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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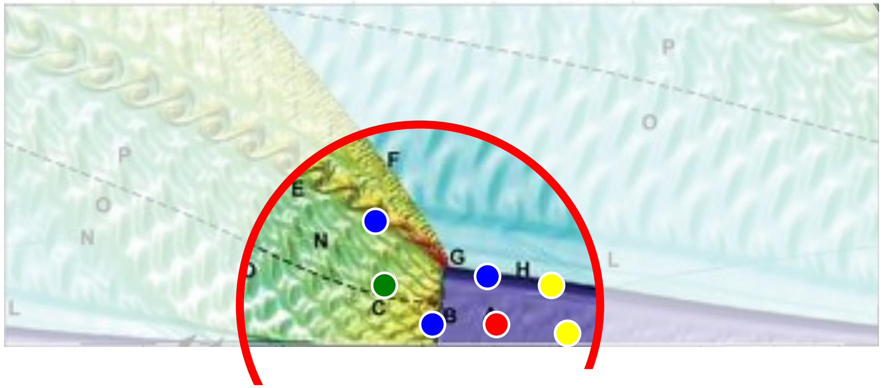
Outline

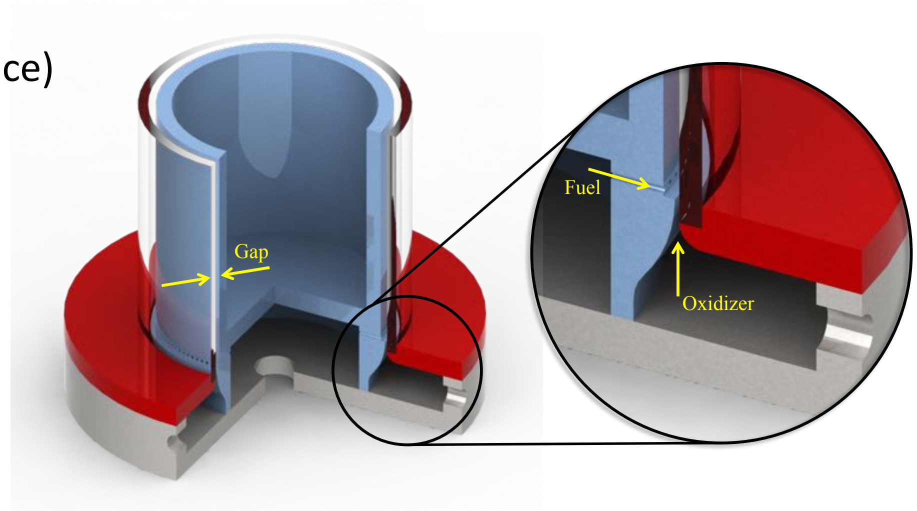
- Introduction to the problem and general approach
- Experimental activities
- Computational activities

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

Today we will discuss

- **Experimental component:**
  - Update on experimental development
  - Overview of race track RDE work
    - Mixing measurements (sector, steady flow)
    - Parasitic combustion effects
  - On going work

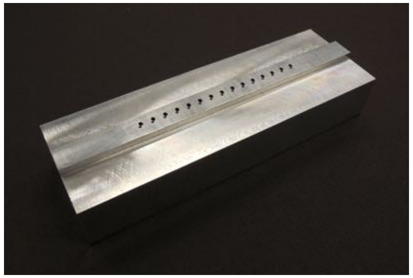
- **Computational component:**
  - Effect of injector mixing on detonation propagation
  - Effect of stratification

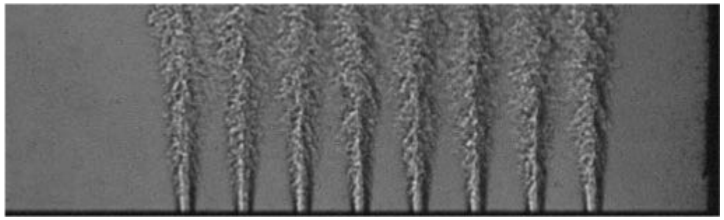
Outline

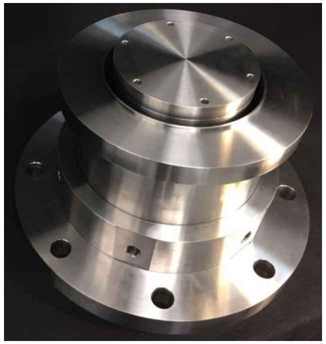
- Introduction to the problem and general approach
- Experimental activities
- Computational activities

RDE experimental program at U-M

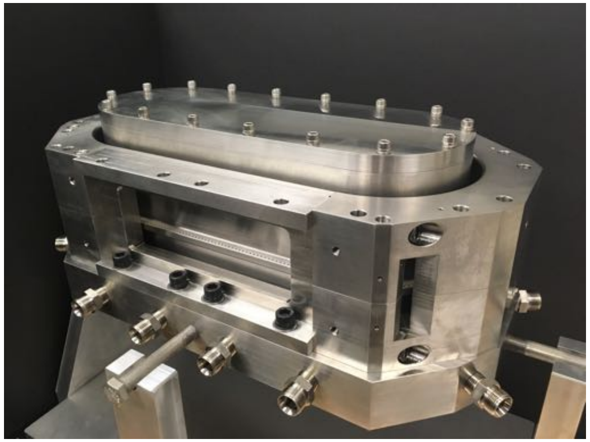
- **Injector sector subassembly**
  - Unwrapped sector of RDE injector
  - Unit problem studies
    - Mixing effectiveness
    - Shock-induced mixing







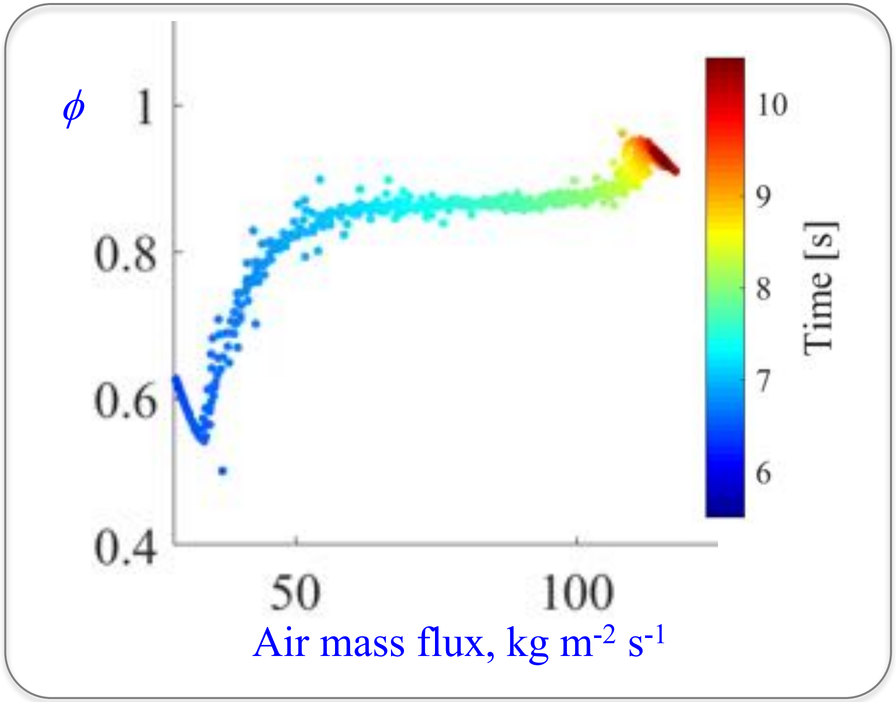
- **Round RDE (6” diameter)**
  - Operational with H_2/Air, various flow rates and equivalence ratios
  - Expanded to operate with multi-component fuels (hydrocarbon blends)
    - Working toward stabilizing HC blends (syngas and NG applications)
  - Instrumentation development is continuously ongoing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

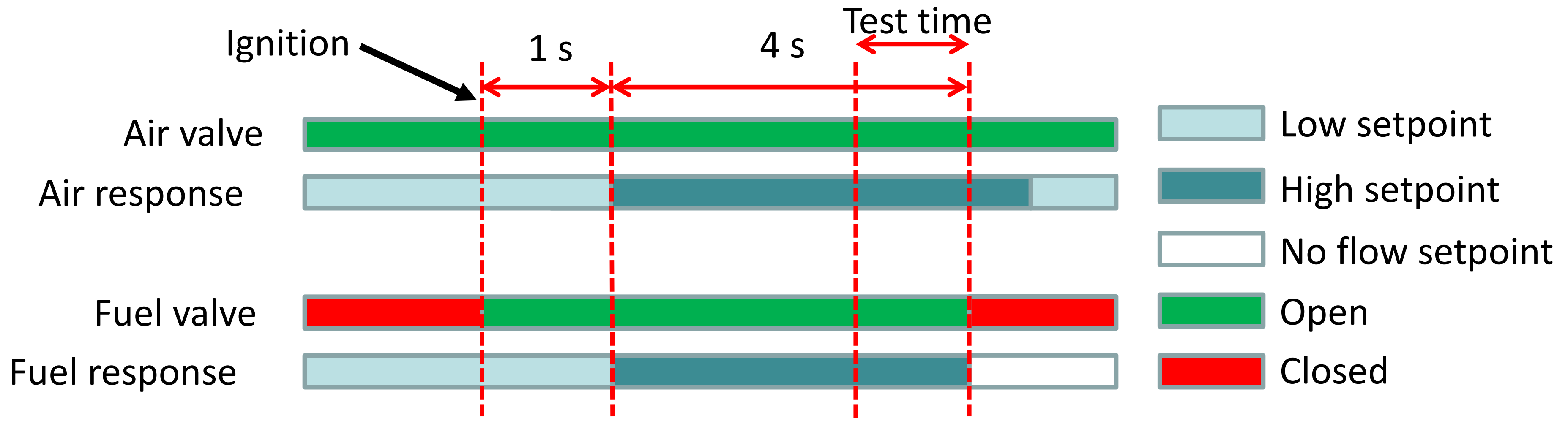


- **Optical RDE (Race-Track RDE)**
  - Fundamental physics in RDE-relevant flowfield
  - Equivalent to 12” round RDE
  - Used for flowfield measurements using laser diagnostics under RDE relevant conditions
    - Imaging for mixing, detonation structure, injector response studies

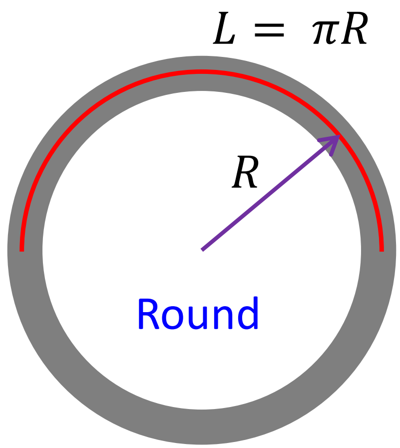
RDE test facility

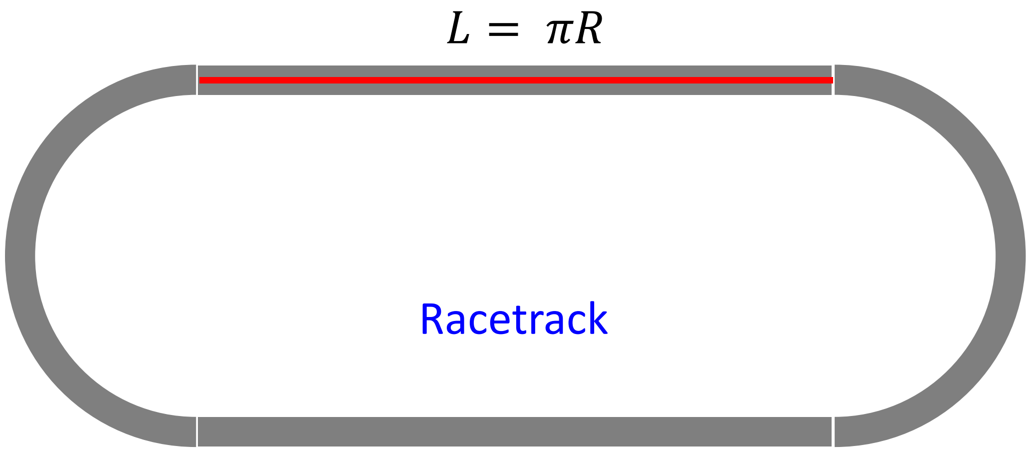
- **Some upgrades made since last year**
  - Needed to operate racetrack RDE
- **Staged operation:**
  - Ignition at low flow rates
  - Fuel/air ramp up to operating flow rate (up to 1 kg/s)
- **Use staging to:**
  - Ignition sequence
  - Transition between fuel types
  - Conduct transient studies, e.g.: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





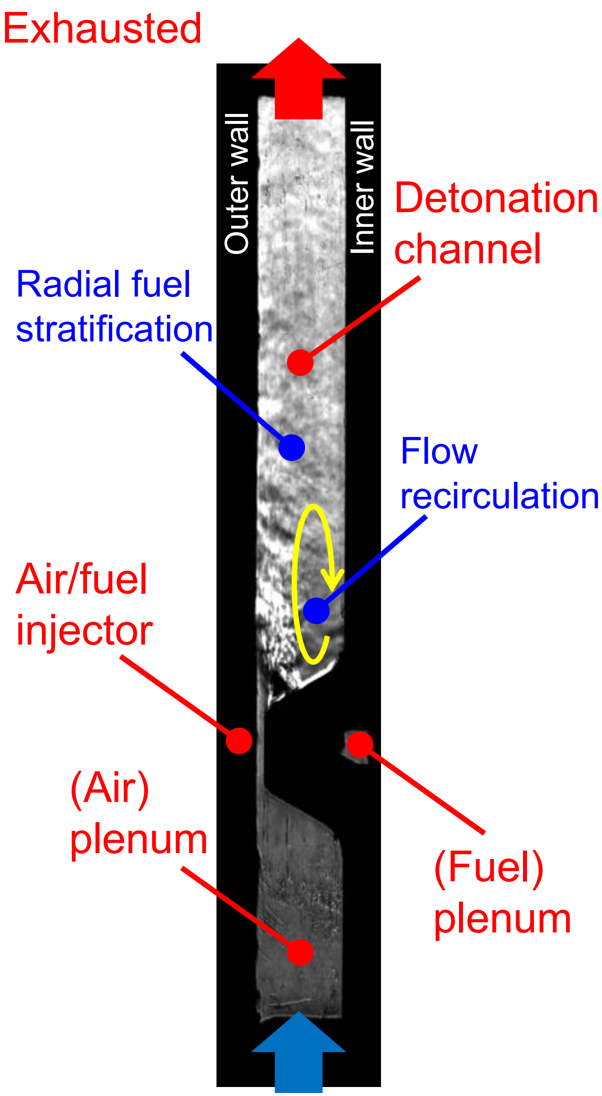
Racetrack RDE concept

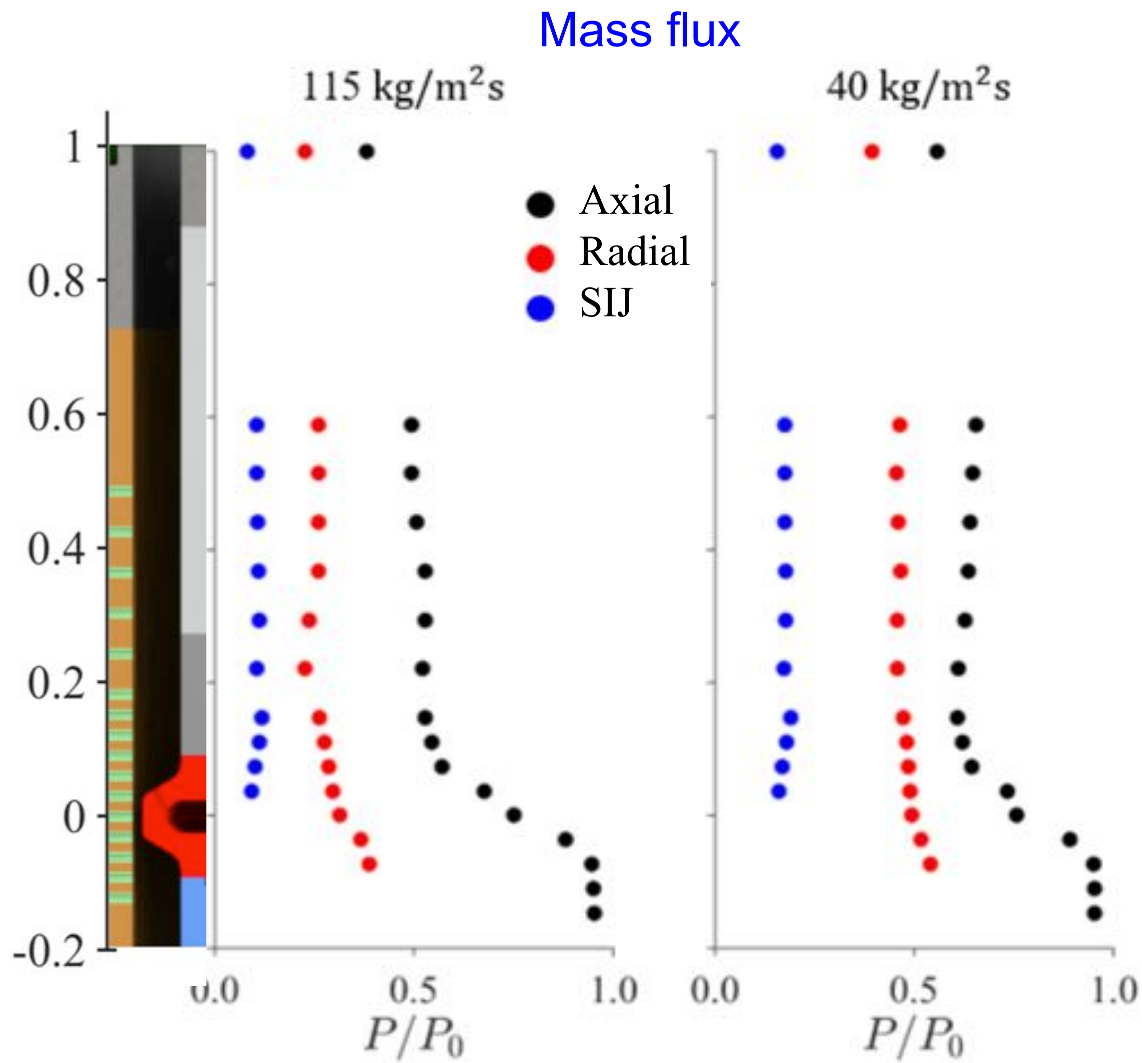




- Key constrains:
  - Allows for imaging
  - Similar to round configuration
- Configuration:
  - Two straight sections, connected by half circles
  - Straight sections for imaging, curved sections to complete the circuit
  - Each section is equivalent to half of the round RDE
- Internal geometry is nearly identical to that of the round RDE
- Injector dynamics depend on operational frequency, therefore the RT-RDE needs to have a circuit length that is an integer multiple of the MRDE
  - Double the length of round RDE
  - Requires operation with two waves

Axial, low(er) loss inlet configuration



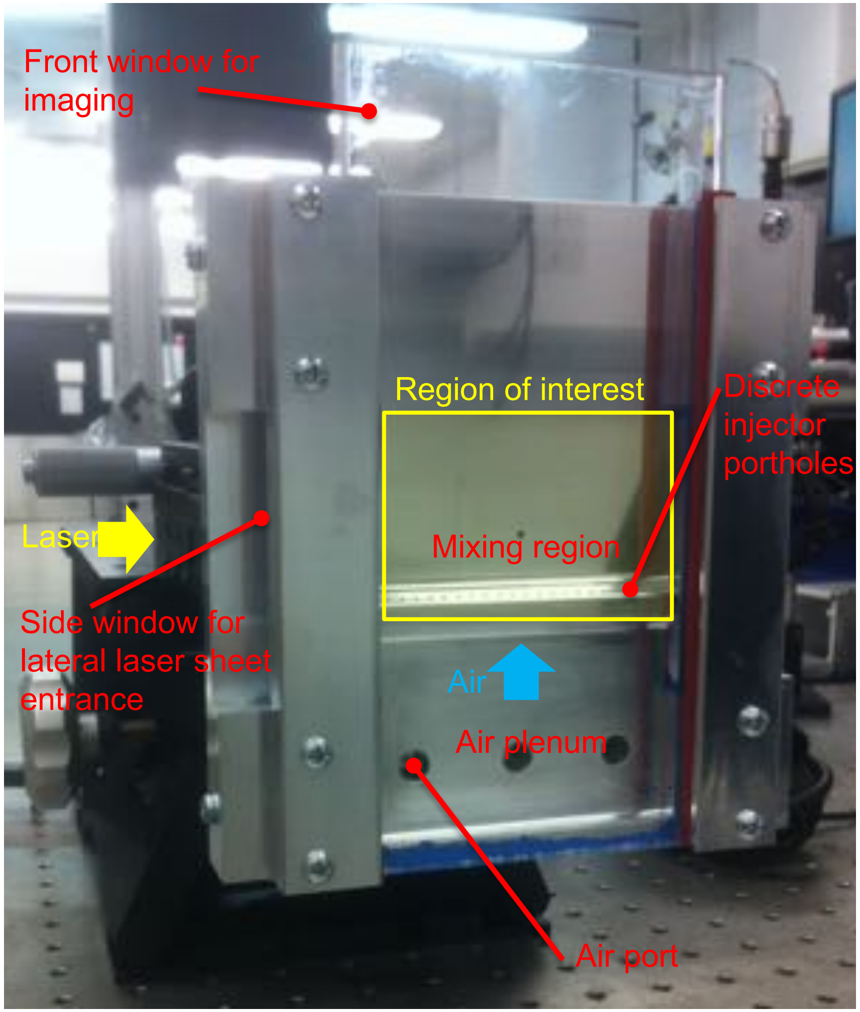


MIXING MEASUREMENTS IN INJECTOR SECTOR

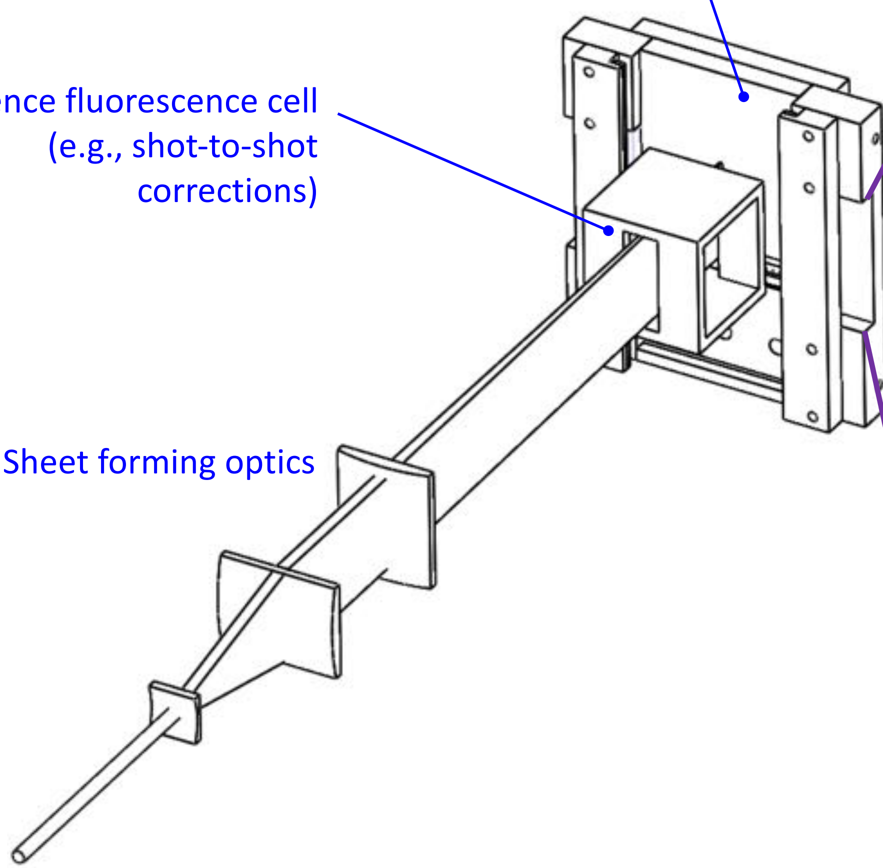
Injector sector subassembly

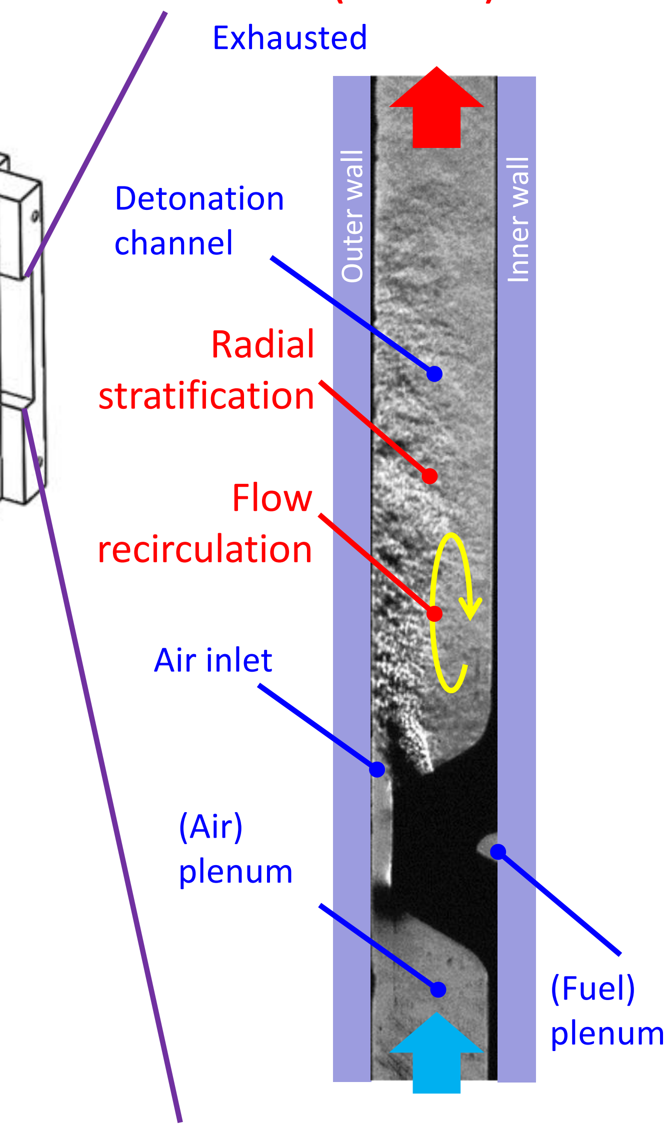
- **Unwrapped sector of 6” round RDE**
  - Same axial air inlet flowpath/fuel injector geometry of round and racetrack RDE
  - 1/8th diameter equivalent of round RDE
  - Optical access for laser diagnostics
  - Steady operation

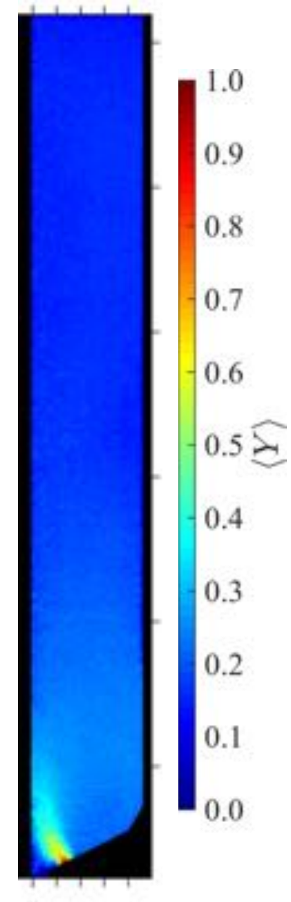
- **Used in support of:**
  - Mixing measurements (steady state)
  - Injector flowfield evaluation



Injector sector subassembly: example of use







Important parameters affecting mixing

Momentum flux:

$$q = \rho u^2 = \gamma p M^2$$

Momentum flux ratio:

$$J = \frac{q_{Fuel}}{q_{Air}}$$

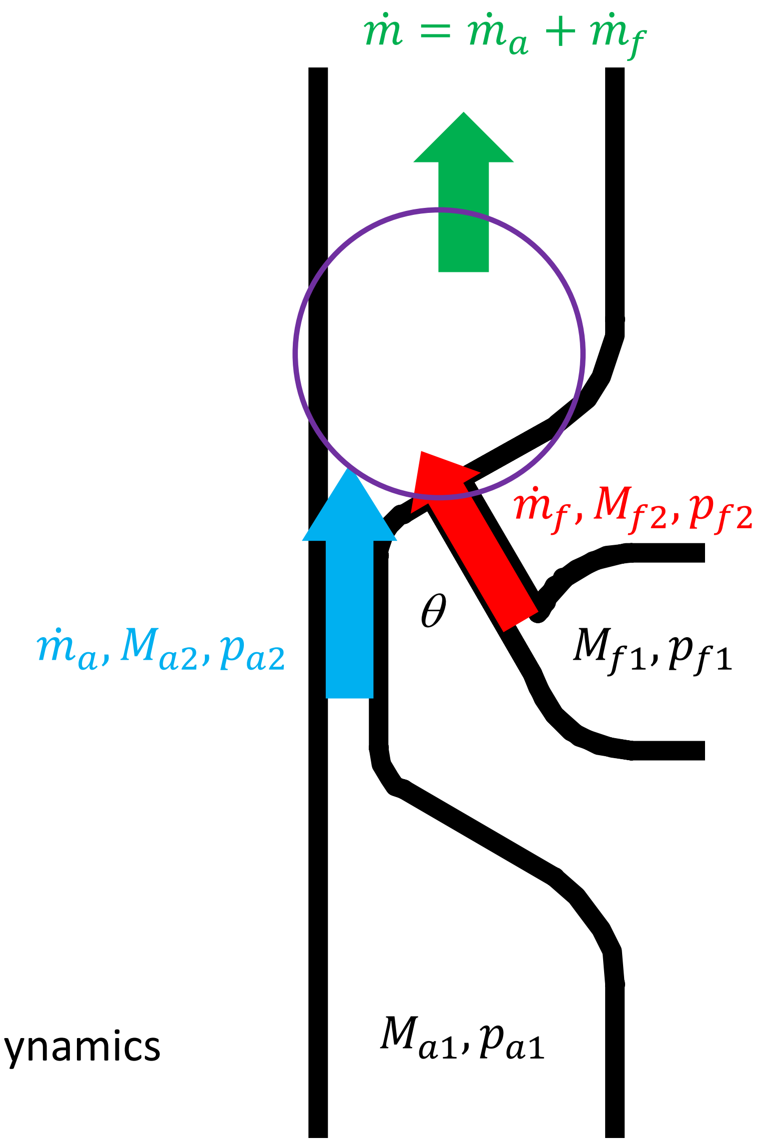
Stream Mach numbers:

$$M_a \ \& \ M_f$$

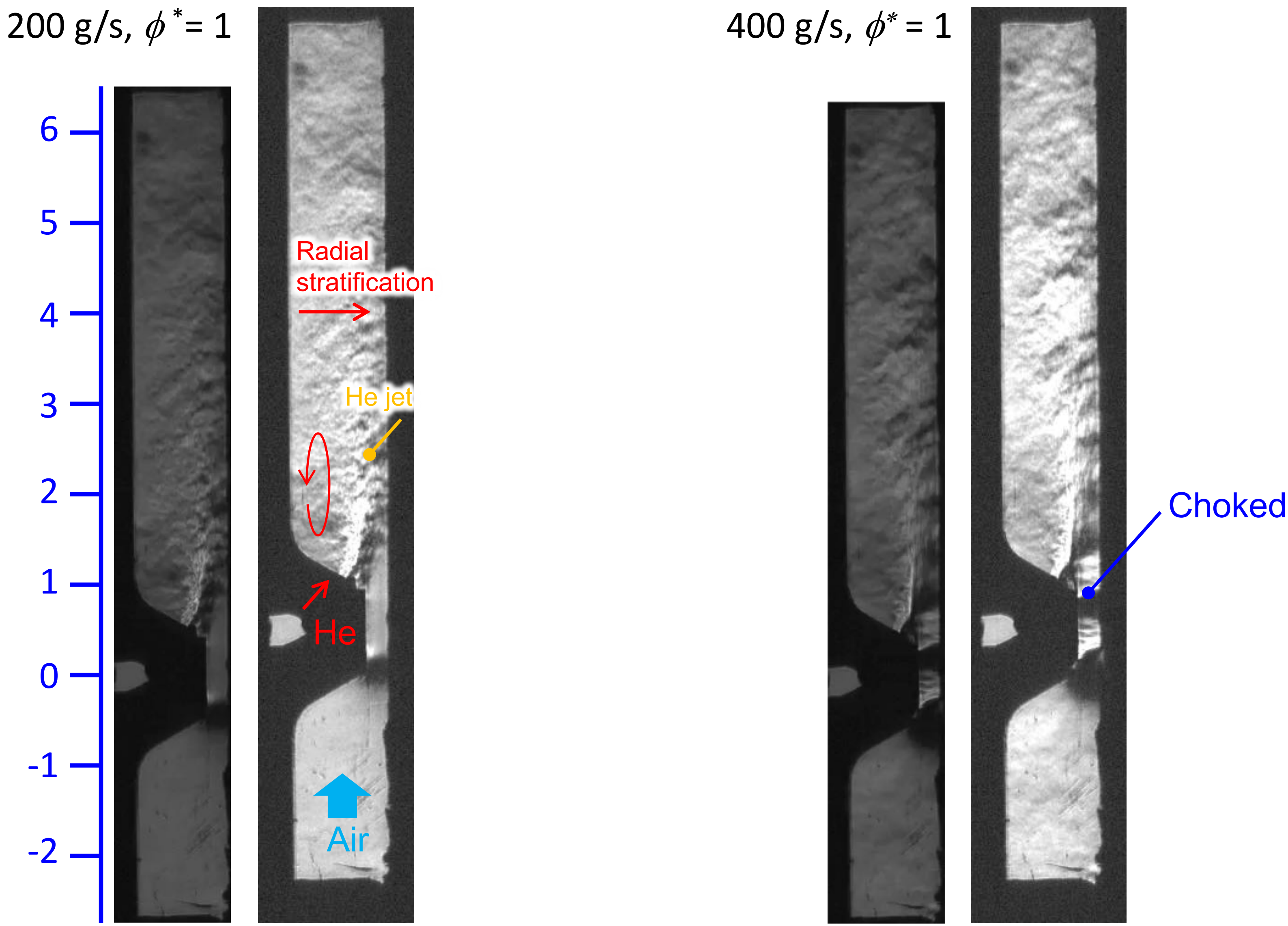
They affect:

- Fuel/air penetration
- Mixing rates and profiles
- Injection system response
- Detonation/injection system coupled dynamics

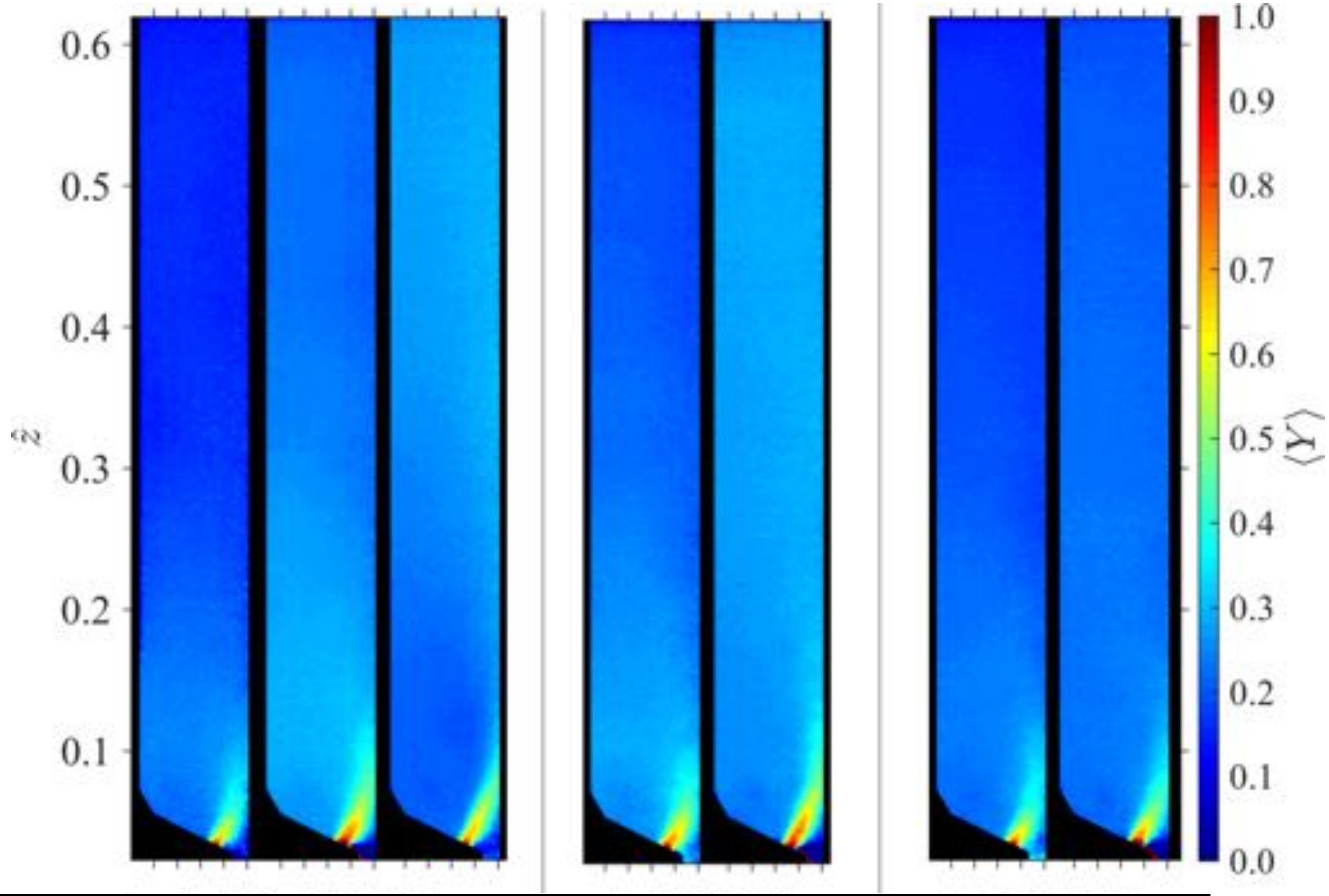
We have matched both J and Mach numbers



Axial air inlet flowfield (Cold-flow visualization on linearized sector)



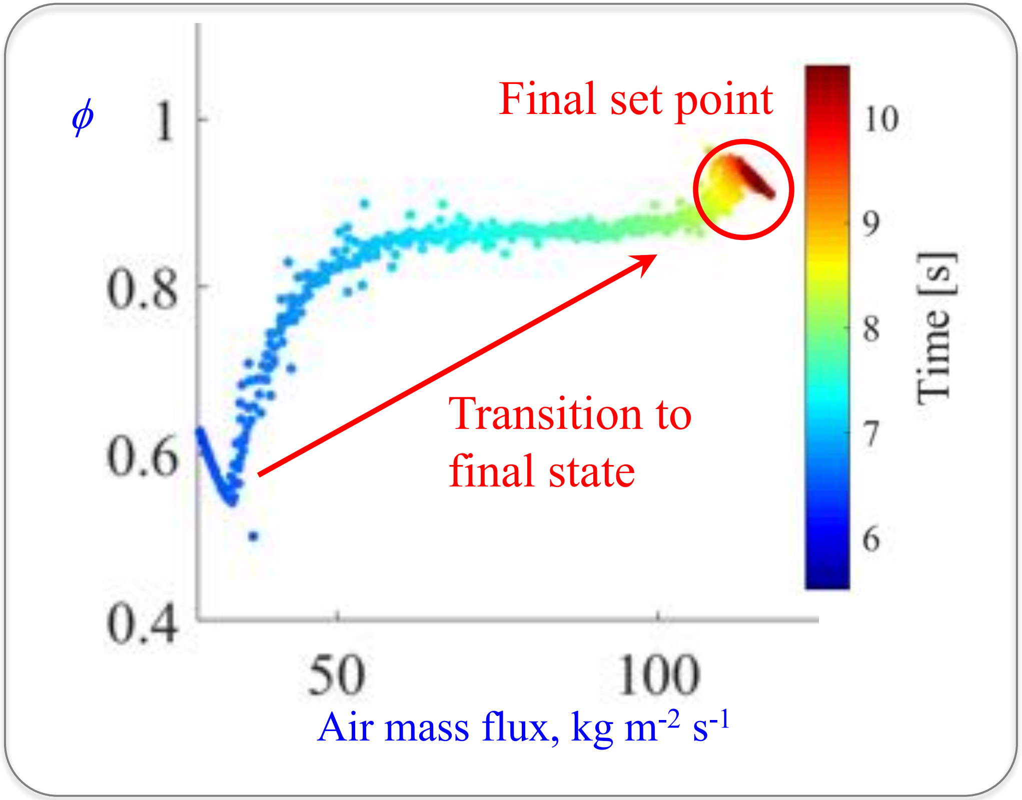
Mean injectant mole fraction field (midplane of fuel injector)



J	0.61	1.07	2.17	0.55	2.14	0.42	1.20
M_a/AMF [kg/m^{2}s]	0.55 / 40			0.65 / 70		1.00 / 70	

INVESTIGATE PARASITIC COMBUSTION IN RACETRACK RDE

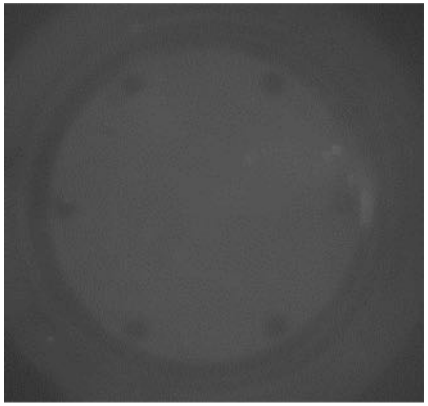
RT-RDE: it sort of works!

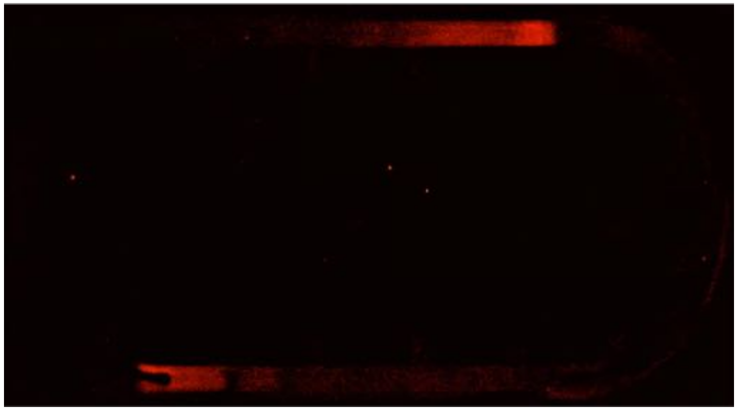


- Ignites at low flow rate at equivalence ratio of 0.6
- Ramp up flow rates to a final set point
- Total run time of 5 second

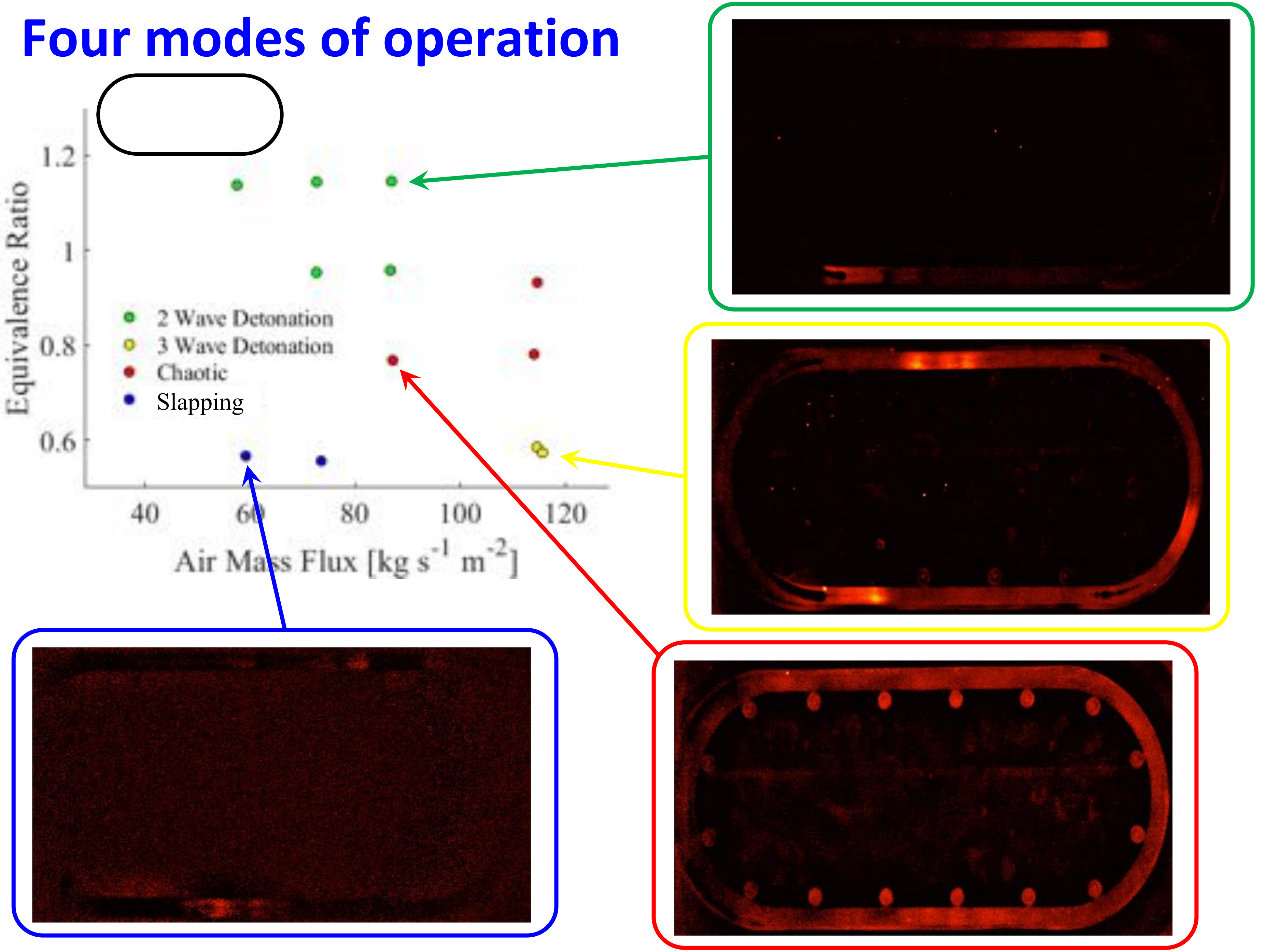
Operation of round RDE and RT-RDE is fairly similar

- We have characterized the operation of the racetrack to ensure it operates similarly to the round RDE:
  - **Plenum Pressures:** air plenum pressures match, fuel plenum pressure increase. Stiffer fuel injectors.
  - **Momentum Flux Ratio:** shifted operational regime.
  - **CTAP:** same normalized profile, increased back pressure causes shift in absolute profile.
  - **Wave Speed:** speeds are approximately 80 m/s slower than equivalent MRDE wave.
  - **Spectral Content:** broader tones, caused by increased instability induced by round-to-curved transition points.

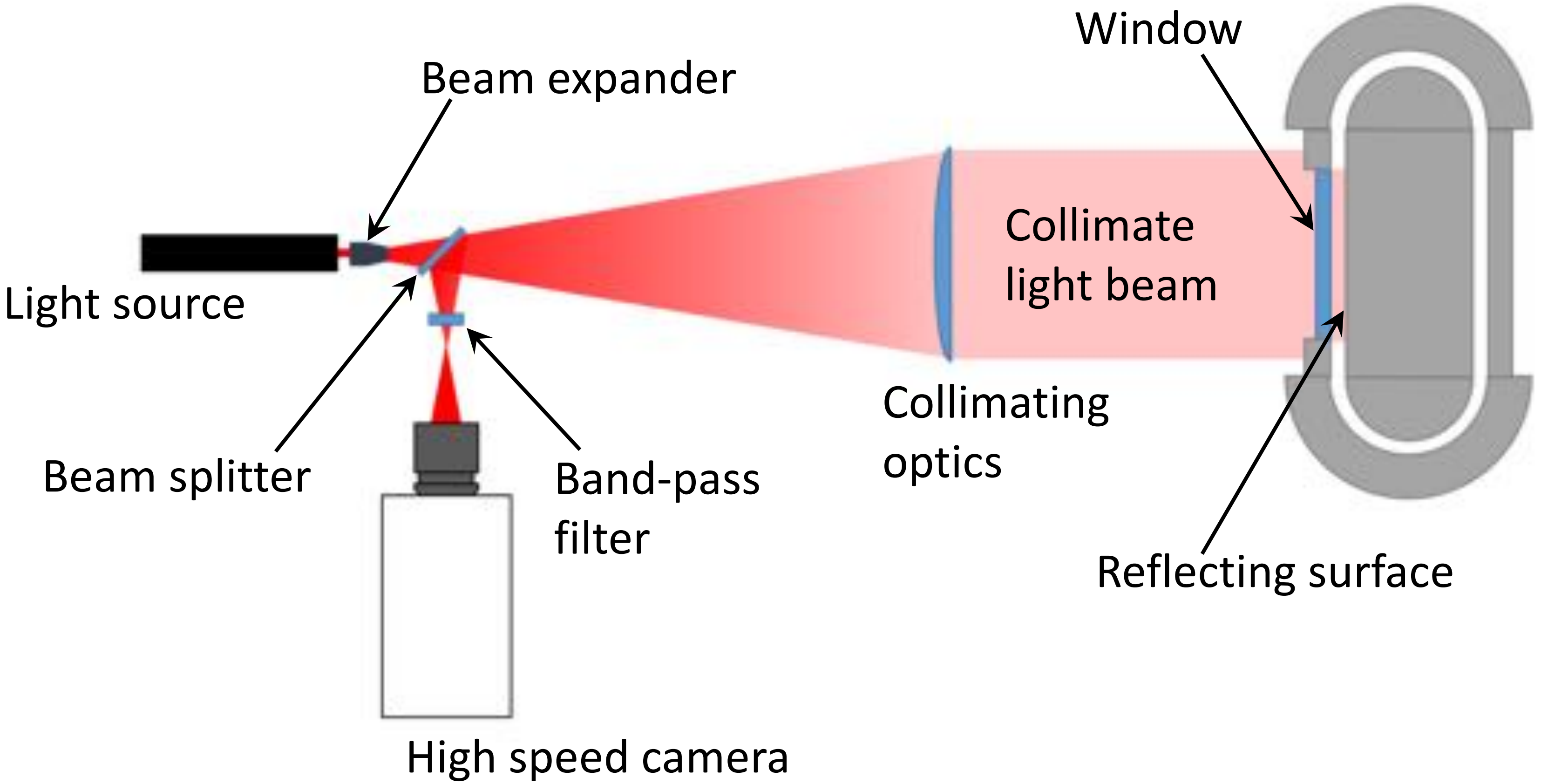




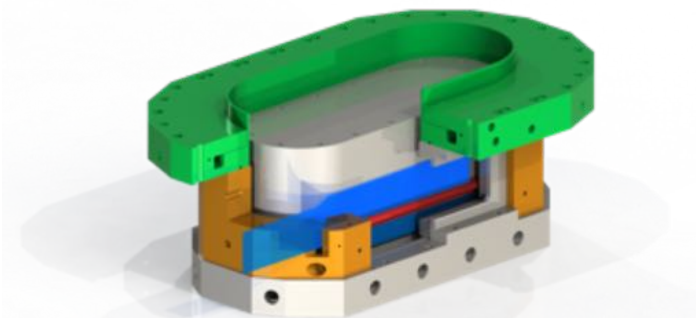
Four modes of operation

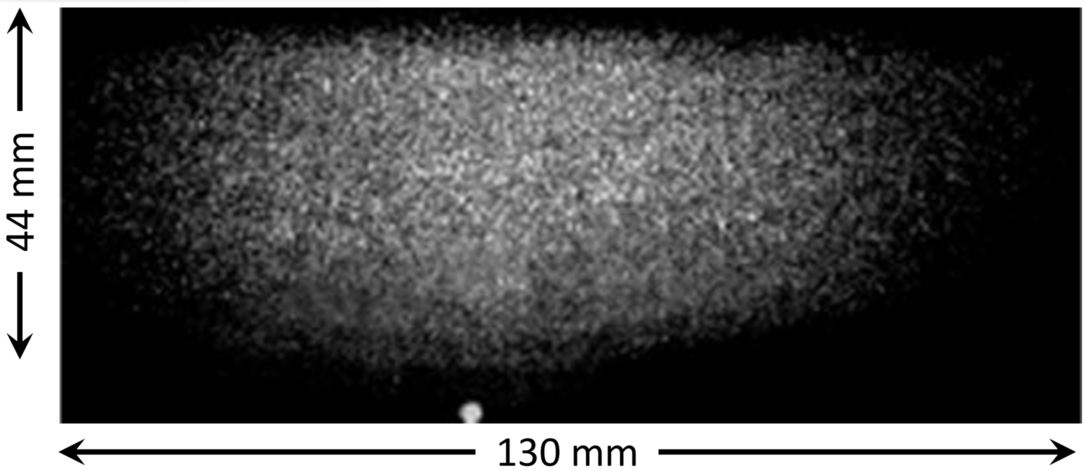


Exploring schlieren/shadowgraph imaging in the RT-RDE



First round of schlieren imaging in straight section

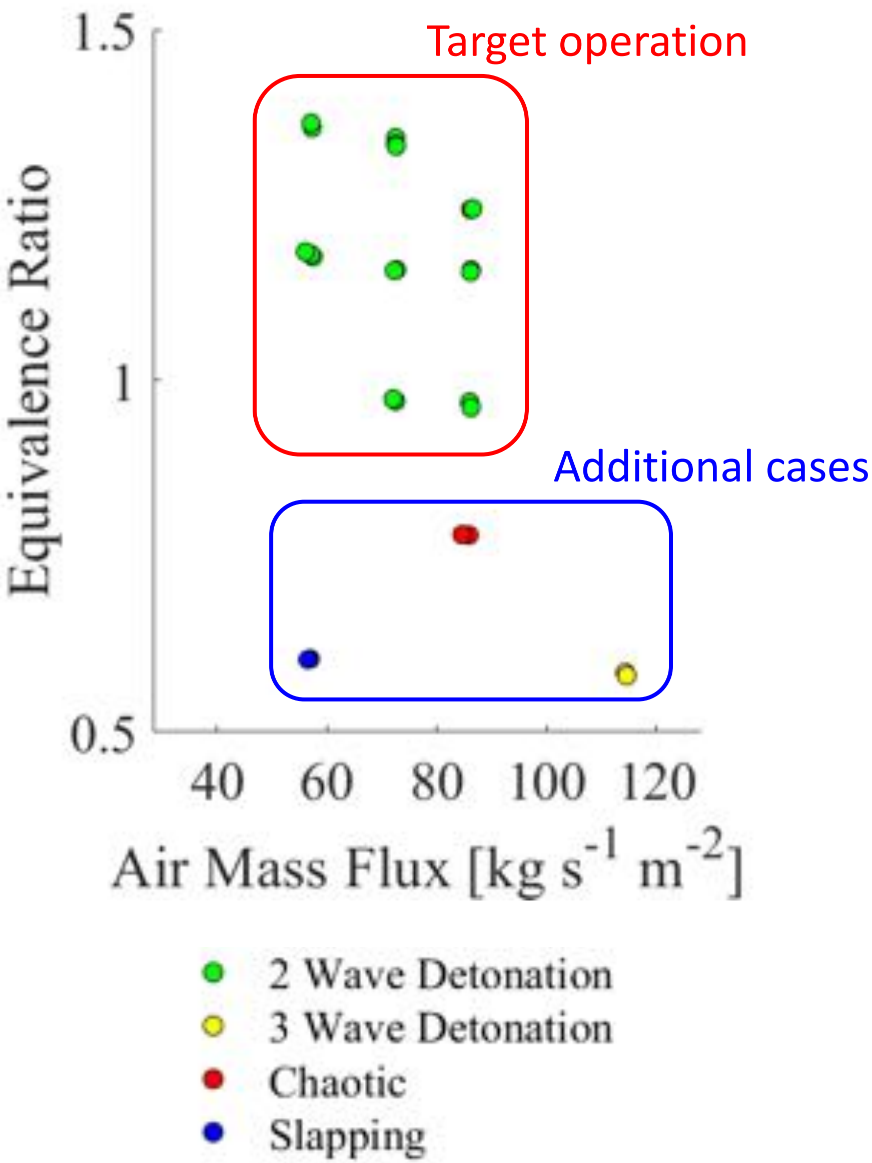




Framing rate: 170,000 fps

- Modified the hardware and optical setup three times to get it to work
- Quality not quite there yet
- We have modified the hardware (to be delivered)
- We are improving the Schlieren imaging system (better optics, higher signals) to evaluate:
  - Detonation wave position and structure
  - Injector response and flow structure

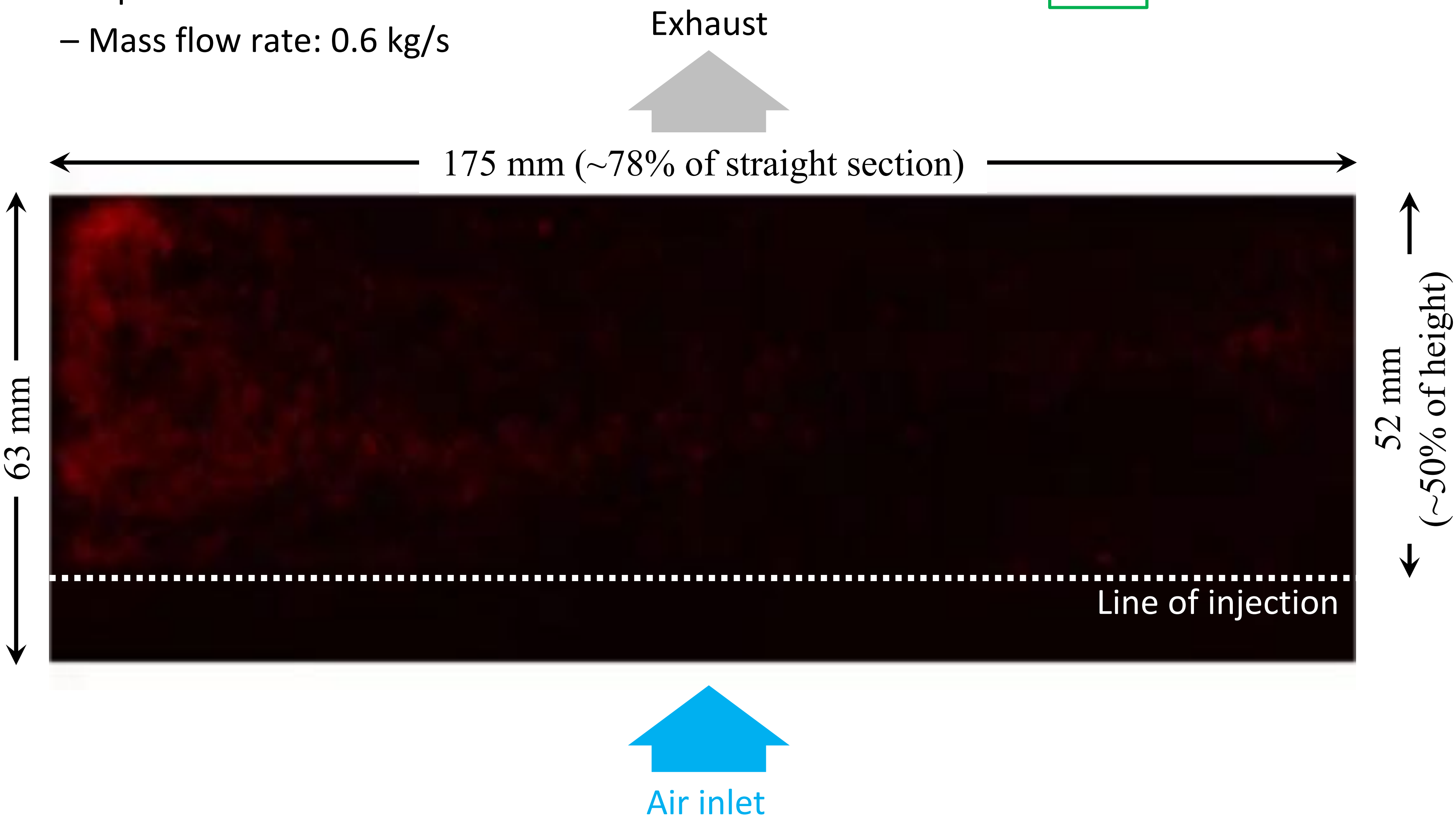
Exploring parasitic combustion with the RT-RDE



- High-speed chemiluminescence movies of OH* emission
  - Spectral range from 305 – 310 nm (bandpass filter)
  - Used to mark regions of heat release
  - Framing rate: 80 kfps
  - Exposure: 2 μs
  - Longer exposure to emphasize regions where deflagration occurs

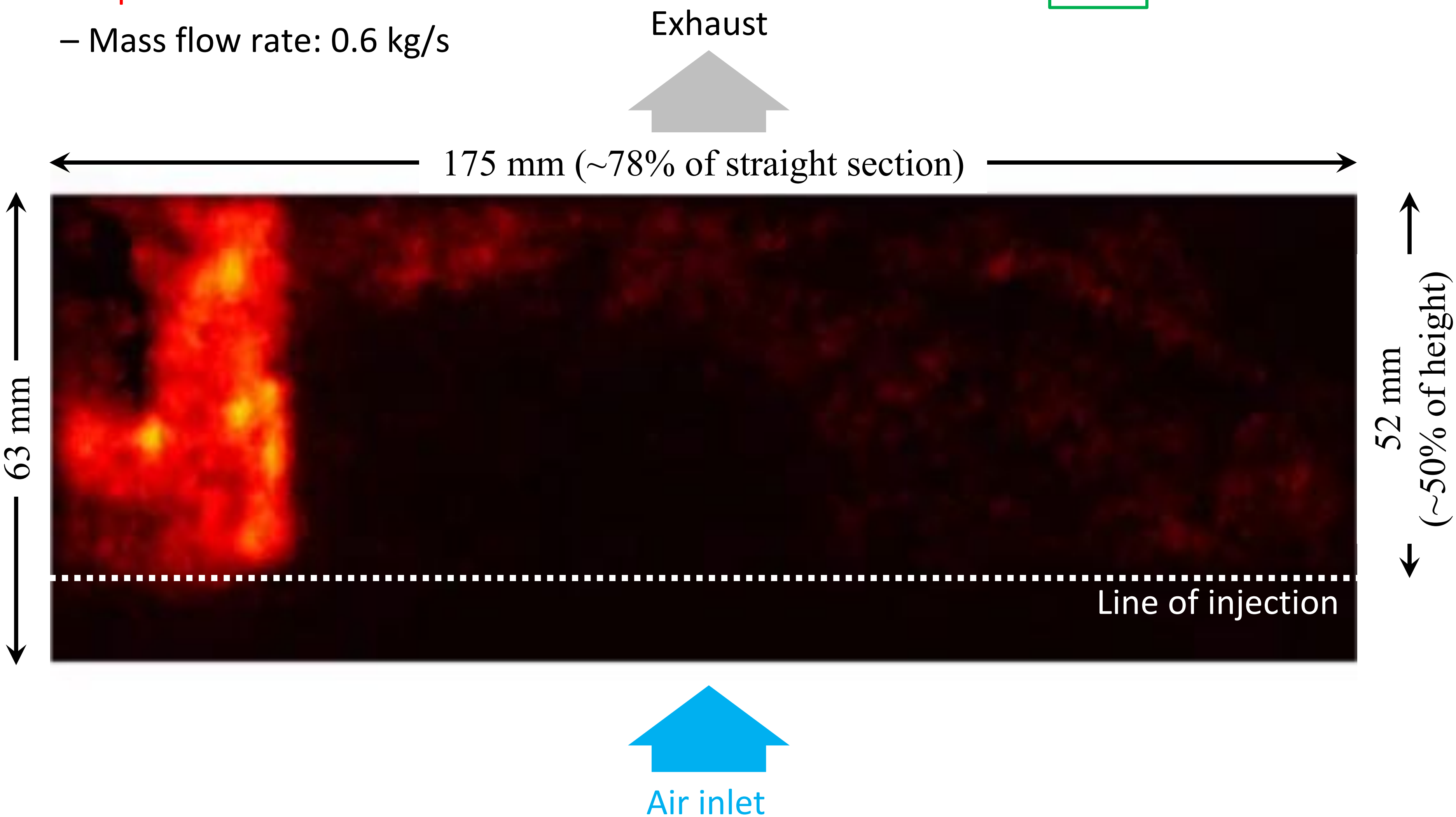
Exploring parasitic combustion with the RT-RDE (1)

- Operation conditions:
  - Fuel: Hydrogen
  - Equivalence ratio: 1.3
  - Mass flow rate: 0.6 kg/s



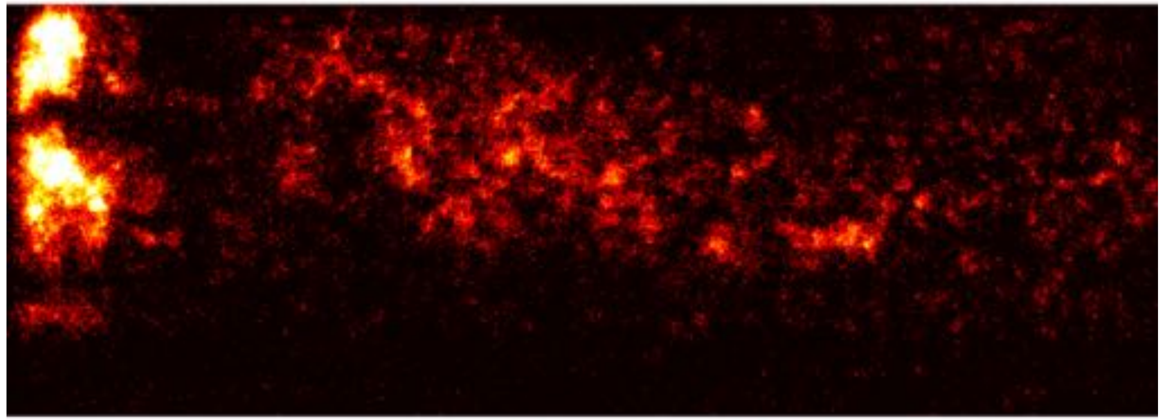
Exploring parasitic combustion with the RT-RDE (2)

- Operation conditions:
  - Fuel: Hydrogen
  - Equivalence ratio: 1.0
  - Mass flow rate: 0.6 kg/s

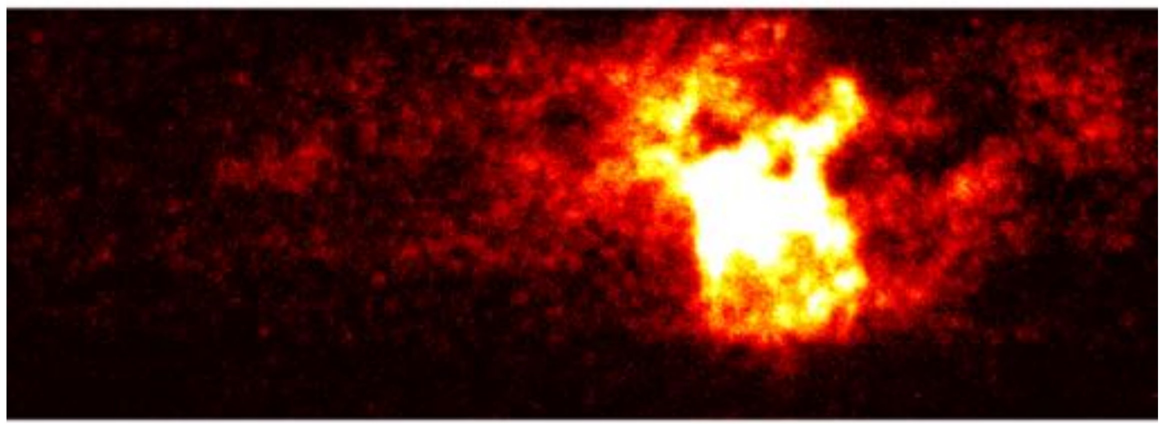


Other modes

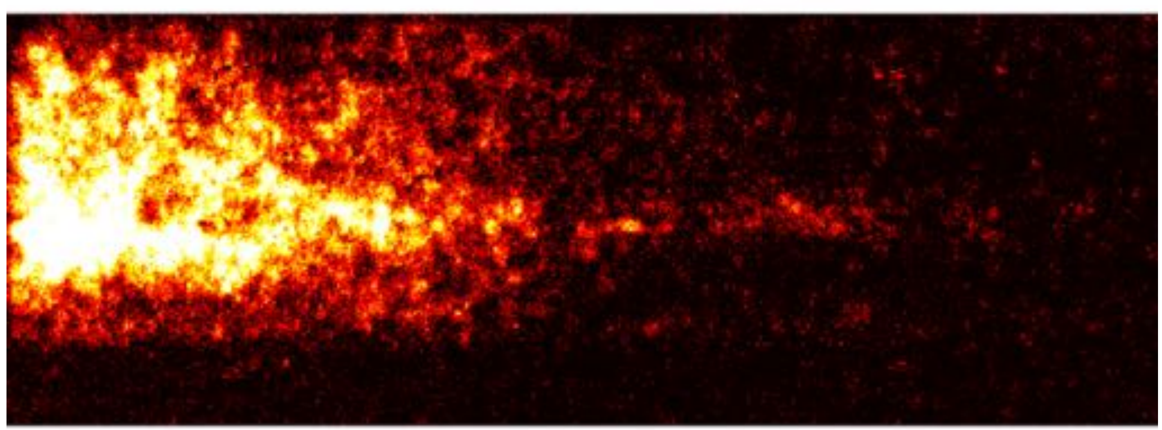
Three-wave



Chaotic



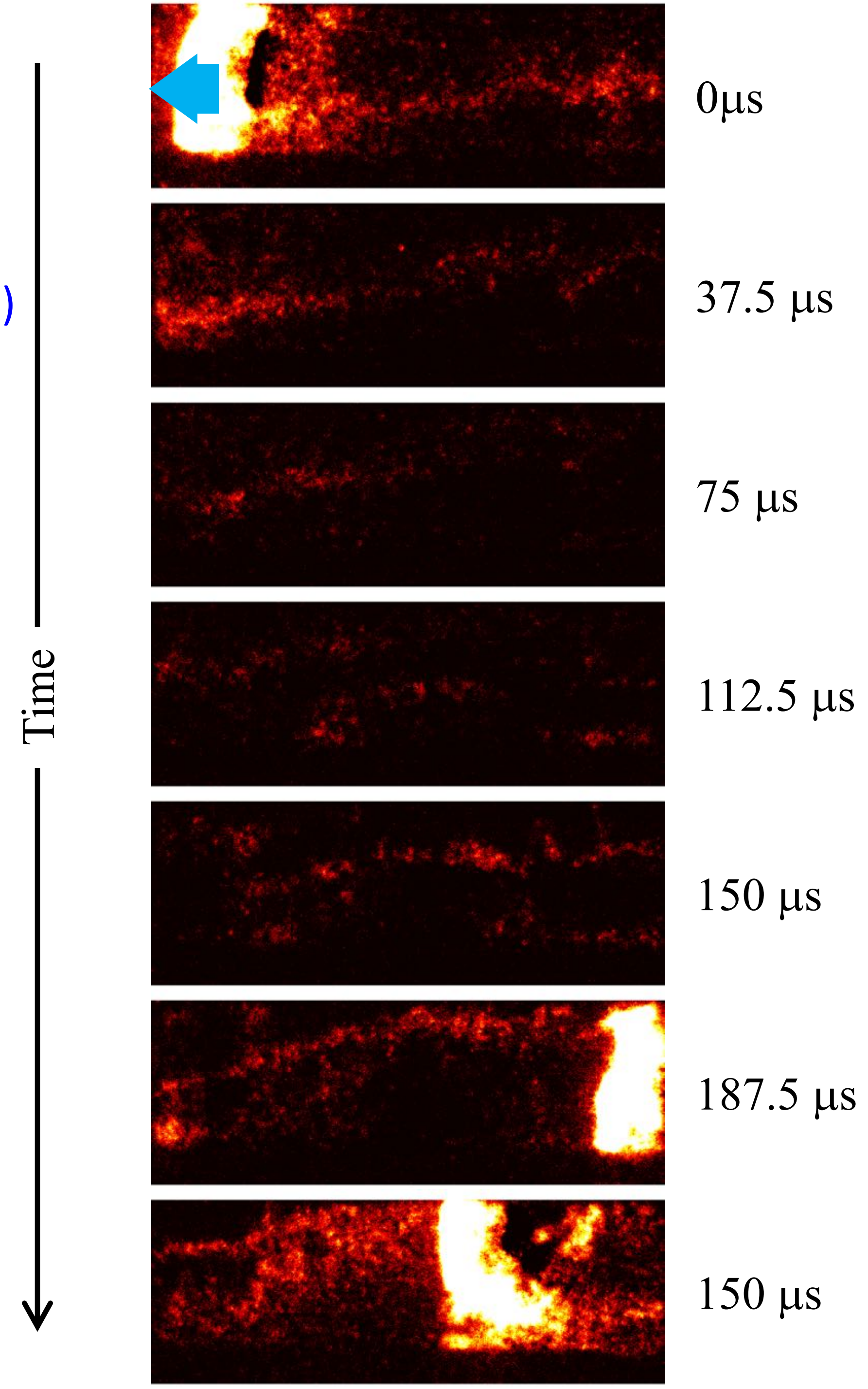
Slapping



0.6 kg/s, ϕ = 1.3

Time sequence example:

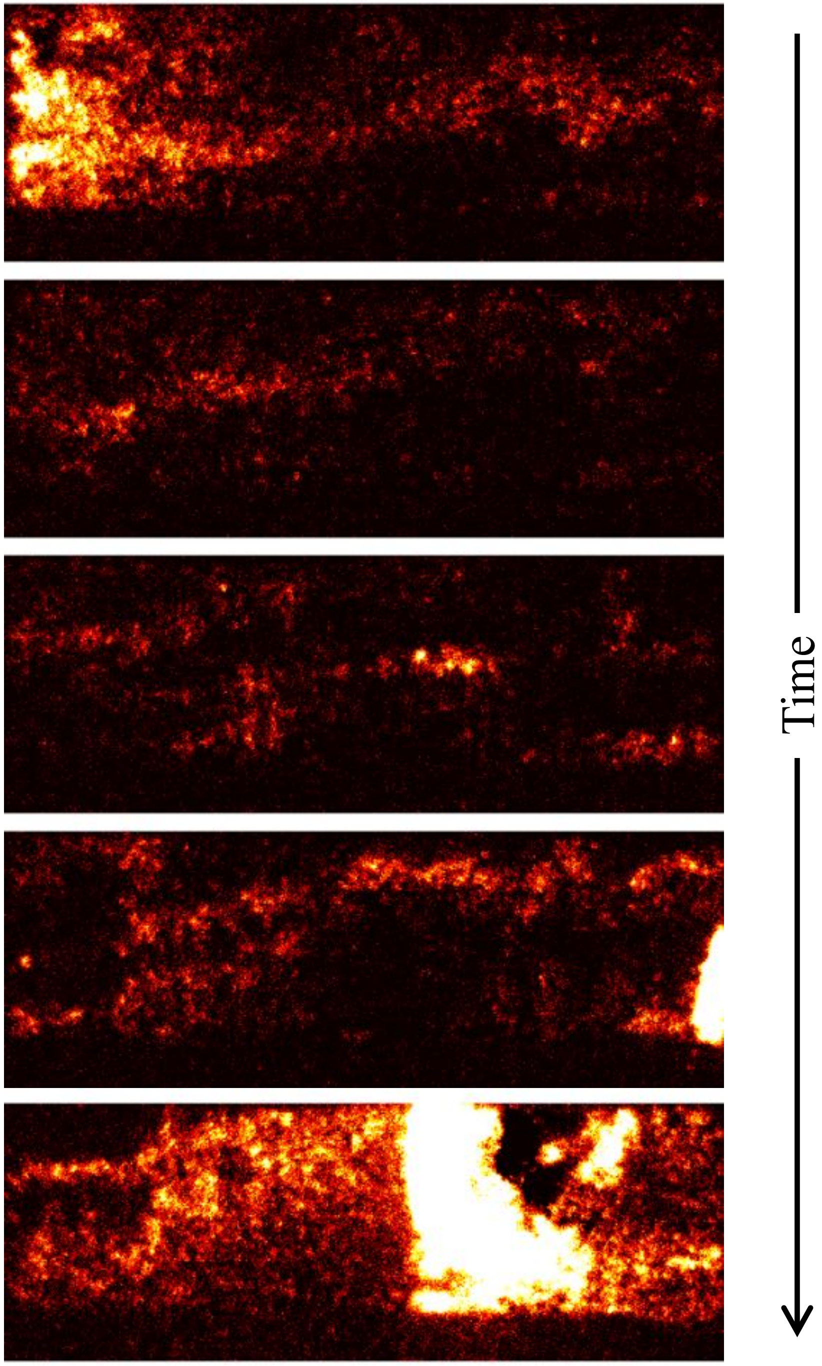
- Long exposure (2 μs, high gain) to emphasize parasitic combustion
- After contrast stretching to emphasize regions of parasitic combustion

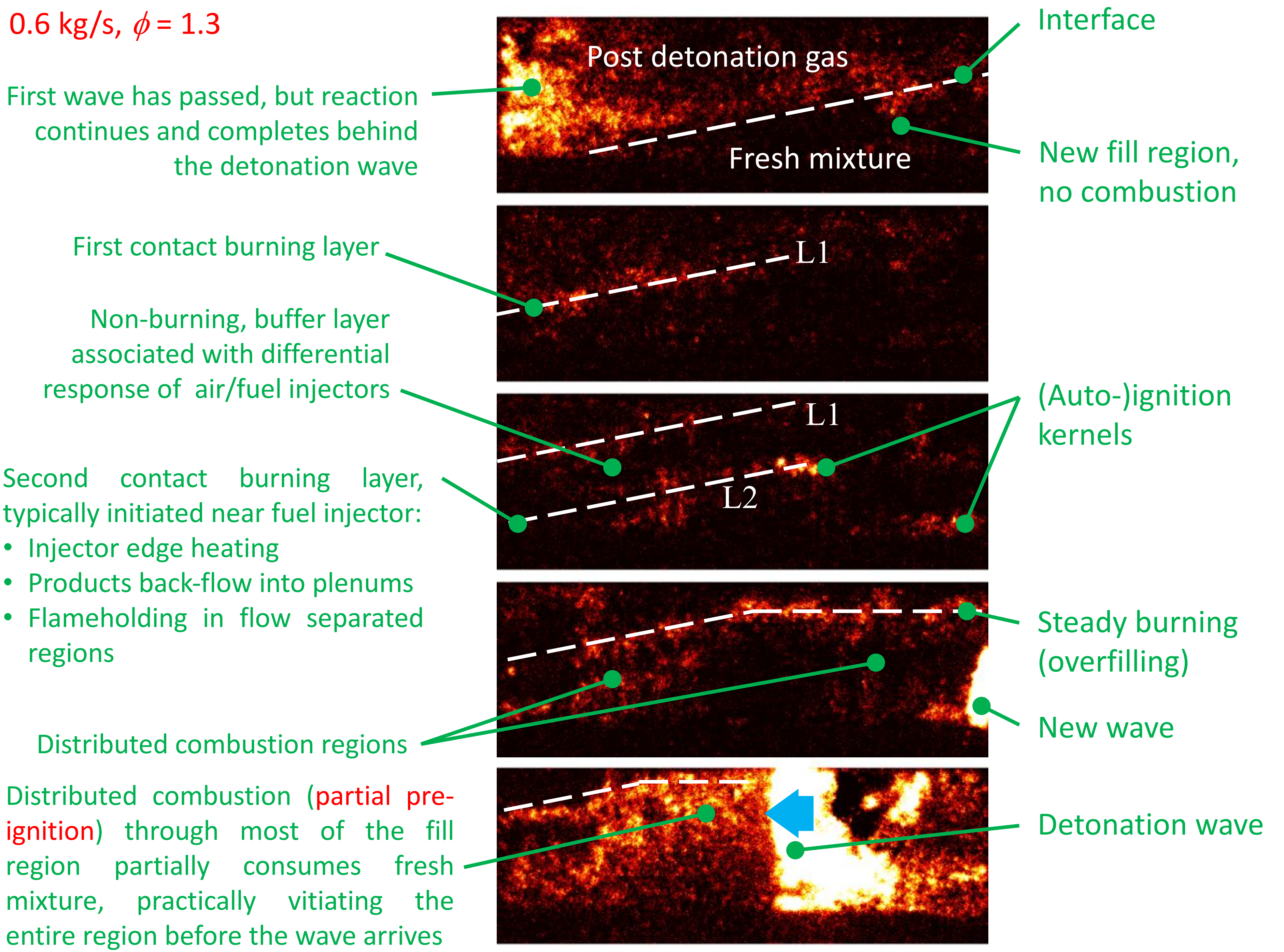


0.6 kg/s, ϕ = 1.3

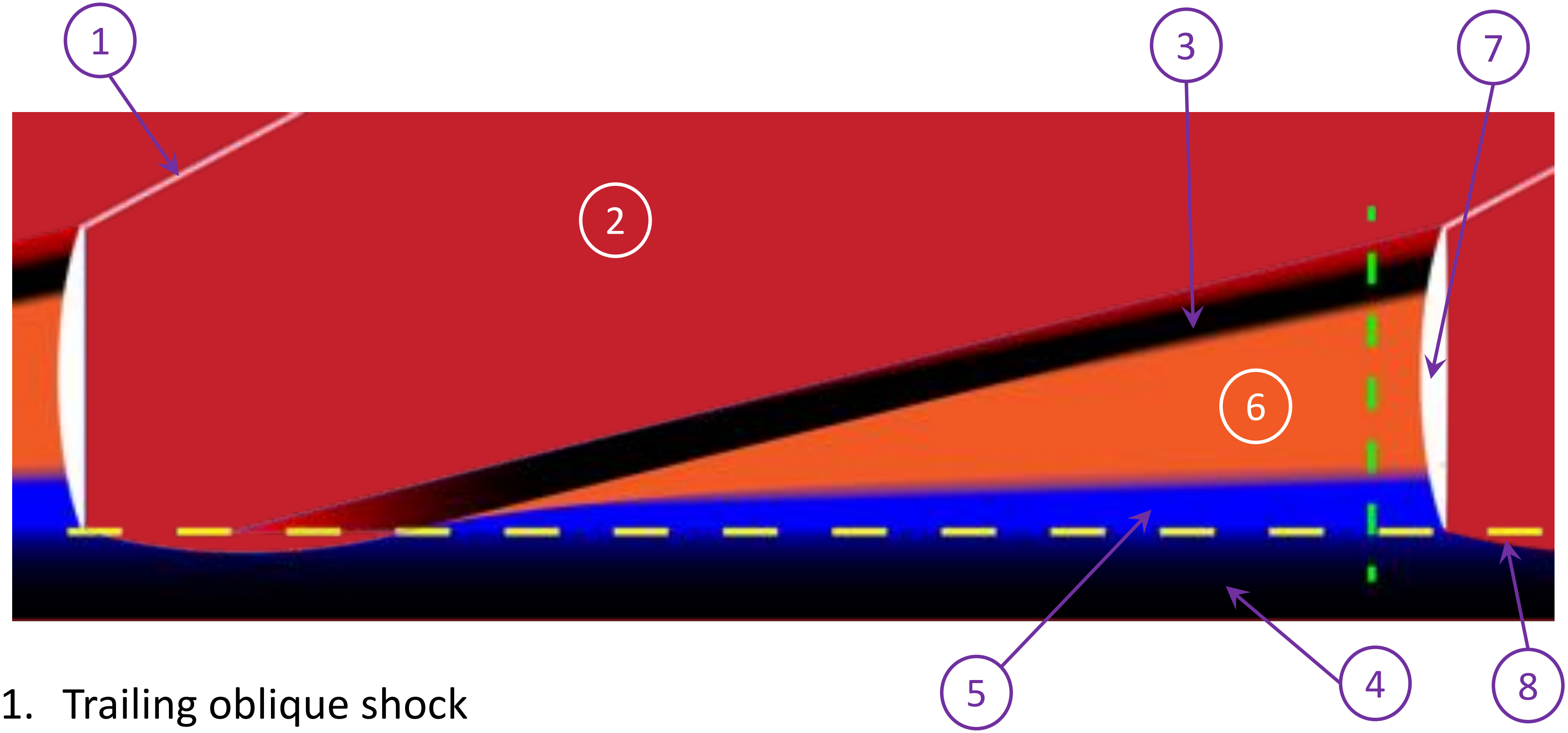
Time sequence example:

- Long exposure (2 μs, high gain) to emphasize parasitic combustion
- After contrast stretching to emphasize regions of parasitic combustion
- Down-sampled to capture only the most important features



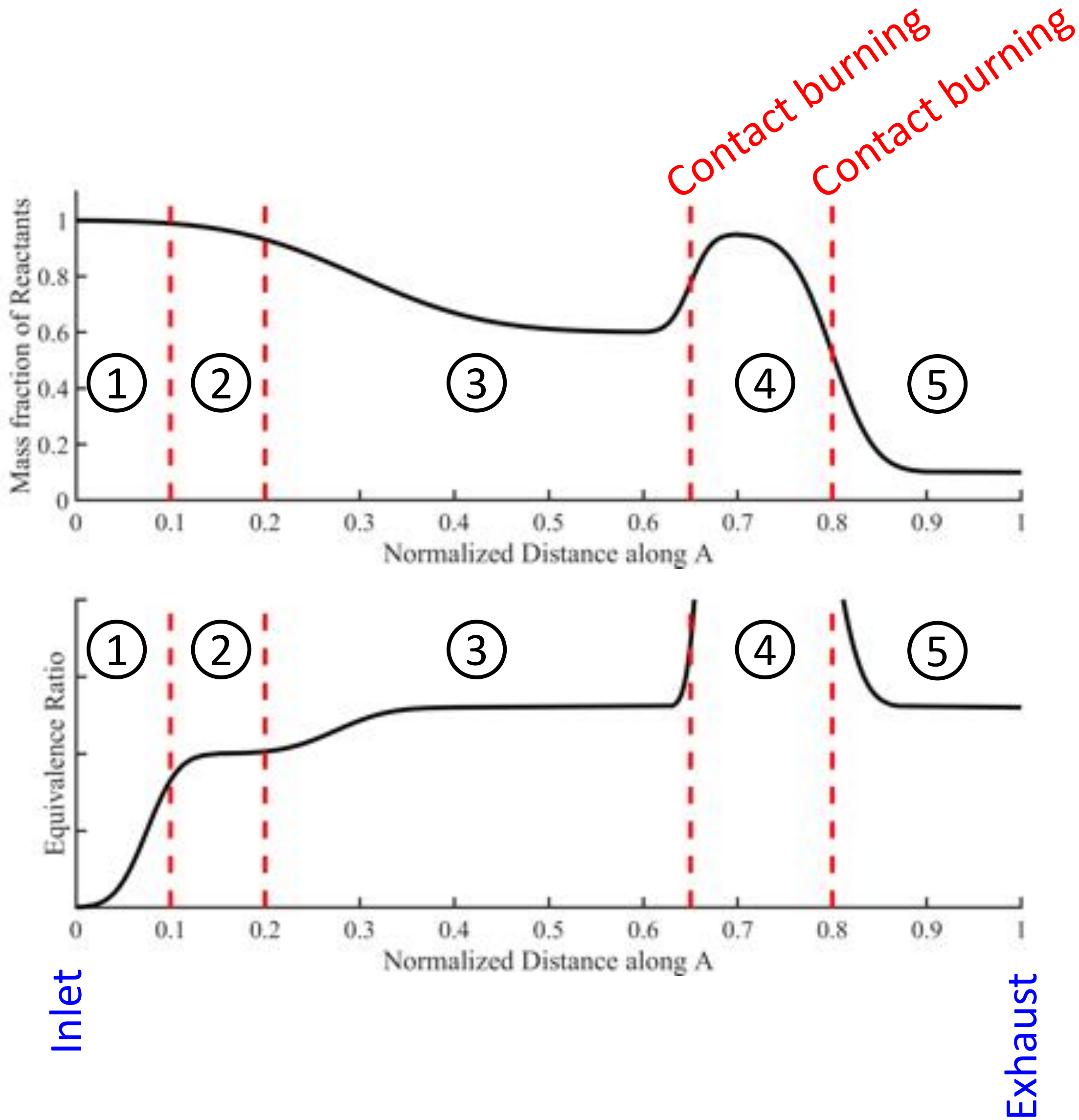

0.6 kg/s, ϕ = 1.3
Post detonation gas
Fresh mixture
Interface
First wave has passed, but reaction continues and completes behind the detonation wave
New fill region, no combustion
First contact burning layer
L1
Non-burning, buffer layer associated with differential response of air/fuel injectors
L1
L2
(Auto-)ignition kernels
Second contact burning layer, typically initiated near fuel injector:
• Injector edge heating
• Products back-flow into plenums
• Flameholding in flow separated regions
Steady burning (overfilling)
New wave
Distributed combustion regions
Distributed combustion (partial pre-ignition) through most of the fill region partially consumes fresh mixture, practically vitiating the entire region before the wave arrives
Detonation wave

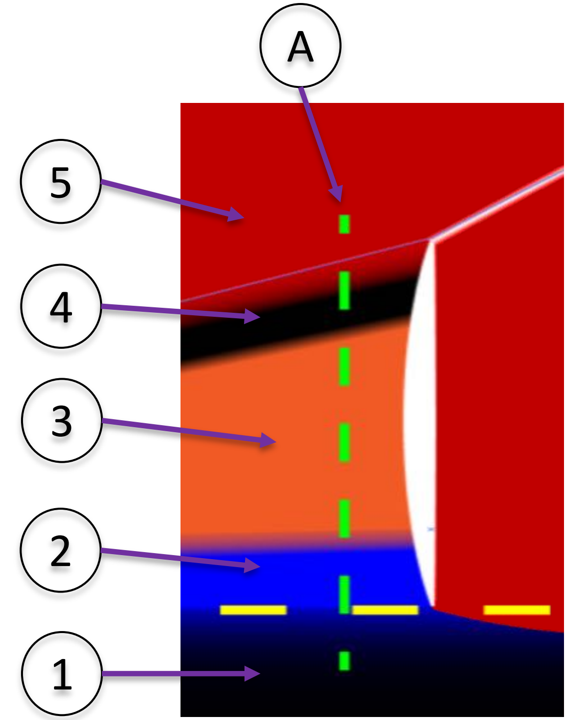
Summary of parasitic combustion evolution



1. Trailing oblique shock
2. Post-detonation products
3. Buffer layer (pure fuel or pure air)
4. Air inlet
5. Steady flow, non-vitiated fill region
6. Partially reacted/vitiated fill region
7. Detonation wave
8. Fuel injection ports

Combustion dynamics can result in a complex distribution of air/fuel/products

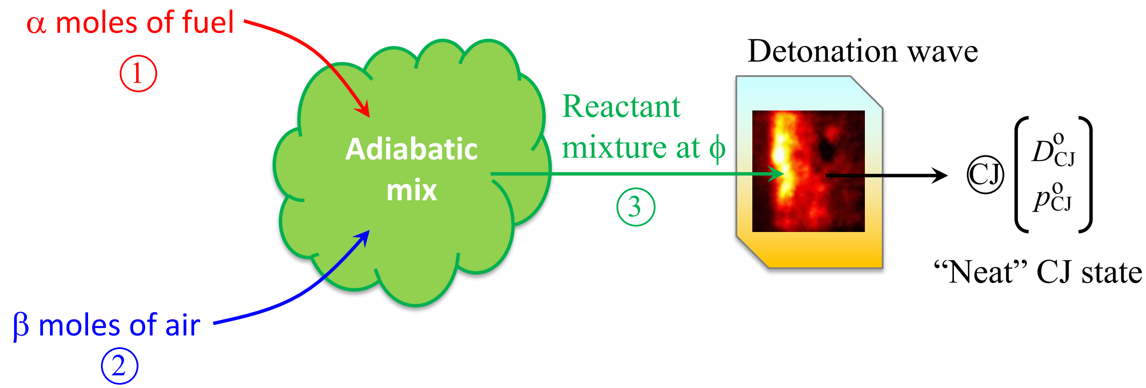




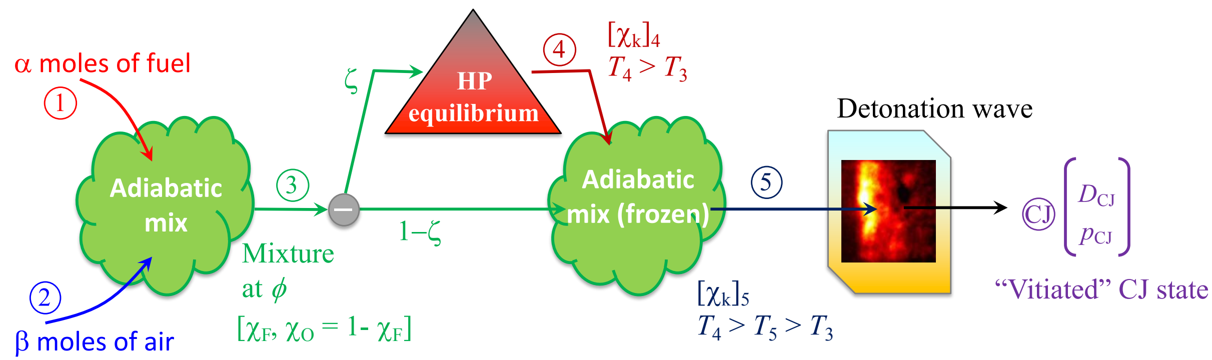
1. Air inlet
2. Steady non-vitiated fill region
3. Partially vitiated fill region
4. Buffer region
5. Products

Parasitic combustion decreases pressure rise

Neat fresh mixture path:



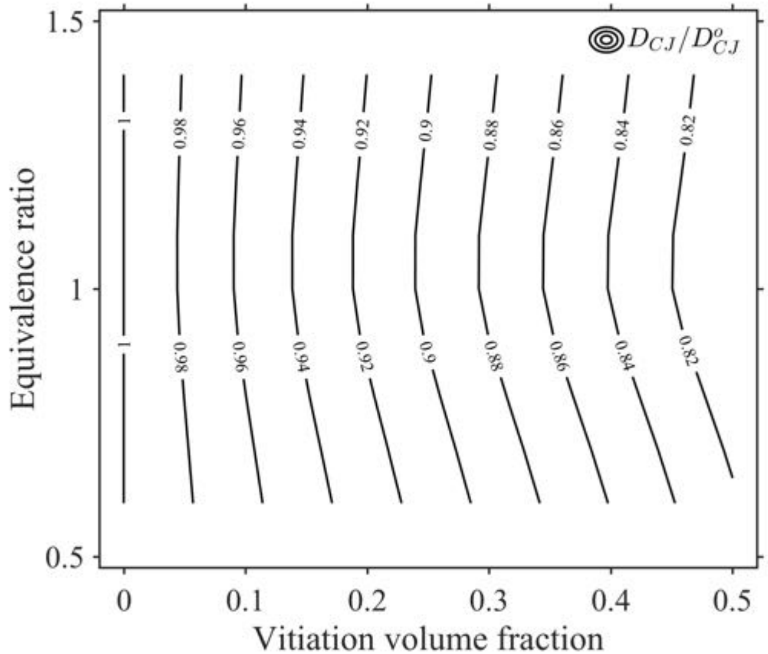
Vitiated fresh mixture path:

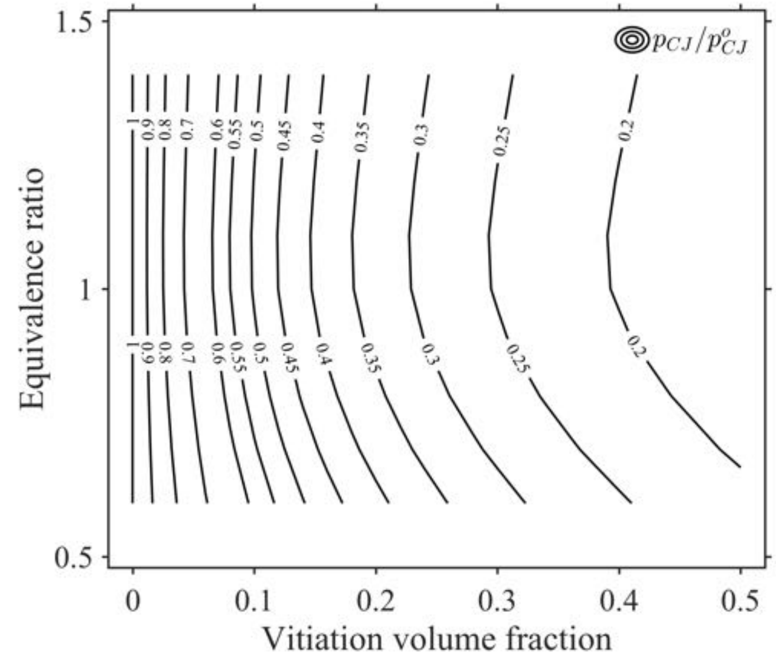


- Main effects of vitiation on detonation properties:
  - Pre-detonation temperature is higher
  - Less heat is released across the wave
  - Wave is slower: $D_{CJ} < D^{o}_{CJ}$
  - Pressure rise is lower: $p_{CJ} < p^{o}_{CJ}$

Vitiation slows the wave and decreases pressure rise

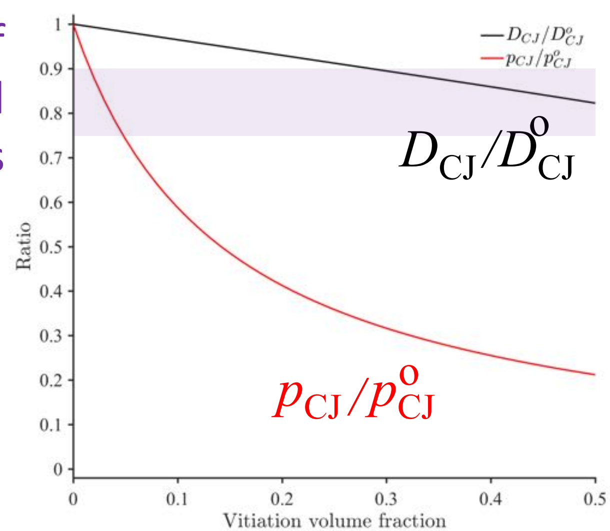
Hydrogen/air detonations, constant initial conditions

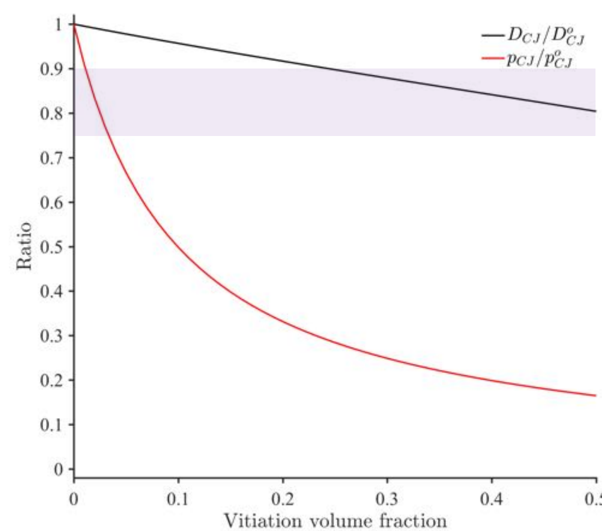




Range of observed values

$\phi = 0.6$





$\phi = 1.2$

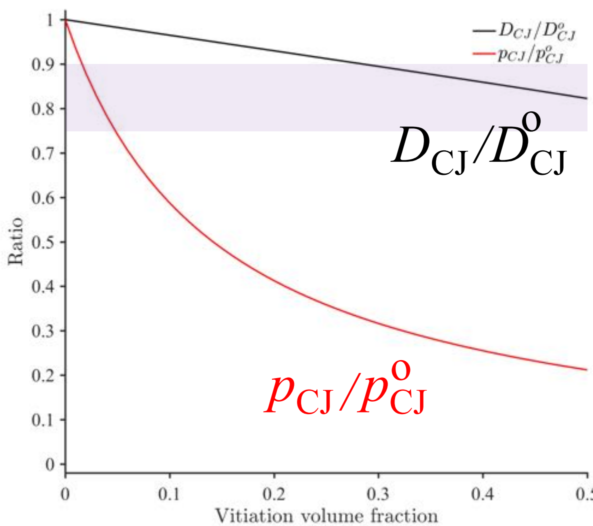
Vitiation slows the wave and decreases pressure rise

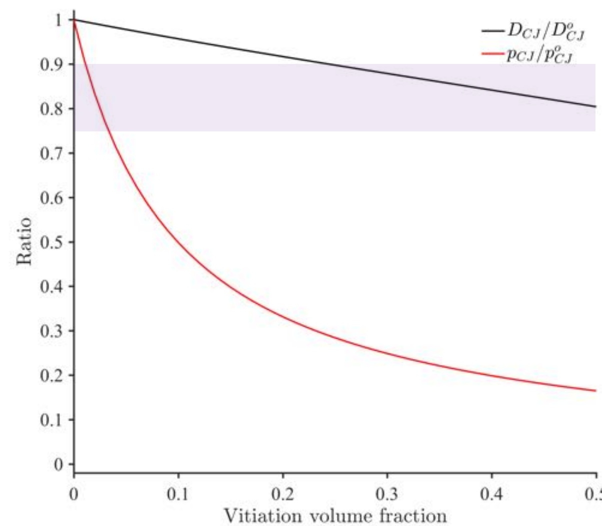
Hydrogen/air detonations, constant initial conditions

- Degree of vitiation can be affected by:
  - Geometry
  - Flowfield structure (e.g., flow separation regions)
  - Unsteadiness of the flow (scavenging)
- Vitiation may be one of various causes for loss of pressure rise; others might be:
  - Curvature effects
  - Lateral relief
  - Incomplete mixing
  - Partial heat release (incomplete combustion)

Range of observed values

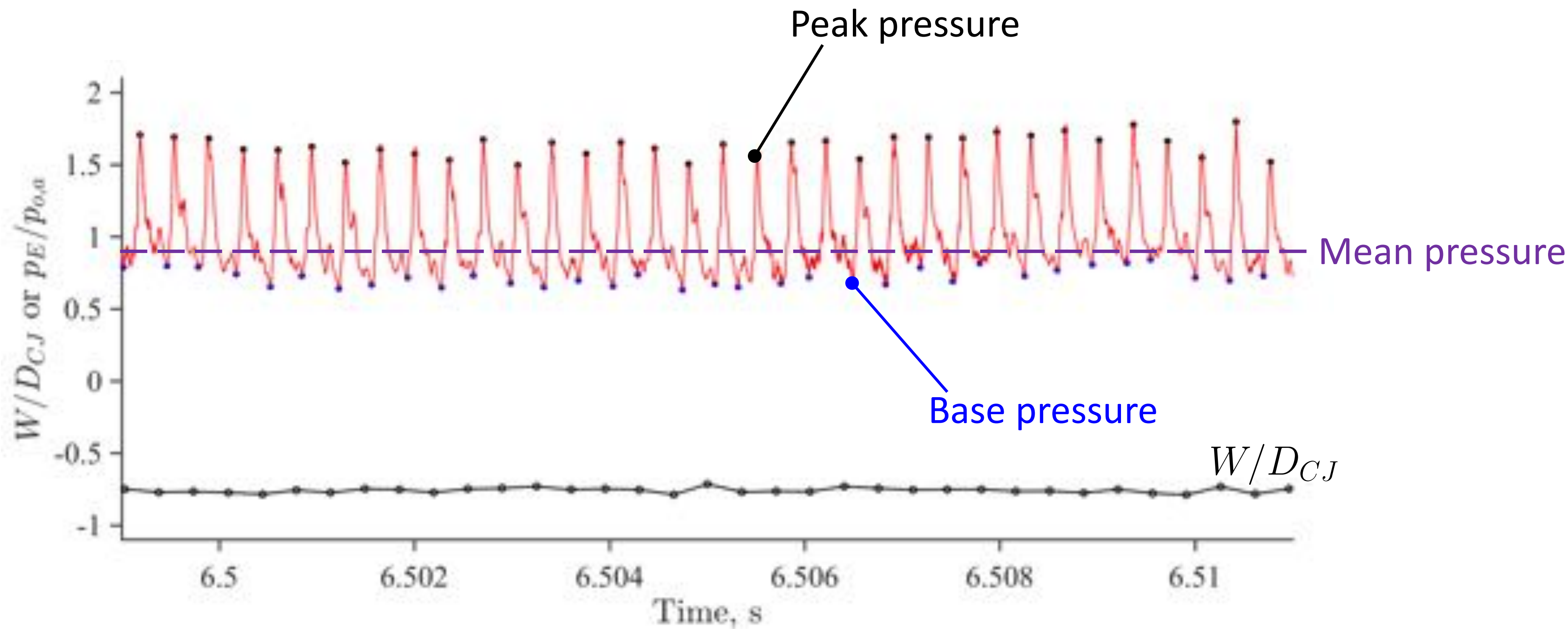
$\phi = 0.6$



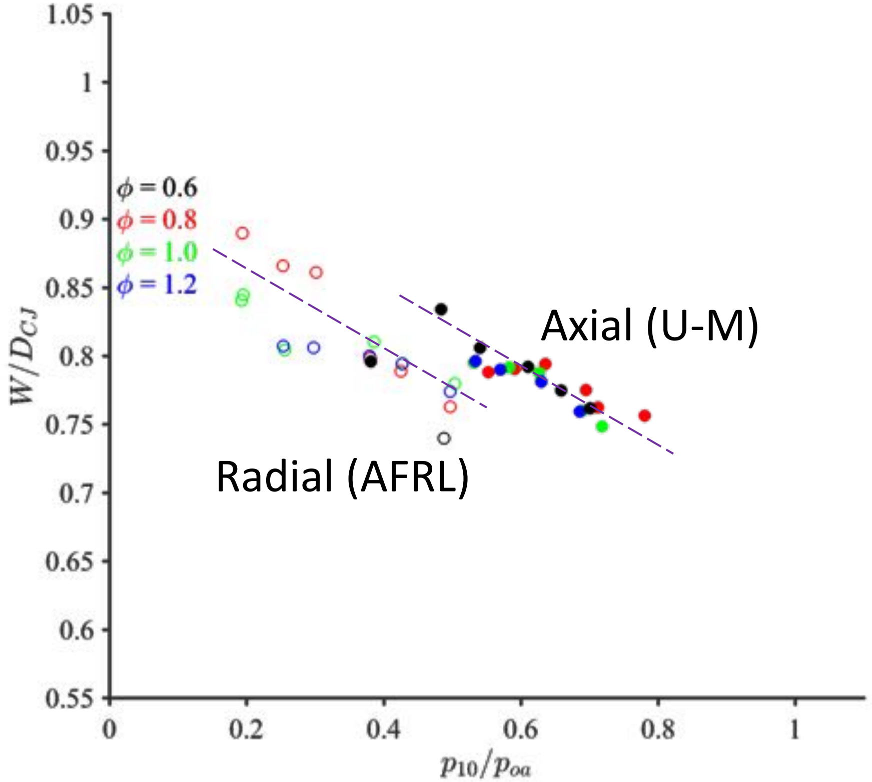


$\phi = 1.2$

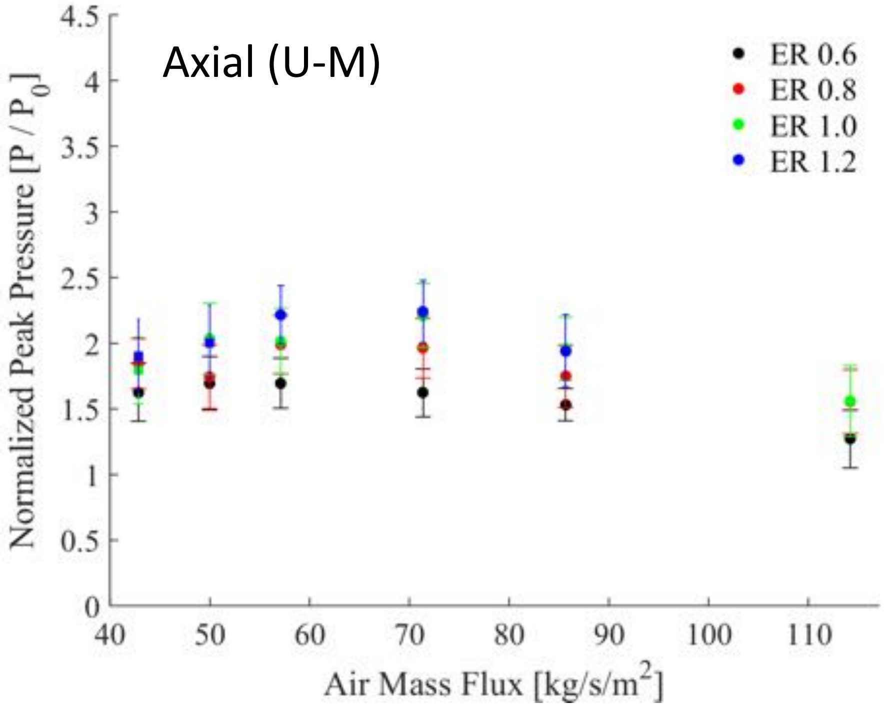
Comparison with measurements



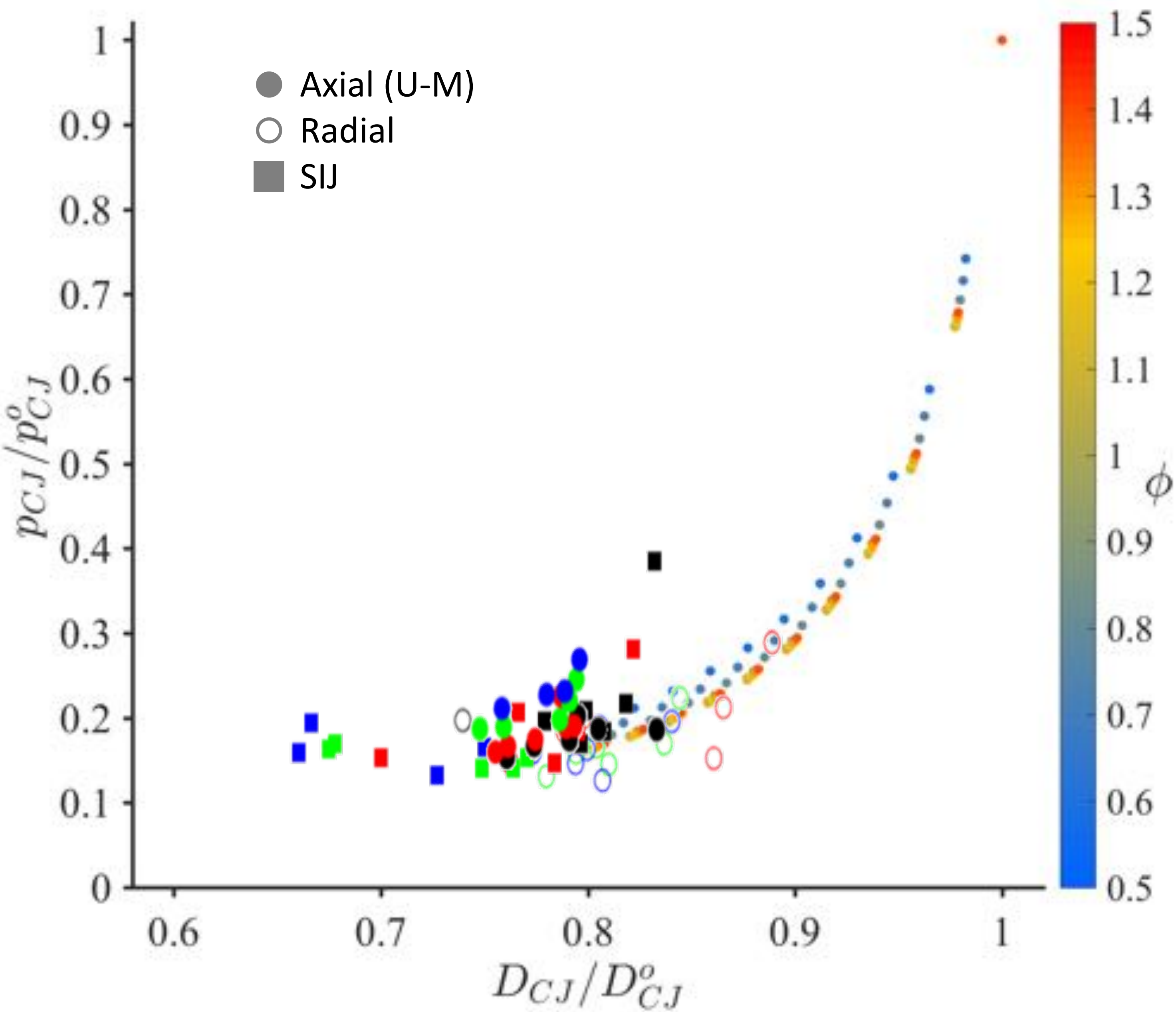
Comparison with measurements



Chamber to air plenum mean pressure ratio



Comparison with measurements



Lesson learnt

- **Mixing under steady operation is fairly rapid**
  - How different is unsteady mixing?
- **Racetrack was demonstrated to behave similarly to a round RDE**
  - However, additional wave reflections at straight-to-curve transitions are found, limits operation stability
- **About the distribution of heat release**
  - Not all heat is released across the detonation wave
    - Mixture leakage, possibly due to instantaneous unmixedness
    - Parasitic combustion consumes mixture before wave arrival (partial pre-ignition)
  - Complex distribution of parasitic combustion regions
    - Depends on operating conditions
    - Possibly affected by differential response of air inlet / fuel injector
    - Scavenging and backflow might play a role
- **Leakage and parasitic combustion can:**
  - Effectively vitiate fresh mixture
  - Reduces wave speed and peak pressure across wave

Next steps for experimental program

- **Steady mixing**
  - Improving measurement system to reduce uncertainties
  - New calibration cells just delivered
  - Repeat measurements over range of J, Mach numbers, and on different planes
- **Racetrack RDE**
  - Conduct visualizations (schlieren/shadowgraph) to visualize response of air inlet and fuel injector
  - OH PLIF imaging to identify location of detonation wave vs deflagration regions
  - (Qualitative) mixing measurements to evaluate
    - Acetone PLIF measurements
    - Unsteady mixing characteristics
    - Air inlet and fuel injector response

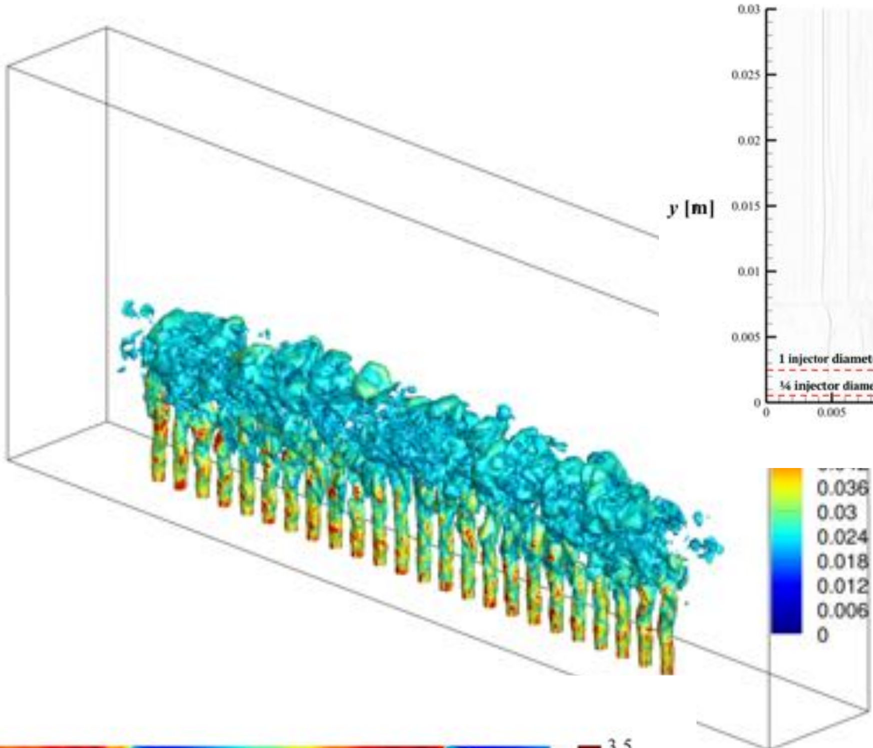
Outline

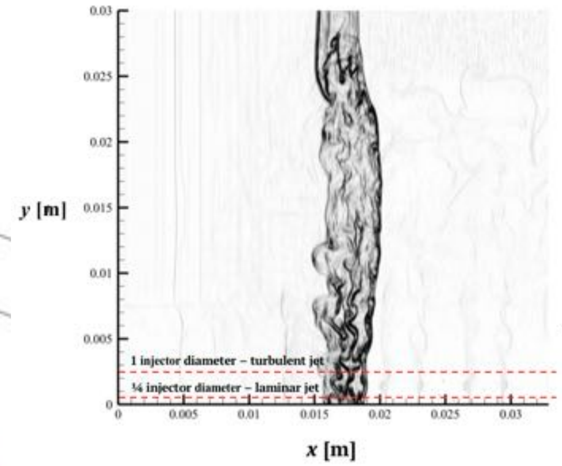
- Introduction to the problem and general approach
- Experimental activities
- Computational activities

Detonation Structures in Stratified Flows

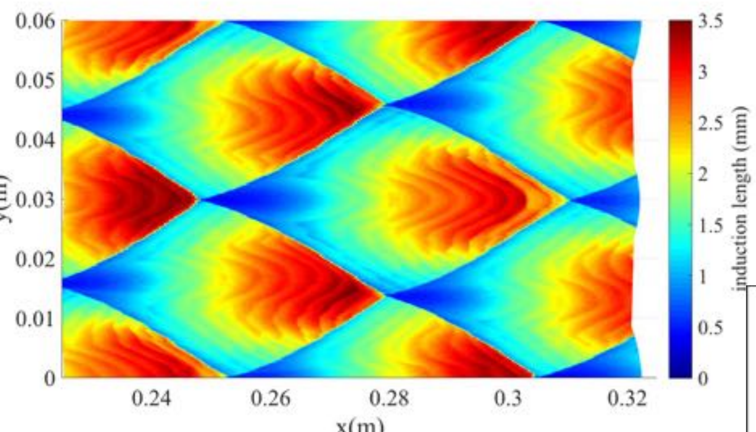
Supraj Prakash, Takuma Sato, Venkat Raman

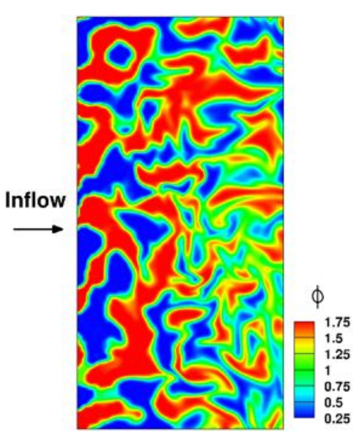
UM Computational Program on RDEs



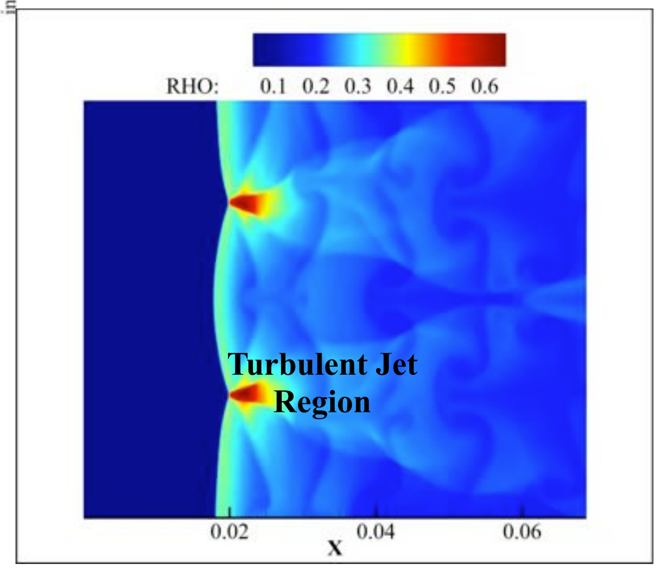


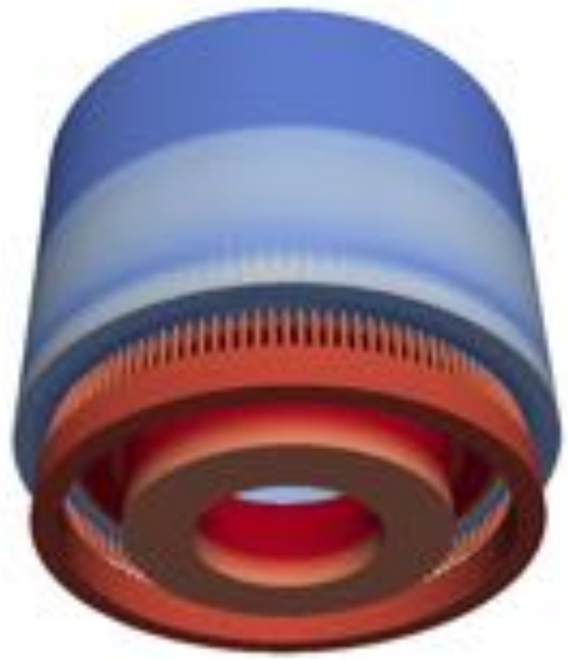
Basic Research

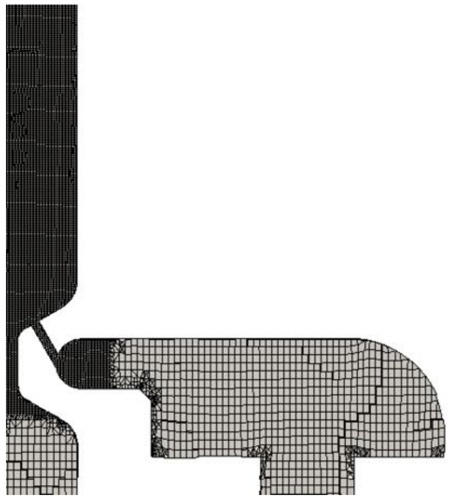


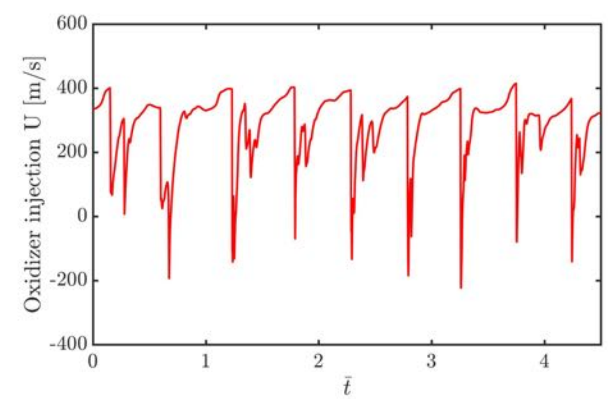


Laminar Jet Region



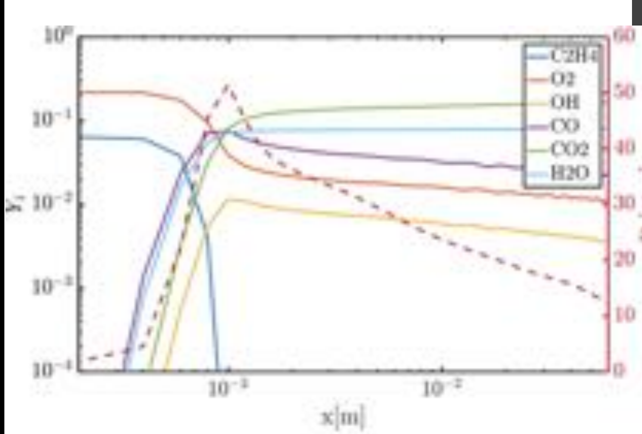


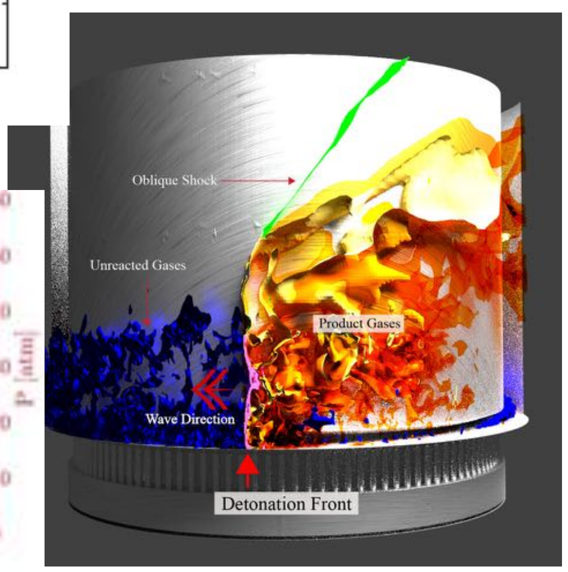




Full scale systems

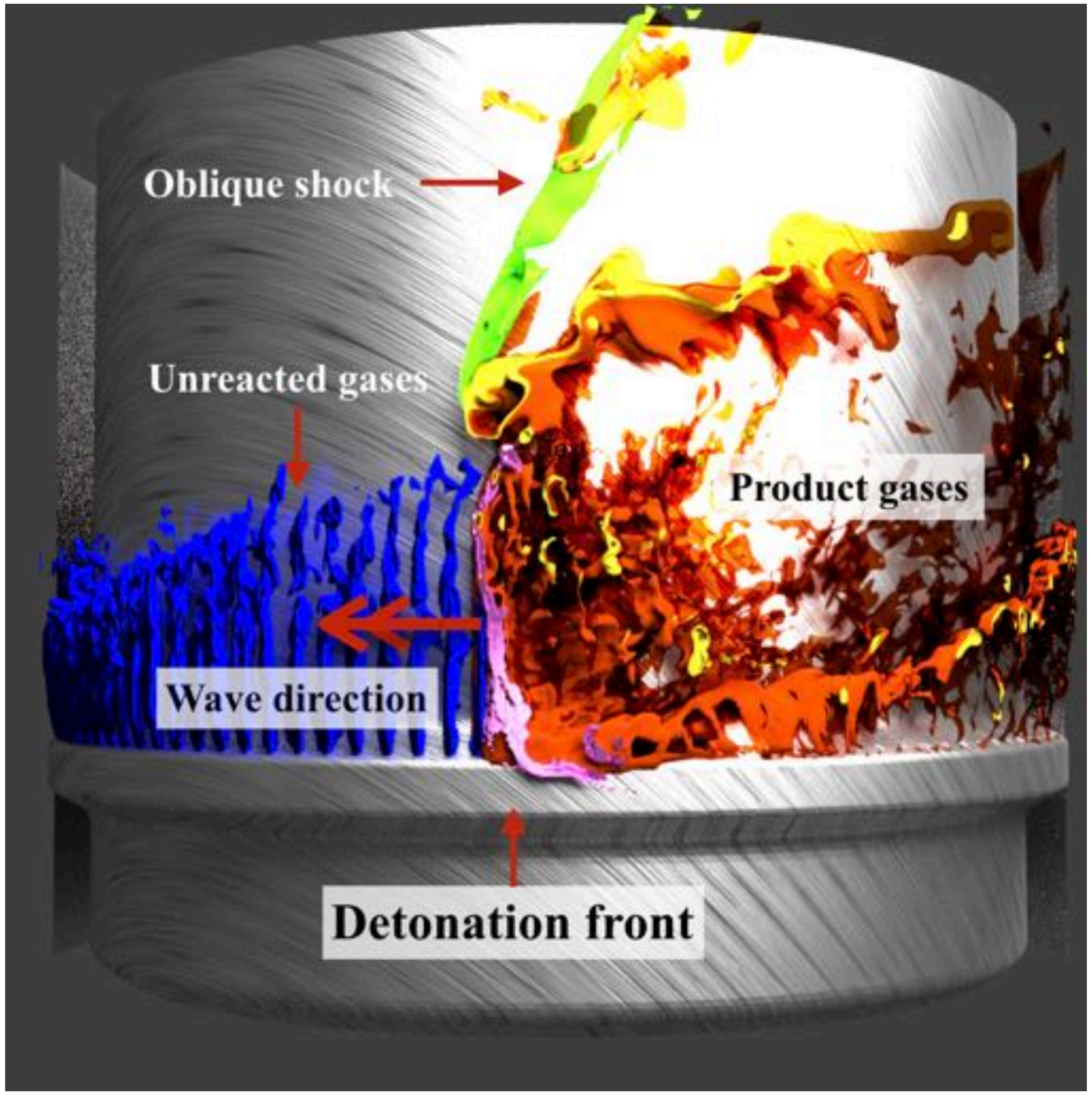
- Scalable Solvers
- Full Chemistry





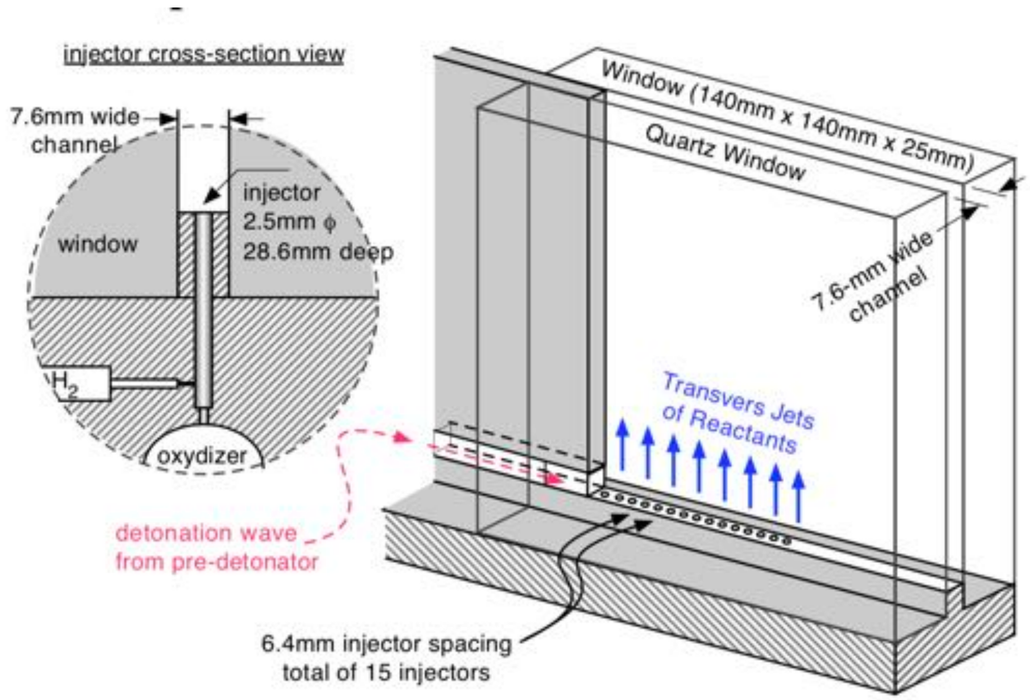
Effect of Fuel Stratification

- **Fuel-air mixing not complete before wave arrives**
  - Strong spatial variations in equivalence ratio
- **What is the effect of such variations**
  - Structure of detonations in stratified mixtures

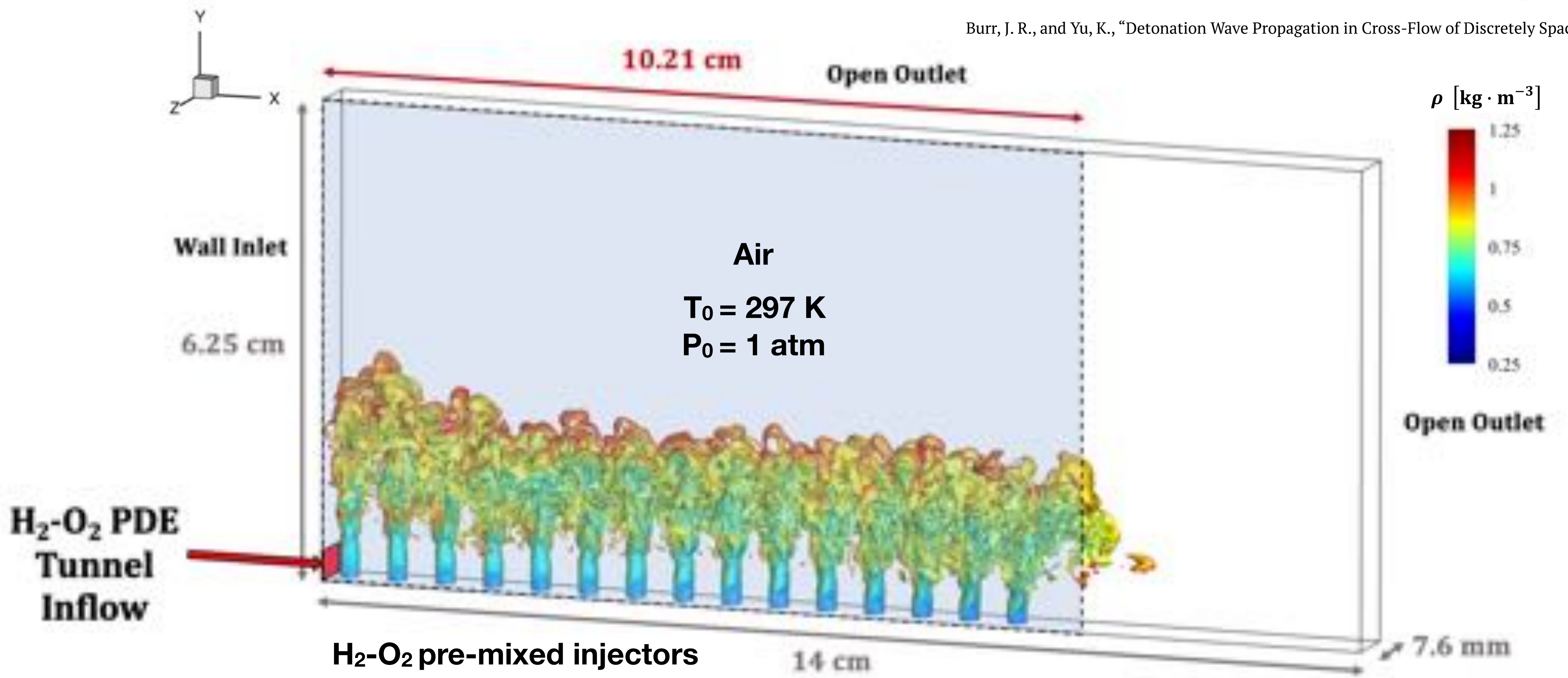


LMDE Configuration

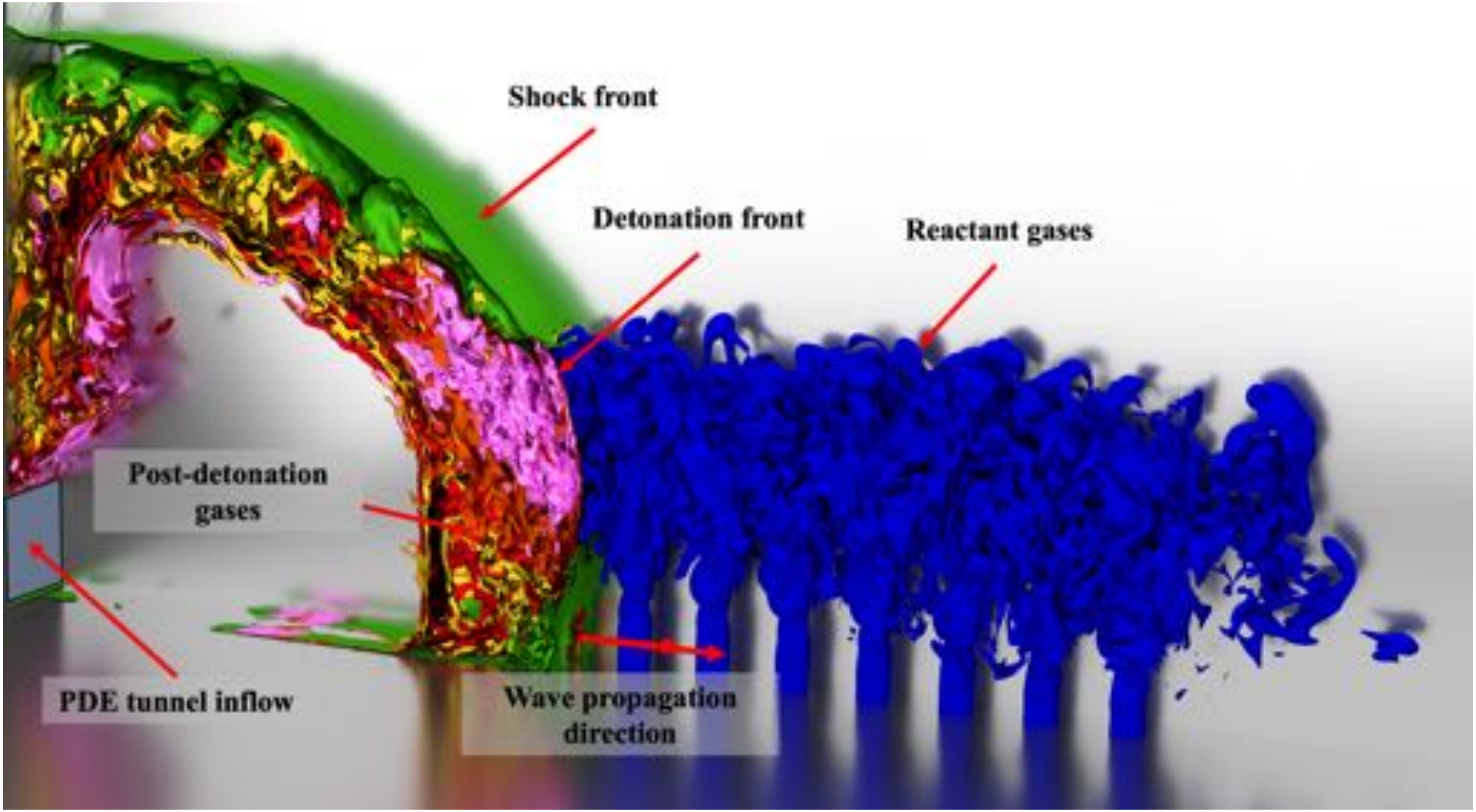
- **Canonical RDE geometry**
  - 15 premixed injectors of 2.5 mm diameter
  - 6.4 mm center-to-center spacing
  - Pulse detonation engine (PDE) inflow



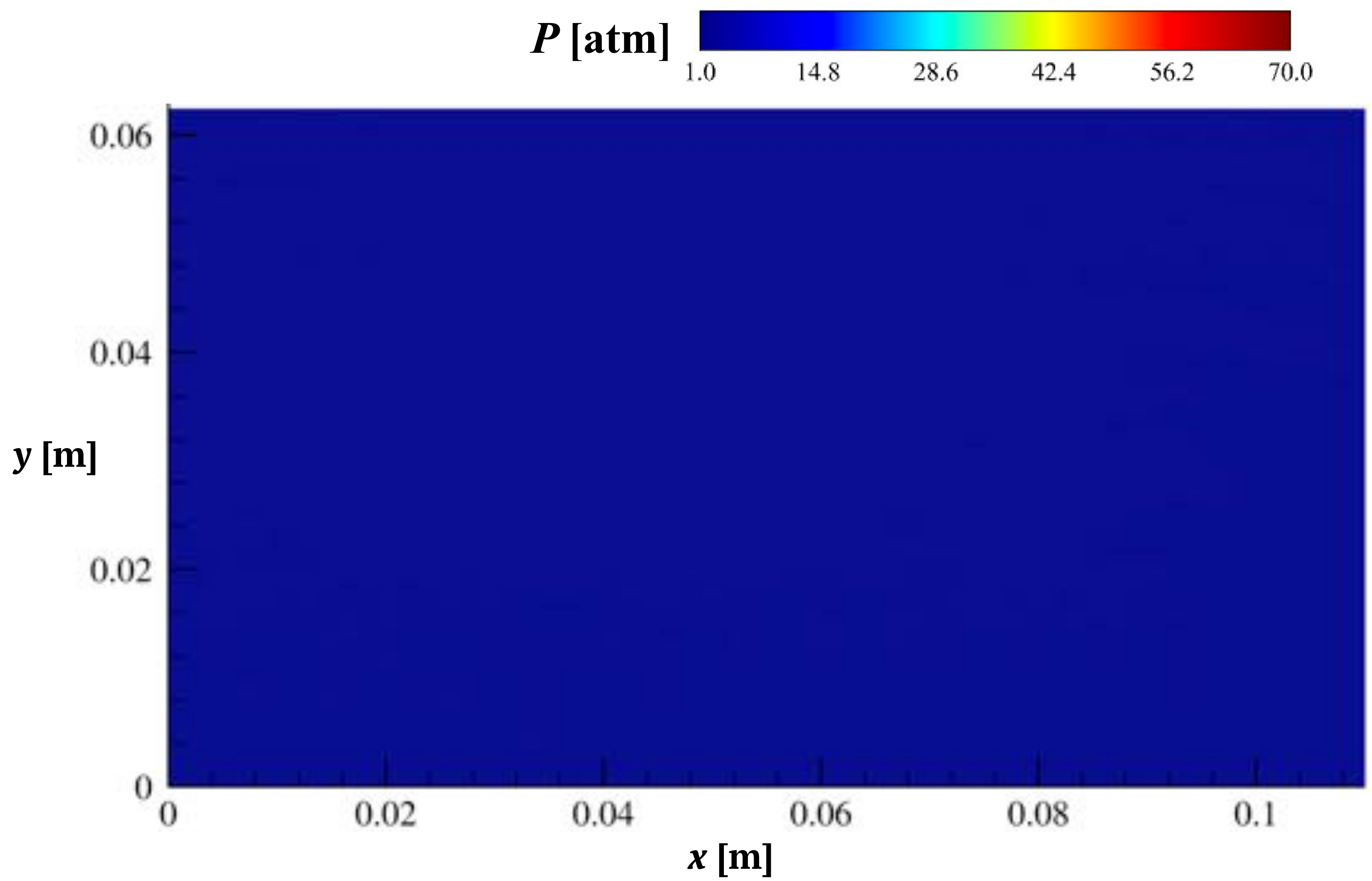
Burr, J. R., and Yu, K., “Detonation Wave Propagation in Cross-Flow of Discretely Spaced



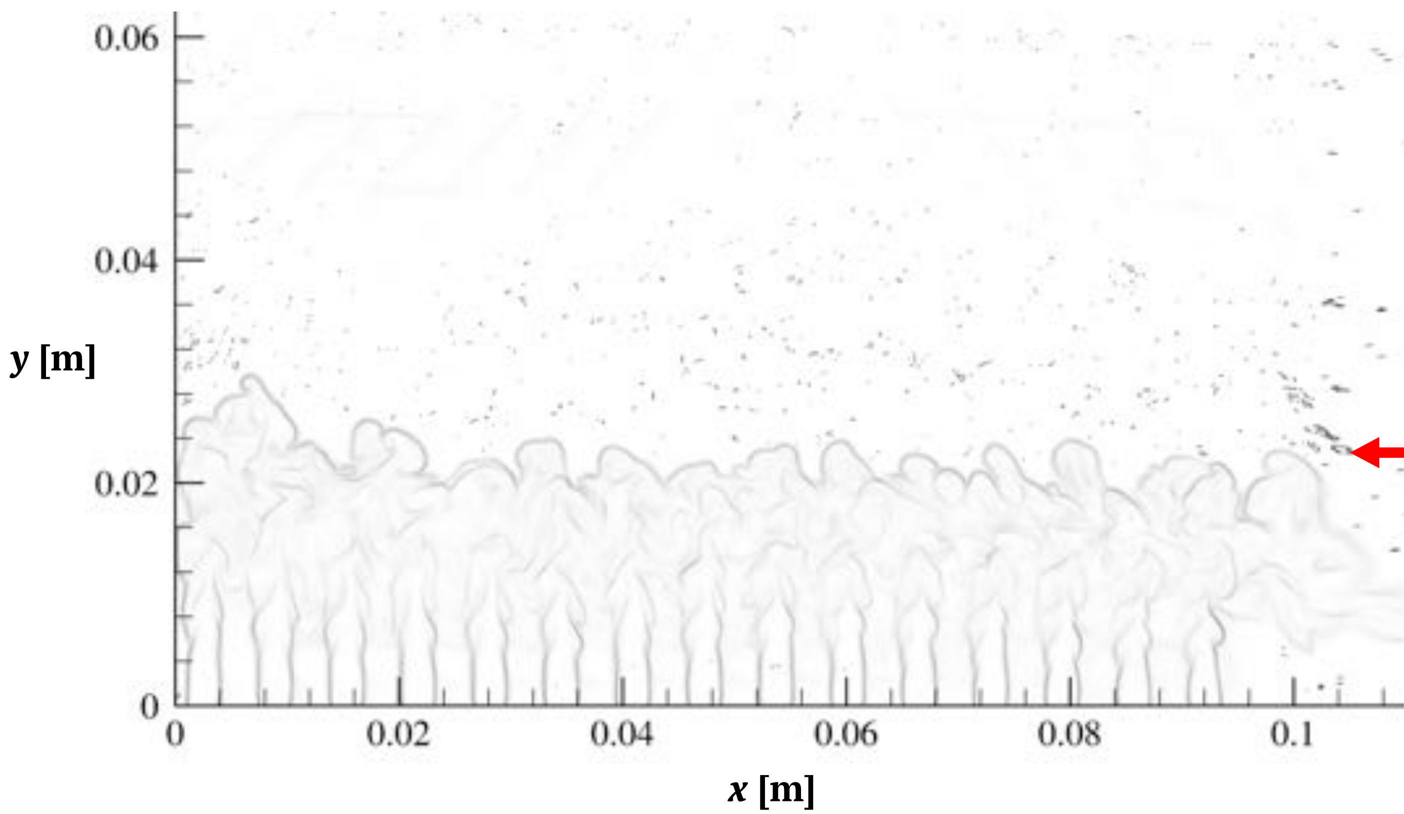
Detonation Structure



LMDE Detonation Wave



- **Clear presence of triple points**
- **Reaction zone broadens with bands of deflagration zones**

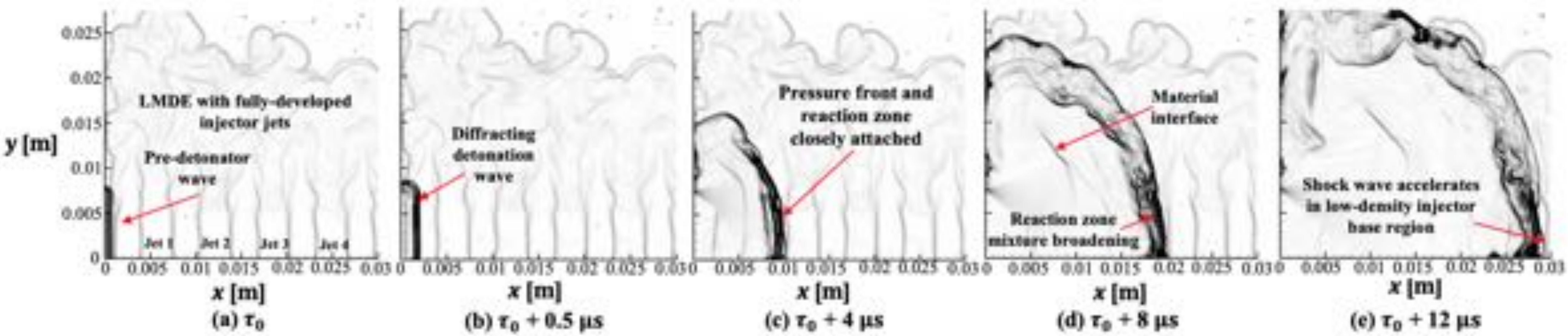


Detonation edge height as shock and reaction fronts separate

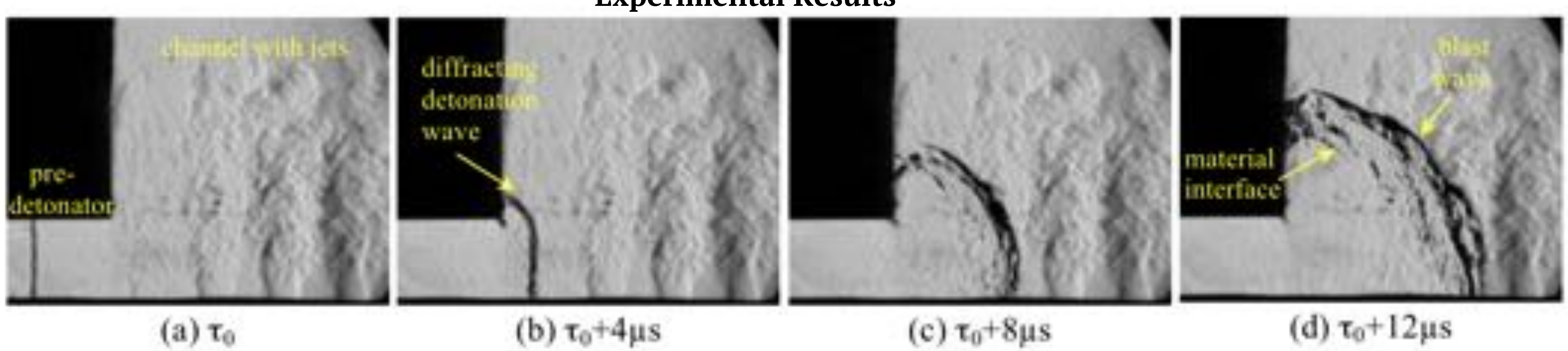
Detonation Wave Behavior in LMDE

- **3D detonation wave consists of complex reaction zone**
  - Broadening reaction zone with detonation to deflagration regions
  - Turbulent mixing of post-detonation and intermediary gases behind triple points

Numerical Schlieren



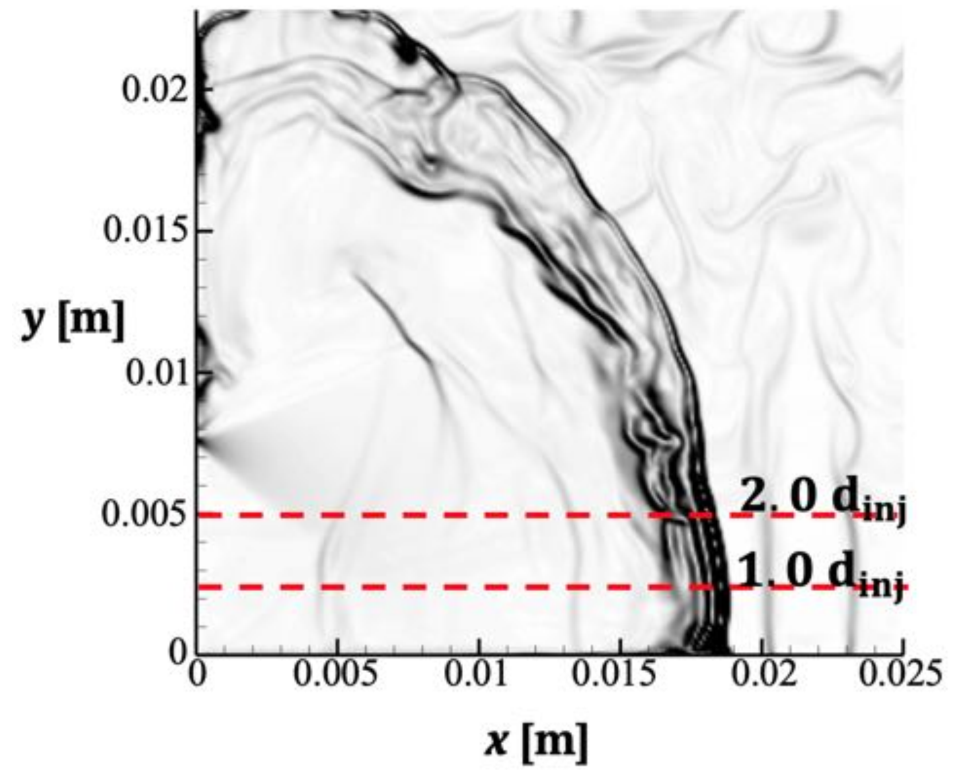
Experimental Results



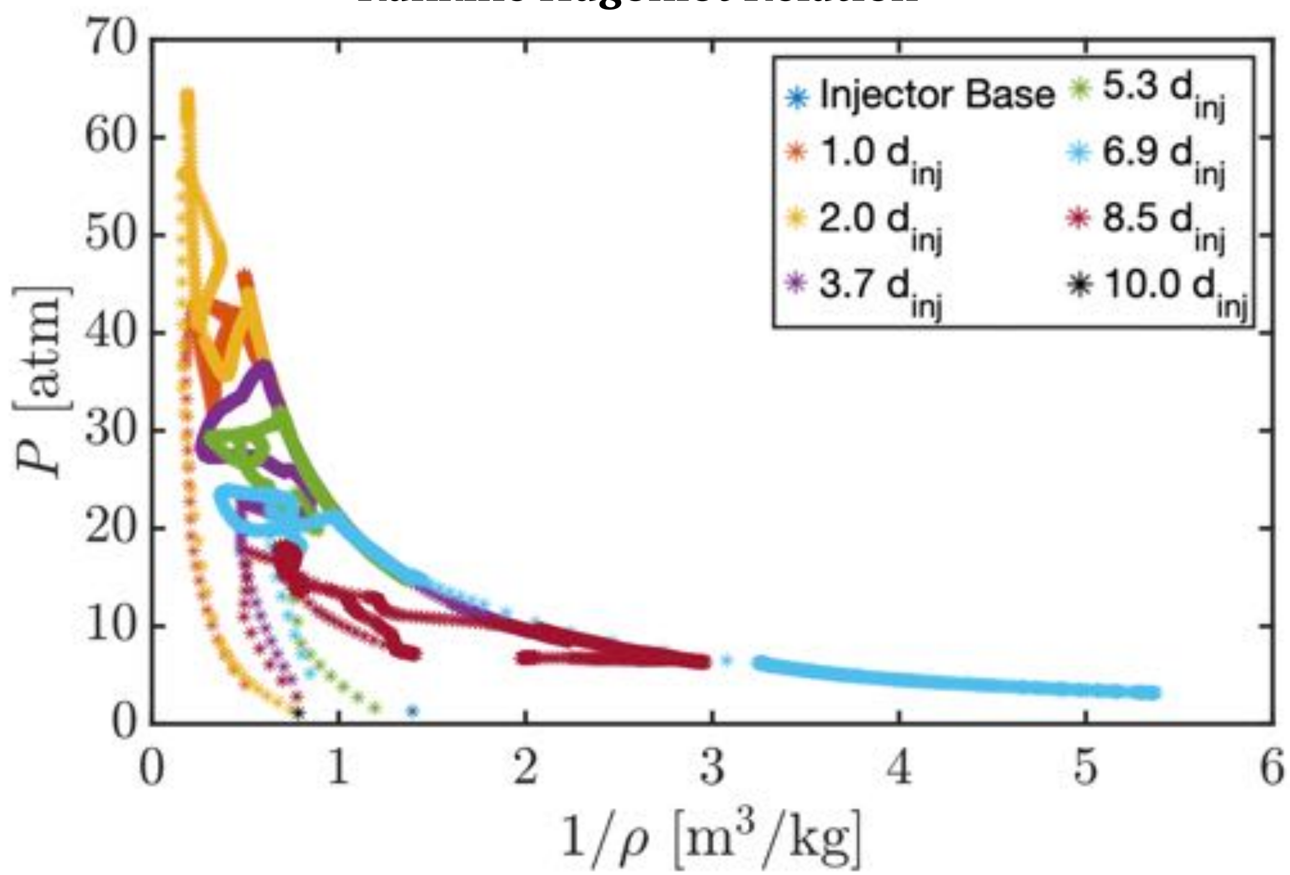
Numerical results closely resemble experimental detonation behavior

Detonation Analysis

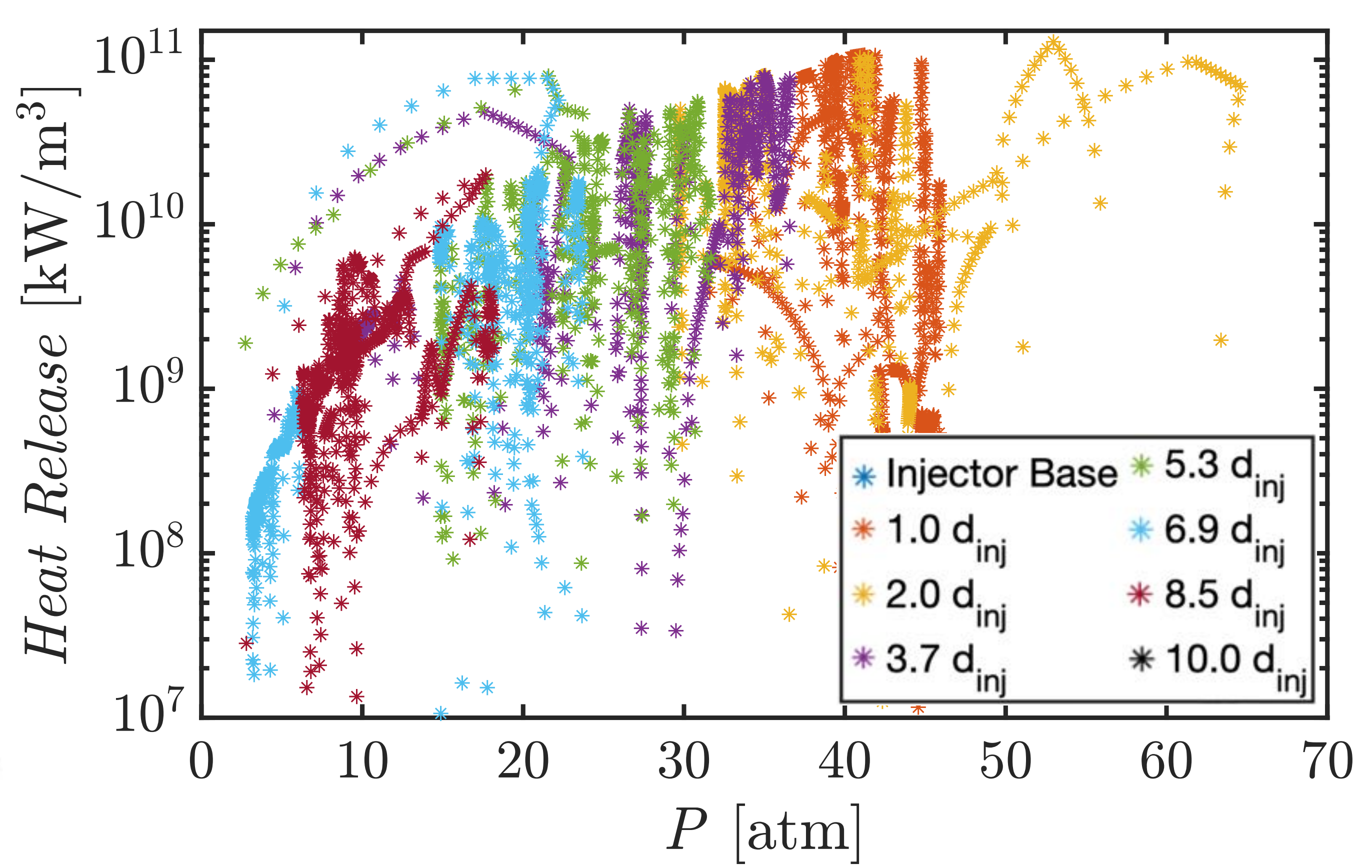
- **Strong detonation at twice jet diameter**
- **Transition to deflagration at 5.3-6.9 injector diameters from base of channel**
    - Heat release local maxima in deflagration region
- **Peak heat release at von Neumann pressure of H_2-O_2 detonation**
    - Local maxima at ~42 atm - von Neumann condition
    - Additional peaks correspond to triple point collisions



Rankine Hugoniot Relation



Heat Release per Unit Volume Relation



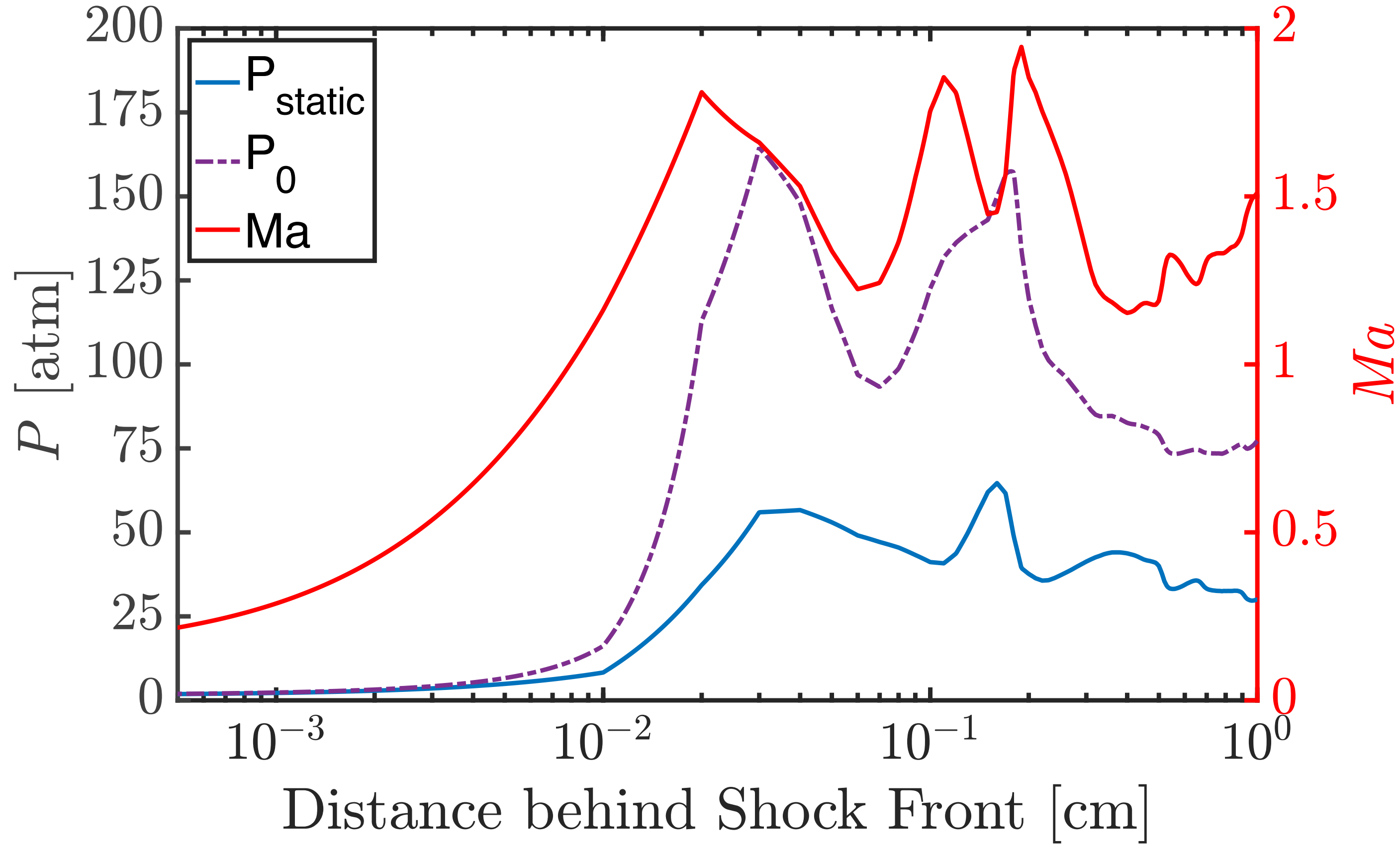
Shock-normal Profiles

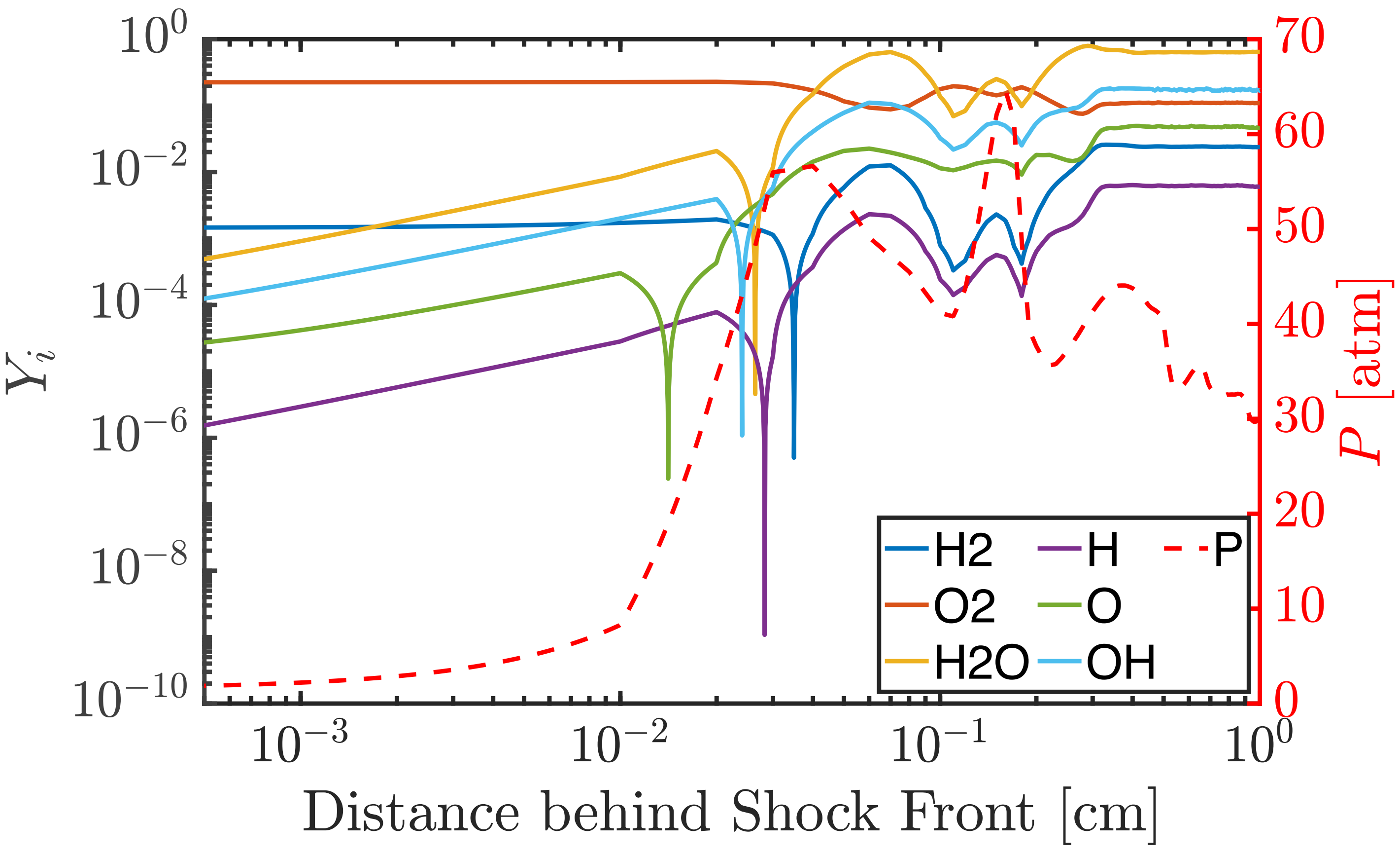
- **Structure behind detonation wave affected by prior injectors**

- **Complex reaction zone with multiple pressure peaks - fuel stratification affects profile**

  - Residual post-detonation products from previous injectors captured in reaction zone

  - 2 “buckets” corresponding to the 2 processed injectors

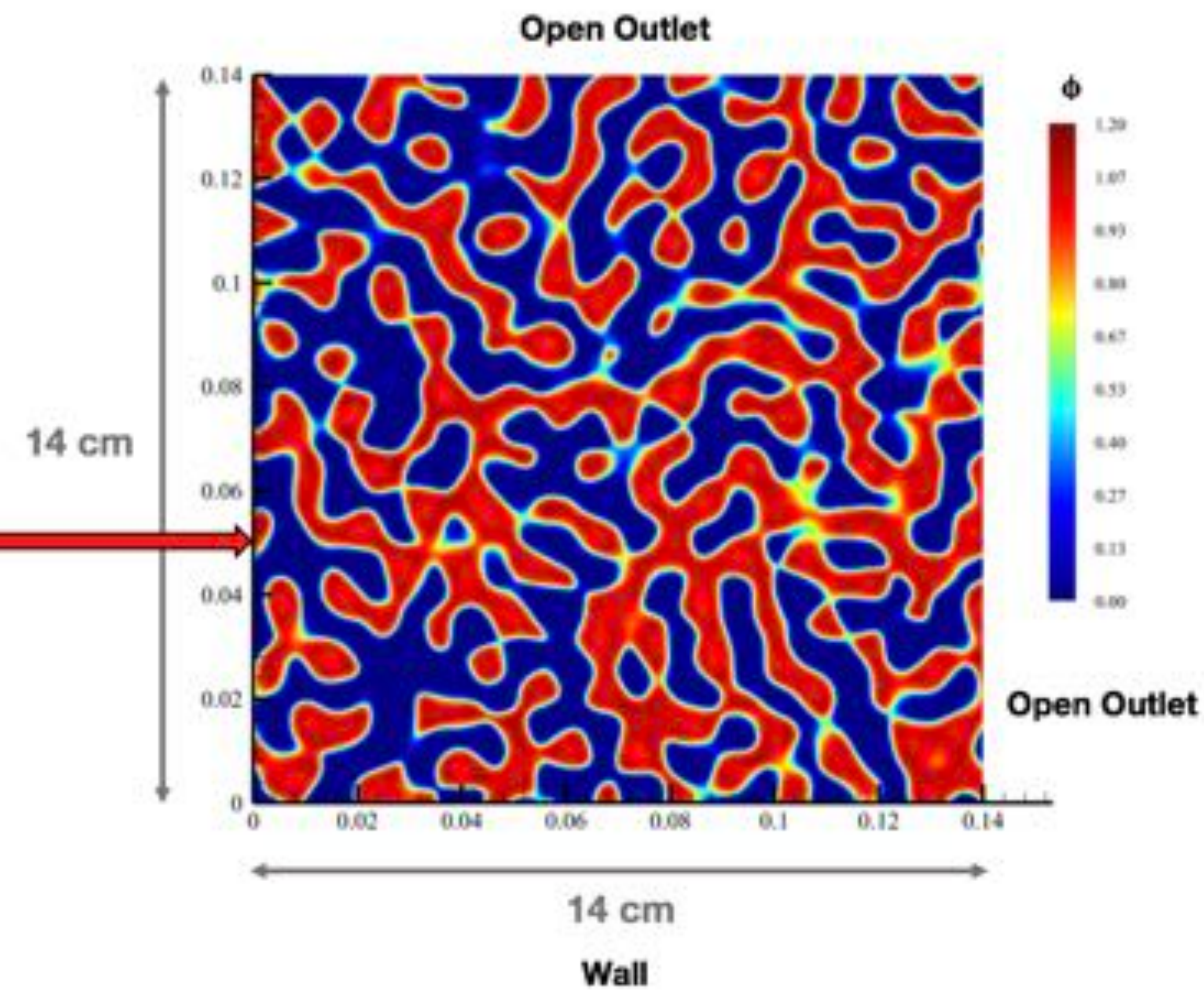


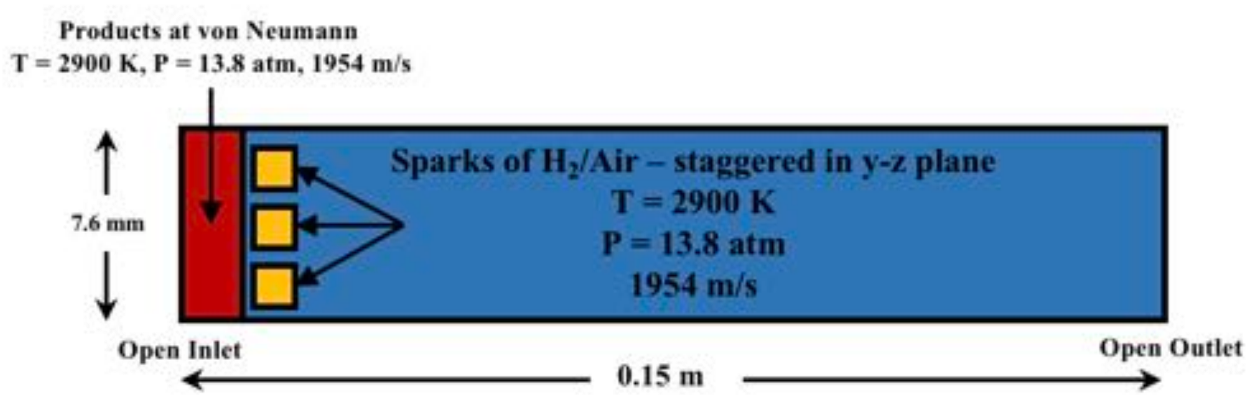


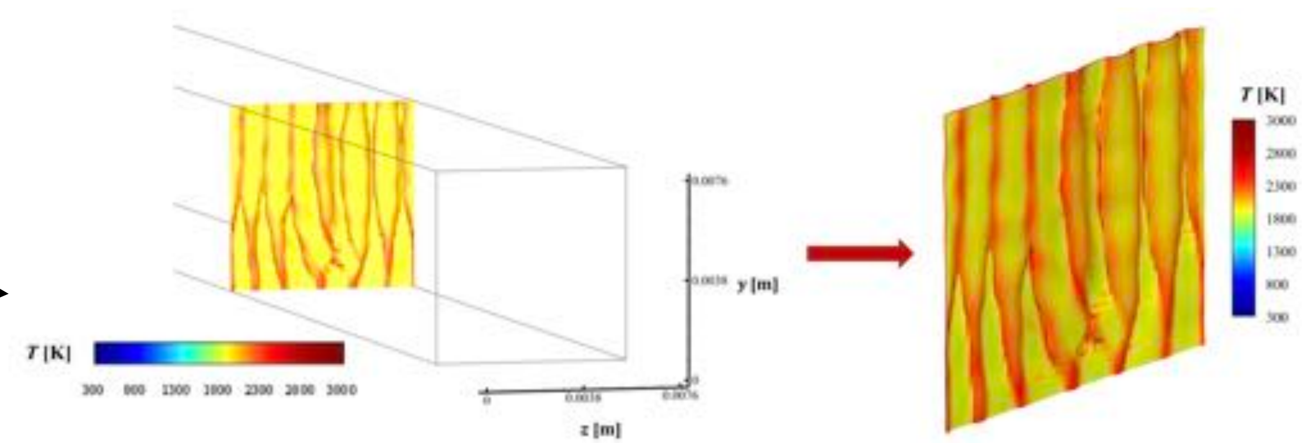
Stratified Detonation

- **H_2/air fuel-air mixture**
- **Air background mixture**
    - P_{amb} = 0.5 atm
    - T_{amb} = 297 K

Full LMDE Inlet Inflow

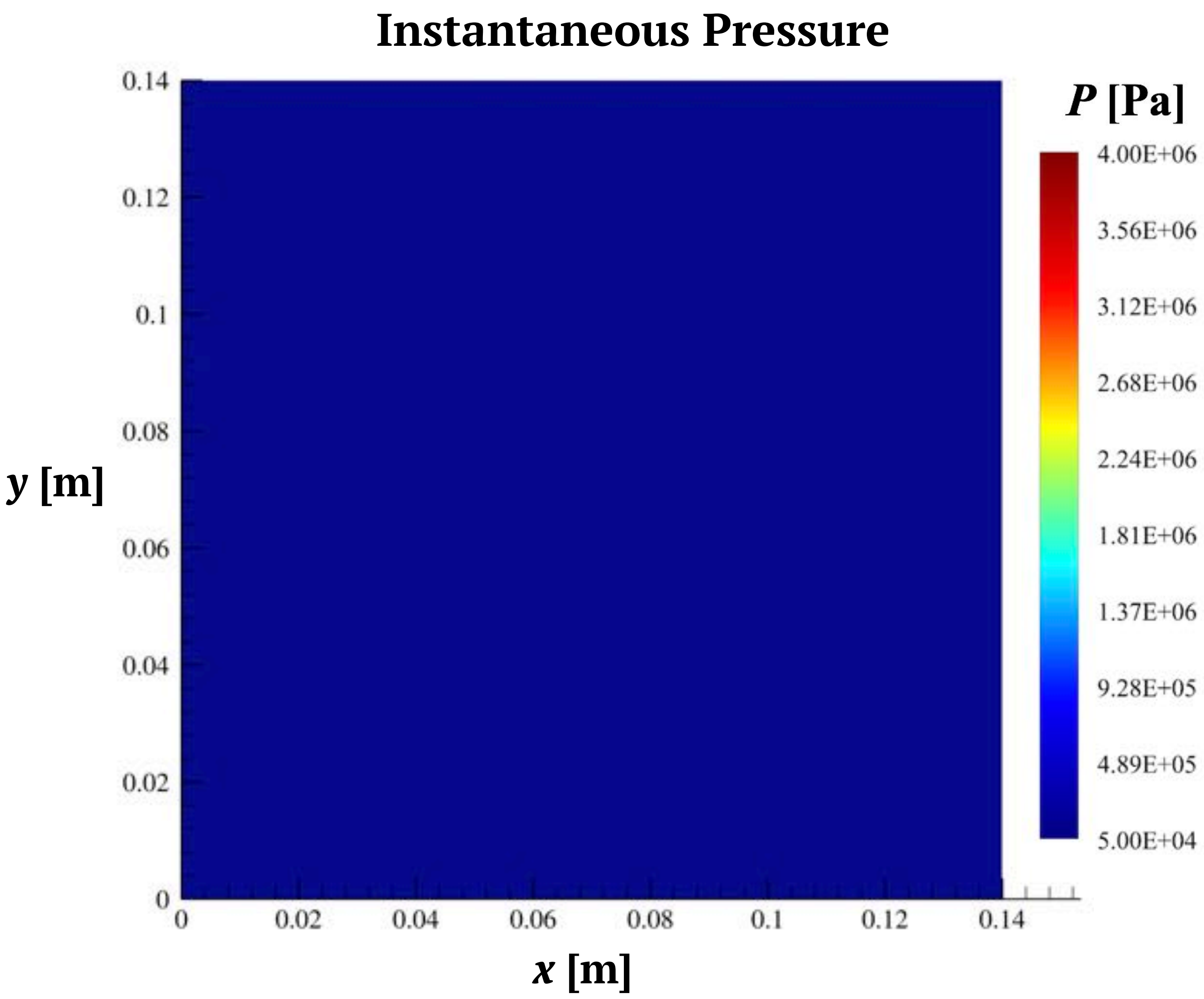


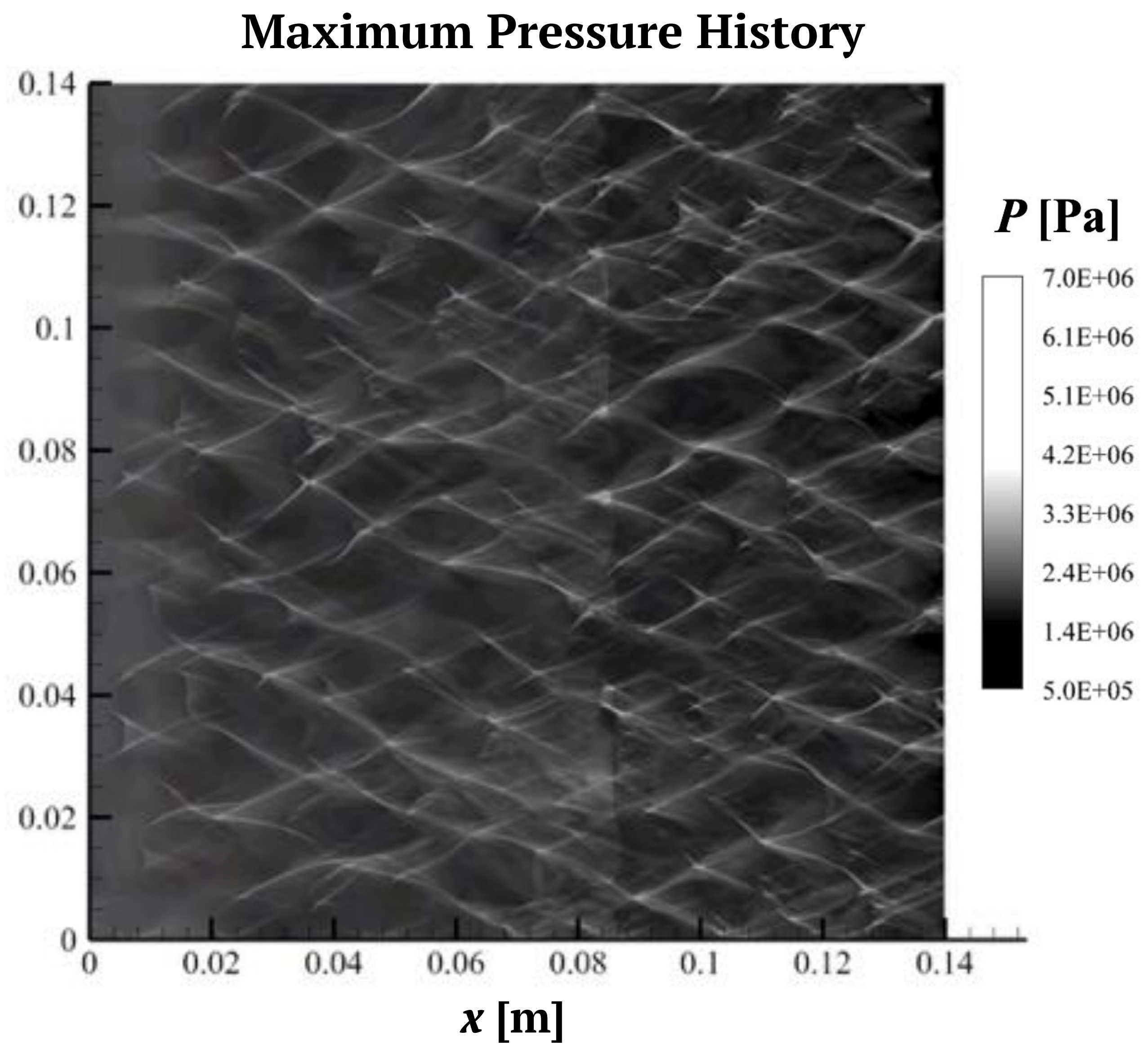




Detonation Wave Behavior

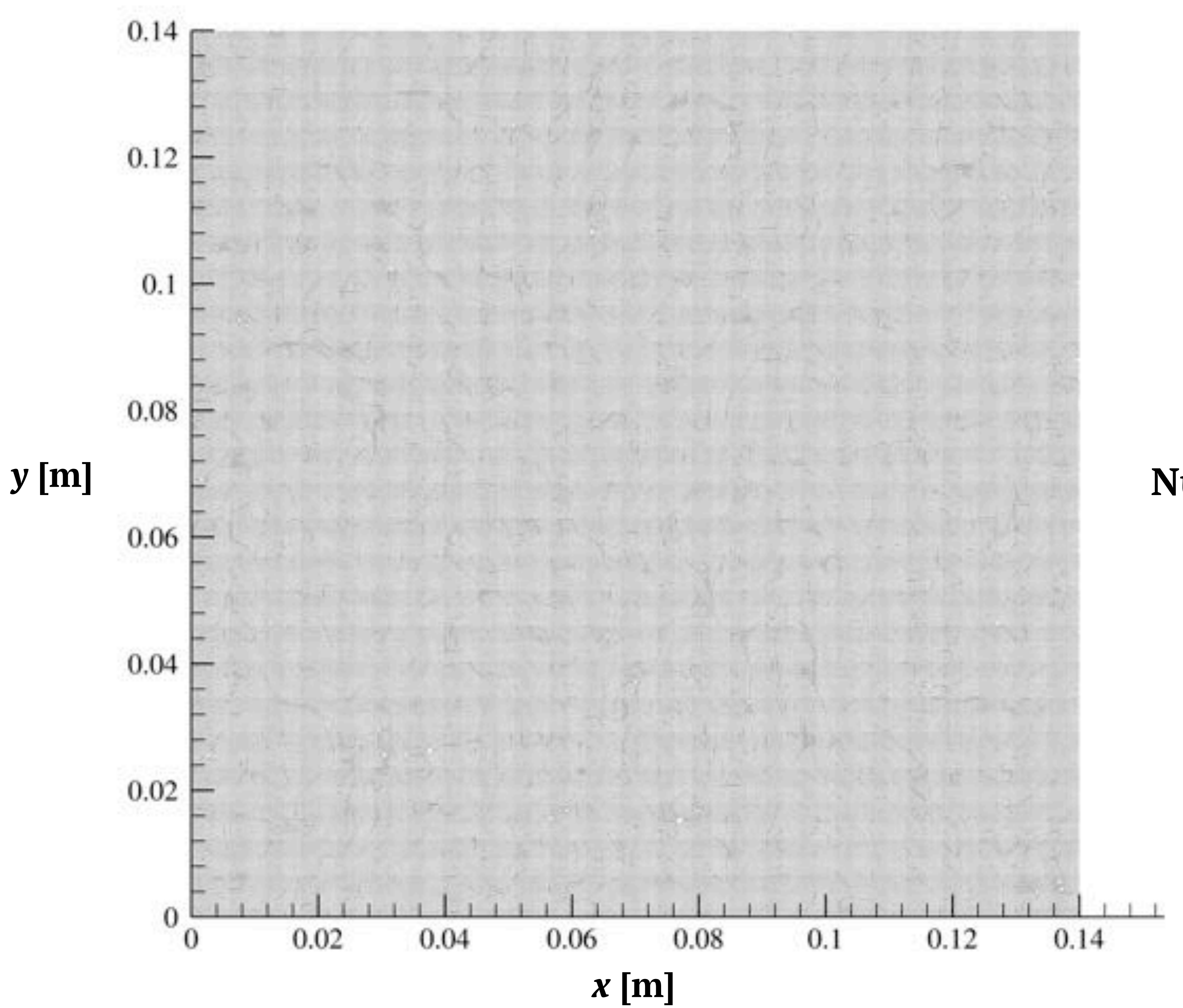
- **Triple points form as detonation wave interacts with fuel-air mixture**
- **Detonation wave maintains regular "fish-scale" cell structure as detonation wave stabilizes**
    - Variation in fuel-air mixture temporarily alter detonation cell size





Detonation Onset and Turbulent Mixing

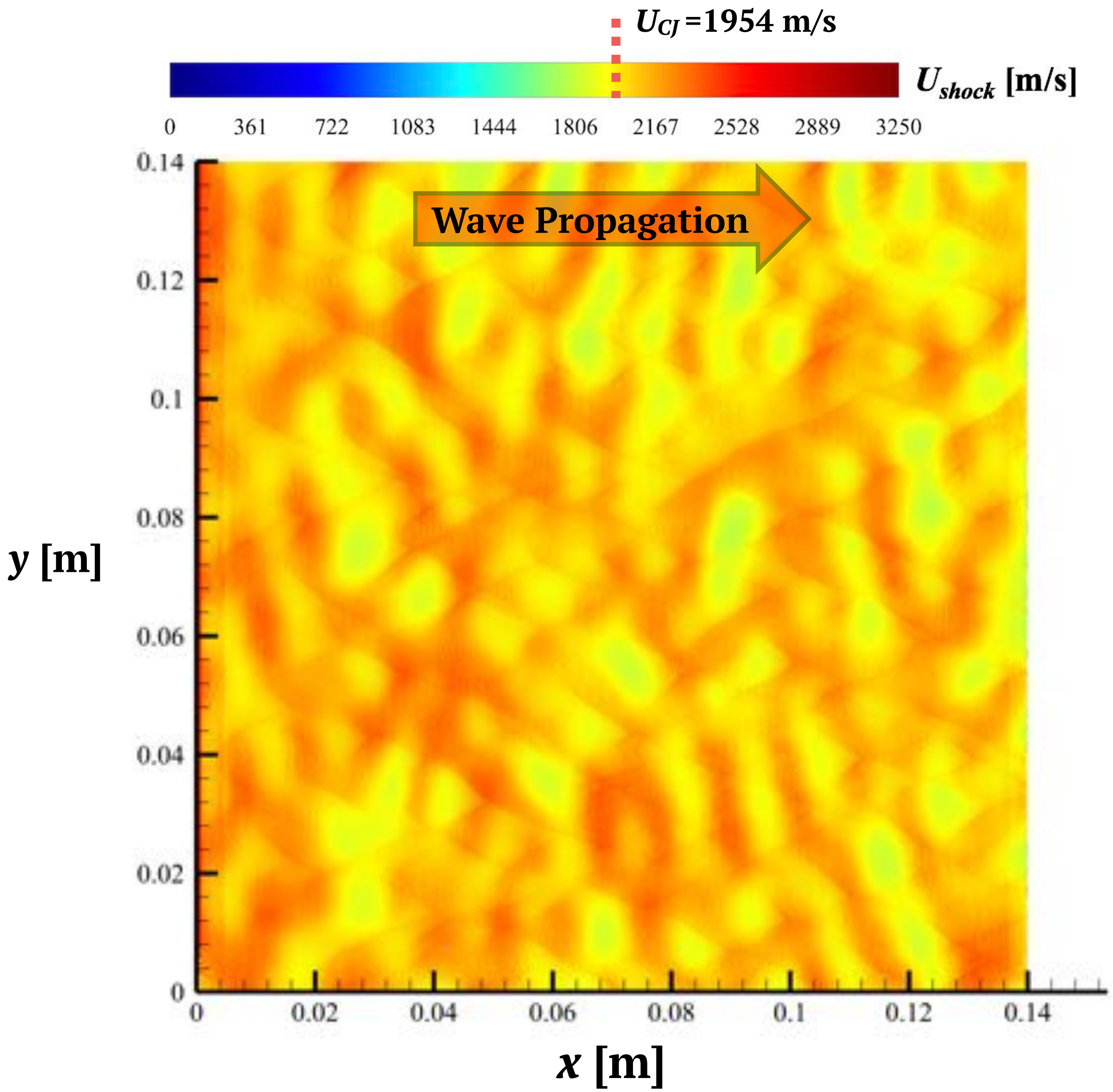
- **Reflection of pressure waves from triple points sustain detonation wave**
- **Complex reaction zone with residual post-detonation products mixture**

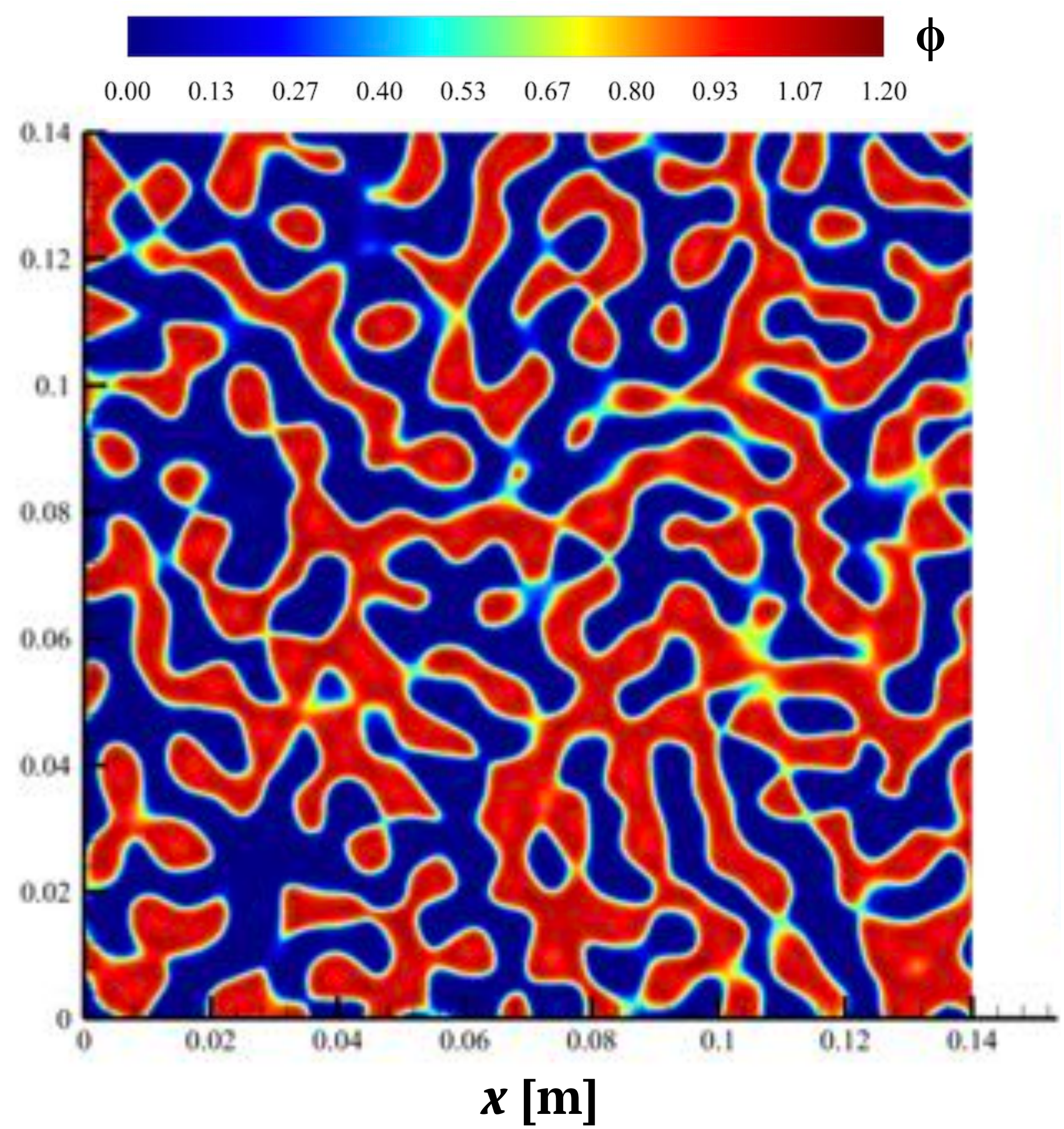


Numerical Schlieren

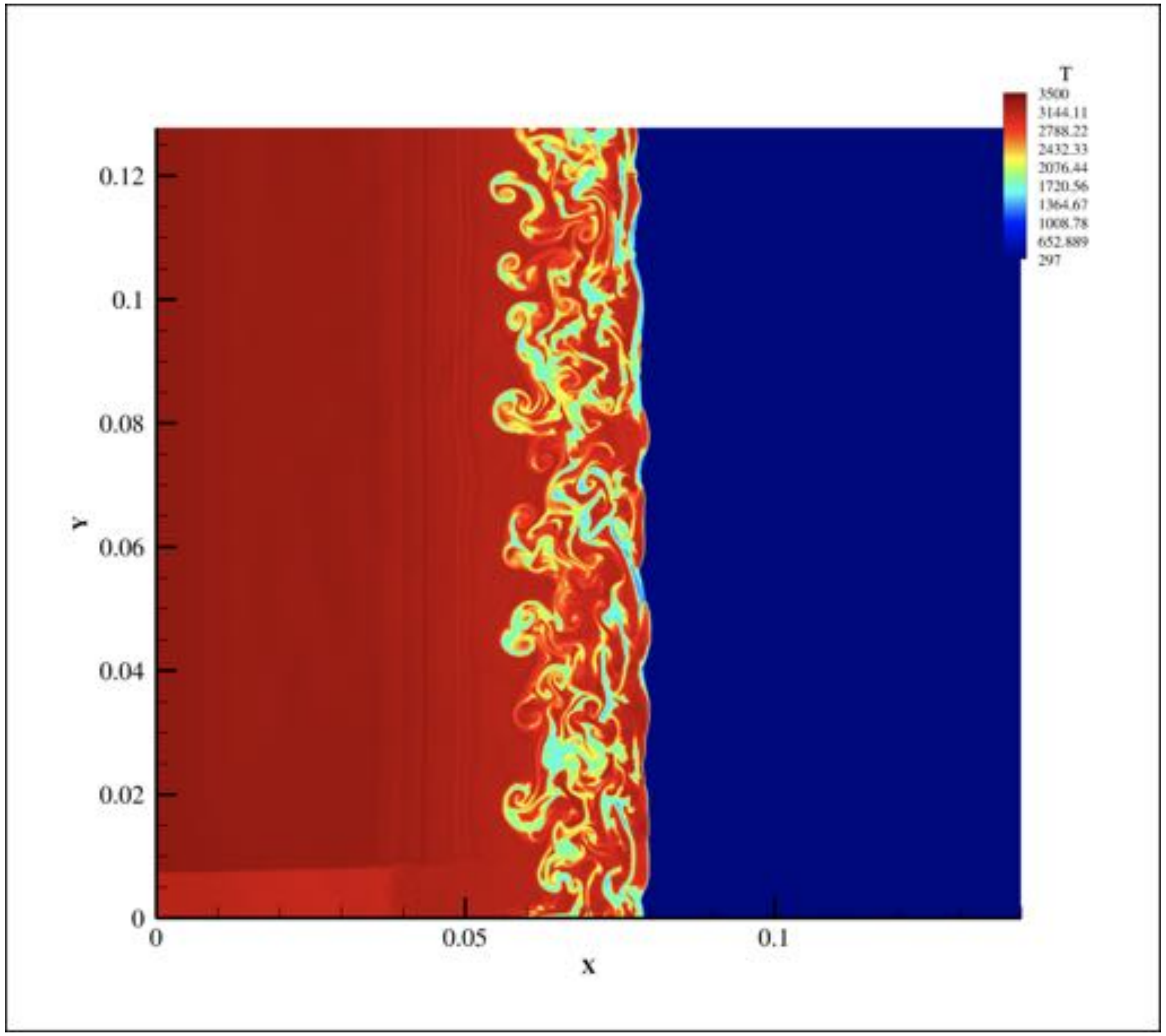
Shock Front Velocity

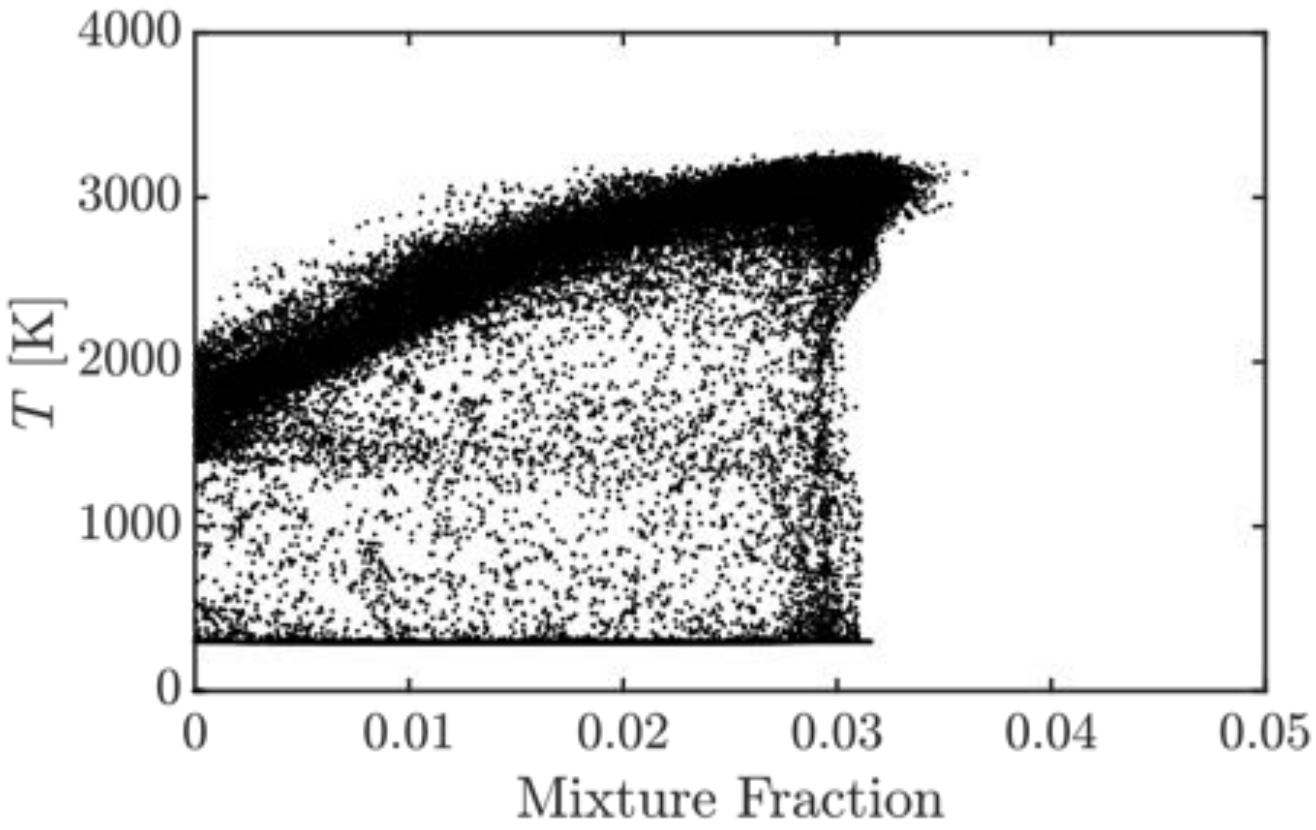
- **Shock front acceleration shortly after fuel-air mixture patch - due to ignition delay**
- **Locations of high shock front velocity corresponds to rich fuel-air regions**
- **Slight decay in peak velocity with axial distance - due to drag effects of wave passing through background air**





Detonation Structure





- **Presence of inert fluid prevents strong detonation**
  - Different from conventional ZND structure

2D Unwrapped RDE with Multiple Fuels

H2/Air (Verification)

A: Detonation wave, B: Oblique shock

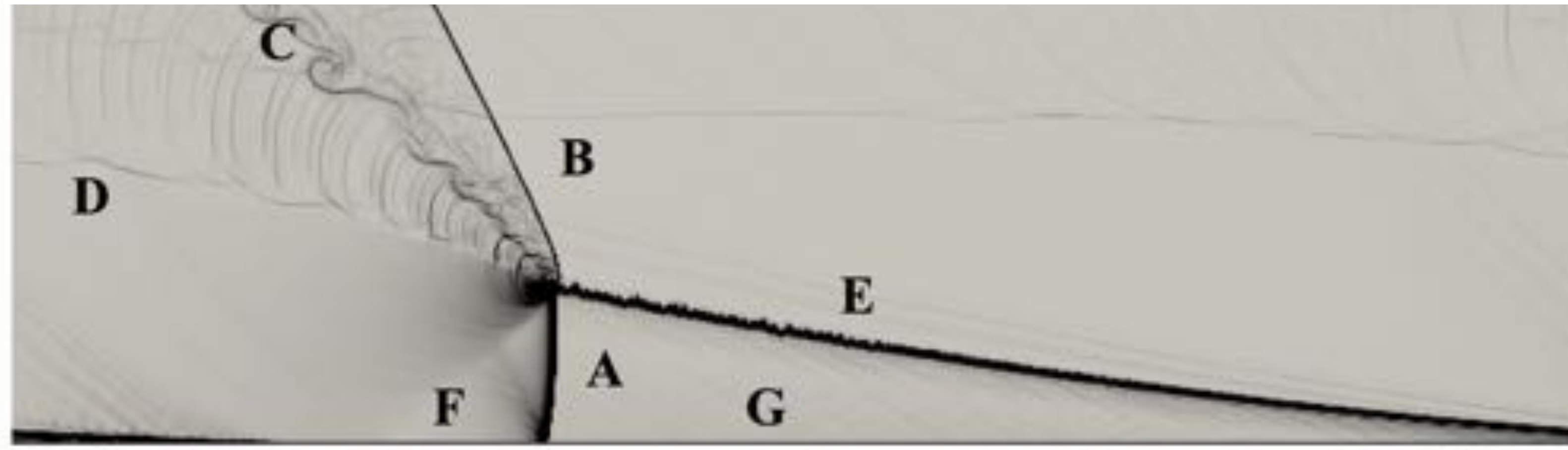
C: Slip line, D: Secondary weak shock

E: Region of mixture and product gases

F: Blocked injection

G: Unreacted gases

- **Verification with H2 chemistry — General structure**

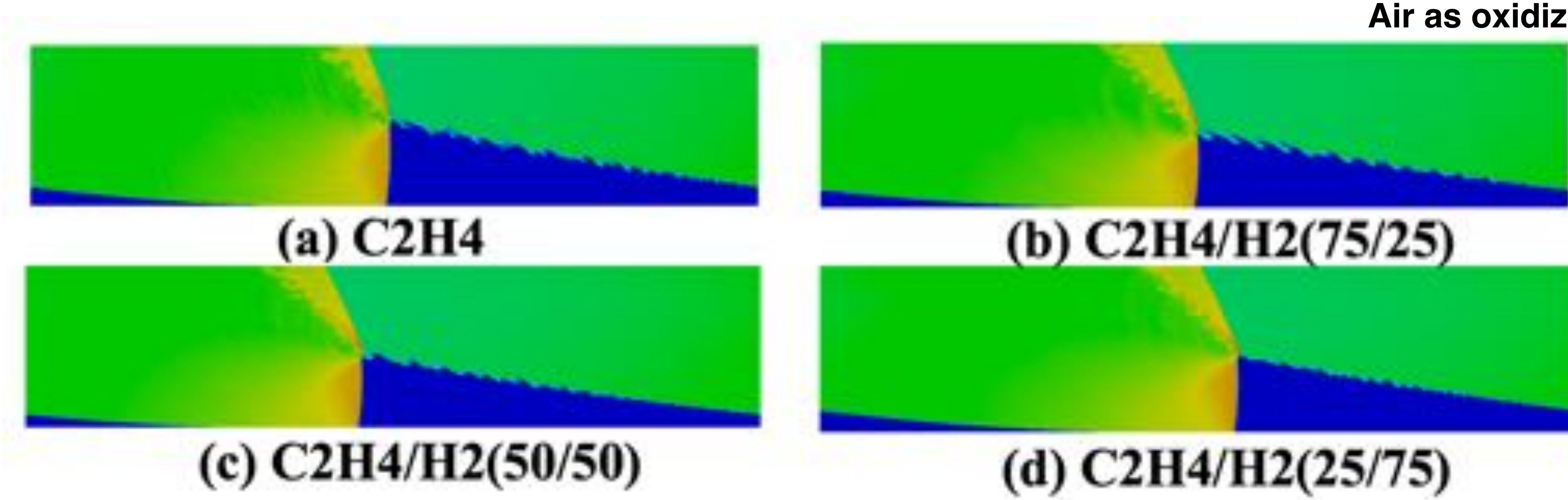


Reproduced the similar flow field as the previous research

C2H4/Air (AFRL geometry)

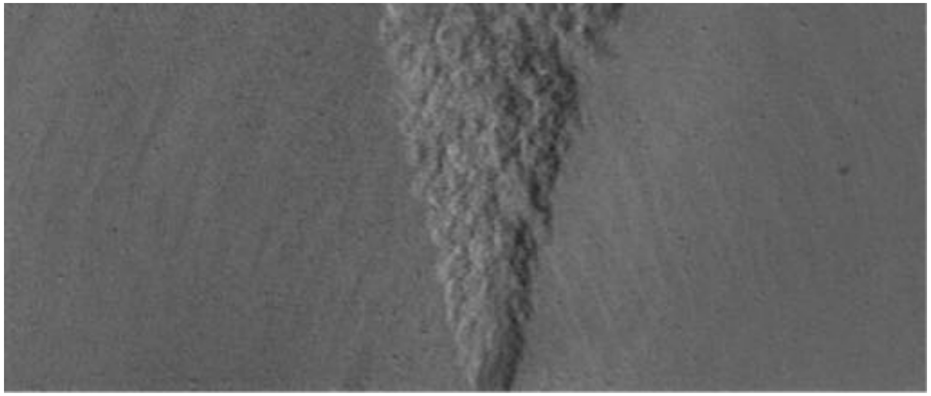
Currently analysis on detail flow field is ongoing

P0_inj = 10 atm,
T0_inj = 300K,
P_back = 1 atm
Air as oxidizer



Lessons Learnt

- **Stratification alters the detonation structure**
  - Post-detonation profiles different from 1D structure
- **Stratification can lead to parasitic deflagration**
  - Constant-pressure combustion significant in jet injection cases
  - Pockets of non-detonated fuel-air mixtures in stratification cases
- **Modeling potential**
  - DNS shows that a reduced-order flamelet-type model is feasible for detonation
    - Will allow detailed chemistry to be incorporated



Questions?