Isolator Shock Train Response to Dual-Mode Scramjet Throttling-Like Forcing

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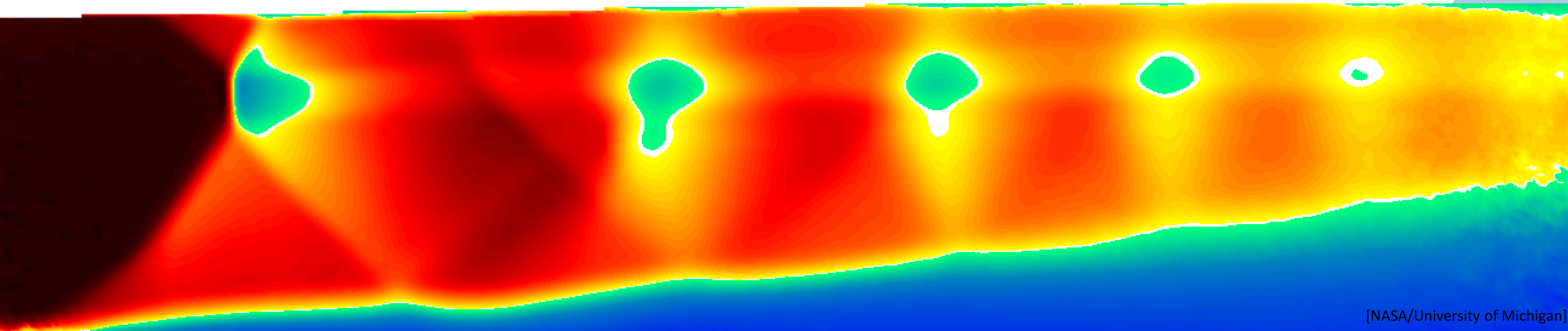
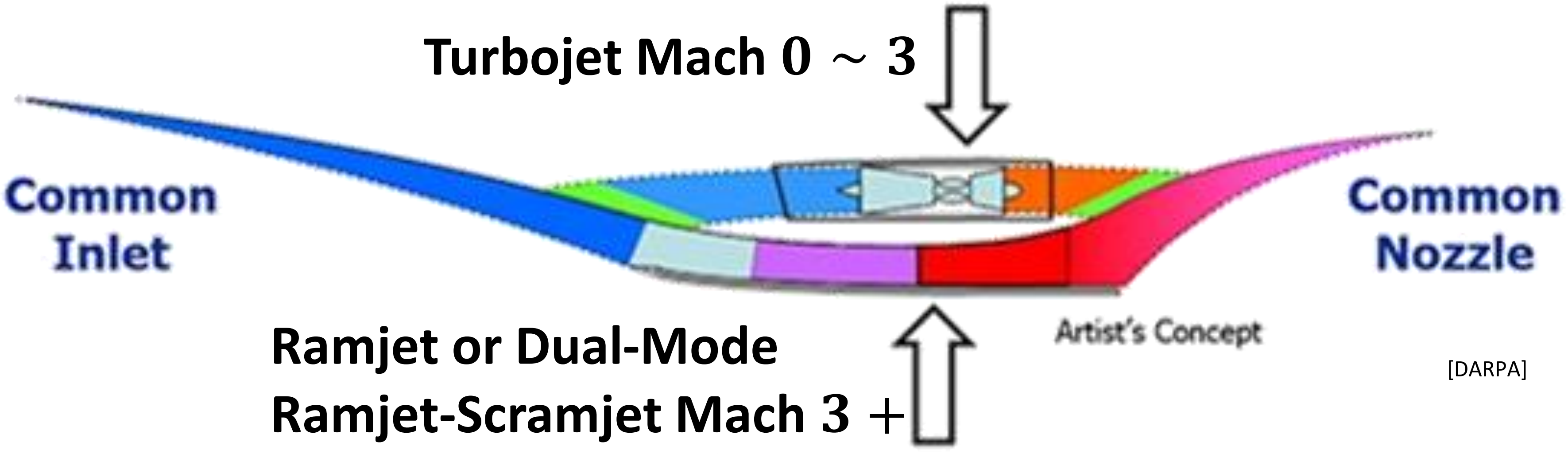


[NASA/University of Michigan]

Commercial Hypersonics

- **NASA Commissioned Studies on Commercial Supersonics/Hypersonics**
  - “Independent Market Study: Commercial Hypersonic Transportation” – SAIC (NTRS 20210015472)
    - Best Business Case: **Mach 3 Vehicle** over 302 viable commercial routes, 299 private/charter Routes
  - “Commercial Hypersonic Transportation Market Study” – Deloitte (NTRS 20210014711)
    - Best Business Case: **Mach 2-3 Vehicle** over 90 viable commercial routes
    - Marginal Business Case: **Mach 5 Vehicle** primarily for private/charter routes
- **Implies the use of Turbine Combined Cycle Engines (Turbojet Over a Ramjet or DMRJ)**



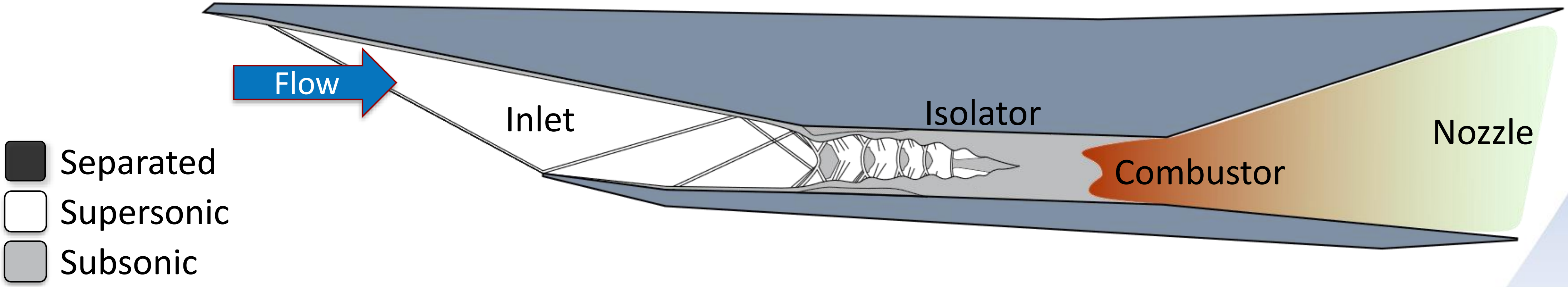
Turbojet Mach $0 \sim 3$

Ramjet or Dual-Mode
Ramjet-Scramjet Mach $3 +$

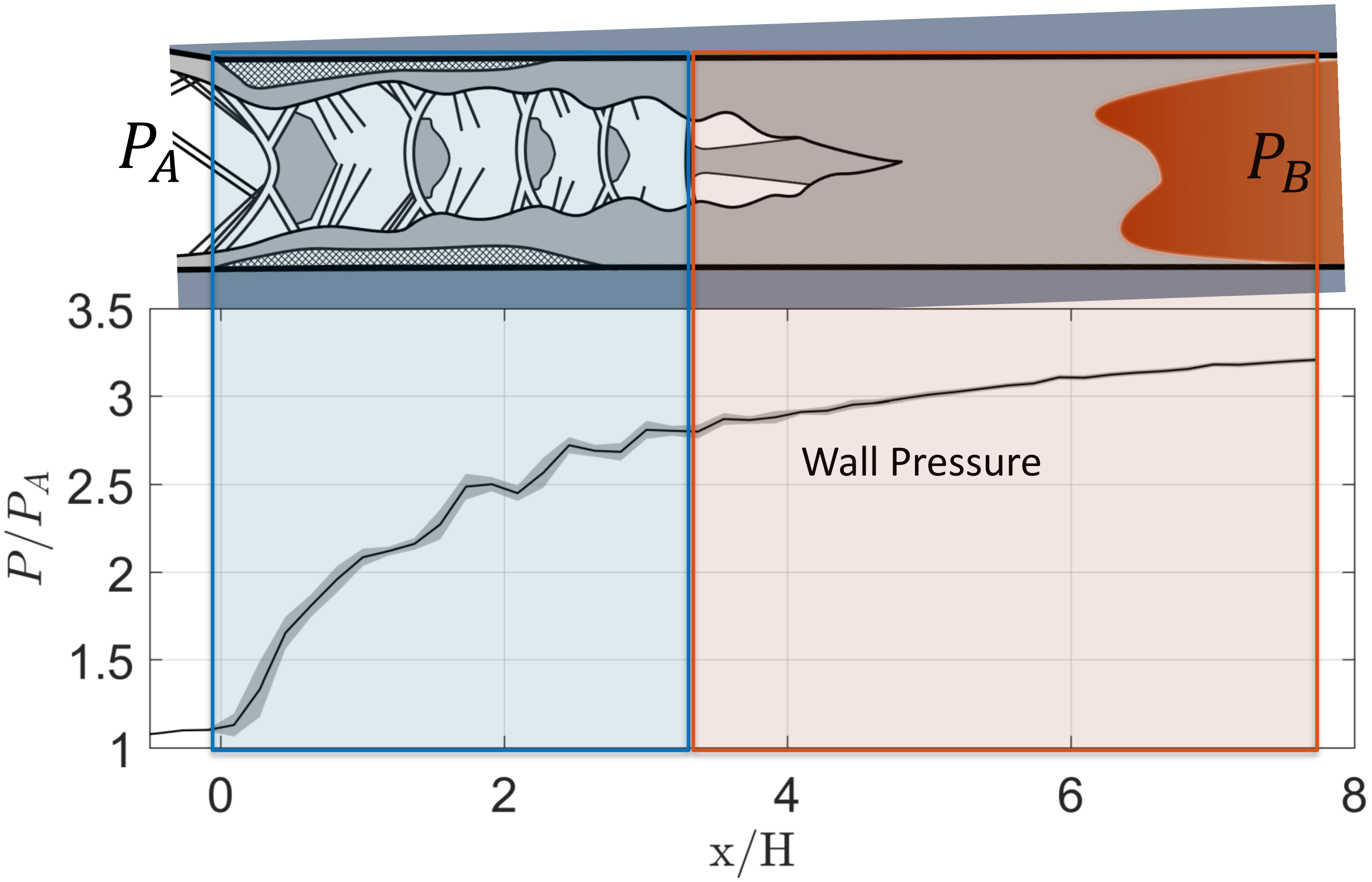
[DARPA]

Dual-Mode Scramjet Engine Flowpath

- Operates as a ramjet Mach $3 \sim 5$ and a scramjet Mach $5 +$
- This study **focuses control of ramjet** engine operation.
- Ramjet flow path is mechanically simple, fluid dynamically complex
- **Isolator:** Duct between the inlet and combustor containing the **pseudo-shock** during ramjet operation to compress flow for combustion



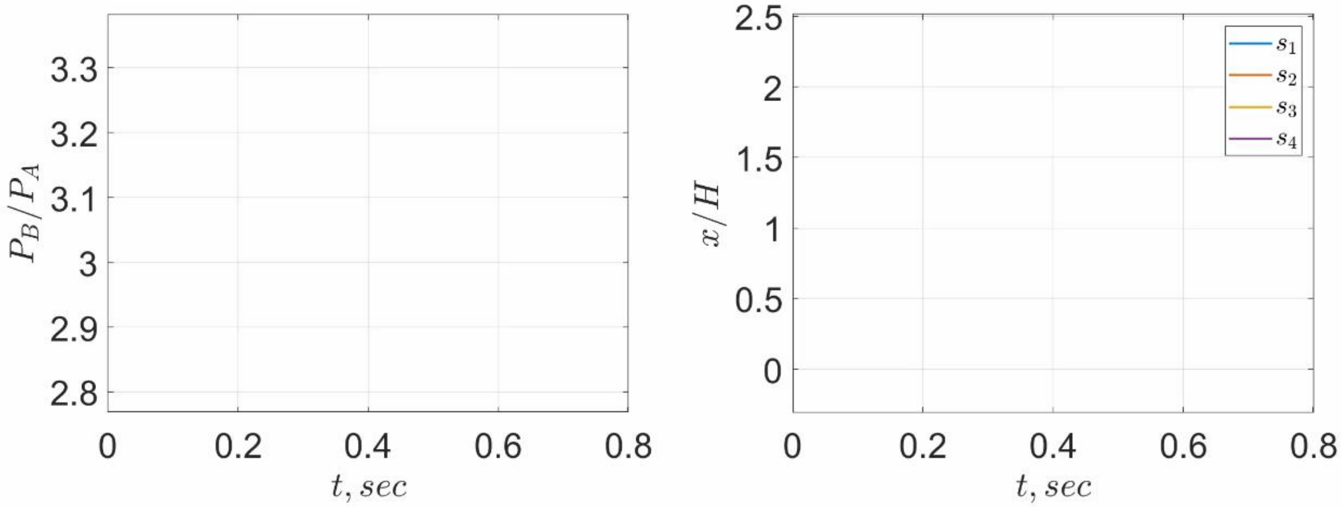
Pseudo-Shock: Shock Train and Mixing Region

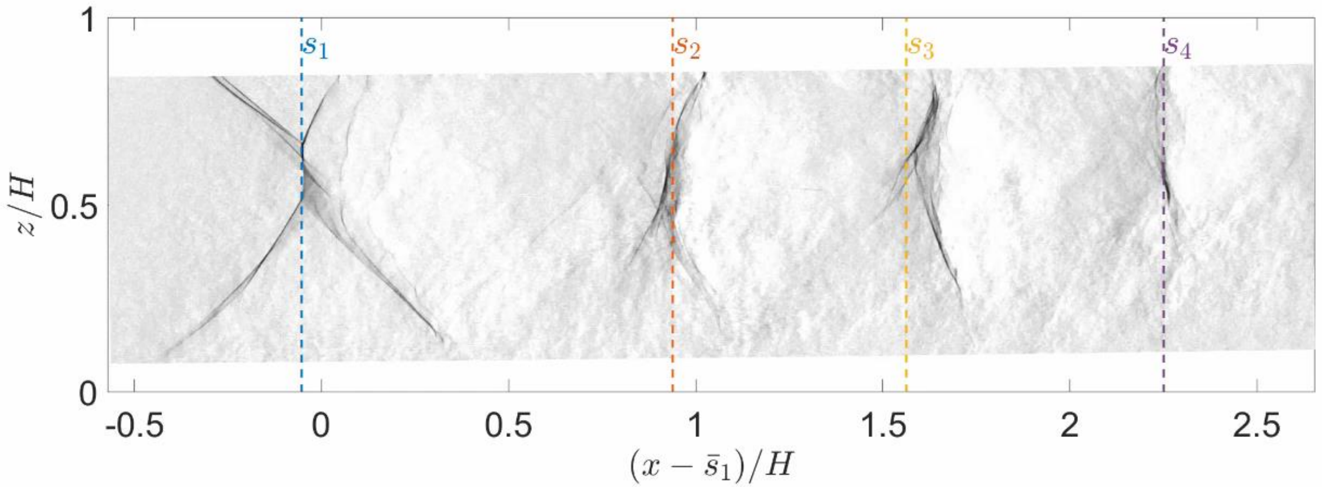


■ Separated
□ Supersonic
▒ Subsonic

- **Shock Train:** Series of interconnected Shock Boundary Layer Interactions (SBLI)
- **Mixing Region:** Turbulent, mixed sub/supersonic flow

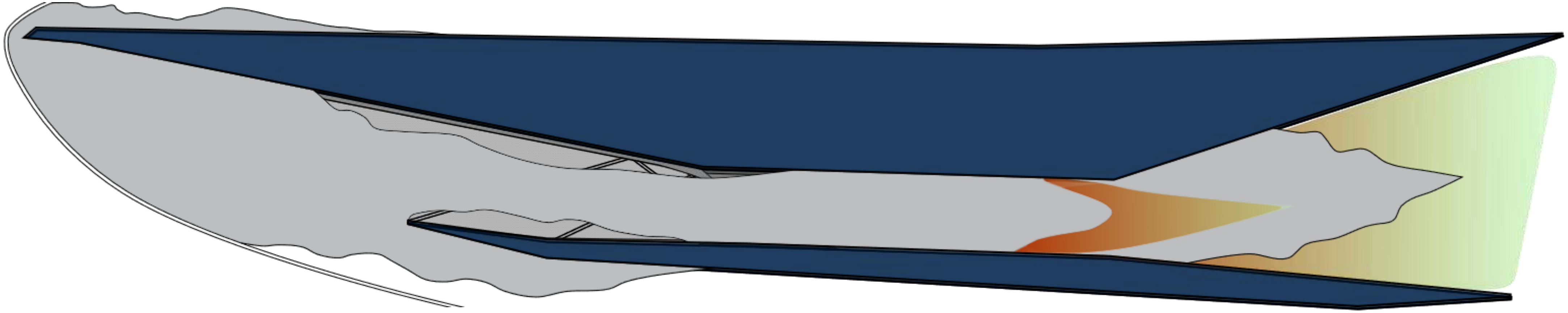
Normal Ramjet Operation: Quasi-Steady State





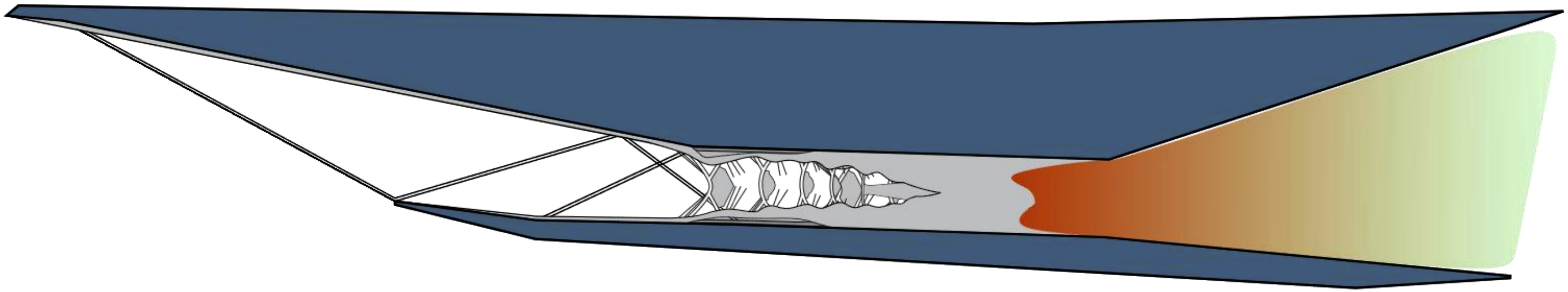
- **Quasi-Steady:** Shock train varies in structure and position at a low-magnitude, self-contained **inherent unsteadiness** around a time-averaged position.

Critical Failure Mode: Isolator Unstart



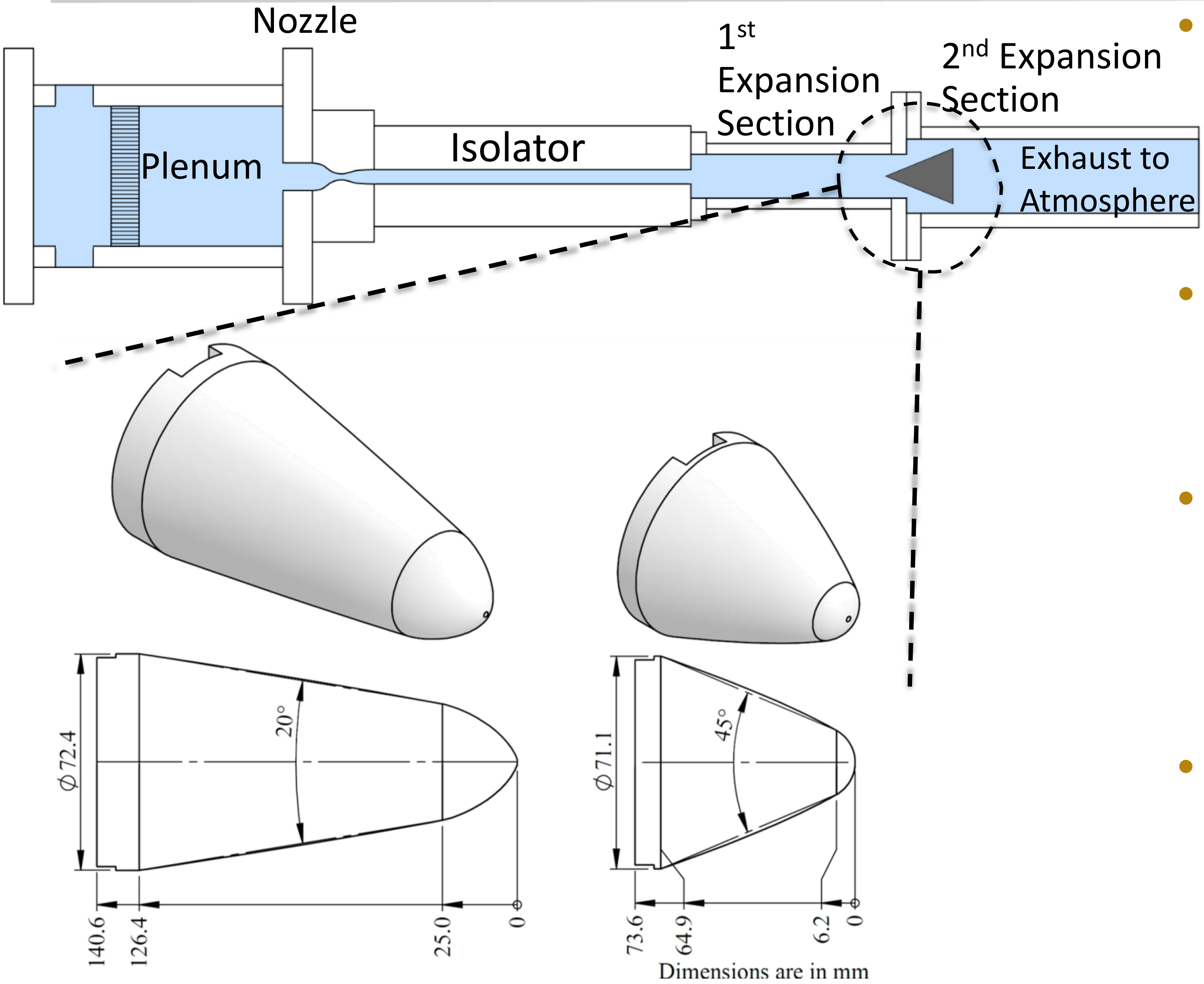
- Pseudo-shock compresses flow from the inlet to meet downstream boundary condition in the combustor.
- As combustor pressure increases, the shock train shifts upstream to increase compression in the mixing region
- When combustor pressure rises beyond a threshold, unstart occurs.

Middle Case: Forced Transients



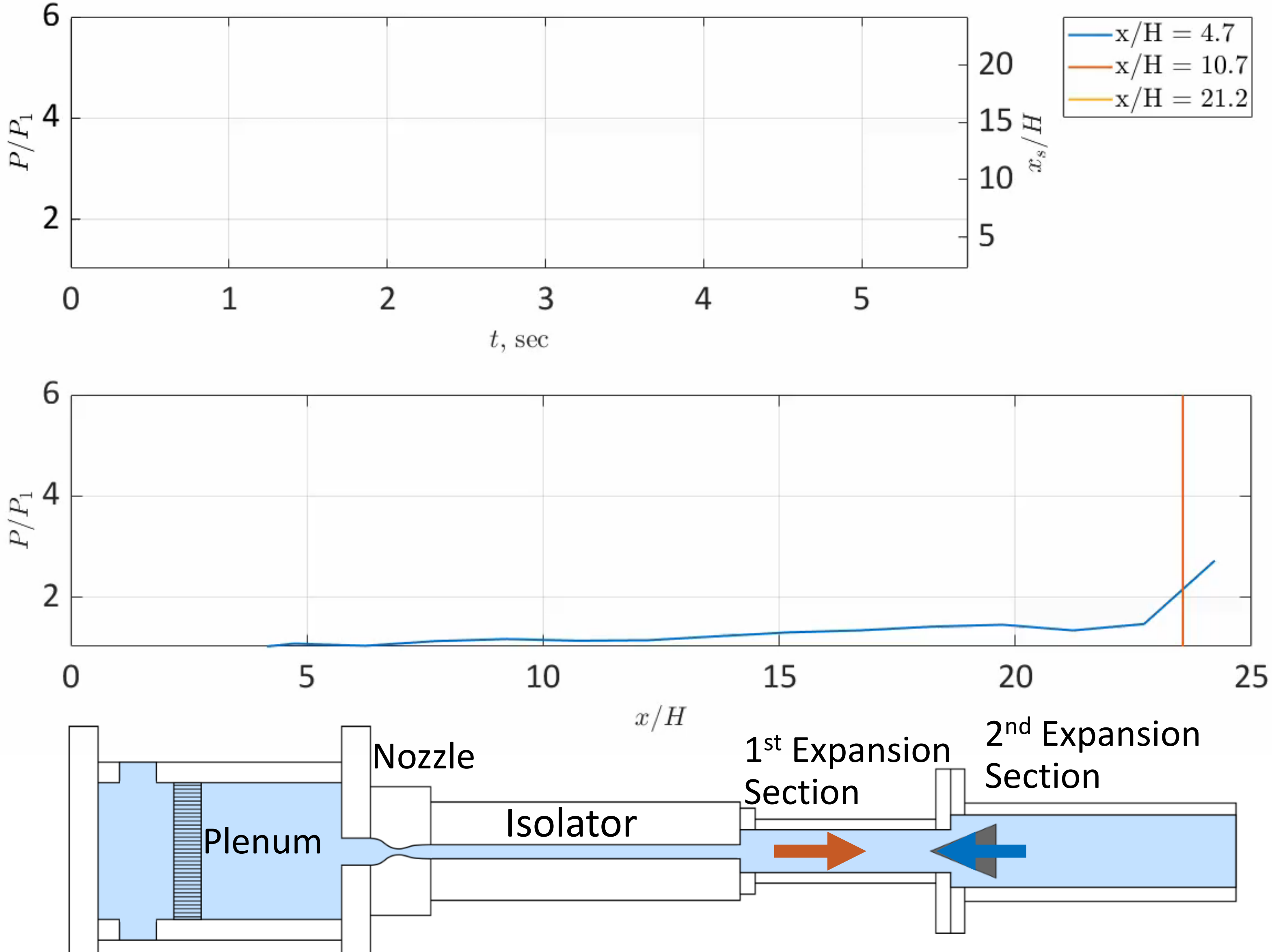
- Induced by changes in downstream pressure due to combustor perturbations do not immediately induce unstart.
  - i.e. aggressive throttling, combustor instability
- **Requires a longer isolator** to maintain operational safety margin from gradual or incipient unstart.
- Creates an engine with **added volume and weight**

Experiment: Isolator Dynamics Research Lab



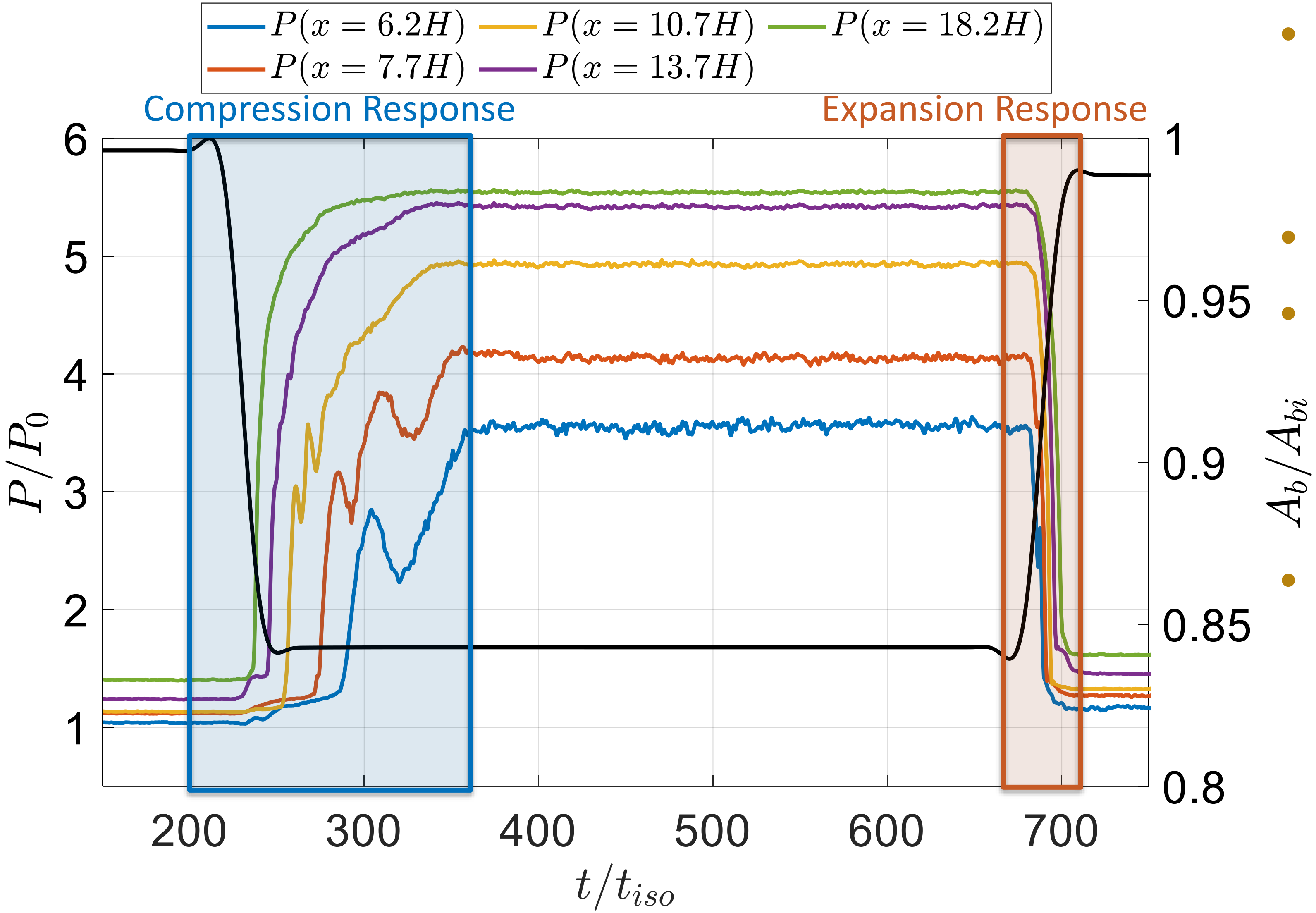
- 16 dynamic pressure sensors flush to the wall streamwise centerline track static pressure profile along the isolator.
- **Isolator Inflow Parameters:**
  - $M = 2.5\,; P_t = 125 - 250\ PSI$
  - $AR = 2.0\,; H = 25.4\ \mathrm{mm}$
- Back pressure cone on a linear ballscrew adjust back pressure to generate and perturb the pseudo-shock
- **Representative of an isolator followed by a flame holder cavity during throttling.**

Mechanical Downstream Forcing Cycle



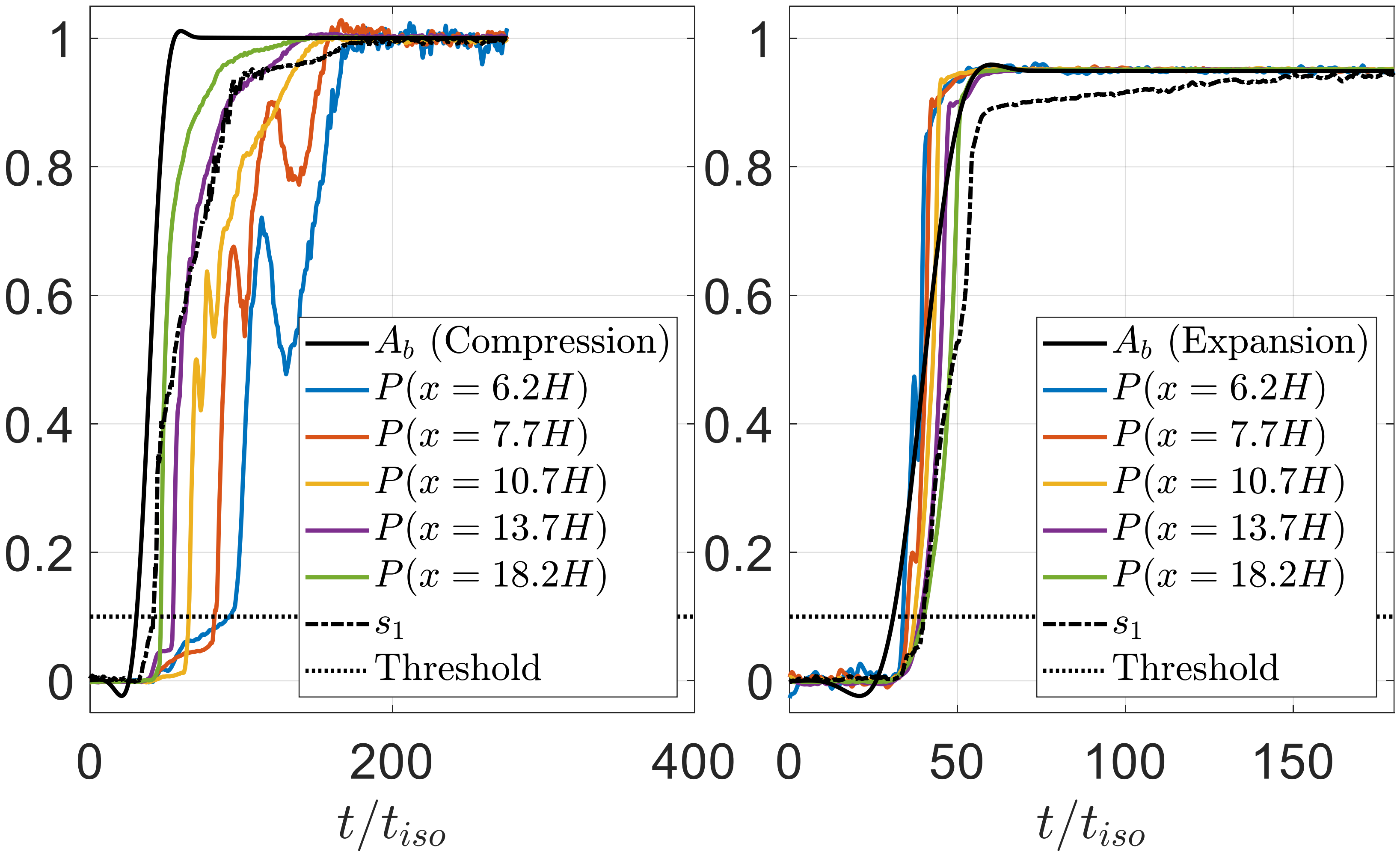
- Compression:
  - Upstream-Moving
- Allow pseudo-shock to stabilize upstream
- Expansion:
  - Downstream-Moving
- Allow pseudo-shock to stabilize downstream
- Repeat

Phase Averaging IDRL Forced Dynamics



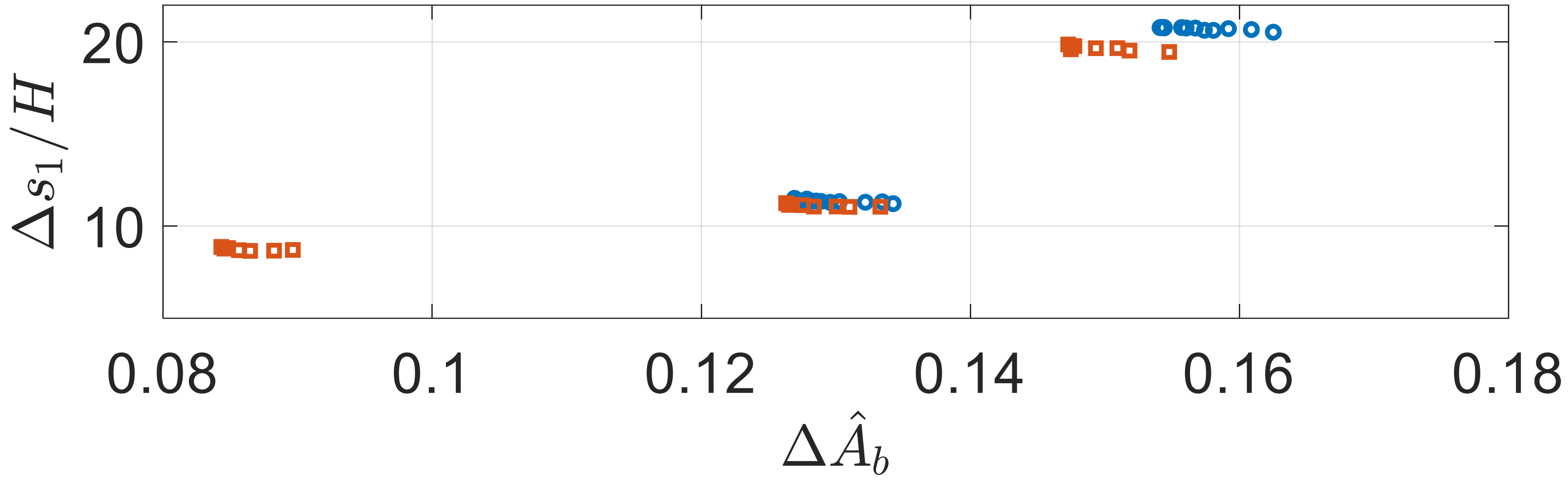
- Phase lock wall static pressure measurements using the relative area change A_b/A_{bi}
- Average over all forcing cycles
- Divide into:
  - Compression Response
  - Quasi-Steady Period
  - Expansion Response
- Normalize time by isolator acoustic time
  - $t_{iso} = \frac{L_{iso}}{a_0} = 3.1\text{ms}$

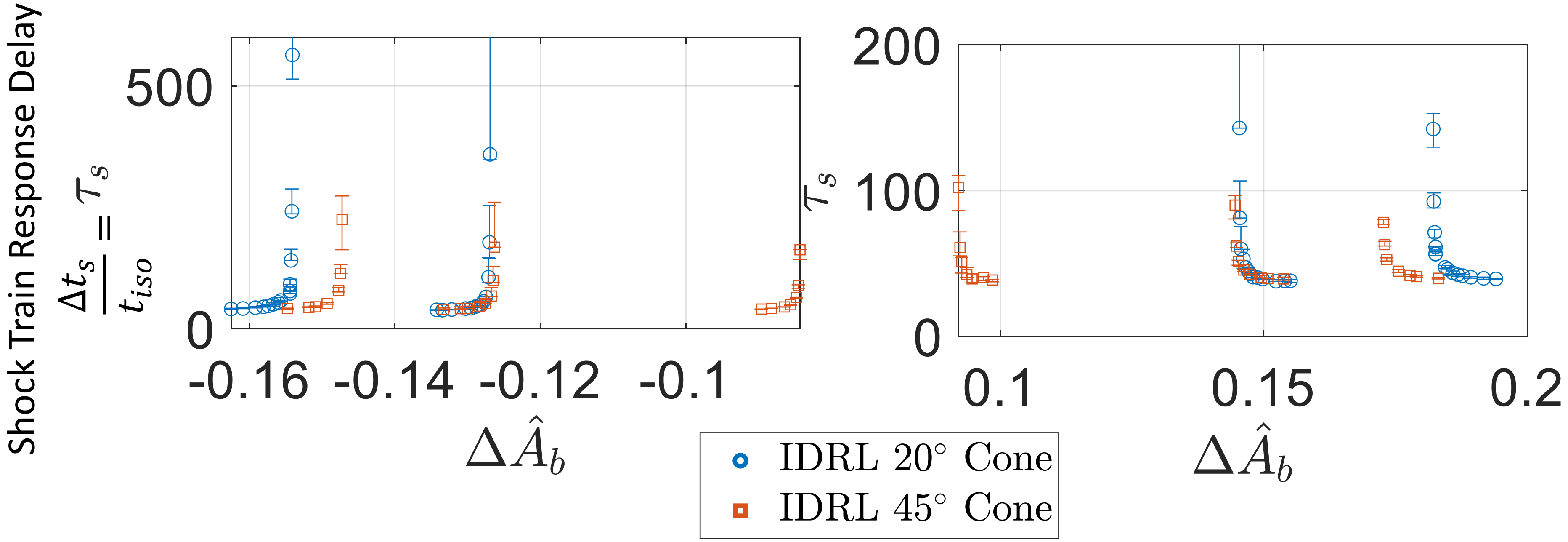
Normalized Bilevel Time Delay Analysis



- Min-max normalized by modes of bi-level phase-averaged signal
- $0 =$ Initial Position,
- $1 =$ Final Position
- Time delay from onset of forcing, τ, measured when the normalized signal reaches 0.1

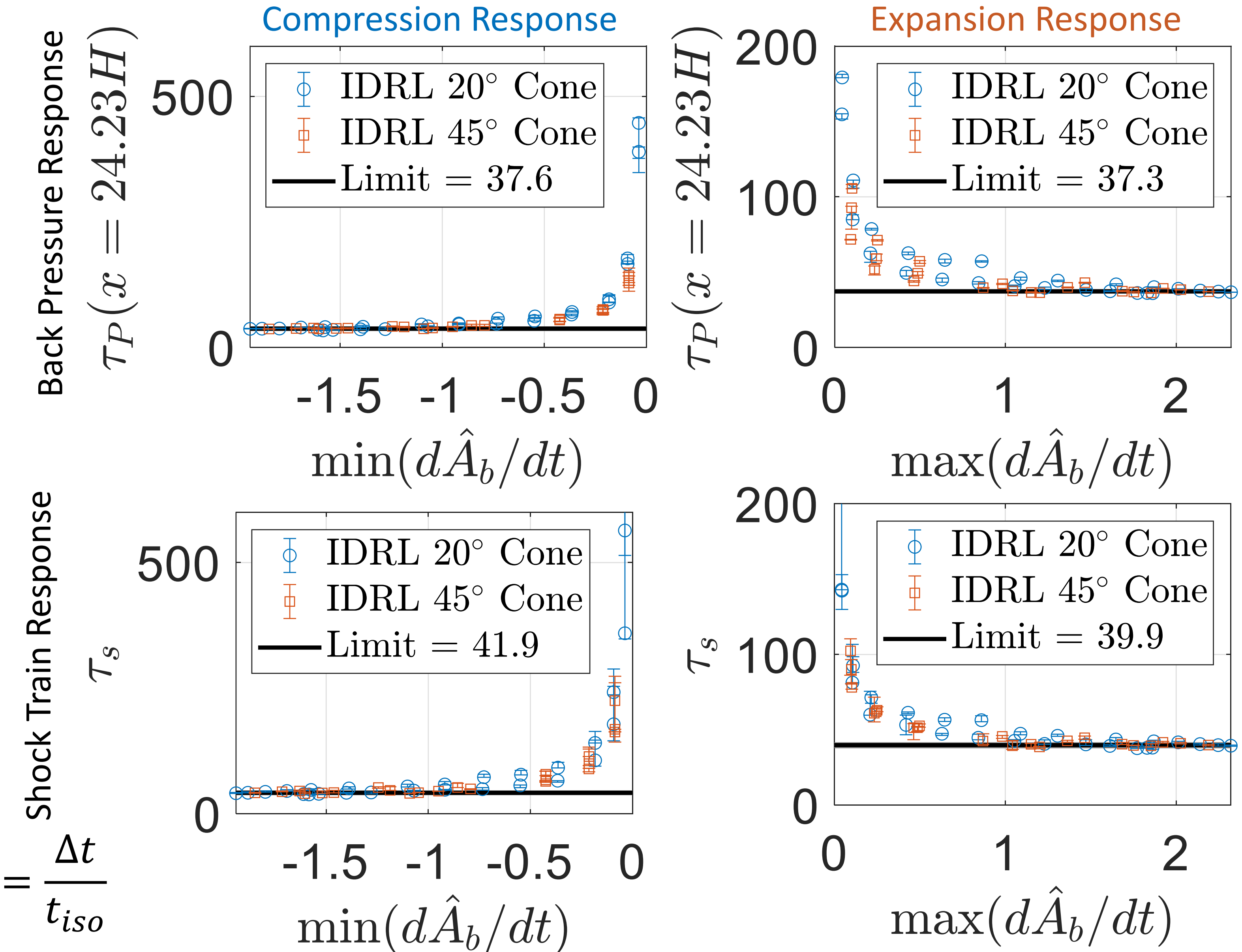
Shock Train Response to Forcing Magnitude

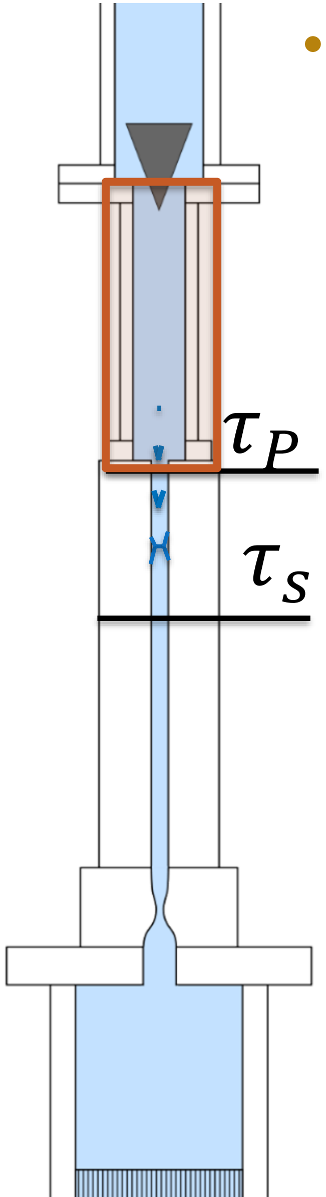




- Shock train streamwise movement, Δs_1, directly related to the magnitude of the blockage change $\Delta \hat{A}_b$.
- No correlation between $\Delta \hat{A}_b$ and shock train response delay, τ_{s_1}.

Response Dependence on Area Rate of Change





- Response delay of the isolator shock train system to back pressure pulses saturate.

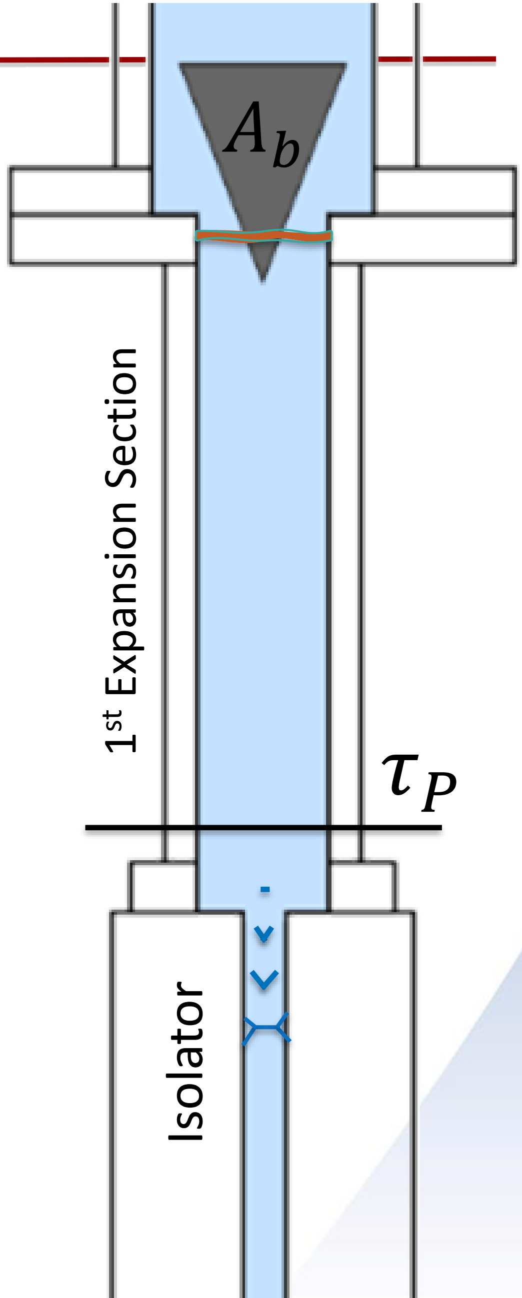
$$\tau = \frac{\Delta t}{t_{iso}}$$

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

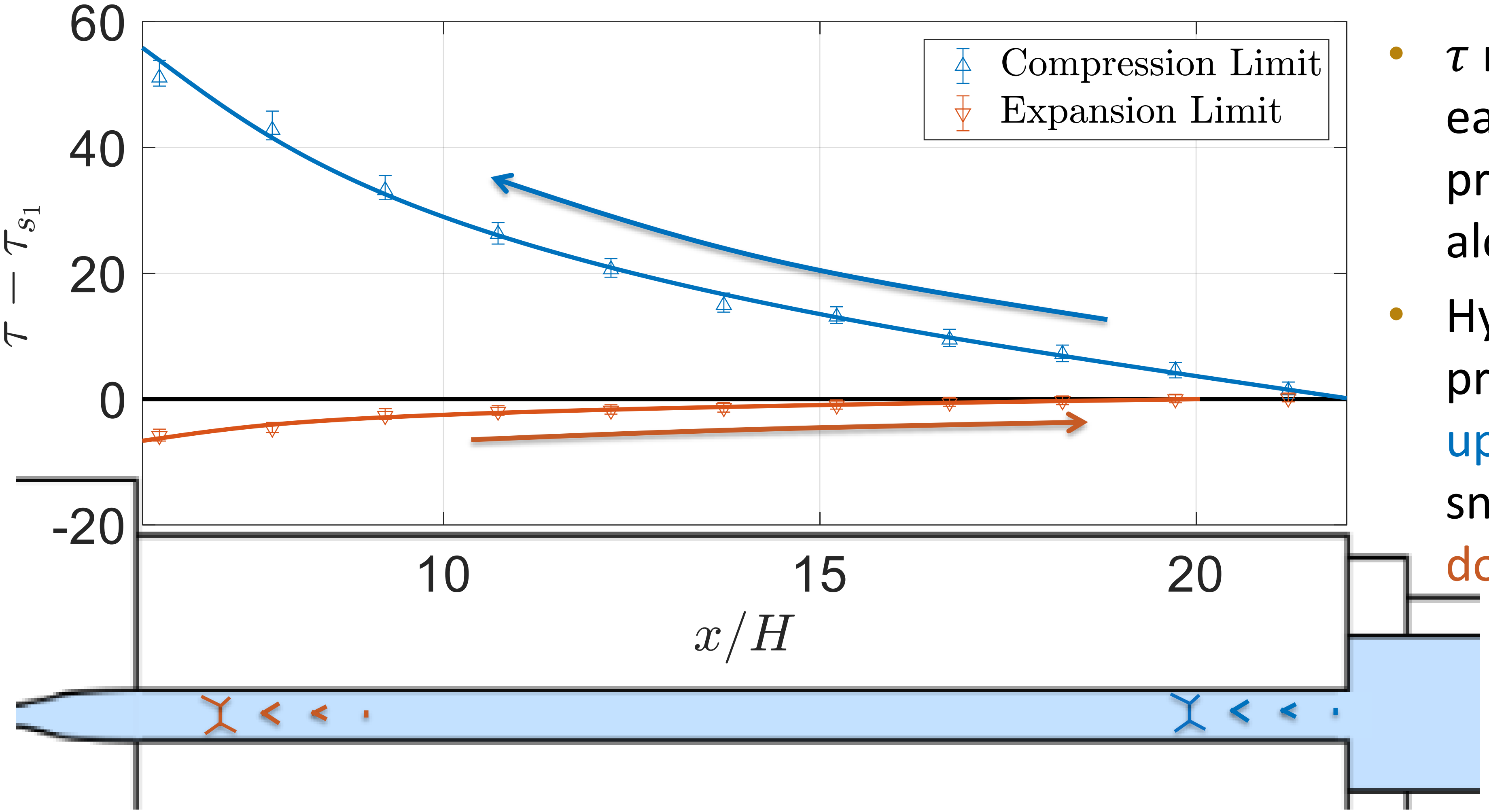
- τ_P and τ_s are indicators of when the shock train system initially responds

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
5. 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

- **Similar perturbation flow path to ramjets or scramjets with a flame-holder cavity**

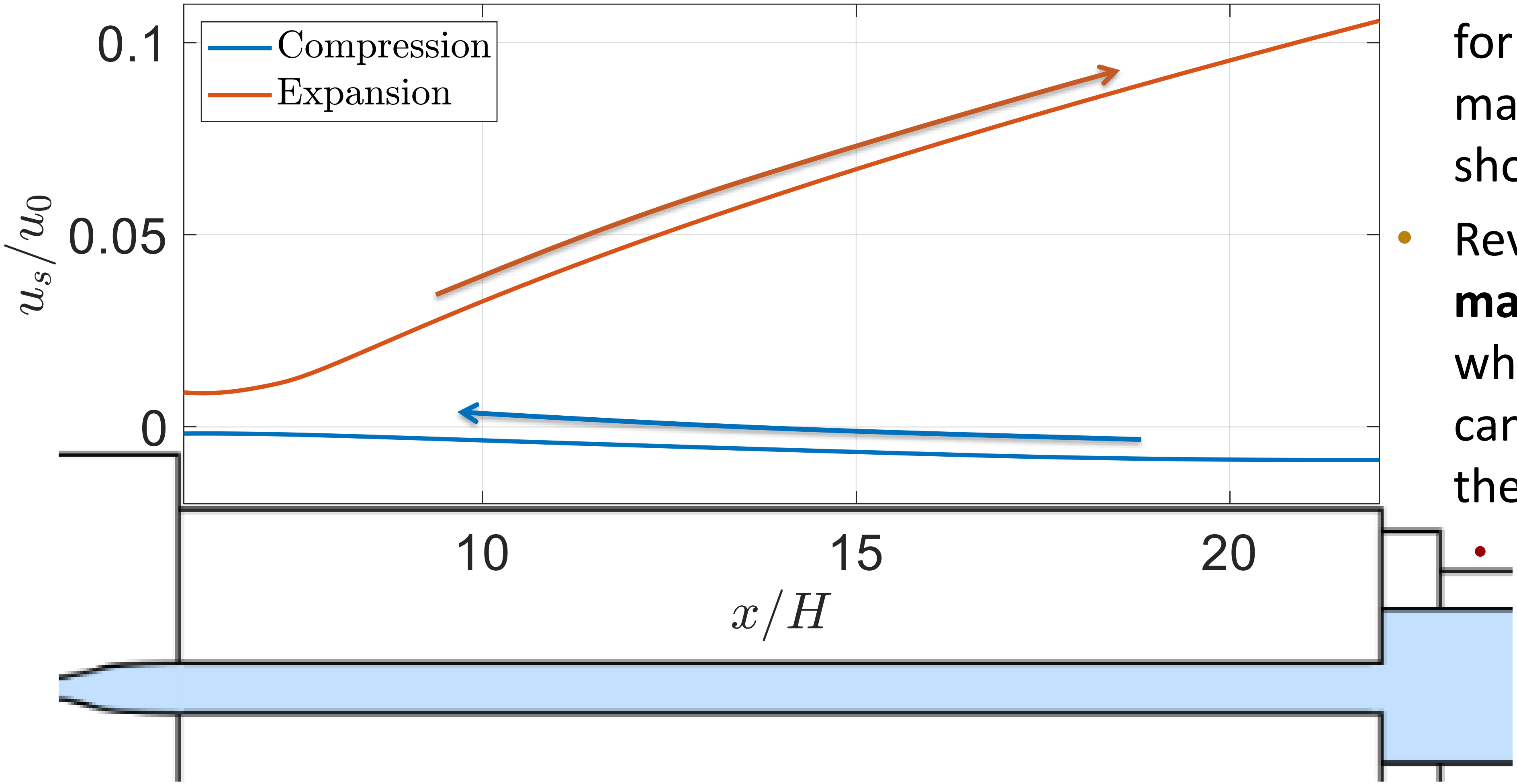


Limiting $d\widehat{A}_b/dt$ Time Delay Behavior



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

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



- Gradient of time delays for all forced magnitudes yields local shock train speeds
- Reveals there is a **local maximum speed** at which the shock train can propagate along the isolator
  - u_0 = Freestream Velocity at Isolator Inlet

Summary & Conclusions

- For throttling-like forced transients: the time delay between input and shock train response does not depend on the magnitude of the impulse.
- Streamwise motion of the shock train saturates to local maximum speeds with upstream and downstream-moving hysteresis.
- Control system design should be conscious of time delay and $\frac{d\hat{A}b}{dt}$ saturation point.
- Engine designers may be able to leverage flame holder cavity volume and response hysteresis to passively bias an isolator-combustor control algorithm towards stability.

Questions?