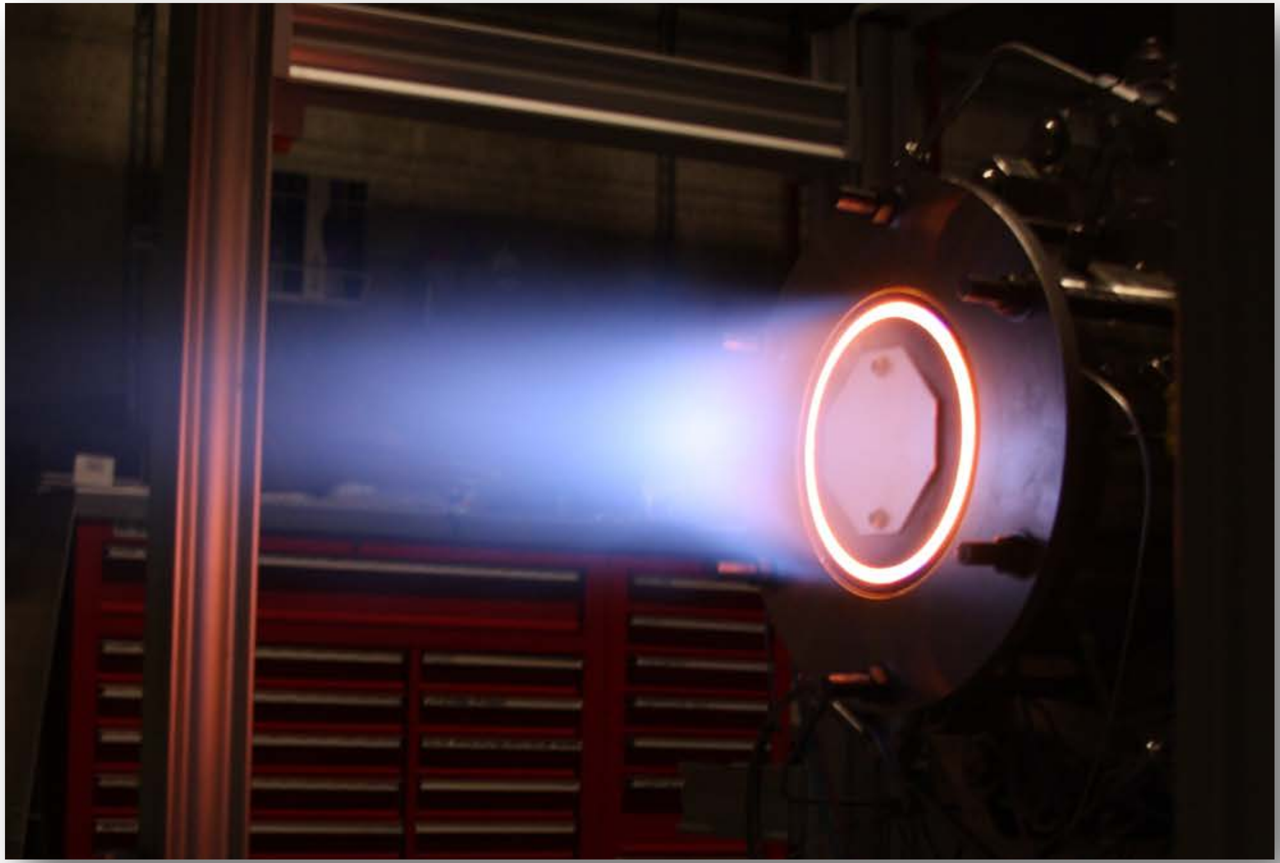
Advancing Pressure Gain Combustion in Terrestrial Turbine Systems

2018 UTSR Project Review Meeting

Prof. Stephen D. Heister
Prof. Carson D. Slabaugh
Ian Walters
Kyle Schwinn
Christopher Journell
Dr. Rohan Gejji
Dr. Swanand Sardeshmukh

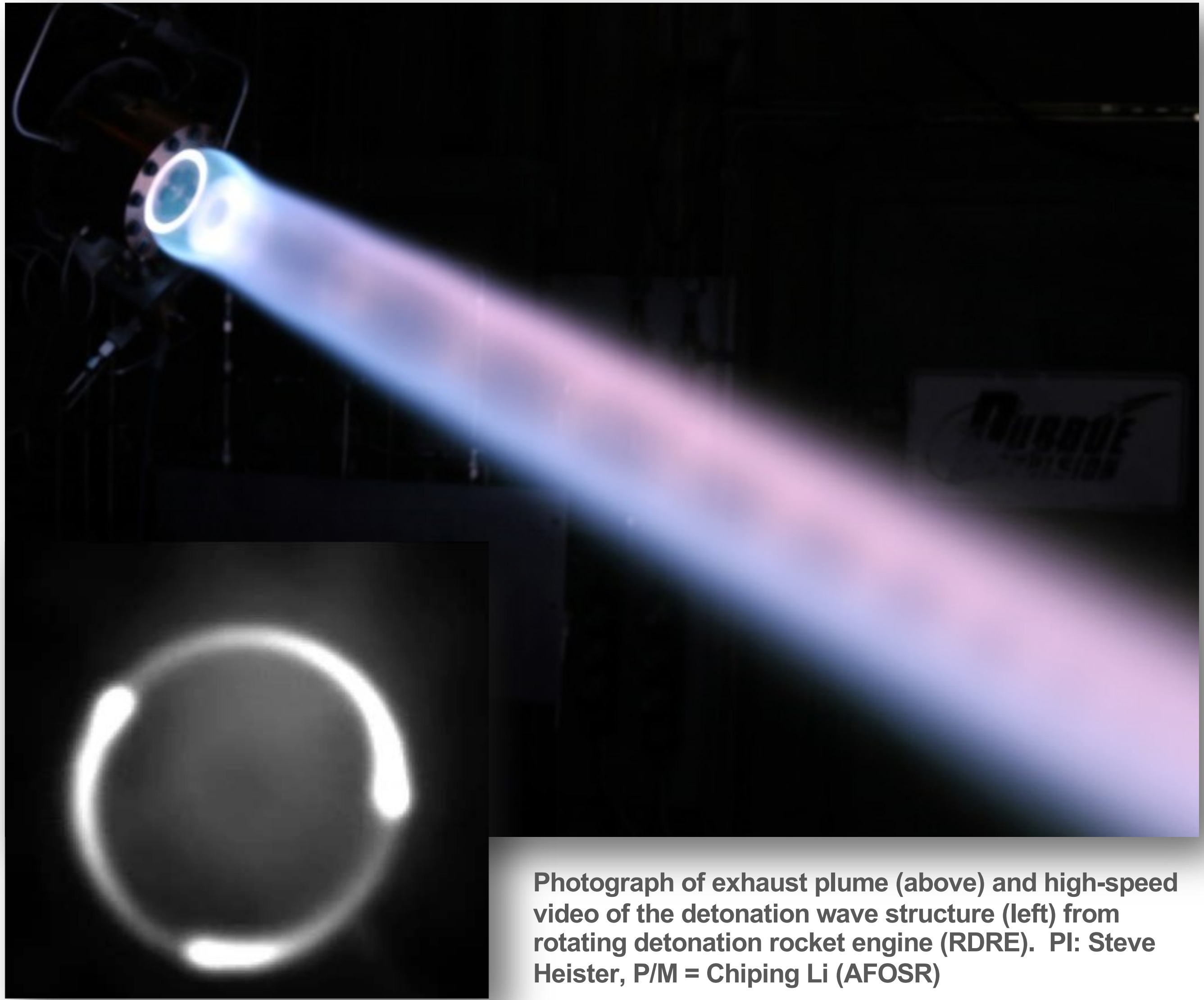
School of Aeronautics and Astronautics
Purdue University
West Lafayette, IN



Introduction

Background and Motivation

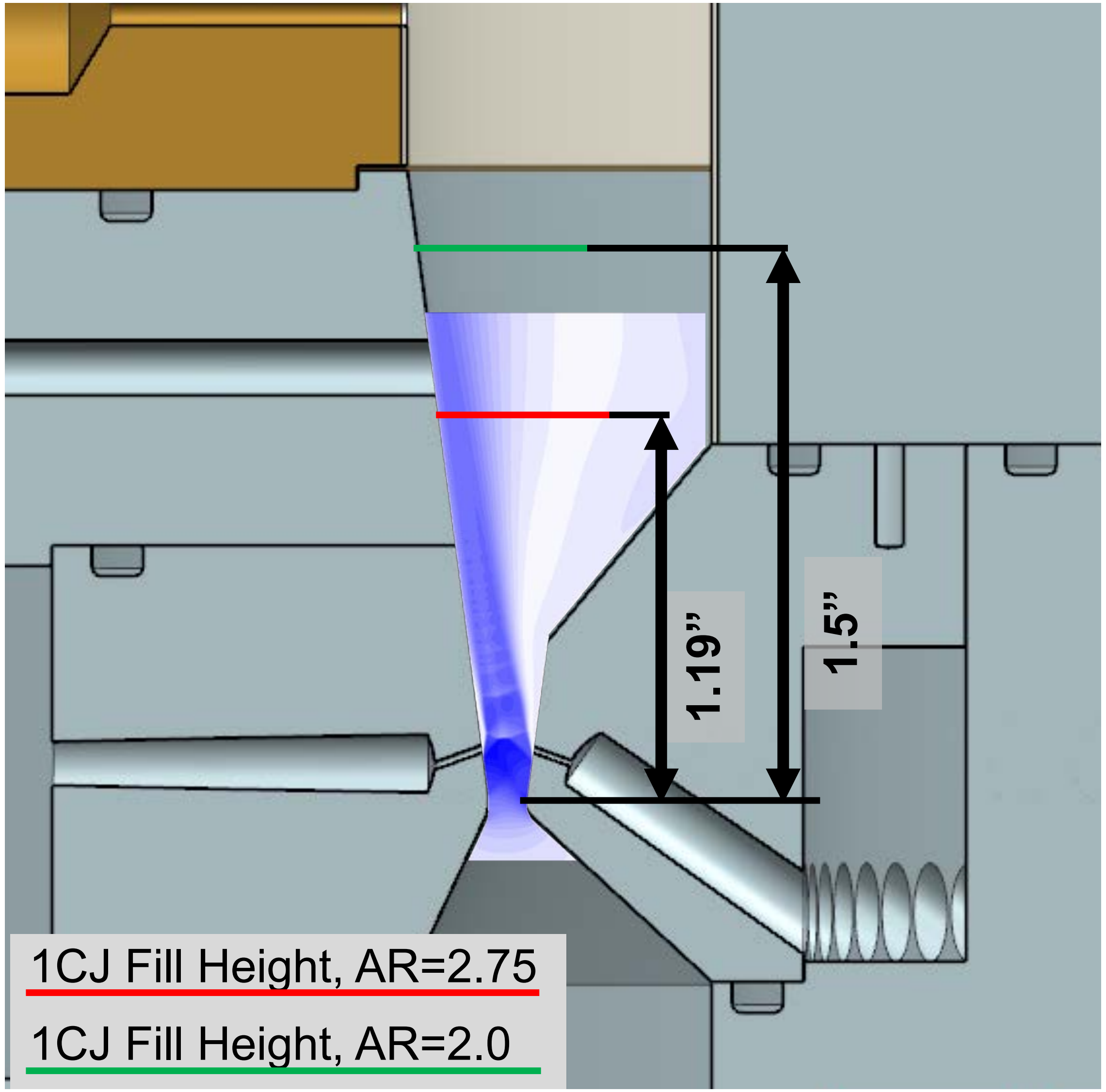
- RDEs show significant promise for improved **cycle efficiency** and thermal **power density.**
- Key questions:
  - Can a total pressure gain be realized?
  - How bad is the NOx emission going to be?
- Operability:
  - Unsteady mixing and stratification
  - Detonation propagation physics
  - Parasitic deflagration losses
  - Shock Losses
- Integration:
  - Propellant supply coupling
  - Material survivability
  - Realistic propellants and flow conditions
- Limited prior work on PGC for land-based power generation applications, with many challenges remaining unaddressed.



Photograph of exhaust plume (above) and high-speed video of the detonation wave structure (left) from rotating detonation rocket engine (RDRE). PI: Steve Heister, P/M = Chiping Li (AFOSR)

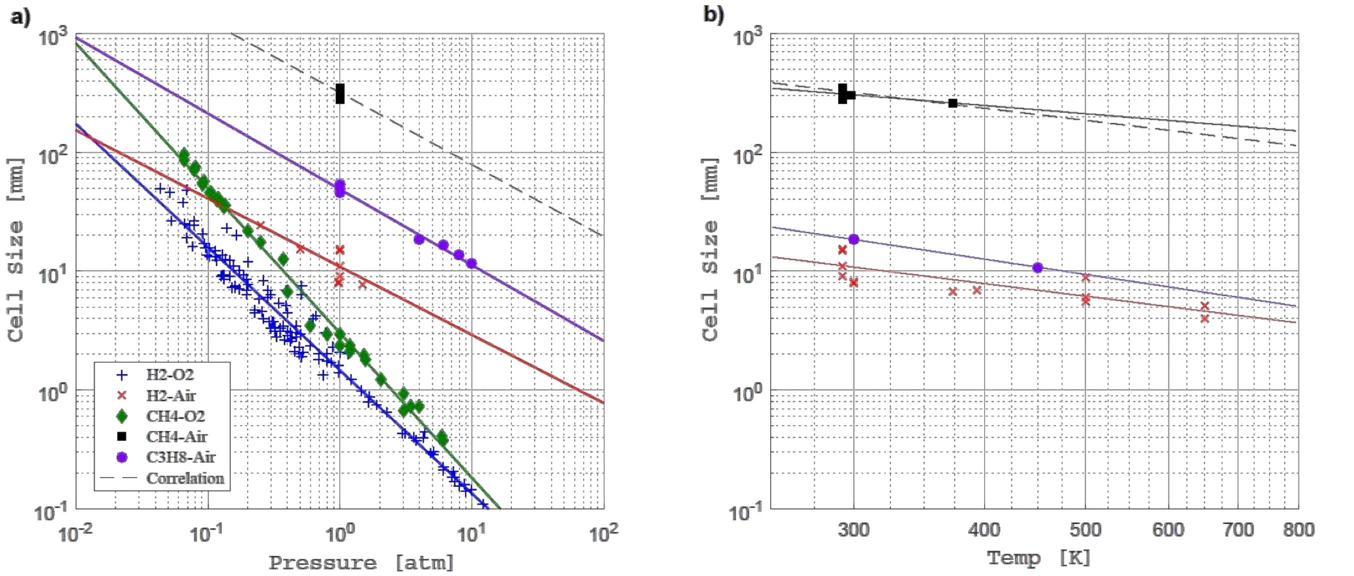
Introduction

Unique Aspects of Methane-Air RDEs



Contours of Mach number overlaid with injector geometry

- Design heuristics based on reactant fill height and detonation cell size at inflow conditions.
  - Detonation cell size for methane detonation with air at 2.0 MPa (300 psi) and 650 K (700 F) is about 20 mm.
  - Propellant mass flux requirement, based on one-dimensional fill-height is of order 200 kg/s/m^2
- Scaling of injection and mixing systems is very unclear due to unsteady flow separation and stratification.
- Hardware scale to test ideas is cost prohibitive.



Introduction

Objectives

Task 1.0: Project Management and Planning

Task 2.0: Injection Dynamics Characterization

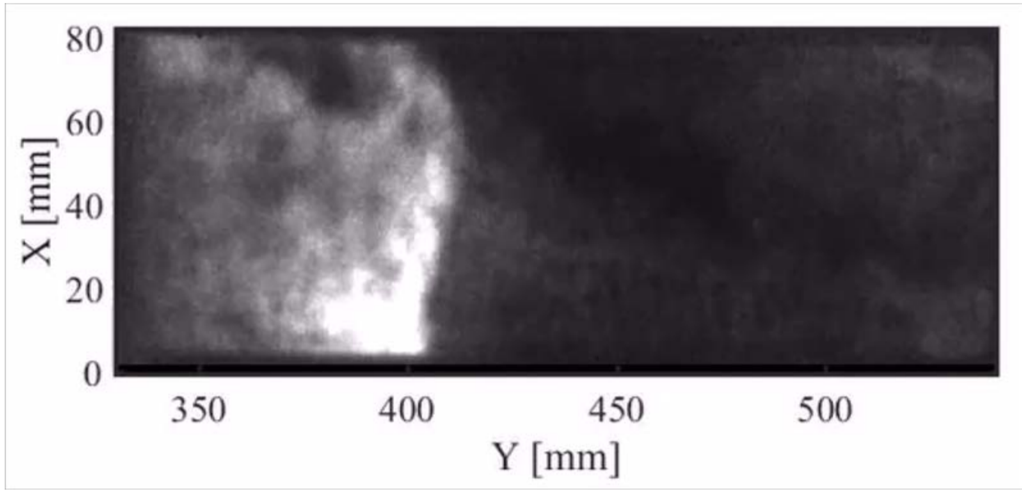
Task 3.0: Subscale Combustor Development

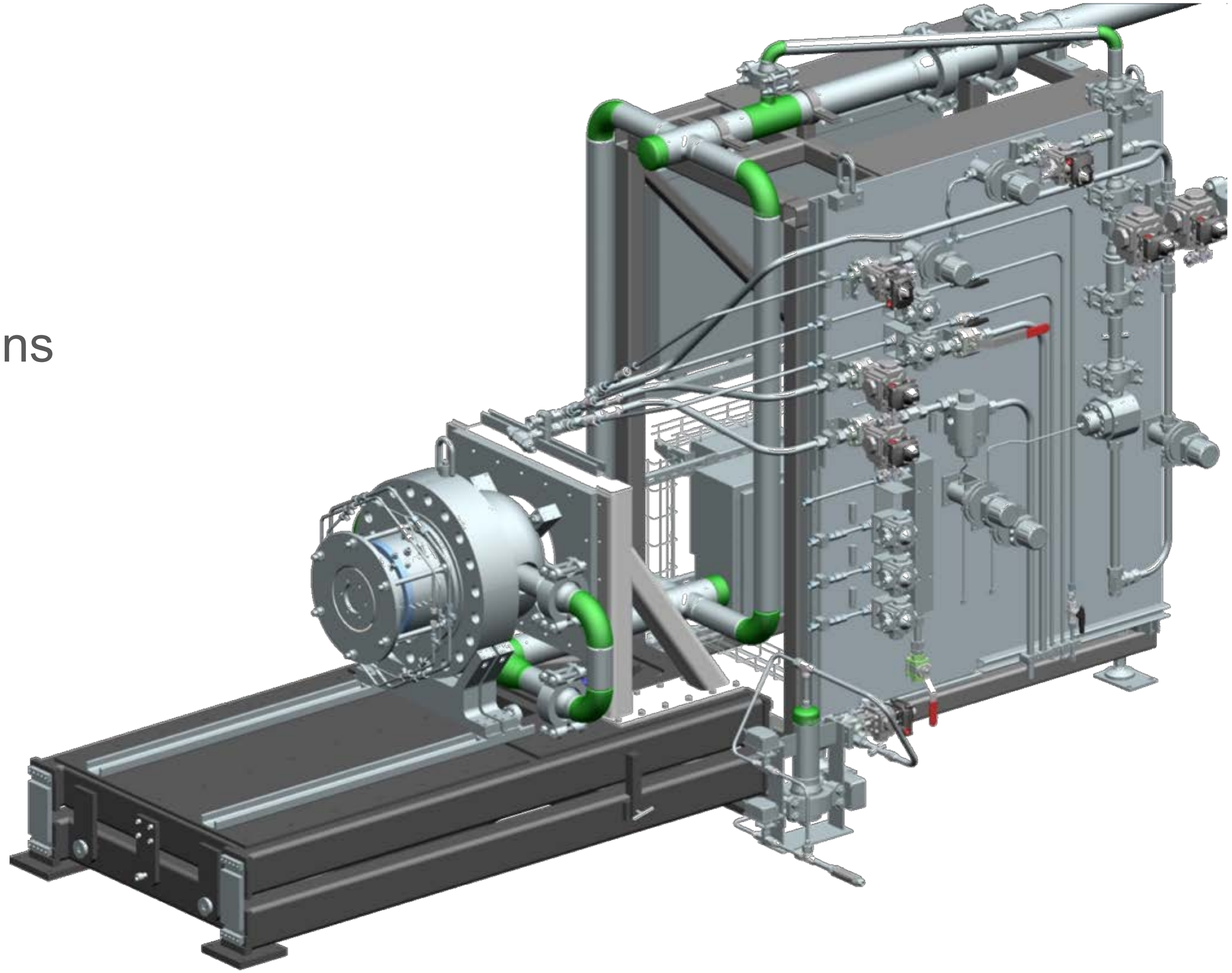
Task 4.0: Evaluation of Pressure Gain

Task 5.0: Detailed Measurements of Exit Conditions

Task 6.0: Emissions Measurements

Task 7.0: Model Development

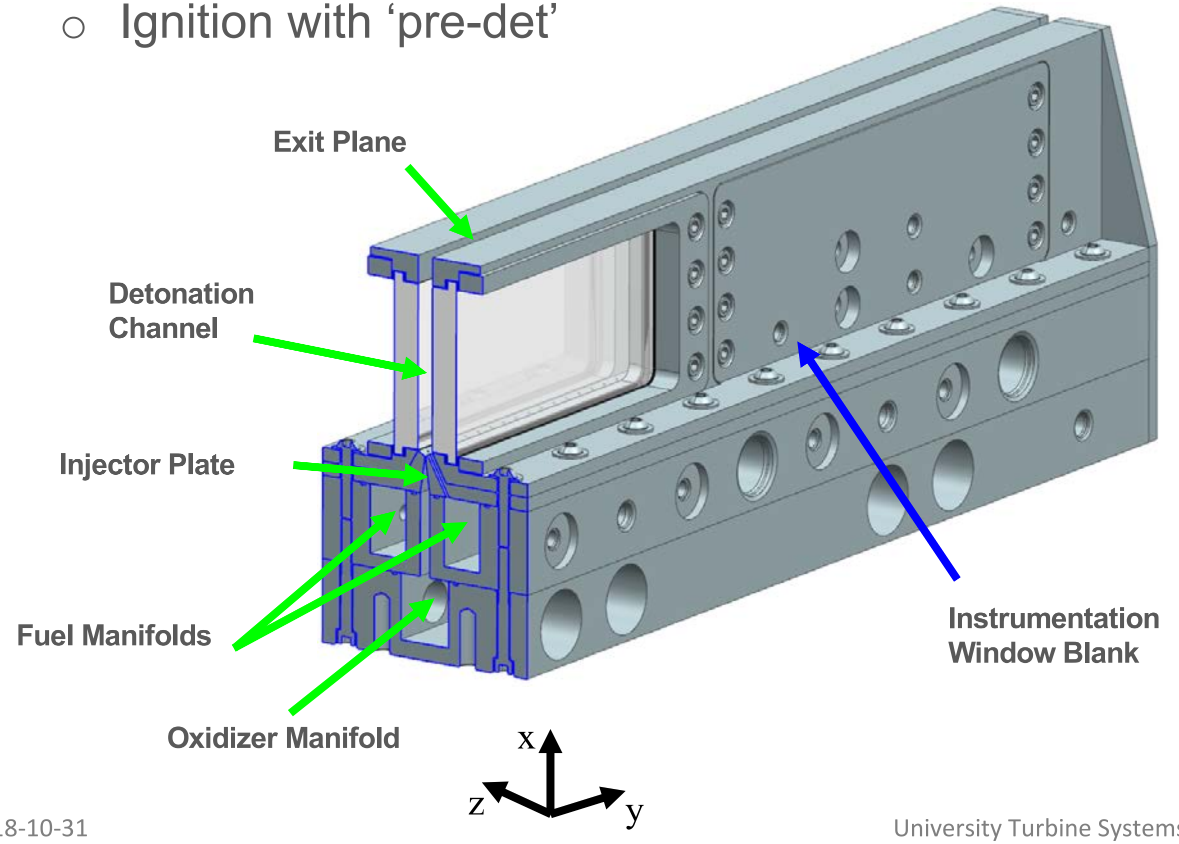


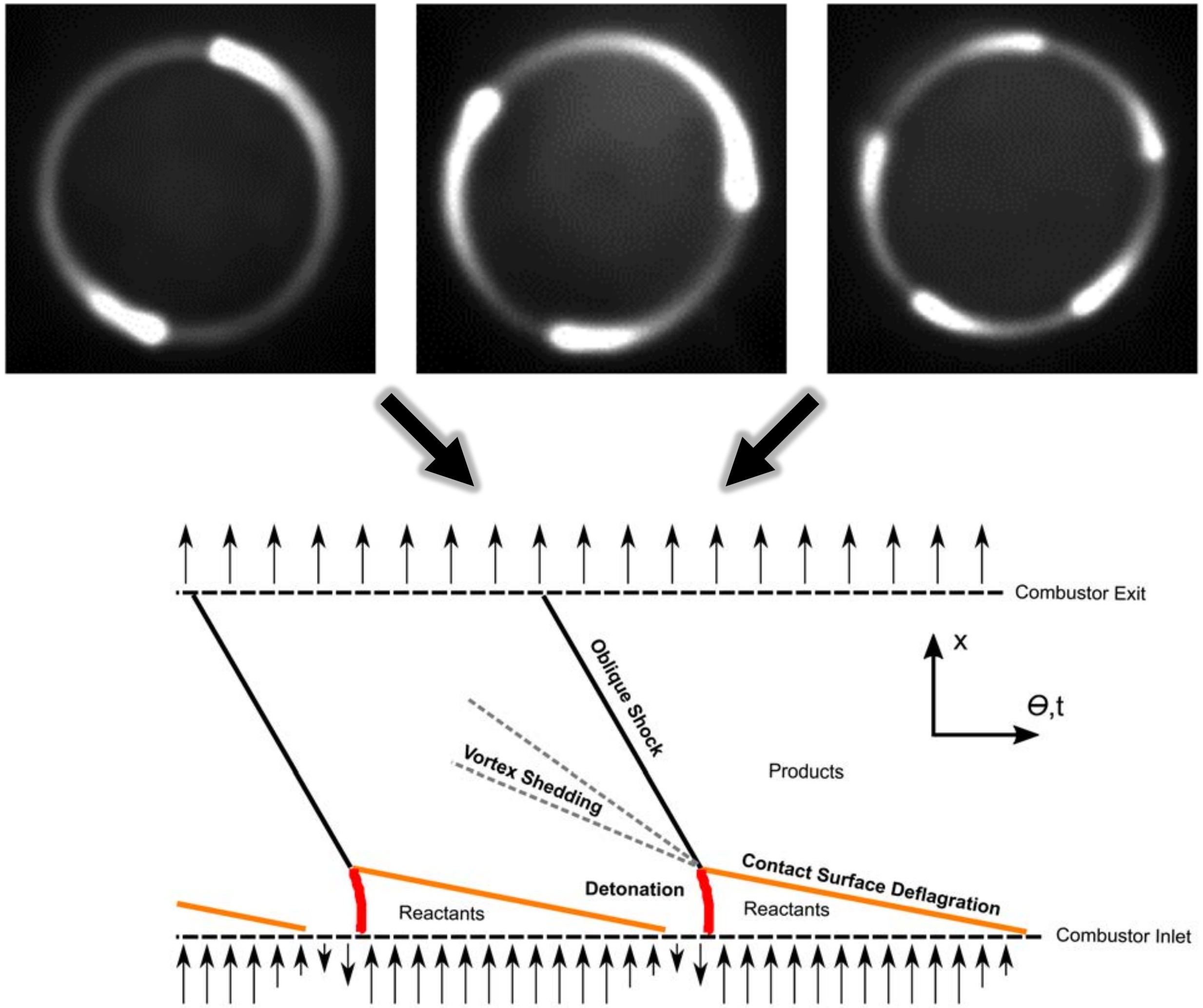


Injection Dynamics

Detonation Rig for Optical, Non-intrusive Experimental measurements

- DRONE is an ‘unwrapped’ semi-bounded, linear detonation channel experiment
  - Enabling optical diagnostics for quantitative analysis
  - Methane – oxygen propellant combination maintains hardware scale
  - Ignition with ‘pre-det’

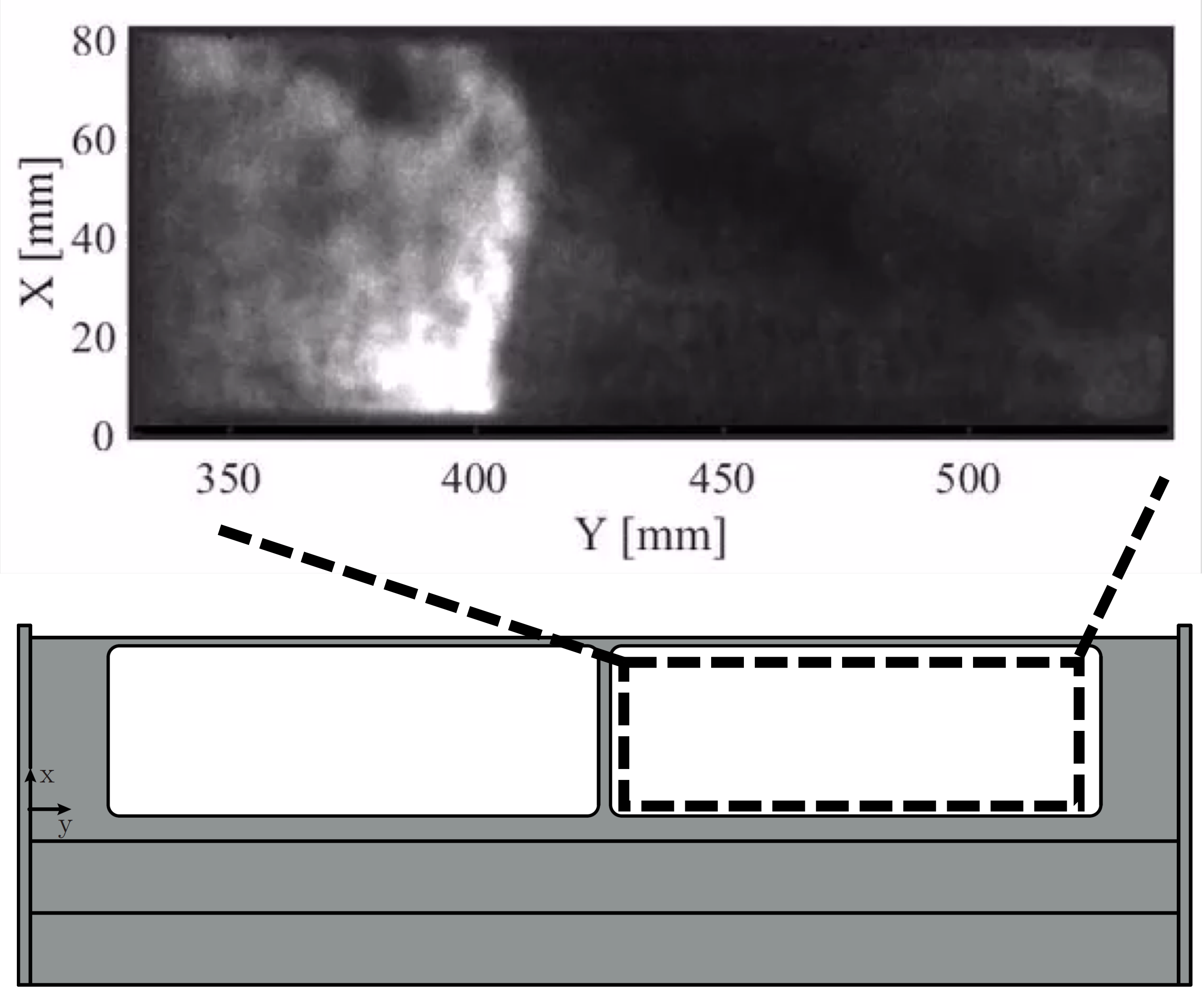


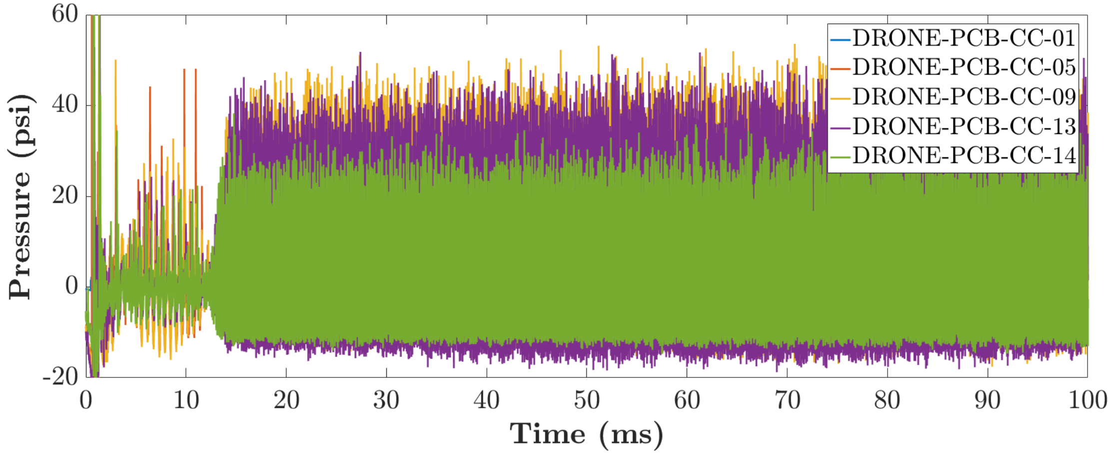


Injection Dynamics

Self-Sustained, High-Frequency Detonation Wave Generation

- Wave speed: $1500 - 1900\ m/s$
- Pressure ratio: 2 - 4 (relative to CTAP)
- CTAP pressure range: $\approx 25 - 40\ psia$
- The wave structure generated is akin to that in an annular geometry
  - Very compact heat release
  - Oblique shown from the fill-shock-product triple point
  - Vortex shedding through product gases

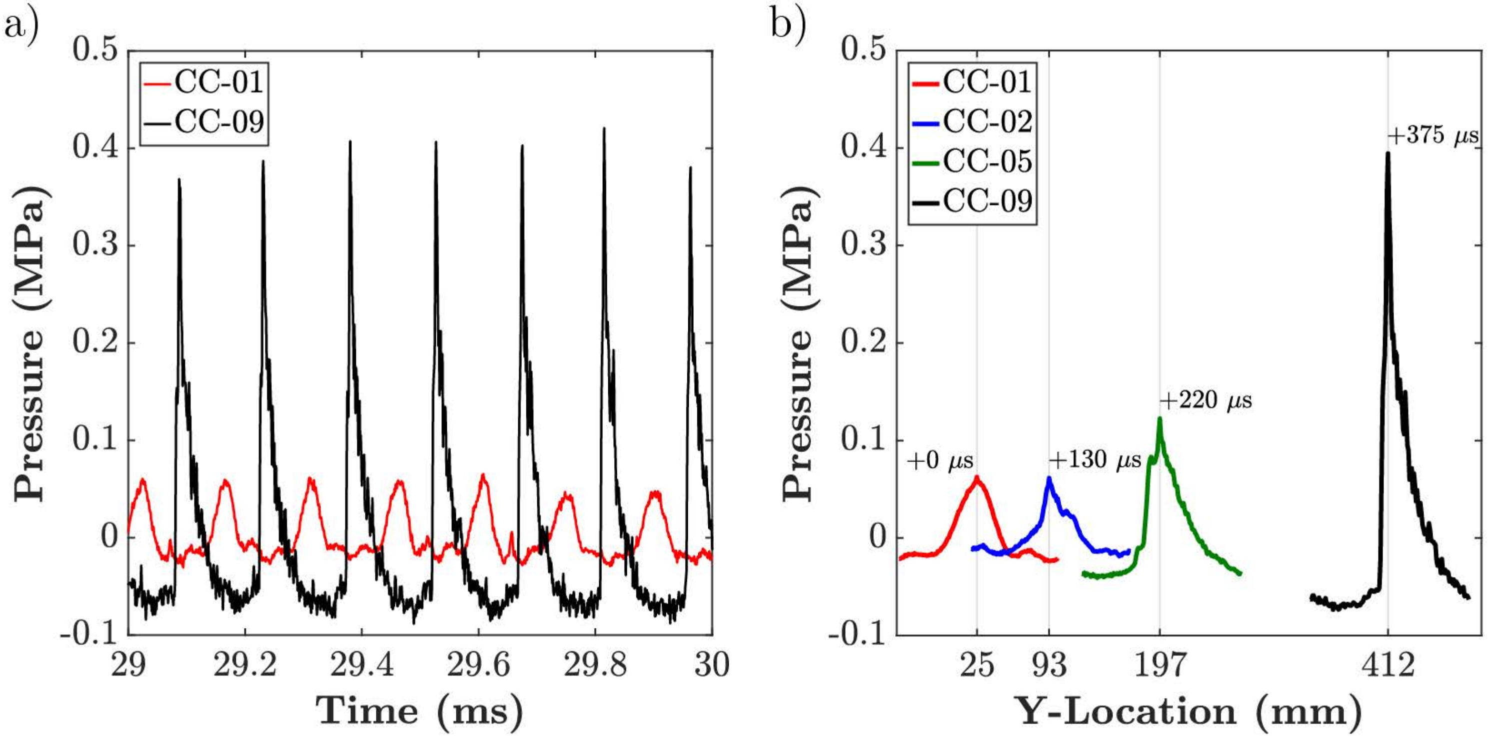


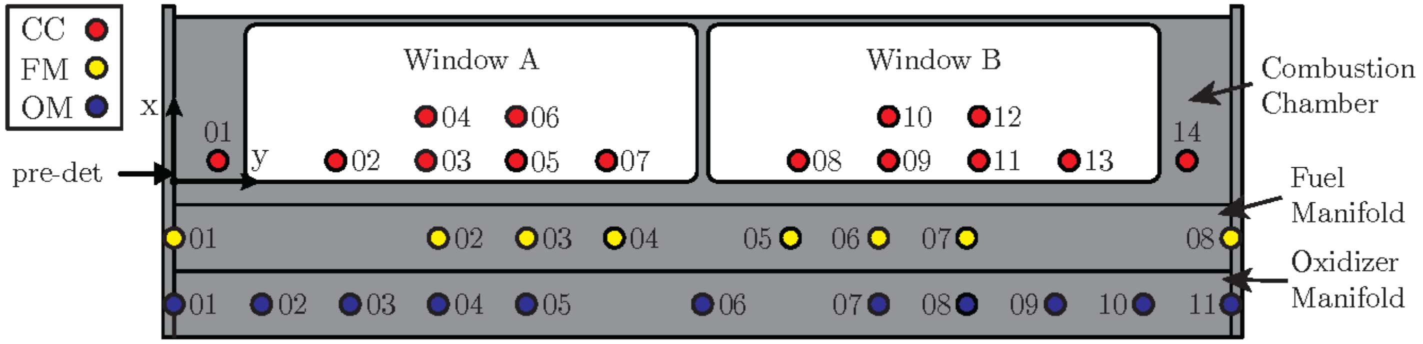


Injection Dynamics

Self-Sustained Detonation Generation

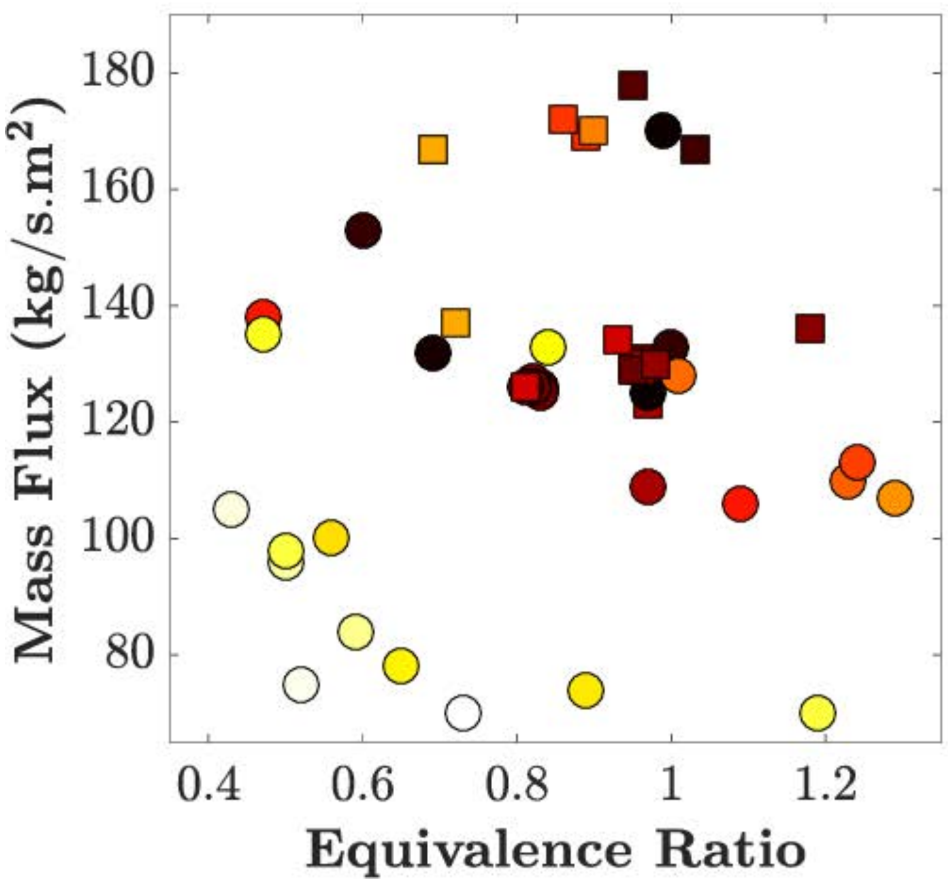
- Low amplitude oscillation present after ignition at location (CC-01).
  - Frequency varies (with test condition) between 6 kHz and 12 kHz
- Pressure wave-coupled flame fronts accelerate across injector face (+ y-direction).
  - Develop into steep-fronted waves in short distances.
- Wave-steepening process proceeds at the frequency of the low amplitude combustion instability.
- Self-sustained behavior is robust across a range of mass fluxes and equivalence ratios.

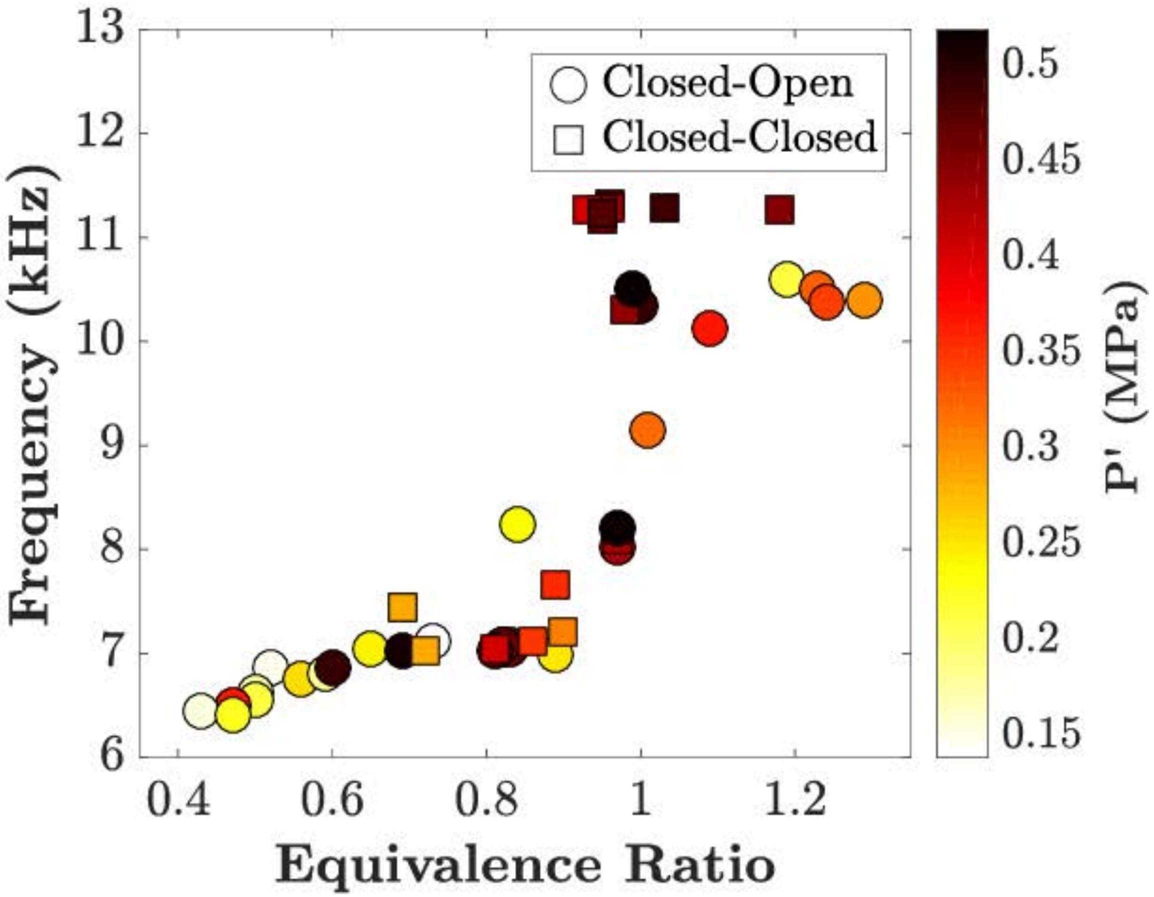




Injection Dynamics

Self-Sustained Detonation Generation



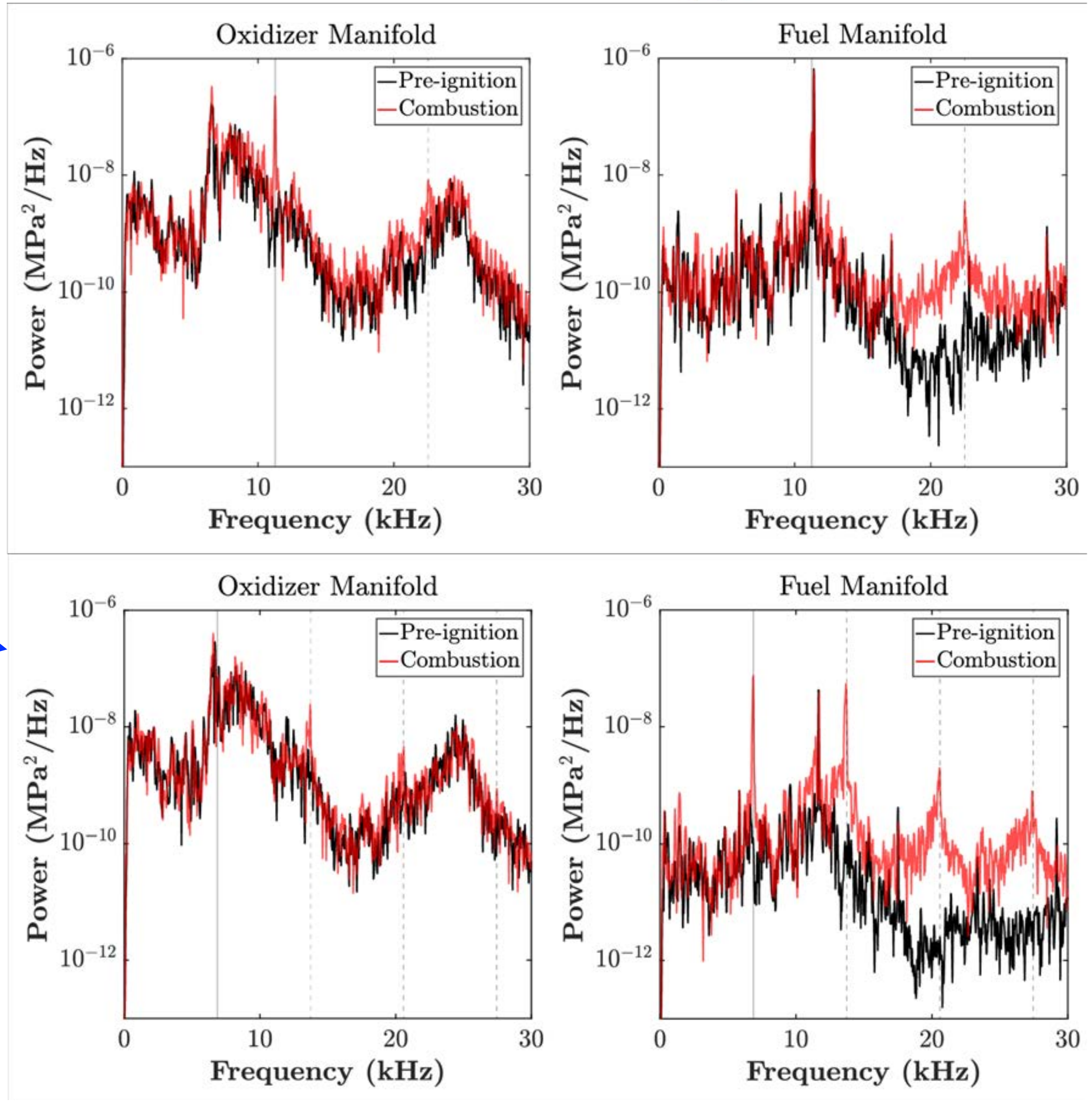


Limit-cycle frequency appears to be tied to the propellant equivalence ratio.

Injection Dynamics

Influence of Propellant Manifolds

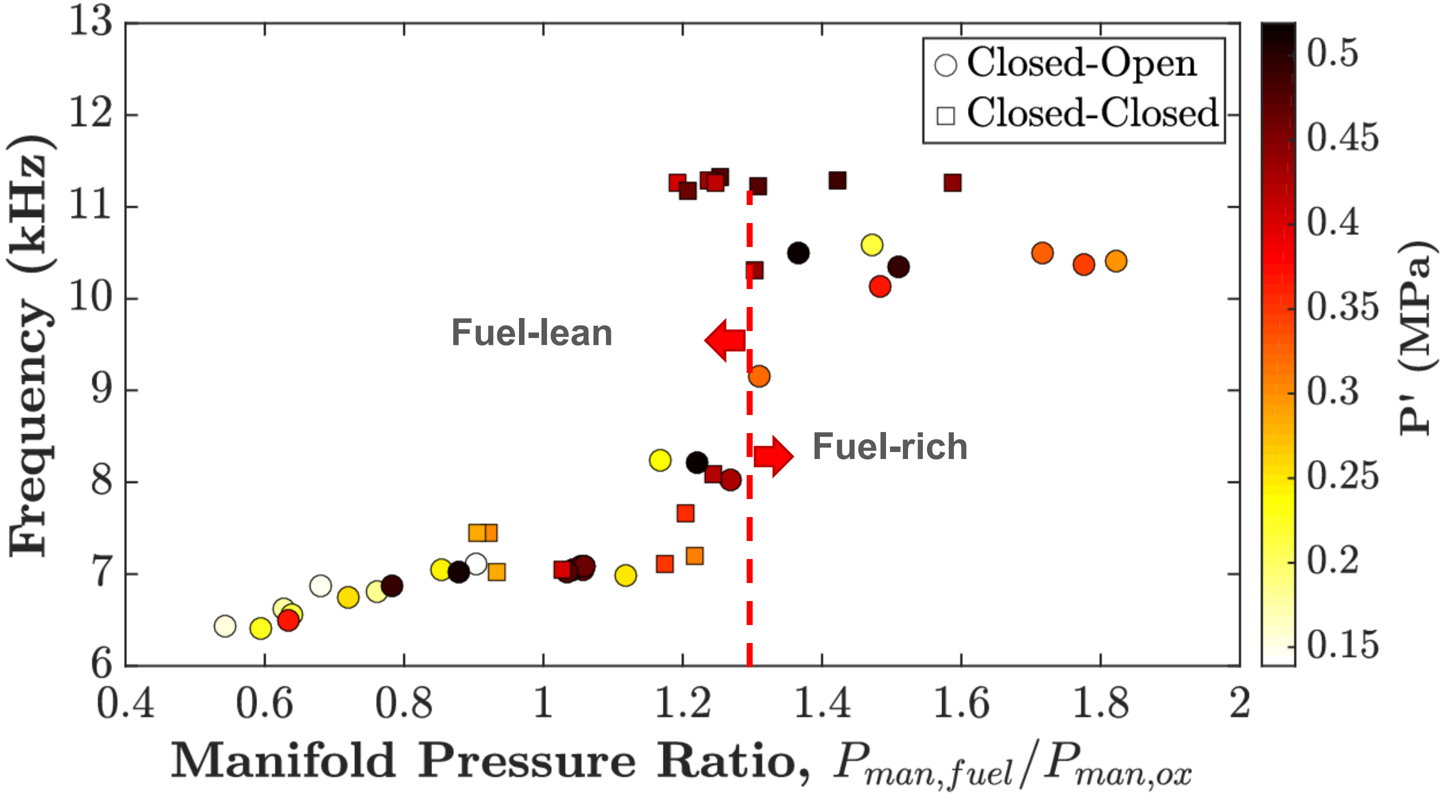
- Frequency analysis of pre-combustion pressure time series indicates strong inherent dynamics that are attributes of each manifold.
    - $f_{ox} \approx 6\ kHz$
    - $f_{fu} \approx 11\ kHz$
- Under fuel-rich conditions, the combustion chamber dynamics match the fuel manifold dynamics.
- When fuel-lean, the combustion chamber dynamics match the oxidizer manifold frequency
- Detection of combustion-driven frequency content in the manifolds indicates pressure communication across the injector (unchoking).

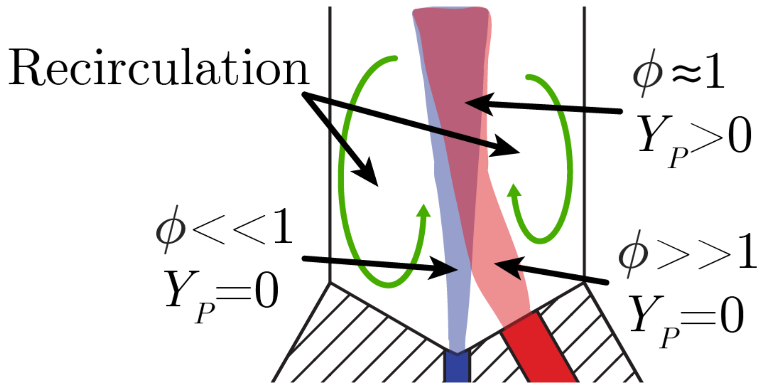


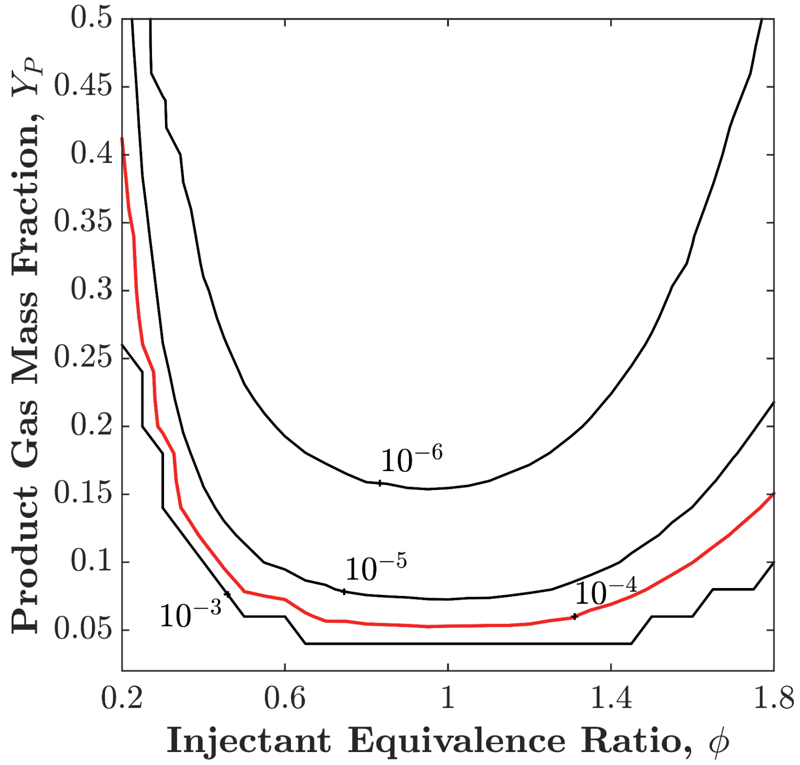
Injection Dynamics

Influence of Propellant Manifolds

- The injection system imposes dynamics on the chamber.
  - The system with the higher pressure dominates
- Flame acceleration and pressure amplification is determined by the mixing and ignition characteristics of the reactant fill.



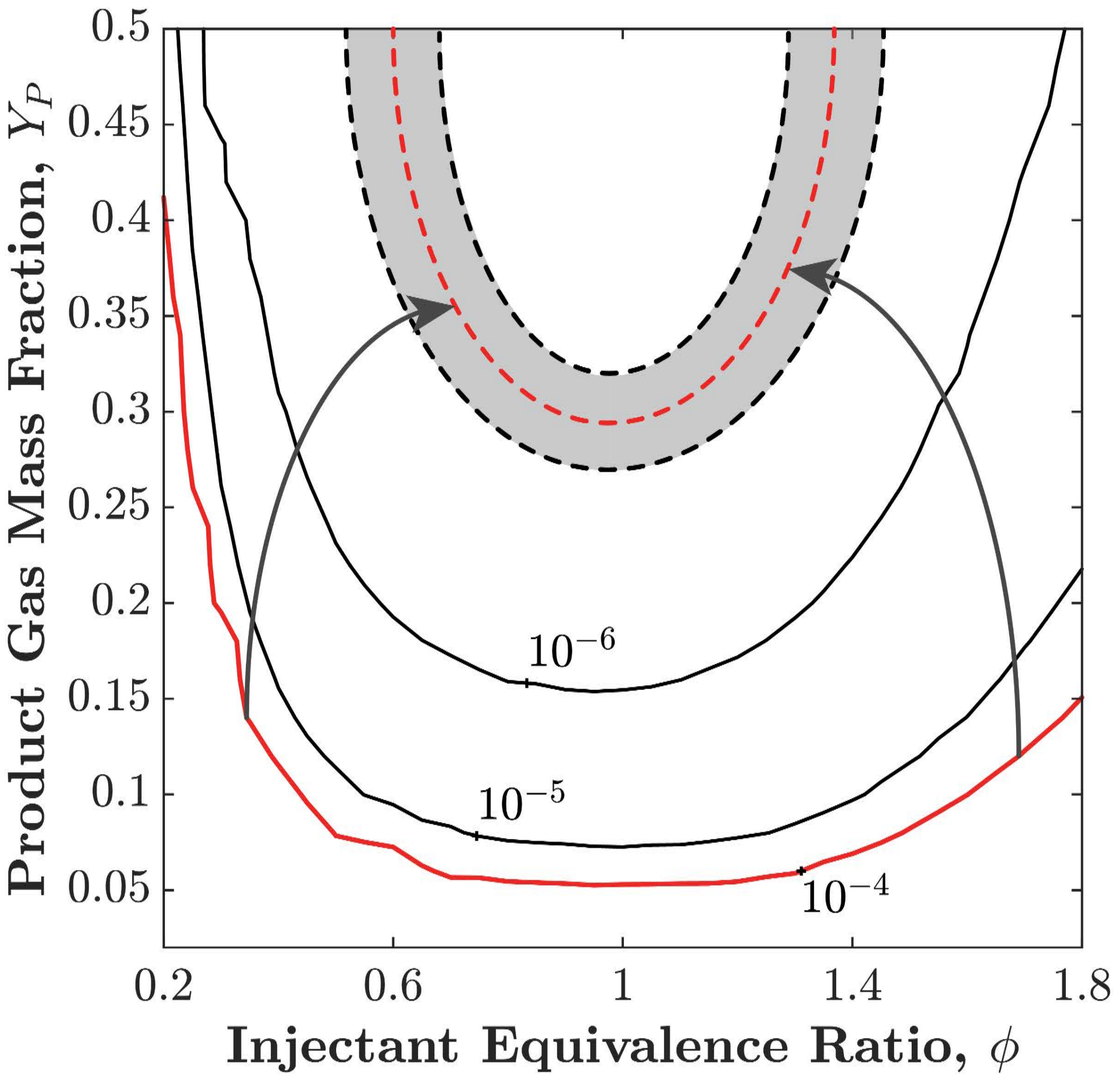




Injection Dynamics

Sensitivity to Oxidizer Dilution

- There is a unique dichotomy between cycle frequency and wave-speed
  - Can we use this to understand more about the rate-controlling processes an RDE? A CH4-Air RDE?
- Dilution of the oxidizer narrows the range of operability by stressing the transport requirements to sustain the high-speed combustion process
  - Combustion product temperature is reduced
  - Ignition limits are narrowed
- More recirculation of product gases is required to return energy to reactant jet.



Injection Dynamics

Sensitivity to Oxidizer Dilution

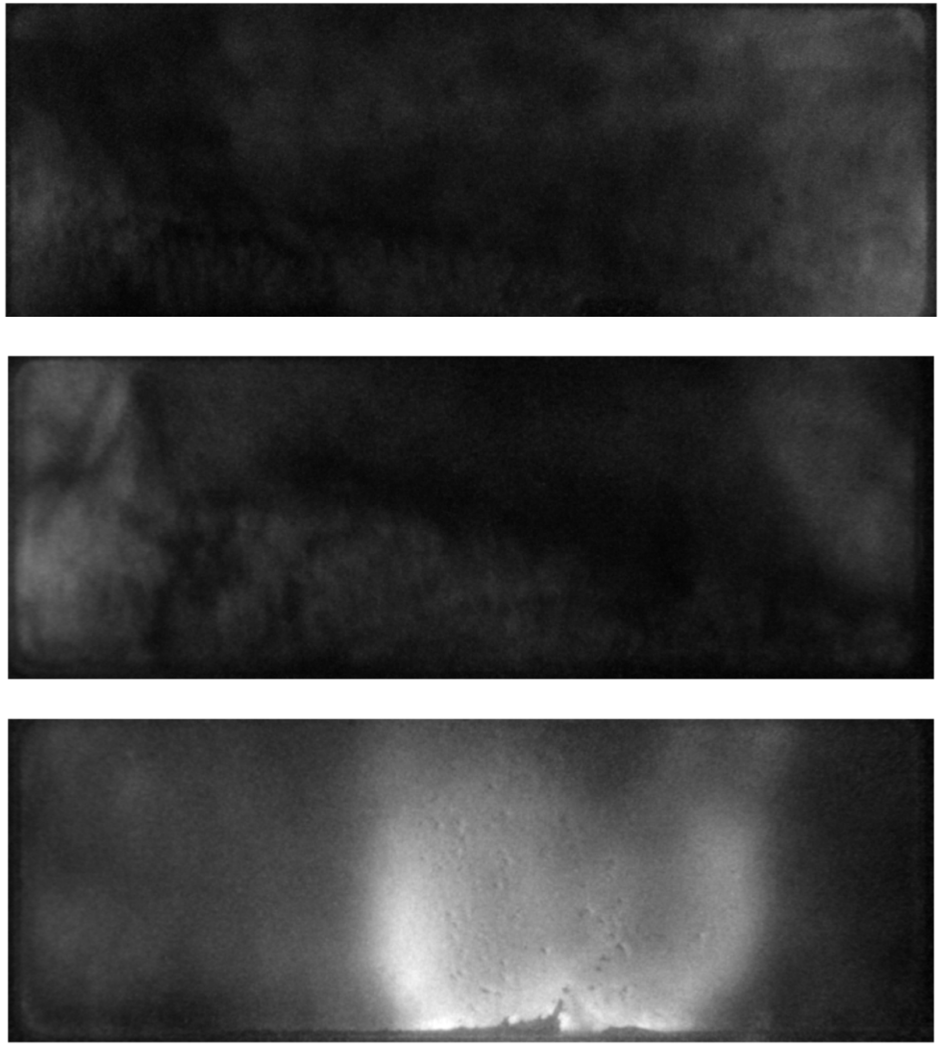
- Decreasing oxygen content has an immediate effect on the wave structure
  - Elongation in the axial direction
- For cases with Y_{O2} < ~70%, the dynamics are no longer correlated with manifold.
- For Y_{O2} < ~50%, thermo-acoustics become the dominant source of combustion dynamics.

	$\dot{m}''\left(\frac{kg}{m^2 s}\right)$	ϕ	Y_{O_2} (%)
A	170	0.96	86
B	173	0.93	64
C	175	0.93	49

A

B

C



Injection Dynamics

Key Conclusions

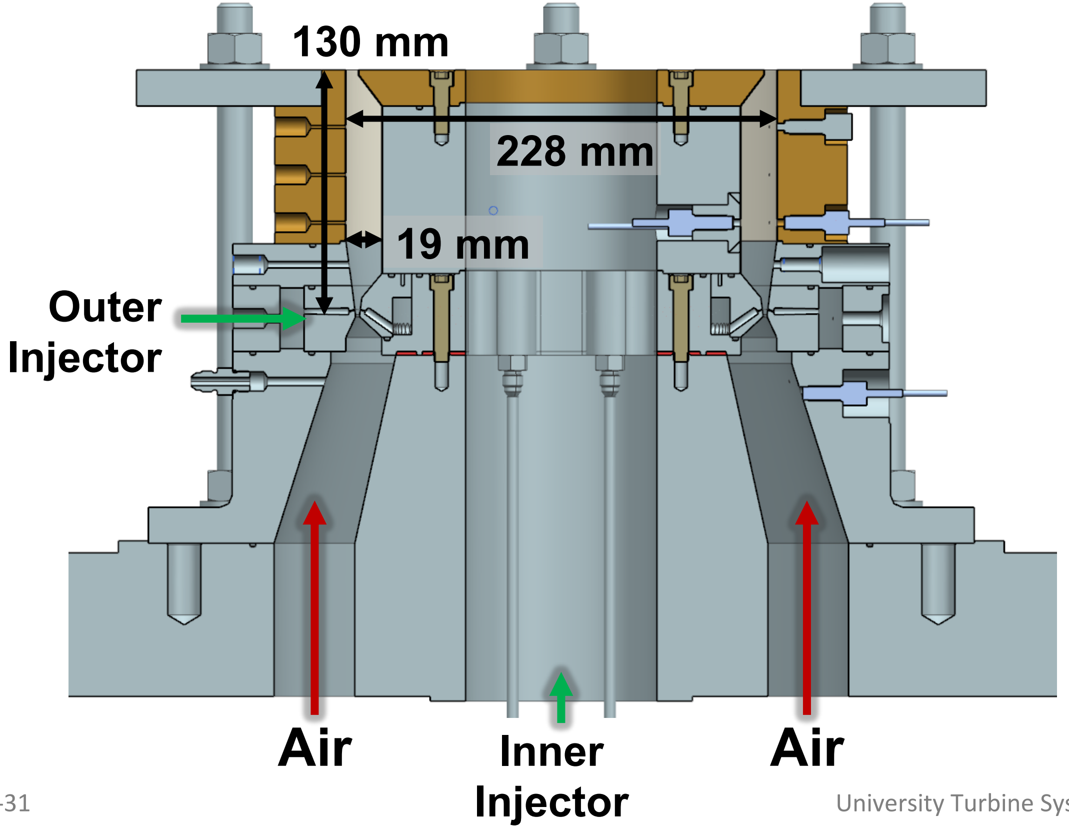
1) For sufficiently power-dense combustion process, small amplitude perturbations from a propellant supply can be amplified into traveling detonations and sustained as long as the propellant supply dynamics continue.
2) Under such conditions,
   a) The wave speed is determined purely by the flow conditions and boundary conditions in the reactant fill region.
   b) The wave spacing can vary independent of chamber geometry.
3) It could be possible to exploit these characteristics to improve turn-down and extend operating range, especially with propellants that have unfavorable detonation characteristics.

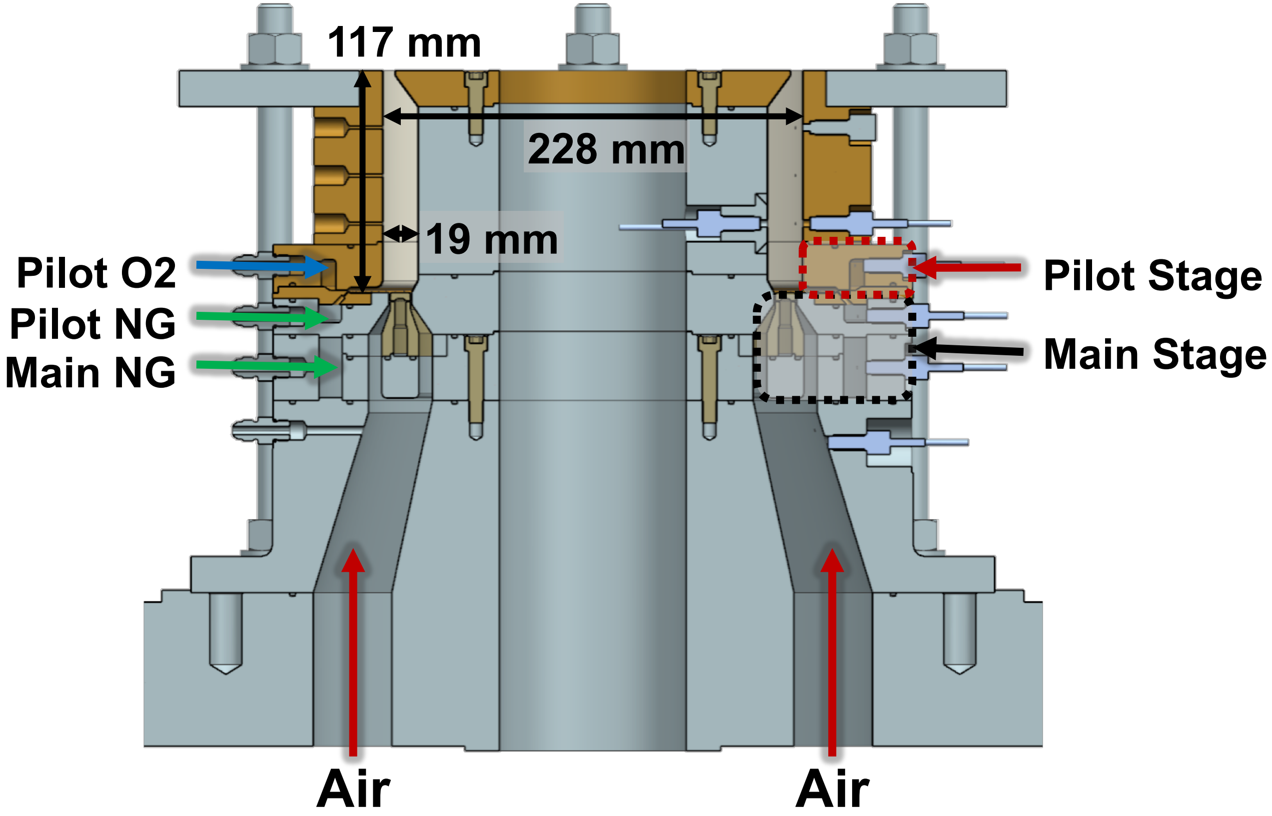
Subscale RDE Development

Toward Operability at Representative Engine Conditions

- Two designs, guided by results from Task 2.0
- Minimum diameter to gap ratio of 10
- Potential for enriching air or fuel to enhance detonability

$\dot{m}''\left[\frac{kg}{m^2 s}\right]$	ϕ	T_3 [K]	$\%O_2$	P_c [MPa]
150-500	0.80-1.20	500-700	23.2-35	0.3-2.0

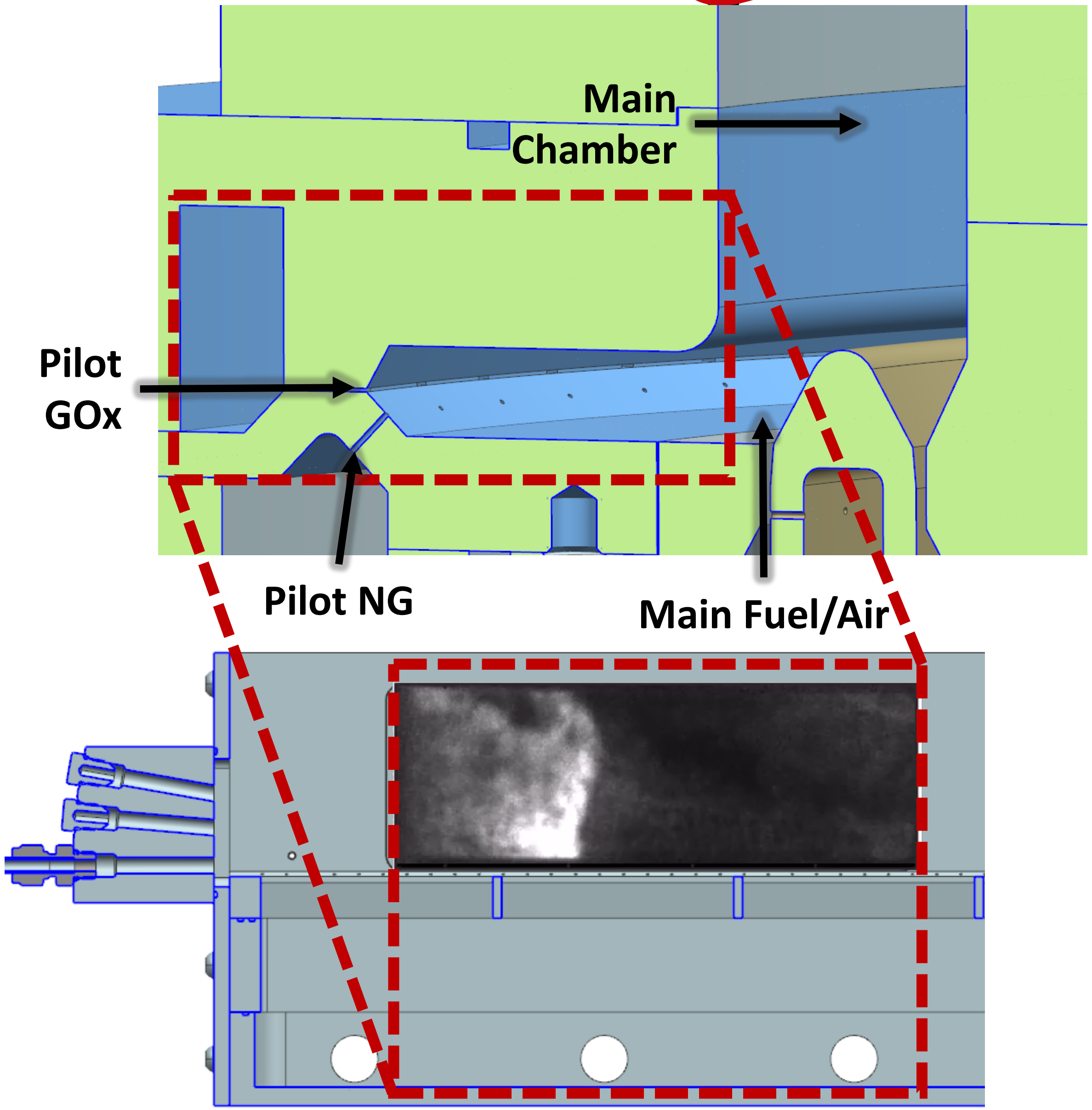




Subscale RDE Development

A Resonator – Amplifier Approach

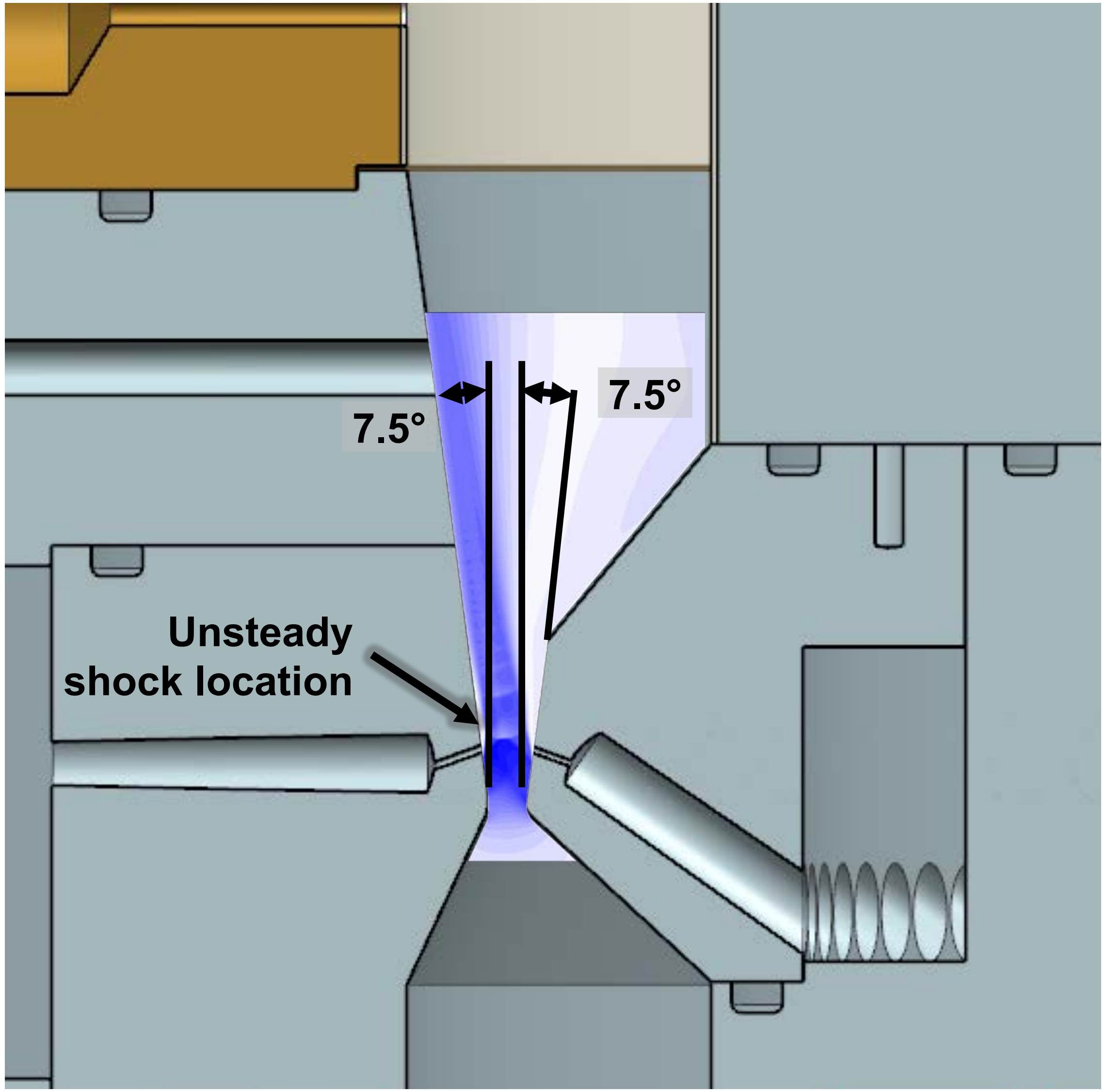
- Use a smaller, NG-GOx RDE as a "pilot" that drives a main-stage NG-Air RDE
- Main-stage combustion "locks in" to pilot wave
- Borrows from GT staged combustor design concept
- Motivation and (potential) benefits:
  - Improved detonability at startup
  - Thermal power scaling (turn-down, load following)
  - Control of dynamics



Subscale RDE Development

Toward Operability at Representative Engine Conditions

- Design parameters
- Air injection
  - Manifold stiffness: 1.6 – 2.2
  - Manifold/throat area ratio: 8.5
  - Chamber/throat area ratio: 8.5
- Fuel injection
  - Manifold stiffness: 2.5 – 3.5
  - Area ratio in air flow-path where fuel is injected: 1.4
  - Downstream injection promotes coupling with chamber dynamics
  - Fuel jets “cover” 25% of cross-sectional area at injection plane
- Backpressure nozzle contraction ratios: 1.9 and 2.75
  - Used to control manifold stiffness

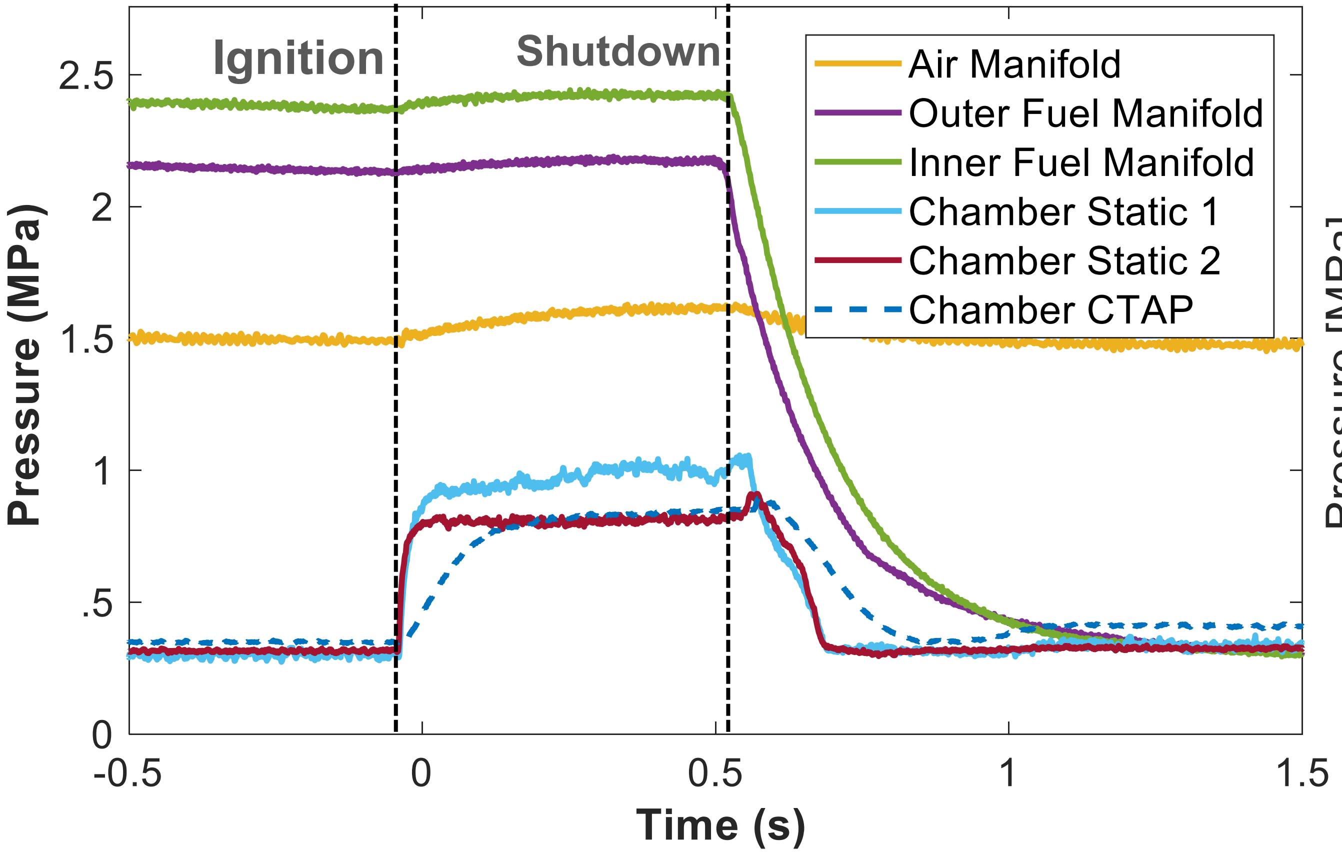


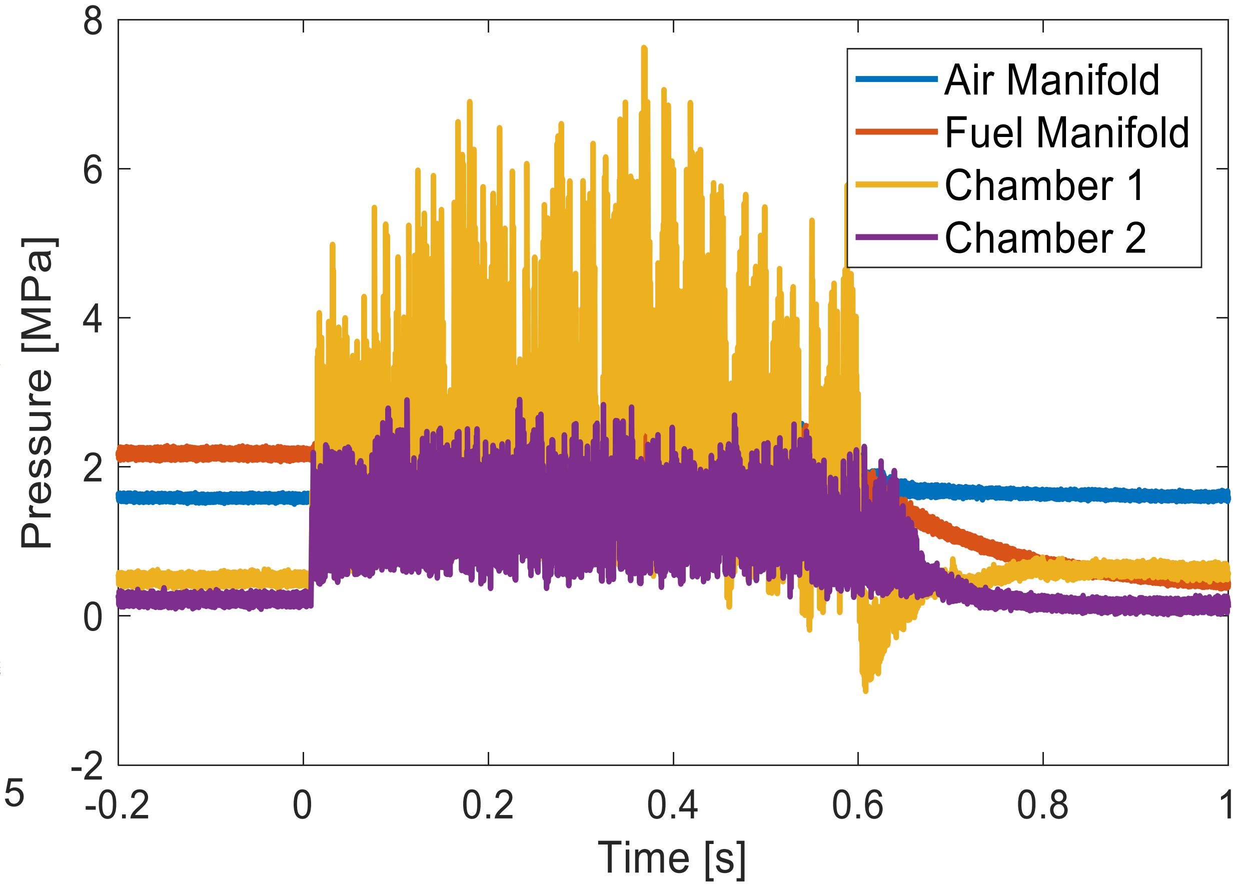
Parametric Testing

Typical Test Sequence

- Test article preheated to T3 prior to ignition
- Oxygen flow established prior to fuel introduction, when applicable.

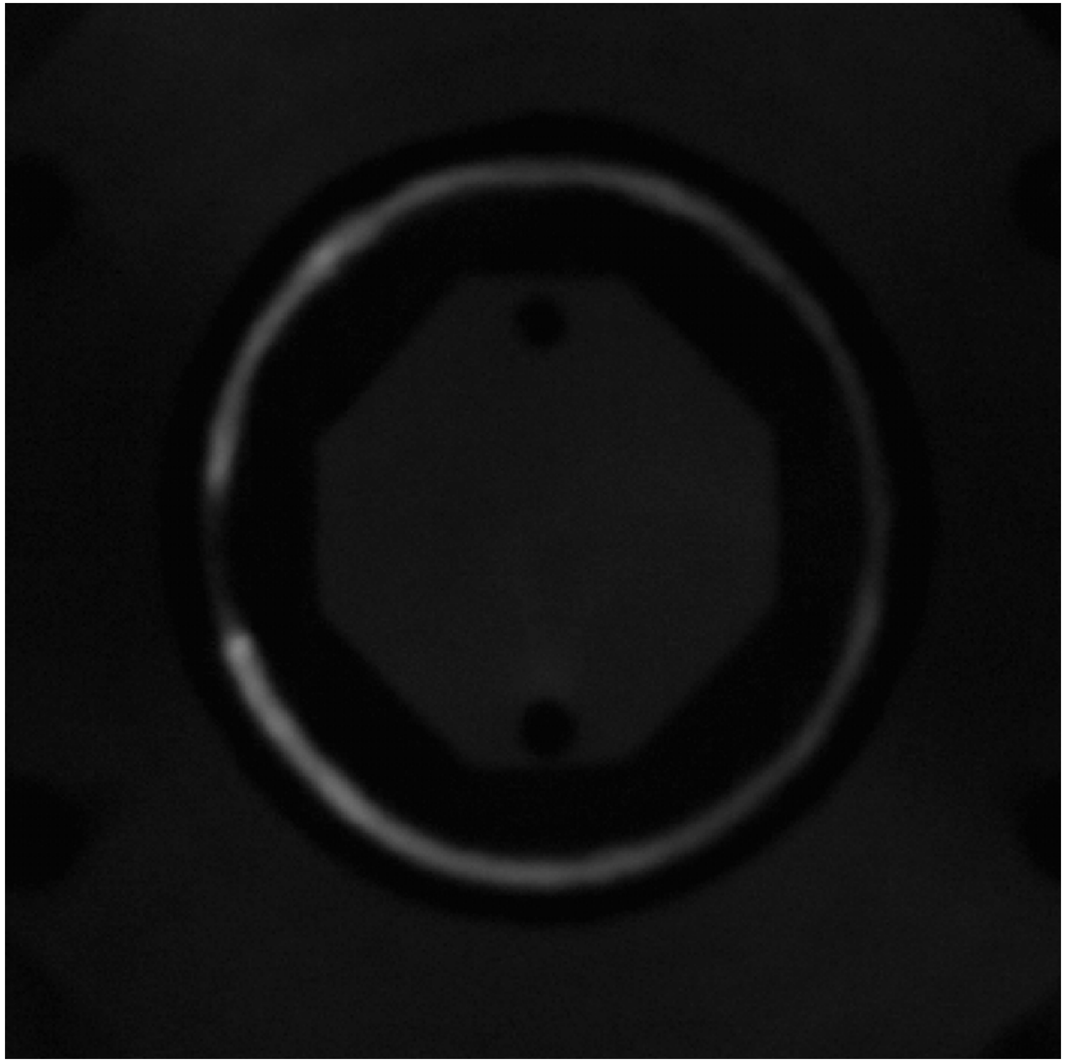
$\dot{m}''\ \left[\frac{kg}{m^2 s}\right]$	ϕ	T_3 [K]	$\%O_2$	P_c [MPa]
200-500	0.9-1.0	575-750	23.2-31	0.7-1.6



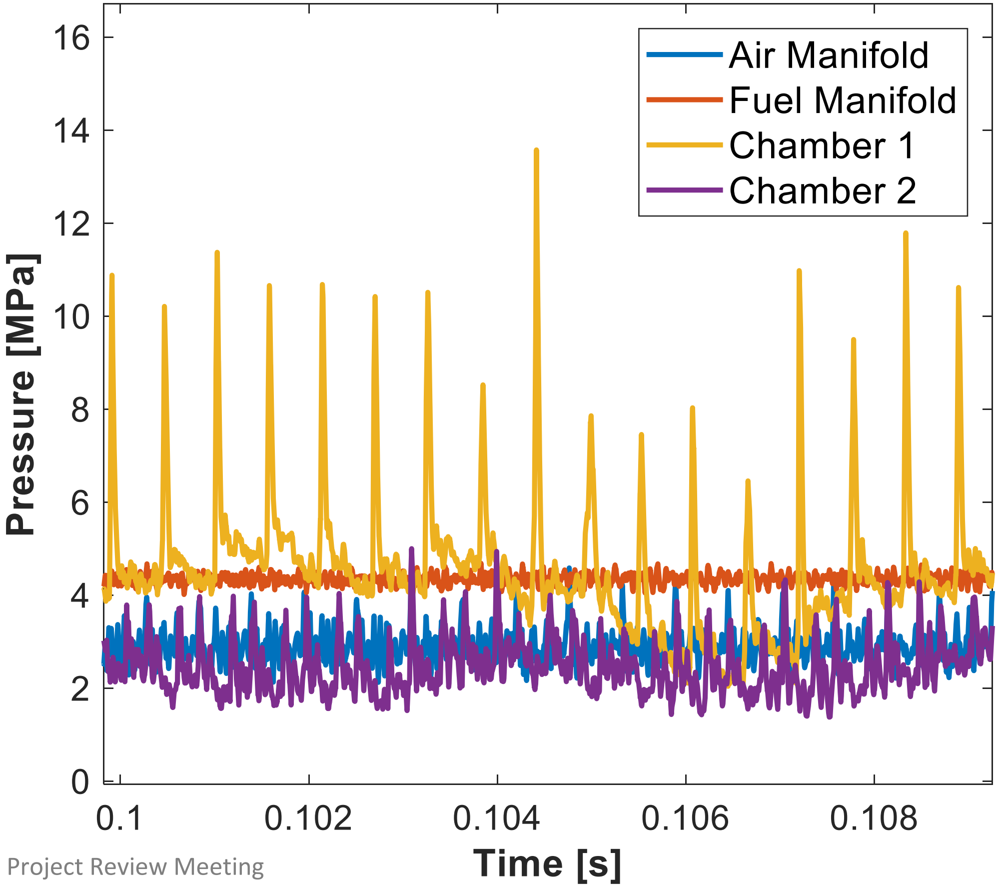


Parametric Testing

Representative Case (Test 102)



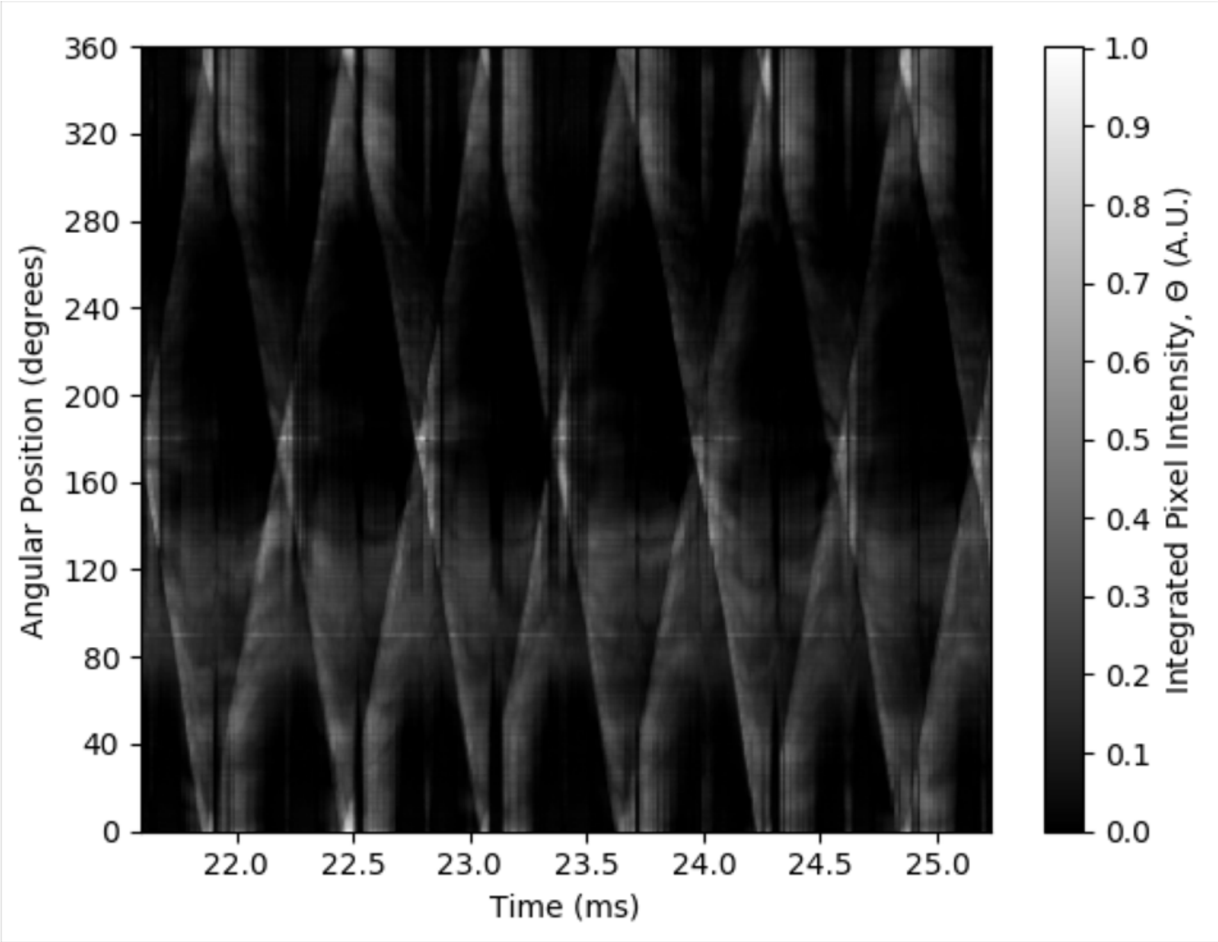
$\dot{m}''$ $\left[\frac{kg}{m^2 s}\right]$	Φ	T_3 [K]	$\%O_2$
500	1.00	575	26.0

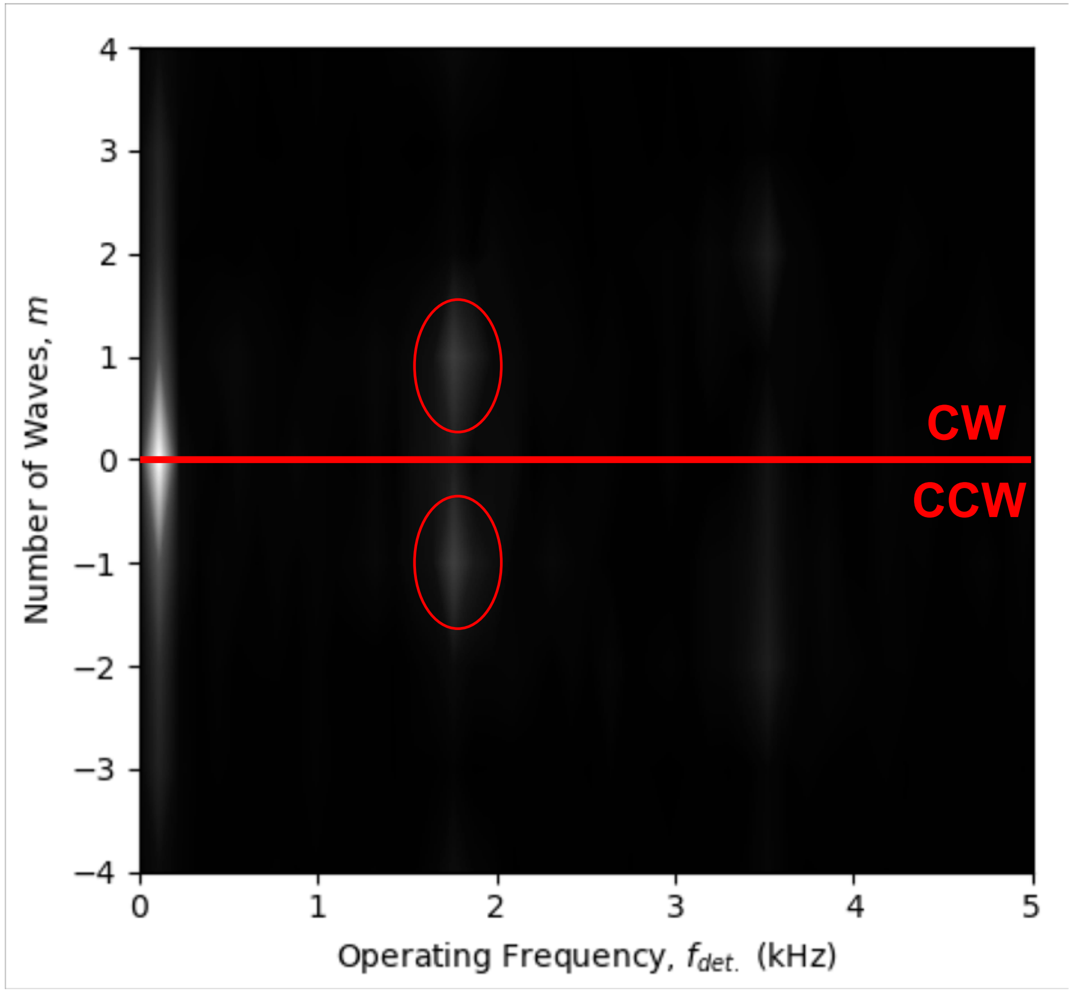


Parametric Testing

Representative Case (Test 102)

- Detonation surface plots quantify wave-speed and wave number to corroborate measurements from discrete probes.

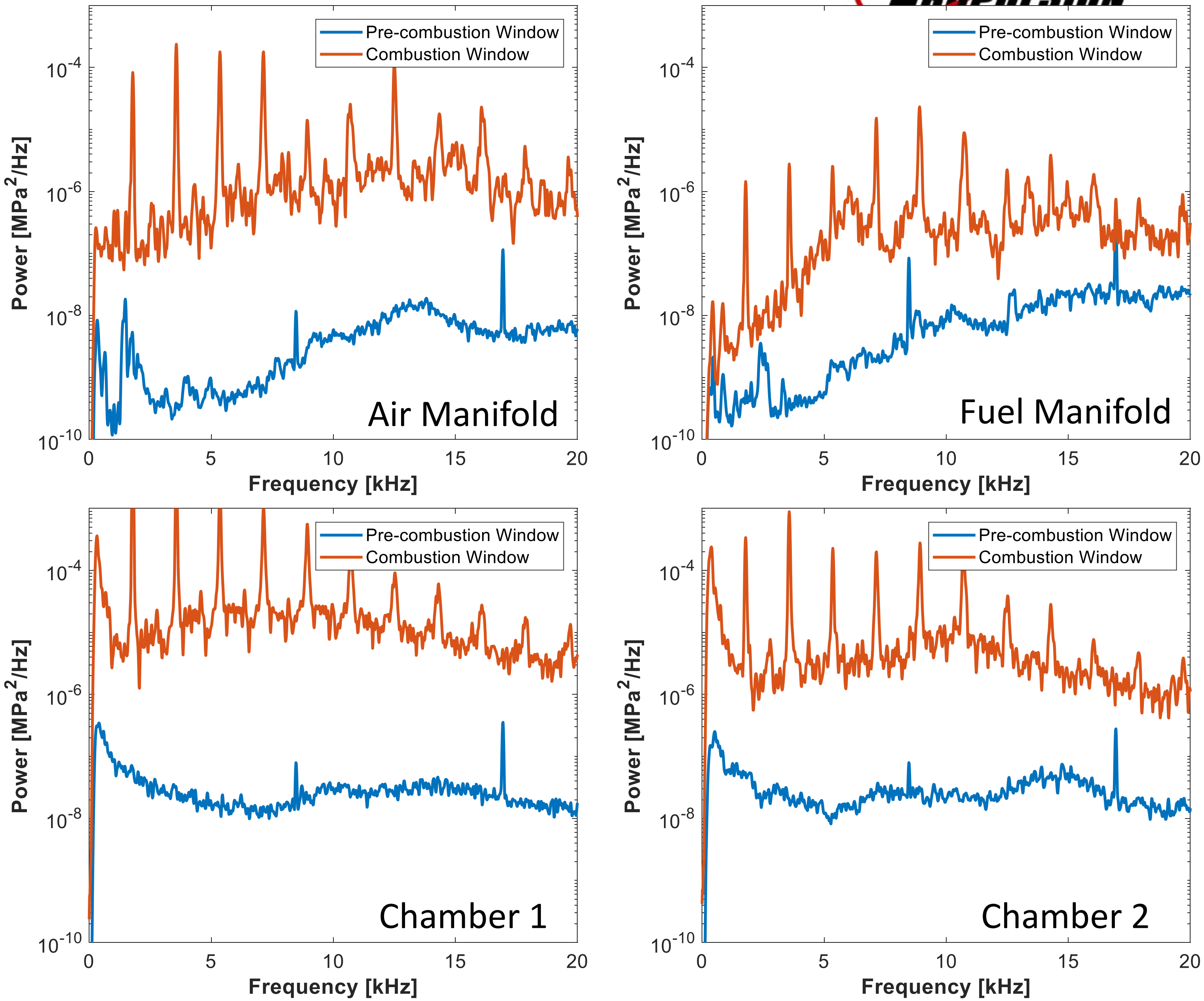




Parametric Testing

Representative Case (Test 102)

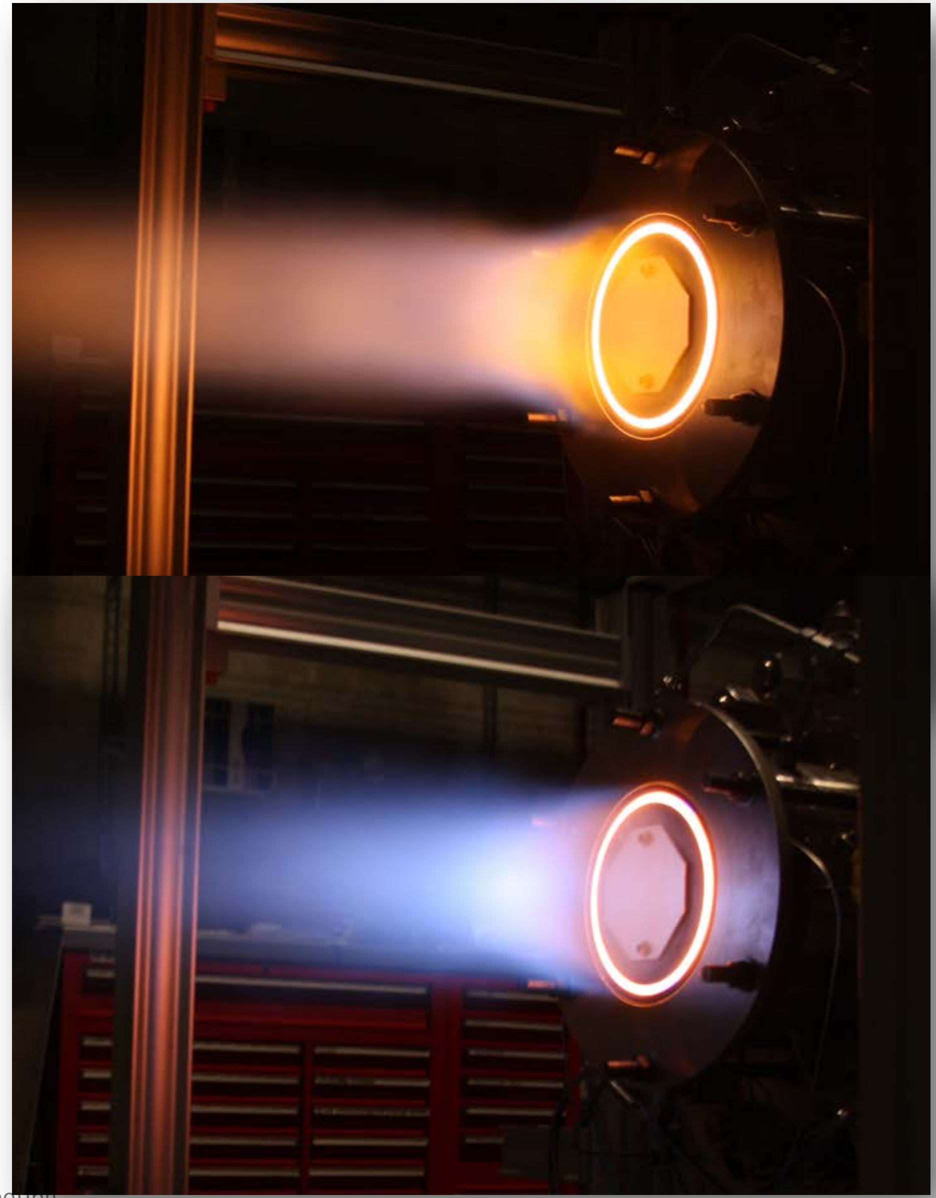
- Manifold dynamics are strongly coupled to the unsteady combustion chamber pressure, post-ignition
- Counter-rotating ('slapping') modes persist throughout the test
  - Intersection points slowly circumscribe the central axis
- Extreme pressures realized at the wave intersections



Parametric Testing

Trends from Experimental Measurements

- Increasing mass flux (Φ, O2%, T3 constant)
  - Increases fundamental frequency and wave number
  - Makes pressure history more chaotic
  - Decreases coherent coupling with manifolds
- Increasing oxygen content (G, Φ, T3 constant)
  - There exists a band of oxygen supplementation that supports a very stable slapping mode, even at low T3.
  - Beyond this range, the pressure histories become more chaotic.
  - The range shifts to lower O2% at higher T3, but appears to shift to another stable region at high O2% and high T3
- Changing Fueling Distribution (G, Φ, T3, O2% constant)
  - Biased fuel injection to outer injector supports a more stable slapping mode
  - Pure air cases are more affected



Introduction

Objectives

Task 1.0: Project Management and Planning

Task 2.0: Injection Dynamics Characterization

Task 3.0: Subscale Combustor Development

Task 4.0: Evaluation of Pressure Gain

Task 5.0: Detailed Measurements of Exit Conditions

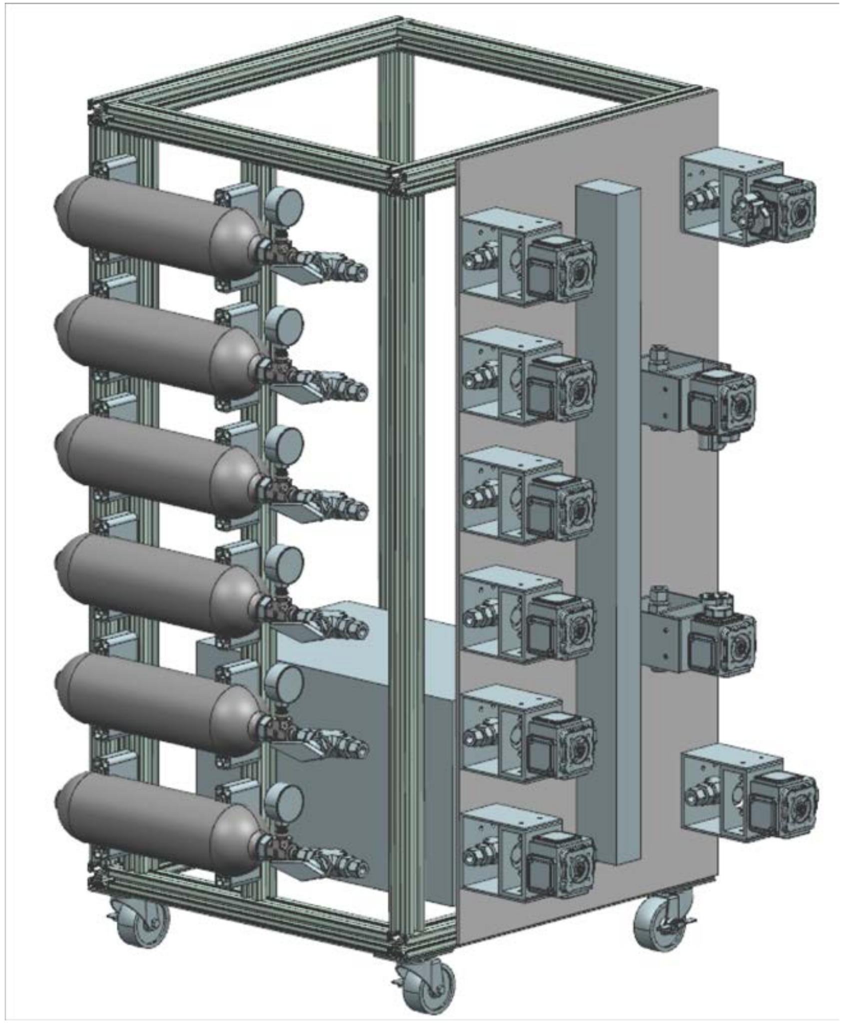
Task 6.0: Emissions Measurements

Task 7.0: Model Development

Emissions Characterization

Extractive Sampling and Post-Test Analysis

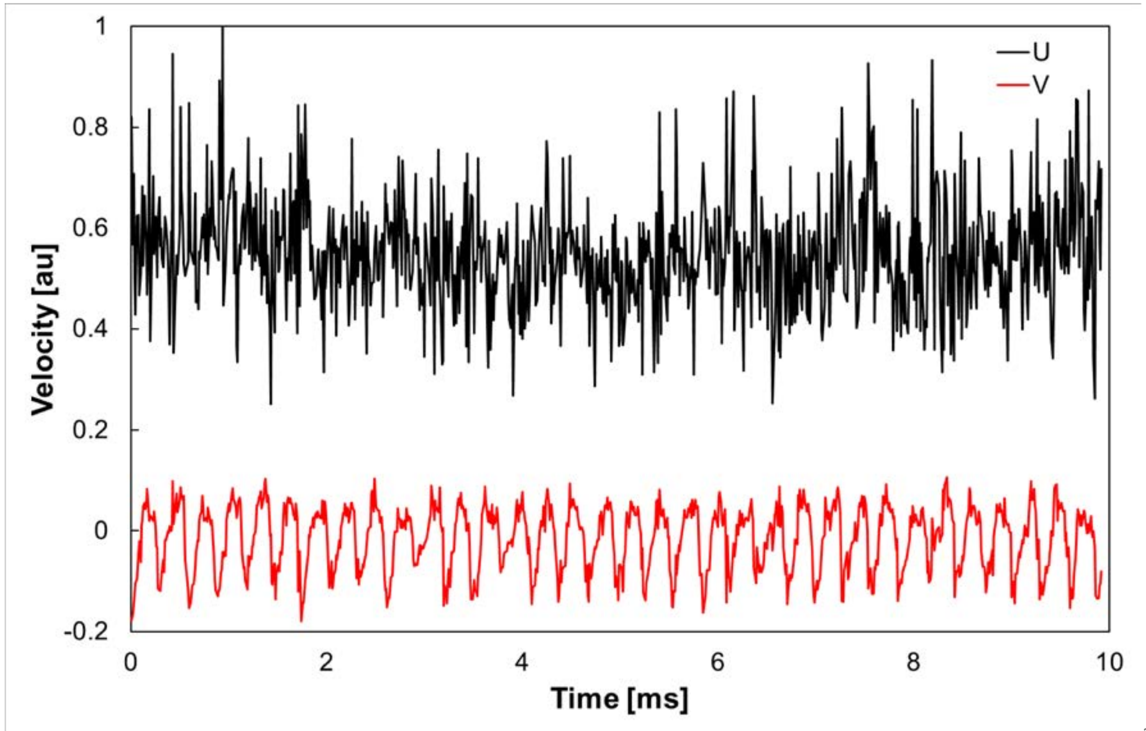
- Short experiment durations mandate a cylinder-based extraction approach.
- The system is drawn to a vacuum to begin the test.
- A low pressure maintained to ensure a hard choke across the sample orifices.
- Gas composition is analyzed with an HFID and FTIR to measure volume fractions of major pollutant emissions:
    - CO, CO_2, NO, NO_2, H_2O, UHC, O_2
- Detection limits of order 10 ppb for CO, CO_2, NO_2 and 100 ppb for NO.

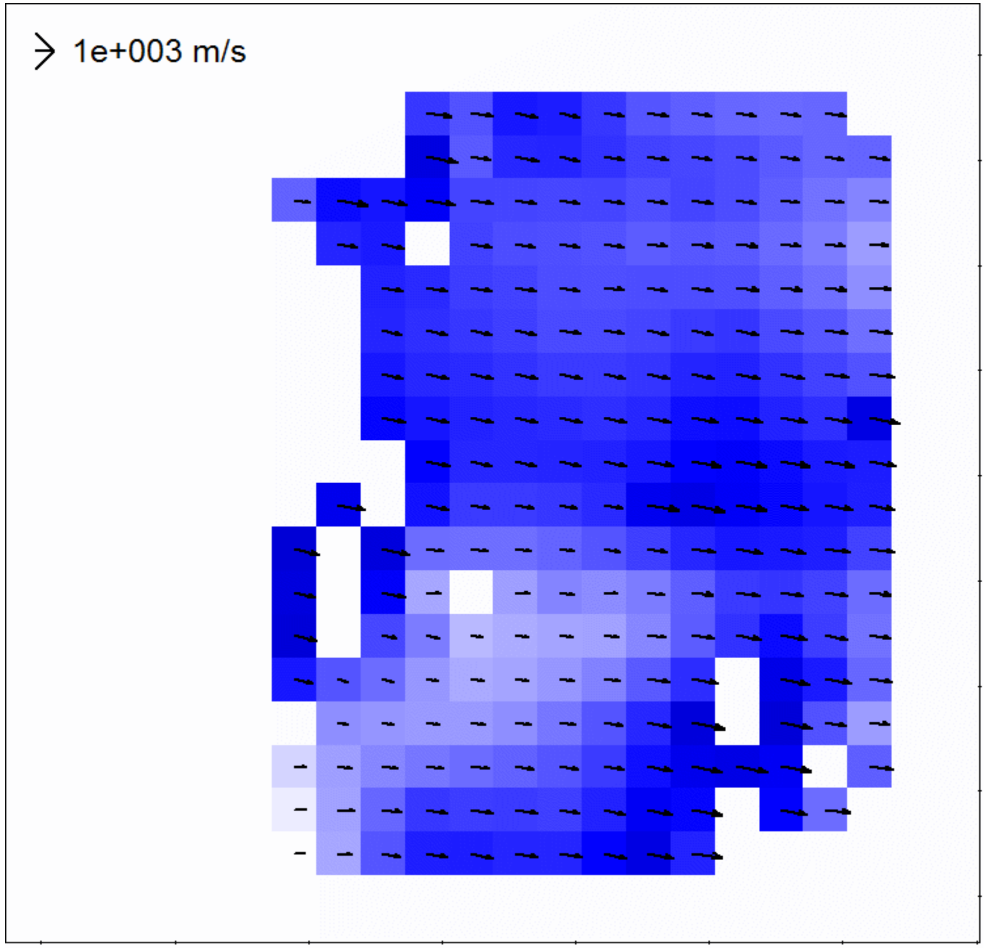


Detailed Measurements at the RDE Exit

Time-Resolved Particle Image Velocimetry at the Annulus Exit

- MOPA-PBL enables measurements at 100 kHz with high signal-to-noise ratio.
- Plume dynamics with respect to wave precession are well-resolved.
- Measurements will be completed for select cases and compared to thrust measurements.





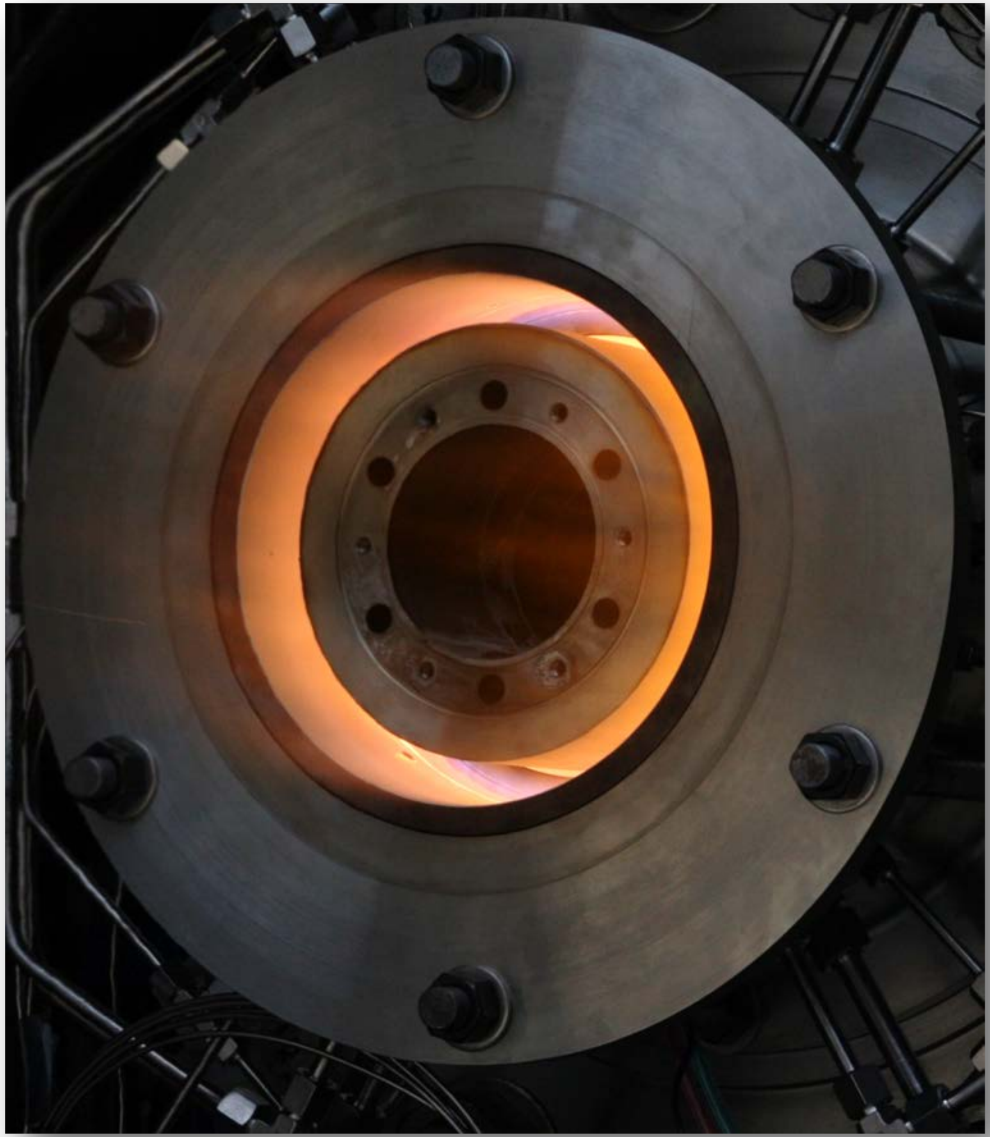
Summary and Outlook

- Multi-tiered experimental and modeling effort underway
- Injection dynamics experiment presents a unique platform for analysis of combustor and propellant supply coupling
- Ongoing modeling efforts focused on dynamic systems analysis of the unwrapped configuration
- Sub-scale RDE operating at representative gas turbine engine cycle conditions
- Closeout of all remaining tasks is imminent, with detailed characterization of select cases remaining in high-pressure, RDE.

"Even considering the improvements possible… the gas turbine engine could hardly be considered a feasible application to airplanes… mainly because of the difficulty with stringent weight requirements."

U.S. National Academy of Sciences, 1940

(including Theodore von Karman)



This research was supported by the University Turbine Systems Research program under contract DE-FE0025343 with contract monitor Mark Freeman. We also gratefully acknowledge support from Dr. Adam Holley and the United Technologies Research Center, our industrial partner on this project.

PURDUE PROPULSION

@SlabaughGroup

@teamhellfire

@PurduePropulsion