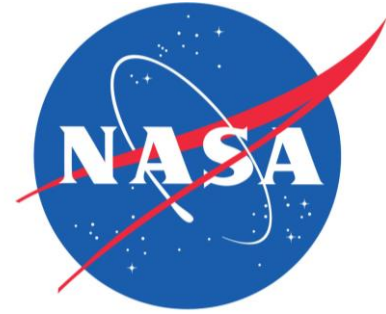




COLLEGE OF ENGINEERING
AEROSPACE ENGINEERING
UNIVERSITY OF MICHIGAN



Physics and Modeling of Quasi-Steady and Forced Shock Trains

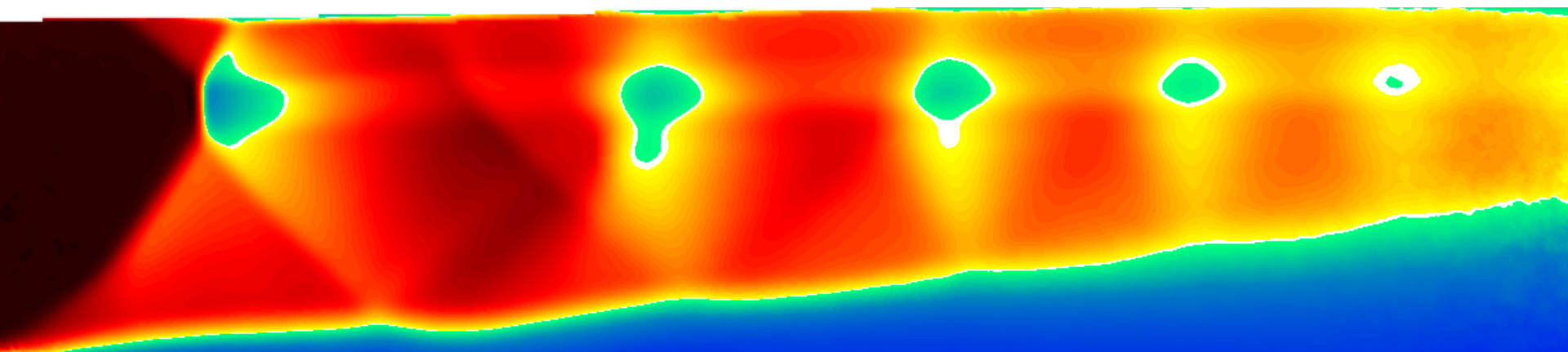
Dr. Louis M. Edelman

Flow Physics and Control Branch

NASA Langley Research Center

Seminar at JAXA Sagami-hara

September 27, 2022



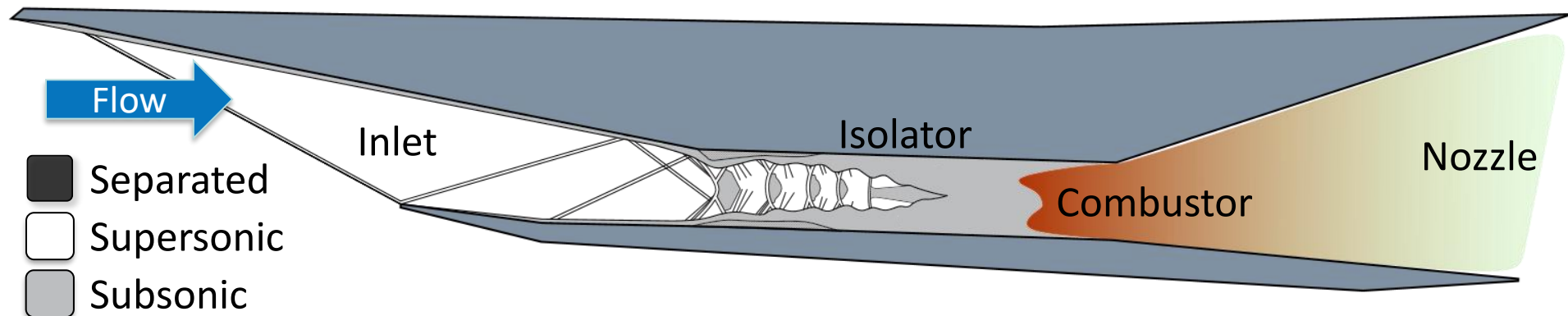
Hypersonic Vehicles

- Boost Glide Vehicles
 - Accelerated to Mach 5+ by a Rocket
 - No Onboard Propulsion
- Atmospheric Entry/Re-Entry
 - Capsules
 - Lifting Bodies
- Cruise Powered Vehicles
 - Ramjet
 - Supersonic Combusting Ramjet (Scramjet)
 - Combined Cycle Engines

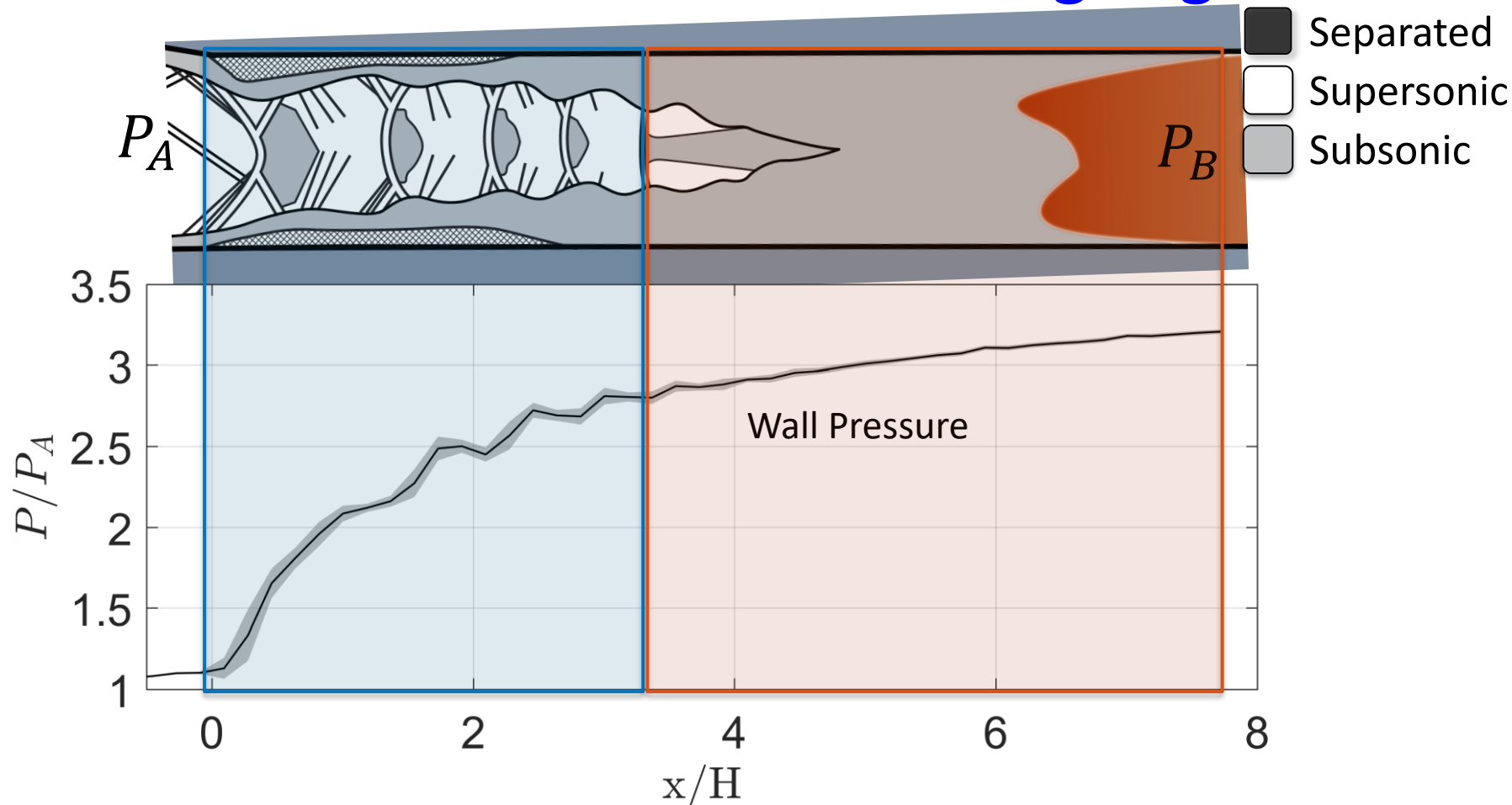


The Dual-Mode Scramjet

- Outgrowth of Ramjets
- Dual-Mode Scramjet:
 - Ramjet Mode: Flight Mach 3 ~ 5
 - Scramjet Mode: Flight Mach ≥ 5
- Military Applications: Hypersonic Cruise Missiles
- Civilian Applications: Reusable First Stage Booster
- **Isolator:** Provides remaining compression from the inlet to the compressor



Pseudo-Shock: Shock Train and Mixing Region



- **Shock Train:** Series of interconnected Shock Boundary Layer Interactions (SBLI)
- **Mixing Region:** Turbulent, mixed sub/supersonic flow
- **Shock Train to Mixing Region** Transition is key measure of minimum isolator length:
 - “Where the flow is no longer shock dominated”
 - “Flow can no longer sustain shocks” i.e., subsonic

Significant and Recent Pseudo-Shock Work in Japan

- 北九州市立大学 University of Kitakyushu

- 松尾 一泰 MATSUO Kazuyasu
- 宮里 義昭 MIYAZATO Yoshiaki

- *“Shock train and pseudo-shock phenomena in internal gas flows”*

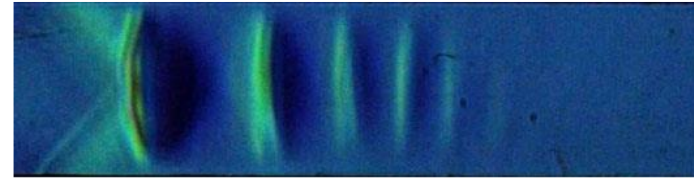
- Progress in Aerospace Sciences 1999

- 中部大学 Chubu University

- 苅田 丈士 KANDA Takeshi

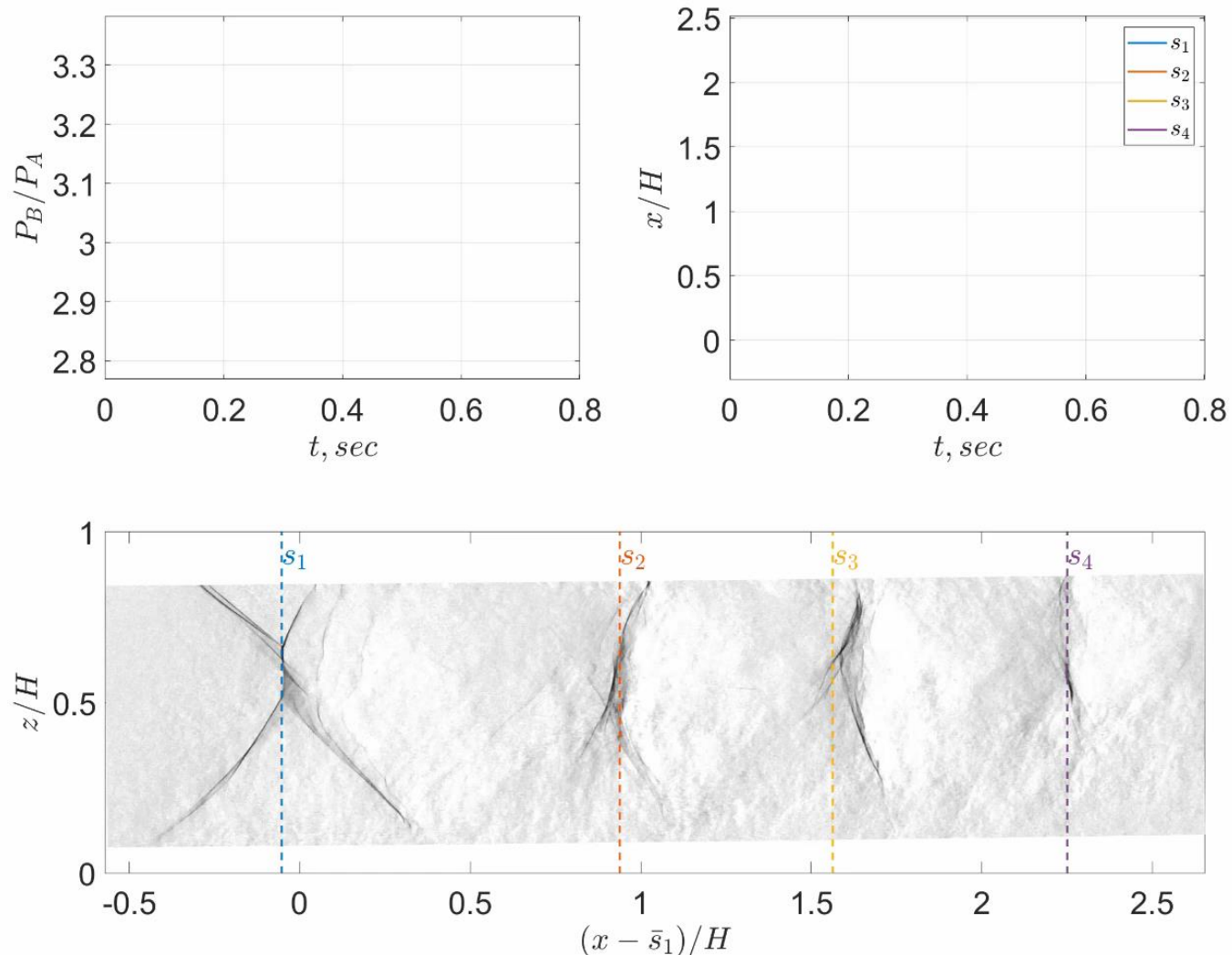
- 角田宇宙センター Kakuda Space Center

- High Enthalpy Shock Tunnel (HIEST)
- Ramjet Engine Test Facility (RJTF)
- University and Commercial Partnerships

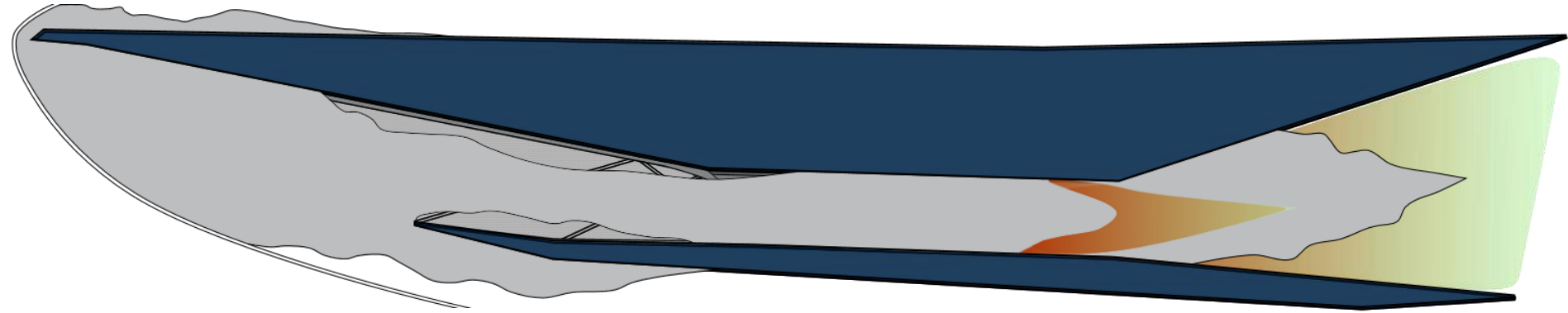


Normal Operation: Quasi-Steady State

- **Quasi-Steady:** Shock train varies in structure and position at a low-magnitude, self-contained **inherent unsteadiness** around a time-averaged position.

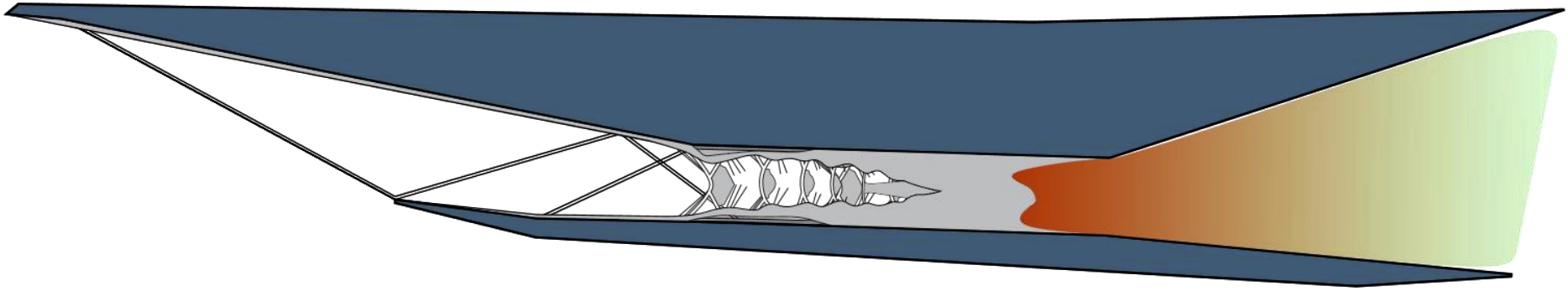


Critical Failure Mode: Isolator Unstart



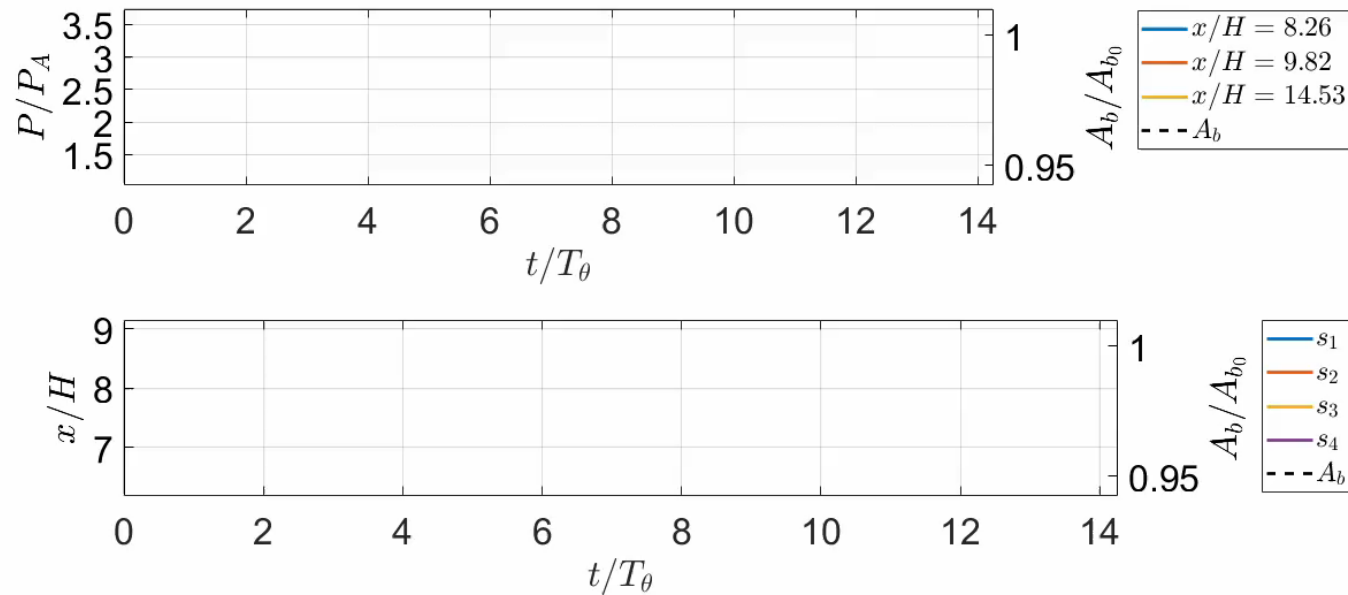
- Pseudo-shock compresses flow from the inlet to meet **downstream boundary condition** in the combustor.
- As combustor pressure increases, the **shock train shifts** upstream to increase compression in the mixing region
- When combustor pressure rises beyond a threshold, **unstart** occurs.

Middle Case: Forced Dynamics



- Oscillations or step/ramp changes in downstream pressure at a slow enough rate and magnitude **not to immediately induce unstart.**
- Sources of forced dynamics:
 - Combustor Fuel Throttling
 - Combustor Instabilities
- Potential Aberrant Behavior:
 - Reduced stability margin
 - Oscillatory thrust
 - Structural fatigue loading

Mode 1 Forcing: Low-Rate Mechanically Induced (University of Michigan Direct Connect Isolator)



Isolator Inflow:

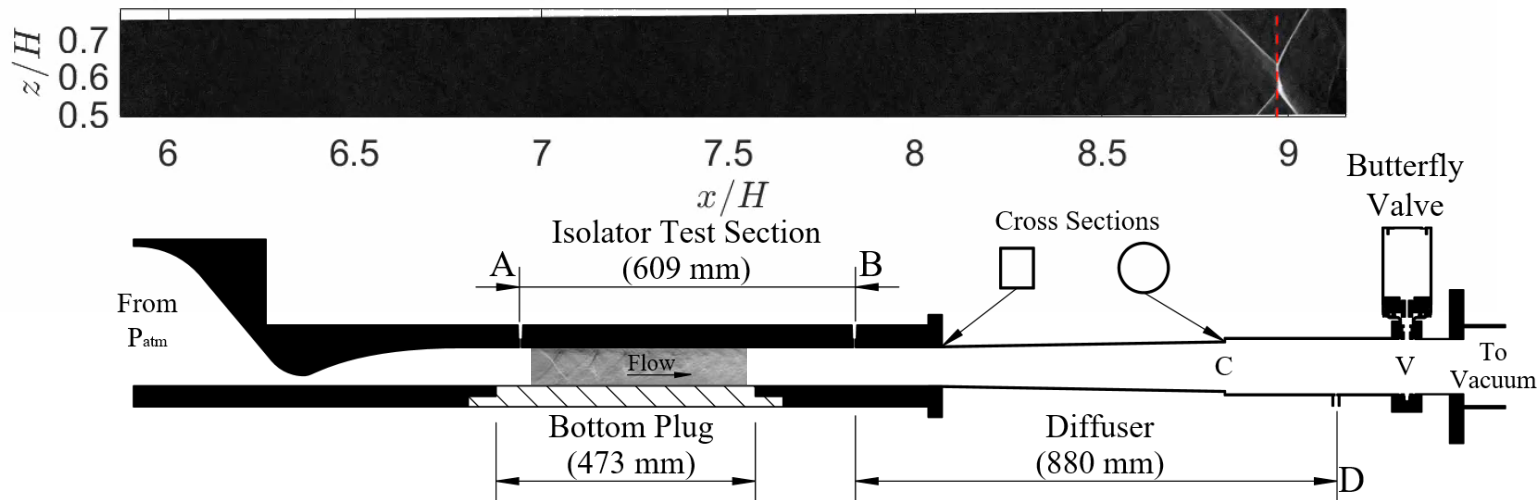
$$M = 2.0$$

$$AR = 1.2$$

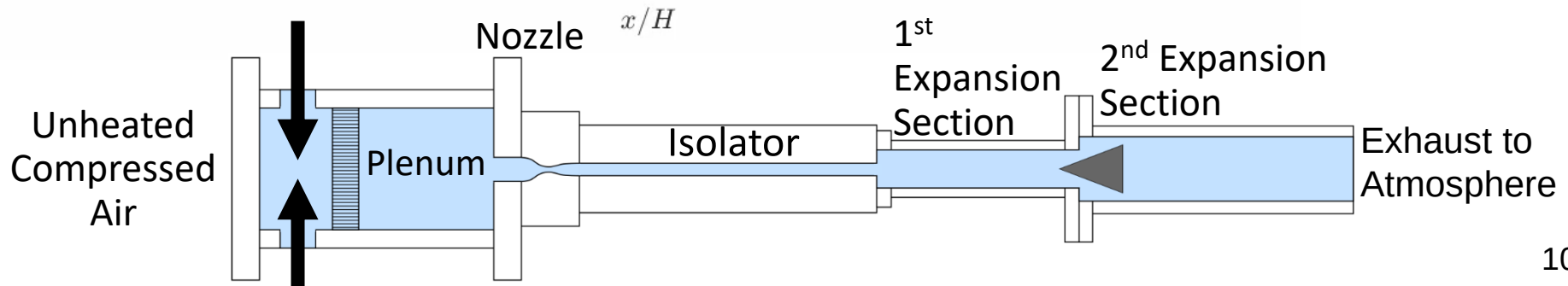
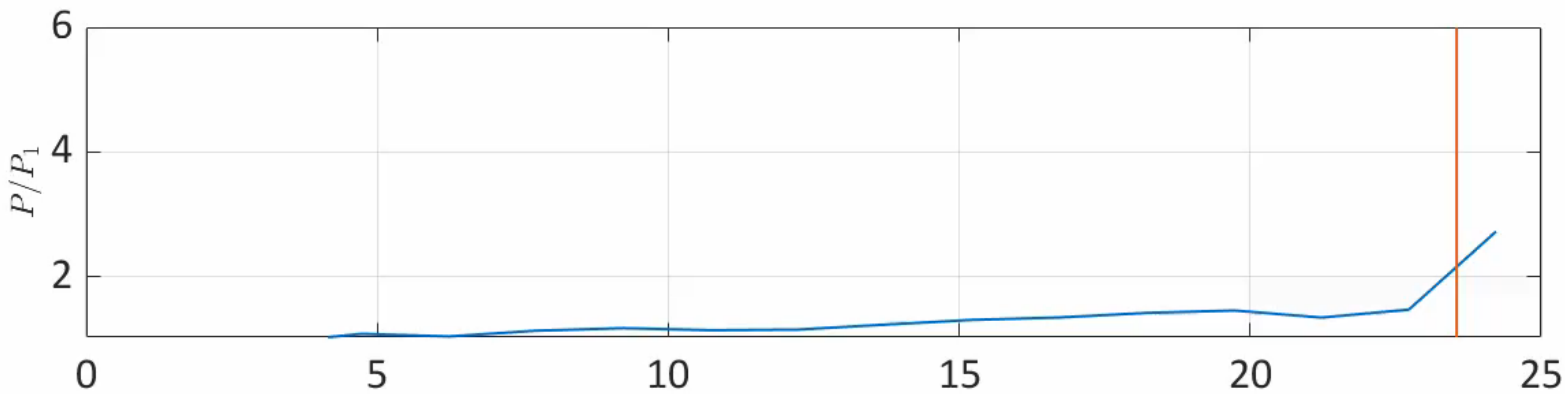
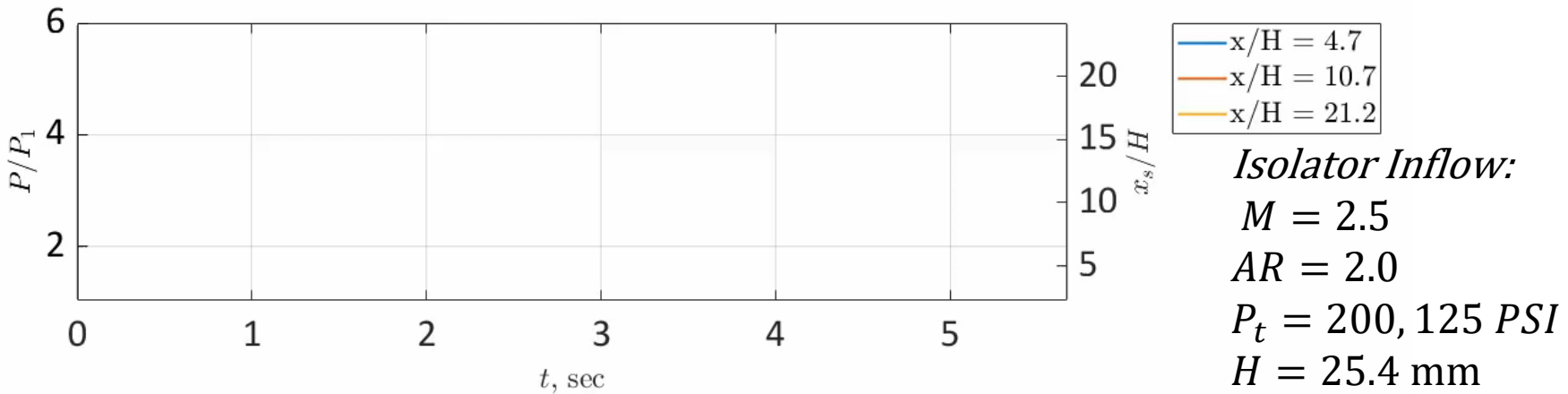
$$P_t = 14.5 \text{ PSI}$$

$$H = 69.8 \text{ mm}$$

(Duct Height)

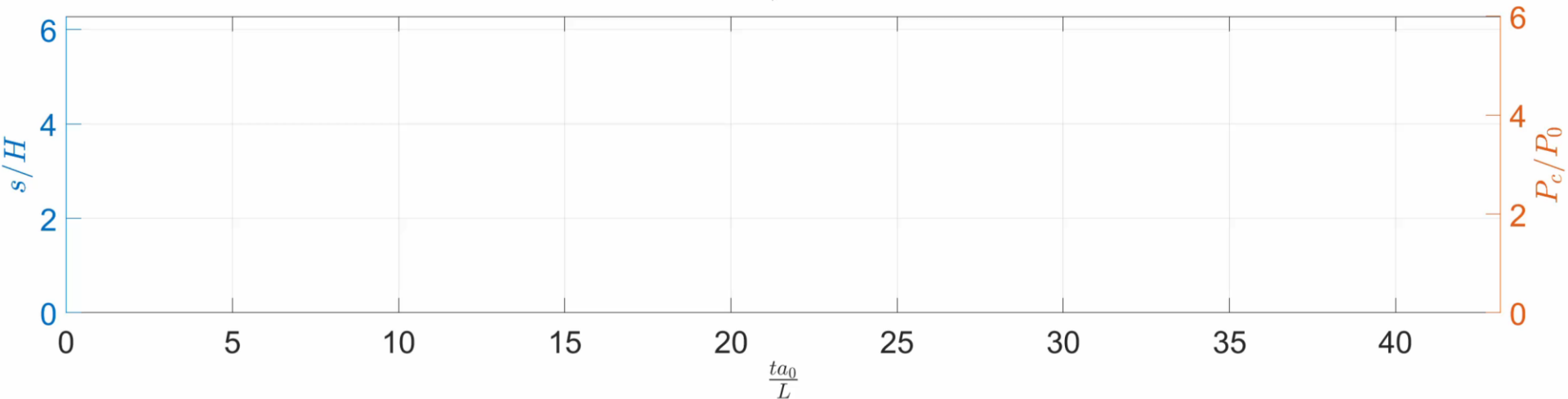
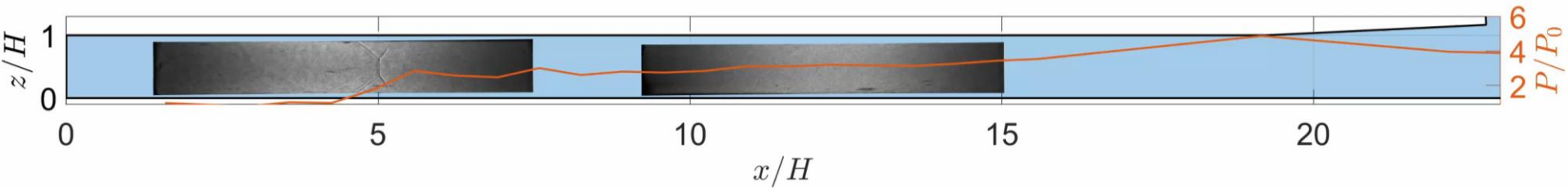
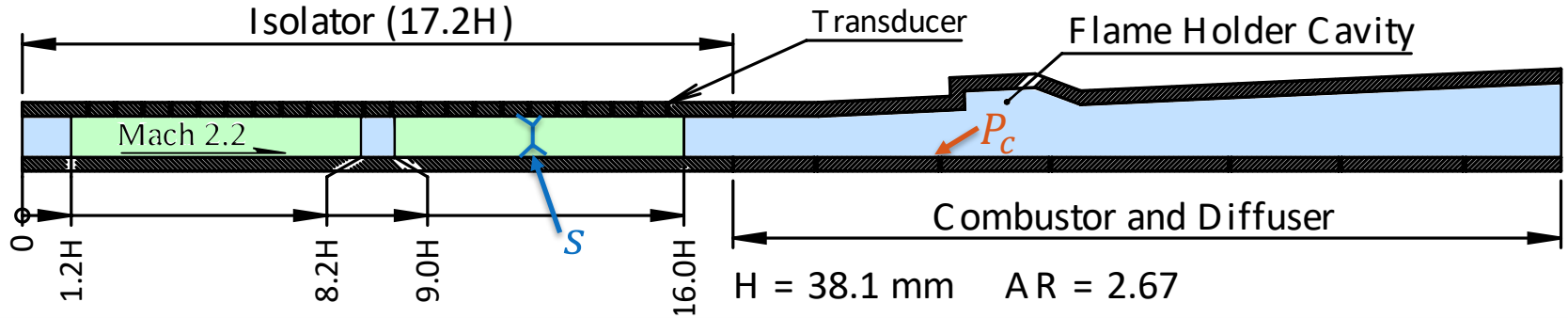


Mode 1 Forcing: Isolator Dynamics Research Lab



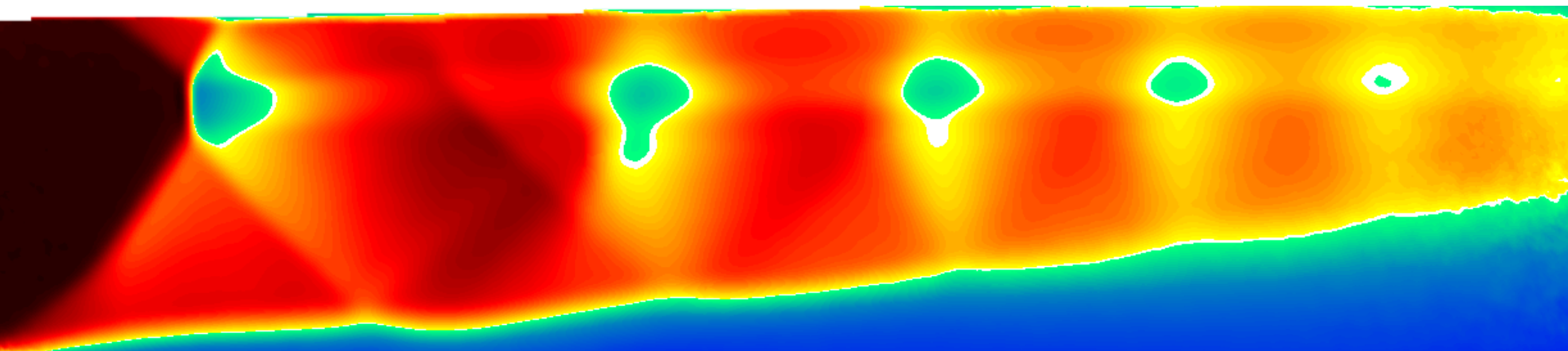
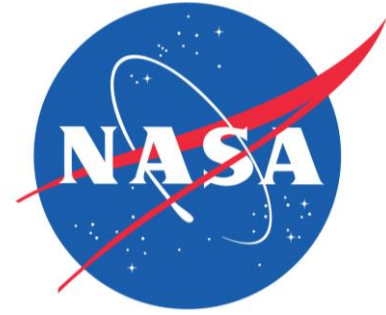
Mode 2 Forcing: Combustion Driven Unsteadiness (AFRL Research Cell 18)

Isolator Inflow: $M = 2.2$, $AR = 2.67$, $P_t = 75, 90, 102 \text{ PSI}$, $H = 38.1 \text{ mm}$



Gaps in Knowledge Addressed in this Work

1. How does boundary layer morphology influence the 3D structure of the shock train?
2. Which of the metrics for shock train to mixing region transition reflect the different qualitative definitions and can they be made more robust?
3. How do the assumptions in state-of-the-art reduced-order models hold-up to the 3D pseudo-shock structure?
4. Can the physical grounding and utility of state-of-the-art models be improved?
5. How well can the pseudo-shock be modeled as quasi-steady during forced dynamics, as is often assumed?
6. What parameters control the response of the shock train to forced dynamics?

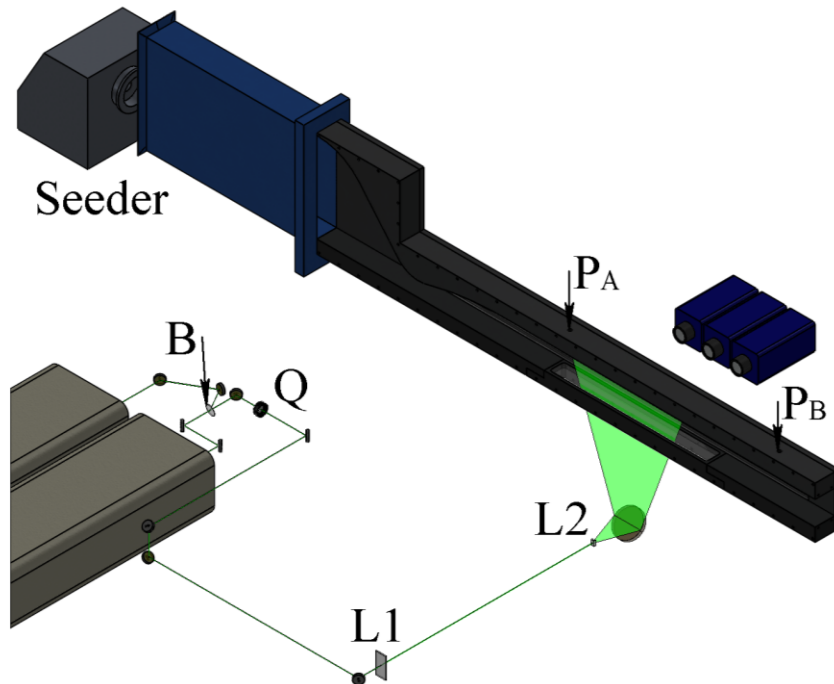


3D STRUCTURE OF AN ASYMMETRIC MACH 2 SHOCK TRAIN IN THE UMDCI

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

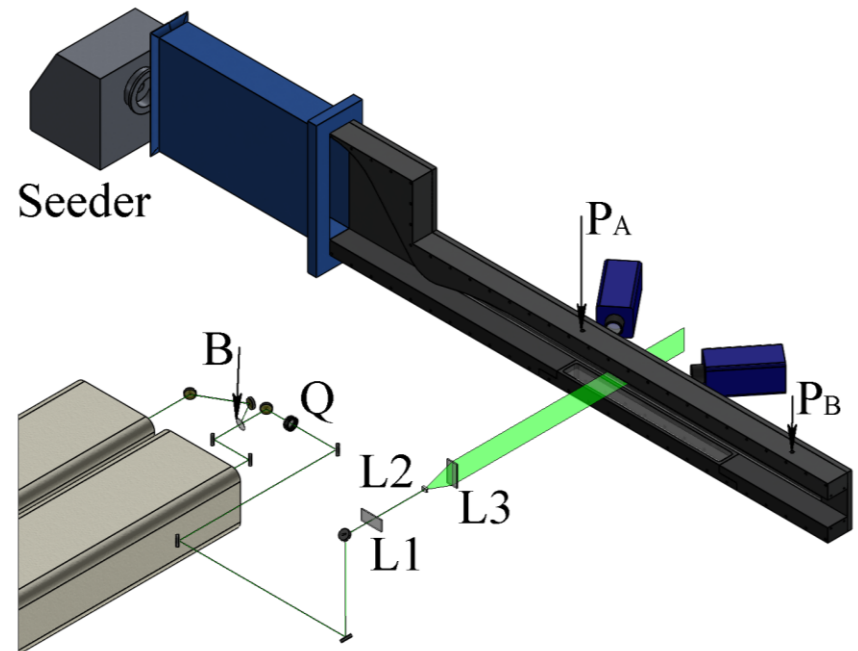
- Side & Bottom Wall Centerlines

3. High-Speed Schlieren Imaging

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

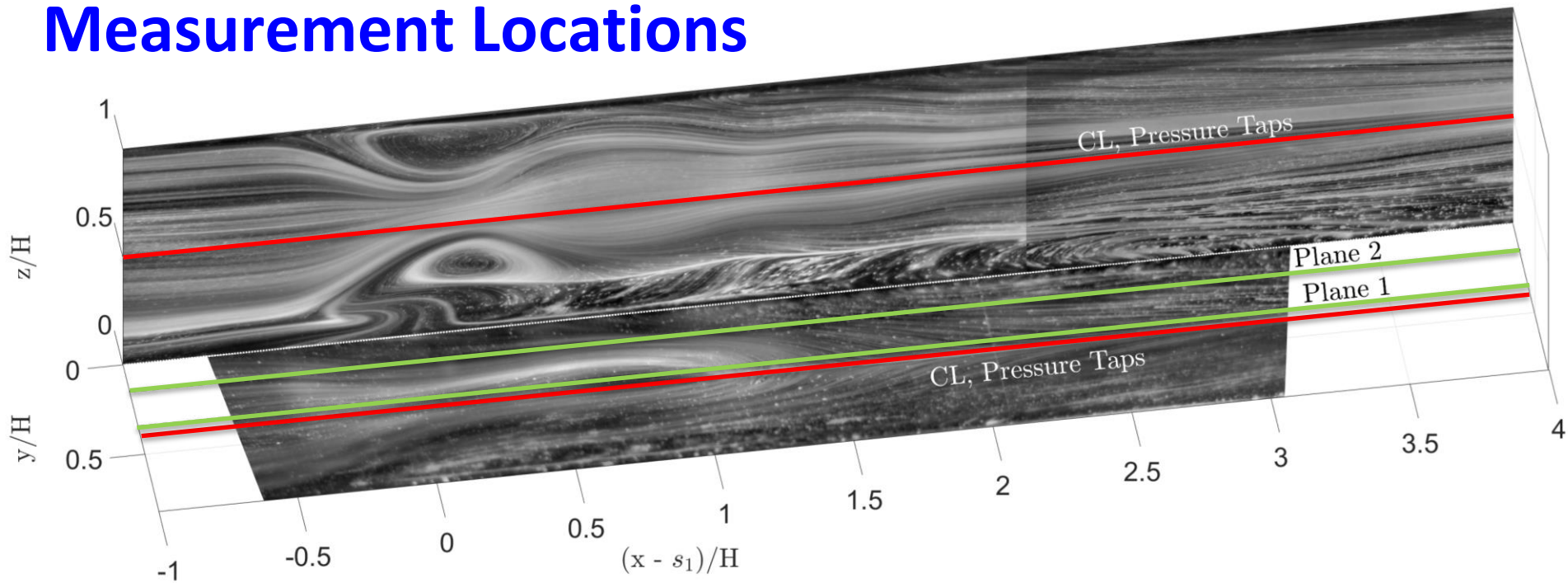
4. Surface Oil Flow Visualization

- 100 cSt Silicone Fluid



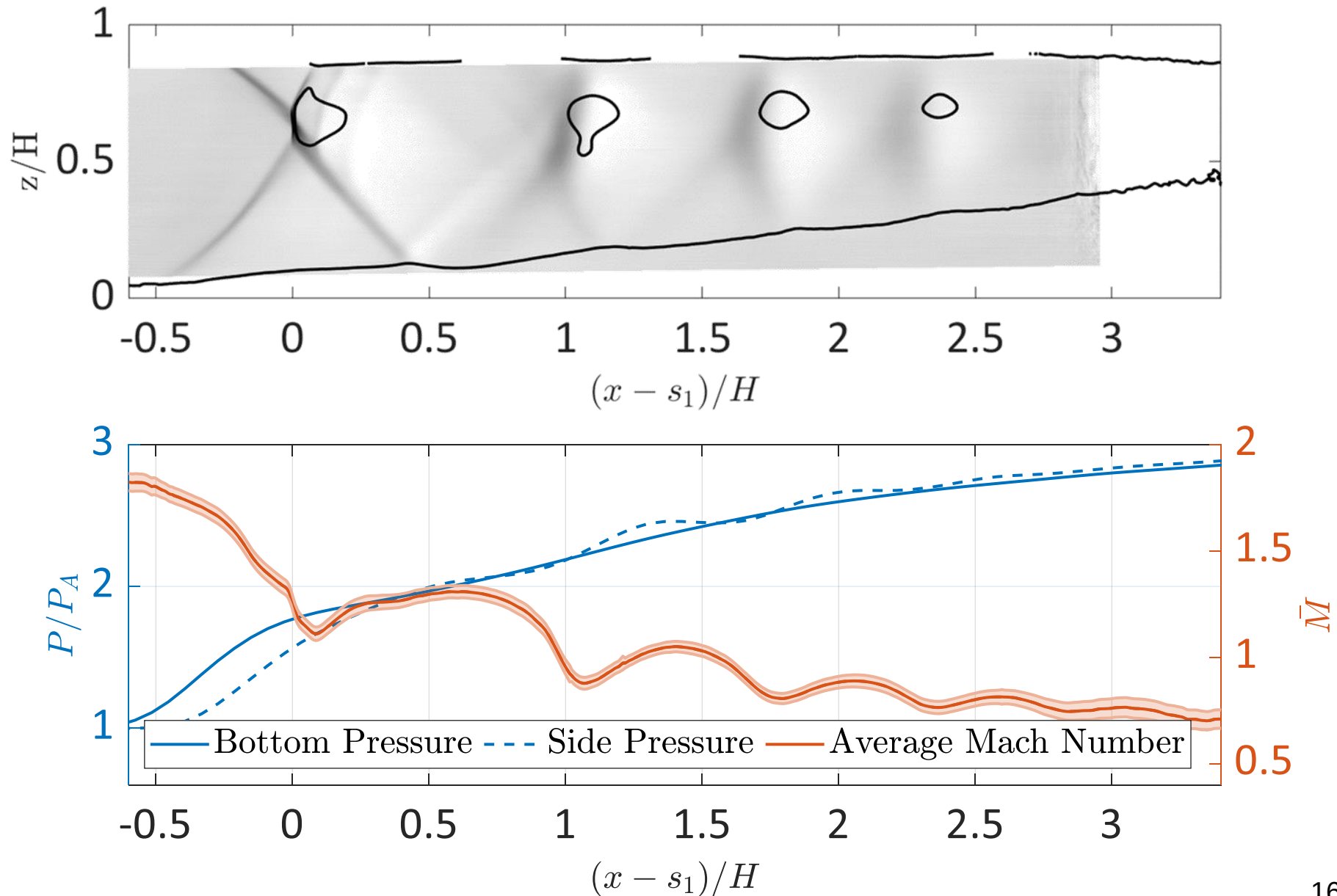
Cross-Sectional Stereo PIV Setup

Measurement Locations

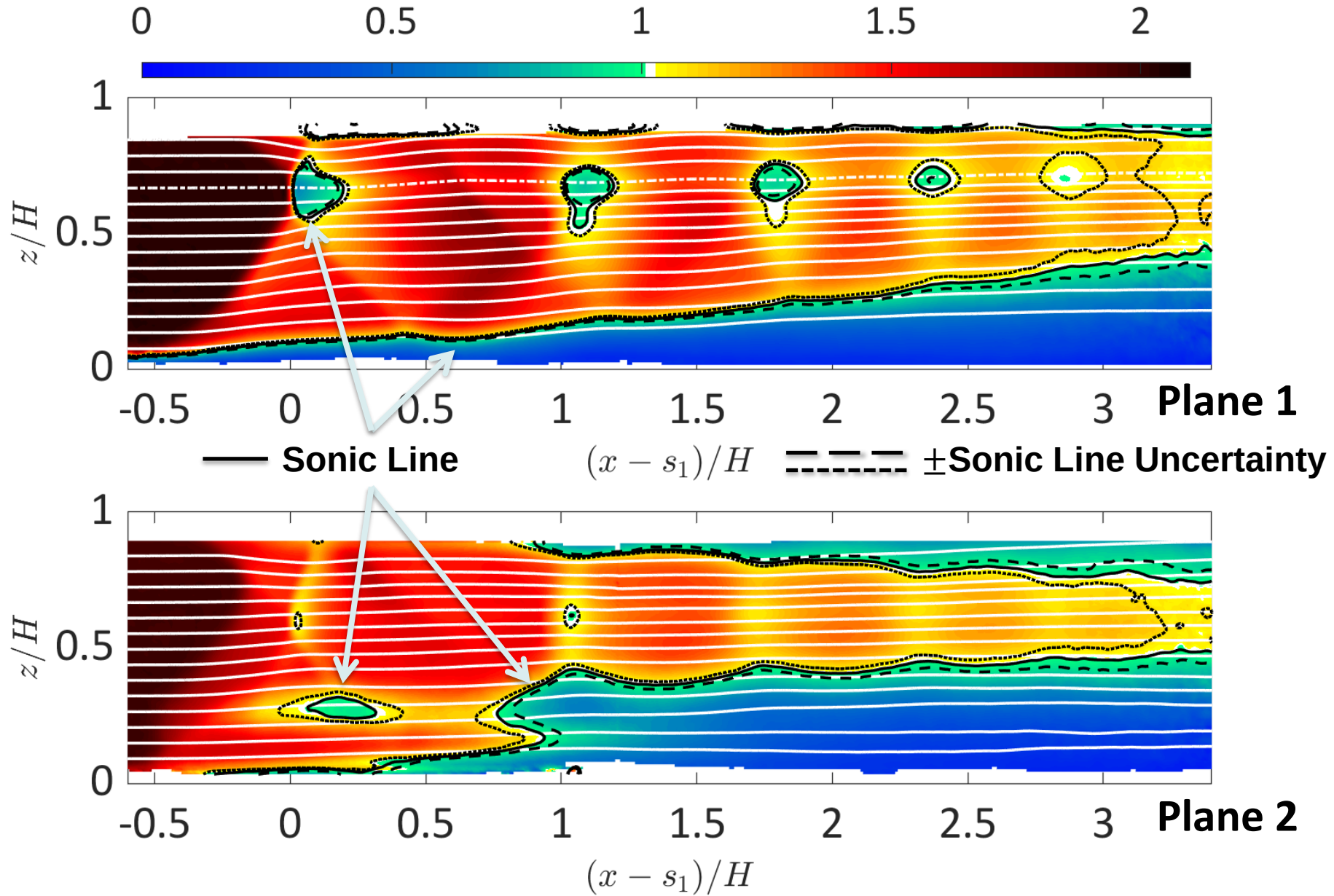


- Wall Pressure Scanners
 - 12.7-25.4 mm pressure port spacing
 - 48 ± 7.2 kPa and 15 ± 103 kPa channels referenced to P_A
- Streamwise 2-Component (u, w) PIV
 - Plane 1: $y = 0.44W = 0.36H$
 - Plane 2: $y = 0.20W = 0.16H$
 - 1200 Samples/Plane
 - 32x32 Gaussian Window yielding 0.63 mm vector field grid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

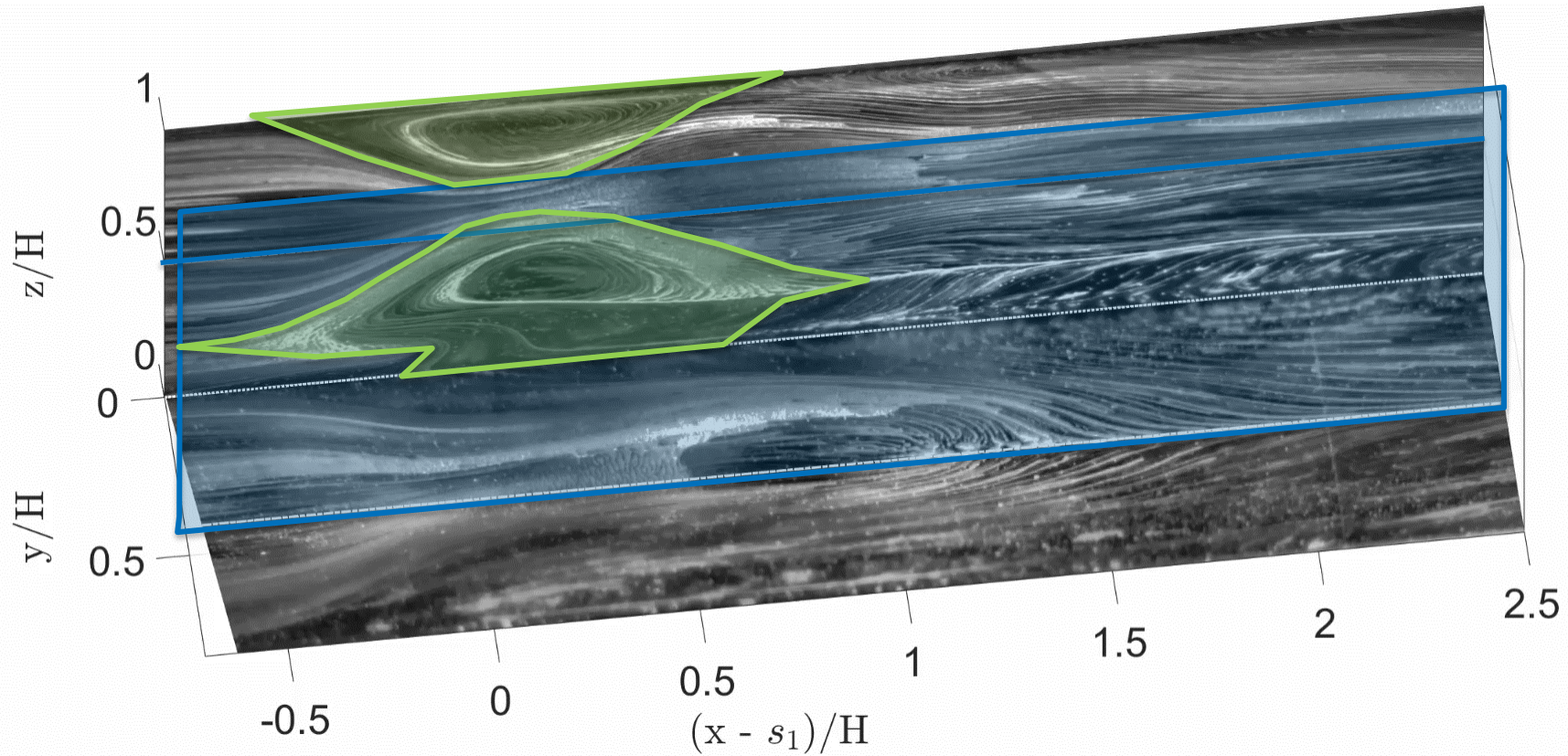
Schlieren & Wall Pressure



Streamwise PIV

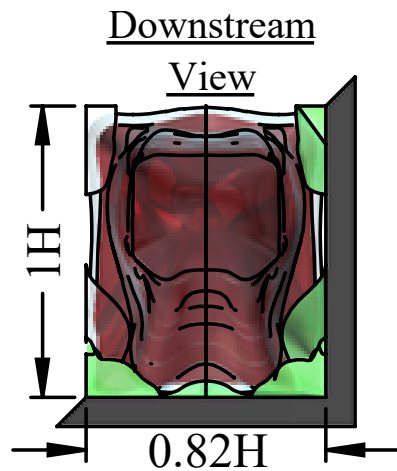
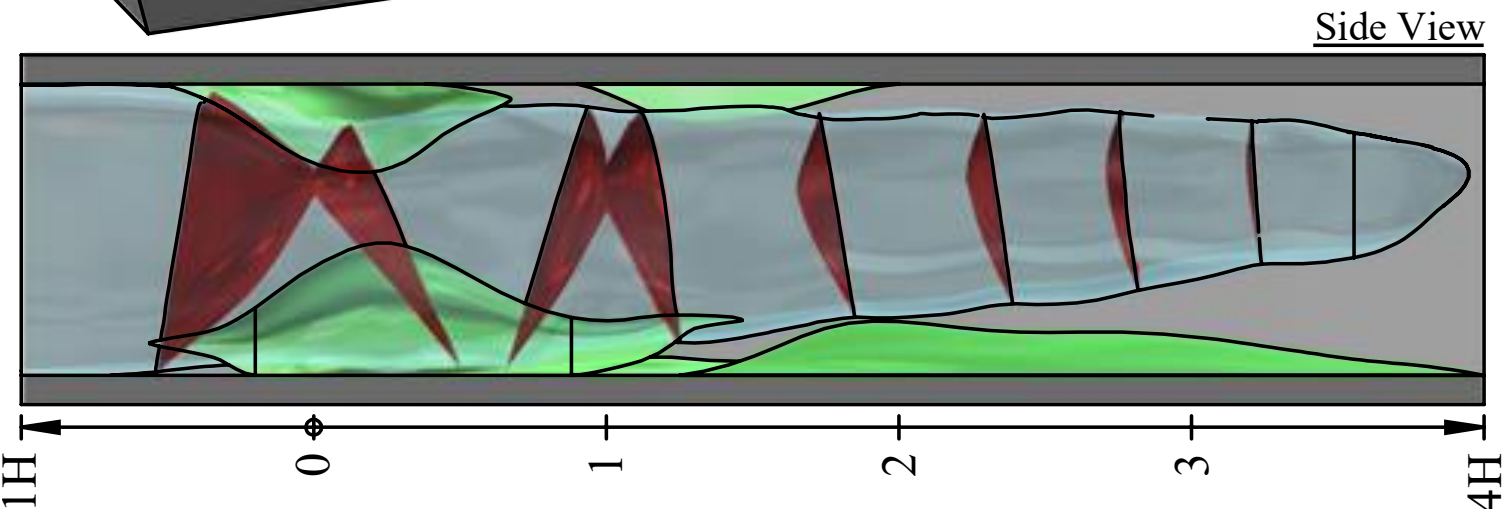
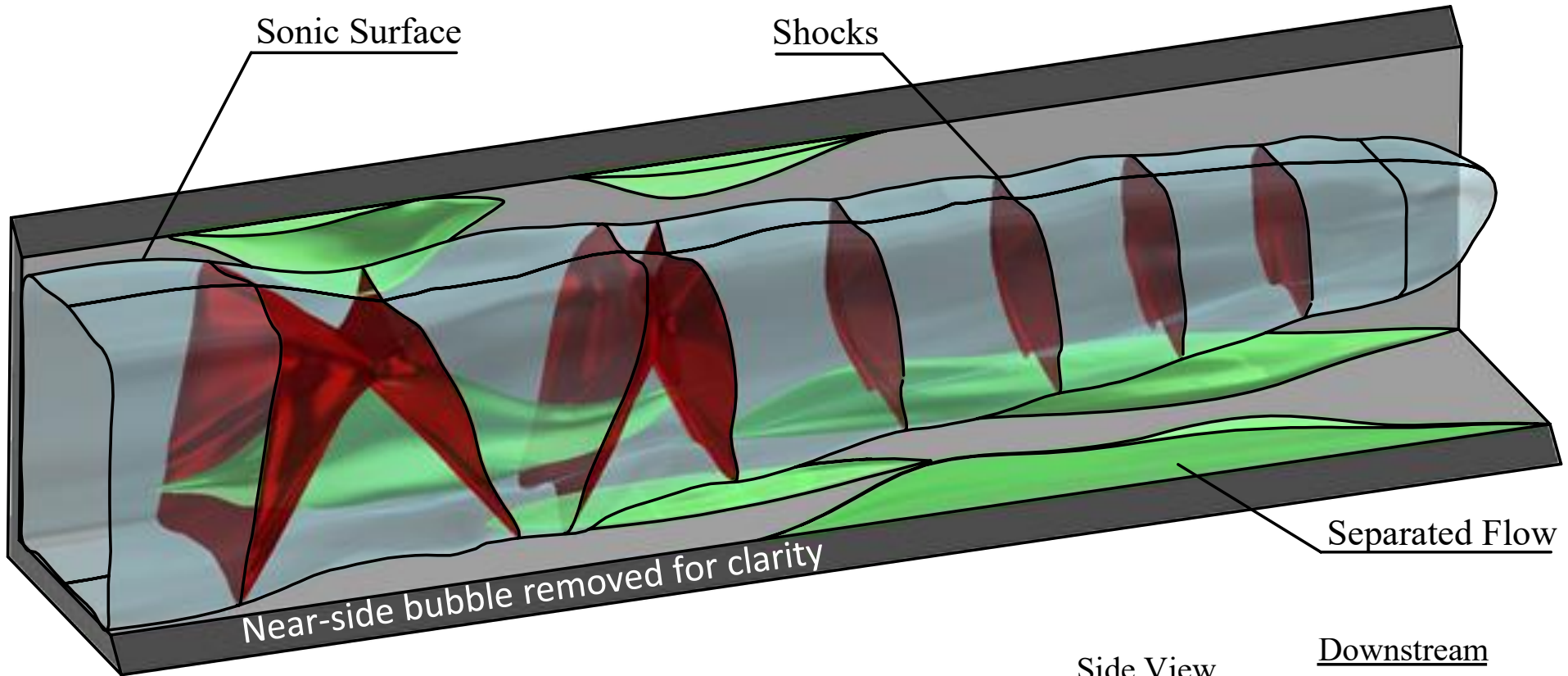


Asymmetry in Leading Separation Bubble Structure

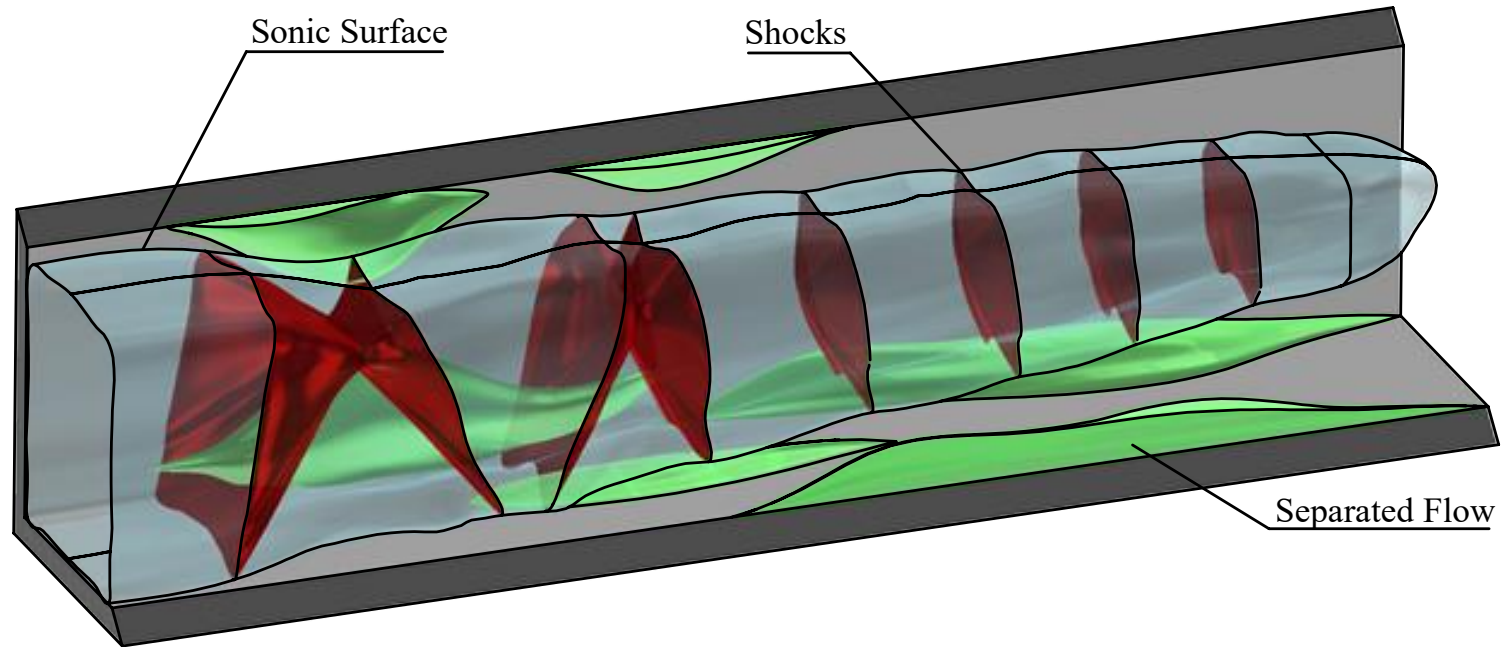


- Laterally Symmetric about the x-z plane
- Vertically asymmetric about the y-z plane
- Top corner separation bubble is bound to the corner and steady
- Bottom corner separation bubble offset from the wall and unsteady

Three-Dimensional Shock Train Structure



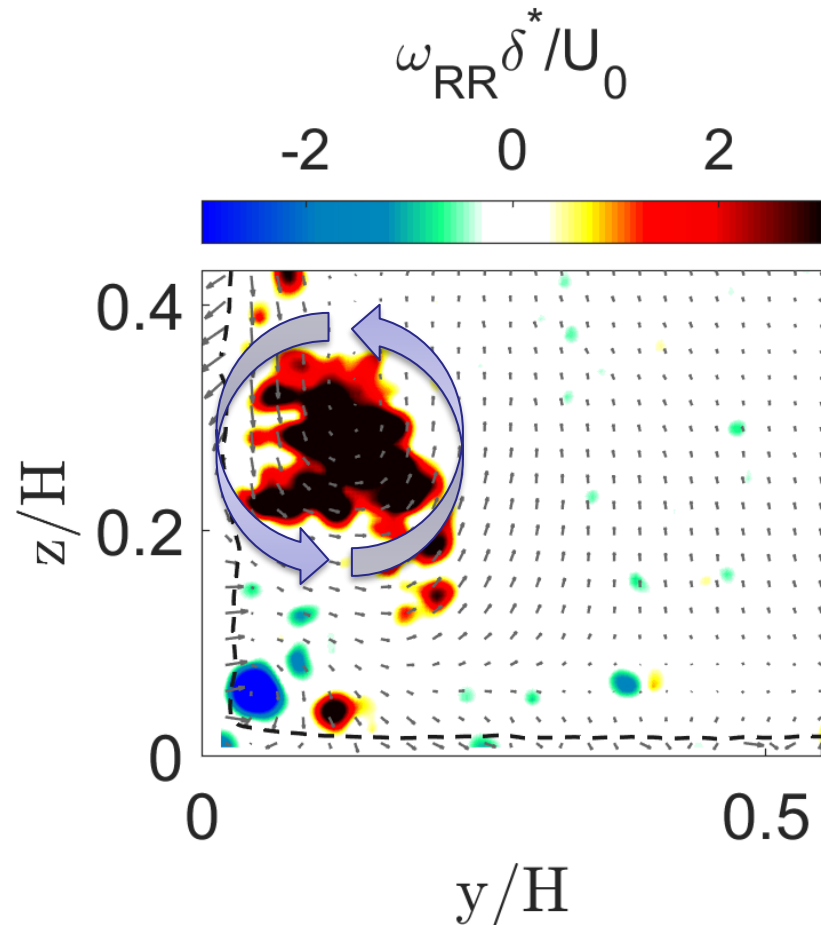
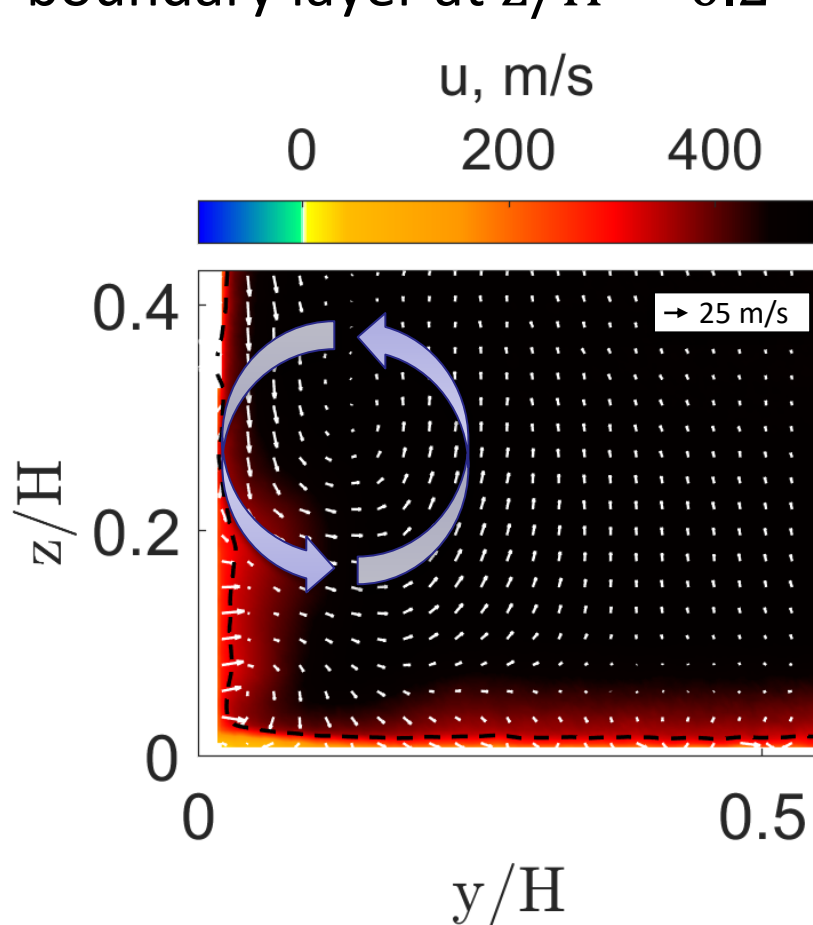
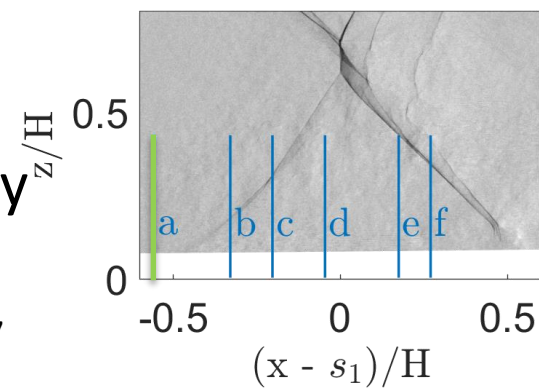
Key Structural Features of the UMDCI Shock Train



- 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)
- Sonic Surface closure inferred from oil and PIV uncertainty

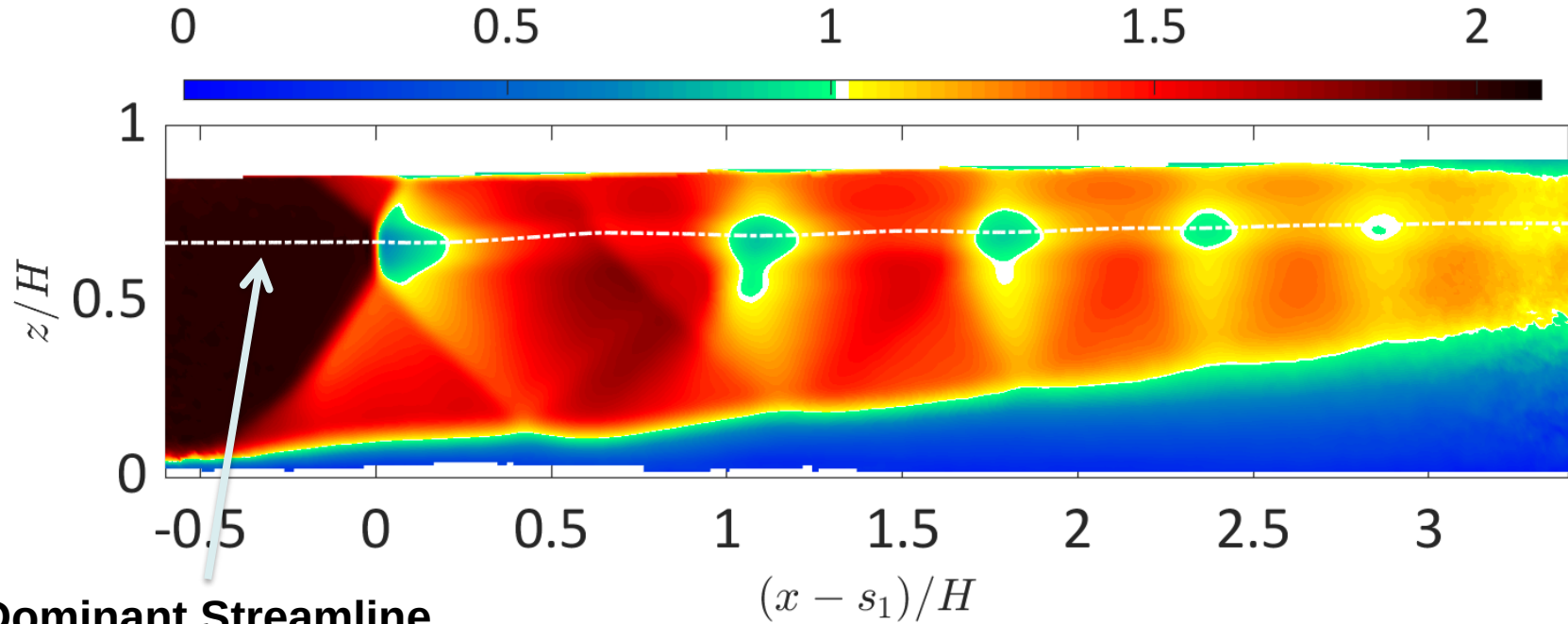
Empty Tunnel Vortex Structure

- 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 $z/H = 0.2$



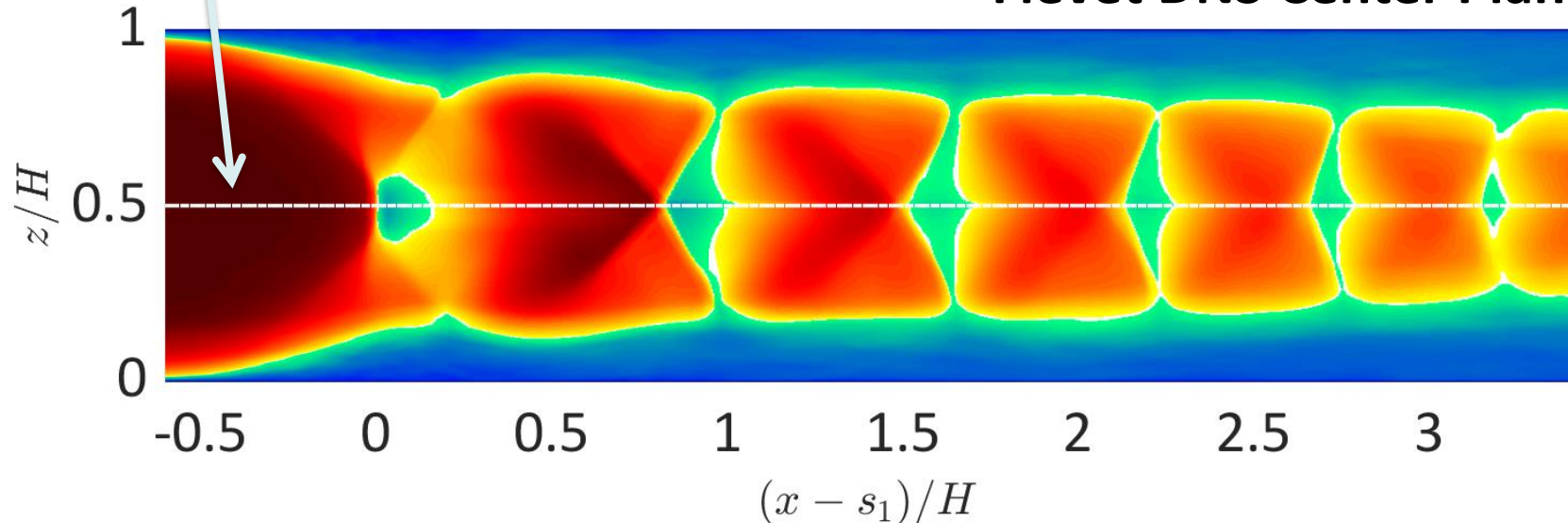
Effect of Asymmetric Core Flow

Plane 1 PIV

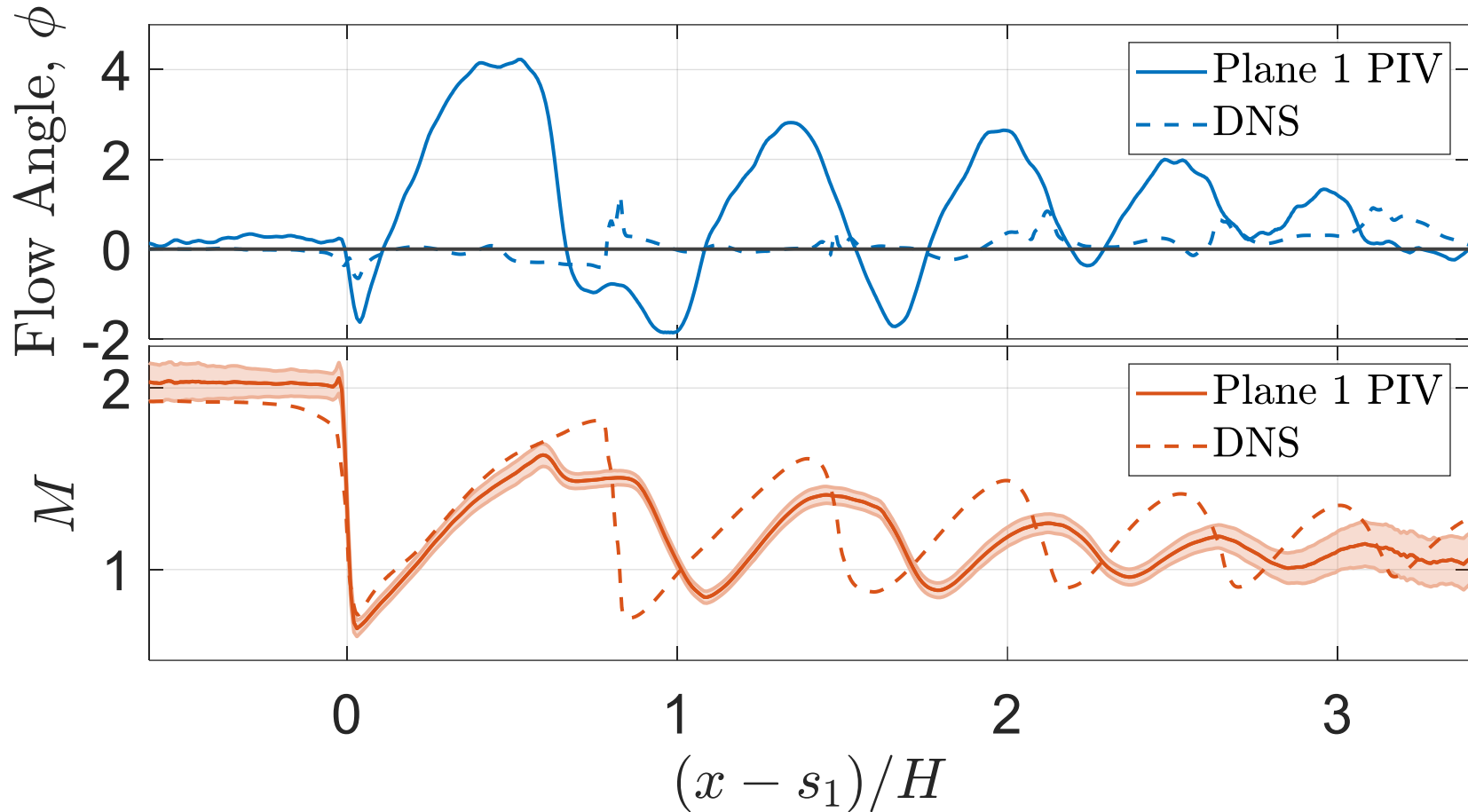


Dominant Streamline

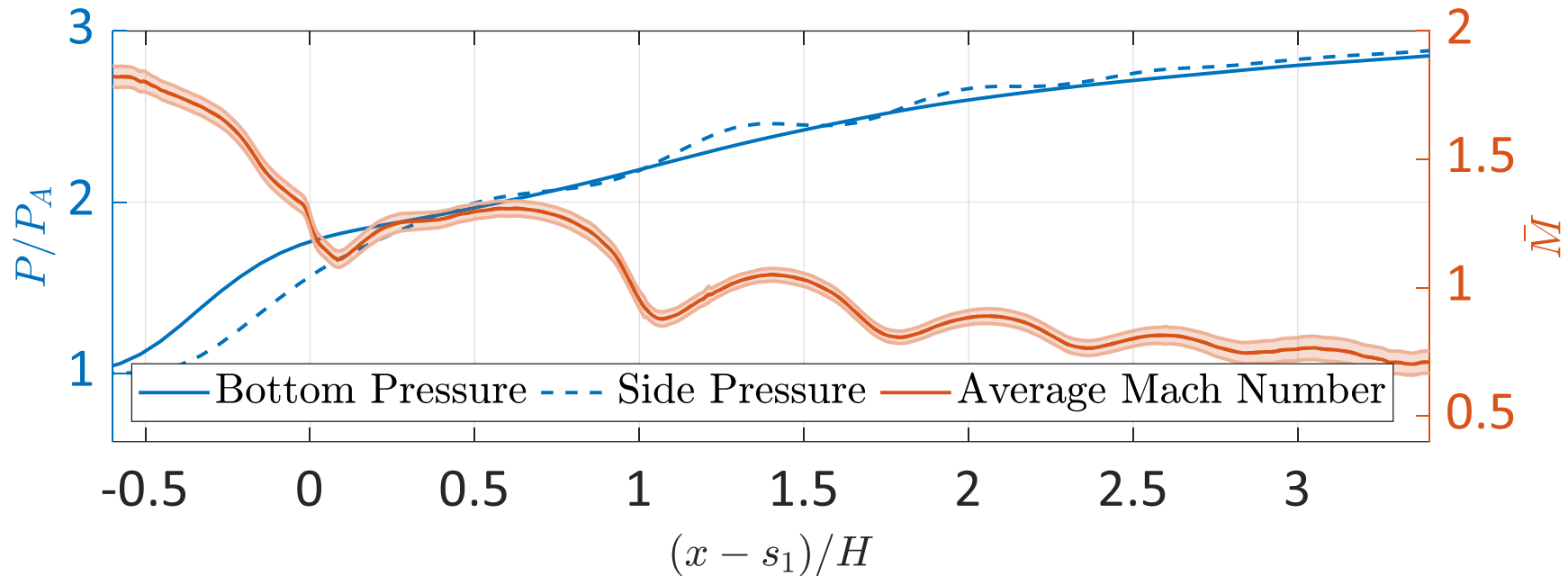
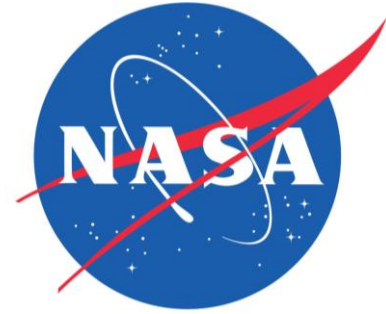
Fiévet DNS Center Plane



Flow Angle Along Core Streamlines



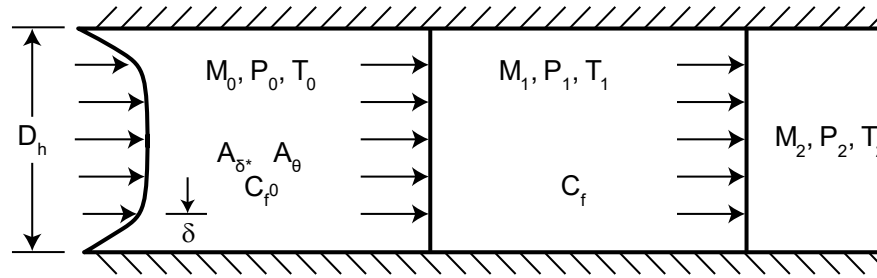
- Flow turning within each shock cell in UMDCl and not the symmetric DNS
 - Resulting net angle of the shock train core: 0.85°
 - Different shock & shock cell expansion strengths
- ➔ Faster drop-off in profile average Mach ➔ Different pressure profiles estimated



REDUCED-ORDER PSEUDO-SHOCK MODELING

Quasi-1D, Quasi-Steady Pseudo-Shock Models

- **Approach Conditions:** The freestream and boundary layer properties entering the pseudo-shock. Computed from CFD of the tunnel without a shock train in it.
 - E.g. Mach Number, Displacement Thickness, Momentum Thickness, Wall Friction Coeff.



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

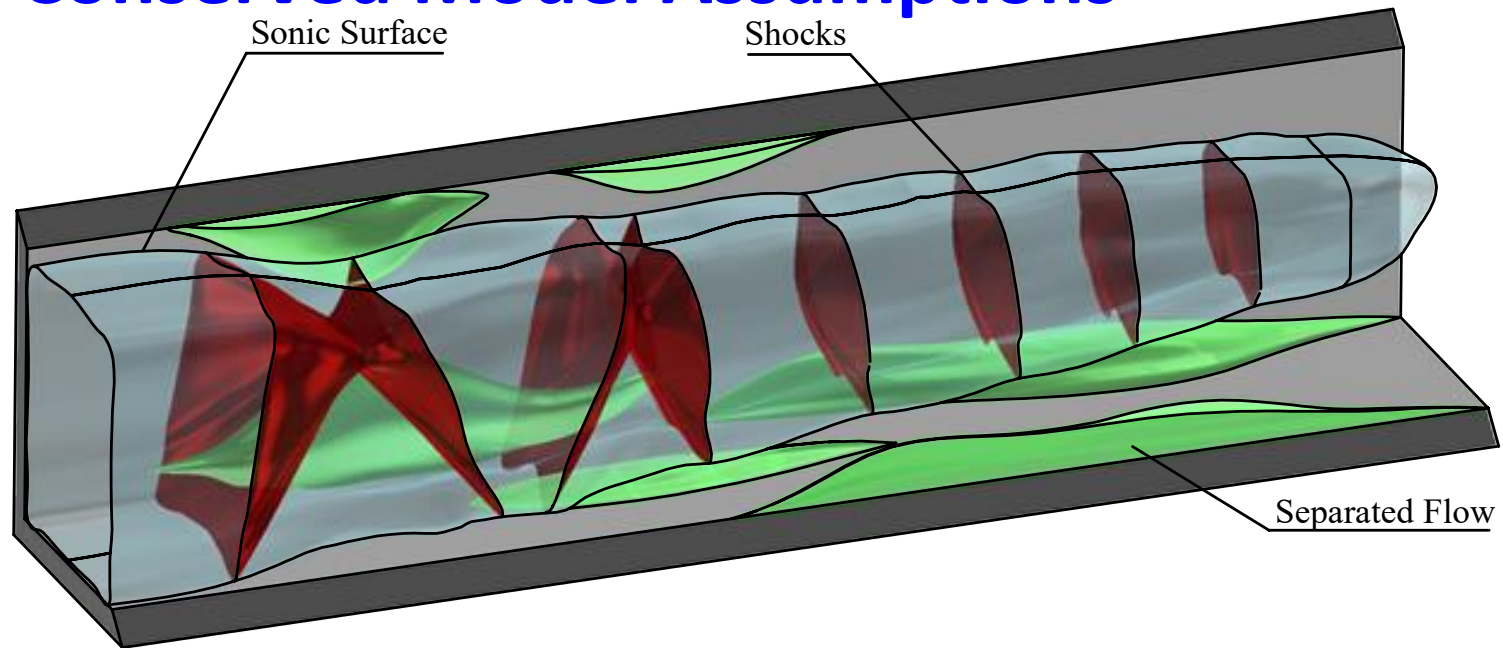
2) **Smart Flux-Conserved Model:** Quasi-1D system of 2 ODE's wrt x

- **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:**

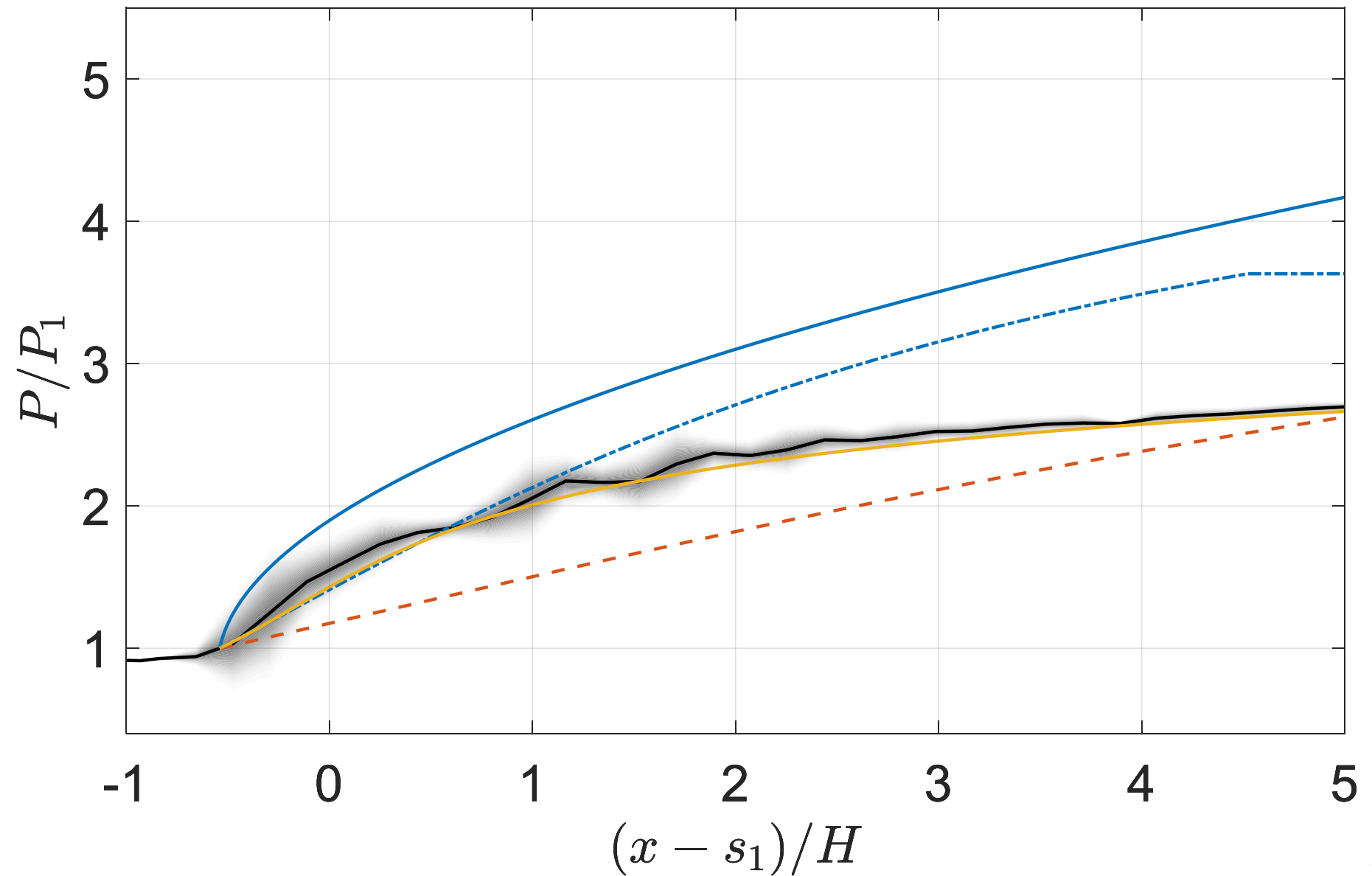
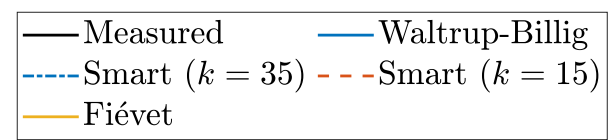
- $$\frac{dP}{dx} = q \frac{k(q, M_1)}{D_h} C_{f0}^\alpha \sigma^\beta; \quad \sigma = \frac{\text{Pseudo-Shock Static Pressure Ratio}}{\text{Equivalent Normal Shock Pressure Ratio}}$$
 - Nine Parameter Model

Flux-Conserved Model Assumptions

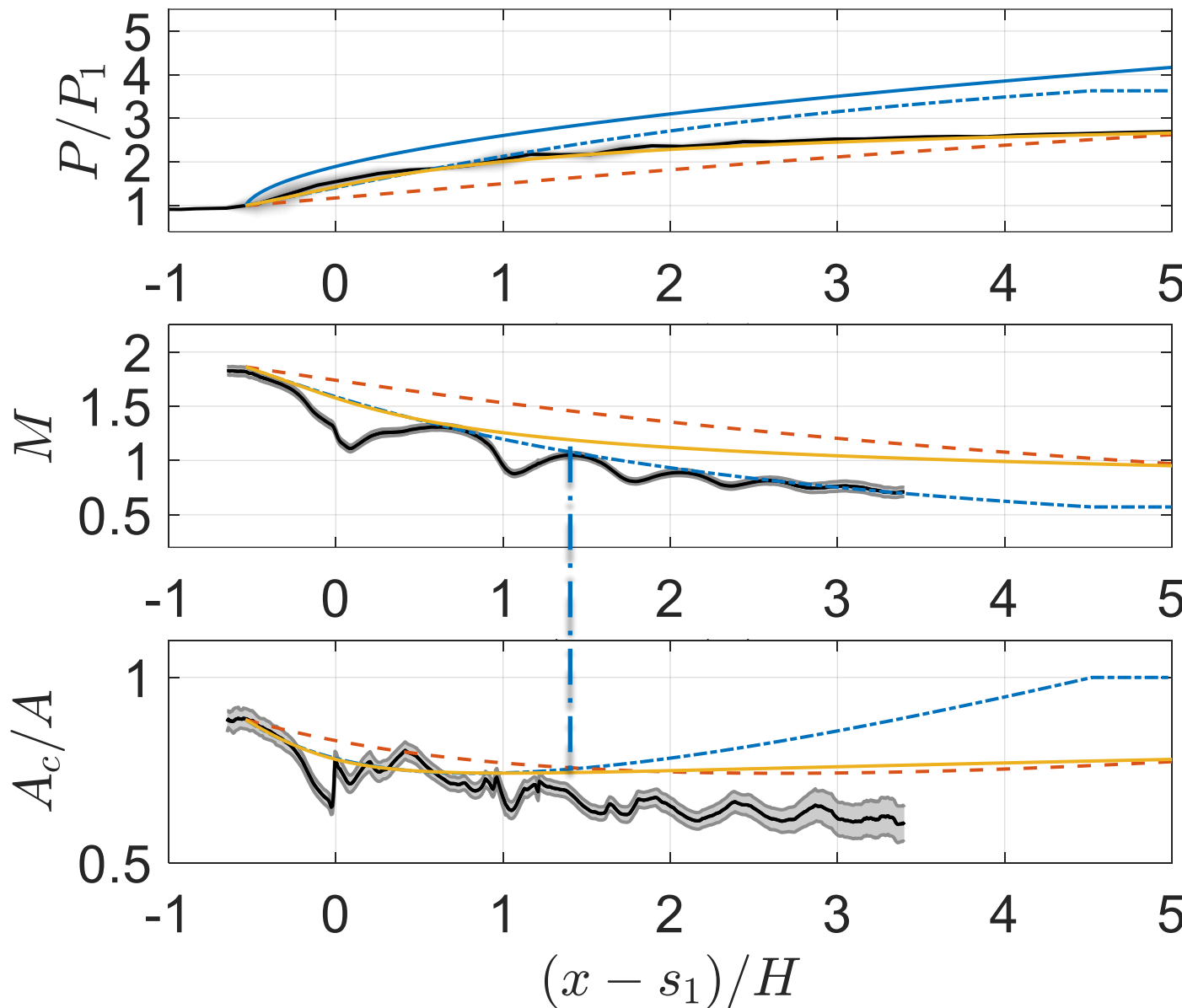
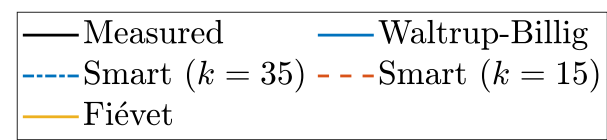


- Separated flow is typically assumed monolithic
 - Wall friction can be neglected
- Mass flow outside the core, $A_c = 1 - A_{\delta^*}$, is negligible
- No transverse momentum accounting
 - $P(y, z) = \text{Constant}, v = w = 0$
- Flow collapses symmetrically to an axisymmetric quasi-1D frame
- Compression due to exchange of kinetic and thermal energy in core

Literature Model Performance: UMDCI Wall Static Pressure Profile



Detailed Model Performance



- **Smart:** Predicts isolator pressure ratio OR initial gradient and Mach number profile. **Not both.**
- **Fiévet:** Optimal pressure prediction, poor prediction of Mach number profile
- All depart A_c at sonic
- **Compression source linking A_c, M, P is missing from these models**

Proposed Process Driven Flux-Conserved Model

- Flux-Conserved ODE Equations (Smart 2015)

Momentum Equation:

$$\frac{dM^2}{M^2} = - \left(1 + \frac{\gamma-1}{2} M^2 \right) \left(\frac{2}{\gamma M^2} \frac{A}{A_c} \frac{dP}{P} + \frac{A}{A_c} \frac{4C_f dx}{D_H} + \frac{dT_t}{T_t} \right)$$

Continuity:

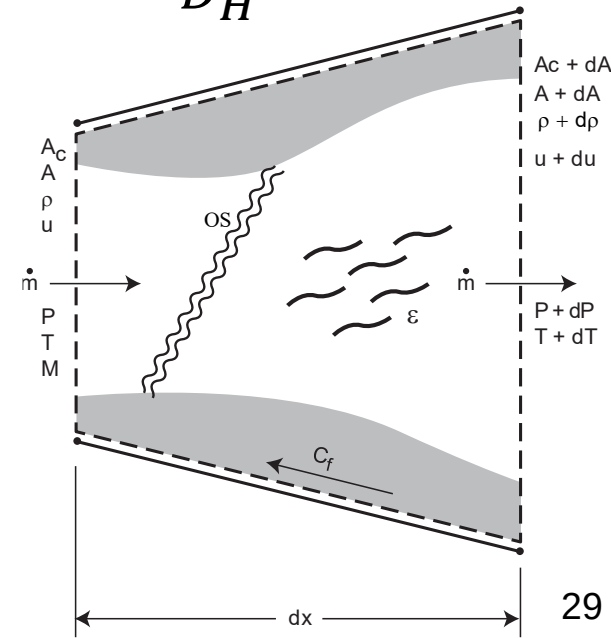
$$\frac{d(A_c/A)}{A_c/A} = \frac{1-M^2(1-\gamma(1-A_c/A))}{\gamma M^2 (A_c/A)} \frac{dP}{P} + \frac{1+(\gamma-1)M^2}{2(A_c/A)} 4C_f \frac{dx}{D_H} +$$

$$\left(1 + \frac{\gamma-1}{2} M^2 \right) \frac{dT_t}{T_t}$$

Energy:

$$\frac{dT_t}{T_t} = \frac{dQ + dH_r}{C_p T} = 0 \text{ (Adiabatic, No Combustion)}$$

Wall Friction Parameter: $C_f = \alpha C_{f_0}$



Process Driven Closure Model: Oblique Shocks

$$\frac{dP}{P} = \left[\frac{dP}{P} \right]_{OS} + \left[\frac{dP}{P} \right]_{\epsilon}$$

$$\left[\frac{dP}{P} \right]_{OS} = \left[\frac{2\gamma M^2 \sin^2(\theta_{OS}) - (\gamma - 1)}{\gamma + 1} - 1 \right] \frac{dx}{D_H}$$

$$\sin^2(\theta_{OS}) =$$

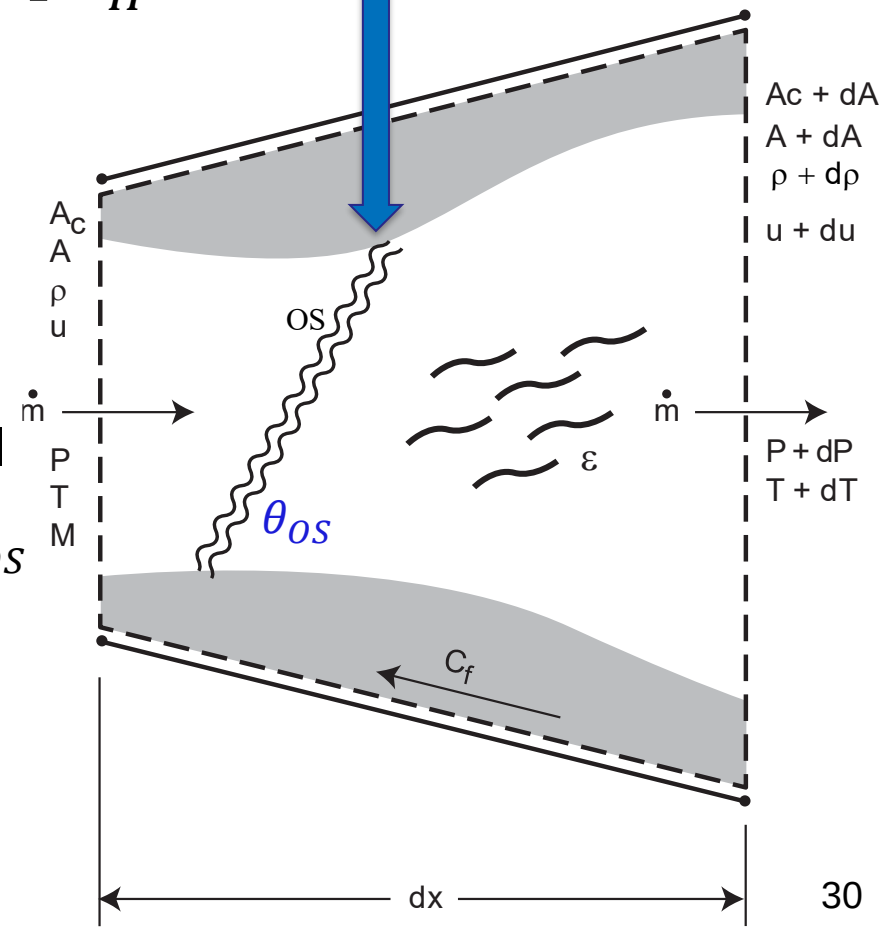
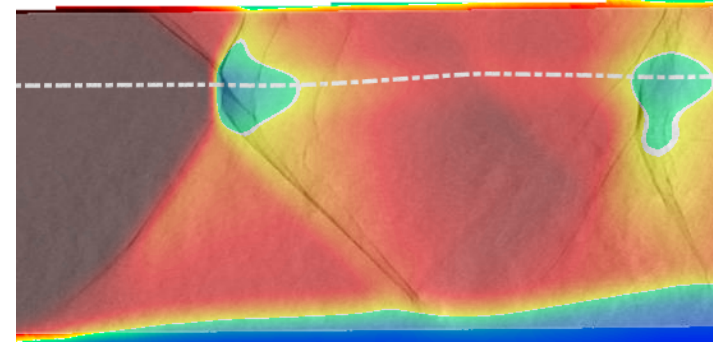
$$\beta \sigma \mathcal{S} \left(1 - \frac{1}{M^2} \right) + \frac{1}{M^2}$$

Normal & oblique shocks average to a level
a single equivalent oblique integration at θ_{OS}

β = Oblique Shock Skewness Parameter

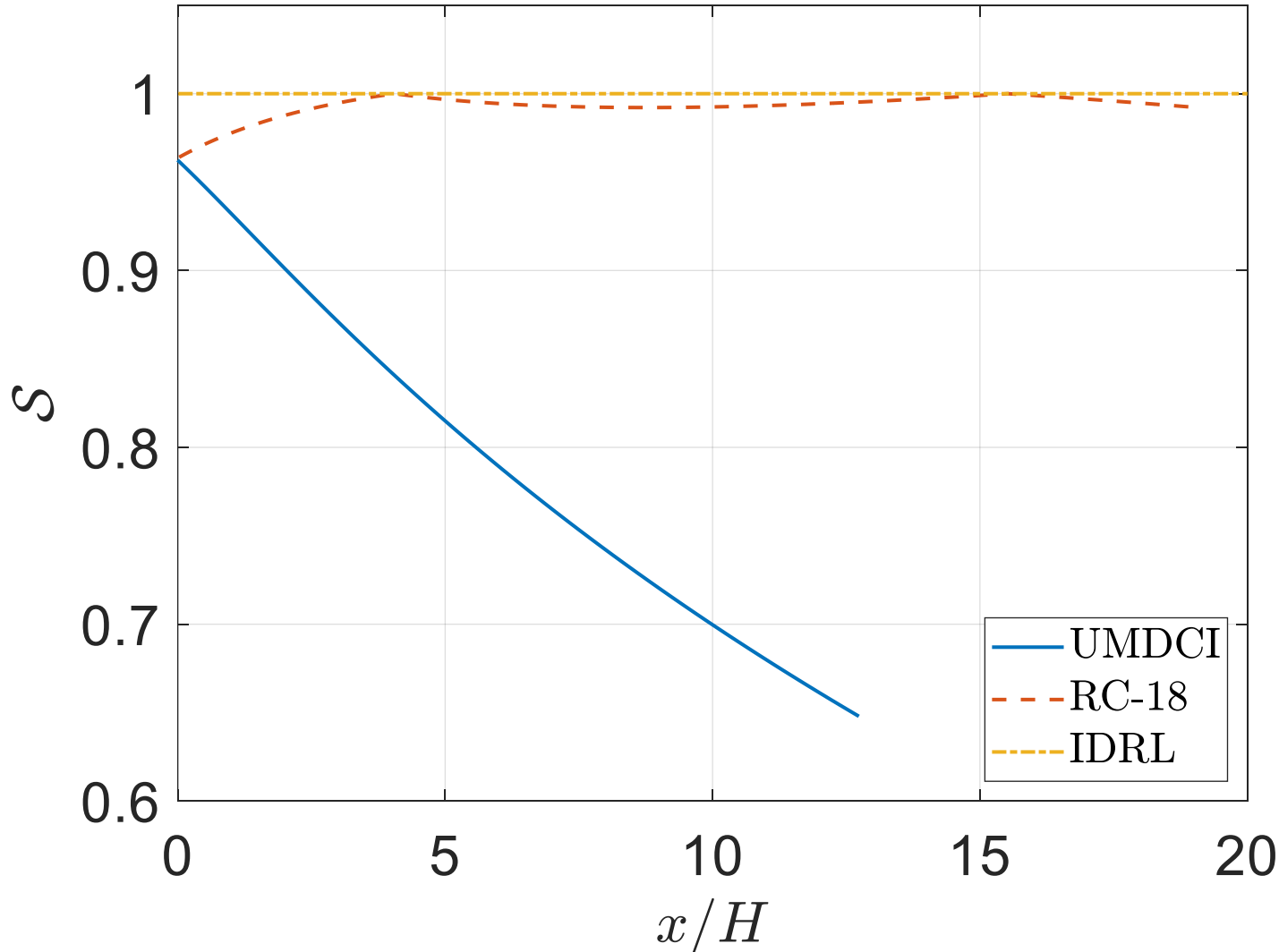
σ = $\frac{\text{Pseudo-Shock Static Pressure Ratio}}{\text{Equivalent Normal Shock Pressure Ratio}}$

$\mathcal{S}$ = Boundary Layer Asymmetry Parameter



Boundary Layer Symmetry Approach Condition

Symmetry Parameter: $\mathcal{S} = \langle \left(1 - \left|\frac{\theta_b}{\theta_c} - 1\right|\right), \left(1 - \left|\frac{\theta_c}{\theta_b} - 1\right|\right) \rangle$



Closure Model: Turbulent Dissipation

$$\frac{dP}{P} = \left[\frac{dP}{P} \right]_{OS} + \left[\frac{dP}{P} \right]_{\epsilon}$$

$$\left[\frac{dP}{P} \right]_{\epsilon} = \frac{\mu \epsilon}{\gamma R T P M^2} \frac{dx}{D_H}$$

$$\epsilon = \frac{\mu^3}{\rho^3 l_t^4}$$

Dissipation Controlled
at Kolmogorov Scale

$$l_t = \frac{\Gamma D_c}{s} \text{Re}_{D_c}^{-\Omega}$$

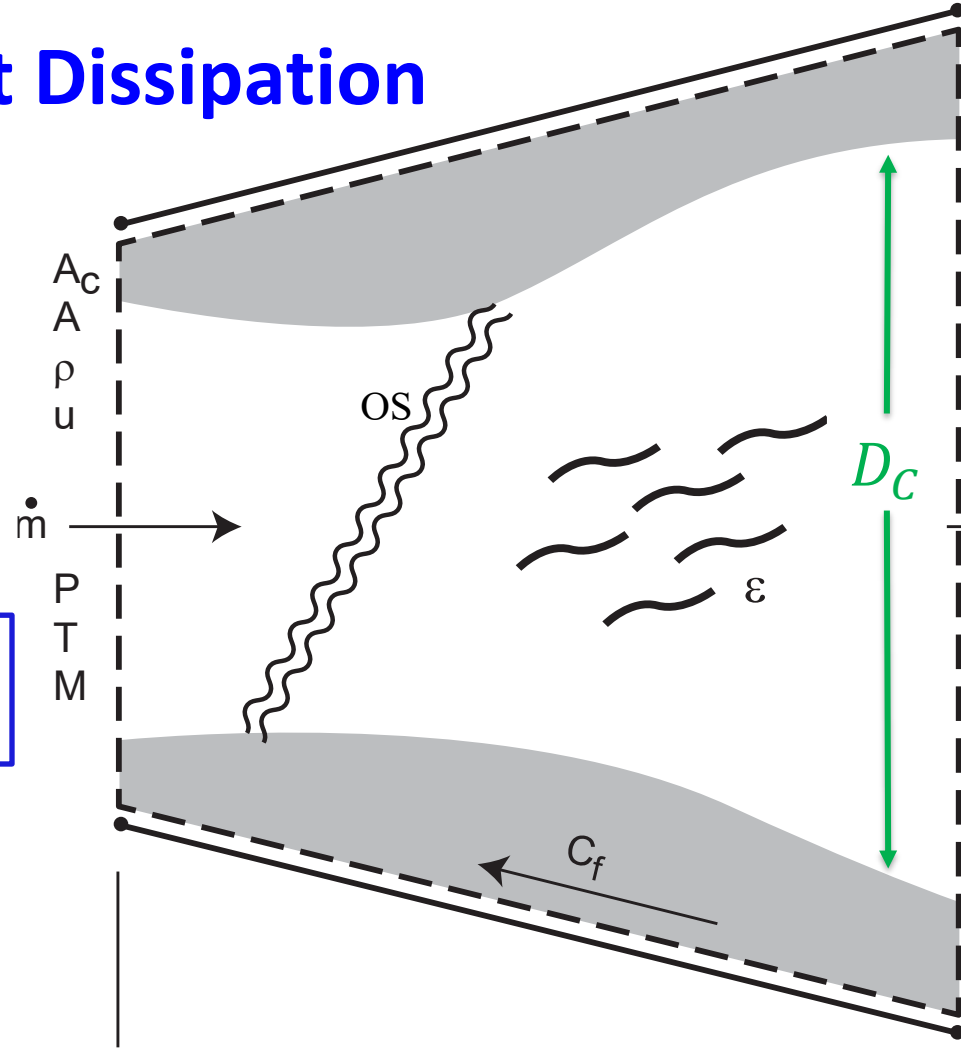
$$\text{Re}_{D_c} = \frac{\rho u D_c}{\mu}$$

$$D_c = \sqrt{\frac{4}{\pi} \frac{A_c}{A}} A$$

Γ = Dissipative Length Scale Ratio to D_c

Ω = Dissipative Scaling Power

$\Omega = 3/4$ For Homogenous Isotropic Turbulence

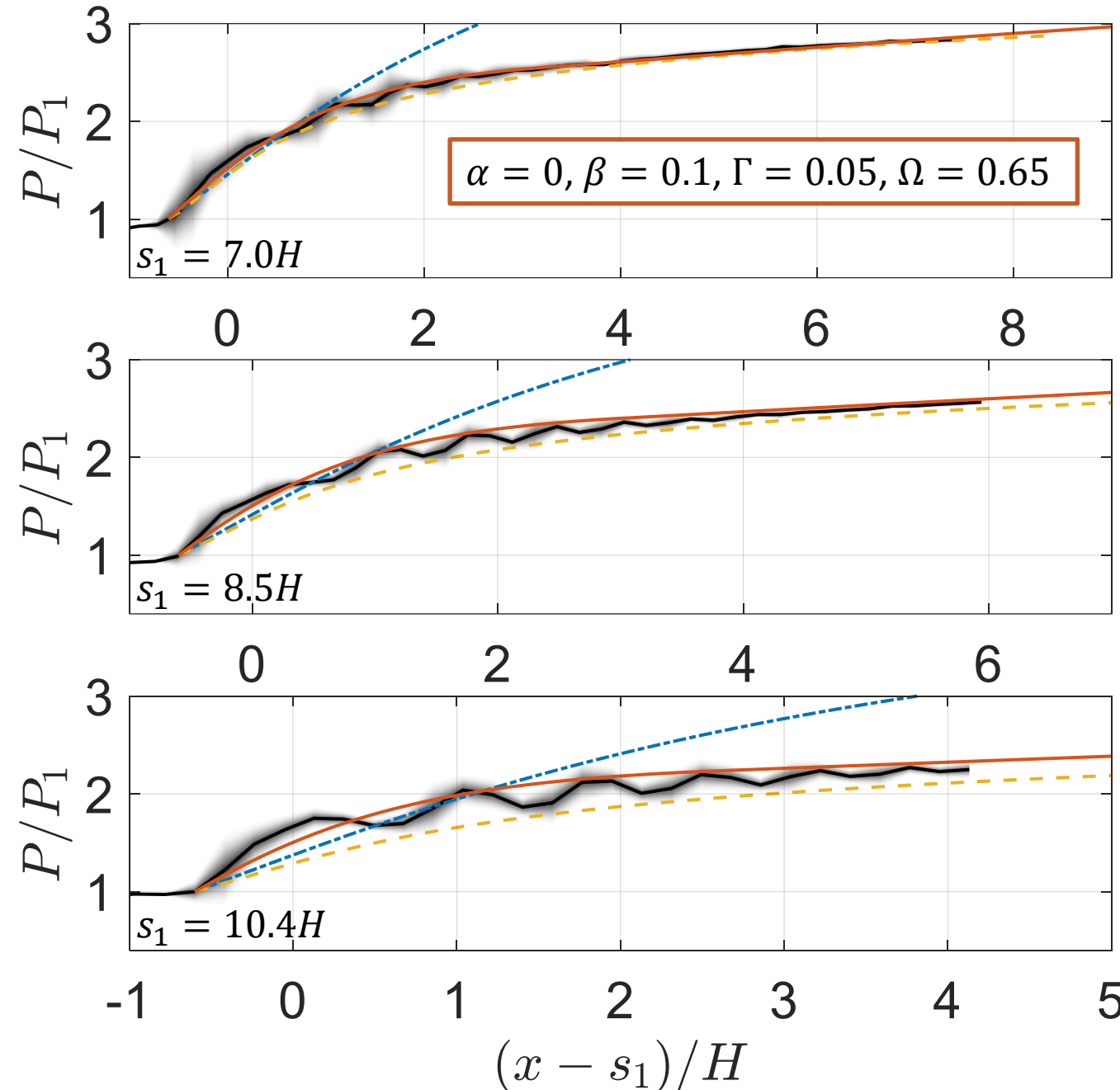


Process Driven Flux-Conserved Model Parameters

- $C_f = \alpha C_{f_0}$
- $\sin^2(\theta_{OS}) = \beta \sigma \mathcal{S} \left(1 - \frac{1}{M^2} \right) + \frac{1}{M^2}$
- $l_t = \frac{\Gamma_{DC}}{\mathcal{S}} \text{Re}_{DC}^{-\Omega}$
- α = Wall Friction Scaling Parameter
- β = Obliqueness Parameter
- Γ = Dissipation Length Scale Proportionality Parameter
- Ω = Dissipation Length Scale Reynolds Number Power
- Each of the four parameters has a precise, physically grounded meaning that relates the 3D flow structure to the quasi-1D integration form.

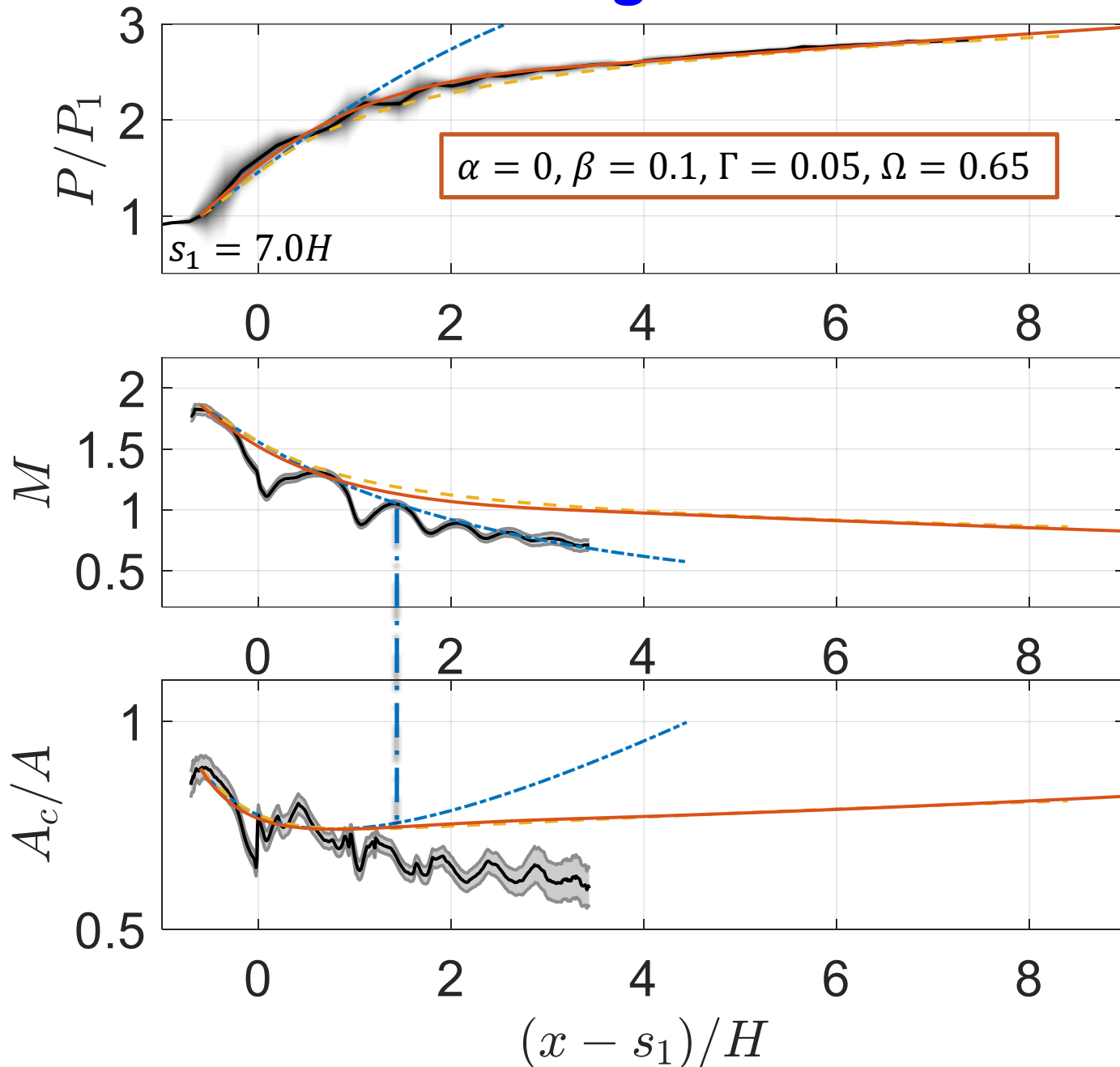
Process Driven Model: UMDCI

— Measured - - - Smart ($k = 35$)
 - - - Fiévet — Process Driven



- **Smart:** Does not perform.
- **Fiévet:** Nine parameters optimize well but fitment falls off at higher s_1 .
- **Process:** Consistently predicts monotonic pressure profile in the same region of the uncertainty band.

Flux-Conserved Integral Parameters

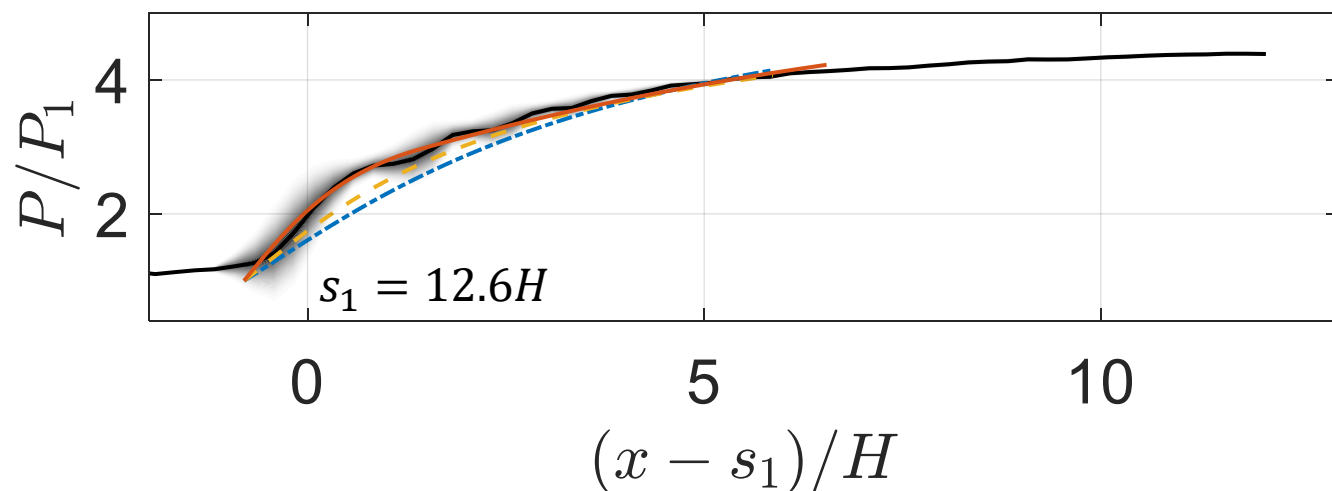
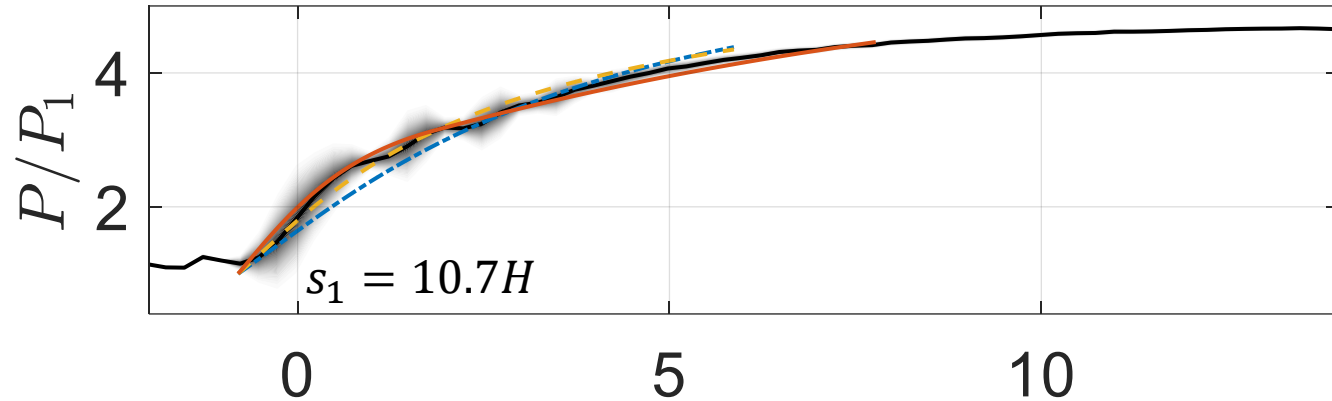
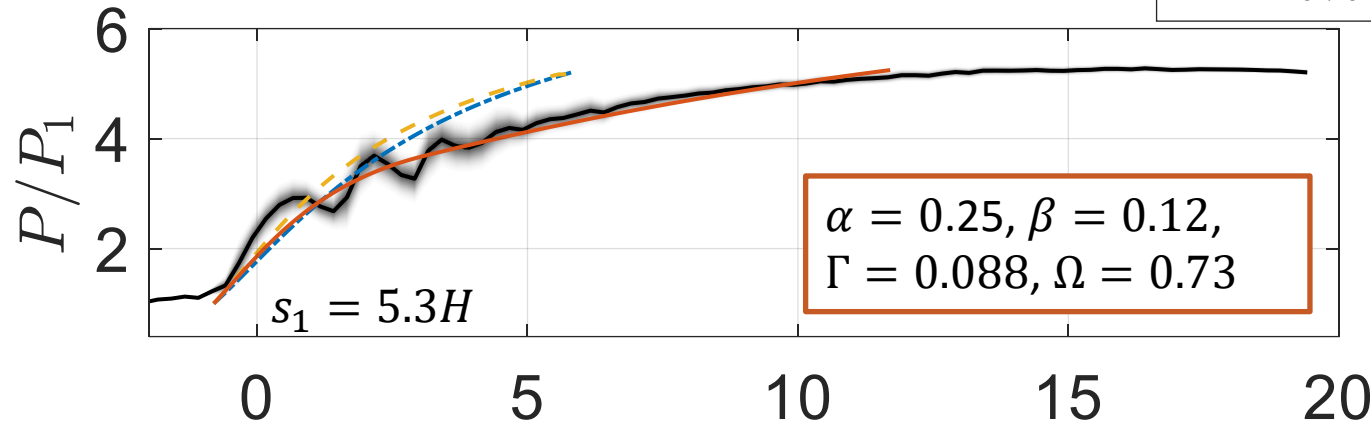


— Measured - - - Smart ($k = 35$)
 - - - Fiévet — Process Driven

- $\alpha = 0$ is optimal even though separation is not monolithic in UMDCI.
- **Fiévet** and **Process** models give identical predictions, but **Process** is only 4 parameters
- **Process** still departs A_c as $M \rightarrow 1$
 - Still some physics missing

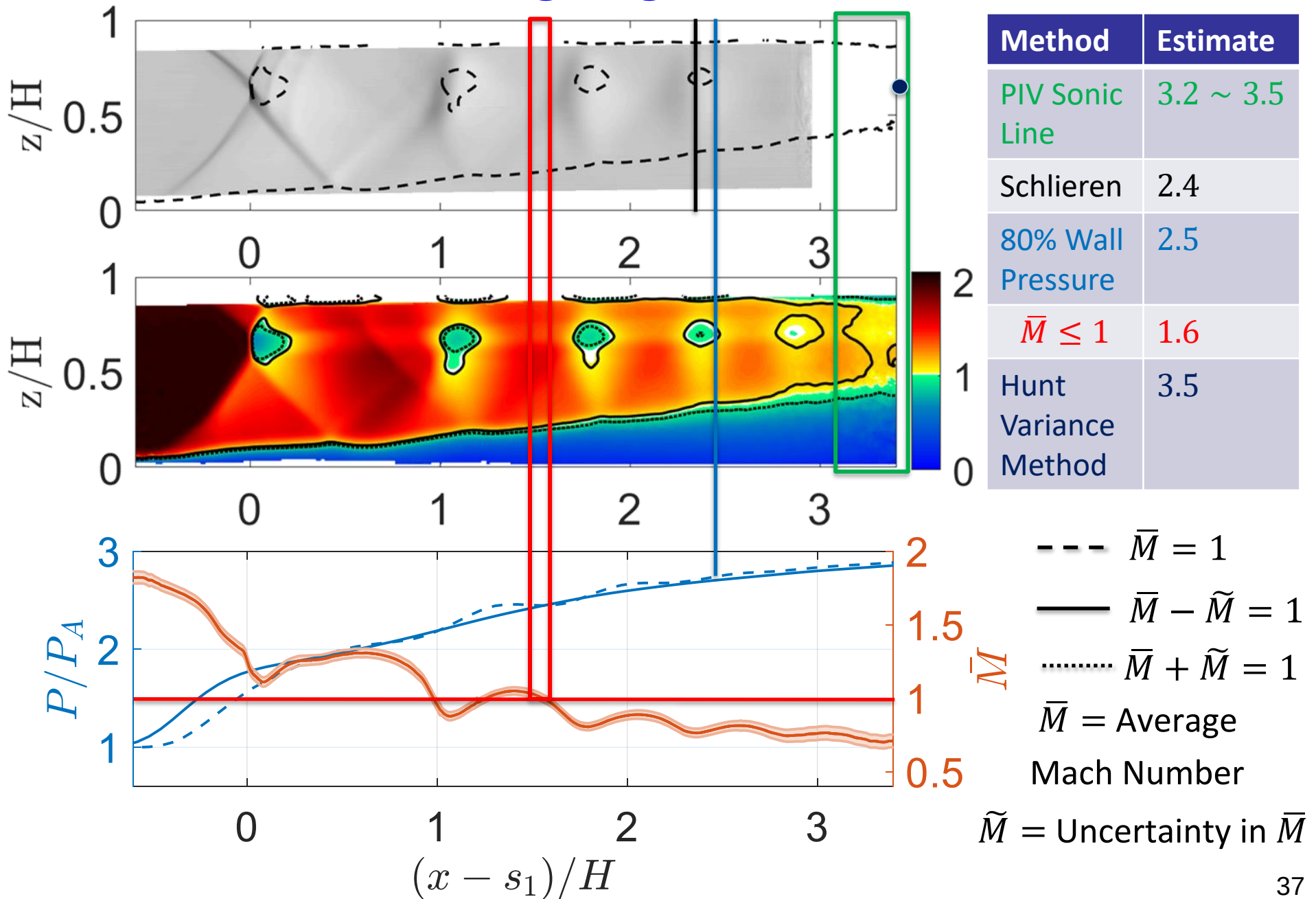
Process Driven Model: IDRL

— Measured - - - Smart ($k = 25$)
 - - - Fiévet — Process Driven

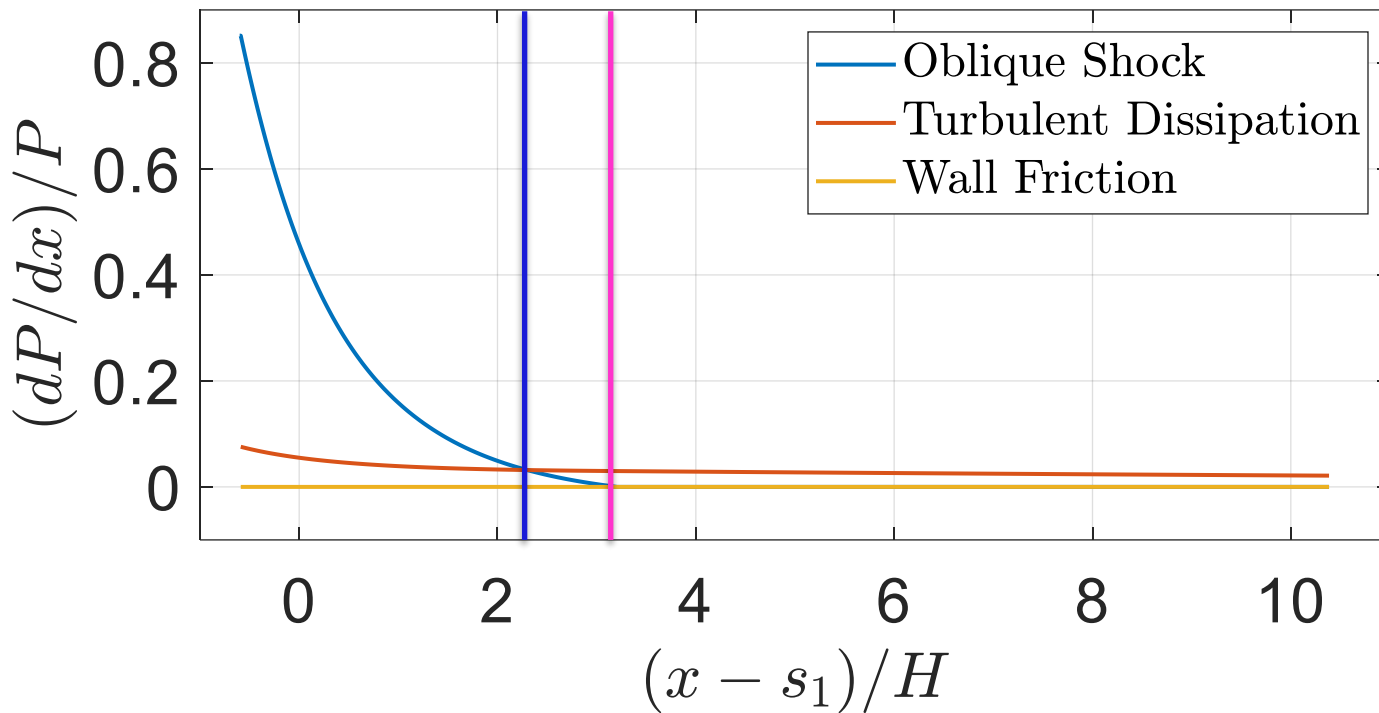


- $\alpha \neq 0$ is optimal
- Integration terminates at $\frac{A_c}{A} = 1$
- Predictions up to just short of maximum streamwise pressure.
- **Process** model performs best, however, still struggles at high pressure ratio cases like IDRL

Shock Train to Mixing Region Transition

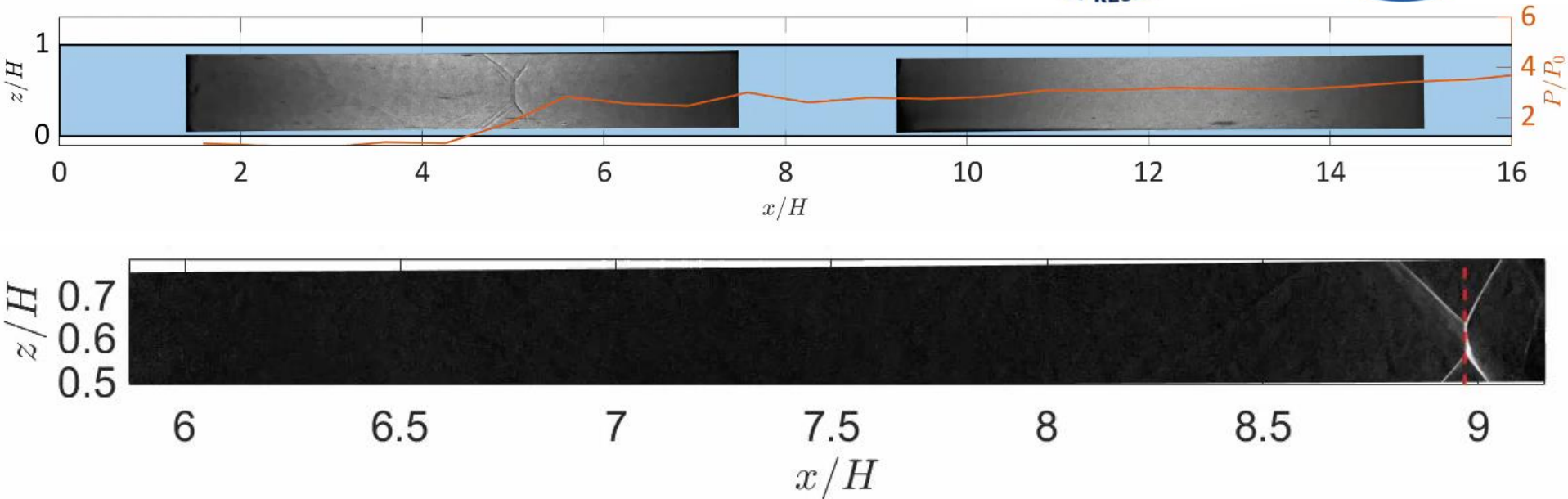
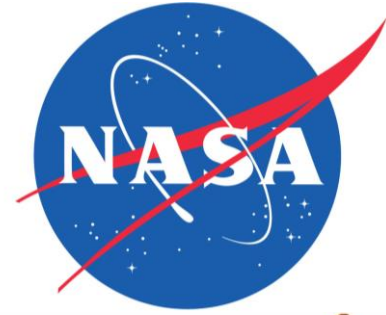


Shock Train to Mixing Region Transition



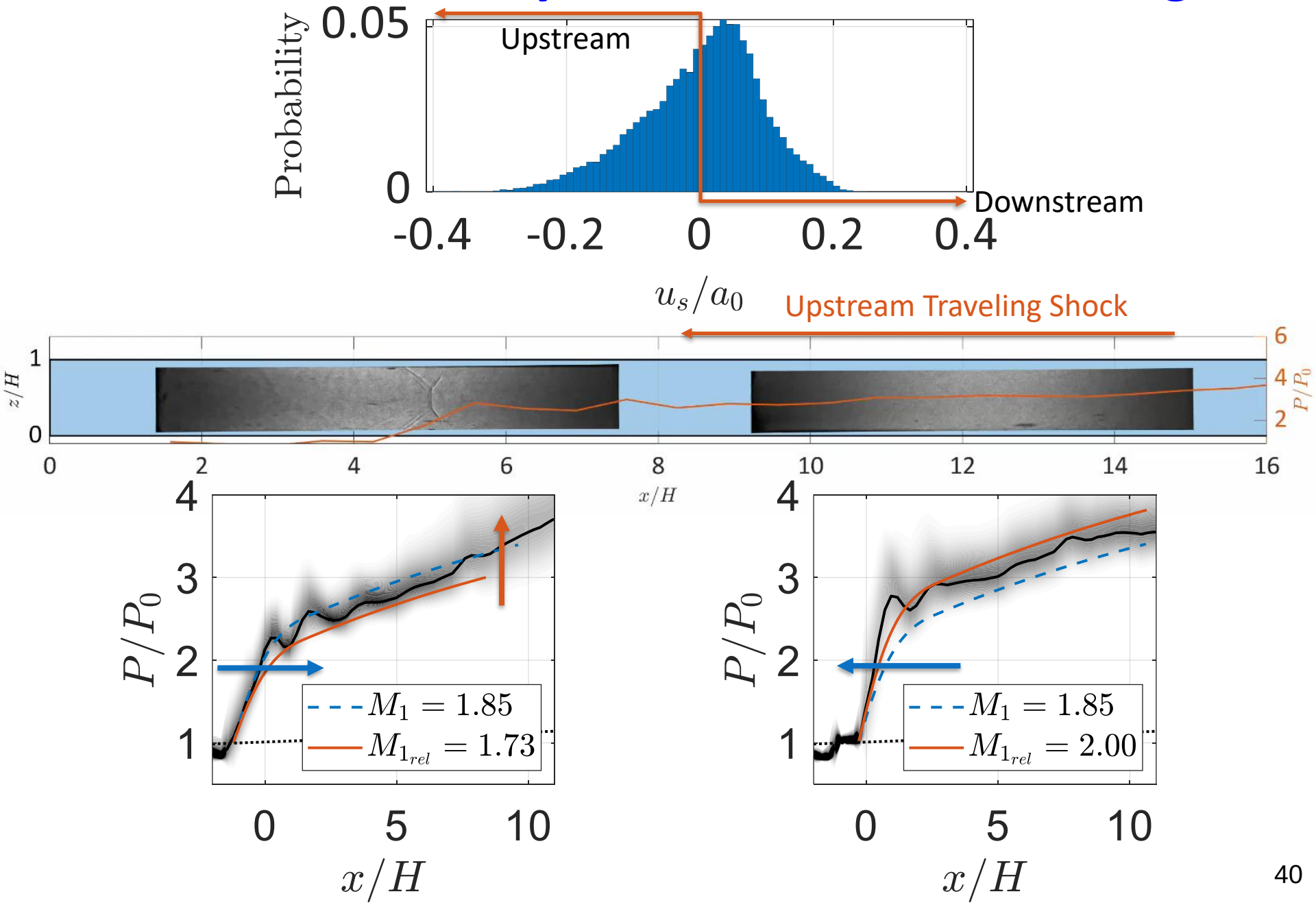
- **Driving Process Method (Shock Dominated):**
 - Where the turbulent dissipation contribution to compression becomes dominant over the oblique shock contribution.
- **Sonic Process Method (Shock Sustaining):**
 - Where the model becomes sonic

Method	Estimate
PIV Sonic Line	3.2 ~ 3.5
Schlieren	2.4
80% Wall Pressure	2.5
$\bar{M} \leq 1$	1.6
Hunt Variance Method	3.5
Driving Process	2.3
Sonic Process	3.2

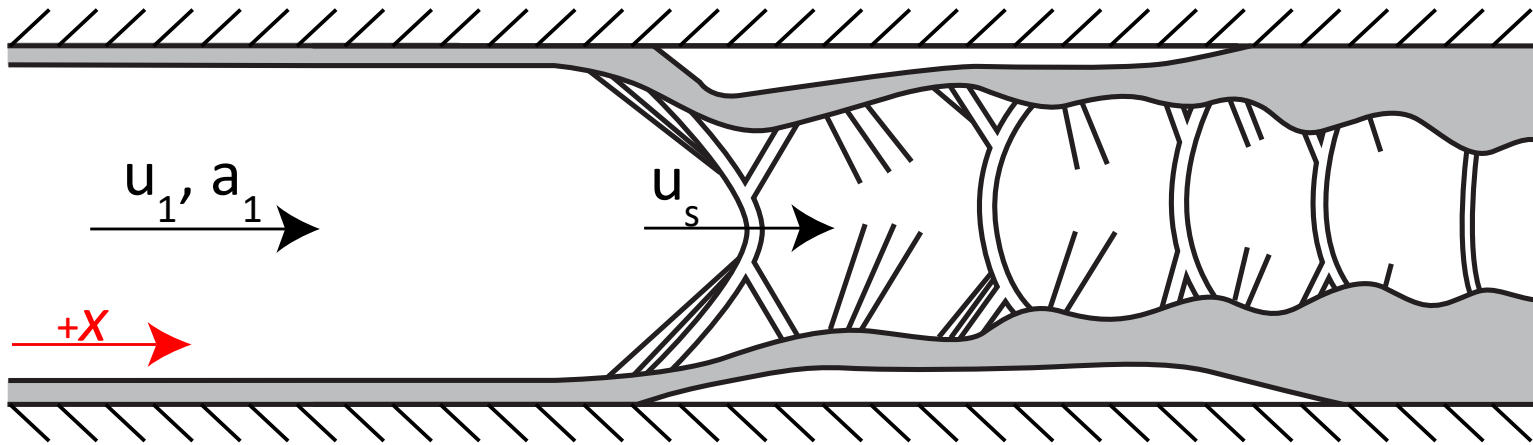


FORCED DYNAMICS

Combustor Instability Driven Shock-Like Pulsing



Modeling in a Shock Stationary Reference Frame

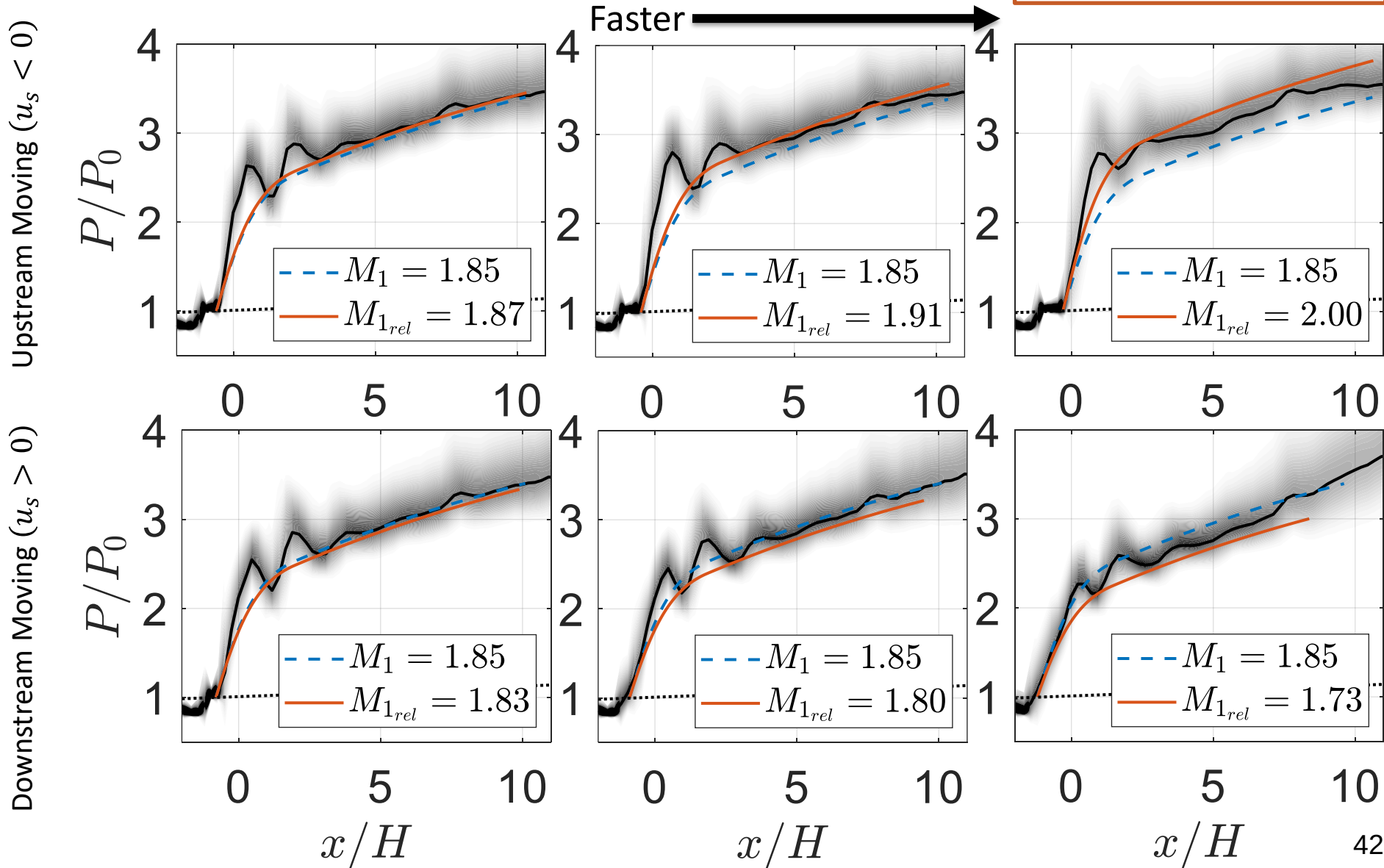


- As with normal shocks, pseudo-shocks should be considered within a **shock stationary** or **relative reference frame** to properly predict the controlling flow physics.
- $M_1 = \frac{u_1}{a_1} \rightarrow M_{1\text{rel}} = \frac{u_1 - u_s}{a_1}$
 - u_1 = Flux-Conserved Approach Velocity
 - a_1 = Flux-Conserved Approach Speed of Sound
 - u_s = Speed of the shock train as measured at the leading shock stem

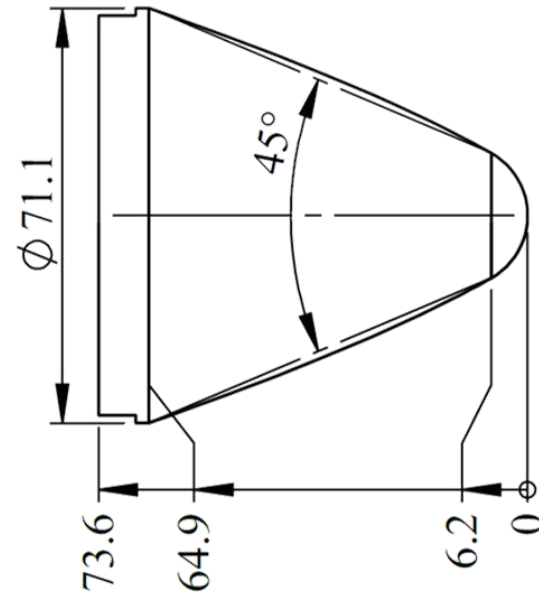
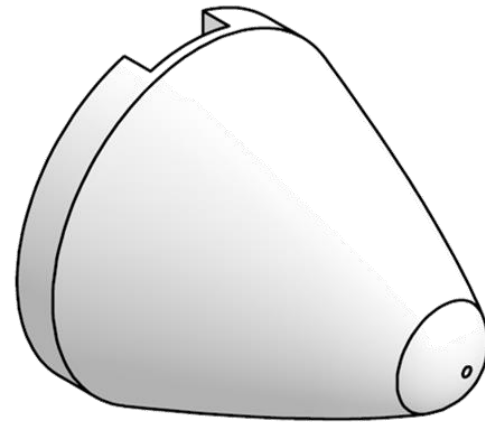
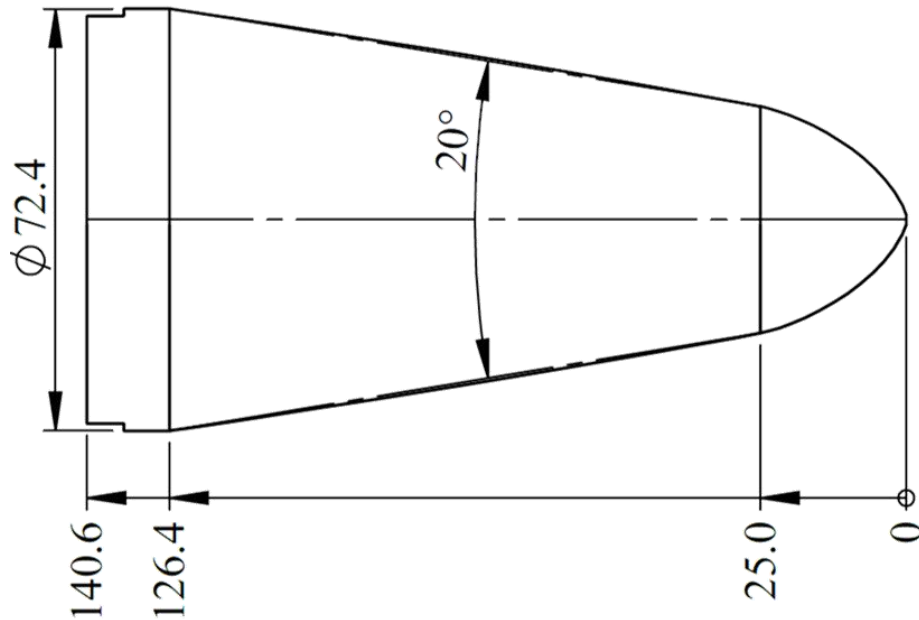
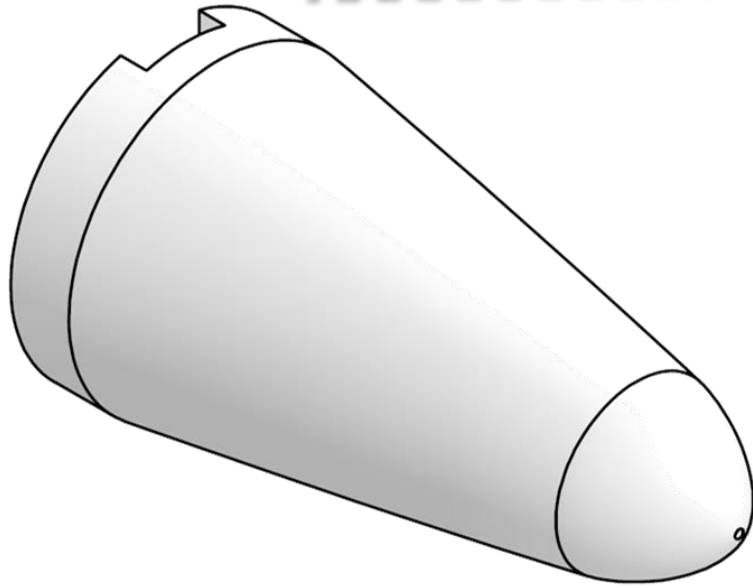
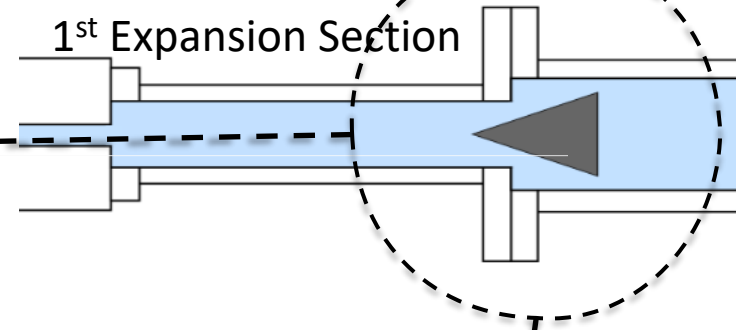
Modeling in a Shock Stationary Frame (RC18)



$$\alpha = 0.15, \beta = 0.12,$$
$$\Gamma = 0.18, \Omega = 0.75$$



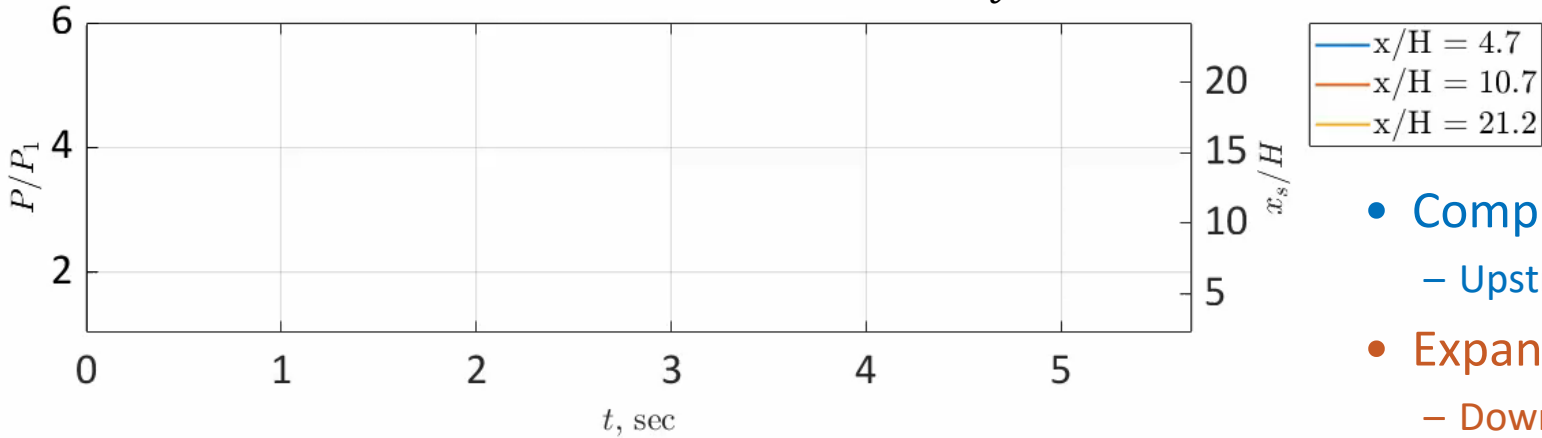
Mode 1 Forcing: IDRL Cones



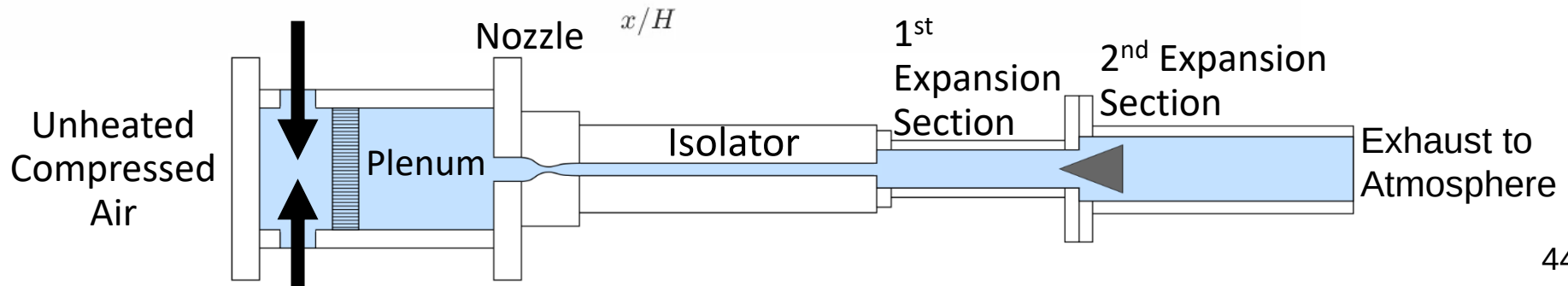
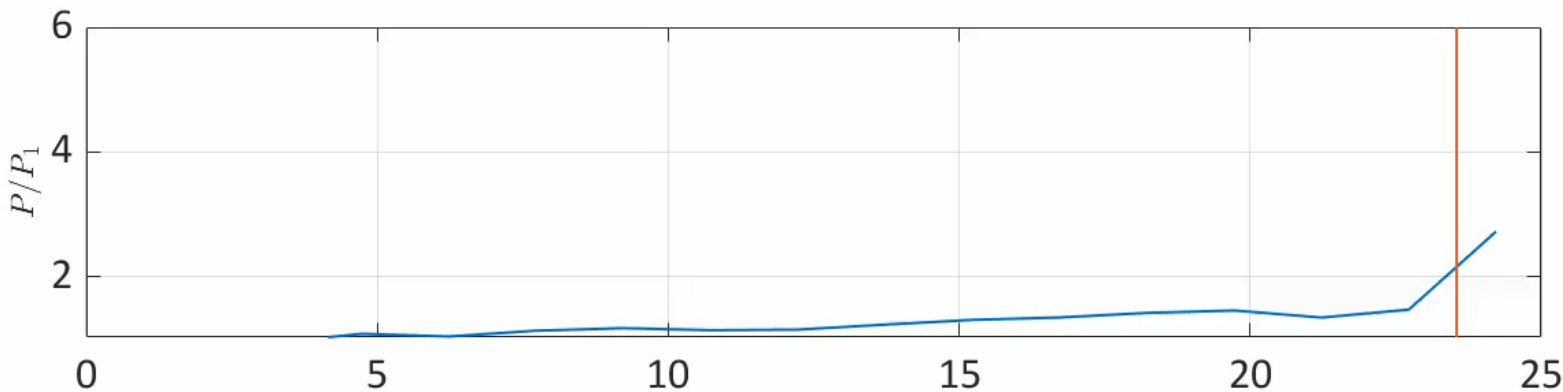
Dimensions are in mm

Mode 1 Forcing: IDRL Response

Isolator Flow Conditions: $M = 2.5$, $AR = 2.0$, $P_t = 200,125 \text{ PSI}$

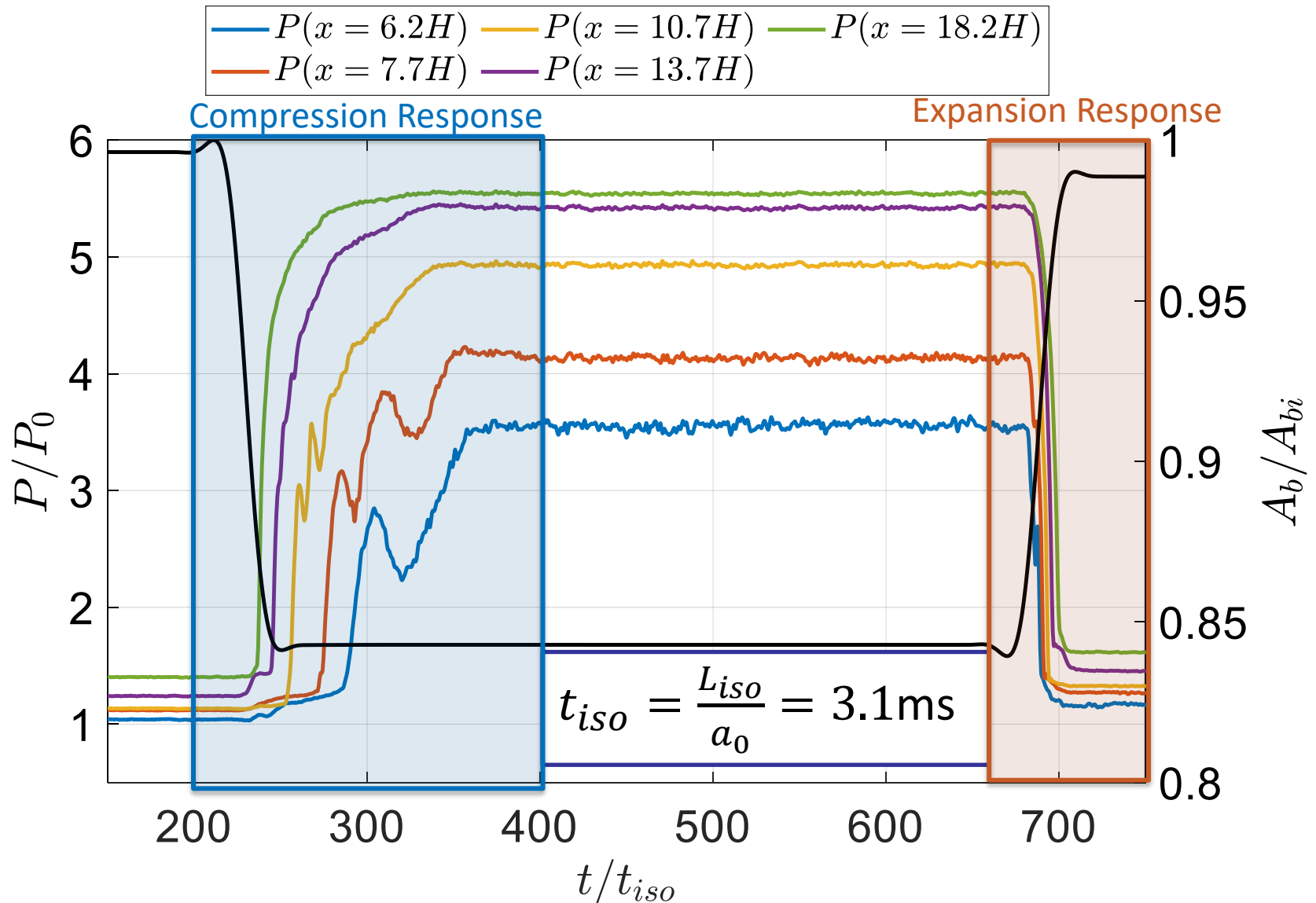


- **Compression:**
 - Upstream-Moving
- **Expansion:**
 - Downstream-Moving



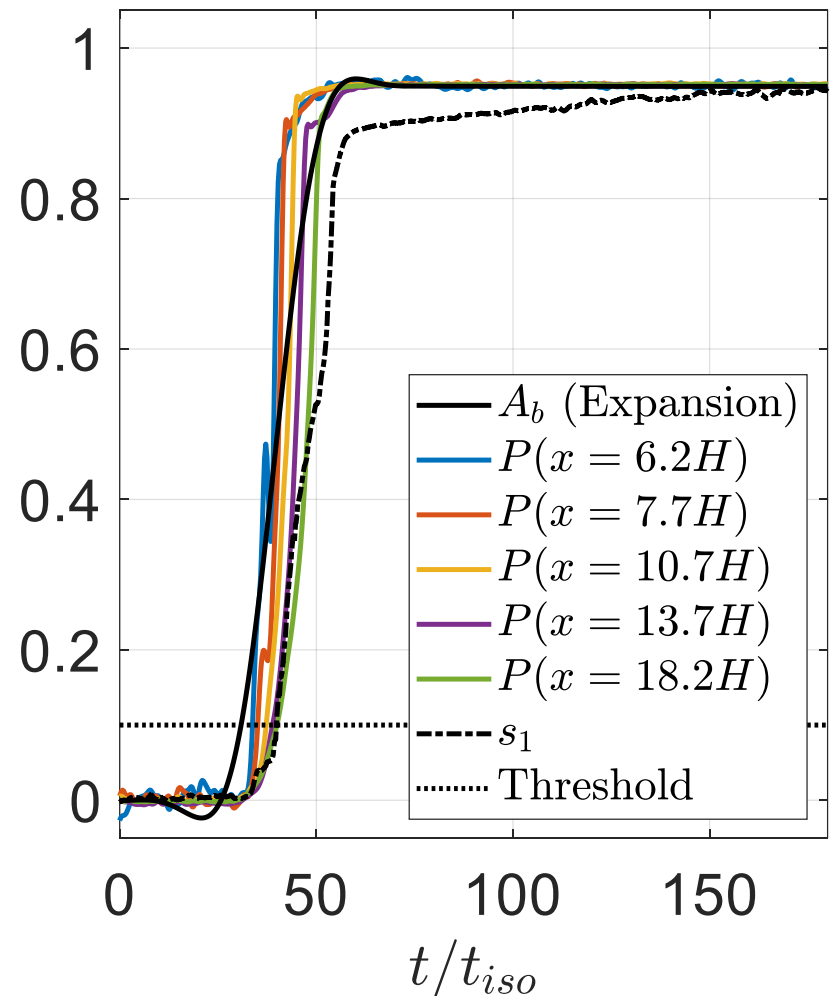
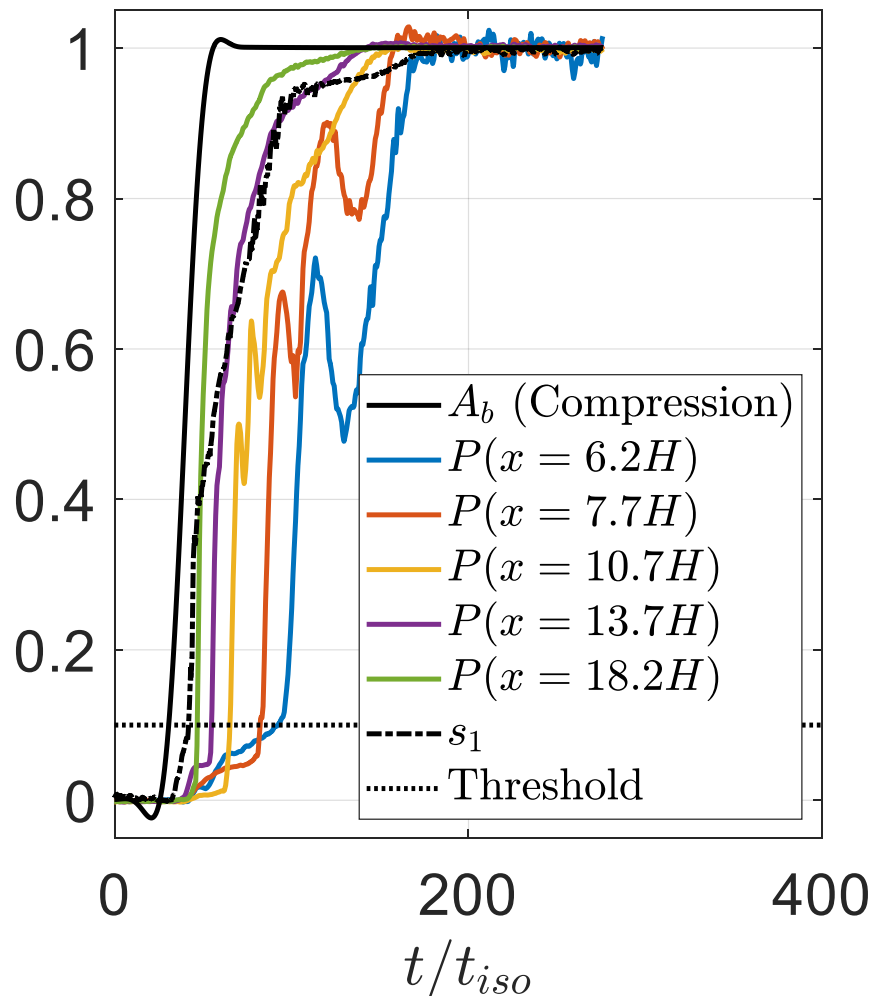
Phase-Averaging IDRL Forced Dynamics

- Shock train stabilizes to quasi-steady state between forcing inputs.

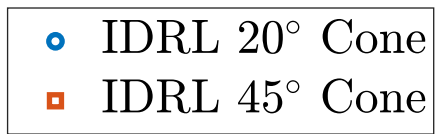


Normalized Bilevel Time Delay Analysis

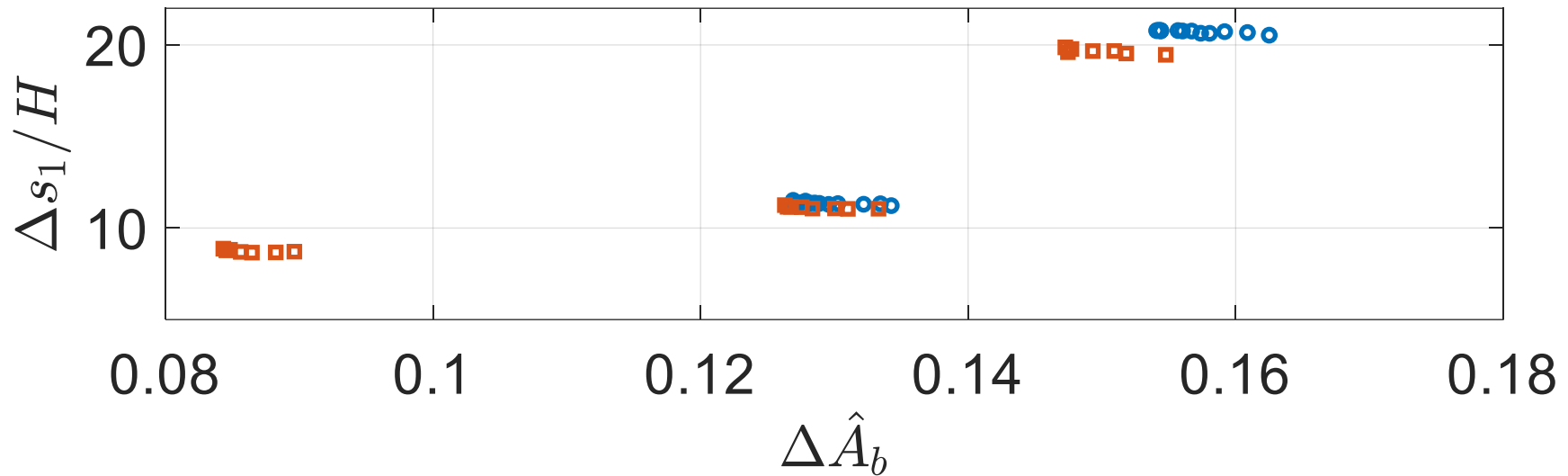
- Min-max normalized by modes of bilevel phase-averaged signal
- 0 = Initial Position, 1 = Final Position for all signals
- Time delay from onset of forcing, τ , when signal reaches 10%.



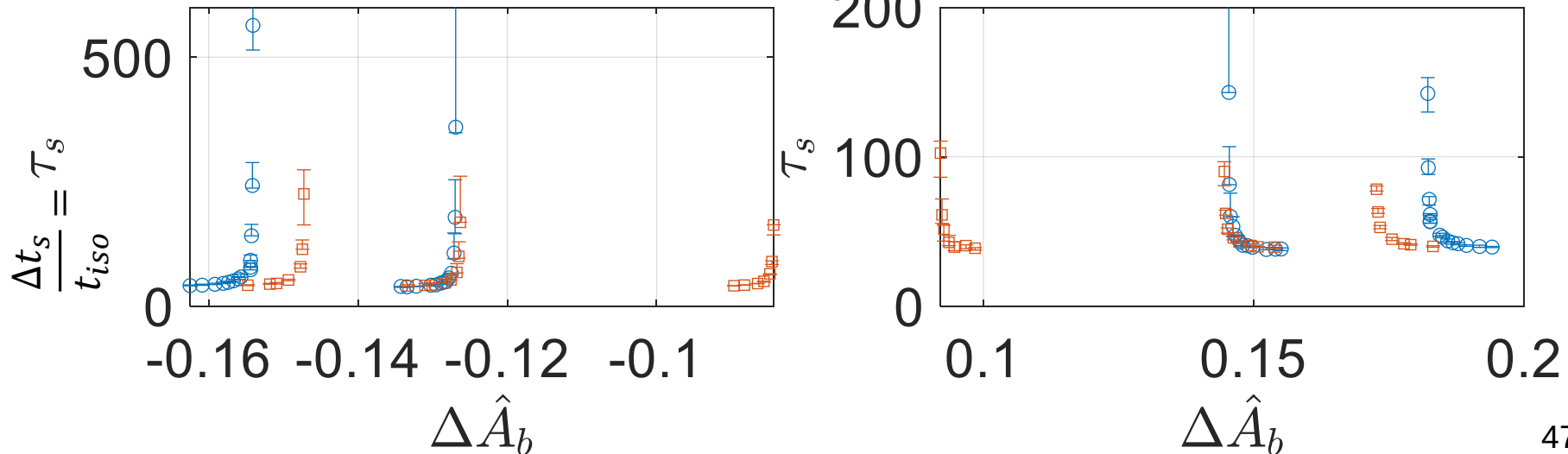
Response to Forcing Magnitude



- Δs_1 magnitude directly related to $\Delta \hat{A}_b$ magnitude for step inputs.
- No correlation between $\Delta \hat{A}_b$ and shock train initial response, τ_{s_1} .



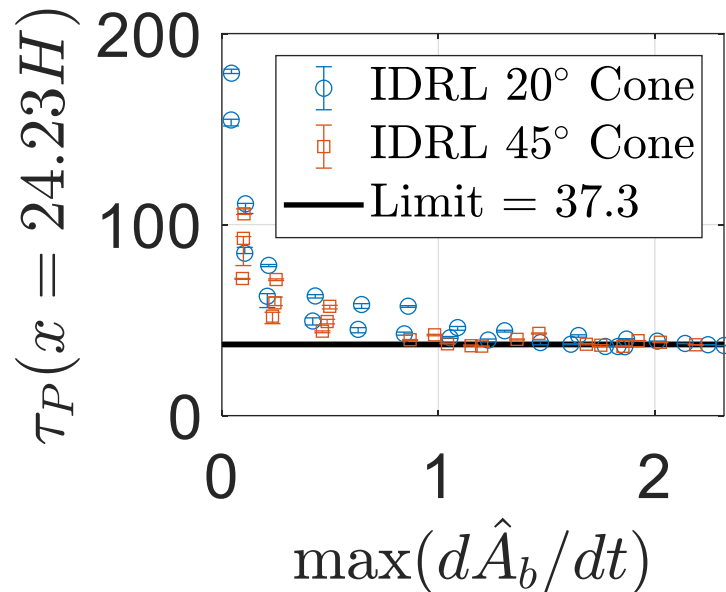
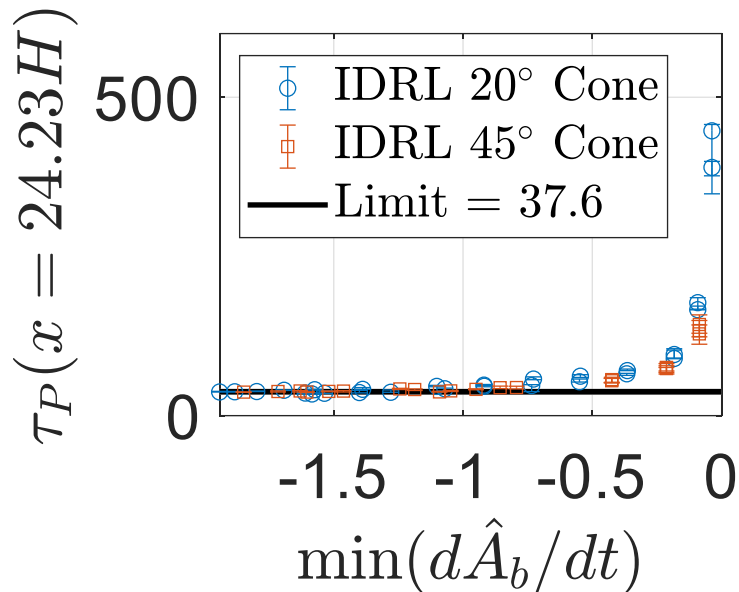
Shock Train Response



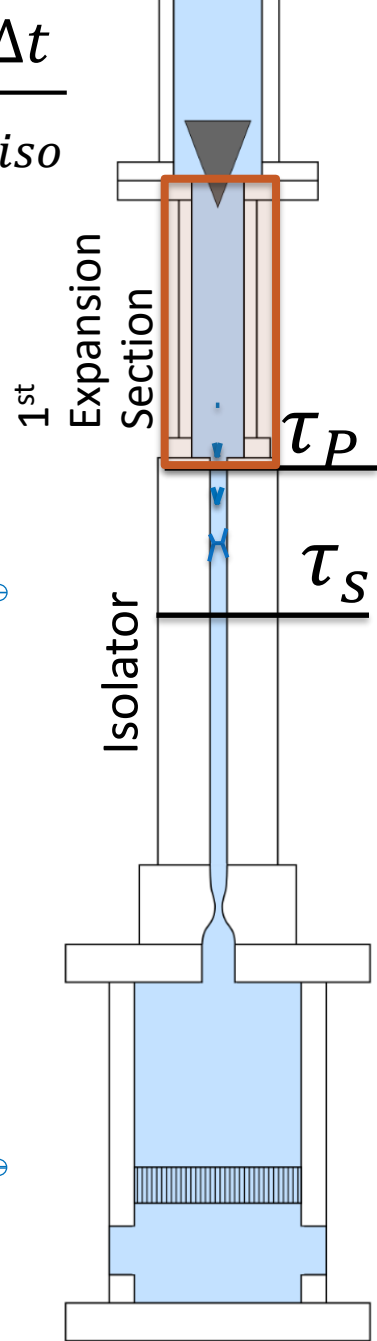
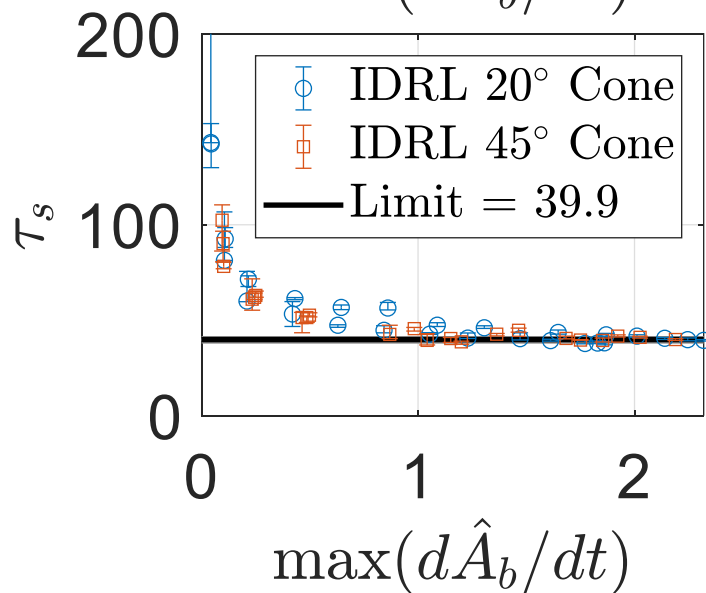
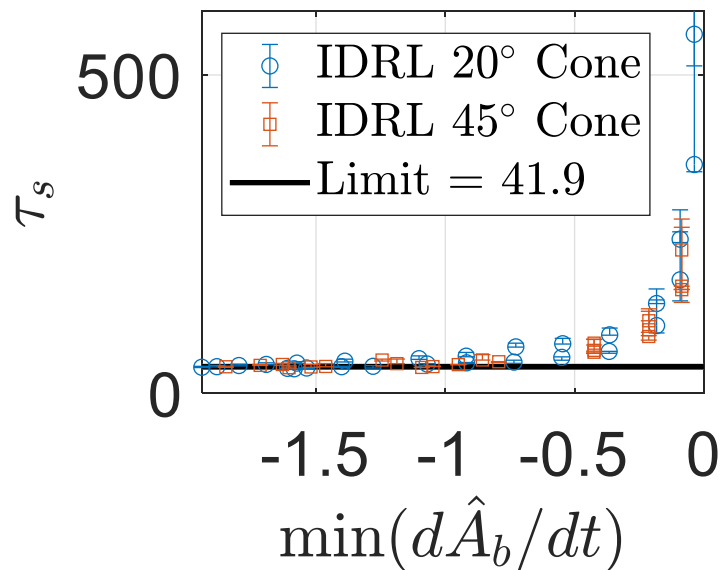
Initial Shock Train System Response

$$\tau = \frac{\Delta t}{t_{iso}}$$

Back Pressure Response

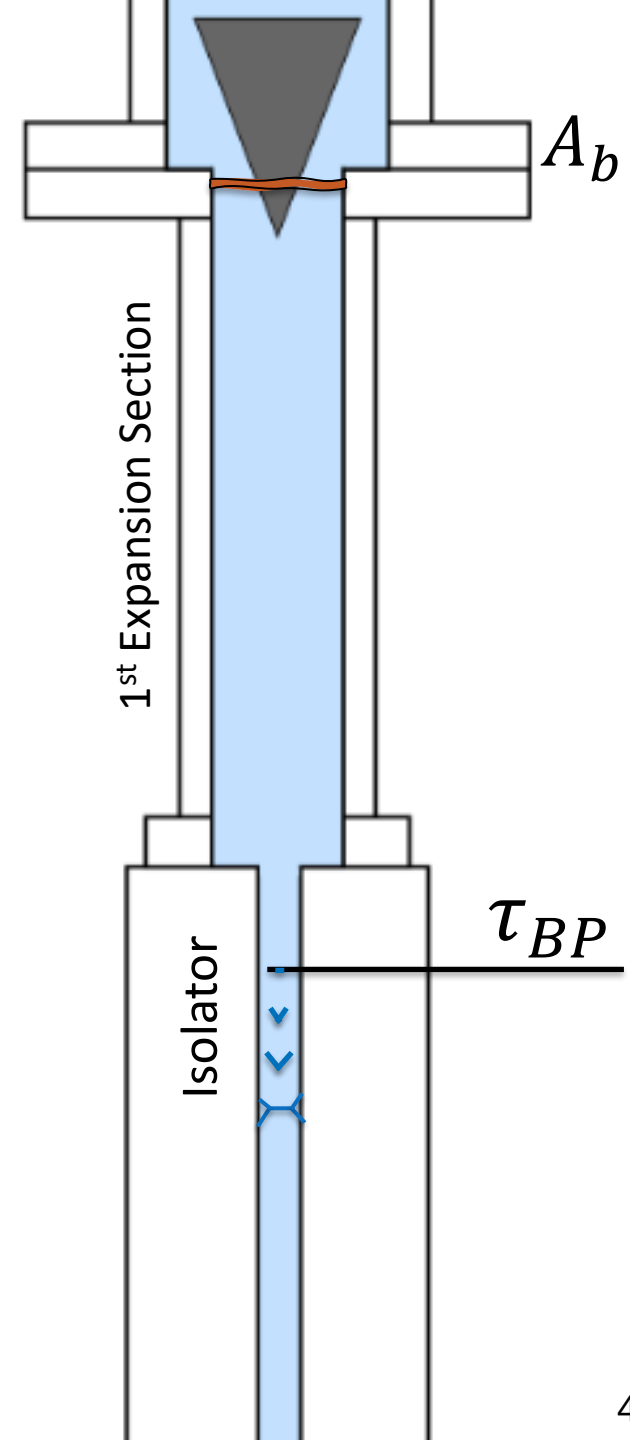


Shock Train Response



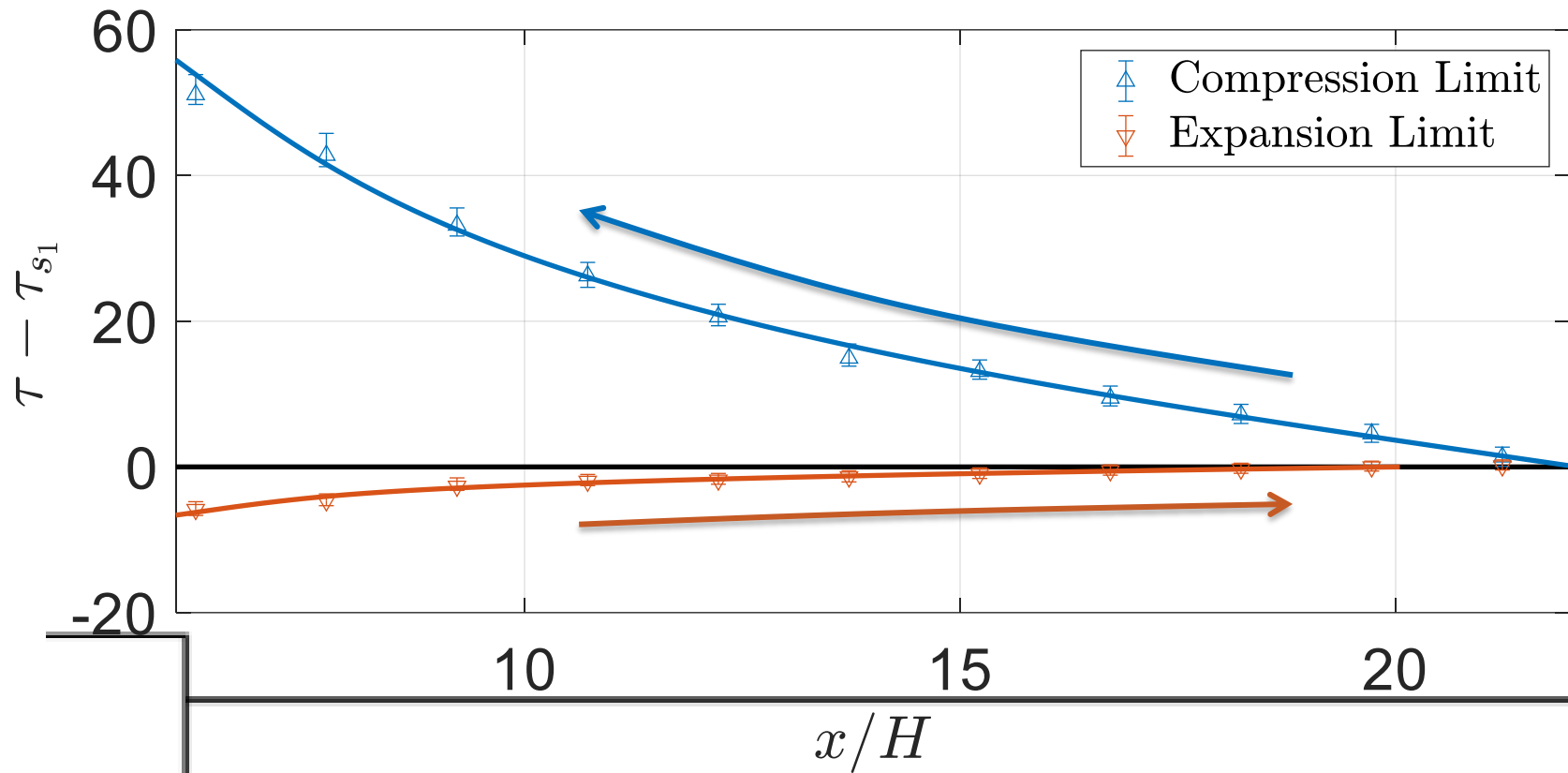
Saturation in the $d\hat{A}_b/dt$ Limit

- τ_{BP} and τ_s are indicators of when the shock train system **initially responds**
 1. Wave system is generated when A_b is changed by the back pressure cone
 2. Travels upstream to process flow in 1st expansion section
 3. Imposes back pressure change on the isolator system
 4. Shock Train responds by moving in the isolator
- Saturation due to **volume capacity** of expansion section volume damping the wave processing as it travels against the **resistance** of the streamwise flow.
 - Acts like a **low-pass RC circuit**



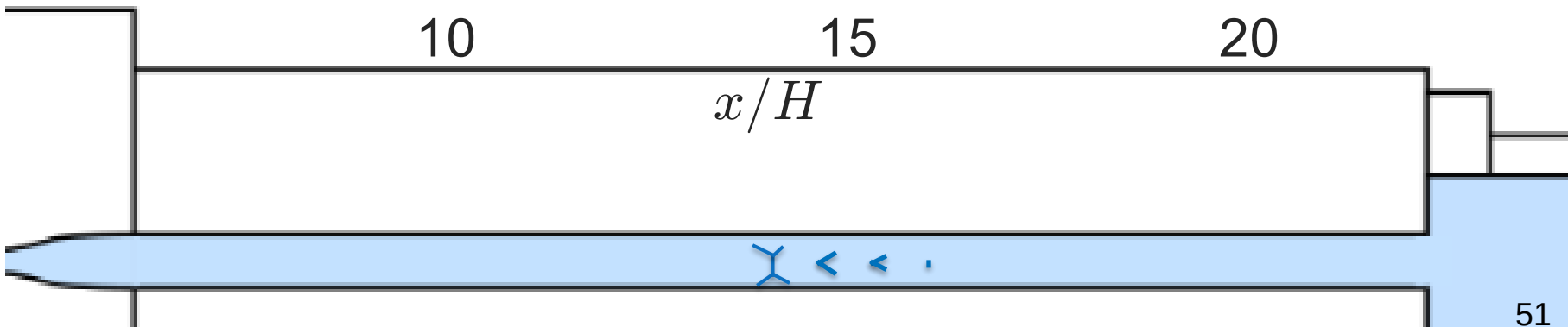
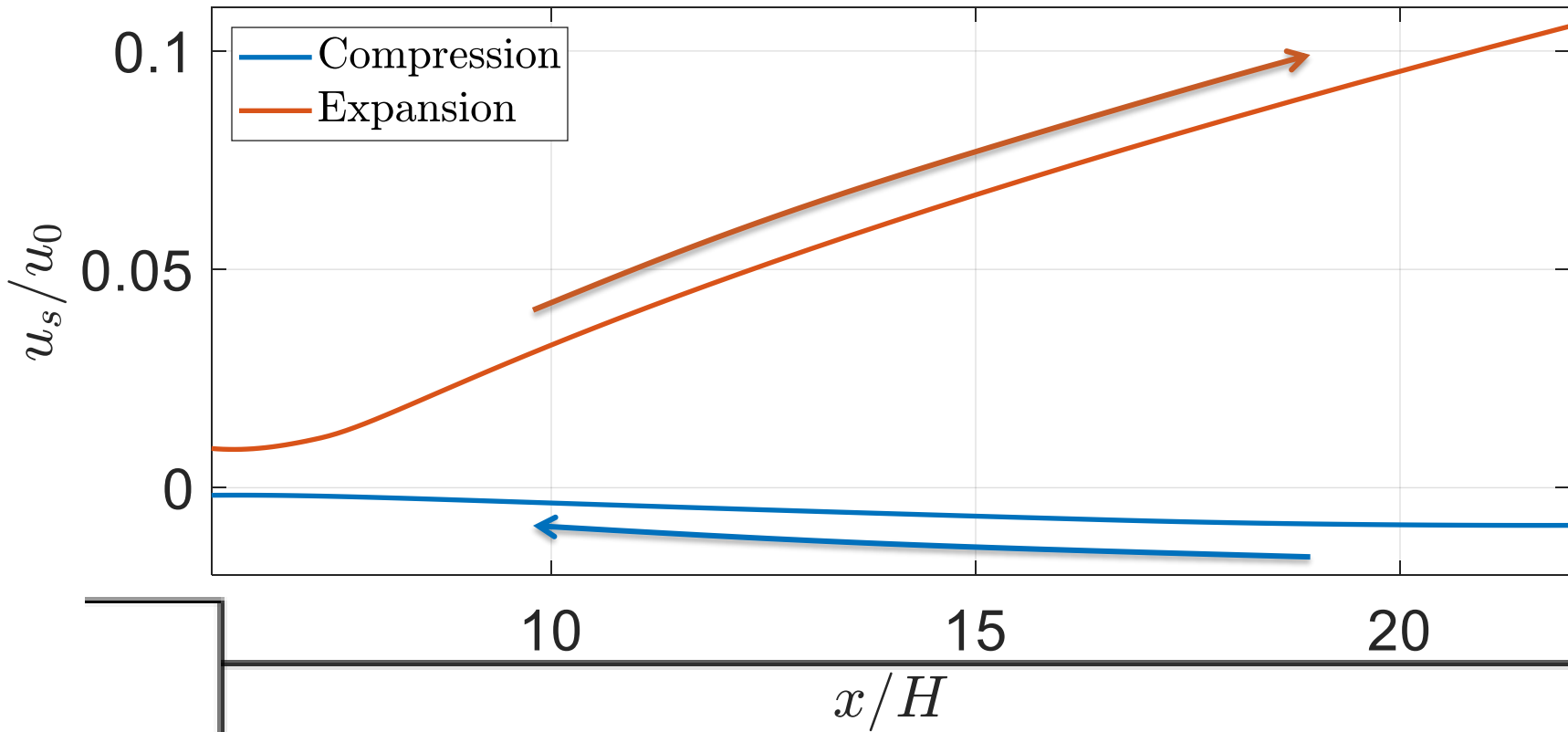
Limit $d\hat{A}_b/dt$ Time Delay Behavior

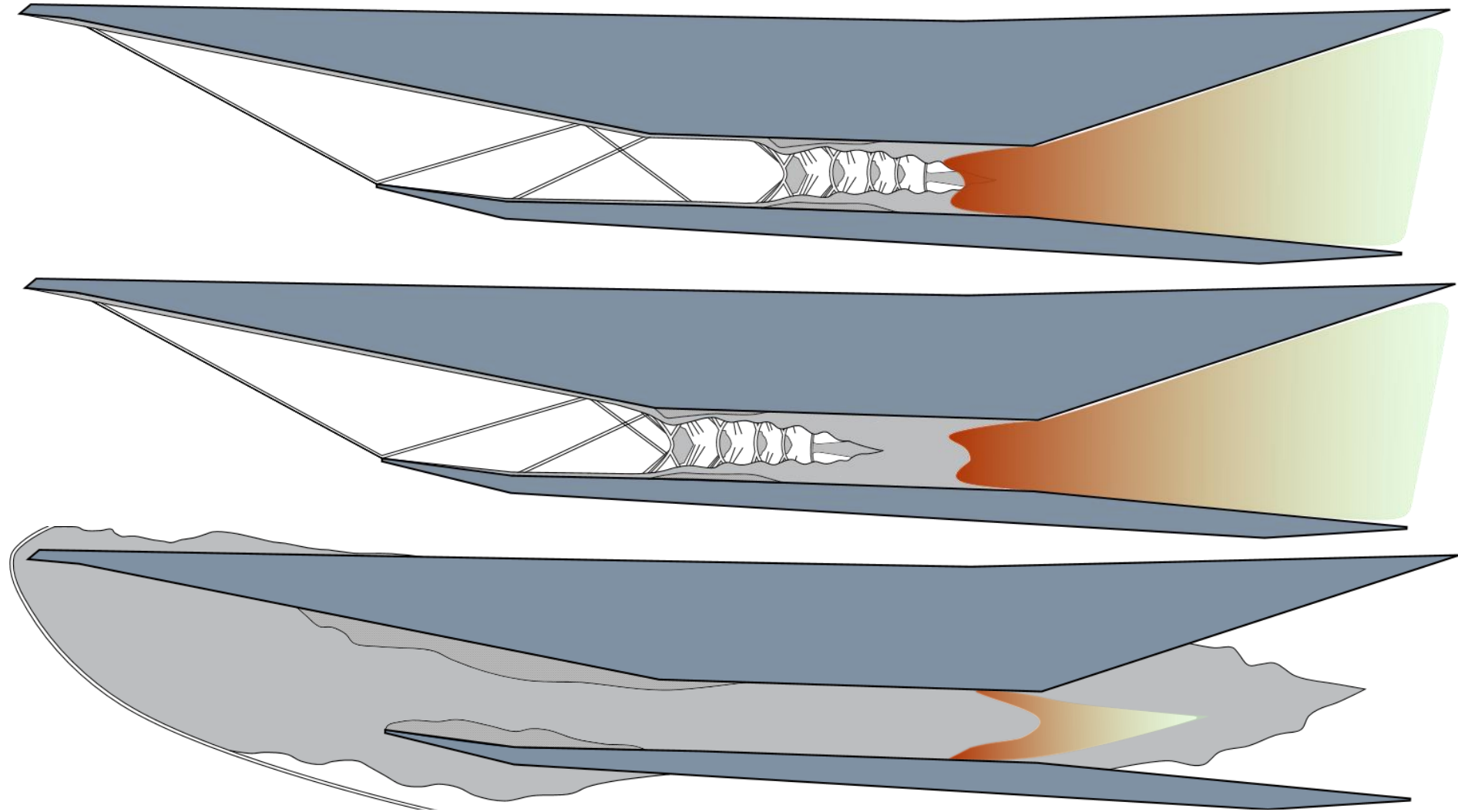
- τ value for each wall static pressure transducer along the isolator
- **Hysteresis** with slow, progressive movement **upstream** and fast, snapping movement **downstream**.



Limit $d\hat{A}_b/dt$ Local Shock Train Speeds

- Gradient of time delays for all forced magnitudes yields local speeds
- Reveals **local maximum shock train response speed** along isolator
 - Likely related to local approach conditions, M , θ , δ^* , etc.





SUMMARY AND CONCLUSIONS

Summary & Conclusions

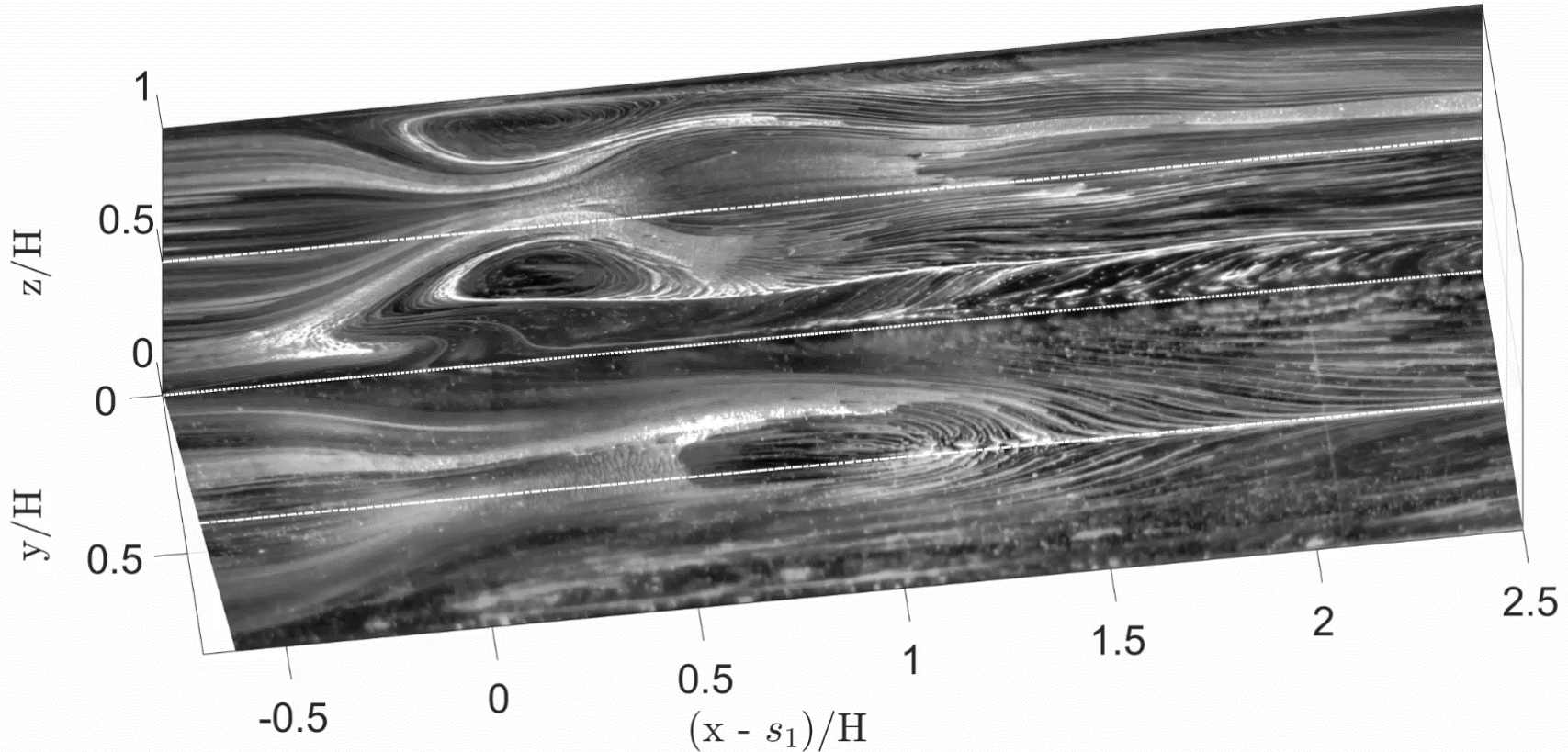
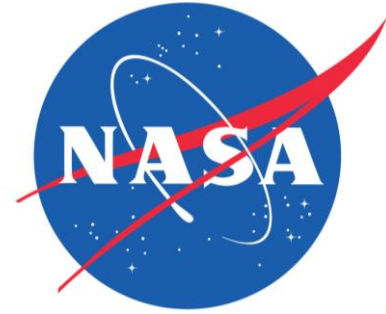
- Revealed the complex, 3D structure of a low AR shock train.
 - Asymmetry is driven by **distorting fluid structures** (i.e. vortices and shocks)
- Found quasi-1D modeling state-of-the-art and their assumptions to be inadequate for modeling the flow physics of the shock train
- Proposed a new **Process Driven Flux-Conserved quasi-1D model**
 - Superposition of shock-driven compression, turbulent kinetic energy dissipation compression, and wall friction losses.
 - **Four, physically grounded parameters**
 - Integration of A_c still diverges from measured data for subsonic regions
- Process Driven model can provide a quantitative measure of the **shock train to mixing region transition**
- Shock train response time to forced dynamics saturates
- Streamwise motion of the shock train saturates to **local maximum speeds** with upstream- and downstream-moving hysteresis

Implications to Dual-Mode Scramjets

- Shocks and vortices shed from the inlet will distort the isolator shock train changing the length and weight of the isolator needed
- The Process Driven Flux-Conserved model provides:
 - A lower dimensional and physical grounded model for iterative isolator design
 - Provides insight on the drivers of isolator performance in different designs
 - Quantitative definition of the end of the shock train improves isolator length optimization
 - Effective during high-rate unsteadiness in a shock stationary reference frame
- There are two modes of forced dynamics to consider in control:
 - Mode 1: Low-Rate Mechanically Induced (Throttling-like) Forcing
 - Mode 2: High-Rate Combustion Driven Forcing
- The time delay between combustor throttling and shock train response is:
 - When the system does not unstart, response time does not depend on ΔA_b
 - Control system design should be conscious of time delay and $\frac{d\hat{A}_b}{dt}$ saturation point

Future Work at NASA Langley

- Understand the influence of variations in geometry and distortion on shock train structure and performance
 - Detailed structural measurements (focused schlieren, PIV) planned in IDRL
 - Measurements with and without isolator distortion
- Refine the proposed Process Driven Flux-Conserved Model
 - Improve performance at high isolator pressure ratios
 - Improved optimization techniques and parameter sensitivity analysis
 - Reconcile divergence of A_c from measured data
 - Reevaluate assumptions needed for quasi-1D models and how to account for them
- Detailed study of forced dynamic measurements
 - Implement higher rate and complexity forcing in IDRL
 - Refined estimation of time-delays
 - Separate forcing input pressure signal from shock train motion pressure signal
 - Determine the transition conditions between Mode 1 and Mode 2 Forcing



ご清聴ありがとうございました、
ご質問がございましたか。