COLLEGE OF ENGINEERING
AEROSPACE ENGINEERING
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Fuel Injection Dynamics and Composition Effects on Rotating Detonation Engine Performance

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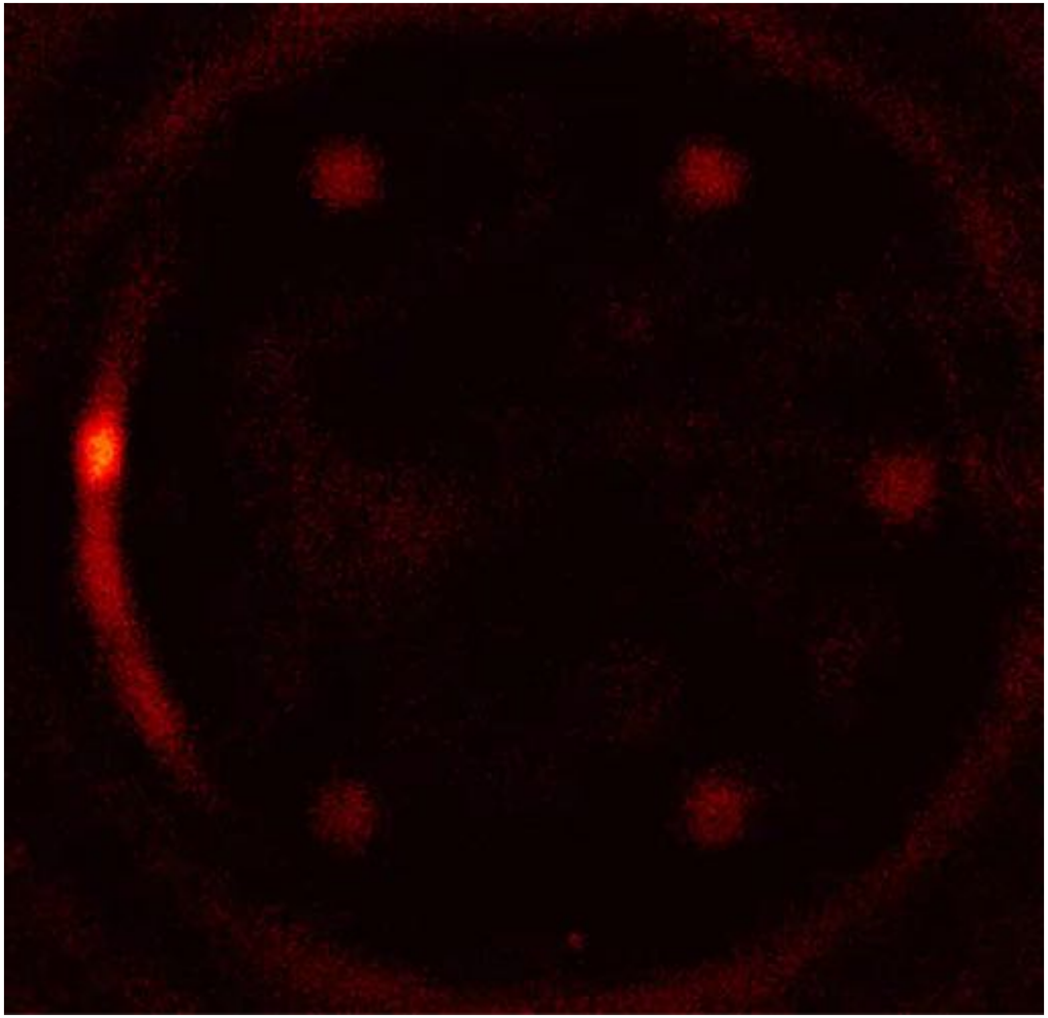
Outline

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

RDE wave dynamics: multiple wave systems

- Flow is comprised of more than just a single discrete detonation wave.

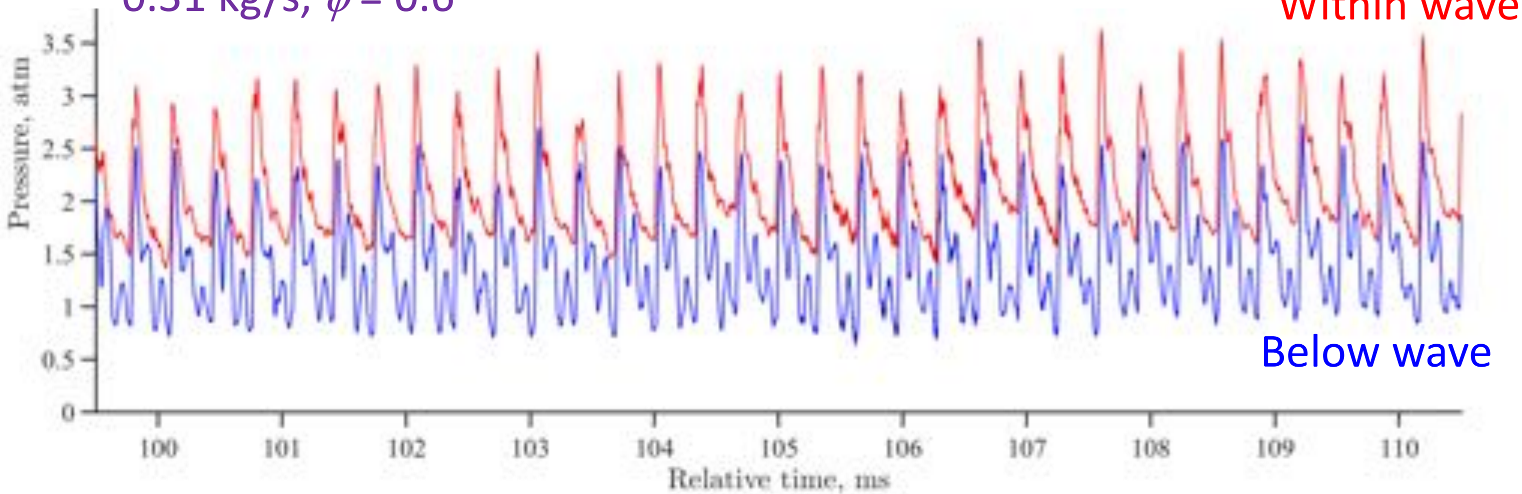
- Secondary Waves are visible to the naked eye, and interactions between waves results in an increased luminosity.



Wave dynamics results in irregular pressure variation signature

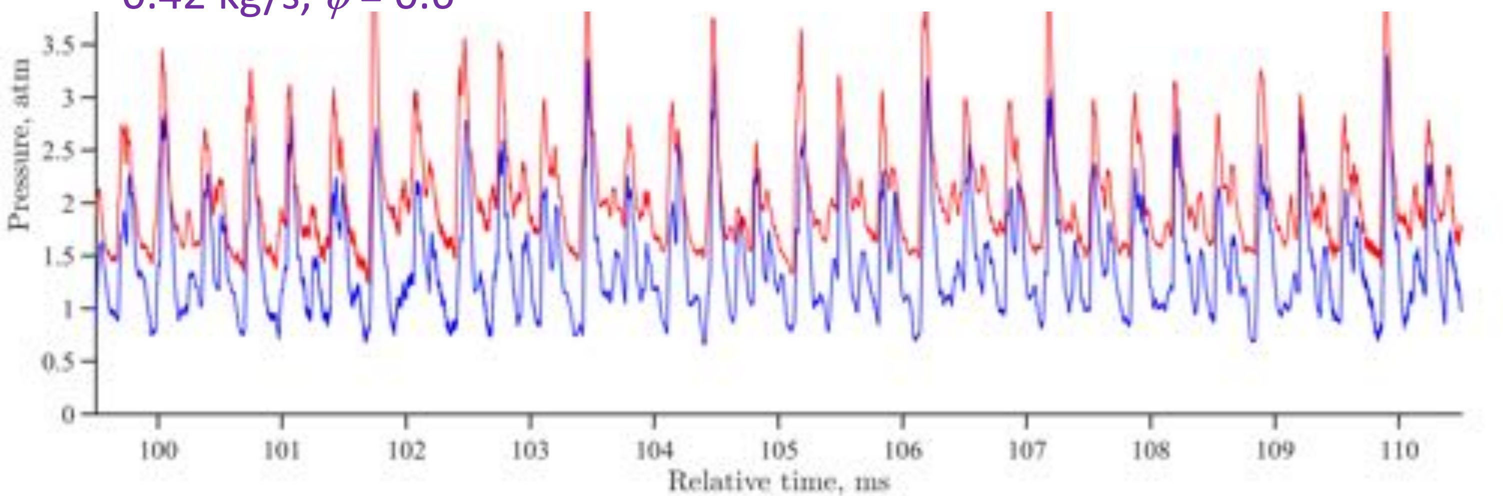
0.31 kg/s, $\phi = 0.6$

More regular but multiple peaks



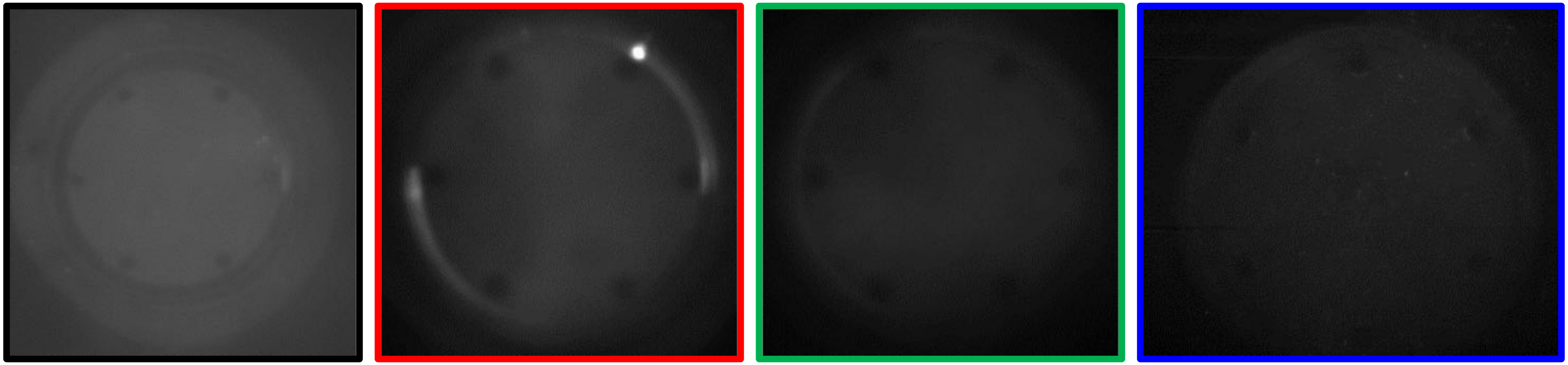
0.42 kg/s, $\phi = 0.6$

More irregular variation of pressure

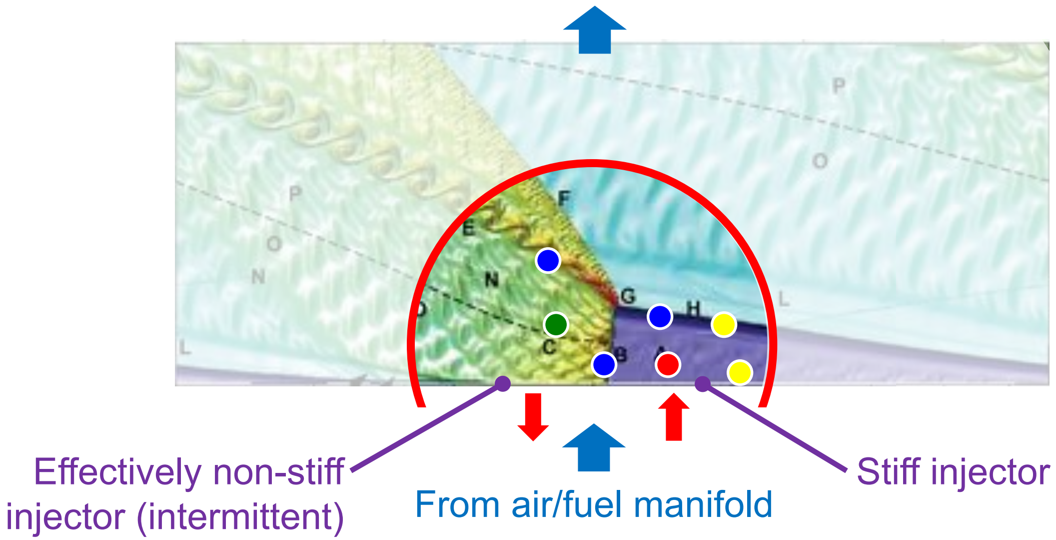


Operation modes observed possibly linked to the coupling of wave with air inlet / fuel injection, and depends on flowpath details

- <u>**Modes of operation previously observed for round RDE**</u>
  - <u>**Mode 1:** Stable detonation</u>, single rotating reaction front
  - **Mode 2:** Stable detonation, two co-rotating reaction fronts
  - **Mode 3:** Rotating deflagration, counter rotating reaction fronts
  - <u>**Mode 4:** Pulsed deflagration</u>, no coherent rotational reaction fronts
  - **Mode 5:** Unstable transitional behavior among modes



RDEs are intrinsically dynamic devices: Dynamics, wave coupling and loss of pressure gain



- **Unsteady operation of injection system**
  - Injector effectively transition from a stiff to a non-stiff injector
  - Post-detonation products backflow into plenums
  - Excite plenum dynamics
- **Strongly coupled system**
  - Response of injection system
  - Back-reflections from diffuser (impedance mismatch and wave reflections)
  - Mixing dynamics and effectiveness
    - Incomplete fuel/air mixing
    - Fuel/air charge stratification
  - Detonation wave dynamics and structure
    - Mixture leakage (incomplete heat release)
    - Parasitic combustion

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

Overarching goals

- **Preamble: Recognize that RDE is an intrinsically dynamic system**
  – Components need to be tuned or be robust to external dynamics for stable op
- **Goals: Understand how operability and performance is affected by**
  – Dynamics of each component
  – Multi-component fuels
- **What needs to be done to understand dynamics**
  1. Identify and classify them
  2. Understand the underlying mechanism for their existence
  3. **Determine whether they are important**
  4. Determine how they scale
  5. Investigate if and how the response of components couple
  6. Understand what components' dynamics and their coupling do to the detonation wave
     - Air inlet / fuel injection dynamics
     - Wave reflections from inlets and exhaust
     - Wave diffraction / reflections
     - Unsteady mixing
     - Susceptibility to onset of deflagration
     - Vitiation effects (scavenging or partial pre-ignition)
     - Fuel chemistry effects

Objective for today

- Experiments
  - Identify and classify system of waves that may exist in an RDE
  - Investigate if they depend on injection scheme

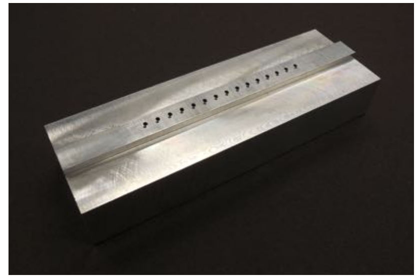
- Computations
  - Full-system calculations
    - Effect of injector design
  - Racetrack modeling
  - Ethylene/air RDE operation

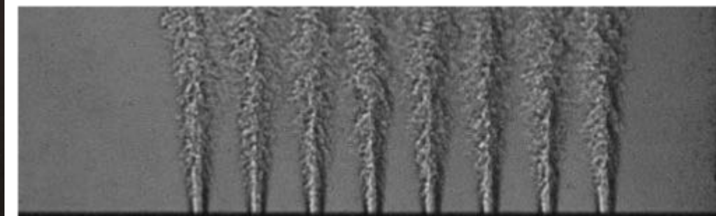
Outline

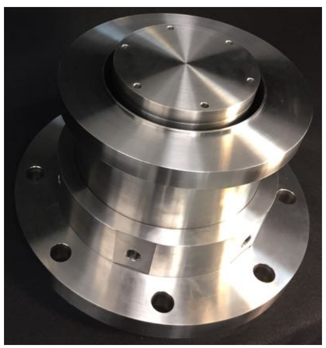
- Introduction to the problem and general approach
- Experimental activities
- Computational activities

RDE experimental program at U-M

- **Injector sector subassembly**
  - Unwrapped sector of RDE injector
  - Unit problem studies
    - Mixing effectiveness
    - Shock-induced mixing





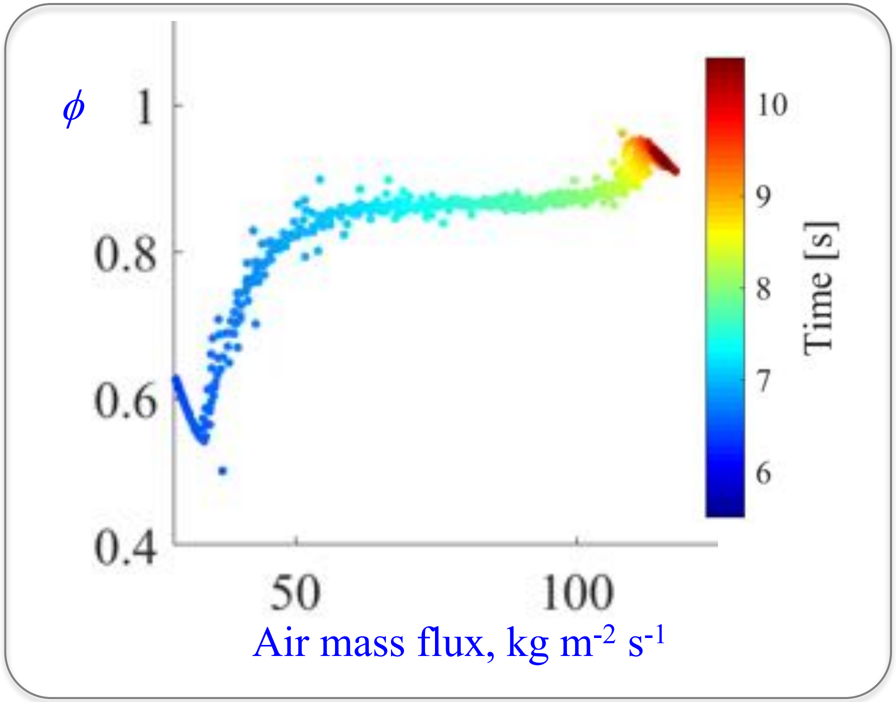


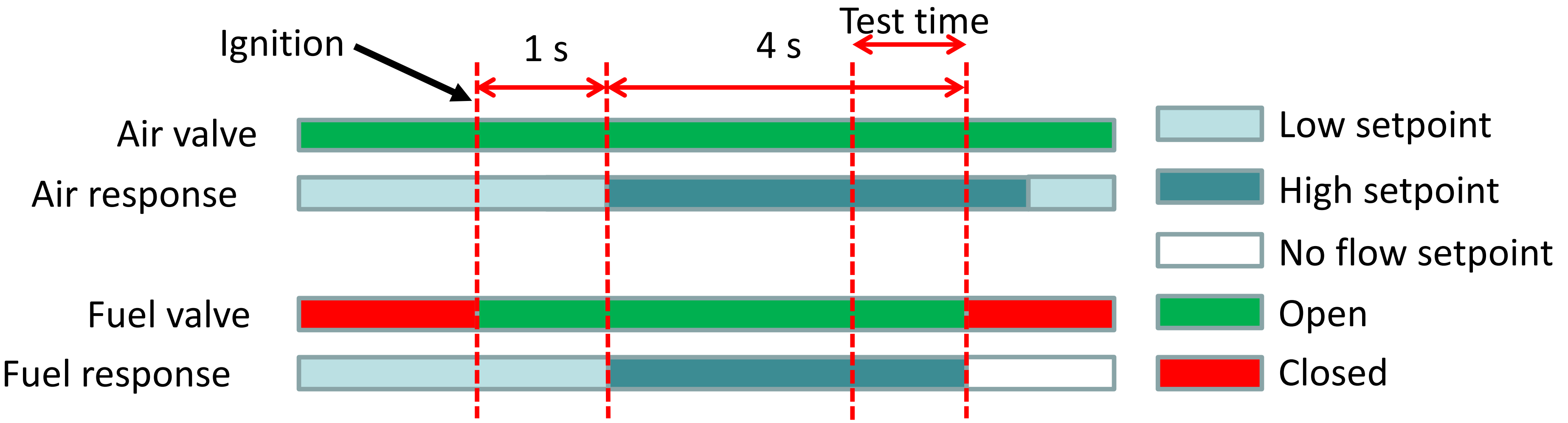
- **Round RDE (6” diameter)**
  - Operational with H_2/Air, various flow rates and equivalence ratios
  - Expanded to operate with multi-component fuels (hydrocarbon blends)
    - Working toward stabilizing HC blends (syngas and NG applications)
  - Instrumentation development is continuously ongoing
    - Combination imaging and quantitative measurements of state

- **Optical RDE (Race-Track RDE)**
  - Fundamental physics in RDE-relevant flowfield
  - Equivalent to 12” round RDE
  - Used for flowfield measurements using laser diagnostics under RDE relevant conditions
    - Imaging for mixing, detonation structure, injector response studies

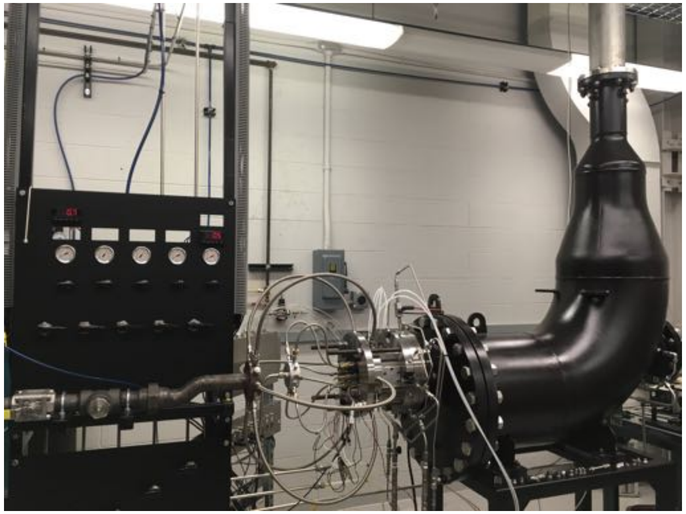
RDE test facility

- **Staged operation:**
  - Ignition at low flow rates
  - Fuel/air ramp up to operating flow rate (up to 1 kg/s)
- **Use staging to:**
  - Ignition sequence
  - Transition between fuel types
  - Conduct transient studies, e.g.:
    - Variable equivalence ratio at fixed mass flow rate
    - Variable flow rate at fixed equivalence ratio





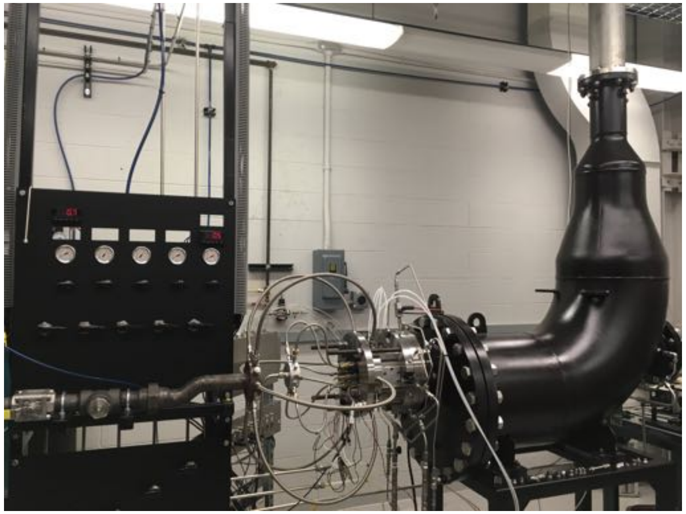
RDE test facility



- **Facility capabilities:**
  - Air and oxygen-enriched air
  - Preheating (up to 600 K)
  - Inlet pressure up to 250 psi (with preheat)
  - Multi-component fuel (up to 5)
    - Mixtures or fuel staging
  - Fuel/air transients

- **(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 and mean pressure (PCB & Kulite)
  - Acoustic signature (external)
  - Optical instrumentation being developed

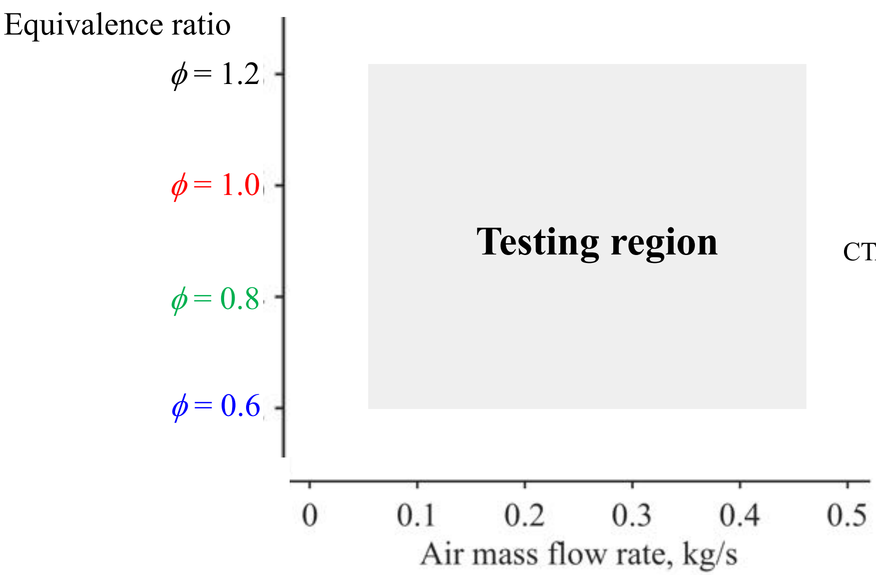
RDE test facility

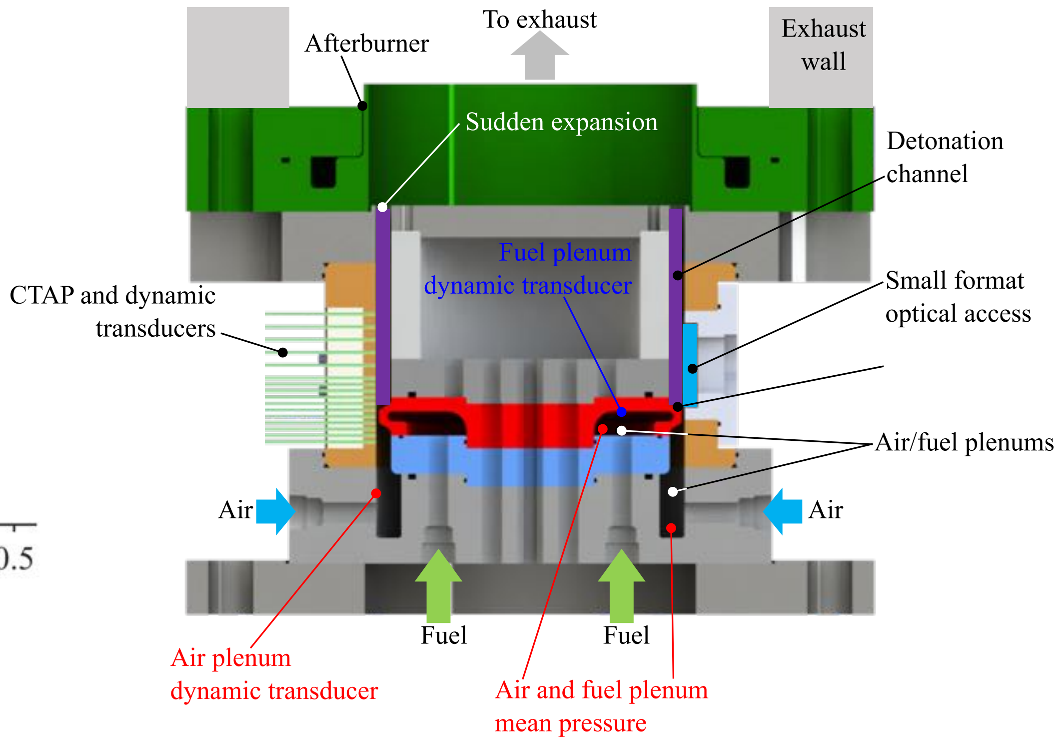


- **What we have/are exploring:**
  - Most work conducted with hydrogen/air
  - Explored methane/hydrogen and ethylene/hydrogen operation
    - Working on it for small scale RDE
    - Requires higher pressure, some air pre-heat, some O_2 enrichment and some *luck*
  - High(er) pressure operation
    - Choke plate (but the exhaust could also be pressurized)
    - Required for hydrocarbon operation
    - But also to assess gain potential and diagnostic needs
  - Detonation initiation without direct source (e.g., pre-det)

6” diameter round RDE

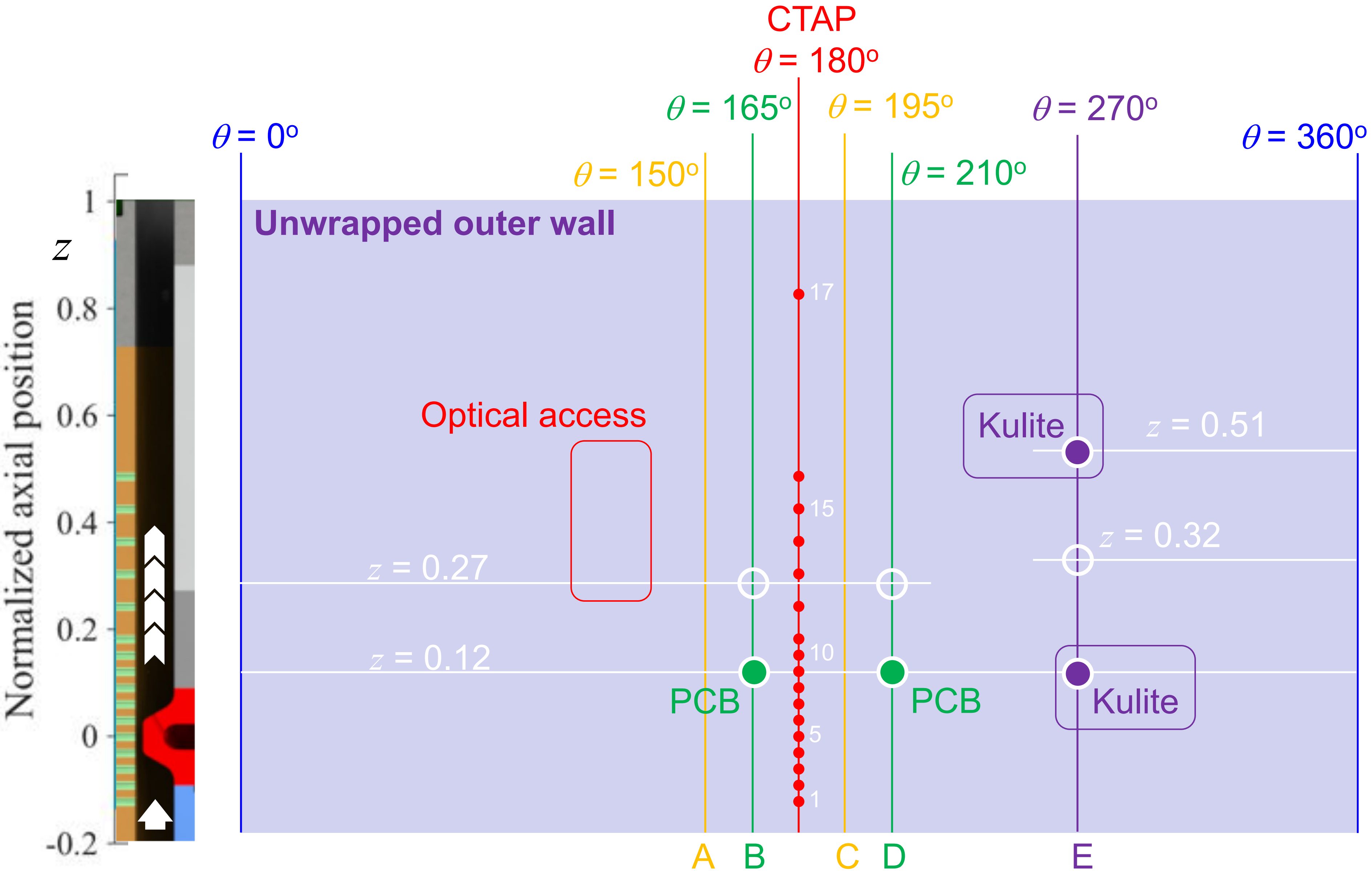
- **Modular configuration in its geometry and operation**
  - Quick replacement/study of injection schemes
  - Parametric studies for geometric scaling studies (e.g., for dynamics study)
- **Multiple injection schemes**





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

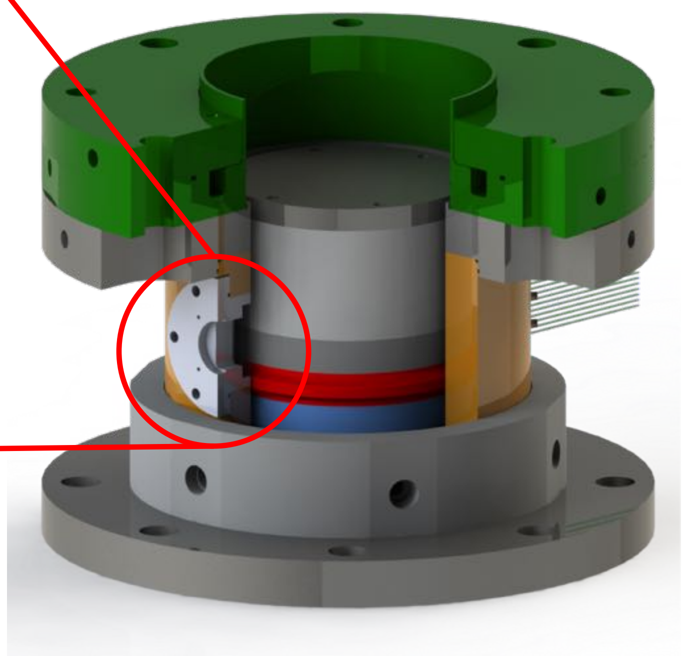
6" diameter round RDE: basic instrumentation



6” diameter round RDE: optical instrumentation

Capabilities we are developing

- Emission spectroscopy
  - Distribution and evolution of reaction fronts
- Thermometry
  - OH absorption
  - H_2O absorption
- IR imaging
  - End objective: time revolved imaging of combustion species
- Wave location detection

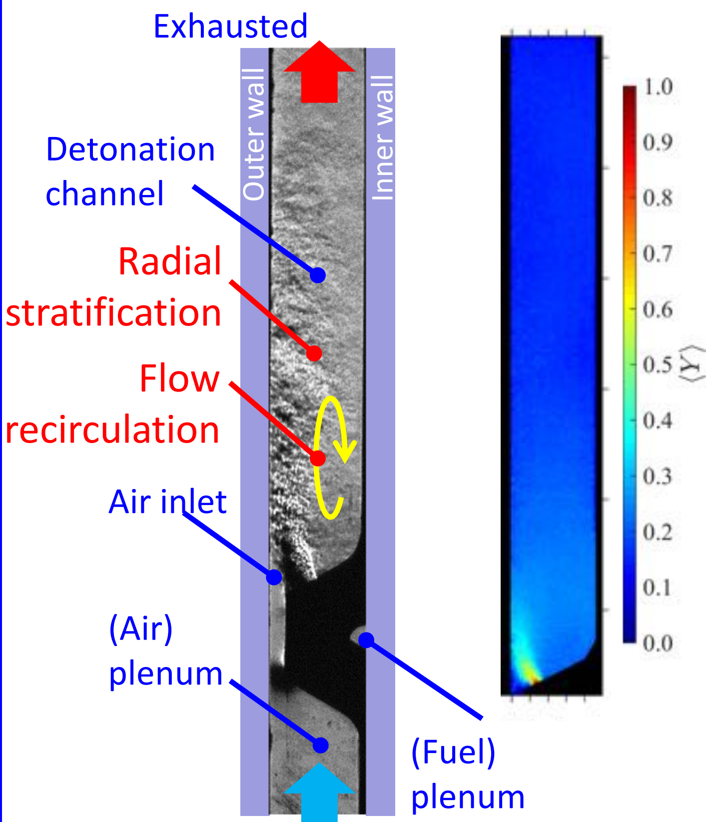


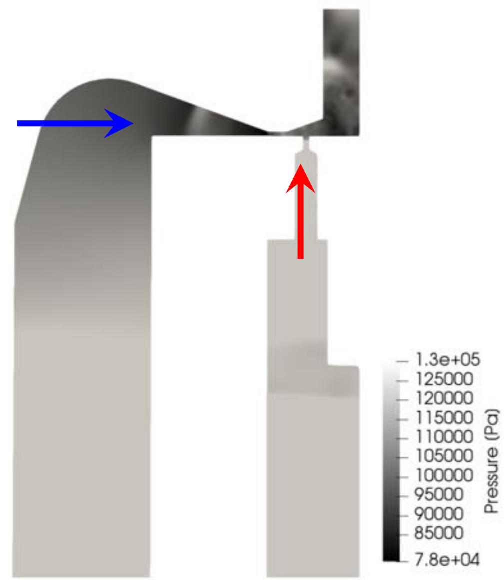
- Hardware and methods mostly ready
- Testing is on the way

Injection schemes considered so far

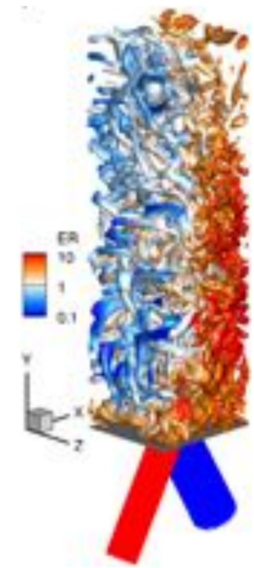
Axial air flow, with transverse injection

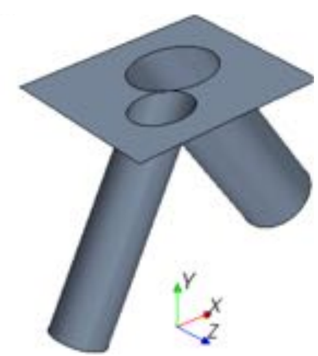
Flow visualization (schlieren) **Mixture fraction**





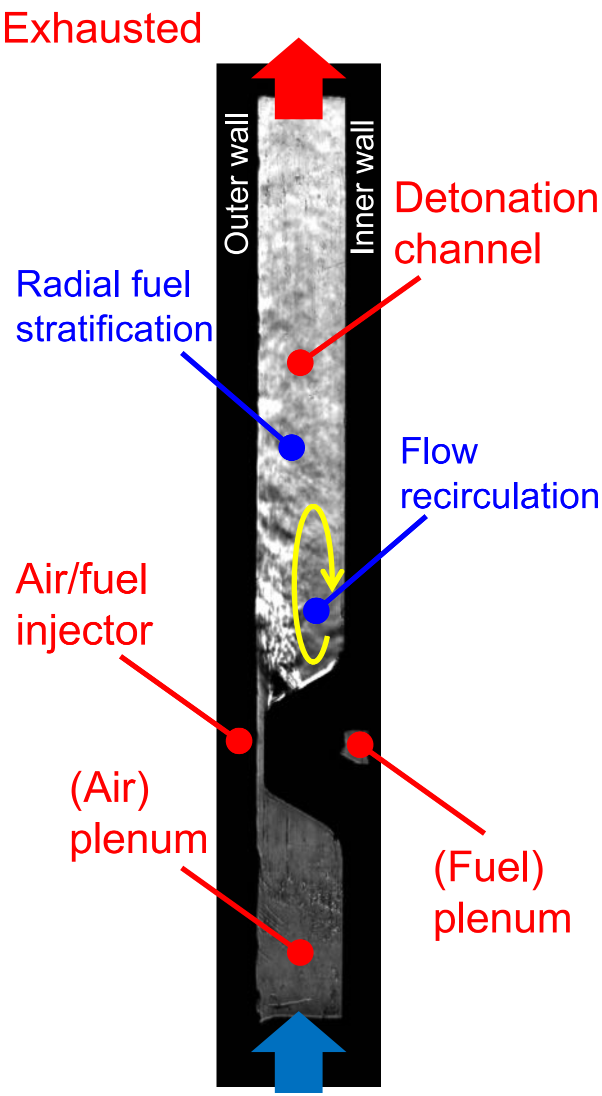
Radial air flow (e.g., AFRL geometry)

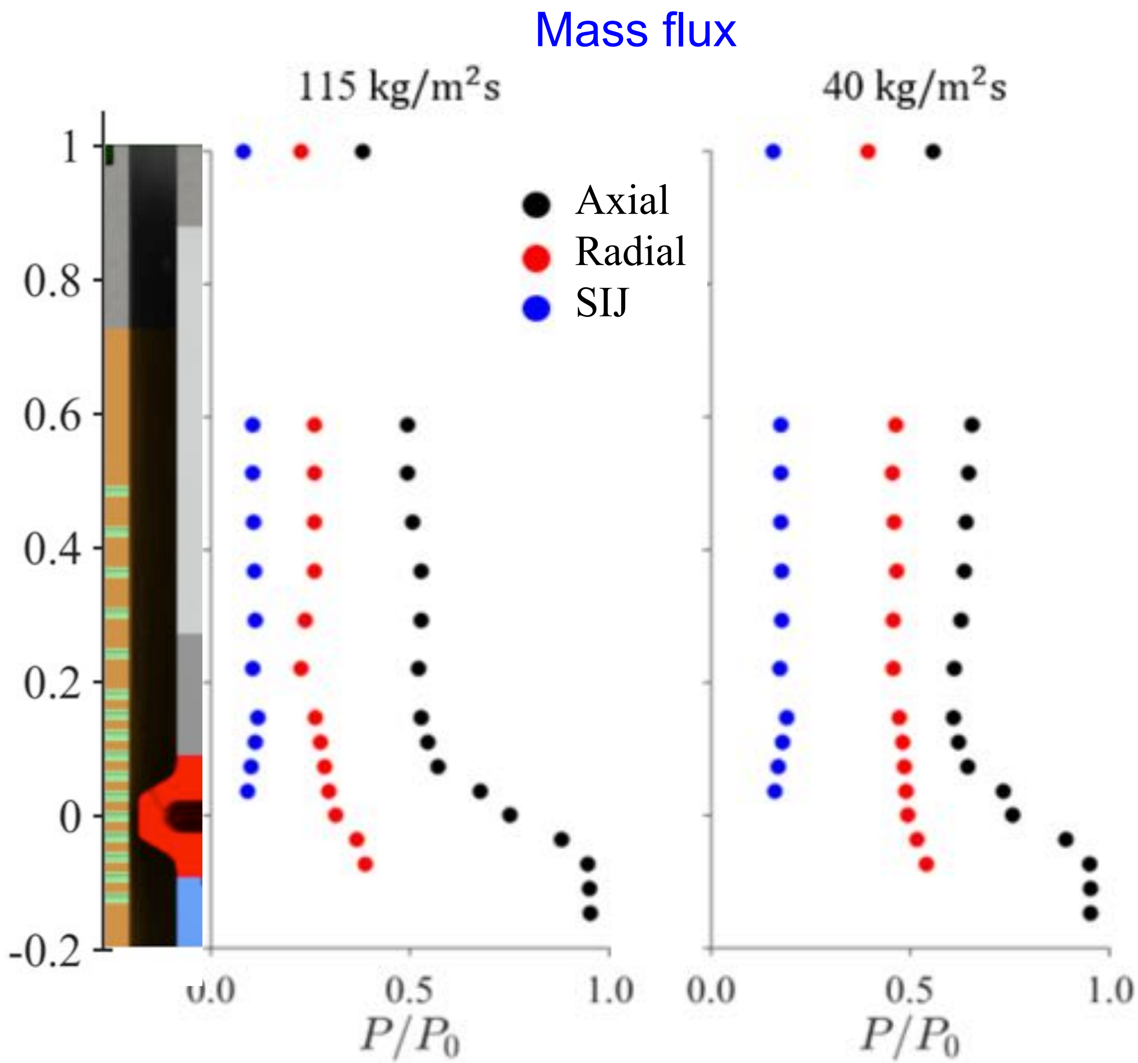




Discrete jets (semi-impinging jets)

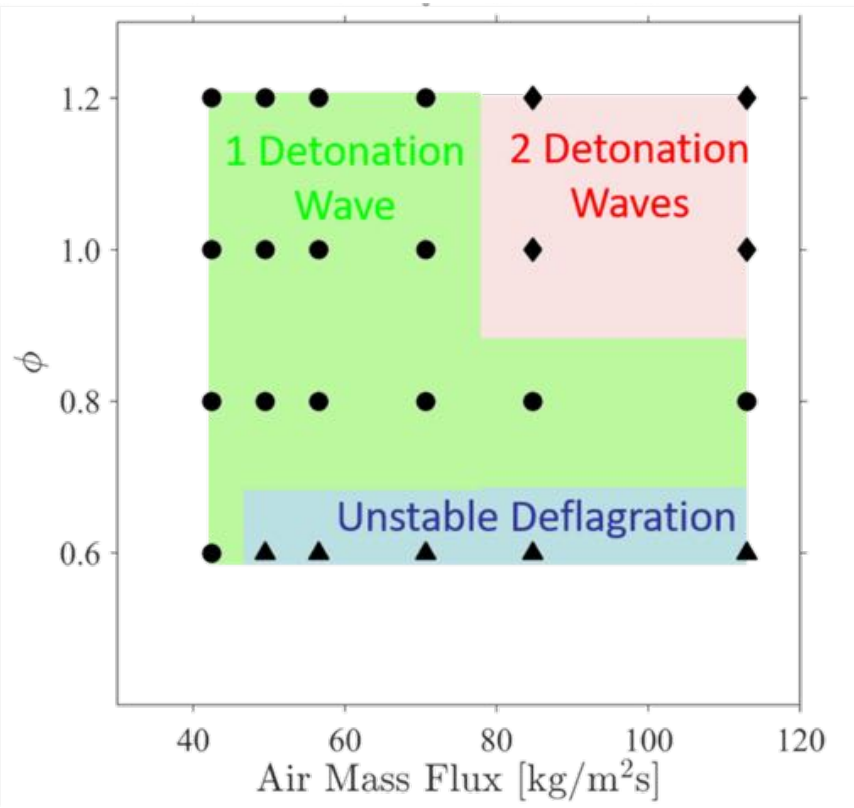
Axial, low(er) loss inlet configuration



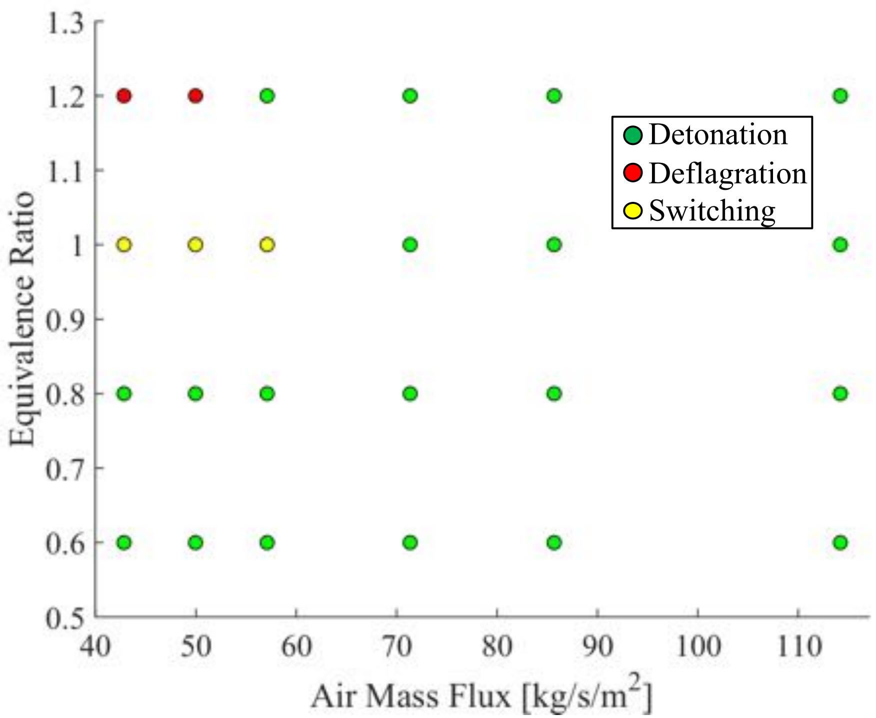


Operability: radial vs axial flowpath

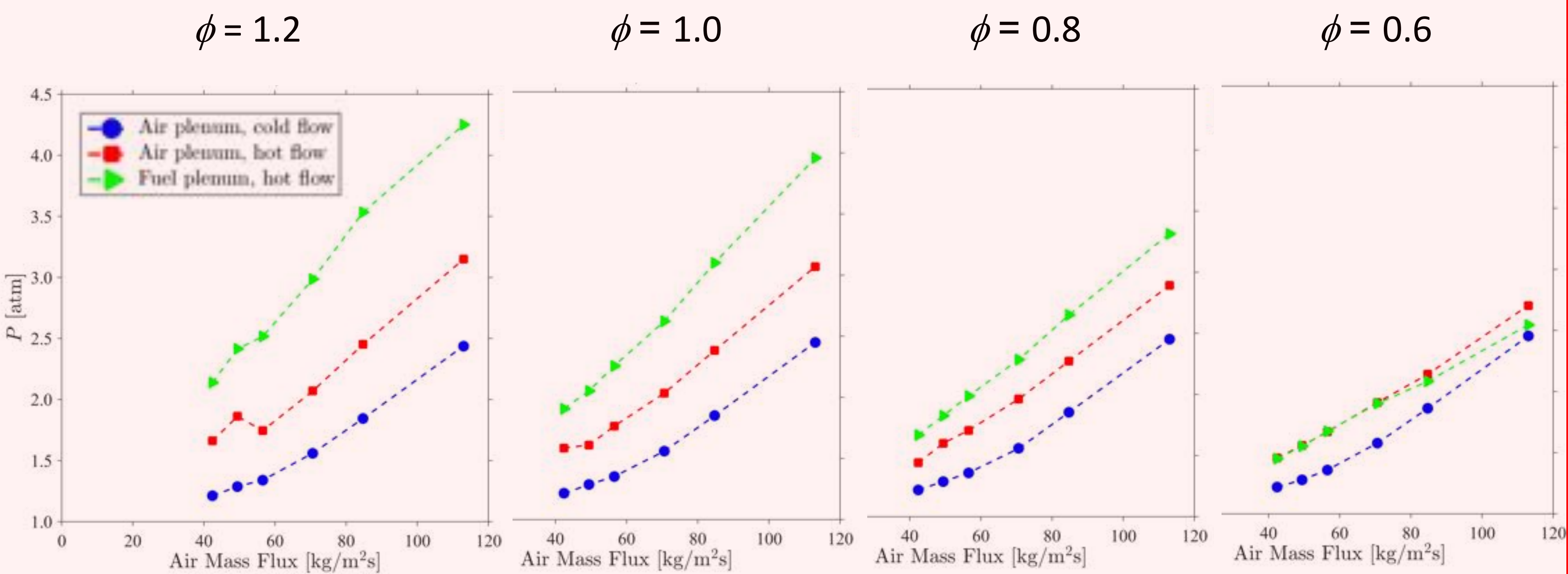
Radial flowpath (AFRL)



Axial flowpath (U-M)



Stable detonation operation as air/fuel plenum pressures become similar (axial flowpath)

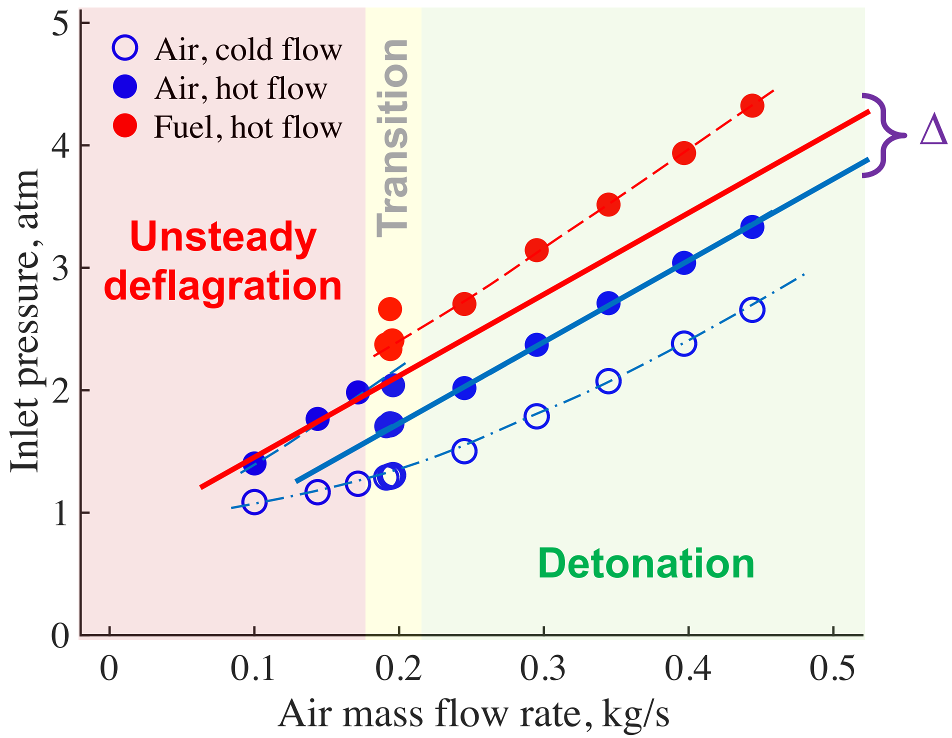


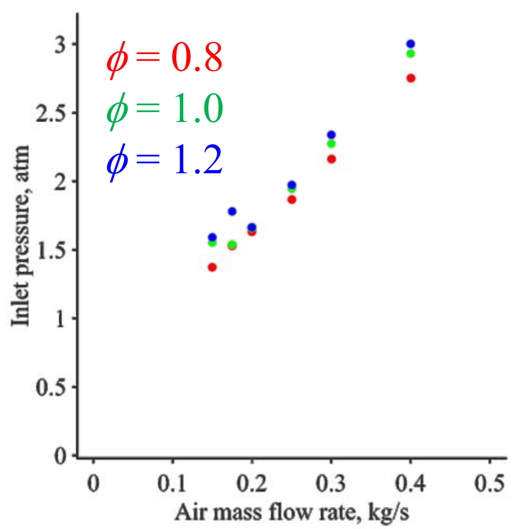
Pulsed deflagration → Stable detonation

Stability: operable (static) with less cycle-to-cycle variation (dynamic)

Tailoring and matching air/fuel injector response is critical

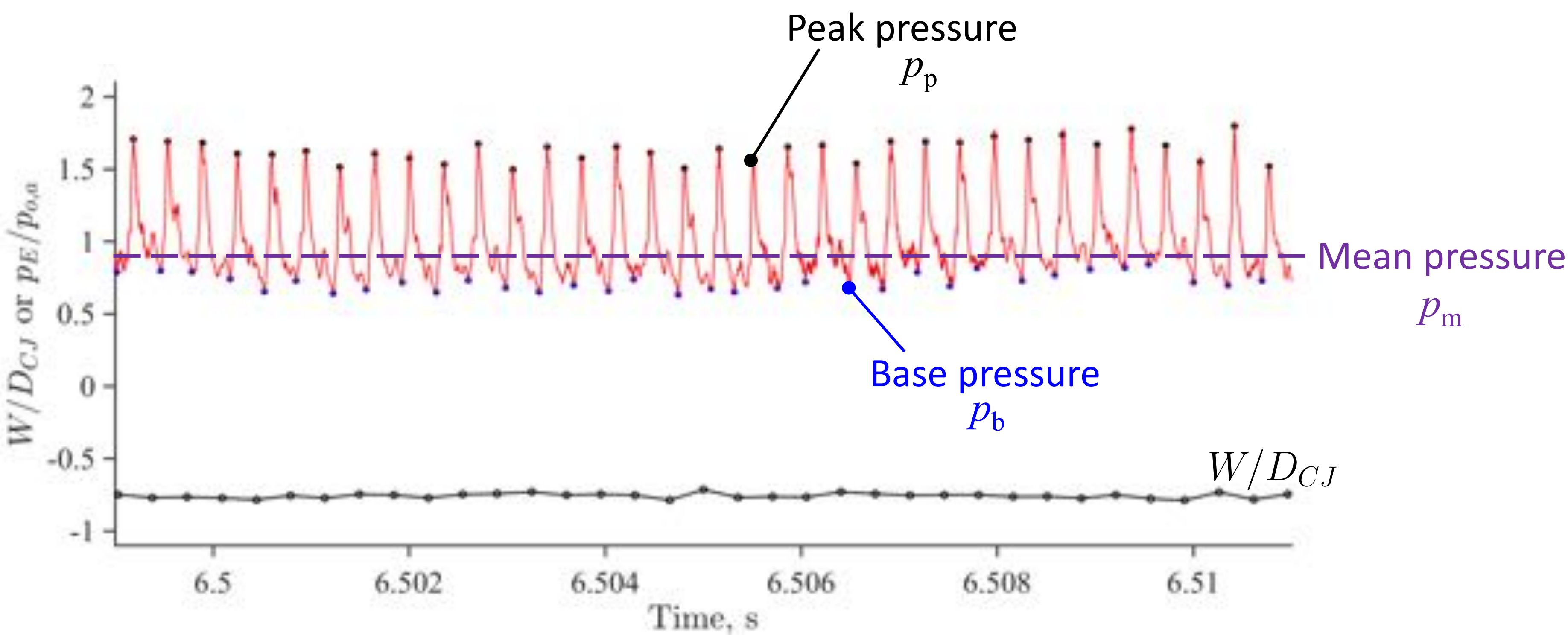
Gain and the *lack of loss*





- 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
  - **This translates into increased efficiency**

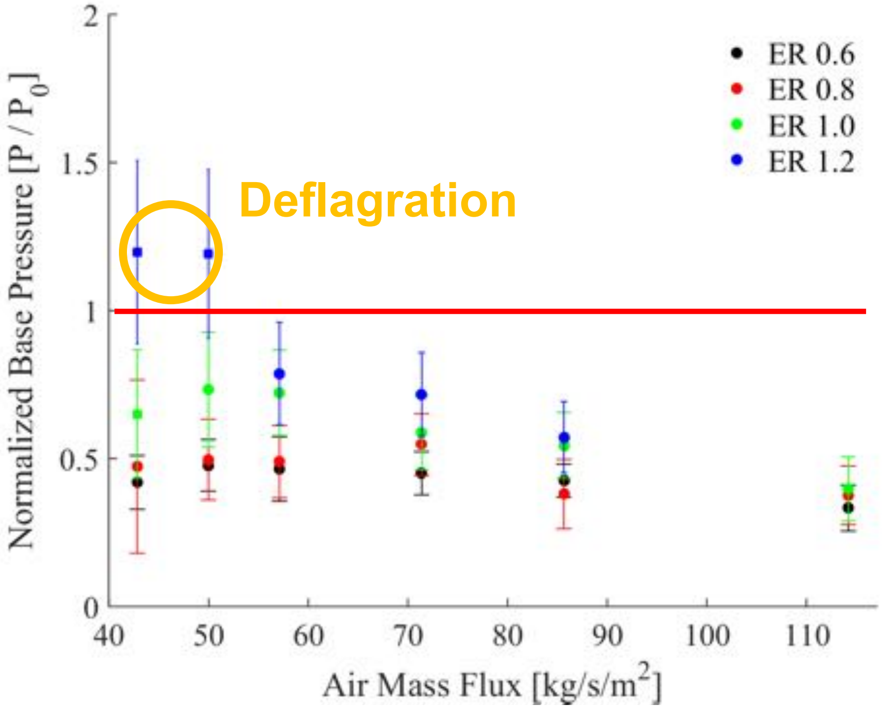
Some definitions



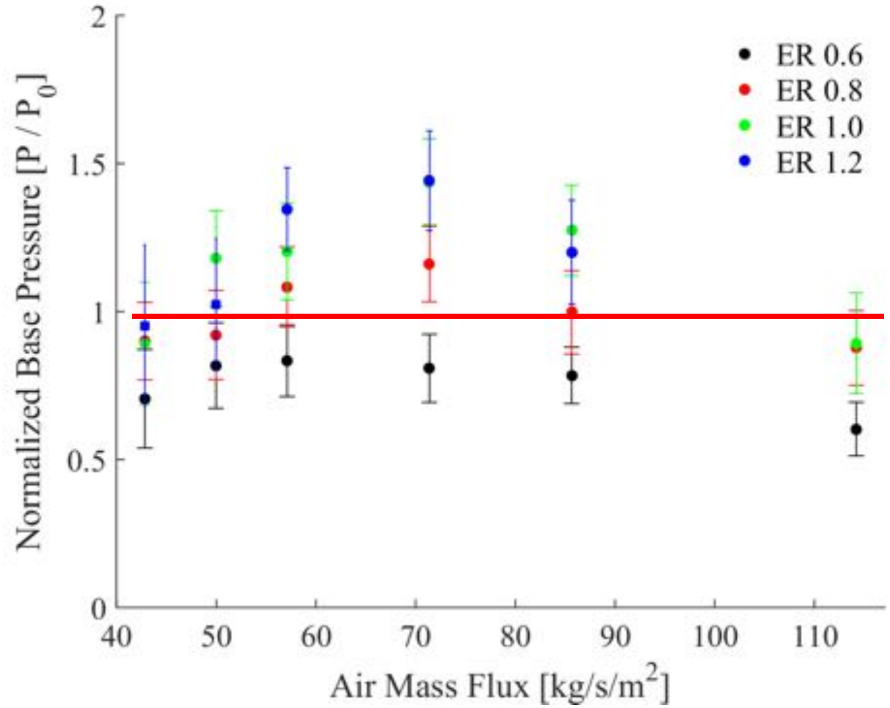
Amplitude $A = p_b - p_b$

Variation of base pressure with operating condition

Upstream of wave

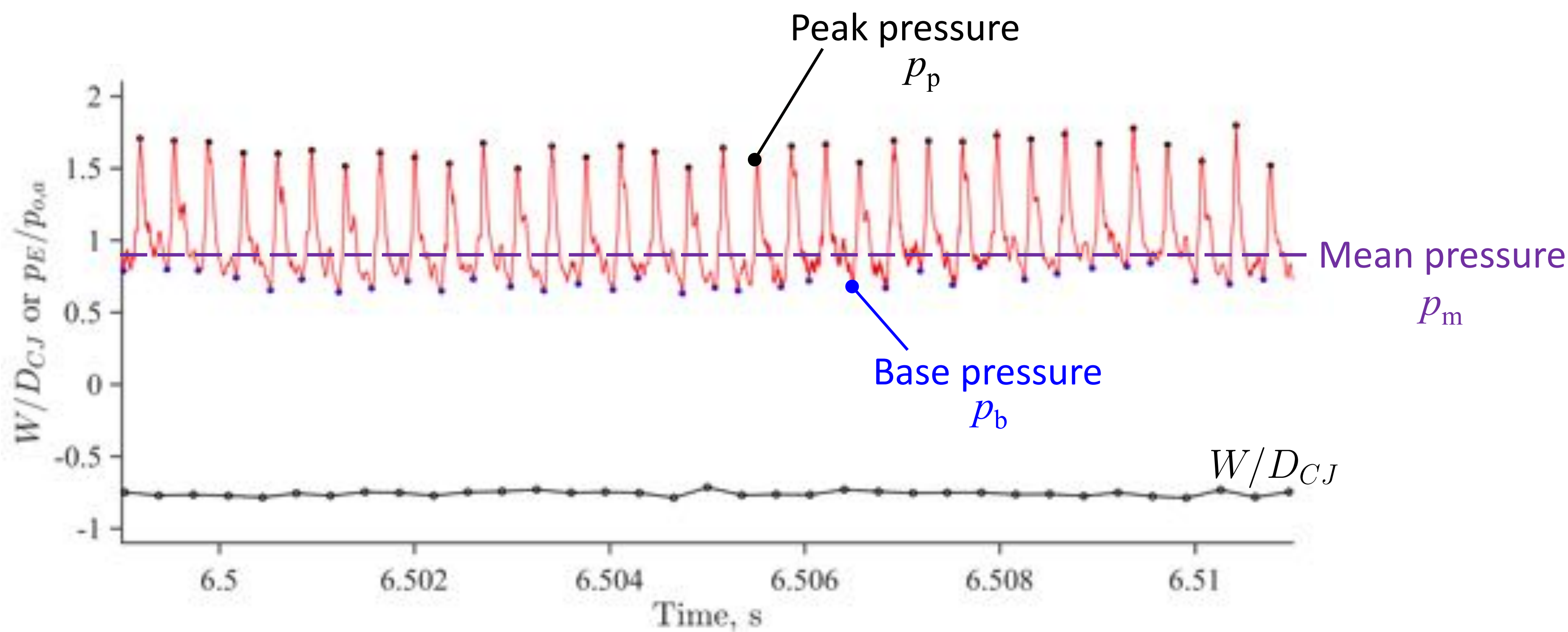


Within the wave



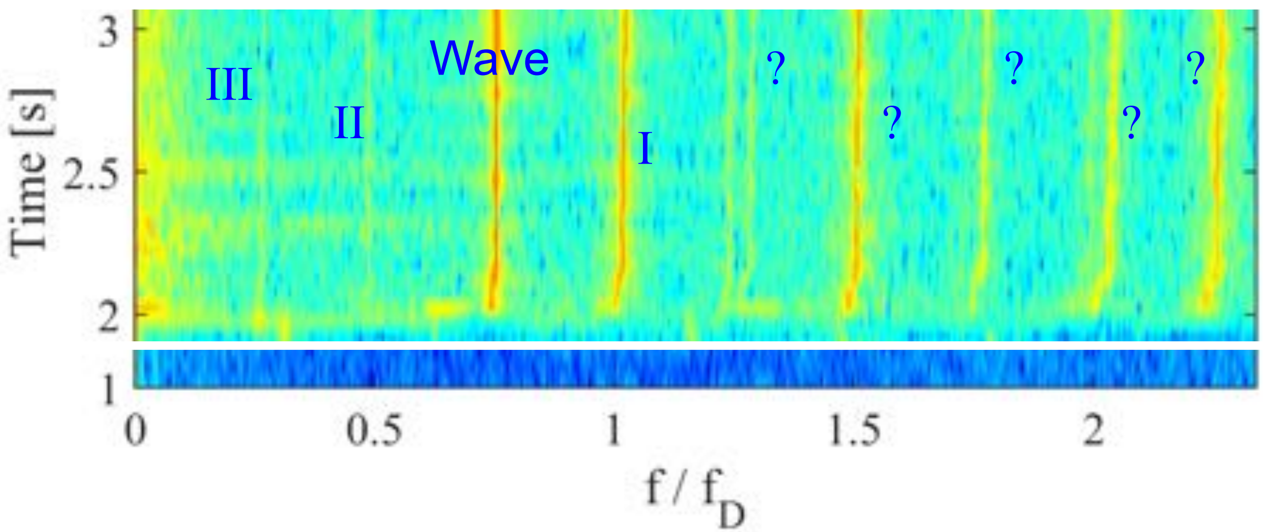
- Base pressure is the minimum pressure during a cycle
- For detonation operation, base pressure **is higher than plenum pressures**

Some definitions



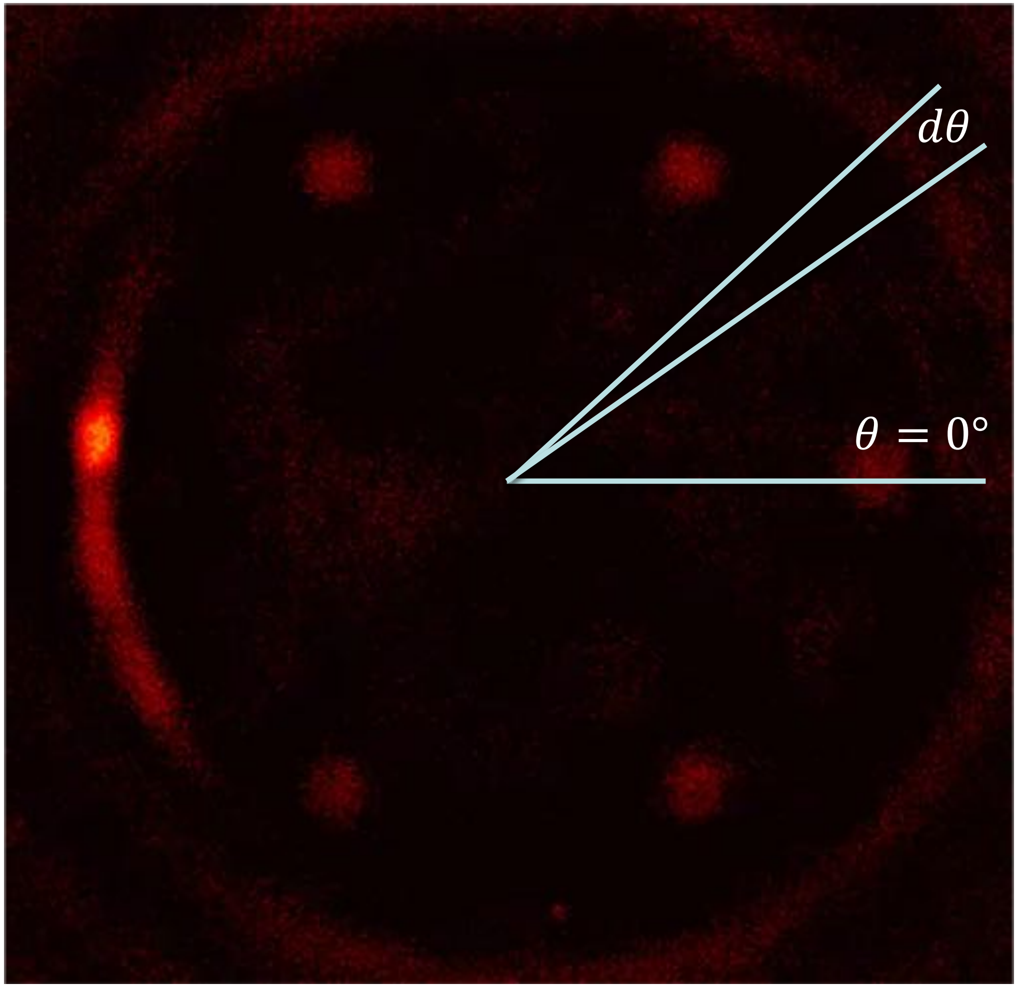
Amplitude $A = p_{\mathrm{b}} - p_{\mathrm{b}}$

Waterfall spectra



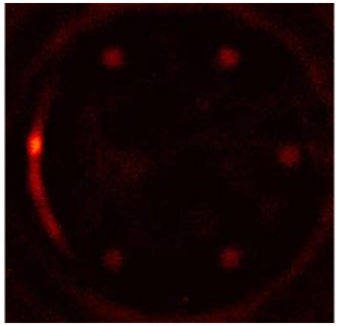
- Multiple, superimposed tones
  - Wave propagation: $f \cong 0.8\, f_D$
  - Tone I: $f \cong f_D$ – Present in detonation mode as flow rate increases, but also in deflagration mode
  - Tone II: $f \cong 0.5\, f_D$ – Present in deflagrating mode
  - Tone III: $f \cong 0.25\, f_D$ – Weak feature present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

Construction of x-t diagrams for wave information extraction

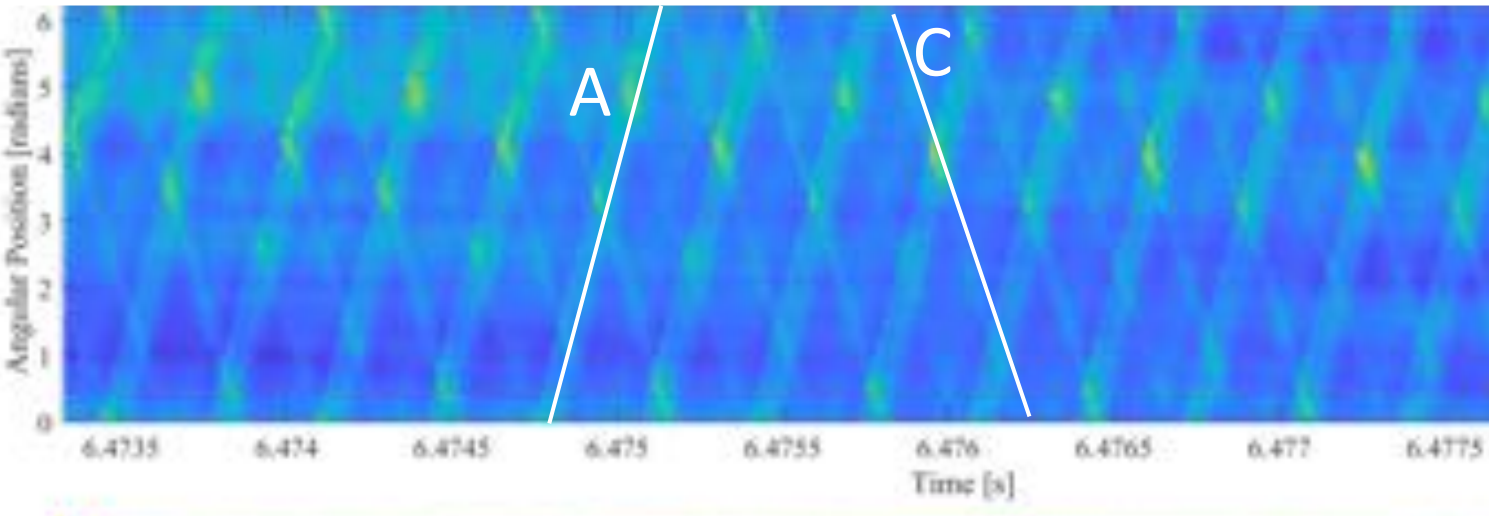


- Each frame is discretized into 101 bins evenly spaced around the annulus.
- Reduces a single frame to column vector
- Combination of the column vectors allow for the creation of x-t diagram

x-t diagrams: additional waves are present



Video



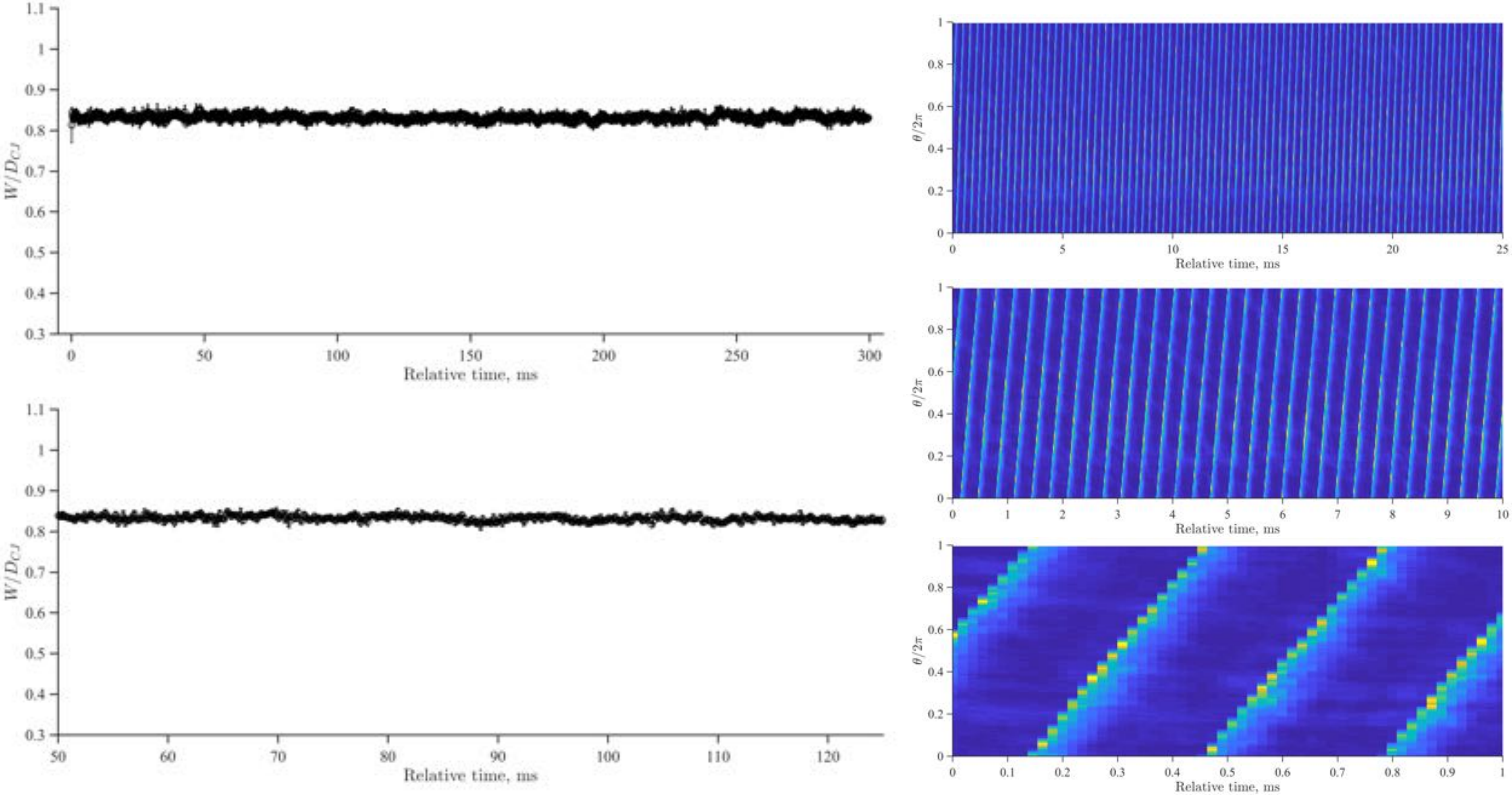
x-t diagram

Primary Detonation Wave (A): travels at 80% of Chapman-Jouguet speed. Easily seen in video and *x-t* diagram.

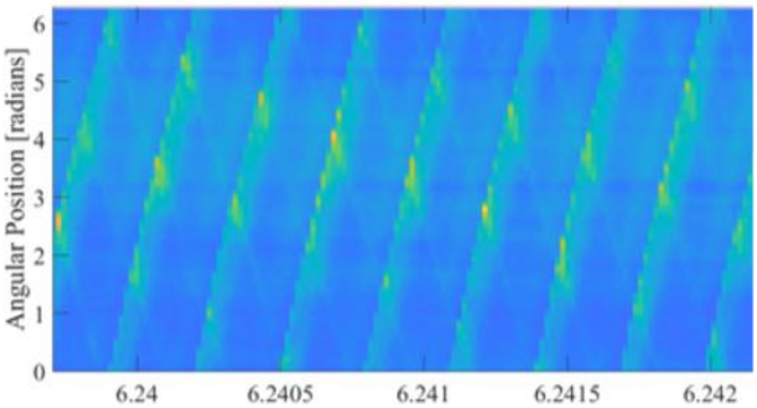
Secondary Wave System (C): Pair of waves traveling counter to the main detonation wave. Travels at approximately 1000 m/s.

Are there others? Need a more direct method for detection.

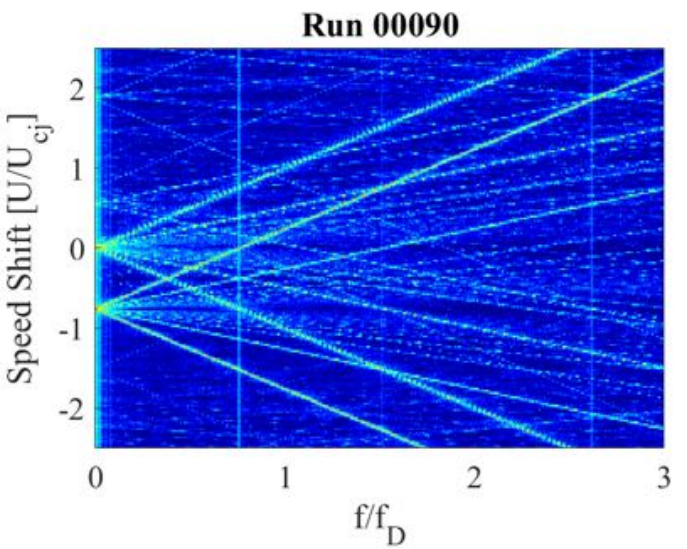
Simple wave detection algorithm not adequate



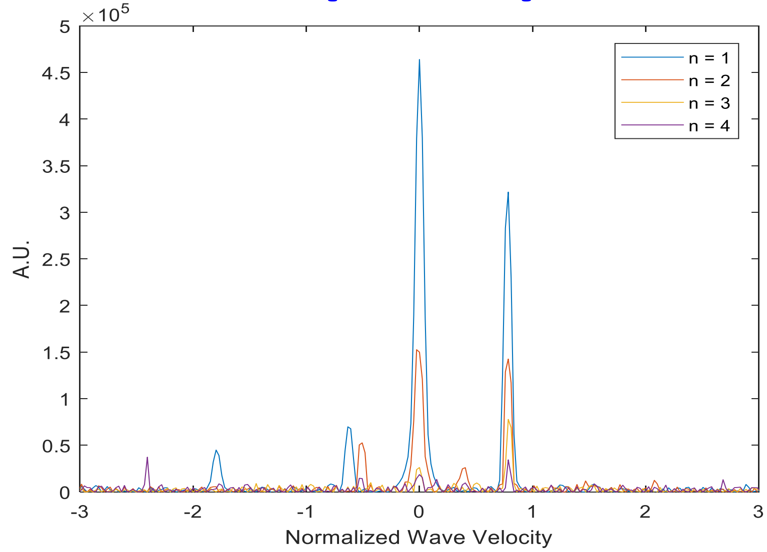
Wave identification method based on Galilean Shifted Fourier Transform (GFST)



1. Take a subsection of the full x-t diagram, (e.g., 171 frames or about 10 waves)



2. Compute the GFST



3. Use a modified Radon transform to reduce the GSFS to a series of curves like the one above.

4. Extract peaks and corresponding information to gather information about the wave systems

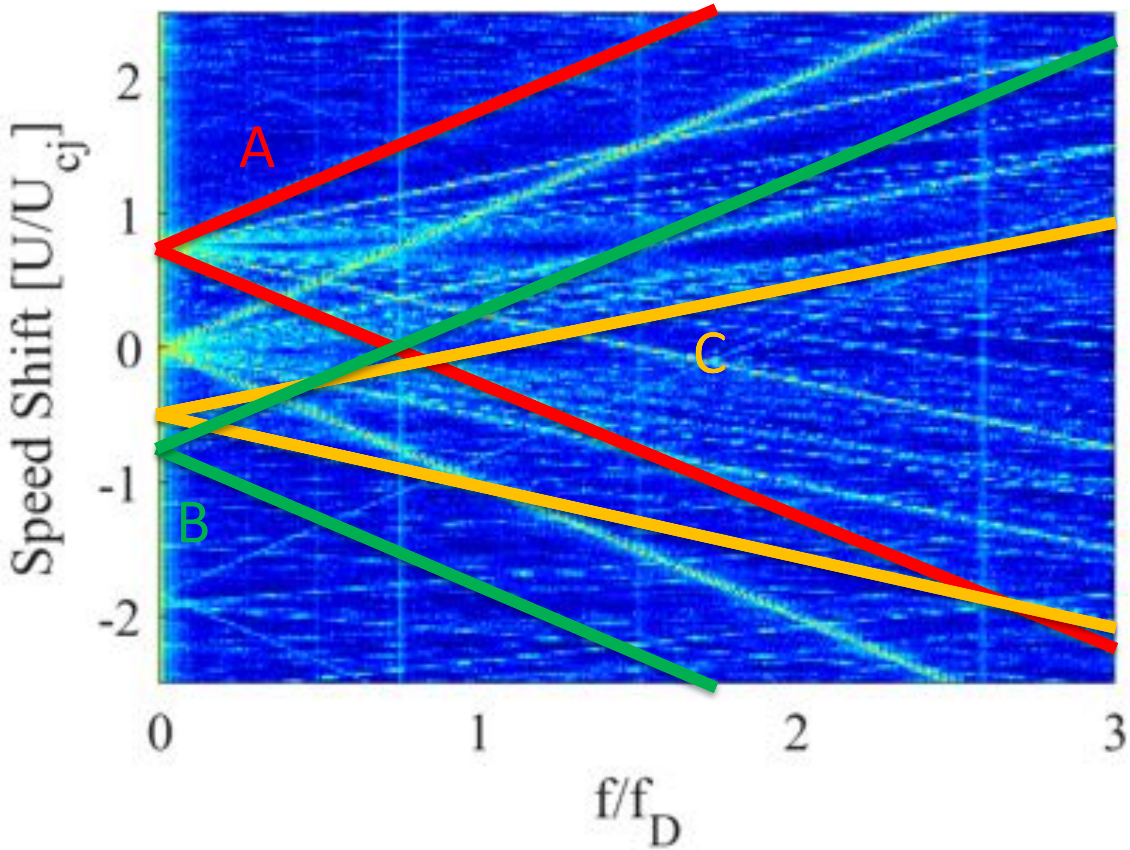
5. Repeat for all subsections of the x-t diagram

RDE Flow Fields: 3 Wave Systems

A: **Primary detonation wave**. Travels at 80% of Chapman-Jouguet speed

B: **Counter rotating fast wave**. Travels counter to the primary detonation wave. Typically travels at approximately the same speed as Primary Detonation. However can move up to 200 m/s slower

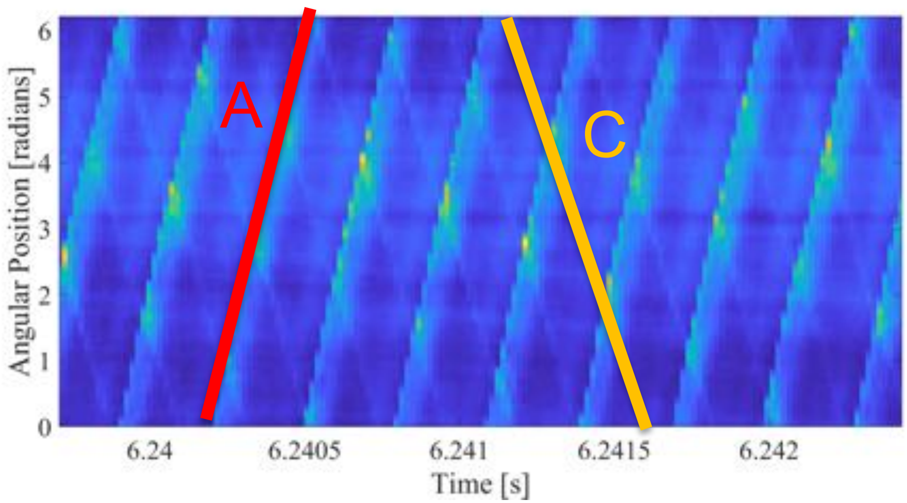
C: **Counter rotating slow wave pair**. Two waves travelling counter to the wave at approximately 1000 m/s

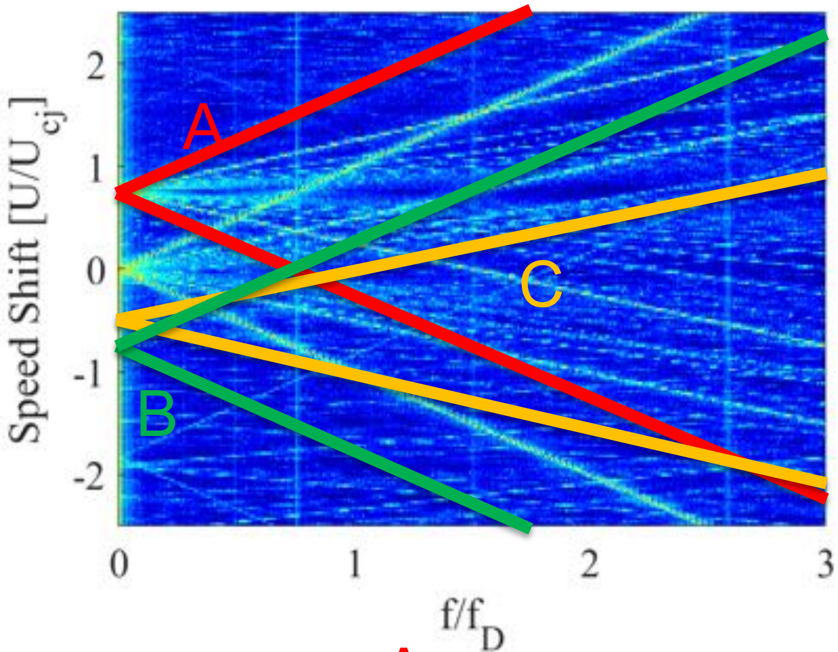


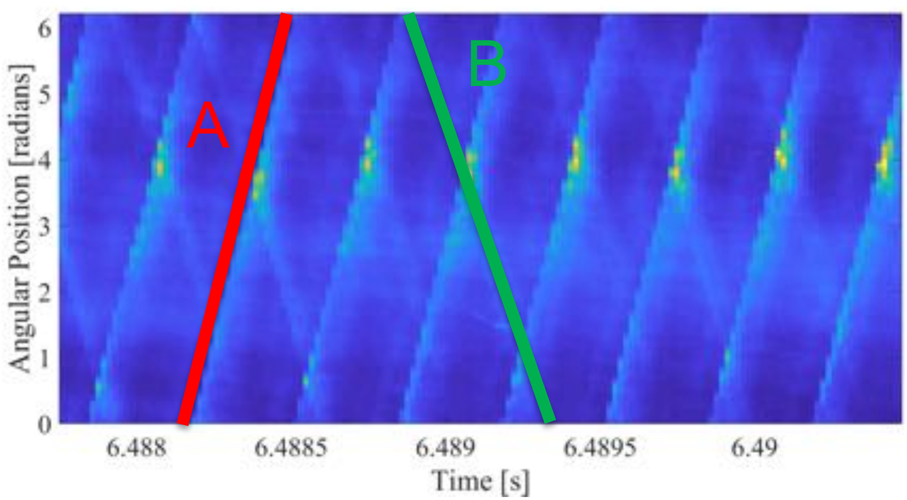
These three waves appear in all injectors

Three Wave Systems In all measurements

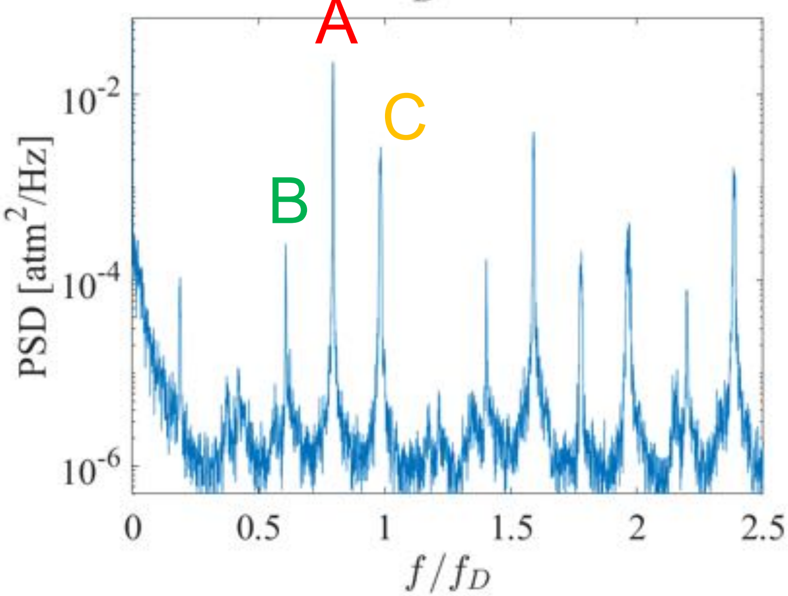
Axial air inlet



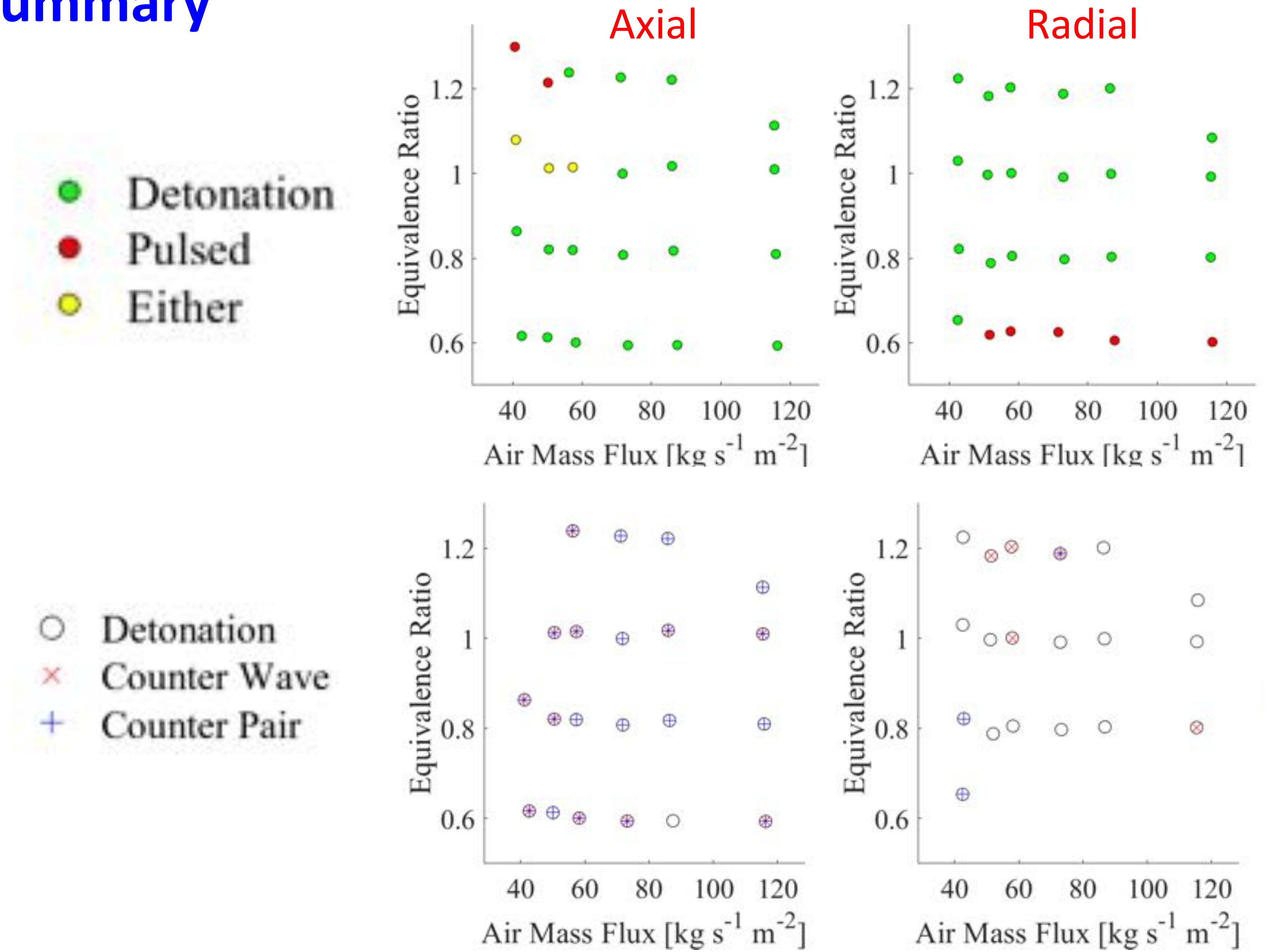




Semi impinging jet

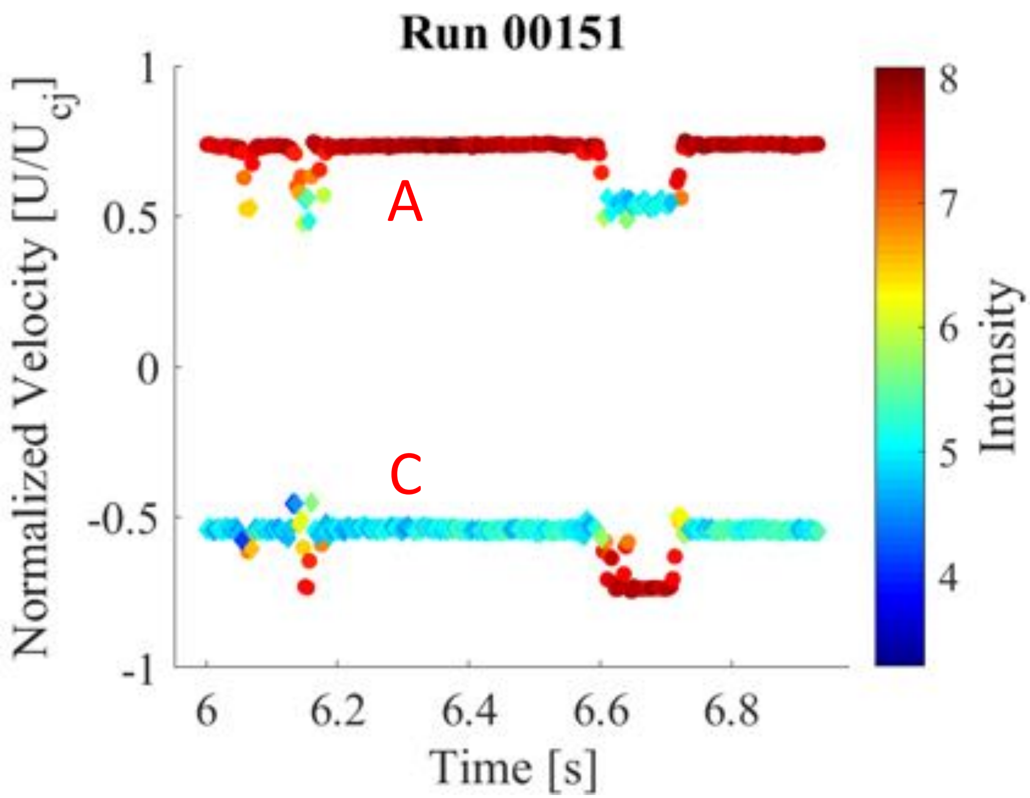


Summary

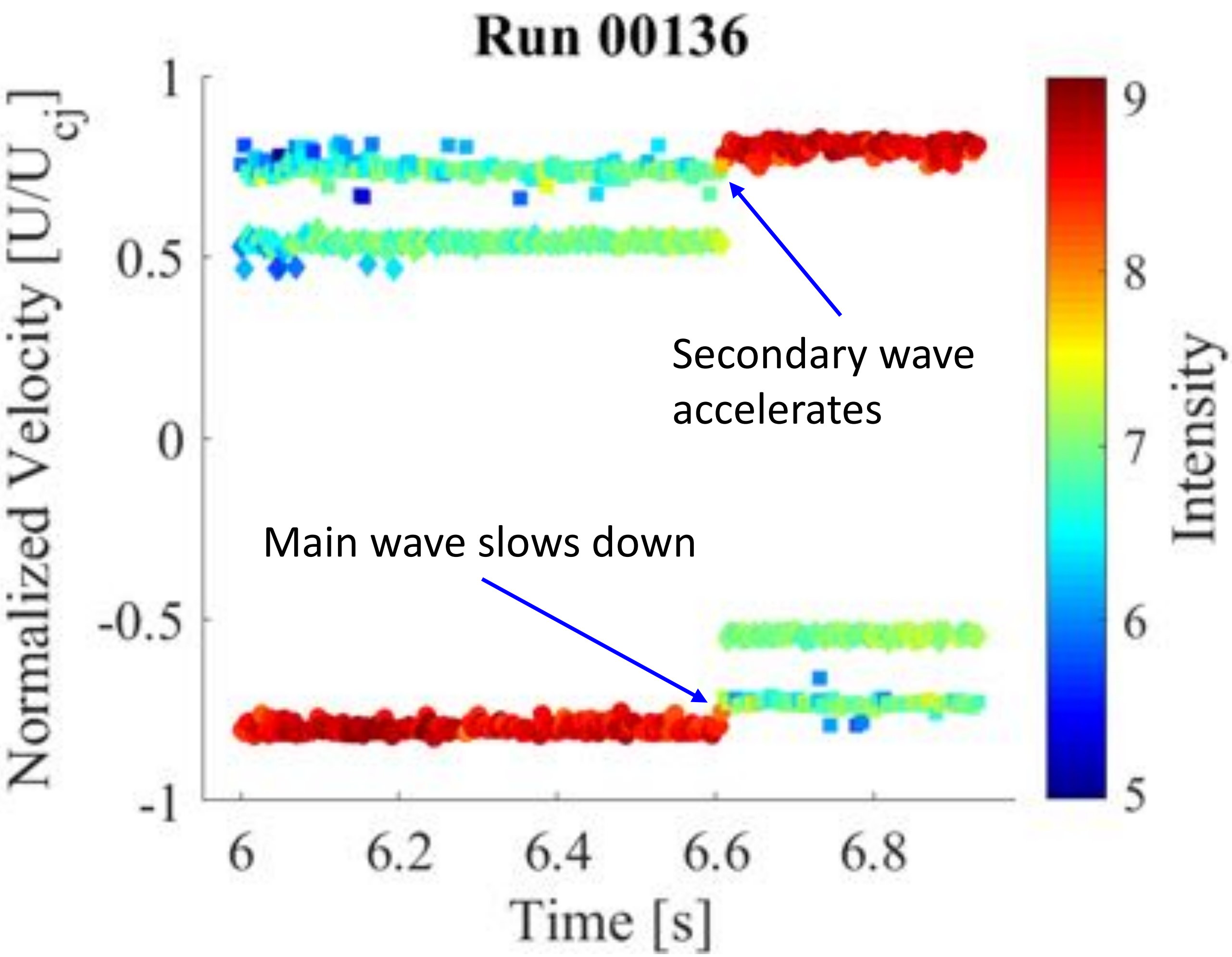

Axial
Radial
Detonation
Pulsed
Either
Detonation
Counter Wave
Counter Pair
Equivalence Ratio
Air Mass Flux [kg s^-1 m^-2]
1.2
1
0.8
0.6
40
60
80
100
120

Temporal information of 3 wave systems

Technique can be applied over short periods of time allowing for temporal variation in wave speed, luminosity for each wave.



Temporal information of 3 wave systems

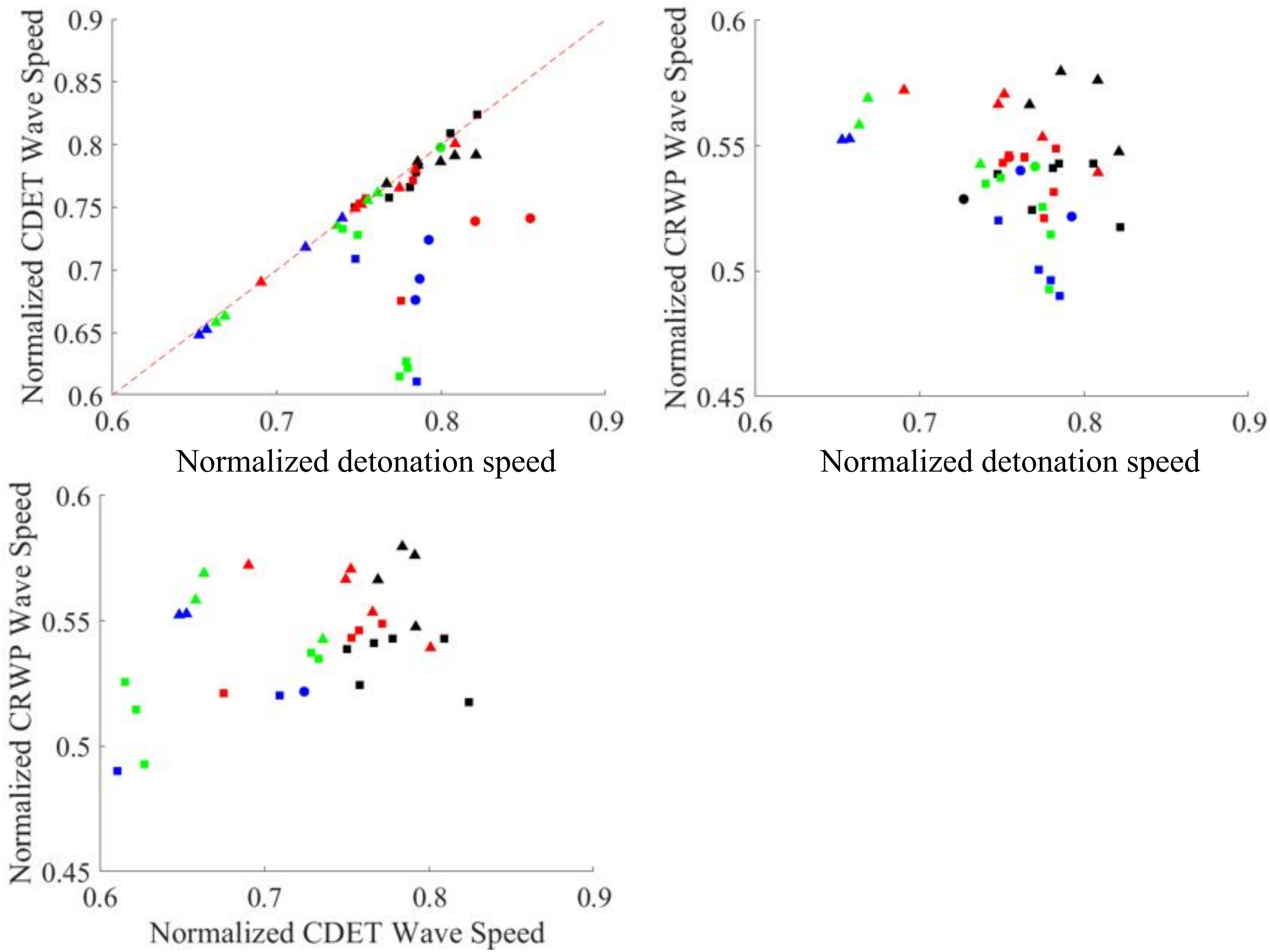


Switching phenomena in this case is the overtaking in strength of the constantly propagating counter wave

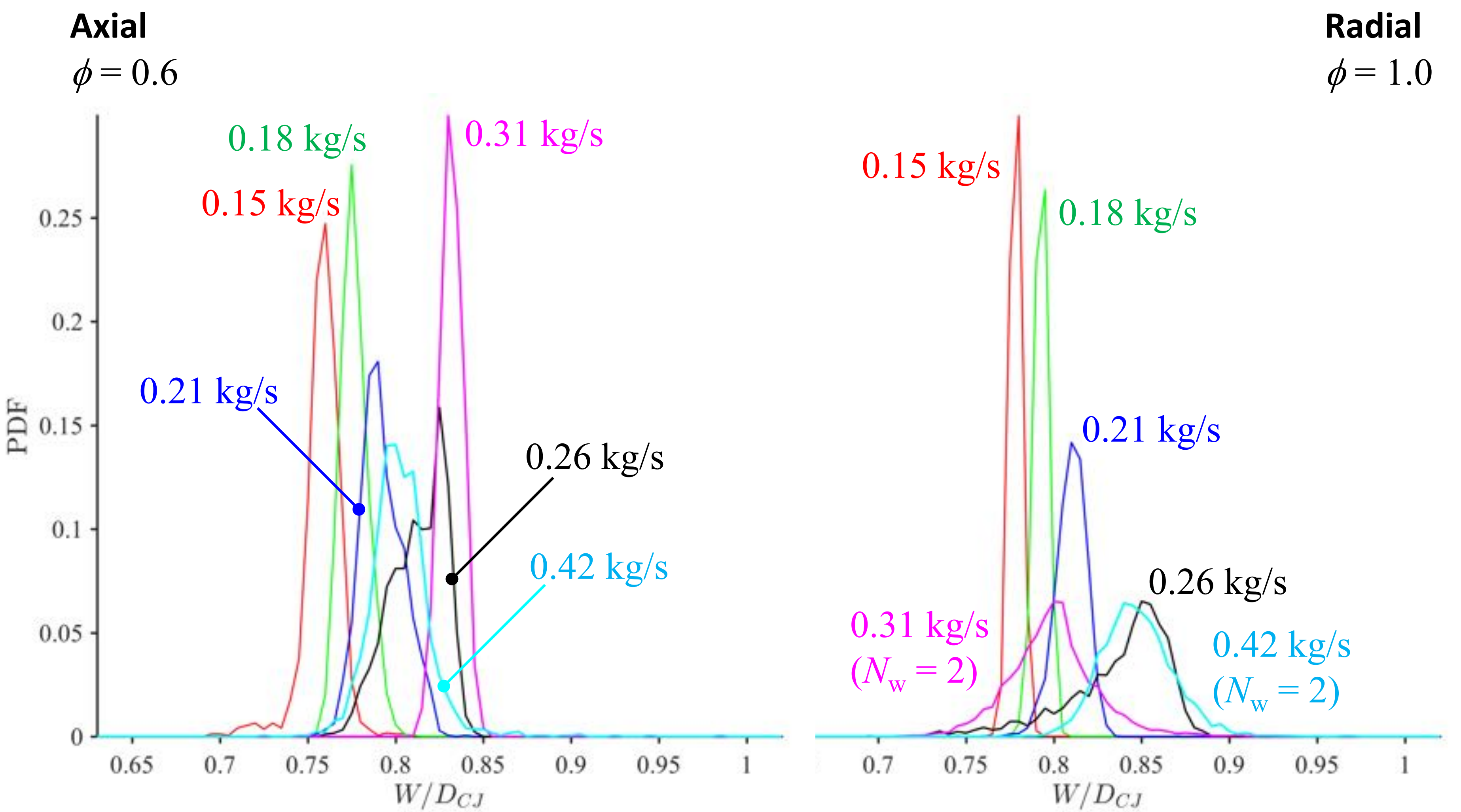
Could be that it is a natural resonance that happens over time

Tertiary waves follow the main detonation wave.

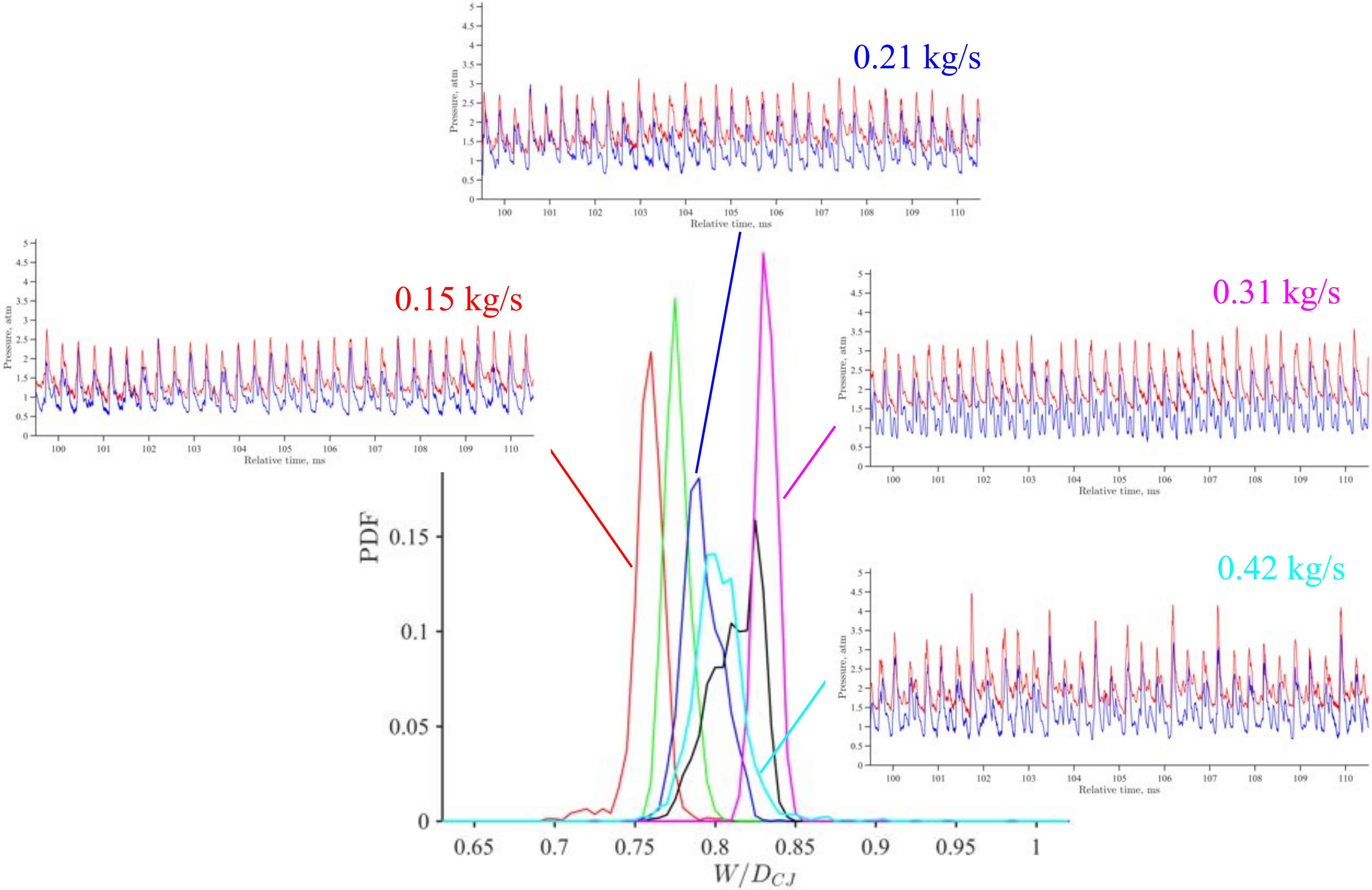
Summary of speeds of each type (normalized by D_{CJ})



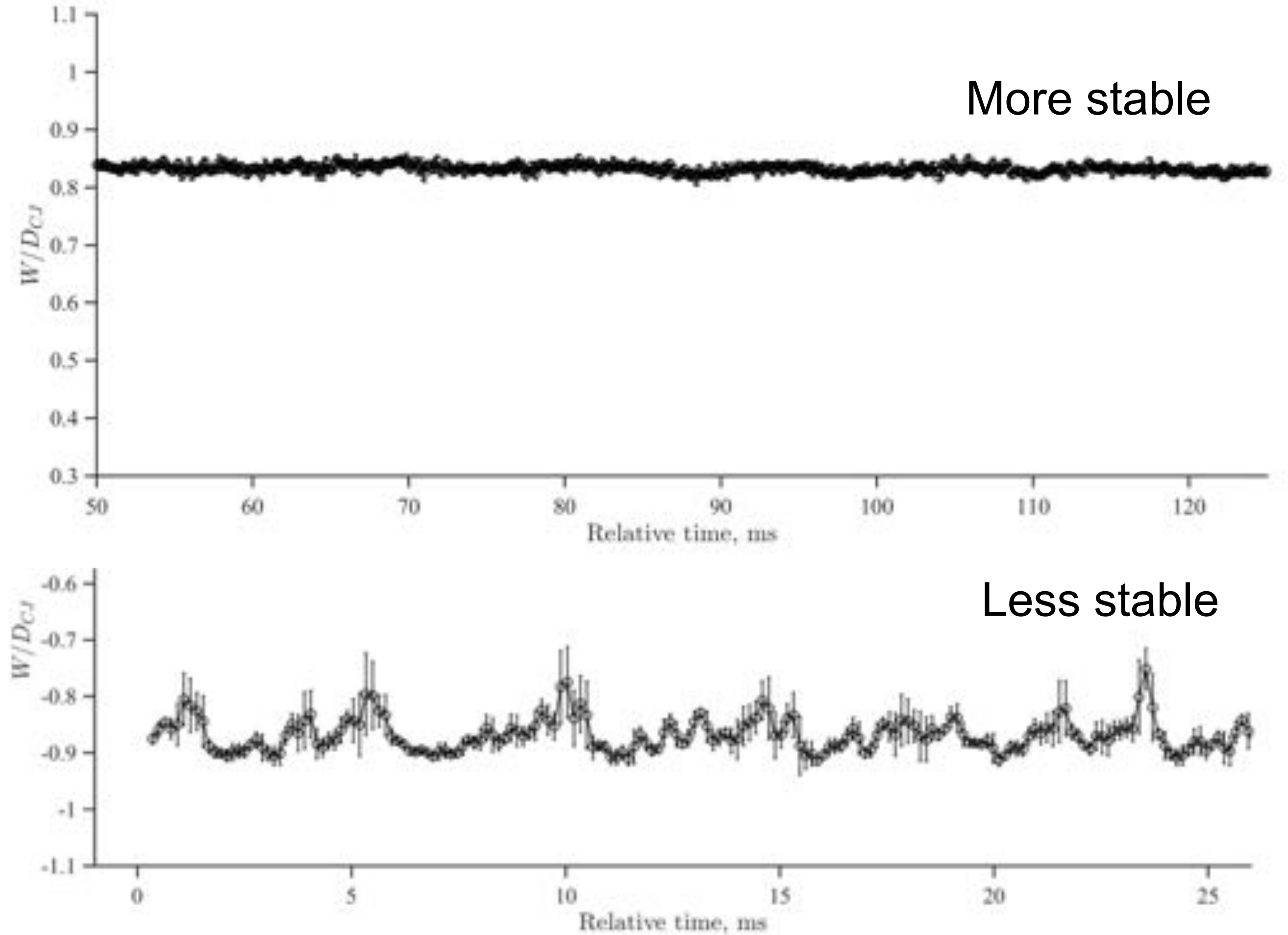
PDF of wave speed for axial and radial inlet flowpath



Constructive/destructive interference of wave systems (Example for axial flowpath, $\phi = 0.6$)



Stability of primary wave thought to depend on operation and strength of secondary/tertiary wave systems, but not proven yet



Question: how do these dynamics affect overall operability and performance?

Lesson learnt

- Further quantified operation of RDE with different inlet/injection geometries

- Identified a complex system of waves
  - Three wave system
  - Affects the operability of the RDE
    - Not yet clear how
  - Linked to operating conditions and geometry
    - But details are not clear yet

Next steps for experimental program

- Continue to understand the system of waves
  - Link to air inlet response
  - Link to fuel injection response
  - Link to mixing and combustion kinetics
  - Effect of exhaust plane
- Main question to be answer
  - How do these dynamics affect the stability and performance?
- To do:
  - Need to define metrics for stability and performance
  - More instrumentation to track dynamics of each component
  - More parametric variations on geometry and operating conditions required

Outline

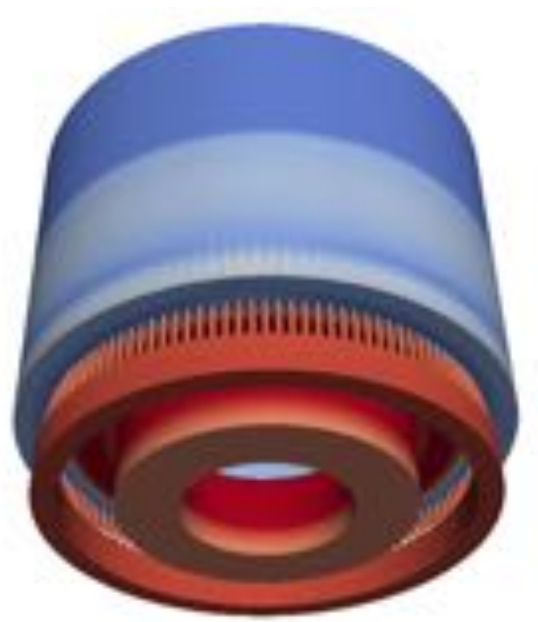
- Introduction to the problem and general approach
- Experimental activities
- Computational activities

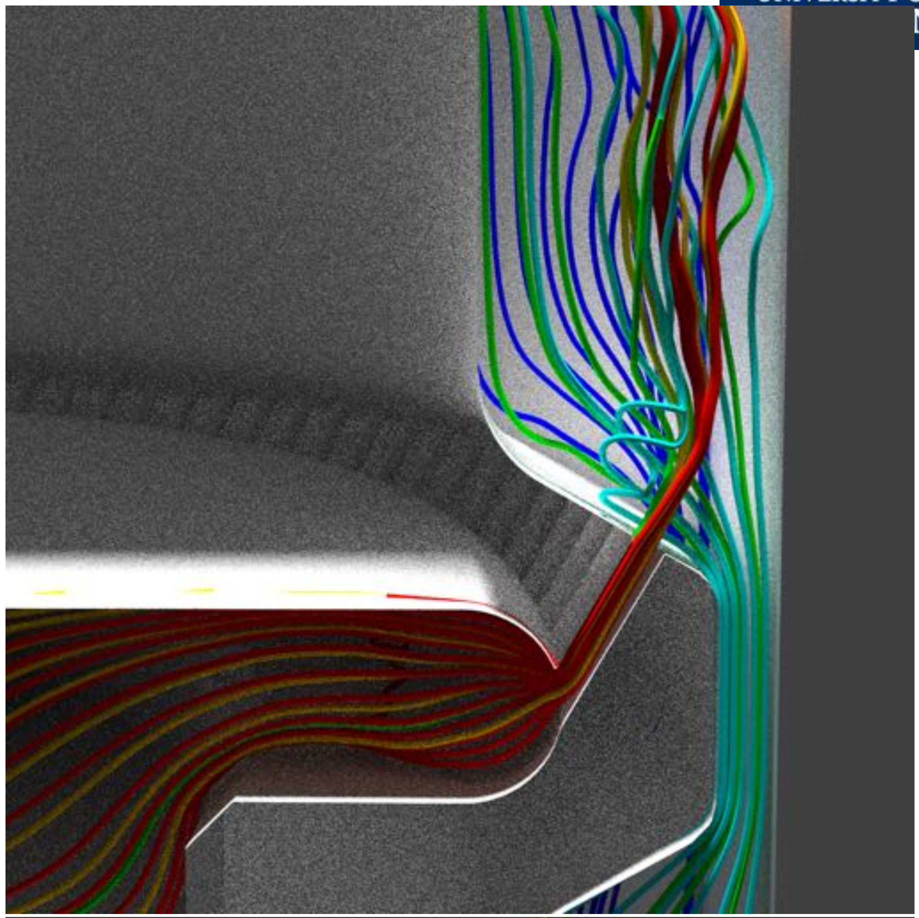
Full-system Simulations of RDEs

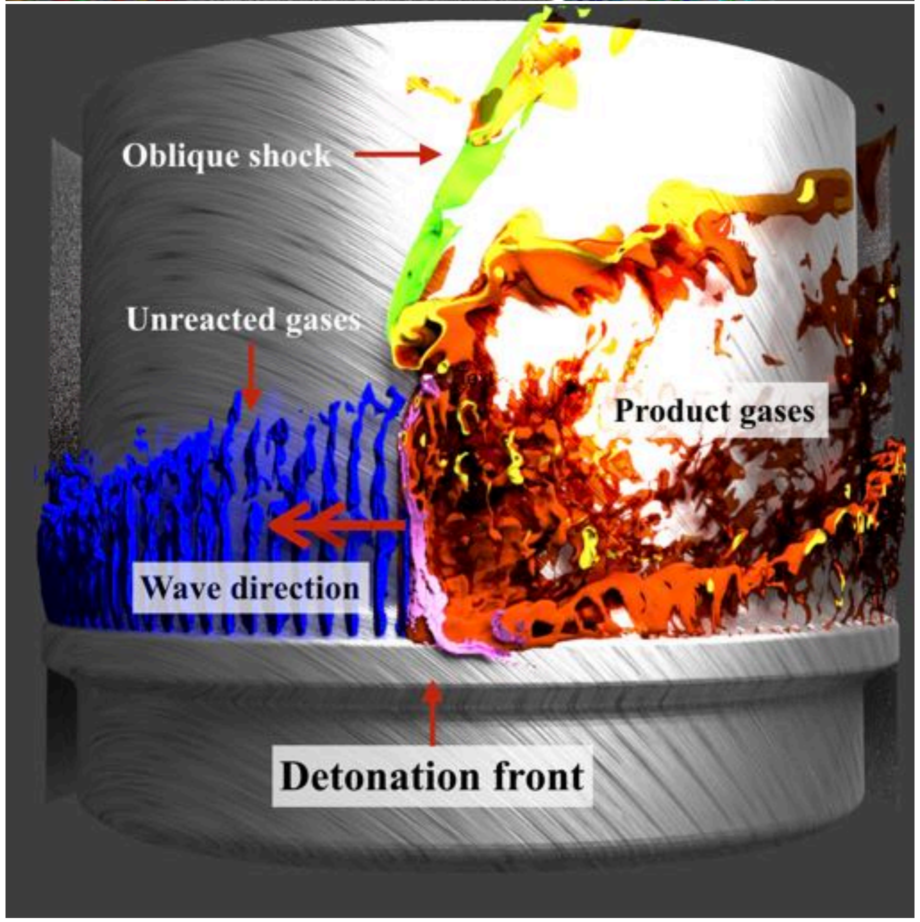
Takuma Sato, Supraj Prakash, Venkat Raman

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 250K cores
    - 4000 GPUs
- **Time to solution**
  - from 8.5 months (UM geometry) to 2 days (NETL)

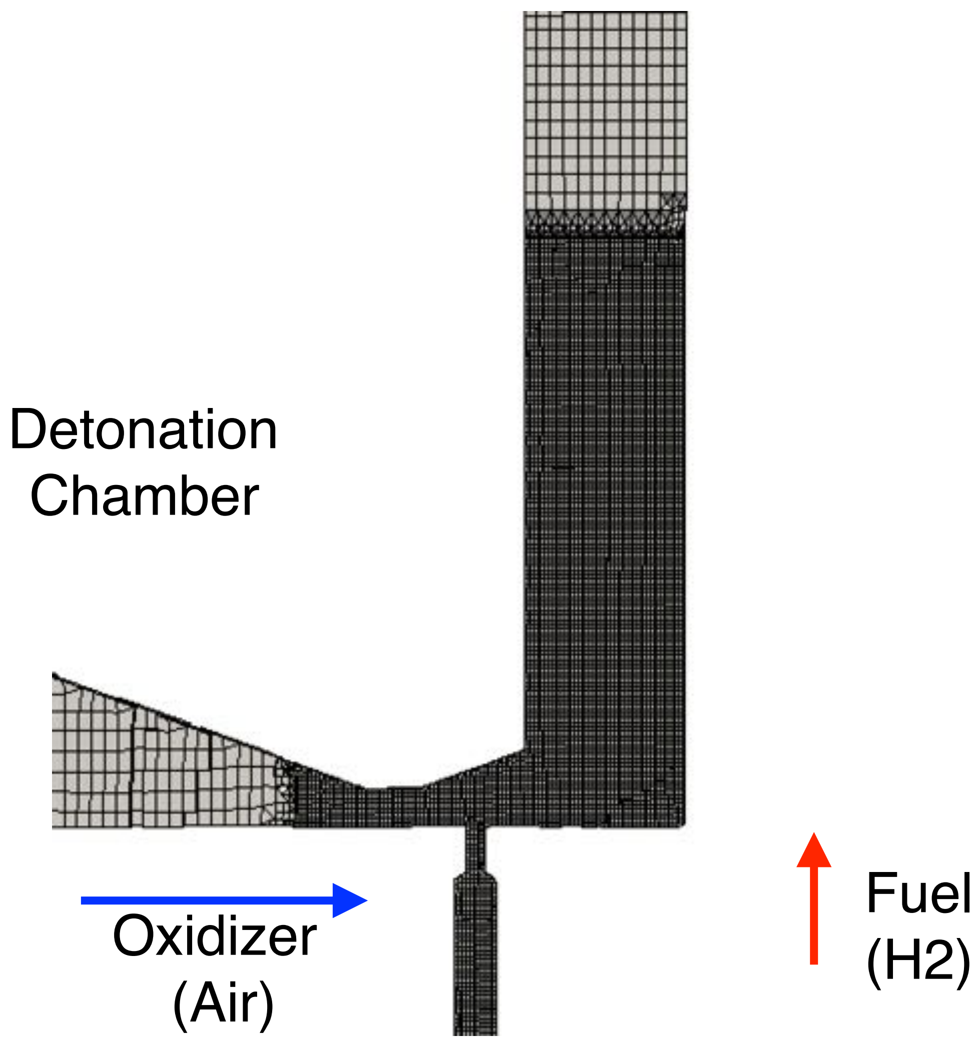




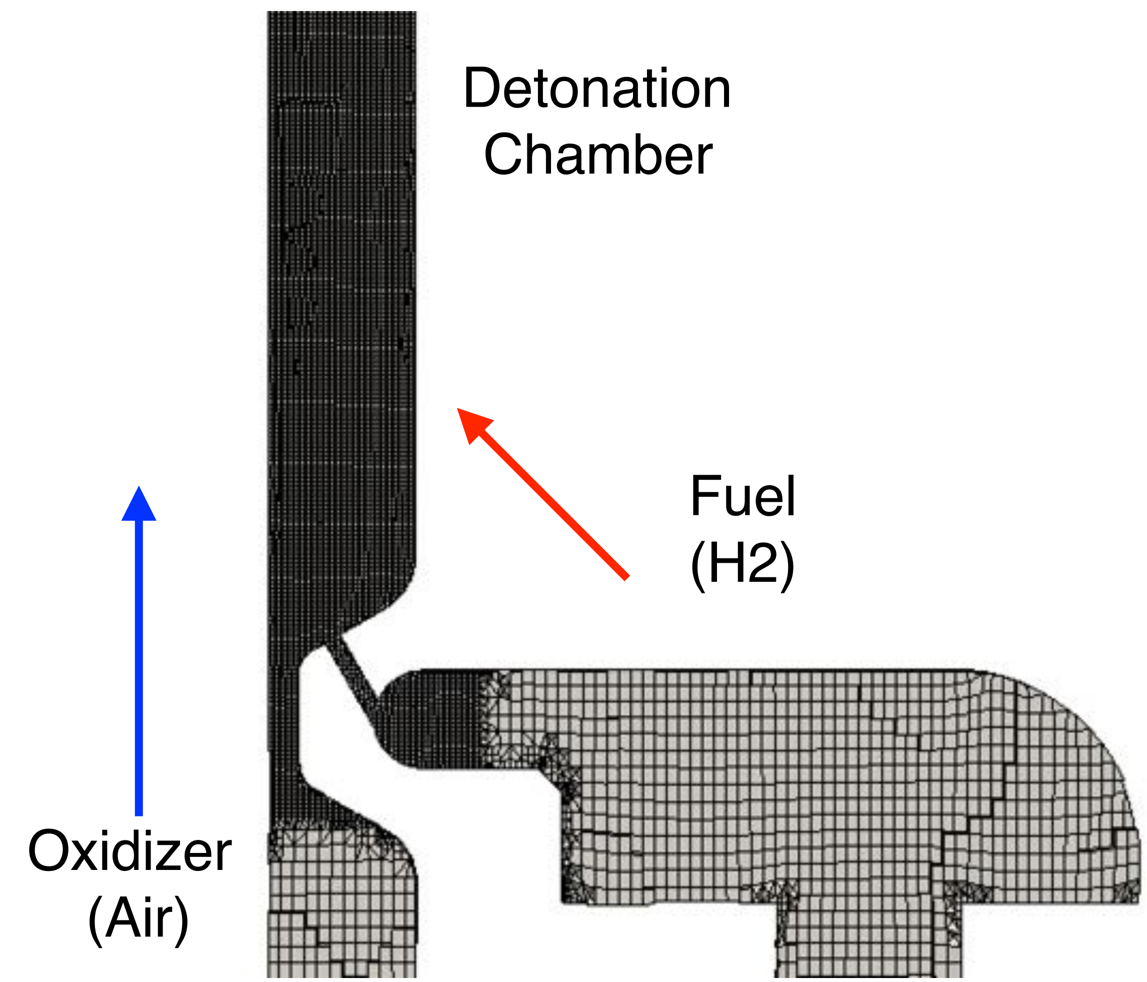


3D full-system simulation

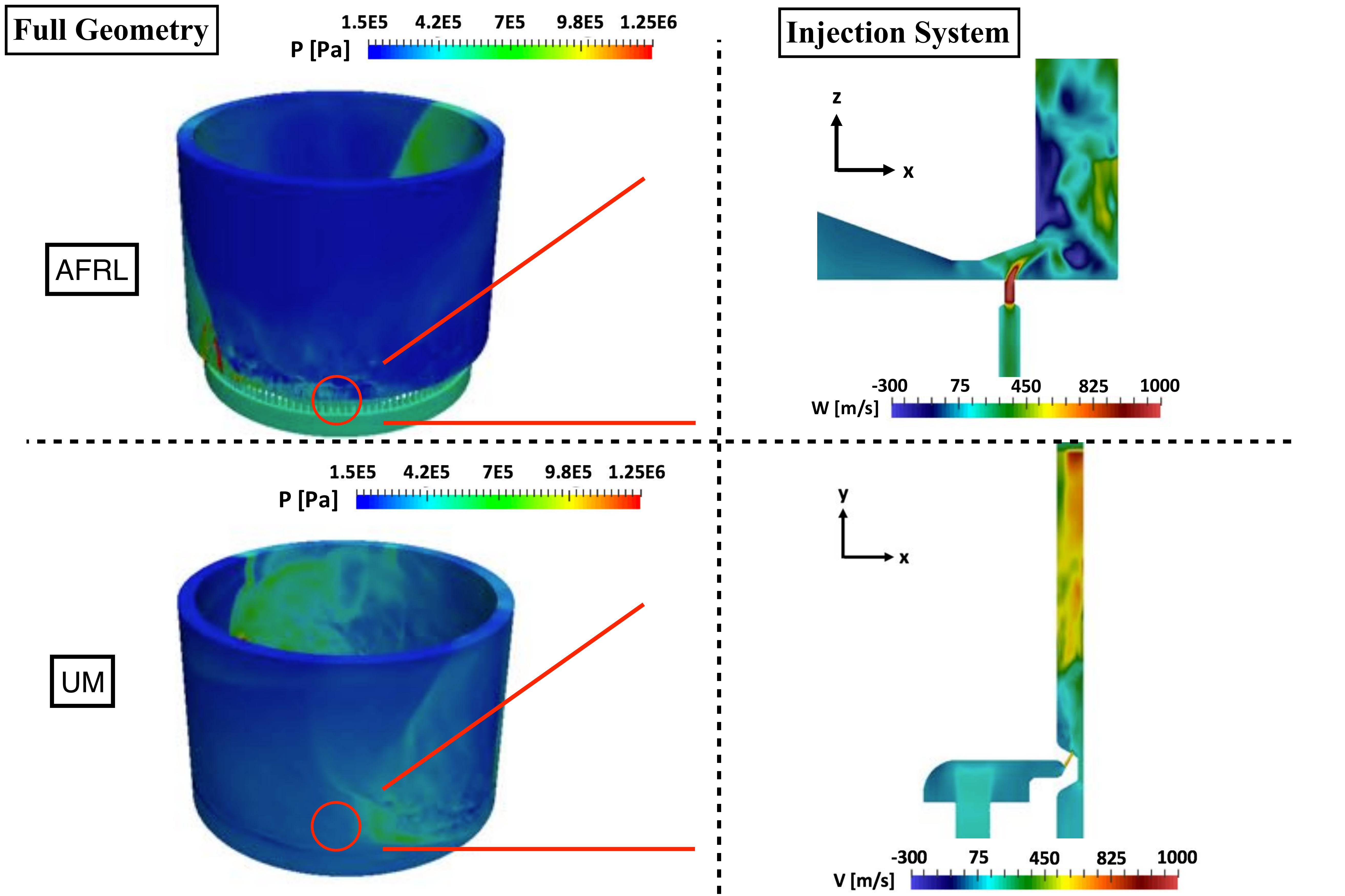
Air Force Research Lab (AFRL)



UM Geometry (Pintle)

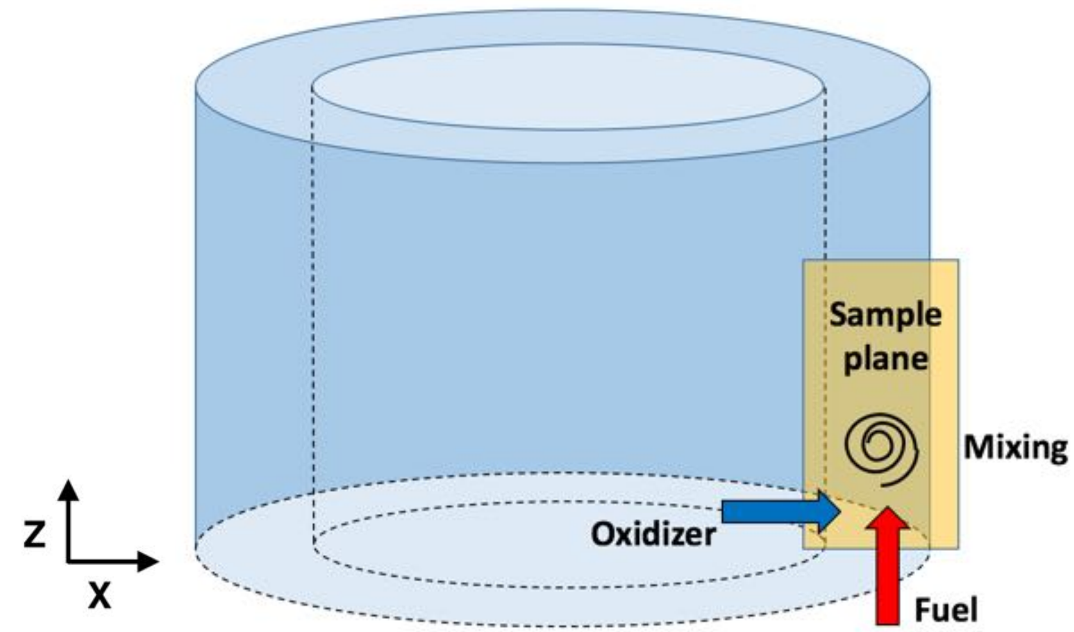


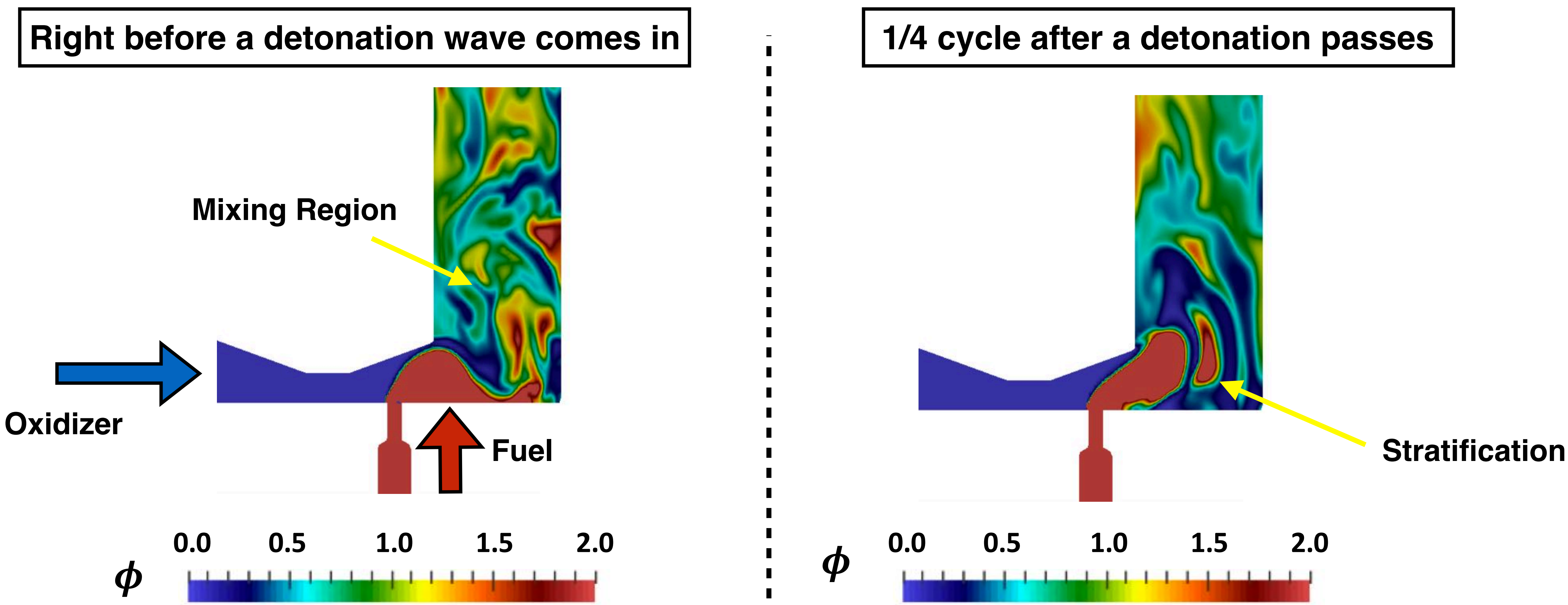
General Behavior



Fuel-air Mixing

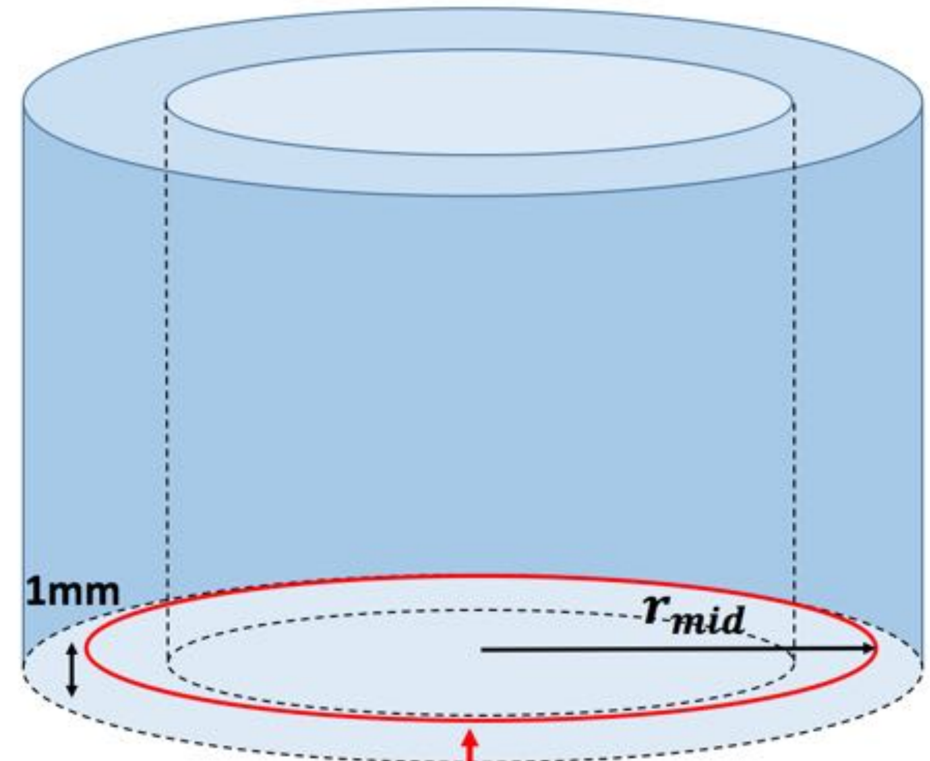
- **Stratification of H2/ air near detonation front**
  - Variation in equivalence ratio
  - Temporal changes in inflow jets due to detonation waves



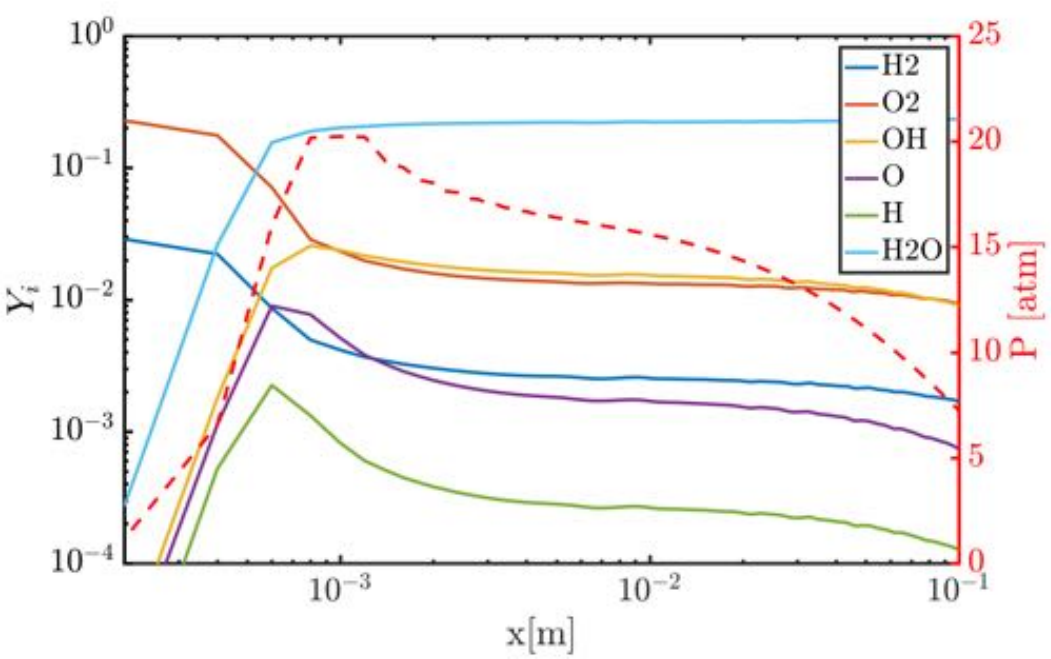


Species Evolution

- **Product gases appears in pre-detonation region**
  - Parasitic combustion,
    old product gases from the previous cycle
  - Peak pressure drops compared to 1D case

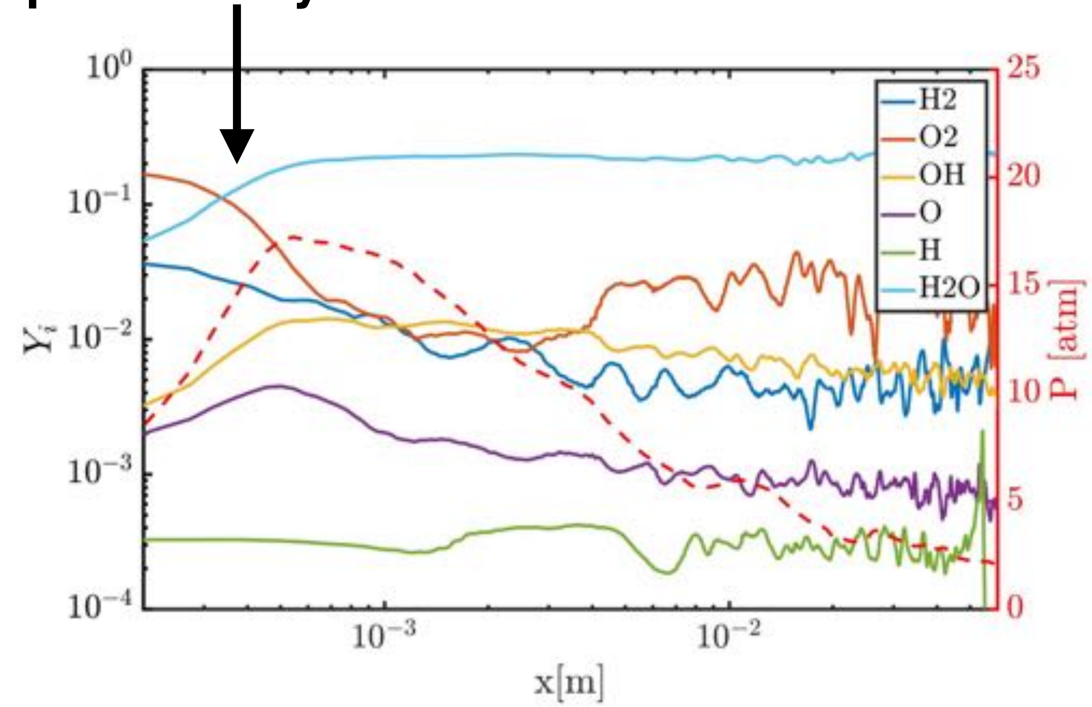


Sampling line
Pressure, species



Ideal case of 1D: H2/ Air (dx = 2E-4 m)
1 atm, 300 K mixture at the stoichiometric condition

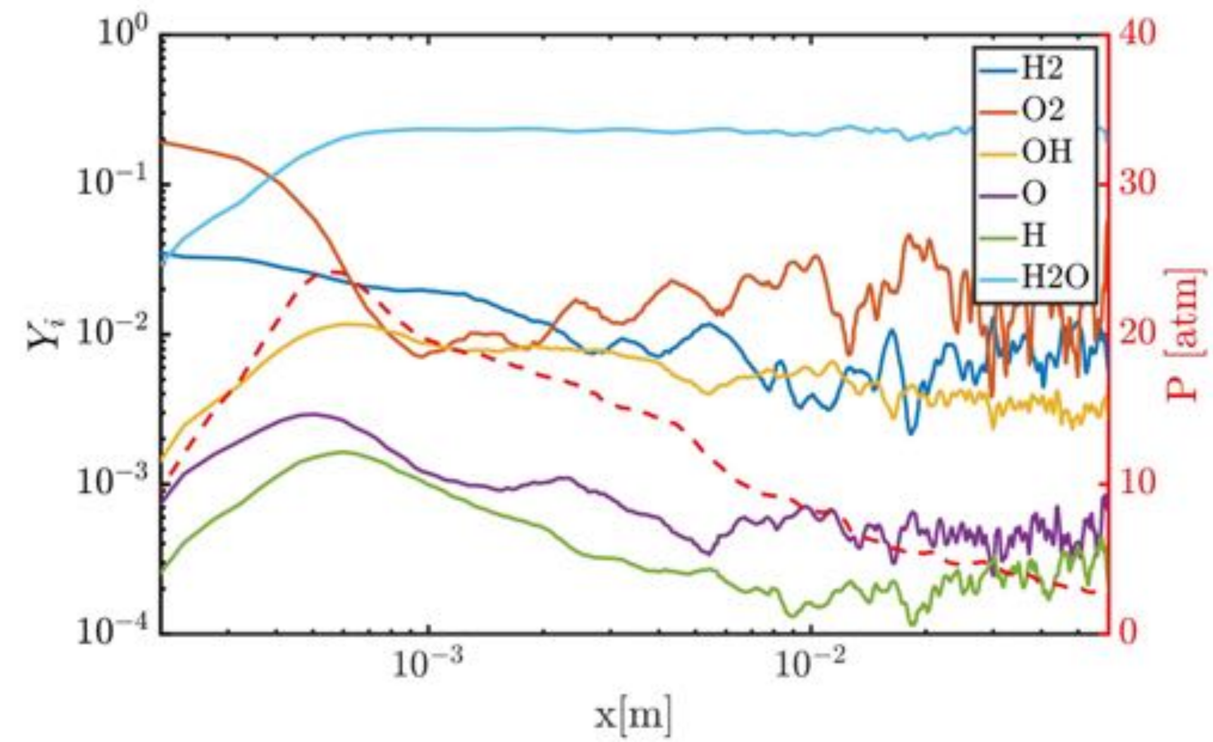
Residual gases from previous cycle

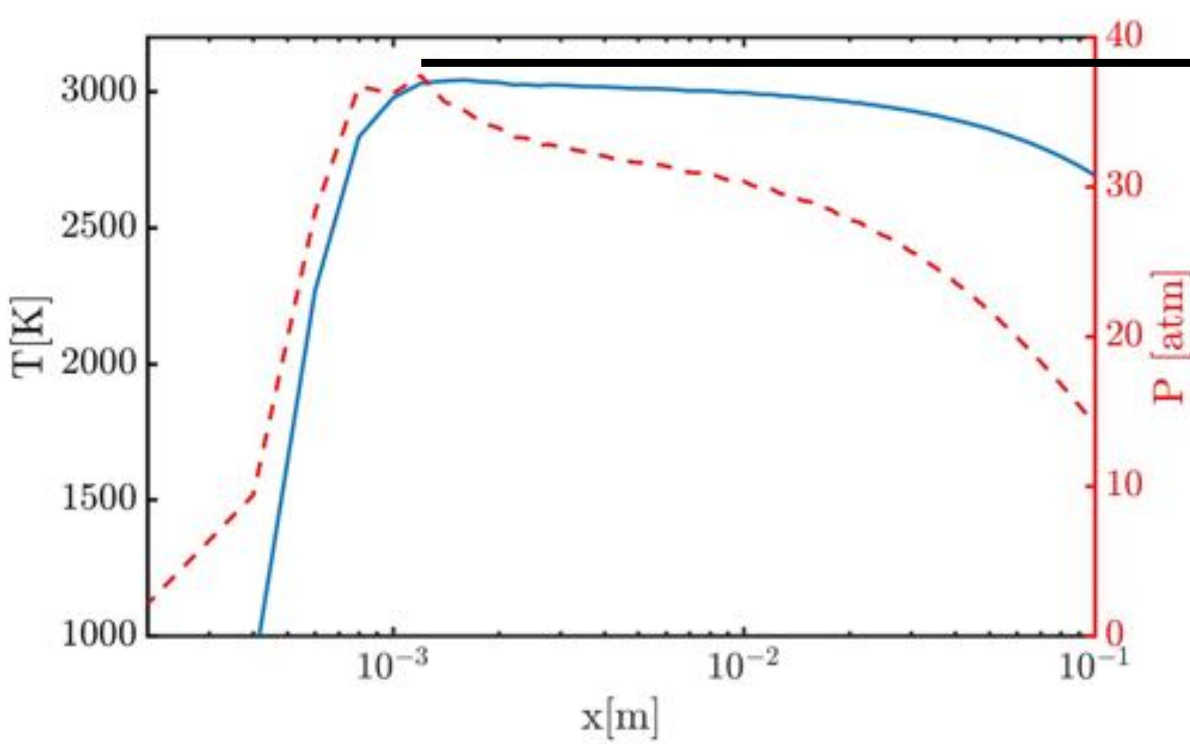


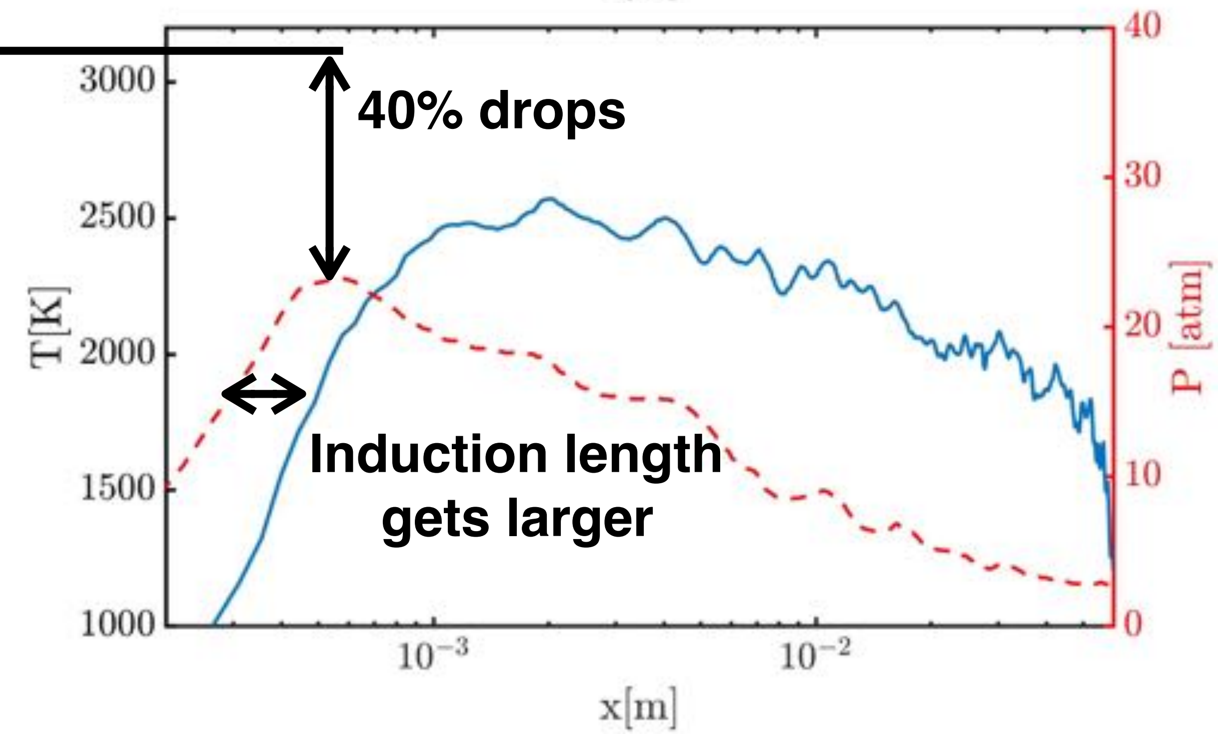
Lowest mass flow case

Species and Temperature Data

- **Pressure loss**
  - Nearly 40 % lower peak pressure
- **Delay reaction**
  - Energy feeding process is not ideal
    - Deteriorate operation





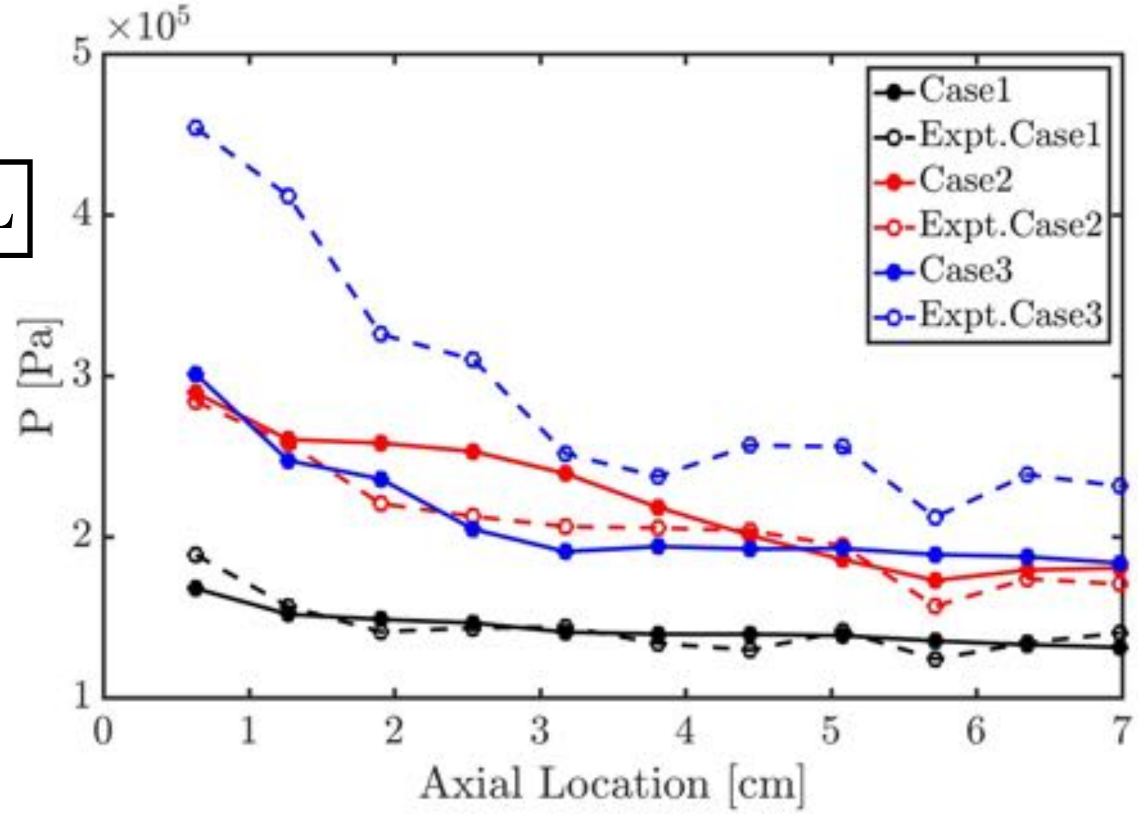


Ideal case of 1D: H2/ Air (dx = 2E-4 m)
2 atm, 300 K mixture at the stoichiometric condition

High mass flow case

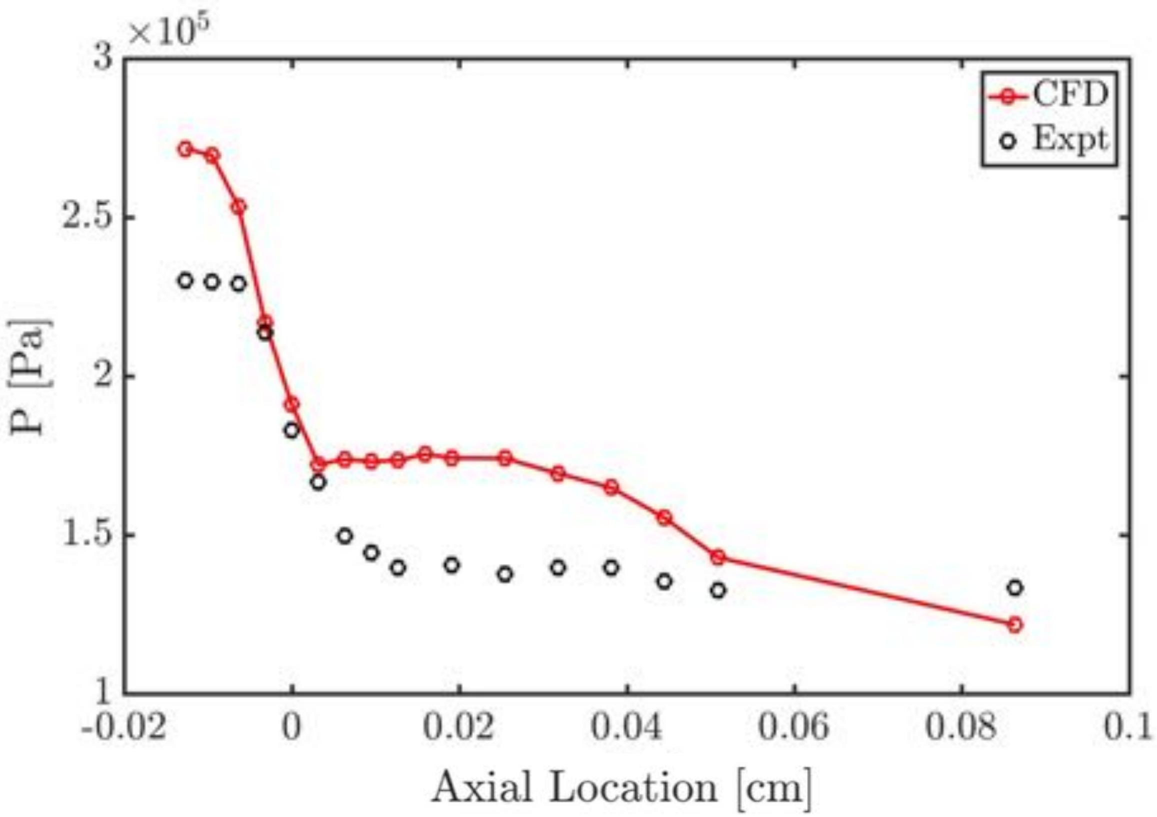
CTAP comparison - Axial pressure

AFRL



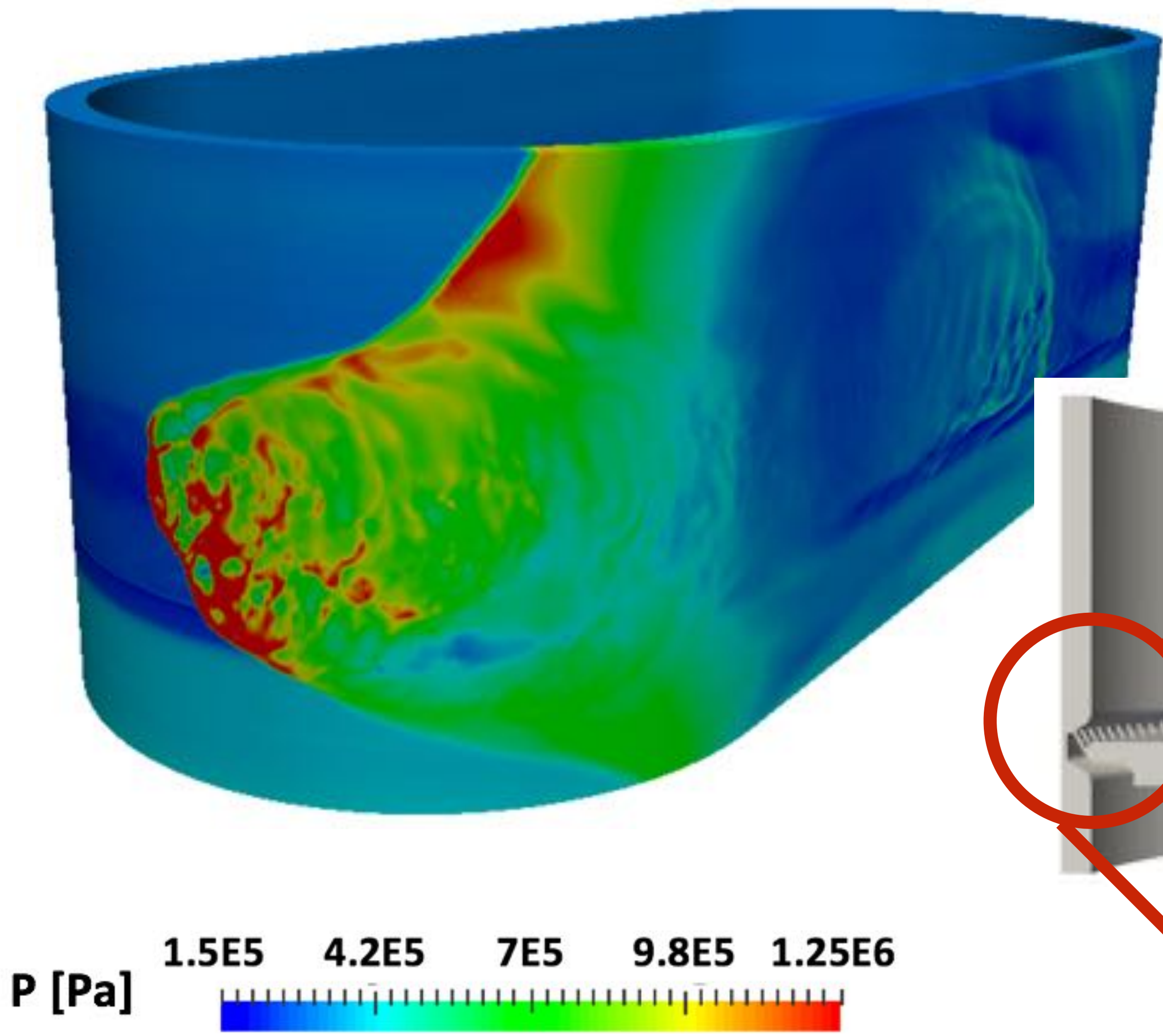
- The pressure decrease with increasing with axial distance due to expansion effects
- The simulations predicts the peak pressure well for case 1&2 while under predicting this value for case 3

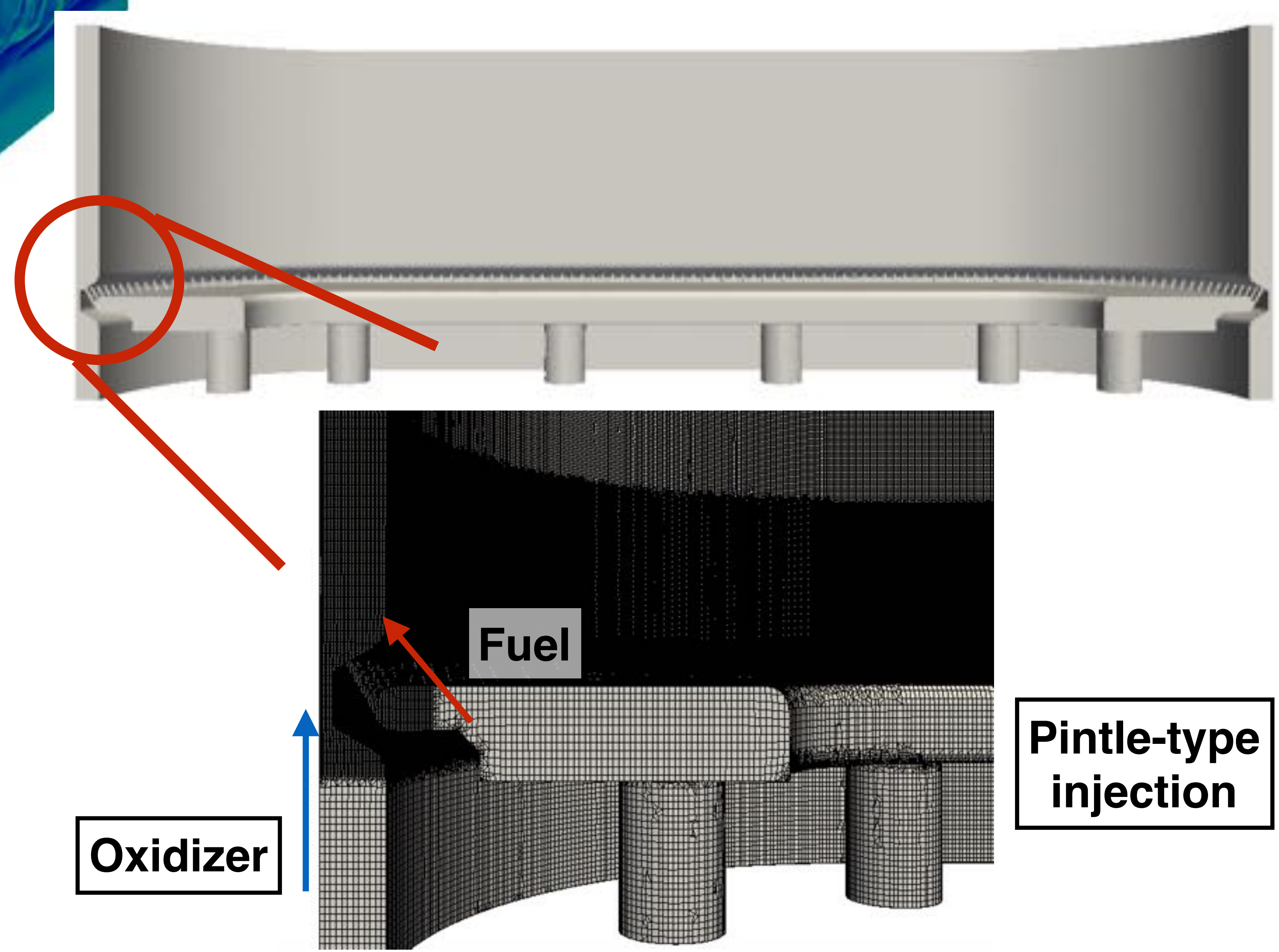
UM



- Overall, simulation predicts higher pressure
  - ➡ stronger flash back into the oxidizer plenum
  - ➡ stronger detonation in the chamber

UM Racetrack geometry



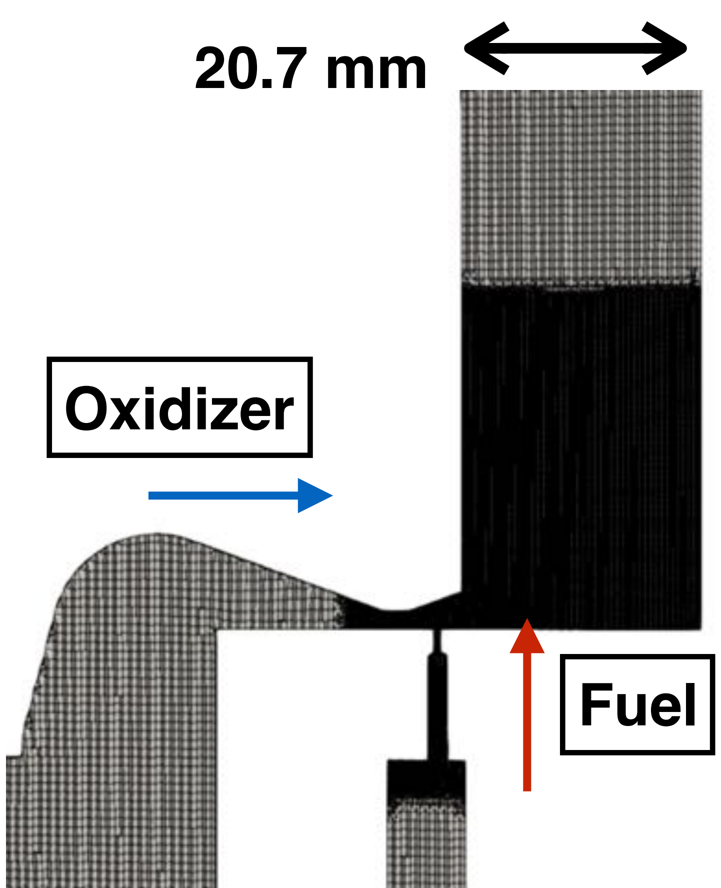


Ethylene/Air Detonations with AFRL Config

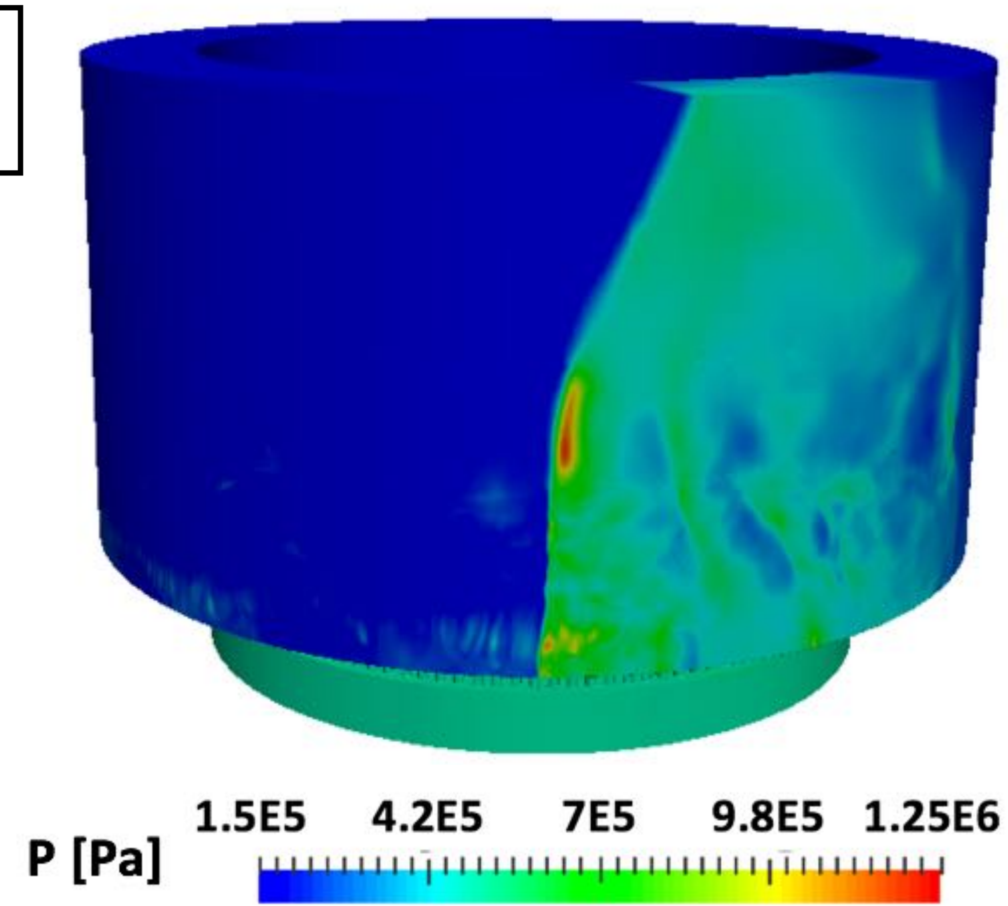
- **Wider channel but same injection scheme as hydrogen/air**
- **Ethylene detonation cell size is larger**
- **Overall weaker detonation wave**

	Channel width (mm)
H2/Air	7.6
C2H4/Air	20.7

Mesh

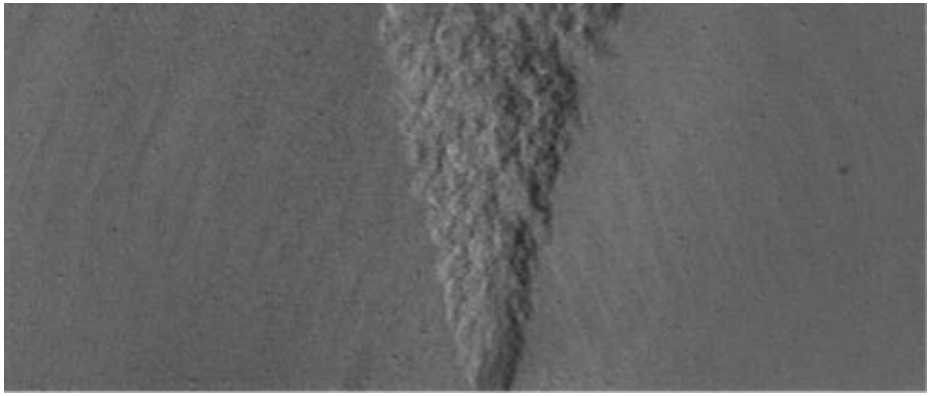


Flow-field (Running)



Conclusions and Current Work

- **Full-scale simulations are beginning to match experimental observations**
  - More confidence in simulations <u>and</u> experiments
- **Stratification plays a crucial role**
  - Interaction with pre-burnt gases reduces pressure peaks
- **Capability to simulate arbitrary fuels and configurations tested**
  - 4 configurations and 6 fuels being simulated now



Questions?