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Advancing Pressure Gain Combustion in Terrestrial Turbine Systems

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School of Aeronautics & Astronautics

UTSR Workshop, 2 November, 2016

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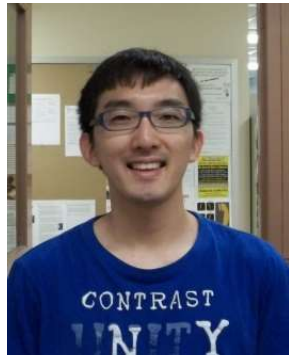

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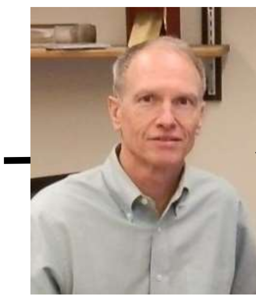

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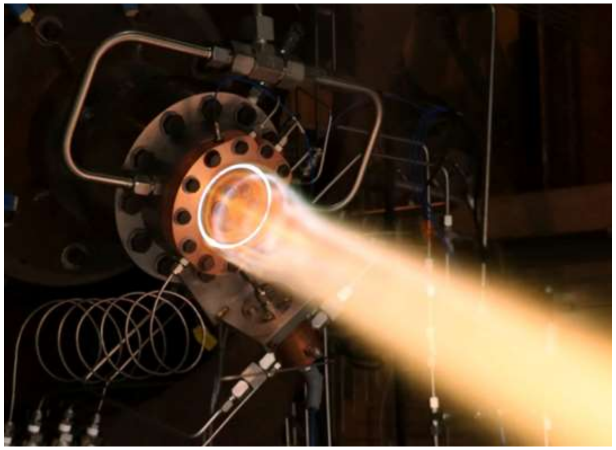
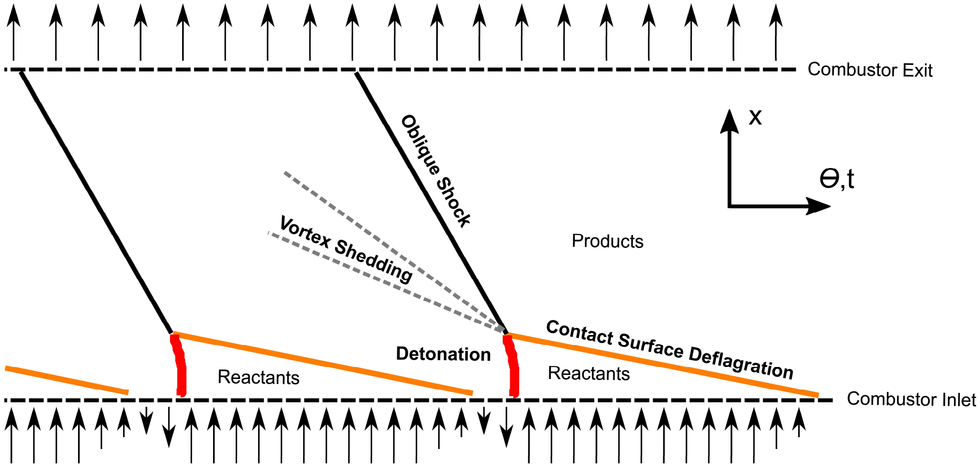
Project Objectives

We seek to understand the nature of injection, mixing, and ignition in rotating detonation combustion processes through the application of advanced measurement techniques. This information will enable the development of predictive models describing these dynamics, which will be verified with experiments at representative cycle conditions

- Task 1.0: Program Management
- Task 2.0: Injection Dynamics Characterization
- Task 3.0: Subscale Combustor Development
- Task 4.0: Evaluation of Pressure Gain
- Task 5.0: Detailed Inlet/Exhaust Measurements
- Task 6.0: Emissions Measurements
- Task 7.0: Model Development





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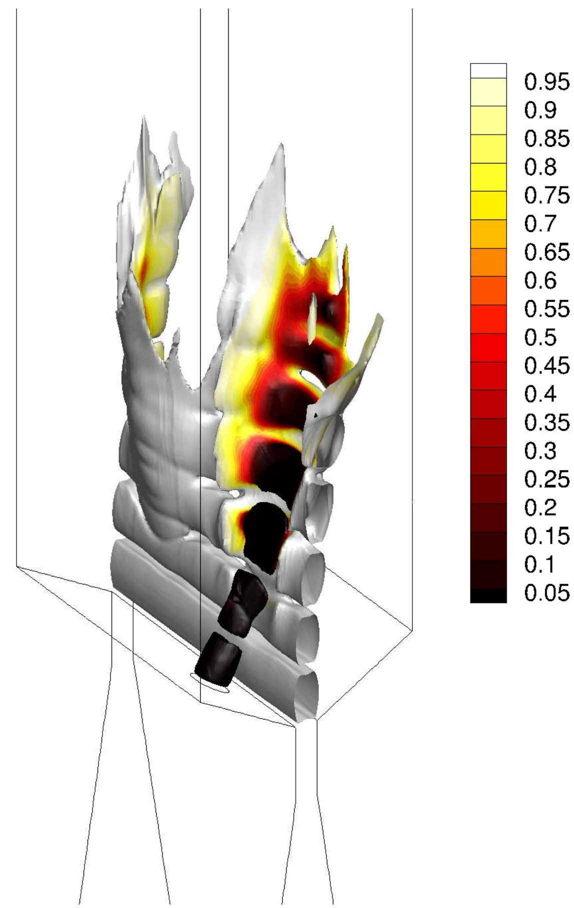
Progress After Year 1

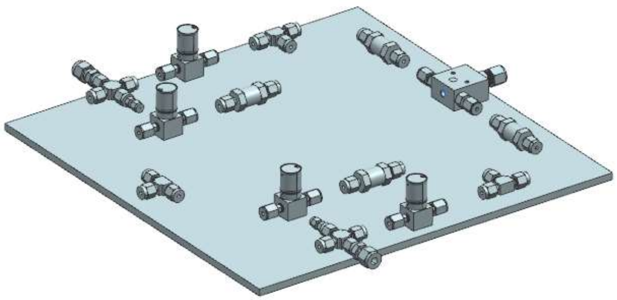
- **Task 2.0: Injection Dynamics Characterization**
  - **Overview of the DRONE experiment**
  - **Results from early testing**
- **Task 3.0: Subscale Combustor Development**
  - **APEX test stand design status**
  - **Test article configuration discussion**
- Task 4.0: Evaluation of Pressure Gain
- Task 5.0: Detailed Inlet/Exhaust Measurements
- Task 6.0: Emissions Measurements
- **Task 7.0: Model Development**
  - **Injection Dynamics Models**
  - **2-D Combustion Model**
  - **Comprehensive 3-D Model**

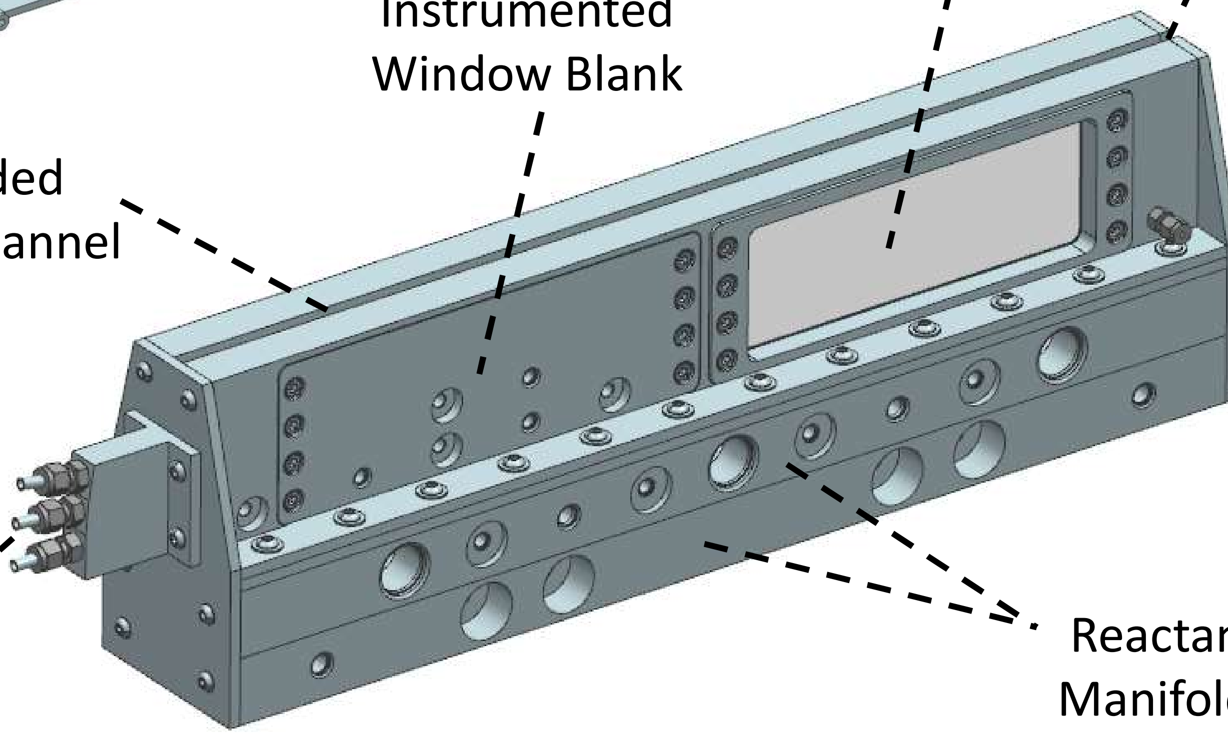


Iso-surfaces of M = 1.35 shaded by equivalence ratio from 3D LES of single fuel-injector hole-pair.

DRONE System Overview

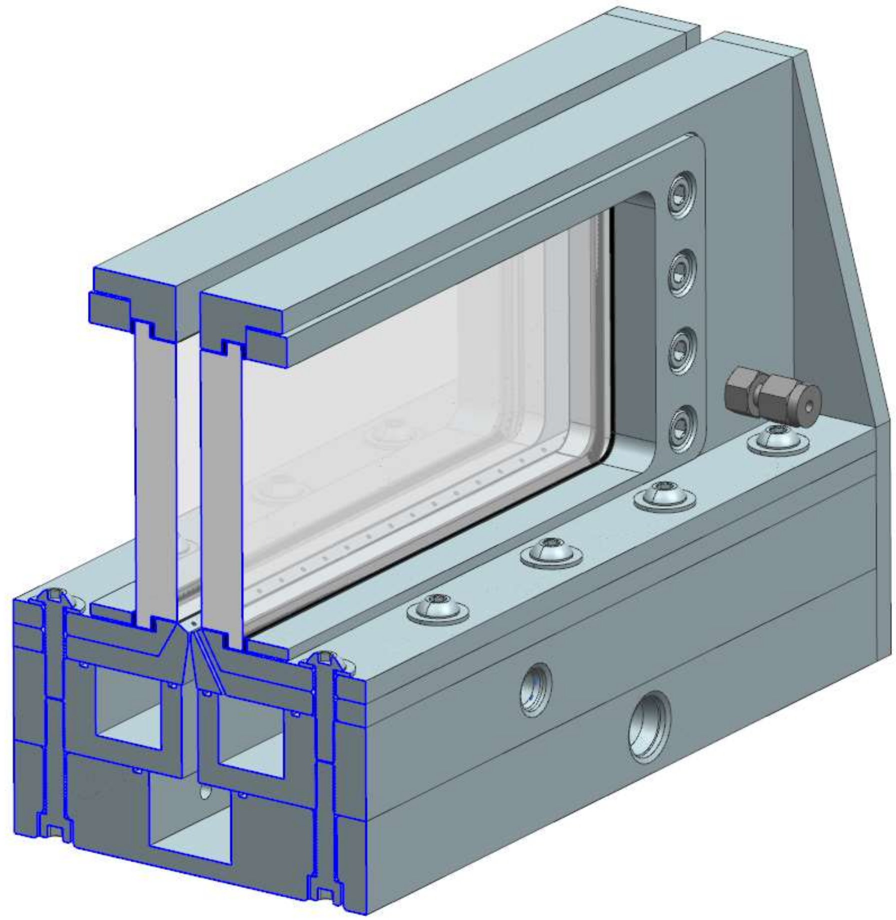
Detonation Initiator System





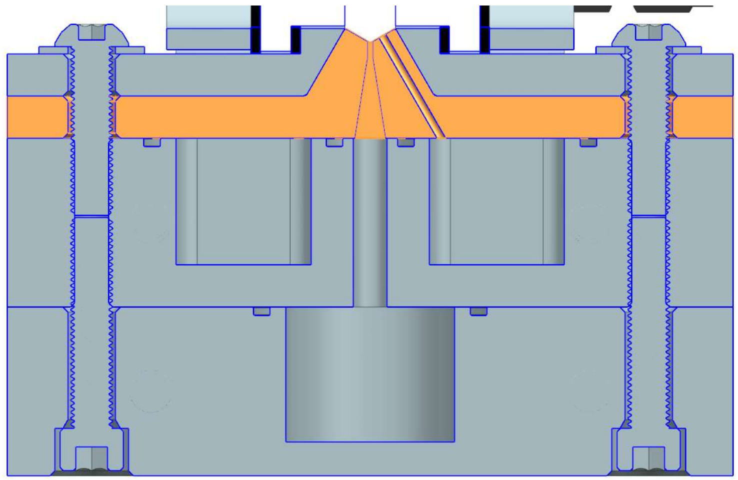
DRONE System Overview

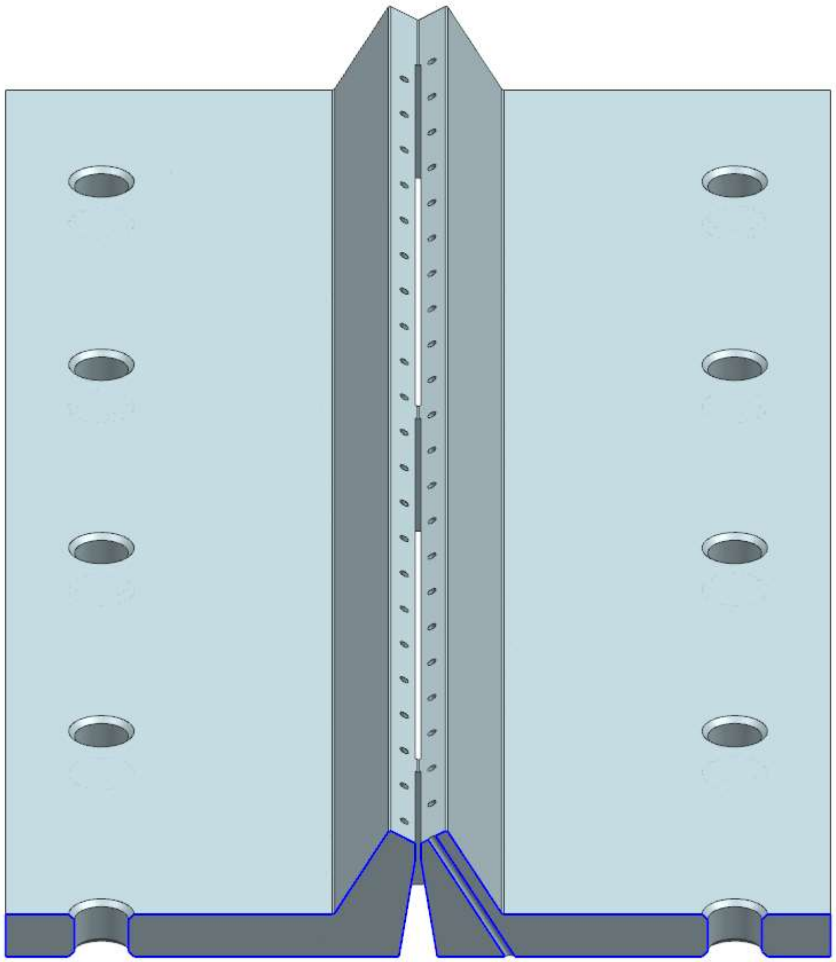
- Designed to enable high-fidelity imaging measurements in the reaction zone
  - Planar Laser-Induced Fluorescence
  - Focused Schlieren
- Methane – Oxygen (GOx)
- Ambient Initial Conditions
- Nominal Cell Size
  - $\lambda = 2.5\ mm$
- Nominal (Ideal) Wave Speed
  - $u_{CJ} = 2390\ m/s$



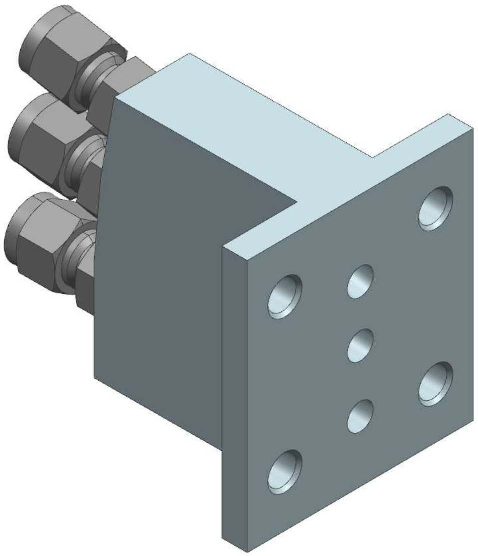
Modular Injector Design

- Staggered Fuel Injection Holes with Central Oxidizer Slot
- Injection Pressure Drops Tuned Between Fuel and Oxidizer for Staged Dynamic Response
- Single Plate Injector Sandwiched Between Walls and Manifolds

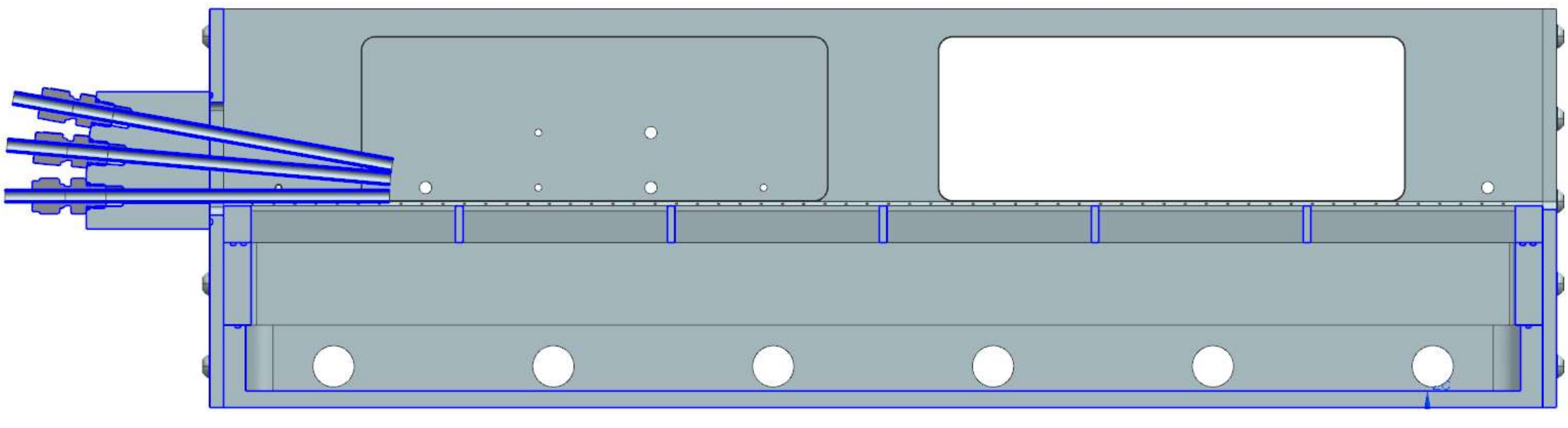




Channel Forcing with Detonator



- Controlling Multi-Pulse Flashback by Staggering Tube Exit into the Detonation Channel
- Modulating Pulse-Separation Delay Lines of Branched Detonation
- Exploiting Dynamic Response of Injector to Refill Channel for Successive Pulses.



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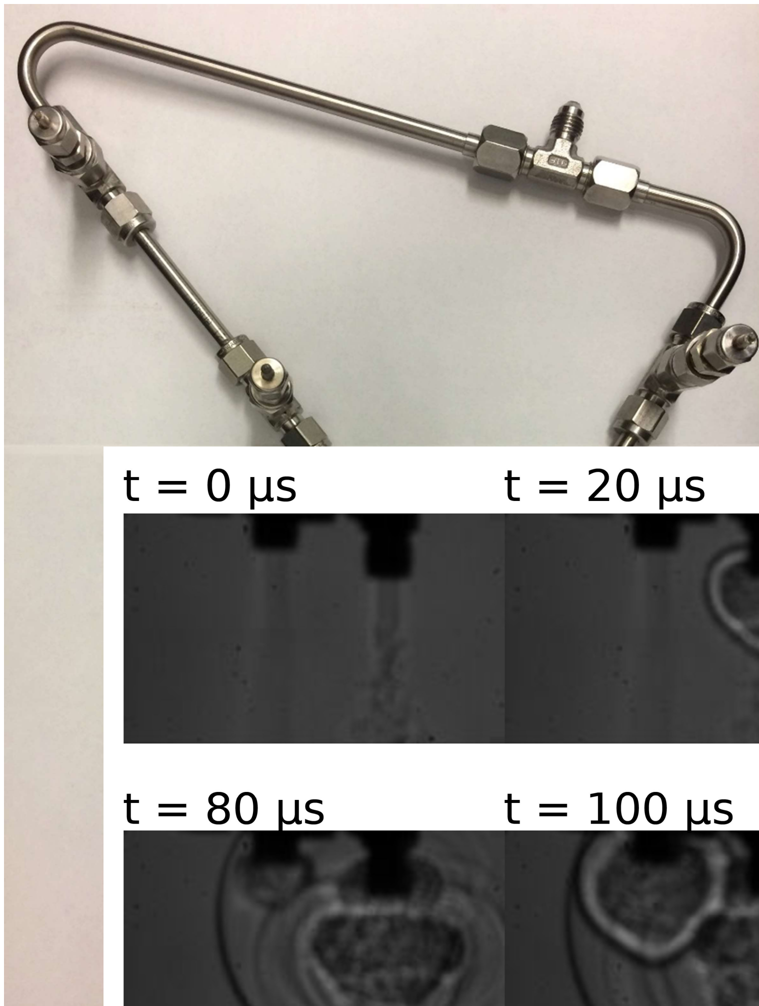
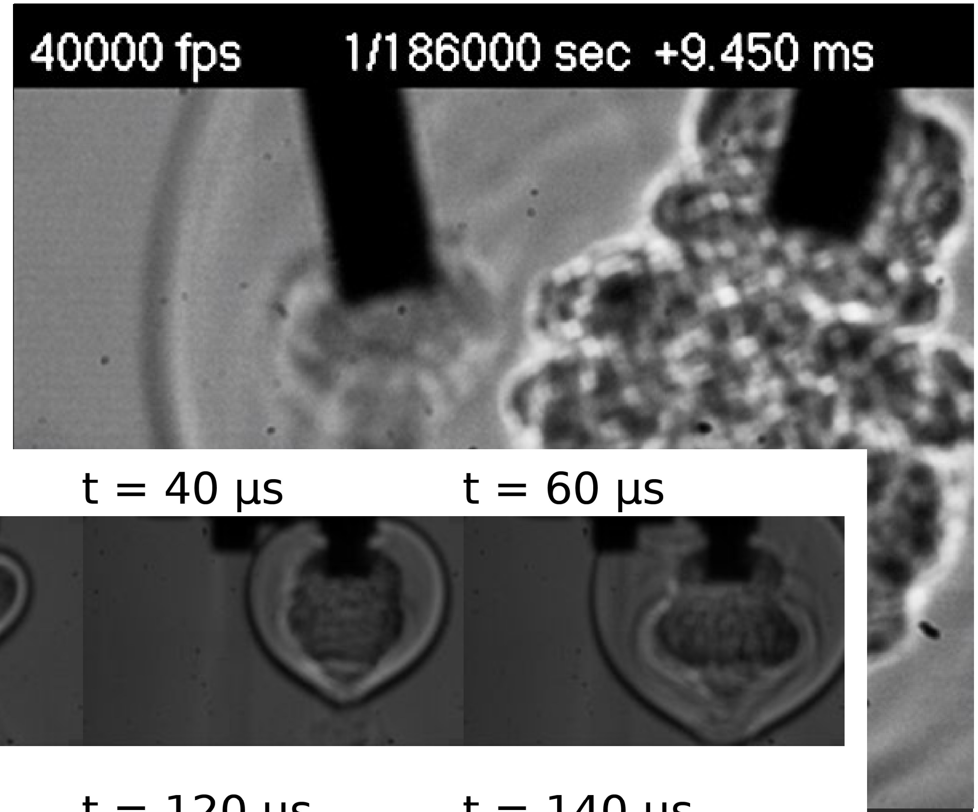
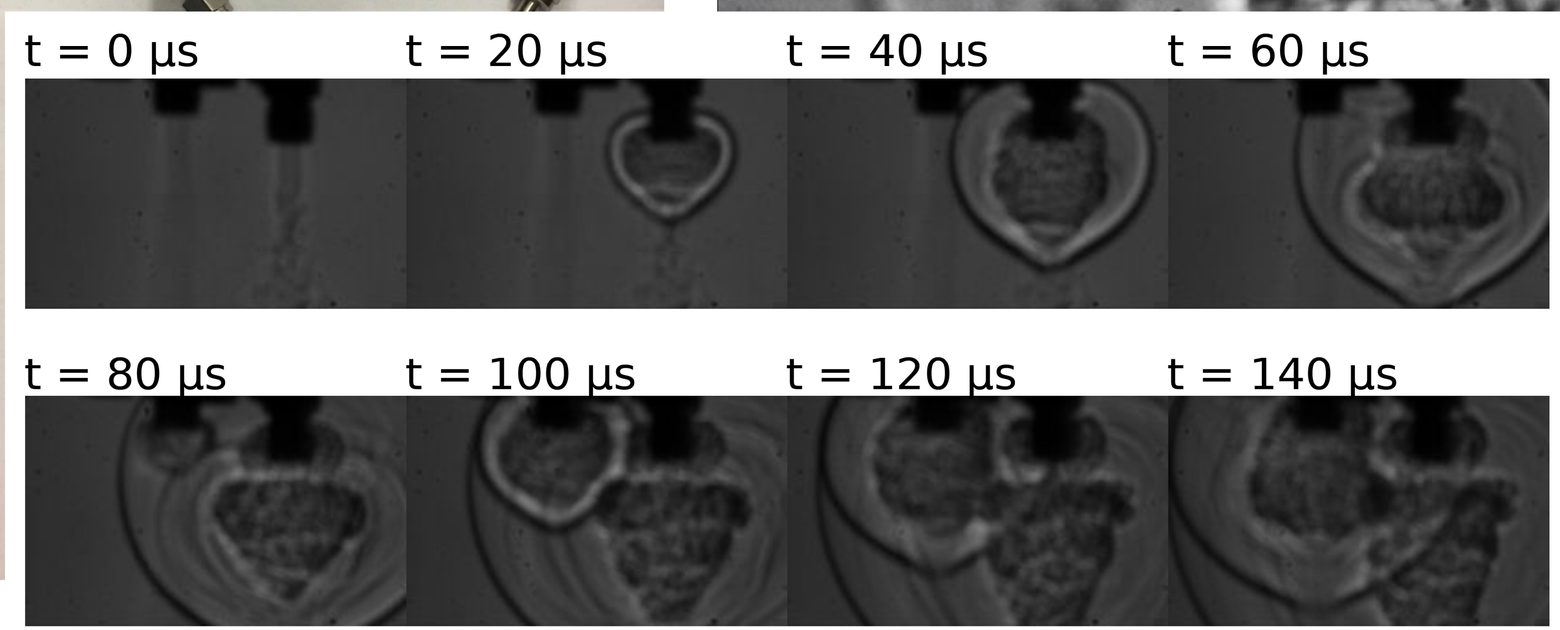
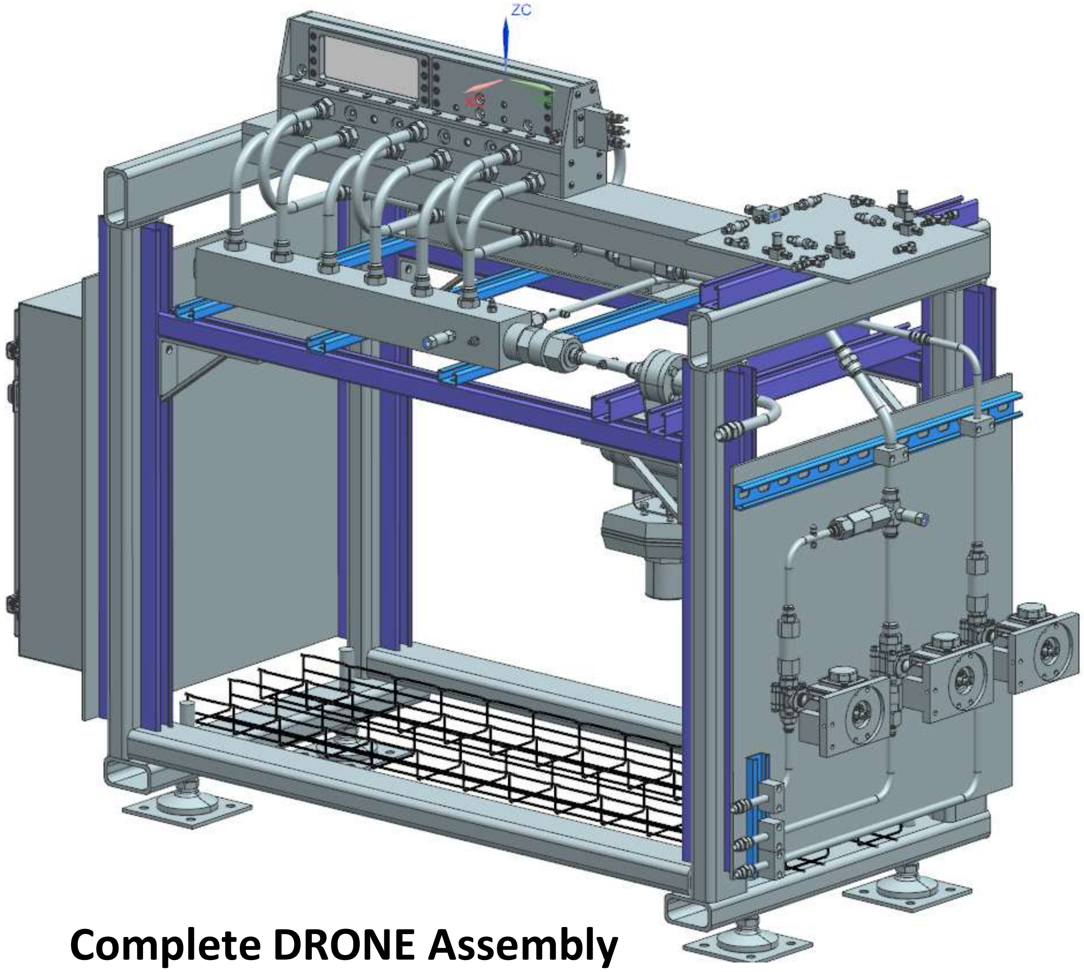


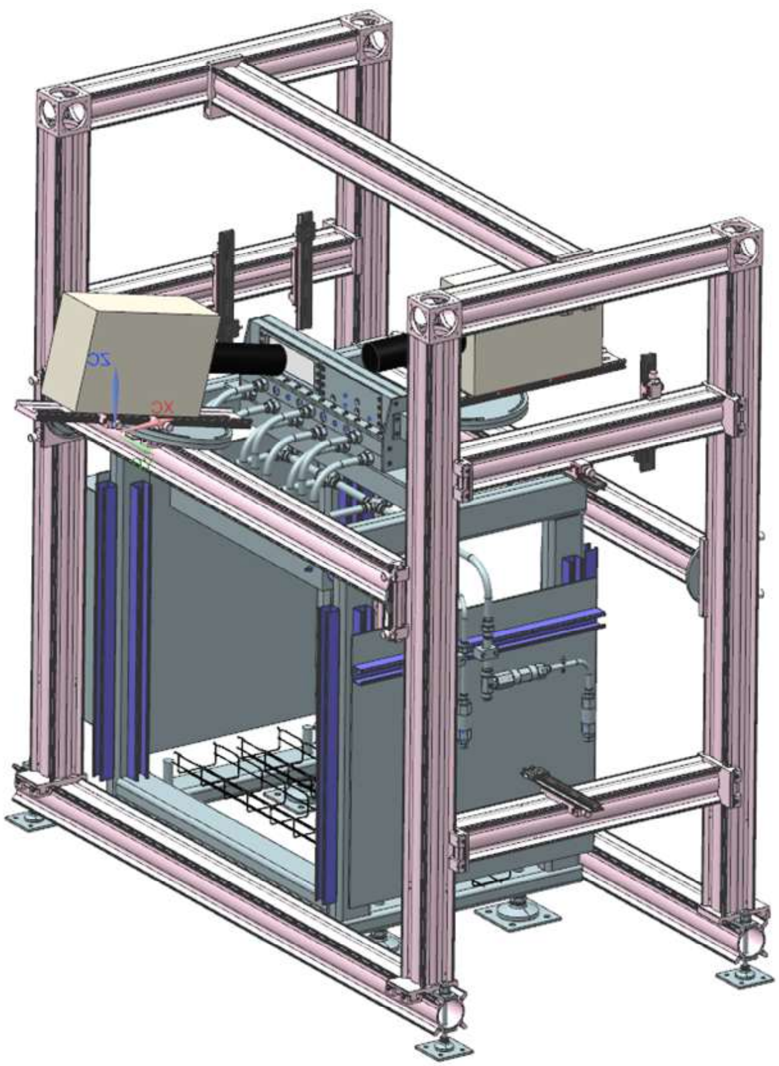




System Integration

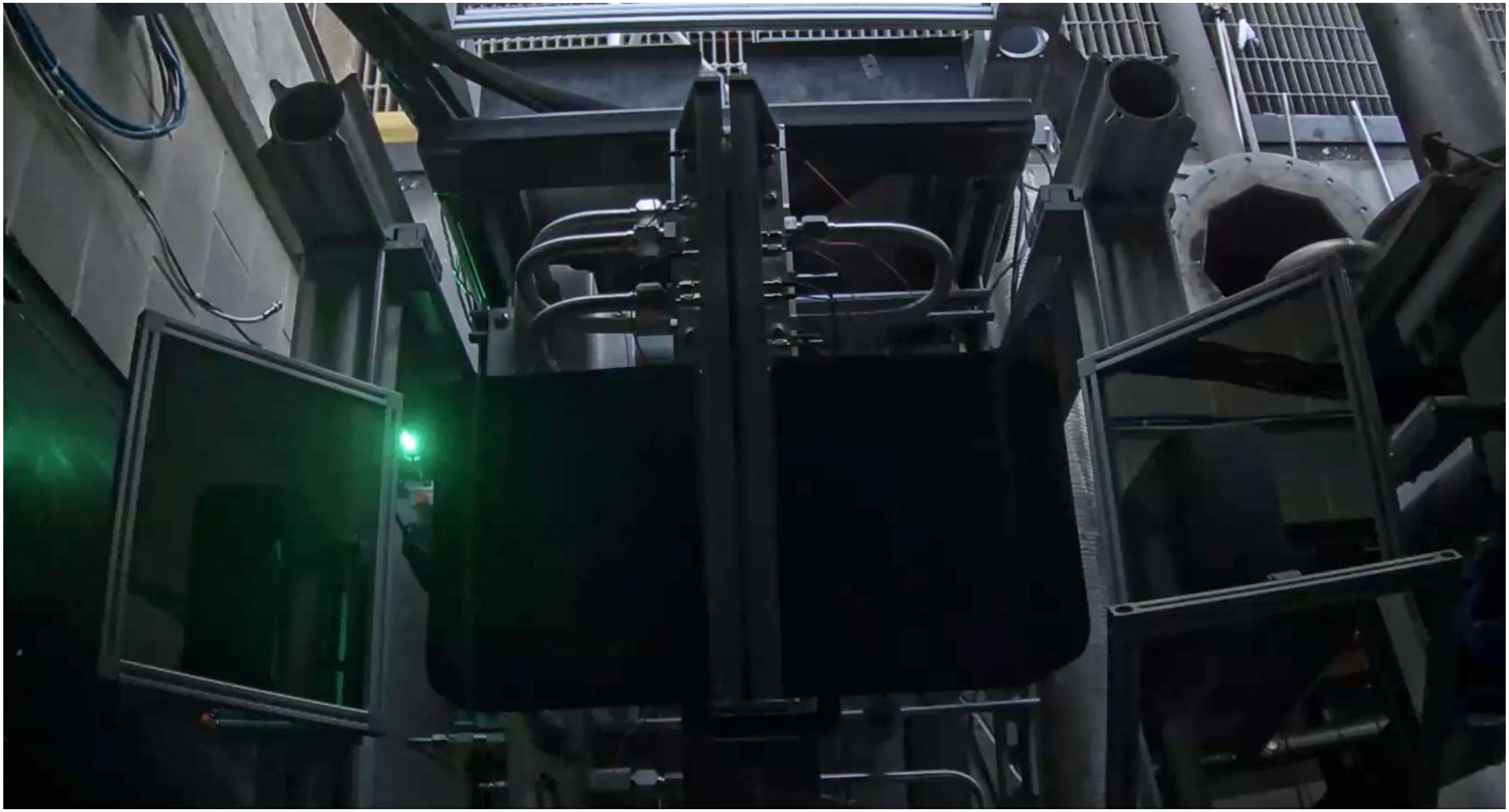


Complete DRONE Assembly



DRONE with Optomechanical Structure

First Hot-Fire



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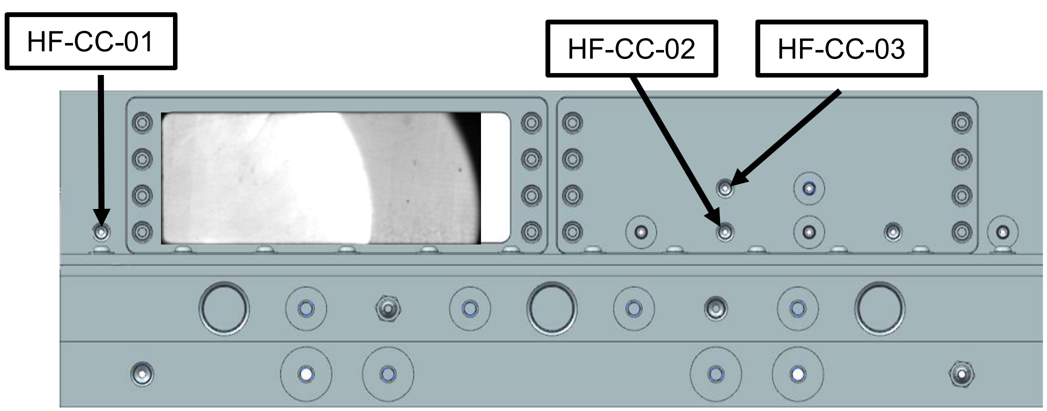
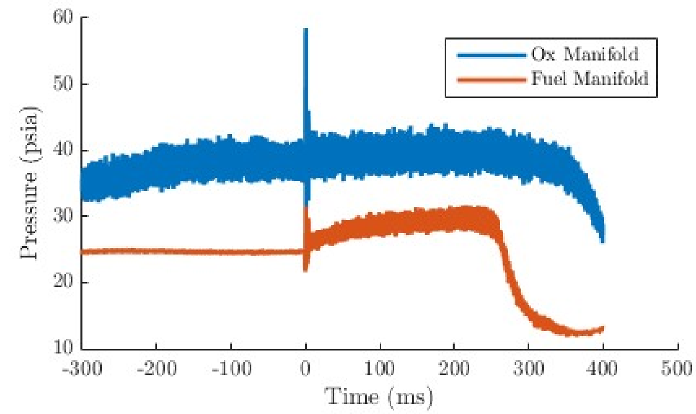
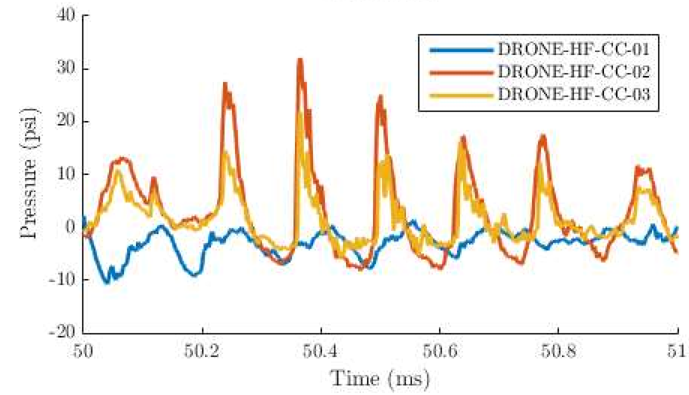
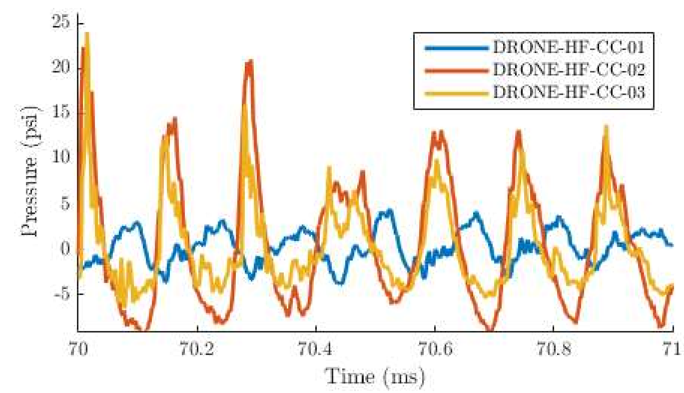
First Hot-Fire

- Transient system response was acceptable:
  - $\phi = 0.92$
  - $\frac{\dot{m}}{A_{chamber}} = 75 \frac{kg}{s\,m^2}$
- A periodic oscillation developed after $\approx 50ms$
  - Remained throughout the entire test
- Fluctuation amplitudes $\approx 10 - 30\ psi$
  - Measured with flush-mounted PCB transduces installed into the combustion chamber wall.









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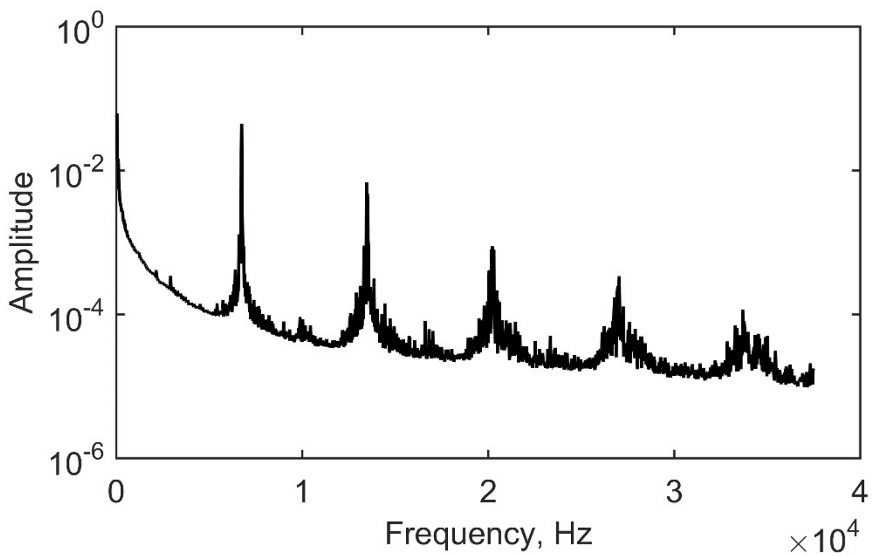
Self-Excited, Multi-kHz Dynamics

Flow Conditions:

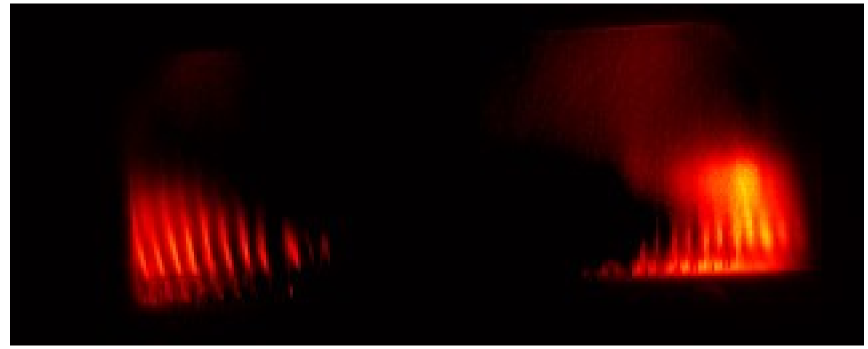
$\dot{m}_o$	$\dot{m}_f$	ϕ	$\dot{m}/A_C$	u_{CJ}	u_i	u_e
$0.39\,\frac{kg}{s}$	$0.054\,\frac{kg}{s}$	0.58	$101\,\frac{kg}{s}\,\frac{1}{m^2}$	$2080\,\frac{m}{s}$	$(1948)\,\frac{m}{s}$	$(1573)\,\frac{m}{s}$

Self-Excited, Multi-kHz Dynamics

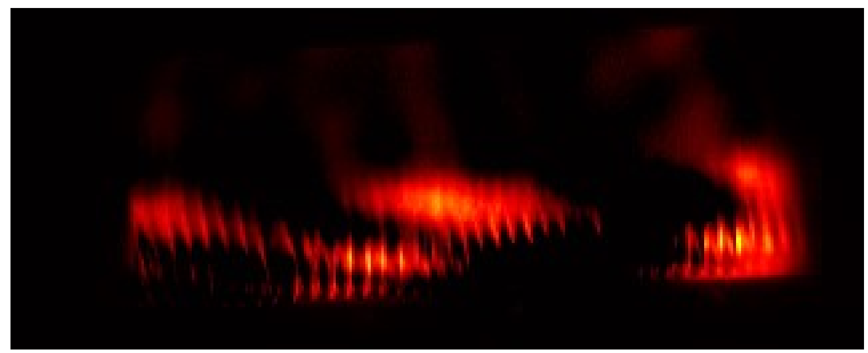
- Dynamic Mode Decomposition of the images reveals strong coherence in spatio-temporal dynamics.
  - Fundamental mode at 6740 Hz
  - Strong periodic content at the harmonics.



6740 Hz DMD Mode



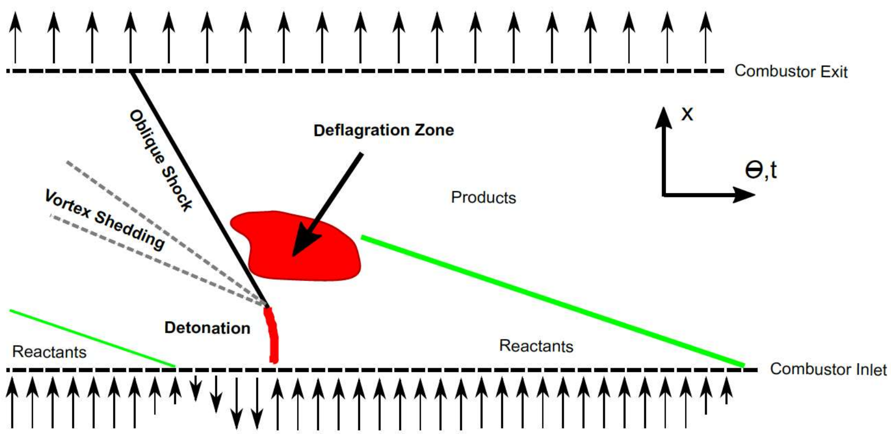
13480 Hz DMD Mode

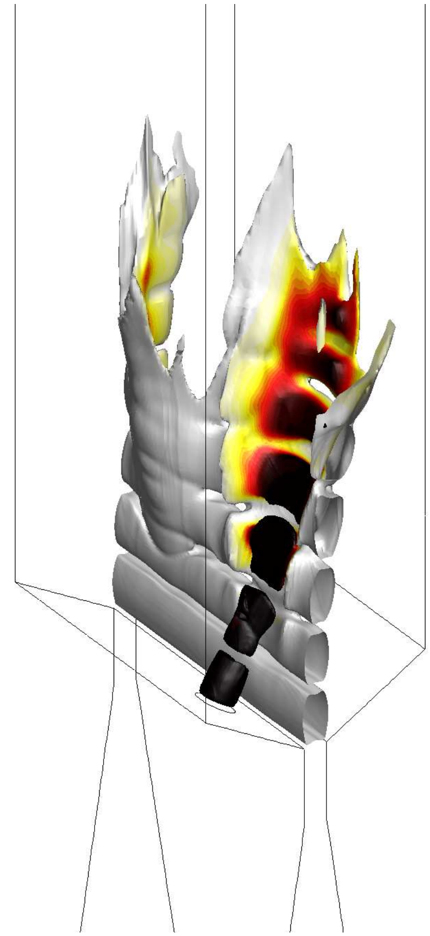


- Transverse motion of the combustion wave is well-resolved
- Injection, ignition, … and transition

(Theories About) Wave Structure

- Observing DDT
  - Acceleration along the injector face
  - Steepening and coalescence
- Product mixing causes contact ‘pocket’ deflagration





Instantaneous flow-field visualization

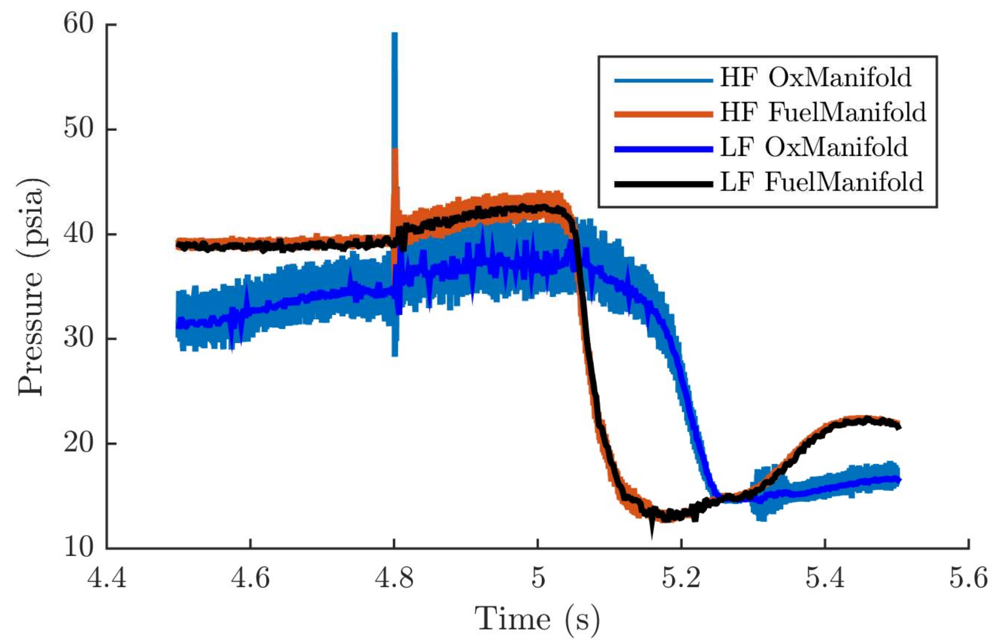
Exploring Parameter Space

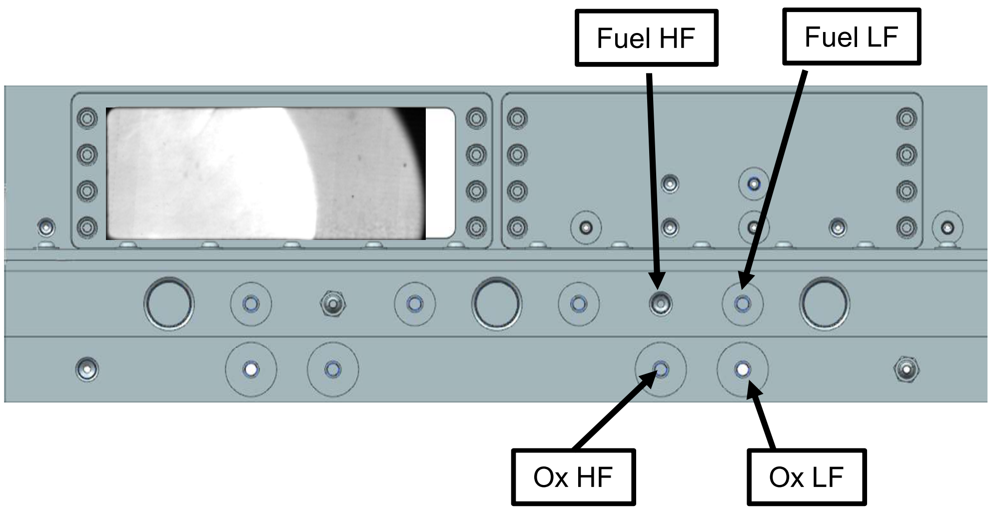
- 23 Conditions Tested
  - Parametric variation of mass-flux ($\sim M_c$) and equivalence ratio
  - Heavily-instrumented with transducers and ion probes in the chamber as well as the propellant manifolds.
  - Focused Schlieren in the (upstream) window location
- Unanimously consistent, self-excited, high-frequency instabilities

$\boldsymbol{Case}$	$\boldsymbol{\dot{m}/A_C}$	$\boldsymbol{\phi}$	$\boldsymbol{u_{CJ}}$	$\boldsymbol{u_i}$	$\boldsymbol{u_e}$
$\boldsymbol{A}$	$77.5\frac{kg}{s}\frac{1}{m^2}$	0.95	$2360\frac{m}{s}$	$(2300)\frac{m}{s}$	$(1500)\frac{m}{s}$
$\boldsymbol{B}$	$108\frac{kg}{s}\frac{1}{m^2}$	0.58	$2080\frac{m}{s}$	$(1950)\frac{m}{s}$	$(1570)\frac{m}{s}$
$\boldsymbol{C}$	$105\frac{kg}{s}\frac{1}{m^2}$	1.24	$2500\frac{m}{s}$	$(2400)\frac{m}{s}$	$(1250)\frac{m}{s}$

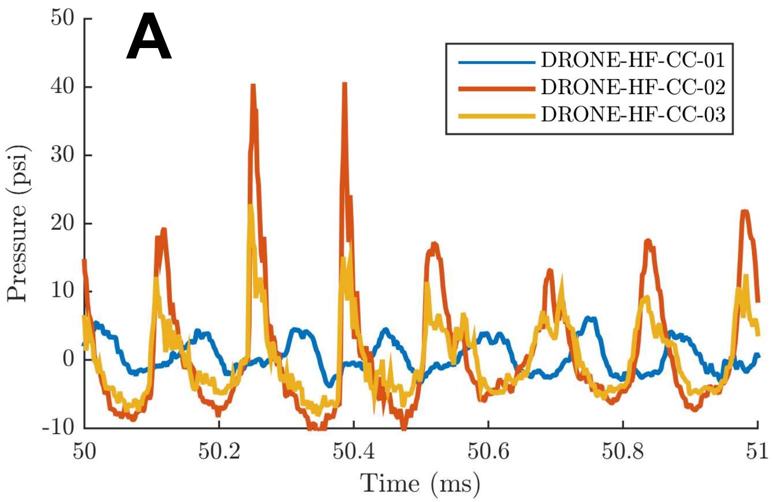
Exploring Parameter Space

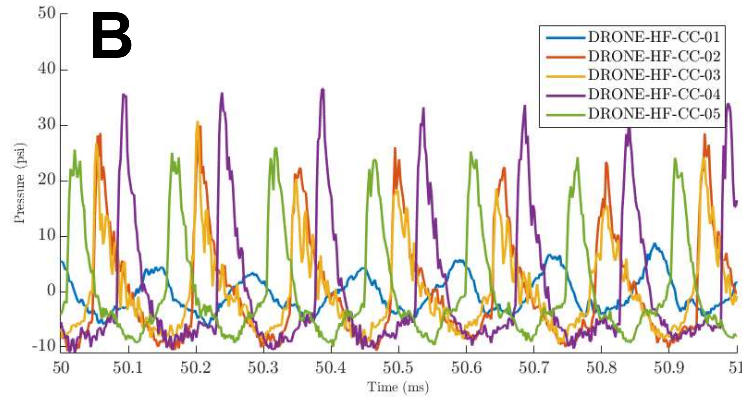
- Typical test sequence
  - $500 - 900\ ms$ of combustion
  - Nitrogen purge pre- and post-
  - Oxygen-lead with timed fuel injection relative to ignition
  - Some transience in both reactant supplies from regulator response
- Good agreement in measured absolute pressures within manifold
  - GE UNIK-5000s sampled at $500 Hz$
  - Kulite WCT-312Ms sampled at 500 kHz

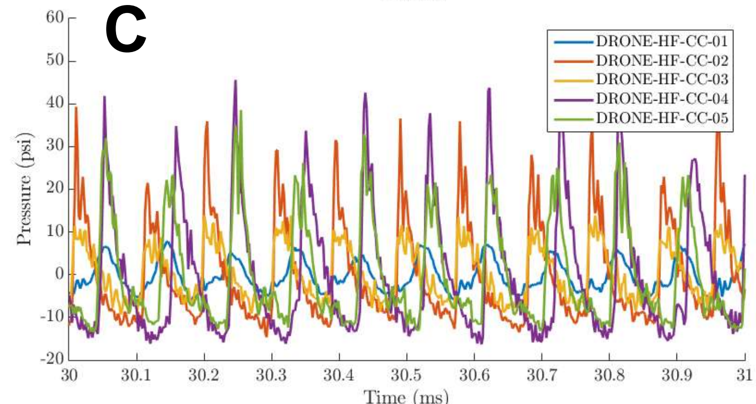




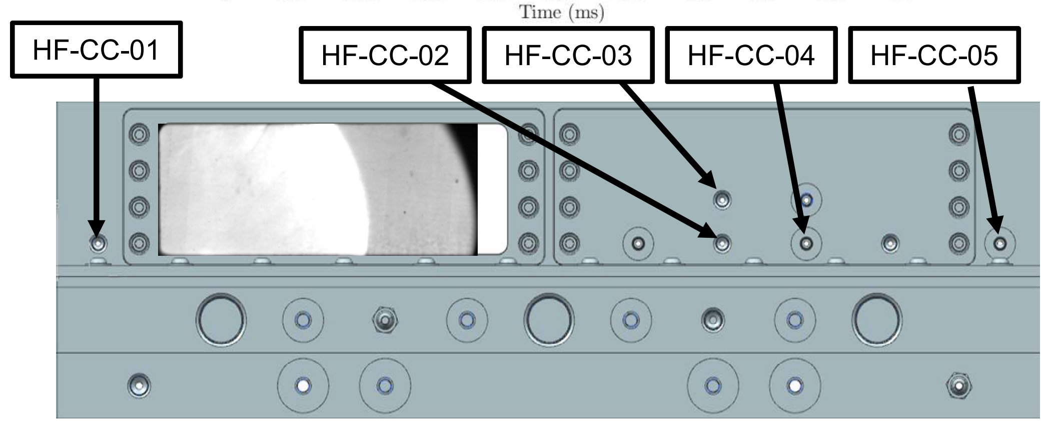
Wave-Form Comparison







Condition	$\dot{m}/A_C$	ϕ
A	$77.5 \frac{kg}{s} \frac{1}{m^2}$	0.95
B	$108 \frac{kg}{s} \frac{1}{m^2}$	0.58
C	$105 \frac{kg}{s} \frac{1}{m^2}$	1.24



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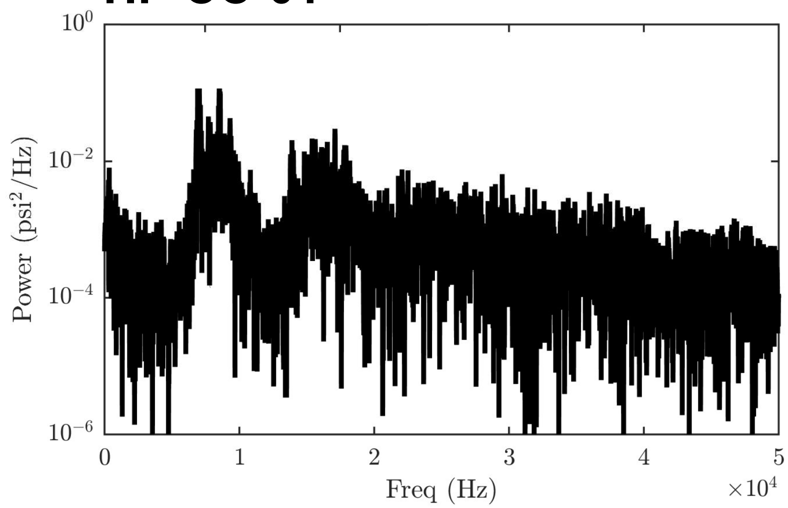
Weak Chamber Dynamics

HF-CC-01



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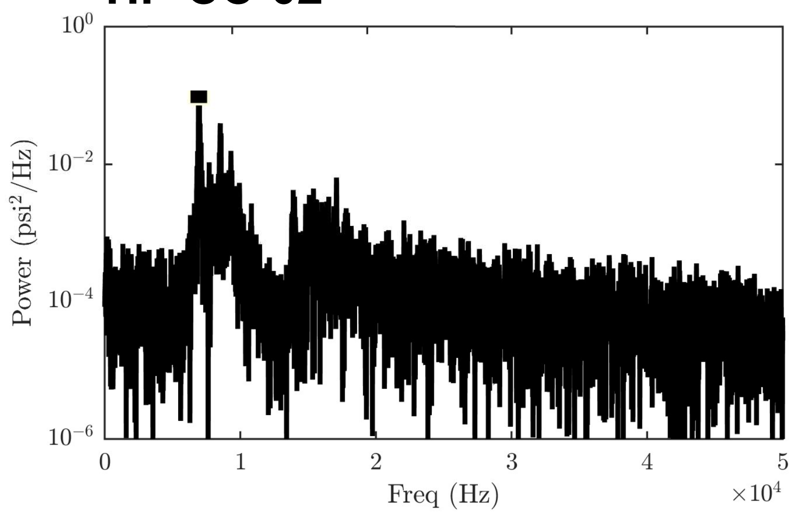
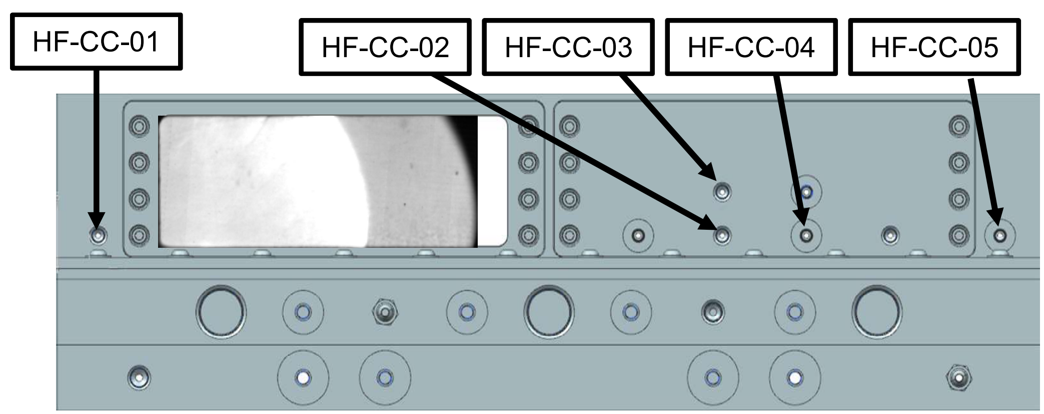


- Condition A
  - Near Stoichiometric
  - Lowest Mass flux
- Very little distinction in spectral content measured at different locations.
- Effects of amplitude modulation evident.



Narrowband Amplification

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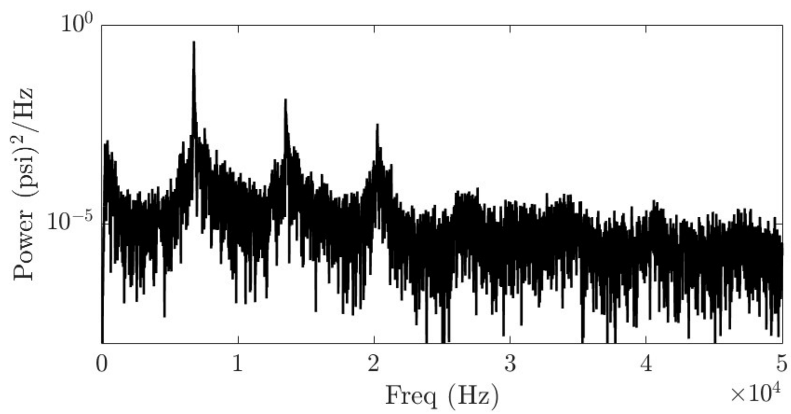

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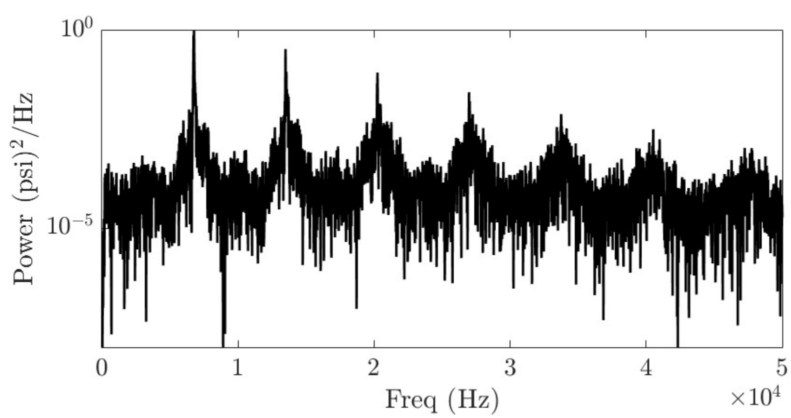
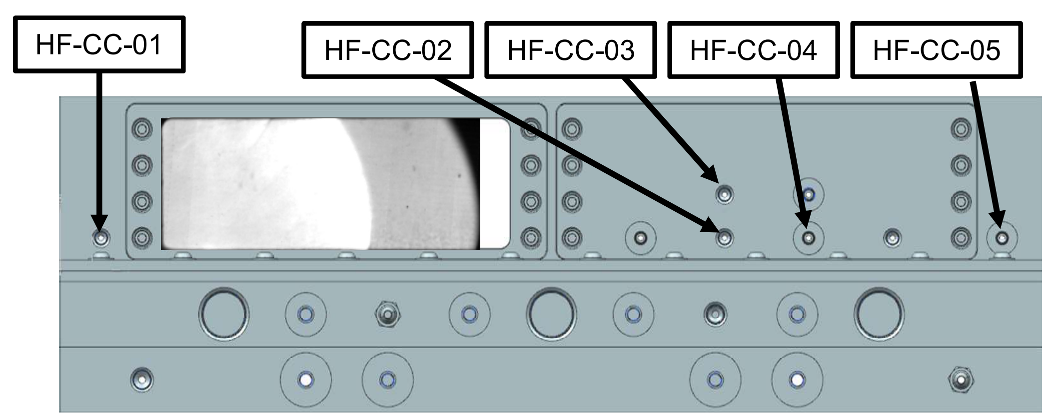


- Condition B
  - Fuel Lean ($\phi = 0.58$)
  - Increased Mass Flux
- Strong periodic content, even at the closed end.
- Steepening and amplification of the wave across the injector face
- Fundamental frequency = 6760 Hz



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(More) Narrowband Amplification

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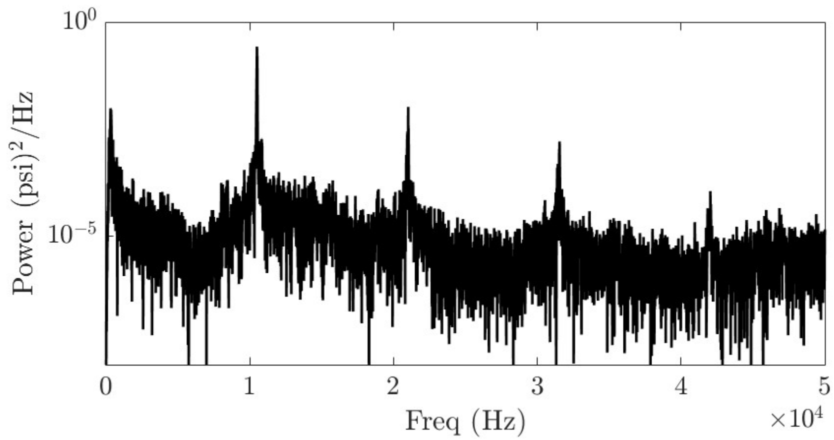

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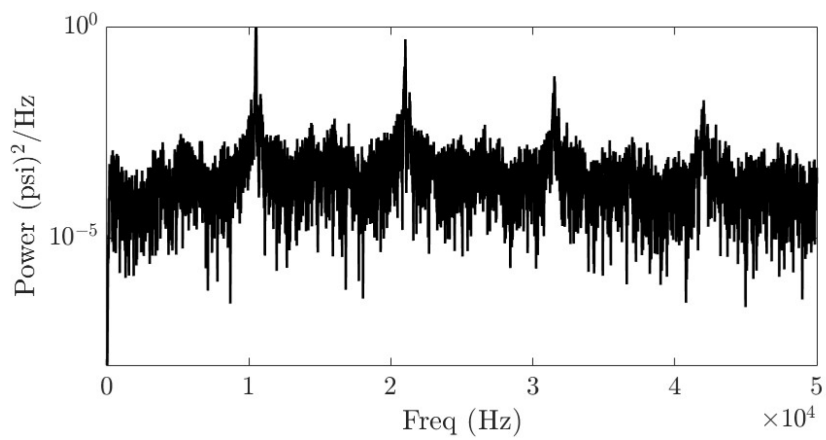
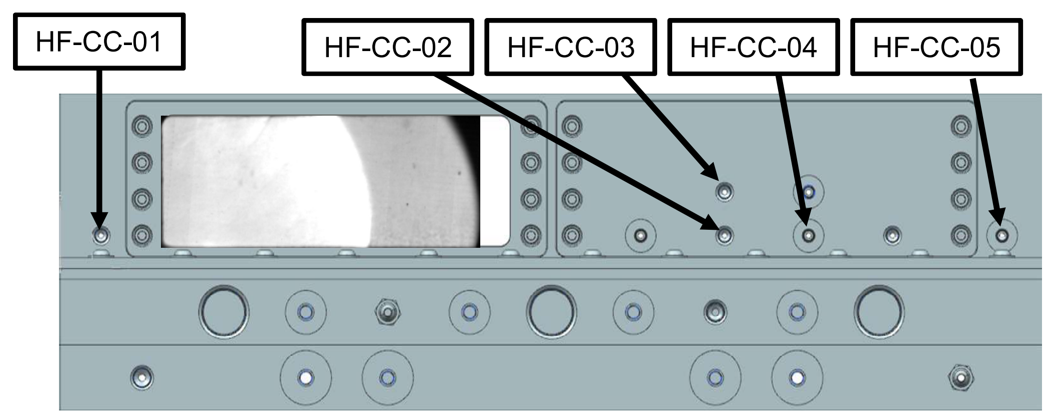


- Condition C
  - Fuel Rich ($\phi = 1.24$)
  - Increased Mass Flux
- Strong periodic content, even at the closed end with increase strength of harmonic content across the injector face
- Increased fundamental frequency
  - 10050 Hz



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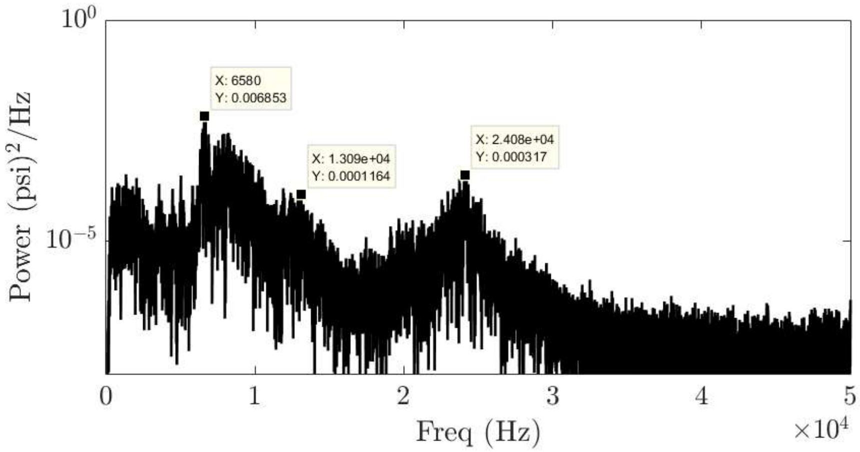
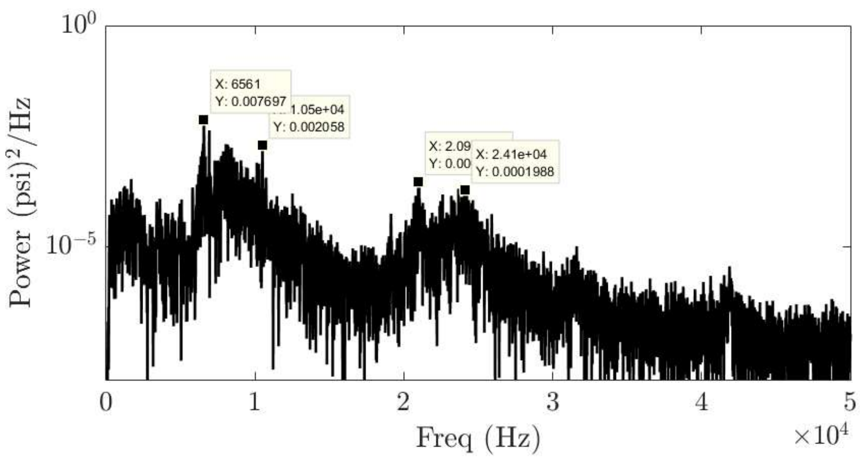
Oxidizer Manifold Coupling (?)



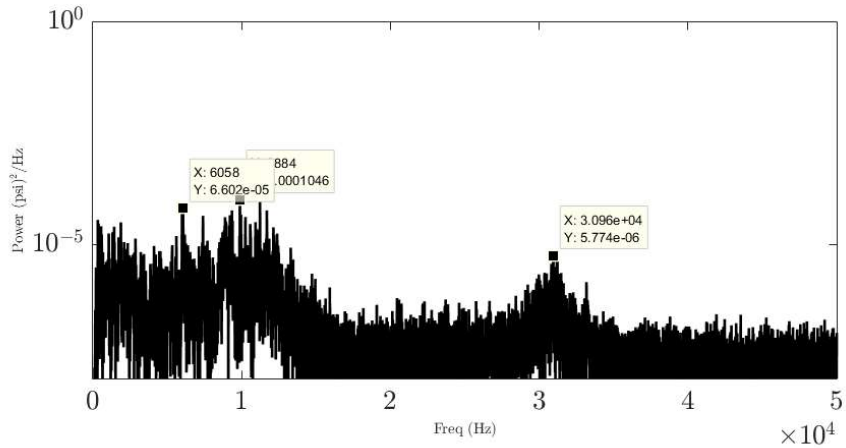
Pre-combustion (T-200ms to T+0ms)



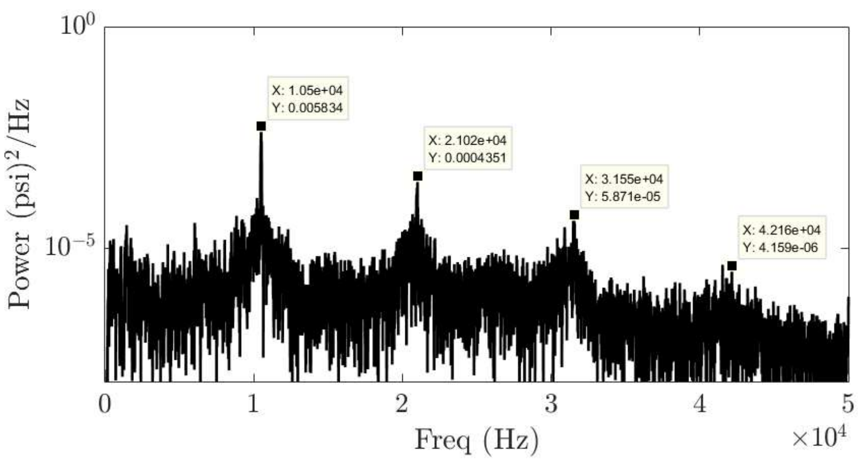
Combustion (T+50ms to T+100ms)

- Oxidizer manifold shows no clear presence of these frequencies
  - At condition C, there exists a very weak peak at 10050 Hz, only during the hot-fire.
  - In general, there is no shared frequency with the chamber PSD
- $\overline{p}_{ox} \approx 50\, psi_a$
- $p'_c \approx 50\, psi$

Fuel Manifold Dynamics



Pre-combustion (T-200ms to T+0ms)



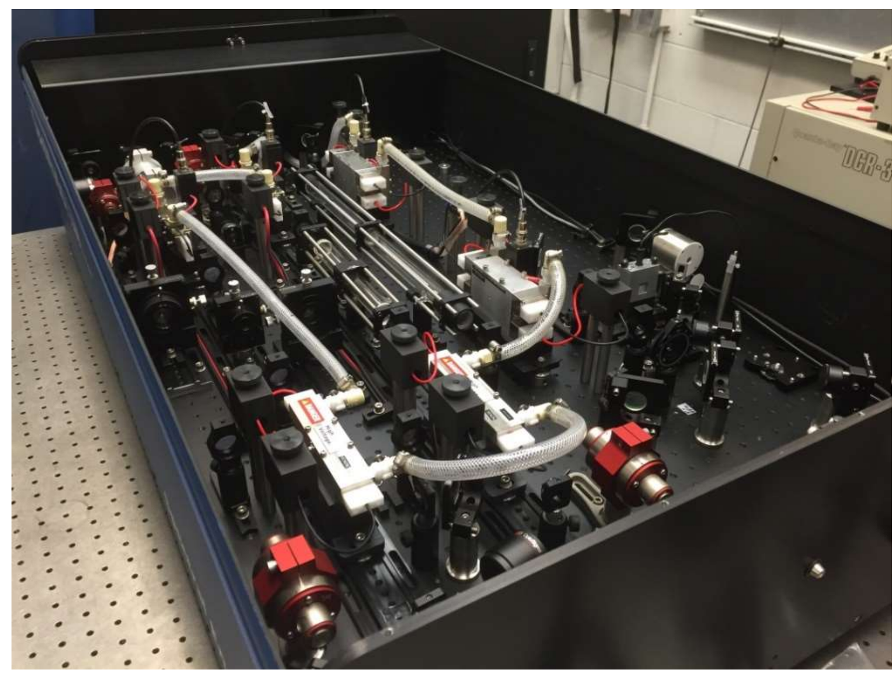
Combustion (T+50ms to T+100ms)

- The fuel manifold couples very strongly with the chamber dynamics.
  - No significant coherence in the pre-combustion spectral content
  - Exact correspondence to the chamber measurements once combustion is initiated
- This is despite the fact that the mean fuel manifold pressure is significantly greater than the oxidizer manifold pressure.

PURDUE UNIVERSITY Imminent Measurements in DRONE

- Planar laser-induced fluorescence
  - OH (10 kHz, with DPSS)
  - CH2O (10-100 kHz, with MOPA-PBL)
  - Simultaneous Schlieren
  - Resolving flame structure

- MOPA-PBL System online
  - $O(10^2)$ Increase in Pulse Energy at 10 kHz Repetition Rate
- Tradeoff with DPSS
  - Complexity
  - Signal Strength
  - Resolution (in time and space)



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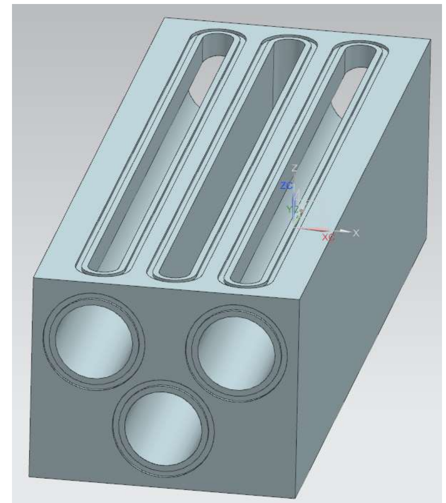
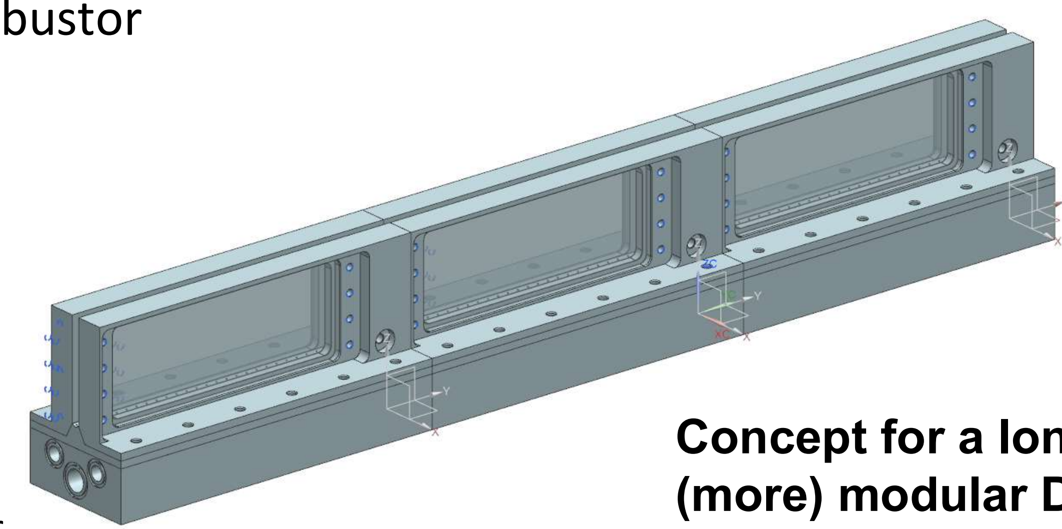
Trajectory for DRONE (and beyond)

- Further exploration of multi-kHz excitation mechanisms:
  - Injection, mixing, ignition, and DDT
  - Manifold-chamber coupling
- Translation of this understanding into a reduced-order, system model
  - Working towards a design tool for an unsteady combustor

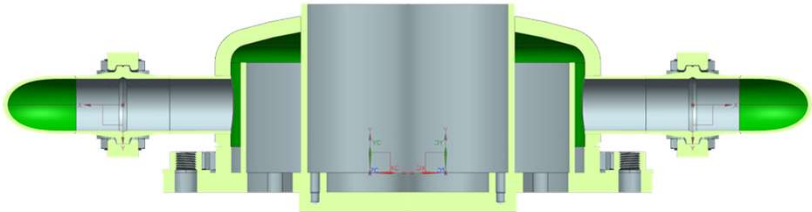


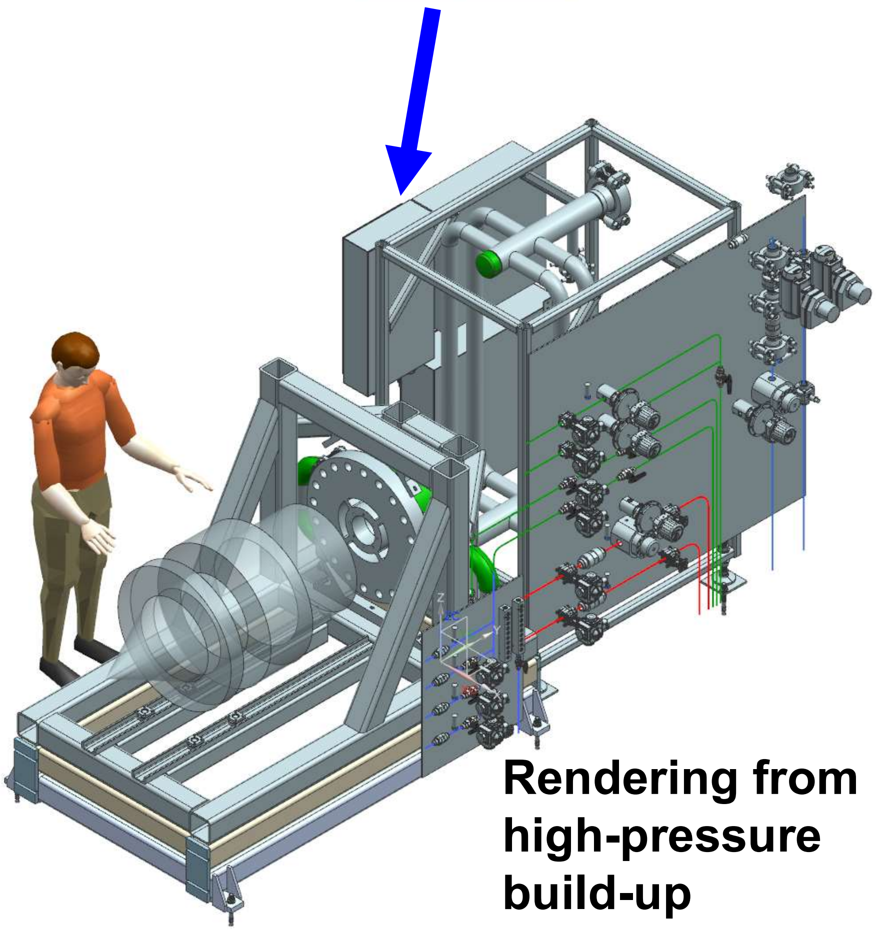


Concept for a longer, (more) modular DRONE

Scaling to Cycle Conditions

- Leveraging of that model into the second phase of this experimental work, at high pressure.
  - Subscale Combustor Development
  - Evaluation of Pressure Gain
  - Detailed Inlet/Exhaust Measurement
  - Emissions Measurements





Rendering from high-pressure build-up

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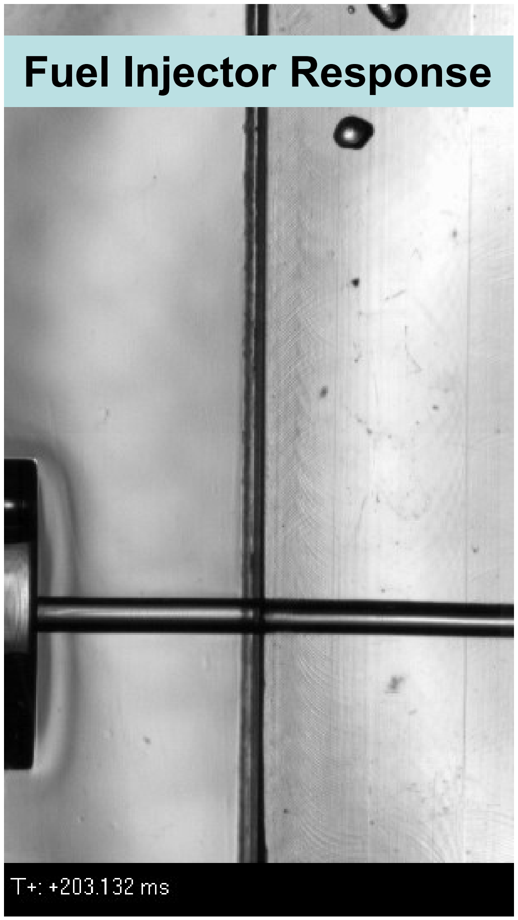
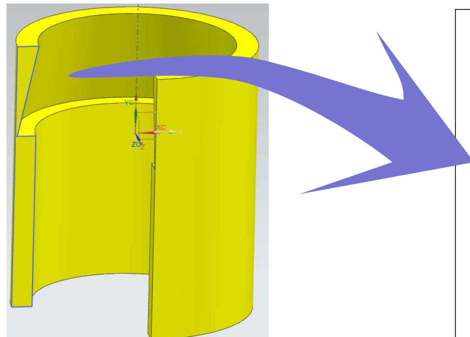
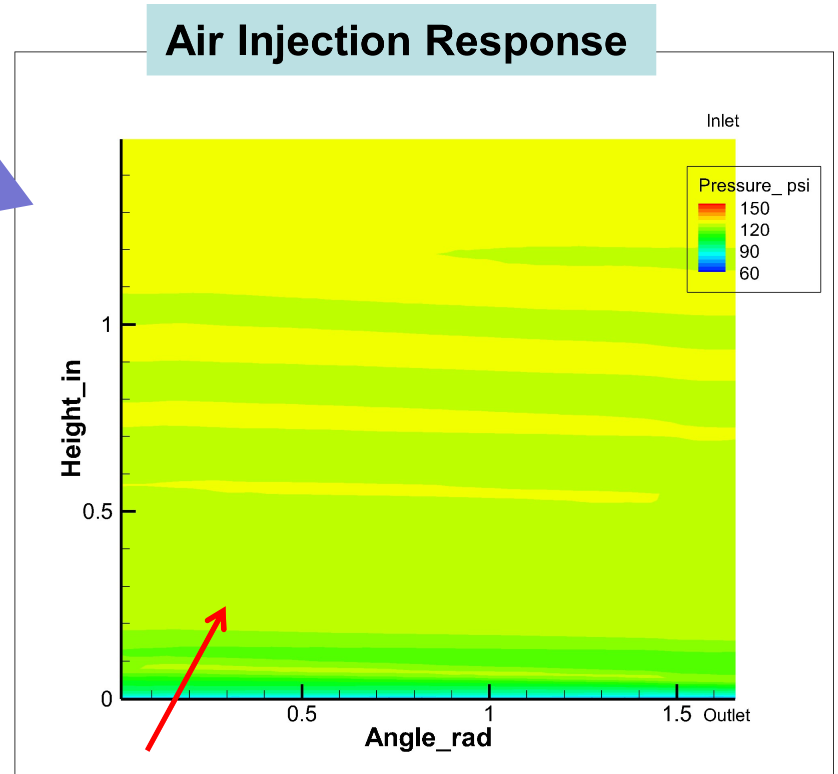
RDE Operability and System Model

- To bring RDE to production, we desperately need system model.
  - How does performance (# of waves) change with throttle setting?
  - How does injector response influence performance?
  - How does manifold response influence performance?
  - How does chamber length/width influence performance?
  - How does engine start?
- System response is primarily due to:
  - Injection system dynamic response
  - Transient mixing characteristics
  - Propellant combination, operating conditions, etc…

Injector Response Crucial Element of Operability Model



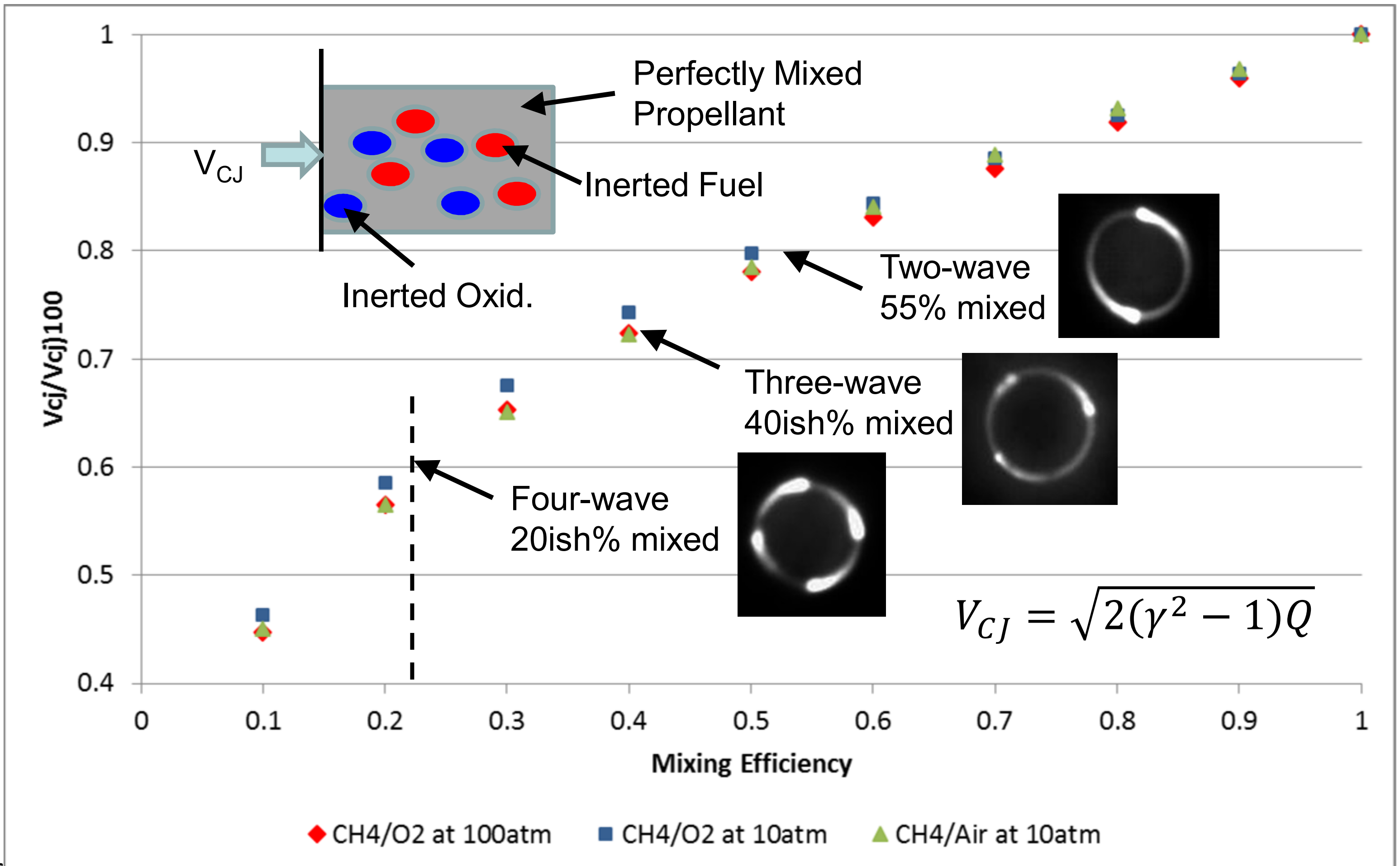




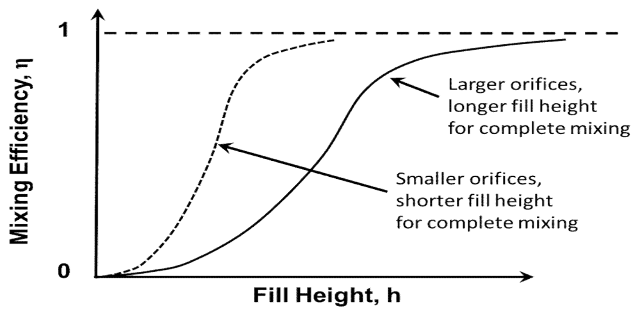
Pressure waves propagating upstream into manifold

Mixing Profile Affects Wavespeed

- CEA calculation at ϕ=1 with portion of propellants inerted for C-J calculation
- Measured wavespeeds agree with trend – larger number of waves has smaller amount of time to mix



Quasi-Steady Operability Model



$$\eta = \eta(h)$$
$$q = q(\eta)$$

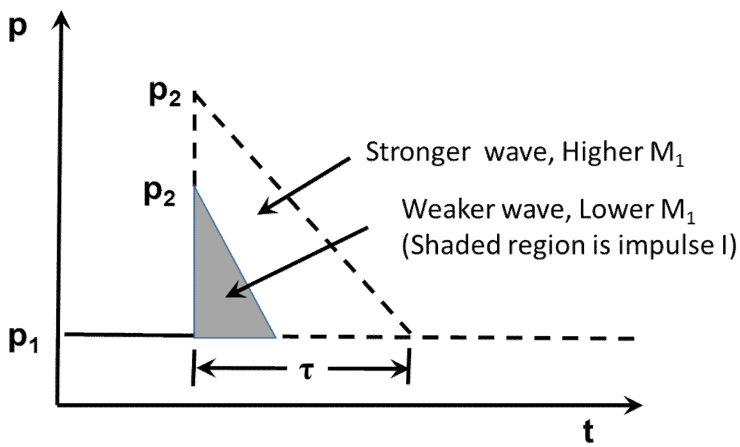
Input mixing effcy
Heat release from CEA calculation

$$\gamma_1 p_1 M_1 / \sqrt{T_1} = \gamma_2 p_2 M_2 / \sqrt{T_2}$$

$$p_1(1+\gamma_1 M_1^2) = p_2(1+\gamma_2 M_2^2)$$

$$T_1\left(1+\frac{\gamma_1-1}{2}M_1^2+\frac{q}{C_{p1}T_1}\right) = T_2\left(1+\frac{\gamma_2-1}{2}M_2^2\right)$$

Jump conditions (p_2, T_2, M_2 from conservation laws



$$\frac{dv_i}{dt} = \frac{d^2 h_i}{dt^2} = fct(p_m(t), p_i(t))$$

Fill height from injection dynamics

$$I = \tau(p_2 + p_1)/2 \quad \text{with} \quad \tau = \tau(h)$$

Wave impulse from jump condition and fill height

- Coding of model nearly complete - fully 1-D unsteady model also in work
- As community we need to think more about mixing efficiency profiles

Summary

- DRONE platform exhibits self-excited, detonative behavior
  - Strong dependence on equivalence ratio and mass flux observed
  - Continued exploration underway
  - Future work in characterization of manifold dynamics, injector geometry, …
- Multi-dimensional combustion modeling of DRONE unsteady injection, mixing, and ignition.
- System modeling in work to assess operability and aid in combustor design
- Large-scale test stand development underway
  - Supporting both UTSR and Aerojet Rocketdyne efforts
- Initial test article design to begin in the coming months, informed by the most recent understanding from DRONE and modeling efforts.