CFD Validation Experiment of a Mach 2.5 Axisymmetric Shock-Wave/Boundary-Layer Interaction

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Background

- Experimental investigations of specific flow phenomena, e.g., Shock Wave/Boundary-Layer Interactions (SWBLI), provide great insight to the flow behavior but often lack the necessary details to be useful as CFD validation experiments.
  - Undefined Boundary Conditions
  - Inconsistent Results
  - Undocumented 3D Effects (CL only Measurements)
  - Lack of Uncertainty Analysis

Background

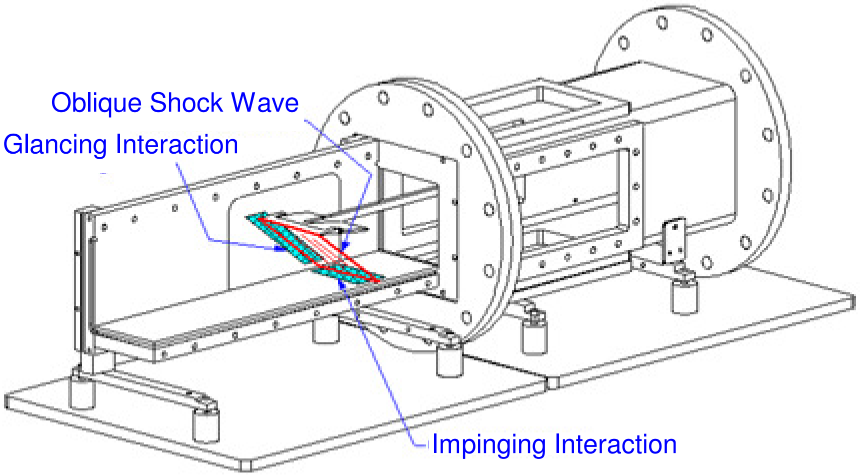
- The Transformational Tools & Technologies (TTT) Project under NASA's Transformative Aeronautics Concept (TAC) Program is tasked, in part, with providing quality experiments for the purpose of validating CFD codes and turbulence models.

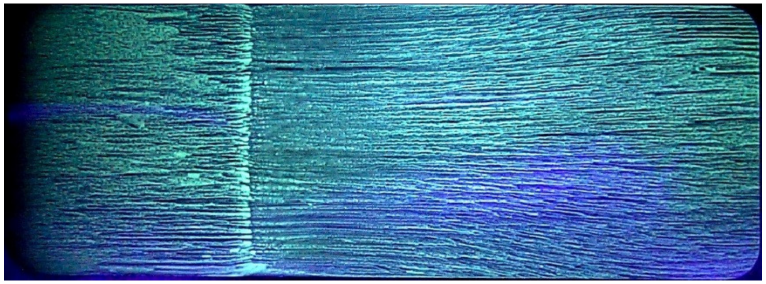
- Goal - Provide in-house experimental database to support inlet and nozzle CFD validation efforts.
  - Allows code/model developers to have direct input into experiment design.
  - Allows experiments to be re-visited if deemed necessary.

- A Mach 2.5 SWBLI has been identified as one of the test cases desired.

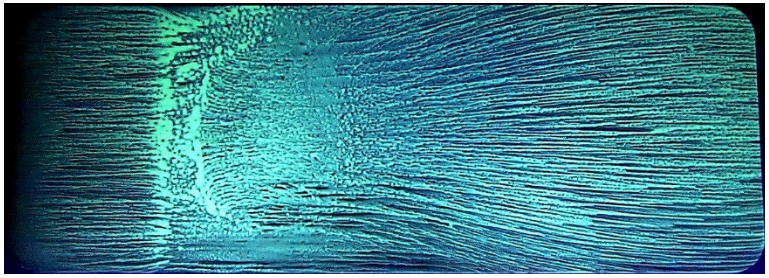
Background

- SWBLI CFD validation experiments performed in non-circular wind tunnels pose a particularly challenging problem, as streamwise and transverse pressure gradients induced by the SWBLI turn a nominally two-dimensional flow-field into a three-dimensional flow-field.





α=7.5°

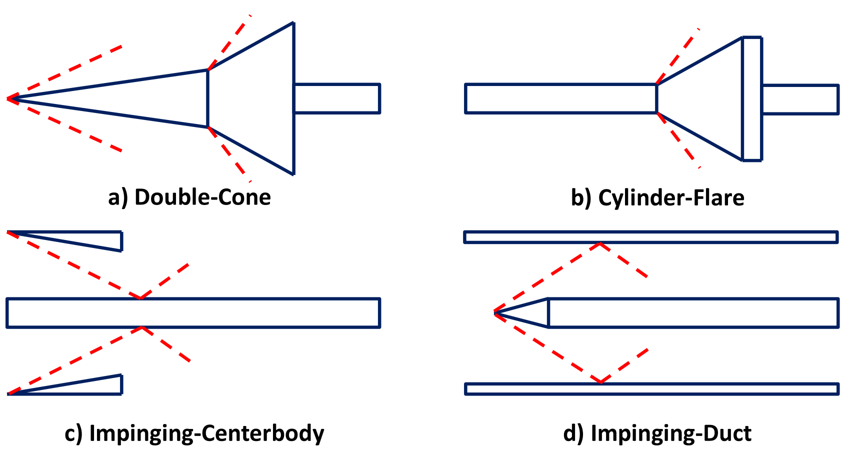


α=9.5°

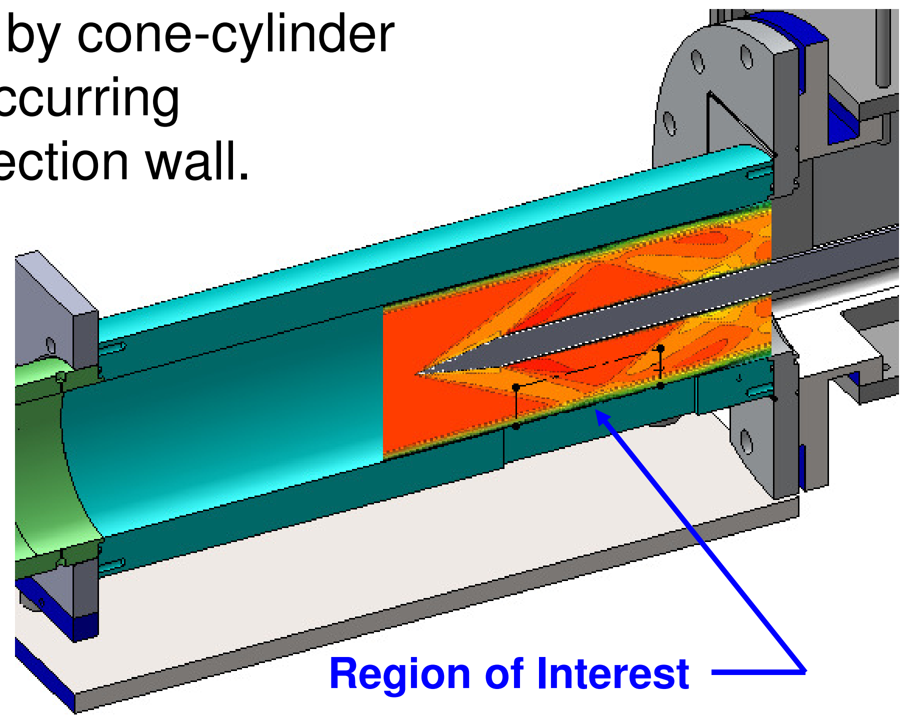
Mach 2.0 SWBLI in 15x15 cm SWT.

Background

- In order to avoid the pitfalls of a rectangular configuration, an axisymmetric configuration is proposed that is two-dimensional in the mean.
  - 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

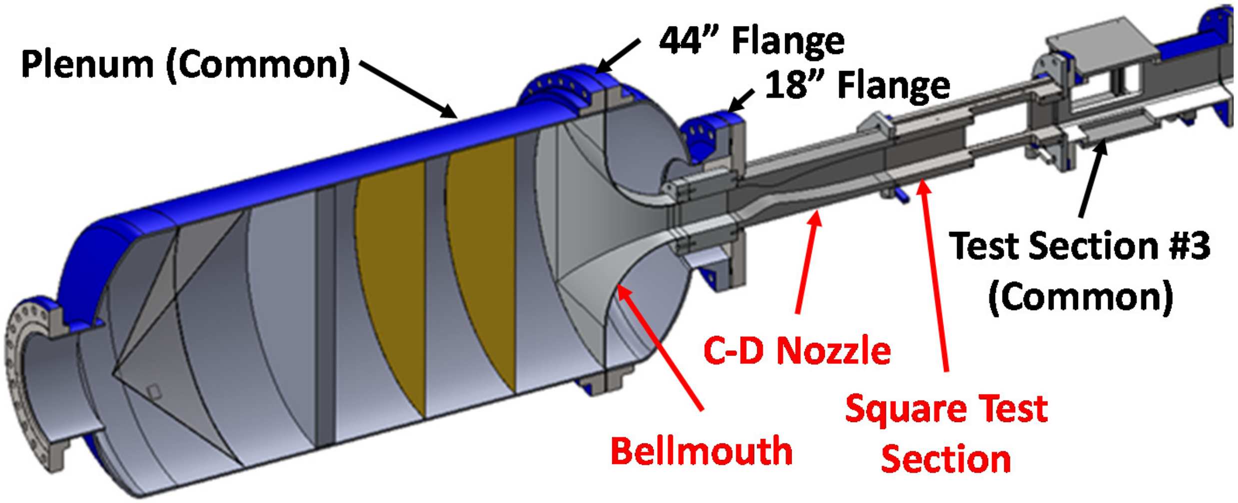


FACILITY

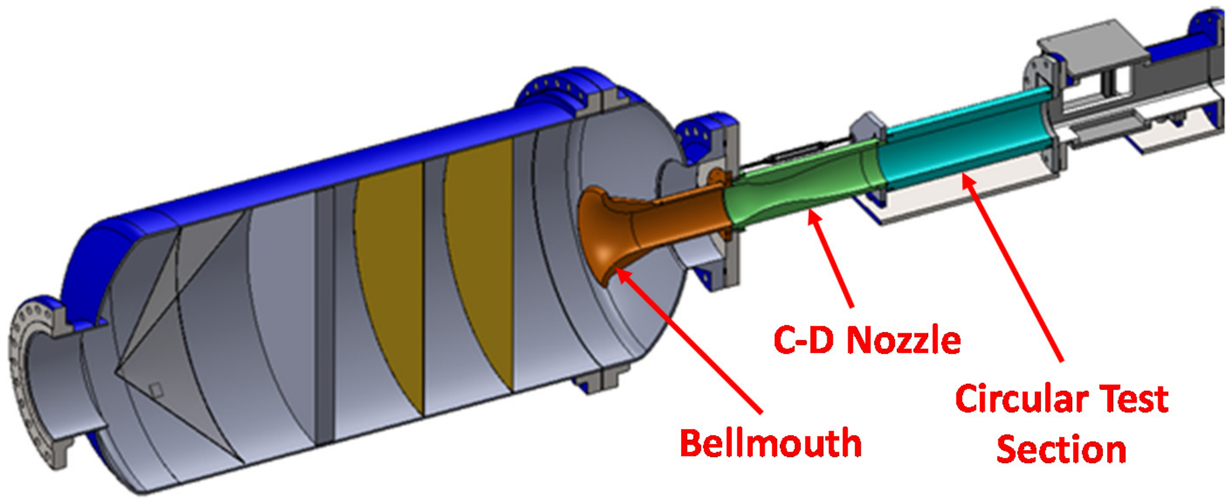
Facility

- At the time the project was initiated, there were no supersonic axisymmetric facilities at NASA GRC.
- In order to keep costs within budget, the existing 15x15 cm Supersonic Wind Tunnel (SWT) was modified to add an axisymmetric capability.
- This required design and fabrication of three major axisymmetric components:
  - Bellmouth
  - Convergent-Divergent (C-D) Nozzle
  - Test Section
- A goal of the design was to minimize the effort required to change between the rectangular and axisymmetric configurations.

Facility



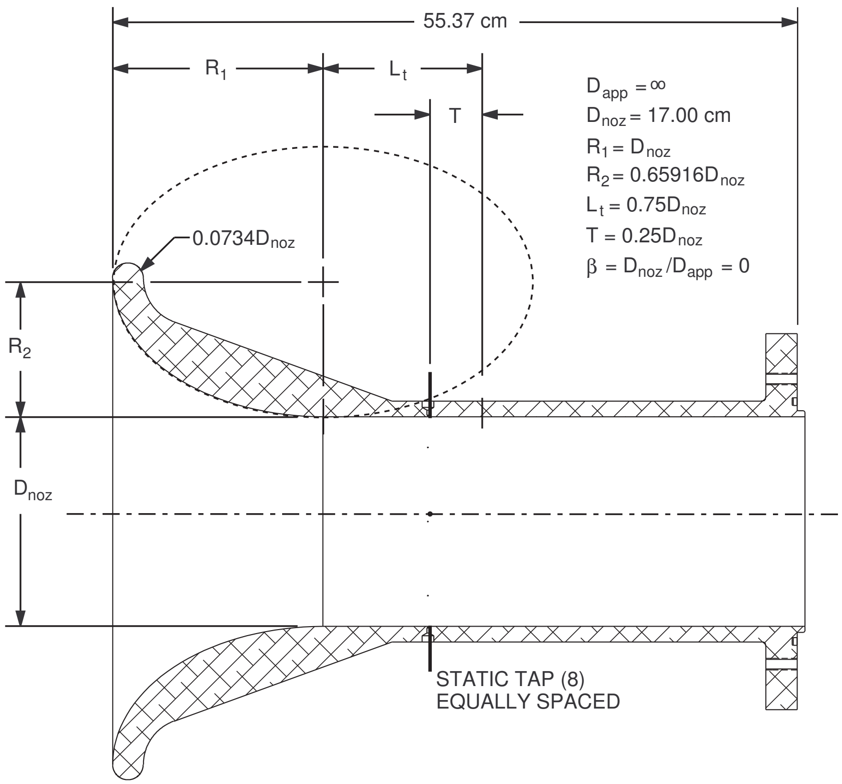
15x15 cm SWT

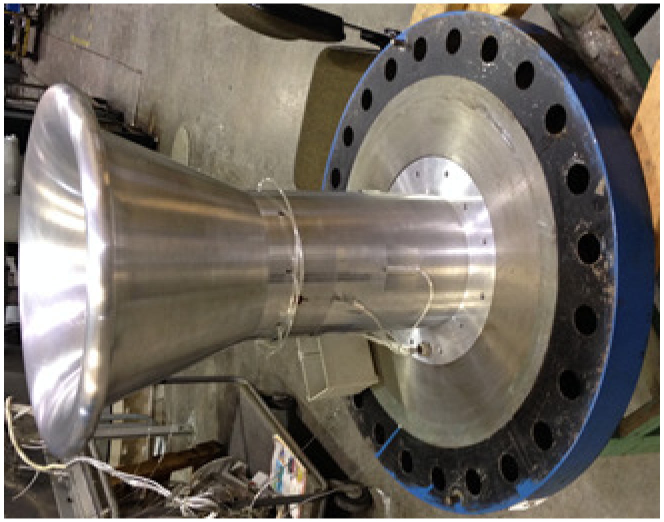


17 cm Axi-SWT

Bellmouth

- The bellmouth is based on a Low-β ASME Long-Radius Nozzle with throat taps.
- NASA GRC has extensive experience with this type of nozzle.



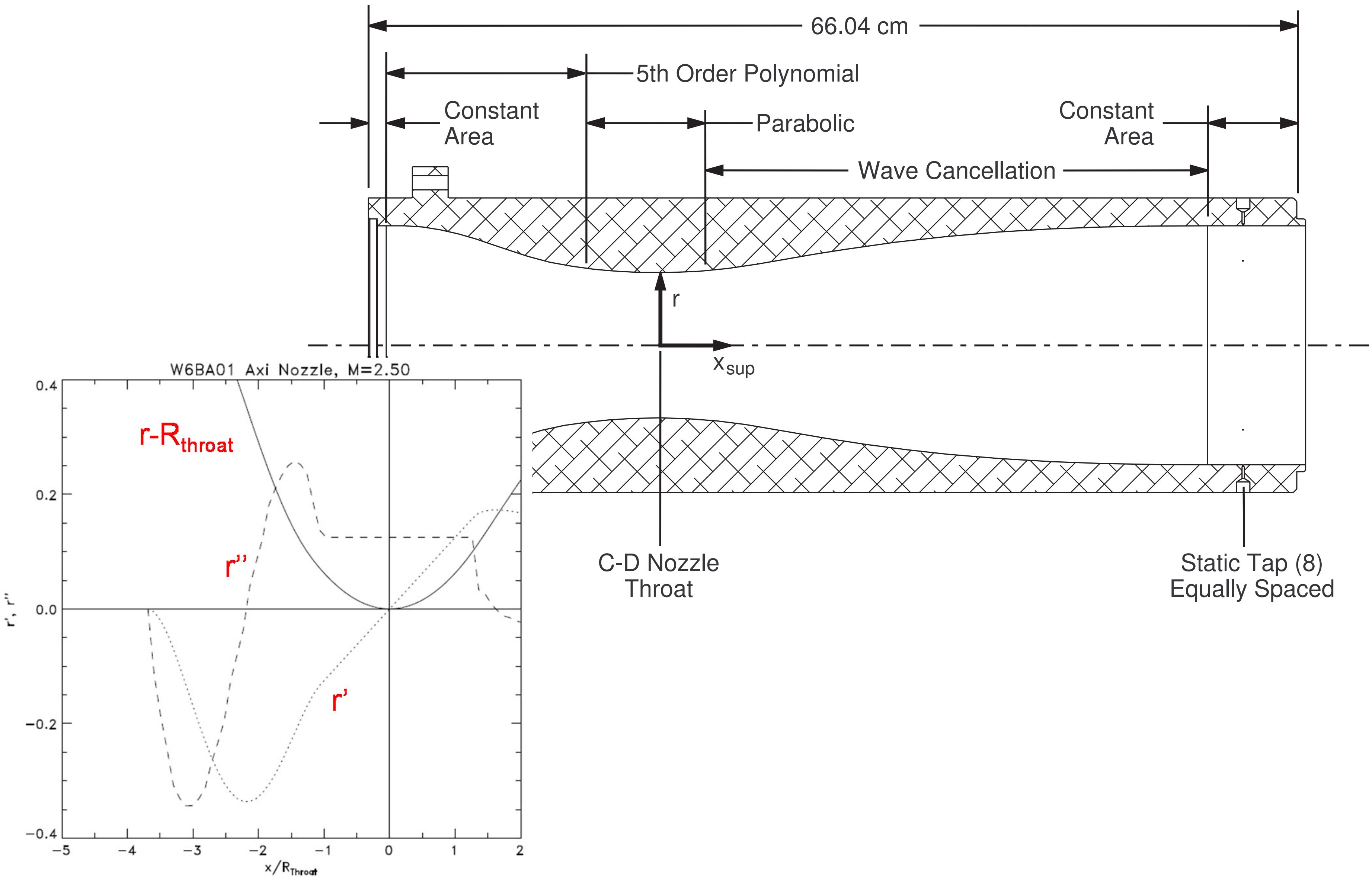


With the Mach 2.5 nozzle, bellmouth throat Mach number is approximately 0.21

Mach 2.5 C-D Nozzle

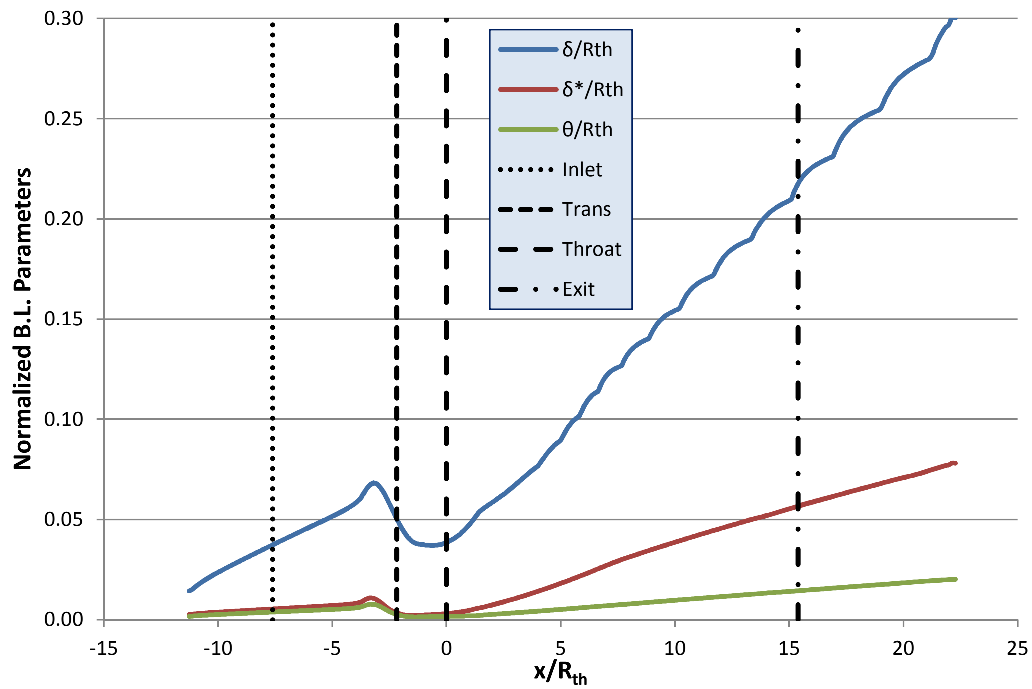
- The requirements for the C-D nozzle design included:
  - Exit Mach number of 2.5
  - Inlet and exit diameters equal (17 cm).
  - Length approximately the same as 15x15 SWT nozzles.
- The steps for designing the nozzle included:
  - Define inviscid, shock-free supersonic contour (MOC).
  - Define subsonic contour.
  - Correct supersonic contour for boundary-layer development.
  - Adjust subsonic contour to match.

Mach 2.5 C-D Nozzle

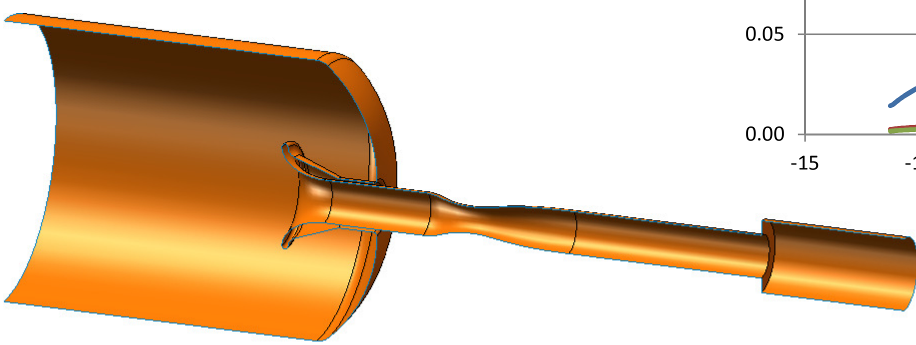


C-D Nozzle Boundary-Layer Correction

- The Wind-US flow solver was used to estimate the boundary-layer growth in the nozzle.



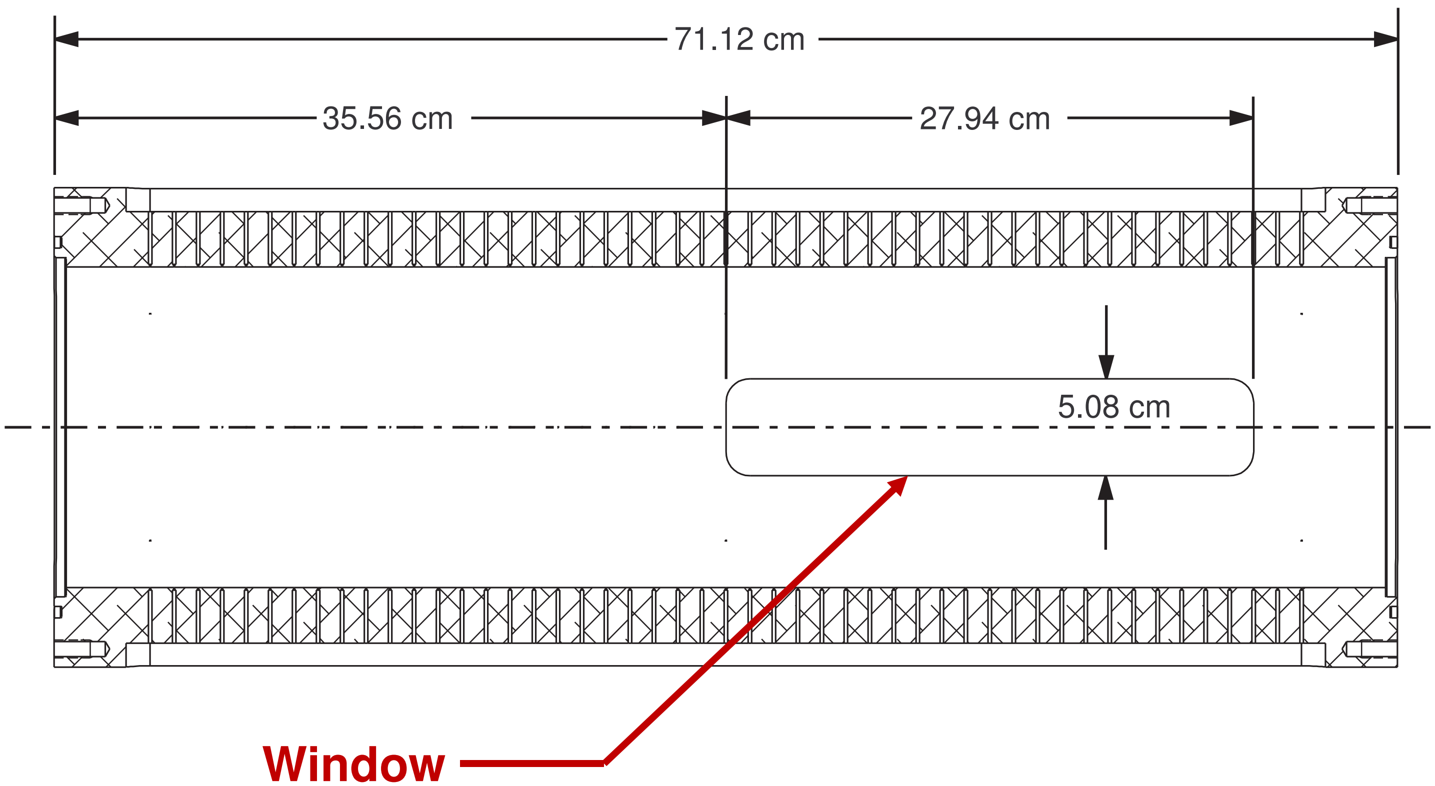
Boundary-Layer Parameters



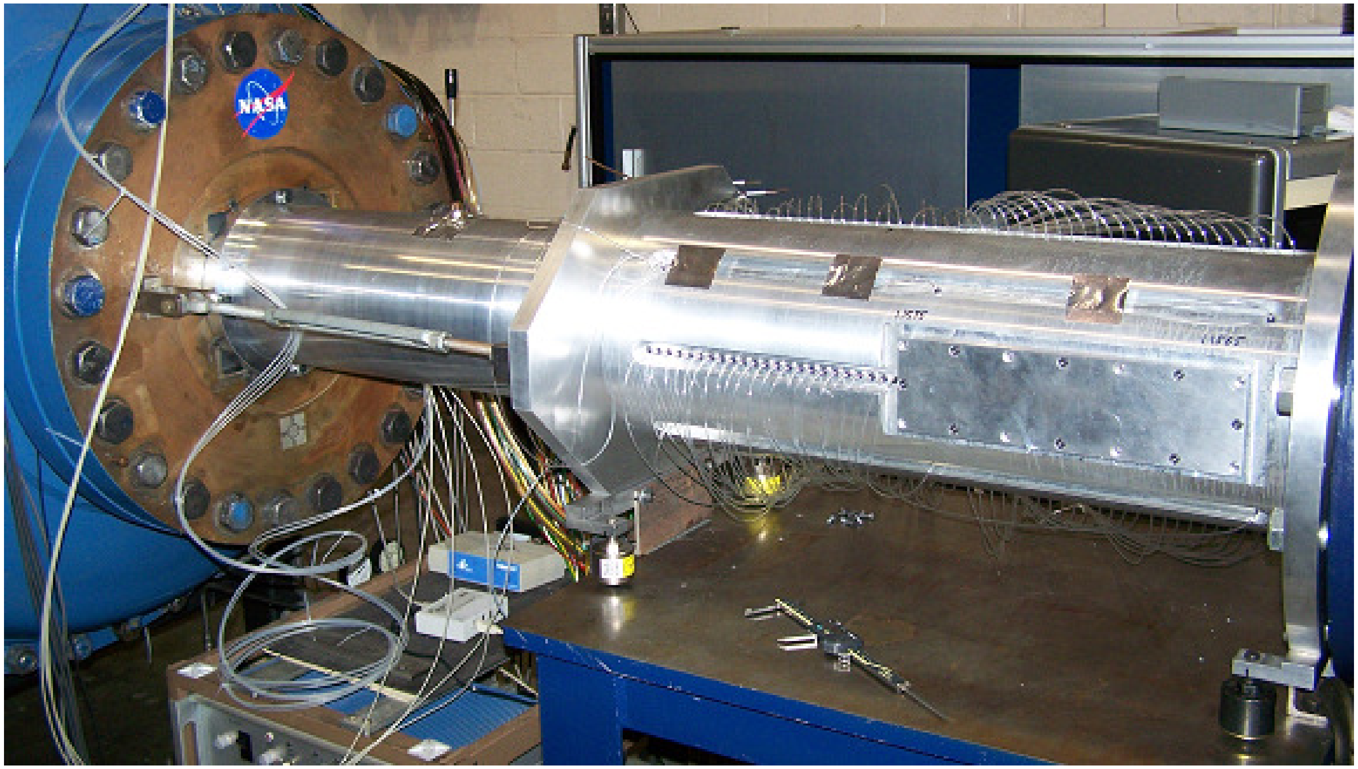
Computational Domain

Test Section

- The test section is a simple circular cross-section. Two were fabricated:
  - “Conventional” Test Section – static taps and two access windows.
  - “Blank” Test Section - future modification for PIV system.



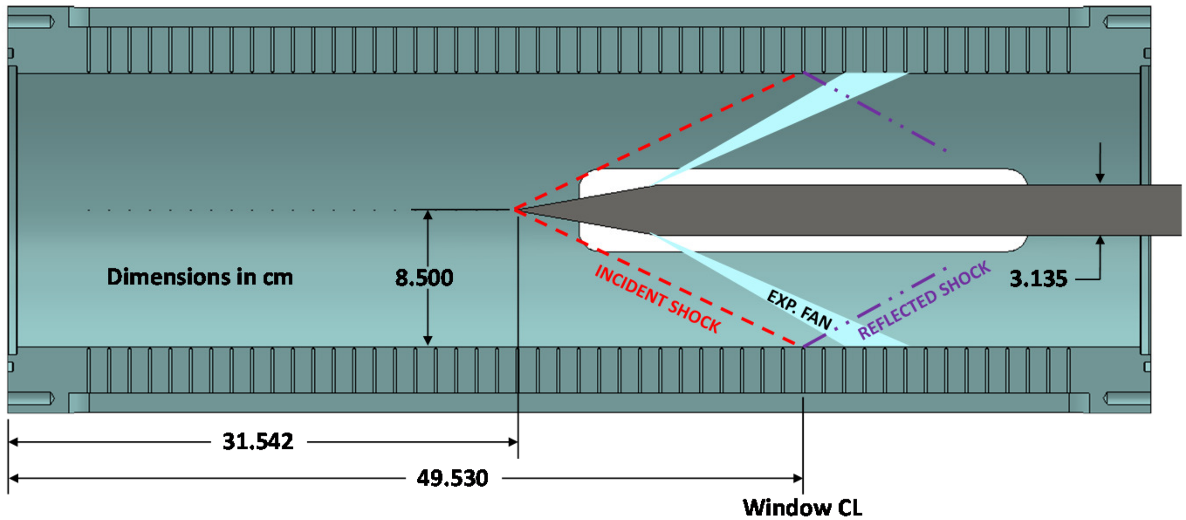
C-D Nozzle and Conventional Test Section

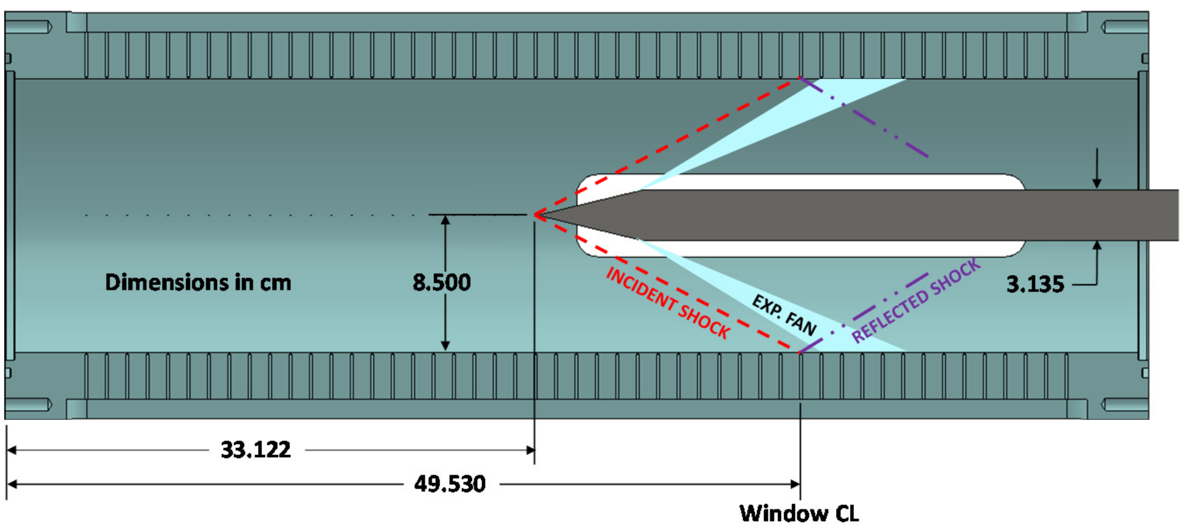


Shock Generator Assembly

- For the initial testing, two shock generator configurations were selected:

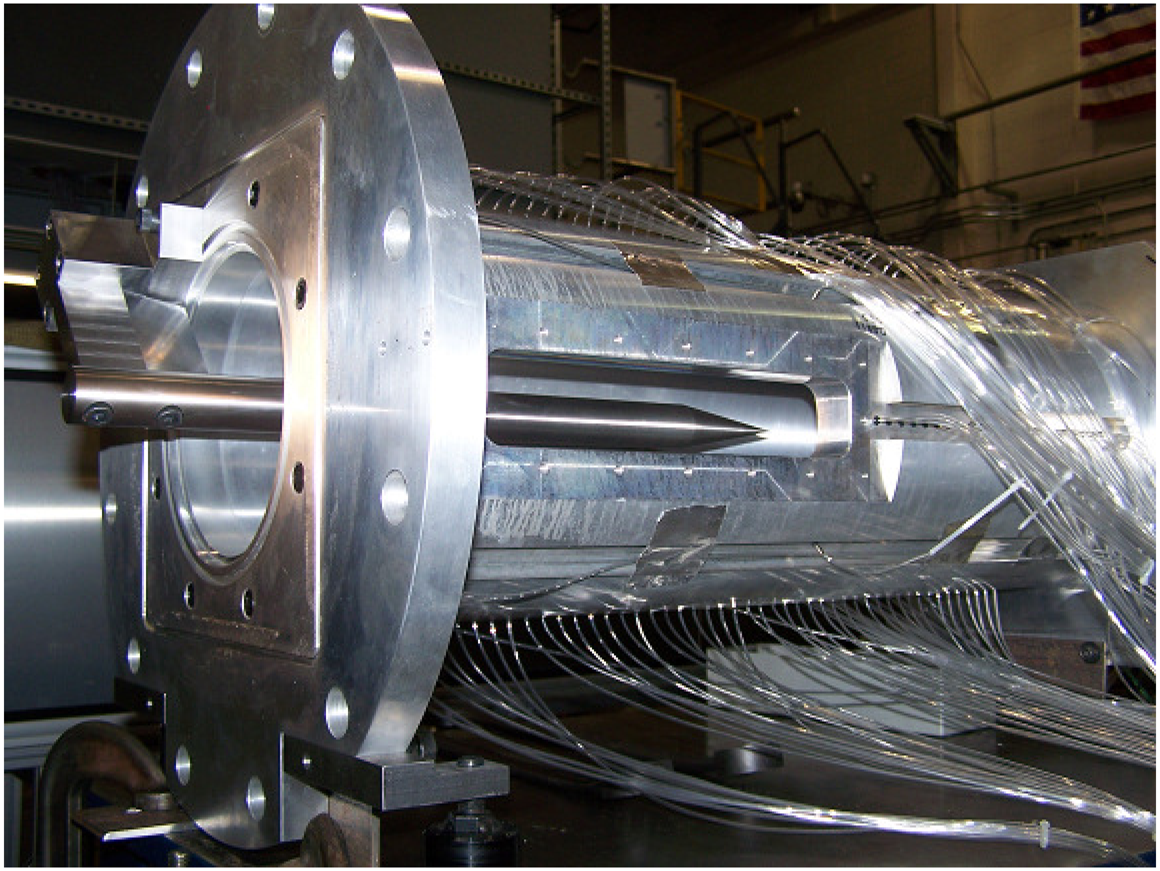
10.0° Cone (Fully-Attached B.L.)





13.5° Cone Incipient Separation

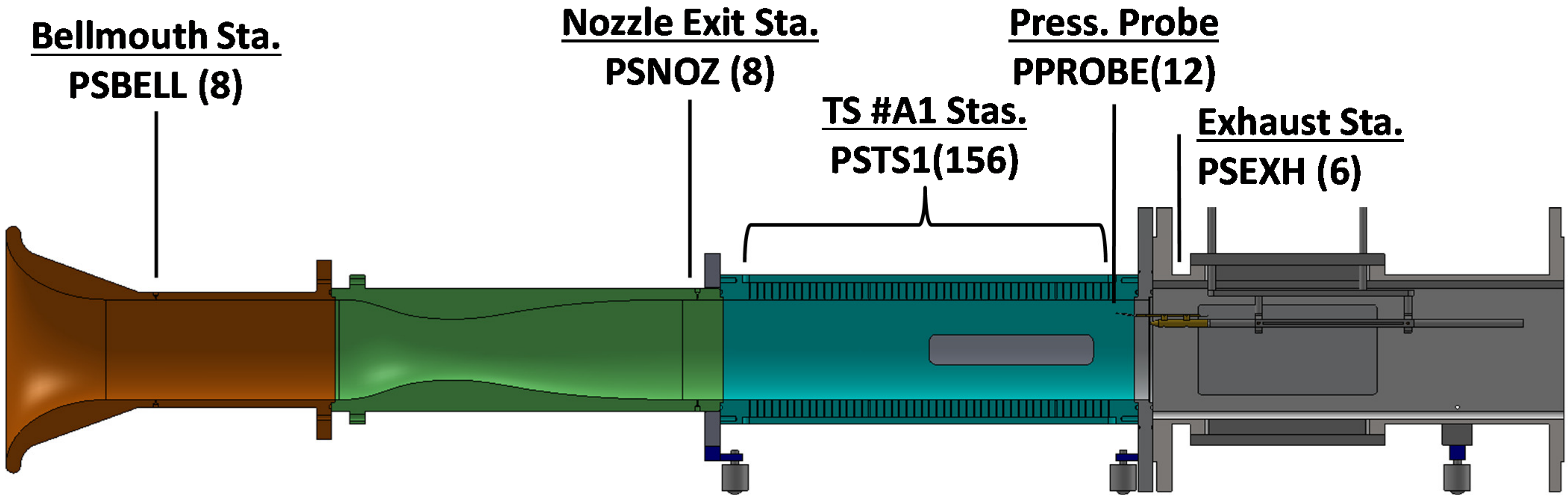
Shock Generator Assembly



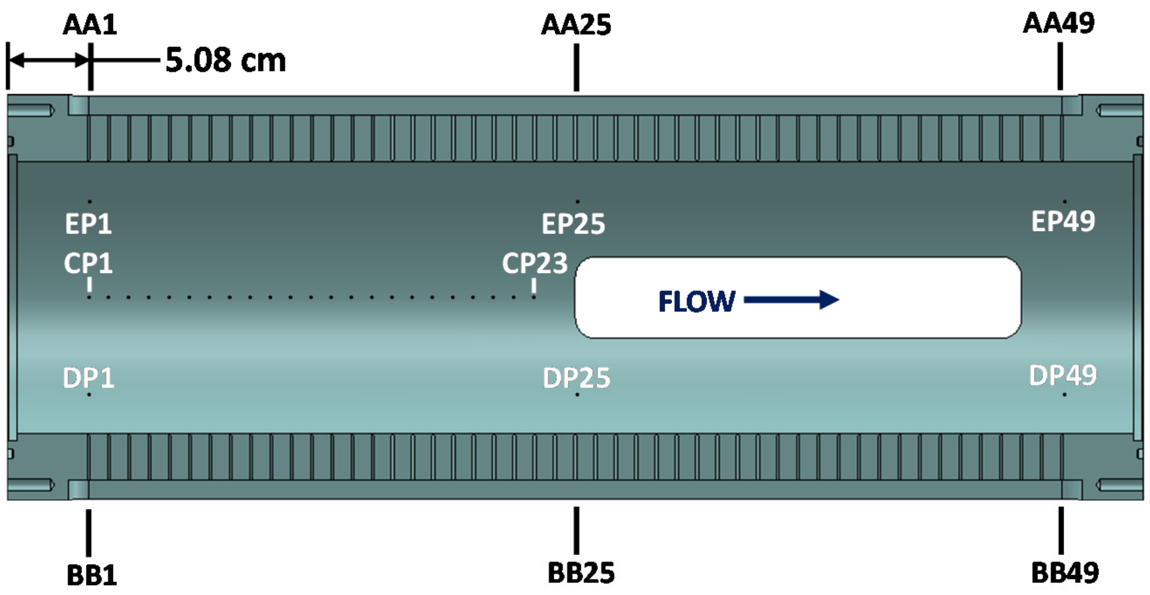
INSTRUMENTATION

Test Entry #01

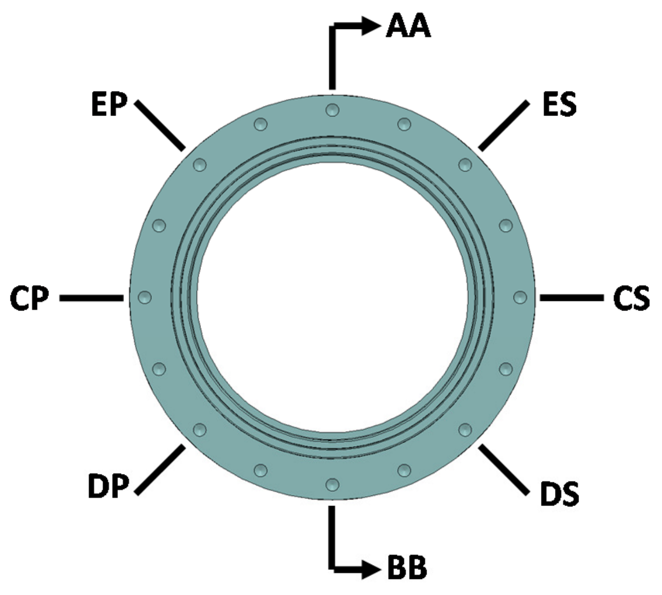
Instrumentation



Test Section Static Taps



VIEW AA-BB



VIEW LOOKING UPSTREAM

Uncertainty Considerations

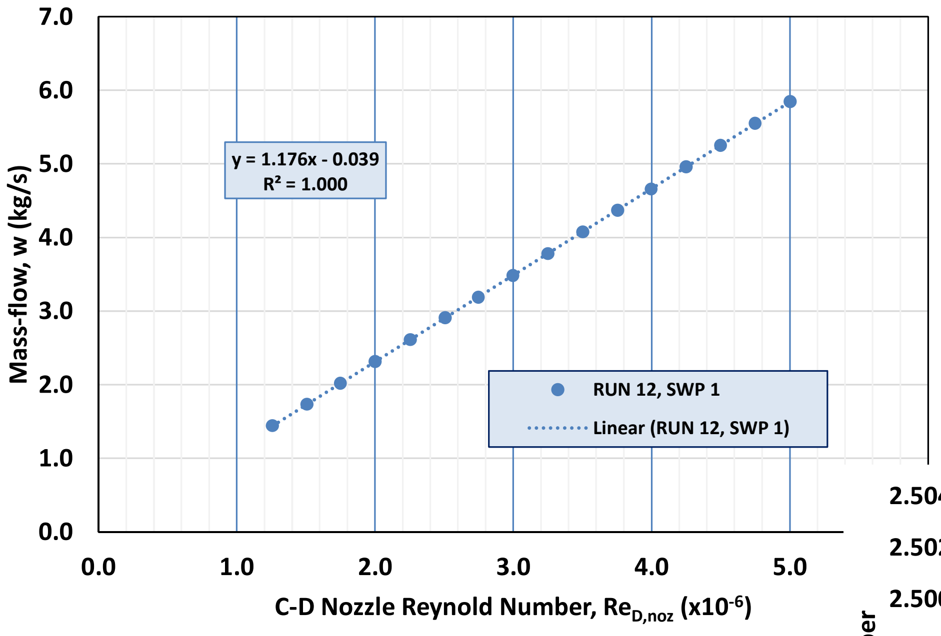
- Uncertainty analysis is in progress. In addition to sensor uncertainty, the following are also being considered:
  - Geometric uncertainty
  - Static tap uncertainty
  - Total pressure probe uncertainty
    - Probe configuration
    - Near-wall effect
    - Position

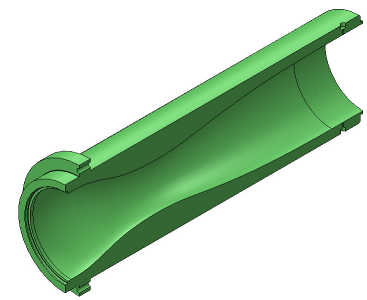
i	Description	X_i	δX_i	N	δX_i	Units
1	Plenum total temp.	$T_{t,0}$	1.39	2	0.98	°K
2	Plenum total pressure	$p_{t,0}$	0.0689	1	0.07	kPa
3	Bellmouth throat static pressure	p_{bm}	0.0255	8	0.0090	kPa
4	Bellmouth throat diameter	D_{bm}	0.0013	1	0.0013	cm
5	Bellmouth discharge coefficient	$C_{D,bm}$	0.01	1	0.01	-
6	C-D nozzle exit plane static pressure	p_{noz}	0.0621	8	0.0219	kPa
7	Probe position, x	x_{prb}	0.0064	1	0.0064	cm
8	Probe position, y	y_{prb}	0.0064	1	0.0064	cm
9	Probe position, z	z_{prb}	0.0064	1	0.0064	cm
10	Probe pitot pressure	p_{prb}	0.0621	1	0.0621	kPa

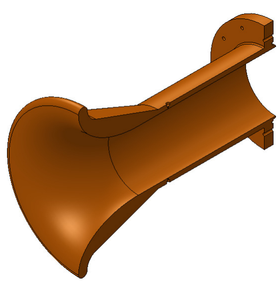
RESULTS

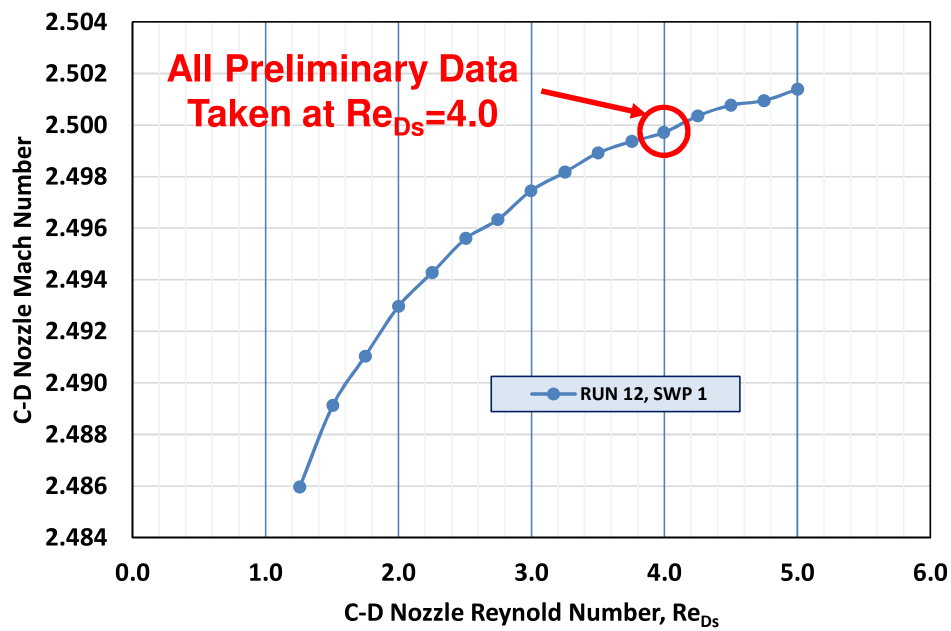
Test Entry #01

BM Flow Rate and C-D Nozzle Mach Number



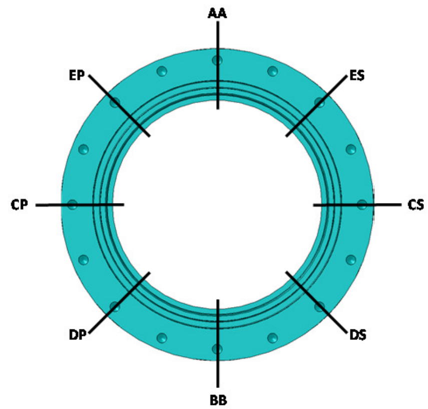




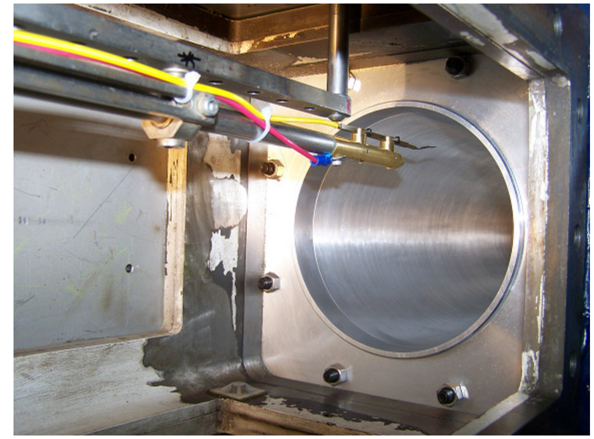


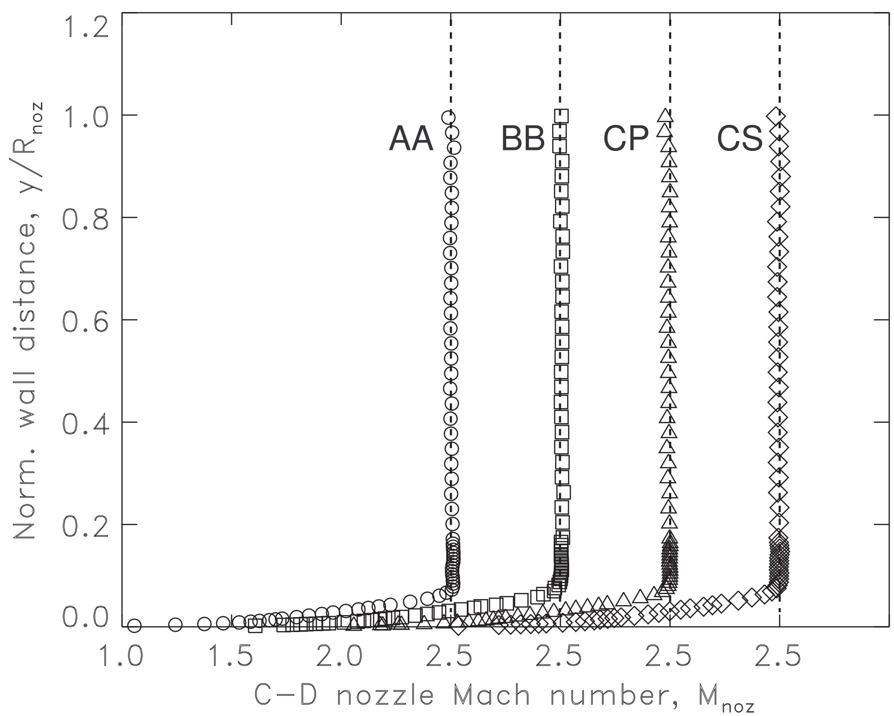
CFD-based calibration

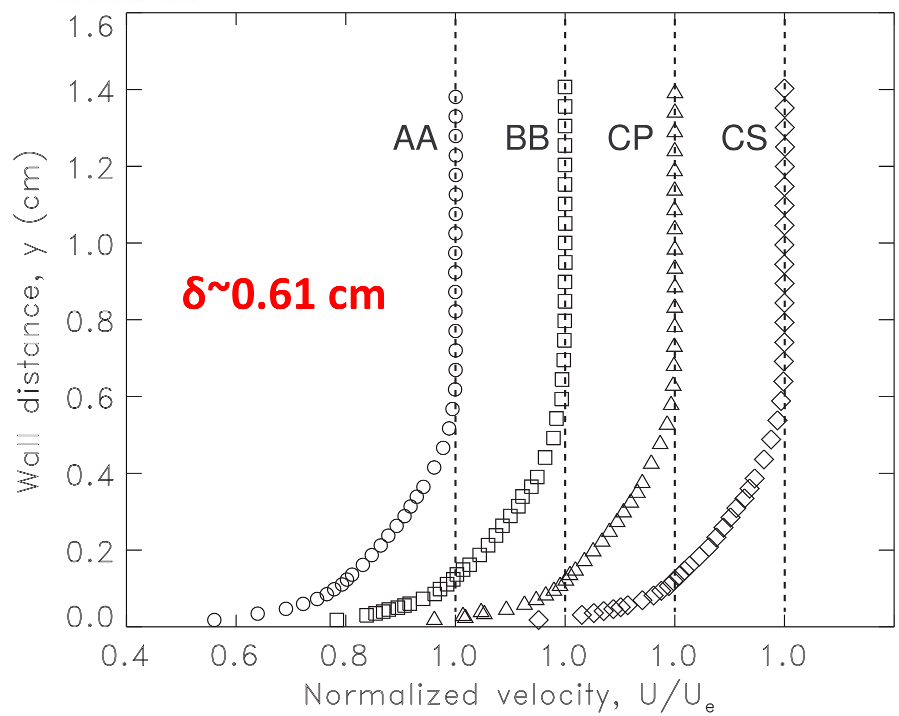
Nozzle Exit Condition



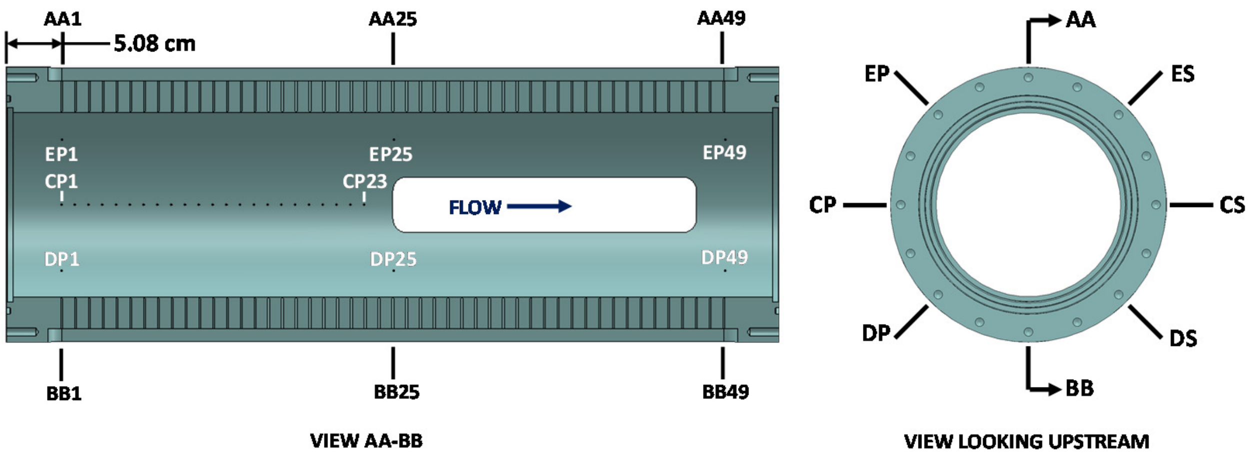
VIEW LOOKING UPSTREAM

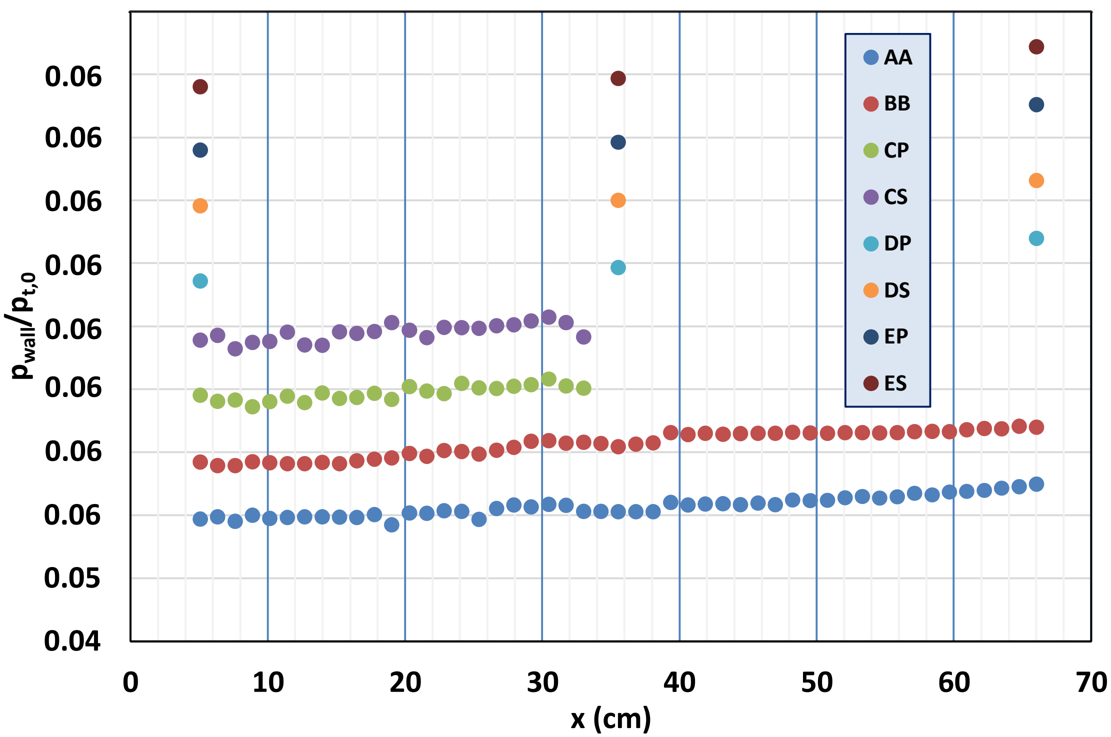




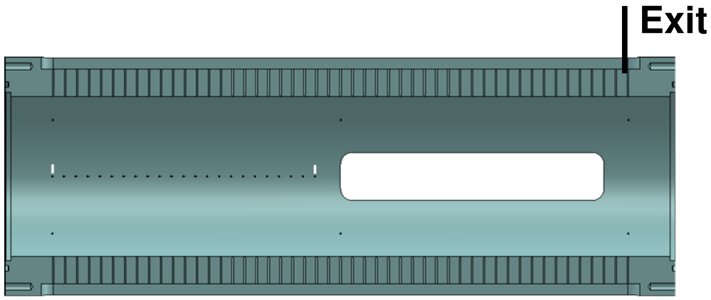


Clean Test Section

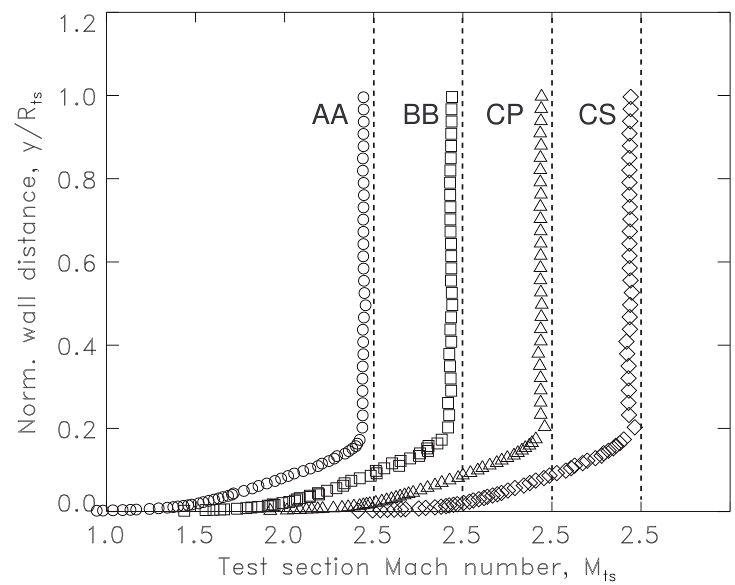


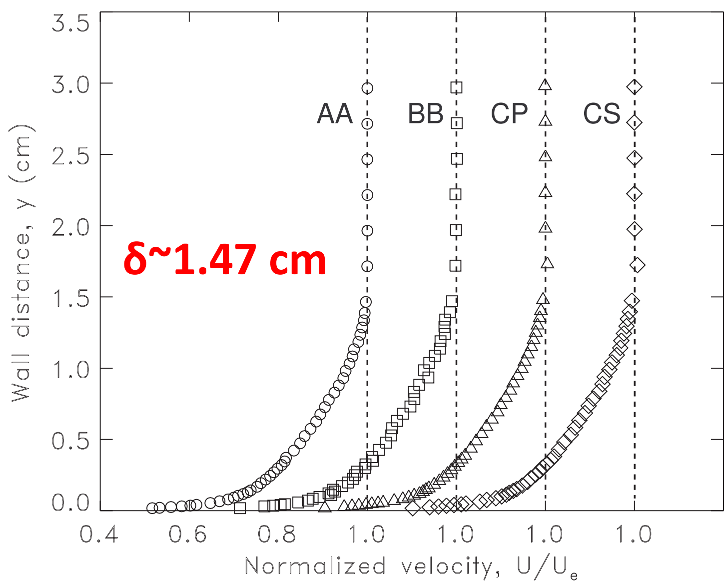


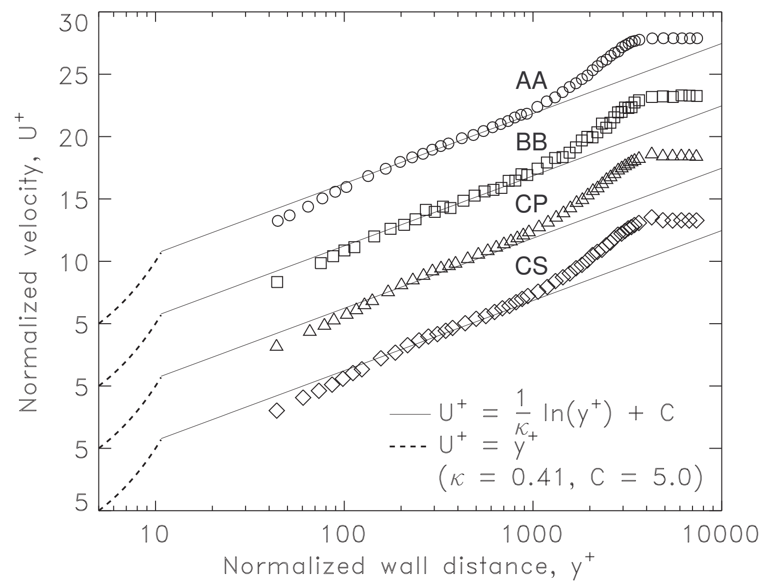
Test Section Exit Condition (x=66.0 cm)



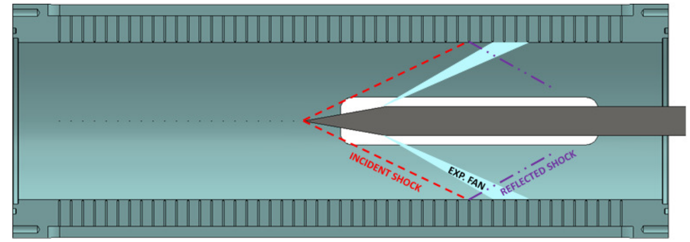
	x (cm)	M_e	δ (cm)	δ^* (cm)	θ (cm)	H_i	C_f
WIND	-3.81	2.46	0.693	0.162	0.041	-	-
EXP	-3.81	2.50	0.608	0.161	0.041	1.39	0.00186
EXP	43.2	2.44	1.312	0.334	0.090	1.33	0.00157
EXP	66.0	2.44	1.465	0.389	0.106	1.31	0.00152

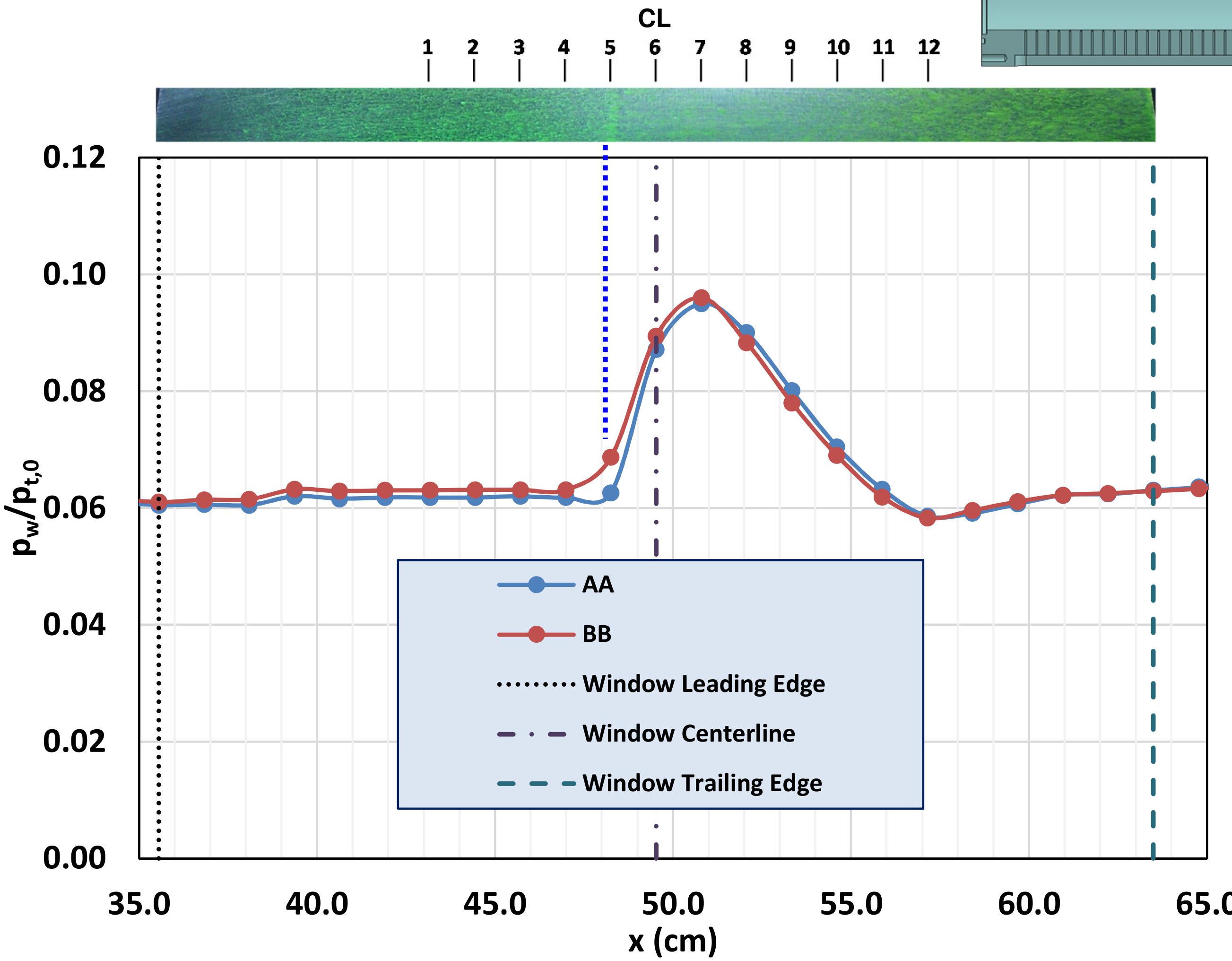




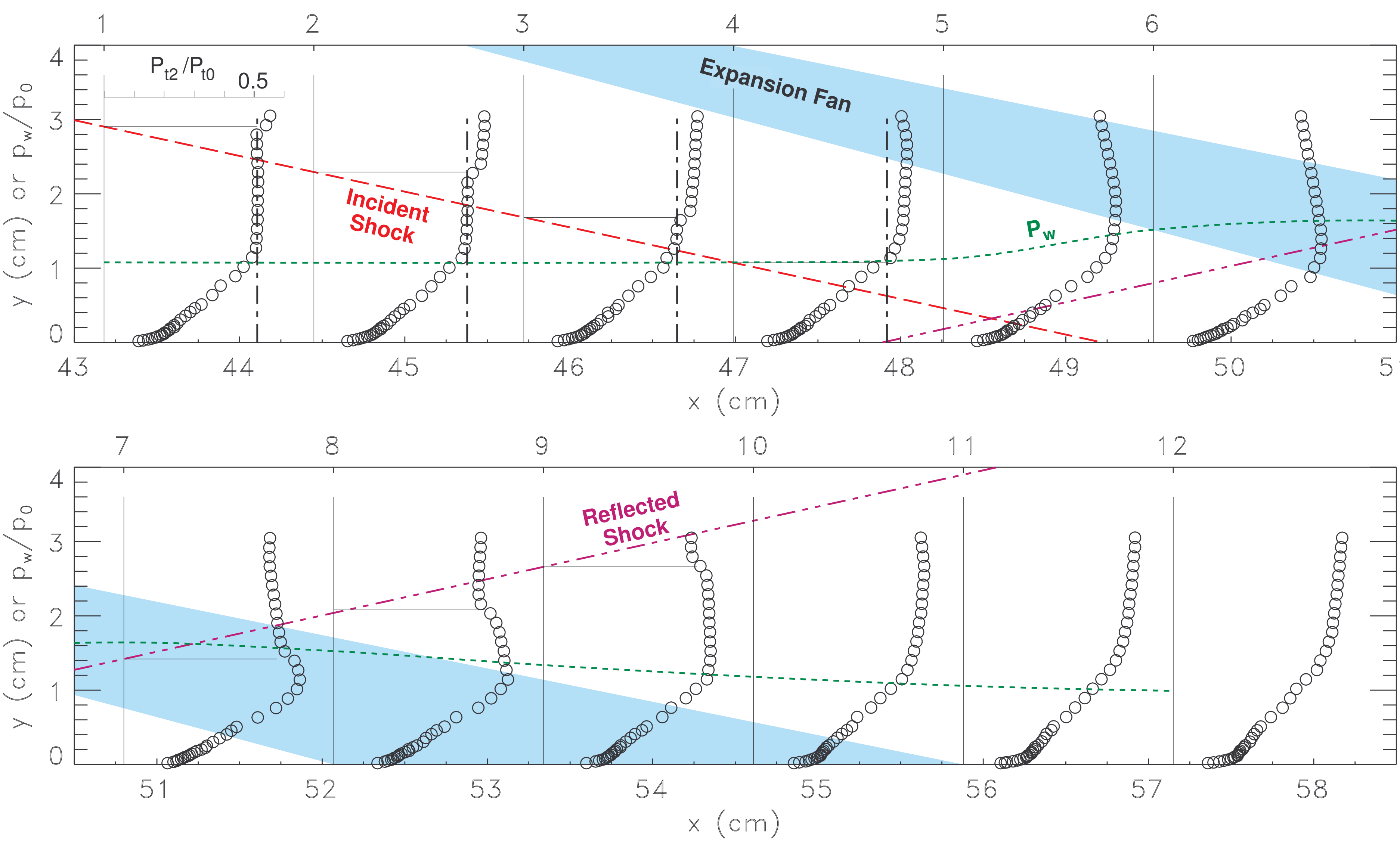


SWBLI Interaction, α=10.0°

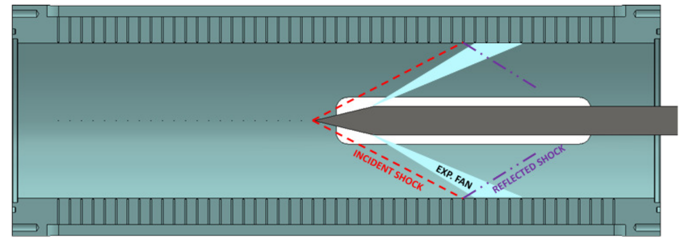


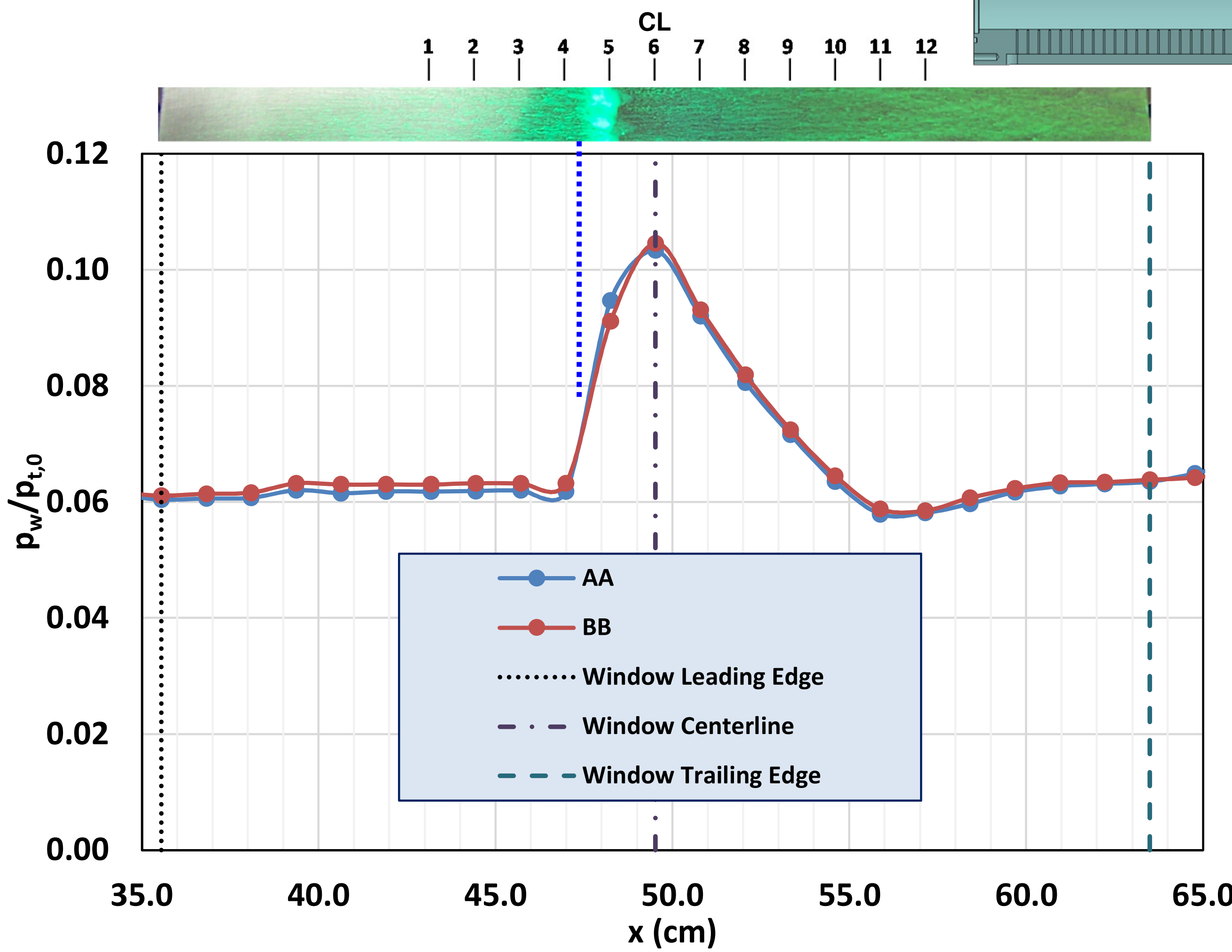


SWBLI Interaction, α=10.0°

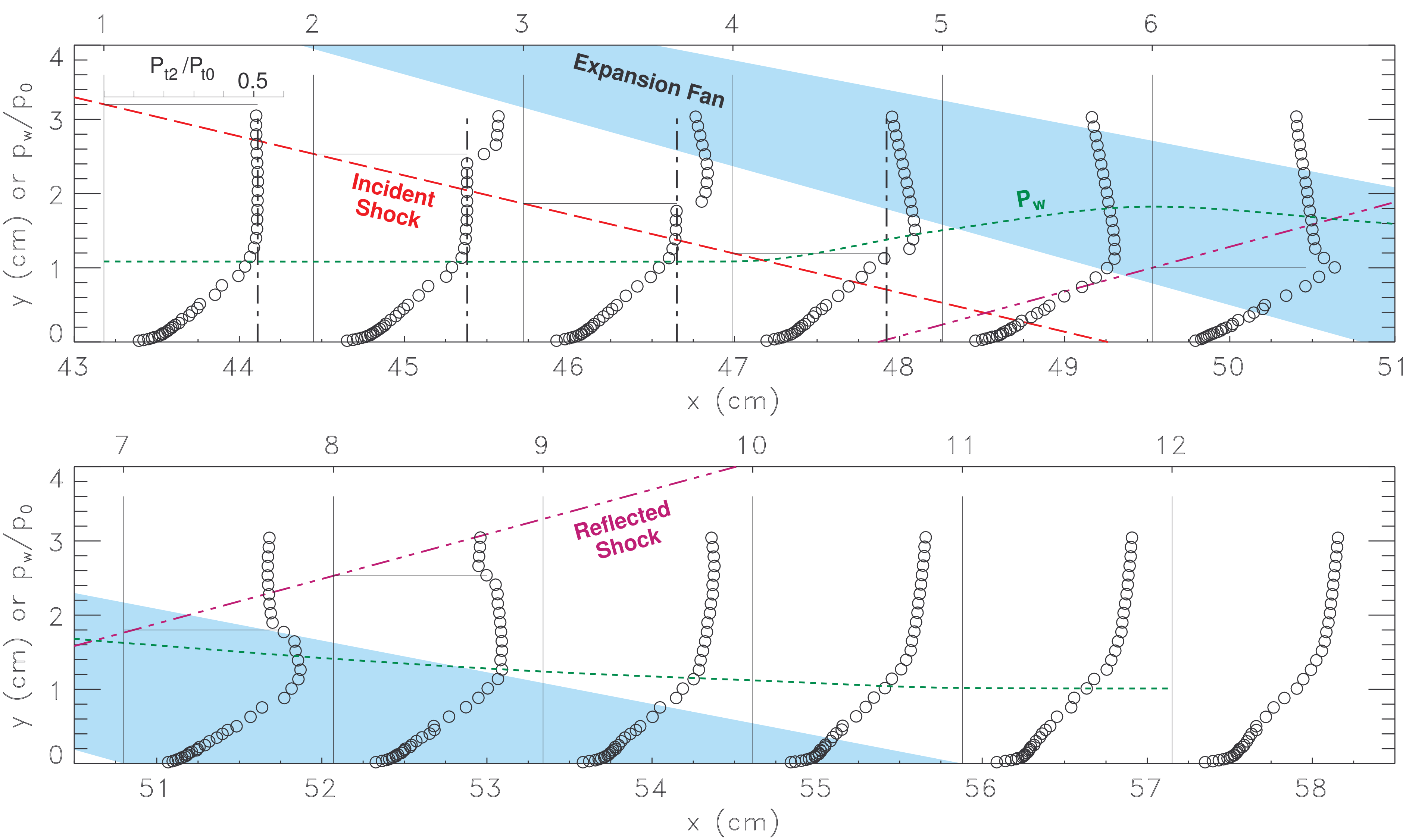


SWBLI Interaction, α=13.5°





SWBLI Interaction, α=13.5°

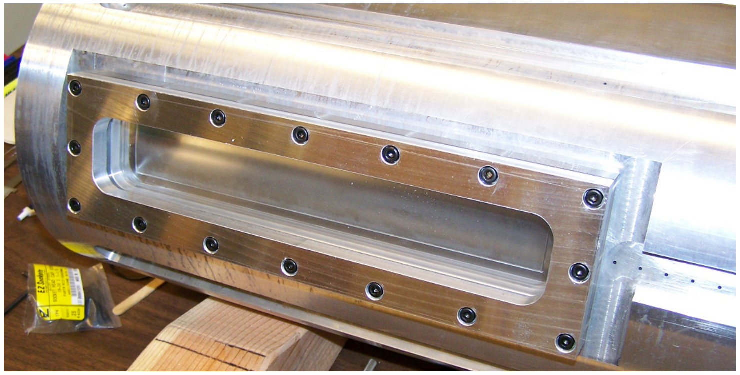


TCFDVE Status

- A new axisymmetric facility has been assembled for investigating two-dimensional SWBLI.
- Preliminary data indicates that the facility is suitable for CFD validation studies, but some refinements are necessary:
  - Improved facility Reynolds number control.
  - Refined tunnel/shock generator alignment - fabricate fixture.
  - Upgrades to probe position encoders.
  - Source of facility debris and elimination required before hot-wire measurements commence.

TCFDVE Status

- The facility has also recently been used to checkout Surface Stress Sensitive Film (S3F) and dynamic Pressure Sensitive Paint (PSP) in collaboration with Innovative Scientific Solutions Incorporated (ISSI).



- From preliminary data, refined flowfield measurement stations and surface dynamic pressure locations will be identified.

Questions?