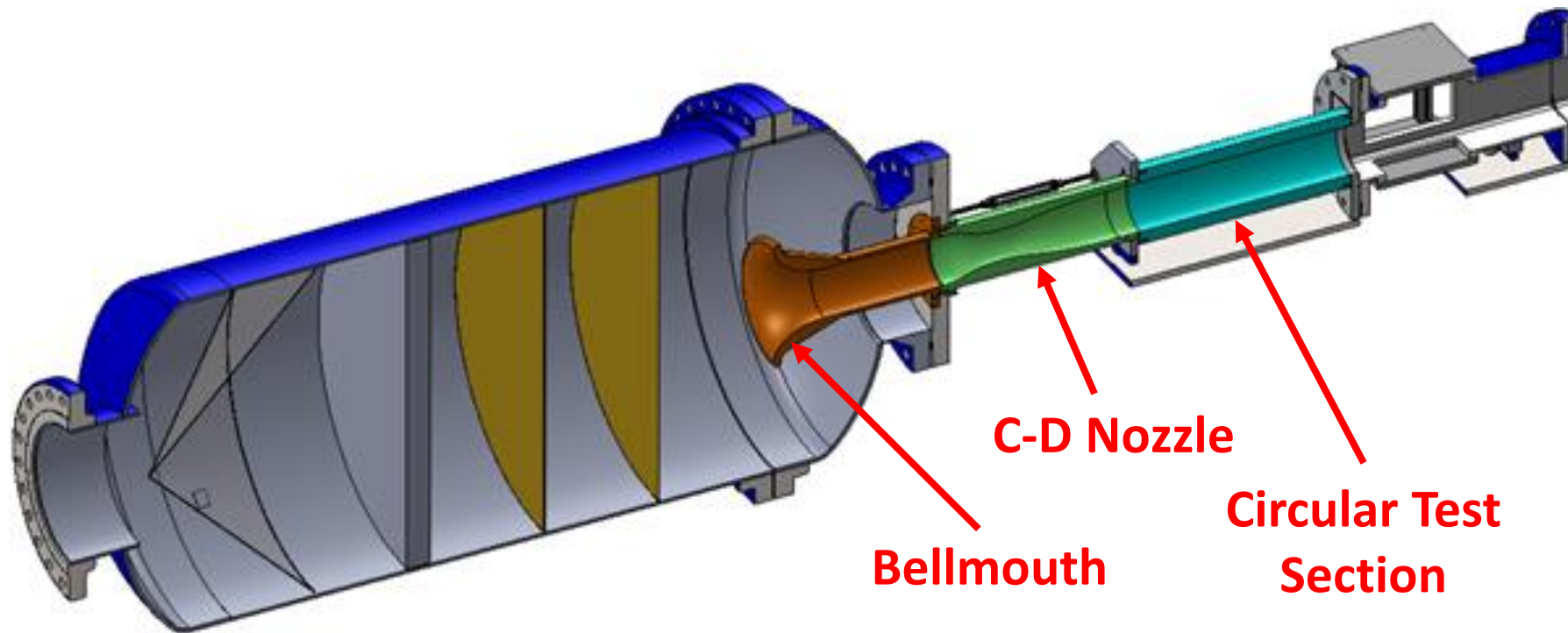
Mach 2.0 SWBLI in 15x15 cm SWT.

- In order to avoid the pitfalls of a rectangular configuration, an axisymmetric configuration that is two-dimensional in the mean was used to gather benchmark quality data.
 - Circular test section.
 - Cone-cylinder located on the centerline.
 - Shock/expansion generated by cone-cylinder interacts with the naturally occurring boundary layer on the test section wall.

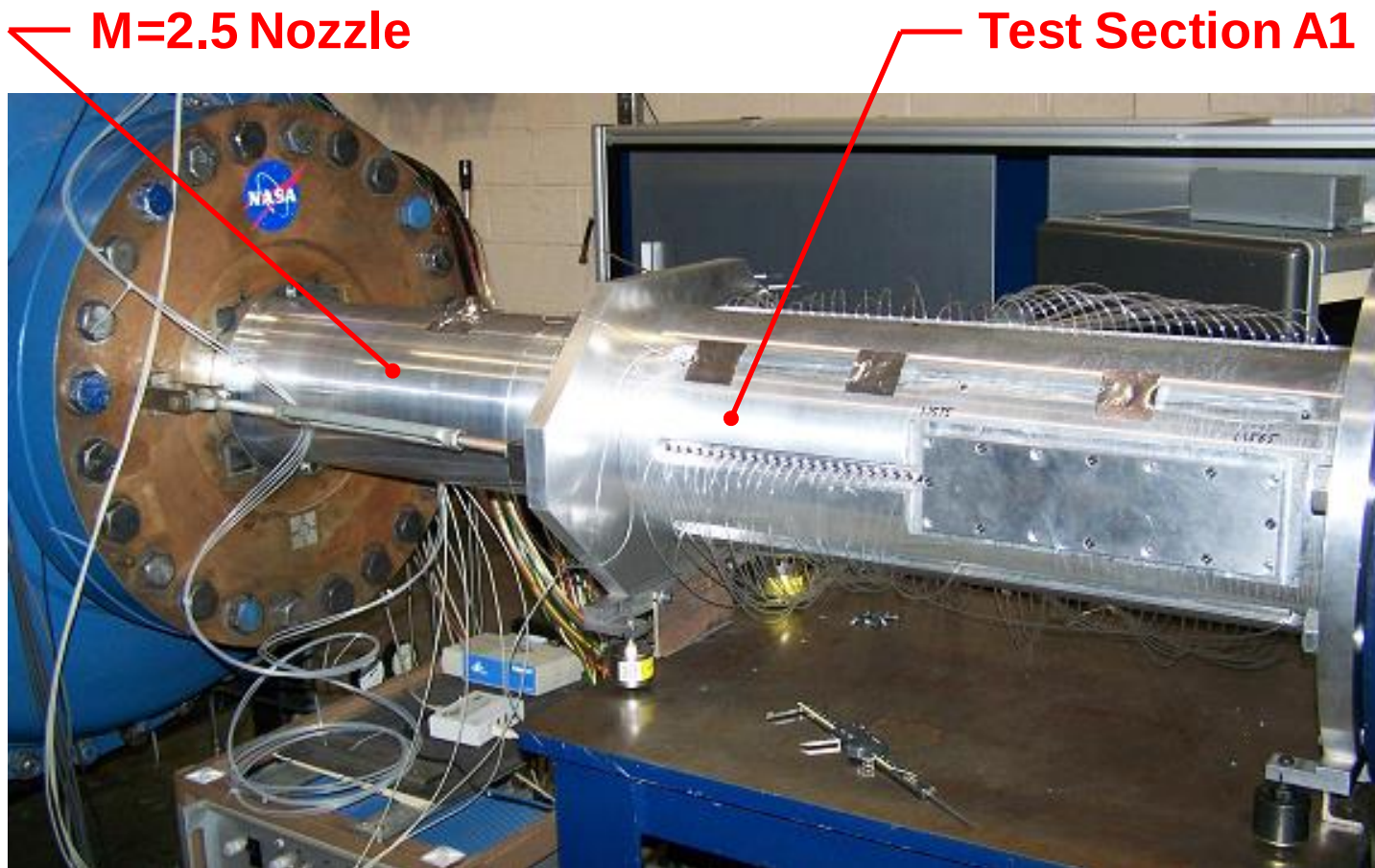


Axisymmetric SWBLI

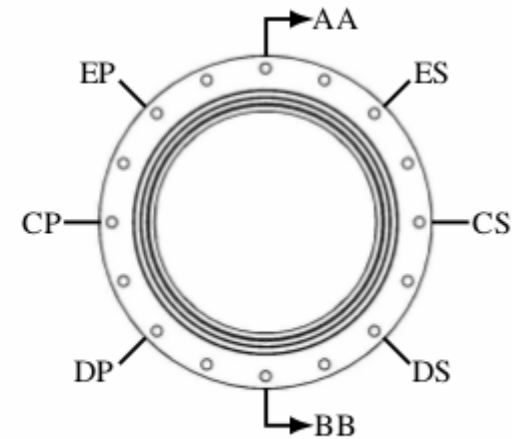
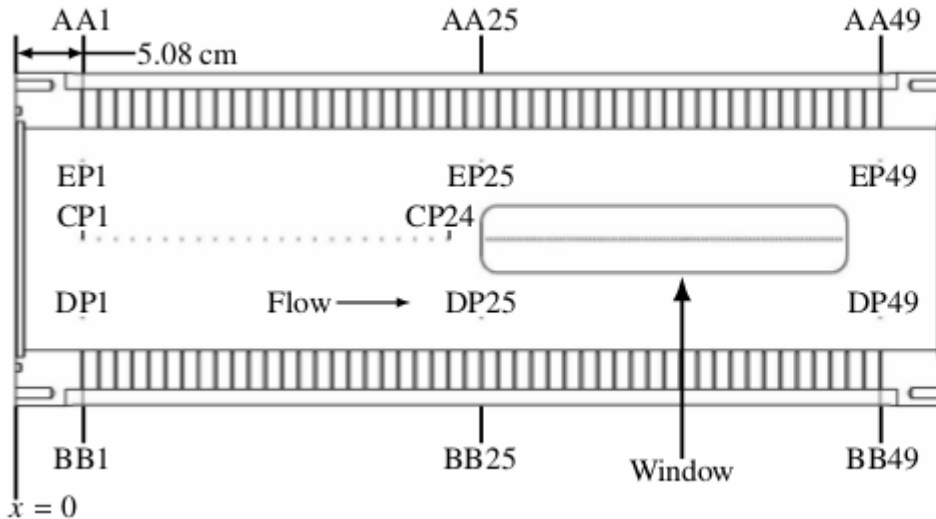
- Characteristics of validation experiment:
 - Simple Geometry:
 - Round pipe with cone-cylinder on centerline.
 - 2D in the mean, but 3D created by offsetting cone-cylinder.
 - Inflow Boundary: Supersonic developing pipe flow
 - Outflow Boundary: Wholly supersonic
 - Redundant measurements
 - Surface and pitot pressures
 - Hot-wire measurements (total temperature, mean and fluctuating mass flux, turbulence intensities)
 - PIV (mean velocities, Reynolds stresses)
 - Comprehensive Uncertainty Analysis



17 cm Axi-SWT

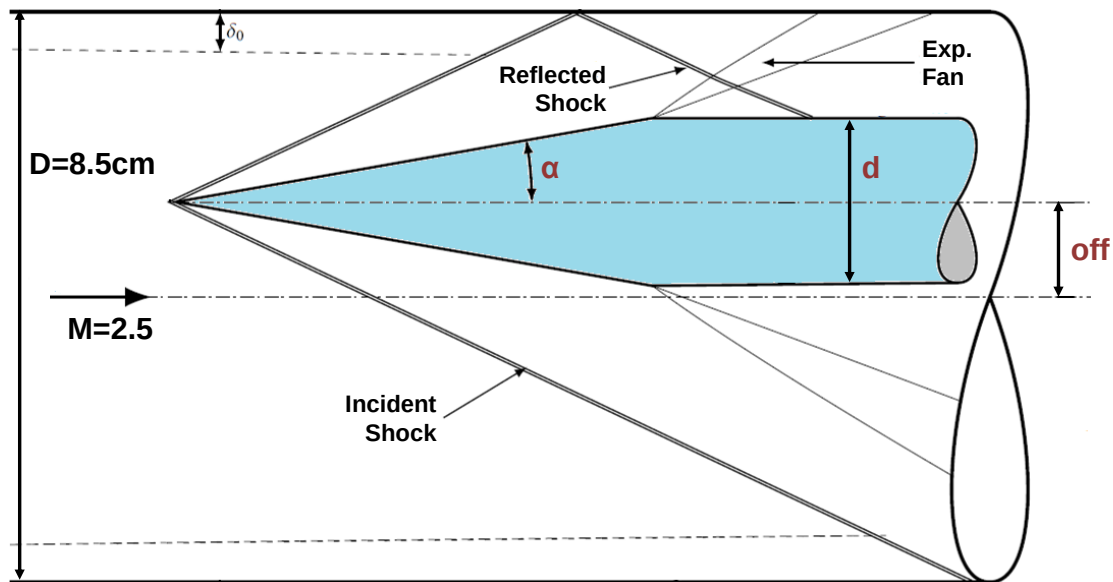


**225 sq-cm Axisymmetric (17.0 cm I.D.) Supersonic Wind Tunnel
(Flow L-R)**

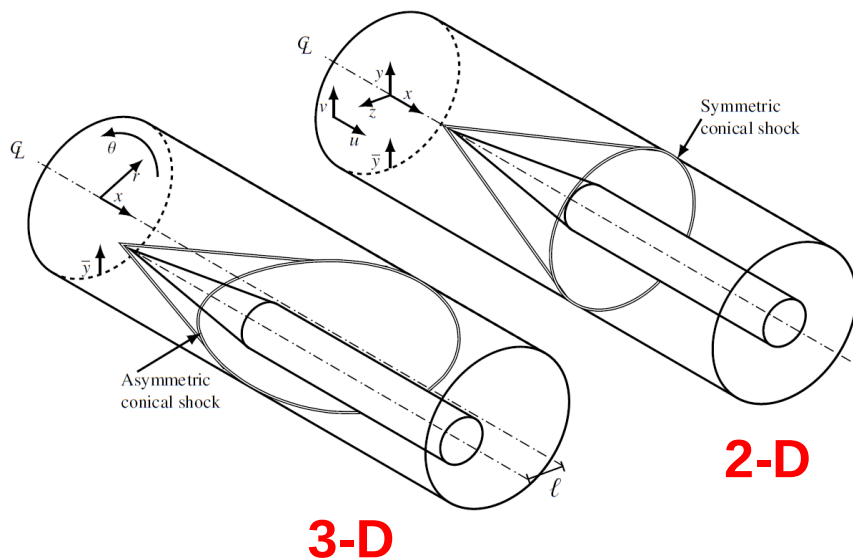


- Shock generator tip placed such that shock impinges on center of window when mounted on the centerline
- Window has 85 static pressure taps (0.125" spacing)
- Surface pressure measurements taken on window
- Probe measurements taken along station BB, on the bottom of the test section
- Shock generator can rotate around test section centerline to take measurements along any circumferential location





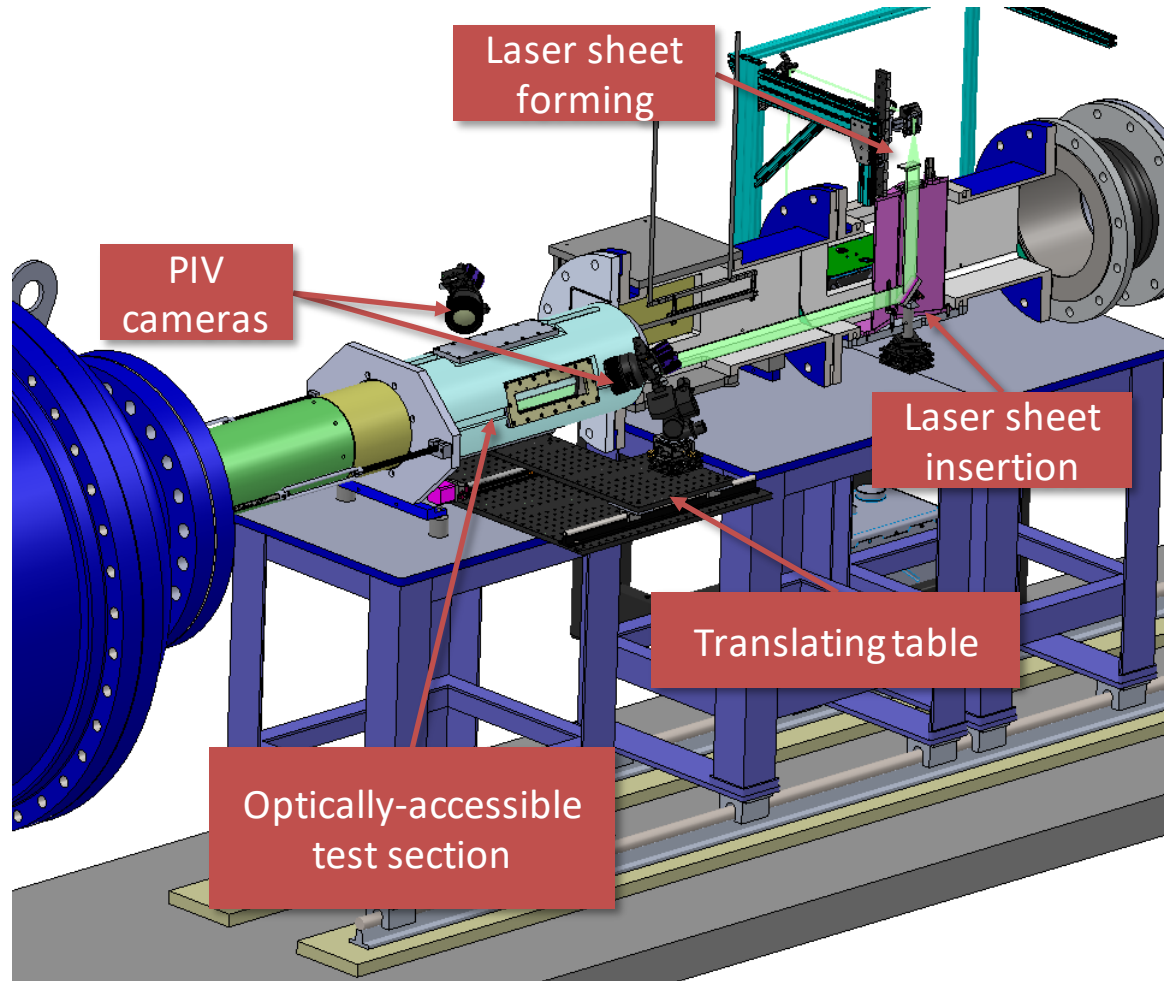
Config. No.	α (deg)	d (cm)	off (cm)
1	10.0	3.135	0.000
2	13.5	3.135	0.000
3	16.0	3.135	0.000
4	10.0	5.000	0.000
5	13.5	5.000	0.000
6	16.0	5.000	0.000
7	10.0	5.000	2.125
8	13.5	5.000	2.125
9	16.0	5.000	2.125
10	10.0	5.000	2.833
11	13.5	5.000	2.833
12	16.0	5.000	2.833



- Surface flow visualization
- Surface pressure taps
 - Upstream influence
 - Circumferential pressure gradients that result in secondary flows
- Flowfield pressure probes
 - Concentration of points near the wall
 - Only for clean, centerline, and circumferential angles 0° and 180°
 - Broad surveys used to determine region of interest for hot-wire measurements
- Normal Hot-Wire Anemometry
 - Mean mass flux
 - Mean total temperature
 - Turbulence intensities and correlations
- Particle Image Velocimetry (PIV)
 - Three component velocity
 - Reynolds stresses



- Difficult to obtain optical access without disturbing the flowfield; unique test section fabricated for PIV
- Seed particles introduced locally to region of interest
- Laser sheet glancing on tunnel floor to reduce flare
- Stereoscopic PIV
 - All 3 velocity components
 - Cameras view from opposite sides of the laser sheet which are rotated upward and aft of the region of interest.
- A translating table for synchronous translation of the PIV cameras.
 - Allows data to be collected at multiple streamwise locations without interrupting facility operation.



In-depth detail of PIV system in upcoming paper in AMT-09, Tuesday at 9:50

θ	Asymmetric ($\ell_{OF1} = R/4$)			Asymmetric ($\ell_{OF2} = R/3$)		
	$\alpha = 10$ (unsep.)	$\alpha = 13.5$ (sep.)	$\alpha = 16$ (sep.)	$\alpha = 10$ (unsep.)	$\alpha = 13.5$ (sep.)	$\alpha = 16$ (sep.)
ζ	s, p, h	s, p	s, p, h	$\leftarrow$ symmetric		
0°	o, s, p	o, s, p	o, s, p, h	s	s, p	s
22.5°	s	s	s	s	s	s
45°	s	s	s	s	s	s
67.5°	s	s	s	s	s	s
90°	o, s	o, s	o, s	s	s	s
112.5°	s	s	s	s	s	s
135°	s	s	s	s	s	s
157.5°	s	s	s	s	s	s
180°	o, s, p	o, s, p	o, s, p, h	s	s, p	s

o= oil-flow visualization

s= static surface pressure measurement

p= pitot tube measurement

h= hot-wire measurement

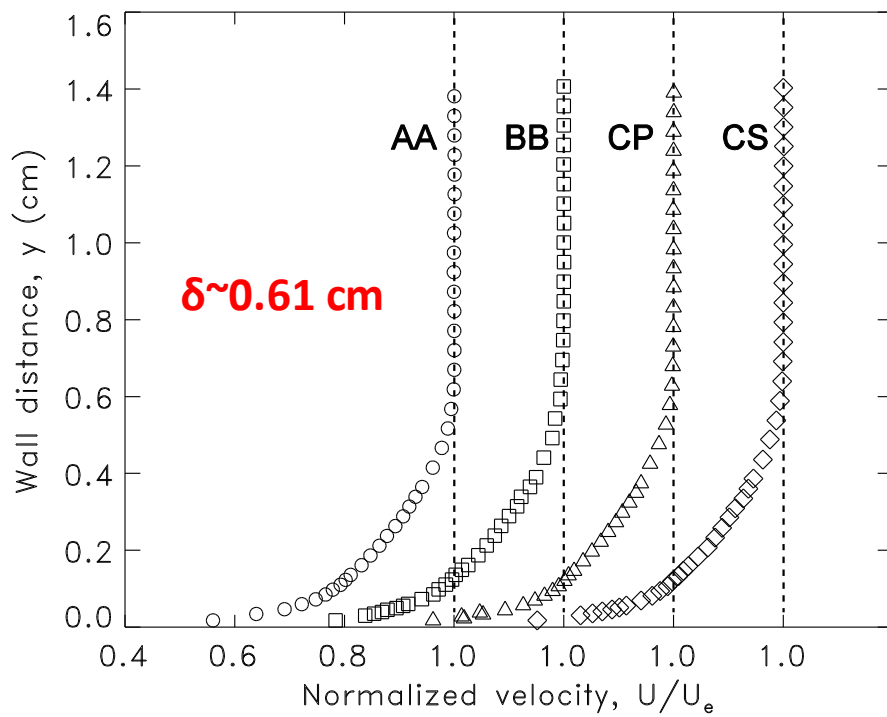
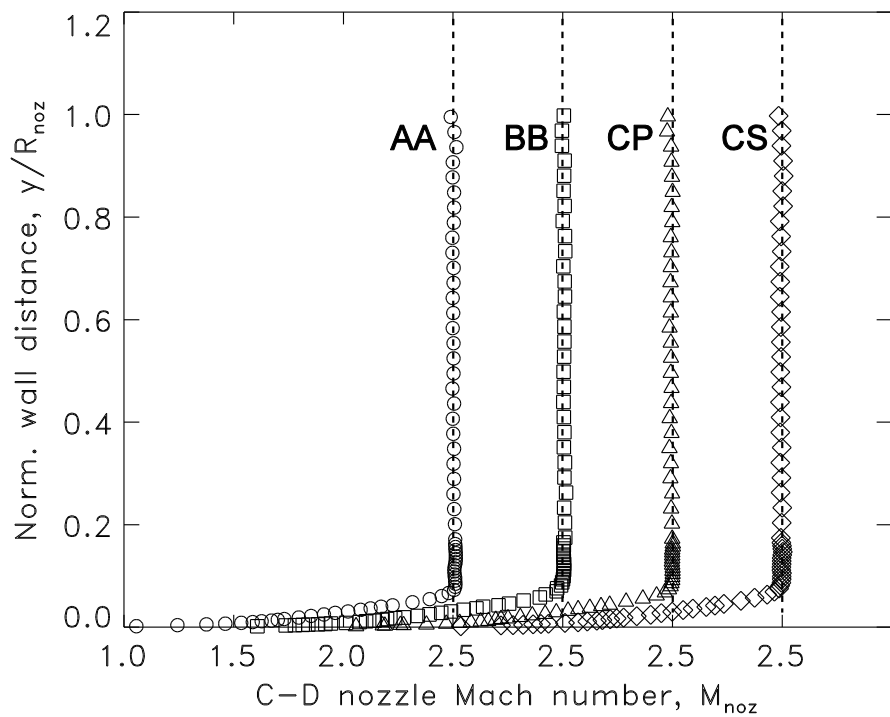
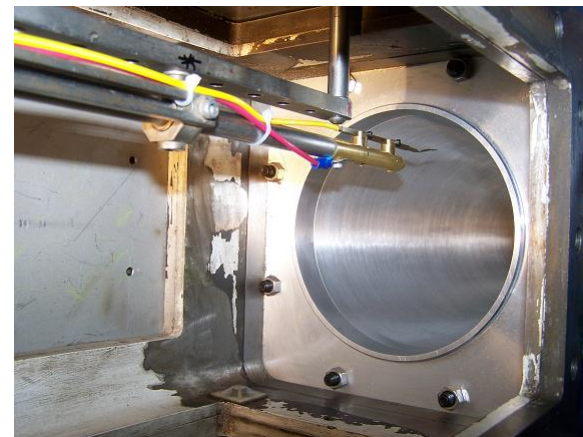
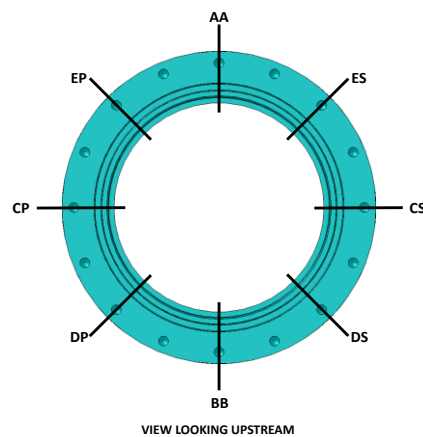
Test matrix for probe measurements, $Re_D = 4.0 \times 10^6$

	$\alpha = 10^\circ$			$\alpha = 13.5^\circ$			$\alpha = 16^\circ$		
$Re \rightarrow$ $\theta \downarrow$	2×10^6	3×10^6	4×10^6	2×10^6	3×10^6	4×10^6	2×10^6	3×10^6	4×10^6
$\mathbb{Q}$	×		×	×		×	×	×	×
0°	×		×	×		×	×	×	×
90°	×		×	×		×	×	×	×
180°	×		×	×		×	×	×	×

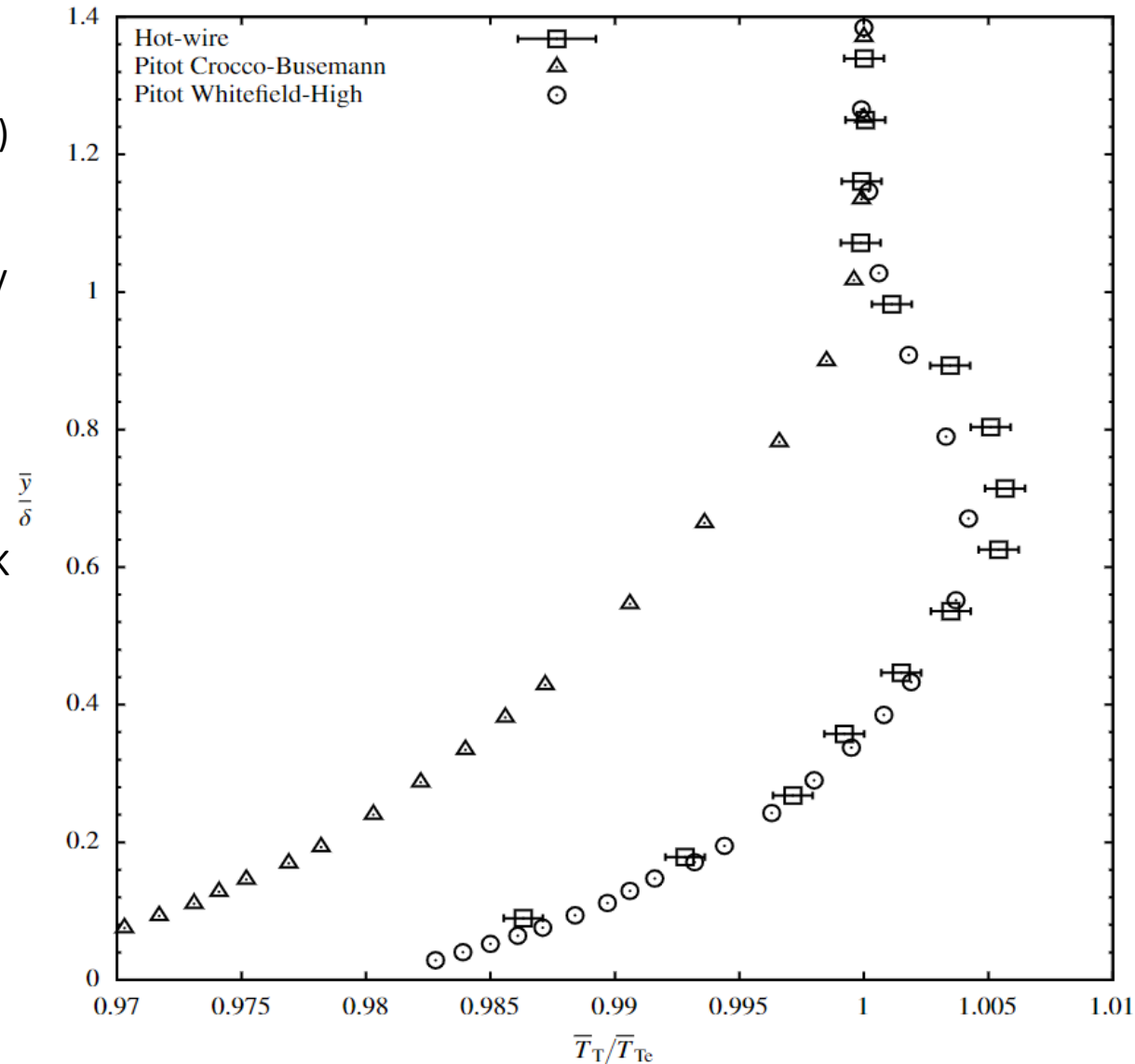
All PIV data on offset shock generator is at $\ell_{OF} = R/4$.



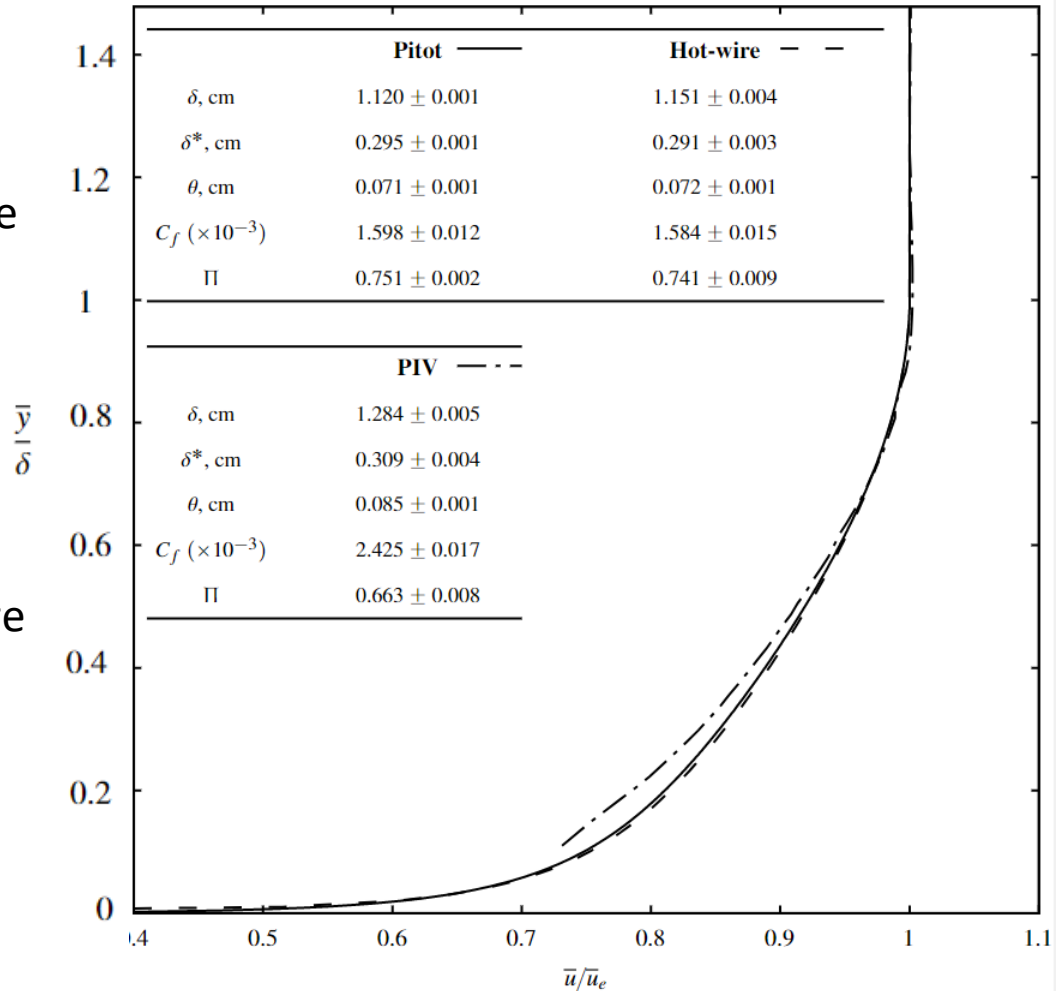
Sample Results



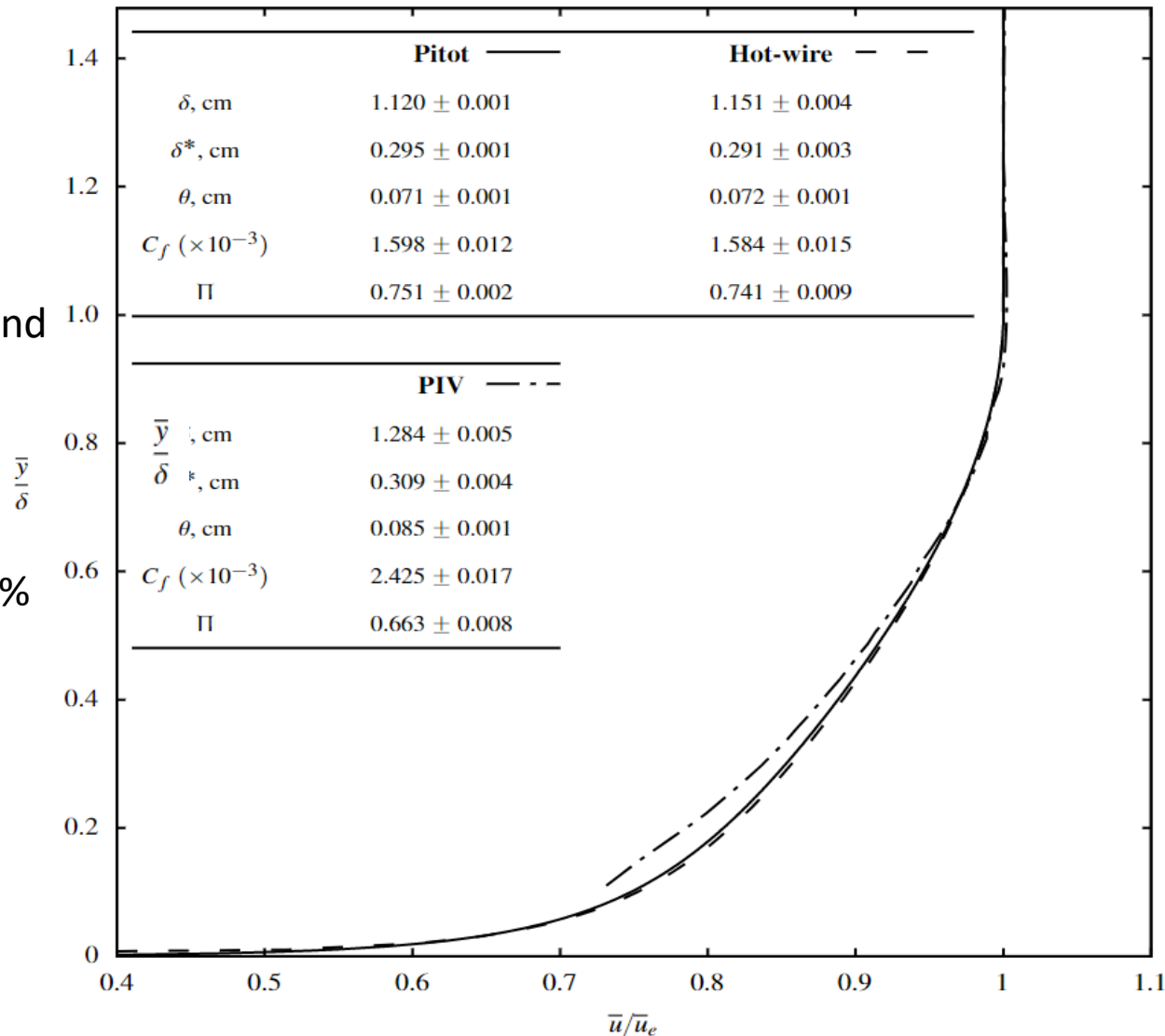
- Measured portion of profile where local total temperature exceeds freestream (plenum total)
- Comparing pitot data reduced with and without overshoot:
 - 0.57% max difference in velocity profile
 - 5.3% in wall-wake parameter
 - 6% in momentum thickness
 - 8.2% in $H = \delta^* / \delta$
- Freestream Mach based adiabatic wall temperature= 292.47 ± 0.93 K
- Measured wall temperature= 290.7 ± 0.5 K



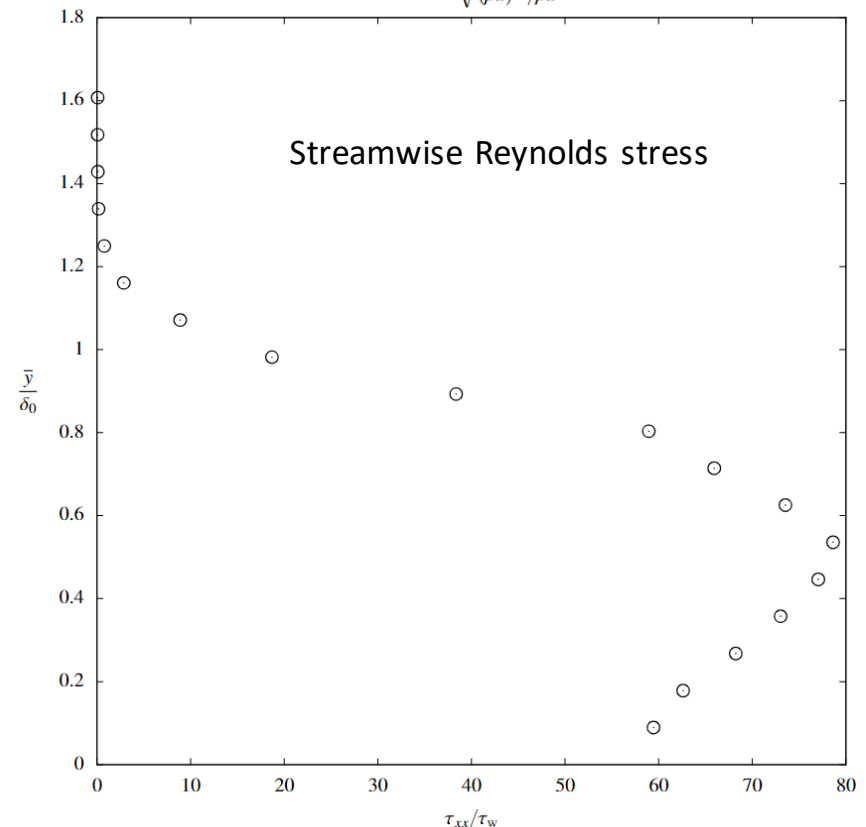
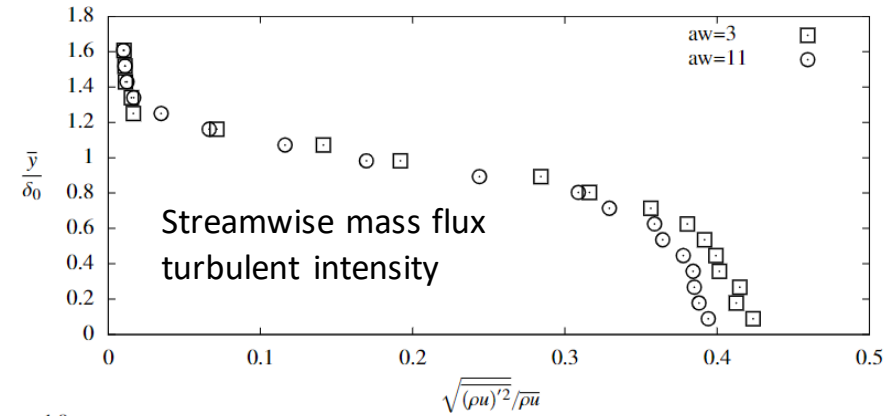
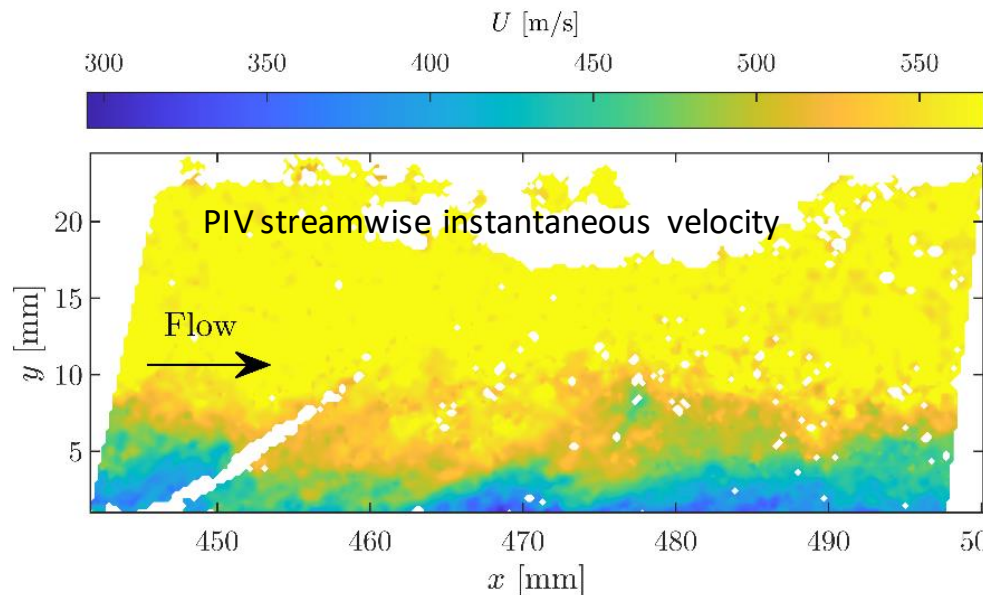
- Freestream Mach number = 2.47
- Nozzle exit Mach number = 2.50
- Difference between pitot and hot-wire velocity <0.5%
 - Boundary layer parameters are within uncertainty bounds
- Max difference between PIV and hot-wire data is 4.86%
 - PIV profile measured 6.5 cm downstream of pitot and hot-wire profile
- Uncertainty in velocity is +/- 2%

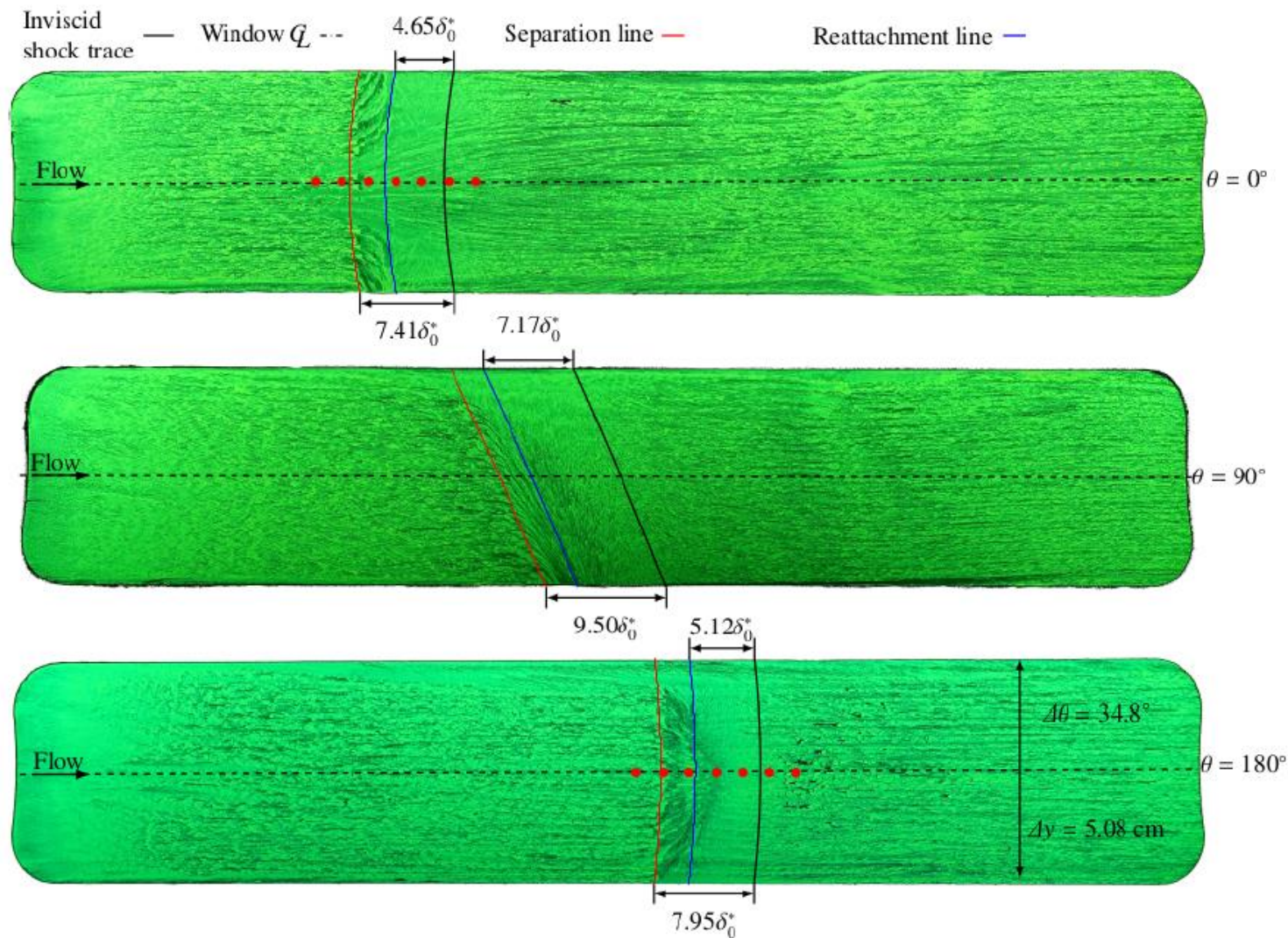


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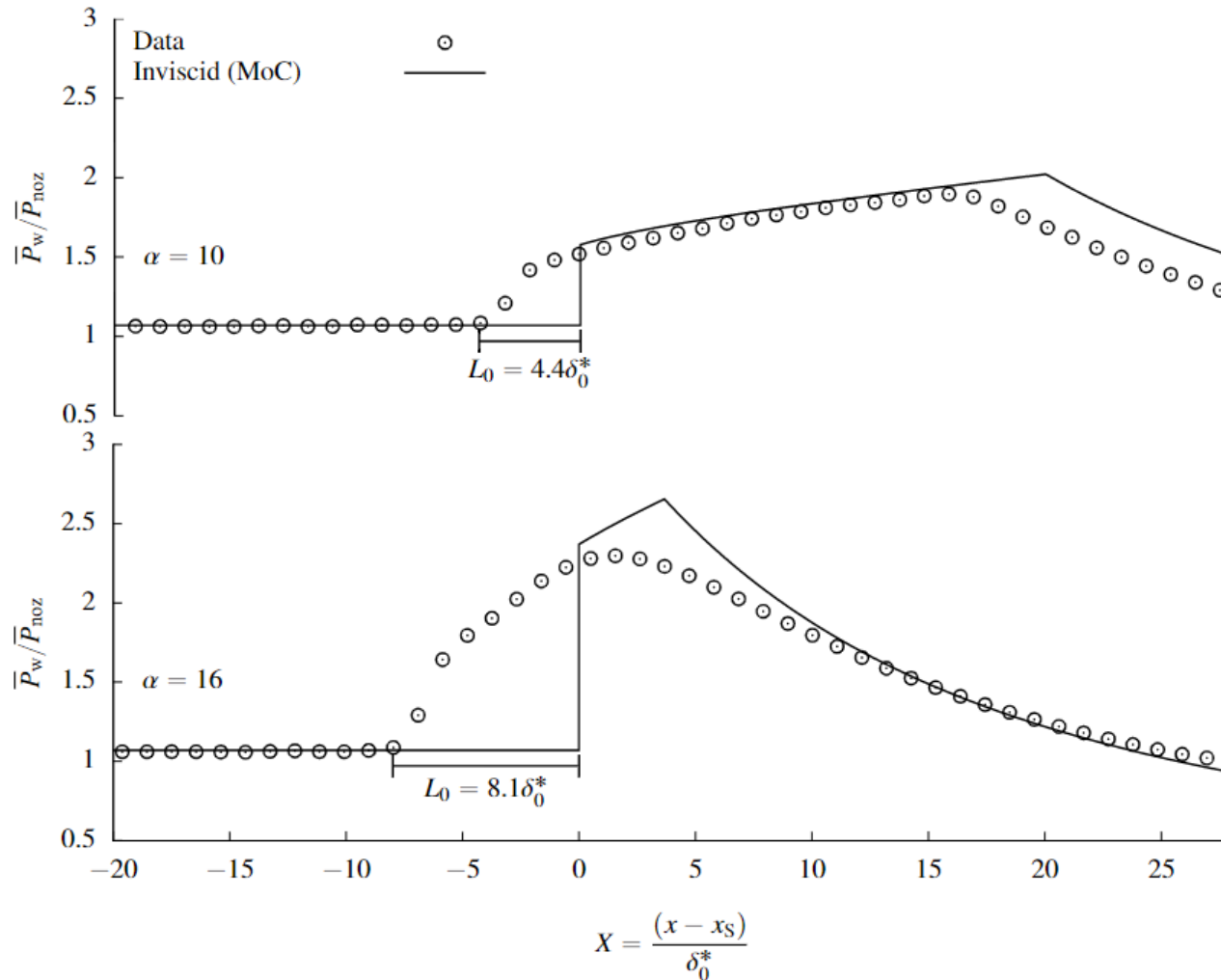
- Hot-wire data obtained at 11 different overheat parameters
- Streamwise Reynolds stress computed for incoming boundary layer.
- Hot-wire measures mass flux, and velocity (in supersonic flow).
 - Cannot separate product of density and velocity.
 - Cannot compute Reynolds stresses for SWBLI region.

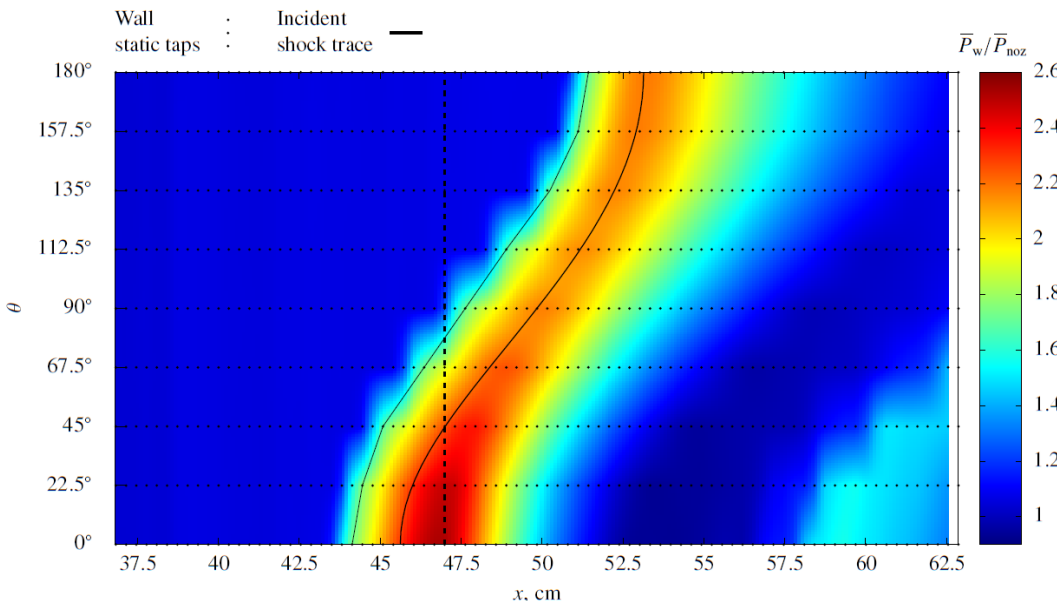
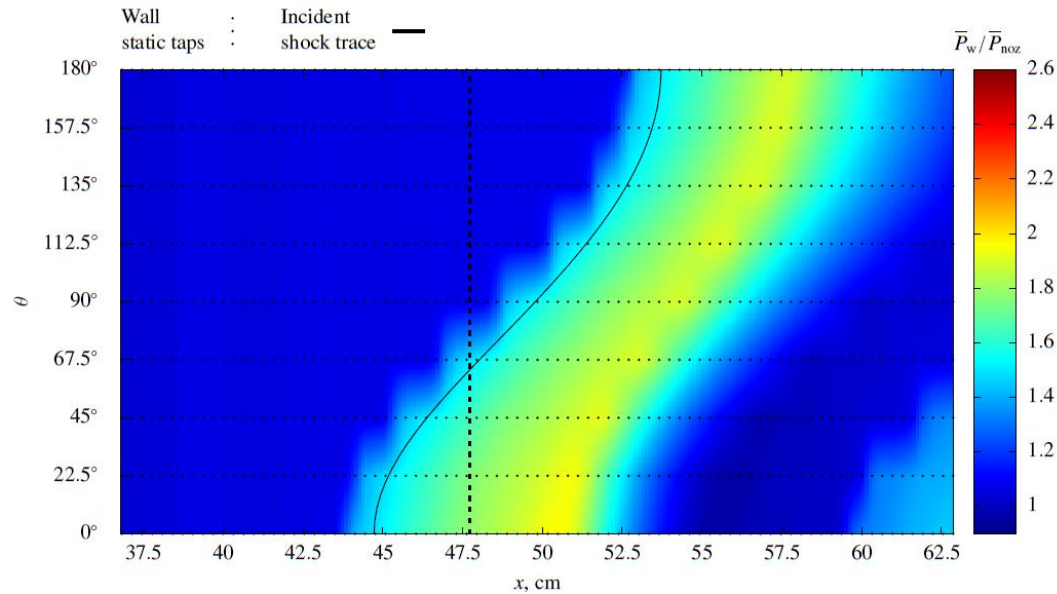




$\alpha=16.0^\circ$, $d=5.0 \text{ cm}$, $\text{off}=2.125 \text{ cm}$

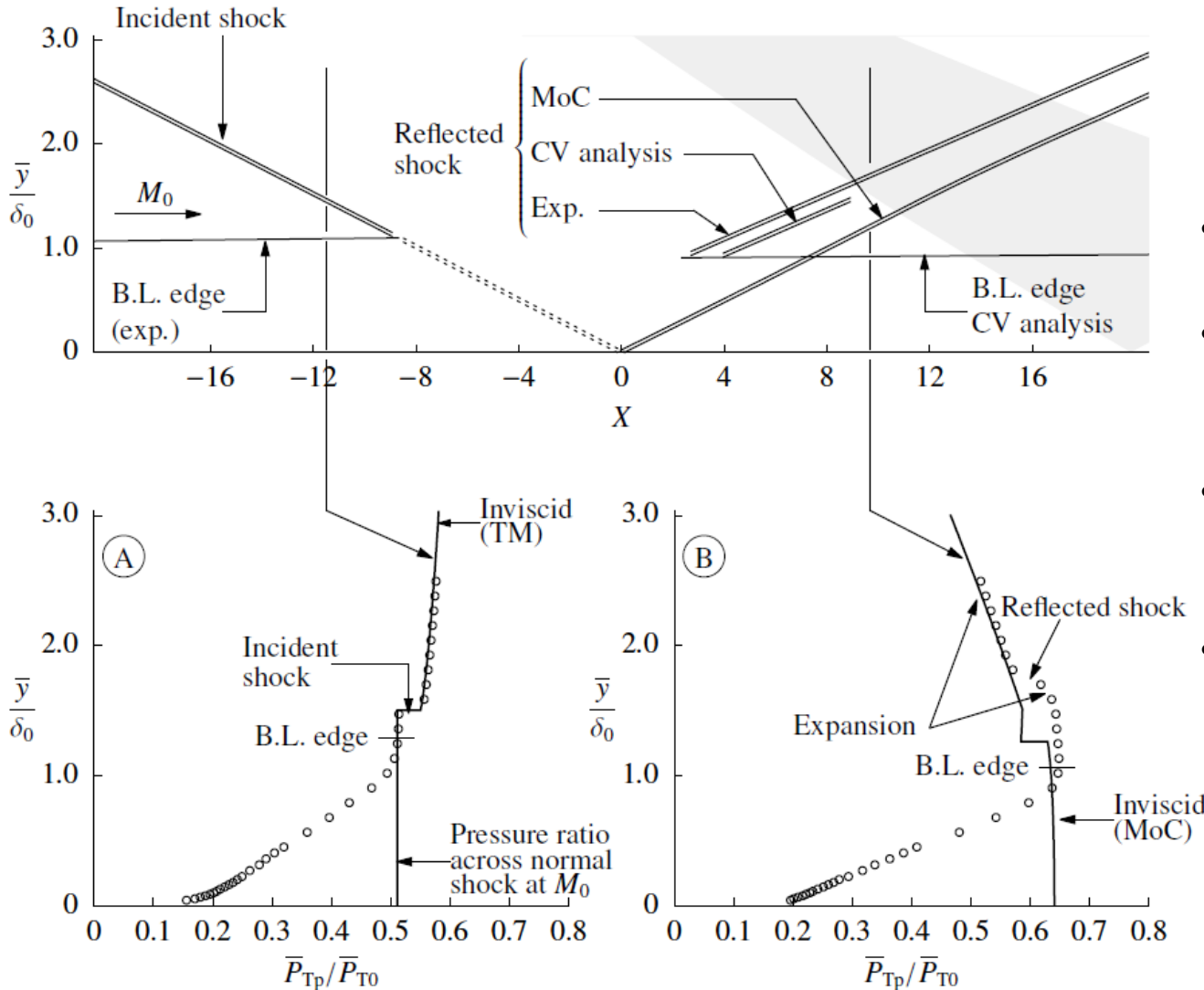
- Effects of incident shock propagate upstream
- Pressure continuously rises downstream of impingement point due conical flowfield
- Distance between shock and expansion fan impingement decreases with increased cone angle
- Truly two-dimensional or axisymmetric since there are no sidewalls





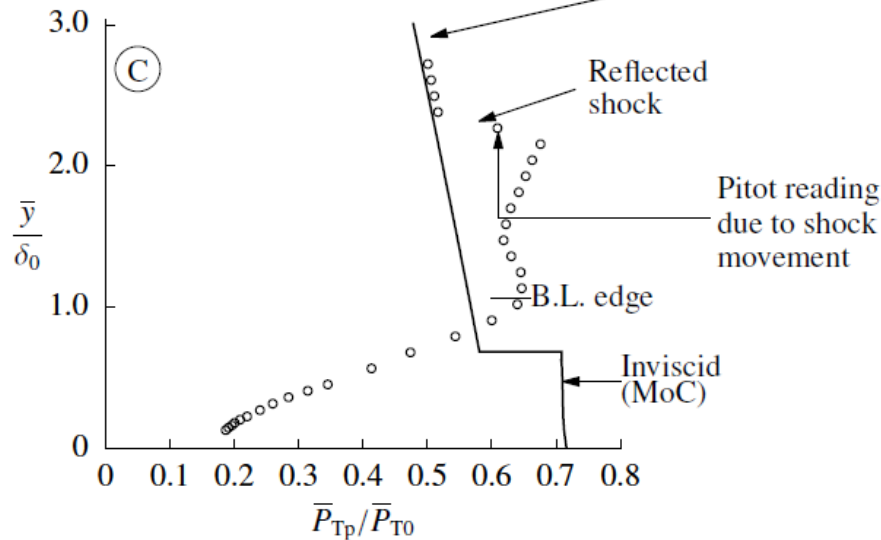
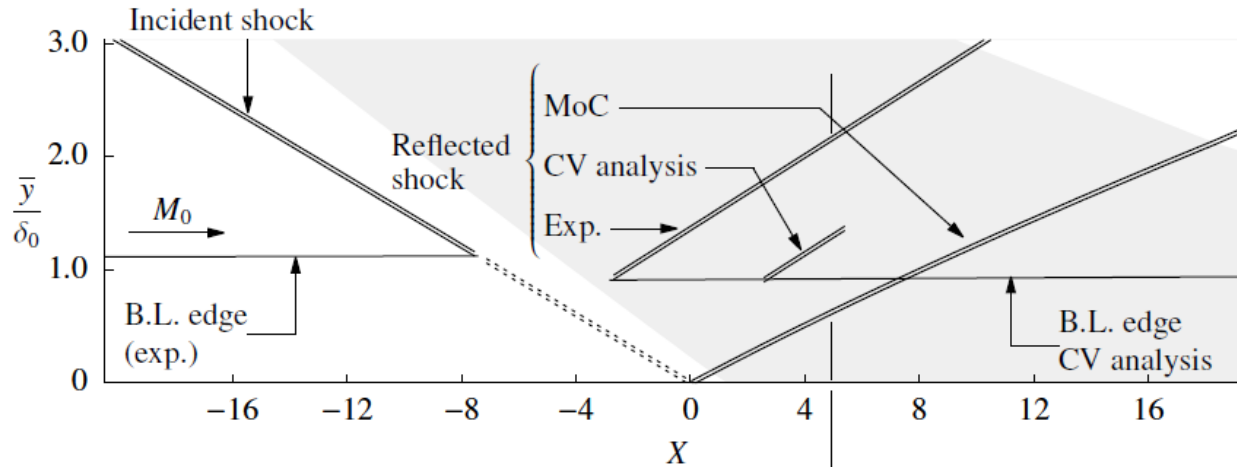
Cone half-angle: 10° and 16°
Offset: $R/4 = 2.125 \text{ cm}$

- Created circumferential pressure gradients and secondary flows without sidewall interference
- Previous “two-dimensional” experiments with spanwise pressure gradients were three-dimensional in reality due to test section sidewalls



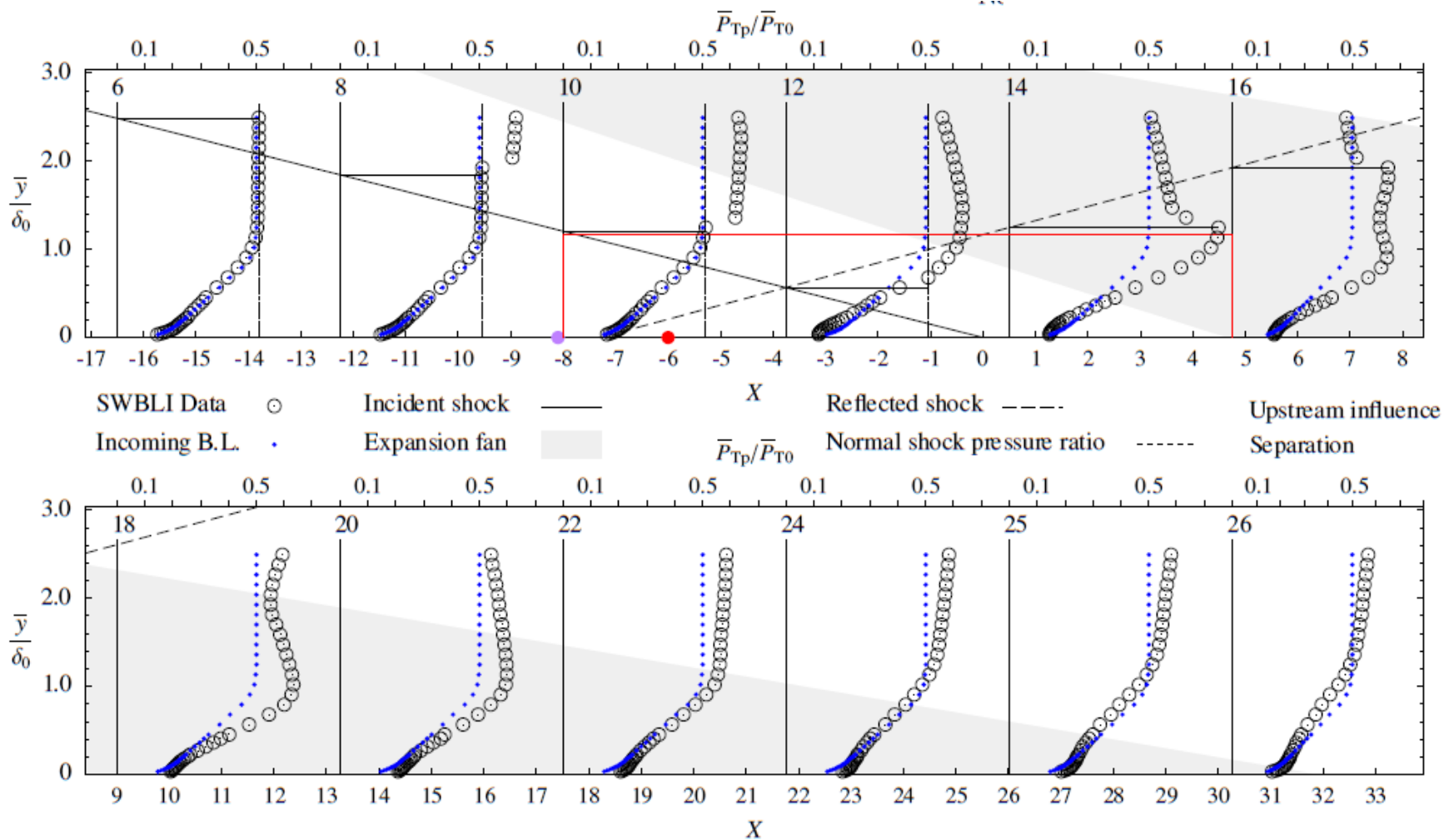
$\alpha=10^\circ$, $d=5.000$ cm, $\text{offset}=0.0$ cm

- Cone half-angle: 10° symmetric
- Agreement with inviscid solutions outside of boundary layer
- Reflected shock moves upstream compared to the inviscid solution
- Inviscid solution approximates the reflected shock strength

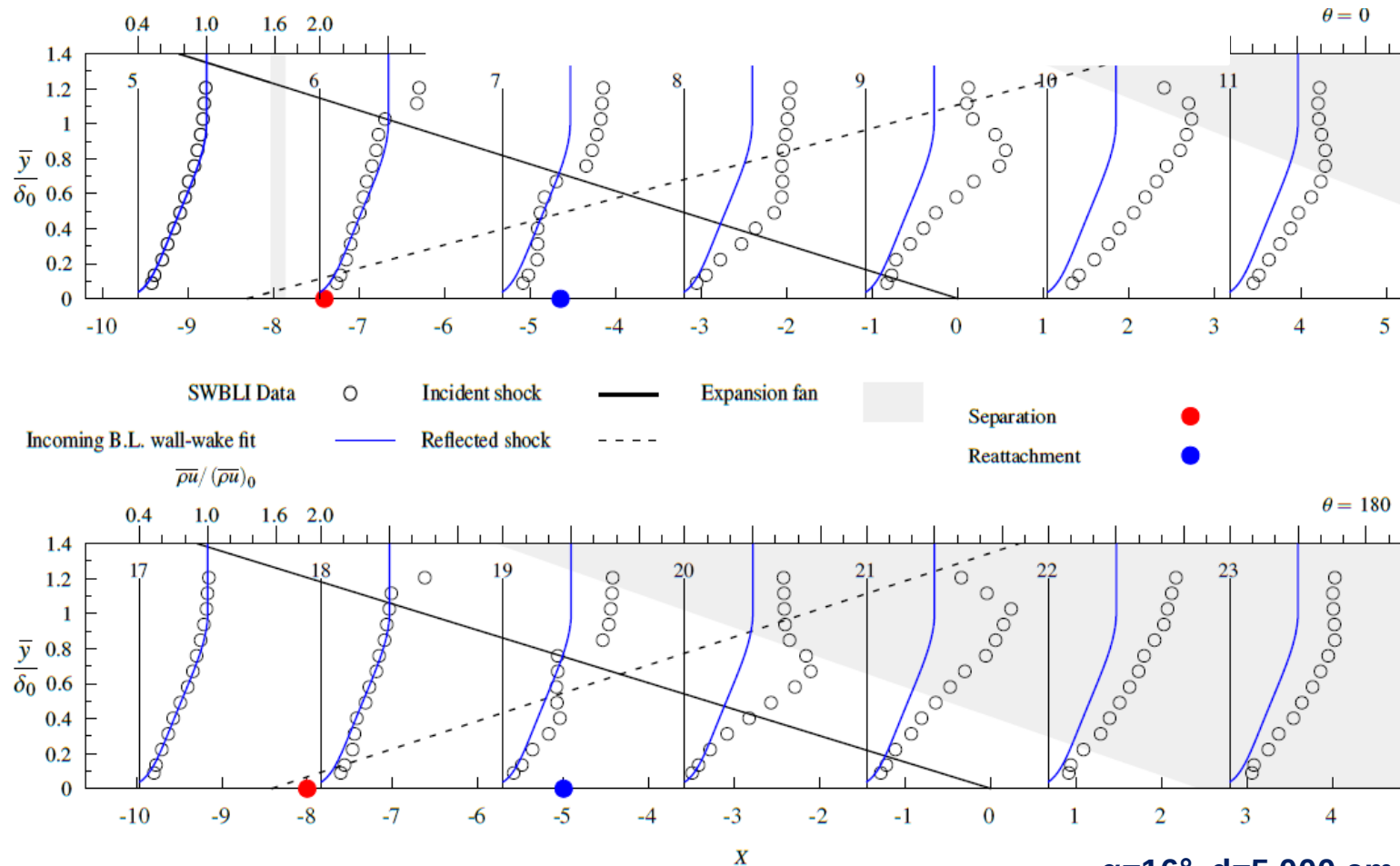


$\alpha=16^\circ$, $d=3.135$ cm, offset=0.0 cm

- Cone half-angle: 16° symmetric
- Agreement with inviscid solution above shock
- Reflected shock appears to be unsteady $\rightarrow$ careful investigation with hot-wire measurements
- Regions of compression and expansion downstream the reflected shock $\rightarrow$ attributed to separation and expansion fan



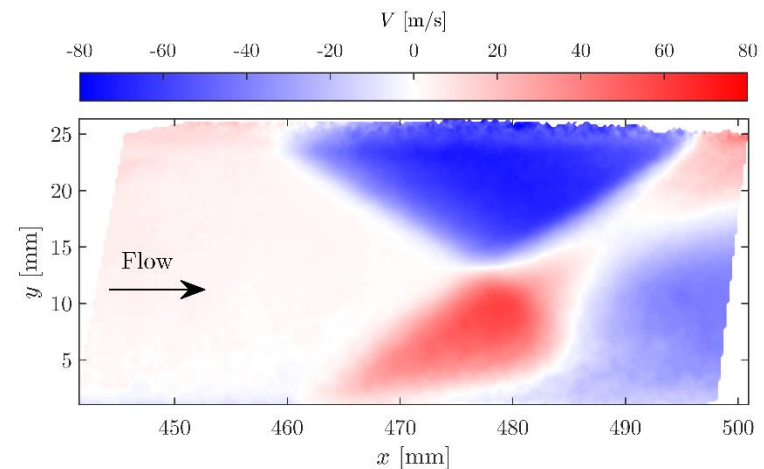
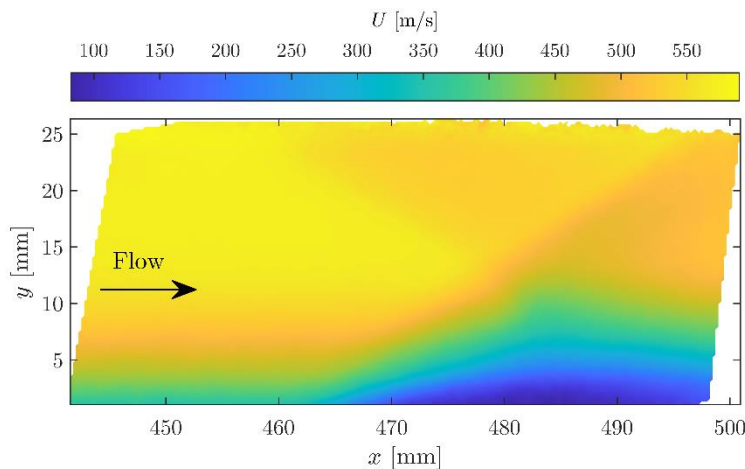
- For each shock generator and circumferential location, 12-14 axial stations (1.27 cm apart) were surveyed from the wall into the freestream to establish mean flow structure
- Additional surveys were taken 0.635 cm apart in regions of interest for hot-wire surveys



$\alpha=16^\circ$, $d=5.000$ cm, offset=2.125 cm

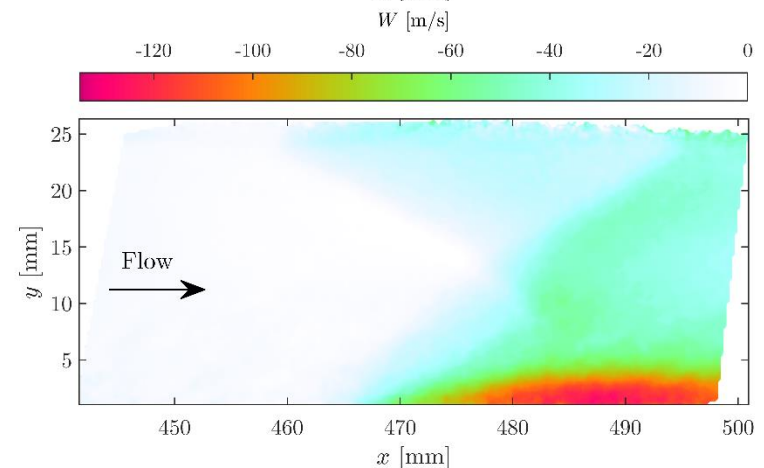
- Two circumferential locations
- Limited to circumferential locations 0° and 180° with normal wire due to flow angularity
- Need crosswires to determine flow angle
- Separation and reattachment as determined from oil-flow

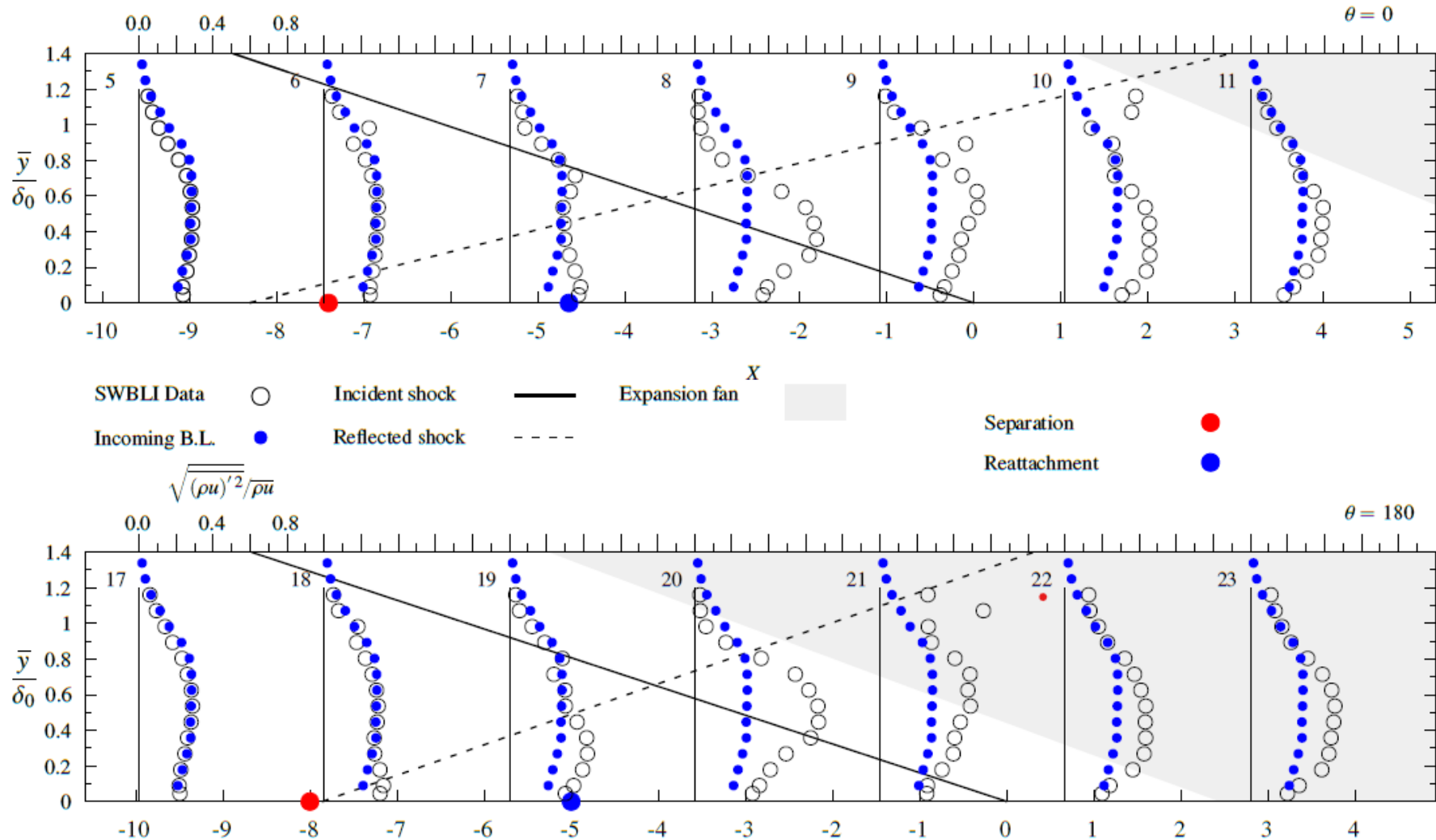
- PIV allows for surveys in areas difficult to measure with probes
- All 3 velocity components (mean and statistics)
- Ensembles of 1000 image pairs were collected within and downstream of interaction region
- 500 pairs were taken in regions upstream of incident shock
- Example: $\alpha = 16^\circ$ at $\theta = 90^\circ$ where the flow is rapidly turning due to swept interaction



$\alpha=16^\circ$
 $d=5.000$ cm
offset=2.125 cm

Detailed analysis of results ongoing
 Plan to report at SciTech 2024





- First entry of turbulence intensities for fully separated SWBLI in a circular test section
- Increase near reflected shock crossing $\rightarrow$ shock is unsteady
- No significant change in flow structure for $\alpha = 16^\circ$ at $\theta = 0^\circ$ and $\theta = 180^\circ$

- Benchmark quality experiment of impinging SWBLI for CFD validation.
 - No sidewall interference.
 - Detailed characterization of incoming boundary layer.
 - Includes mean, turbulent, statistical and spectral properties of mass flux.
- Static pressure distributions.
 - First entry where secondary flows are truly part of the interaction and configuration.
- Normal hot-wire measurements of unseparated and separated interactions
 - Cannot calculate Reynolds stresses in interaction region.
- No significant changes in streamwise measurements between axisymmetric and asymmetric configurations
 - Calculate Reynolds stresses with PIV
 - Follow up with cross-wires to get $\rho'v'$ and $\rho'w'$ contributions