COLLEGE OF ENGINEERING
AEROSPACE ENGINEERING
UNIVERSITY OF MICHIGAN

Fuel Injection Dynamics and Composition Effects on Rotating Detonation Engine Performance

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DOE FE0031228 with Dr. Robin Ames as Program Monitor

Outline

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

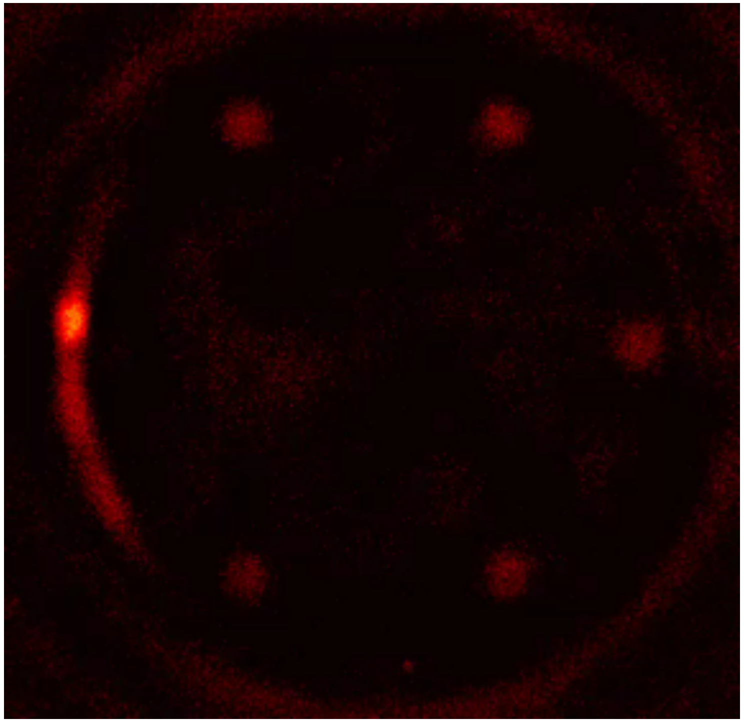
Overarching objectives of the project

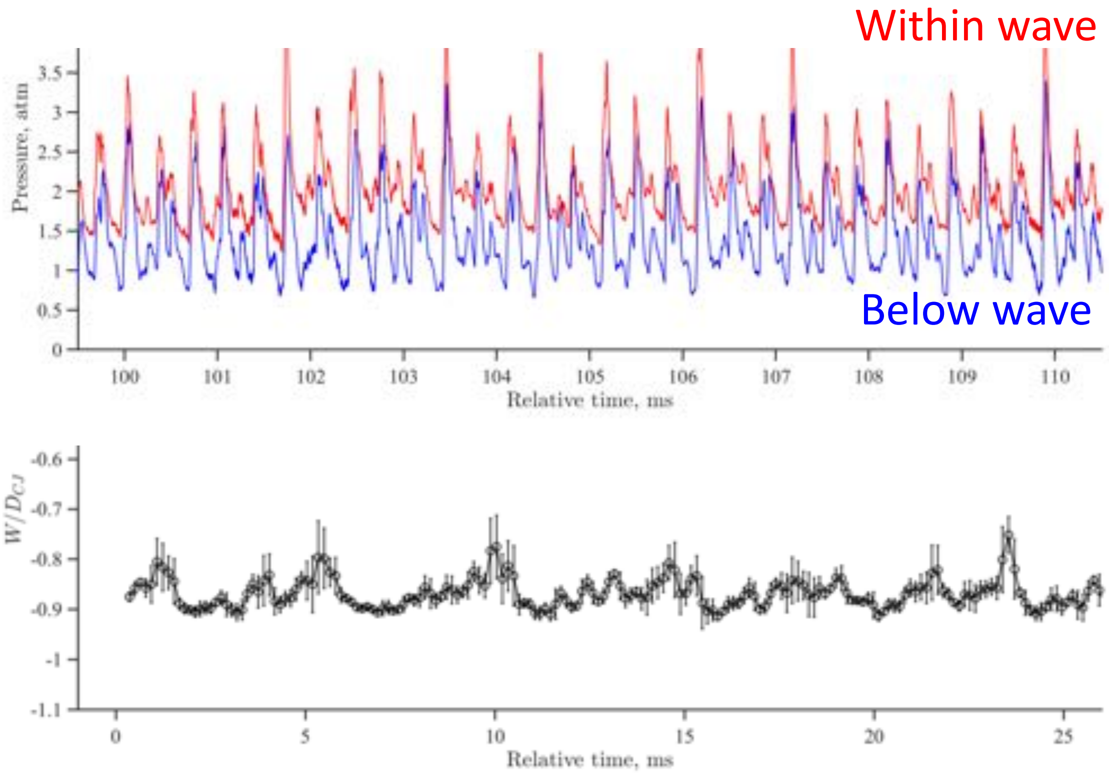
- **Objective 1:**
  Develop a comprehensive understanding of injector dynamics, coupling with plenums & diffuser back-reflections, and their impact on RDE mixing, operation and performance.

- **Objective 2:**
  Develop a comprehensive understanding of multi-component fuels (syngas and hydrocarbon blends) on RDE detonation structure and propagation, operation and performance.

- **Objective 3:**
  Develop advanced diagnostics and predictive computational models for studying detonation propagation in RDEs, with arbitrary fuel composition and flow configuration.

Multiple wave systems and erratic behavior





Although detonation occurs:

- Wave speed and max pressure are generally less than ideal
- Behavior can appear erratic (large and aperiodic cycle-to-cycle variations)

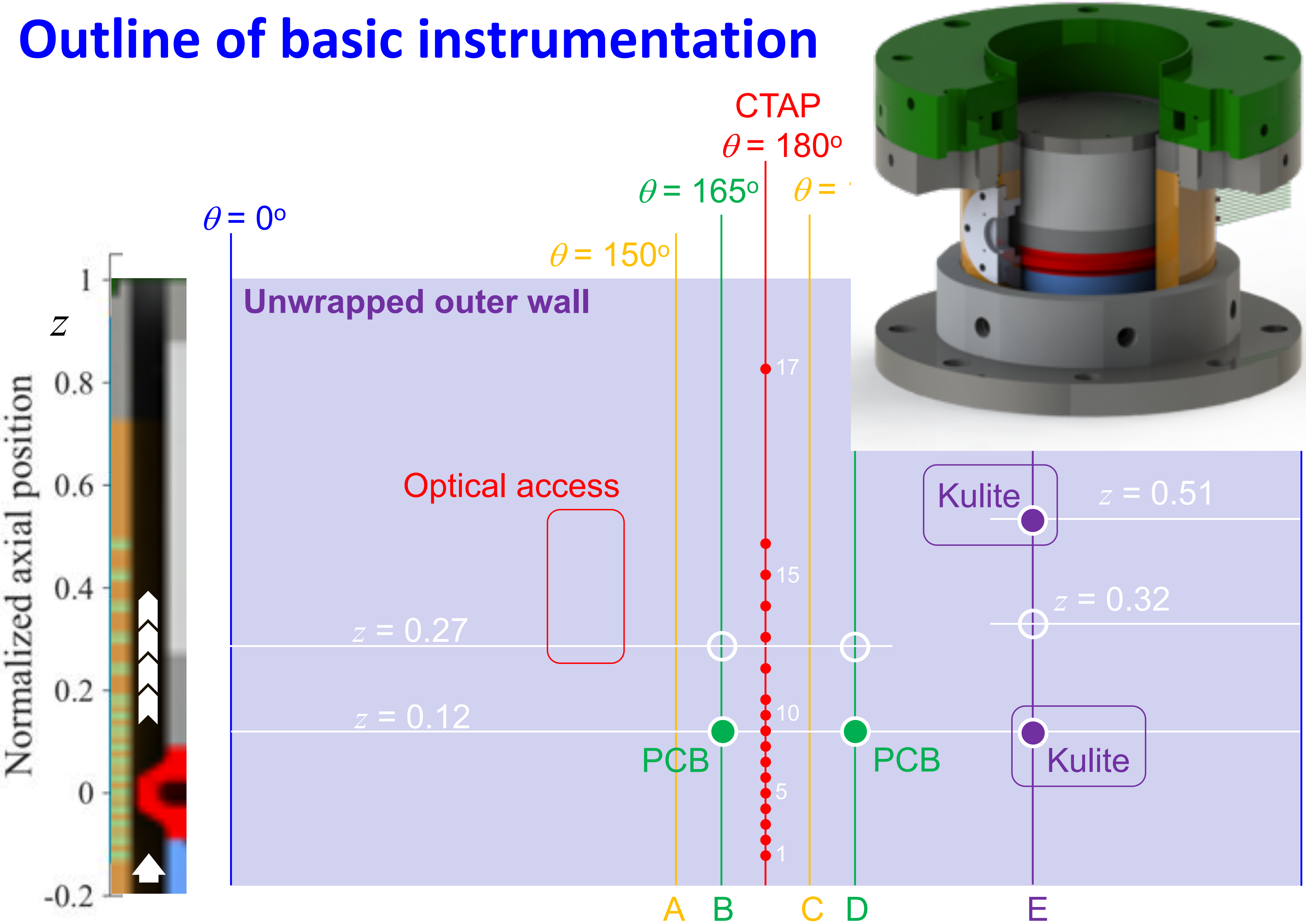
Overarching goals on RDE dynamics

- **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 how the dynamics of components couple 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

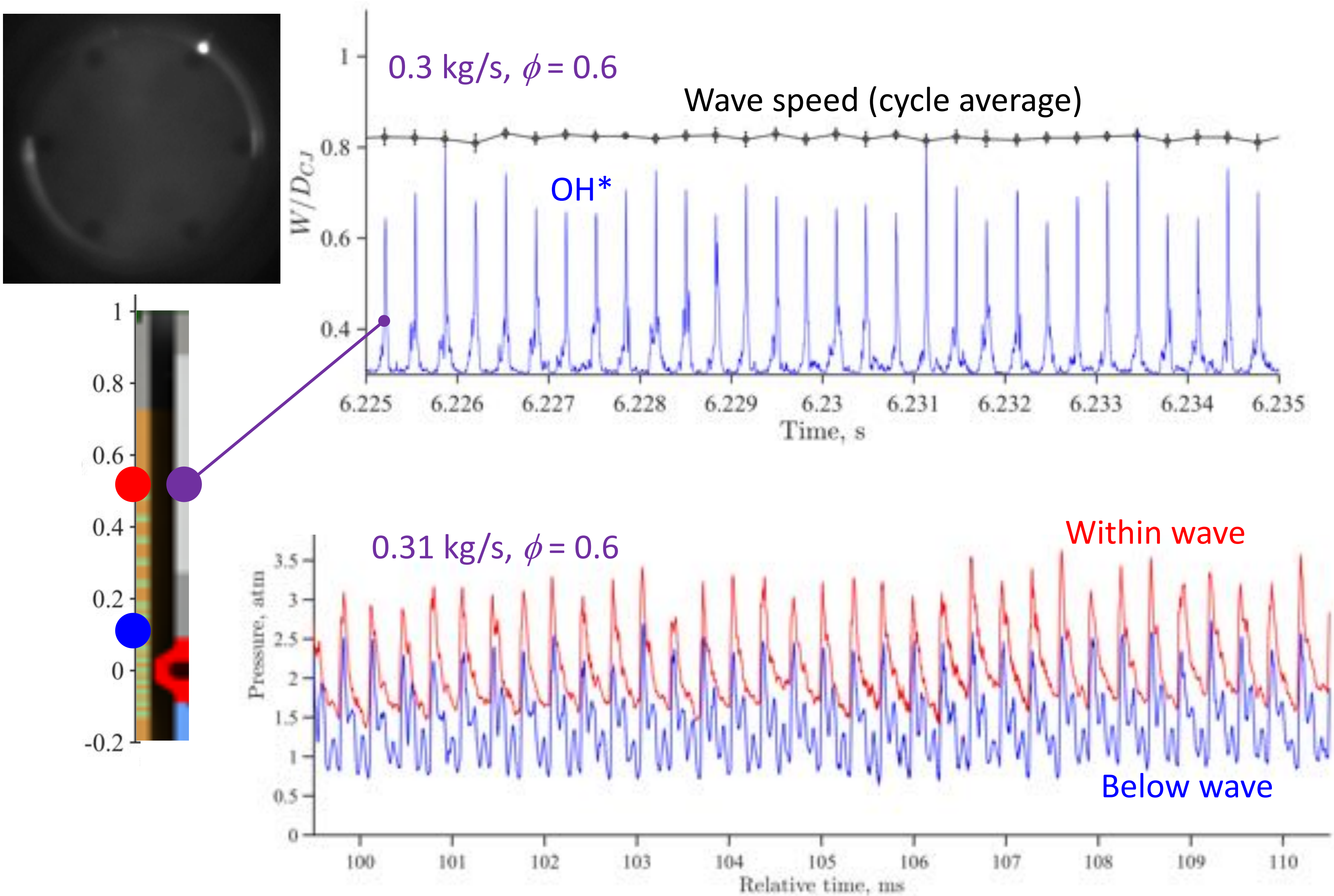
Outline

- Introduction to the problem and general approach
- Experimental activities
  - Identify and classify system of waves that may exist in an RDE
  - Investigate how they affect the operation of an RDE
  - Discussion of some of the important underlying mechanisms and implications
- Computational activities

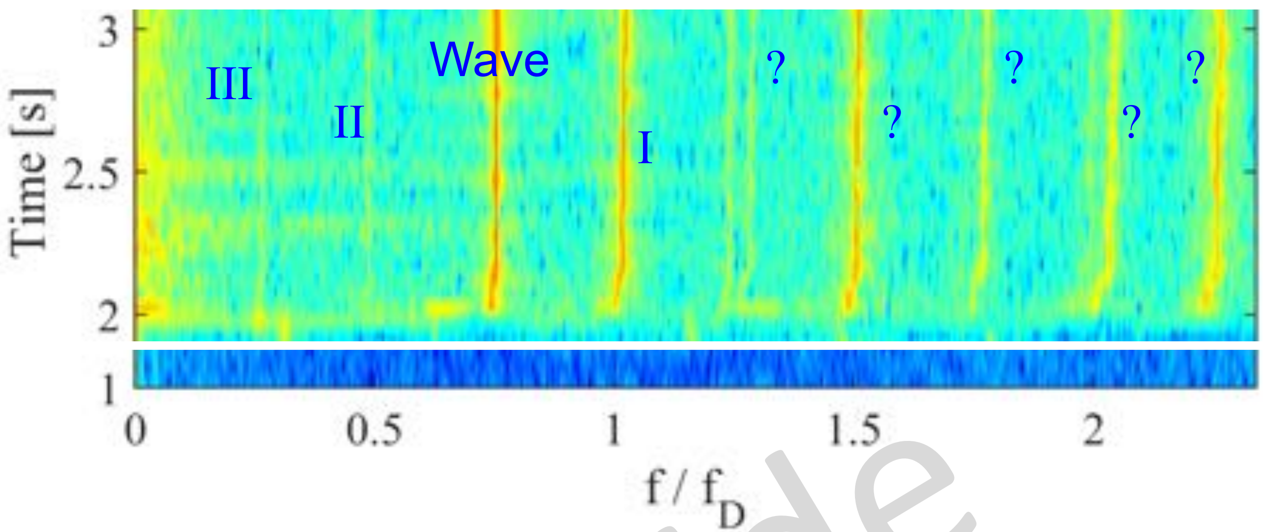
Outline of basic instrumentation



Pressure and OH* variation signature

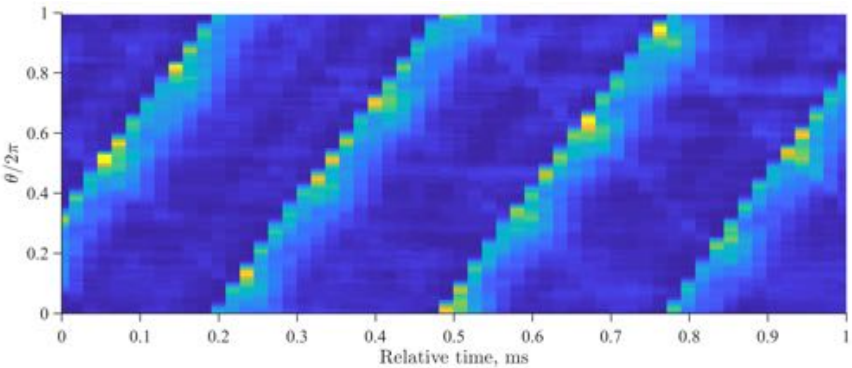


When we started, we look at frequency content…

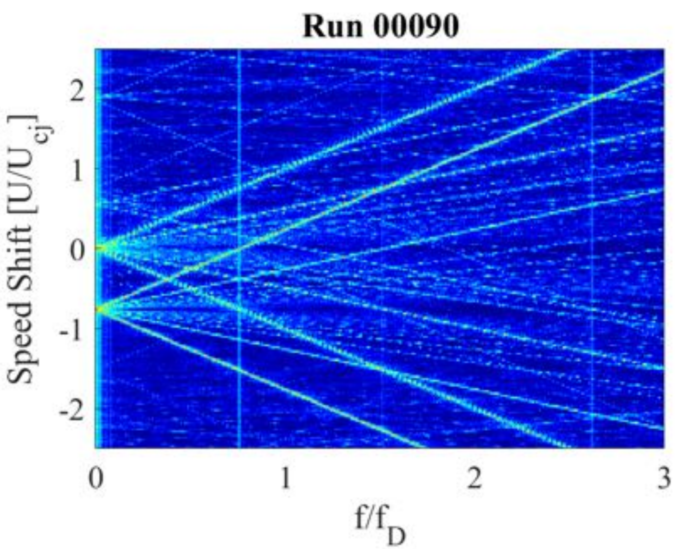


- Multiple, superimposed tones
  - Wave propagation: $f \cong 0.8\, f_D$
  - Tone I: $f \cong f_D$ – Present in detonation mode as flow rate increases, but also in deflagration mode
  - Tone II: $f \cong 0.5\, f_D$ – Present in deflagrating mode
  - Tone III: $f \cong 0.25\, f_D$ – Weak feature present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

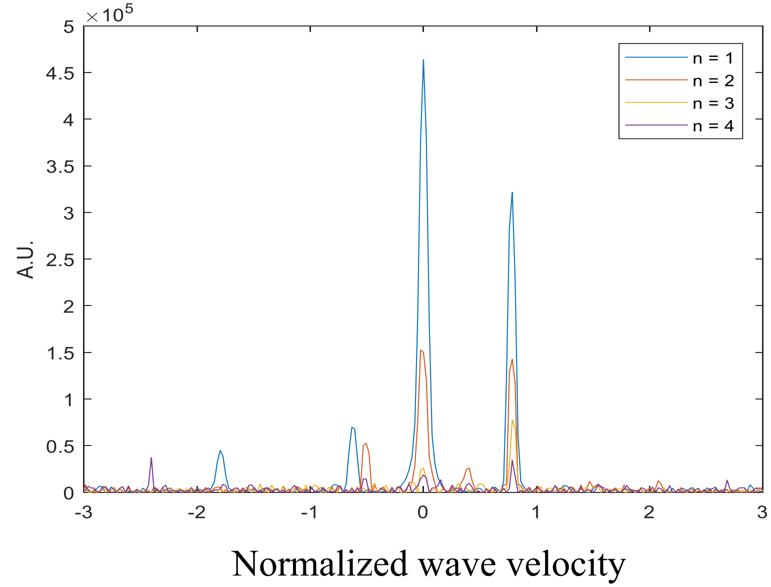
Development of Circuit Wave Analysis for the identification of arbitrary waves



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



2. Compute the Galilean Shifted Fourier Transform (GSFT)



3. Use a modified Radon transform to reduce the GSFT 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

RDEs operate under a complex system of waves

Three-wave system appears in different systems under several operating conditions:

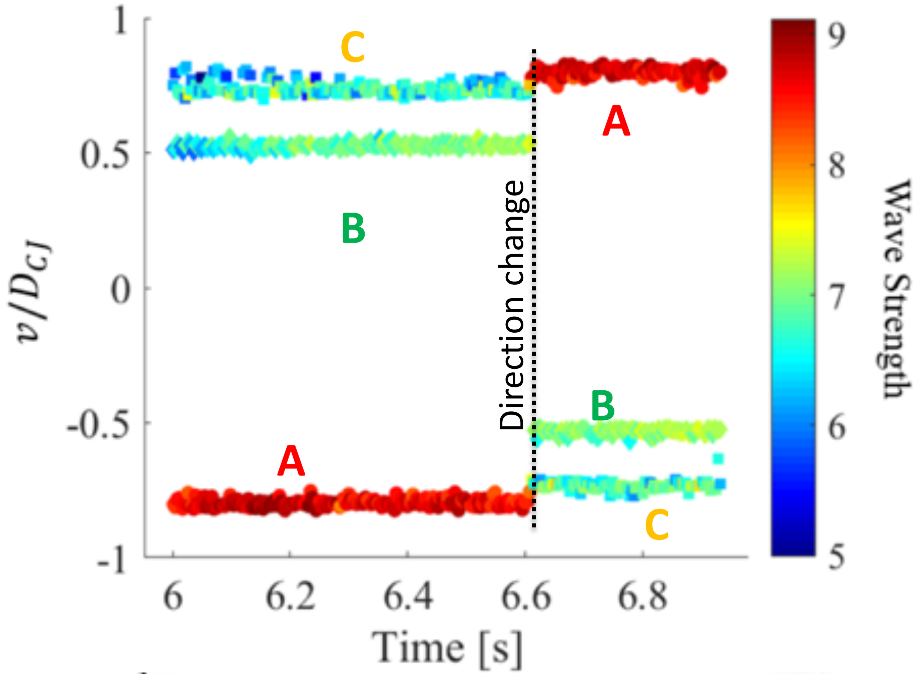
A: **Primary detonation wave.** Travels at 80% of Chapman-Jouguet Velocity

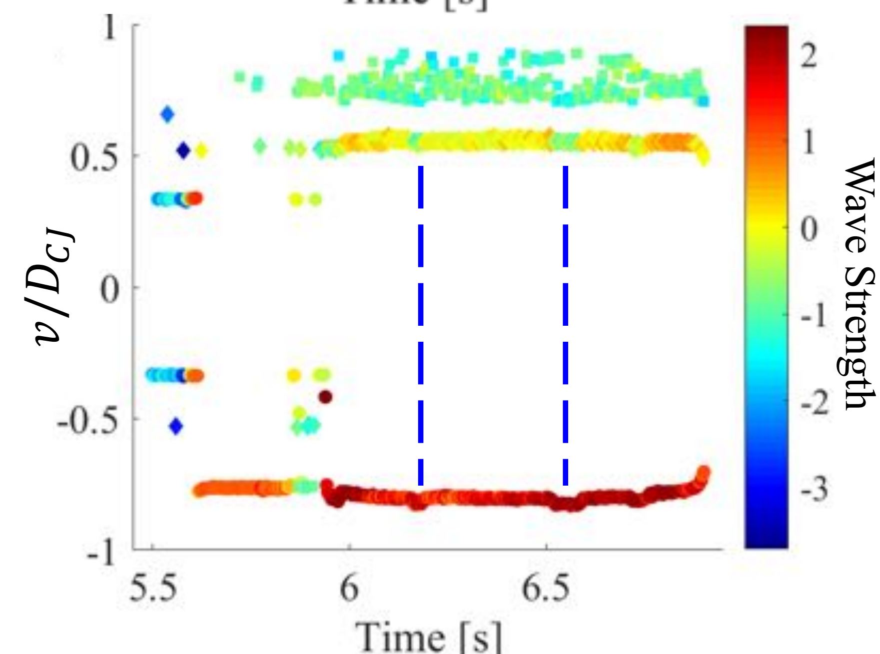
B: **Counter rotating fast wave.** Travels counter to the primary detonation wave. Typically travels at approximately the same speed as Primary Detonation. However can move up to 200 m/s slower

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

There might be others depending on geometry/conditions

Wave speeds up as the strength of secondary waves decreases





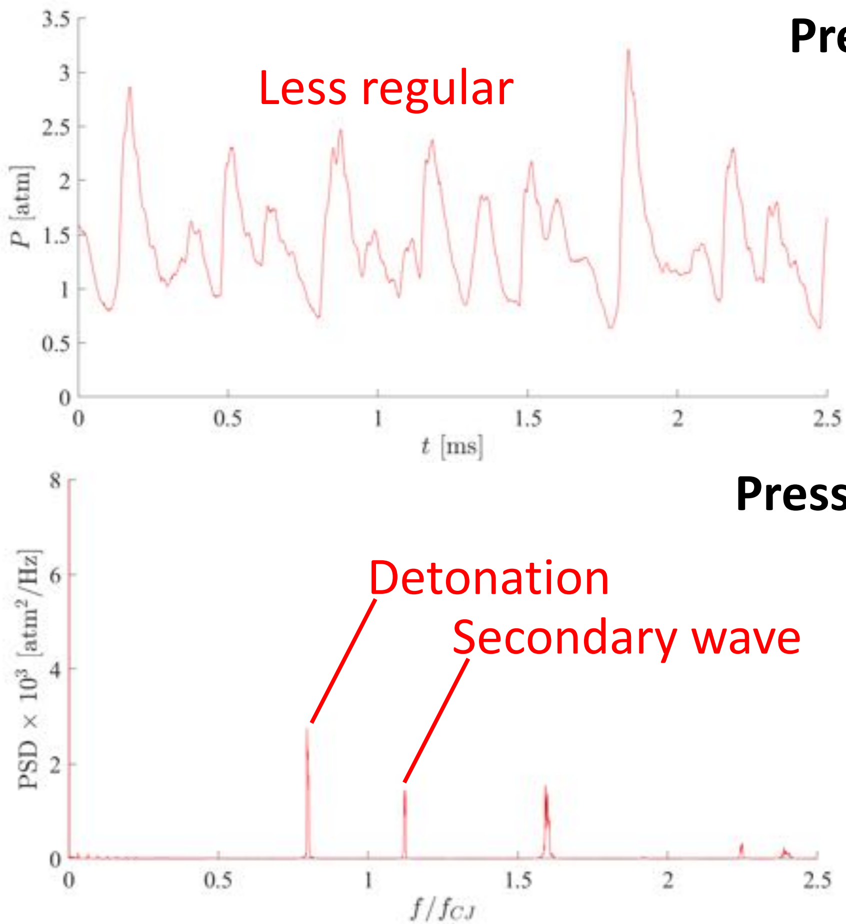
But secondary wave(s) can be controlled (suppressed)

- Identical condition of operation, but:
  - Naturally hops between modes (with and without)
  - Secondary wave is suppressed

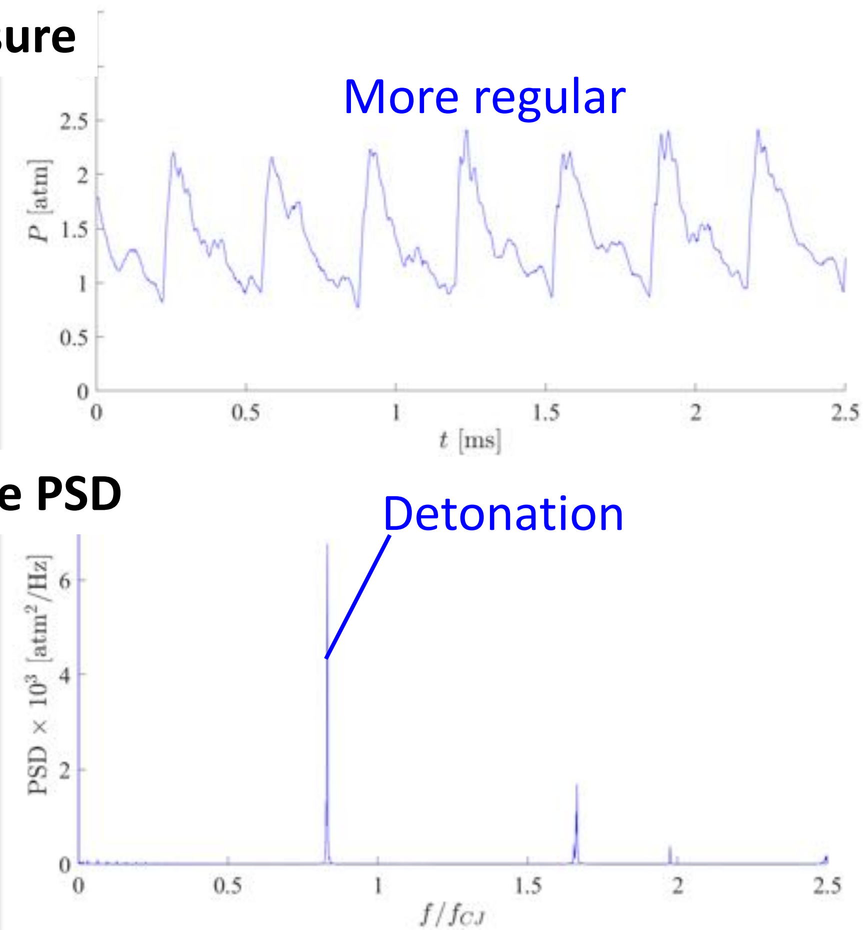
Pressure

Pressure PSD

Strong secondary wave



Weak secondary wave



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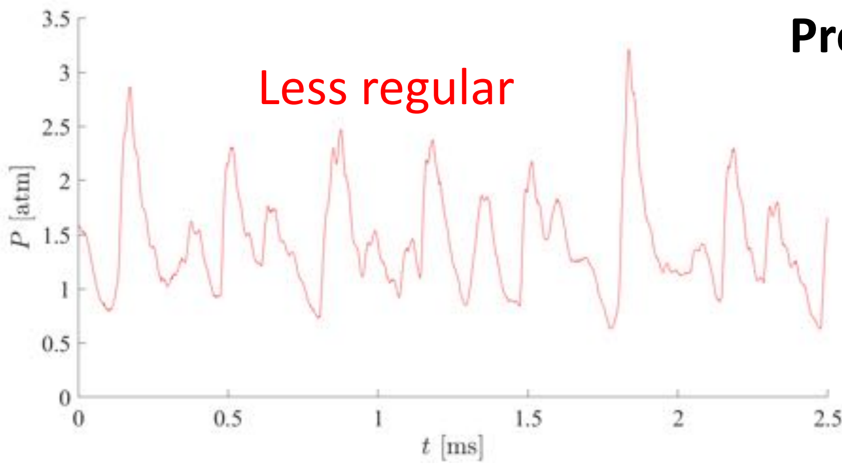
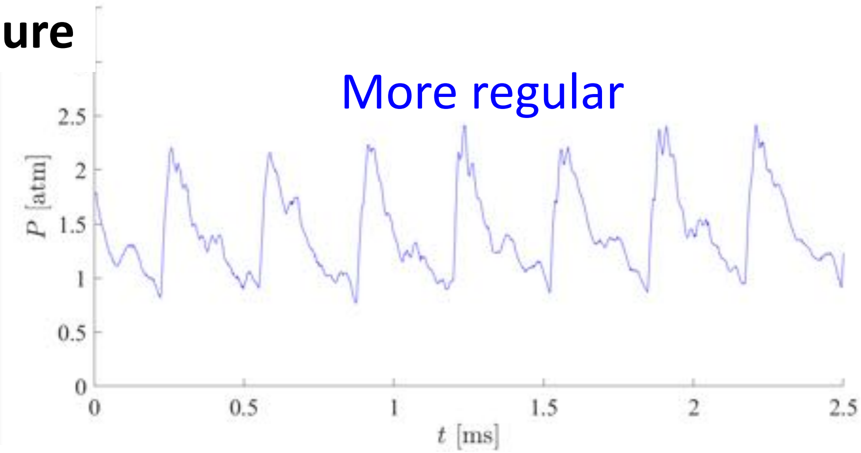
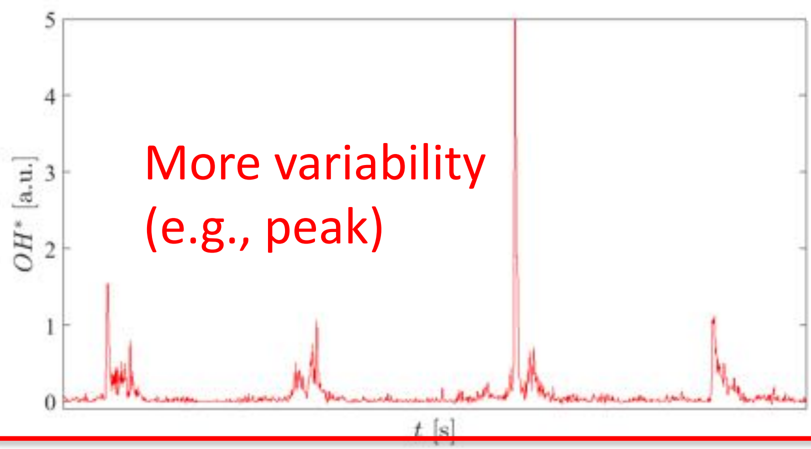
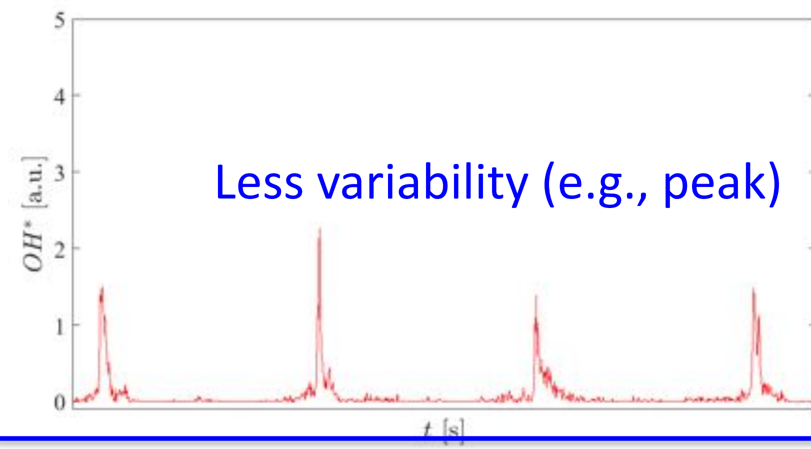




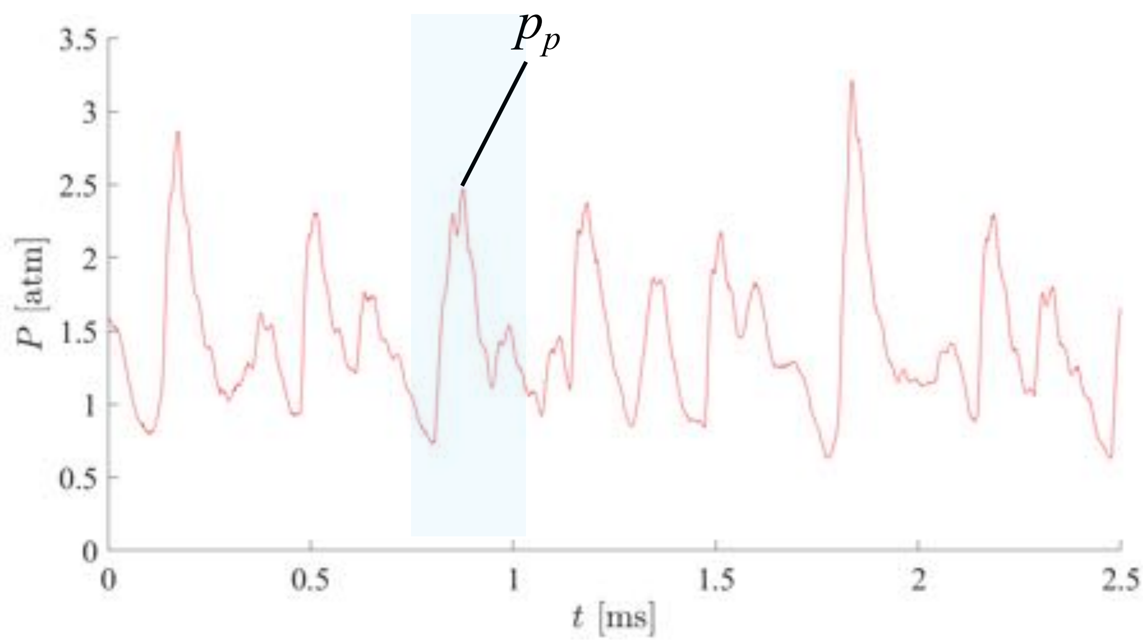
OH*



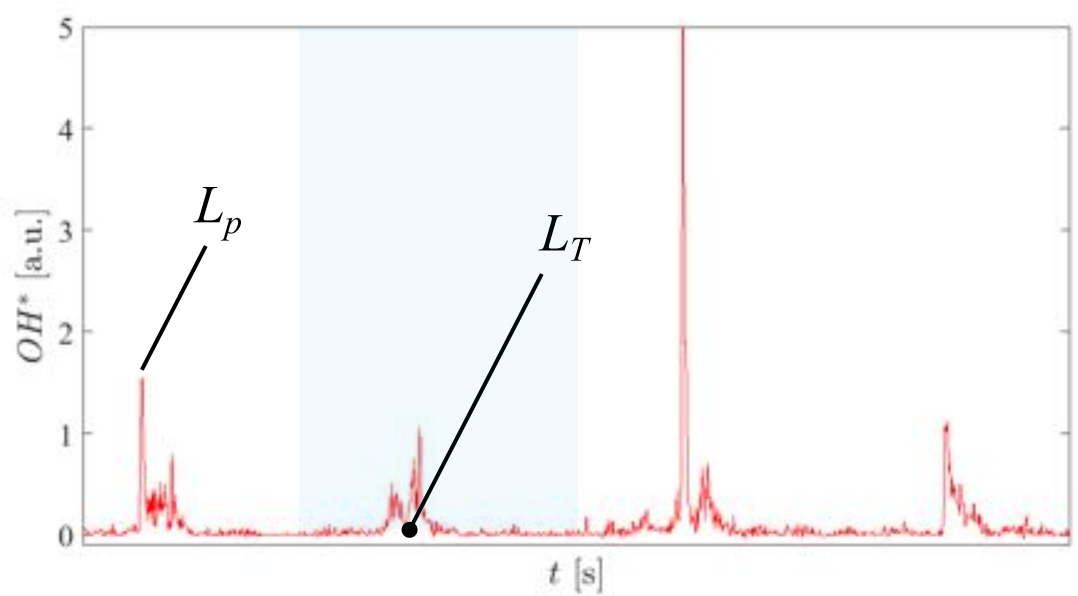


Some definitions

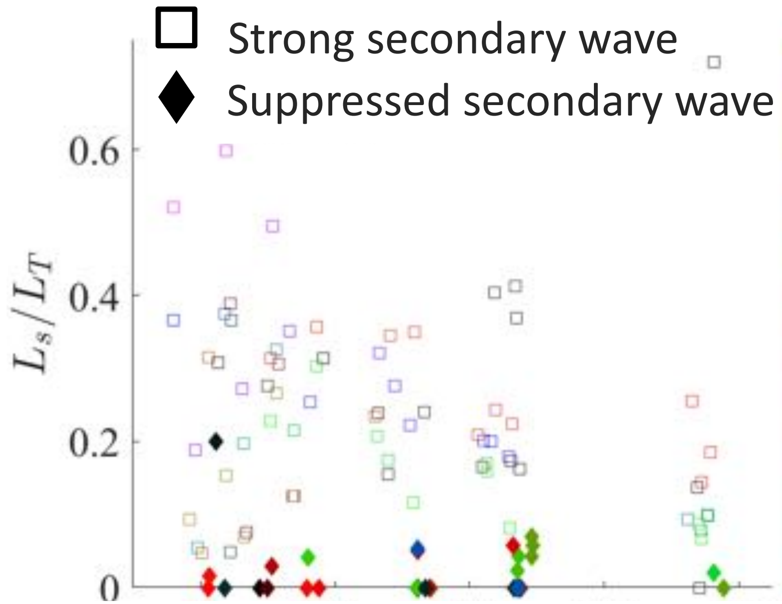
Peak pressure in the cycle

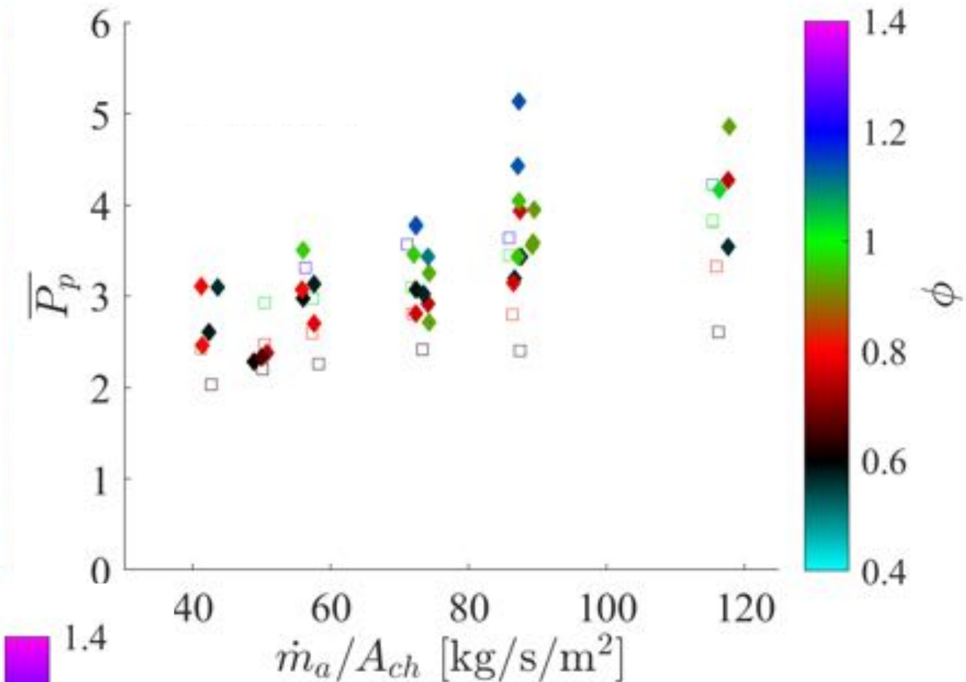


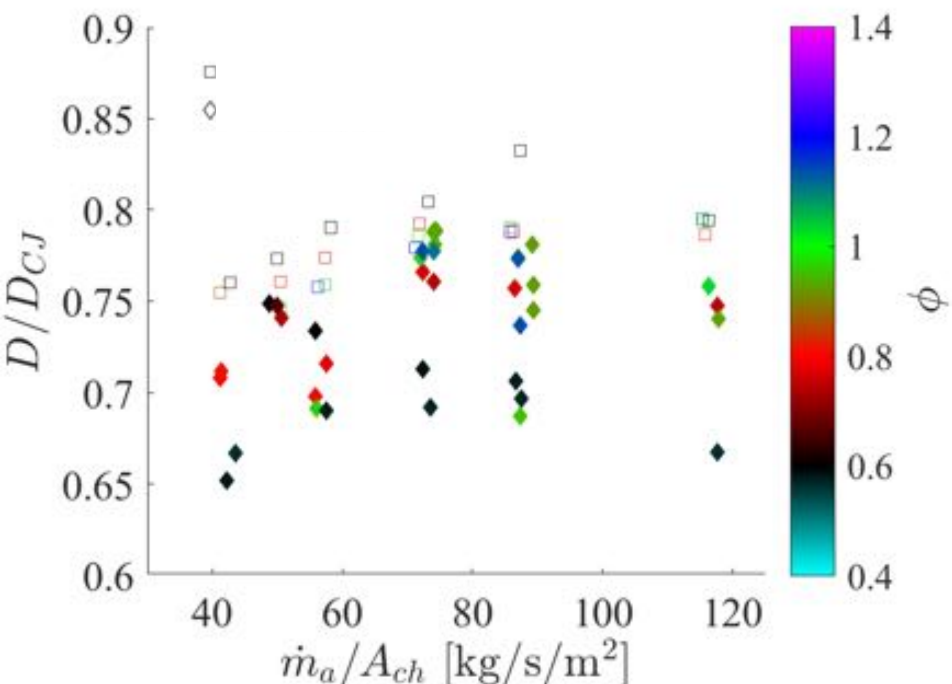
"Brightness" L_p and integrated emission L_T



More properties & impact of secondary wave







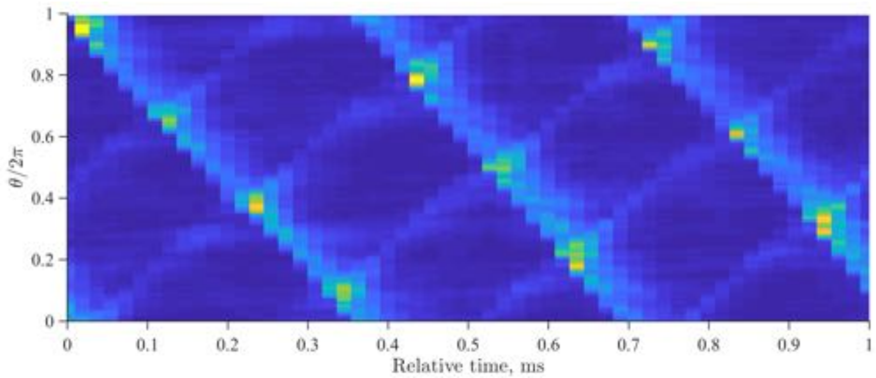
- **Secondary waves can be suppressed**

- **Suppressing the secondary wave:**
  - Slows the detonation wave
  - Raises peak pressure

Conditional phase-average property distribution

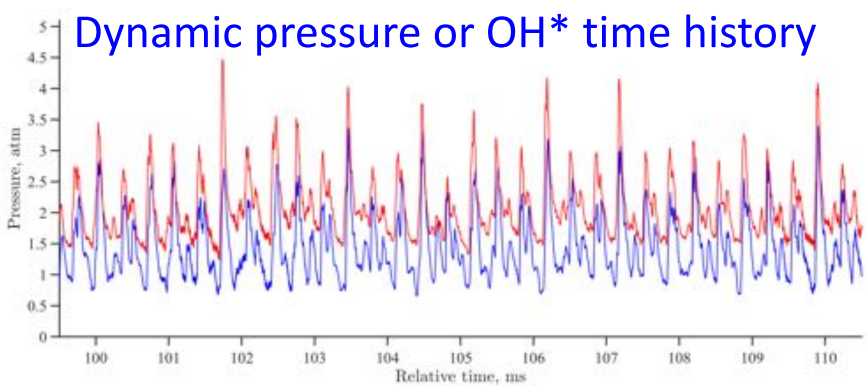
- Combine information of x-t diagrams, with dynamic pressure
  - Generate a measure of the impact between primary and secondary wave coupling (modulation of primary wave)

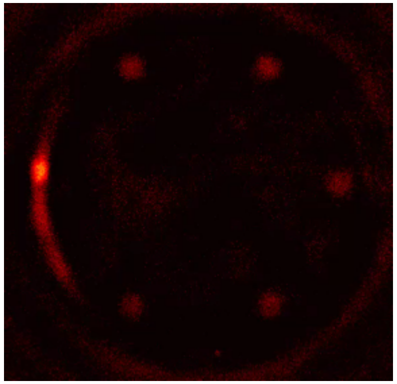
x-t diagram (unfolded aft-movies)

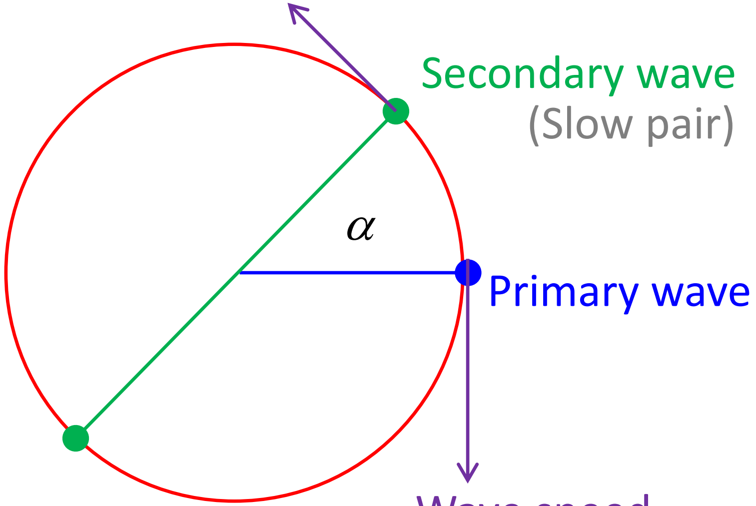


+

Dynamic pressure or OH* time history

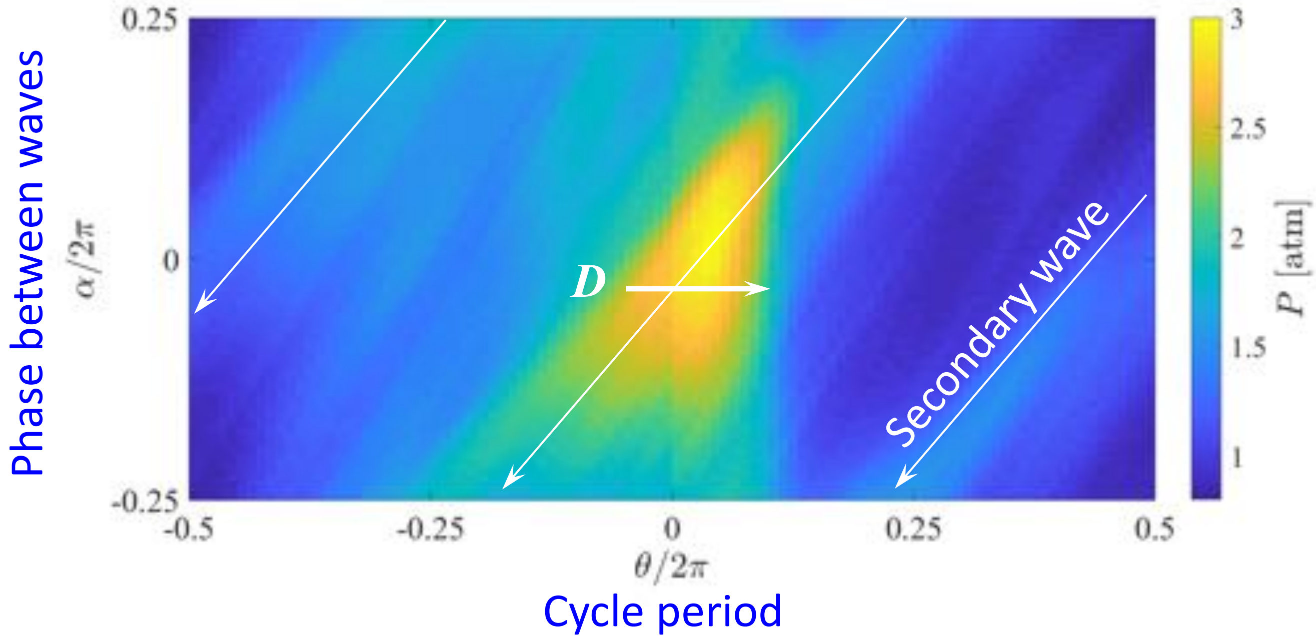


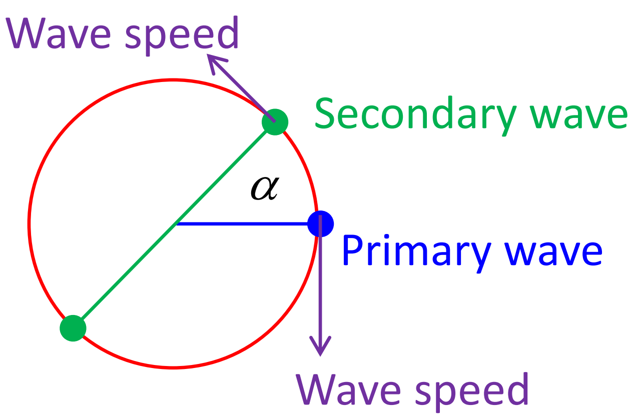




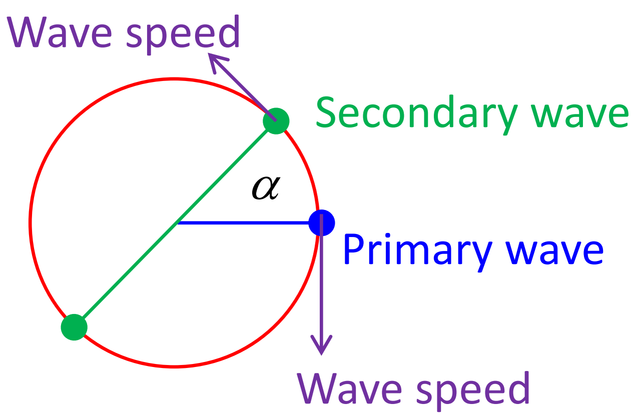
Conditional phase-average distribution: pressure

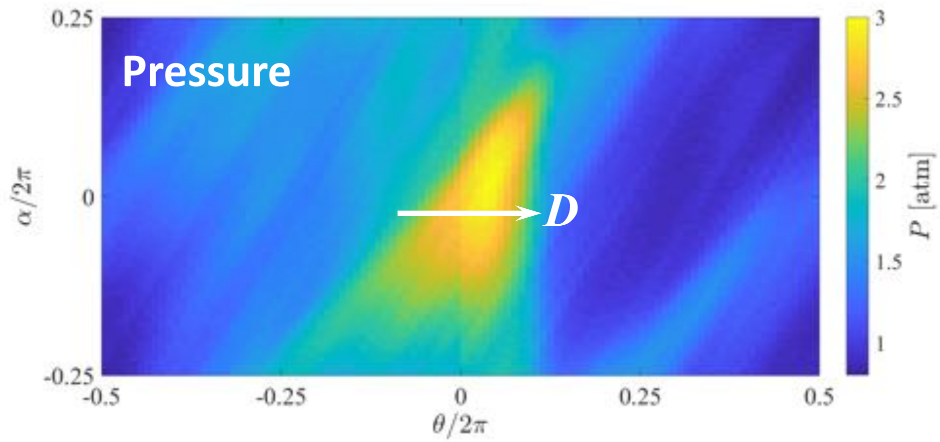
- Measure of variation of cycle pressure profile conditional to the phase of secondary wave
- Measure of the impact between primary and secondary wave coupling (modulation of primary wave)



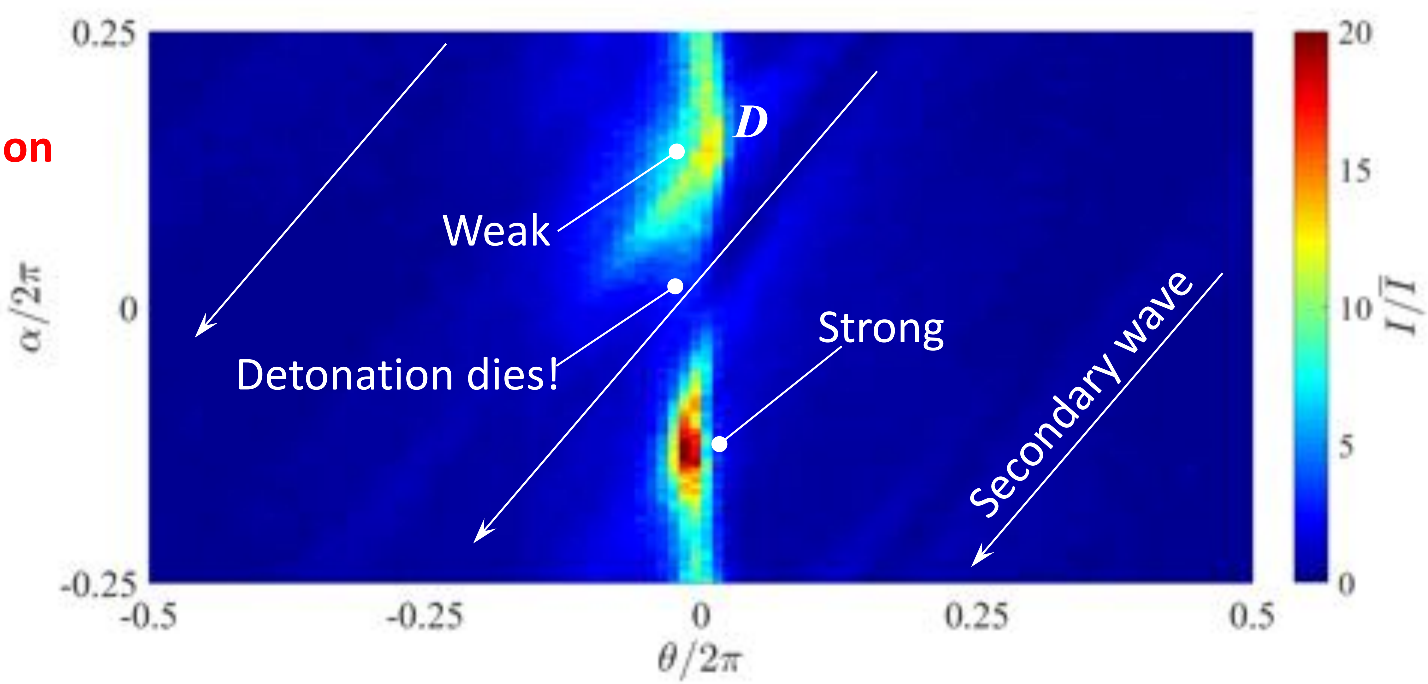


Conditional phase-average distribution: OH* emission

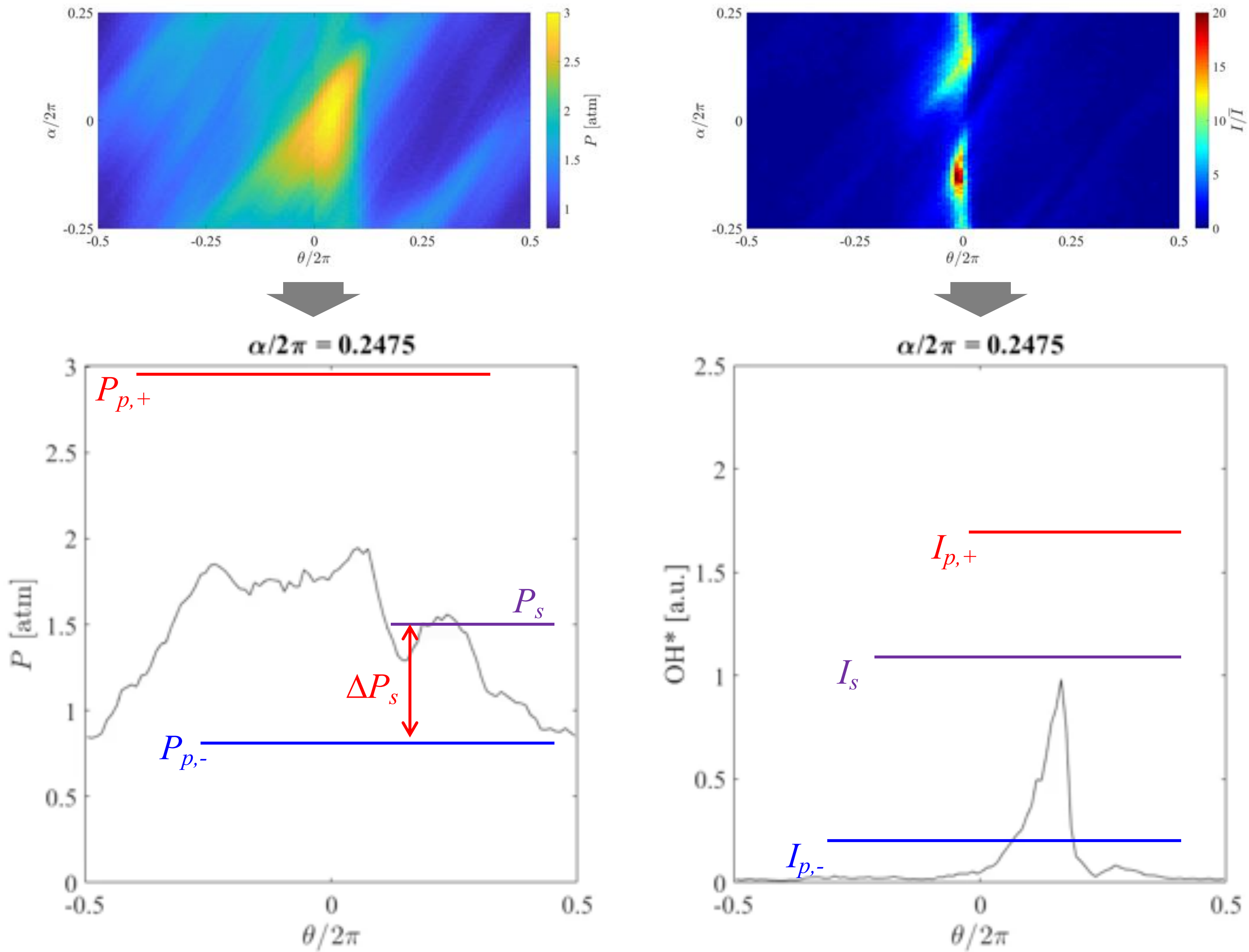




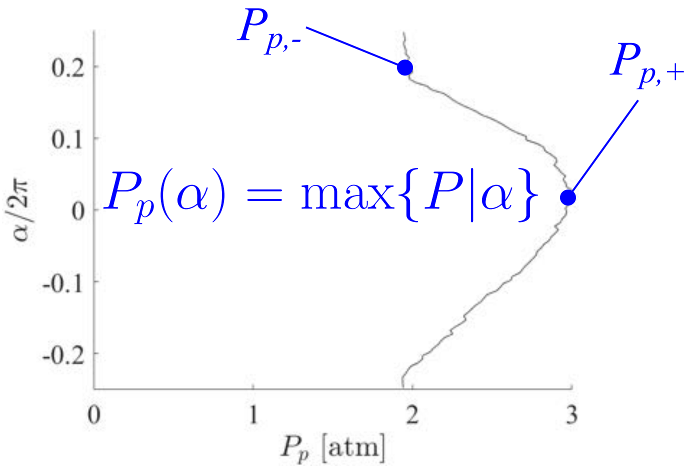
OH* emission

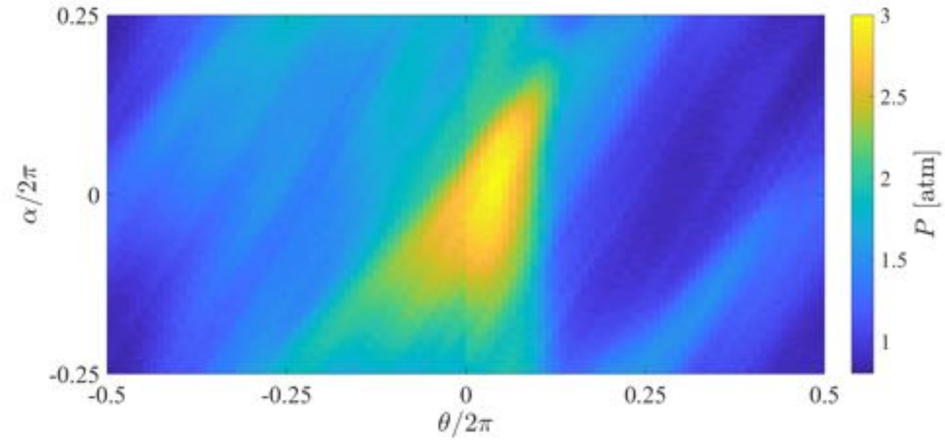


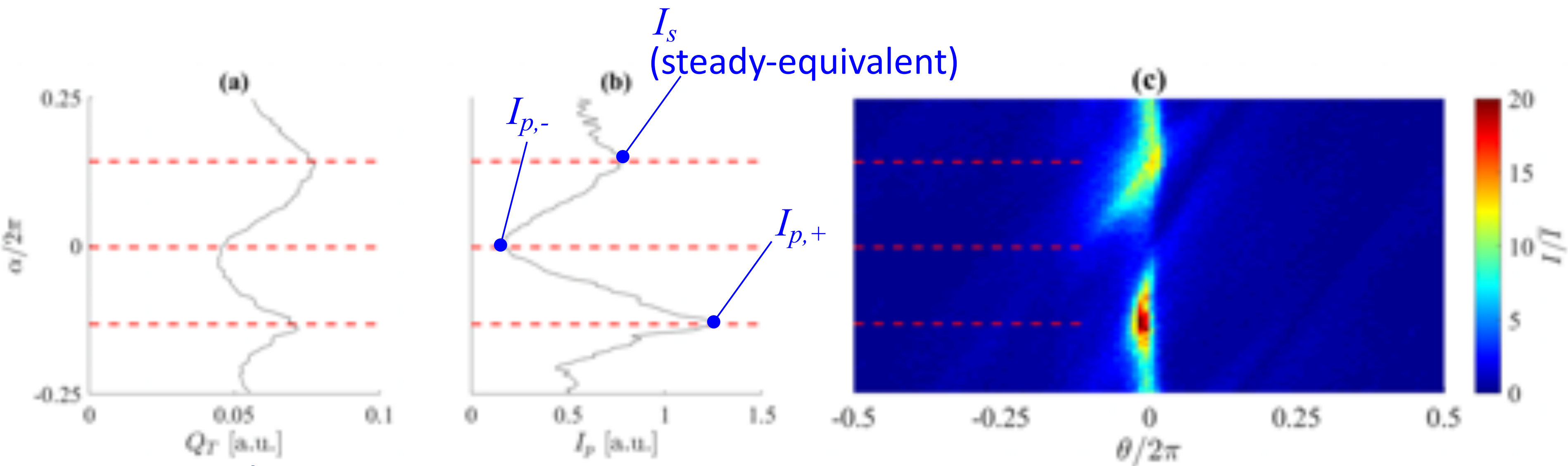
Conditional phase-average distribution: different view



Conditional phase-average distribution: combine info

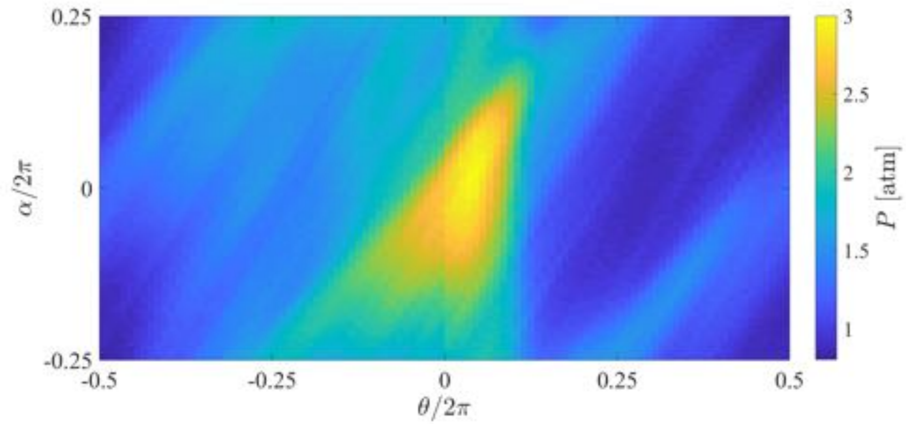


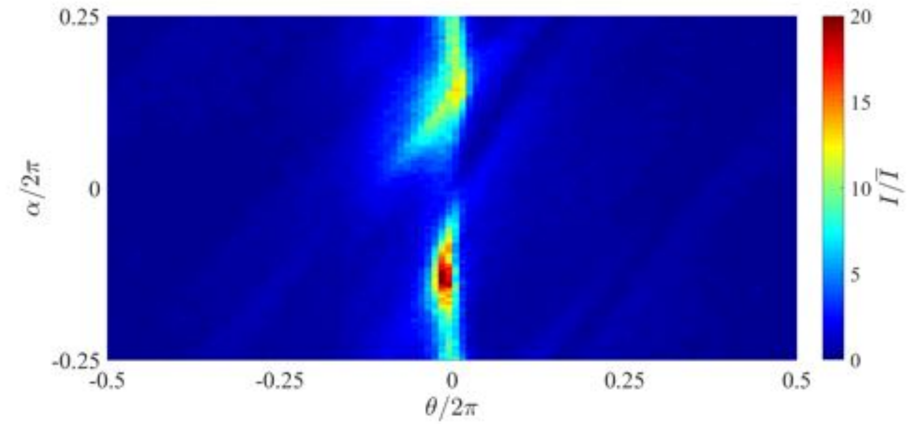


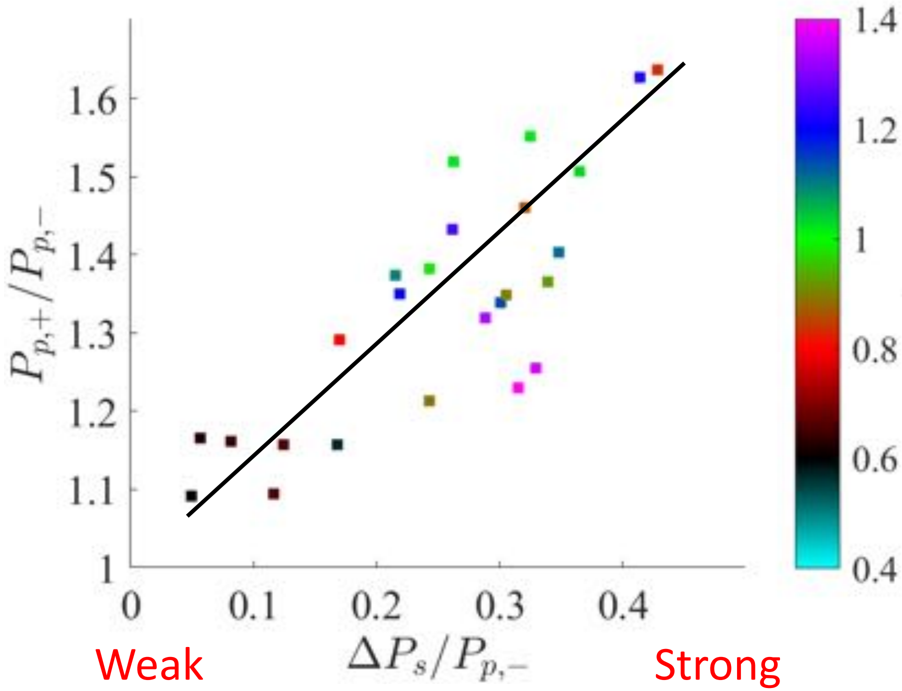


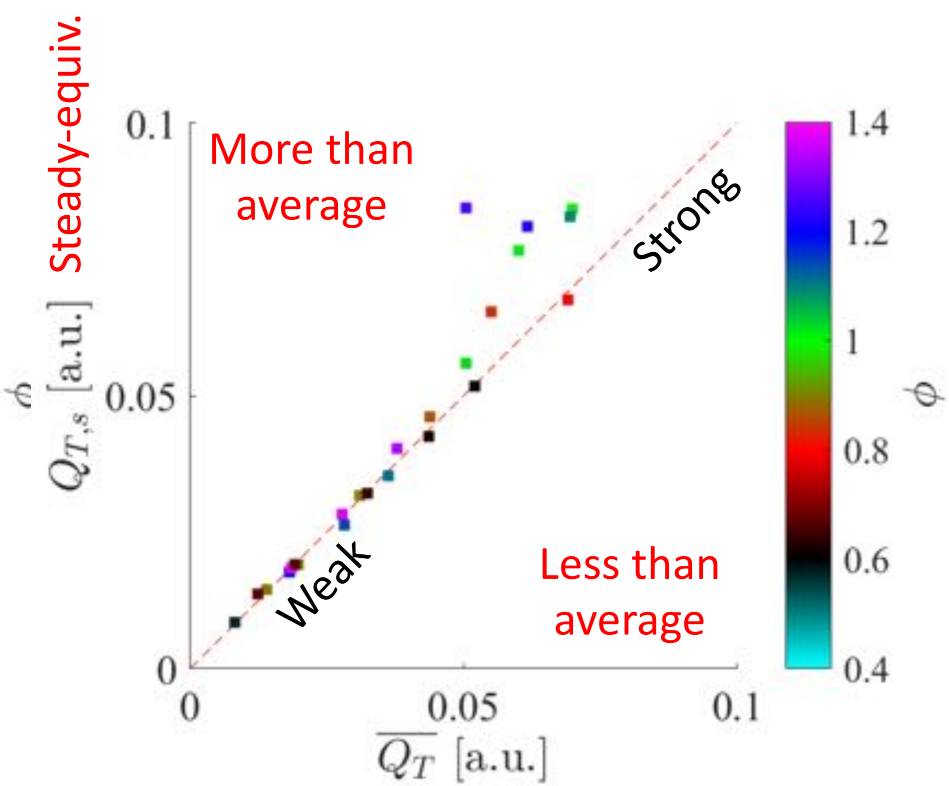
$$Q_T(\alpha) = \int_0^{2\pi} I(\theta, \alpha)\mathrm{d}\theta \qquad I_p(\alpha) = \max\{\mathrm{OH}^*|\alpha\}$$

Secondary wave affects primary detonation wave

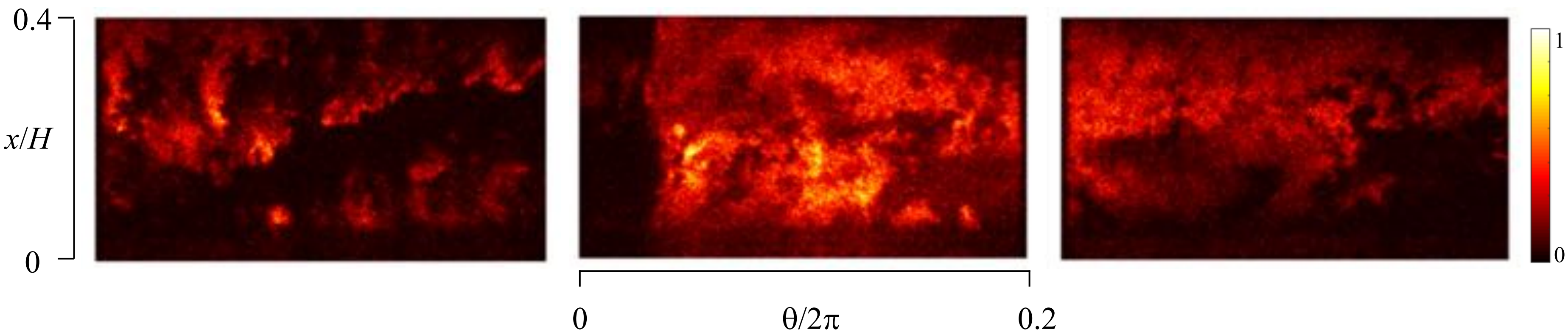


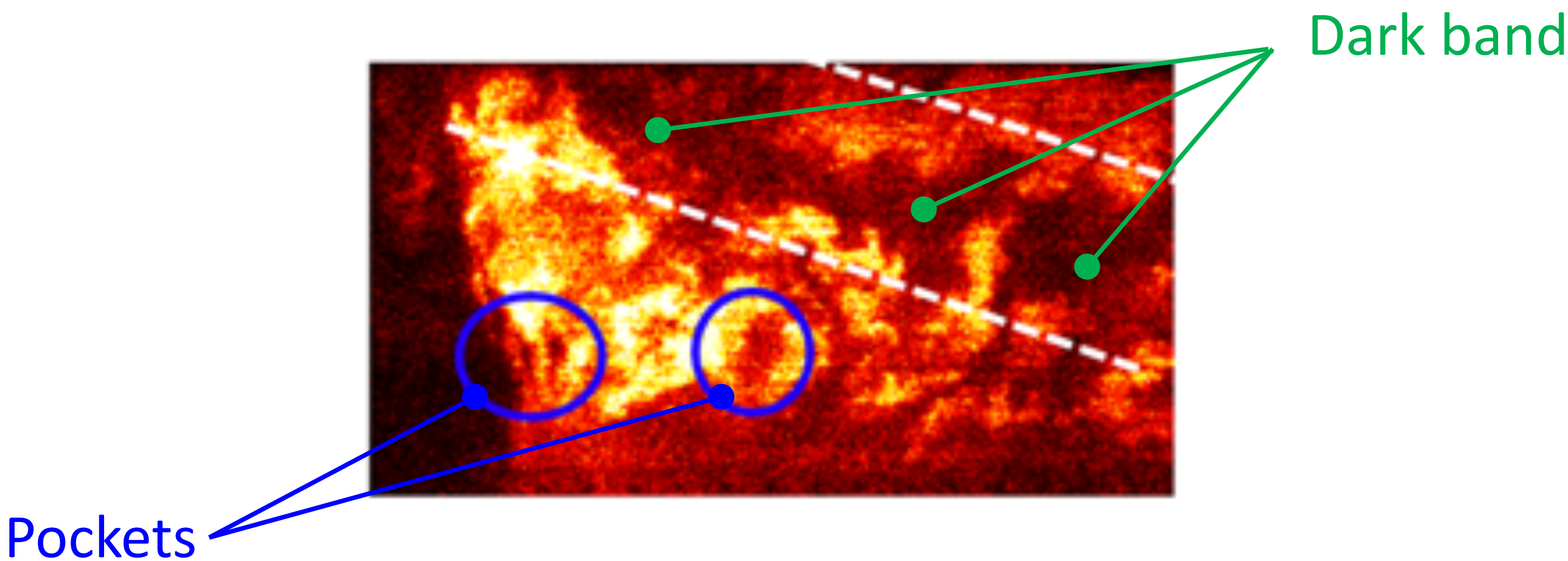






Let's look back at OH distribution (from OH PLIF imaging)





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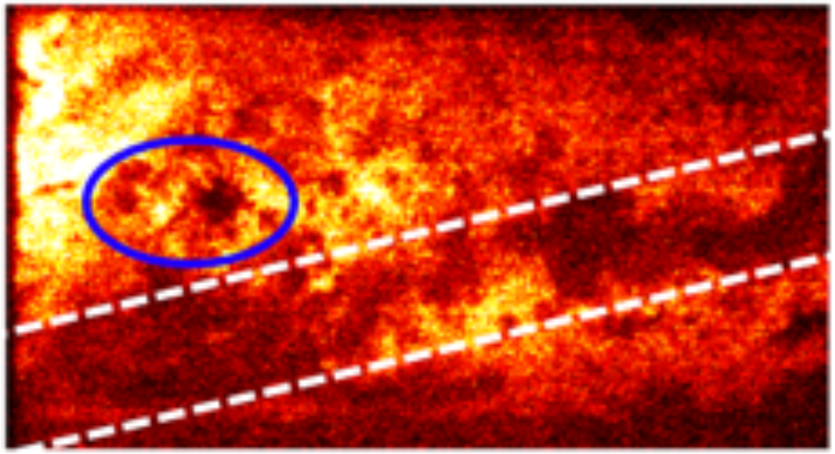

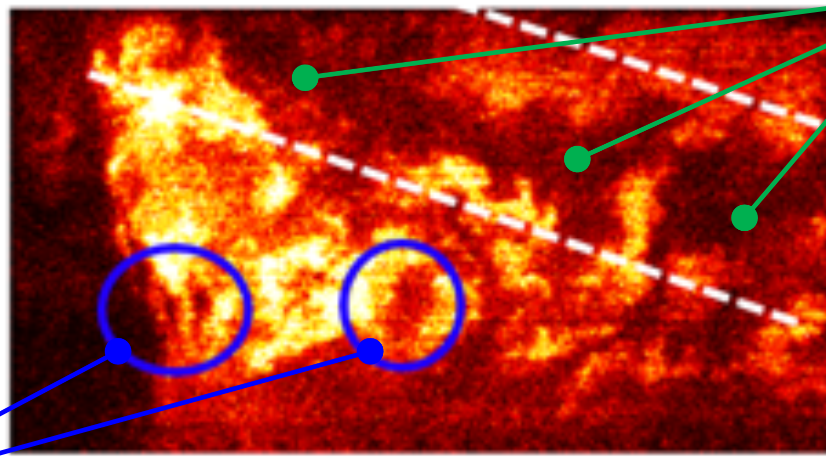

Dark band

- Consistent variation
- Suggests continuous source
- Suggests structured, axial stratification

Pockets

Quenching, poor mixing, non-ideal detonation structure

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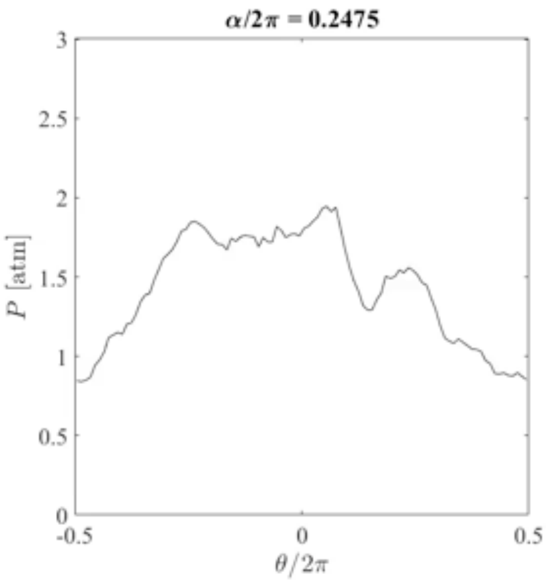
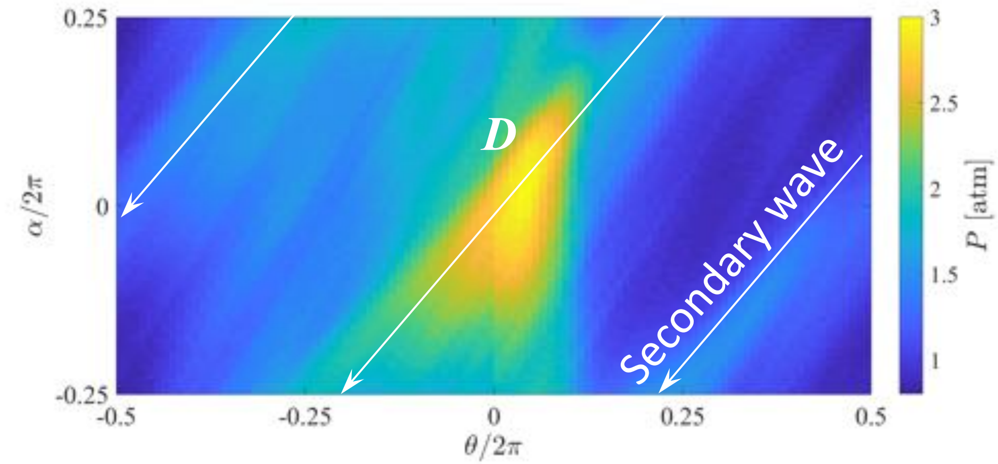
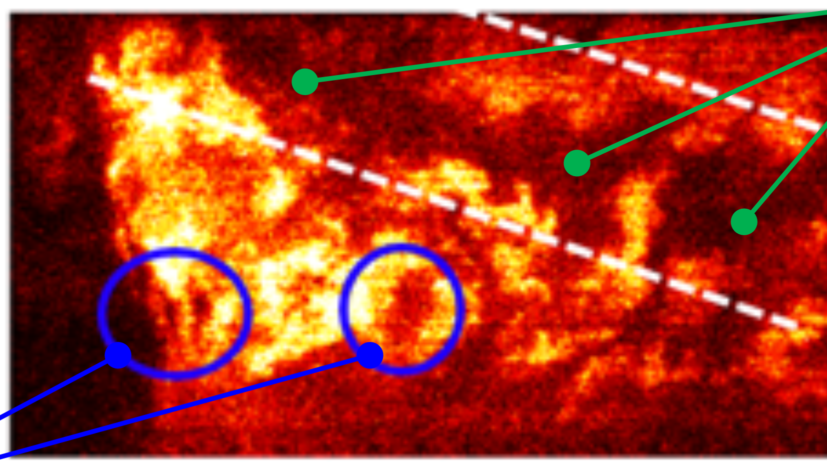






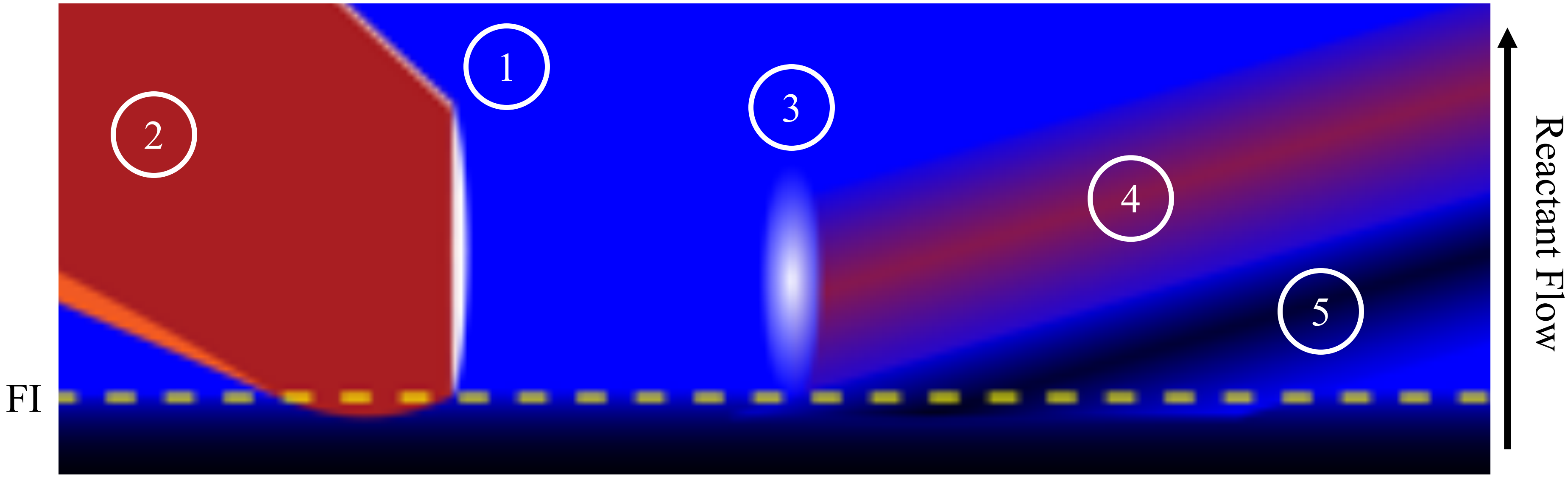
Dark band

- Consistent variation
- Suggests continuous source
- Suggests structured, axial stratification
- Hypothesis: due to interaction of secondary wave with air/fuel injection, which modulates injection rates

Pockets

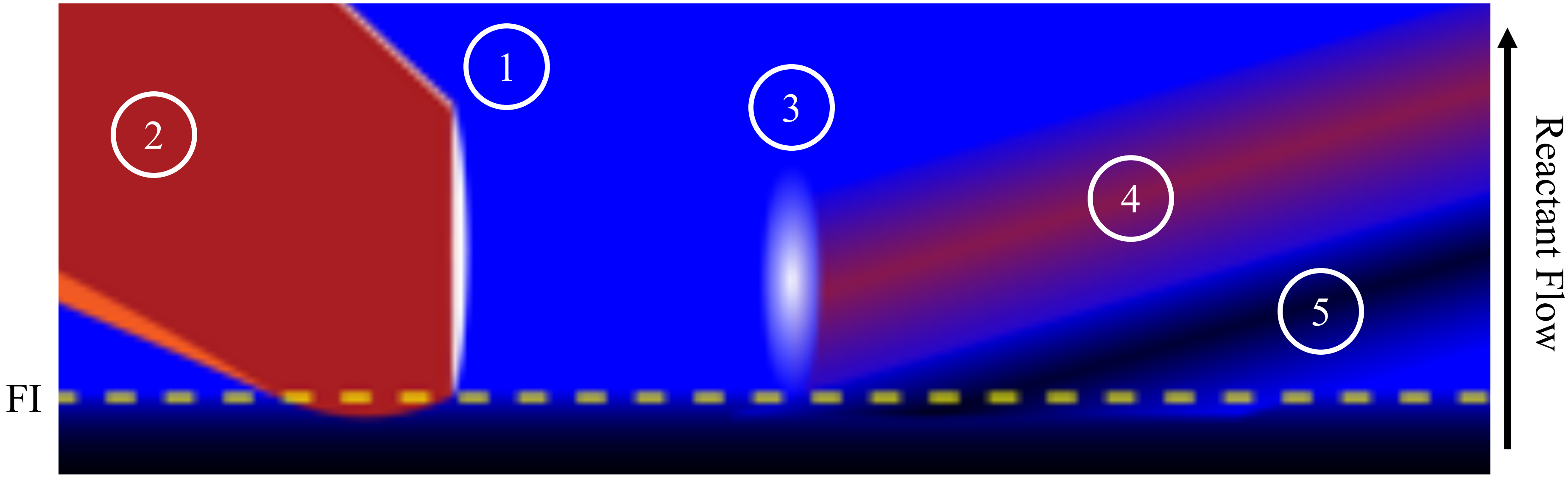
Quenching, poor mixing, non-ideal detonation structure

Large Scale Structure: Secondary Wave Effect; Proposed Mechanism

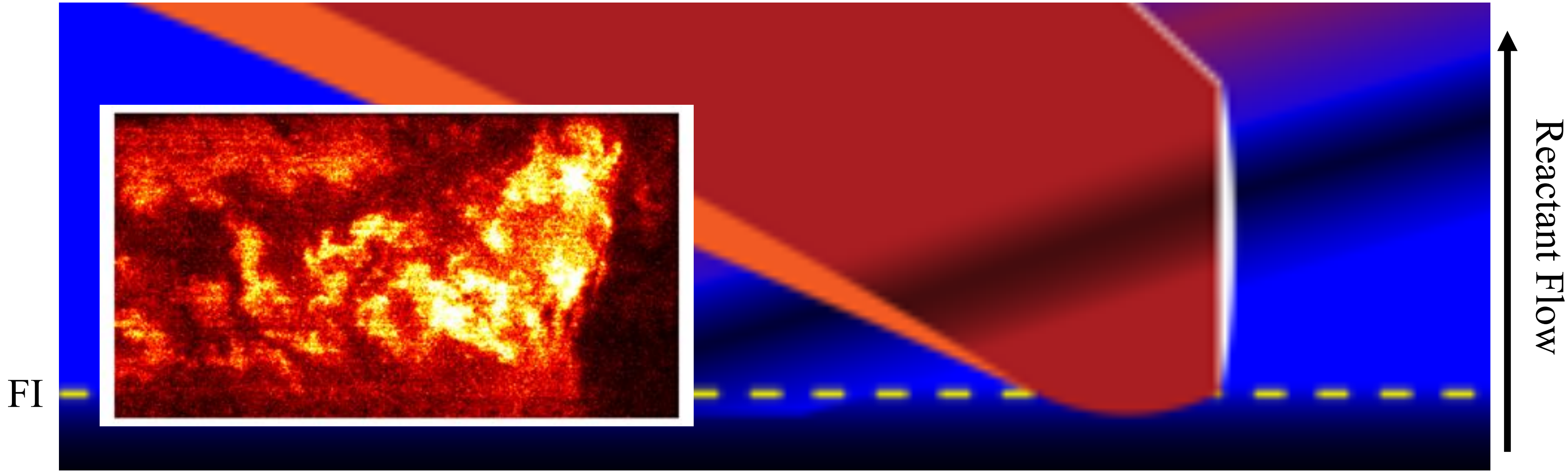


1. Detonation wave(s), steady propagation to right
2. Hot products, expanding and convecting downstream
3. Secondary wave, steady propagation to left
4. Partial reactions associated with secondary wave (Parasitic Combustion)
5. 'Pressure wake' caused by secondary wave propagation
   - As secondary wave propagates, it influences injection causing an axial/azimuthal stratification

Large Scale Structure: Secondary Wave Effect; Proposed Mechanism



After collision and passing through one another…



Lessons learnt

- **Presence and properties of secondary waves can be quantified**
- **Identified a complex system of waves**
  - Three wave system
  - Affects the stability of the RDE, but in a predictive manner
    - Mechanisms are not fully understood
- **Secondary waves couples with & increases secondary combustion**
  - Secondary-wave-induced deflagration quenches detonation
  - Direct effect
- **Secondary wave introduces additional injector dynamics**
  - Spatially and temporally varying stratification is created
  - Indirect effect
- **Secondary wave can be somewhat manipulated (suppressed)**

Outline

- Introduction to the problem and general approach
- Experimental activities
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Mixing and Detonation in Axial Injection Systems

Venkat Raman
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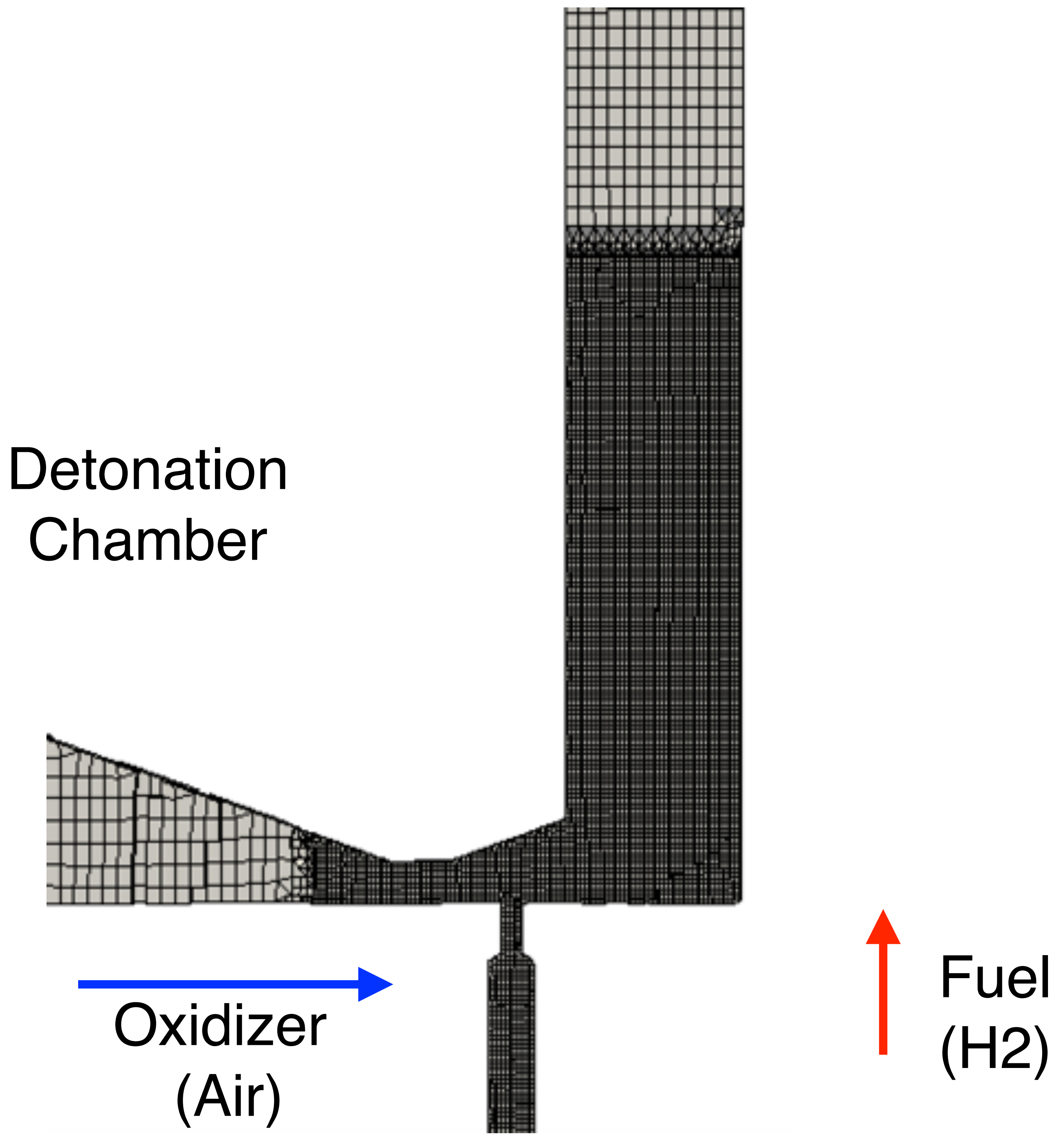
APCL

CFD Focus

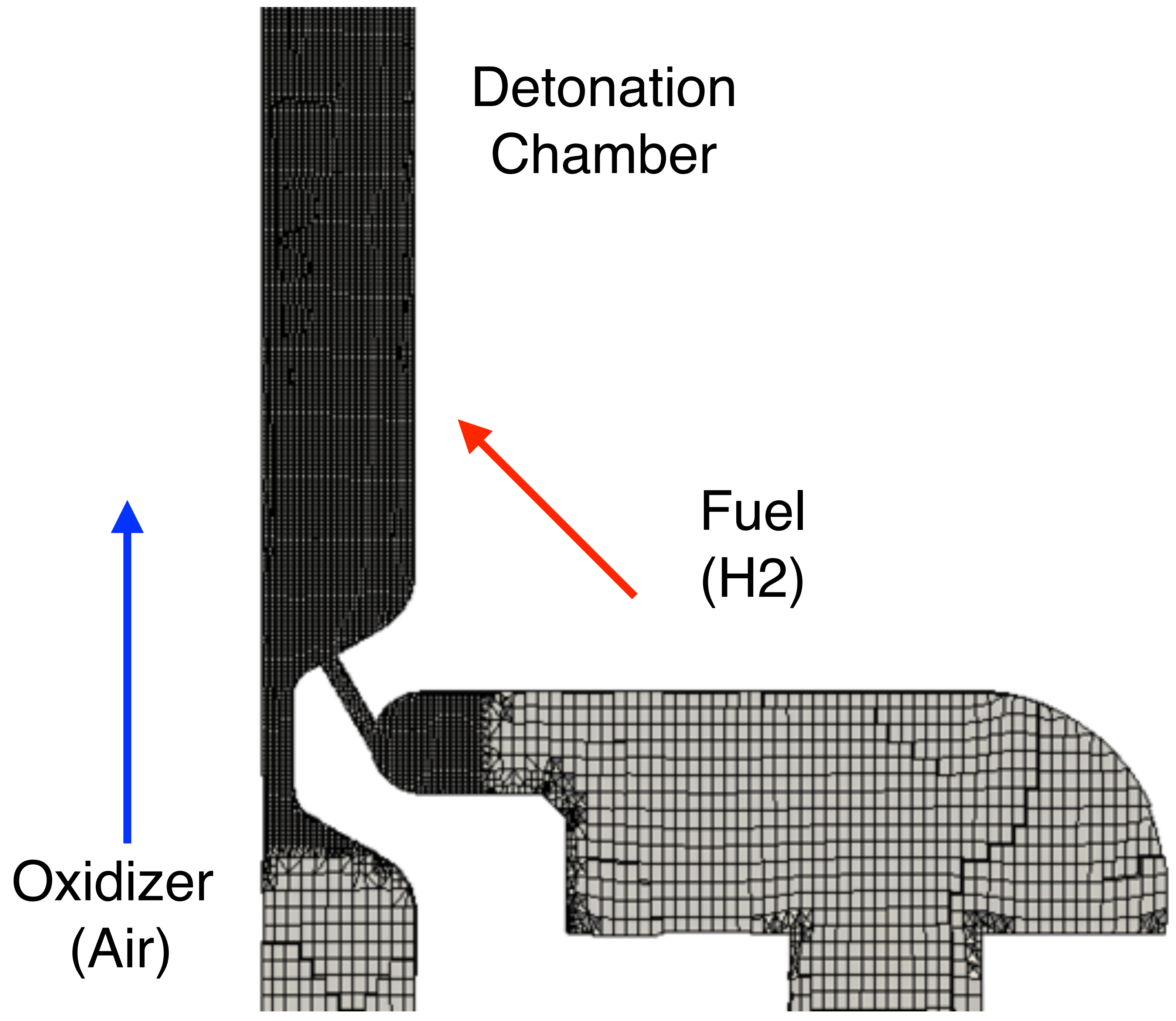
- **Full system RDE simulations**
- **Axial injection systems**
  - ➡ How is mixing different in axial systems
  - ➡ Comparison with experiments
  - ➡ What are the sources of efficiency loss

3D full-system simulation

Air Force Research Lab (AFRL)



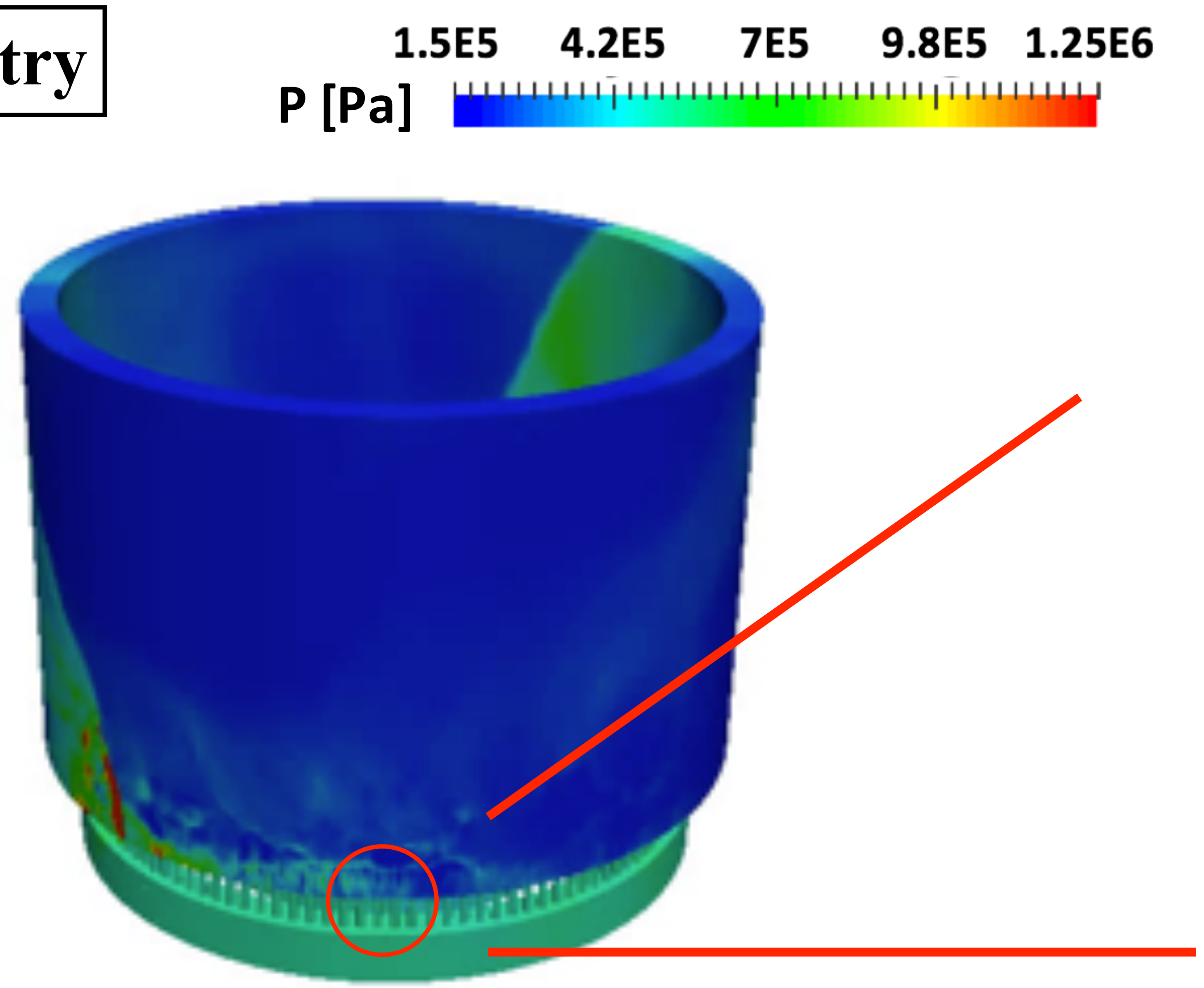
UM Geometry (Pintle)



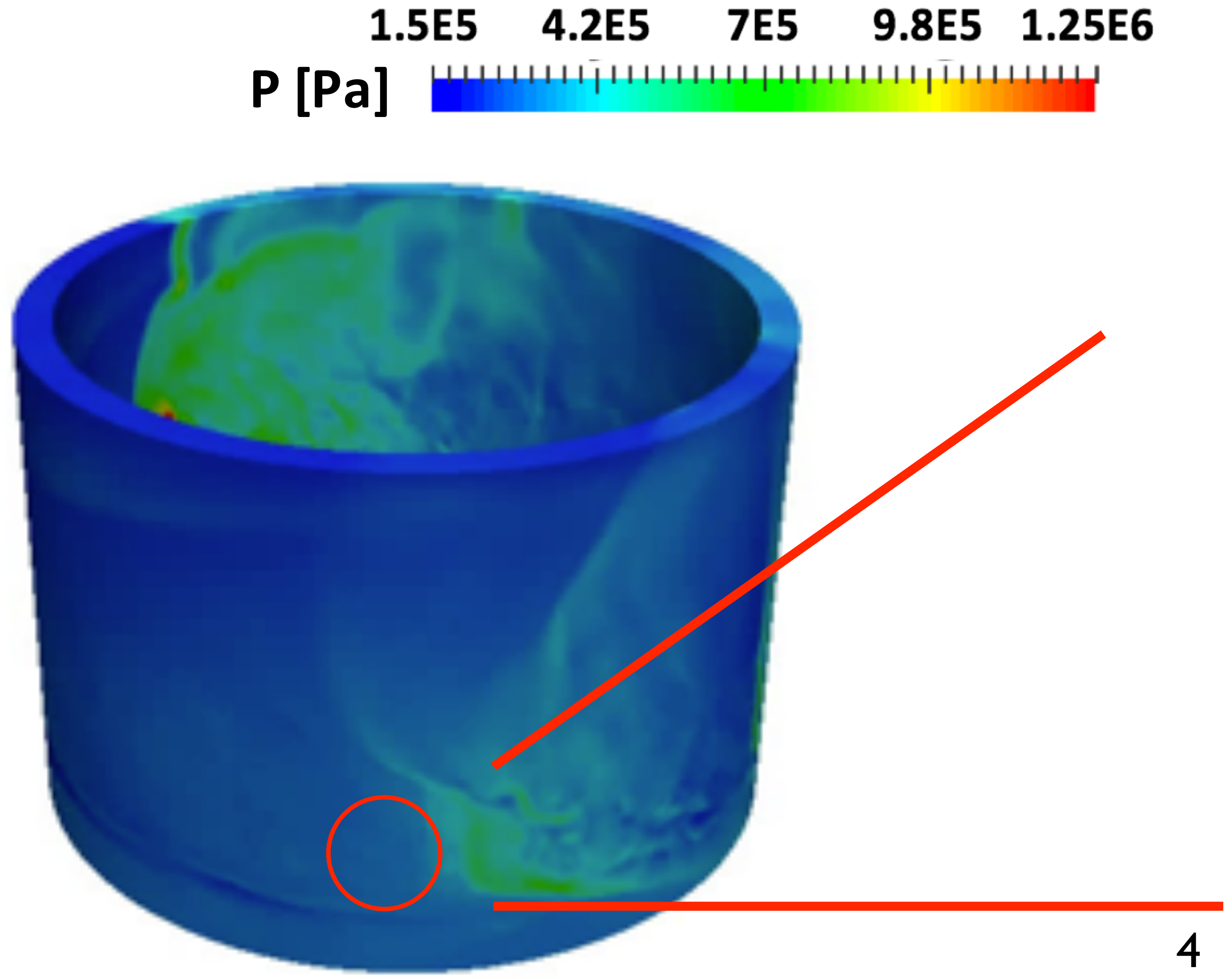
General Behavior

Full Geometry

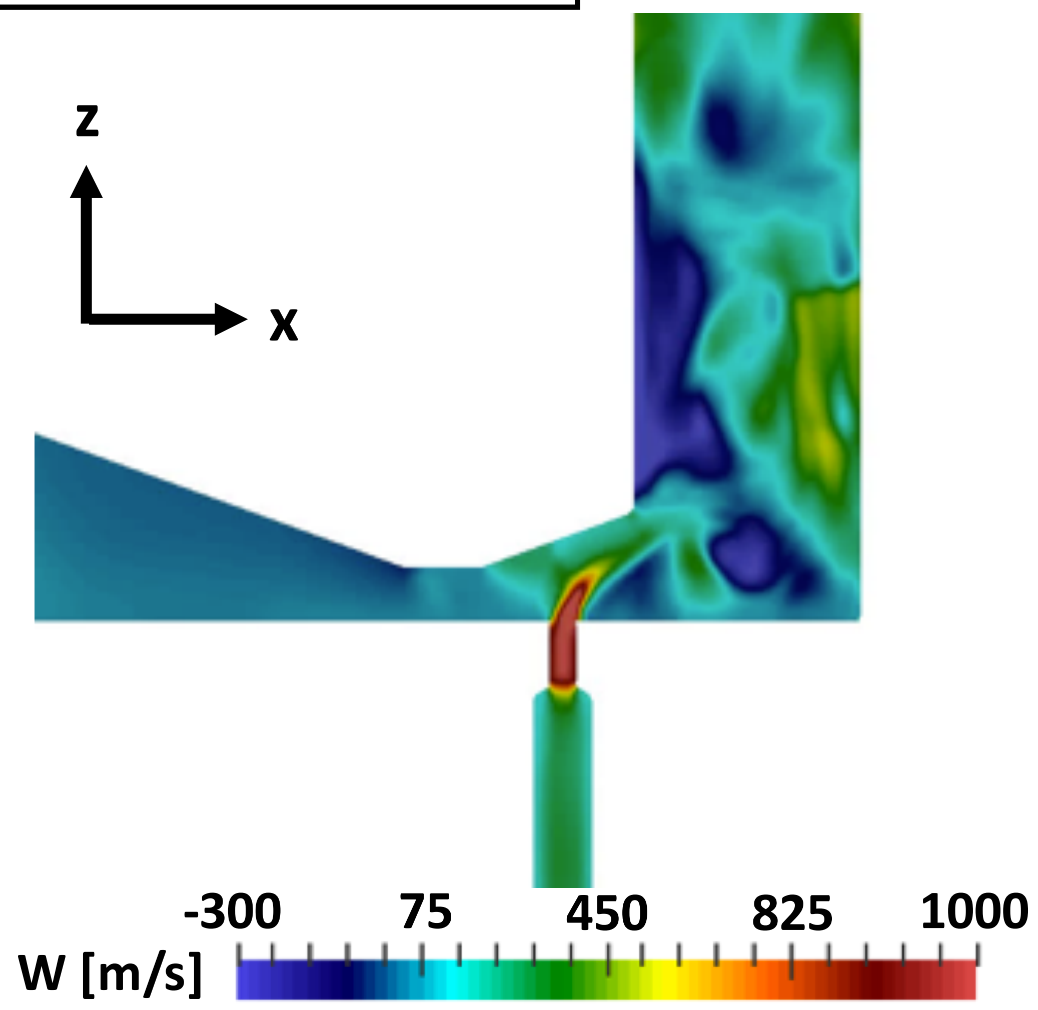
AFRL

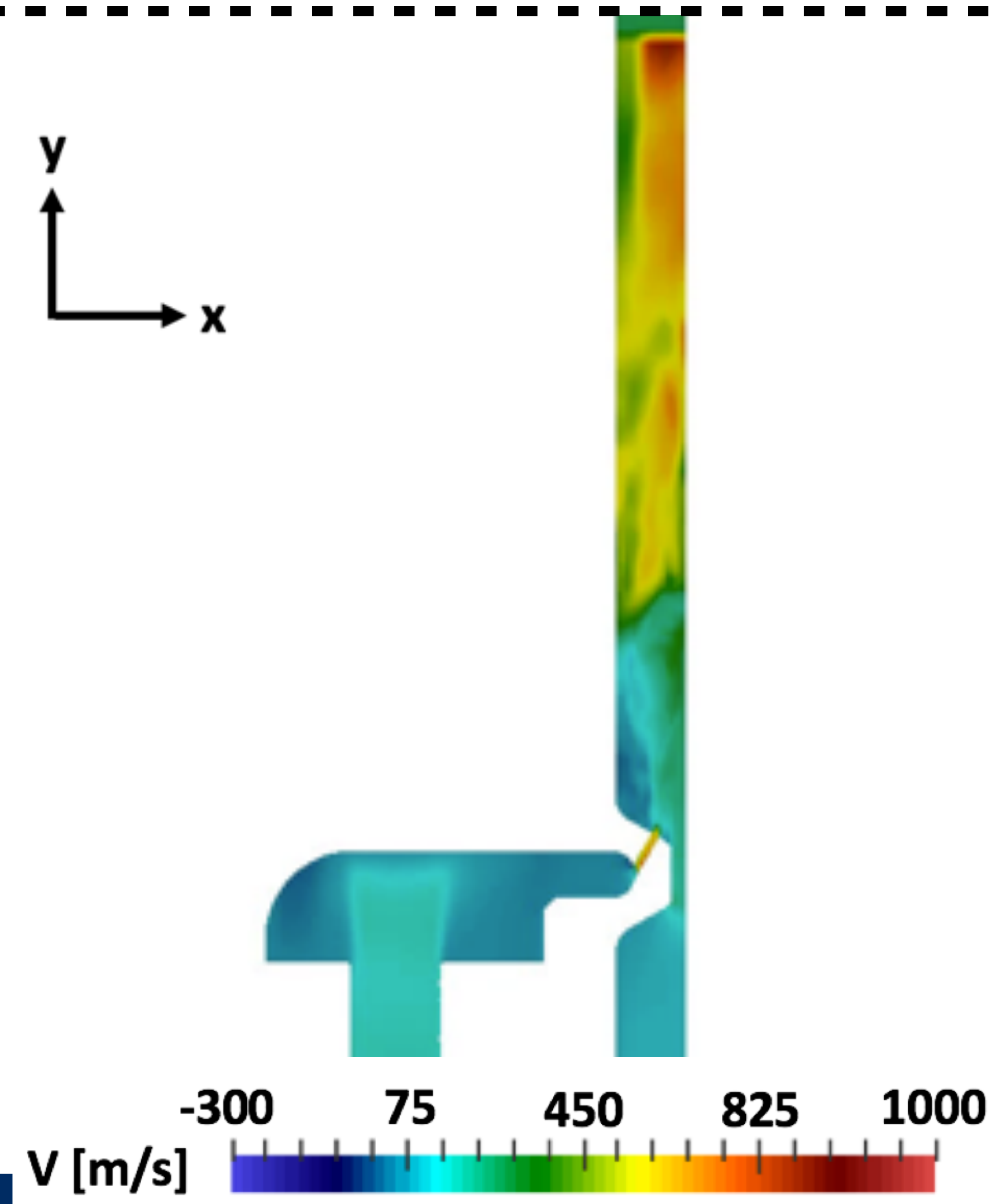


UM



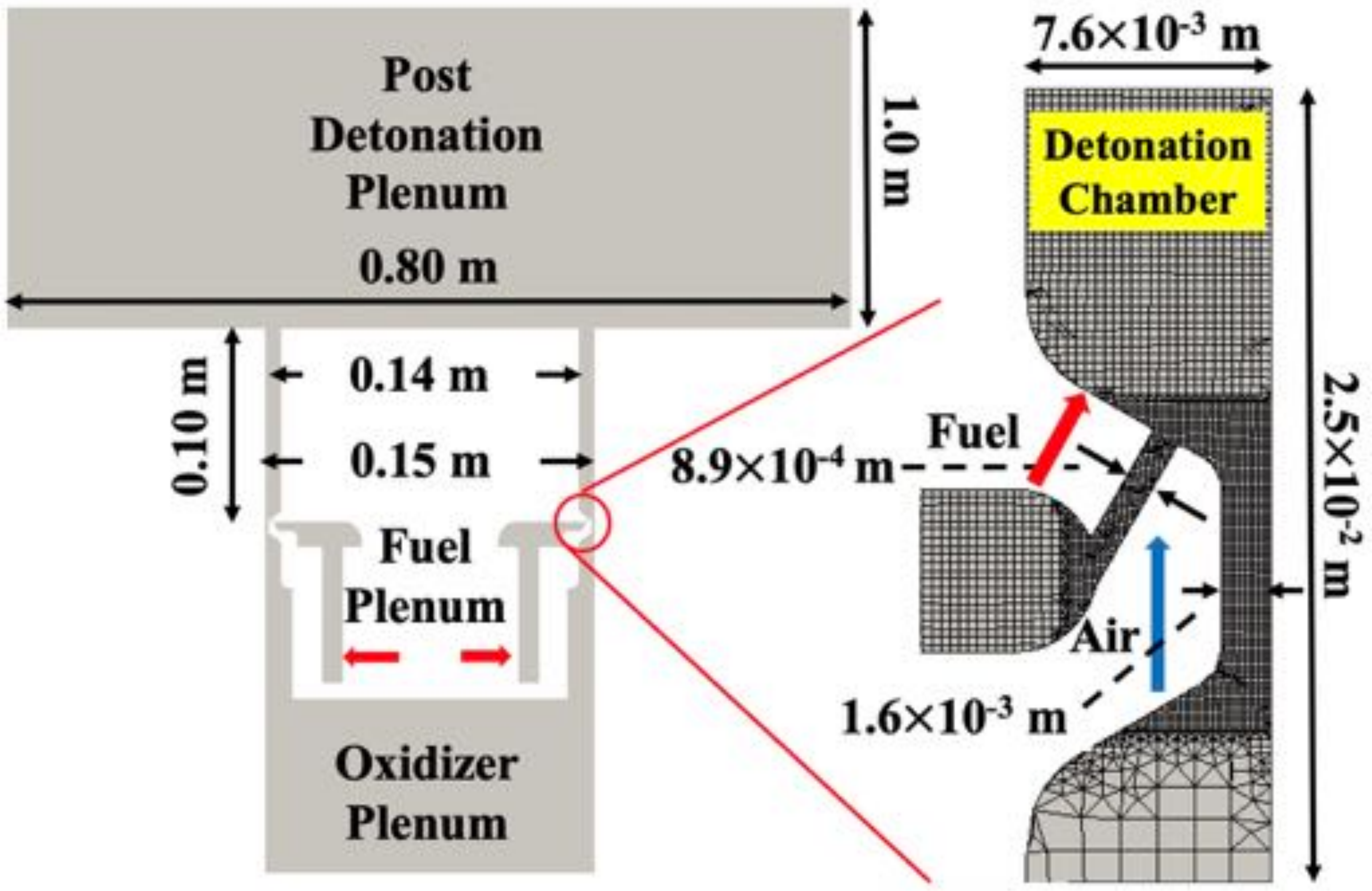
Injection System



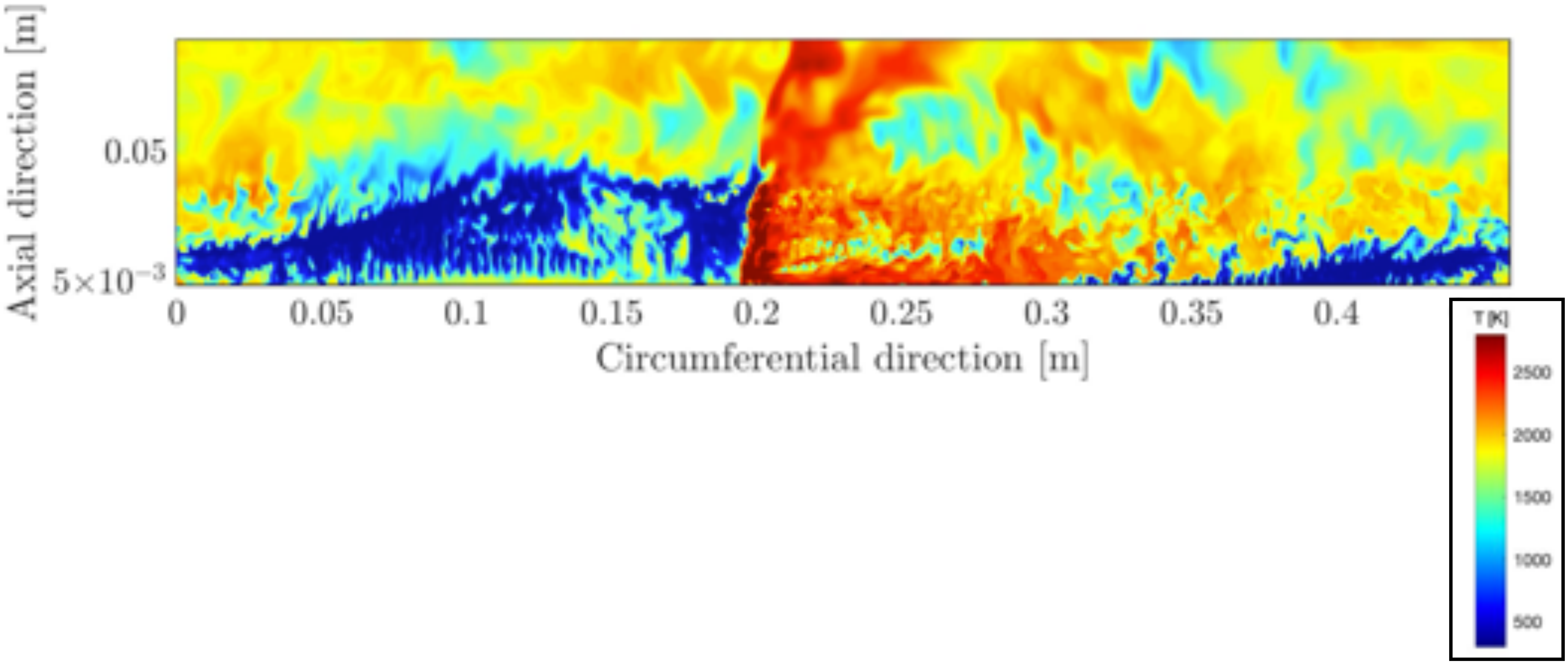


Simulation Details

- **Detailed chemical kinetics**
  - ➡ 9 species, 19 steps
- **Detonation front resolved using 10 grid points**
  - ➡ Note that waves are thickened due to mixing losses
- **Roughly 30 million CVs**
  - ➡ 4000 cores
  - ➡ 3-5 days to complete full scale statistics
  - ➡ ~15-20 cycles

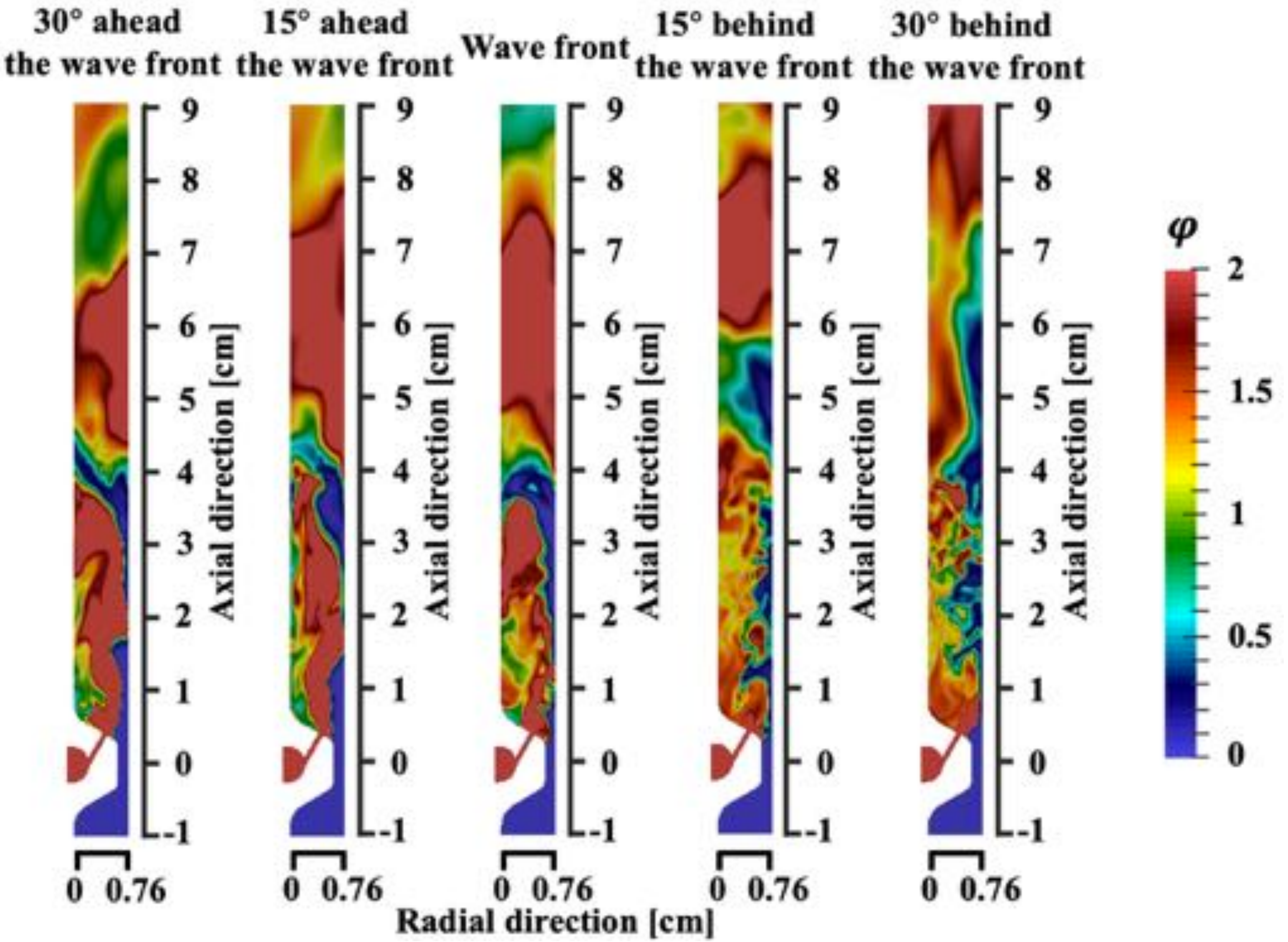


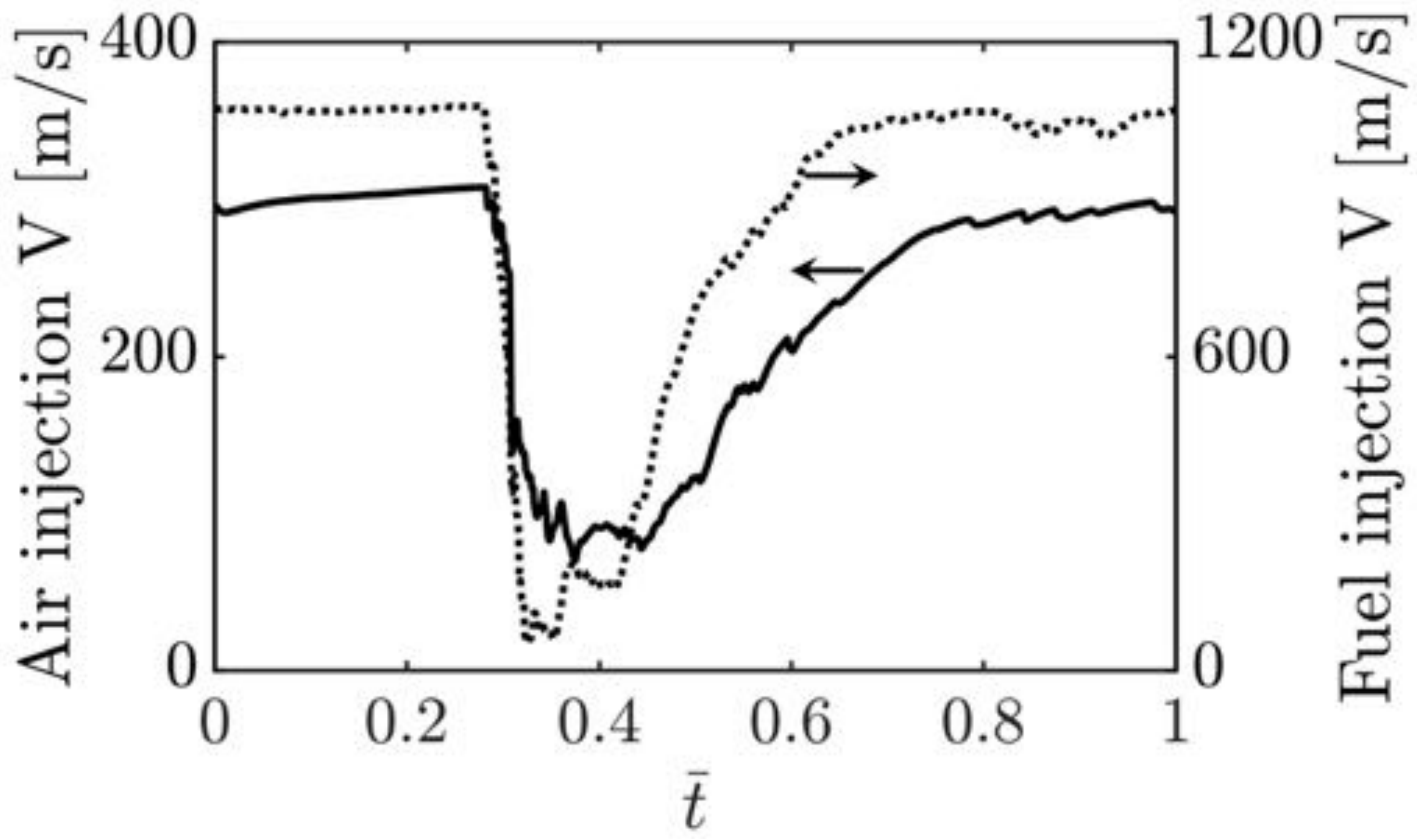
3D Unwrapped Axial Injector System



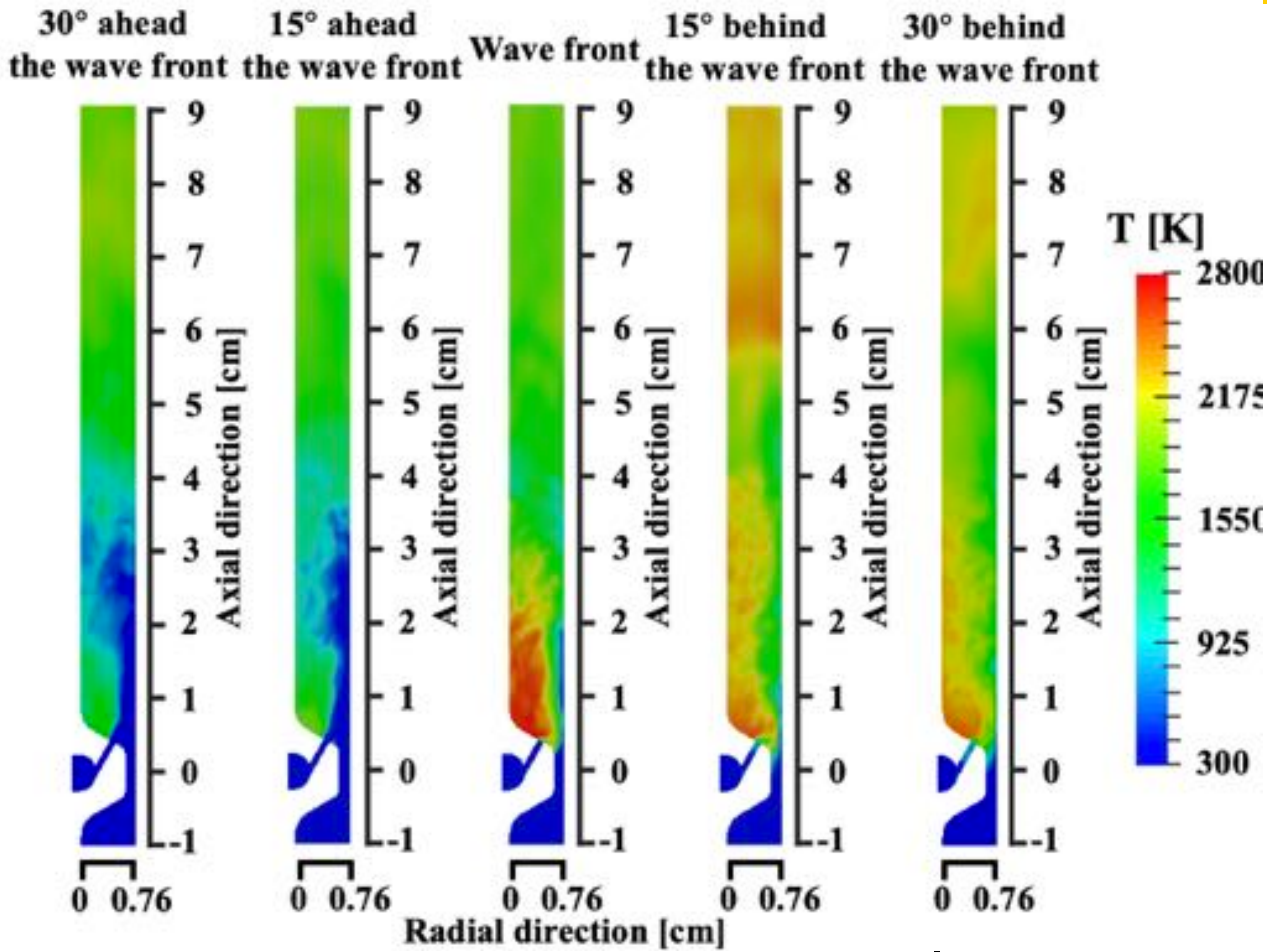
Comparison with OH-PLIF Data

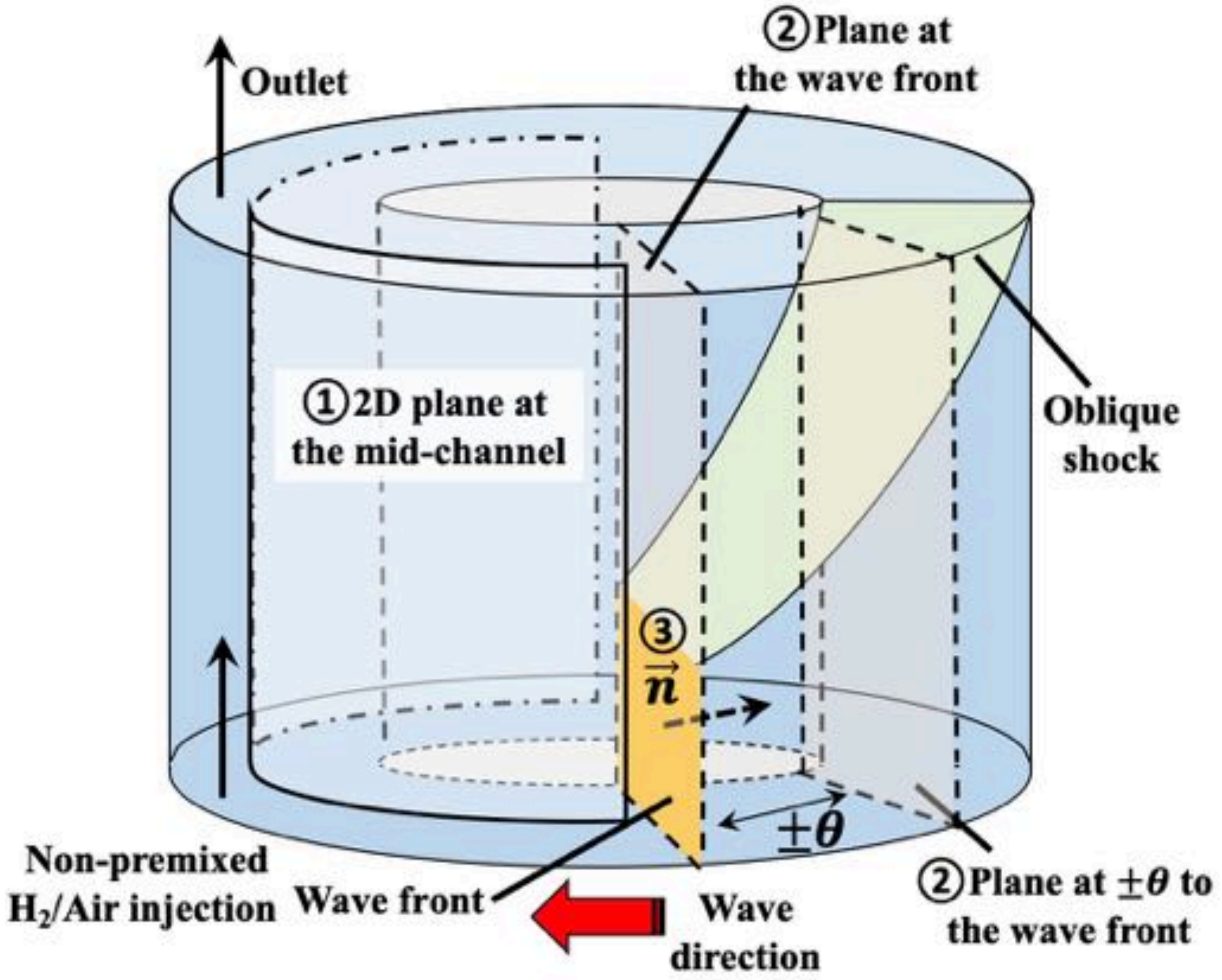
Injector Recovery





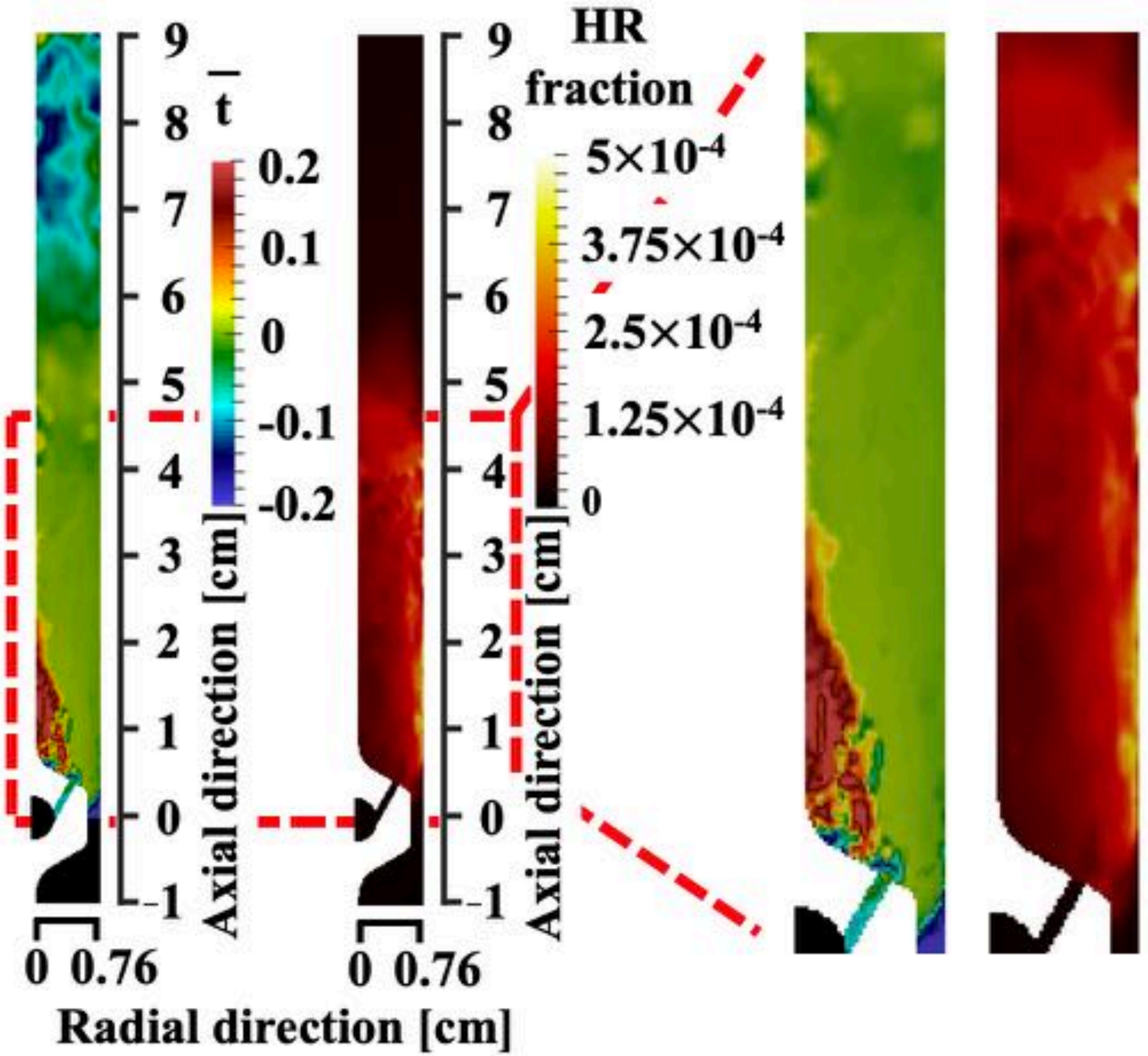
Wave-conditioned Temperature





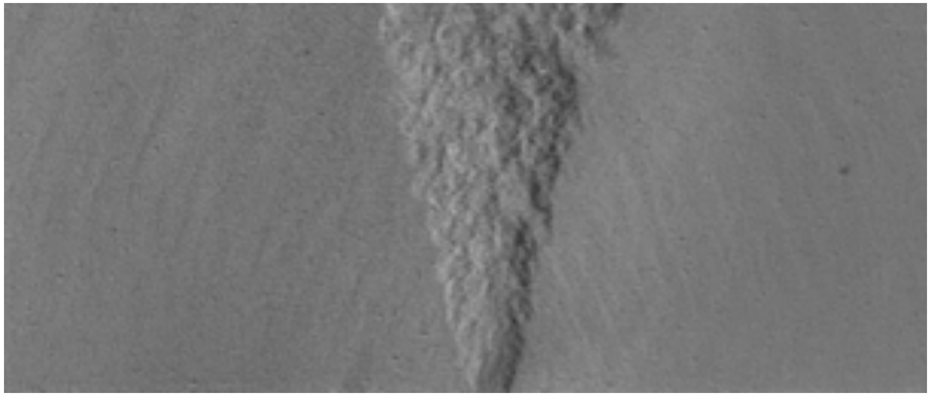
Heat Release

Time of peak heat release relative to wave



Conclusions

- **Two deflagration regions identified**
  - ➡ May not be always present
  - ➡ For instance, AFRL Edwards rocket combustor has single contact layer
- **Flame-anchoring observed**
  - ➡ Large recirculation region
  - ➡ Reduces flame speed
- **A comprehensive understanding of detonation physics**
  - ➡ Three-way link: a) injector recovery; b) unsteady mixing; c) incomplete detonation
  - ➡ Provides basis for modeling



Questions?