



Three-Dimensional Structure and Modeling of a Normal Bifurcated Shock Train from Experimental Measurements

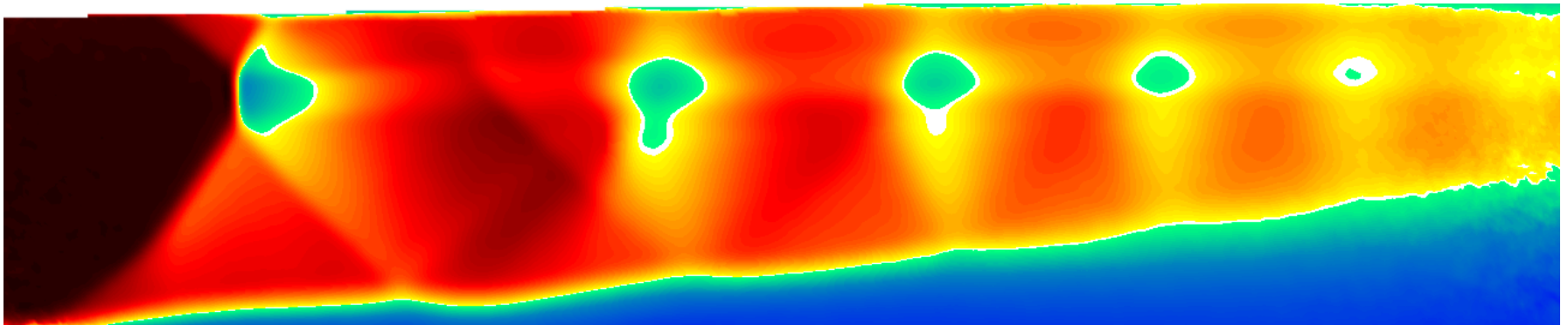
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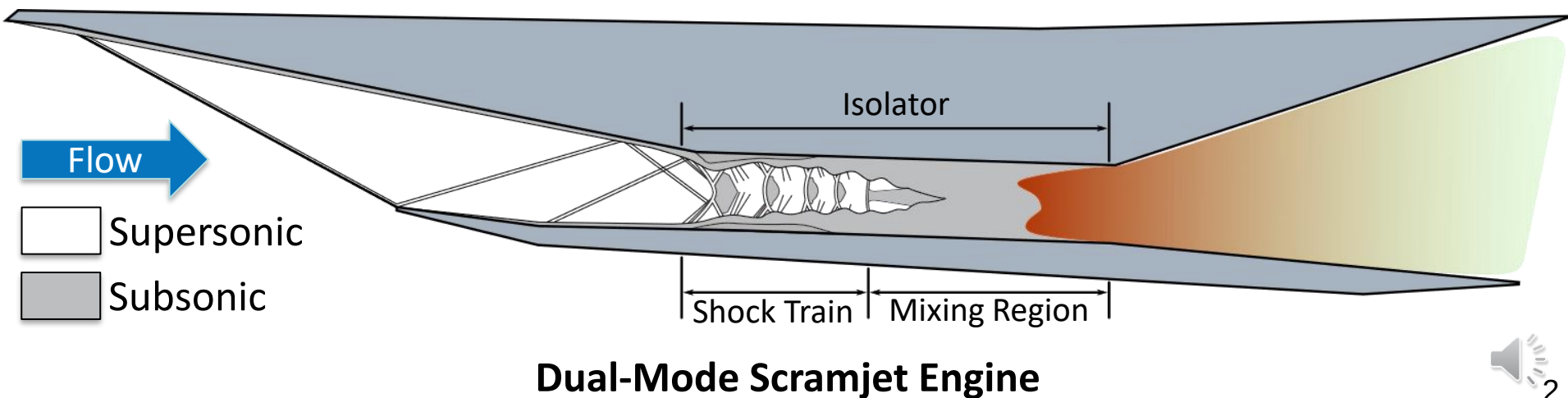
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2022 AIAA Science and Technology Forum



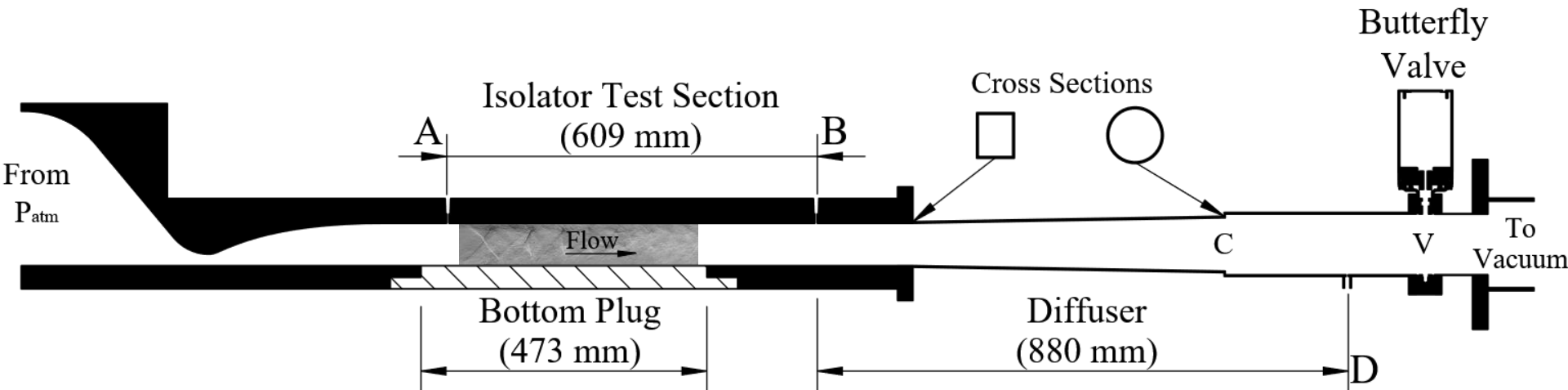
The Pseudo-Shock in This Study

- Pseudo-shock is assumed **quasi-steady** and divided into Shock Train and Mixing Region
- Focus on the **shock train** as a series of SBLI's
- **Objectives:**
 1. Synthesize various measurements to render a **3D representation** of the shock train flow structure
 2. Assess the **validity of literature models** at predicting pressure loading in an isolator for the purpose of design or control

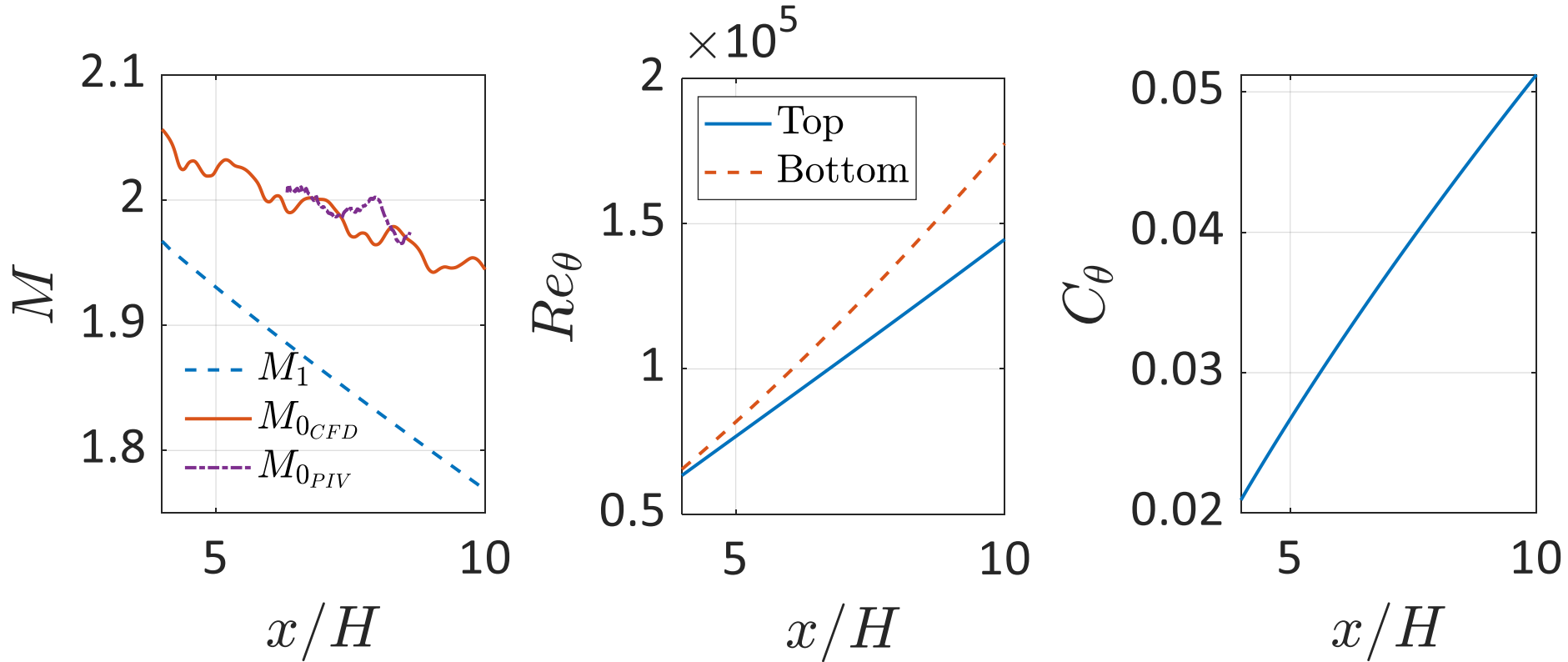


University of Michigan Direct Connect Isolator

- Suction-type supersonic wind tunnel
- **Mach 2.0** nozzle
- **57.2 mm × 69.8 mm** ($W \times H$) cross-section, $AR = 1.22$
- 800 mm streamwise constant-area test section (full optical access)
- **High-speed wall static pressure sensors** along bottom wall
- Butterfly valve back pressure controller
- Simultaneous wall static pressure and optical measurement



Approach Conditions in the UMDCI

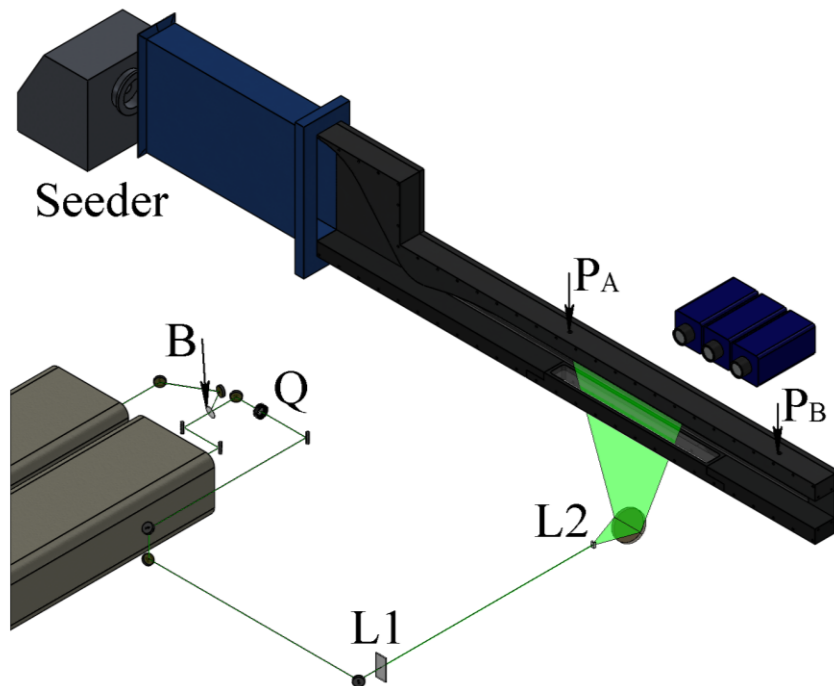


- The freestream and boundary layer properties entering the pseudo-shock. Computed from CFD of the un-backpressured isolator without a shock train in it.
 - E.g. Mach Number, Momentum Thickness Reynolds Number, Momentum Blockage, Wall Friction Coefficient

Measurement Techniques

1. Particle Image Velocimetry

- 2-Component Streamwise Planes
- 3-Component Stereo Cross-Sections
- $0.7\mu\text{m}$ Diameter PAO Oil Seeding
- 3.33 Hz



Streamwise PIV Setup

2. Wall Static Pressure Scans

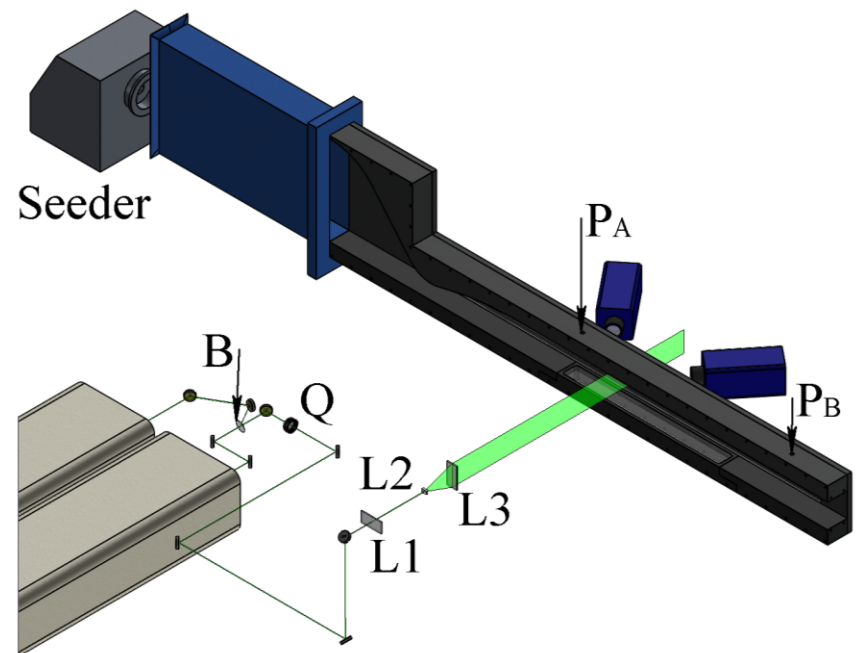
- Side & Bottom Wall Centerlines

3. High-Speed Schlieren Imaging

- 3.28H FOV, 10 kHz, $\partial\rho/\partial x$

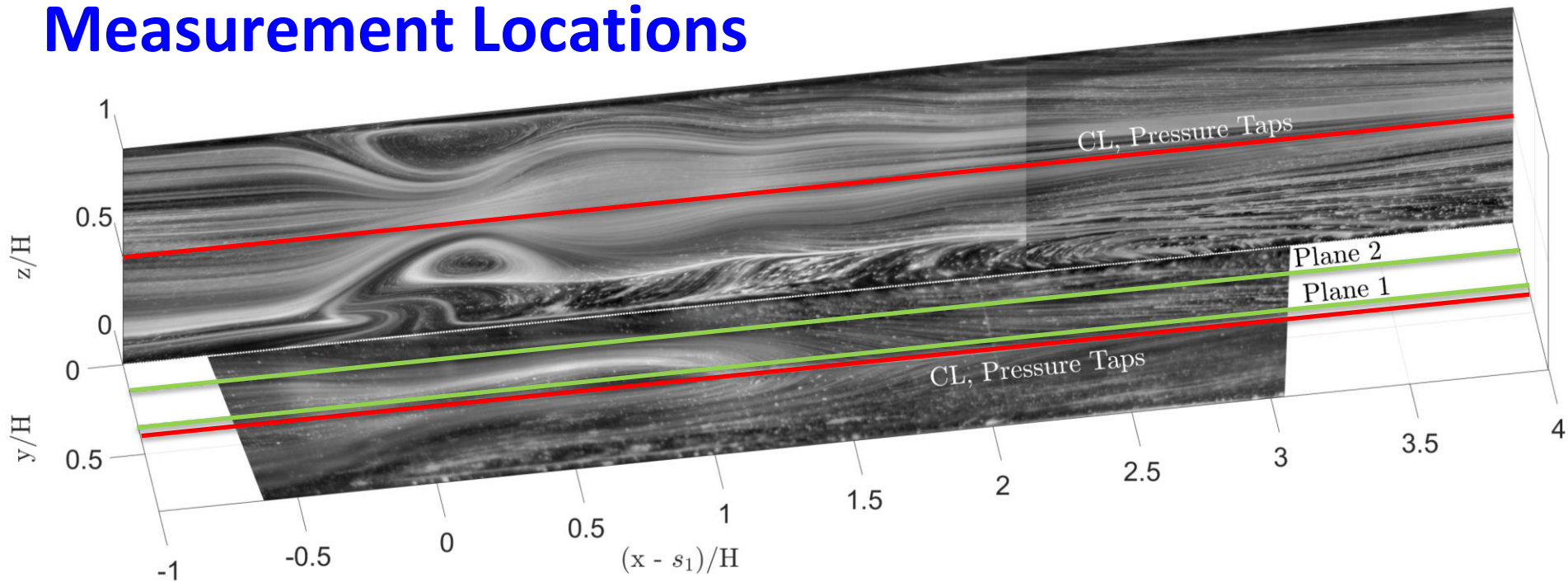
4. Surface Oil Flow Visualization

- 100 cSt Silicone Fluid



Cross-Sectional Stereo PIV Setup

Measurement Locations

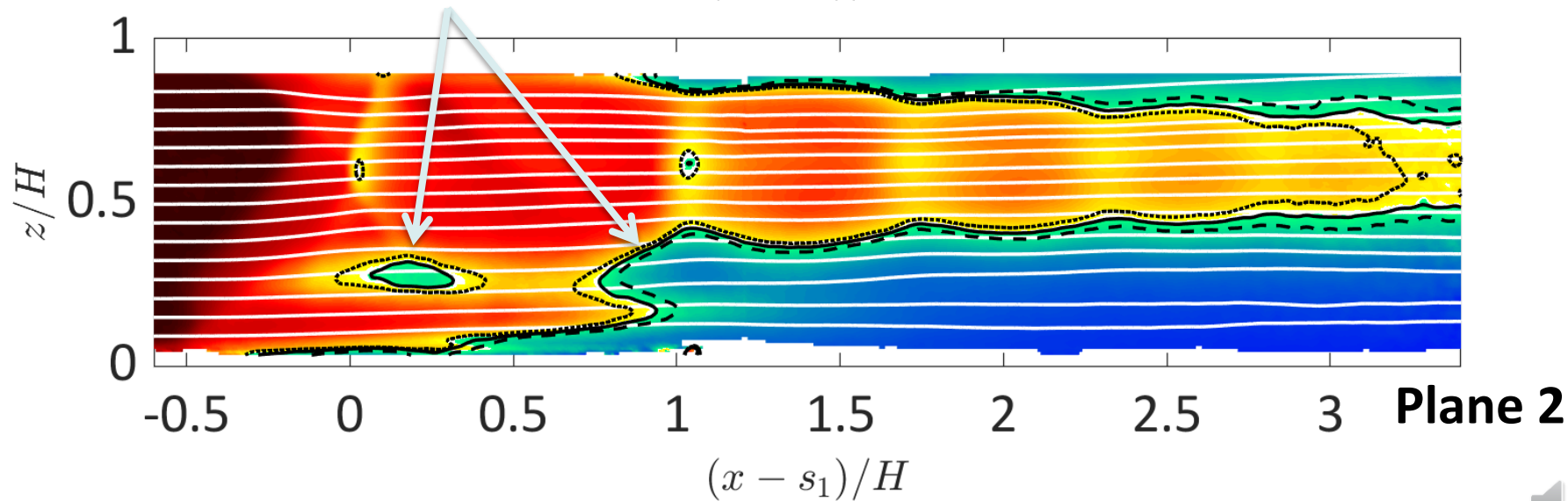
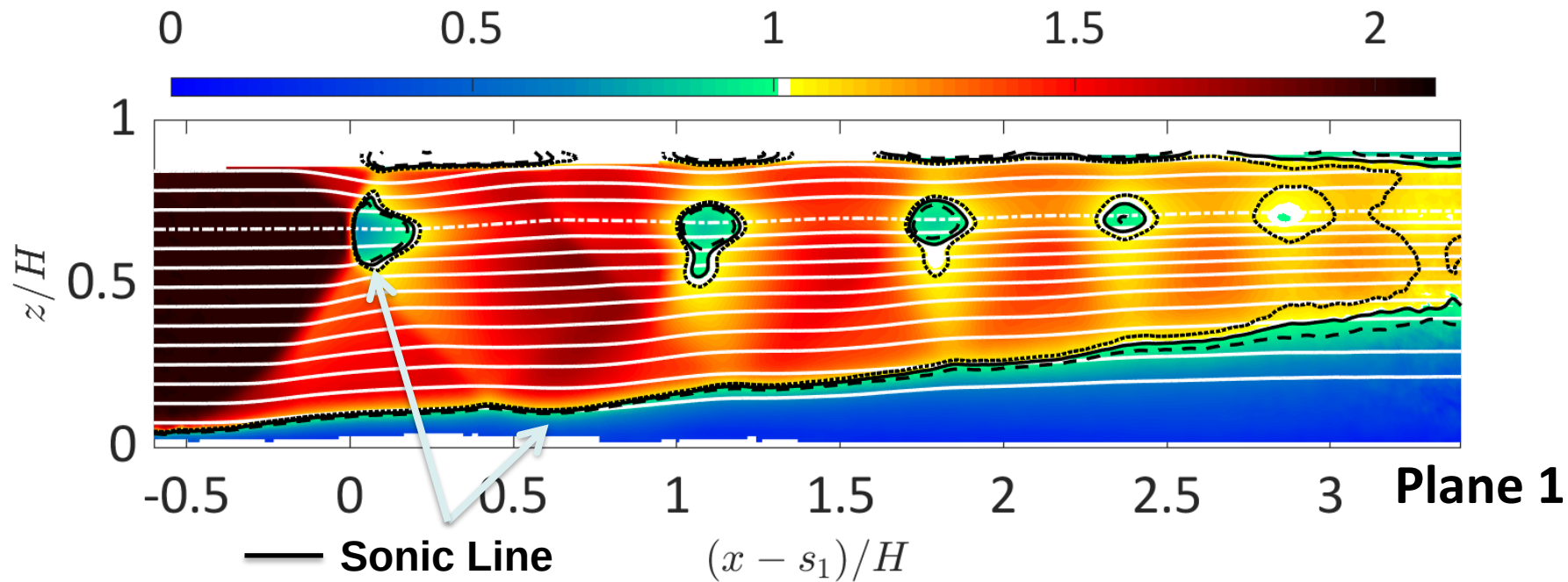


- Wall Pressure Scanners
 - 12.7-25.4 mm pressure port spacing
 - 48 ± 7.2 kPa and 15 ± 103 kPa channels referenced to P_A
- Streamwise 2-Component (u, w) PIV
 - Plane 1: $y = 0.44W = 0.36H$
 - Plane 2: $y = 0.20W = 0.16H$
 - 1200 Samples/Plane
 - 32x32 Gaussian Window yielding 0.63 mm vector field grid resolution

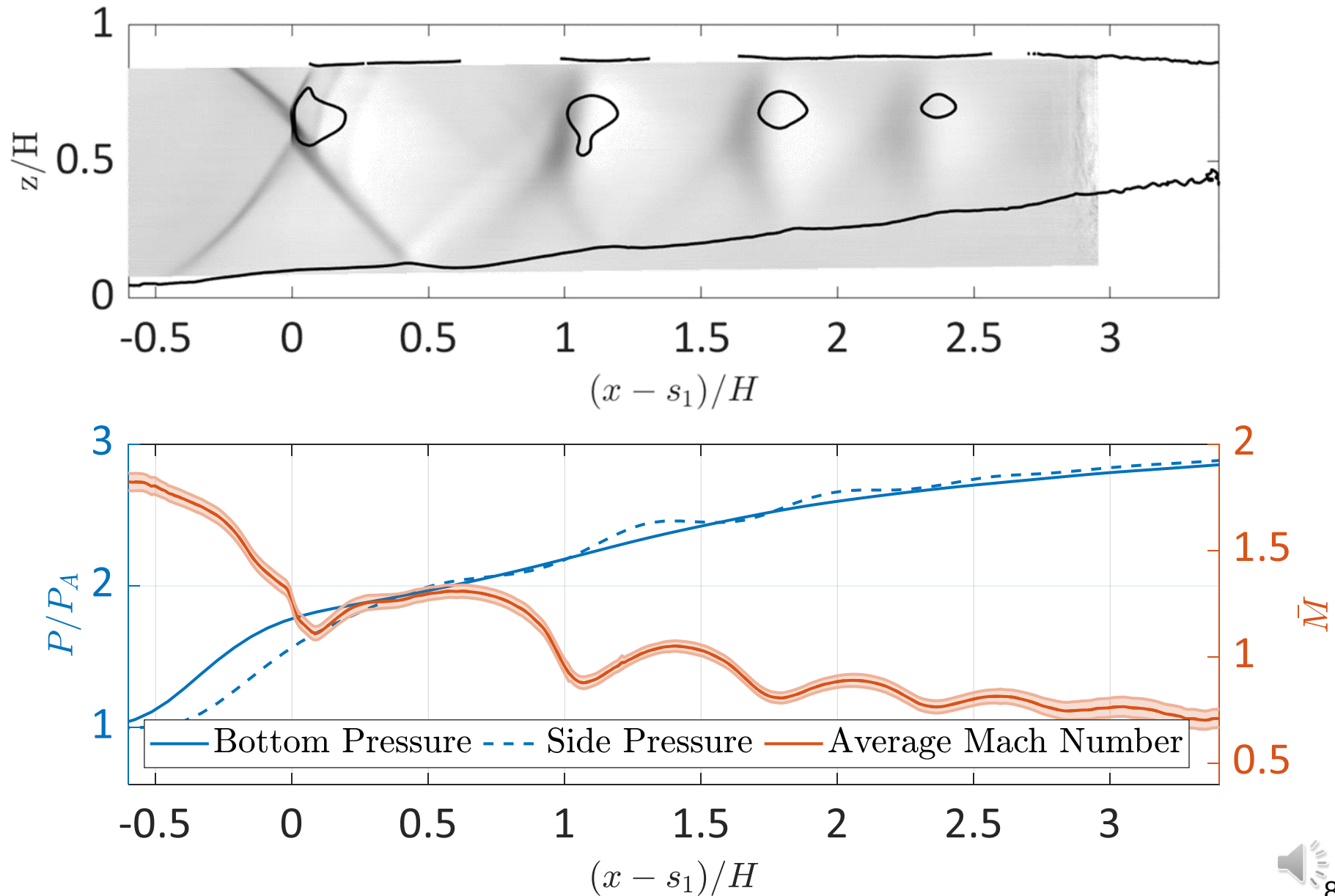


Streamwise PIV

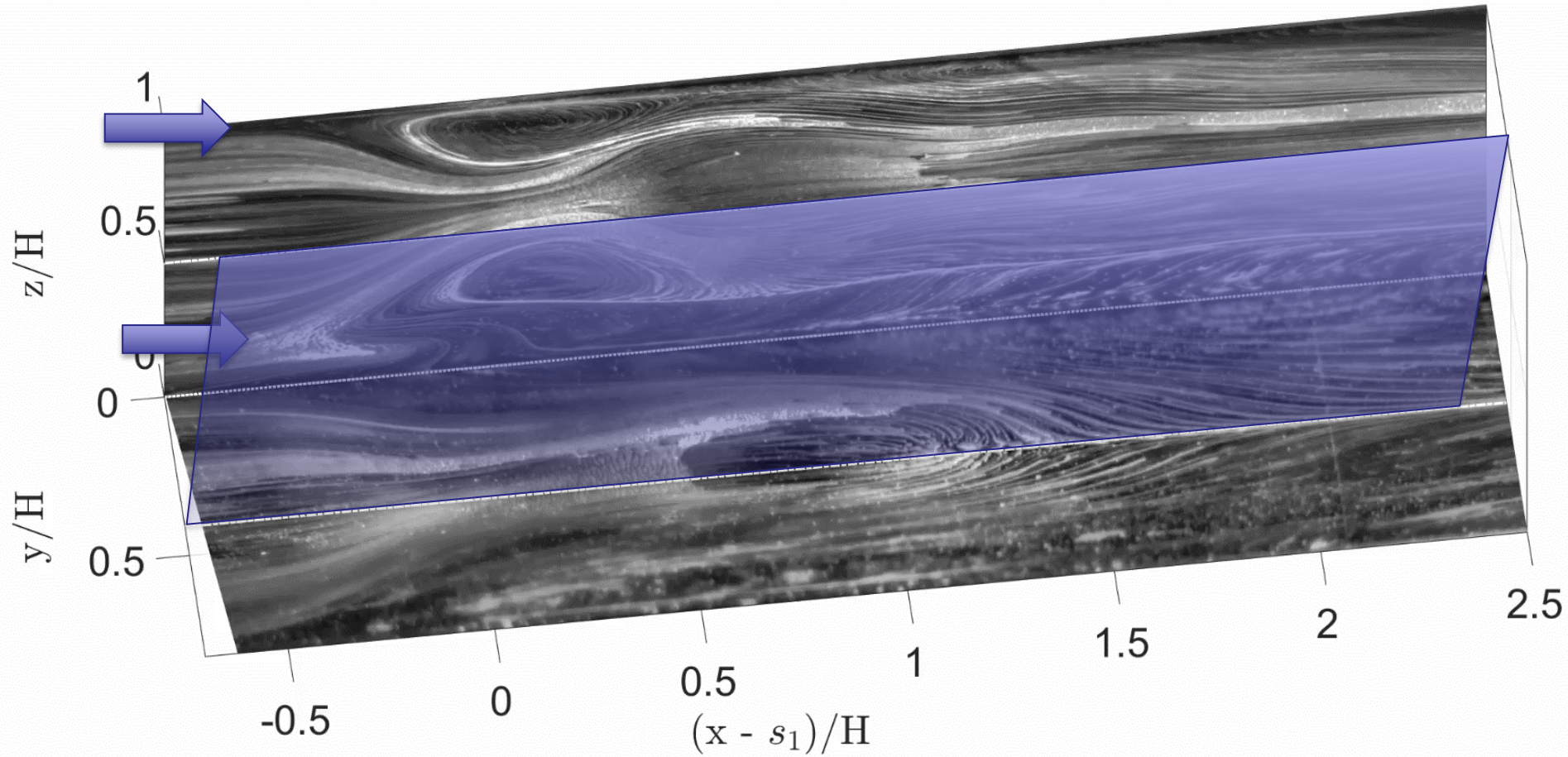
--- $\pm$ Sonic Line Uncertainty



Schlieren & Wall Pressure

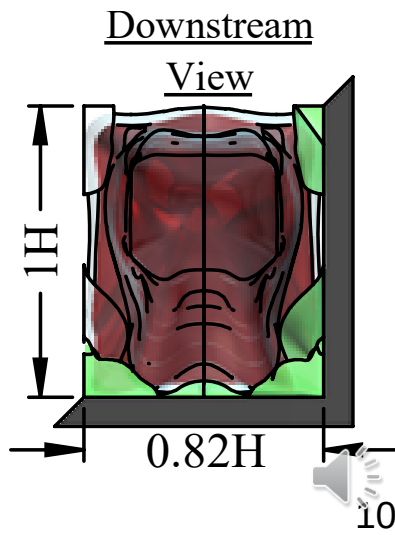
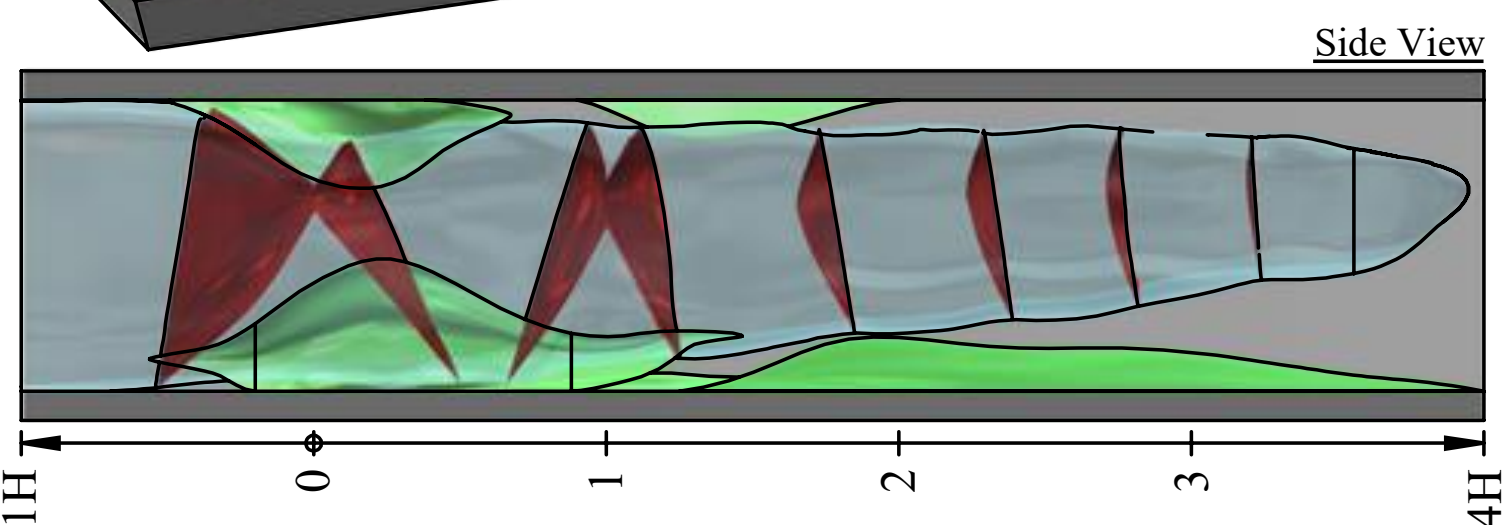
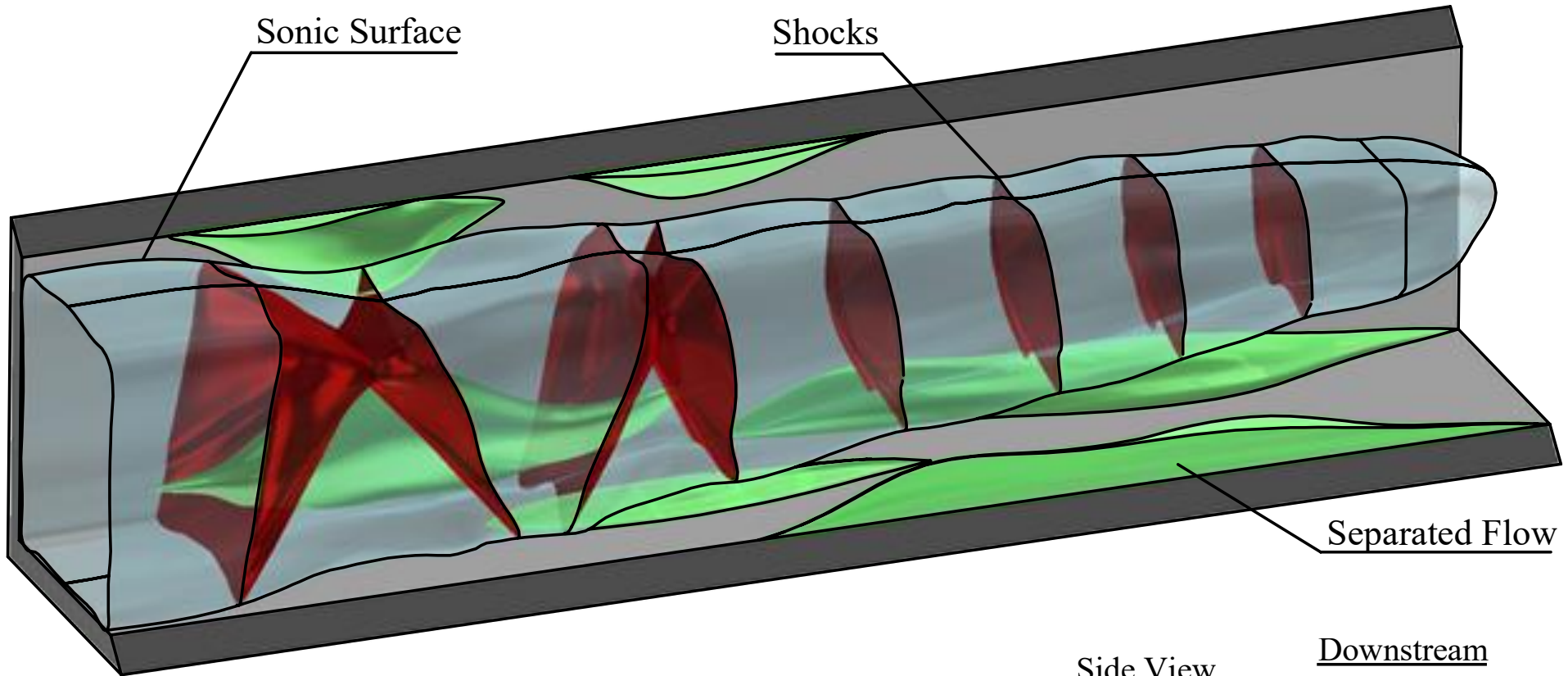


Leading SBLI Oil Flow Visualization

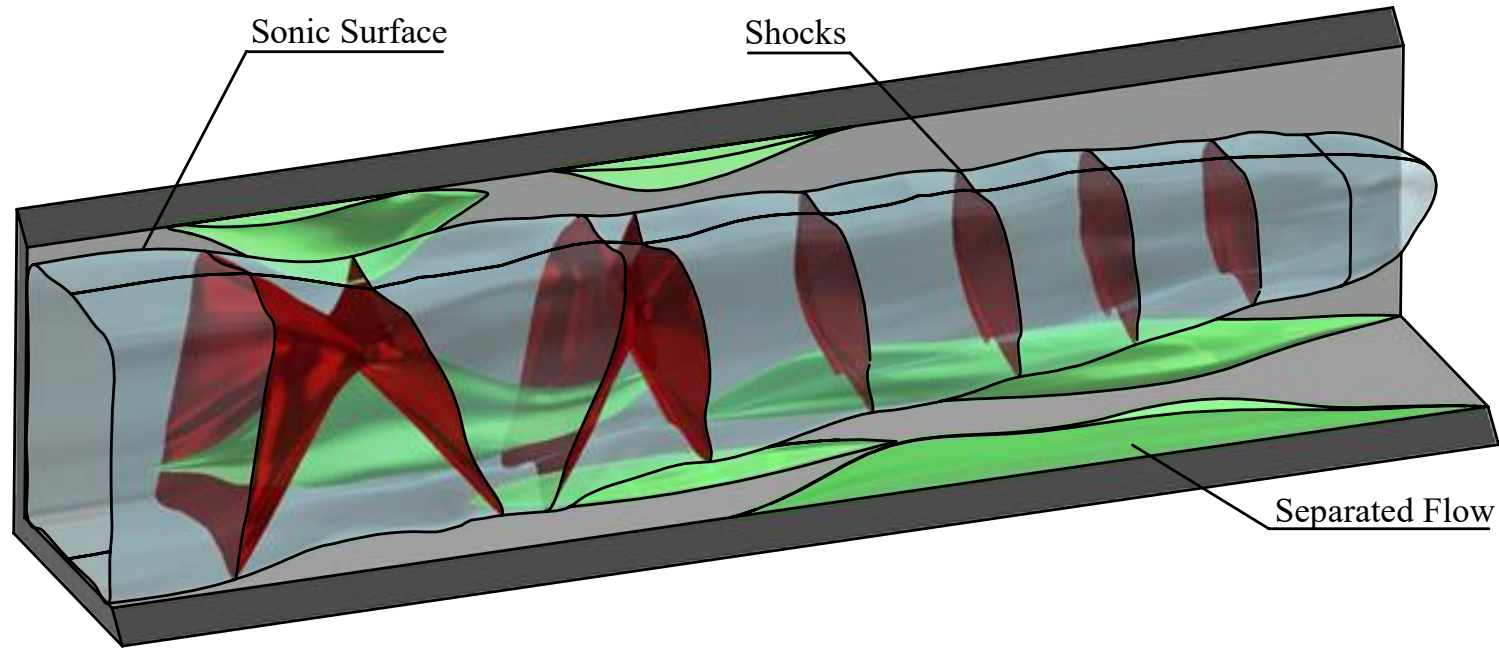


- Lateral symmetry, vertical asymmetry in the SBLI structure.
- Top separation begins in the corner
- Bottom separation begins on the side wall, not directly in the corner

Three-Dimensional Shock Train Structure



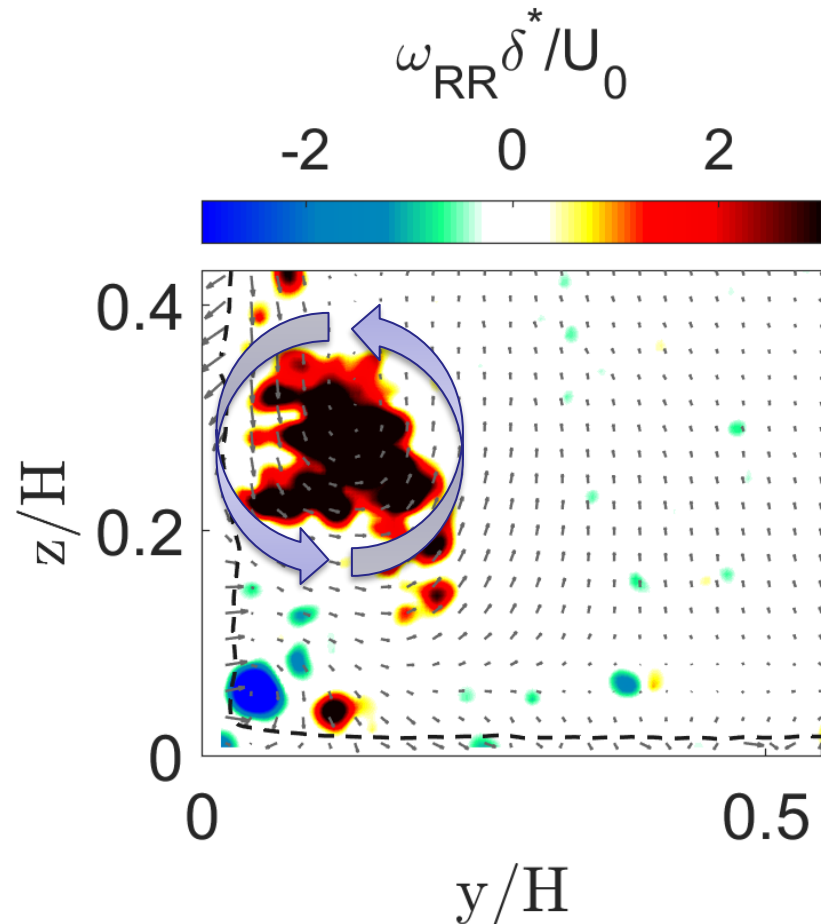
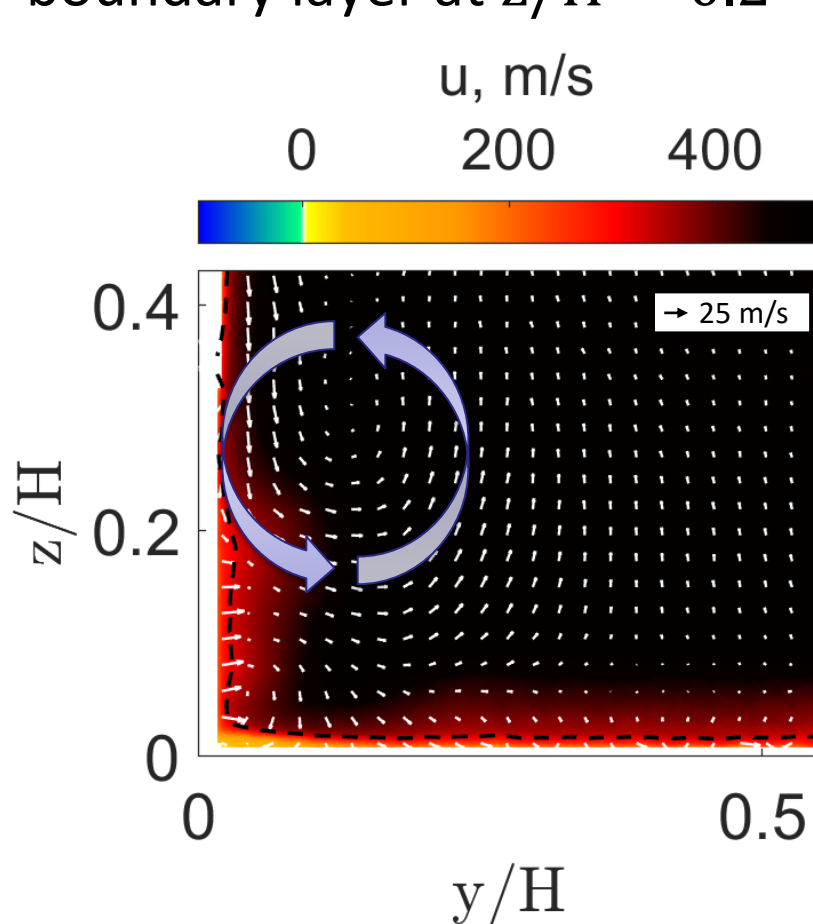
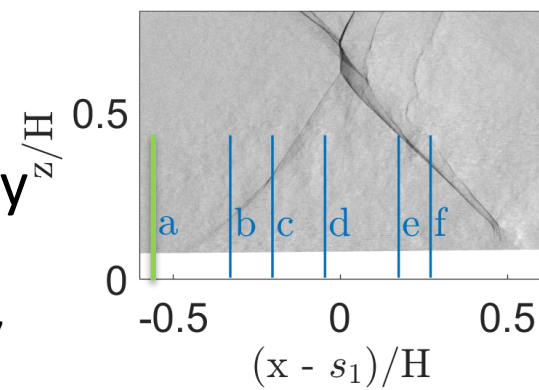
Key Structural Features of the UMDCI Shock Train



- Upward skew to the supersonic shock train core
- Bottom boundary layer is starved of more momentum than the top
 - More significant separated flow is present below than above the core
- Each subsequent shock structure is weaker than the last
 - Fully bifurcated (1) too nearly normal (6)
- By the notional definition of “end of the shock dominated region”, the UMDCI isolator does not contain a mixing region

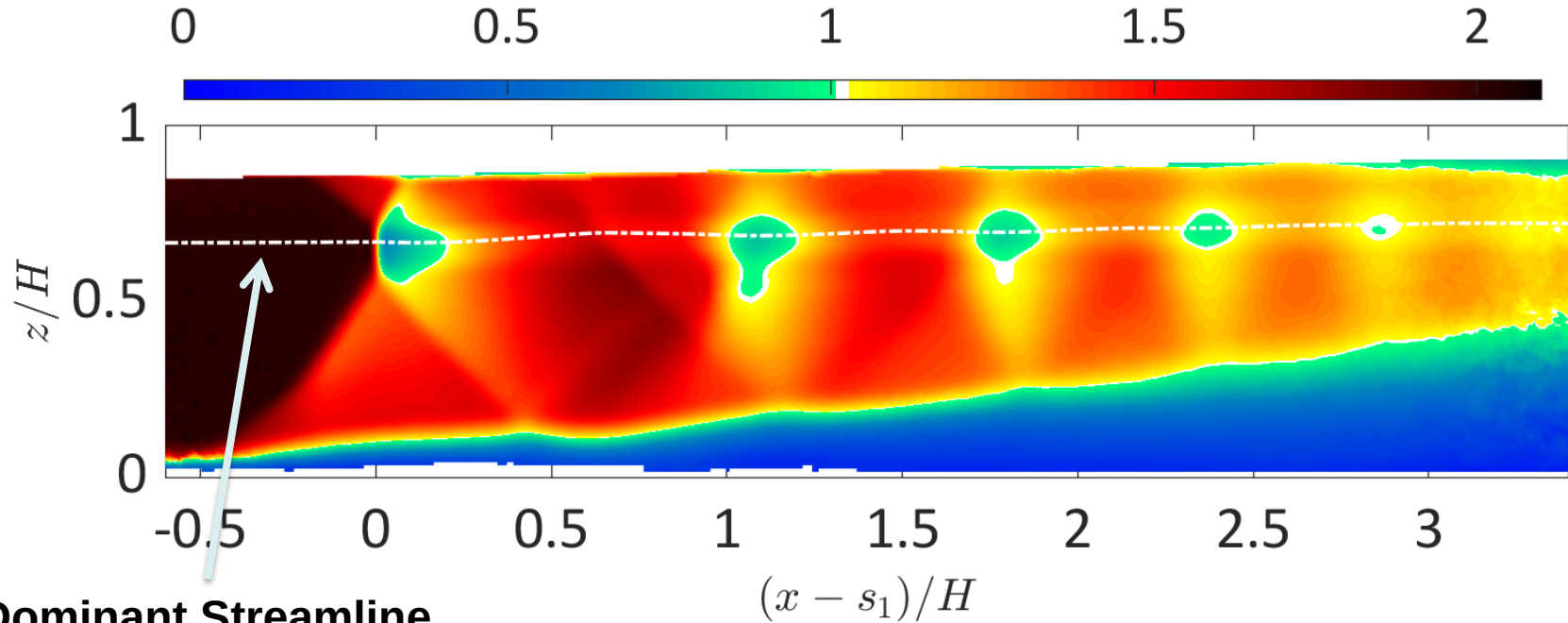
Empty Tunnel Vortex Structure

- ω_{RR} = Rigid body rotation component of vorticity
 - Computed by Triple Decomposition of Motion
 - Kolar, *Vortex Identification: New requirements and limitations*, 2007
- Large side wall vortex destabilizing the side wall boundary layer at $z/H = 0.2$

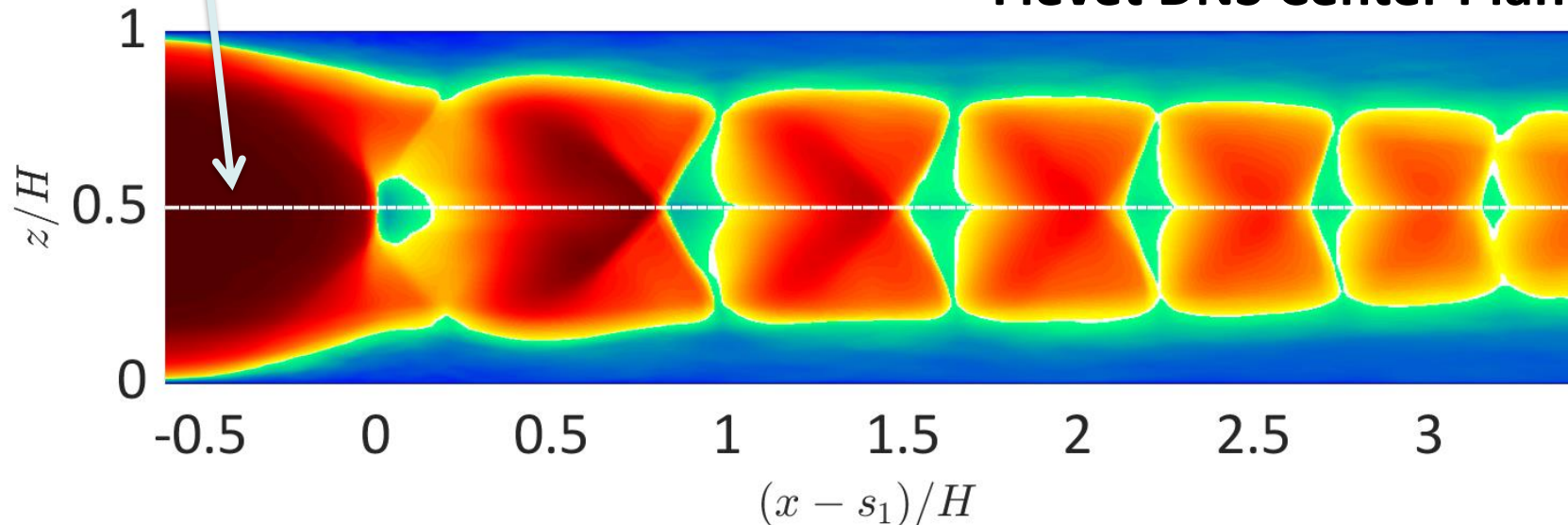


Effect of Asymmetric Core Flow

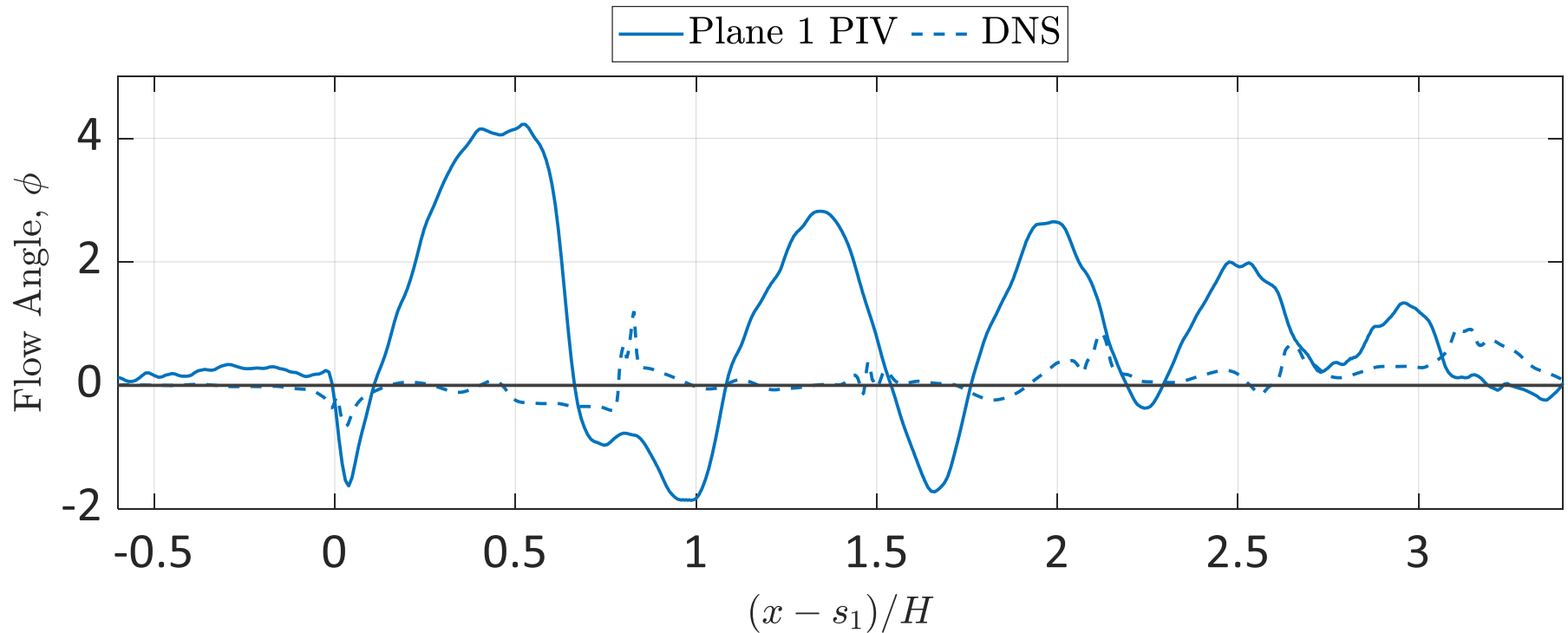
Plane 1 PIV



Fiévet DNS Center Plane



Flow Angle Along Core Streamlines



- Flow turning within each shock cell in asymmetric UMDCI and not the symmetric DNS
 - Resulting net angle of the shock train core: 0.85°
 - Different shock & shock cell expansion strengths
- ➔ Different pressure profiles estimated

Literature Pseudo-Shock Models for Comparison

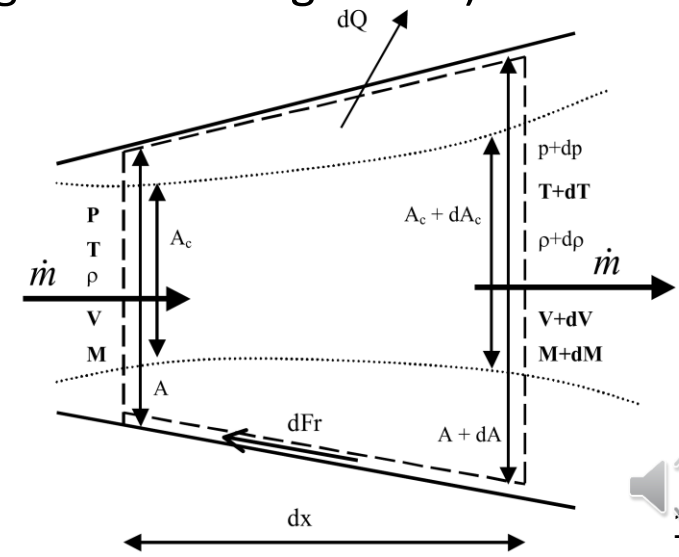
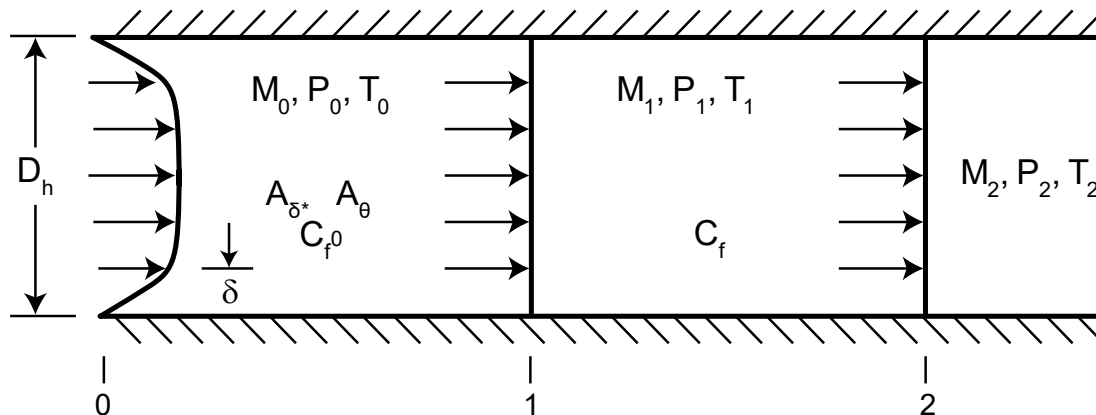
1) Waltrup-Billig Correlation:
$$50 \left(\frac{P}{P_0} - 1 \right) + 170 \left(\frac{P}{P_0} - 1 \right)^2 = \frac{x(M_0 - 1)Re_\theta^{1/5}}{\sqrt{H\theta}}$$

2) Smart Flux-Conserved Model: Quasi-1D system of 2 ODE's wrt x

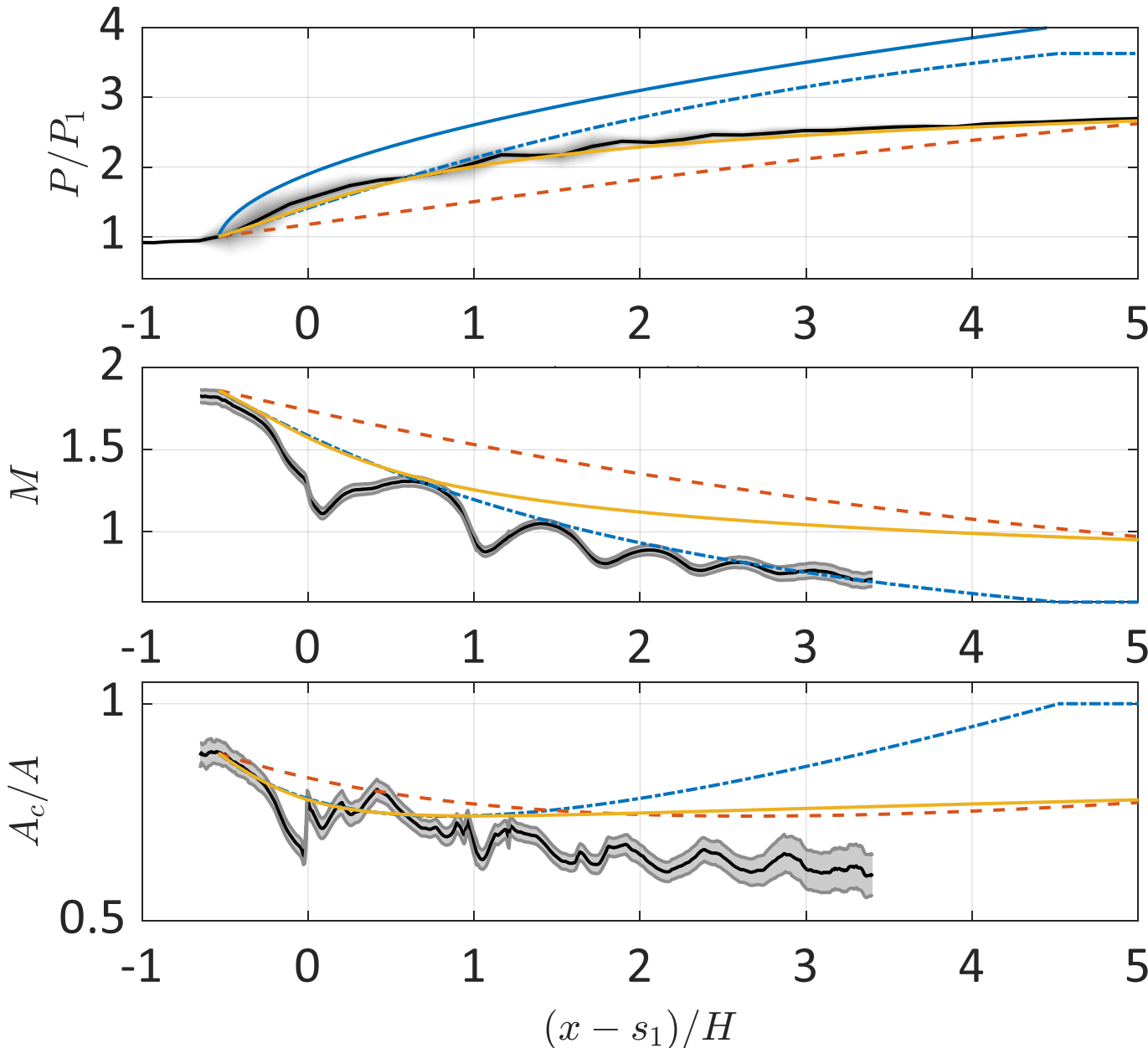
- Ortwerth Diffuser Model: $\frac{dP}{dx} = q \frac{k_1}{D_h} C_{f0}; \quad q = \frac{\gamma P M^2}{2}$
 - Single Parameter Model

3) Fiévet Data-Driven Flux-Conserved Model:

- $\frac{dP}{dx} = q \frac{k(q, M_1)}{D_h} C_{f0}^\alpha \sigma^\beta; \quad \sigma = \frac{\text{Pseudo-Shock Static Pressure Ratio}}{\text{Equivalent Normal Shock Pressure Ratio}}$
 - Nine Parameter Model (Optimized using a Genetic Algorithm)



Comparison to Prevailing Models



- **WB:** Departs rapidly from pressure data
- **Smart:** Predicts isolator pressure ratio OR initial gradient and Mach number profile. Not both.
- **Fiévet:** Optimal pressure prediction, poor prediction of Mach number profile
- **Sources of compression linking M and P is missing from these models**

Summary & Conclusions

1. Constructed a **3D representation of the asymmetric, bifurcated normal shock train** in the University of Michigan Direct Connect Isolator Facility from experimental measurements
2. The **incoming flow morphology**, specifically a strong sidewall bound vortex, preconditions the system to separate away from the corner, **skewing the SBLI's and shock cells** in the shock train
3. The **prevailing literature shock train models** in the literature do not model both the pressure profile and profile averaged Mach number
 - **Waltrup-Billig Correlation, Smart Flux-Conserved Model, Fiévet Flux-Conserved Model**
4. Ongoing work includes the development of a new model including additional source terms for compression
 - Turbulent dissipation, wall cooling, combustion heat release



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THANK YOU

