Advancing Pressure Gain Combustion in Terrestrial Turbine Systems

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Purdue Propulsion

Introduction

Motivation and Objectives

Project Goals

- o Demonstrate and characterize operation of RDE at conditions relevant to land-based power generation
- o (Better) understand injection and scaling

Operational Requirements

- o Natural gas – Air operation with potential for GOx enrichment
- o Chamber Pressure: 300 psia
- o Preheated Air Temperature: 600 – 800 °F

Measurement Approach

- o Integral thrust and chamber pressure
- o High frequency chamber and manifold probes
- o Plume flow-field measurements w/ Stereo PIV
- o Chamber emissions

Key Challenges

- o Ensuring operability with natural gas – air propellant combination
- o Achieving rapid mixing

Research Team

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Postdoctoral Researcher

Summary/Status of Efforts

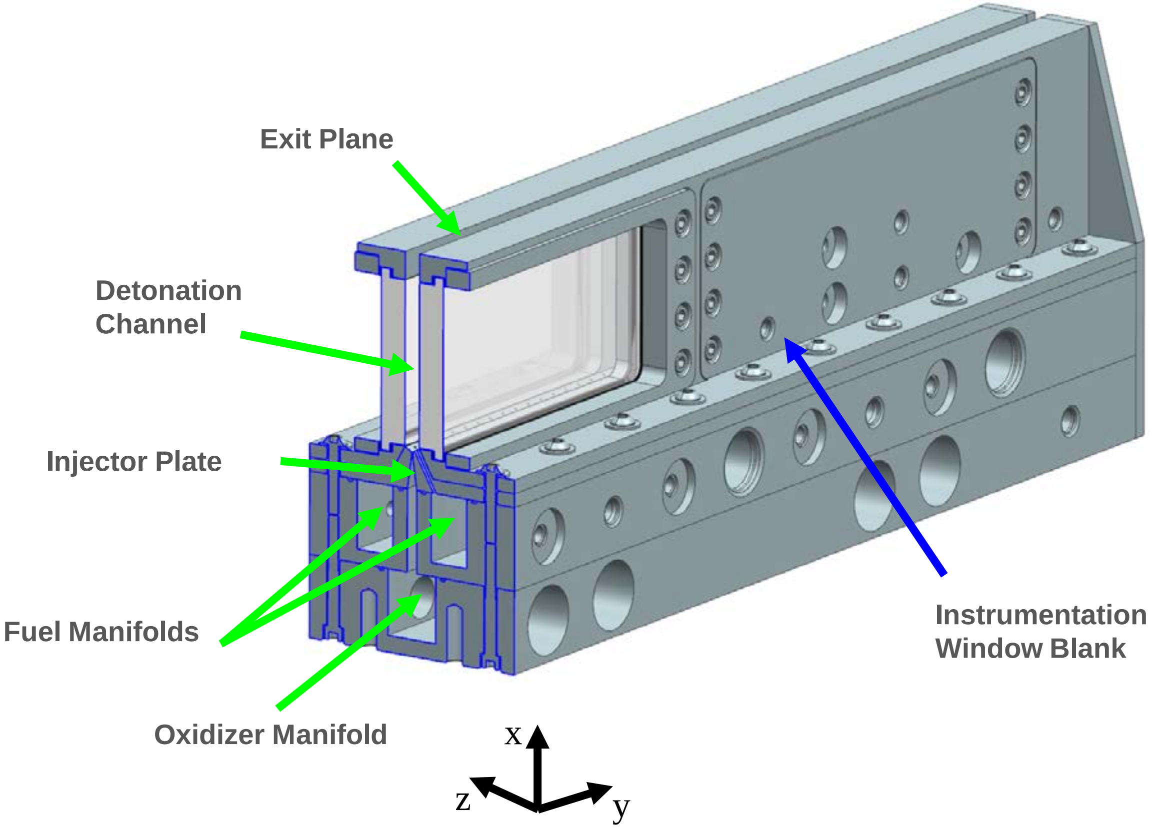
- Effort Includes Seven Major Tasks
- Task 1.0 – Project Management and Planning
- Task 2.0 – ***Baseline Canonical Experiments***
- Task 3.0 – ***Subscale Combustor Facility Development***
- Task 4.0 – Integral Measurement of Pressure Gain
- Task 5.0 – Detailed Measurements of Exit Conditions
- Task 6.0 – Emissions Measurements
- Task 7.0 – ***Computational Model Development***

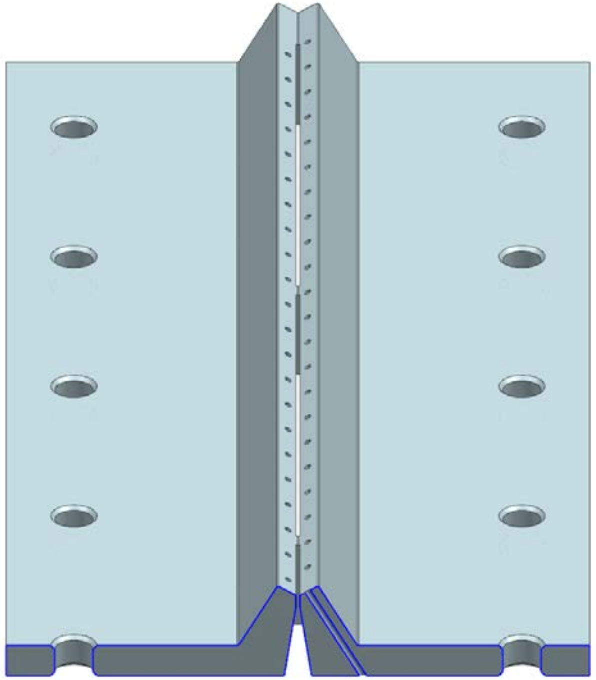
- Also ***– A few head scratchers from AFOSR Rocket RDE project***

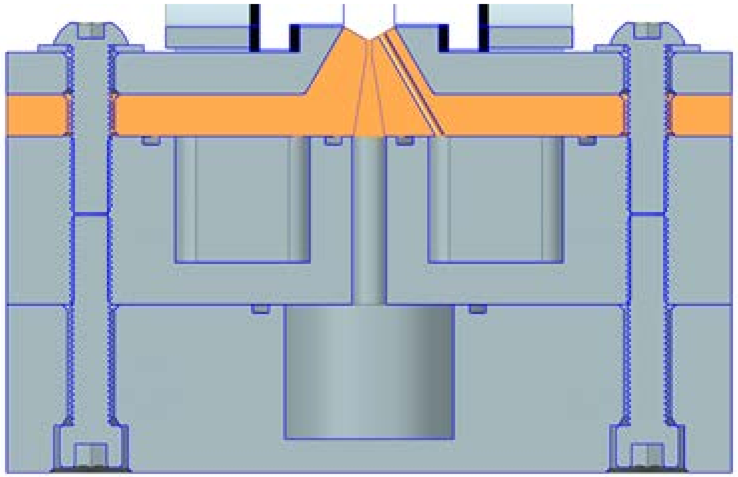
Baseline Canonical Experiment – DRONE Rig

Detonation Rig for Optical, Non-intrusive Experimental measurements

- DRONE is a semi-bounded, linear detonation channel experiment
  - Enabling optical diagnostics for quantitative analysis
  - Simplified geometry conducive to complementary numerical modeling



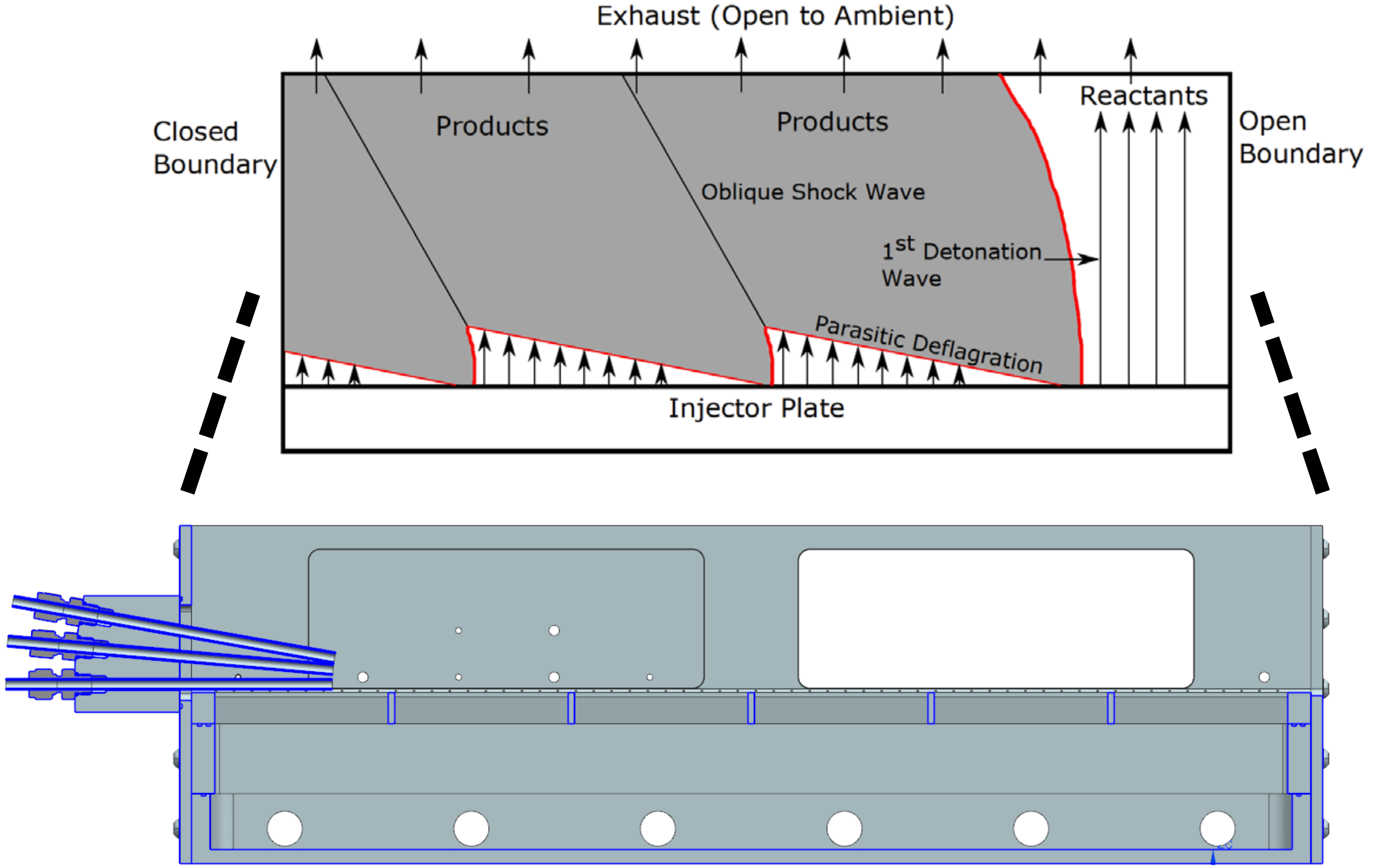




Injection Dynamics

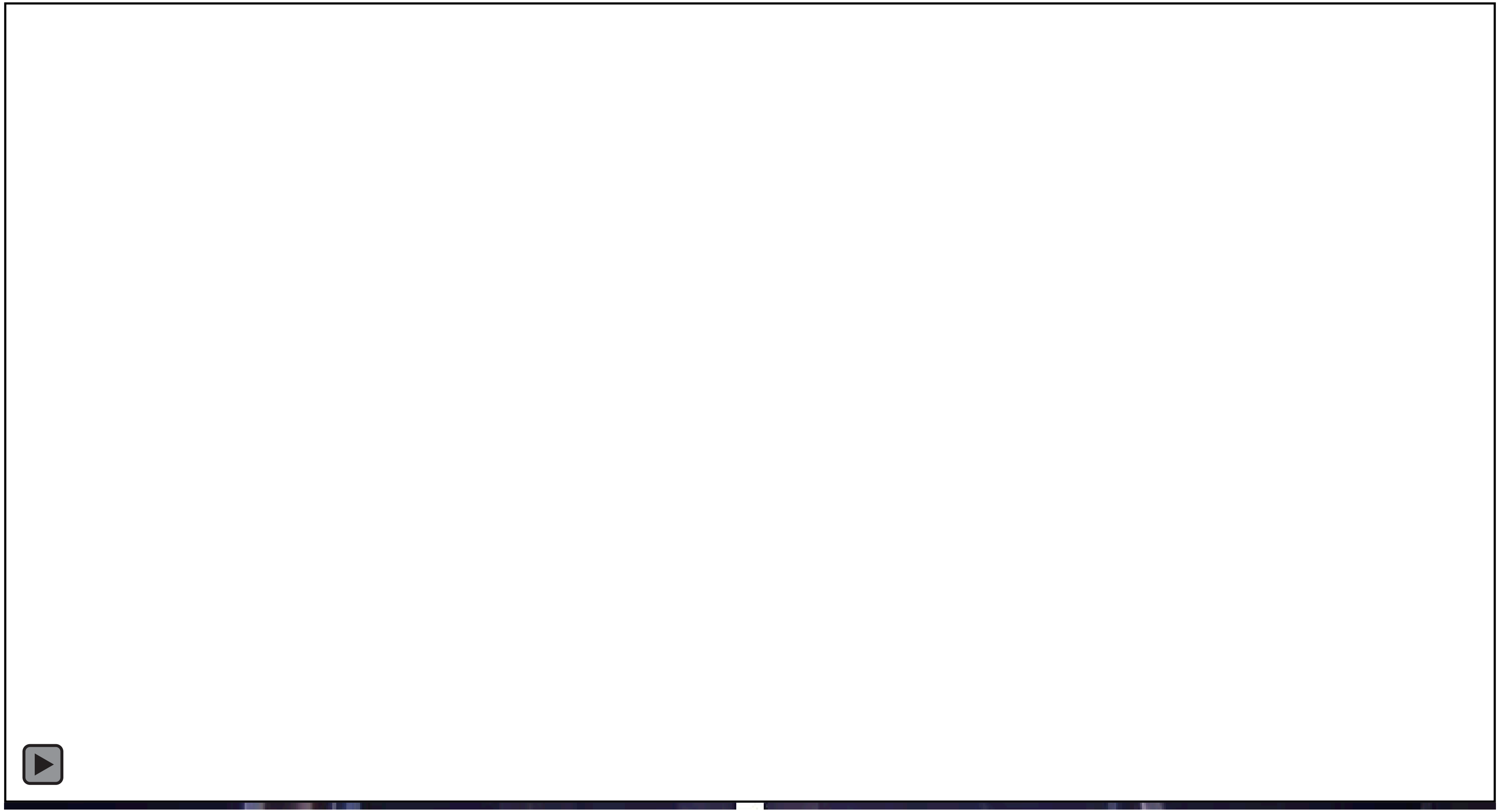
Detonation Rig for Optical, Non-intrusive Experimental measurements

- Designed to enable advanced optical measurements in the reaction zone
  - Planar Laser-Induced Fluorescence
  - Focused Schlieren
  - Chemiluminescence imaging
- Methane – GOx
- Ambient initial conditions
  - Nominal cell size: $\lambda = 2.5 \text{ mm}$
  - CJ speed: $u_{CJ} = 2390 \text{ m/s}$
- Modulating pulse-separation delay lines of branched detonation
- Exploiting dynamic response of injector to refill channel for (relevant) pulse timing



Injection Dynamics

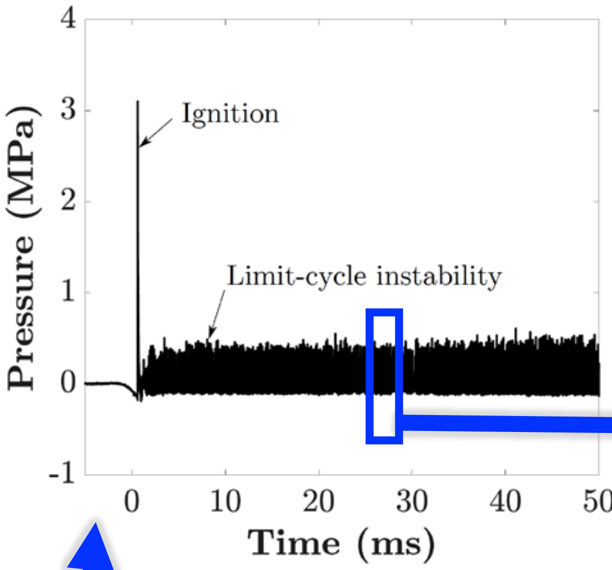
Typical Test Sequence

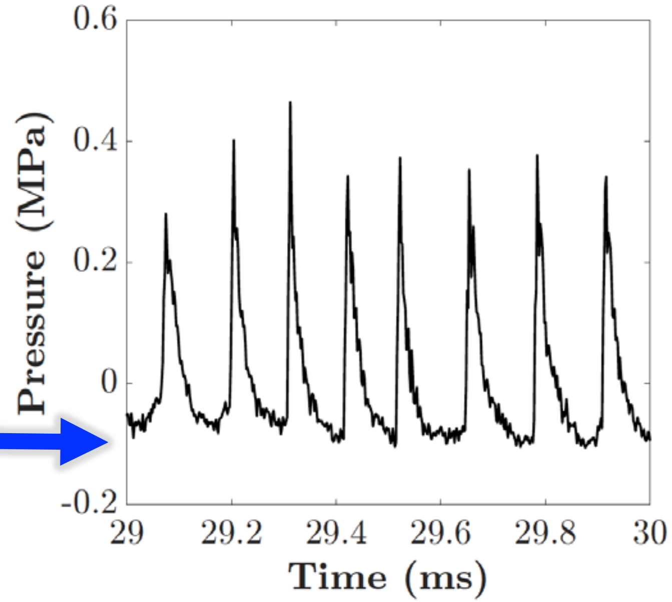


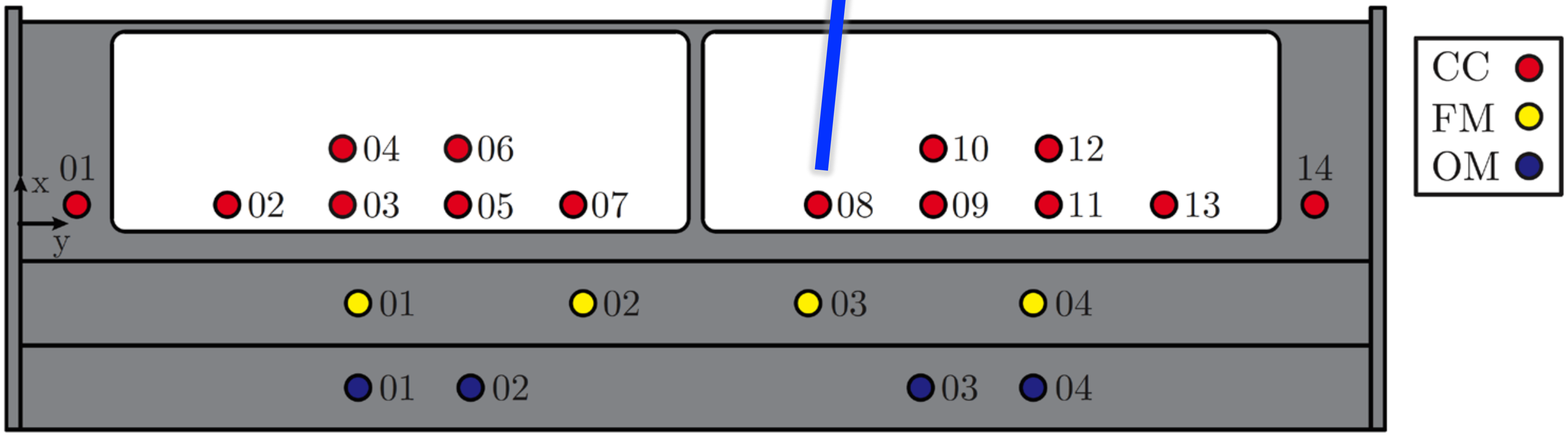
Injection Dynamics

Self-Excited, Multi-kHz, Instability… (without forcing)

- Self-excited dynamics reach a limit-cycle within $1 - 10\ ms$
  - Multi-kHz, steep-fronted waves
  - Nominal pressure fluctuation amplitudes $0.4 - 0.7\ MPa$
- High-frequency behavior is robust
- No coherent participation from propellant manifolds



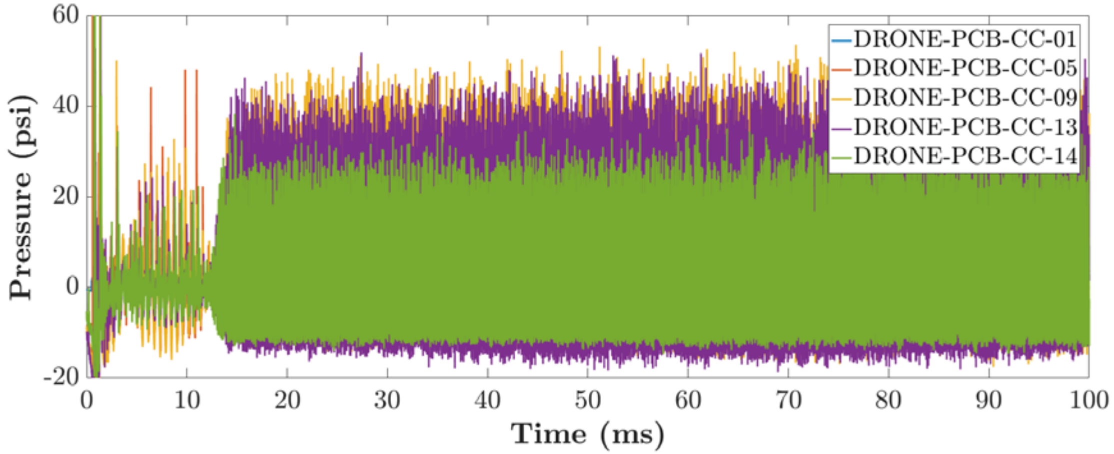


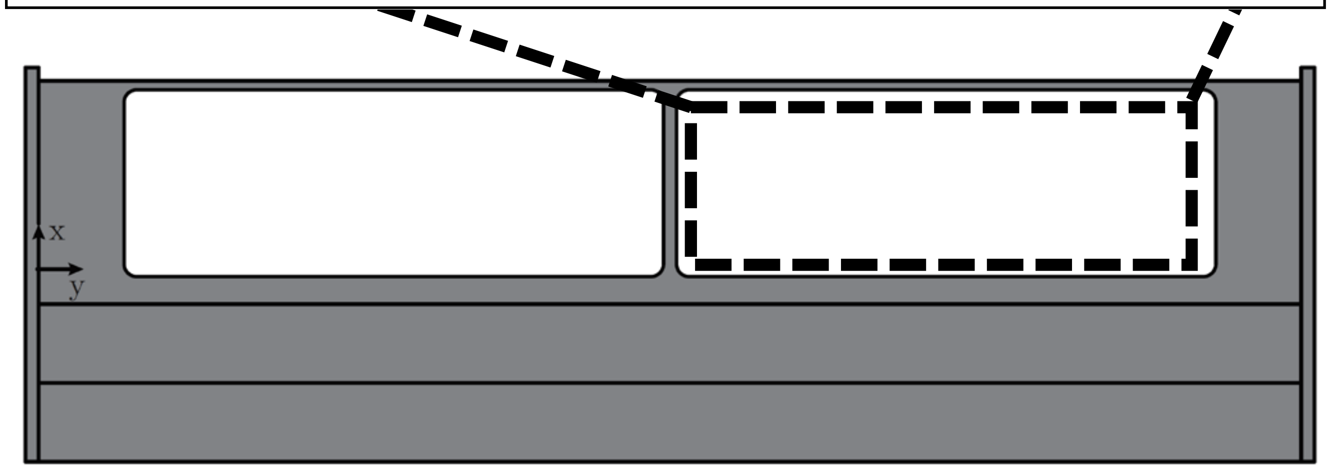


Injection Dynamics

Developed Wave Structure

- The wave structure generated is akin to that in an annular geometry
  - Significant turbulent burning in the fill-region, post-wave
  - Vortex shedding region at greatest axial extent
- Wave speed: $1500 - 1900\ m/s$
- Pressure ratio: 2 - 4 (relative to CTAP)
- CTAP pressure range: $\approx 25 - 40\ psia$

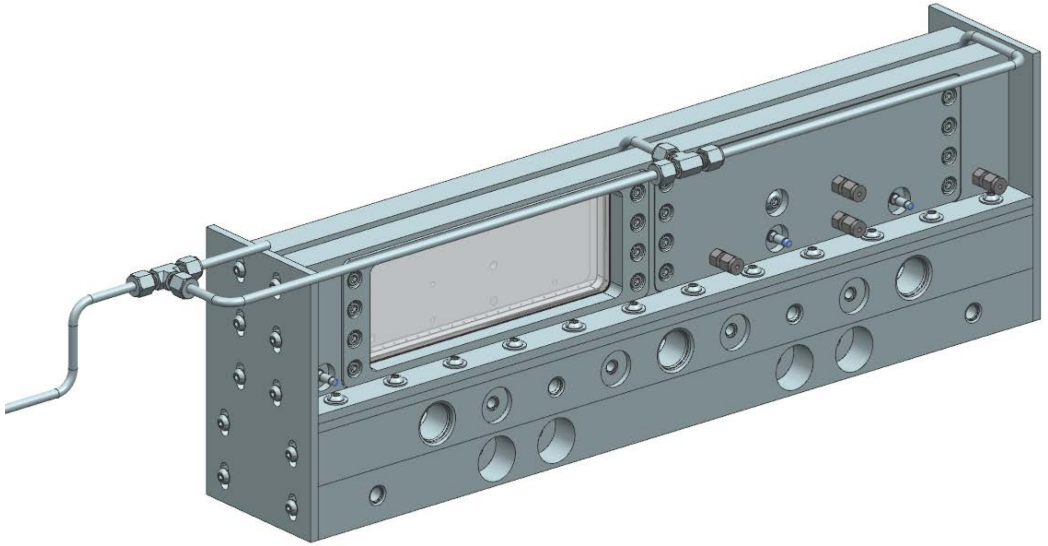


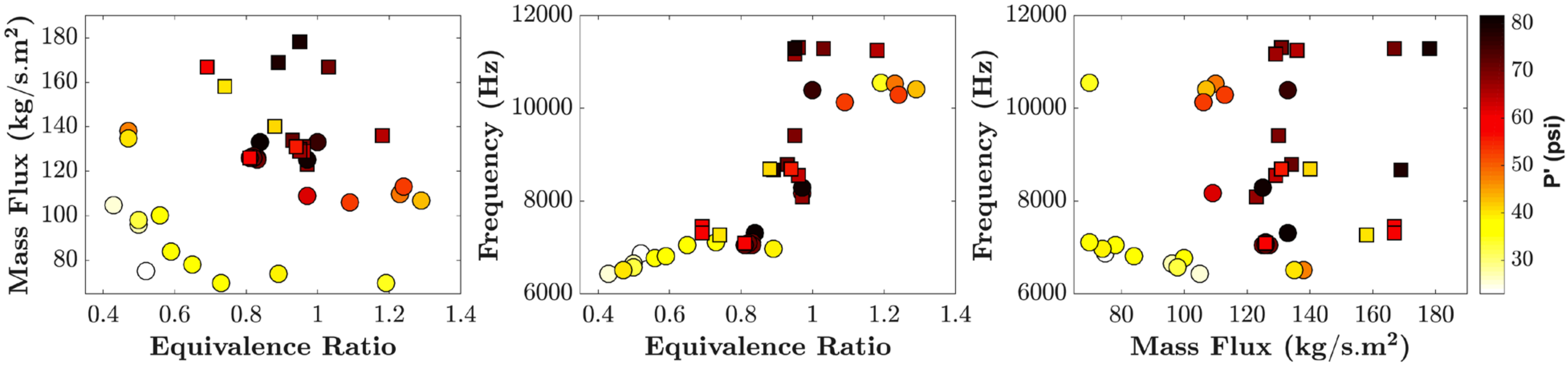


Injection Dynamics

Robust Behavior Throughout Parameter-Space

- Over 60 conditions tested
  - Overall mass-flux, equivalence ratio, …
  - Initiation method
  - (Transverse) Acoustic boundary condition
- Optimal equivalence ratio range: $\phi = 0.8 – 0.9$
- Higher $\dot{m}''$ results in higher p', u – need to be above 100 kg/s.m^2 to generate harmonic response

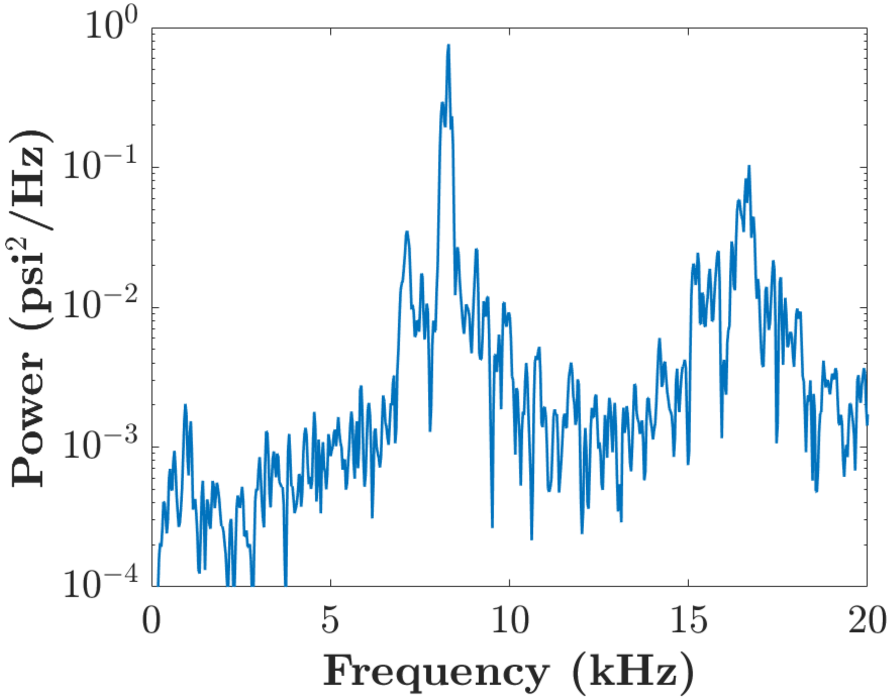


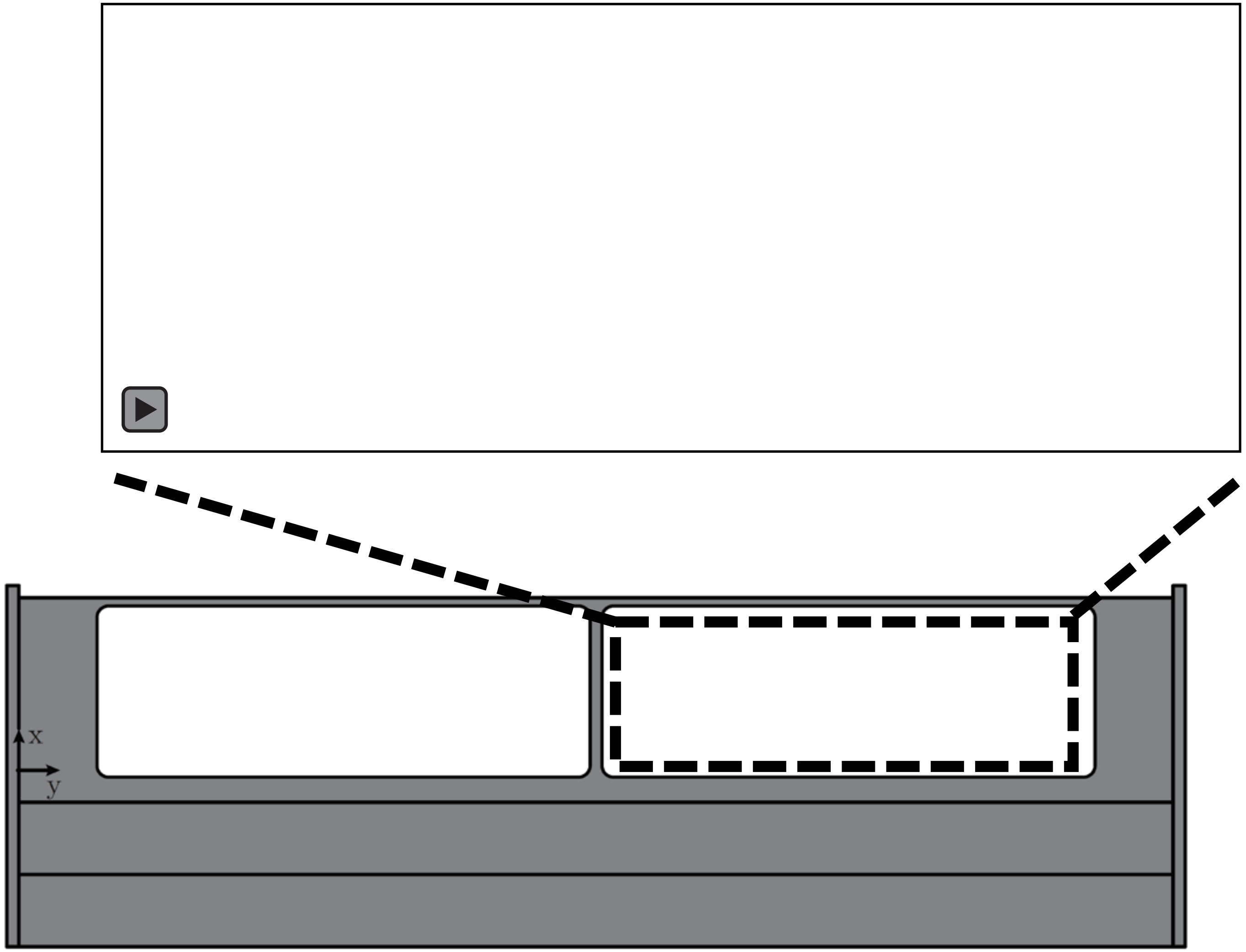


Injection Dynamics

Asymmetric Transverse Boundary Conditions (Closed-Open)

- Four primary peaks
  - Primary Peak at $8300\ Hz$
  - Narrowband peak at $600\ Hz$
  - (weaker) satellite peaks sum-difference frequencies
- Computed 1T resonant frequency $= 540\ Hz$



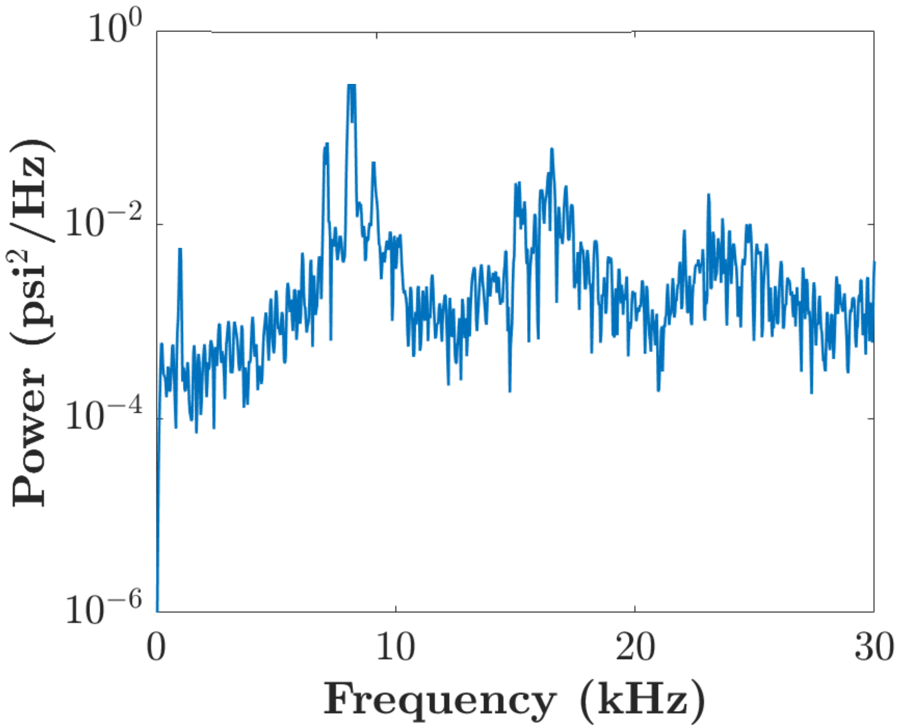


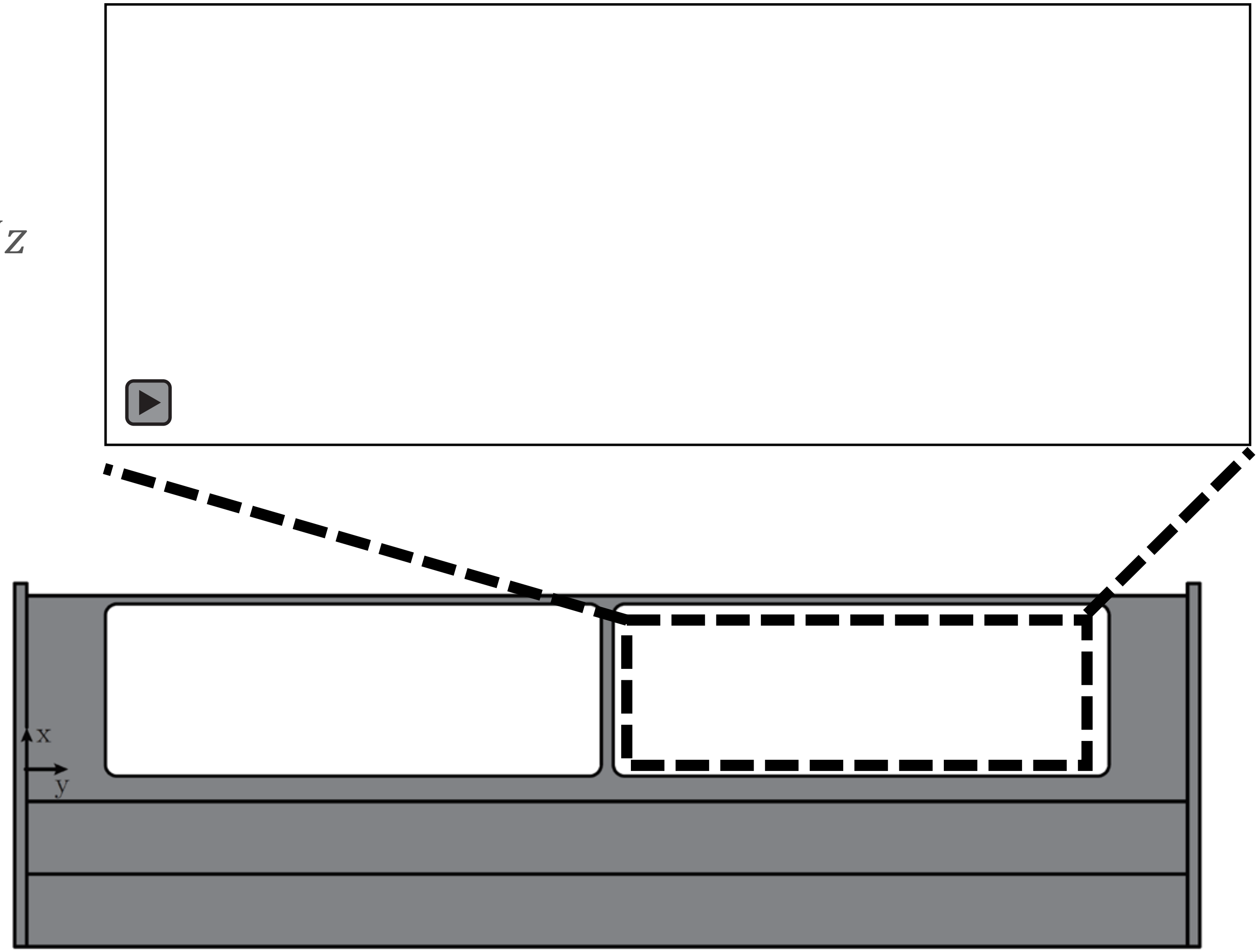
$\dot{m}'' = 123\ kg/s.m^2;\ \phi = 0.97$

Injection Dynamics

Symmetric Transverse Boundary Conditions (Closed-Closed)

- Four primary peaks
  - Primary Peak at $8160\ Hz$
  - Narrowband peak at $1000\ Hz$
  - Satellite peaks at $8160 \pm\ 1000\ Hz$
- Computed 1T resonant frequency $=\ 1070\ Hz$

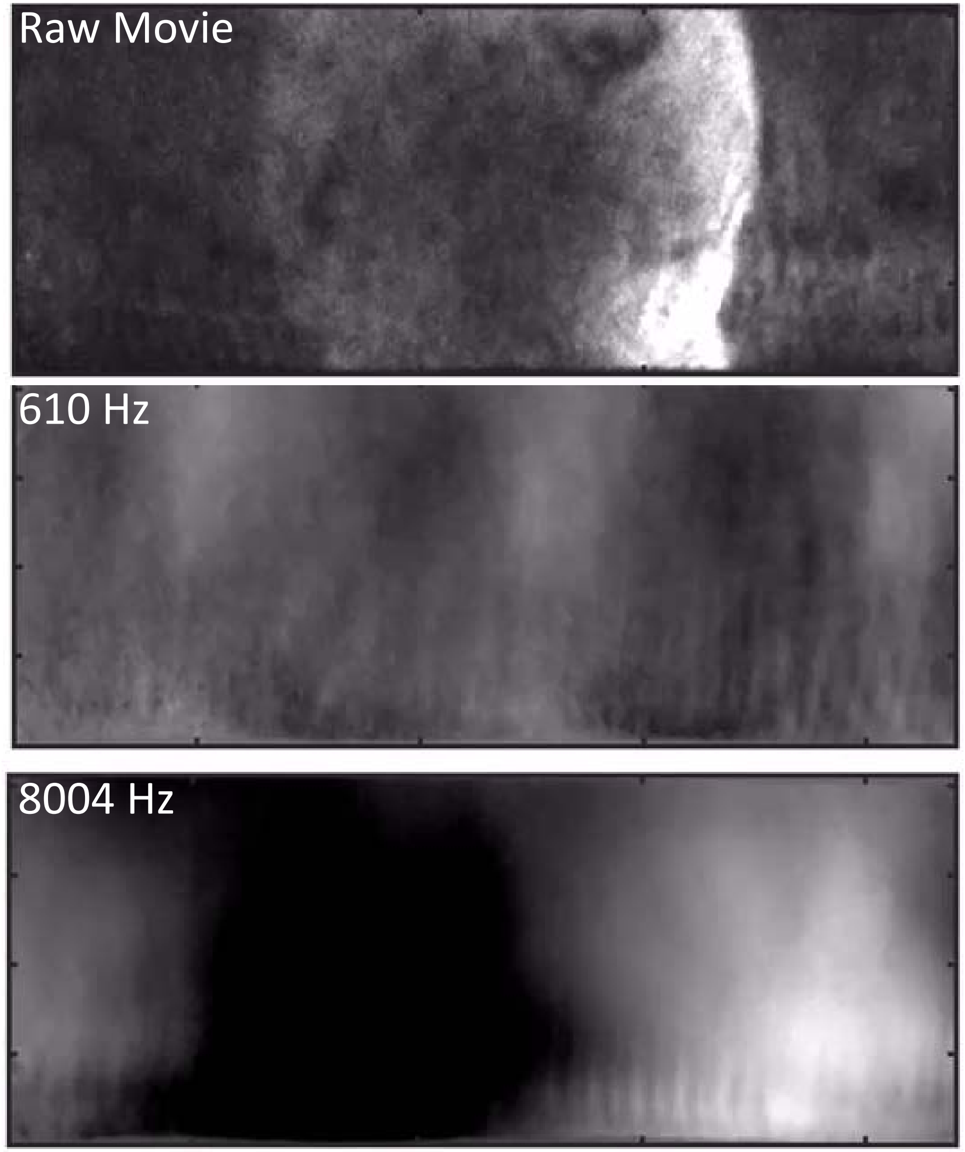




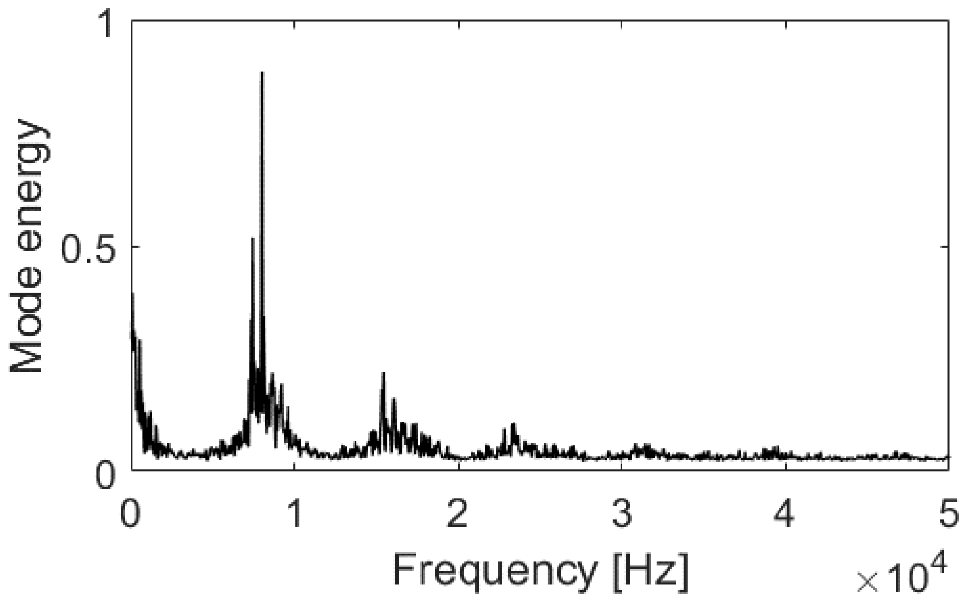
$\dot{m}''\ =\ 123\ kg/s.m^2;\ \phi\ =\ 0.97$

Injection Dynamics

Asymmetric Transverse Boundary Conditions (Closed-Open)



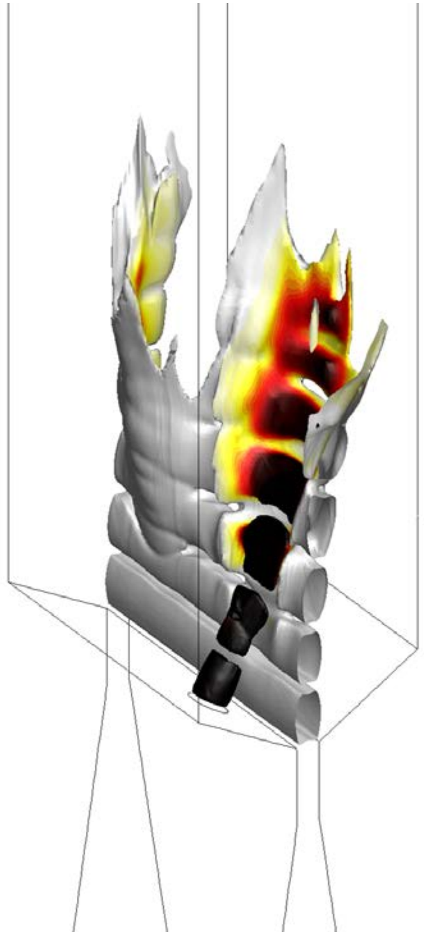
- Dynamic mode decomposition analysis reveals four robust modes
  - A 'bulk' intensity oscillation at the 1T frequency
  - Right-running (+Y) wave motion at $8\ kHz$
  - Sum-difference frequencies $8\ kHz \pm 610\ Hz$



Summary from the ‘unwrapped’ rig

Did this even help?

- DRONE platform exhibits *self-excited*, highly-nonlinear behavior
  - Variation of 1T boundary condition isolated acoustic interactions that are not participatory in the primary mode of operation.
  - The gradient-based DDT mechanism is a likely cause of the wave-steepening process.
    - Ignition of “sensitive” reactant/product mixture
    - Likely this will be strongly influenced by chemical kinetics (TBD)
  - Dynamic response of feed system plays strong role
- At realistic conditions, with the right reactants, these instabilities will happen.

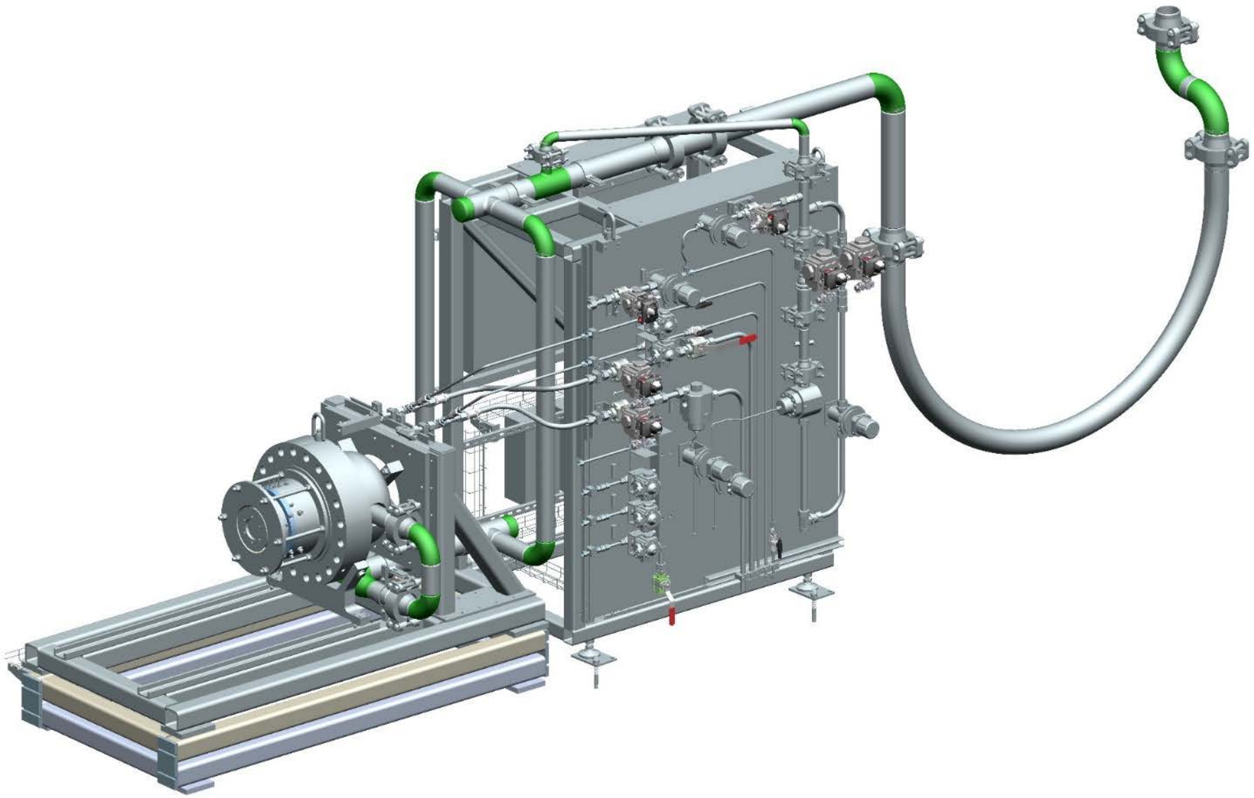


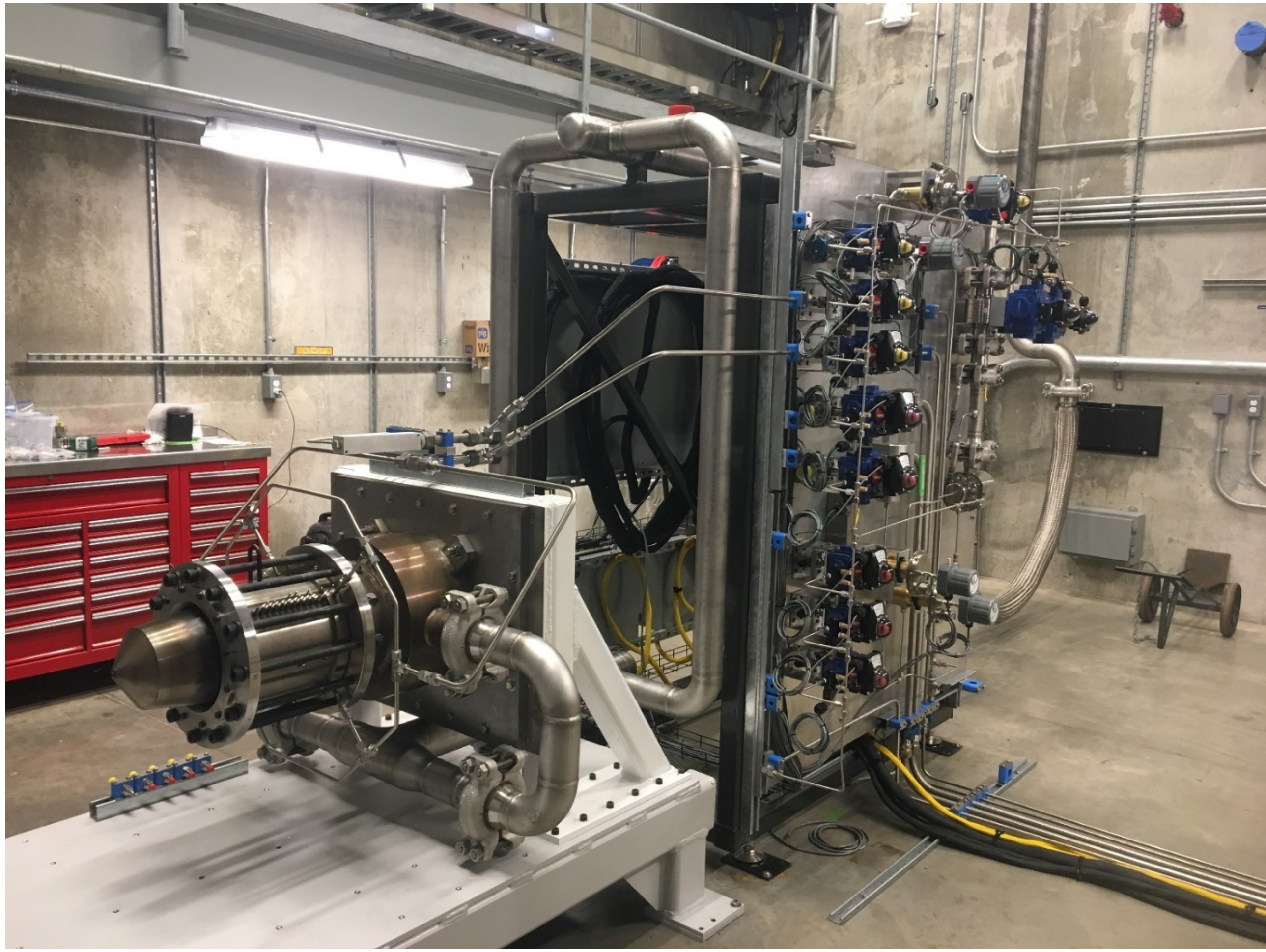
Subscale Combustor Facility Development - Status

- New Purdue lab formally dedicated on 22 Sept.
- 1500 F air piping completed last week
- DOE facility TRR held on Monday of this week and we flowed air in rig yesterday
- Aerojet-Rocketdyne hardware to be tested over next few months
- Purdue hardware testing to initiate in Spring, 2018

Carson’s Facility Team

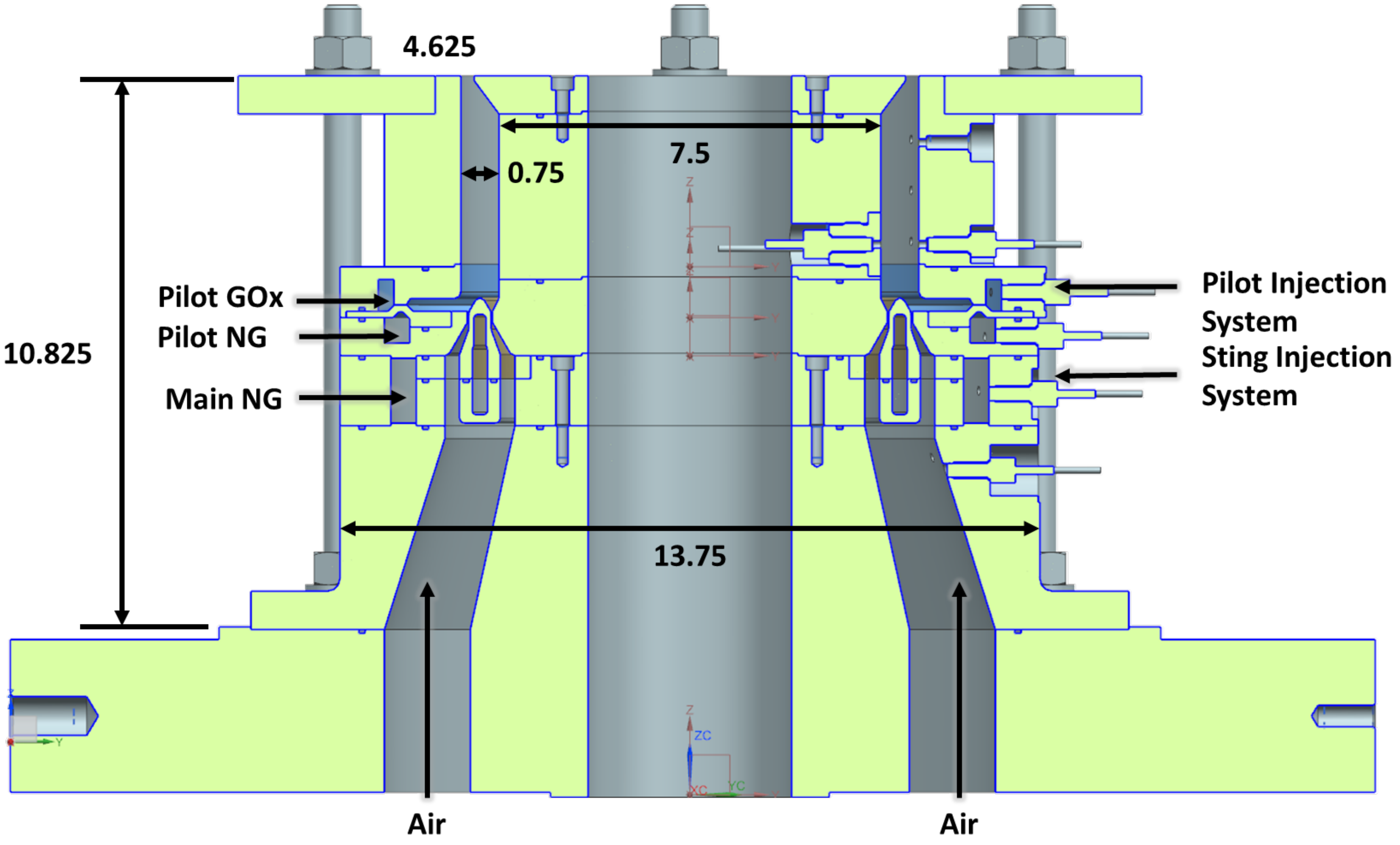
Ian Walters
Chris Journell
Aaron Lemcherfi
Andrew Pratt
Rohan Gejji
Carson Slabaugh





Subscale Combustor Facility Development

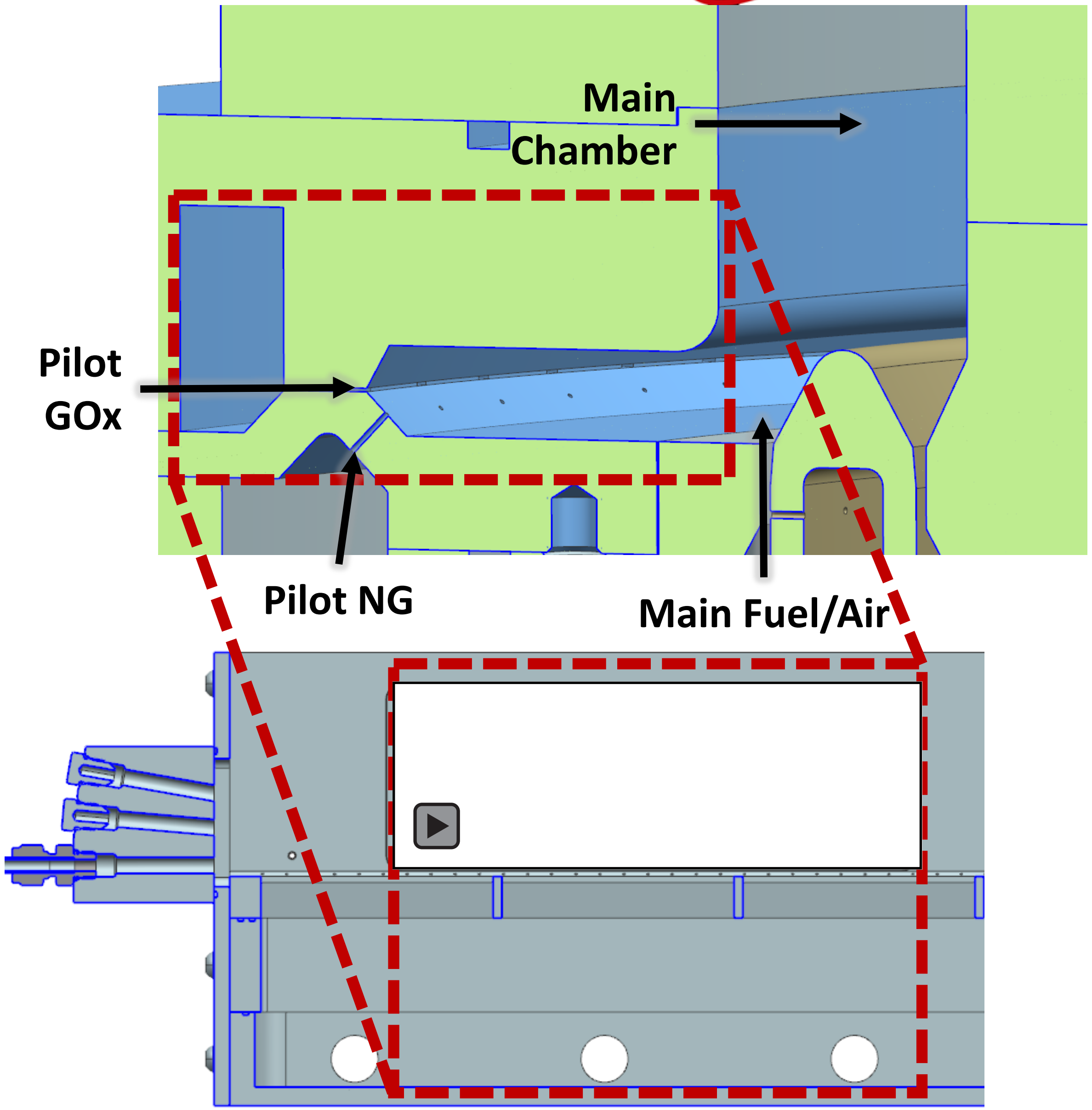
Nominal Operating Conditions	
Airflow, lbm/s	20
Fuel flow, lbm/s	1.1
P_chamb, psi	300
T_air, F	620
V_wave, m/s	1750
P_max, psi	2400
f, Hz	2900



Piloting Concept

A Resonator – Amplifier Approach

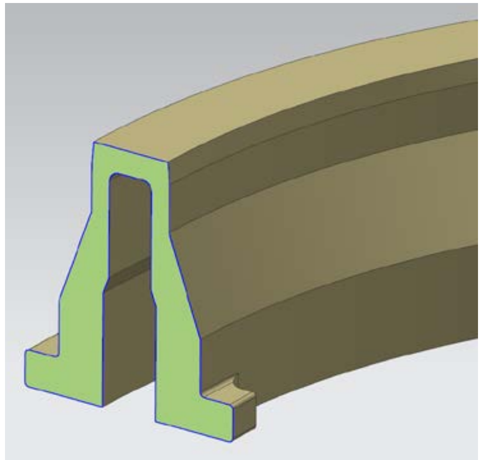
- Use a smaller, NG-GOx RDE as a “pilot” that drives a main-stage NG-Air RDE
- Main-stage combustion “locks in” to pilot wave
- Borrows from GT staged combustor design concept
- Motivation and Potential Benefits:
  - Trying a different approach…
  - NG-Air detonability: RDEs likely to have challenges with startup due cell size considerations at atmospheric pressure
  - Scaling thermal power: Provides ability to add additional air stages to increase volume of detonating mixture
  - Control of dynamics: Main-stage locks-in to pilot dynamics and reduce variation in wave dynamics (e.g. number, bifurcation) due to changing operating condition (Φ, $\dot{m}''$)



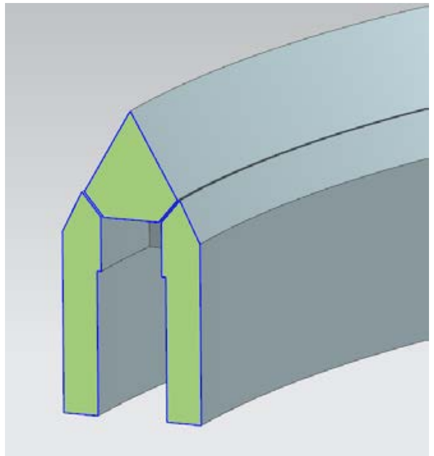
Sting Injection Concept

Exploring Critical Sensitivities of Dynamics

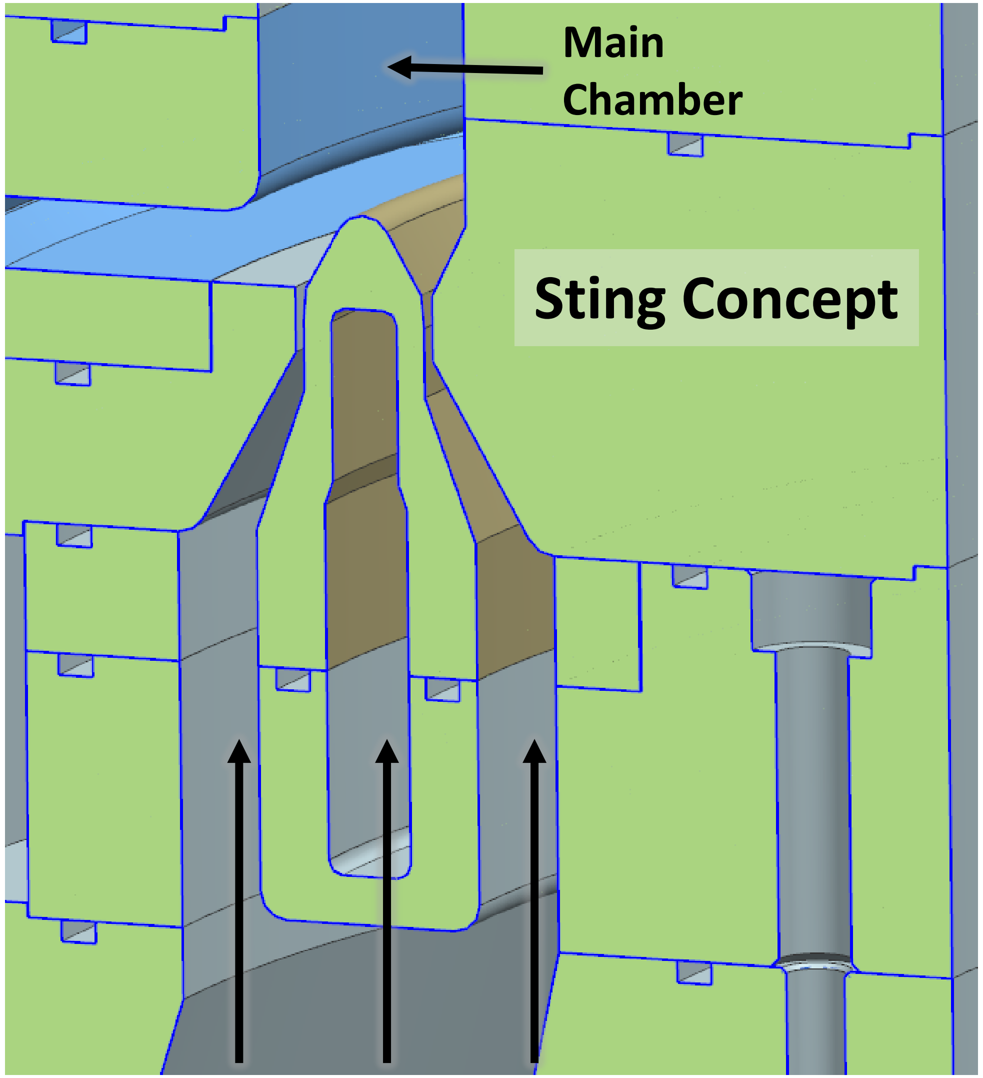
- Similar to an annular pintle injector
- Sting element provides opportunity to investigate multiple injector geometries/configurations with minimal system redesign/cost
- Small, measured changes in sting location to significantly affect reactant flow velocities and fuel injection stiffness
- Reduce required fuel jet penetration distance



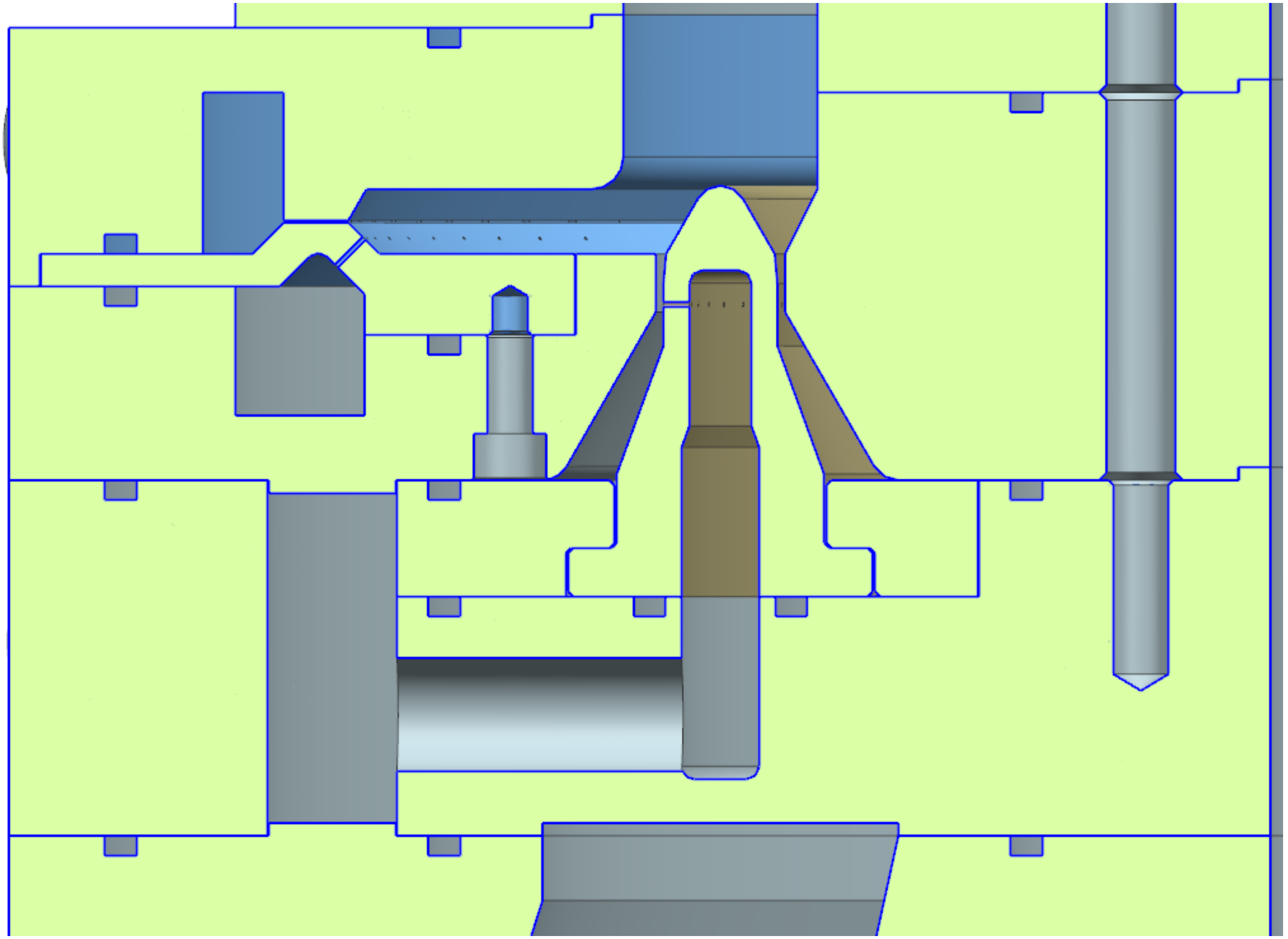
Bluff Aft-facing Step

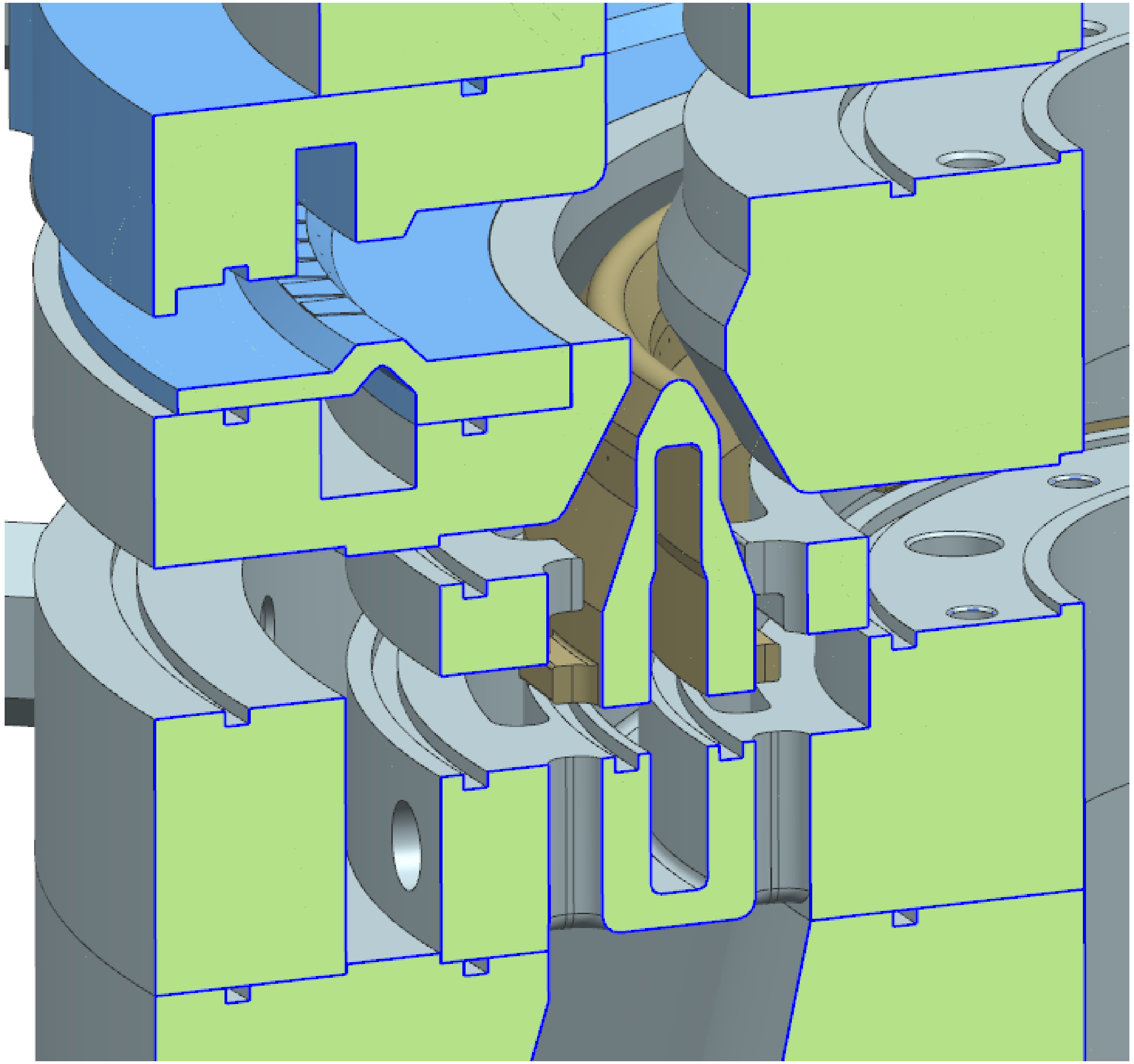


Angled Slots (Less developed)



Design Overview: Fuel Injector

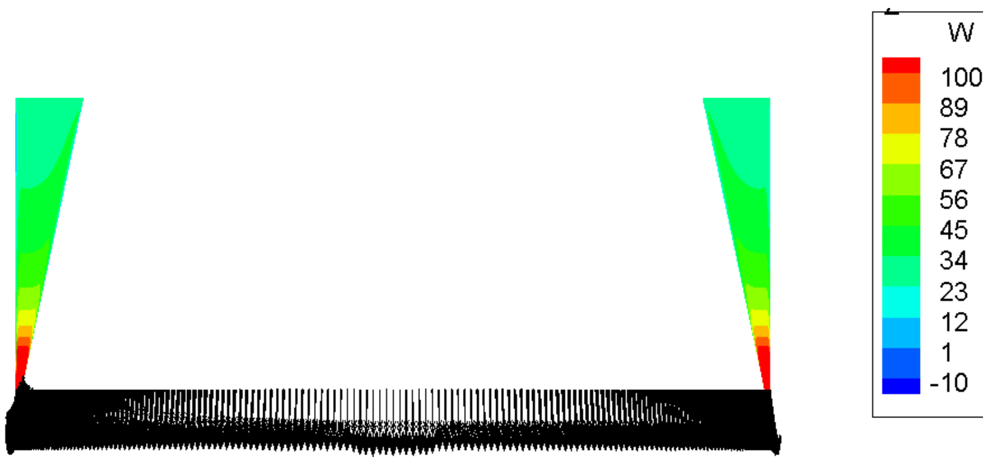




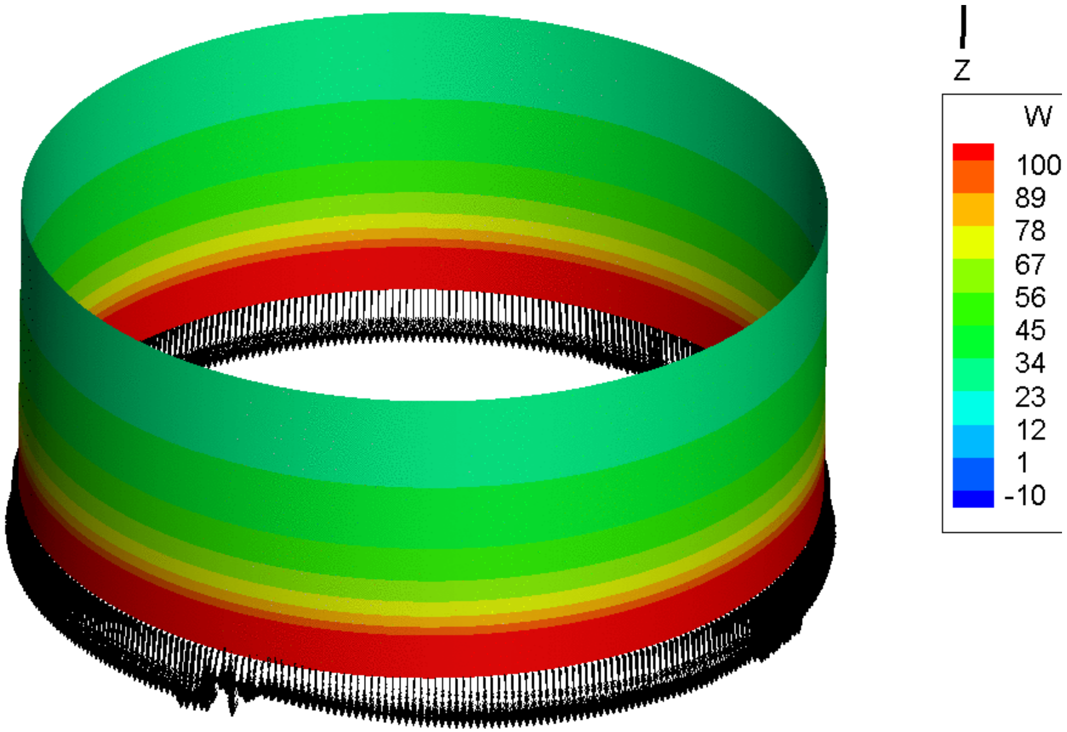
- Current air injector geometry achieves manifold pressure of 600 psi at 15 lb/s and 620F
- Area ratio of 8.4

Computational Model Development – Injector Response

- 3-D nonreacting study to assess annular air injector response to rotating detonation waves
  - o Reflective inlet boundary assumed
- Simple triangular waves imposed – wave height/impulse, speed, and number have all been studied



Axial Velocity Distribution at Combustor Inlet



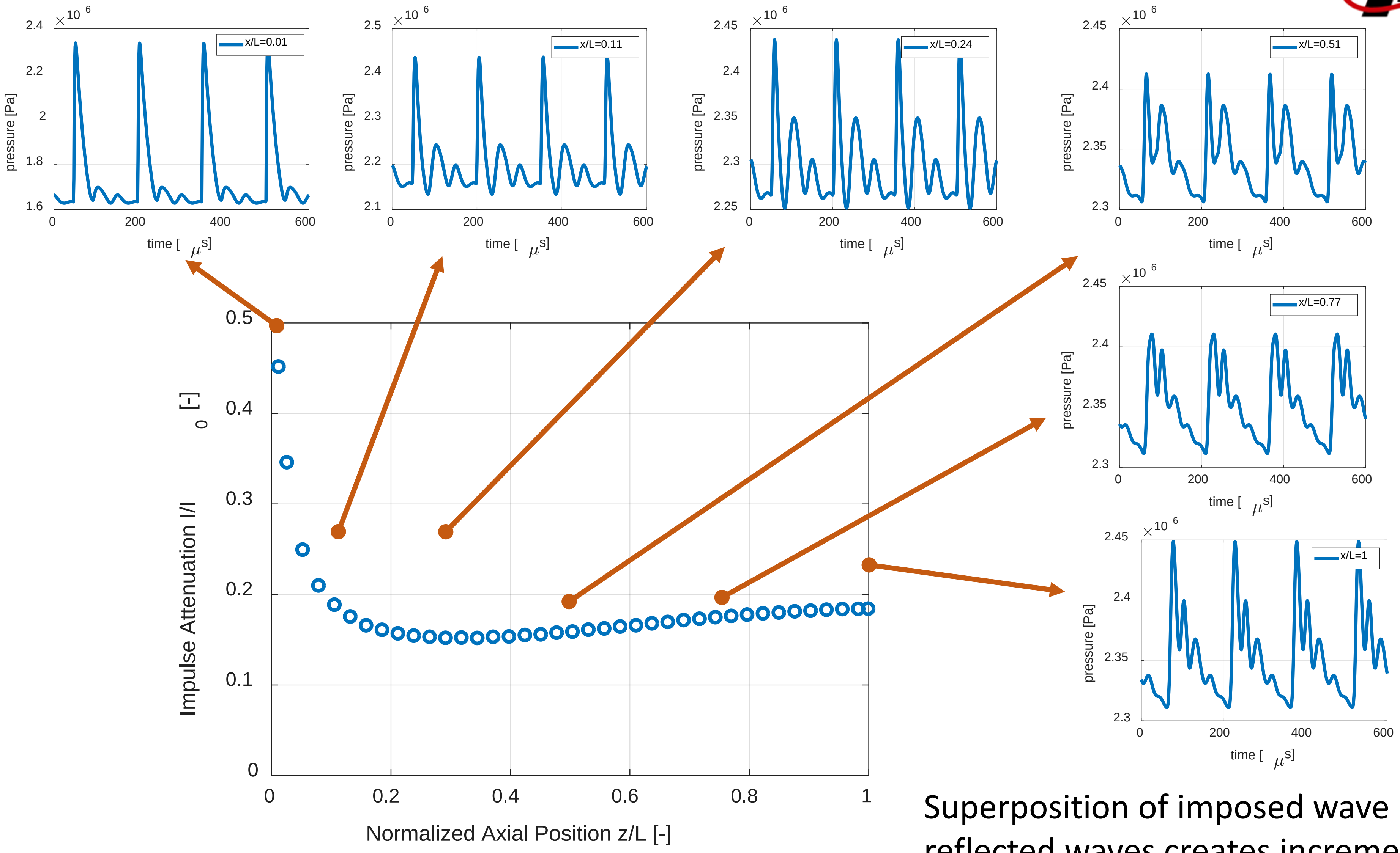
Axial Velocity Distribution at R = const (centerline radius) slice

Typical Pressure Response

- Initial wave propagation is supersonic, but rapidly attenuates to acoustic speed propagation
- Wave reflections complicate signals – inlet struts will substantially effect manifold acoustic response

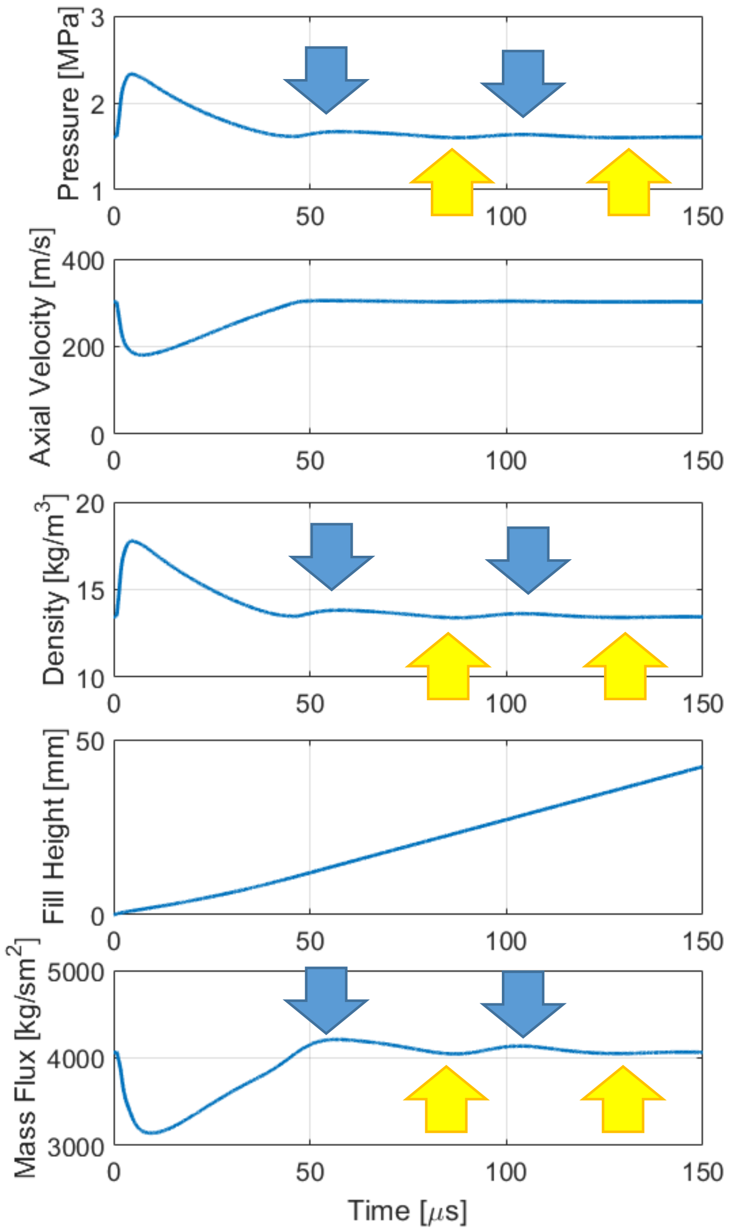
3D Pressure Contour

Impulse Attenuation



Superposition of imposed wave and reflected waves creates increment

Injection History for Wave Pressure Ratio=8



- Pressure and density histories are affected by the reflected waves more than velocity.
- Mass flux fluctuates approximately ±10% from the "steady value" due to the reflection.
  - Reflected waves do create additional impulses and could perhaps spawn additional detn waves?
- Fill height is not affected by the reflection because of the low imposed pressure ratio

Computational Model Development – Kinetics Effects

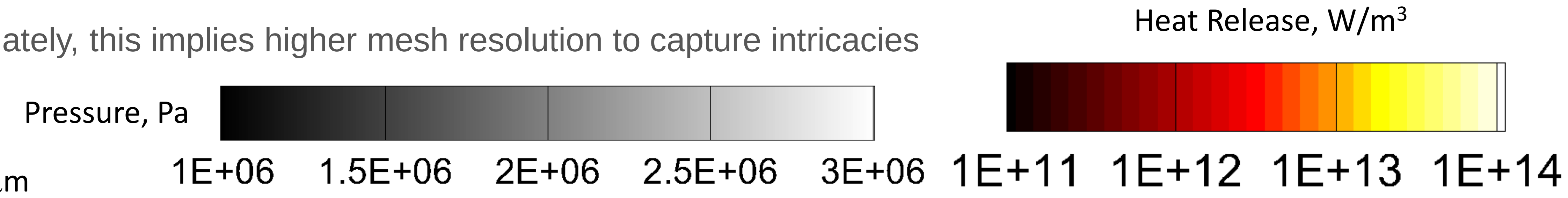
- Heat release is coincident with pressure in global mechanism, but detailed chemistry can reveal complex structures (cell sizes and other features)
- Simulations below are for O2/CH4 with similar meshes
- Detonation structure will become important in near-limit conditions, i.e. large cell size structures like methane/NG

Global Chemistry, V = 2151 m/s

GRI-1.2 Mechanism, V=2250 m/s

Computational Model Development – Mesh Resolution

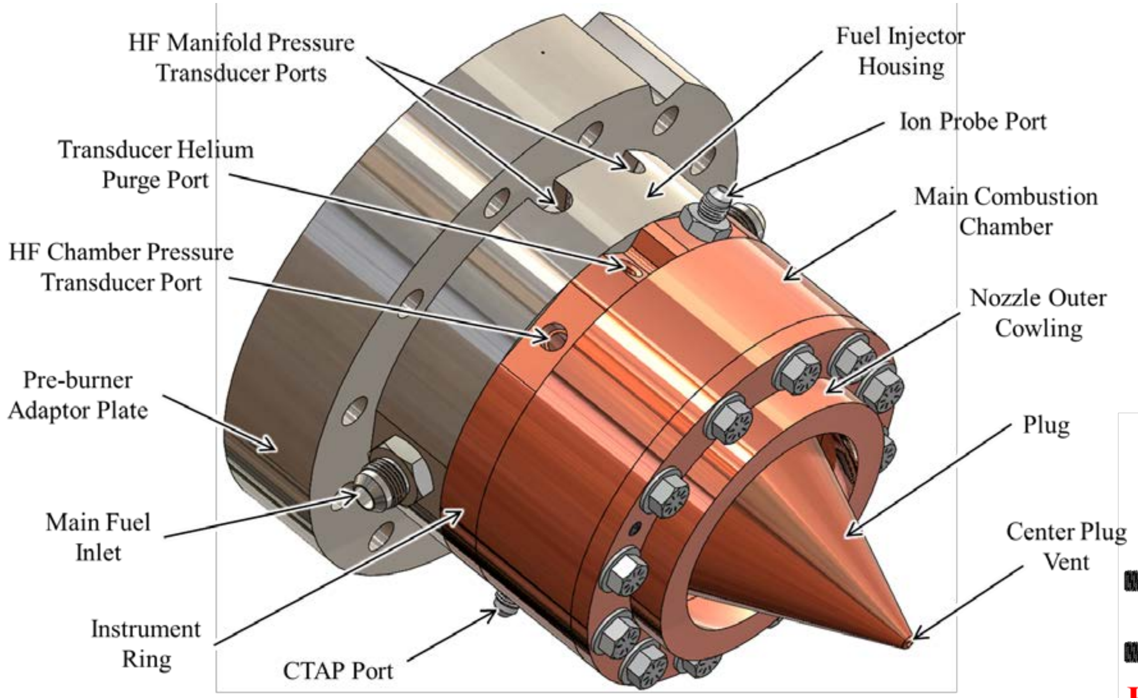
- Higher order chemistry approaches provide for more intricate interactions between pressure and heat release fields
- Unfortunately, this implies higher mesh resolution to capture intricacies

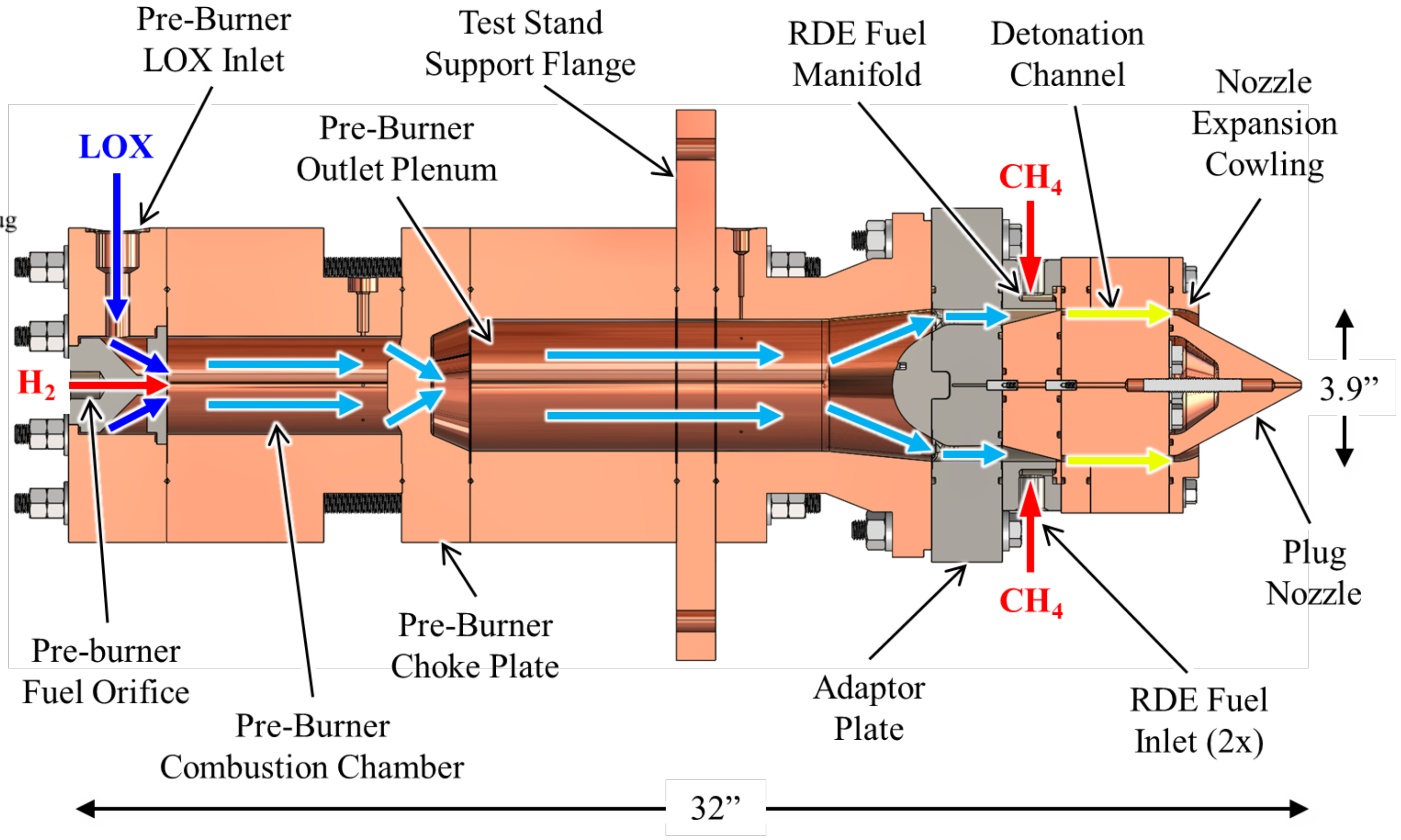


Δx = 12.5 μm

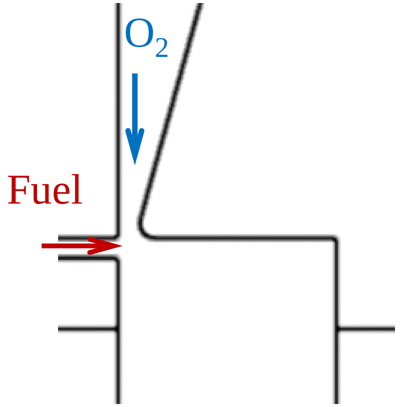
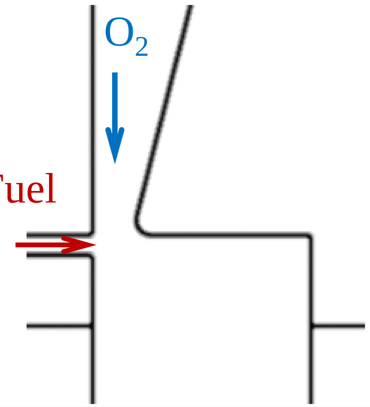
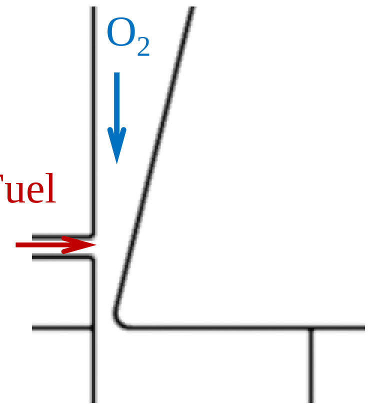
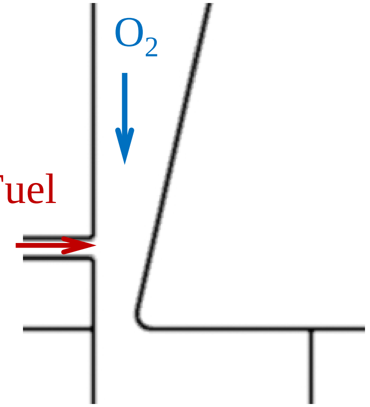
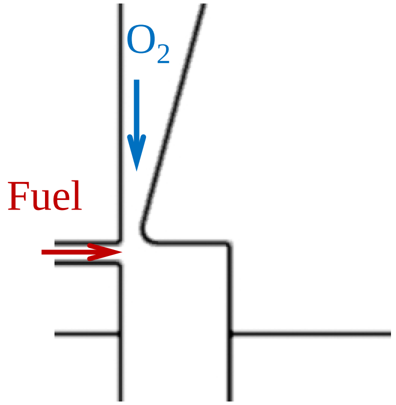
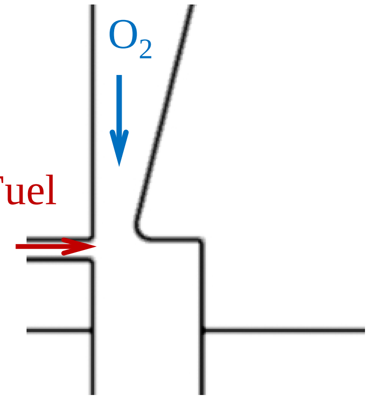
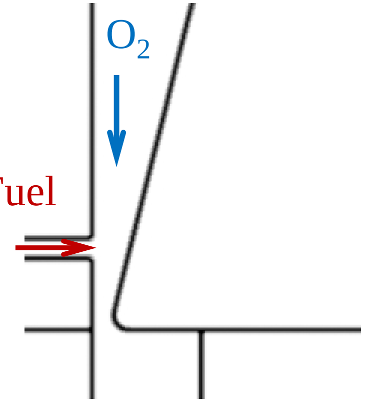
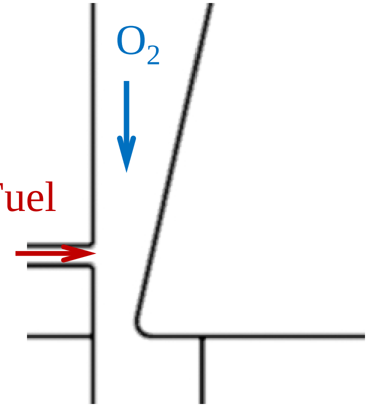
Δx = 2.5 μm

A Few Headscratchers from High Pressure Rocket RDE

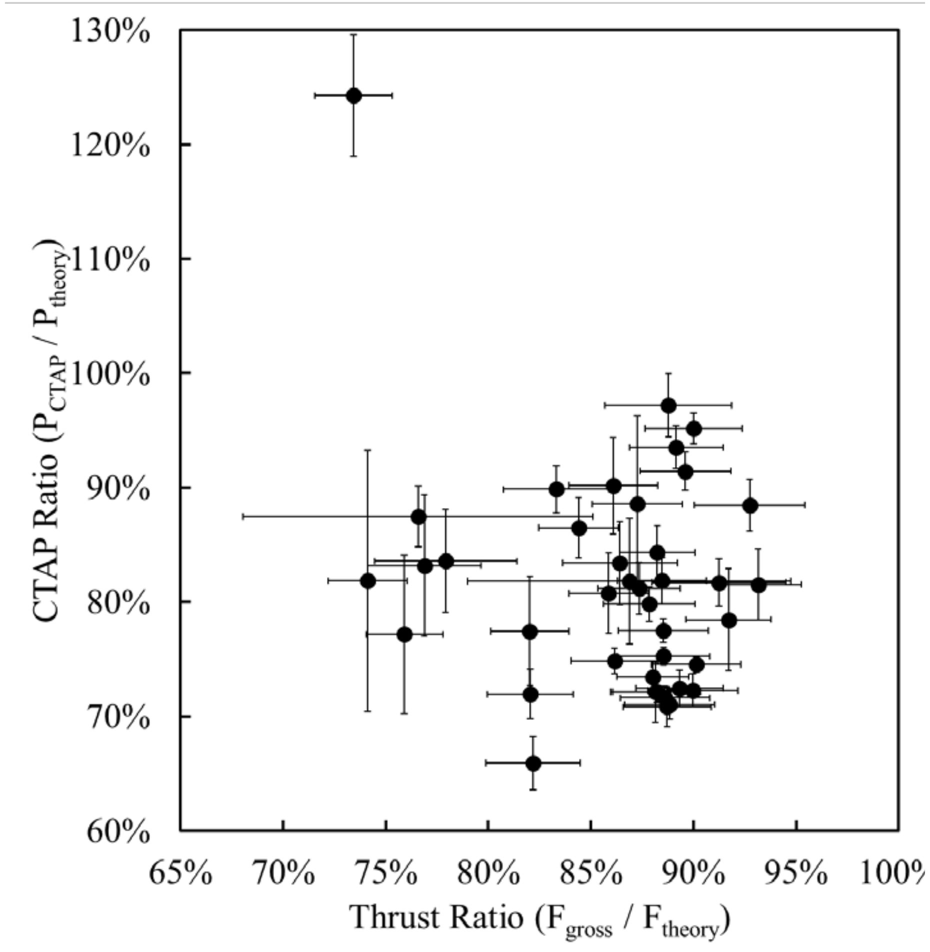


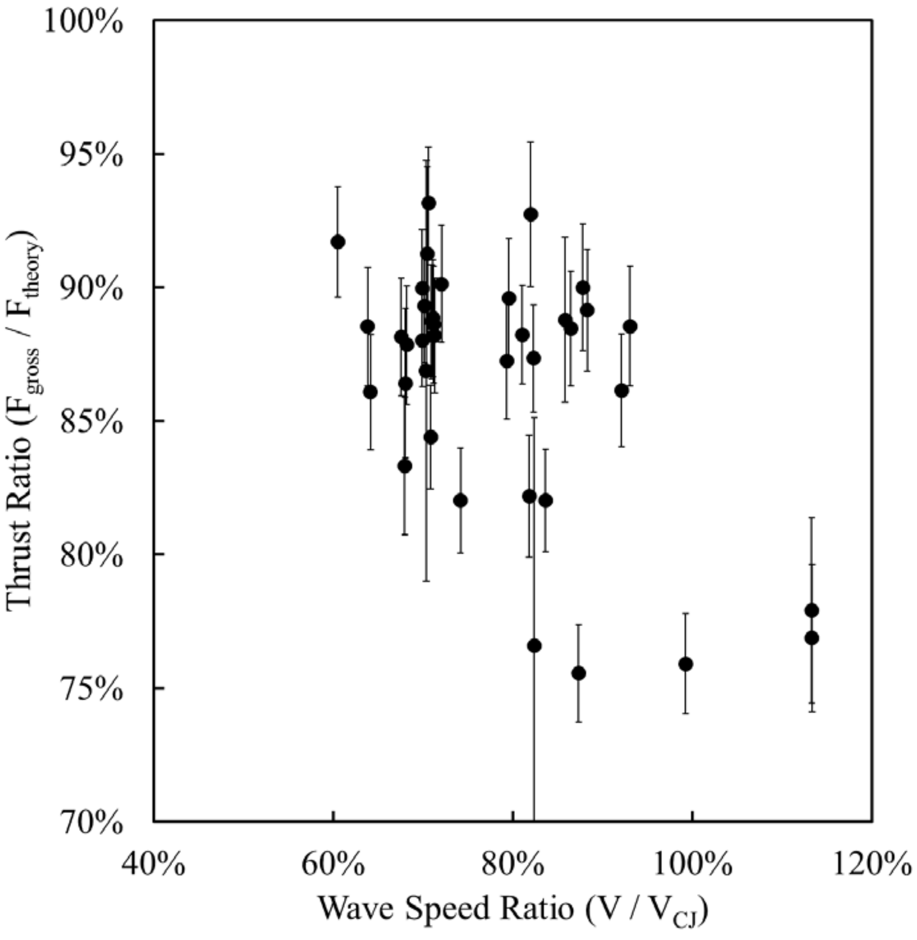


Hardware Variations Studied

Downstream Injection Narrow GOX Gap Wide Channel 	Downstream Injection Wide GOX Gap Wide Channel 	Upstream Injection Narrow GOX Gap Wide Channel 	Upstream Injection Wide GOX Gap Wide Channel 
Downstream Injection Narrow GOX Gap Narrow Channel 	Downstream Injection Wide GOX Gap Narrow Channel 	Upstream Injection Narrow GOX Gap Narrow Channel 	Upstream Injection Wide GOX Gap Narrow Channel 

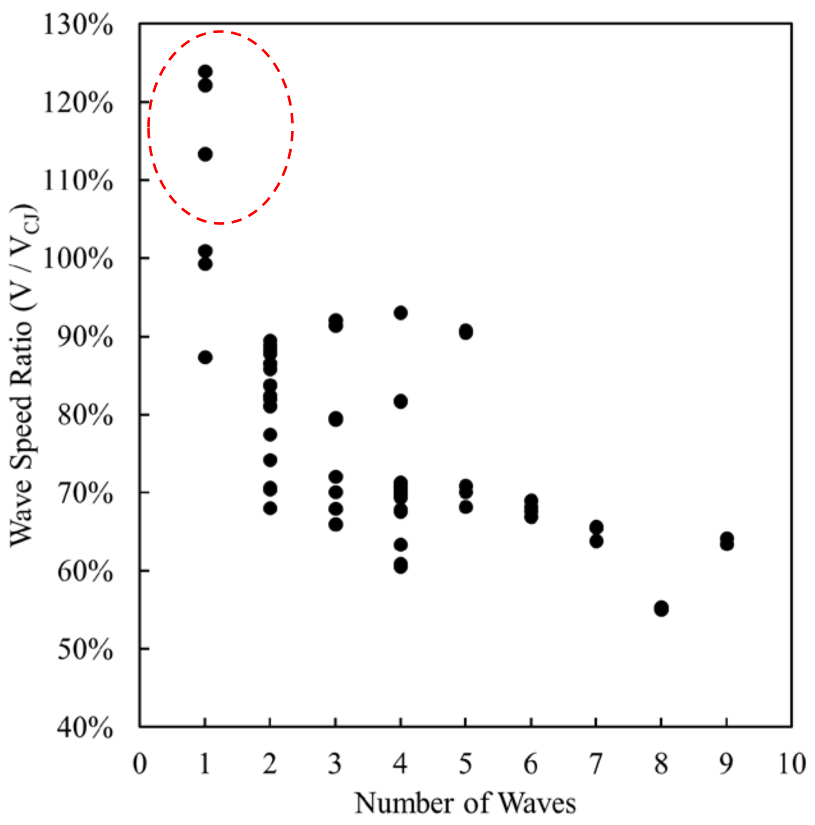
Some painful revelations…

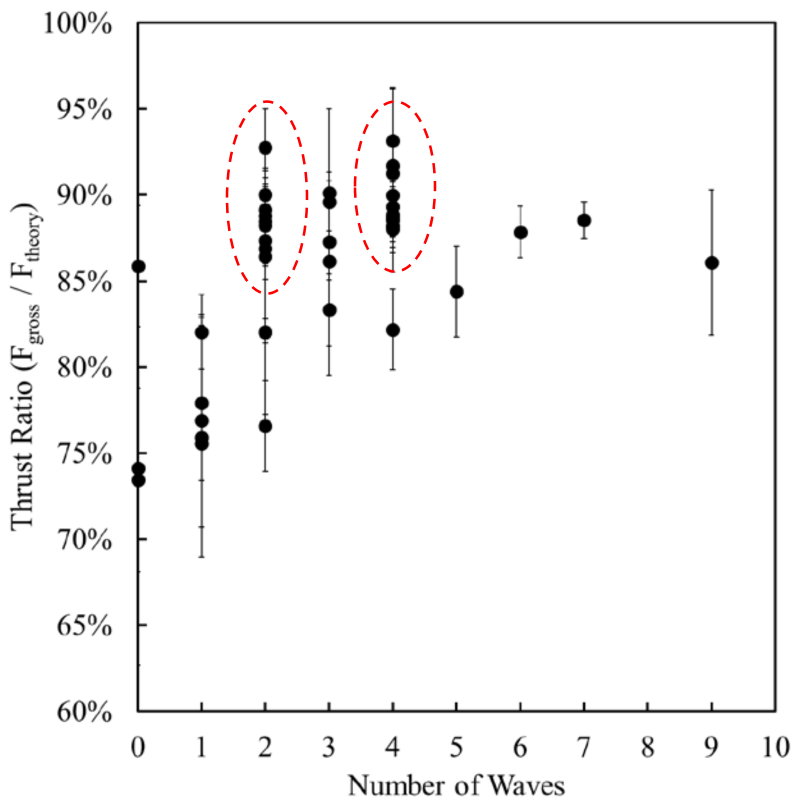




- Thrust does not correlate with CTAP! (but does correlate weakly with wave speed)
- CTAP of 125% of theoretical was measured – shock interaction with the probe site?

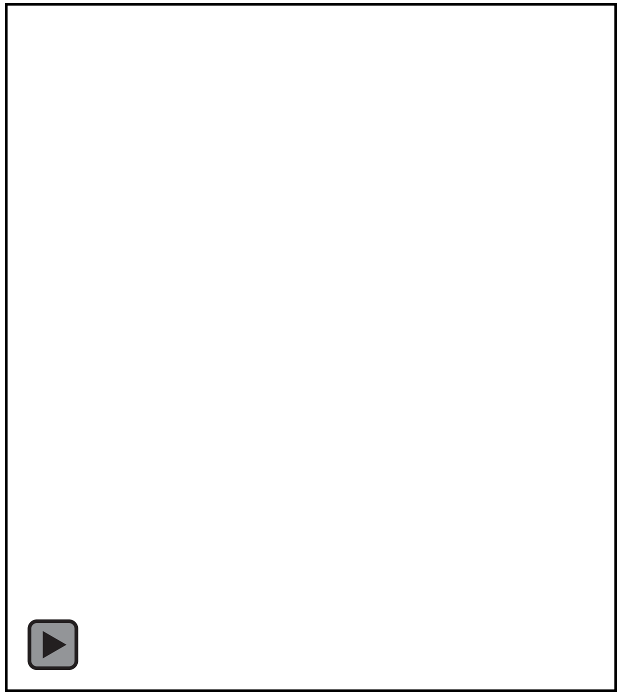
Global Performance Trends

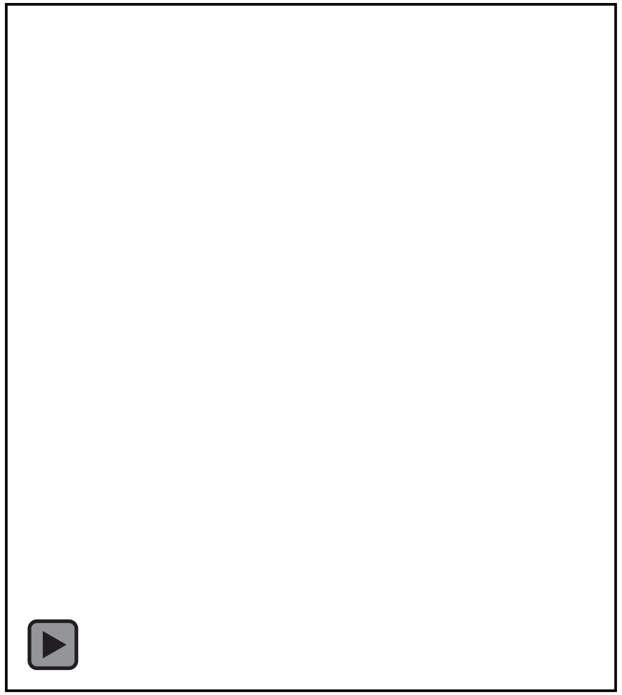


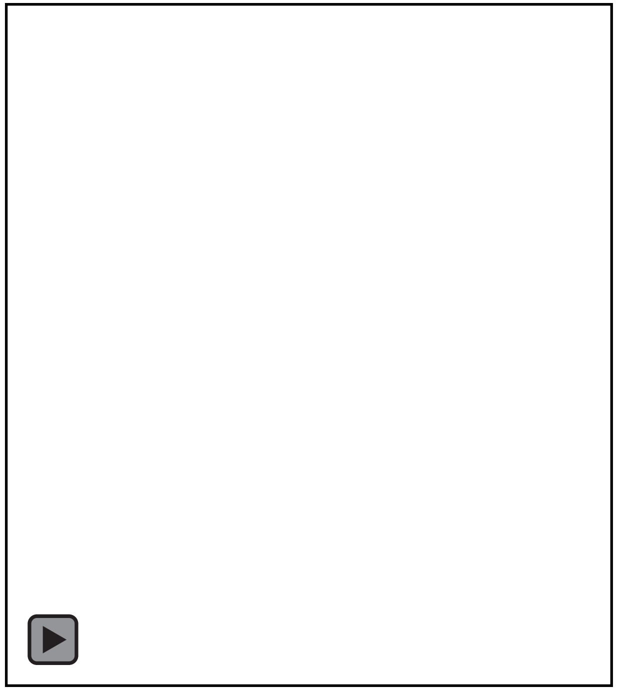


- Wave speeds increase with decreasing number of waves
- Highest thrust obtained with 2 and 4 wave cases with max performance at 93% of theoretical CP device
- Low thrust in single-wave cases likely due to over-filling chamber
- Single wave velocity exceeding CJ is perhaps a periodic DDT

Global Performance Trends

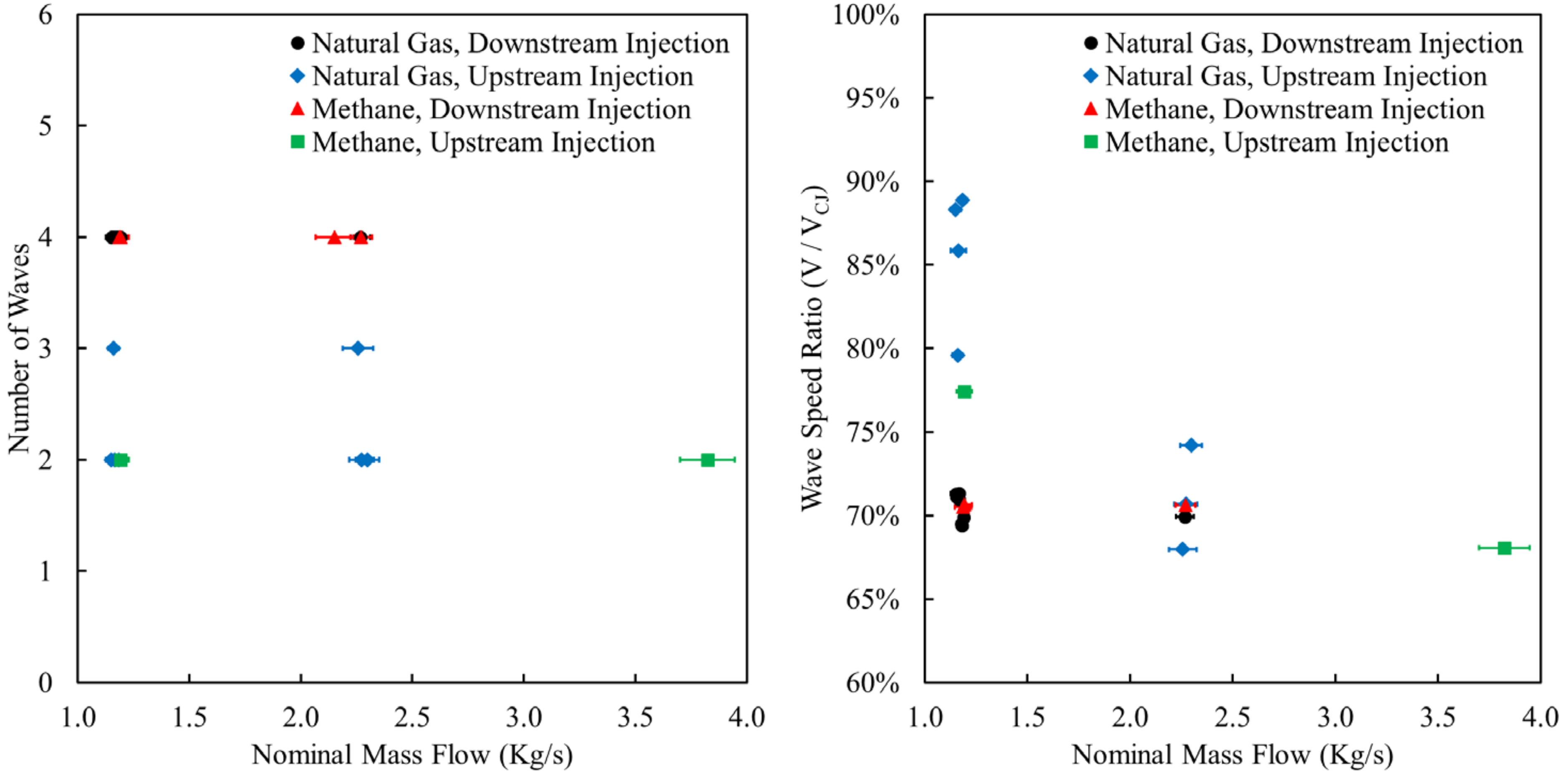






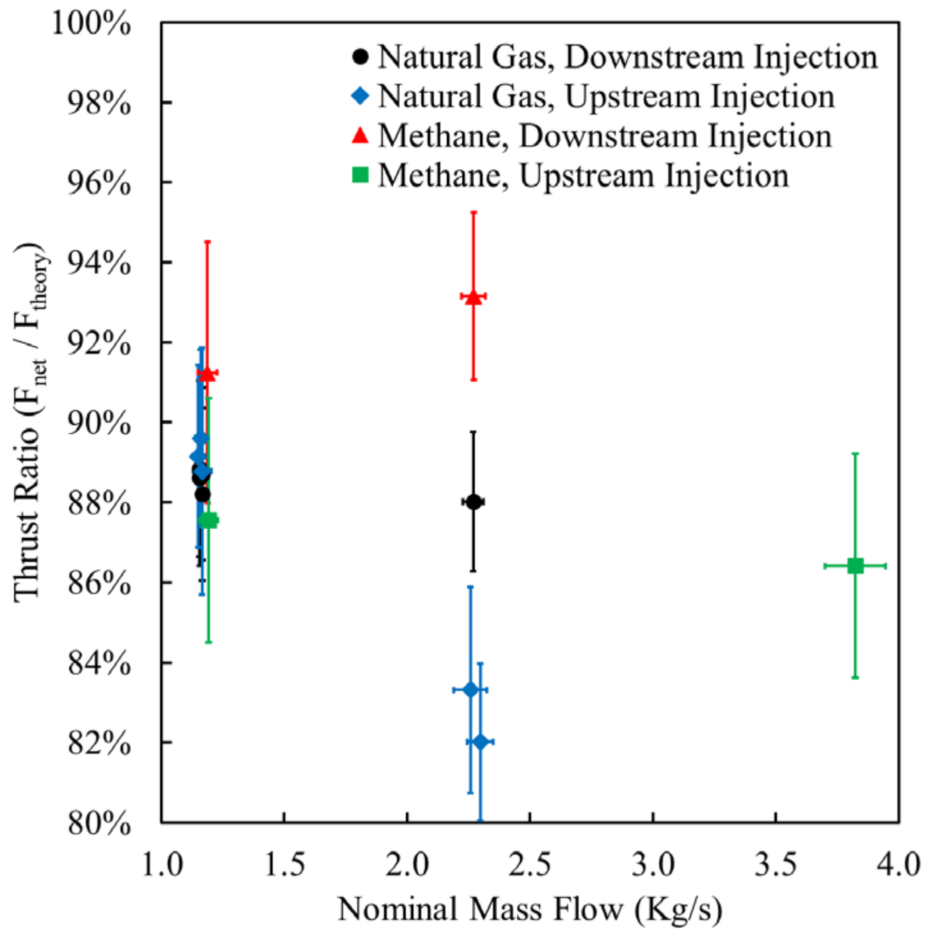
- Video provides best diagnostic we have used – pressure data can be misleading as wave structure is not apparent
- Cases that give high thrust show distinct detn waves with little combustion between waves.
- Bykovskii 4:1 length/ht criteria matched approximately in results

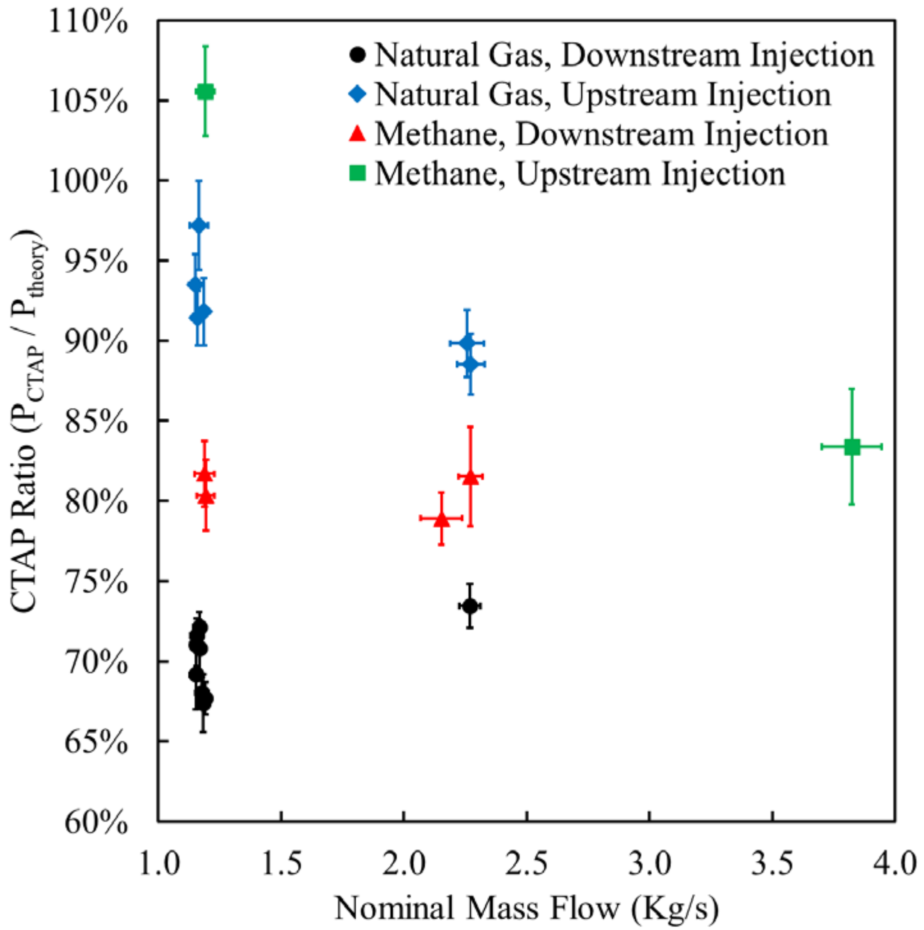
Pressure and Mass Flow Effects



- Wave number invariant over 4:1 throttle range – has anyone seen that before?
- Minimal differences between methane and NG despite cell size differences
  - Perhaps this conclusion is unique to high pressure rocket and not general

Pressure and Mass Flow Effects





- Methane fuel with downstream injection produced best performance so minor flameholding with NG might explain differences
- We are still studying these results and will be for some time

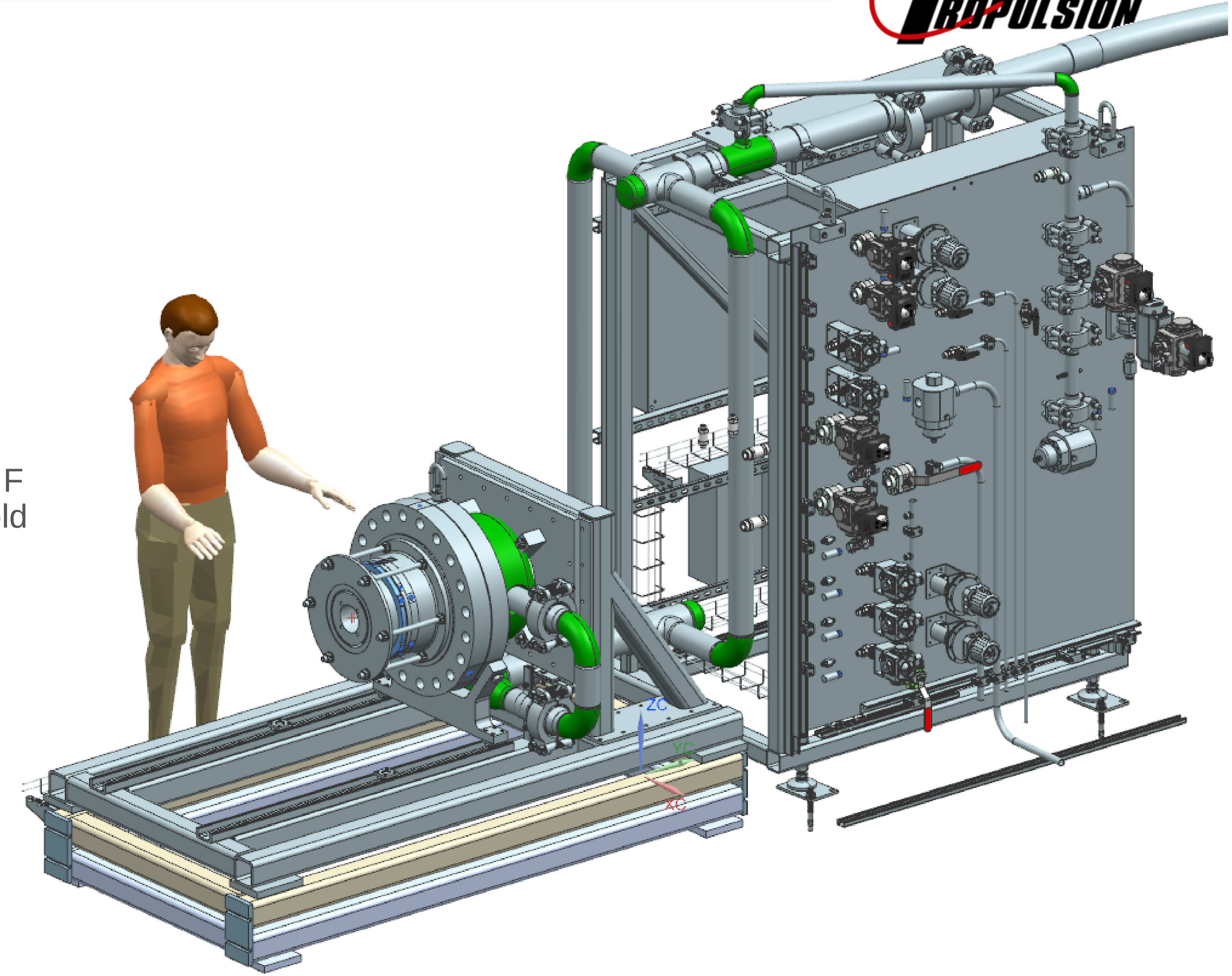
Summary

- DRONE platform exhibits self-excited, detonative behavior
  - Coupled interaction of reactant/product mixing and ignition delay
  - We need to pay attention to these issues relative to RDE cycle times
- High-power/pressure facility came on line this week
  - Aerojet/Rocketdyne testing remainder of this year with Purdue Apex hardware in early 2018
- Inlet/chamber coupling parametric study complete (SciTech 2018)
- Detonation modeling indicates that near-limit conditions with NG will require tiny meshes to capture pressure/heat release interactions
- High pressure rocket work providing some areas to watch
  - Thrust measurement does not line up with CTAP
  - NG is similar to methane in behavior (for most cases)
  - We still have a lot to learn relative to operability/wave topology

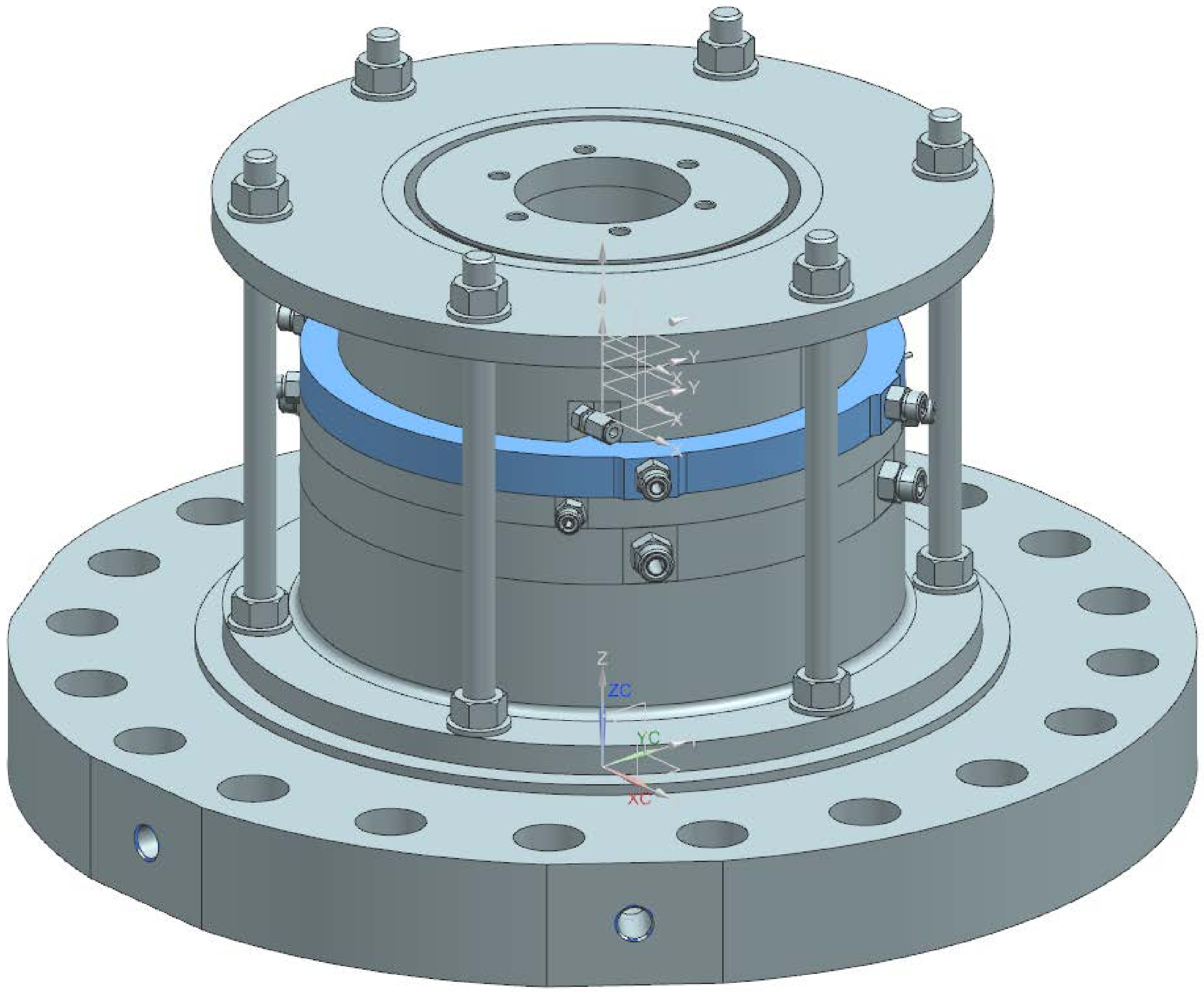
Testing Infrastructure

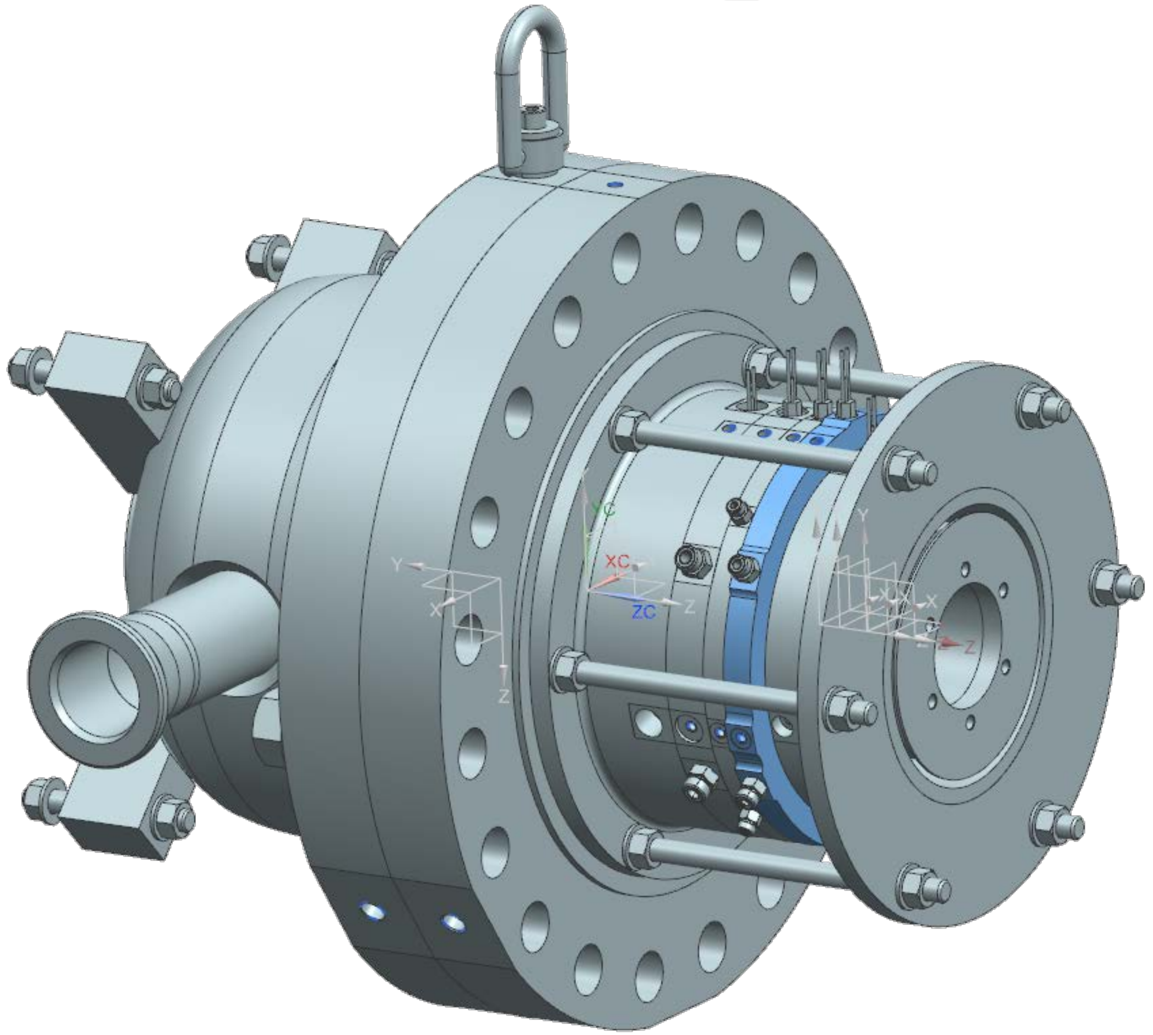
Thrust Stand Development

- Mechanical Design
  - Annular flow manifold with standard flange interface
  - Flow manifold and fluid system interface to thrust measurement system across metric break
  - Ancillary support structure designed
- Fluid system design:
  - Delivering 20 lb/s of air at 300 psi and 800 F to test article through a generalized manifold system
  - Provides natural gas, cooling water, fuel and/or oxygen enrichment.
- Instrumentation:
  - Axial thrust measurement up to 20000 lbf with integrated calibration
  - 128 analog input channels for condition documentation
  - 32 high-frequency measurement channels for dynamic content



Test Article Assembly





Injection Dynamics

(Injection, Mixing, Ignition) + Gradient Mechanism

- Zel'dovich gradient mechanism interacts with injector hydrodynamics to initiate a periodic DDT process.
- Schlieren seems to support this understanding. Confirmation with chemiluminescence is imminent.