COLLEGE OF ENGINEERING
AEROSPACE ENGINEERING
UNIVERSITY OF MICHIGAN

A Joint Experimental/Computational Study of Non-idealities in Practical Rotating Detonation Engines

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DOE FE0025315 with Dr. Mark C. Freeman as Program Monitor

Outline

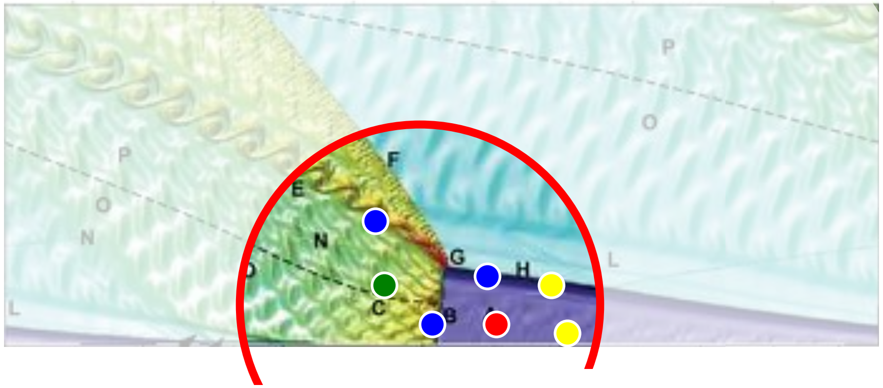
- Introduction to the problem and general approach
- Experimental activities
- Computational activities

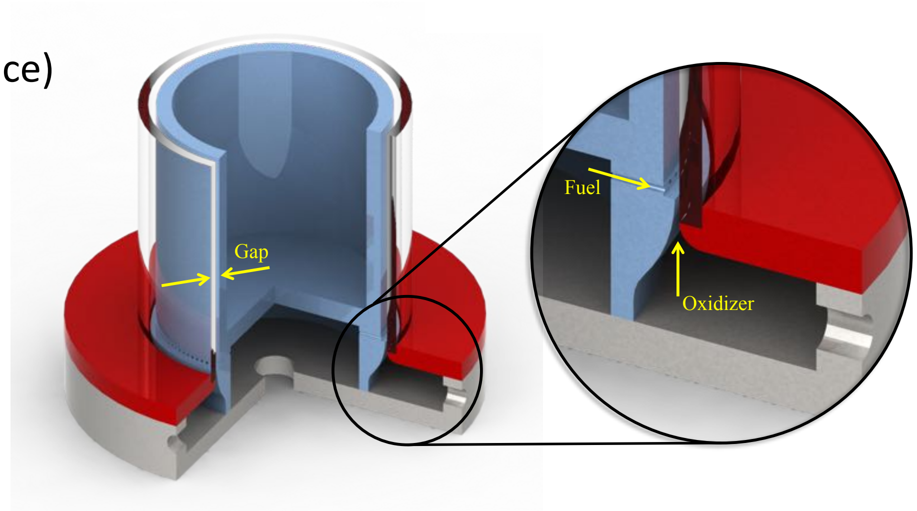
Overarching objectives

- **Use laser diagnostics to:**
  - Develop canonical systems for RDE investigation
  - Understand the physics of RDE in lab- and full-scale configurations
  - Provide data for validation

- **Use high-fidelity simulations to:**
  - Understand basic detonation physics
  - Simulate full scale RDEs

Overarching goal:
investigate non-idealities and their link to loss of pressure gain

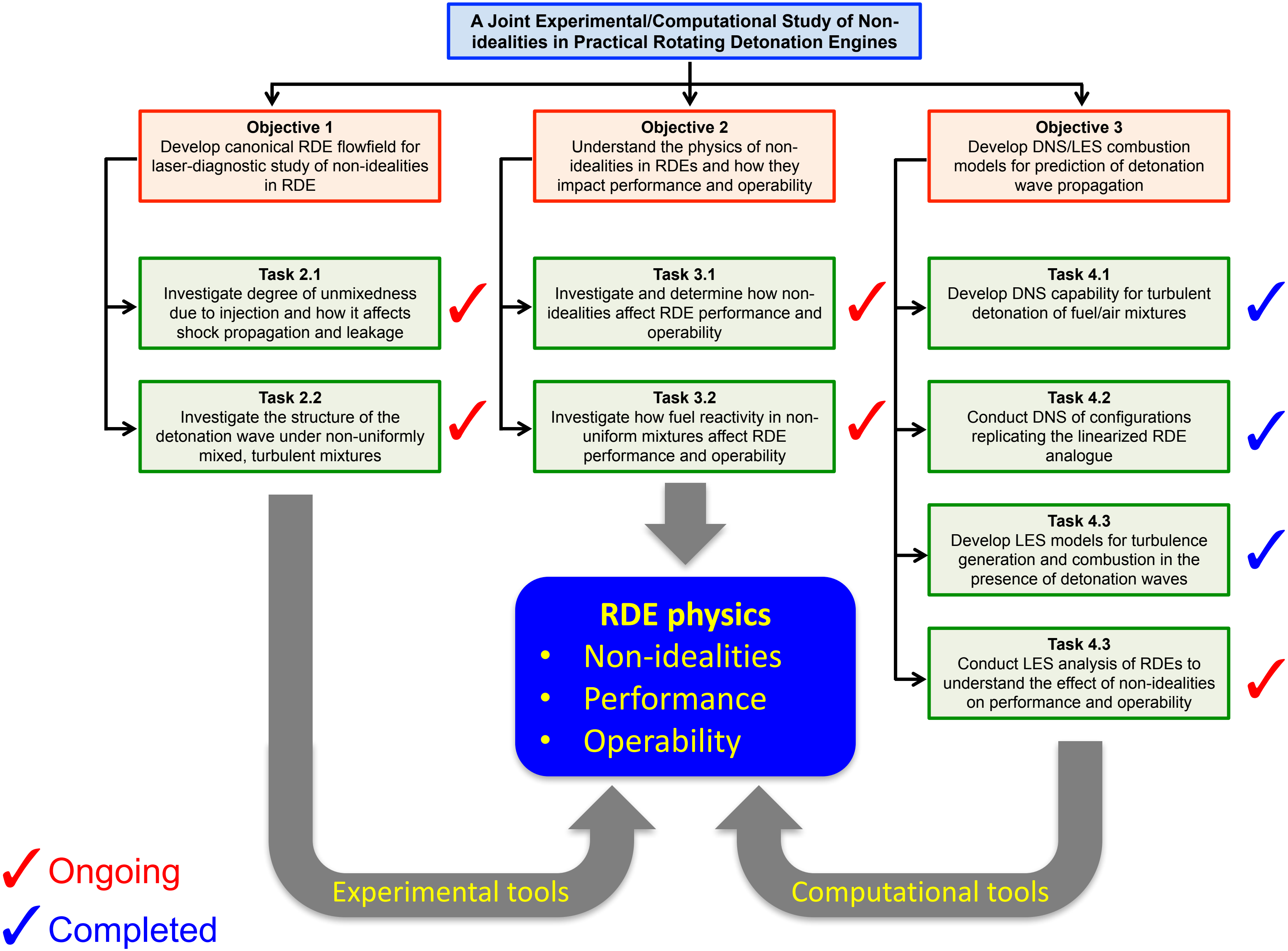




- Detonation non-idealities
  - – Incomplete fuel/air mixing
  - – Fuel/air charge stratification
  - – Mixture leakage (incomplete heat release)
  - – Parasitic combustion:
    - Premature ignition (e.g., burnt/unburnt interface)
    - Stabilization of deflagration (flame)
  - – Detonation-induced flow instabilities
    - Richtmyer-Meshkov (R-M) instability
    - Kelvin-Helmholtz (K-H) instability
- They lead to loss in pressure gain
  - – Linked to loss of detonation propagation
- Additional losses exist during flow expansion
  - – Secondary shock and (multiple) oblique shock
  - – Flow instabilities (e.g., K-H instability)
  - – Mixture leakage through burn/unburnt interface

From:
(top) Nordeen et al., AIAA 2011-0803

Objectives and tasks



Our approach: a multi-level physics study

Practical RDE

↓

Unit-physics decomposition

Diagnostics

- Laser-based imaging
- Mixing measurement
- Detonation structure
- Temperature and species imaging

Injection & mixing

- Multiple injection mixing
- Shock-induced mixing
- DNS/LES modeling
- Experiments

Turbulence & detonations

- Linear analogue
- Detonations in stratified mixtures
- DNS/LES modeling
- Experiments

Detailed modeling

- Variable mixture ignition model
- Homogeneous reactor model with tabulated ignition times
- Non-equilibrium

Today we will discuss

- **Experimental component:**
  - Update on experimental development
  - Overview of round RDE work
  - What we have learnt so far on round RDE
  - Some thoughts

- **Computational component:**
  - Effect of injector mixing on detonation propagation
  - Detonation / plenum interactions
  - Full-system simulations

Outline

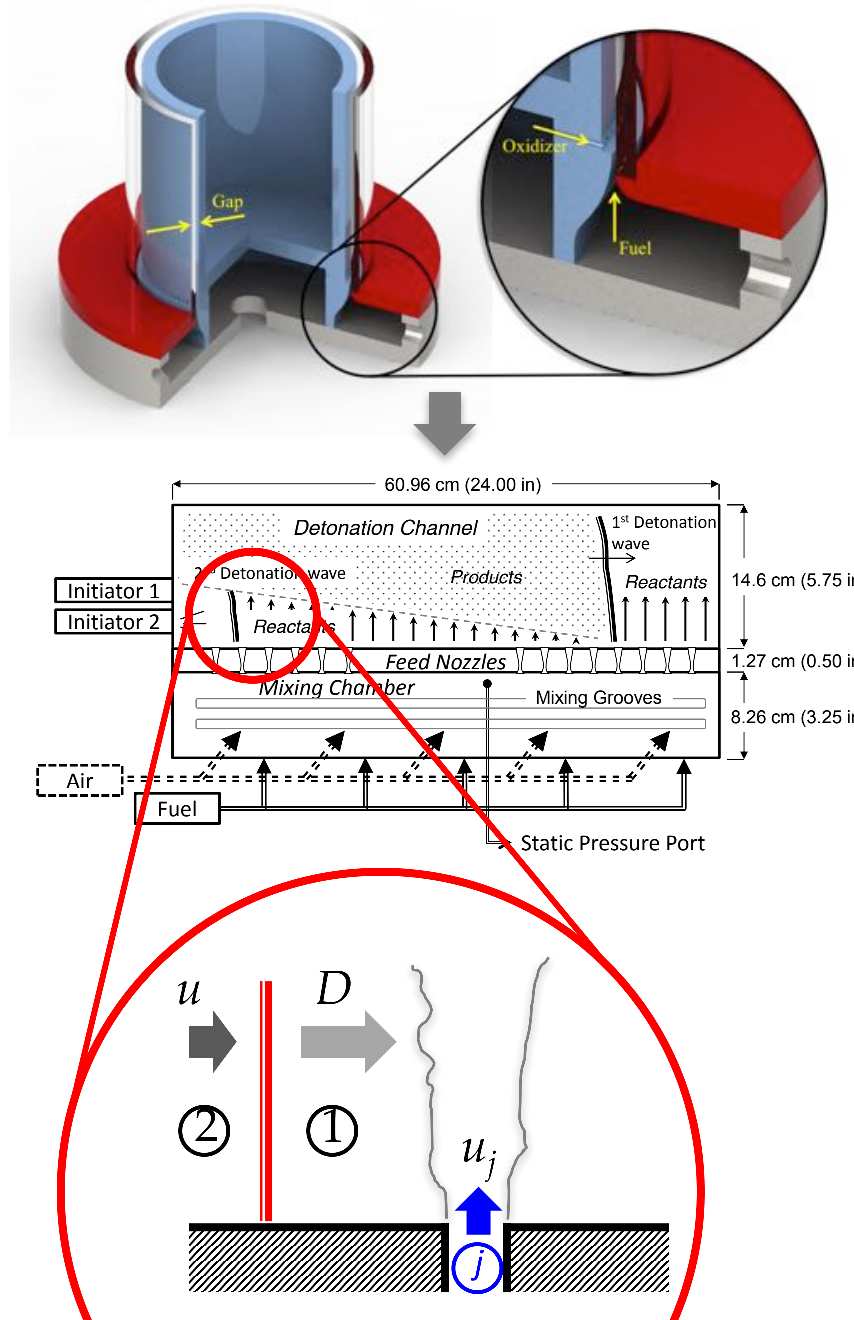
- Introduction to the problem and general approach
- Experimental activities
- Computational activities

Planned experimental multi-level approach

RDE full system:
- Link between mixing and performance
- Design from ISSI/AFRL

Linearized analogue:
- Detonation structure
- Detonation/turbulence interaction
- Detonation in stratified mixtures
- Design from ISSI/AFRL

Single or multiple injectors:
- Mixing studies
- Shock-induced mixing
- Our starting point

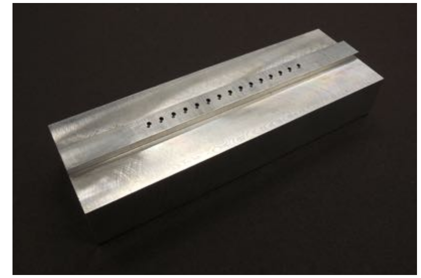


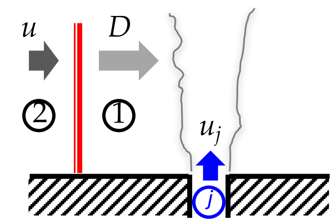
Hierarchy

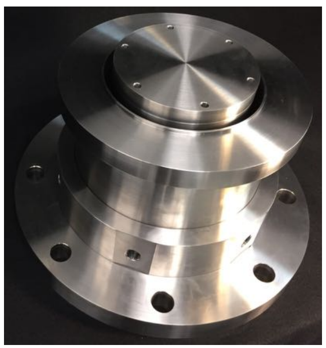
Experimental program in practice

Scope is the same, methods and hardware have improved

- **Injector sector subassembly**
  - Sector of RDE injector for shock-induced mixing and mixing effectiveness measurements

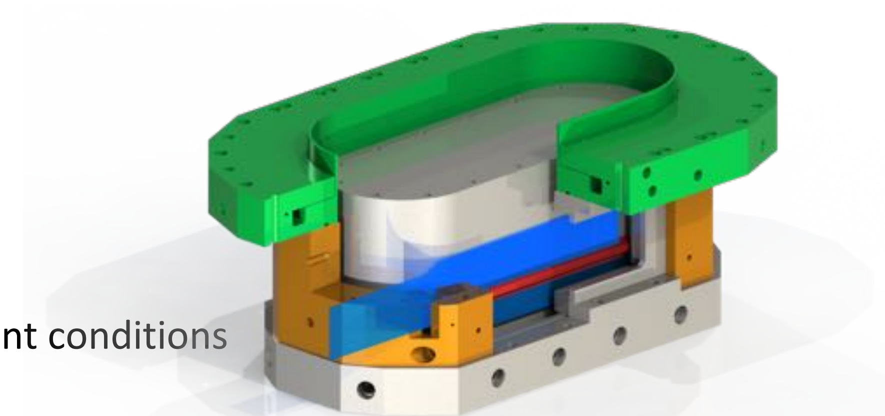






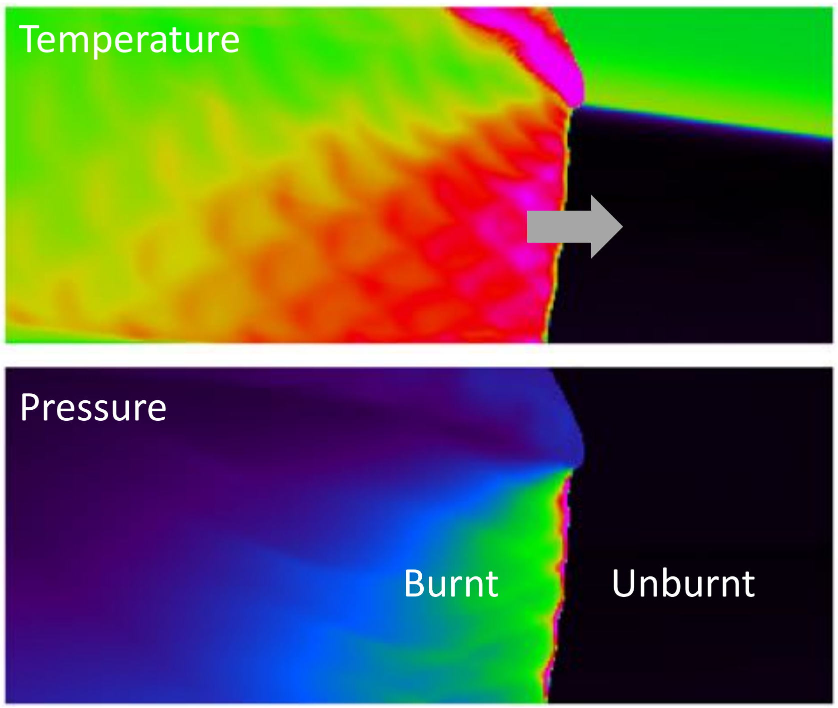
- **Reduced-scale RDE (6” RDE platform)**
  - Operational with H_2/Air, various flow rates and equivalence ratios
  - Being expanded continuously
    - E.g., additional instrumentation added continuously

- **Optical RDE (Race-Track RDE)**
  - Fabrication being completed soon (mid-November)
  - Equivalent to 12” round RDE
  - Used for flowfield measurements under RDE relevant conditions

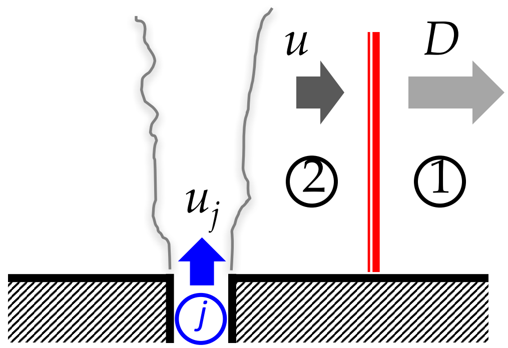


Shock-induced mixing: detonation/shock analogy

Detonation



Shock analogy

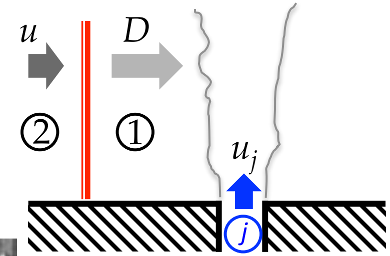


$$\frac{u_2}{u_j} \;\&\; \frac{\rho_2}{\rho_j}$$

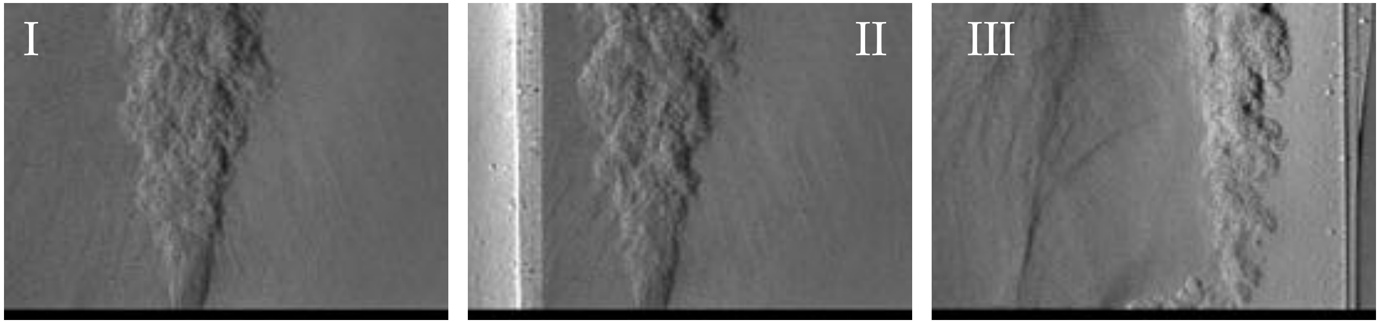
- Important parameters
  - Wave speed *D* (Mach number)
  - Jet-to-ambient (induced flow) density and velocity ratios
  - Injection pressure and configuration

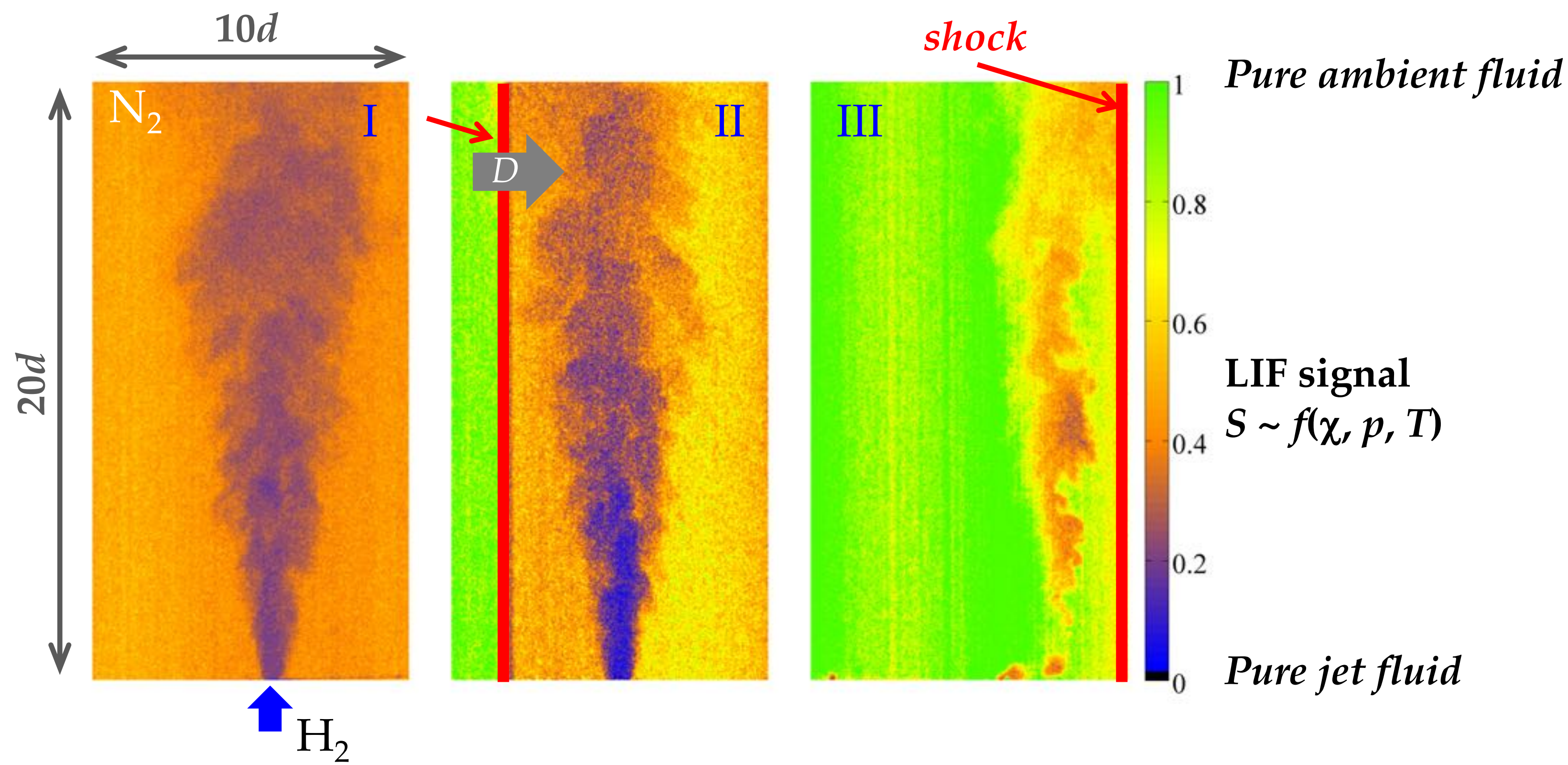
From: Schwer D. A. and Kailasanath K., AIAA 2010-6880

Interaction of shock wave with turbulent jet



From the past…





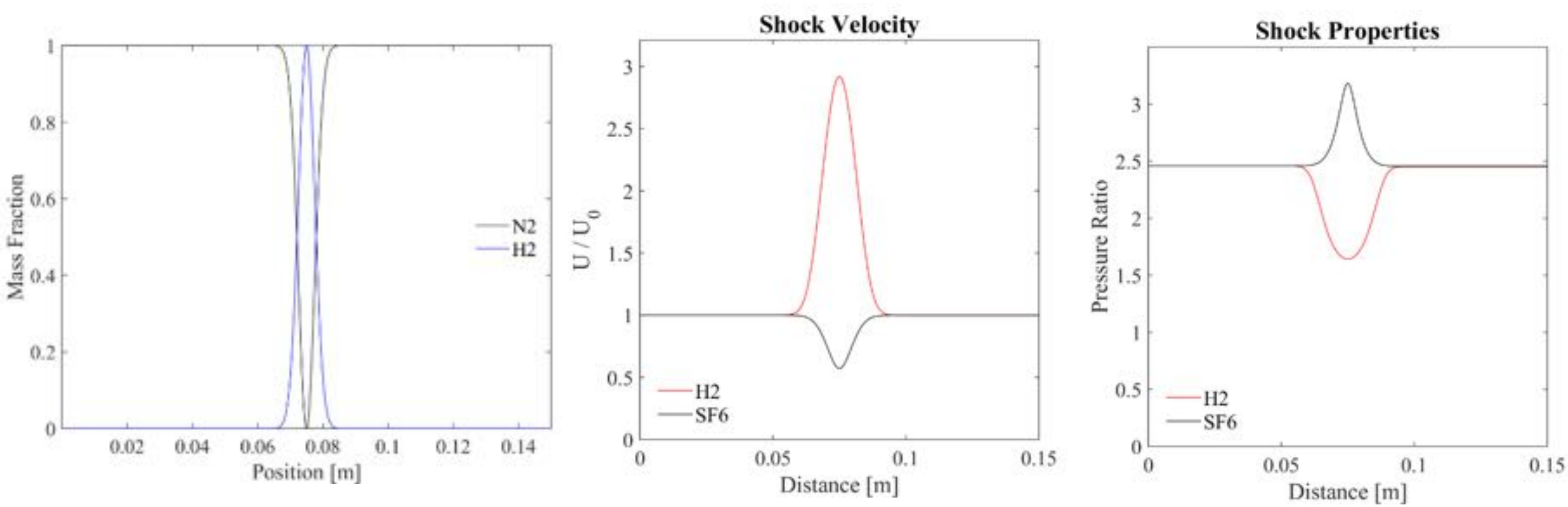
Working toward a theoretical model of shock-propagation through a stratified gas

Based on method of characteristics for multi-isentropic, variable-properties flows:

$$\frac{\delta^+ u}{\delta t} + \frac{1}{\rho a}\frac{\delta^+ P}{\delta t} = \frac{a(\gamma-1)}{\gamma R}\frac{Ds}{Dt} + \frac{a}{\gamma R}\frac{DR}{Dt}$$

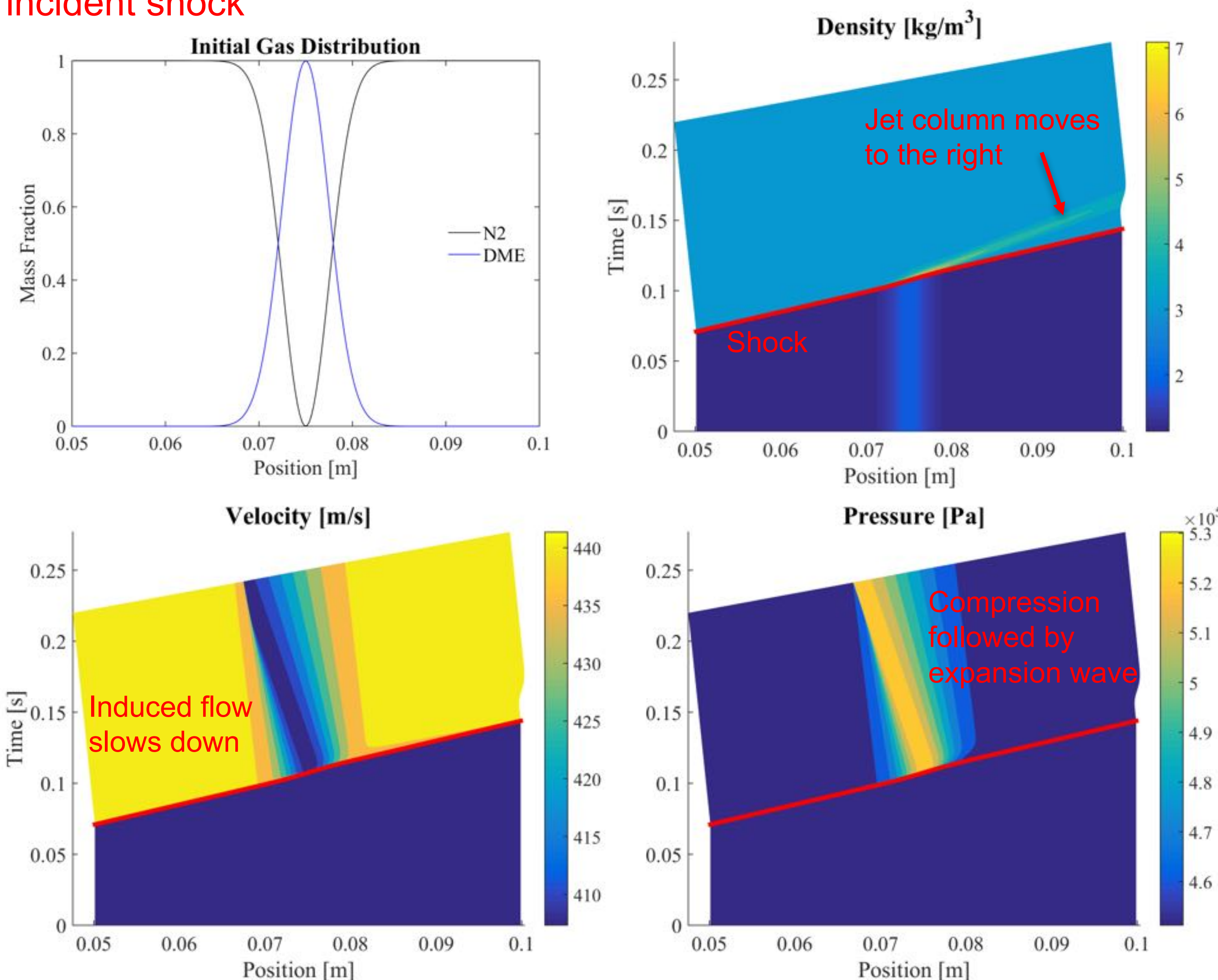
$$\frac{\delta^+}{\delta t}\left(u + \frac{2a}{\gamma-1}\right) = \frac{a}{R(\gamma-1)}\frac{\delta^+ R}{\delta t} - \frac{a(\gamma+1)}{\gamma(\gamma-1)^2}\frac{\delta^+ \gamma}{\delta t} + \frac{a}{\gamma R}\frac{\delta^+ s}{dt} + \frac{a(\gamma-1)}{\gamma R}\frac{Ds}{Dt}$$

where $\frac{\delta^+}{\delta t} = \frac{D}{Dt} + a\frac{d}{dx}$



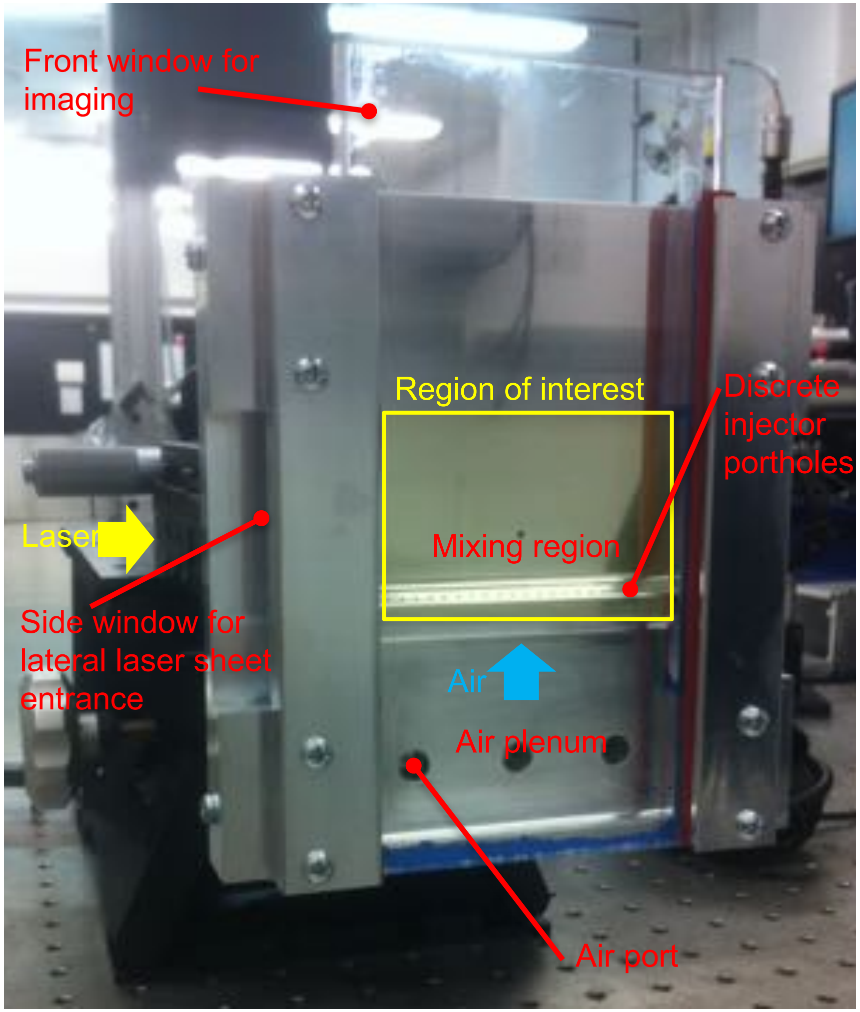
Example: propagation of shock wave across a heavy jet

DME jet into Nitrogen
Mach 2 incident shock

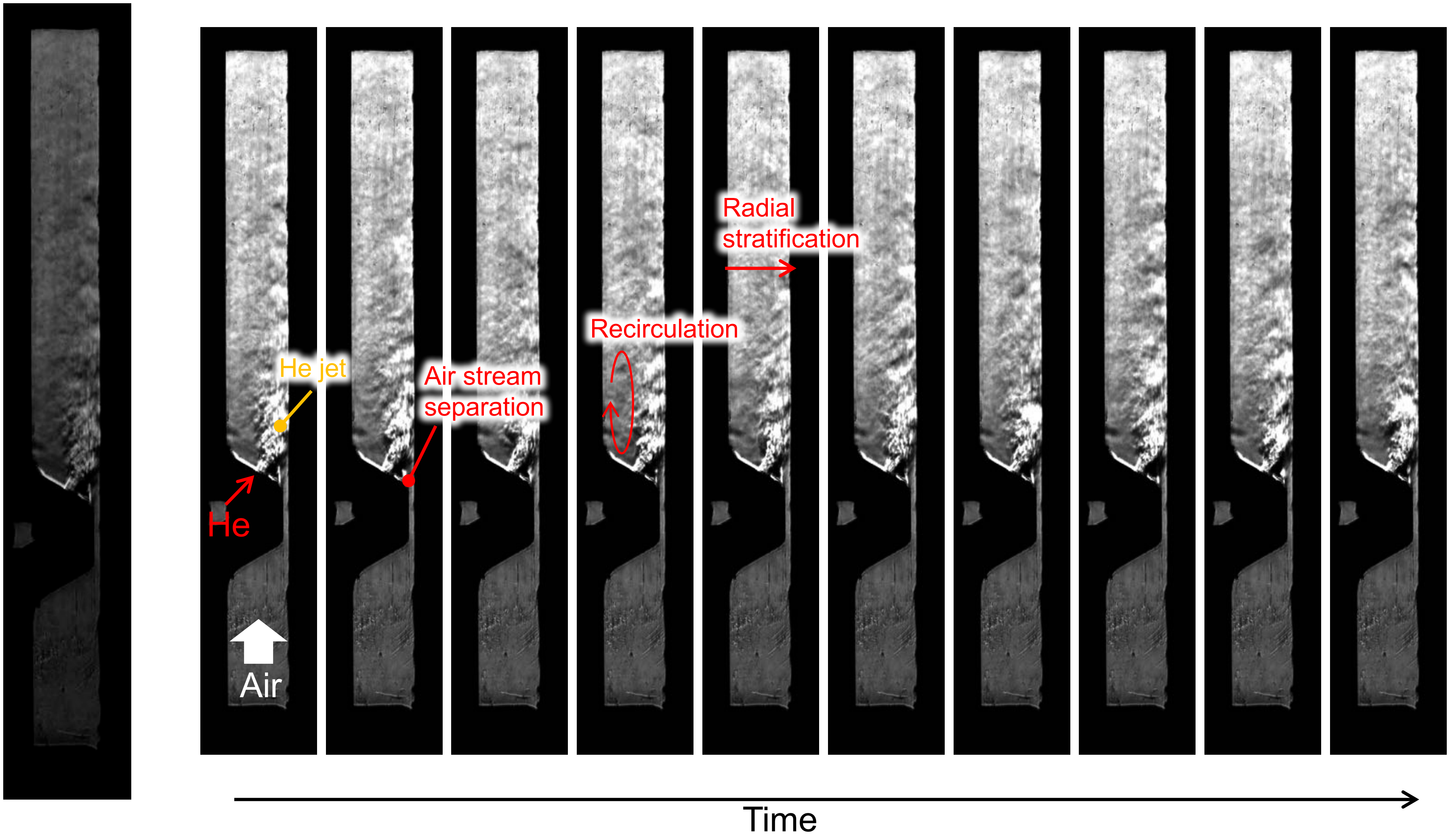


Added a benchtop injector sector (photograph of pintle)

- Sector of 6” round RDE geometry
  - Same injector
  - 1/8th diameter equivalent of round RDE
  - Optical access for laser diagnostics
- Used in support of”
  - Mixing measurements
  - Injector flowfield evaluation



Schlieren imaging to identify flow structure (non-reacting mixing)



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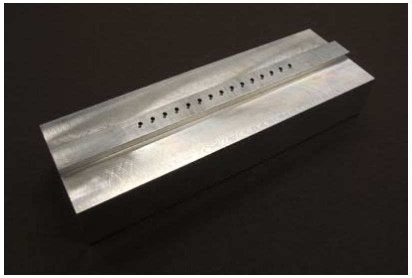
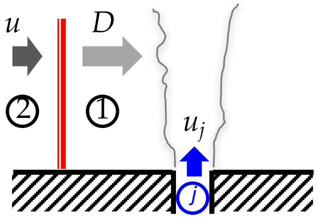
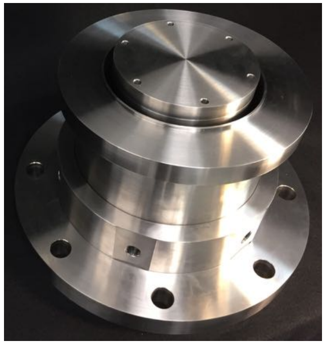
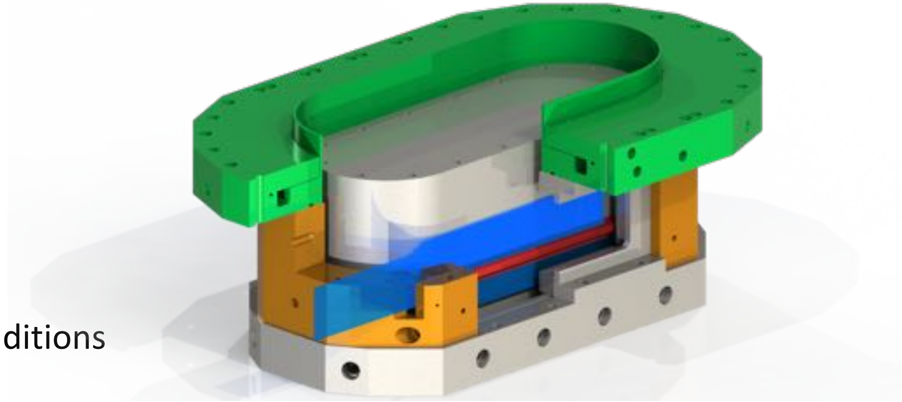






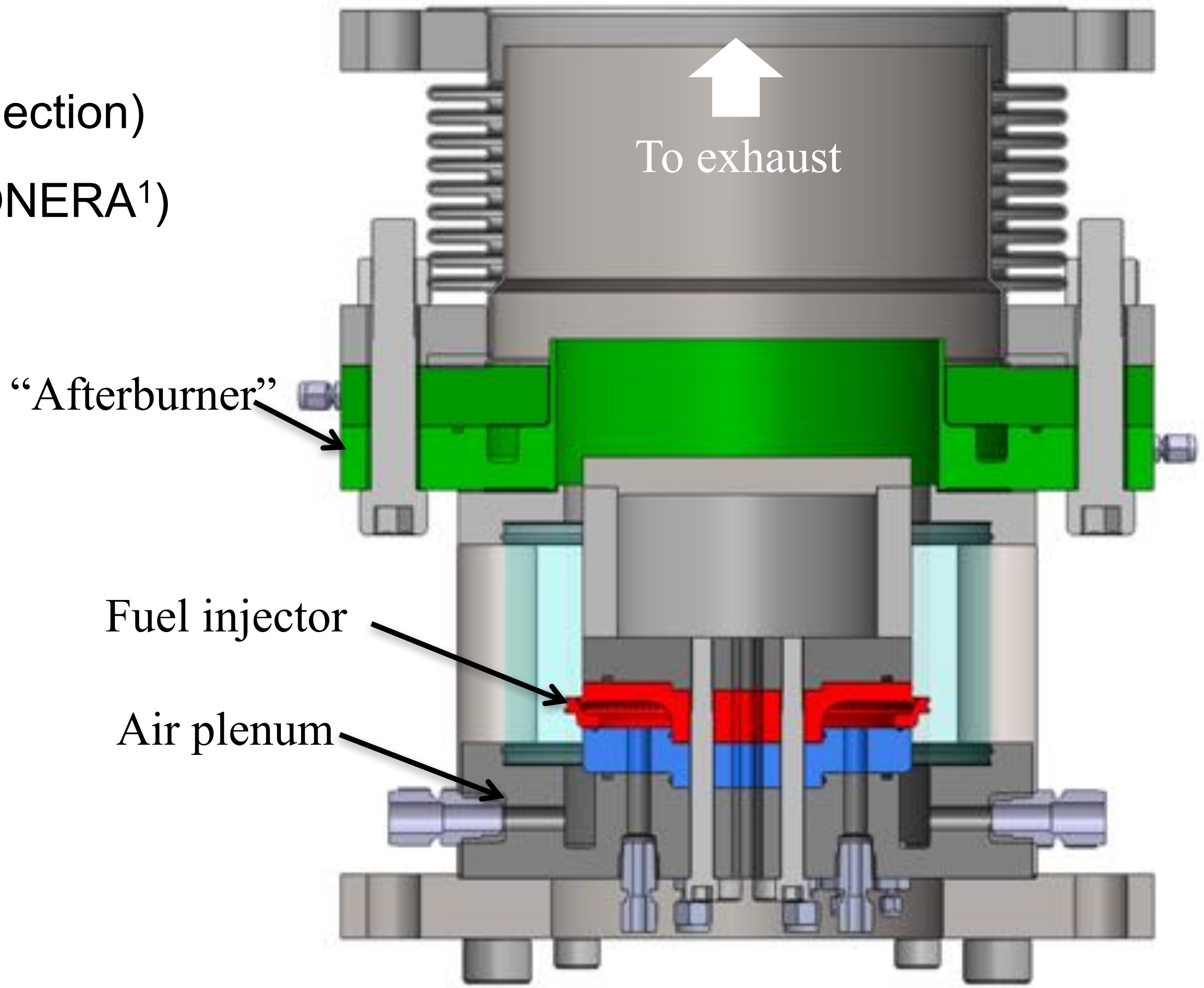
- **Reduced-scale RDE (6" RDE platform)**
  - Operational with H_2/Air, various flow rates and equivalence ratios
  - Will be expanded to include:
    - MCFs capability
    - Additional instrumentation to investigate RDE dynamics

- **Optical RDE (Race-Track RDE)**
  - Fabrication being completed soon (mid-november)
  - Equivalent to 12" round RDE
  - Used for flowfield measurements under RDE relevant conditions



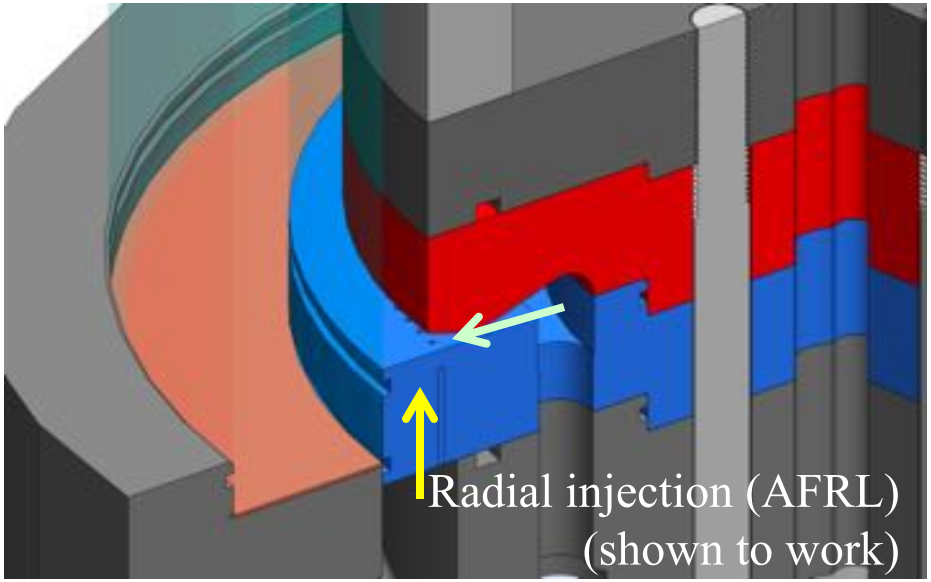
A flexible round RDE at U-M

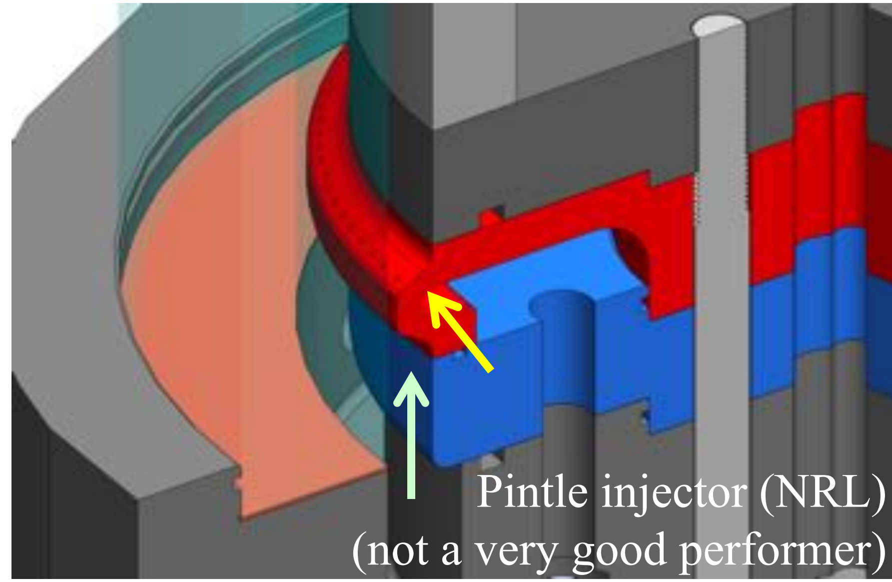
- Modular configuration
- Multiple injection schemes
  - AFRL design (radial injection)
  - Semi-impinging jets (ONERA[1])
  - Pintle injector (NRL[2])

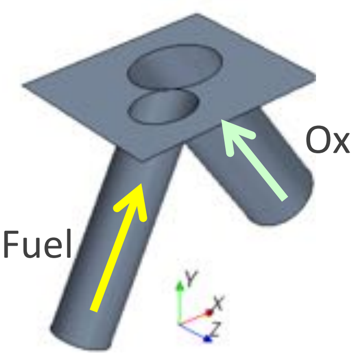


[1] Gaillard et al., Acta Astronautica, 111:334-344 2015
[2] Schwer & Kalaisanath, 2015 AIAA Scitech, AIAA-2015-3782

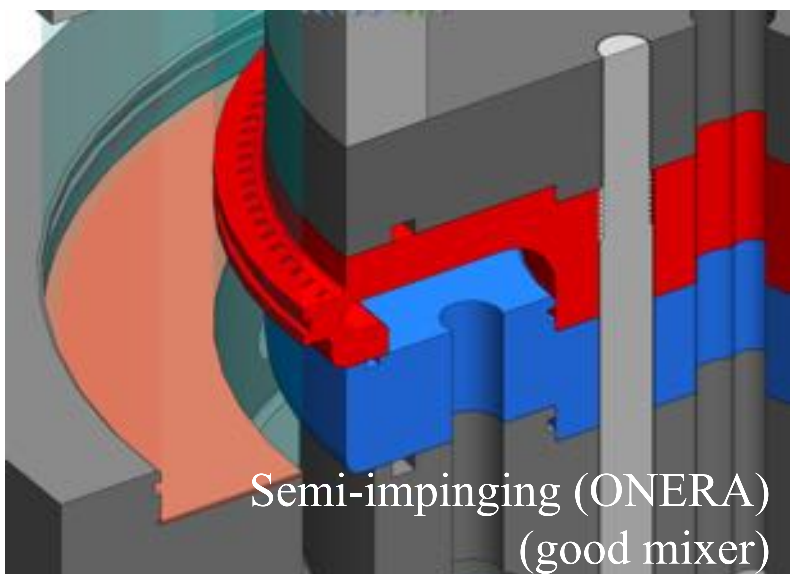
Injection schemes considered so far

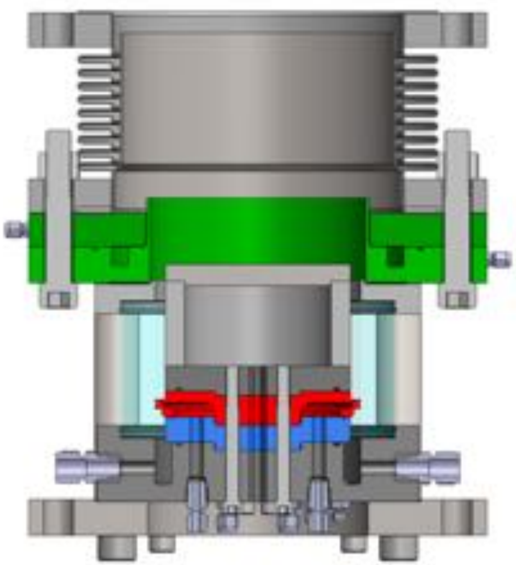






From Gaillard et al., Acta Astronautica, 111:334-344 2015

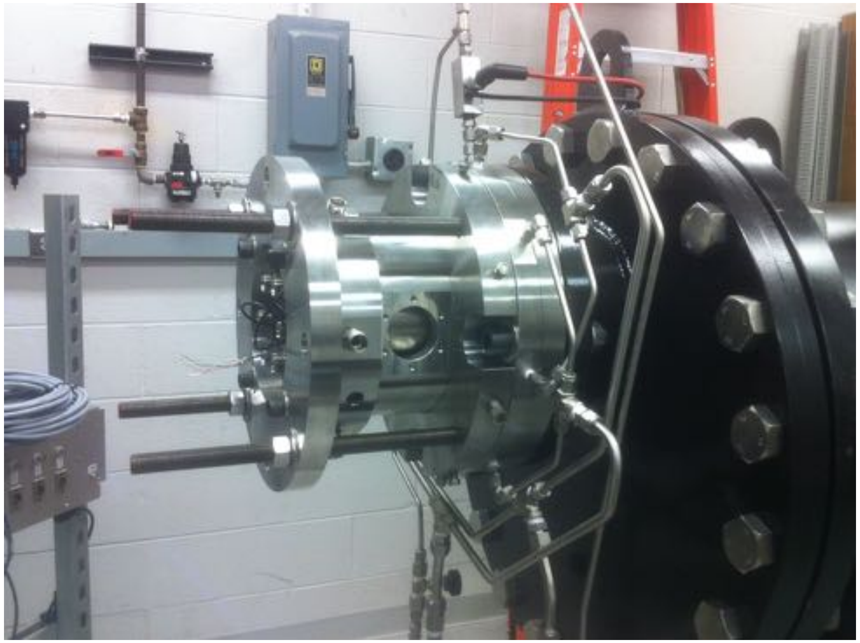




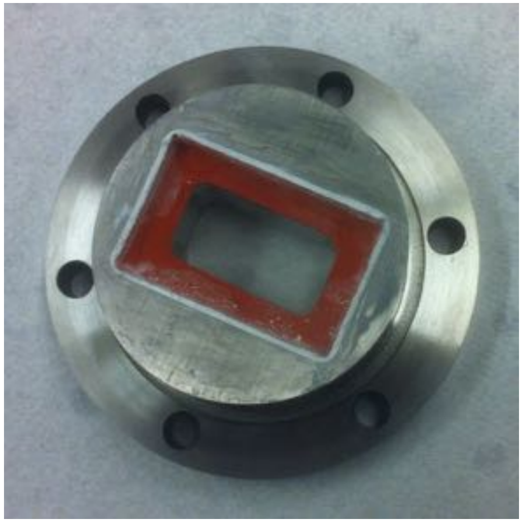
When first assembled

Some changes from last time: additional instrumentation

Modified RDE

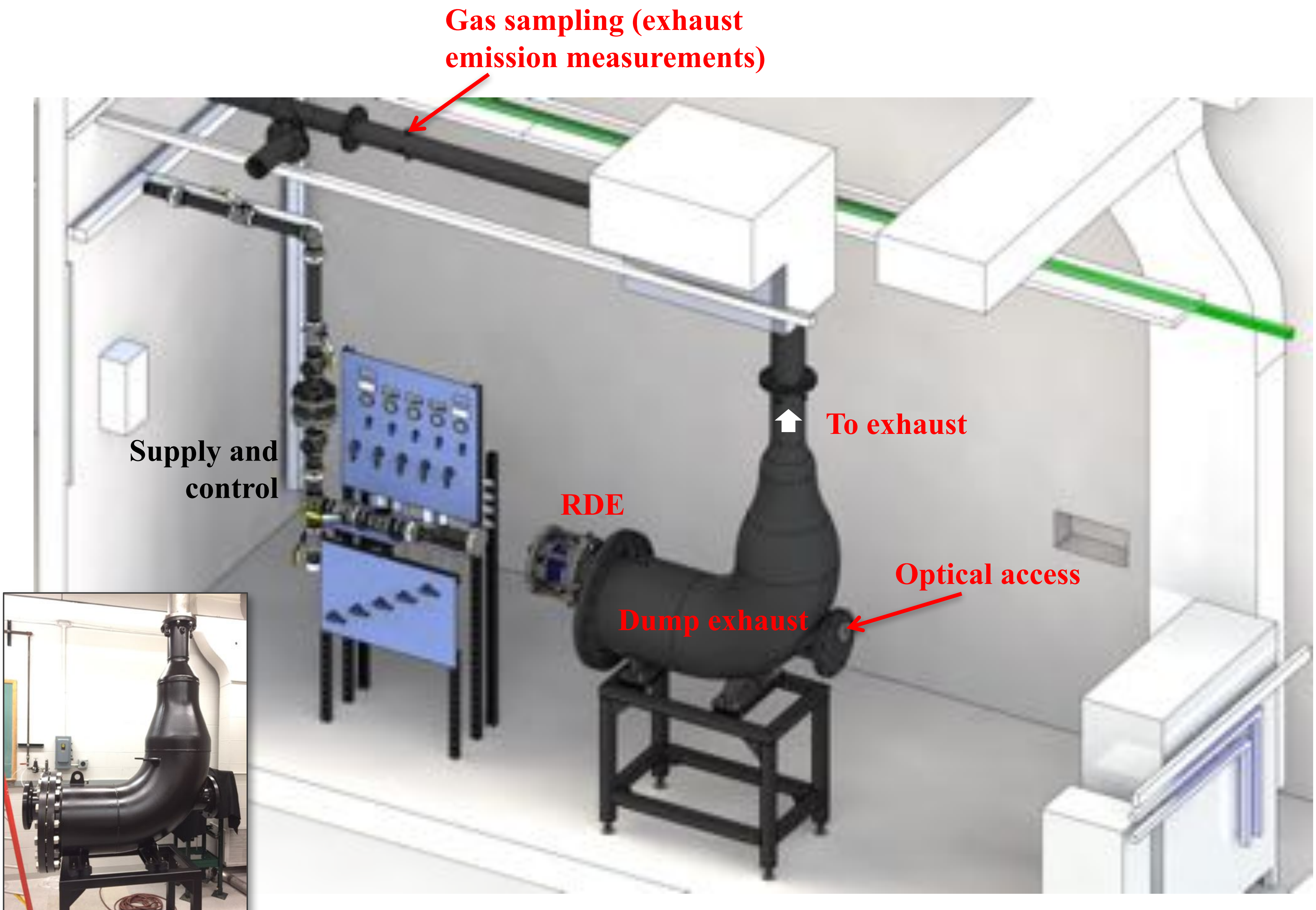


Instrumentation (16-channel CTAP)

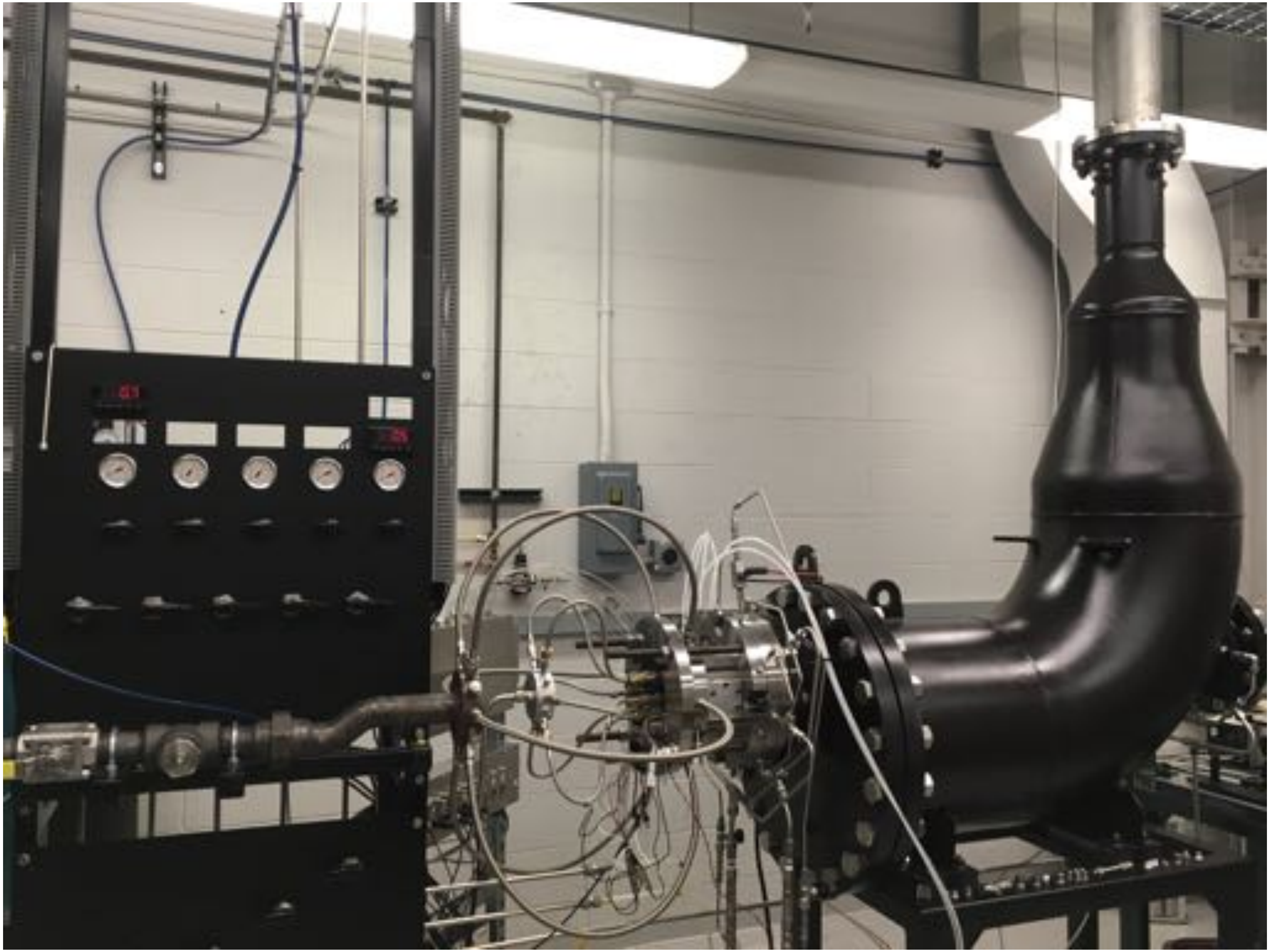


Window mount for round RDE

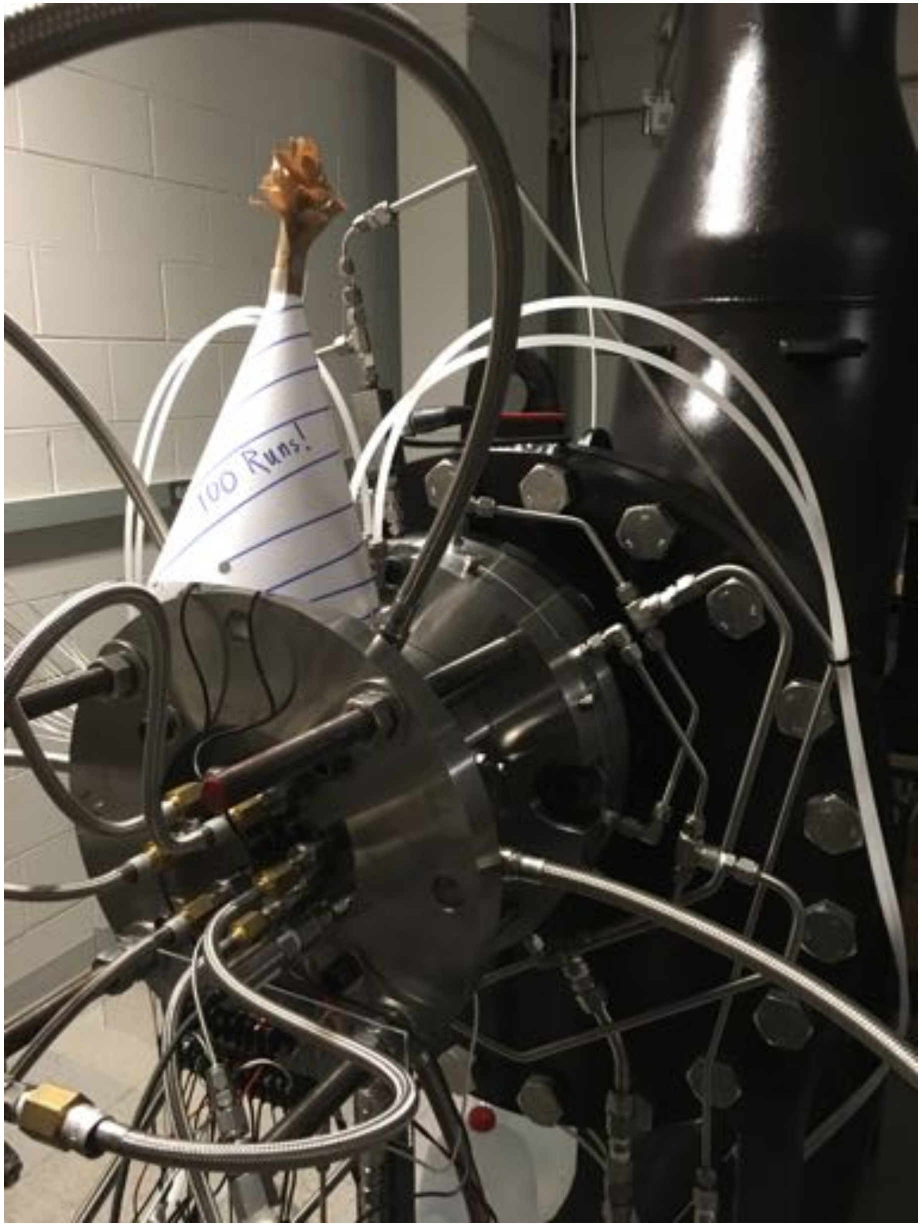
What I said last year: *How it will look like after integration is completed*



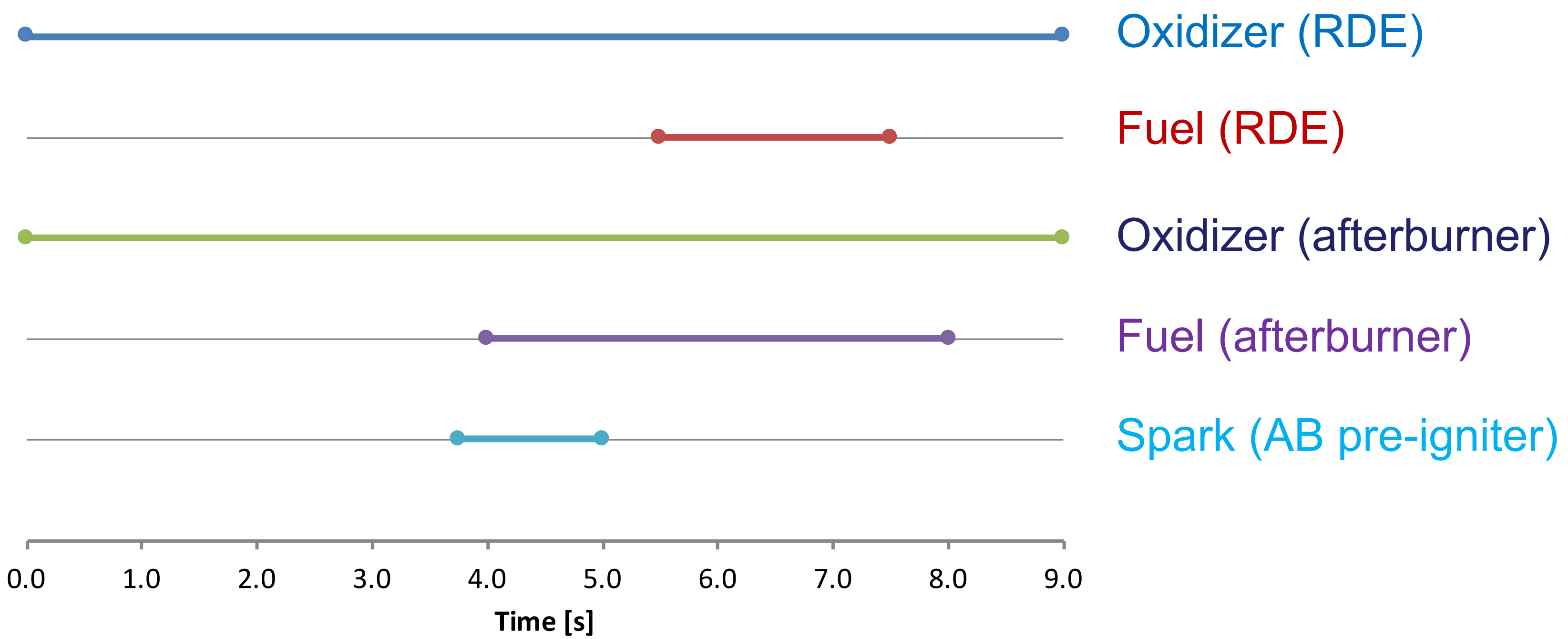
How it actually looks today



… And after many runs: 100th run of the RDE



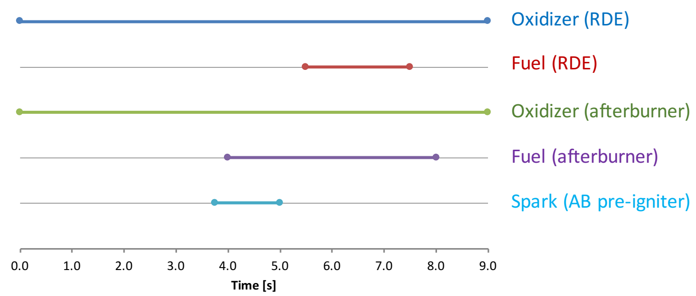
Typical test sequence



- **(Some) instrumentation:**
  - High-speed movies of detonation wave
  - Air/fuel inlet manifold pressures
  - Air and fuel mean plenum pressures
  - Air and fuel plenum dynamic pressures
  - Exhaust pressure measurements
  - CTAP from inlet to exhaust
  - Detonation channel dynamic pressure (PCB)
  - Detonation channel dynamic and mean pressure (Kulite)
  - Acoustic signature (external)

Typical test sequence (camera)

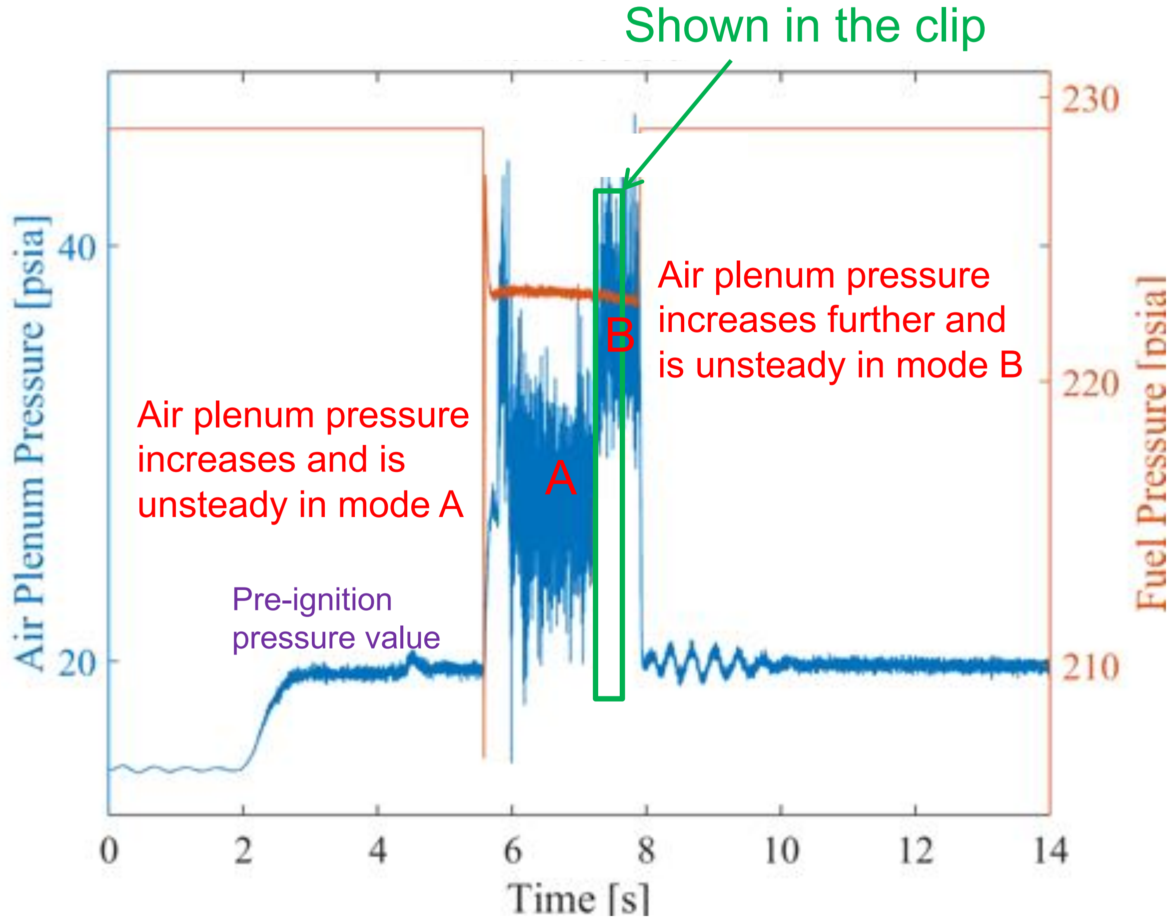
(Mind the noise – perhaps turn down the volume)



30 fps camera view

High speed detonation movie – end view (175 g/s; $\phi = 1$)

High speed chemiluminescence imaging
(end view at 25,000 fps, 25 μs exposure)



Two modes of operation:

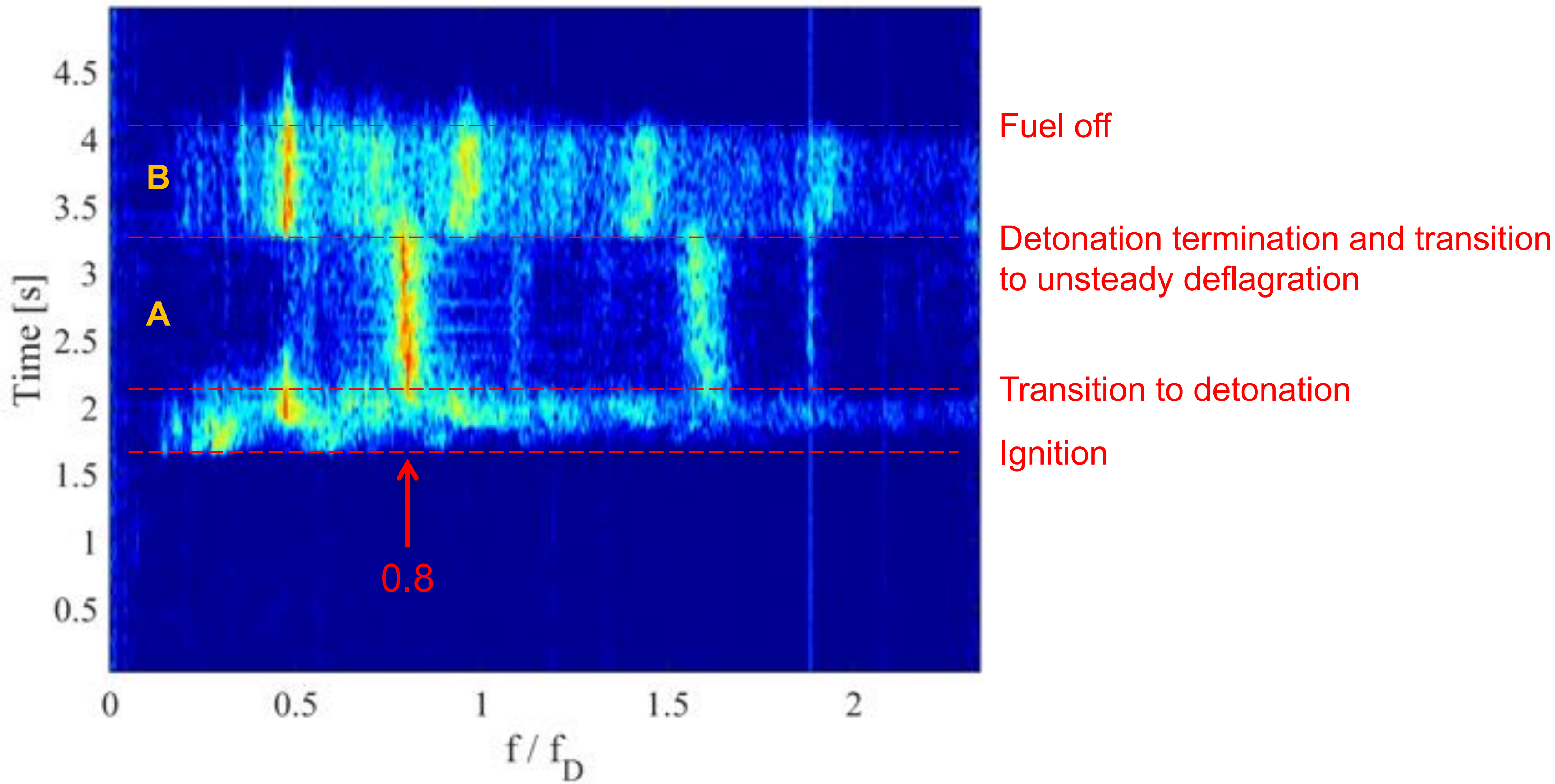
A. Detonation (perhaps?)

B. Deflagration (with axial/azimuthal instabilities)

The mode of operation can be recognized in the video in the left and the acoustic signature

A. Detonating mode: acoustic signature (175 g/s; $\phi = 1$)

Waterfall power spectrum of acoustic signature measured with a microphone:

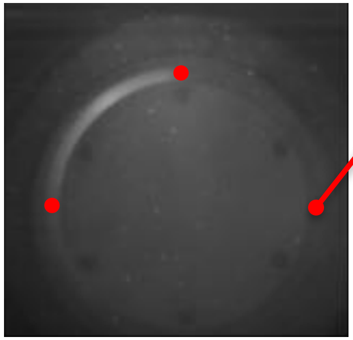


$f_D = \frac{D_{CJ}}{\pi d}$: detonation frequency (≅ 4.1 kHz)

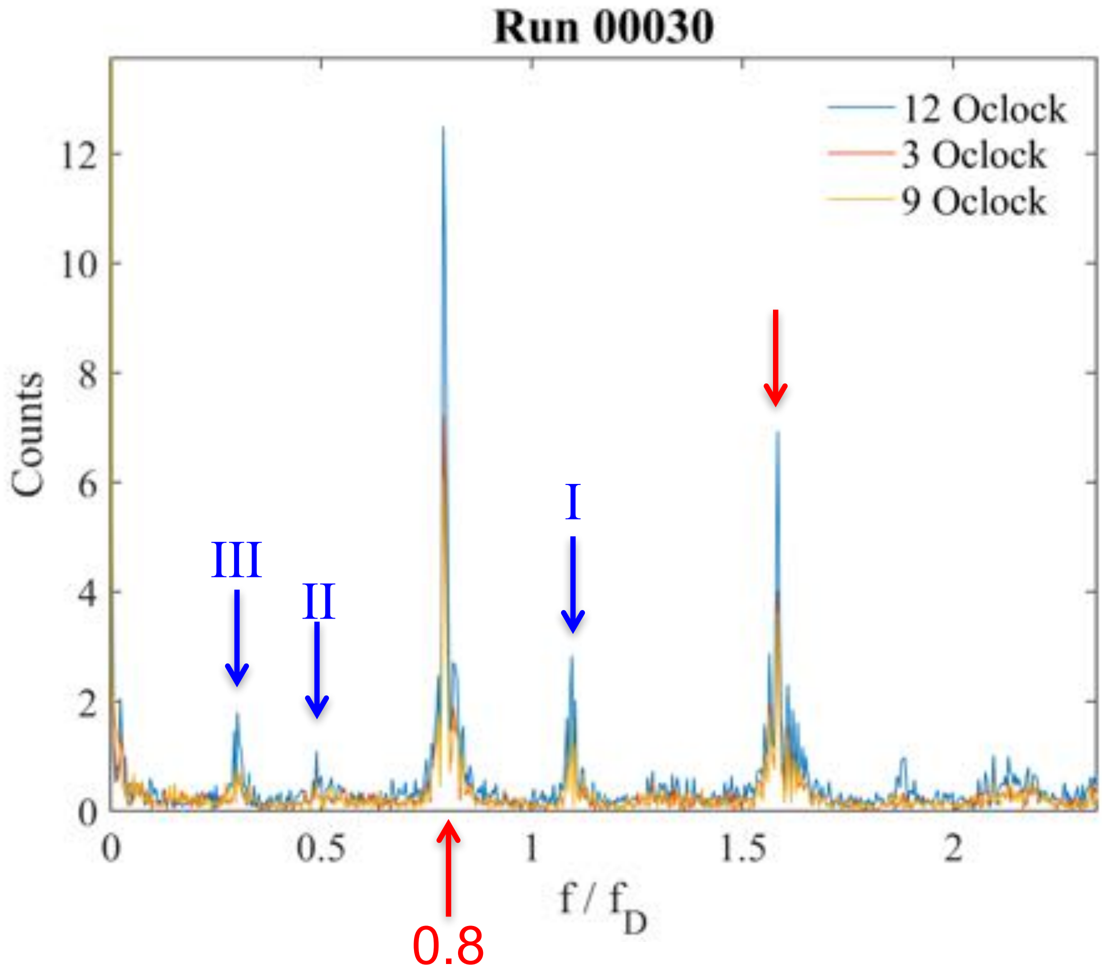
D_{CJ}: C-J detonation speed

d: detonation channel diameter

A. Detonating mode: chemiluminescence (175 g/s; ϕ = 1)

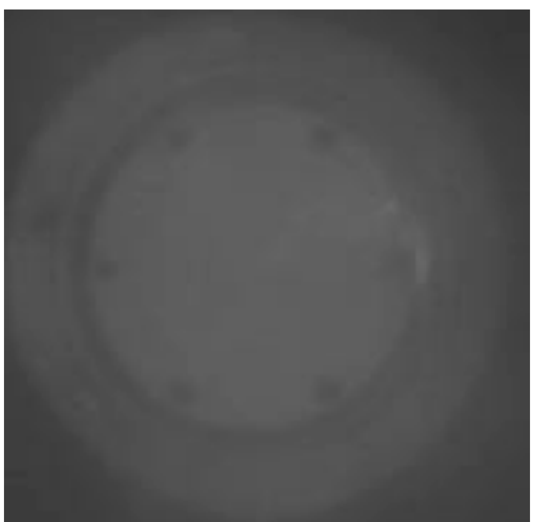


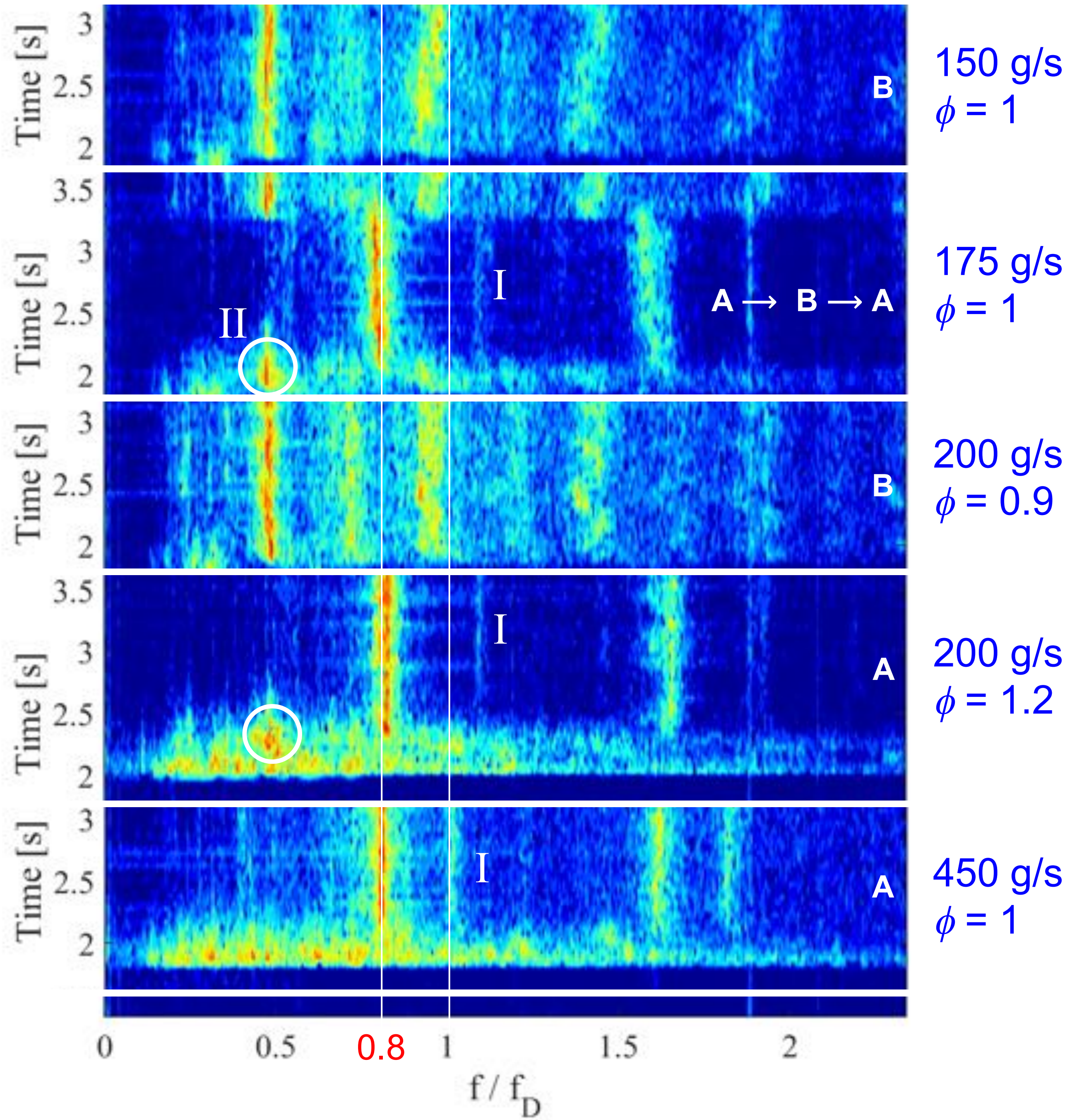
We monitor the time variation of emission intensity at various points in the detonation channel, and extract its power spectrum (shown below)



Variation:

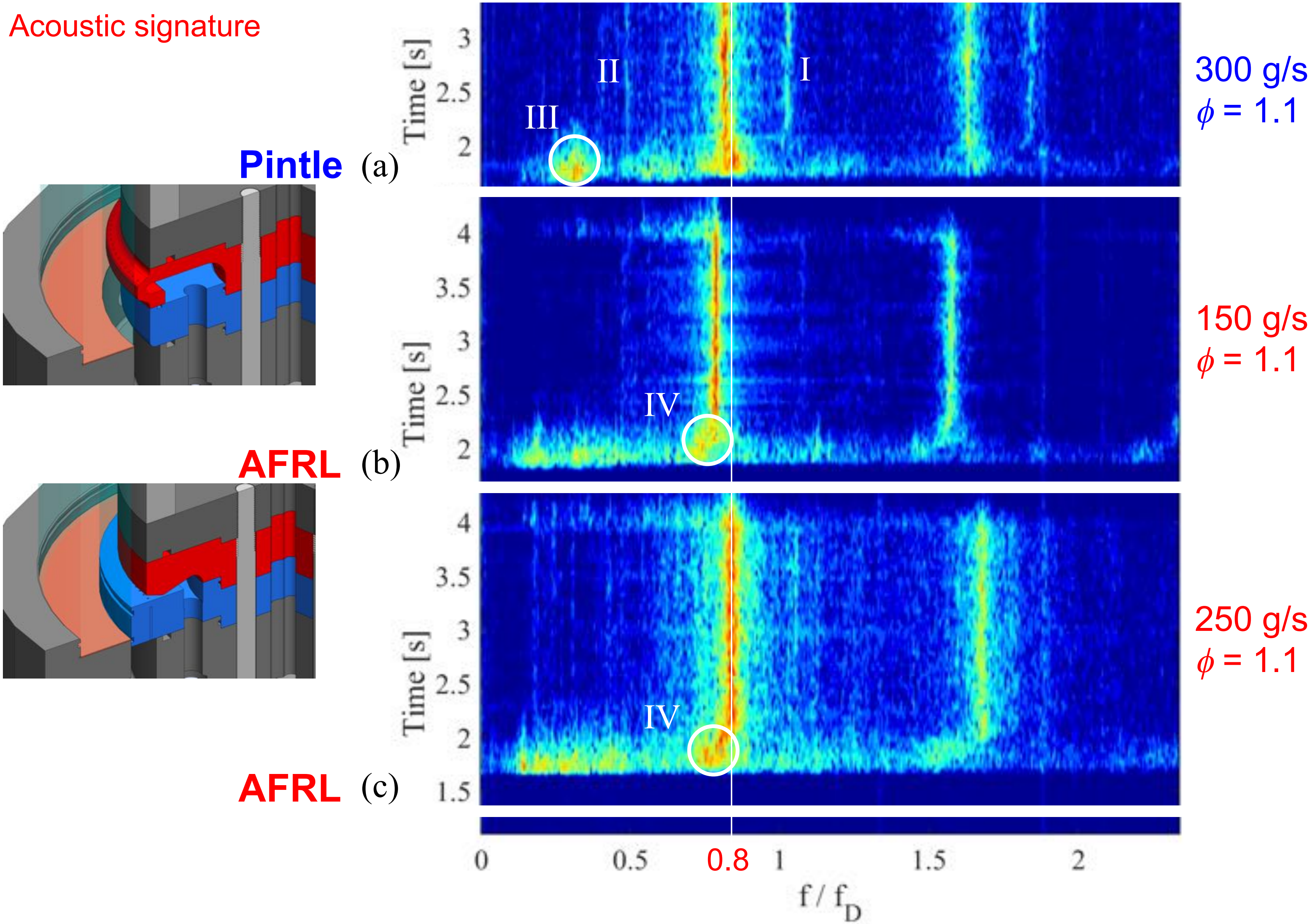
Acoustic signature



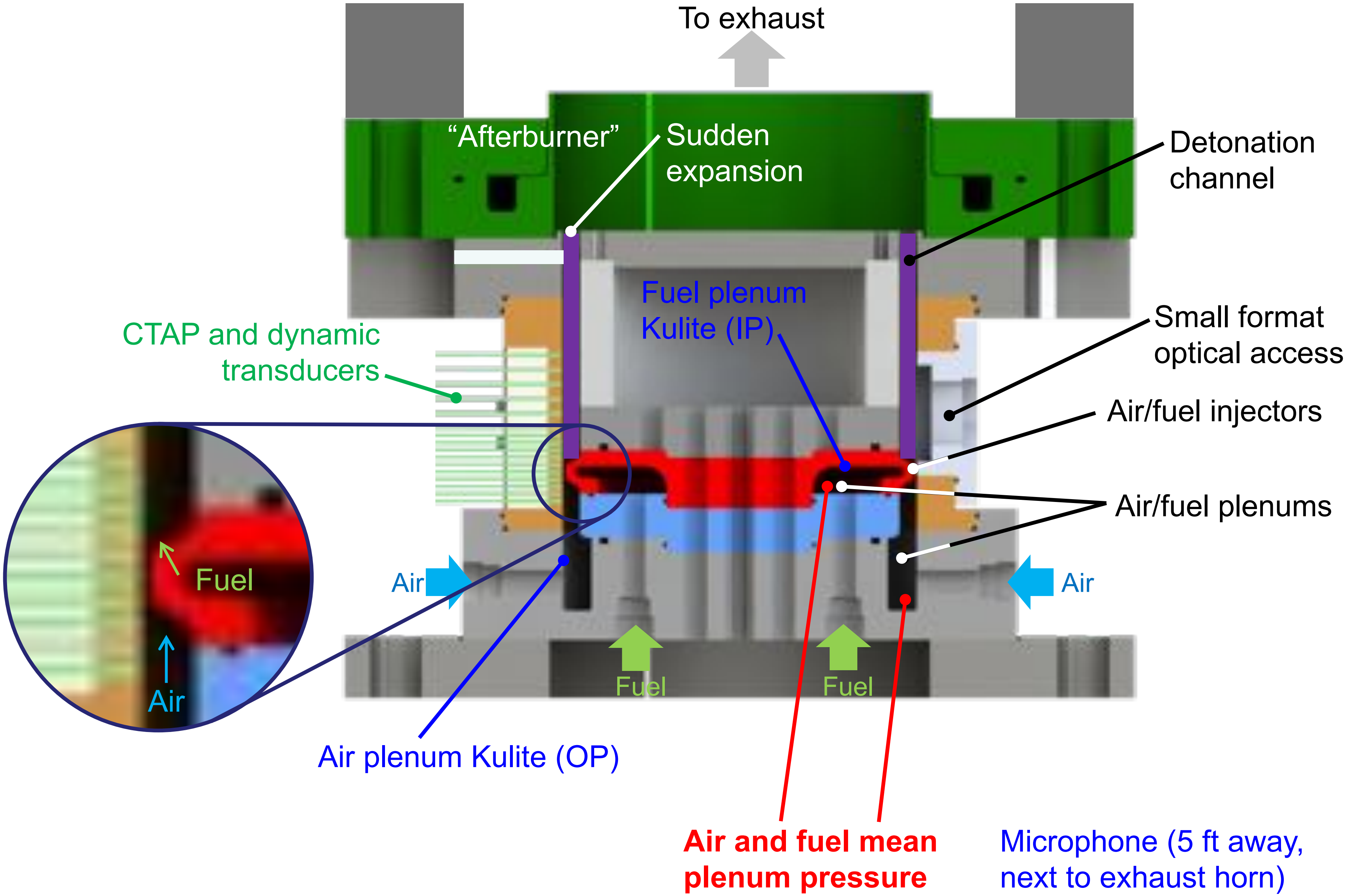


Tone I, II and III characteristic of pintle geometry

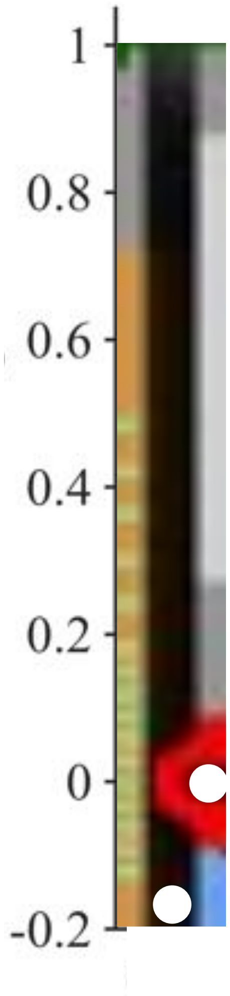
Acoustic signature

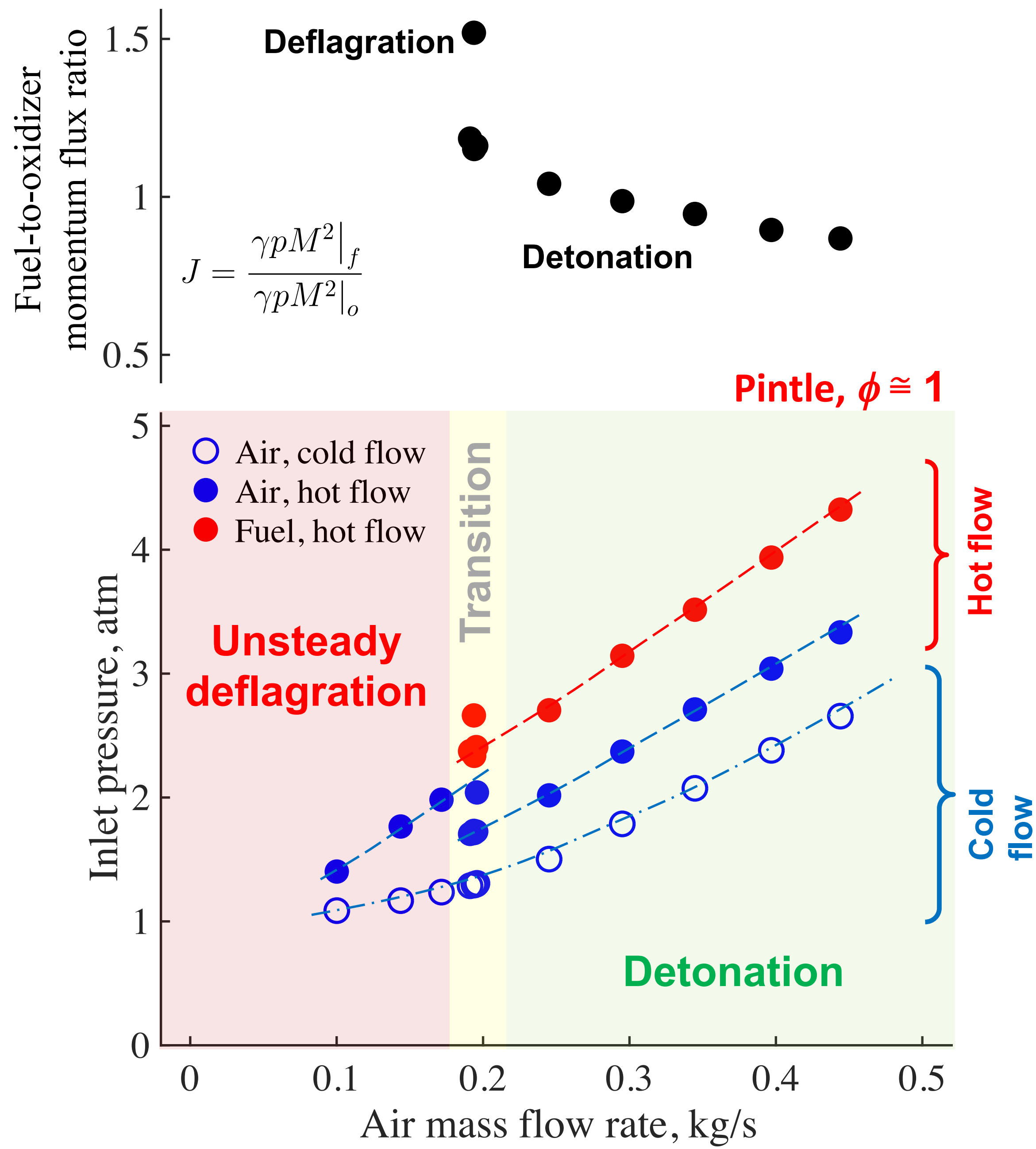


Instrumentation



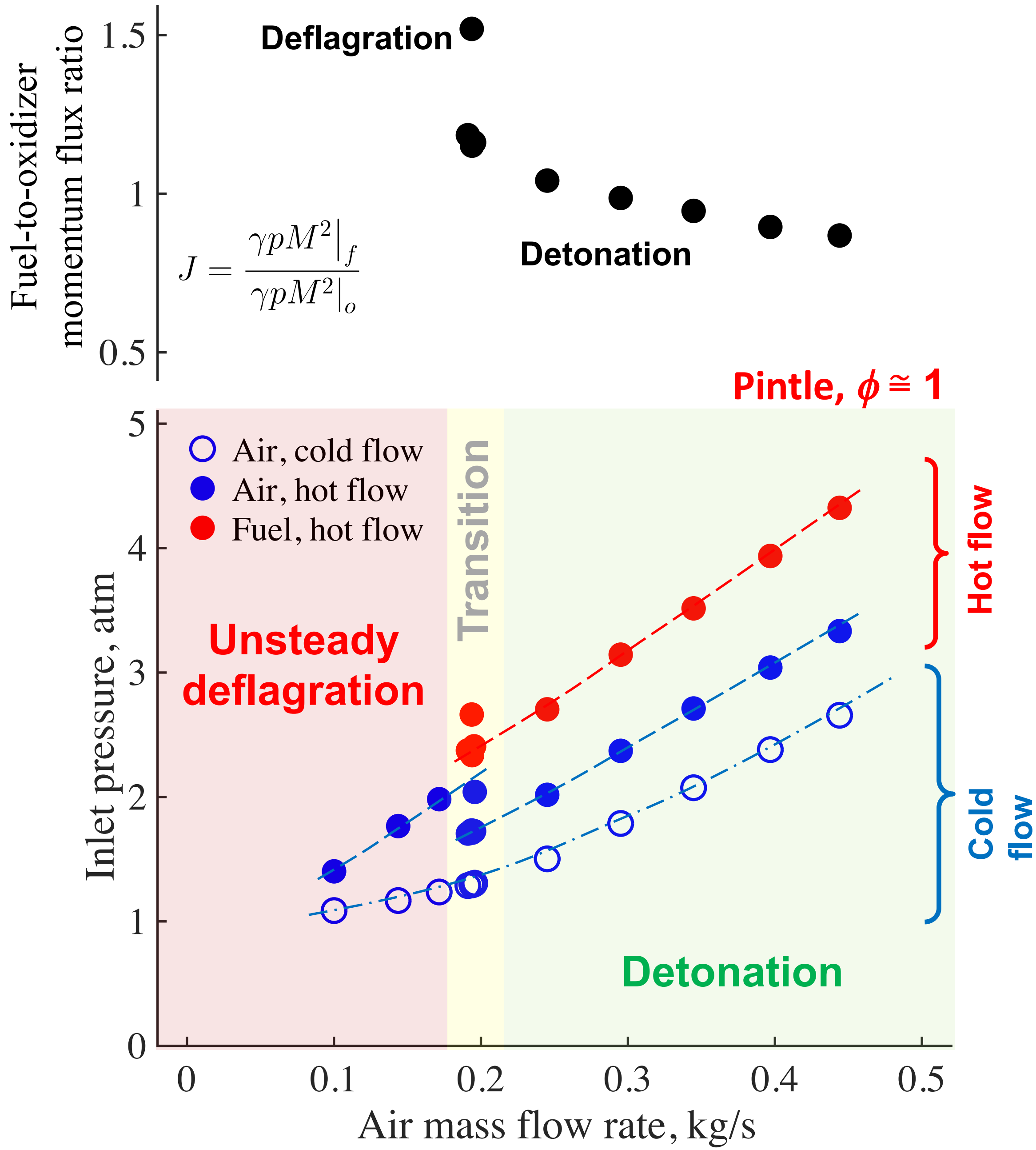
Variation of mean plenum pressures with air mass flow rate



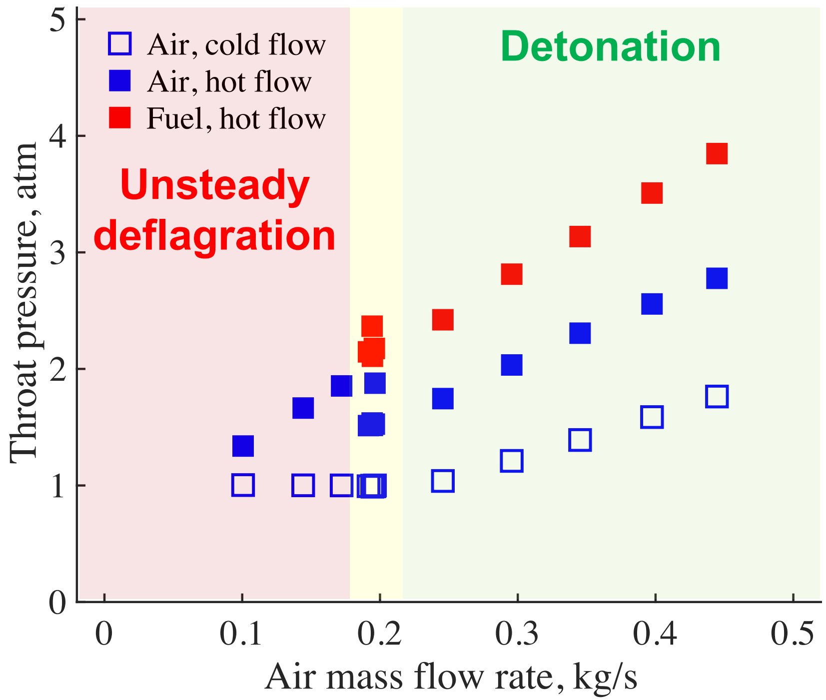


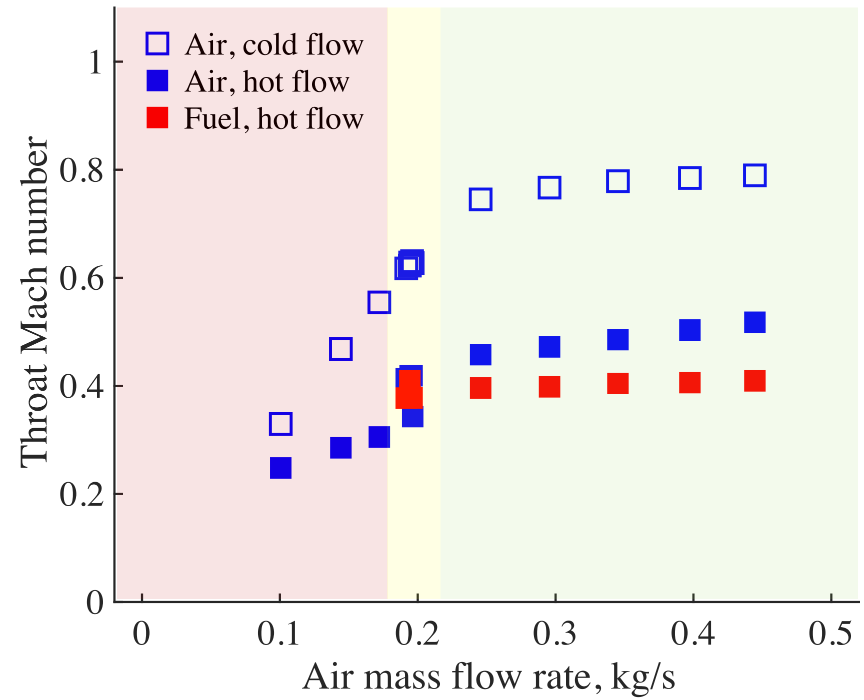
Variation of mean plenum pressures with air mass flow rate

- Inlet (plenum) pressure increases with mass flow rate
- Inlet pressure in deflagration mode higher than when in detonating mode



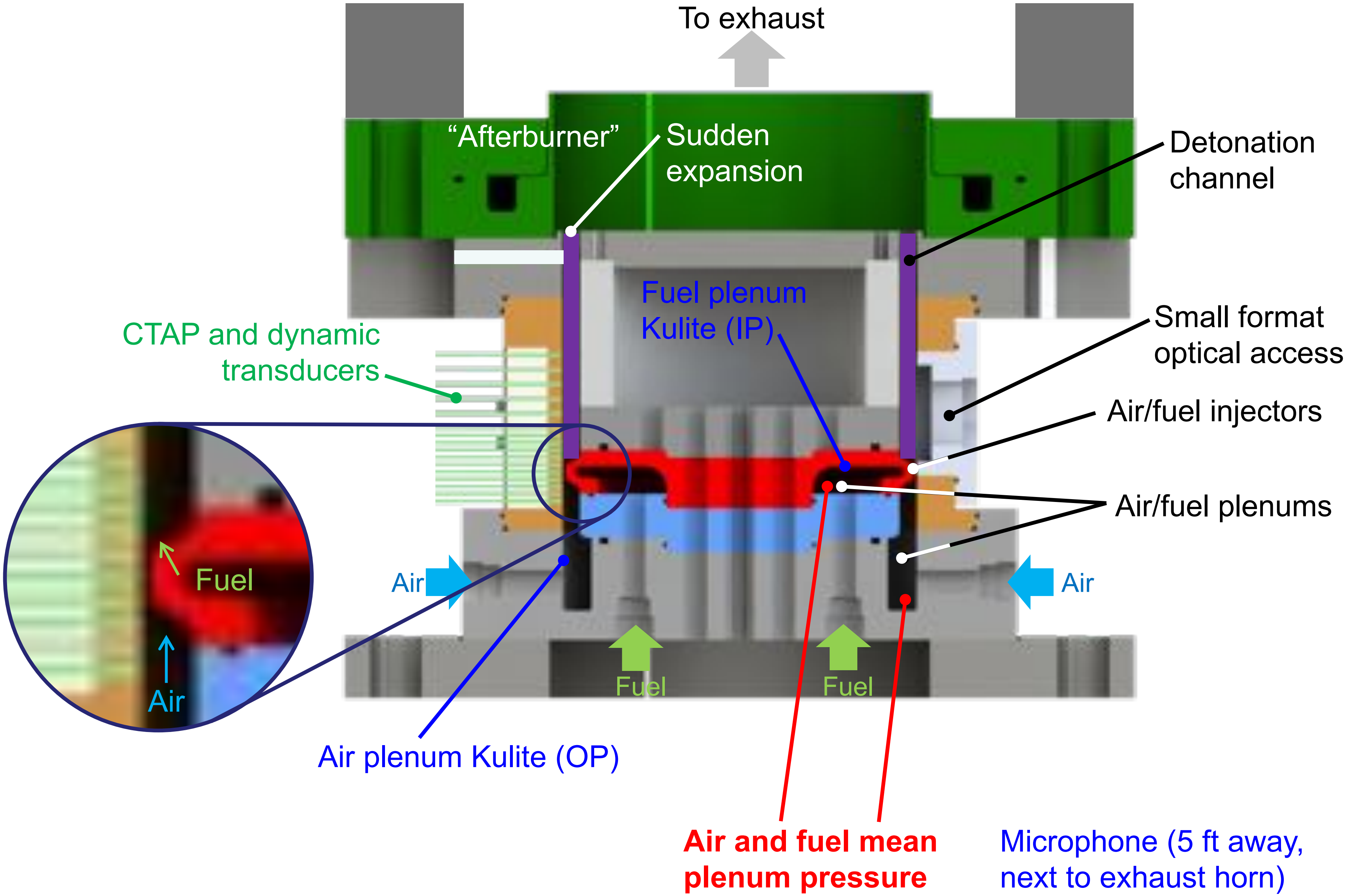
Conditions at injector throat (pintle)



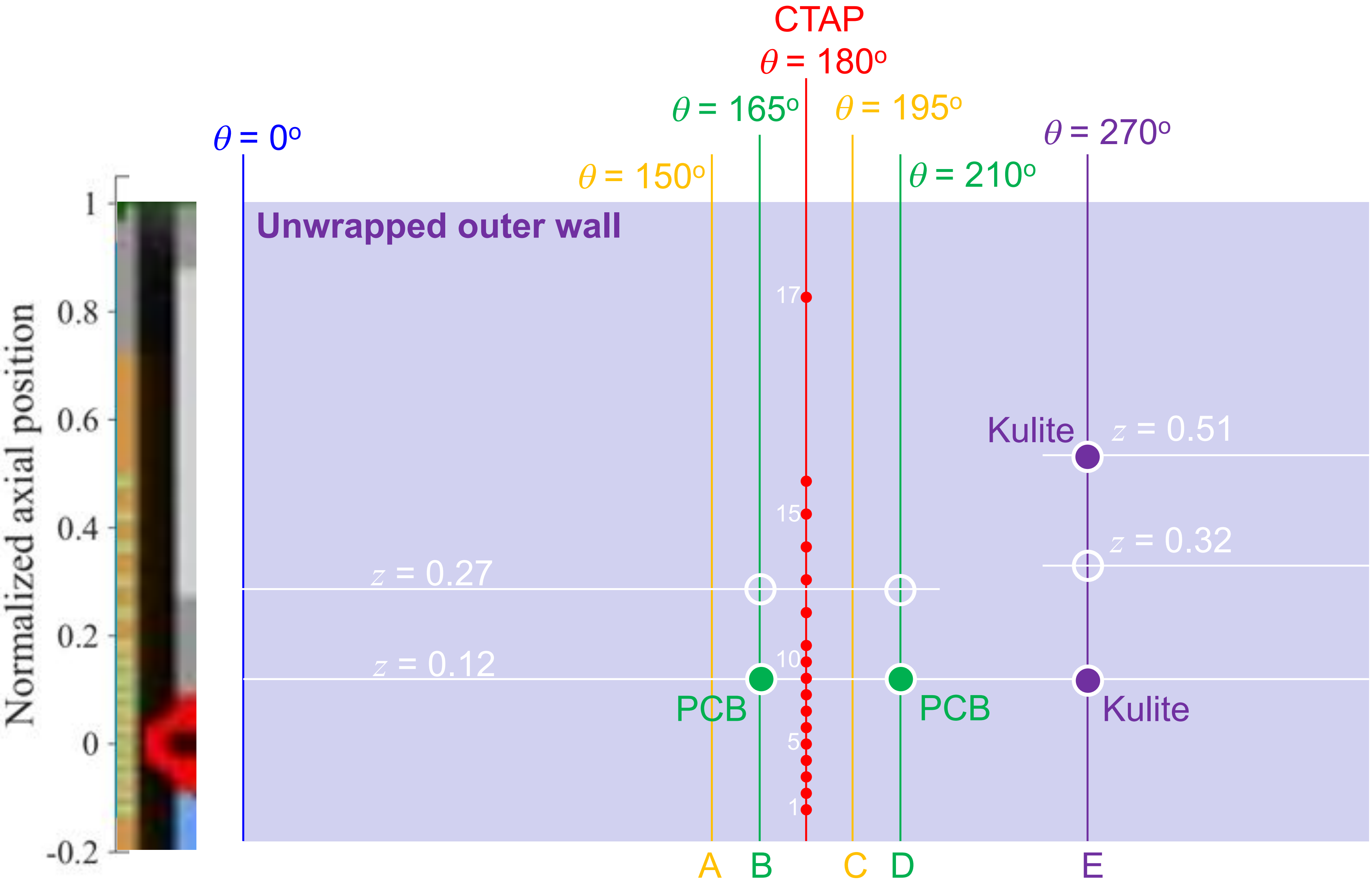


- Evaluated from measured plenum pressure using 1-D isentropic analysis
  - Mean, ideal values
- Cold flow:
  - Air injector throat chokes at 200 g/s
  - Throat Mach number 0.8: possibly due to loses (non-ideal discharge)
- Hot flow:
  - Fuel and air Mach number (at throat) remain constant in detonating mode (but less than 1)
  - Unknown if they remain chocked (even intermittently)

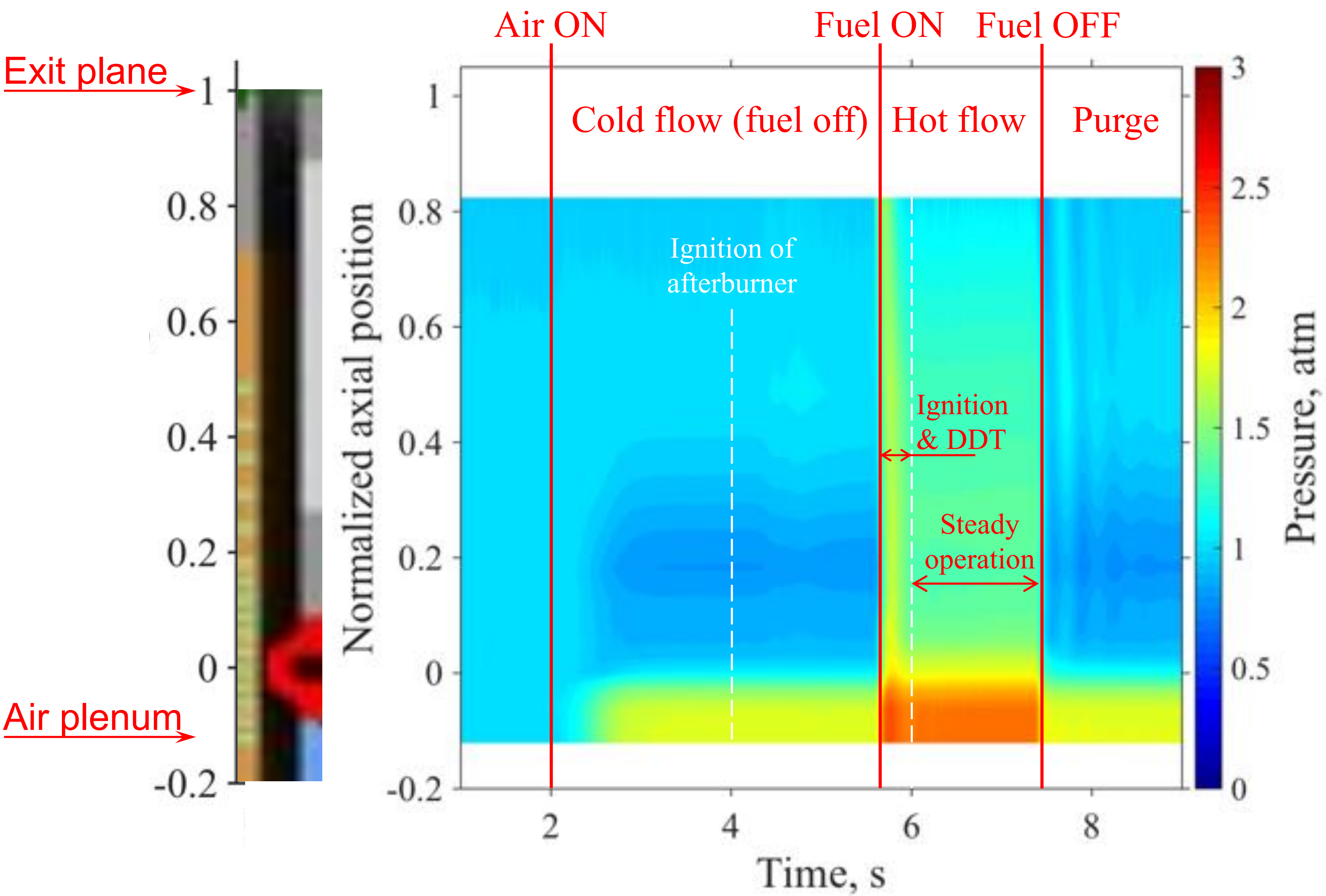
Instrumentation



Distribution of instrumentation in detonation channel

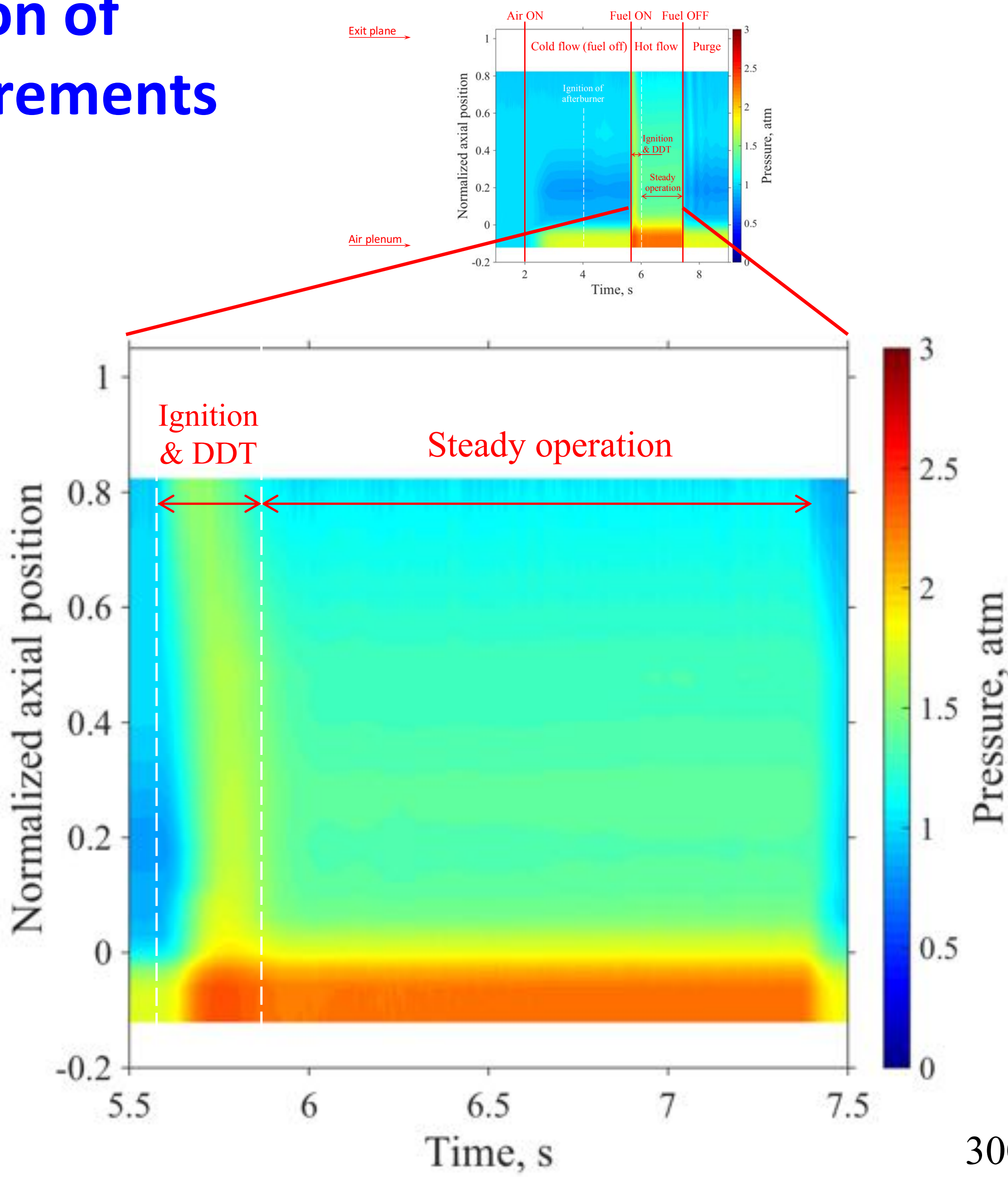


Time variation of CTAP measurements



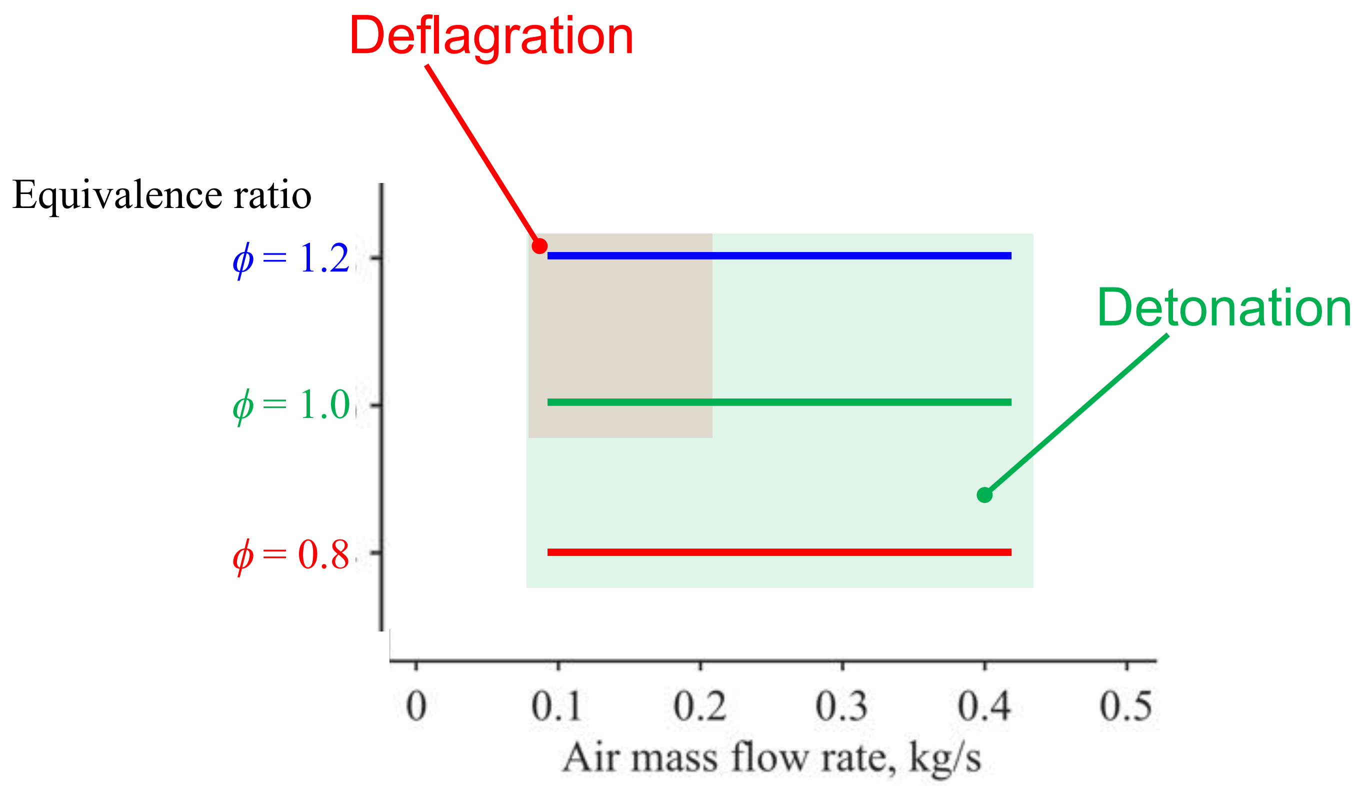
300 g/s, $\phi = 1.0$

Time variation of CTAP measurements



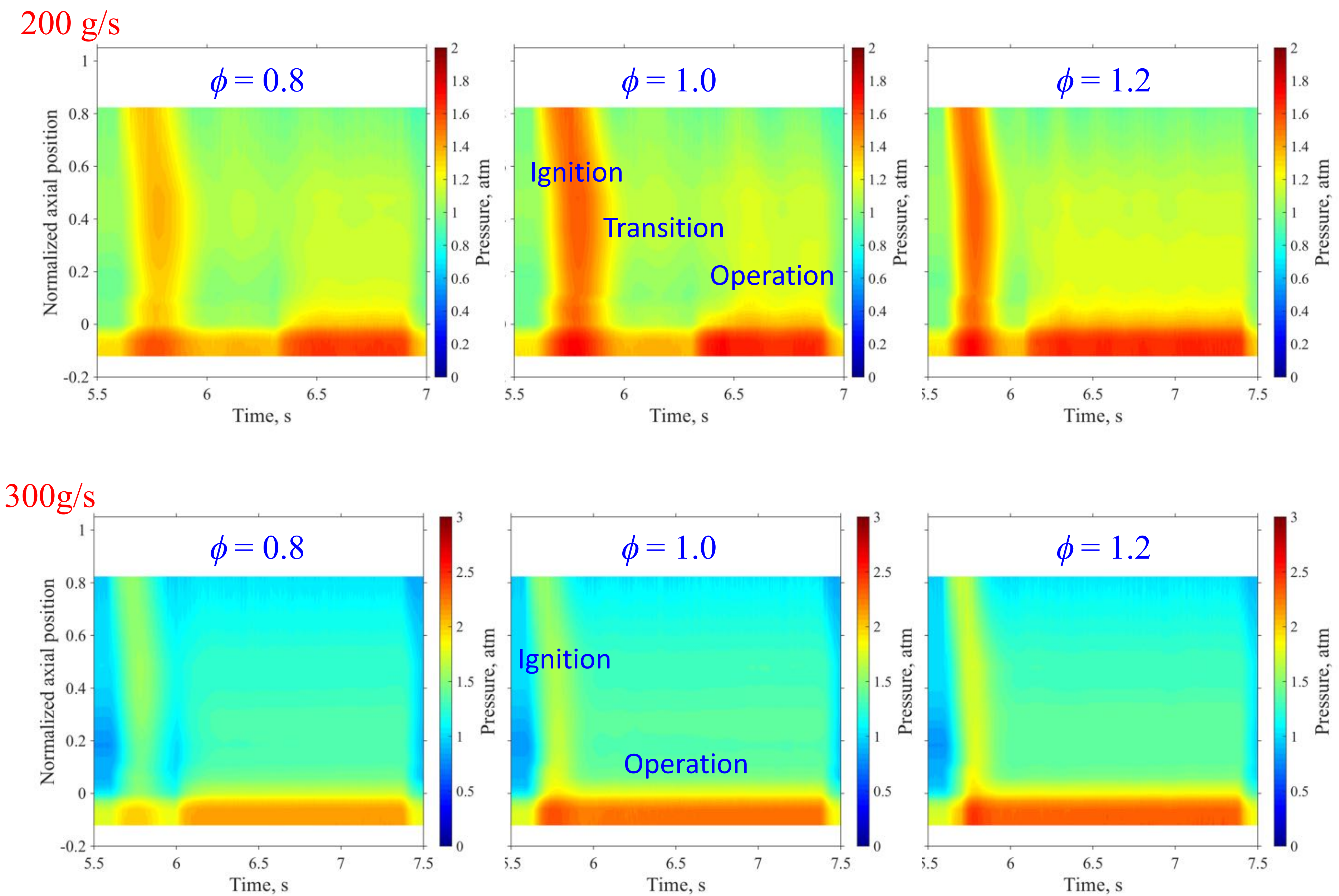
300 g/s, $\phi = 1.0$

Test cases

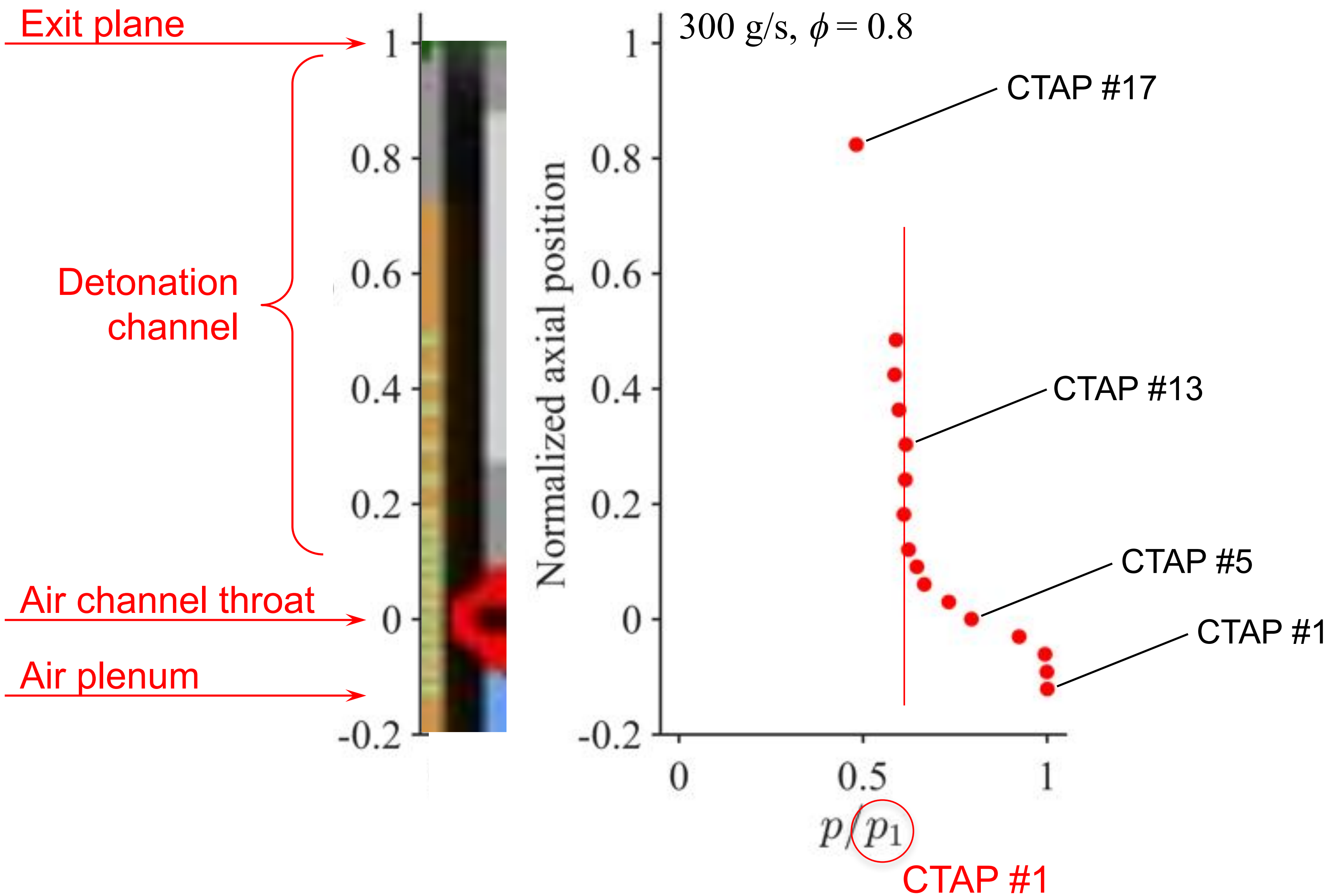


Deflagration
Detonation
Equivalence ratio
$\phi = 1.2$
$\phi = 1.0$
$\phi = 0.8$
0
0.1
0.2
0.3
0.4
0.5
Air mass flow rate, kg/s

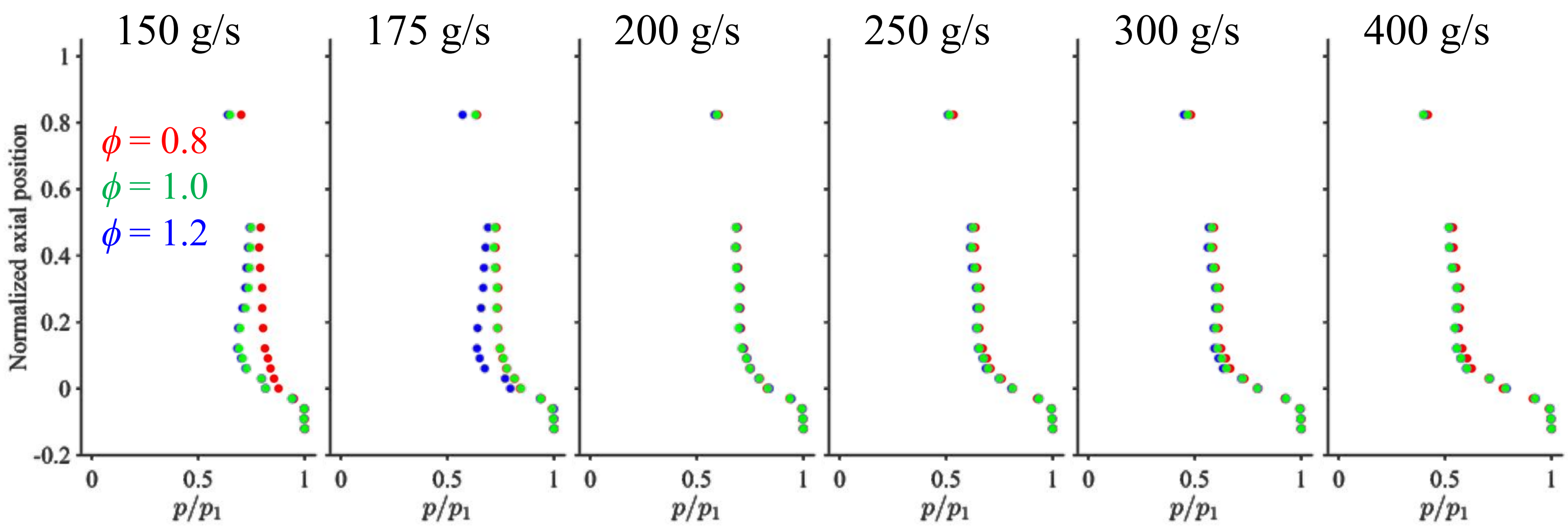
Low frequency (3 Hz) instability at low mass flow rates



CTAP profiles: mean pressure distribution

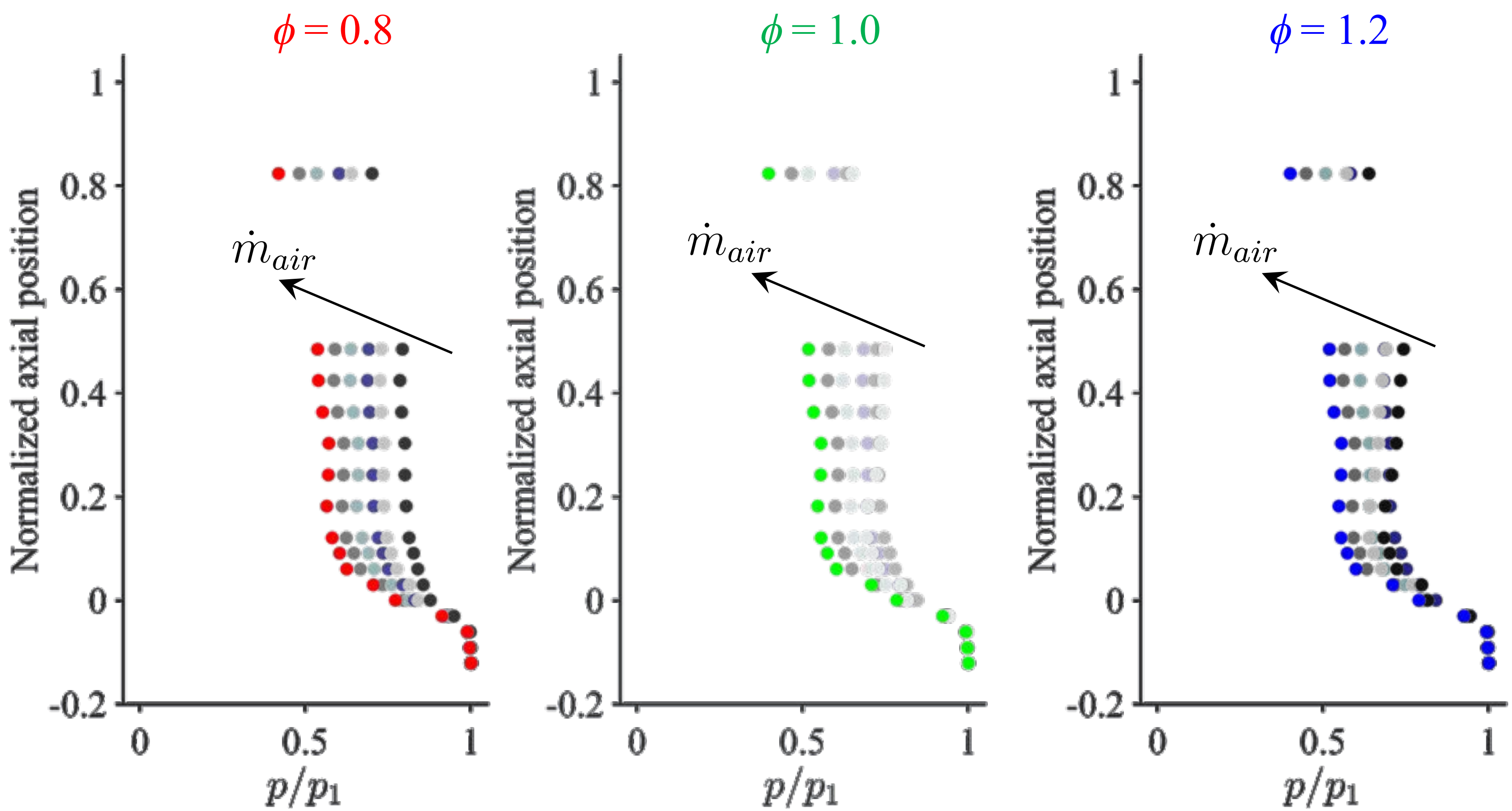


Comparison of normalized pressure distribution along channel

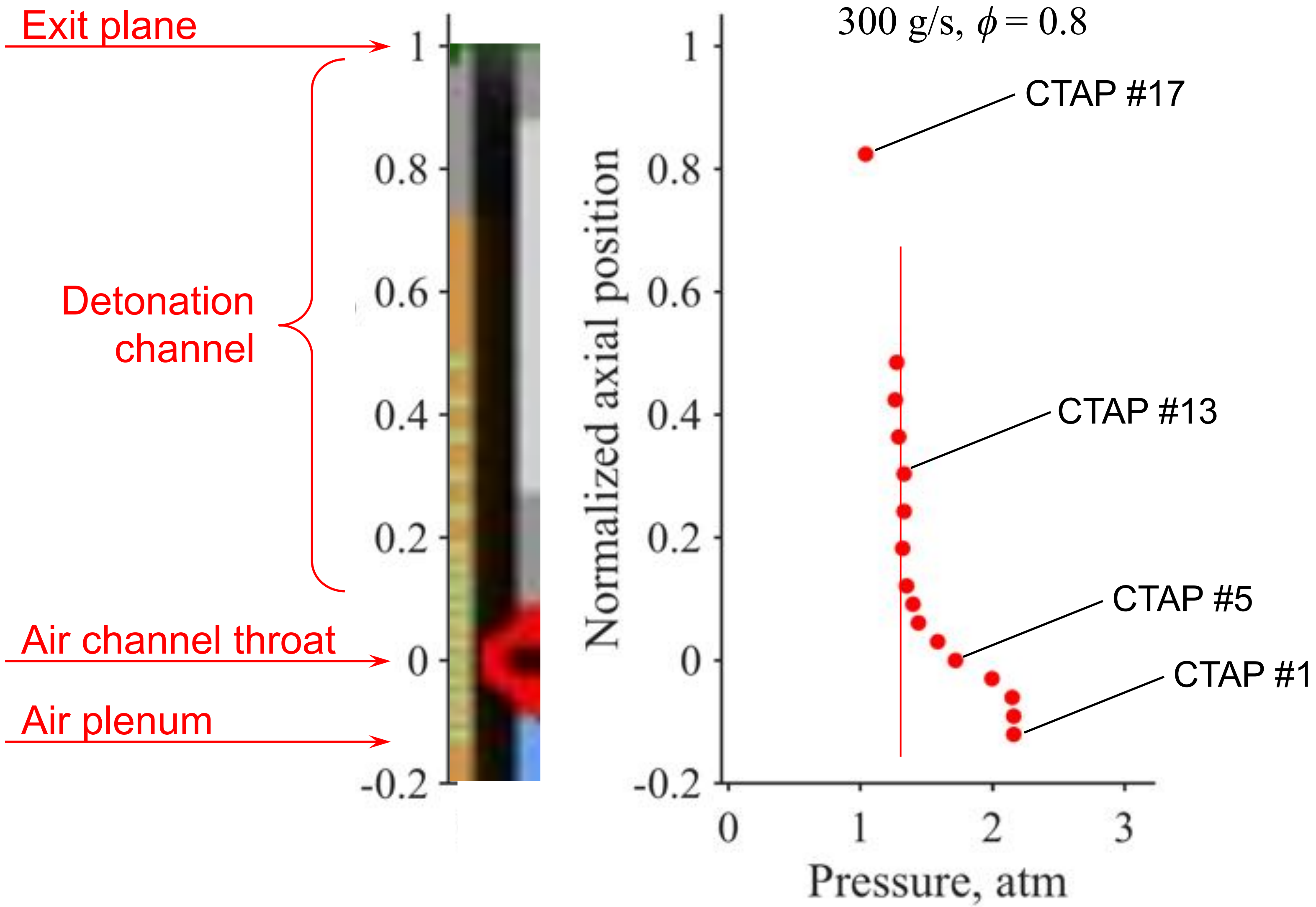


- Pressure distribution self-similar when detonating
  - Small variation with equivalence ratio
- Pressure distribution self-similar when deflagrating
- Pressure across air inlet throat drops faster for deflagrating then detonating mode

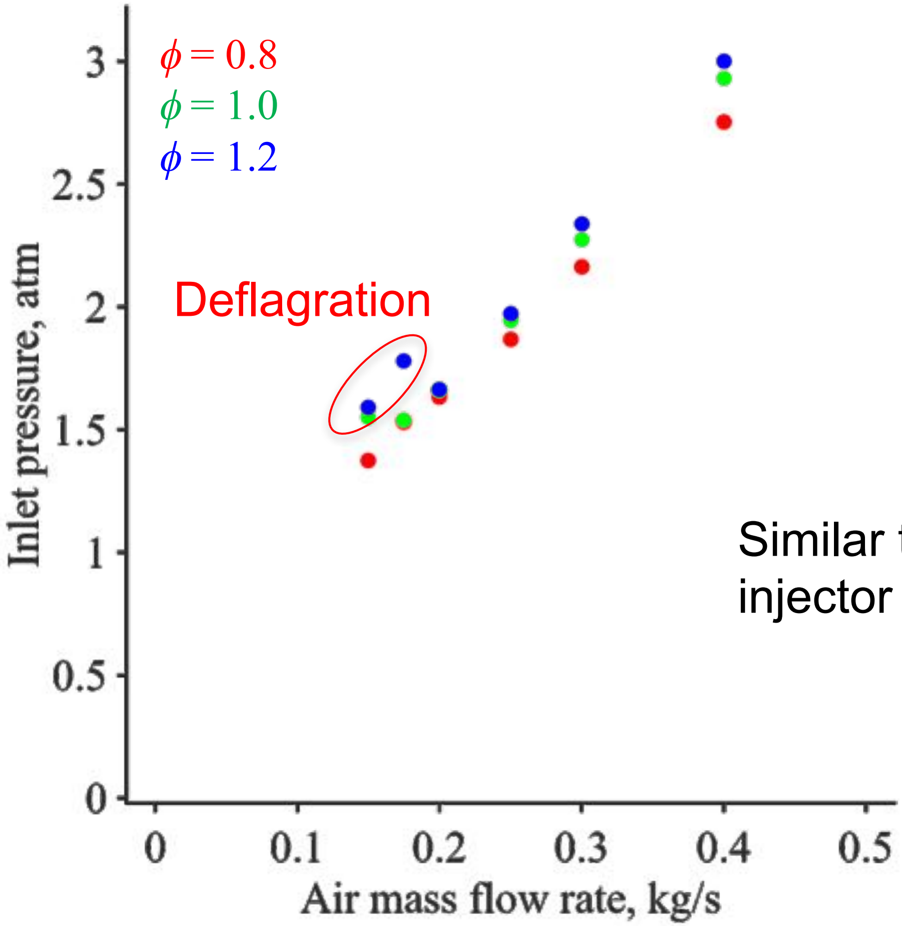
Variation with mass flow rate at constant ER



CTAP profiles: mean pressure distribution (dimensional)



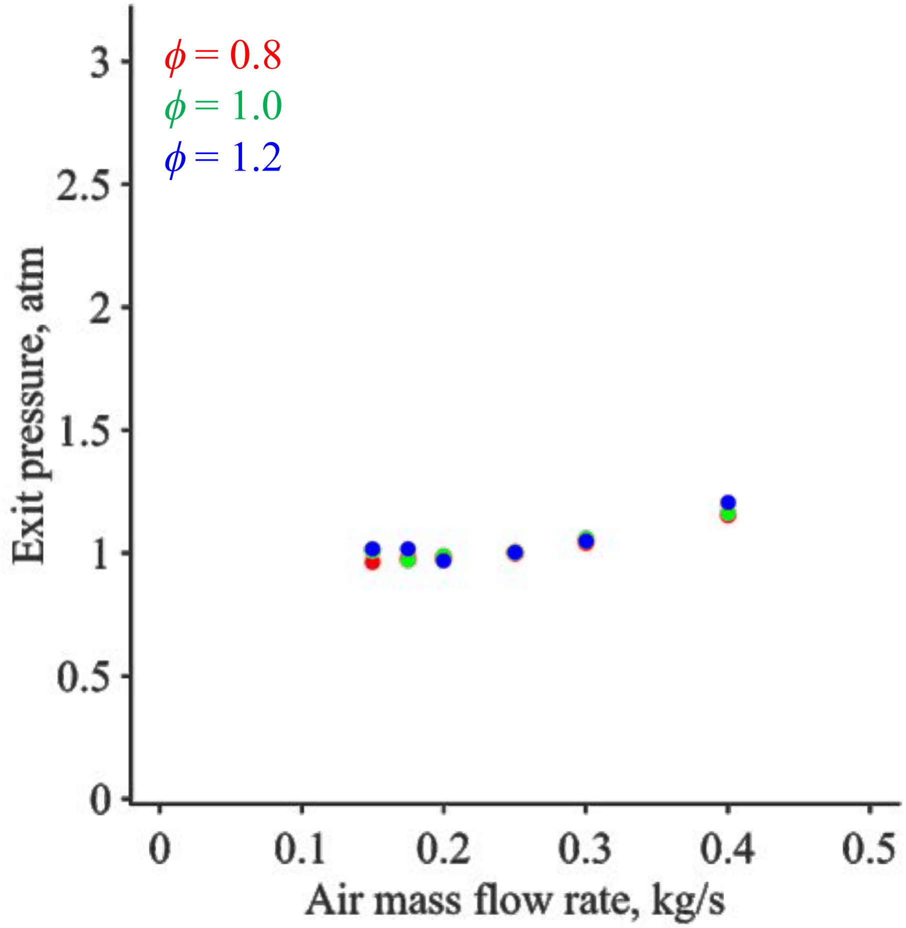
Air injector inlet pressure (CTAP #1)



Similar to pressure at air injector throat

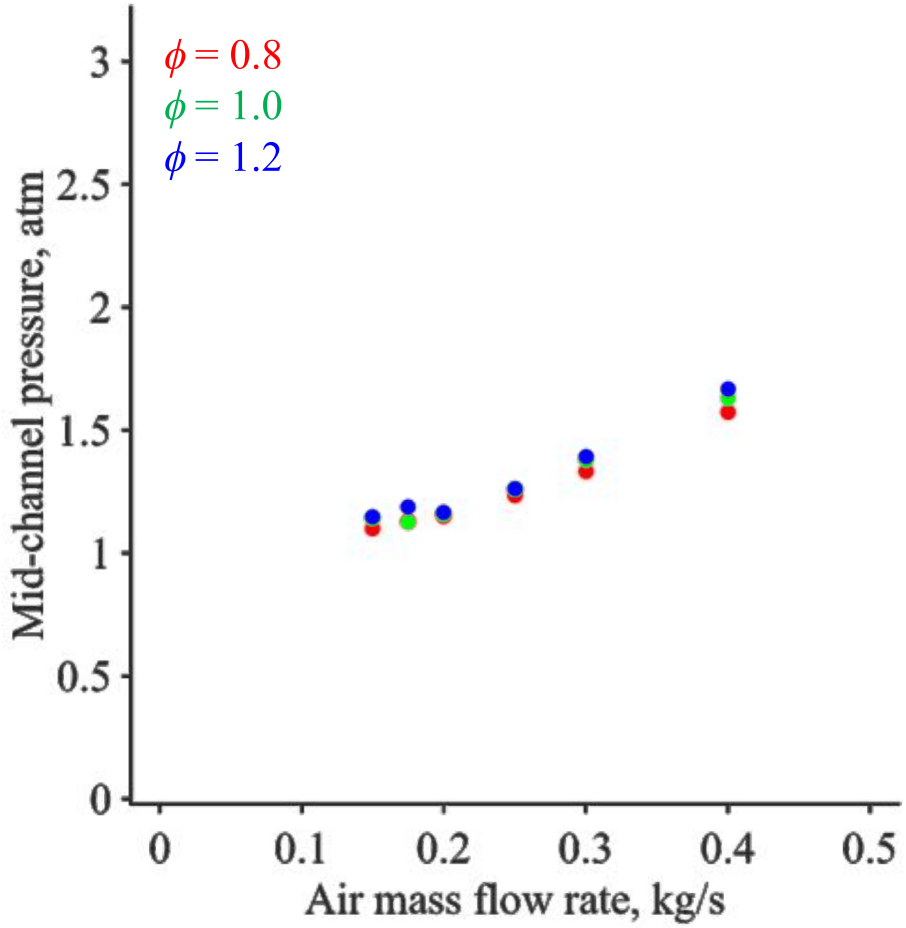
- Lower when in detonating mode
- Decreases with equivalence ratio
  - More stable detonation wave
  - A result of better mixing?

Exhaust pressure (CTAP #17)



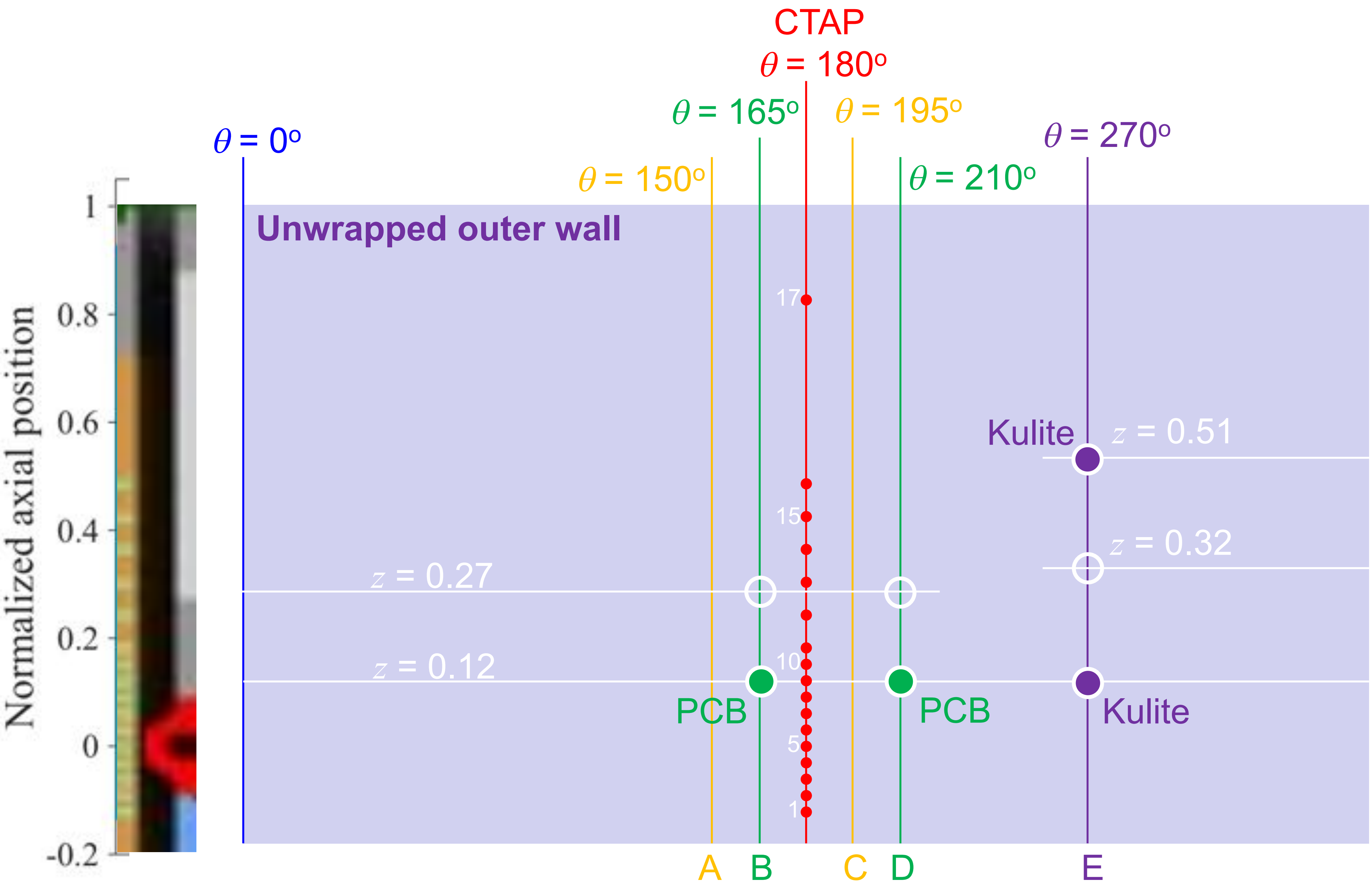
- Nearly constant to ambient pressure
  - Important later

Mid-channel pressure (CTAP #13)



- Similar variation to inlet pressure
- Channel pressure decreases with lower equivalence ratio
  - Note: detonation is more stable at lower ER
  - Recall: pressure profile is insensitive to ER at higher flow rates

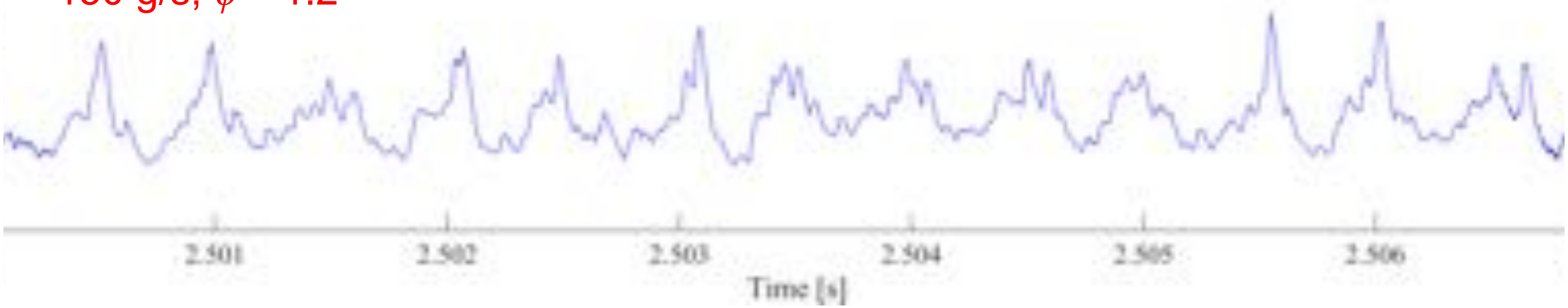
Distribution of instrumentation in detonation channel



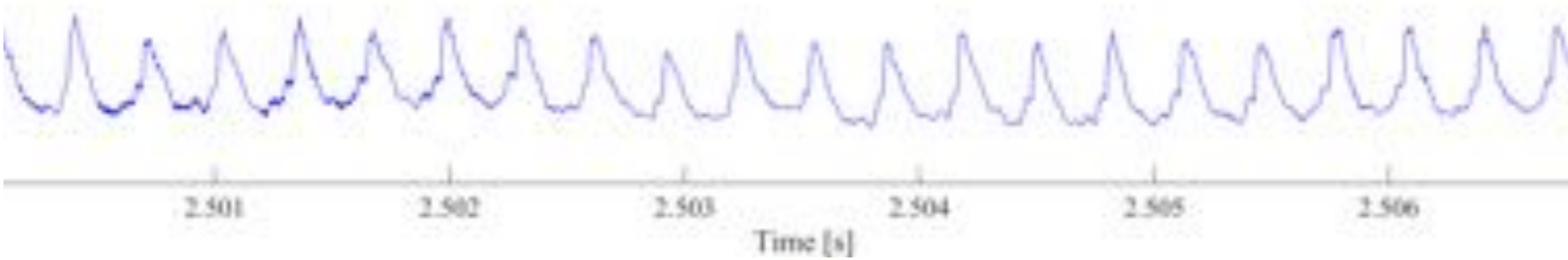
Time traces (mid-channel, z = 0.5, Kulite)

Deflagration
Detonation

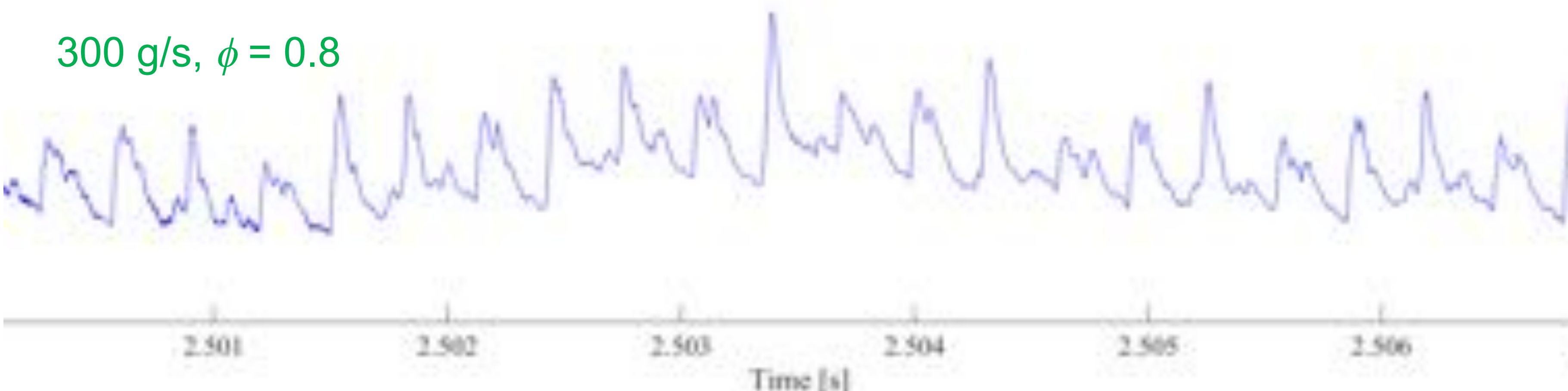
150 g/s, ϕ = 1.2



150 g/s, ϕ = 0.8

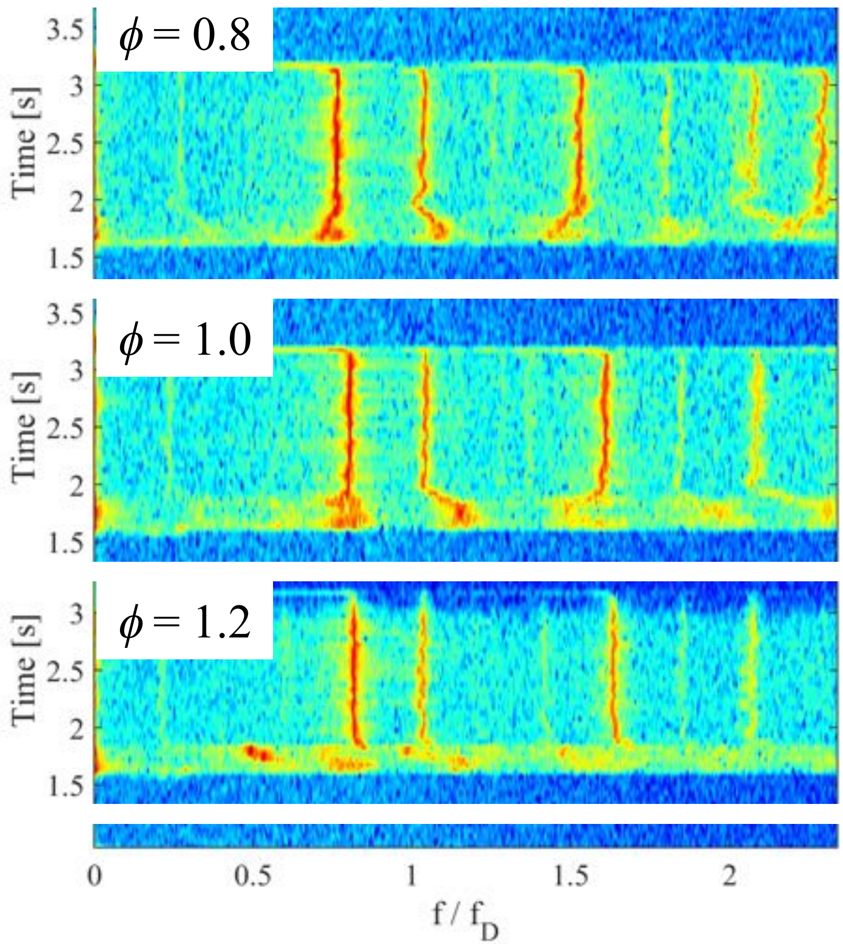


300 g/s, ϕ = 0.8

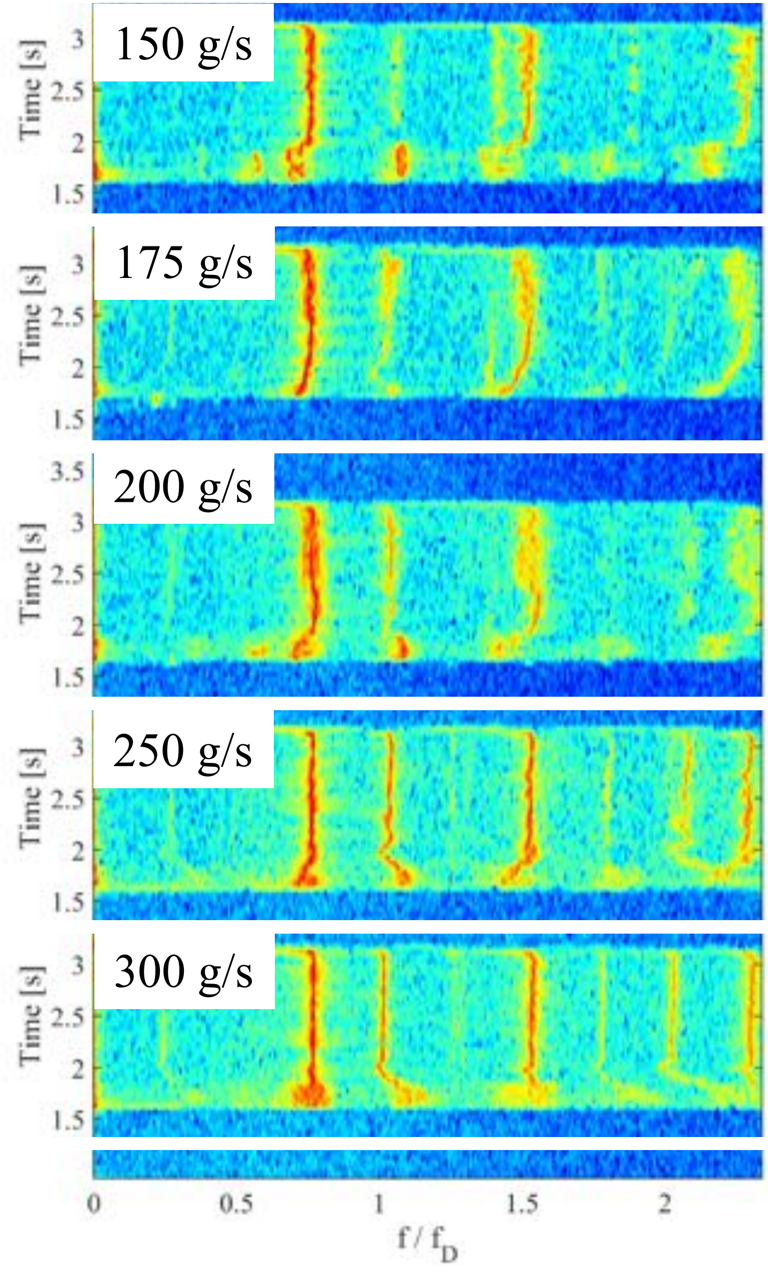


Waterfall spectra from PCB

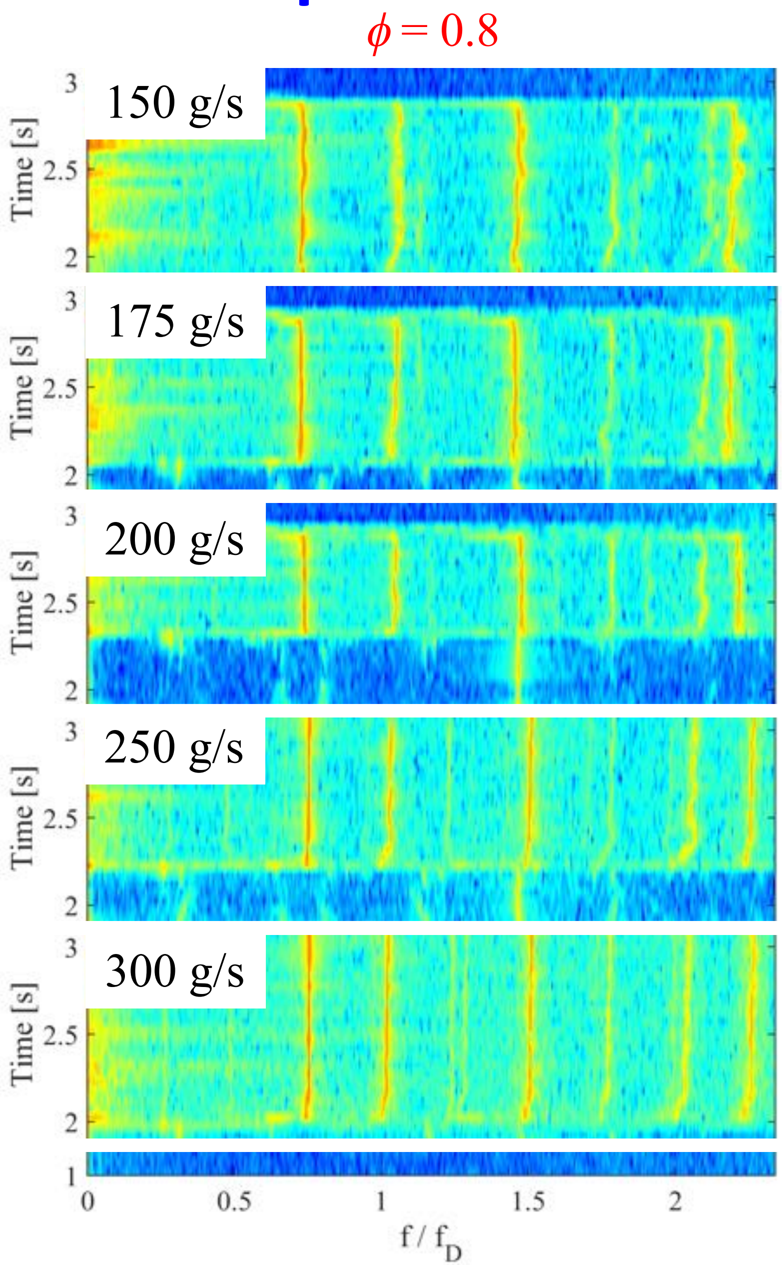
250 g/s



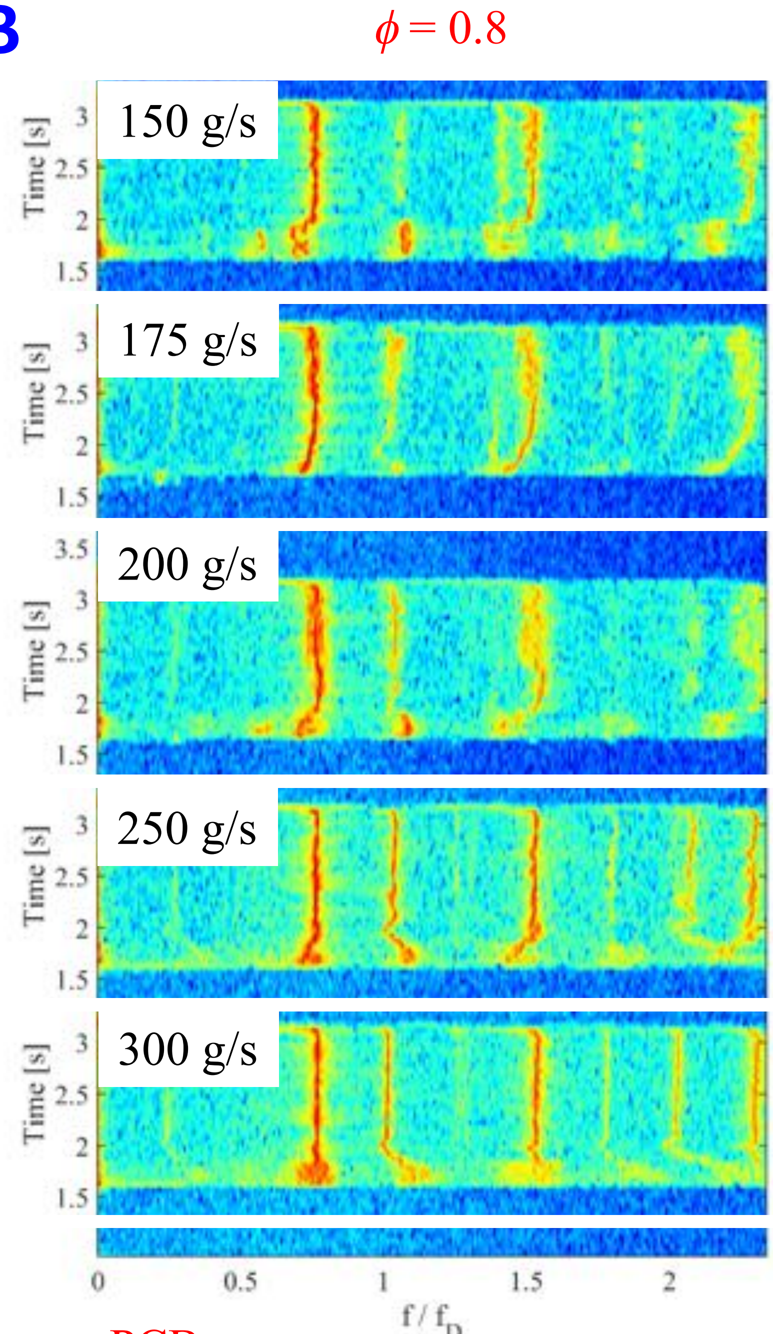
$\phi = 0.8$



Waterfall spectra: Kulite vs PCB

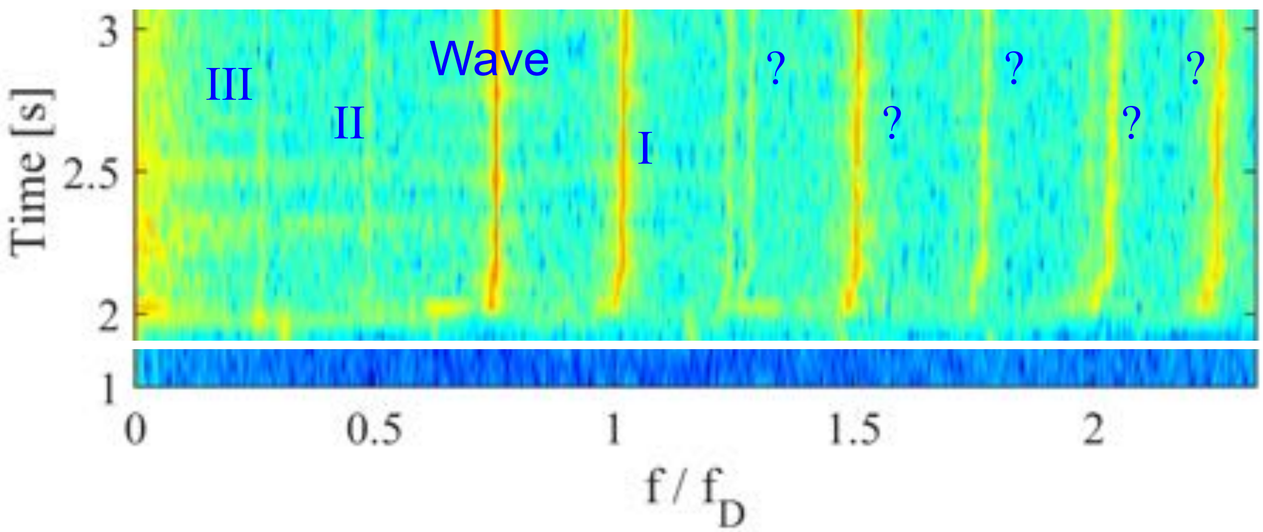


Kulite



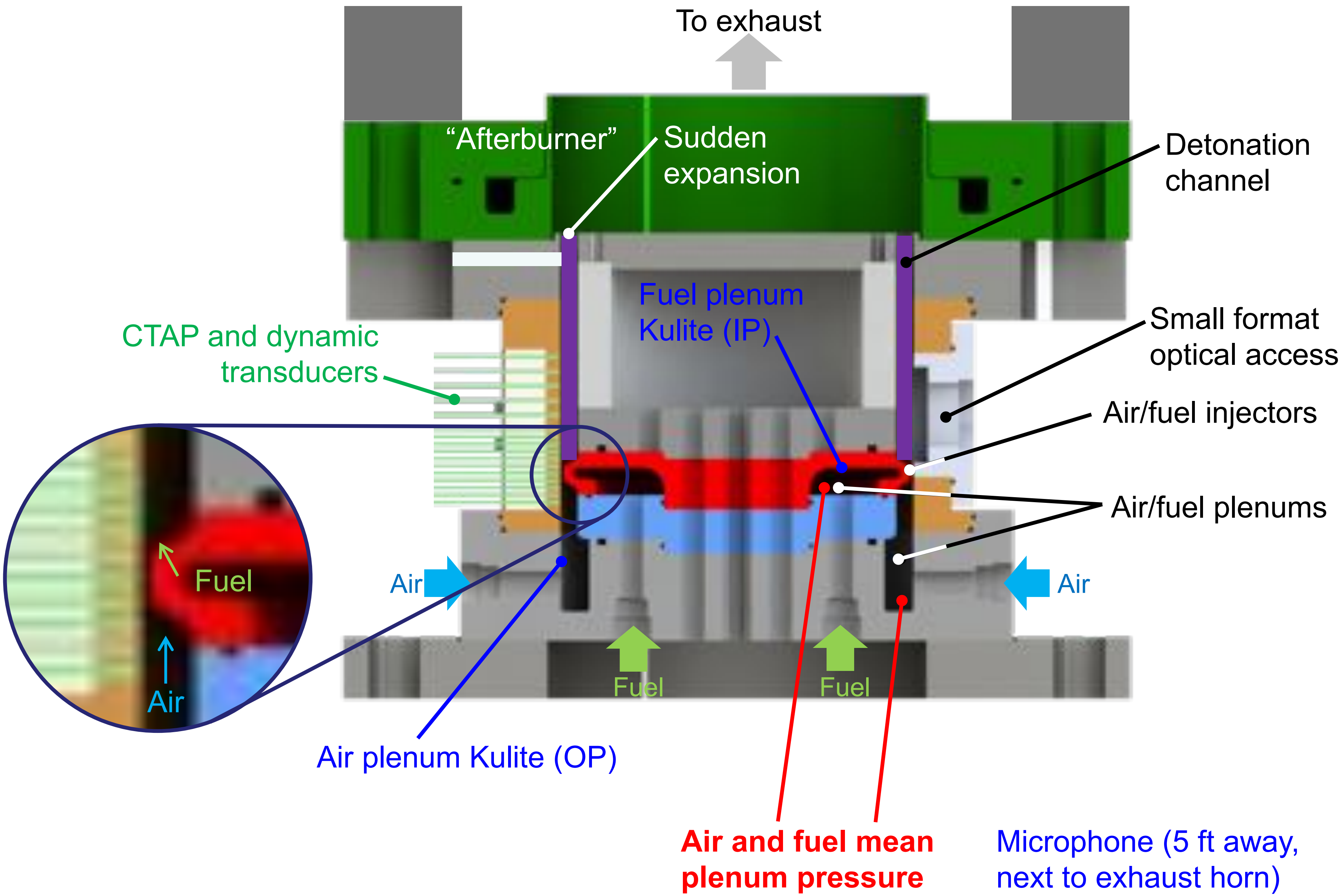
PCB

Conclusion from waterfall spectra

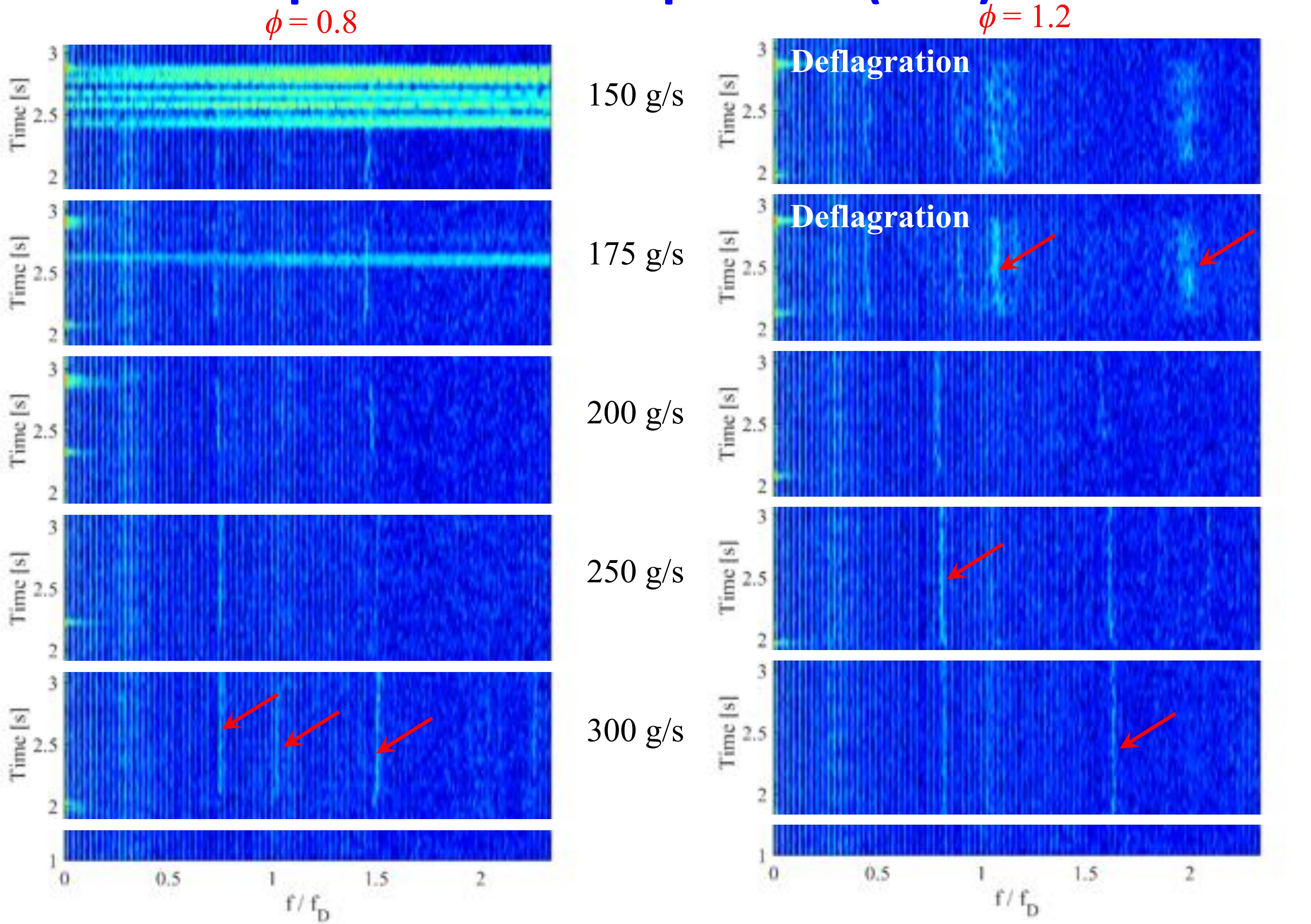


- Multiple, superimposed tones
  - Wave propagation: $f \cong 0.8\, f_D$
  - Tone I: $f \cong f_D$ – Present in detonation mode as flow rate increases, but also in deflagration mode
  - Tone II: $f \cong 0.5\, f_D$ – Present in deflagrating mode
  - Tone III: $f \cong 0.25\, f_D$ – Weak feature present in detonation mode
  - ?: Some not identified
- Hypothesis:
  - Due to coupling with and response of plenums

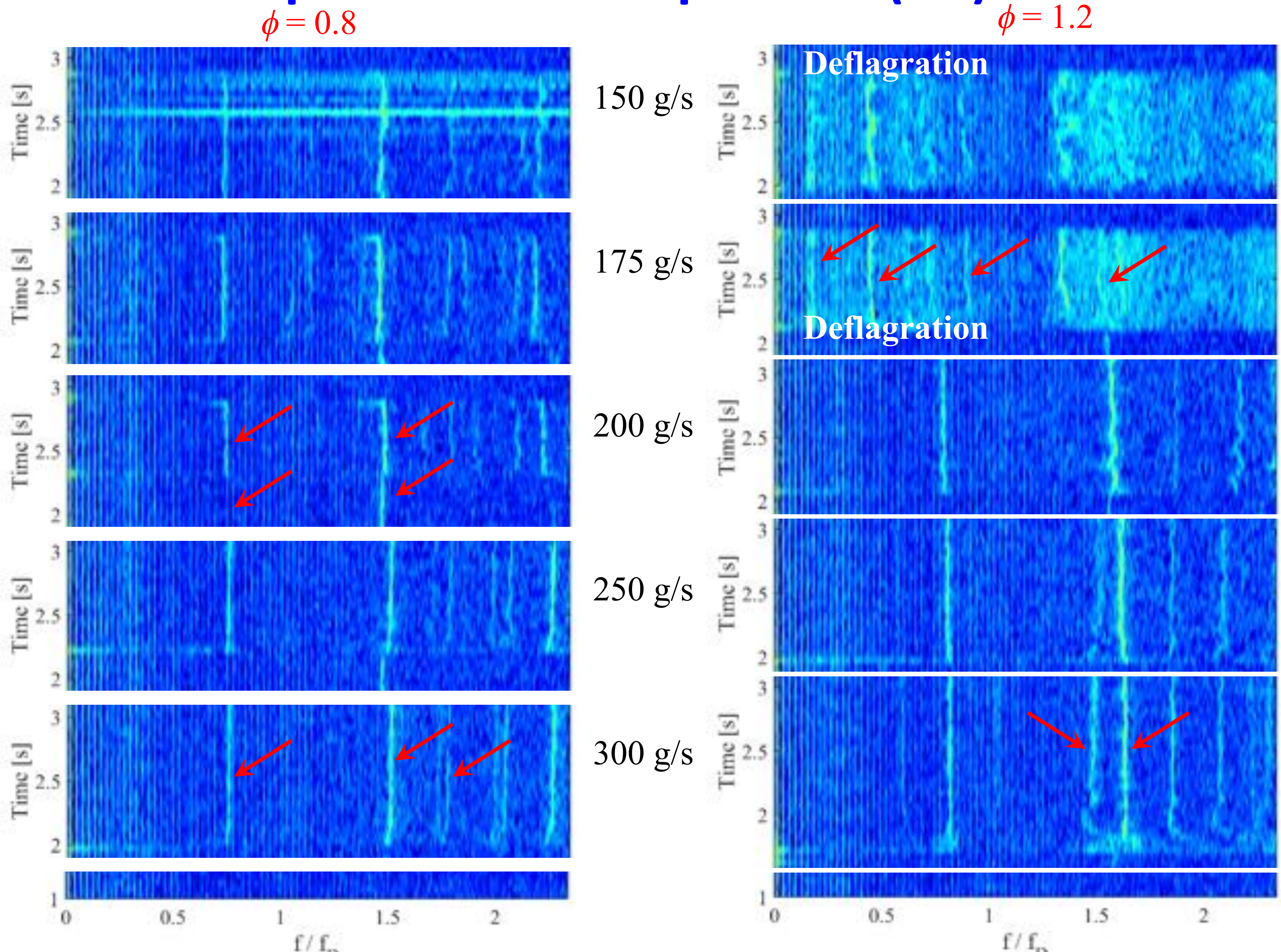
Instrumentation



Waterfall spectra in inner plenum (fuel)

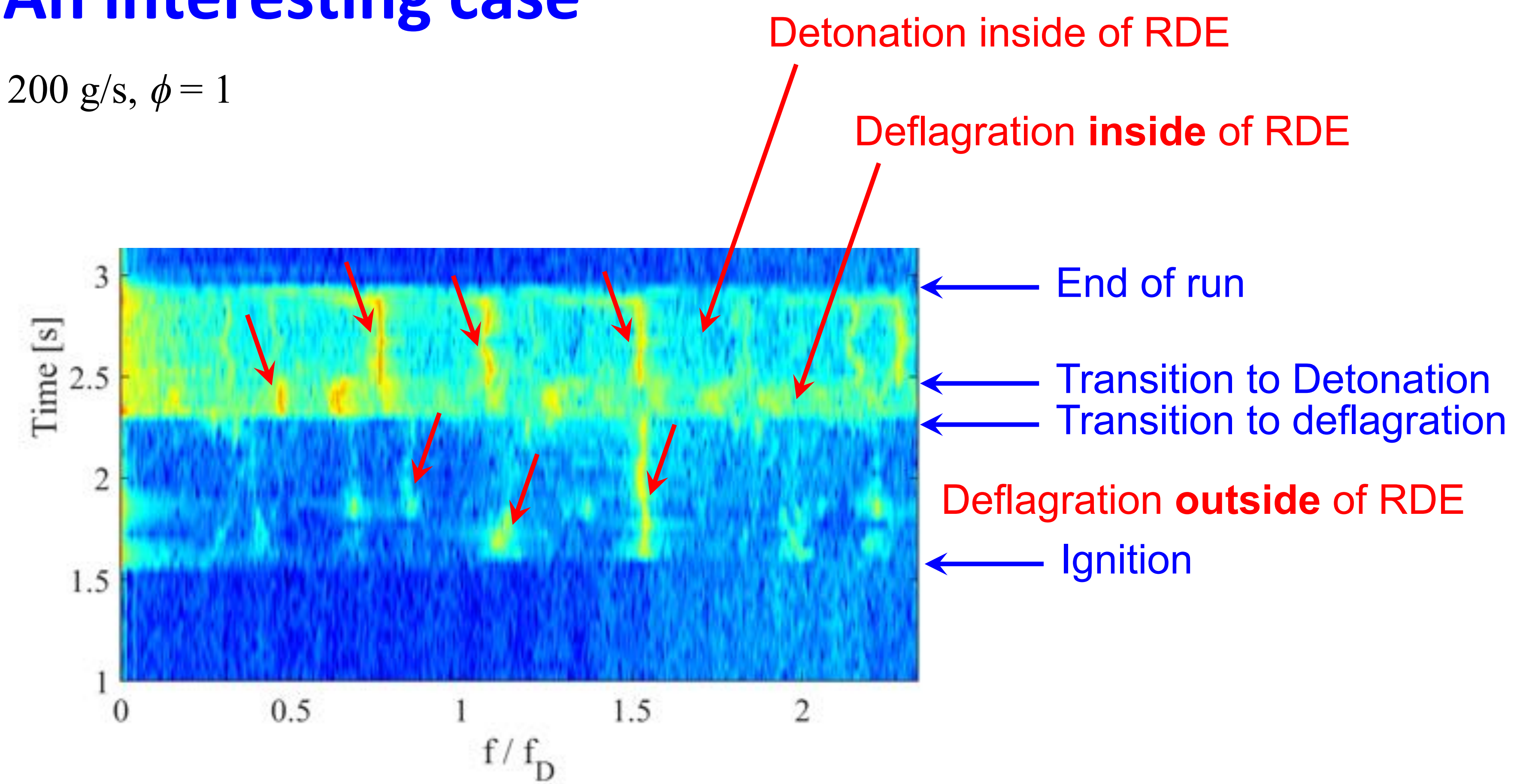


Waterfall spectra in outer plenum (air)



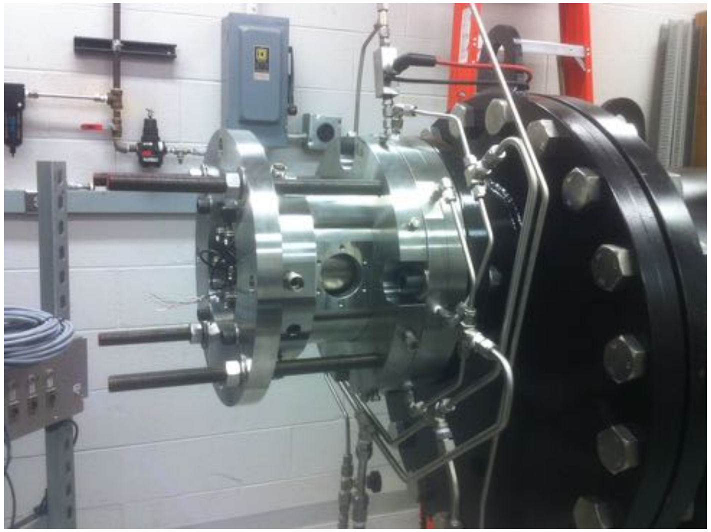
An interesting case

200 g/s, $\phi = 1$

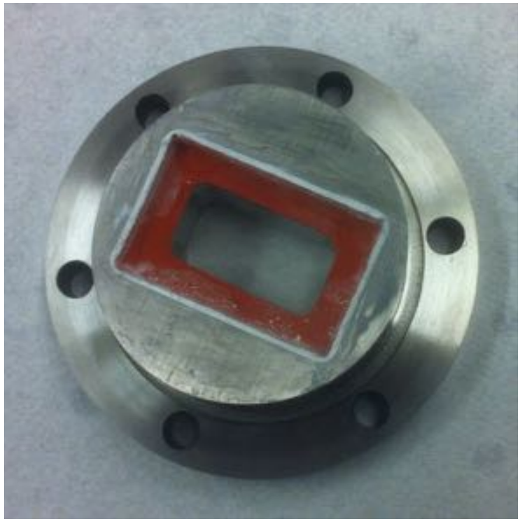


- Conclusion so far:
  - Multiple, superimposed tones – more analysis of pressure time series is needed
  - Not all tones are observed in plenums (I, II and III do not appear in air plenum)
    - Independent acoustic tone at $f \cong 1.6 f_D$ (not harmonic of f_D)
  - Unclear how they are related to acoustic of detonation channel and plenums

Toward imaging

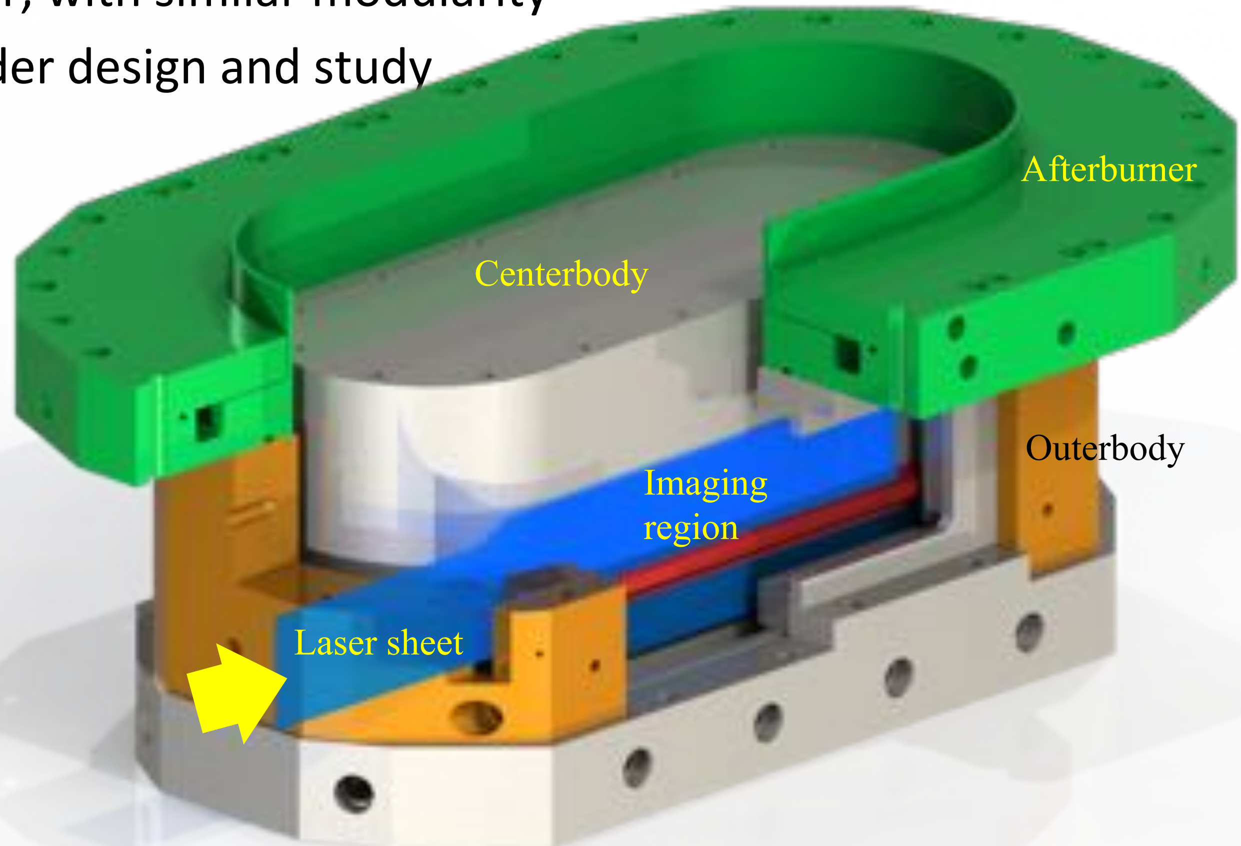


View from side, through side-window, with camera

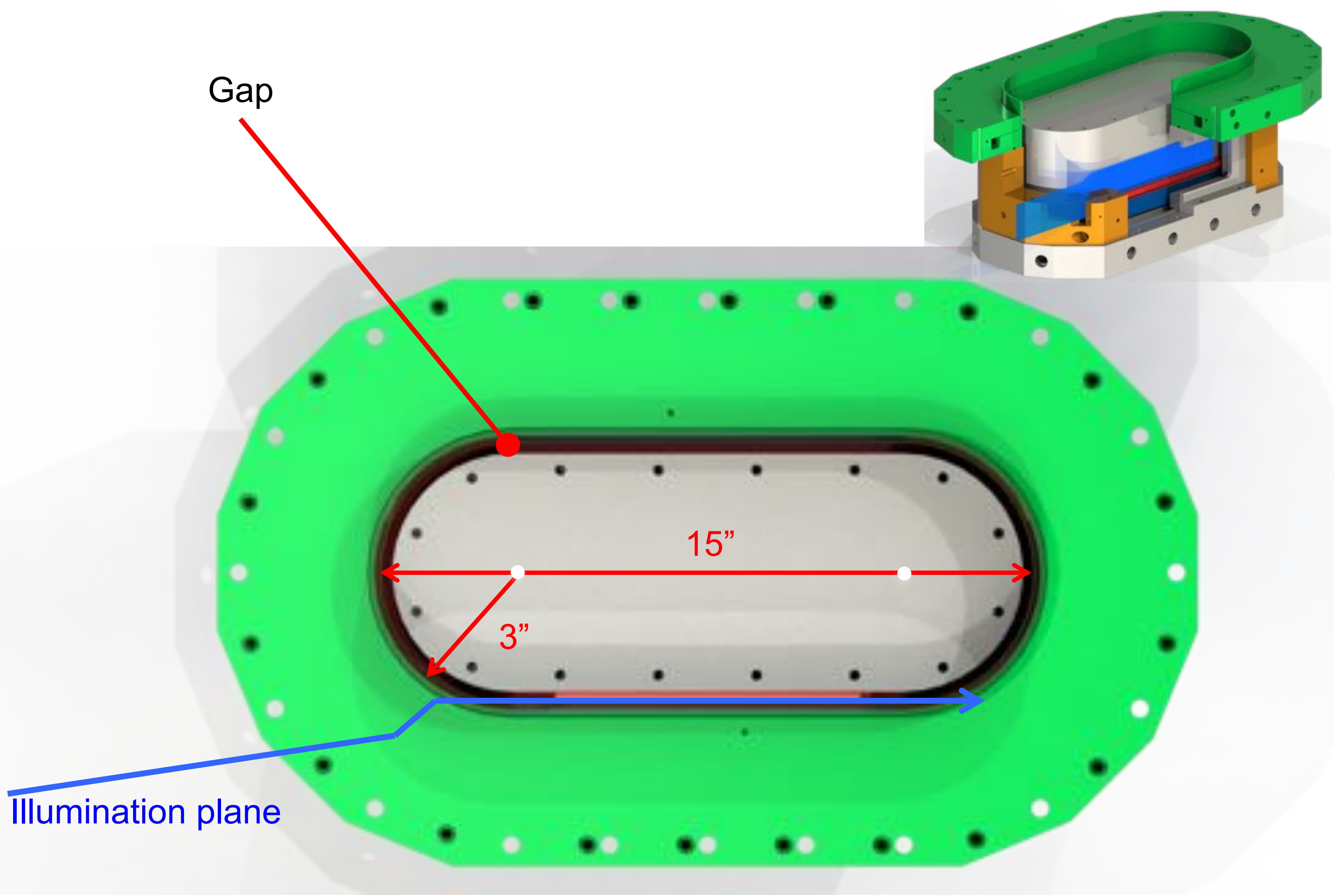


Race-Track RDE (RT-RDE) for optical access (12” diameter equivalent)

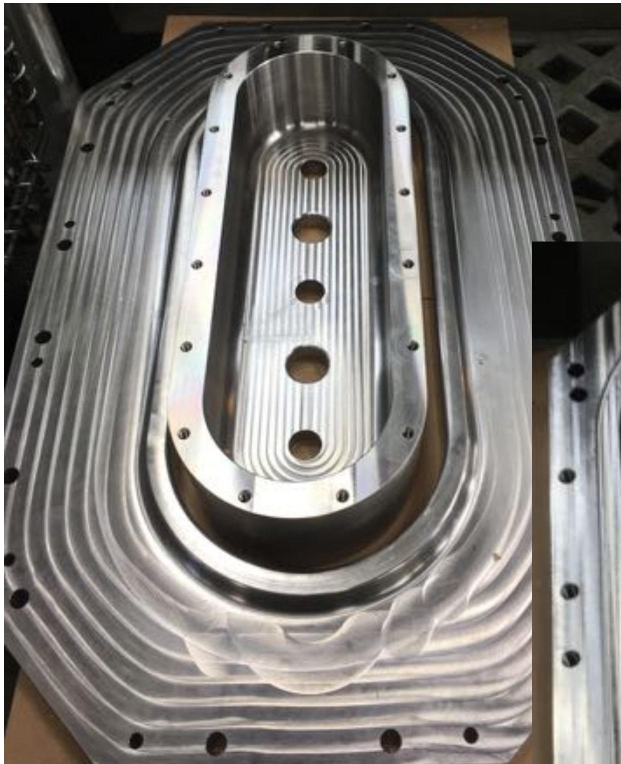
- Designed with optical access in mind
  - Allows for optical access of injection system and detonation chamber
- Fuel injection system
  - Follows modular design approach of round RDE
  - Red/blue pair, with similar modularity
  - Injectors under design and study



Race Track RDE



RT-RDE Being Completed



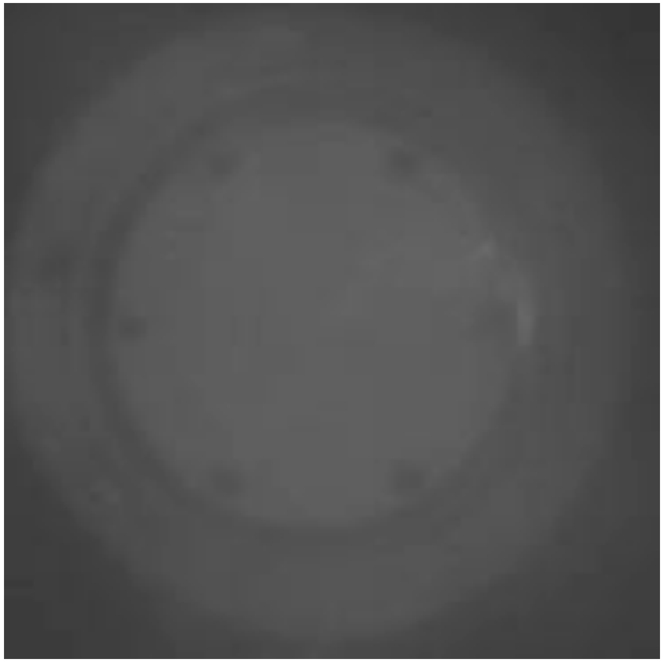
SOME THOUGHTS

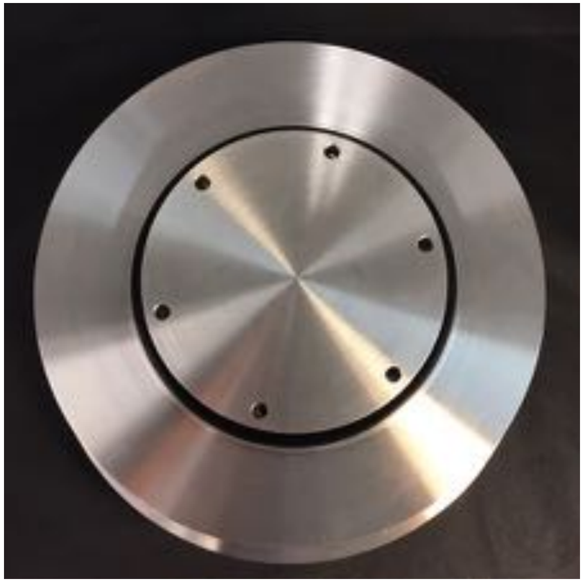
The hunt for Gain

O GAIN, WHERE ART THOU?

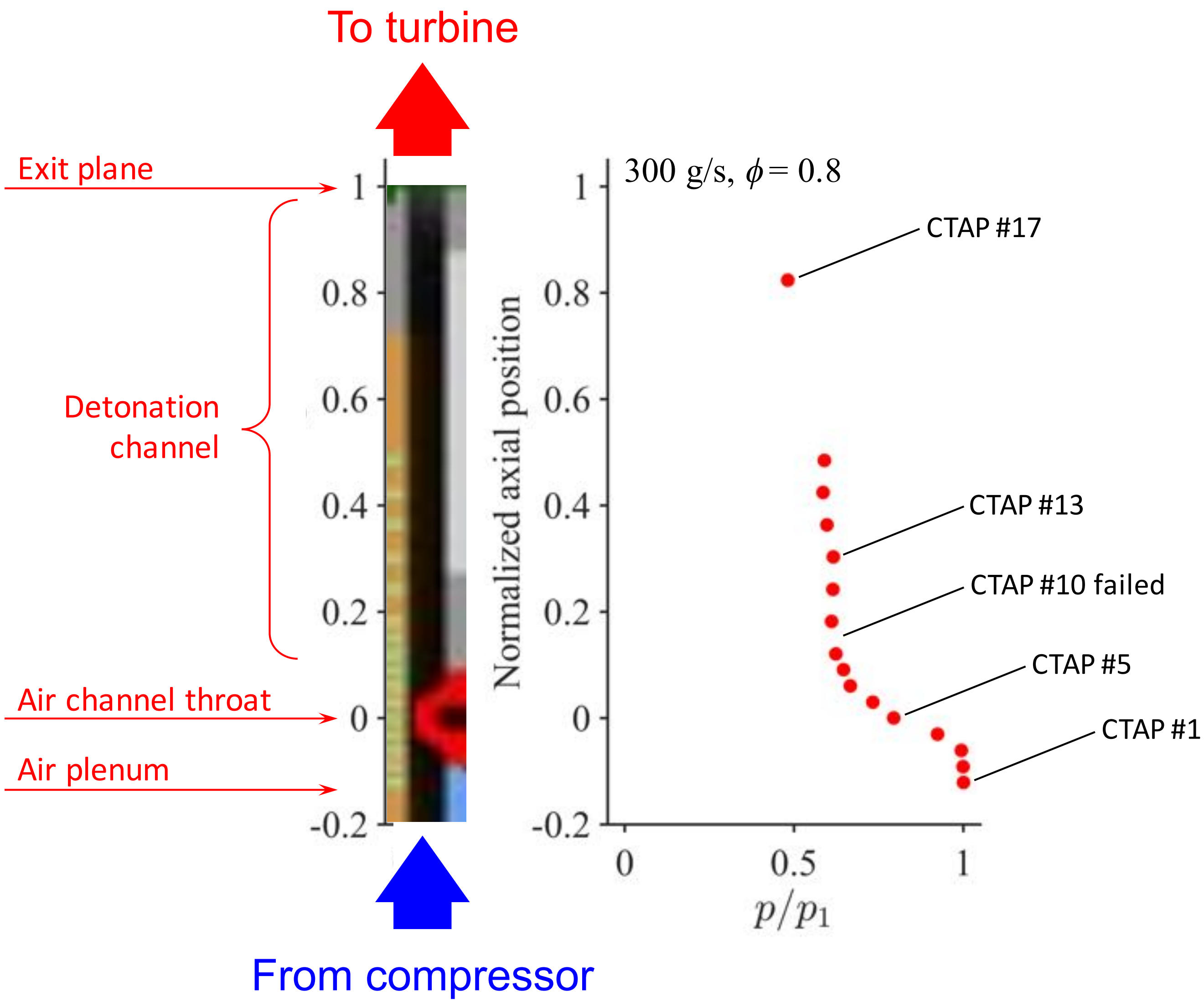
Can we measure the gain produced by this device?

Well, not quite…

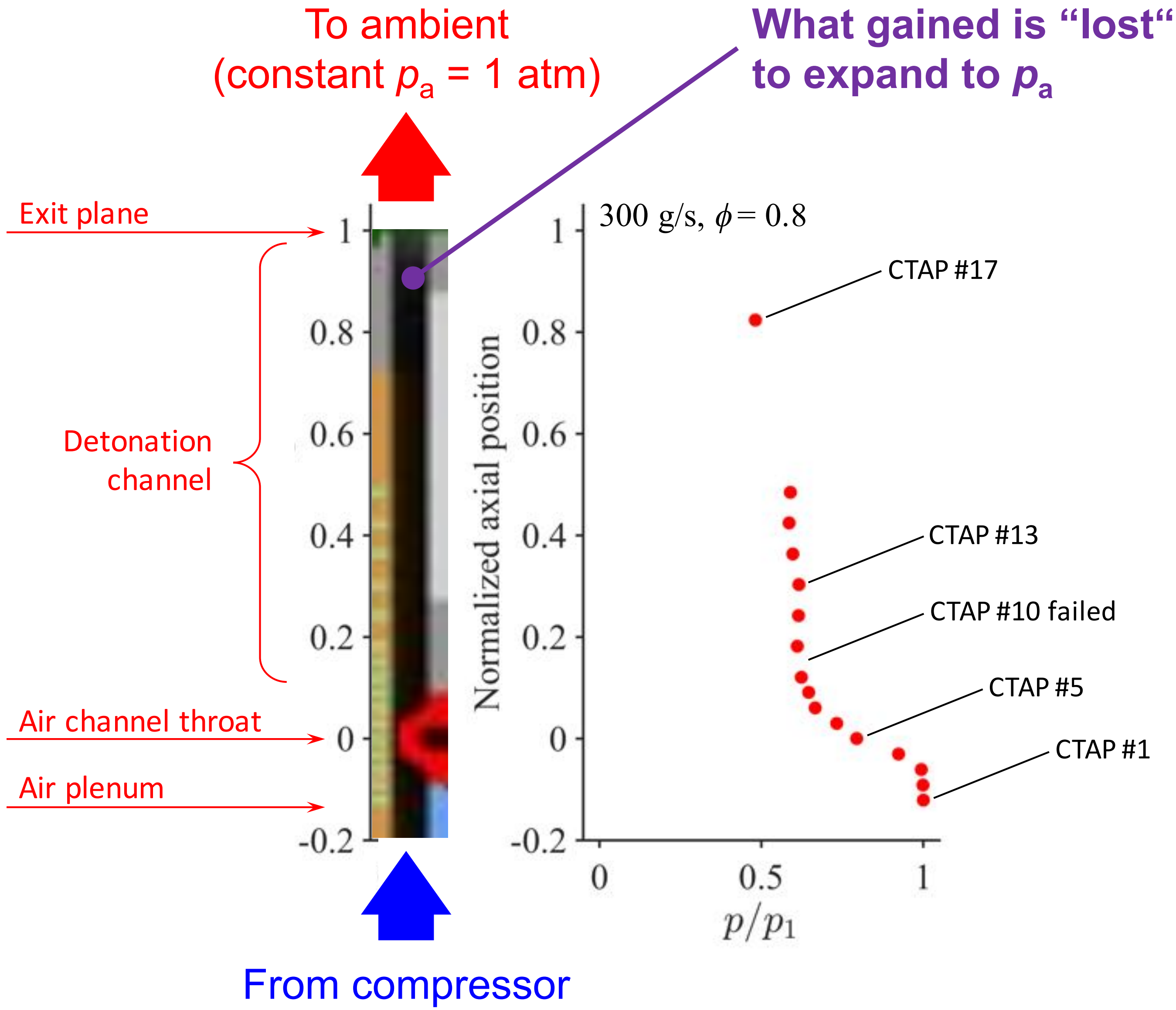




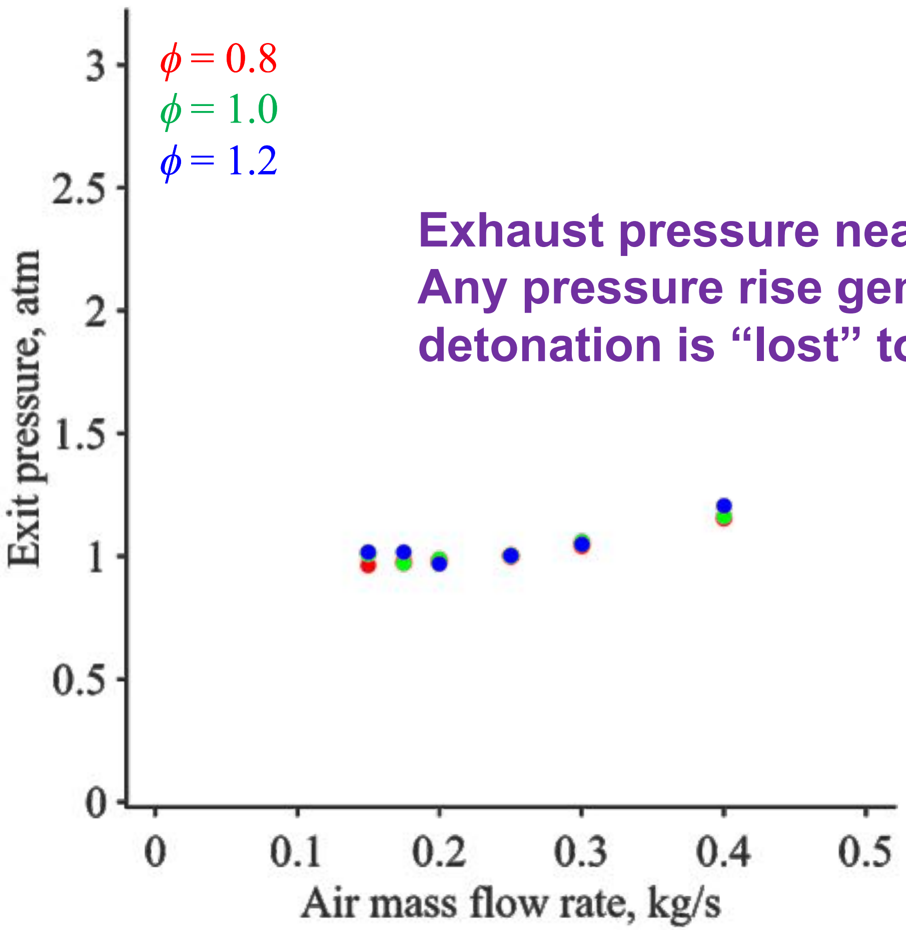
Intended use



Instead we have



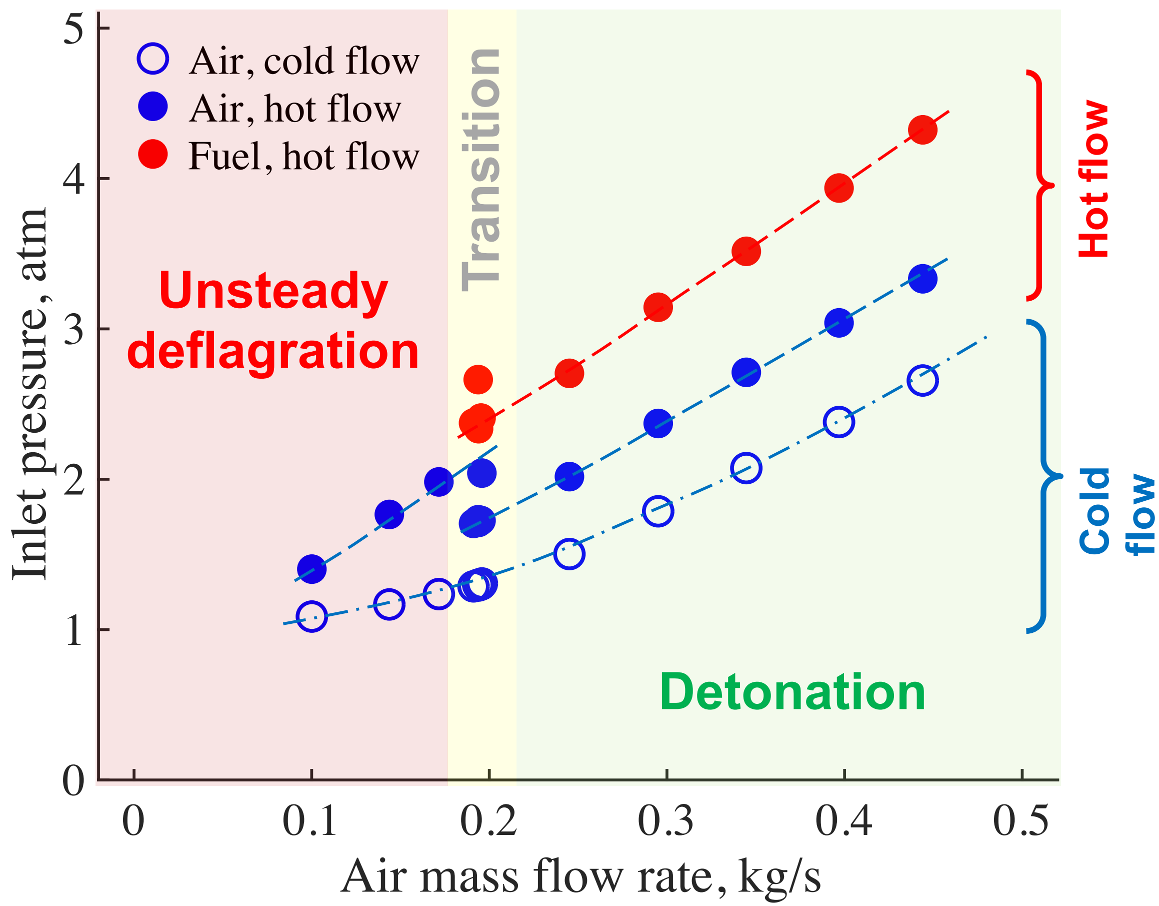
Variation of downstream pressure (CTAP17)



Exhaust pressure nearly constant: Any pressure rise generated at the detonation is "lost" to flow expansion

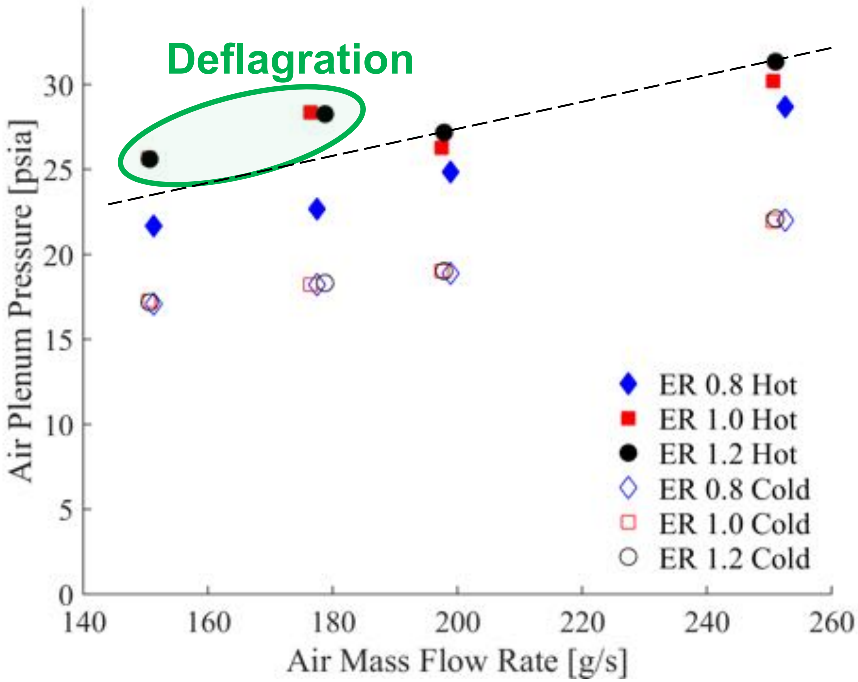
Consider how the air plenum pressure change with operating condition (ER and flow rate)

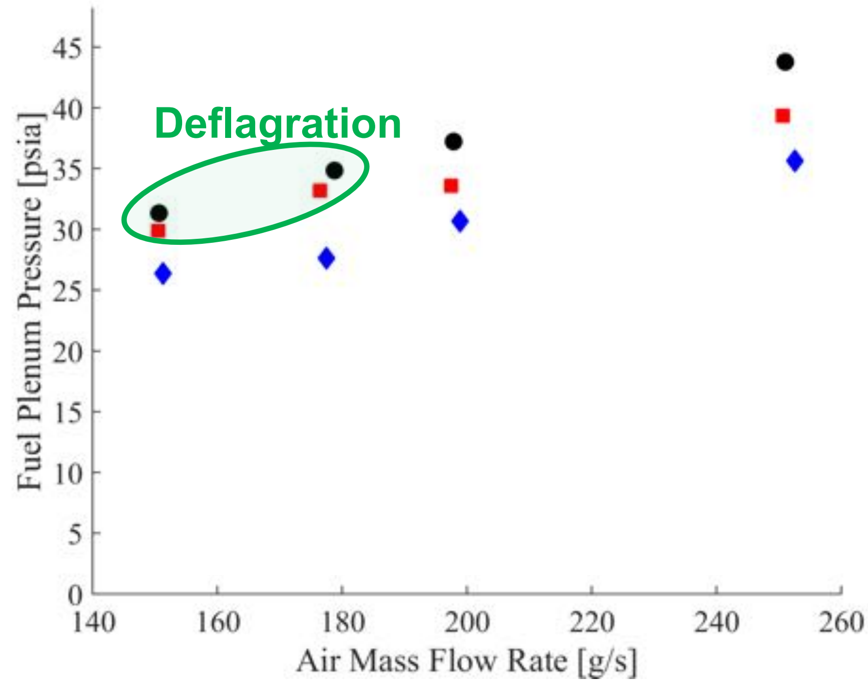
Measurement 1 – some time ago



Consider how the air plenum pressure change with operating condition (ER and flow rate)

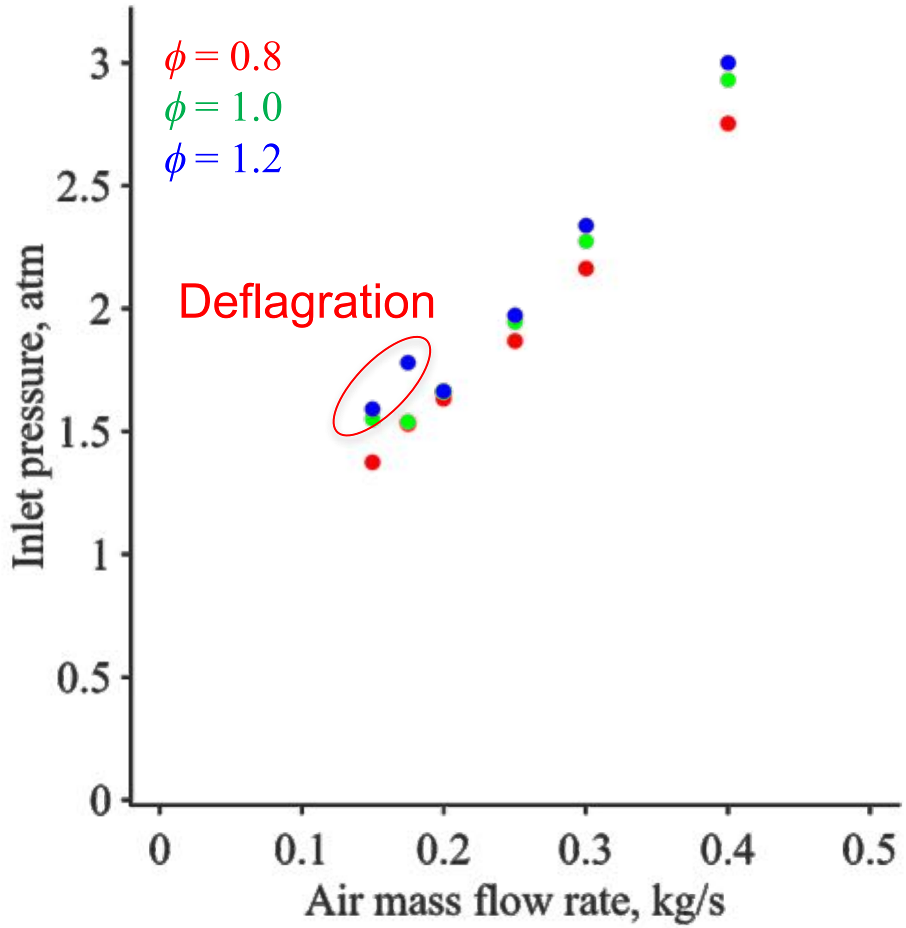
Measurement 2 – after some time with a different sensor in a different location (CTAP)



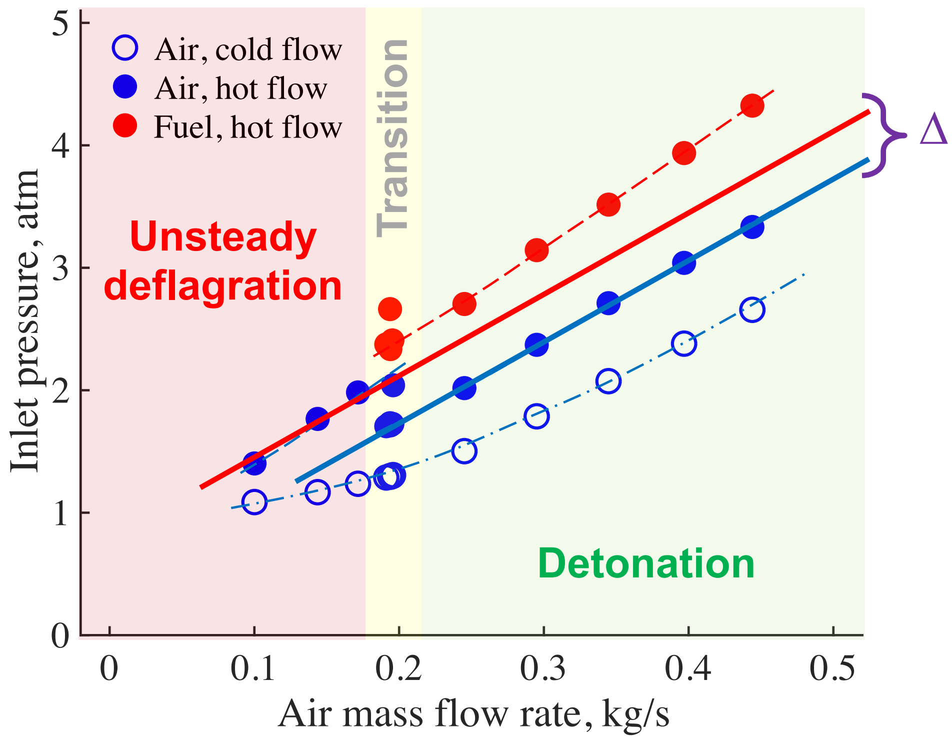


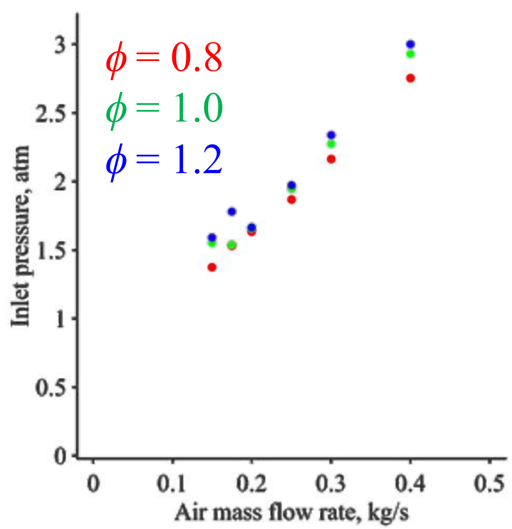
Consider how the air plenum pressure change with operating condition (ER and flow rate)

Measurement 3 – after some more time with a different CTAP sensor at the same location



Gain and the *lack of loss*





- Inlet pressure is lower in detonation than when in deflagration mode at the same ER and mass flow
  - Difference is Δ
  - **Significant amount**
  - **Increases at lower ER (more stable detonation)**
- To move the same mass, at nominally the same enthalpy, we require **less inlet pressure**
- Possibilities:
  - Are losses along channel less in detonation mode?
  - If losses are the same, is there pressure gain that offset them, thus requiring lower inlet pressure
- With the same turbine, operated at the same turbine inlet conditions, a **smaller OPR compressor** could be used
  - **Can this lead to increase in efficiency?**

Outline

- Introduction to the problem and general approach
- Experimental activities
- Computational activities

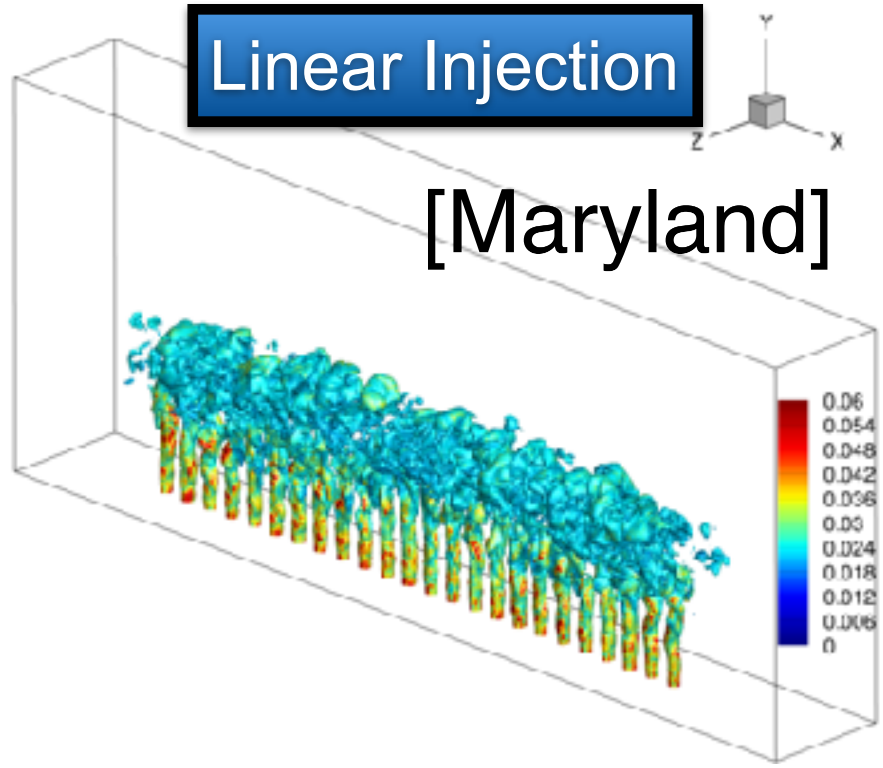
CFD Tools for RDE Applications

Venkat Raman, Mirko Gamba

University of Michigan

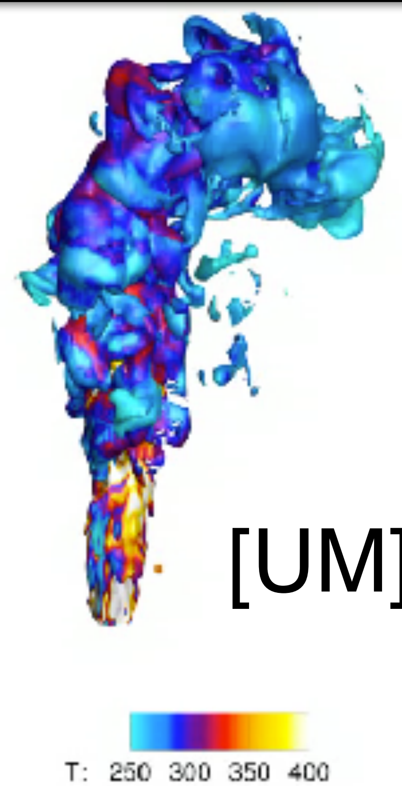
Year 1: Basic Research

Linear Injection



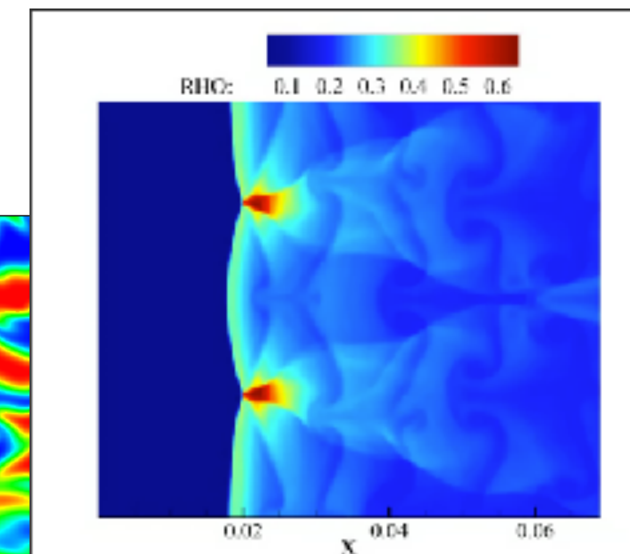
[Maryland]

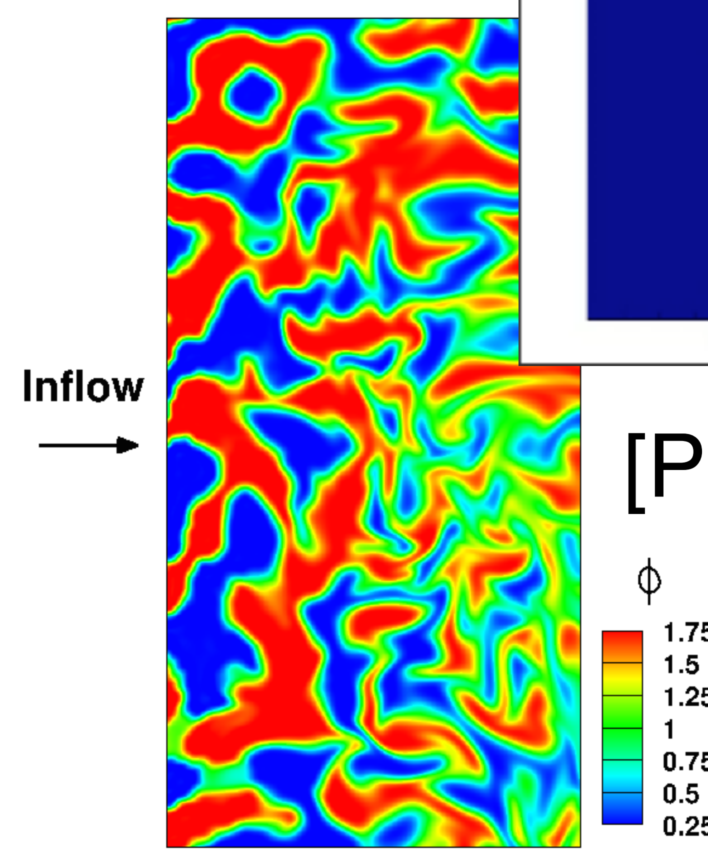
Gamba's SW/Det. Analogy



[UM]

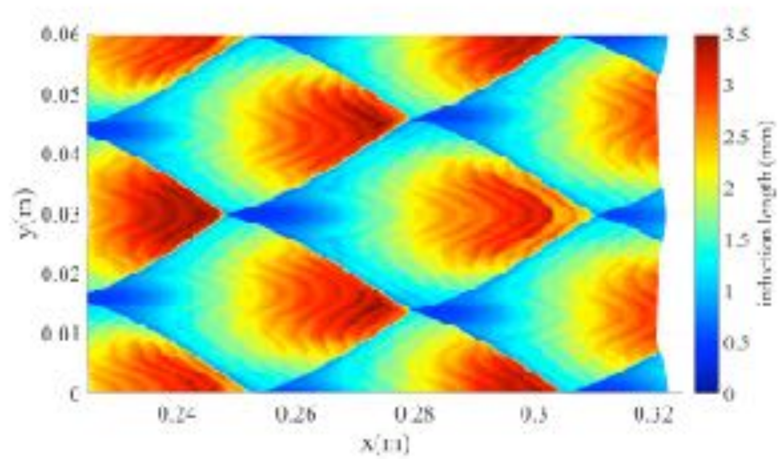
Stratification Effects



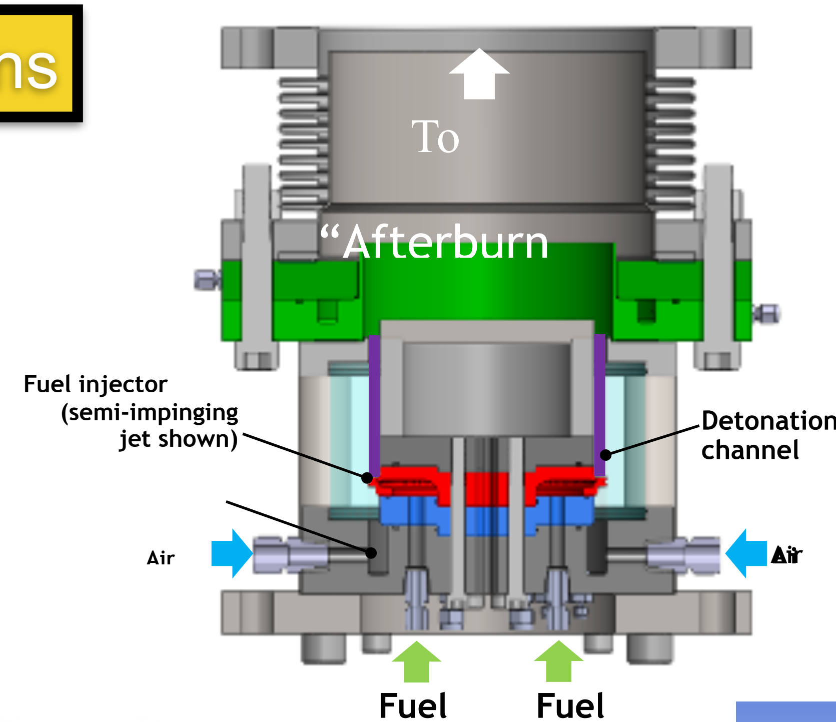


[Penn State]

Chemistry Validation



Year 2 - Full scale Simulations

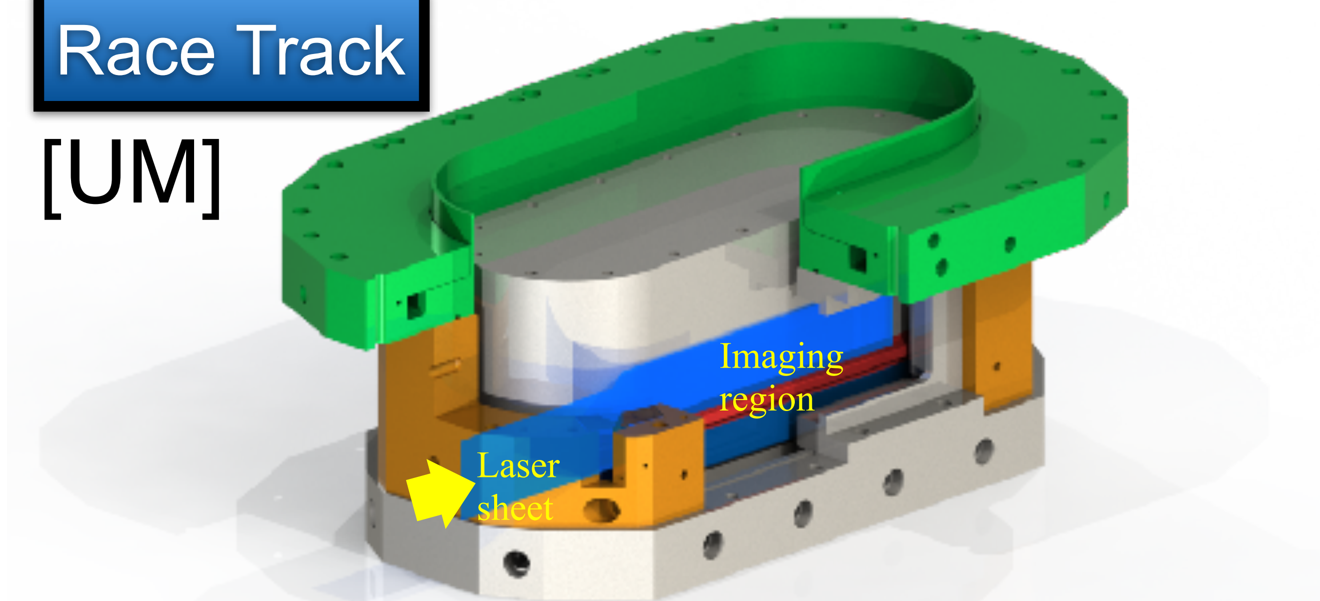


Full Scale

[AFRL/UM]

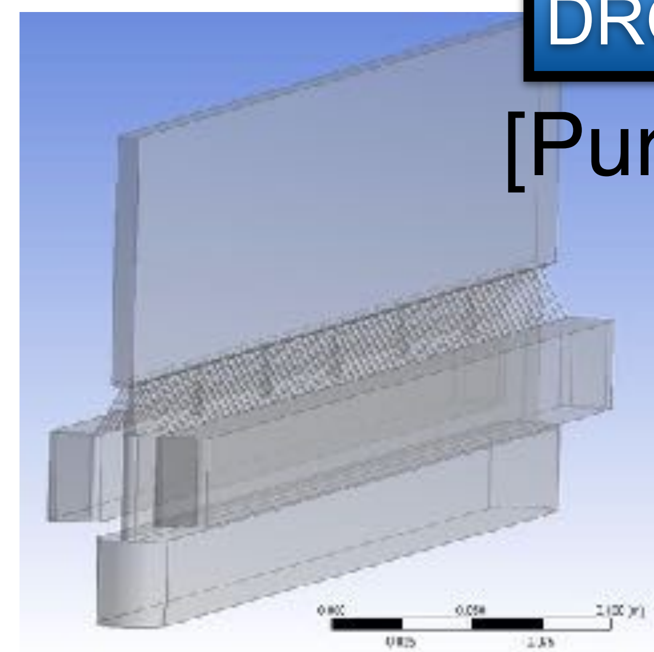
Race Track

[UM]

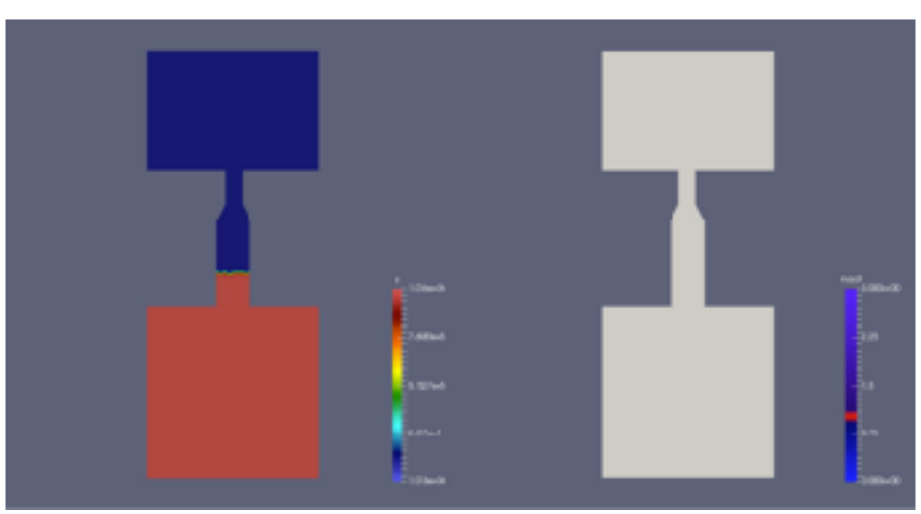


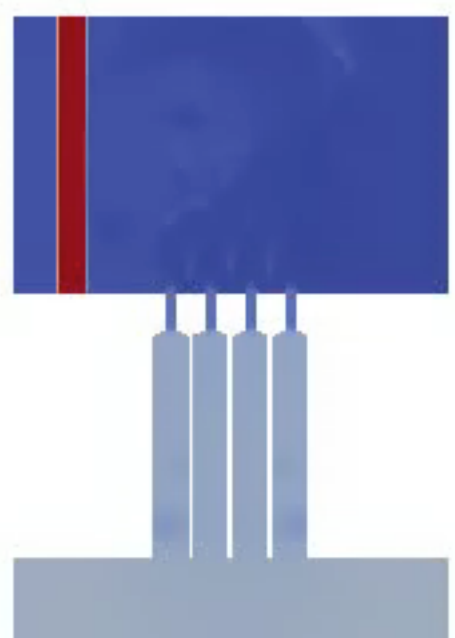
DRONE

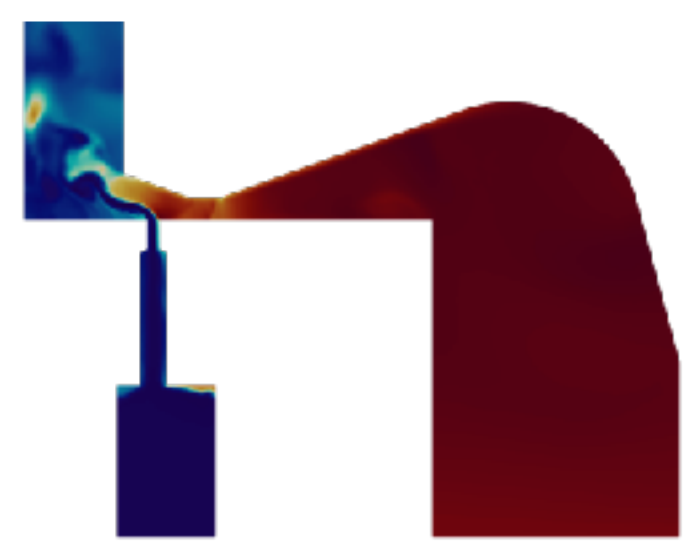
[Purdue]



Increasing Complexity





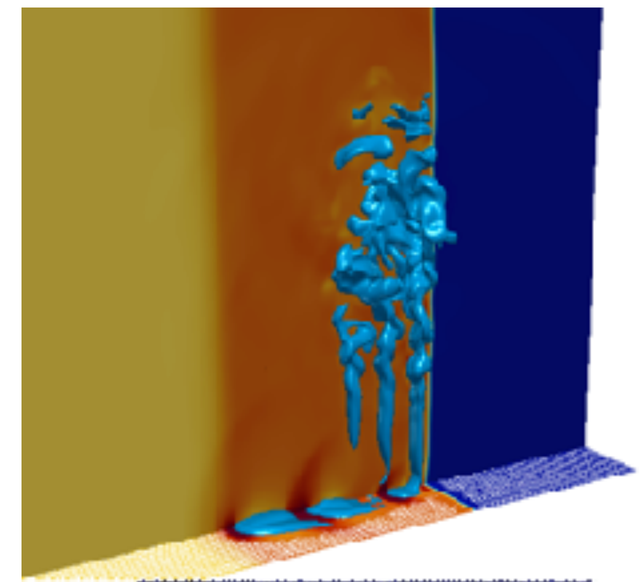


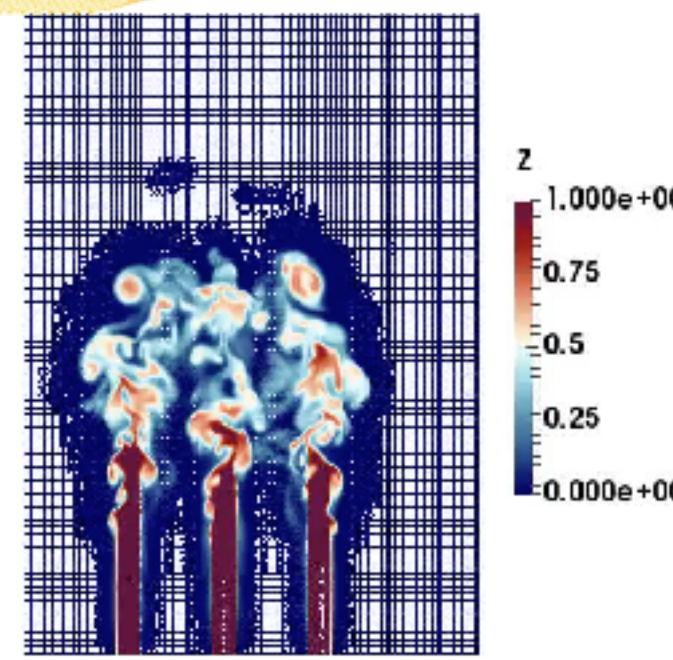
Full-scale Solver with Detailed Chemistry

- **OpenFOAM code base**
  - ➡ Fully rewritten to provide low dissipation shock-capturing
    - Low dispersion/dissipation finite volume approach
  - ➡ Detailed chemistry by integration with Cantera
    - Any chemistry mechanism can be simulated
- **CPU/GPU capability**
  - ➡ Direct chemistry integration
  - ➡ Scaling tested up to 10K cores
    - No bottleneck for 50K cores
- **Time to solution**
  - ➡ Time from obtaining CAD file to full simulation data
  - ➡ Reduced from 8.5 months (UM geometry) to 2 days (NETL)

Adaptive Mesh Refinement

- **Resolving structures of detonation**
  - ➡ Requires Δx ≃ 𝒪(10-6) - 𝒪((10-7)m (Powers et al.)
  - ➡ For full-scale simulations, uniform grid is computationally restrictive



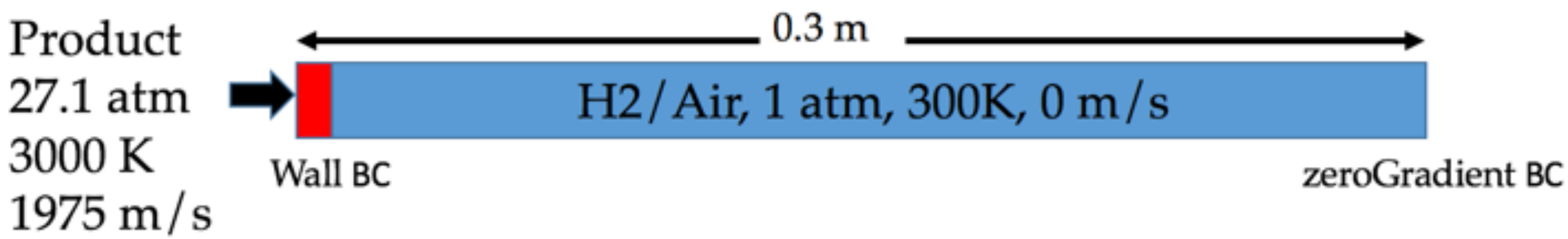


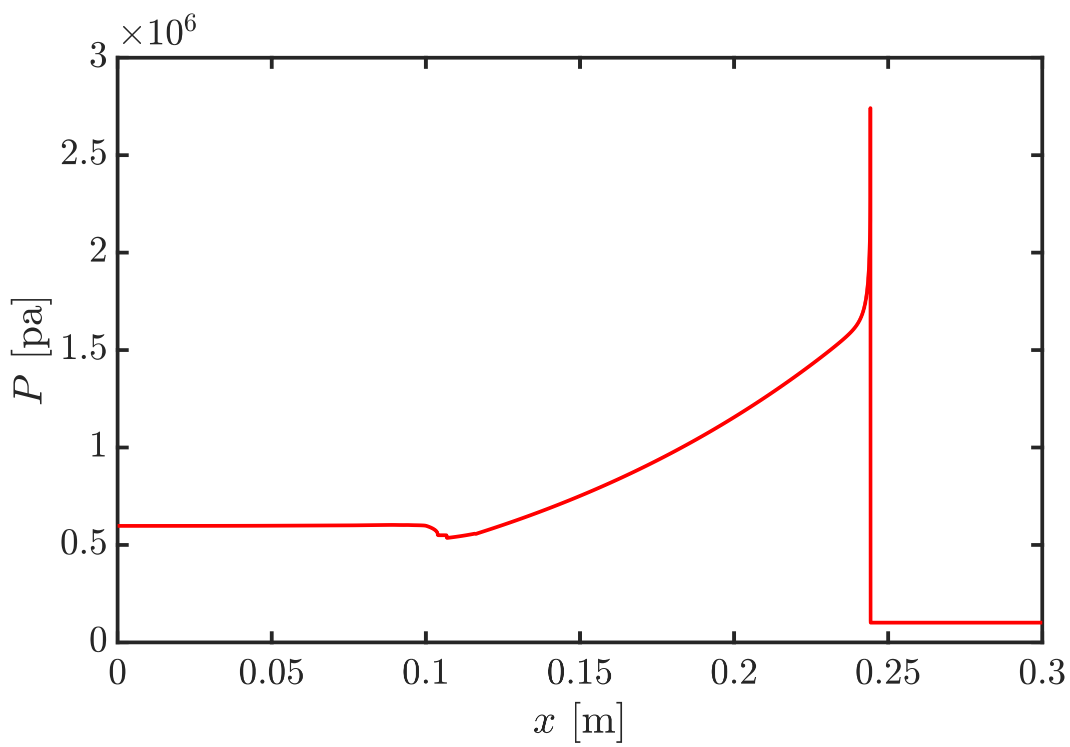
- **AMR advantages**
  - ➡ Gives sufficient resolution to resolve detonation structure
  - ➡ Reduce numerical dissipation
  - ➡ Reduce computational cost

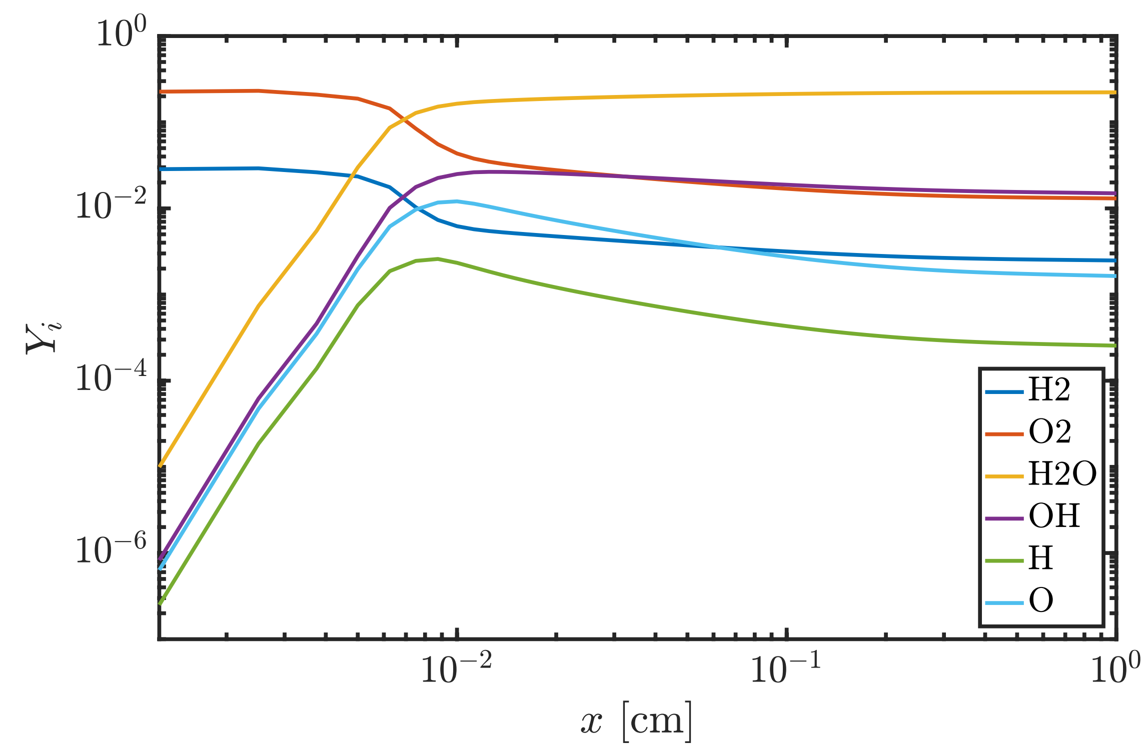
Powers, J.M. and Paolucci, S. "Accurate Spatial Resolution Estimates for Reactive Supersonic Flow with Detailed Chemistry", AIAA JOURNAL, Vol. 43 No. 5, May 2005

UNIVERSITY OF MICHIGAN

1D Detonation Tests

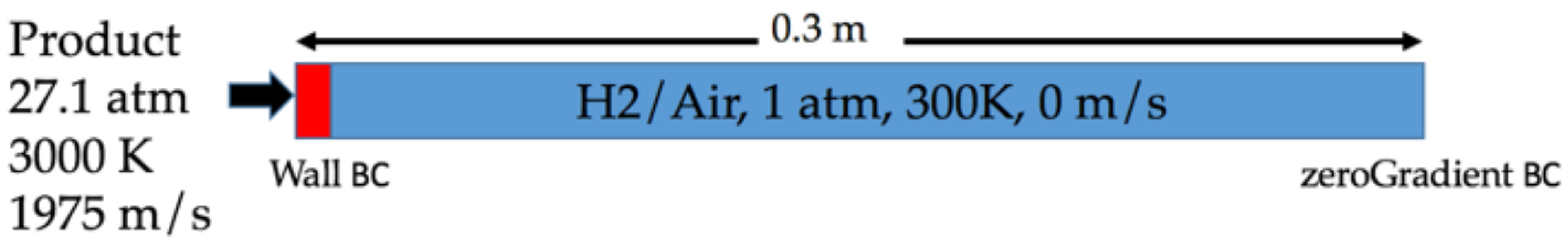


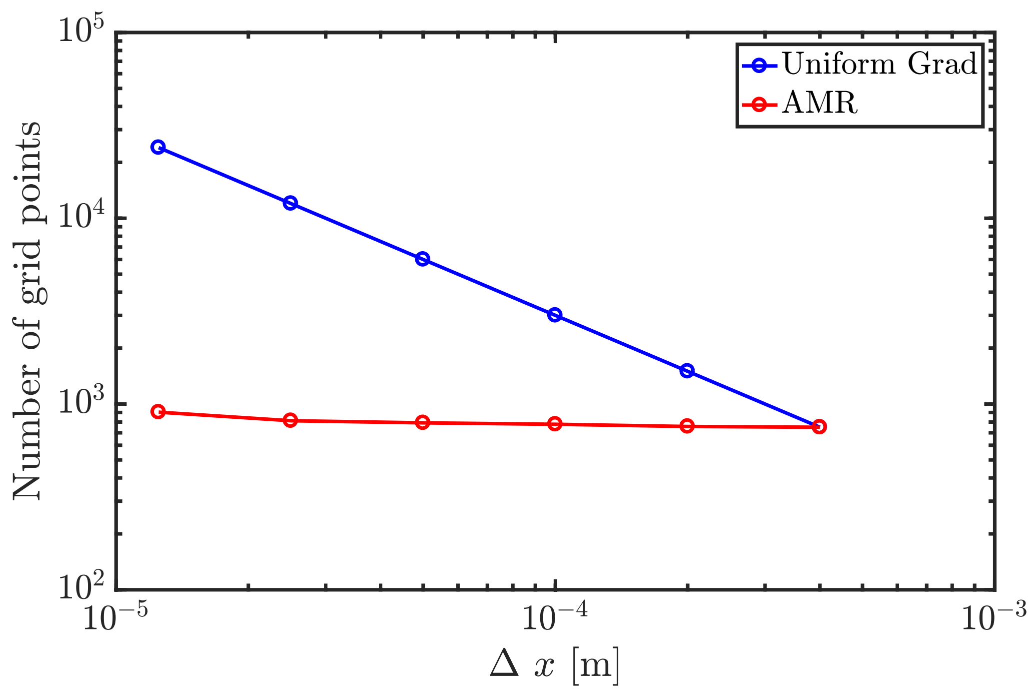


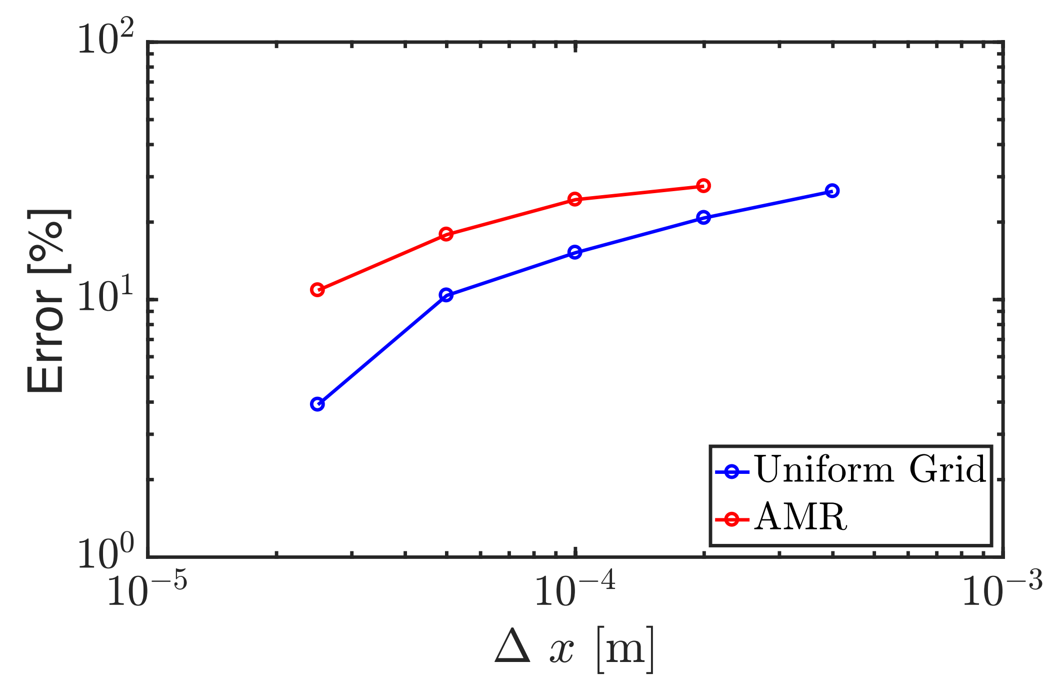


- **Pressure jump followed by delayed ignition captured**
  - ➡ Dynamic meshing ensures that shock is not smeared

1D Detonation Tests

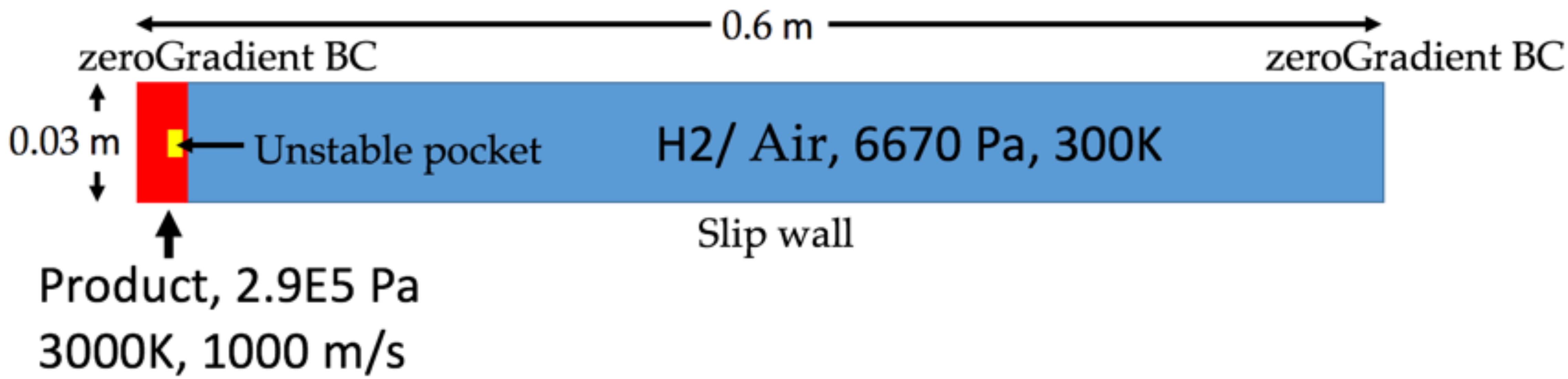


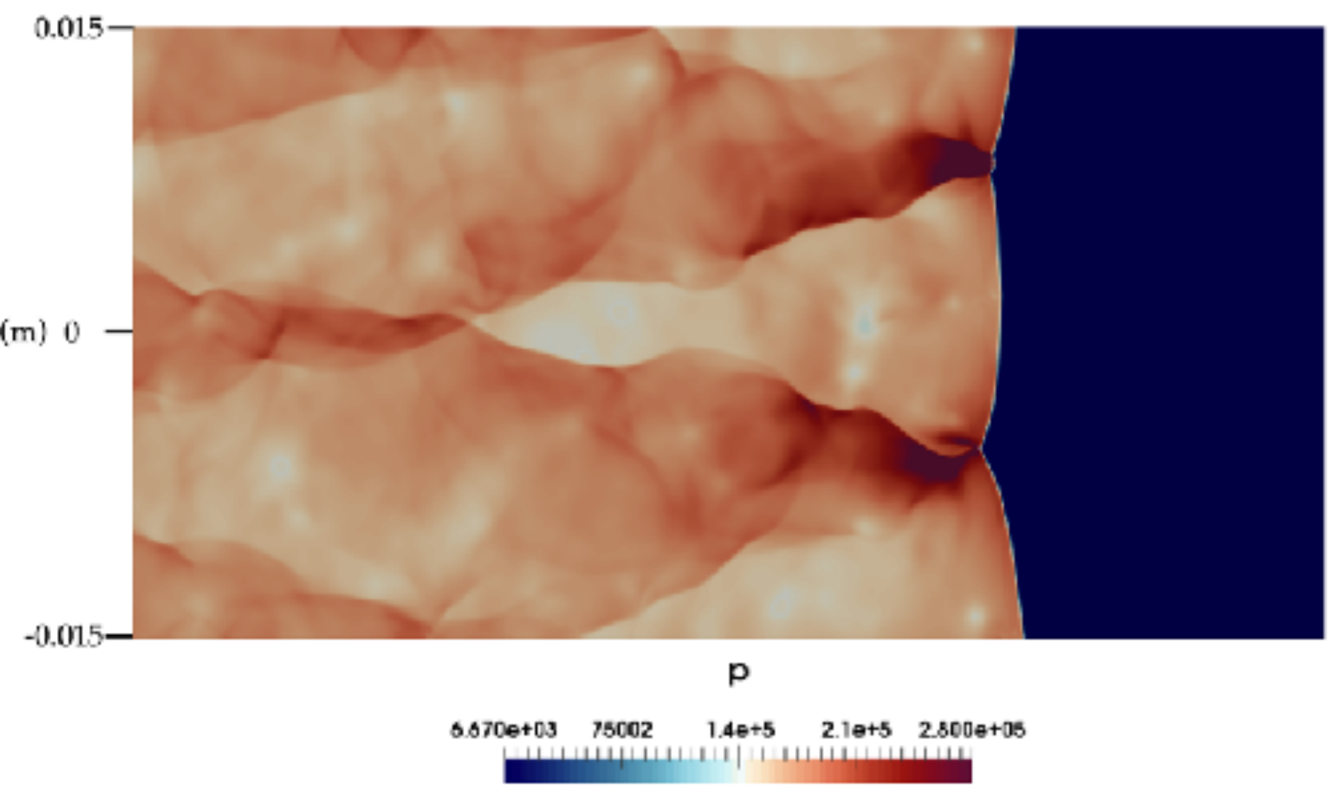


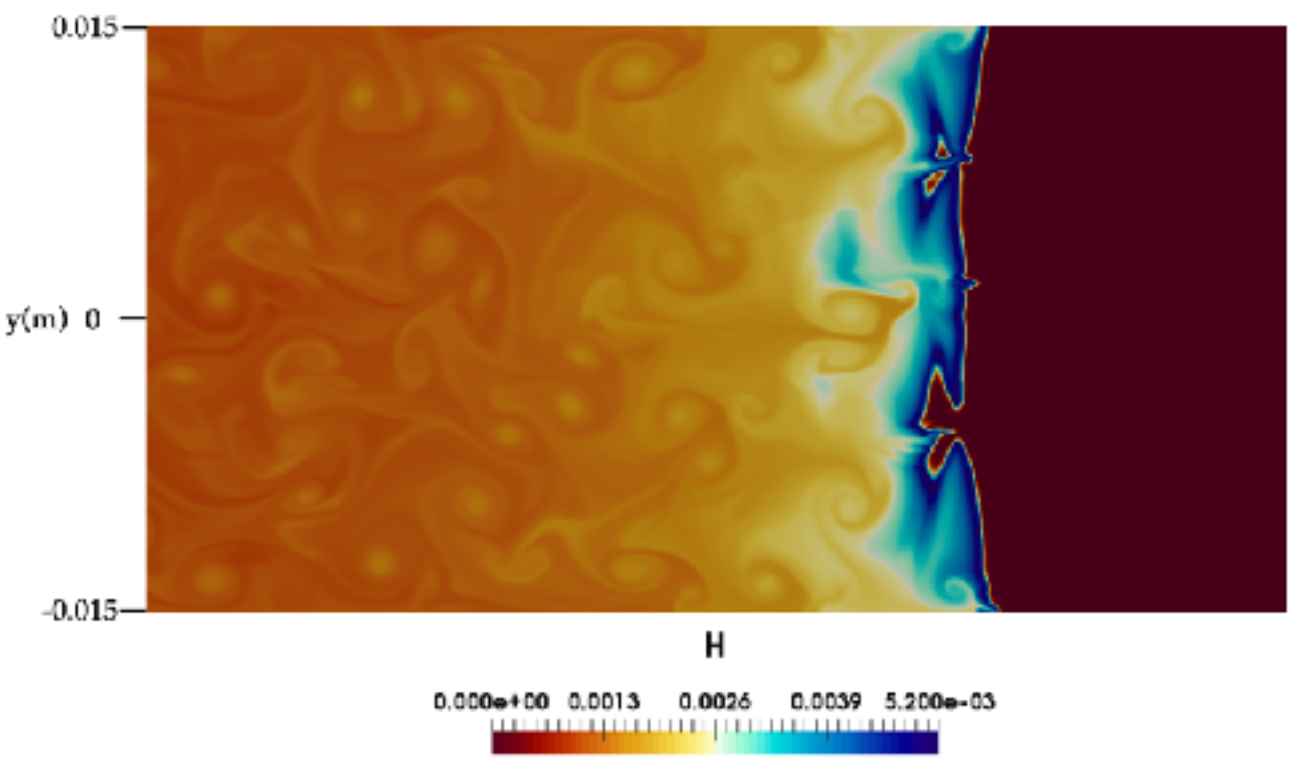


- **AMR provides significant cost advantage**
  - ➡ Choice of refinement criterion is important
  - ➡ Dynamic load balancing needed (currently being implemented)

2D Detonation Tests

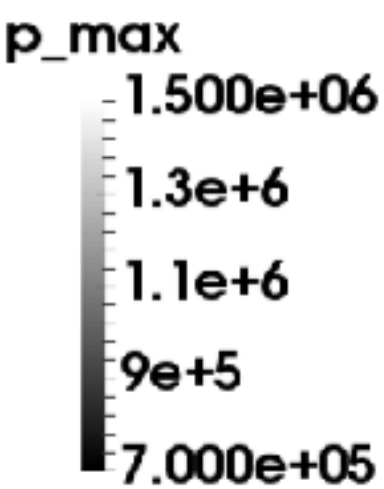




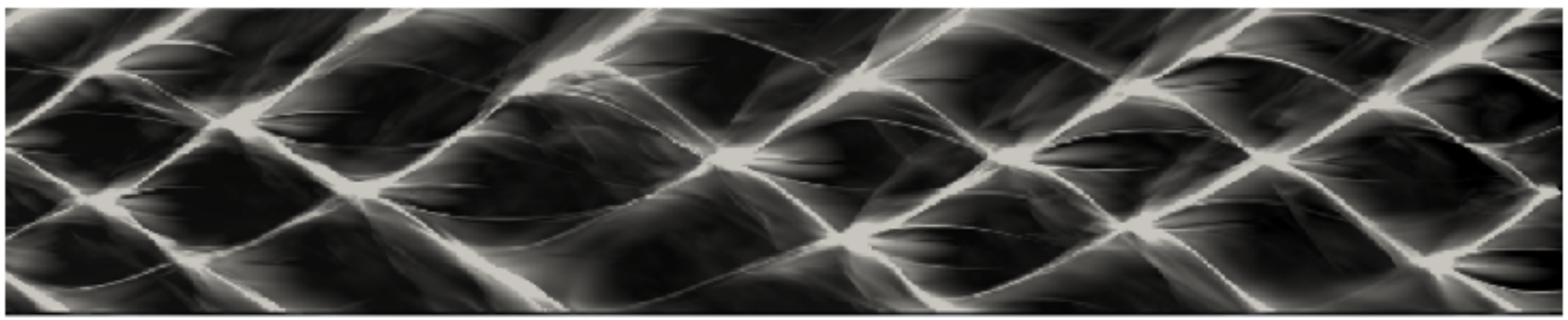


2D ethylene case

- **Cellular structure validation**
  - ➡ longitudinal tracks from the intersection points
  - ➡ 2 cell structure across the channel width



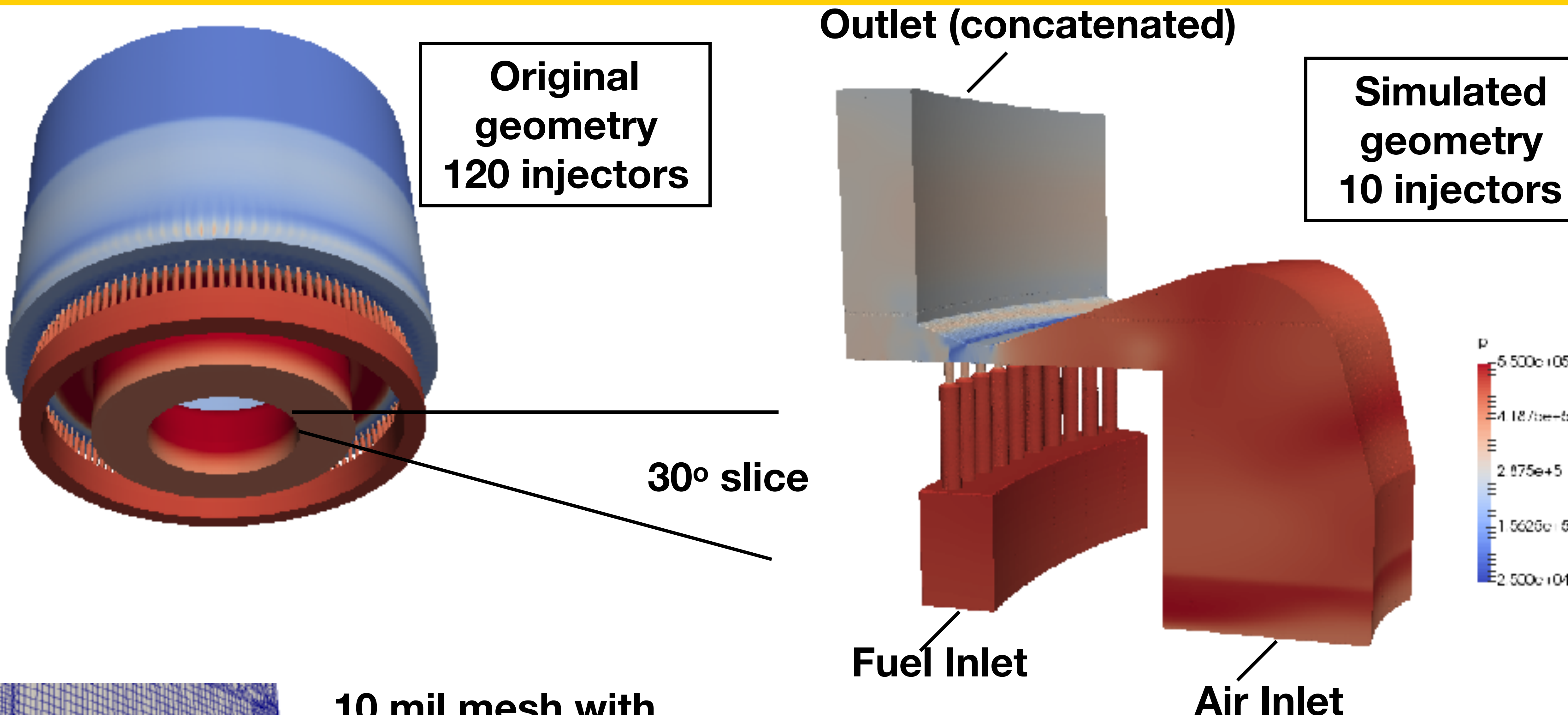
U of M

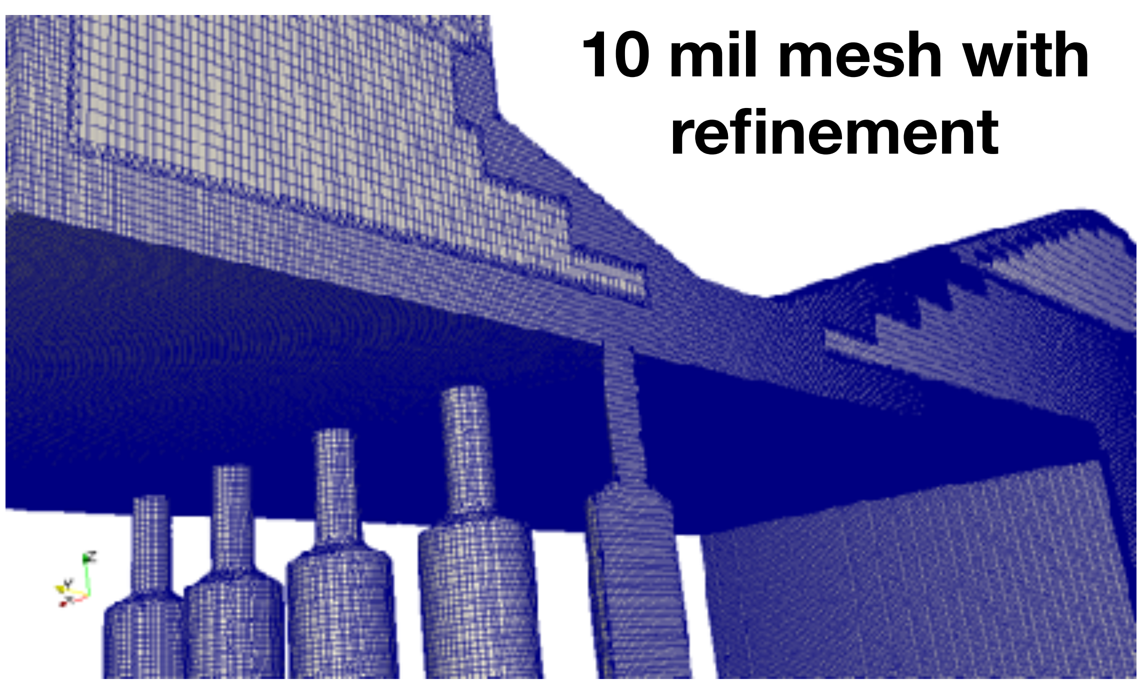


Hayashi et al.

C_2H_4/ O_2, 0.1 atm, 300K
Δ = 3 μm, h = 2 mm

Full Scale Configuration (AFRL)



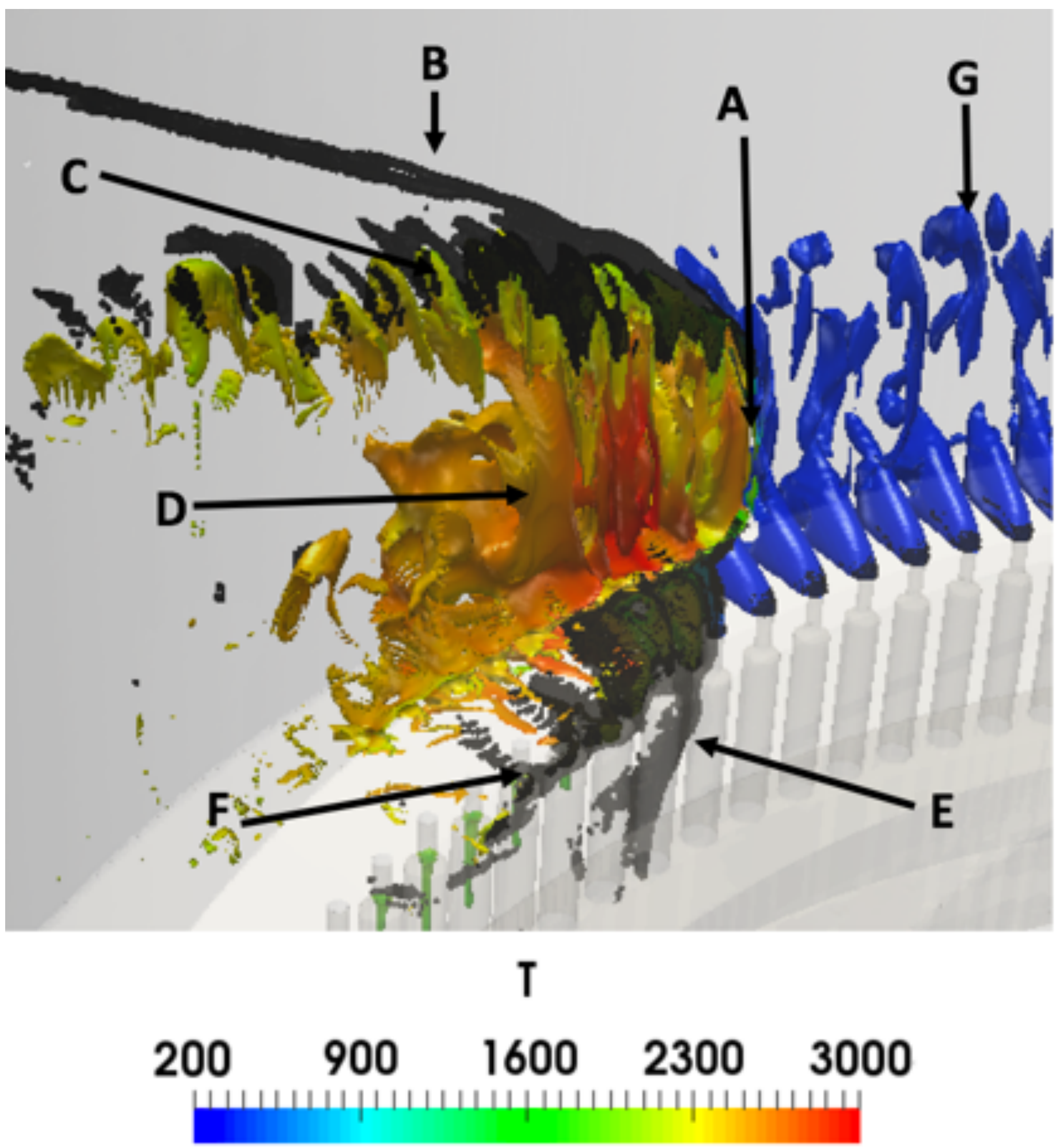


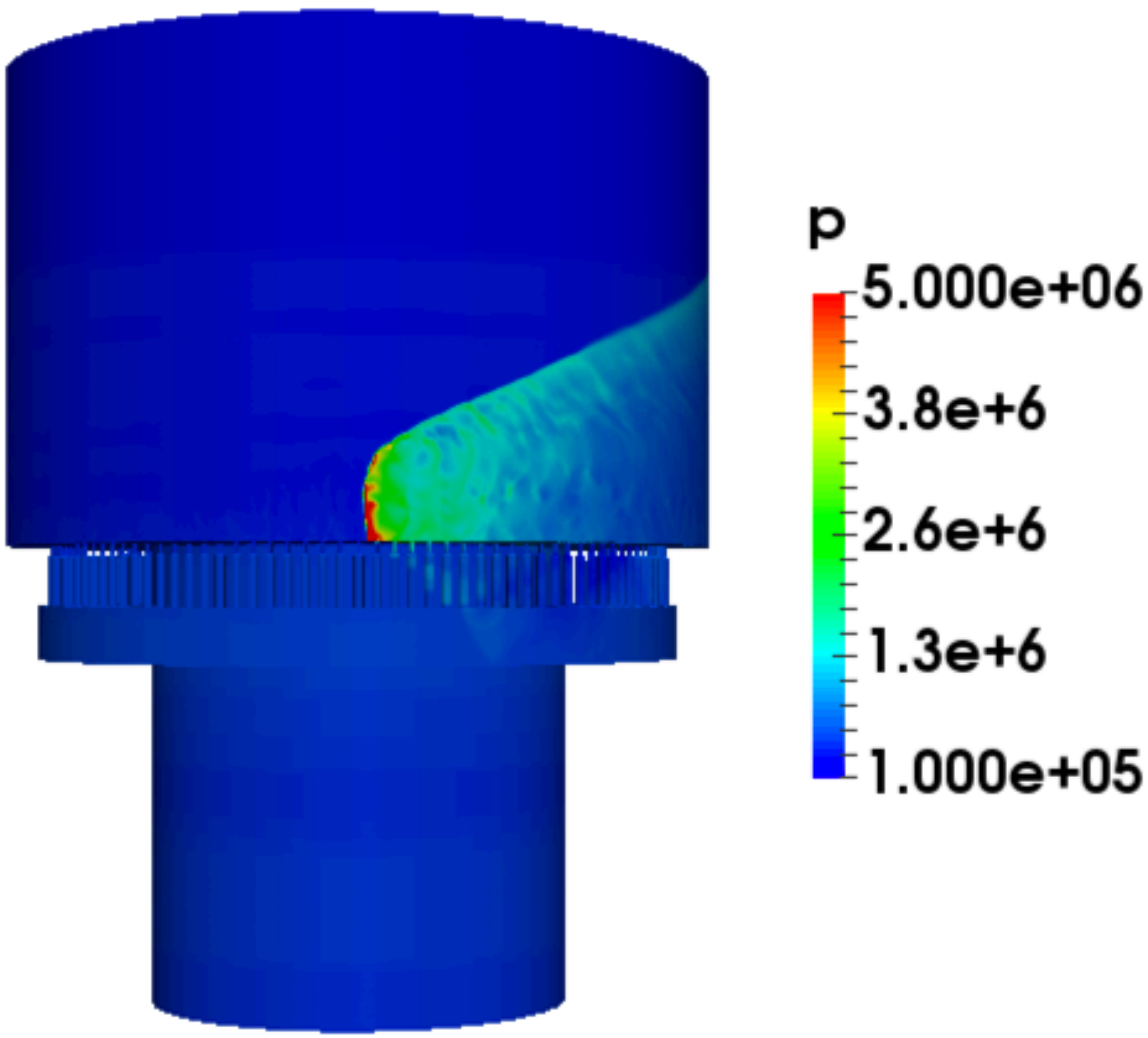
10 mil mesh with refinement

Case	Air mass flow rate [kg/s]	Fuel mass flow rate [kg/s]	Equivalence ratio	Air plenum pressure [kPa]	Fuel plenum pressure [kPa]
3.2.2.1*	0.63	0.018	1.01	431	503

*Rankin, Brent A., et al. "Chemiluminescence imaging of an optically accessible non-premixed rotating detonation engine." *Combustion and Flame* 176 (2017): 12-22.

AFRL RDE Detonation Structure





- **Complex wave structure**
  - ➡ Strong backpropagation into inflow plenums

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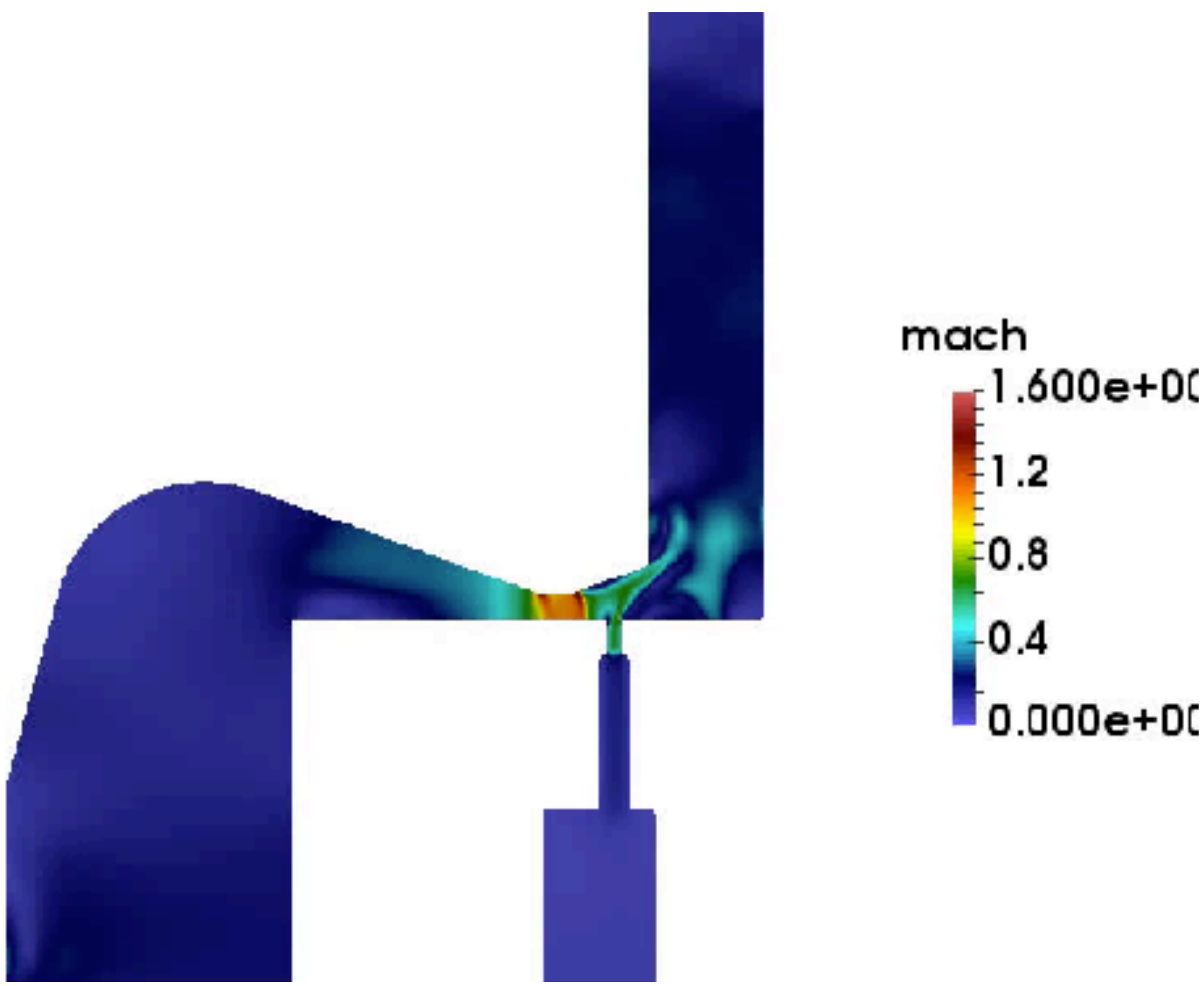
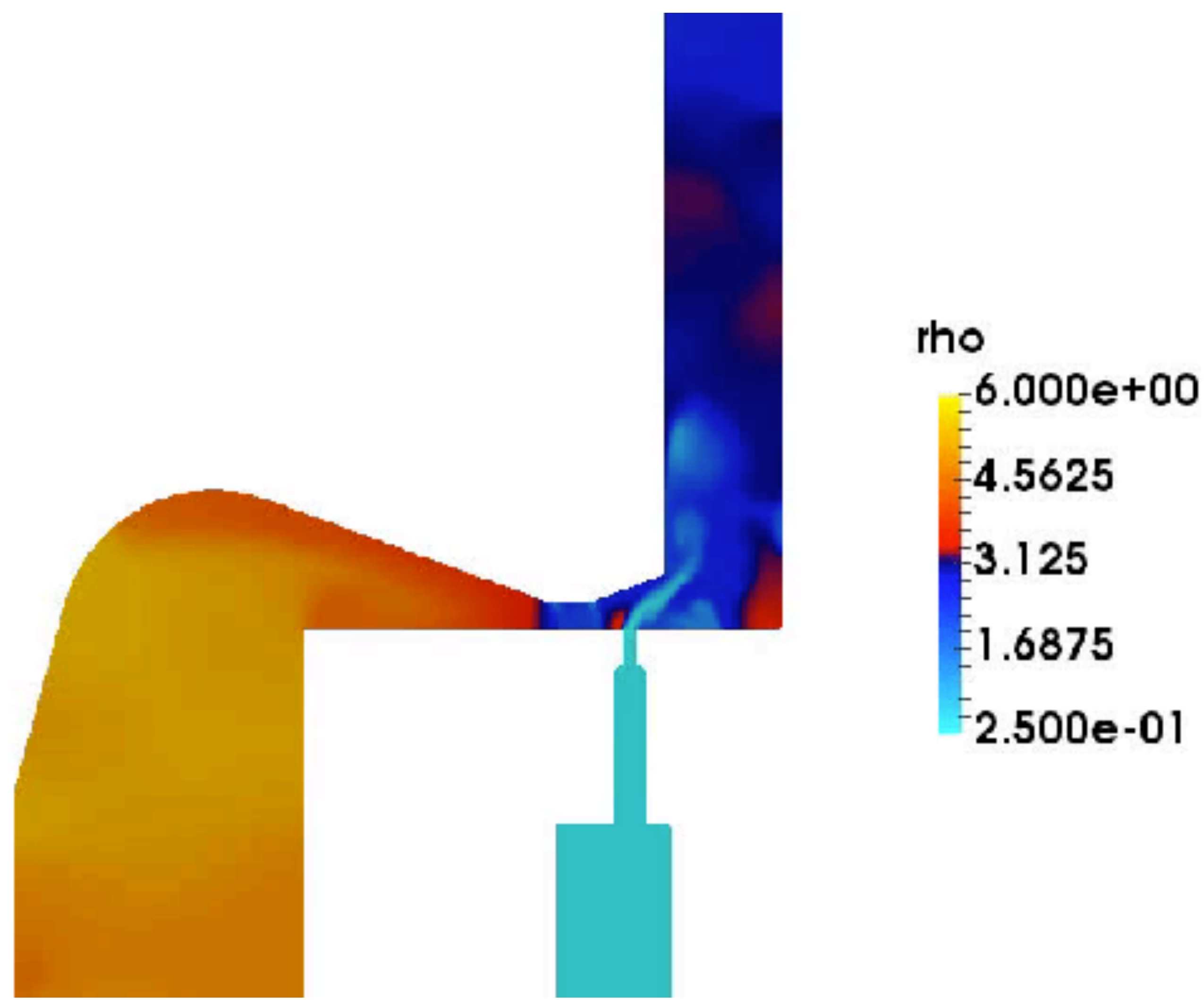
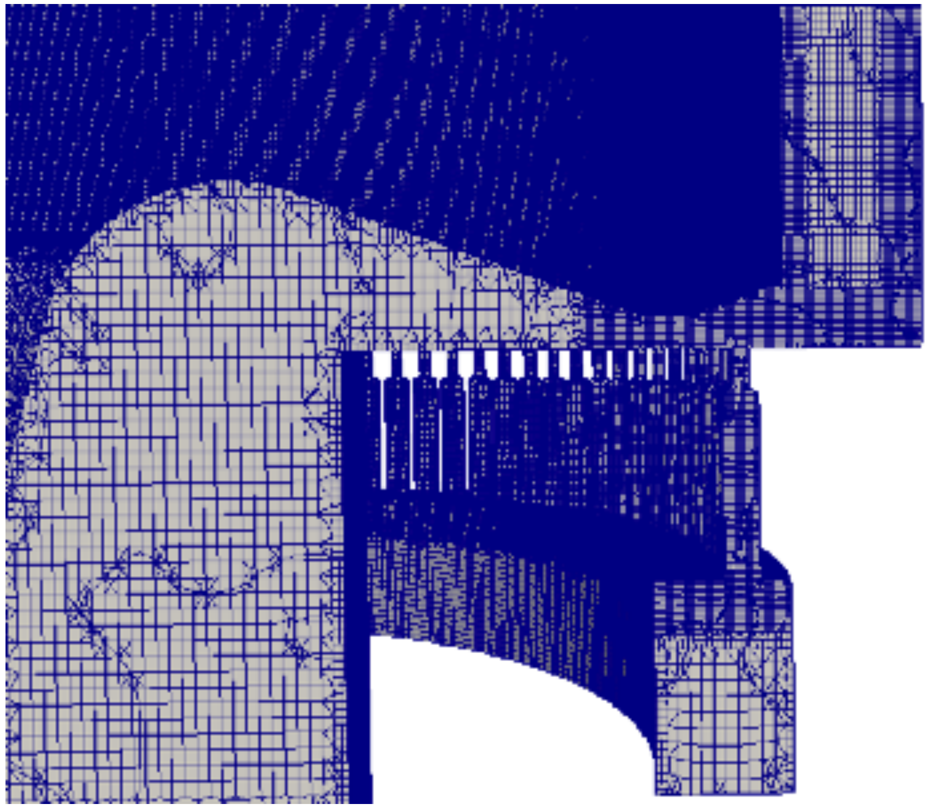
AFRL injection response

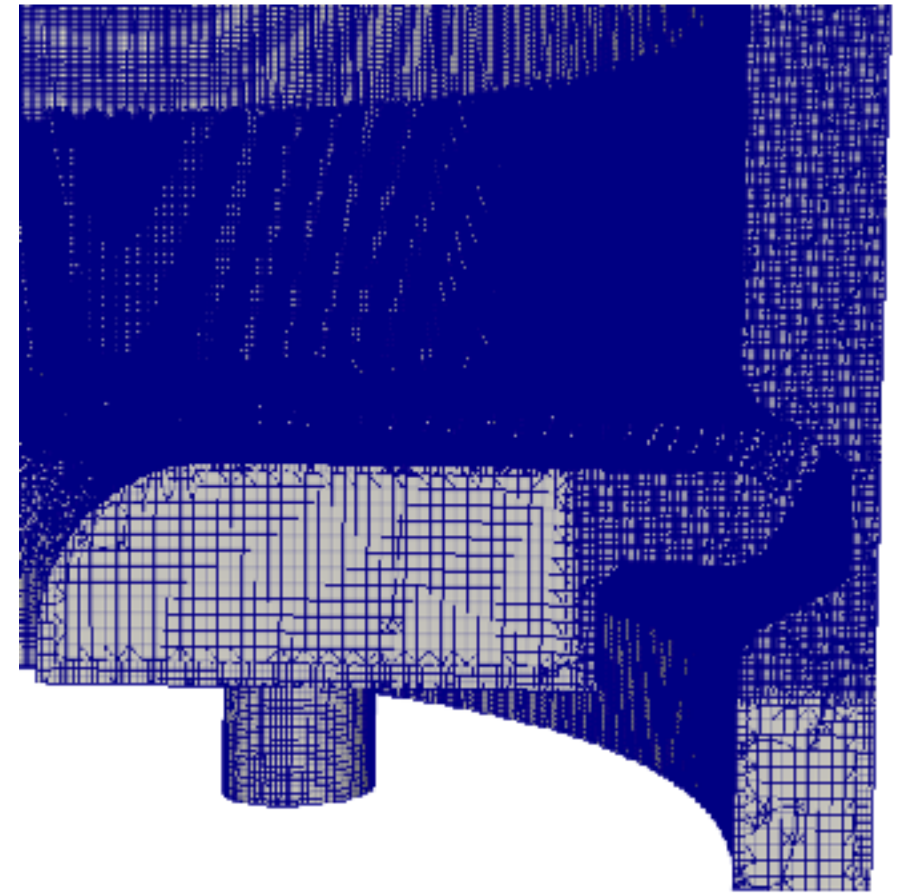
- **Flashback occurs when a detonation pass through**
  - ➡ Mach barrier at the choke point is broken
- **Recovers quickly**
  - ➡ Pushed back due to the plenum pressure

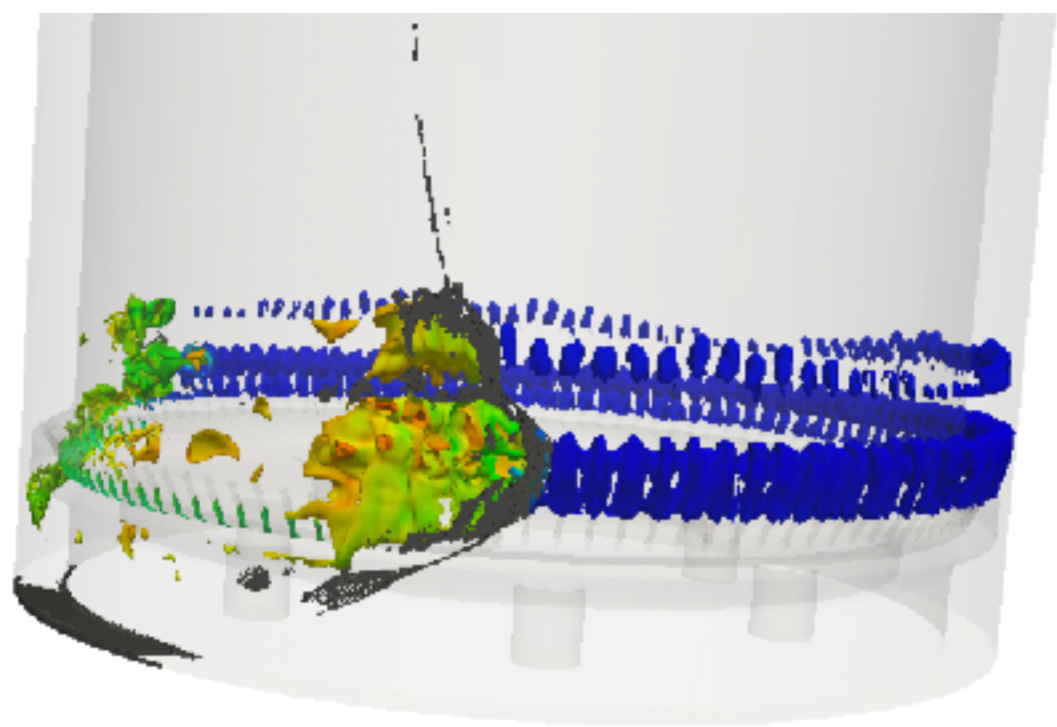




AFRL/UM Geometry

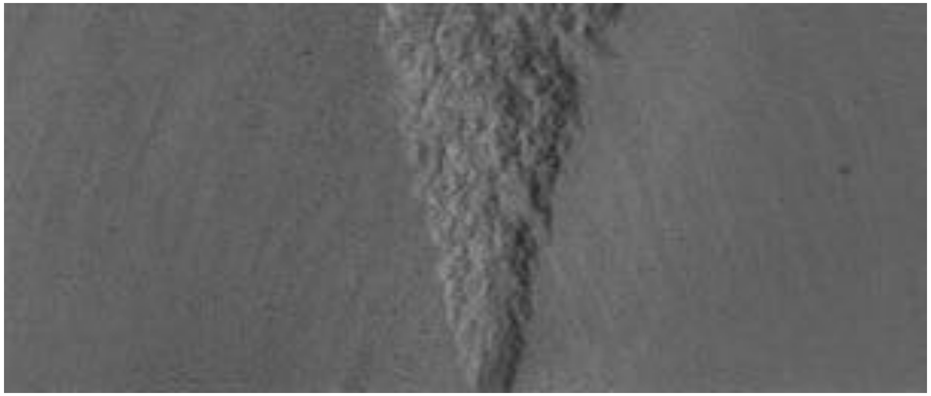






Summary and Future Work

- **Basic research components completed**
- **Full scale simulation tool developed, tested**
  - ➡ Full scale calculations with AFRL/Purdue/UM rigs now being conducted
- **Next step**
  - ➡ Develop response surfaces between operating conditions and RDE performance [For optimization]
  - ➡ Develop sensitivity capabilities within OpenFOAM



Questions?