Fuel Injection Dynamics and Composition Effects on RDE Performance

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Co-I: Venkat Raman

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UTSR/NETL

Summary

- **Title:**
  - Fuel Injection Dynamics and Composition Effects on RDE Performance
- **Funding agency:**
  - University Turbine Systems Research/NETL
  - Funding Opportunity Number: DE-FOA-000117
  - Topic Area 6: Pressure Gain Combustion R&D
  - Project manager: Robin Ames
  - Award: DE-FE0031228
- **Personnel:**
  - PI: Mirko Gamba, University of Michigan
  - Co-I: Venkat Raman, University of Michigan
  - Students currently involved:
    - Fabian Chacon
    - James Duvall
    - Takuma Sato
    - Supraj Prakash
  - Key external collaborators:
    - Dr. John Hoke, Innovative Scientific Solution, Inc. (ISSI)
    - Dr. Fred Schauer, AFRL WP
    - Dr. Venkat Tangirala , GE
    - Dr. William Hargus, AFRL/Edwards
    - Drs. Adam Holley and Peter Cocks, United Technology Research Center (UTRC)
    - Kyle McDevitt, Williams International

Outline

- **Programmatic overview**
- **Introduction to the problem and general approach**
- **Experimental activities**
- **Computational activities**
- **Interactions and collaborations**

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- Programmatic overview
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Overarching objectives

- **Objective 1:**
  Develop a comprehensive understanding of injector dynamics, coupling with 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.

Expected outcomes: RDE physics advancements

- **Outcome 1:**
  Fundamental physical understanding of detonation-induced dynamics of practical injection systems:
  - Coupling with diffuser geometry;
  - Their effect on RDE mixing, detonation structure, operability and performance.

- **Outcome 2:**
  Fundamental physical understanding of multicomponent fuel (MCF) chemistry effects:
  - Detonation wave structure and propagation
  - RDE operability and performance;

Expected outcomes: RDE methods advancements

- **Outcome 3:**
  Detailed experimental measurements under various injection schemes and MCFs
  - RDE performance and detonation structure
    - Creation of experimental databases
  - MCFs representative of syngas and natural gas characterized by a range of detonability properties, ignition delays and Wobbe index
    - Relevance to DOE and industry programs

- **Outcome 4:**
  Computationally efficient detonation models for MCFs for use with DNS/LES modeling of detonations in relevant full-system RDEs under practical MCFs
  - Implementation into open-source platforms; e.g., openFoam
  - Transfer of detonation computational models to industry

Objectives and tasks

Fuel injection dynamics and composition effects on RDE performance

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

- **Task 2.1**
  Experimental study of low loss injector dynamics, their coupling with detonation and exhaust diffuser dynamics, and their effects on RDE operability and performance
- **Task 2.2**
  Investigate how low loss injector dynamics affects detonation mixing and structure in optical RDE using laser diagnostics
- **Task 2.3**
  Full-system simulation of coupled dynamics of air/fuel injector, detonation and exhaust diffuser and their effect on RDE operation

Objective 2
Develop a comprehensive understanding of MCF (syngas and hydrocarbon blends) on RDE detonation structure and propagation, operation and performance

- **Task 3.1**
  Experimental study of RDE detonation properties and performance with hydrocarbon MCFs in optical RDE
- **Task 3.2**
  DNS studies of detonation structure in multicomponent fuels
- **Task 3.3**
  Conduct LES analysis of RDE configurations to understand the effect of multicomponent fuels on performance

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

- **Task 4.1**
  Development of laser diagnostics for the study of detonation waves in optical RDE under relevant conditions
- **Task 4.2**
  Development of structure-based model of detonation waves in stratified mixtures with arbitrary multicomponent fuels

RDE INJECTOR DYNAMICS | **MULTICOMPONENT FUELS** | **METHODS DEVELOPMENT**

ADVANCING PHYSICAL UNDERSTANDING OF:
MIXING
OPERABILITY
PERFORMANCE

Timeline of the project

	Task	Description	Start	Finish	2017	2018				2019				2020		
					Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1	**1.0**	**Project meeting and planning**	10/17	9/20												
	1.1	Project meetings and progress reports	10/17	9/20												
Task 2	**2.0**	**Study of the effects of low loss injector dynamics on detonation mixing and structui and RDE operability and performance**	10/17	9/20												
	2.1	Experimental study of low loss injector dynamics, their coupling with detonation and exhaust diffuser dynamics, and their effects on RDE operability and performance	10/17	3/19												
	2.2	Investigate how low loss injector dynamics affects detonation mixing and structure in optical RDE using laser diagnostics	4/18	3/20												
	2.3	Full-system simulation of coupled dynamics of air/fuel injector, detonation and exhaust diffuser and their effect on RDE operation	10/18	9/20												
Task 3	**3.0**	**Study of the effects of relevant multicomponent hydrocarbon fuels on detonation structure, RDE operability and performance**	4/18	9/20												
	3.1	Experimental study of RDE detonation properties and performance with hydrocarbon MCFs in optical RDE	10/18	9/20												
	3.2	DNS studies of detonation structure in multicomponent fuels	4/18	9/19												
	3.3	Conduct LES analysis of RDE configurations to understand the effect of multicomponent fuels on performance	10/18	9/20												
Task 4	**4.0**	**Develop advanced diagnostics and structure-based detonation models for multicomponent fuels**	10/17	9/20												
	4.1	Development of advanced laser diagnostics for the study of detonation waves in optical RDE under relevant conditions	10/17	9/19												
	4.3	Development of structure-based model of detonation waves in stratified mixtures with arbitrary multicomponent fuels	10/17	3/19												

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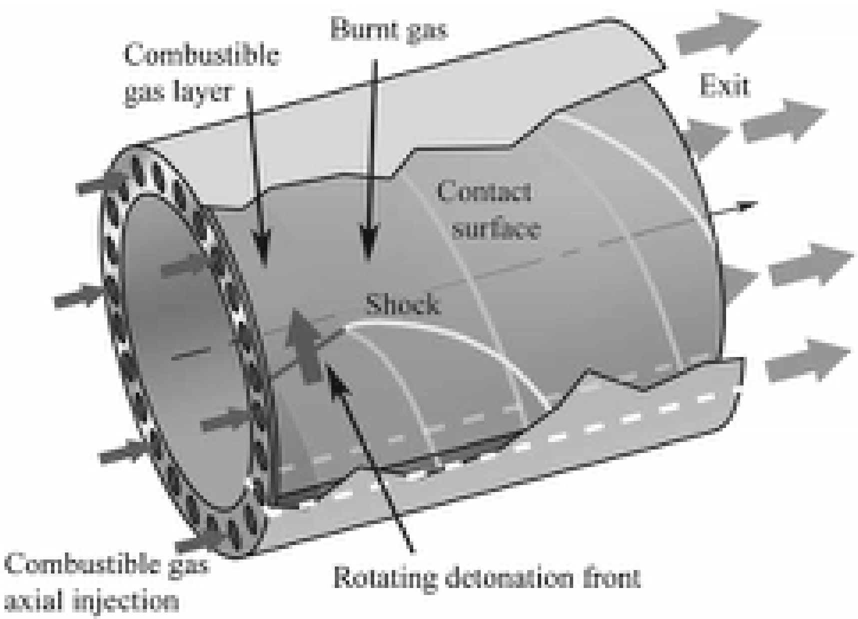
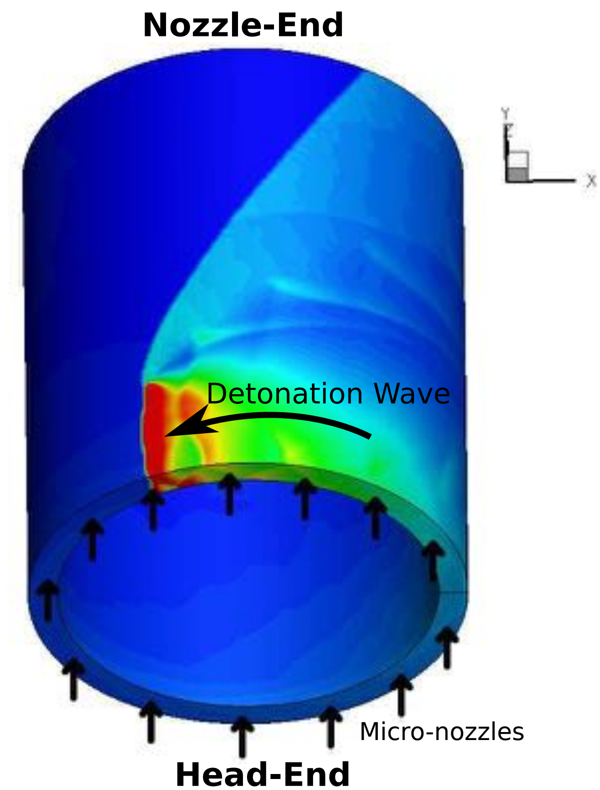
Overview of RDE operation and Pressure Gain (PG)





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(right) Schwer D. A. and Kailasanath K., AIAA 2010-6880

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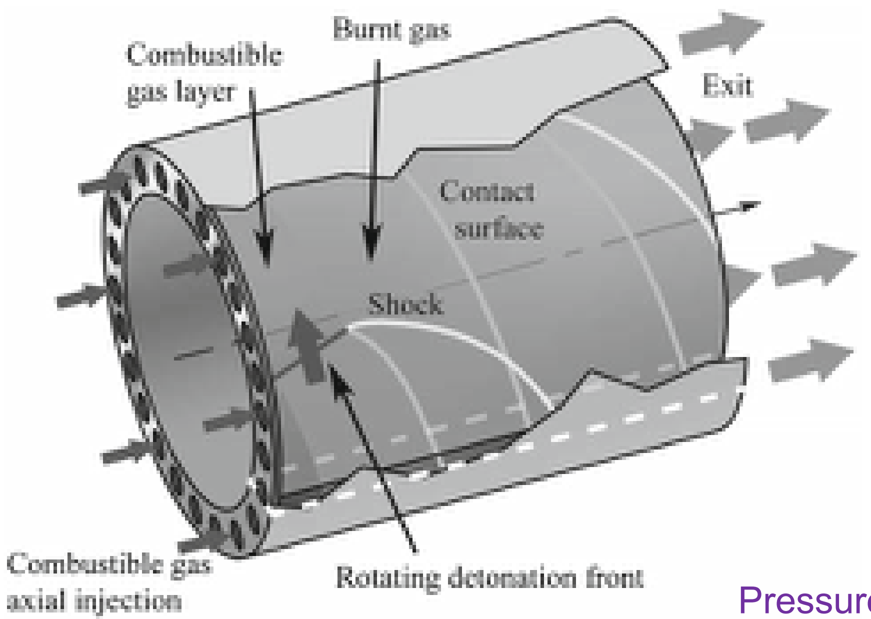

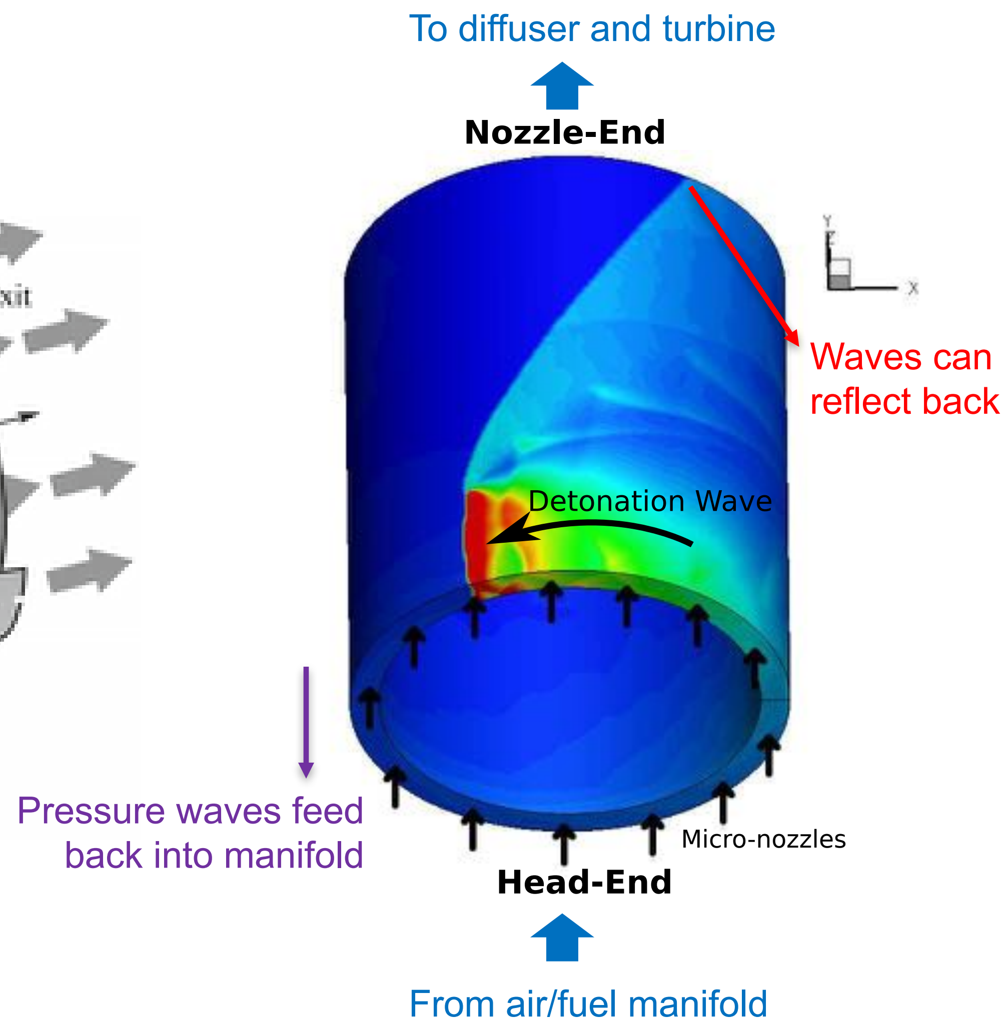

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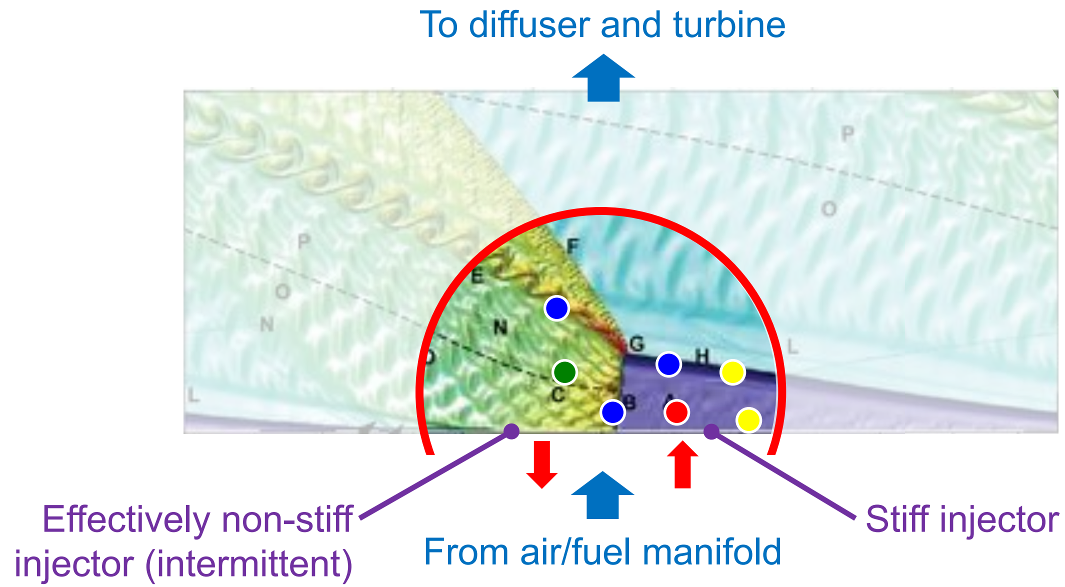
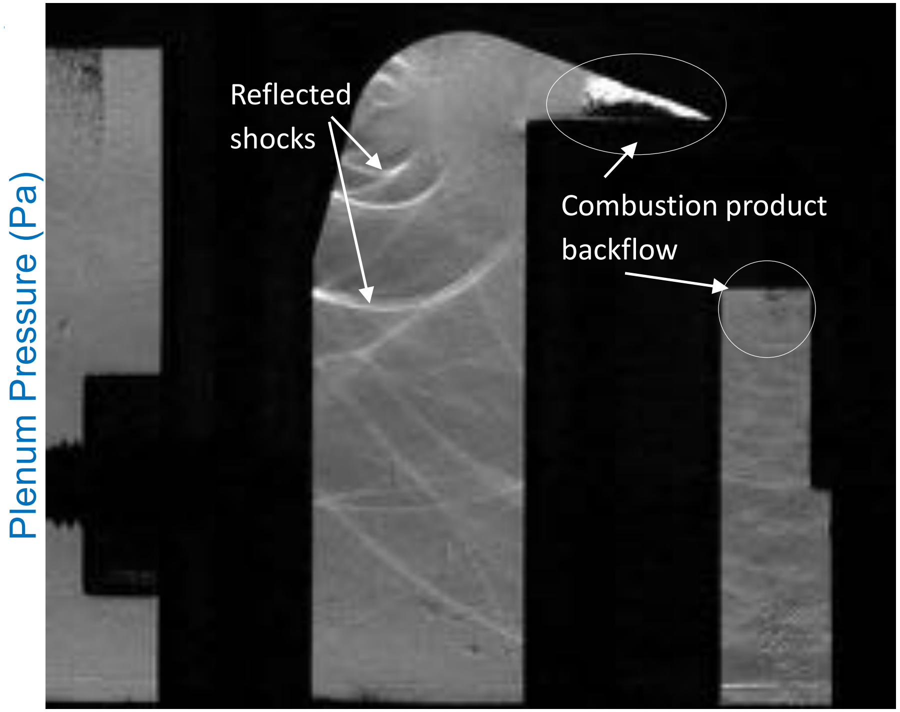
Coupling, dynamics and loss of pressure gain



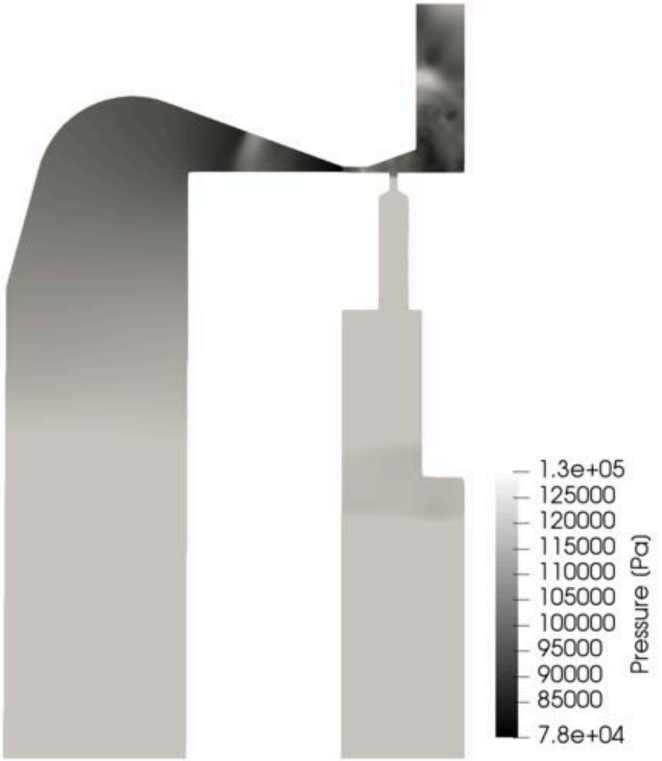
- **Unsteady operation of injection system**
  - Injector effectively transition from a stiff to a non-stiff injector
  - Post-detonation products backflow into plenums
  - Excite plenum dynamics
- **Strongly coupled system**
  - Response of injection system to varying
  - Back-reflections from diffuser (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

Example of upstream propagation of blast wave

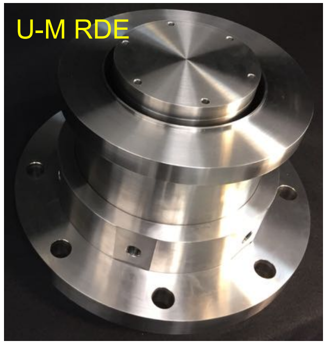


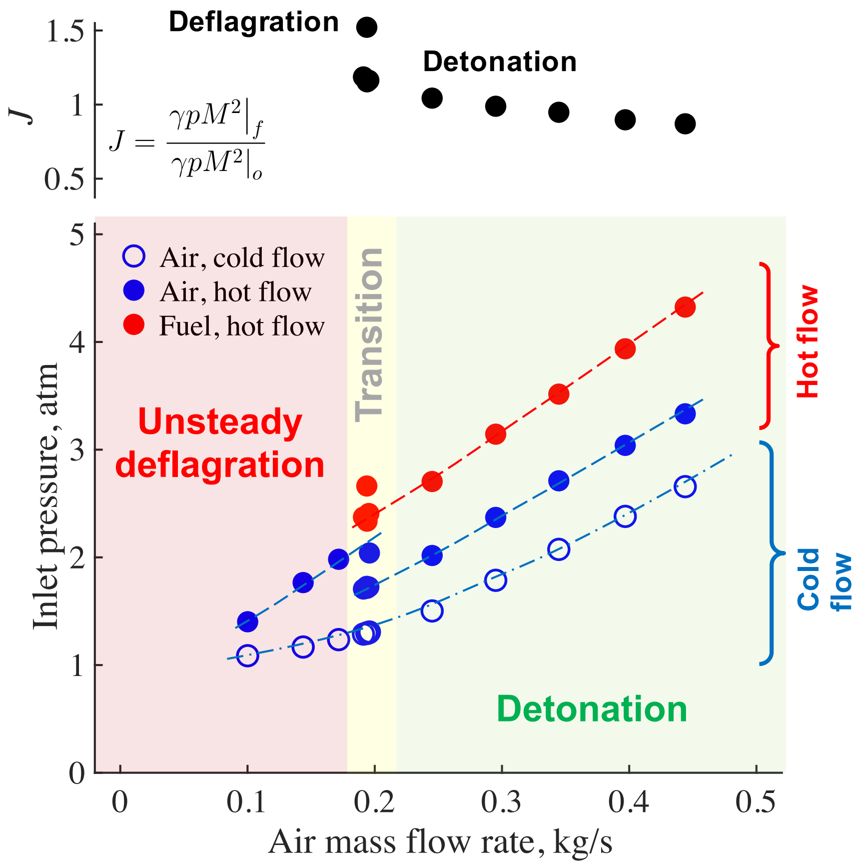
From NETL experiments (Ferguson) on AFRL injector



CFD computation at U-M

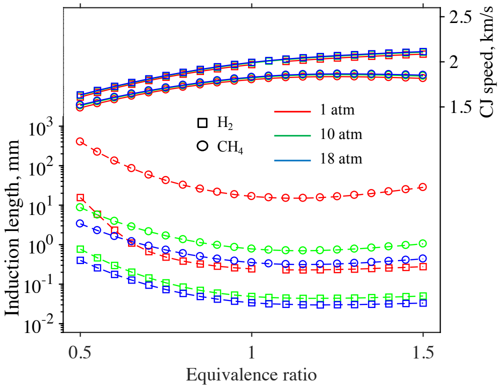
Example of detonation chamber / plenum coupling

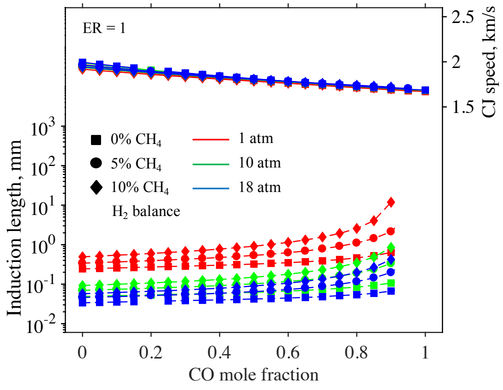


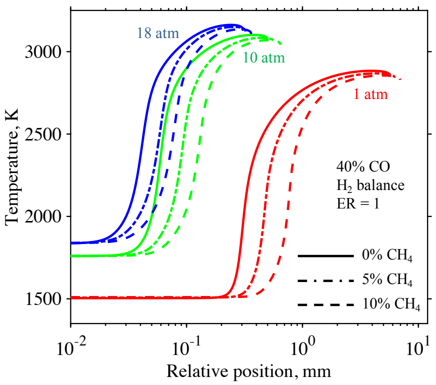


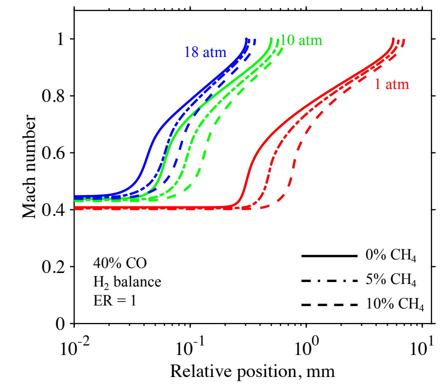
Fuel relevance: Toward operation with NG and syngas

- **Most of work conducted so far:**
  - Hydrogen/air operation
  - Stable detonation in lab-scale RDE enabled by favorable detonation properties
    - Detonability
    - Cell size
- **Application (energy conversion systems) require:**
  - Natural gas and/or syngas operation
  - Fuel flexibility and broad operation (e.g., from part to full load)
- **Anticipated challenges**
  - Stabilization of detonation wave
    - Limits imposed by detonation cell size
  - Fuel blend of relevant species (H_2/CH_4/CO) impacts detonation properties
    - E.g., induction length (cell size and stability) strongly reduced with H_2 addition (contrary to propane/ethylene)
    - E.g., presence of CO_2 shifts CO to CO2 conversion equilibrium, impacting heat release
    - E.g., difference in oxidation time scale of different components can affect overall structure









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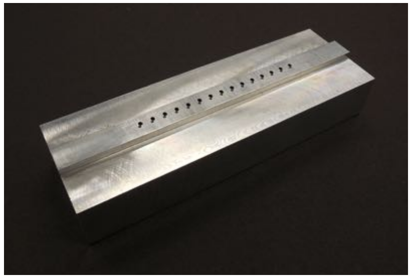
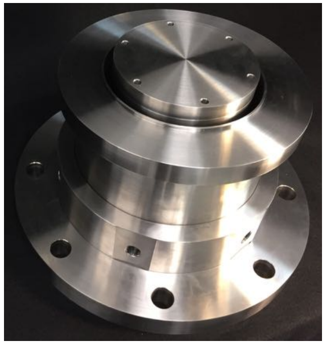
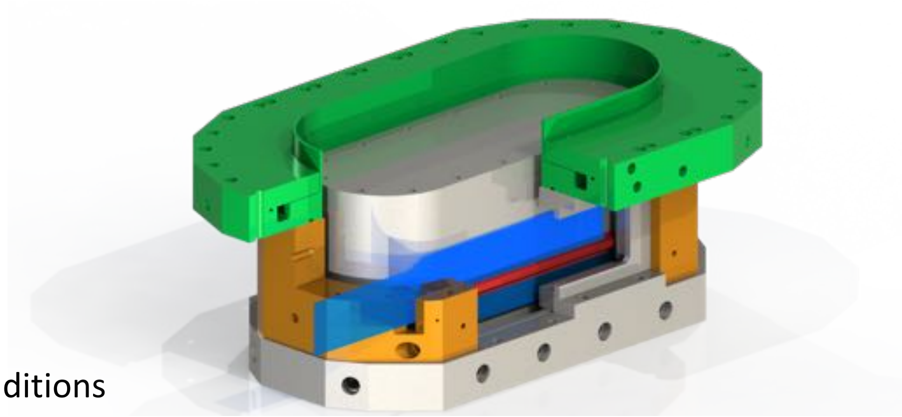
RDE Experimental Infrastructure at U-M

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





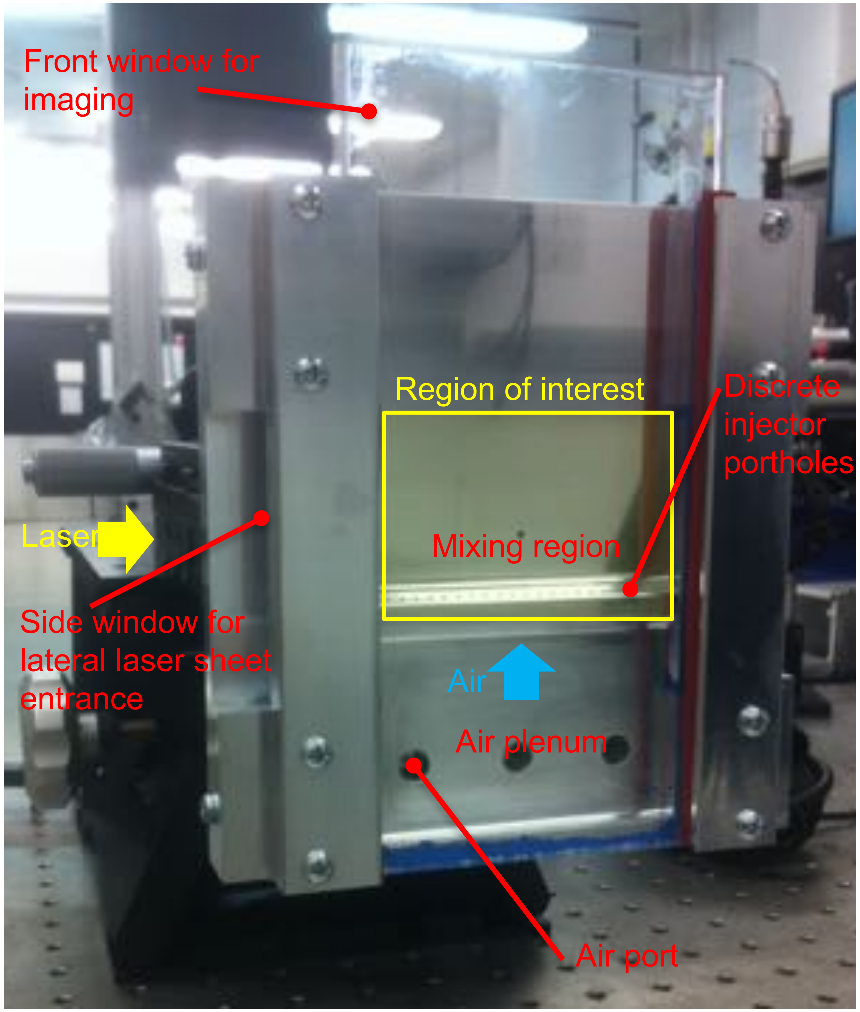
- **Reduced-scale RDE (6” RDE platform)**
  - Developed under previous projects
  - Operational with H_2/Air, various flow rates and equivalence ratios
  - Will be expanded to include:
    - MCFs capability
    - Additional instrumentation to investigate RDE dynamics



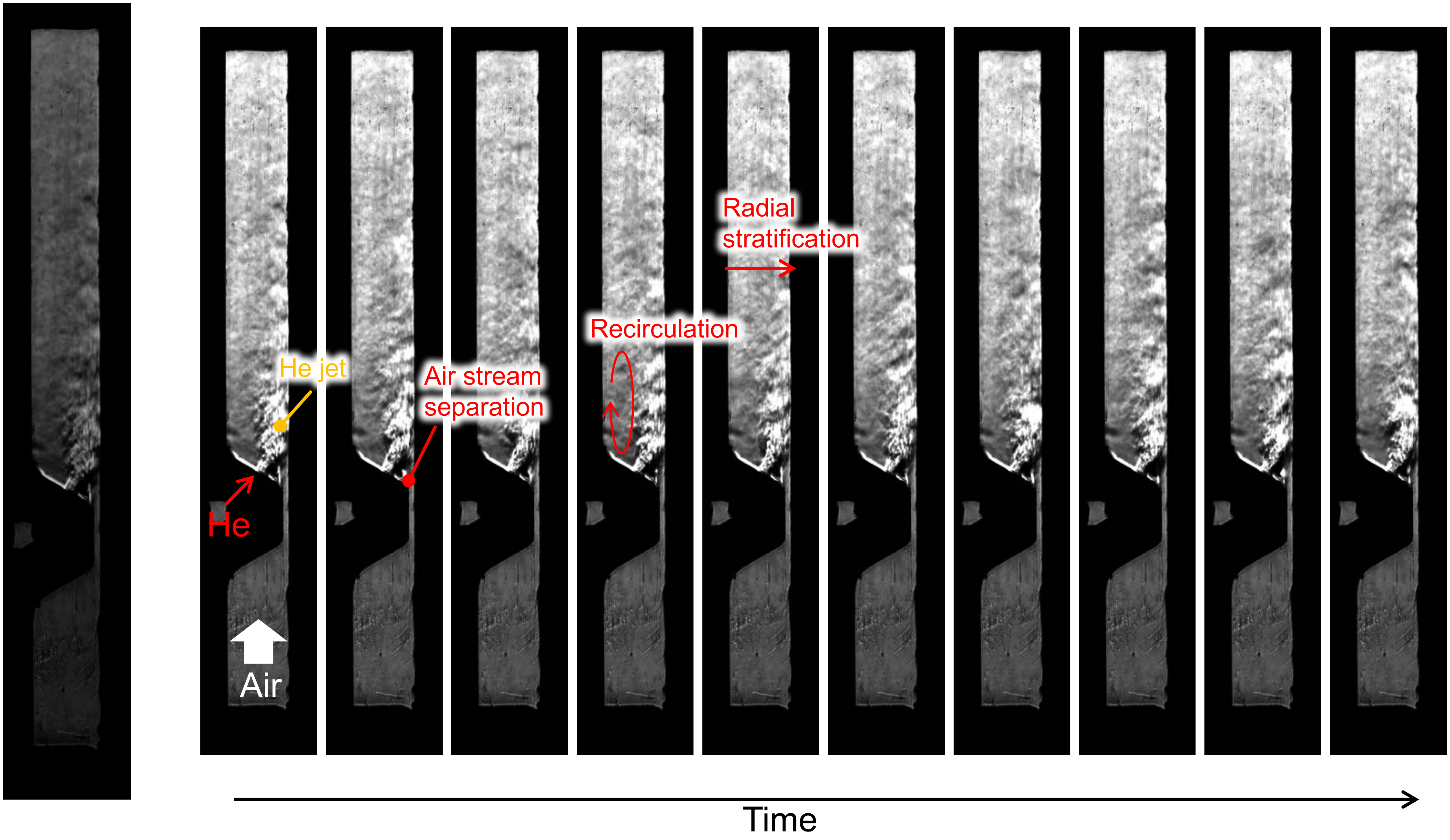
- **Optical RDE (Race-Track RDE)**
  - Fabrication being completed under previous projects
  - Equivalent to 12” round RDE
  - Used for flowfield measurements under RDE relevant conditions

Injector sector example (photograph)

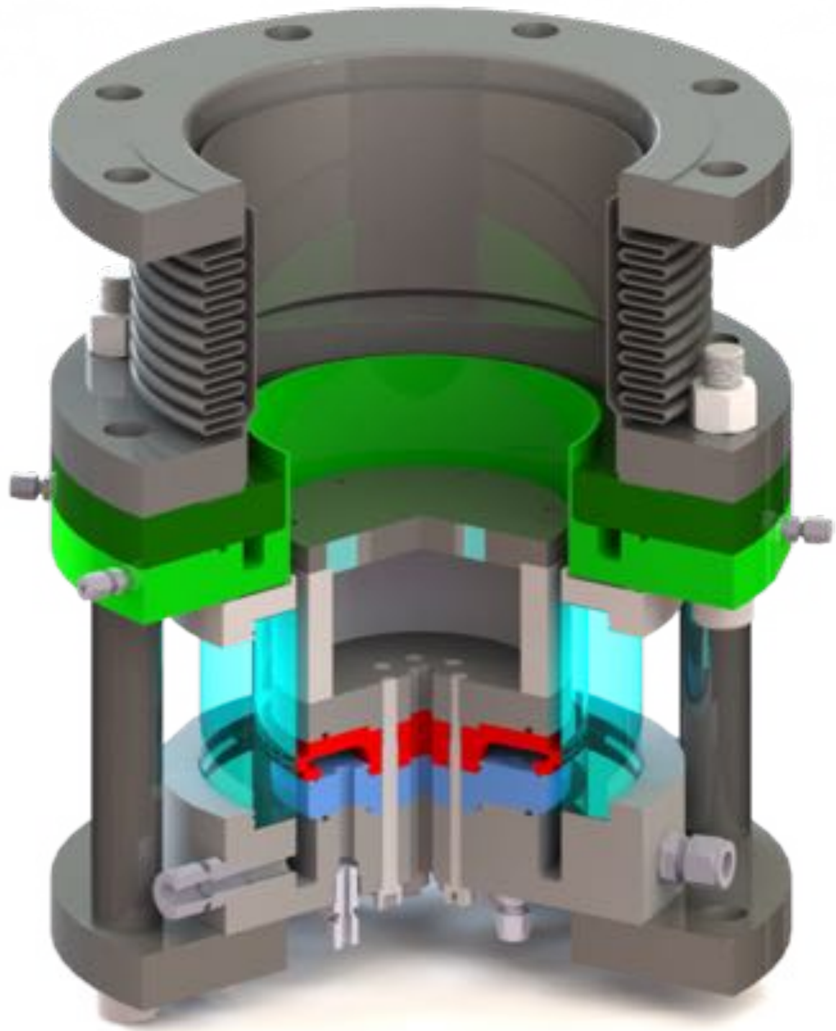
- **Sector of 6” round RDE geometry**
  - Pintle geometry is identical to RDE’s, just unwrapped
  - Air plenum geometry is different than RDE’s
  - Equivalent length about 1/8 of circumference of circular RDE
  - Optical access for laser diagnostics
- **Objective**
  - Conduct flow visualization and non-reacting mixing measurements under different (jet-to-air) velocity and density ratios (momentum flux ratio)
- **This system can be used in support of RDE measurements (flow visualization and mixing)**
  - Used to perform flow structure imaging and mixture fraction measurement using tracer-based laser induced fluorescence measurements
  - Variation of injection design
  - Parametric variation of velocity and density ratios
- **Can be available to project if needed**

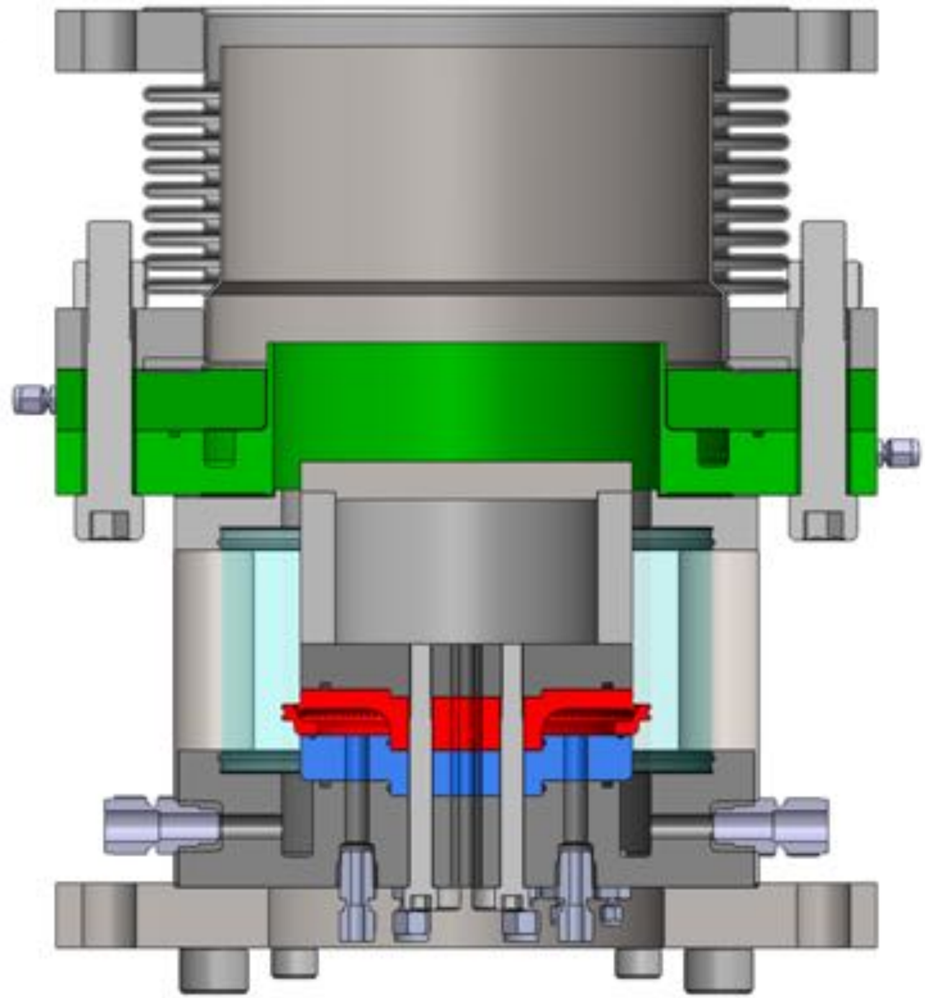


Schlieren imaging to identify flow structure (non-reacting mixing)



3-D rendering of 6” round RDE system

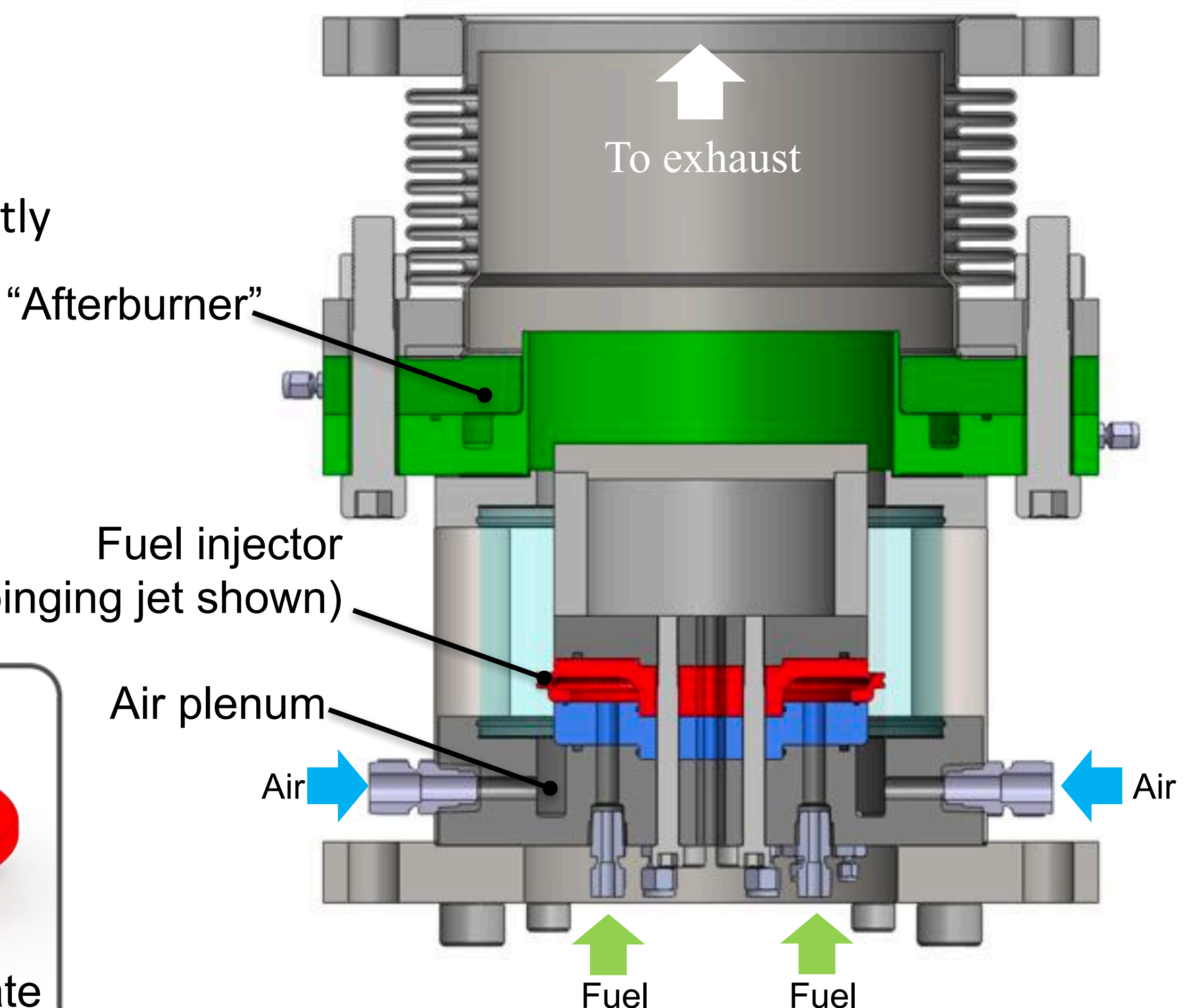




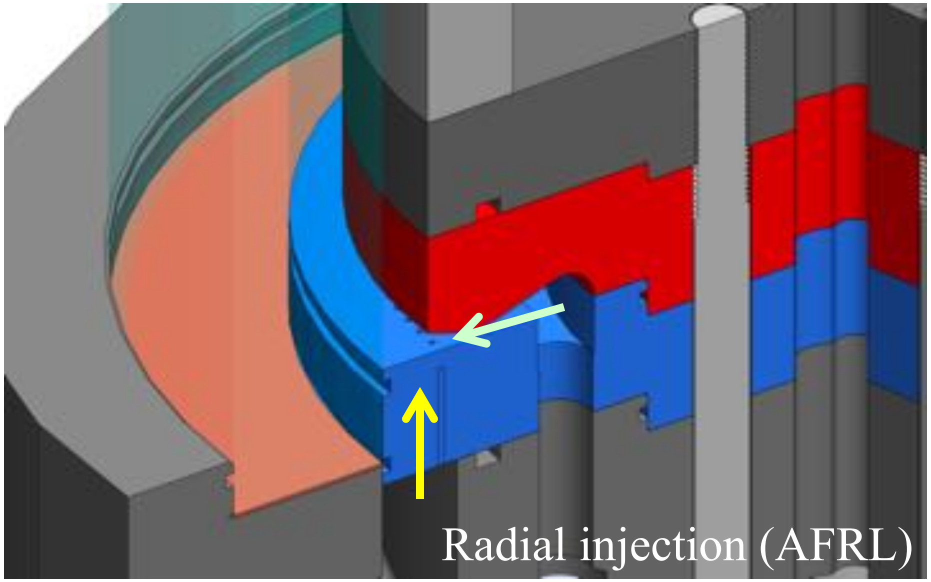
3-D rendering of 6” round RDE system

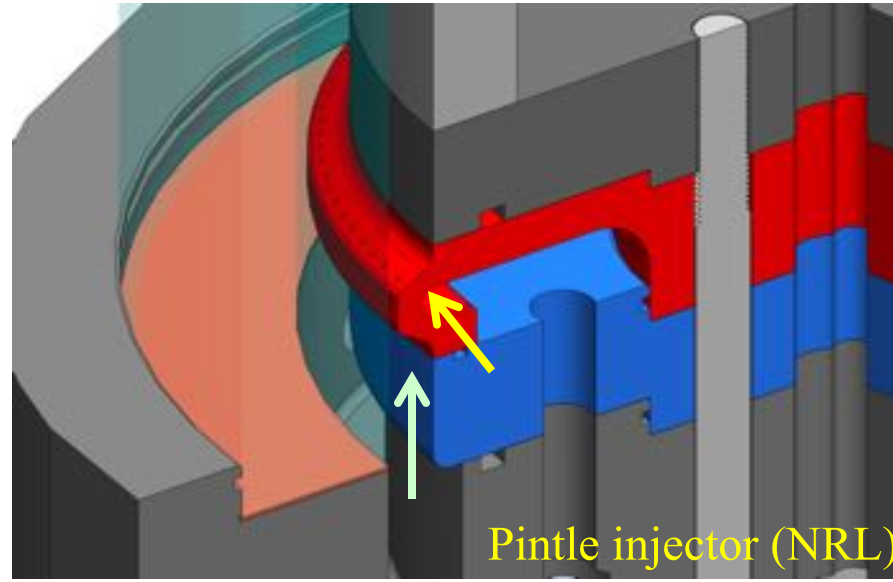
- **Fuel injection system**
  - Red/blue plate pair
  - Modular and readily exchangeable
  - Three designs currently available

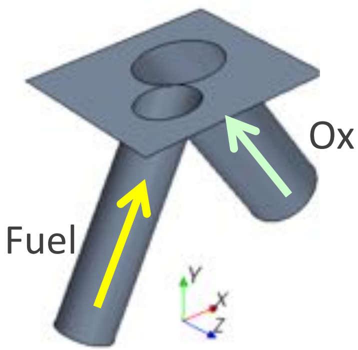
Example injector plate



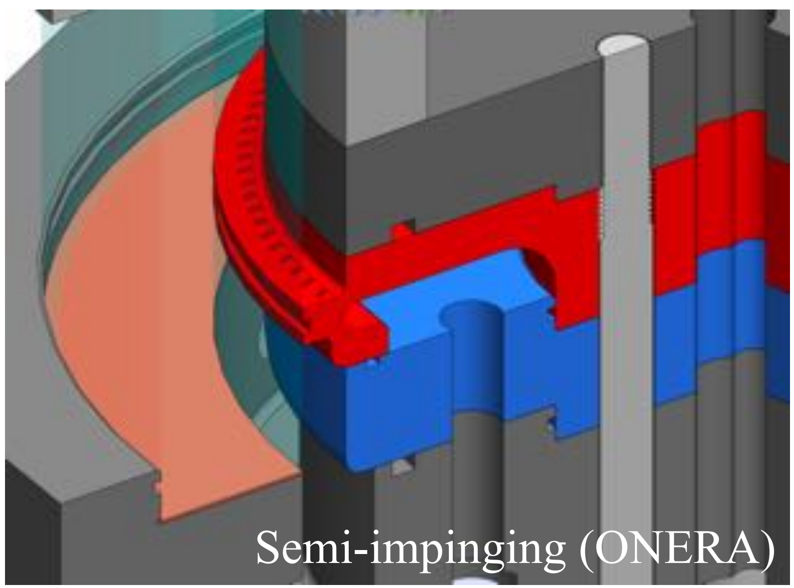
Three injection schemes available for 6” RDE system

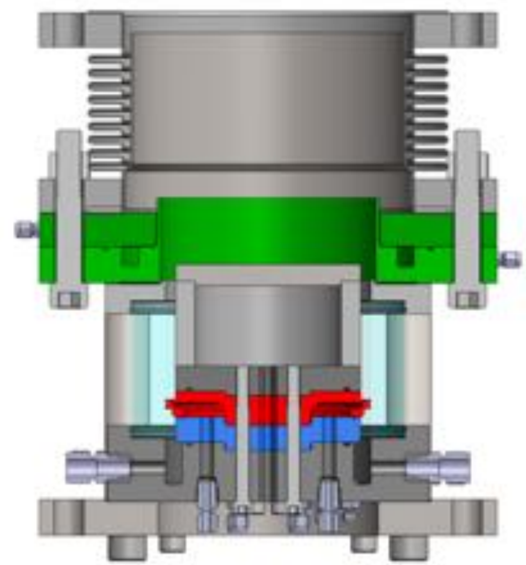






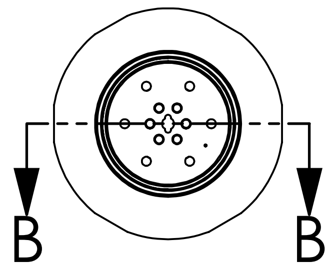
From Gaillard et al., Acta Astronautica, 111:334-344 2015

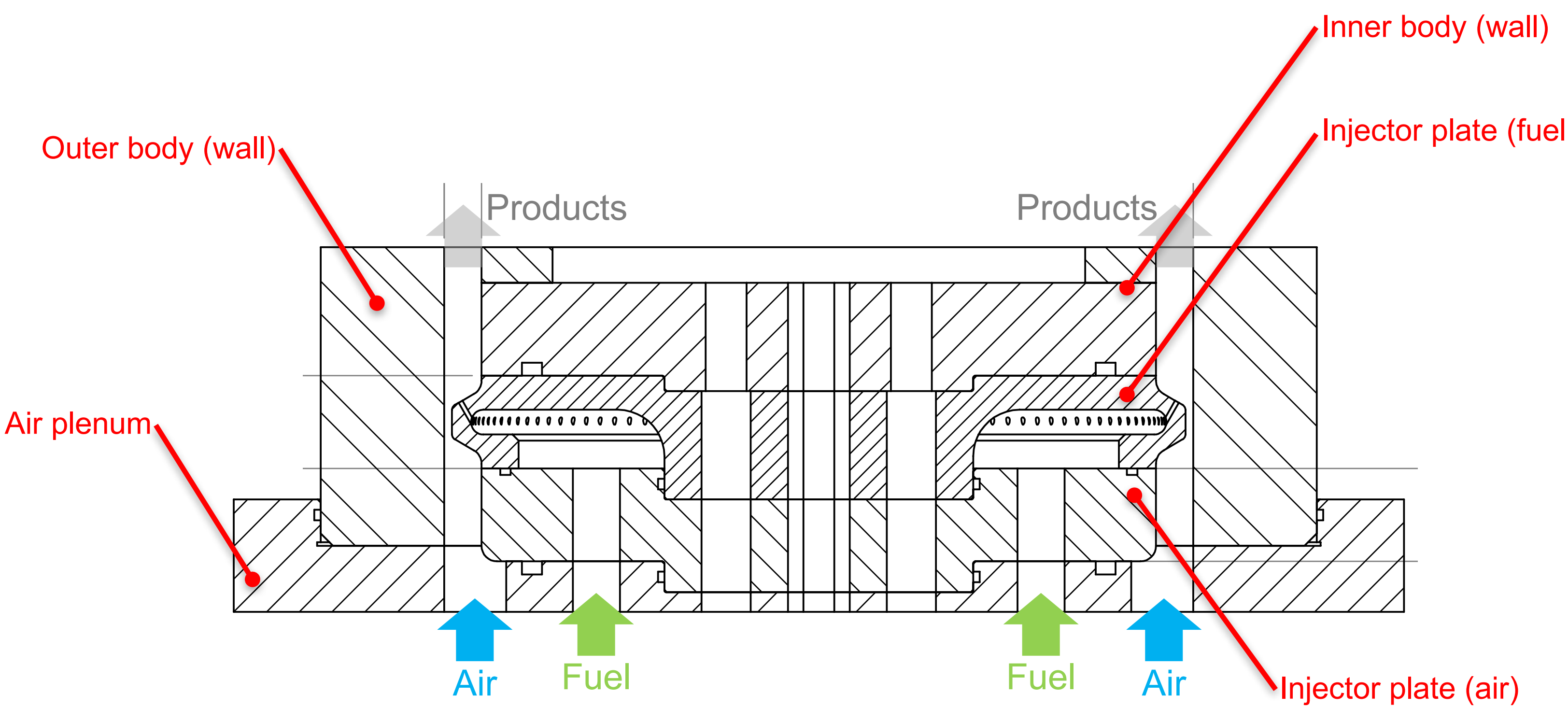




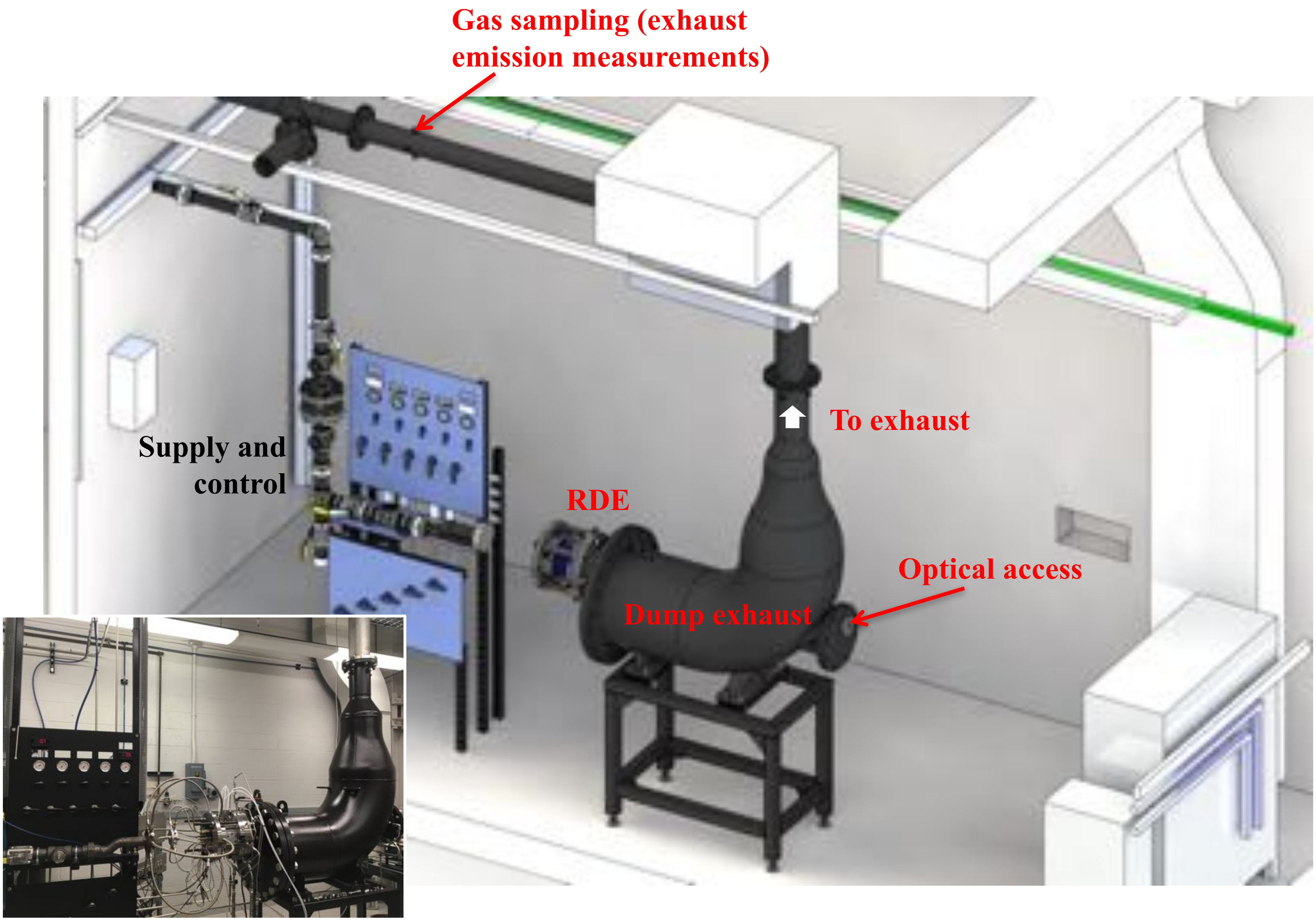
6” round RDE system: pintle injector details

Pintle injector plate

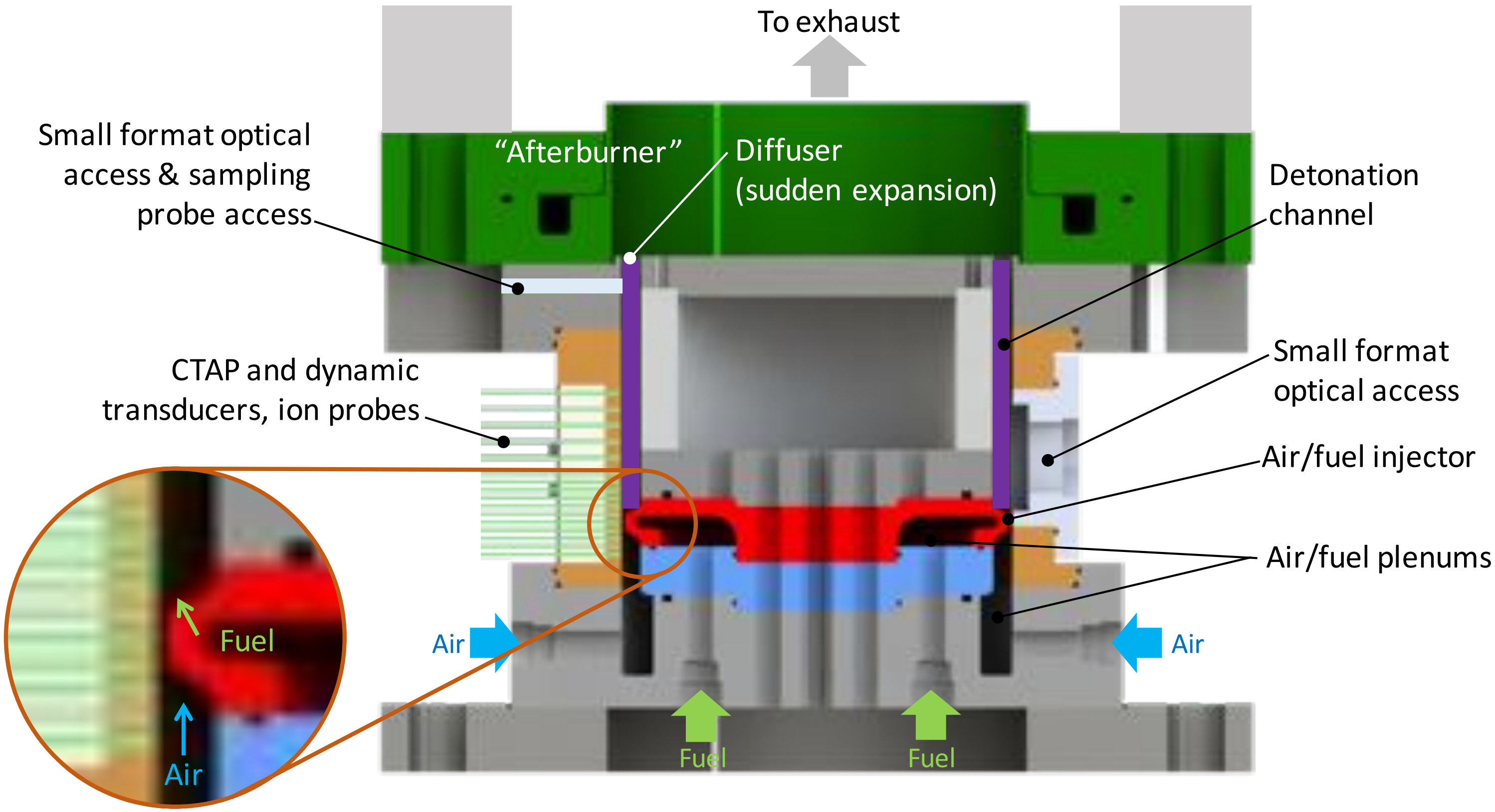




Pictures of RDE hardware (assembled with exhaust)

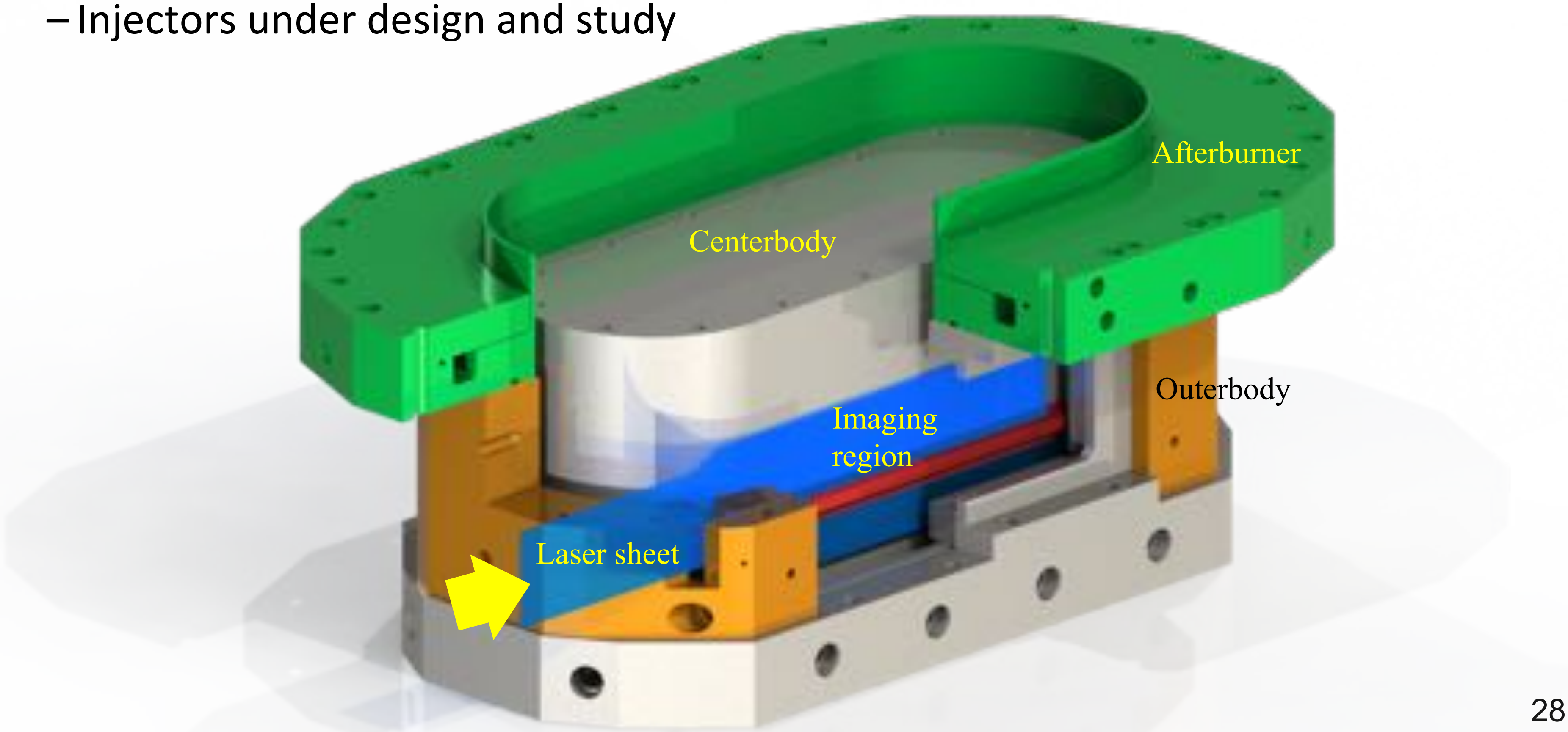


6” RDE system: some instrumentation

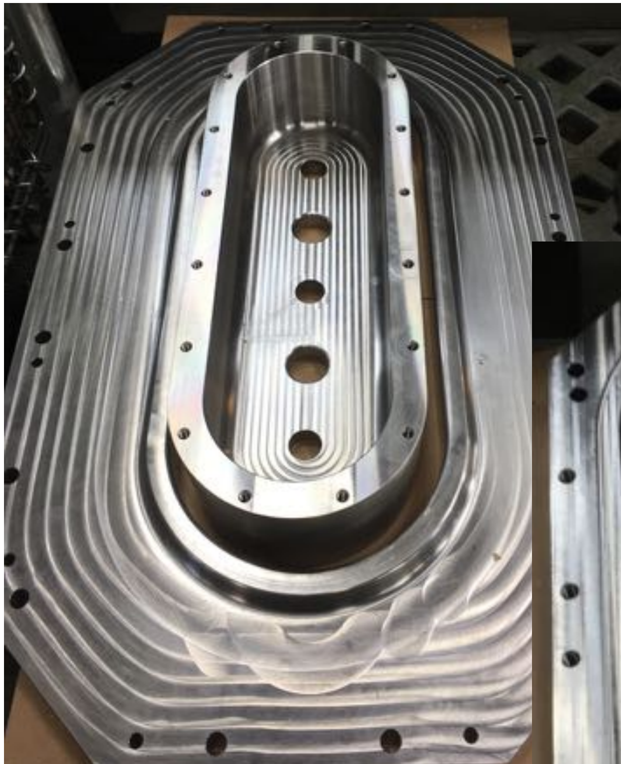
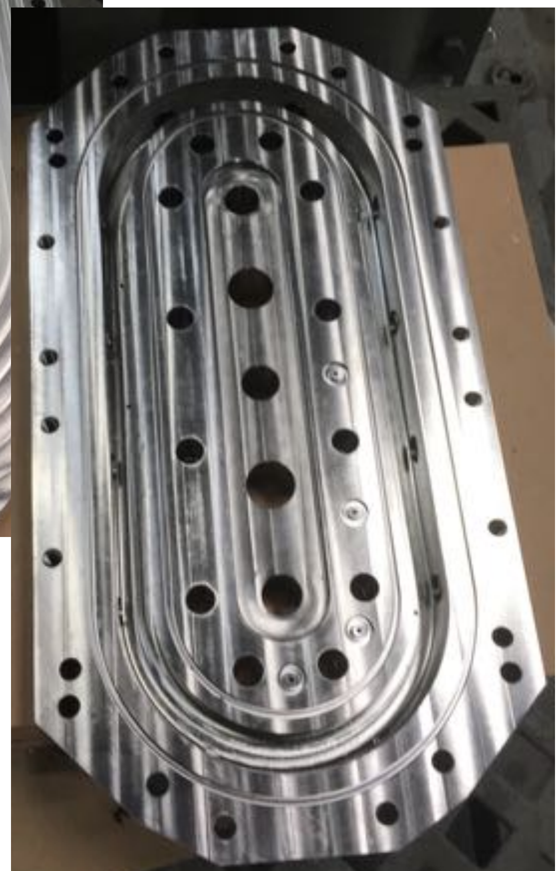


3-D rendering of Race-Track RDE system (12”)

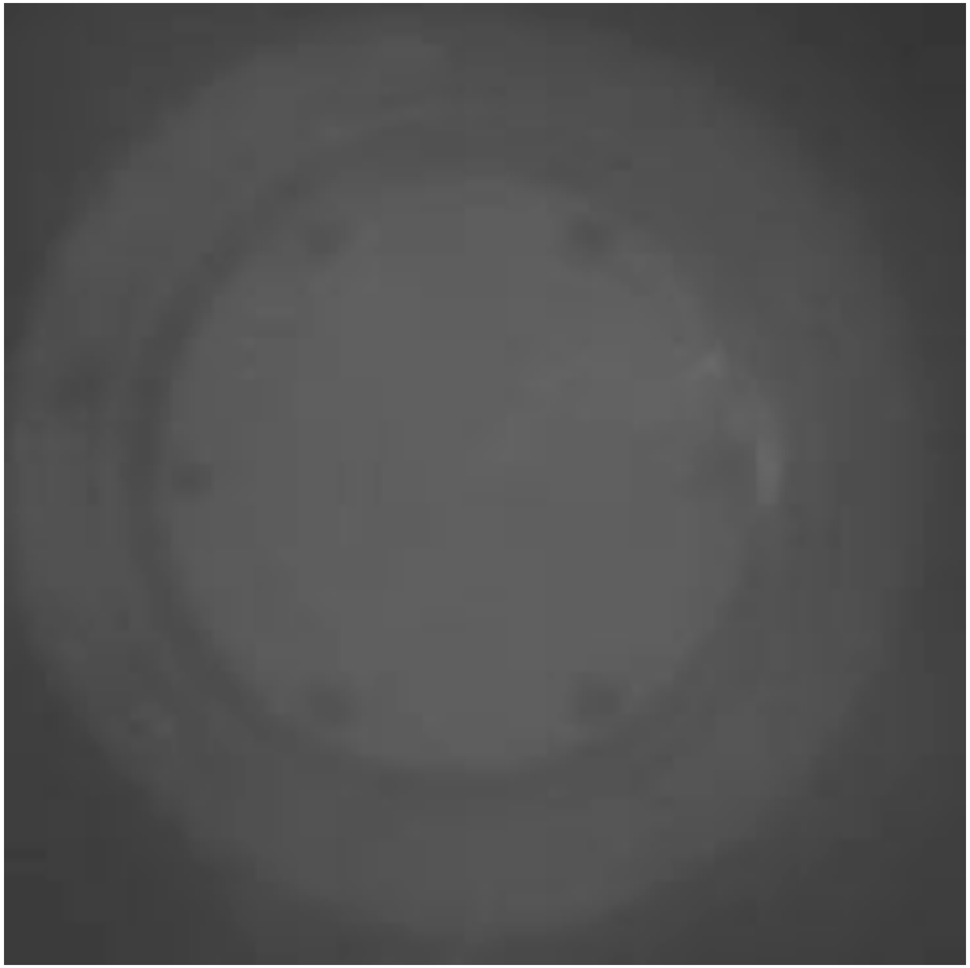
- **Designed with optical access in mind**
  - Allows for optical access of injection system and detonation chamber
- **Fuel injection system**
  - Follows modular design approach of round RDE
  - Red/blue pair, with similar modularity
  - Injectors under design and study



RT-RDE Being Completed

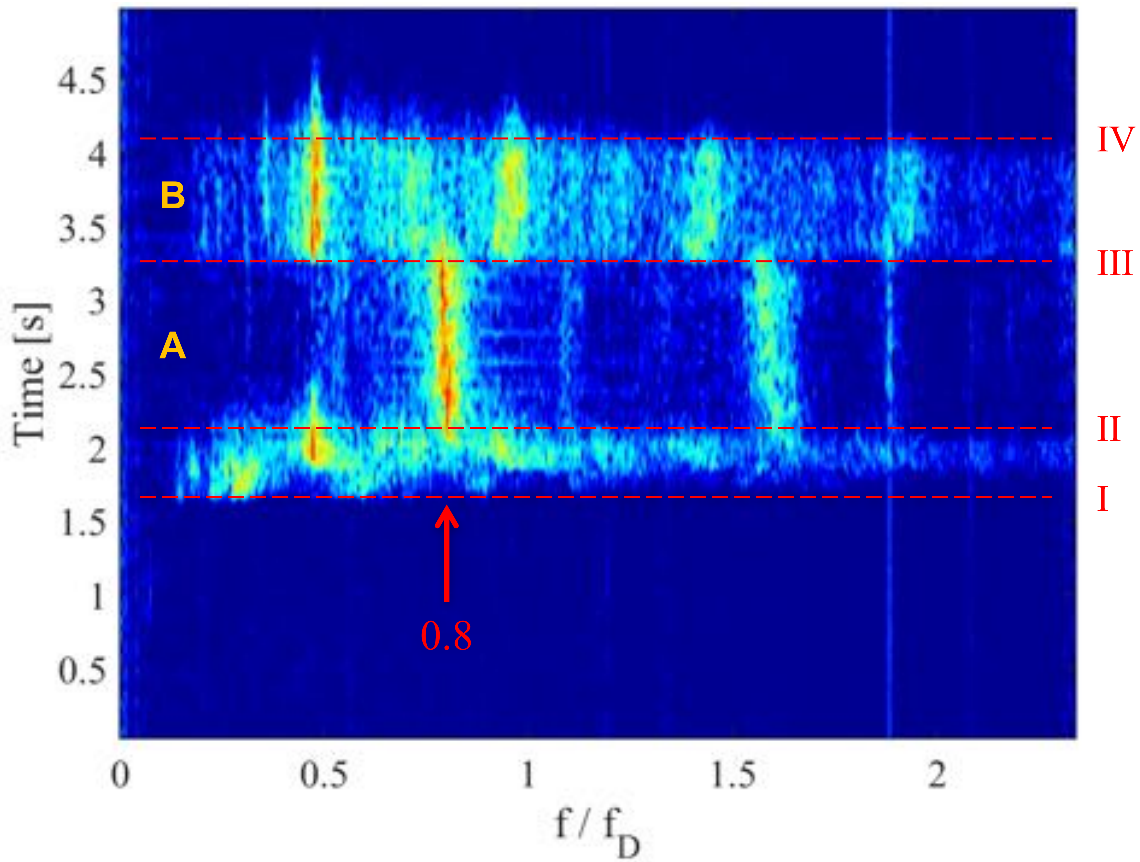
Example of RDE operation



Mixture: H_2/air
Air flow rate: 450 g/s
Equivalence ratio: 1

Test sequence and ignition process (acoustic signature)

I. Ignition
II. Transition to detonation
III. Detonation termination and transition to deflagration
IV. Fuel off



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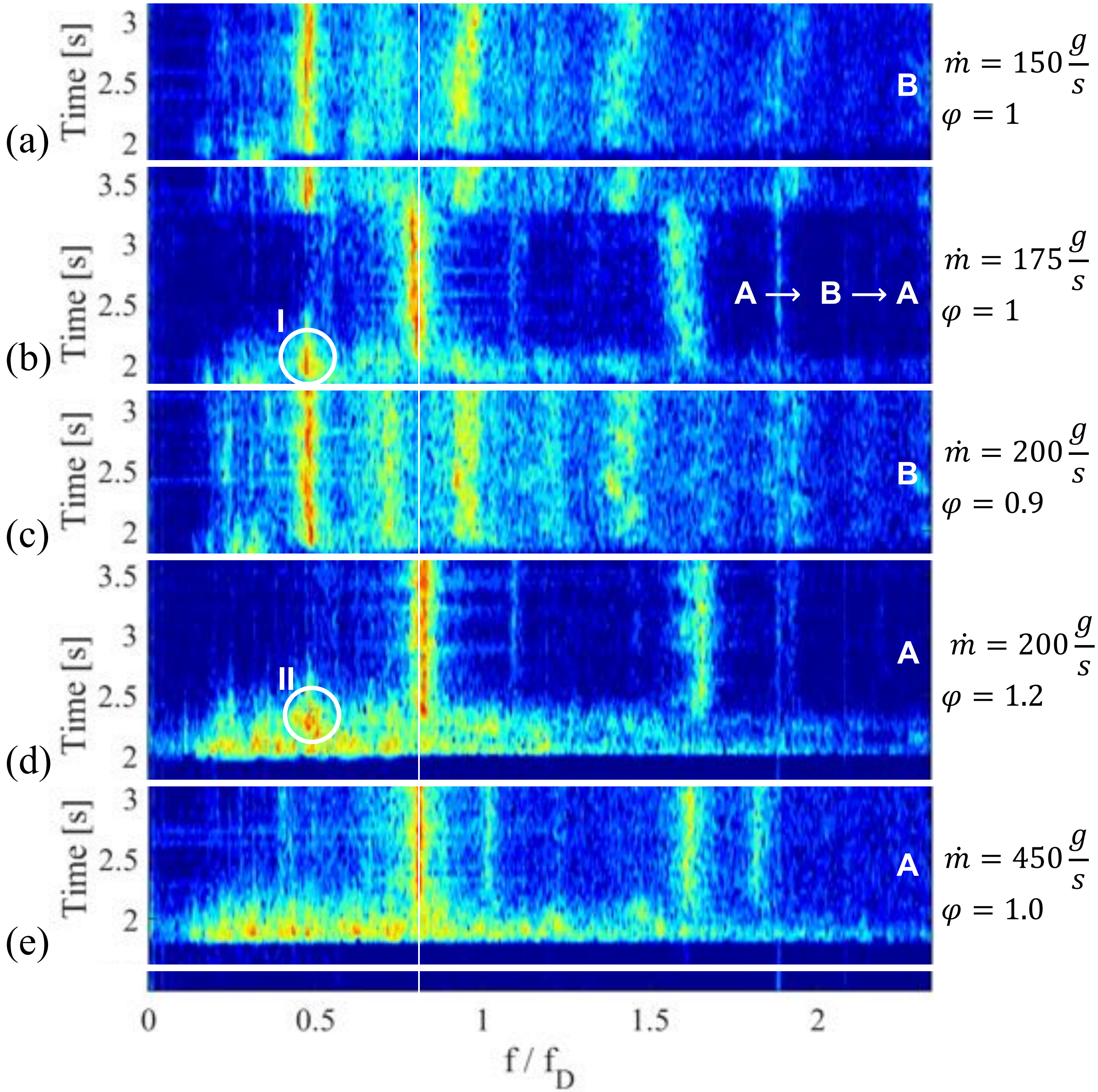
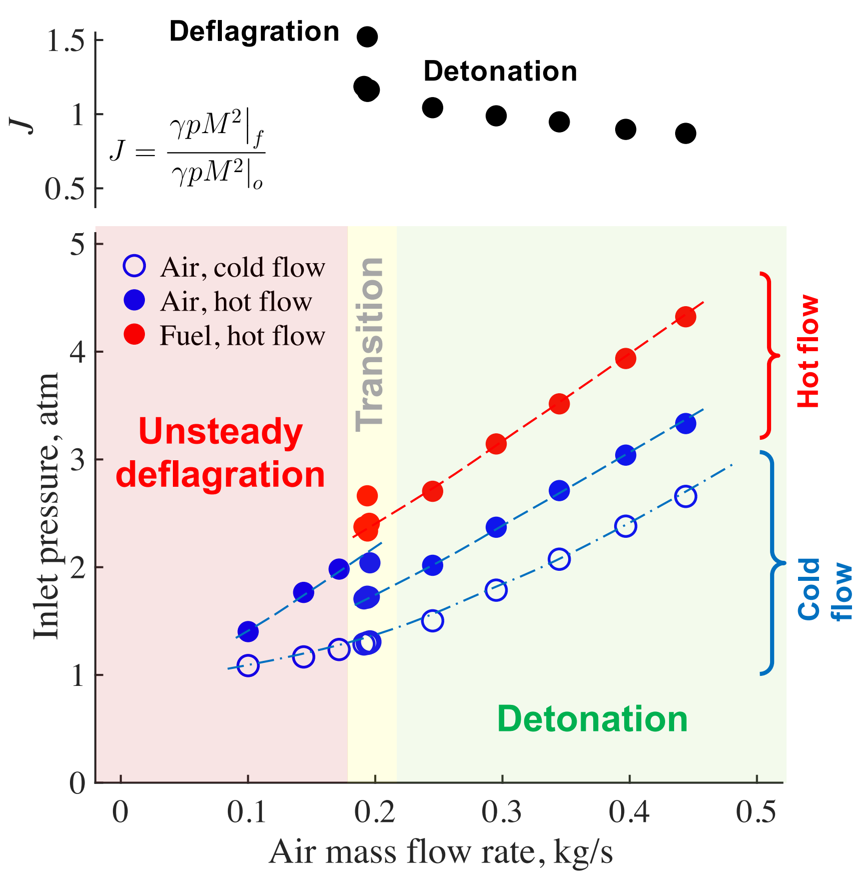
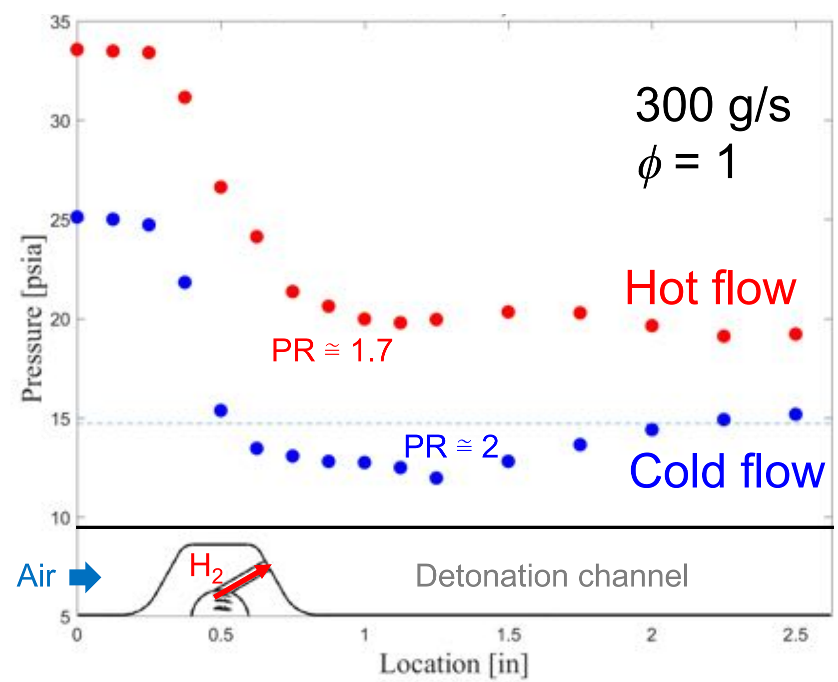


Coupling between operation mode and plenum

- **Inlet conditions depend on operation mode**
  - In detonation mode, plenum pressure **lower** than in deflagration mode



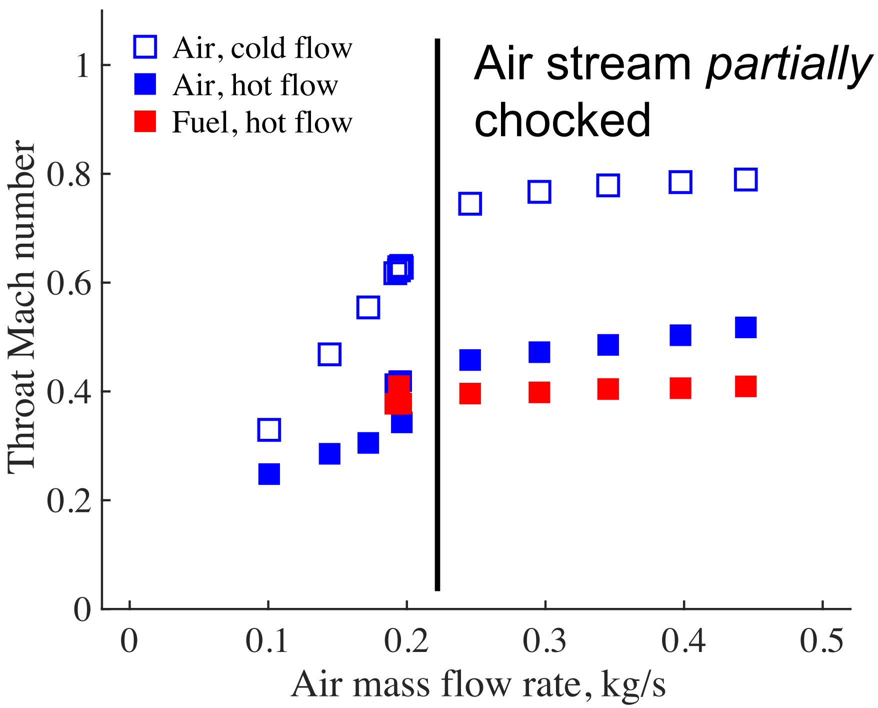


Pressure variation along detonation channel

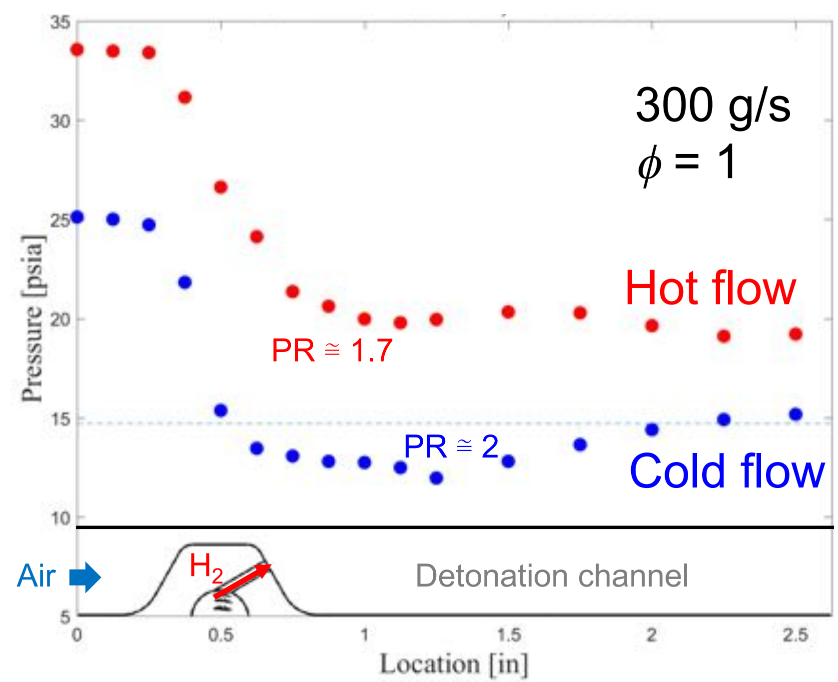
PR = plenum-to-channel pressure ratio

Coupling between operation mode and plenum

- **Inlet conditions depend on operation mode**
  - In detonation mode, plenum pressure **lower** than in deflagration mode
- **Air injection partially (space/time) chokes at high flow rates**
  - Detonation mode is observed (correlation?)
  - Flow possibly separates at injectors (reduced cross-sectional area for flow)
  - Injector stiffness vary over detonation cycle



Estimation of Mach number at air and fuel injection throat



Pressure variation along detonation channel

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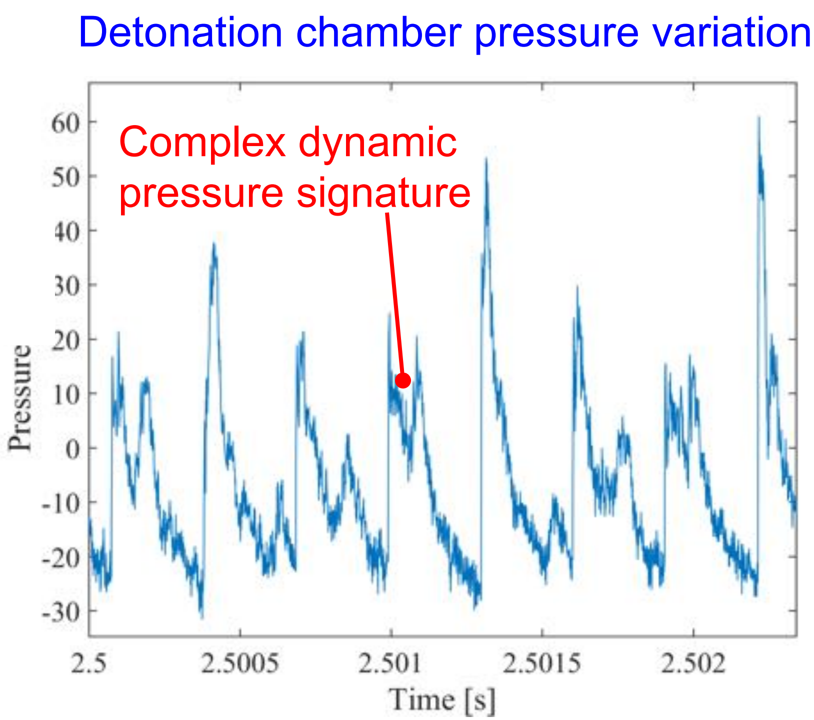
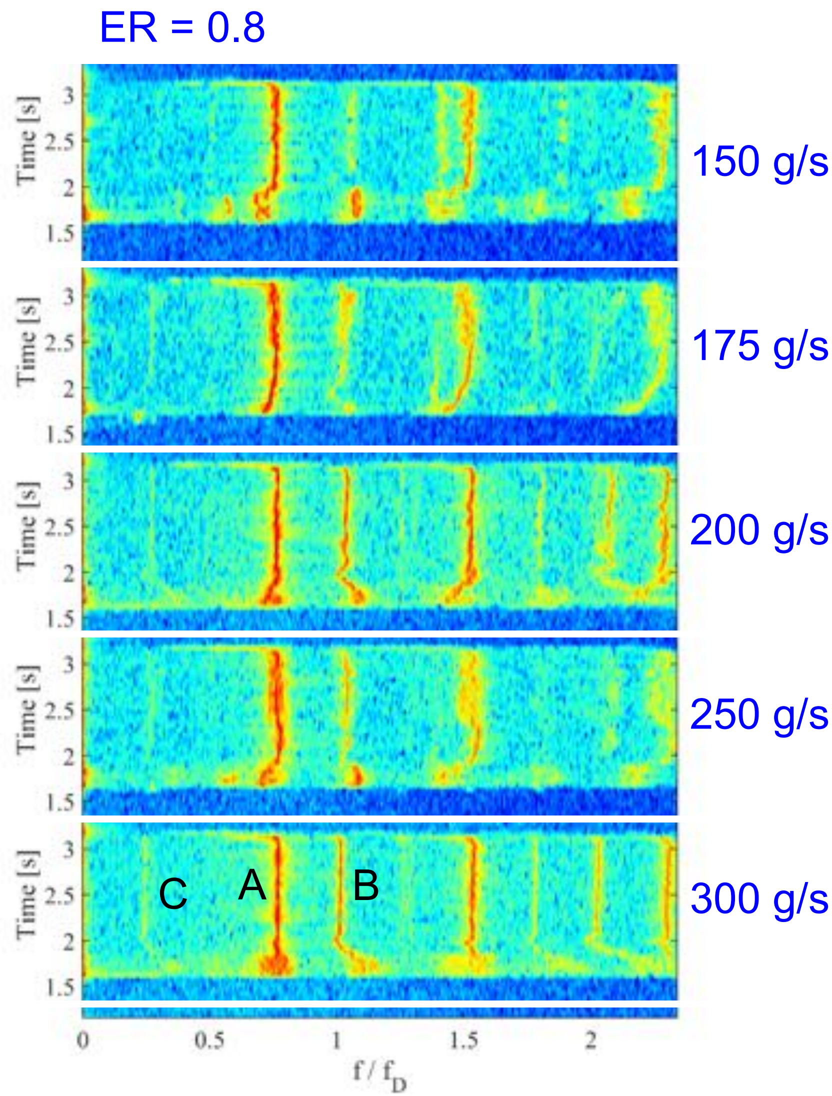
Waterfall spectra of detonation chamber dynamic pressure





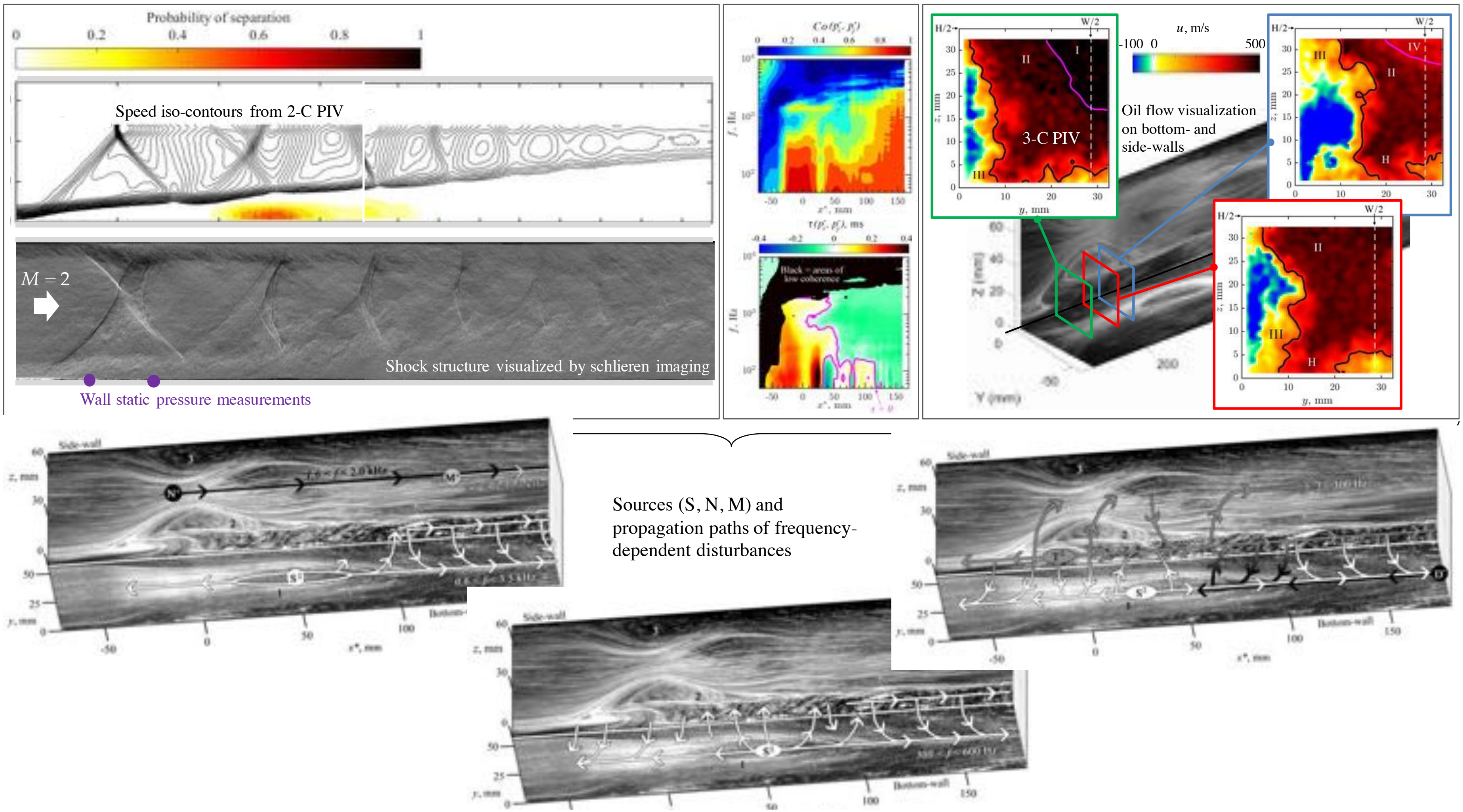
- **3 main modes typically observed**
  - A: wave propagation speed at 0.8 f_D
  - B: Tone at 1 f_D
  - C: Tone at 0.25 f_D
- **Possibly coupling of various dynamics**
  - Plenum dynamics & detonation wave

Focus on project

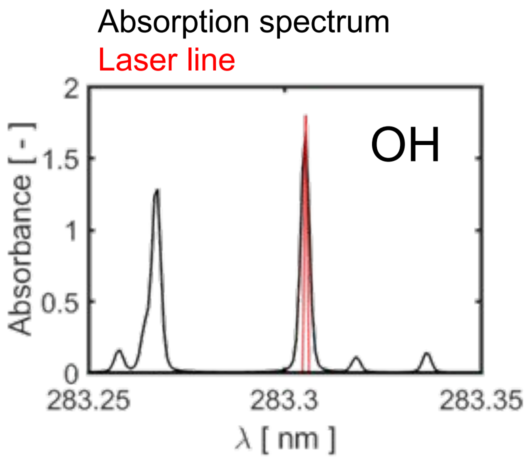
- **Systems upgrade**
  - Instrumentation upgrades (dynamic pressure) to quantify dynamics
  - Addition of variable area diffuser
  - Air injector with variation in area ratio (stiffness)
  - Extend air plenum to evaluate plenum / detonation wave extent of coupling
- **Two major activities / focus**
  - Dynamics: injector/detonation/diffuser dynamics
  - Multicomponent fuels operation
- **Dynamics**
  - Identification and evaluation of RDE dynamics
  - Questions:
    - what are they?
      - Identification from macroscopic observables on round RDE
    - What do they depend on?
      - Geometric and fuel variation on round RDE
    - How do they effect detonation wave structure and overall operation
      - Detailed laser diagnostics for flowfield measurements (mixing, flow velocity and detonation structure)
      - Combined PIV and tracer PLIF (flame marker or mixture fraction) studies in RT-RDE
- **Multicomponent fuels**
  - Evaluation of use of hydrocarbons on
    - RDE operability and performance from macroscopic observables
    - Detonation structure dependence
    - Effect on detonation dynamics
  - Impact of CH_4, and CO additions
  - Impact of C_2H_4 or C_3H_8 additions (contaminants, fuel flexibility)
  - Impact of CO_2 addition on changing heat release profile

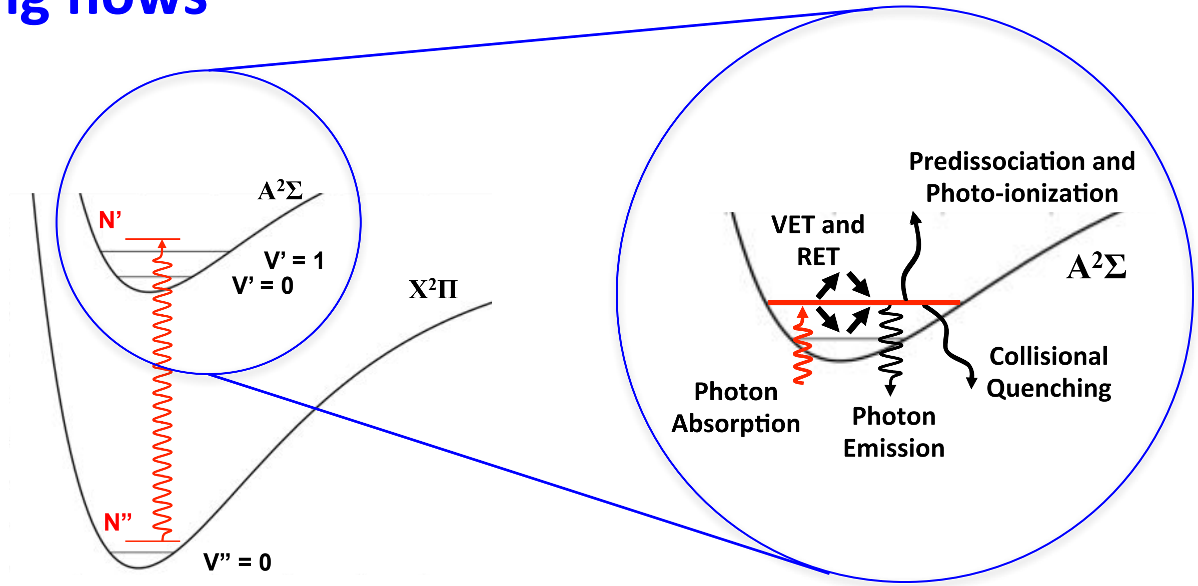
Example of spectral and cross-spectral analysis for system’s dynamics identification

Application to shock train dynamics (supersonic isolator)



Collaboration with AFRL / Edwards on diagnostics: augment laser diagnostics for detonating flows

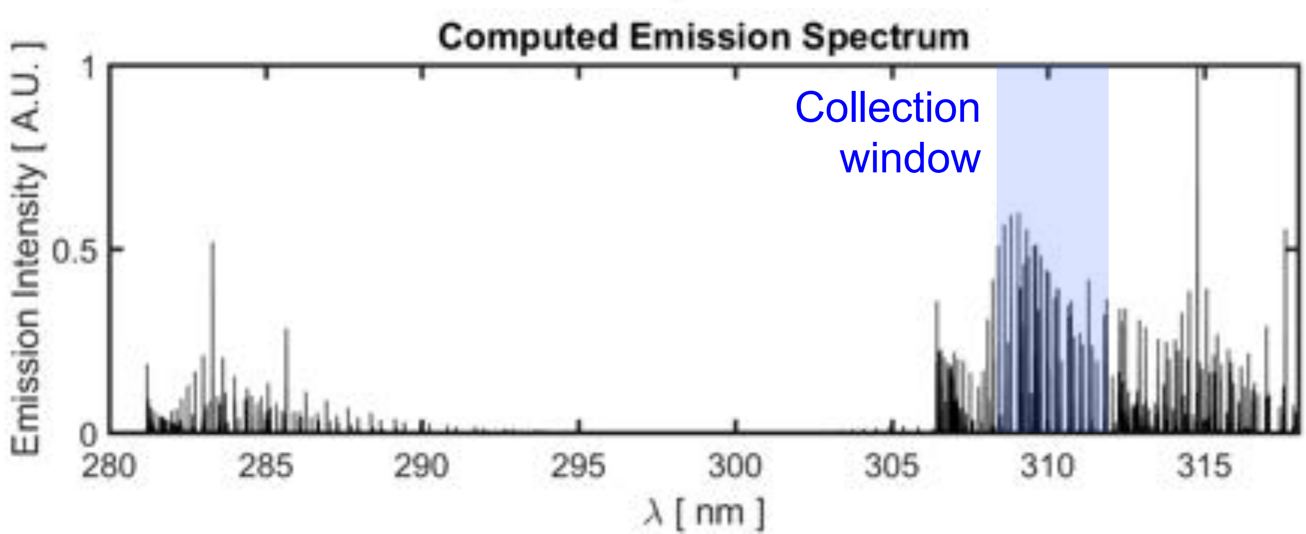




Transition/laser coupling

Absorption (rovibronic electronic transition)

State-resolved energy transfer



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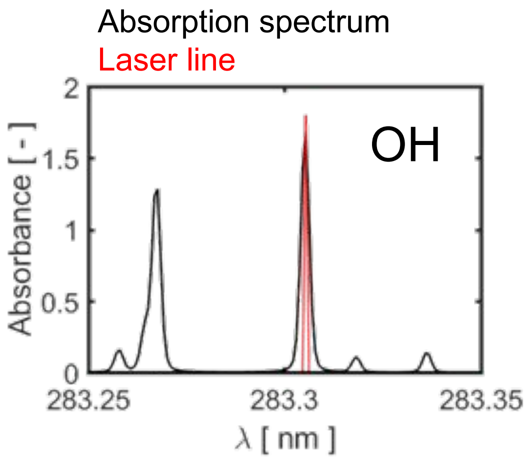
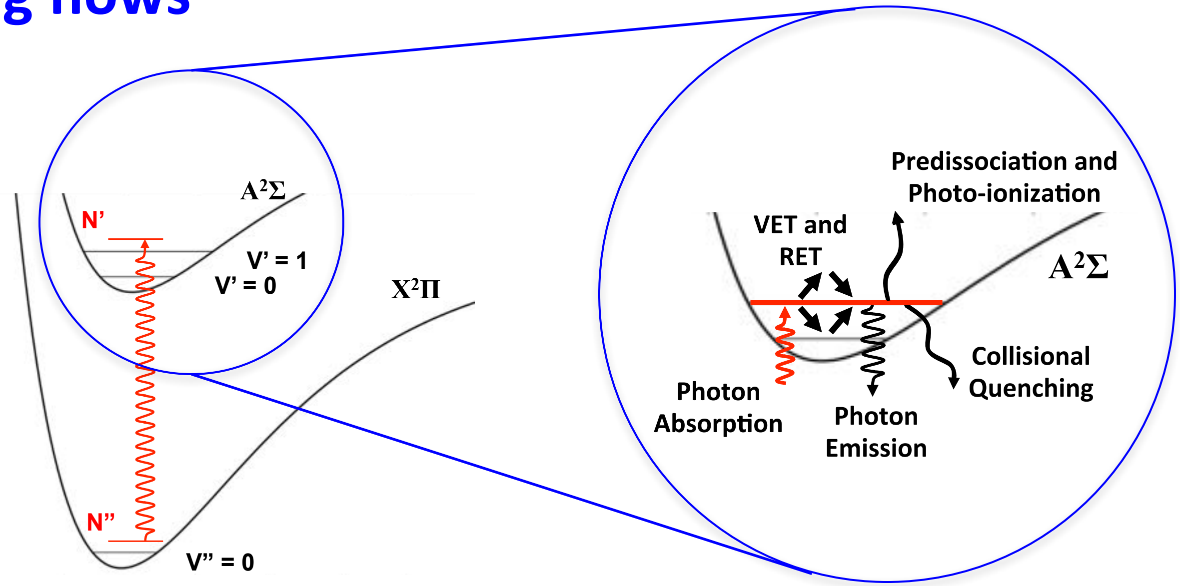




Transition/laser coupling

Absorption (rovibronic electronic transition)

State-resolved energy transfer

- These methods and collaboration gives us a framework to:
  - Evaluate and optimize LIF-based imaging technique for detonating flows
  - Demonstrate methods in RDE relevant flowfields (RT-RDE)
  - Perform measurements on RT-RDE at AFRL/Edwards leveraging their instrumentation and capabilities
    - Anticipated 3 measurements campaigns

Outline

- Programmatic overview
- Introduction to the problem and general approach
- Experimental activities
- Computational activities
- Interactions and collaborations

Goals of CFD Program

- **Develop fully-resolved adaptive mesh compressible solvers for capturing detonation processes**
  - Study structure of detonations in non-premixed systems
  - Develop reduced-order models
  - Study fuel composition effects on stability

- **Assist in the development of the experimental RDE configurations**
  - Provide detailed simulation data to complement experimental measurements
  - Conduct simulations outside of experimental parameters to extend datasets

- **Developments and studies leverage**
  - OpenFOAM suites of codes
  - U-M detonation solvers UMDetFOAM

OpenFOAM Code Development

- **All codes and models developed using the openFOAM open source code base**
  - 10+ years experience in using this tool
    - Several NETL projects successfully completed
  - Easy transfer of code to industry/research community
    - Prior solvers transferred to Siemens Inc.

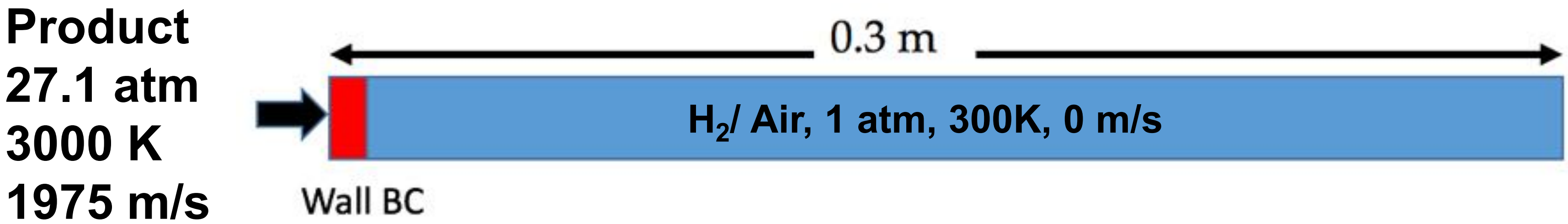
- **Highly scalable and runs on 10K+ processors**
  - Extensive code rewrites to ensure linear scalability

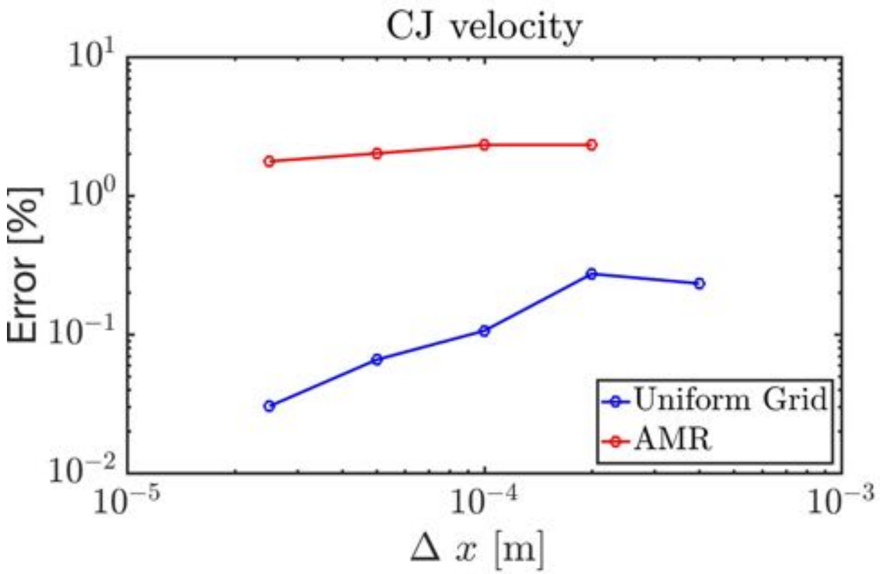
Compressible Detonation Solved UMDetFOAM

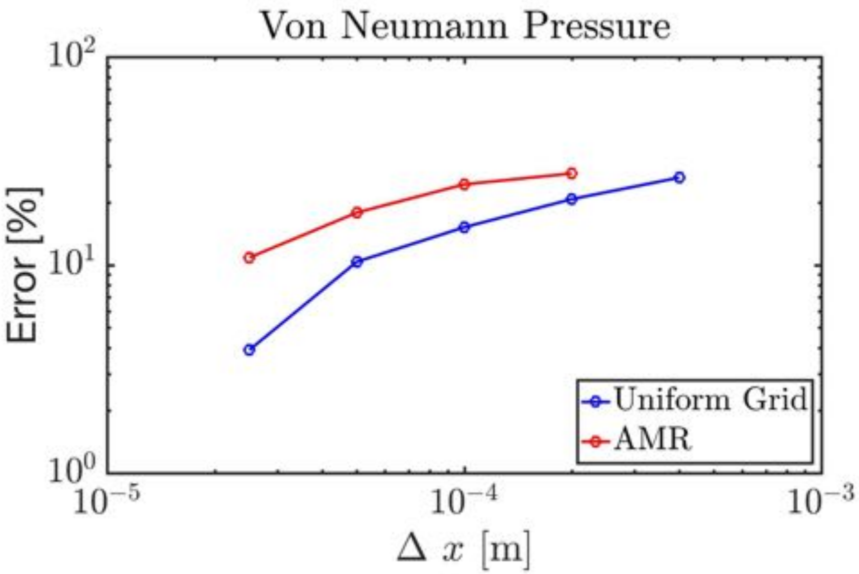
- **Fully explicit solver**
  - Euler and N-S equations
- **Several flux schemes**
  - Locally adaptable to ensure minimal dissipation
- **CANTERA-based chemistry module**
  - Allows any detailed chemistry mechanism to be used
  - Can handle arbitrary number of species
- **Adaptive mesh refinement**
  - Locally adaptive grids to capture detonation structures

Case Studies - 1D detonation with AMR

- **Convergence test with H2/ Air mechanism**
- **The base grid for AMR study is d*x* = 0.4 mm**
  - Shows convergence as increasing the level of refinement

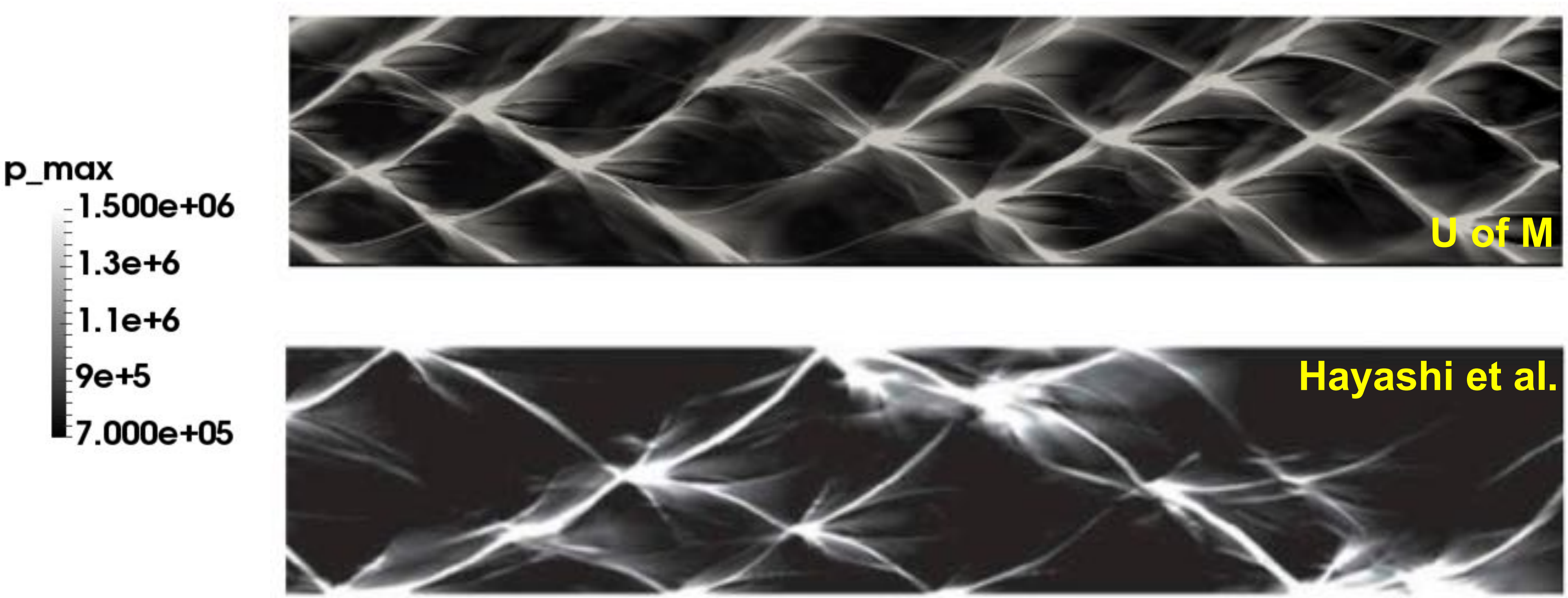






2-D ethylene case

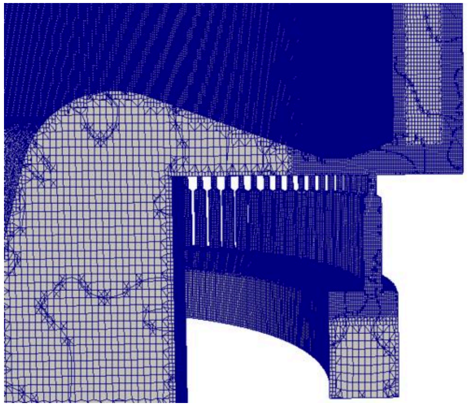
- **Cellular structure validation**
  - Longitudinal tracks from the intersection points
  - 2 cell structure across the channel width



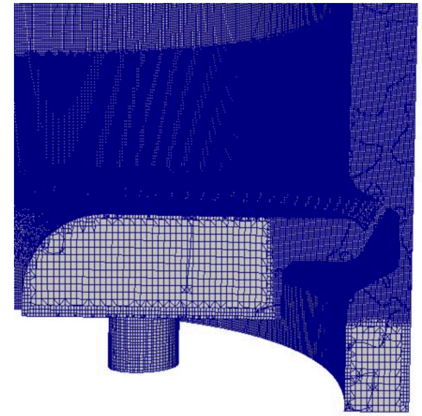
C_2H_4 / O_2, 0.1 atm, 300 K
Δ = 3 μm, h = 2 mm

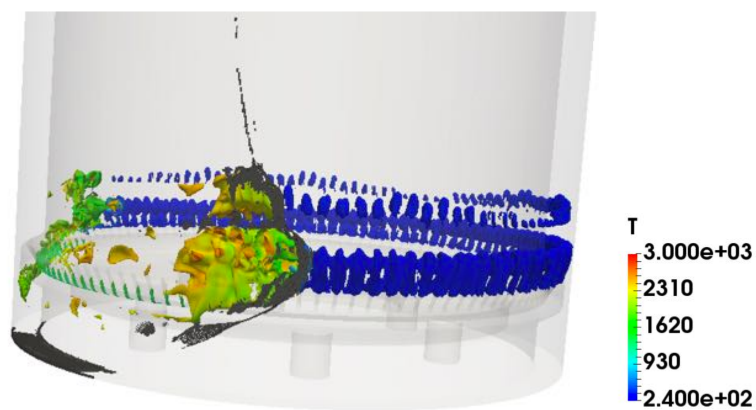
AFRL and U-M Full Geometry Modeling

AFRL geometry



Pintle geometry

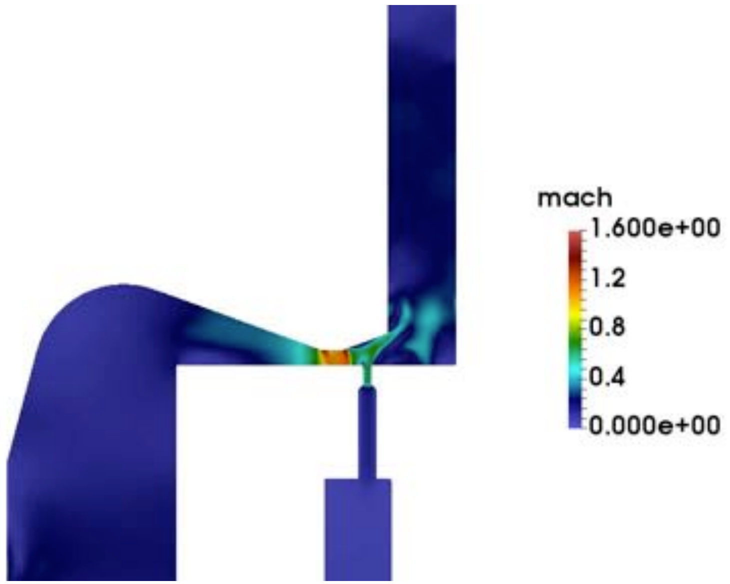


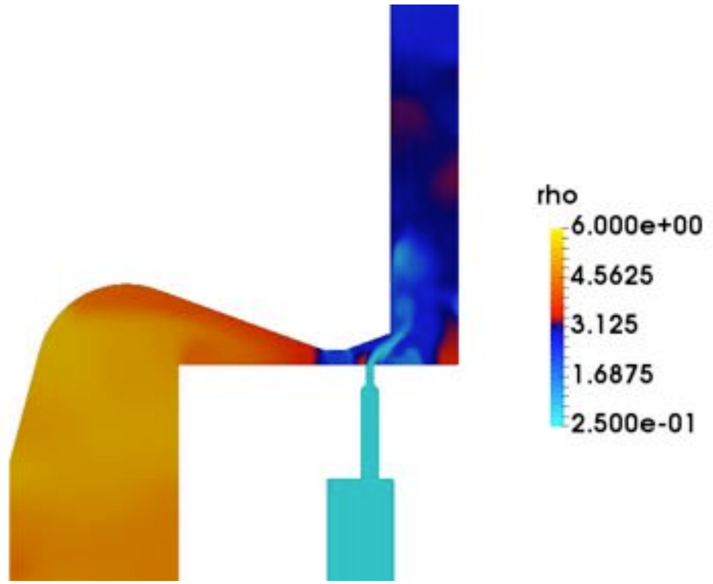


Legend:
Iso-contour of density gradient (black)
Iso-contour of H2 mass fraction (0.1), colored by temperature
Iso-contour of OH mass fraction (0.0075), colored by temperature

AFRL Injector Response

- **Flashback occurs when a detonation wave moves across injector**
  - Chocking is terminated
  - Post-combustion gases propagates back into plenum
  - Blast waves move into plenum
- **Quick injector recovery**
  - Reversed flow pushed back into channel due to high plenum pressure





Focus on the project

- **Simulate fuel effects on cell detonation size**
  - 2D geometry
  - 2D unrolled geometry
  - Full scale geometry

- **Effect of wave structure on detonation process**
  - Coupling between inflow and detonation chamber
  - Interaction of downstream wave structures

- **Modeling detonations**
  - A tabulated modeling approach

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Interactions, collaborations and synergies

- **Strong coupling between experiments and computations**
  - Model development and validation
  - Experiment design and understanding
  - Strong collaborations with external partners
  - Combined investigation of the physics of detonations under MCFs (relevance to application) and impact of injector/detonation/diffuser dynamics on detonation properties and RDE performance

- **Key external collaborations**
  - **ISSI/AFRL WP** (Drs. John Hoke & Fred Schauer) on RDE operation, performance and modeling.
  - **UTRC** (Drs. Adam Holley and Peter Cocks) on detonation and RDE modeling for arbitrary fuels and geometries.
  - **GE** (Venkat Tangirala) on RDE operation, performance and modeling.
  - **AFRL/Edwards** (Dr. William Hargus) on the development and application of diagnostics applied to relevant RDE geometries.
  - **Williams International** (Kyle McDevitt) on detonation and RDE modeling for arbitrary fuels and geometries.

- **Other collaborations/interactions**
  - **NETL** (Dr. Ferguson) on modeling and RDE performance & operation
  - **University of Maryland** (Prof. Yu) on use of experimental data for validation in simple geometries
  - **NRL** (Dr. Kailasnath) on code and combustion model development

Questions?