Investigation of Flame Structure for Hydrogen Gas Turbine Combustion

UTSR Project FE0032074

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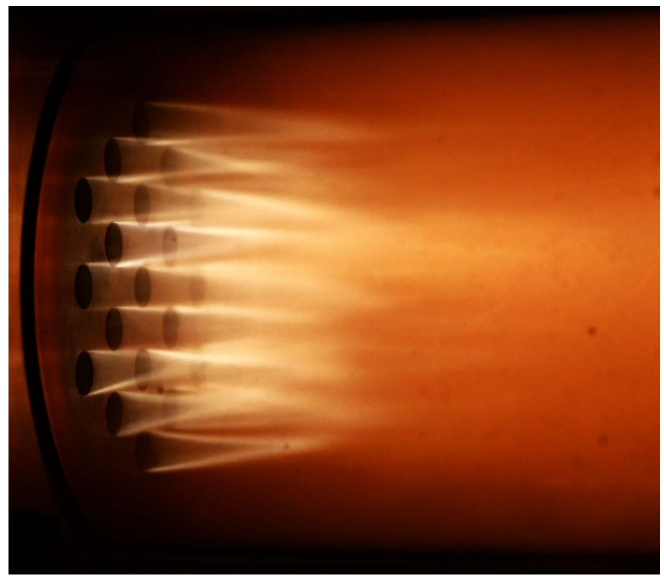
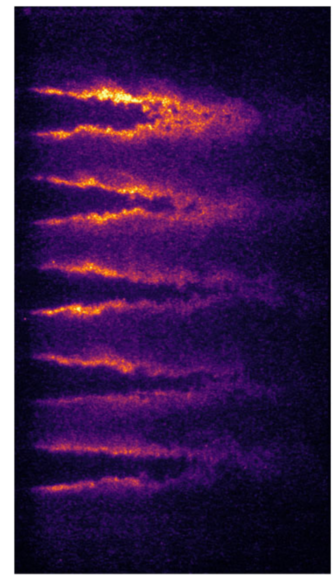




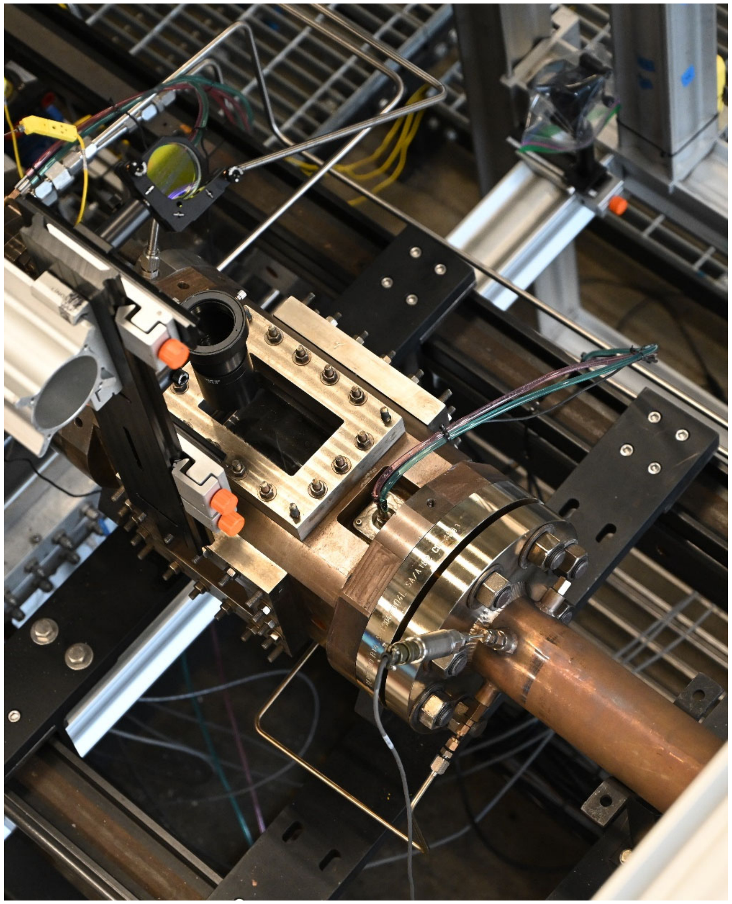
PURDUE PROPULSION

U.S. DEPARTMENT OF ENERGY

Investigation of Flame Structure for H_2 Gas Turbine Combustion

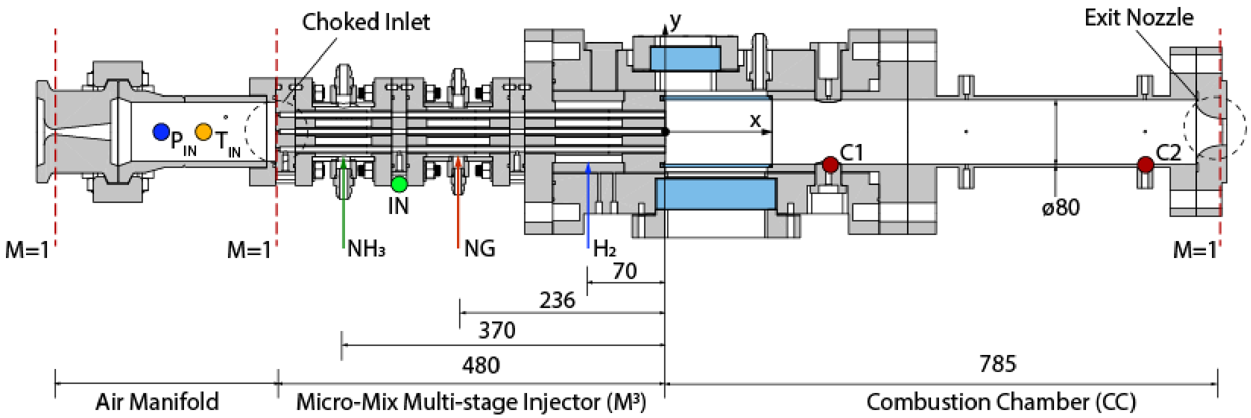
Explore flame structure, dynamics, and emissions with hydrogen, ammonia, and mixtures of these fuels with natural gas

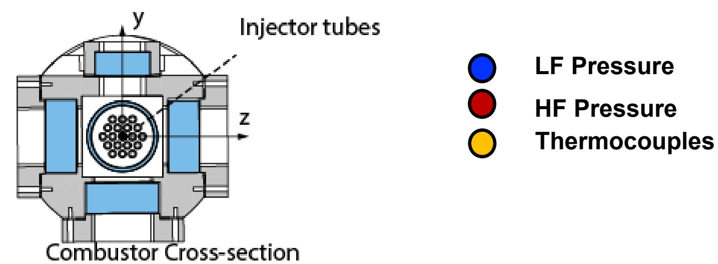
- High-pressure optically accessible combustor designed to operate engine relevant conditions (P_3: 40 bar, T_3: 1080 K)
    - Unsteady configuration for studies of self-excited combustion instabilities
    - Stable configuration for emissions, LBO, flashback
- Research focus on premixed multi-stage, multi-tube, micromix (M^3) injector
    - Canonical injector configuration with well-defined boundary conditions suitable for model validation
- Application of advanced diagnostic methods to study flame structure and dynamics
    - High-frequency pressure measurements, OH* and NH_2* chemiluminescence, OH and NO Planar Laser-Induced Fluorescence (PLIF), High-speed particle imaging velocimetry (PIV), Coherent anti-Stokes Raman scattering (CARS)



Combustor Design

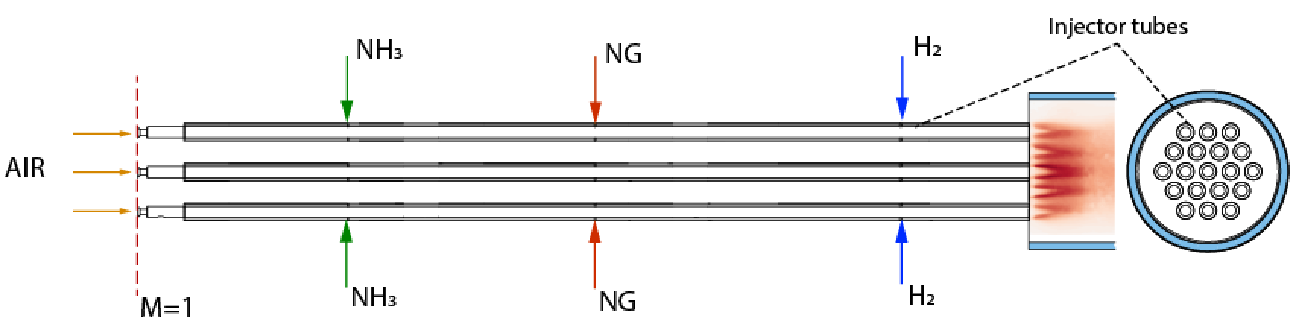
- High-pressure optically accessible combustor
- Modular geometry to tune frequency and amplitude of dynamics with fuels of largely varying HRR
  - Characterization of fuel sensitivity to intrinsic flame instabilities with imposed (forced) dynamics
  - Well-defined flow and acoustic boundary conditions





Instrumentation Locations

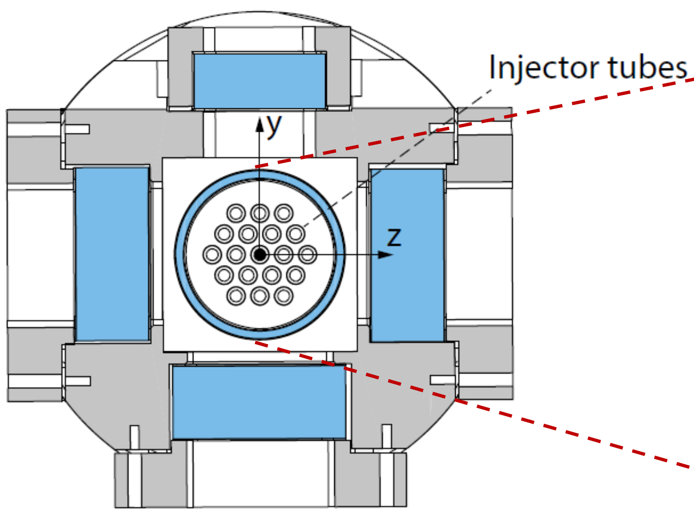
Measurement Location	x [mm]	y [mm]	θ [deg]
IN	-330	-21.5	180
C1	200	-40	180
C2	600	-40	180
P_{IN}	-550	40	180
T_{IN}	-550	-40	0



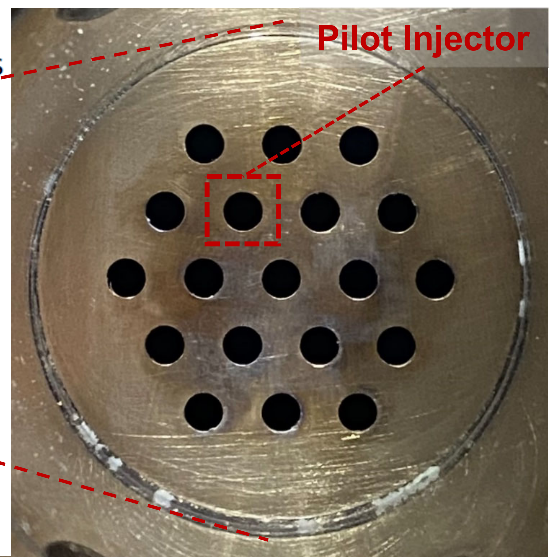
Premixed Staged Micromix Injection Elements (x19) **Injector Layout**

Combustor Design

- Premixed multi-stage, multi-tube, micromix (M^3) injectors distributed in a uniform array in a cylindrical combustion chamber
  - Discrete axially staged sections for NH_3, NG and H_2 injection
  - 19 injector elements with jet in crossflow reactant injection
  - Uniform inter-element separation
  - Injector Mach number between 0.25 – 0.28 at typical flow conditions



Combustor Cross-section



Fuel Composition:

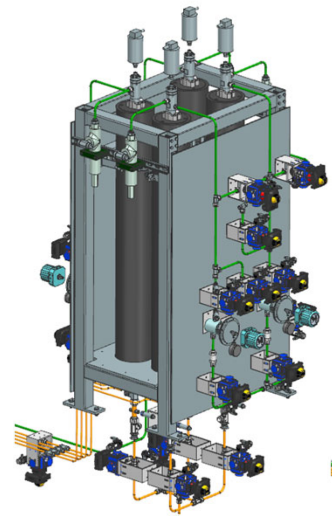
$$\chi\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+(1-\chi)NG$$

Fluid	χ	η	$\dot{m}_{max}\ [lb/s]$
H_2	0.9	0.9	0.01
N_2	0.9	0.9	0.05
NG	0.5	N/A	0.02
NH_3	0.9	0.4	0.04
Air	N/A	N/A	1

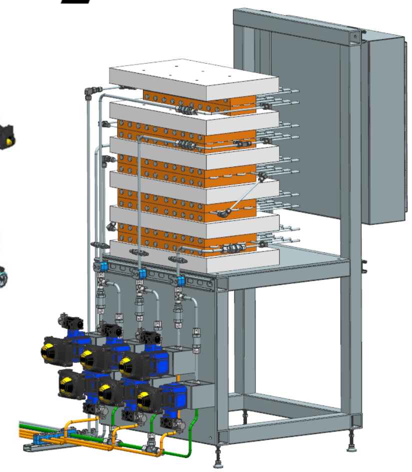
Injector Geometry	
$\emptyset_{element}$	0.245 [in]
Velocity	300 – 400 [ft/s]

Ammonia System Design

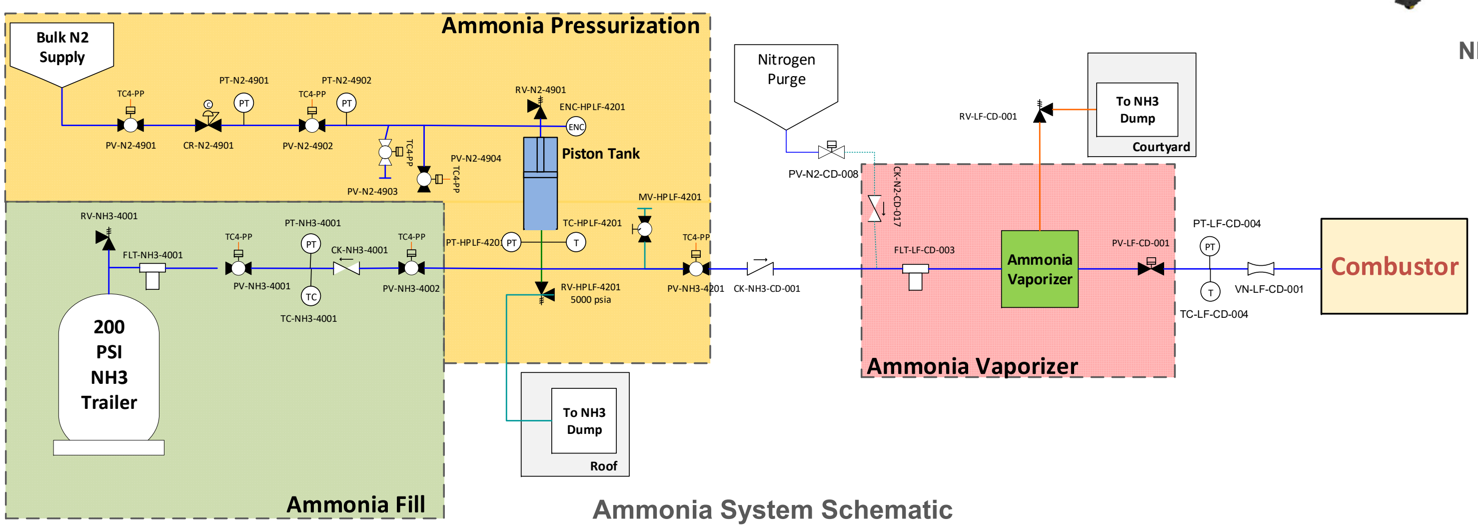
- Ammonia delivered in saturated state pressurized to target conditions in a piston tank
  - 70 kg of ammonia available per test at maximum supply pressure of 345 bar
- Ammonia delivered to steady state vaporizer prior to injection
  - Accommodates liquid NH_3 injection
- Piston tank pressurized with gaseous nitrogen (<345 bar)
- Gaseous ammonia injected into combustor through JICF injector at target conditions



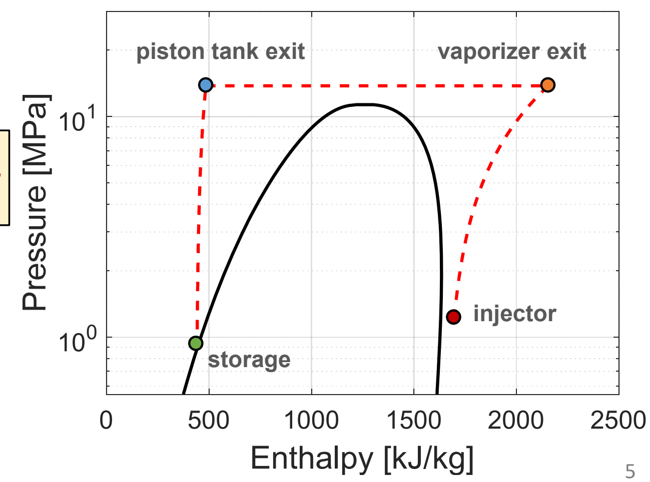
NH_3 Piston Tanks



NH_3 Vaporizer

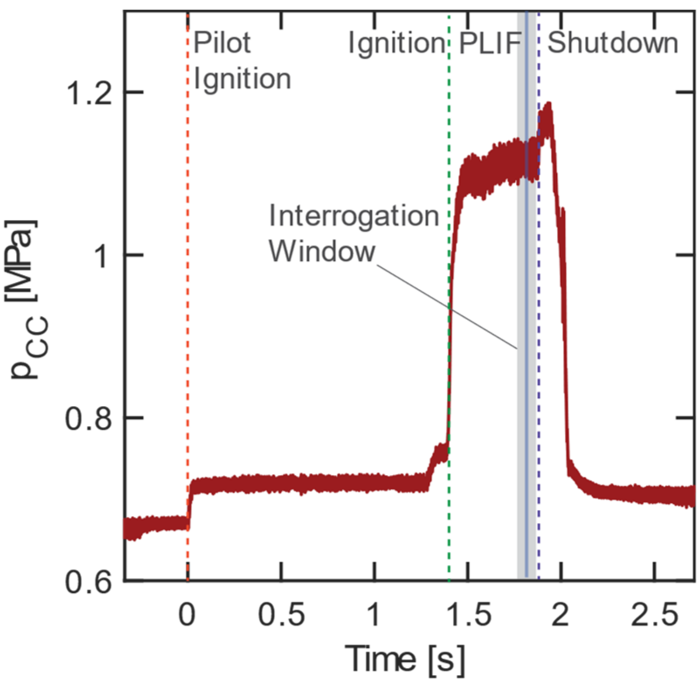


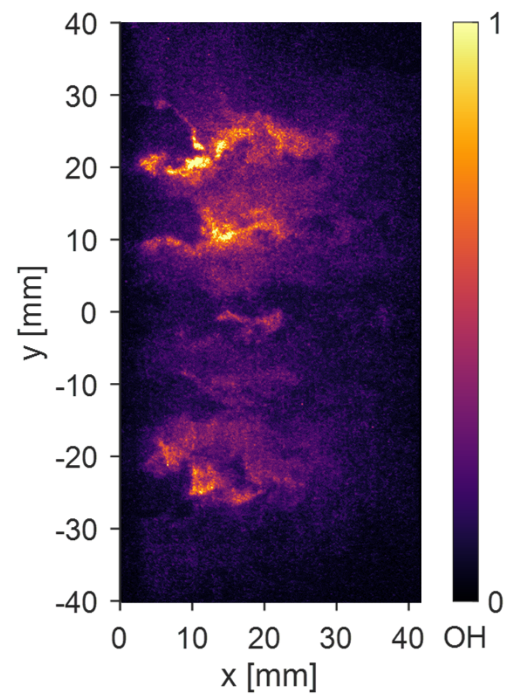
Ammonia System Schematic



Combustor Operation

- Single injector element used as pilot injector for ignition
- Flame ignition achieved with laser-induced spark positioned in the shear layer of the pilot element
  - Reactants introduced through all injector elements following stable pilot ignition
- A 100 ms sample window is used for analysis. 100 kHz OH-PLIF measurements in ~2 ms period during period of stationary dynamics





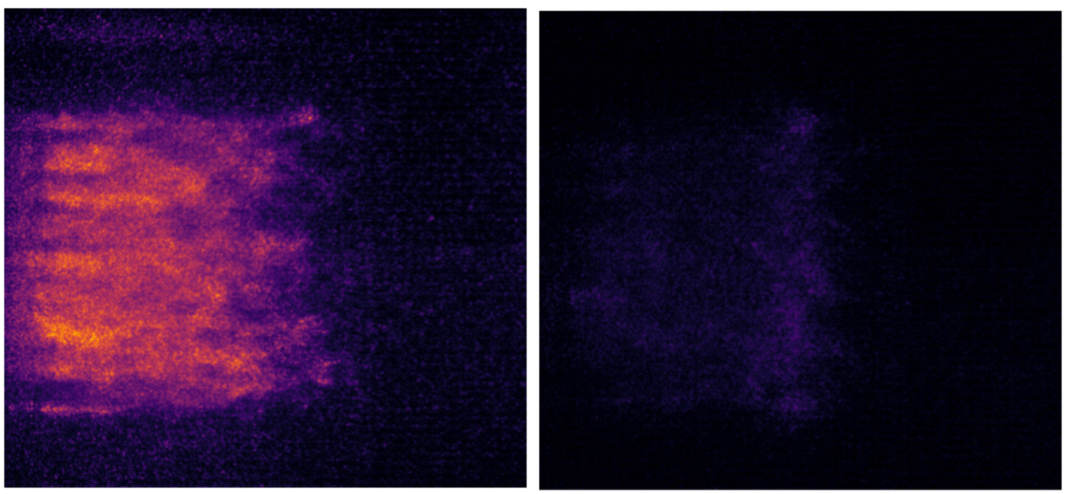
Parametric Survey of Dynamics

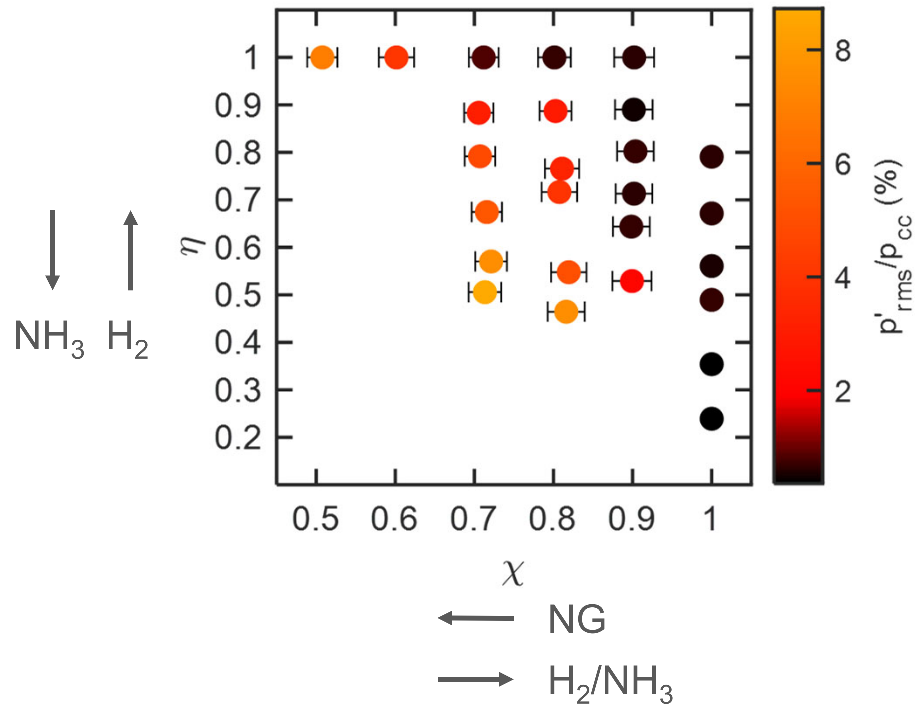
- High amplitude pressure fluctuations (p') observed
  - Hydrogen addition observed to suppress combustion instabilities
  - Combustion instability amplitude is largely invariant to the addition of ammonia in absence of natural gas
  - As hydrogen content is decreased, ammonia addition increases combustion instability amplitudes

Fuel Composition:

$$\chi\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+(1-\chi)NG$$

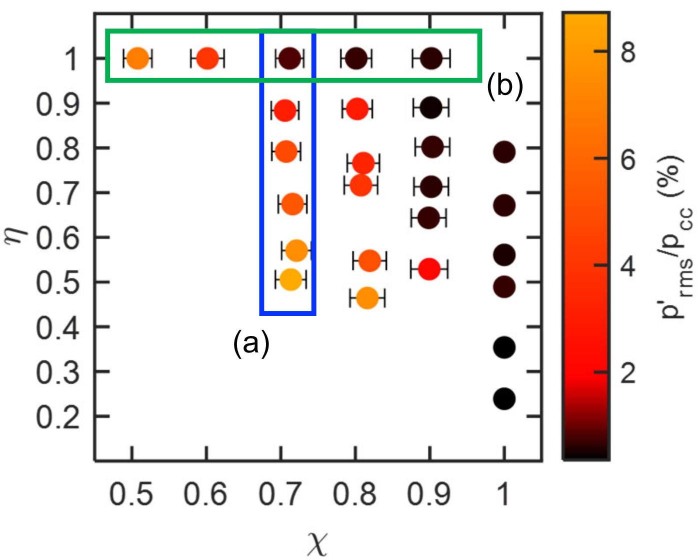
χ = 0.7, η = 1.0 **χ = 0.7, η = 0.7**

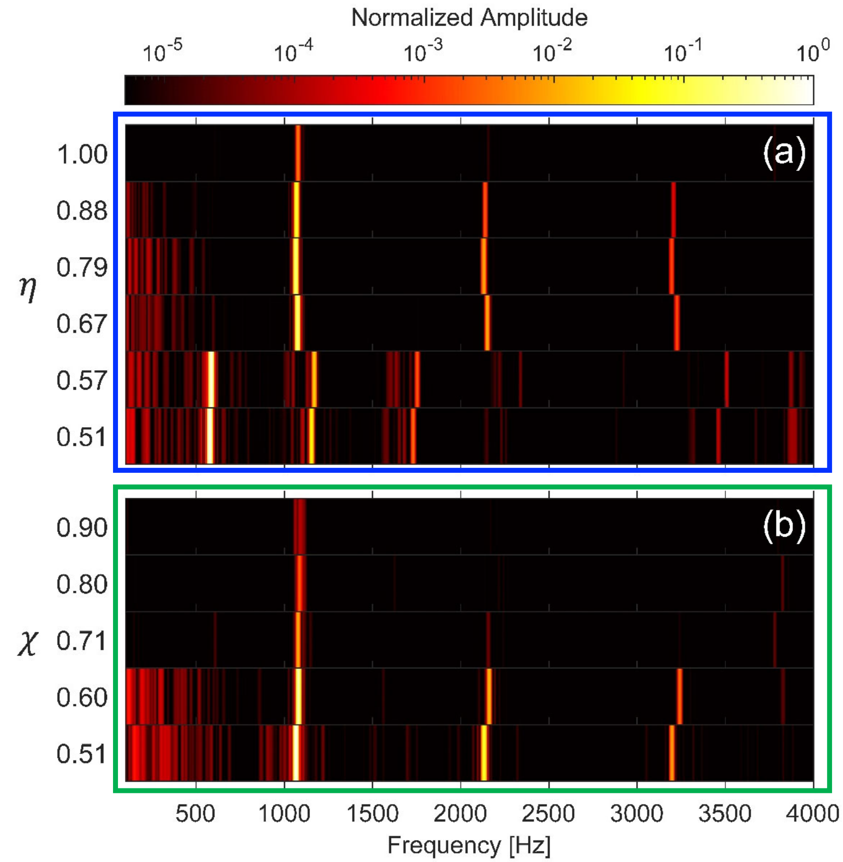




Parametric Survey of Dynamics

- ~1100 Hz frequency corresponds to full-wave (2L) pressure mode shape
- Replacing hydrogen with ammonia results in larger instability amplitude and appearance of harmonics
- Transition to half-wave (1L) mode occurs at $\eta = 0.57$
- Similar trends observed through replacement of hydrogen with natural gas, although transition to 1L mode does not occur

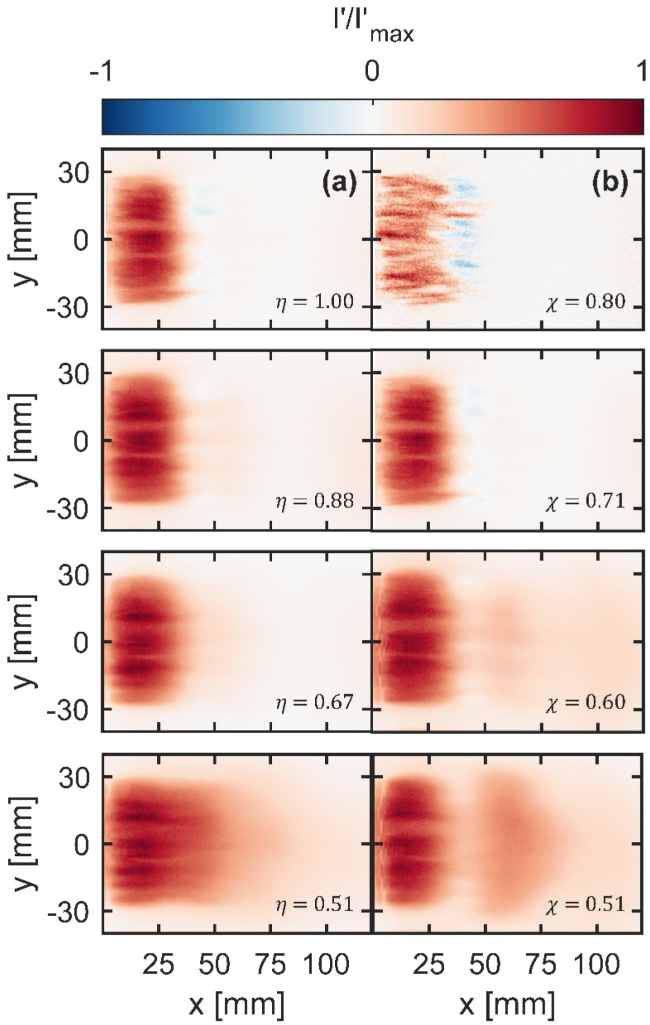


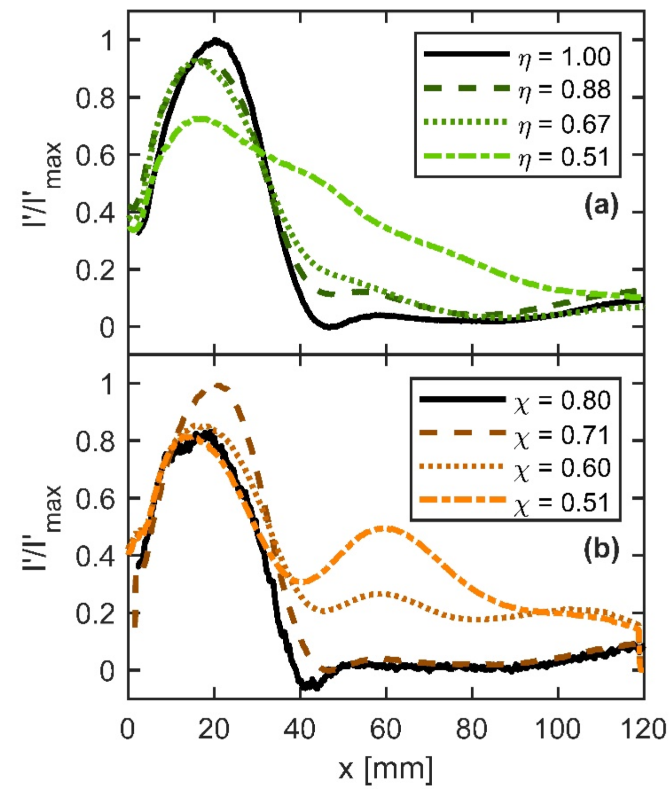


Spectral power distribution

Flame Response to Thermoacoustic Instability

- Spectral Proper Orthogonal Decomposition (SPOD) shows compact intensity fluctuation (I') when flame is stable
- Radially summed intensity shows increase in axial extent of I' as hydrogen decreases
- Significant flame lengthening observed when transition to 1L mode occurs ($\eta = 0.67 \rightarrow 0.51$)

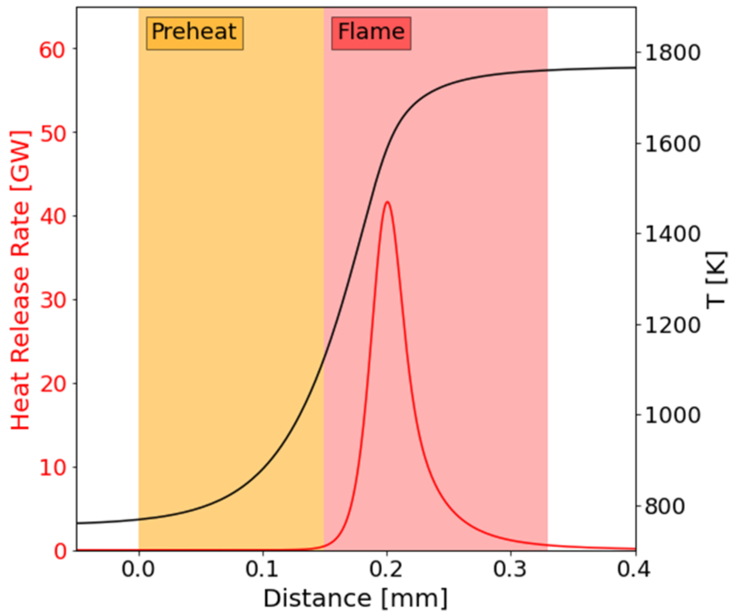


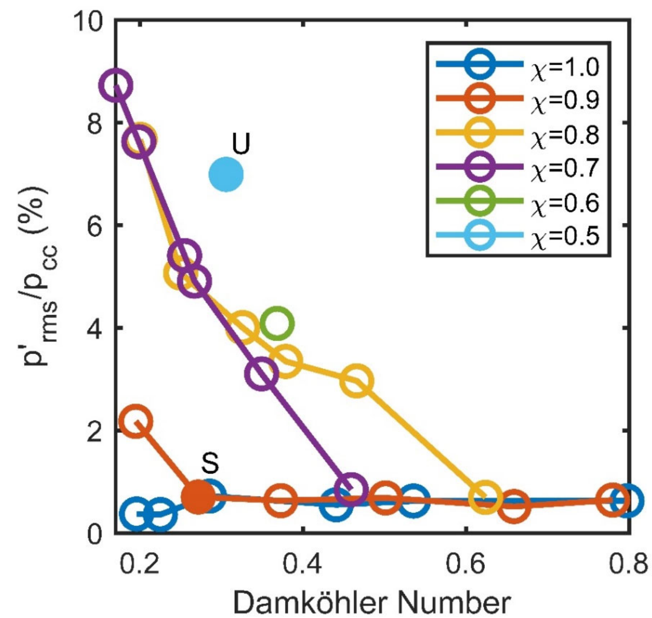


Effect of Reactant Kinetics

- 1D simulations performed in Cantera (CEU-NH_3-Mech 1.1 [1]) to understand role of kinetics on flame stability
- Length of flame zone and kinetic timescale (τ_k) determined for each condition
- Hydrodynamic timescale (τ_{flow}) computed as $D_{inj}/\overline{U}$ for each condition
- Damköhler number (Da) used to identify changes in τ_k with fuel composition
- Linear relationship between p'_{rms} and Da observed for certain χ values, but $\chi \geq 0.9$ invariant with Da

Condition	χ	η	p'_{RMS}/p_{cc} [%]
S	0.90	0.64	0.7
U	0.51	1.00	7.0

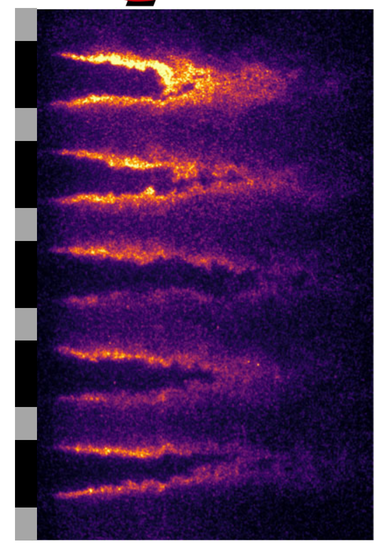




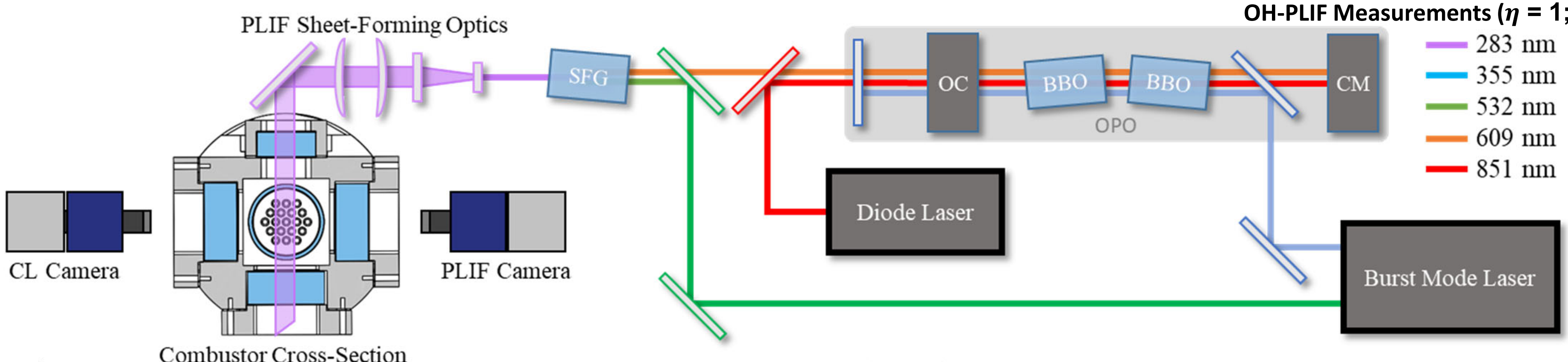
[1] Wang, S., Wang, Z., Chen, C., Elbaz, A. M., Sun, Z., and Roberts, W. L., "Applying heat flux method to laminar burning velocity measurements of NH3/CH4/air at elevated pressures and kinetic modeling study," *Combustion and Flame*, Vol. 236, 2022.

Flame Characterization with OH-PLIF Measurements

- Integration across optical path makes understanding of flame heat release and flame-flame interactions difficult
  - OH-PLIF provide spatially resolved measurement of flame heat release
- 100 kHz OH-PLIF to obtain spatially resolved measurements of unsteady heat release
- Third harmonic of Nd-YAG burst mode-laser (BML) used to pump an optical parametric oscillator (OPO) tuned to a 609 nm cavity signal wavelength
- OPO output mixed with residual 532 nm output from BML to produce ≈284 nm (Q_2(8) line)
- Field of view 105 x 42 mm. Spatial resolution 42 μm/pixel



OH-PLIF Measurements (η = 1; χ = 0.9)

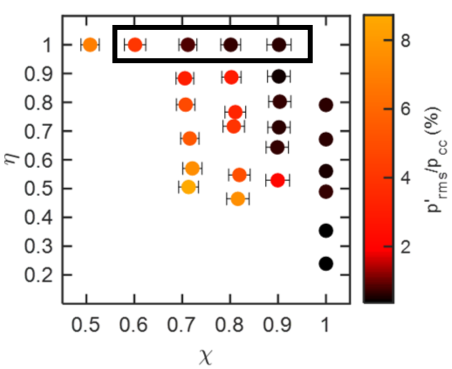


OH PLIF Measurements

- OH PLIF imaging with hydrogen and natural gas mixtures
- Flameholding closer to burner face as hydrogen increases
  - Flame stabilizes along shear layer
- Significant corrugation of the flame surface observed with addition of natural gas
  - Increased heat release rate that promotes instabilities

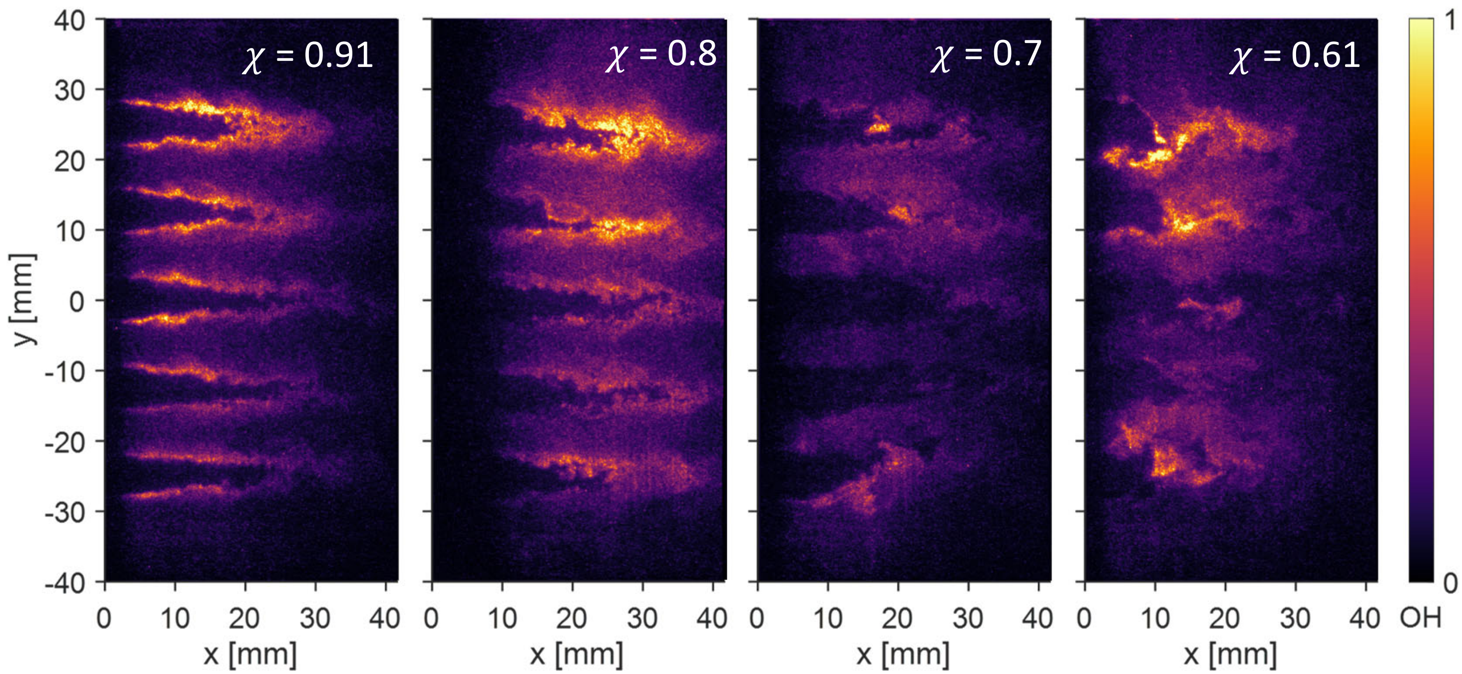
← H_2

→ NG

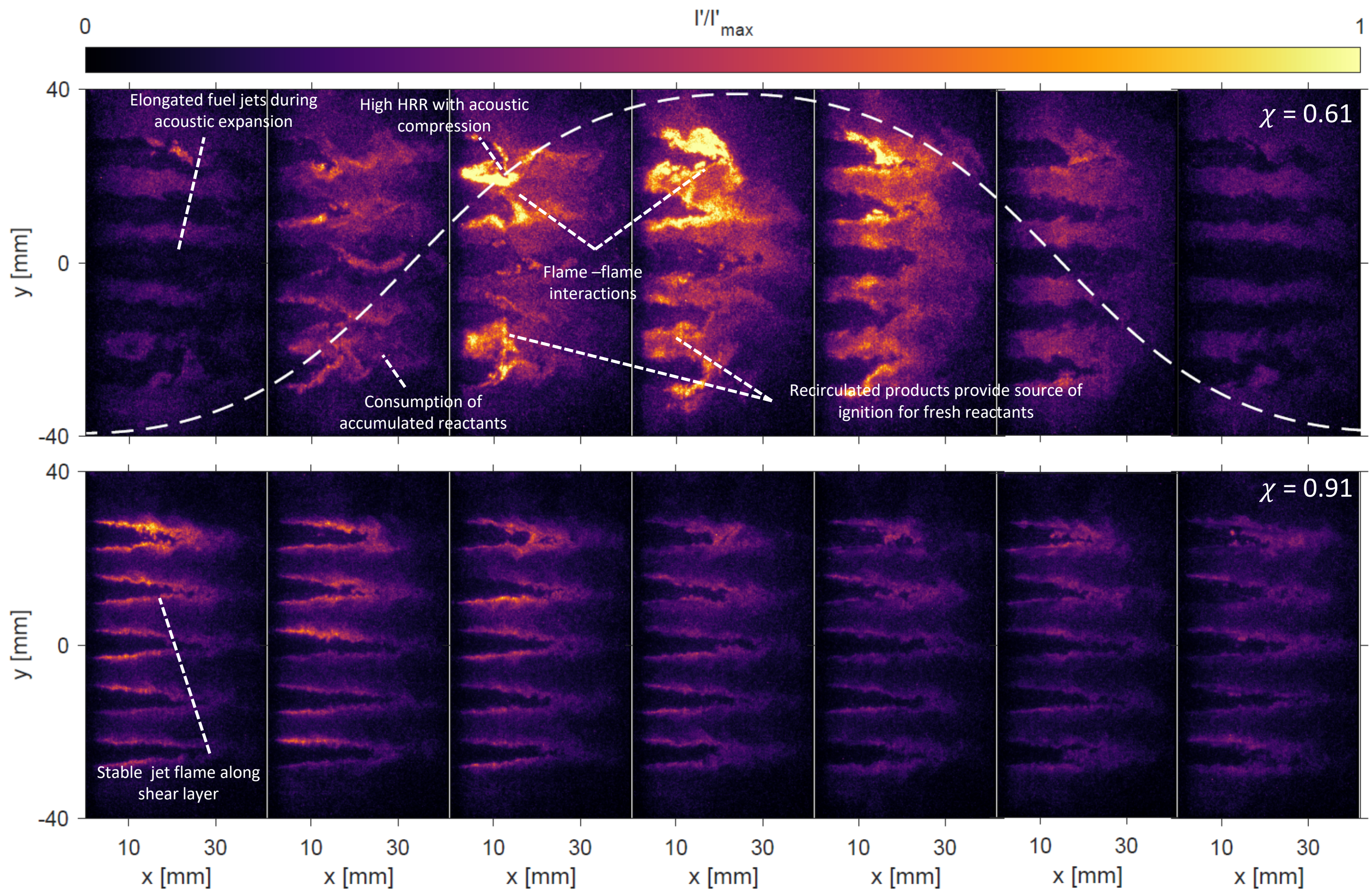


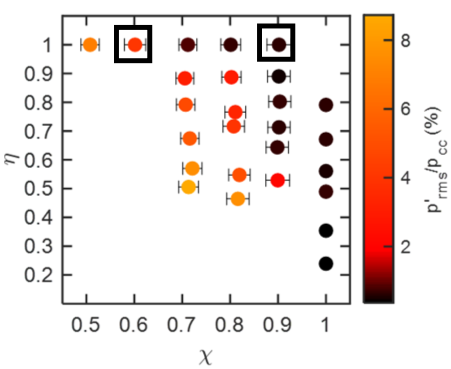
Fuel Composition:

$$\chi\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+\sout{(1-\eta)NH_3}\right]+(1-\chi)NG$$



OH PLIF Measurements



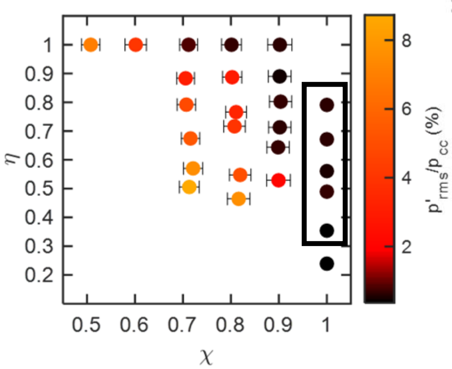


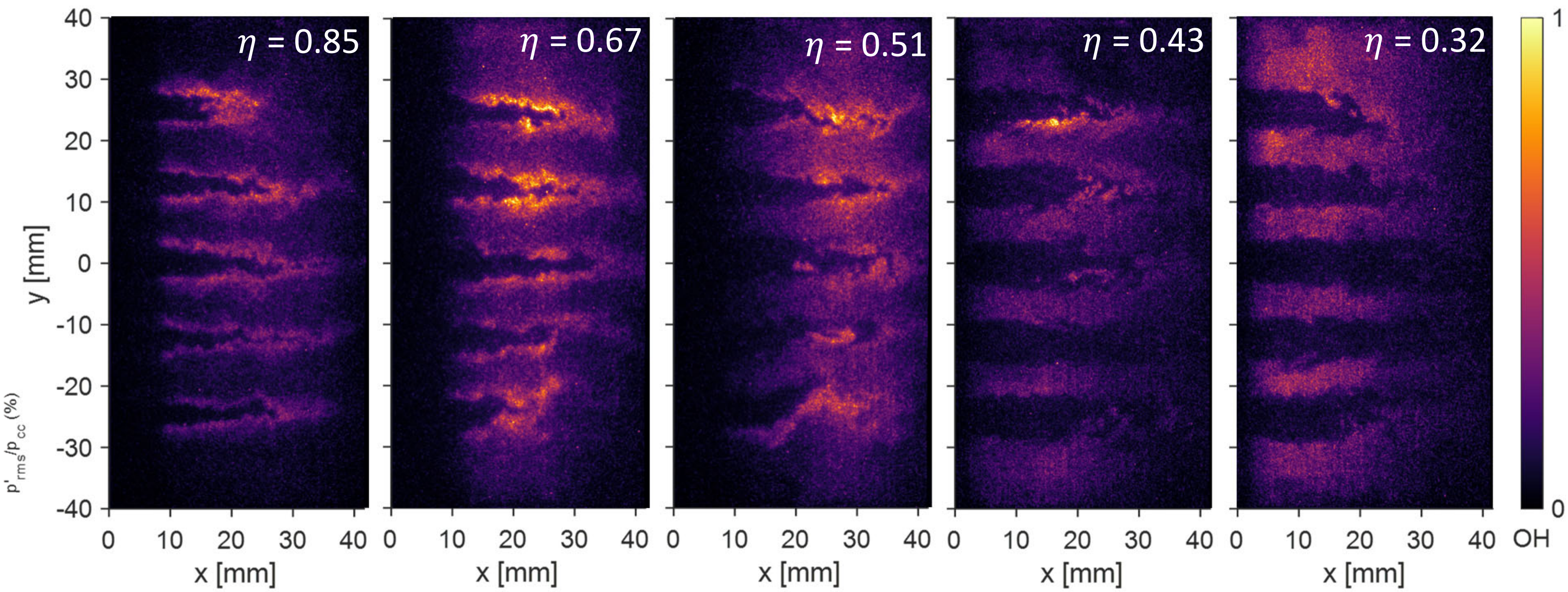
Fuel Composition:

$$\chi\left[\eta\left(\frac{3}{2}H_2 + \frac{1}{2}N_2\right) + \cancel{(1-\eta)NH_3}\right] + (1-\chi)NG$$

OH PLIF Measurements

- OH PLIF measurements with variation in ammonia decomposition efficiency
  - No natural gas addition to fuel



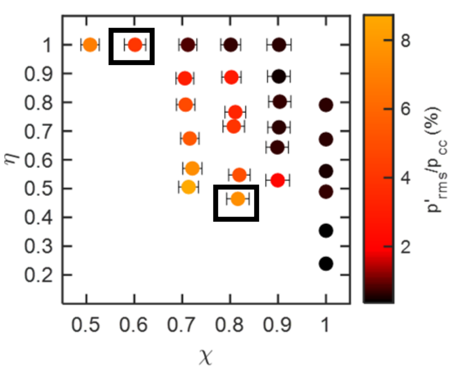


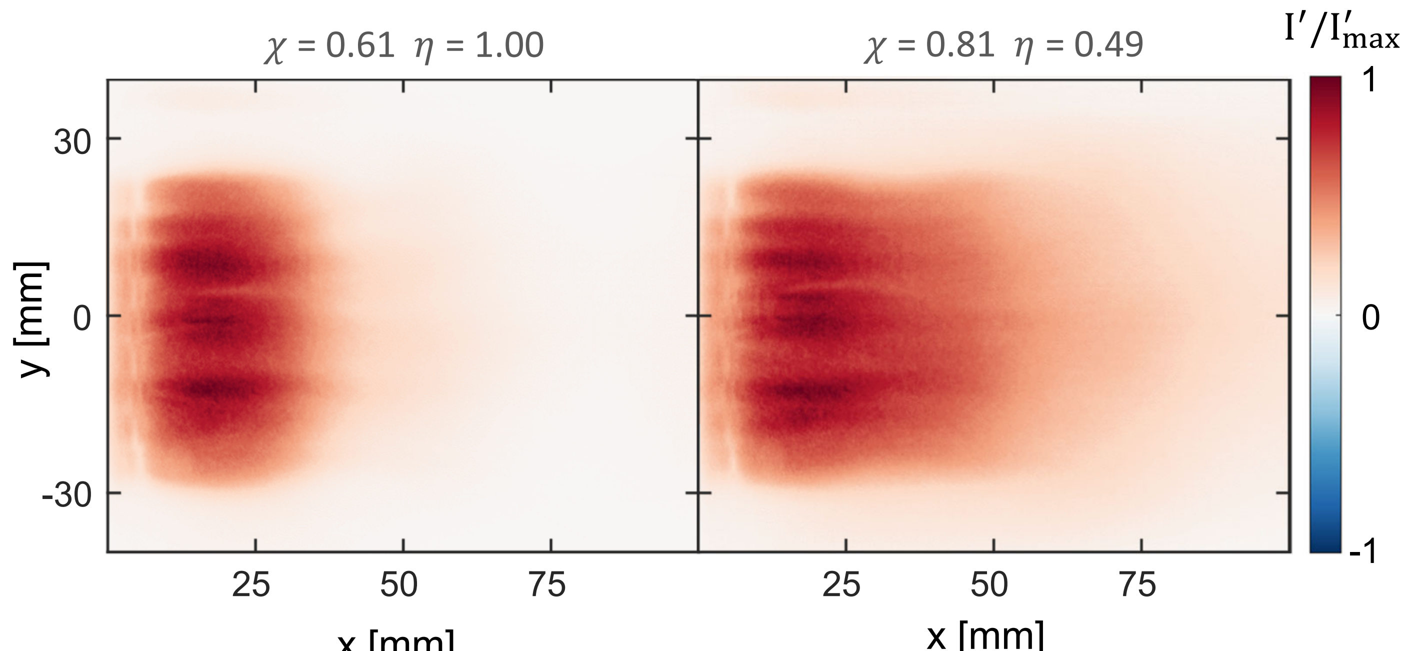
Fuel Composition:

$$\chi\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+\cancel{(1-\chi)NG}$$

Combustion Instability Modes

- Phase evolution of 1L and 2L modes highlight differences in flame response





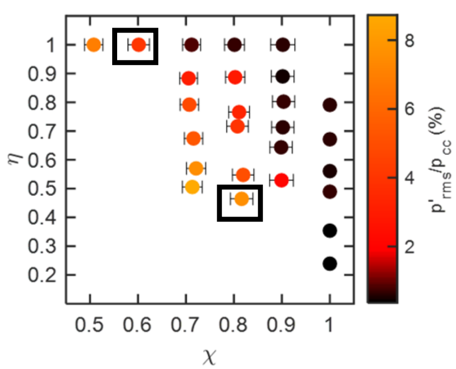
2L 1090 Hz Instability

1L 575 Hz Instability

Fuel Composition:

$$\chi\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+(1-\chi)NG$$

Combustion Instability Modes



Fuel Composition:

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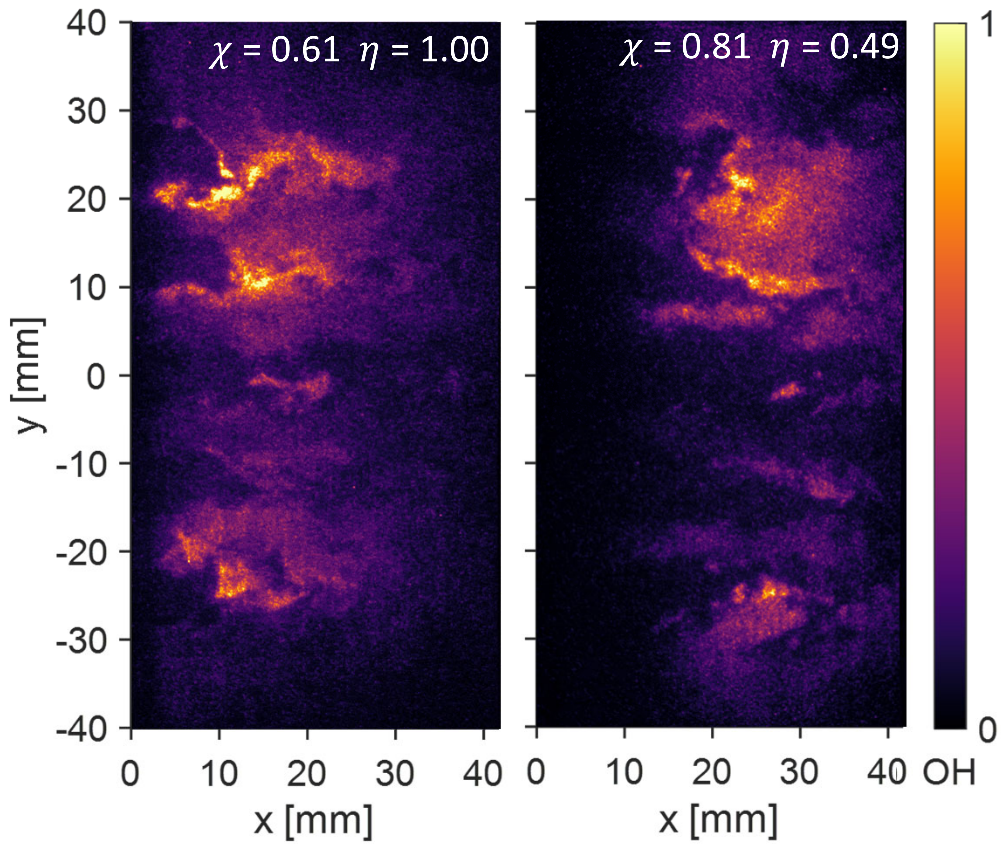


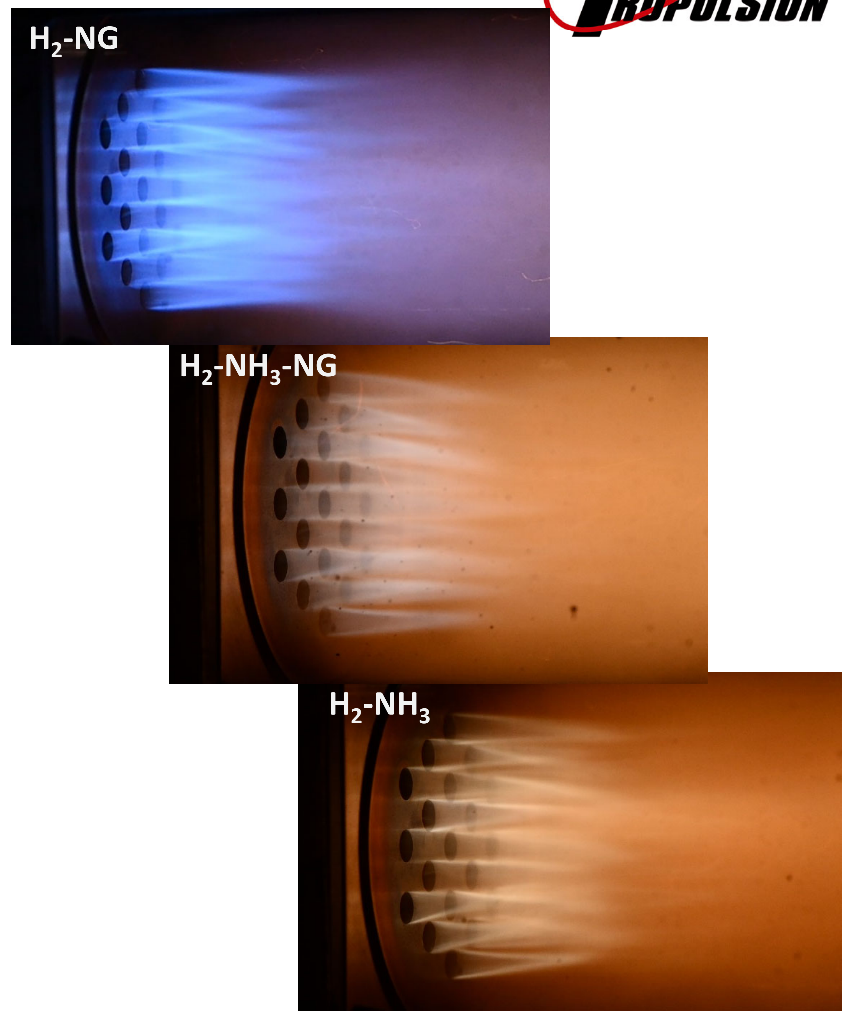
2L 575 Hz Instability **1L 1090 Hz Instability**

Summary

- Characterized influence of NH_3 and H_2 addition on combustion instabilities at elevated pressure with a premixed multi-element micromix injector
  - Disparate flame speeds of ammonia and hydrogen allow stable combustion for a wide range of η
  - Addition of natural gas increases propensity for instability and sensitivity to ammonia addition
- Hydrogen addition observed to suppress combustion instabilities
- Ammonia addition observed to increase instability amplitude when natural gas is present, but sensitivity decreases as natural gas is removed

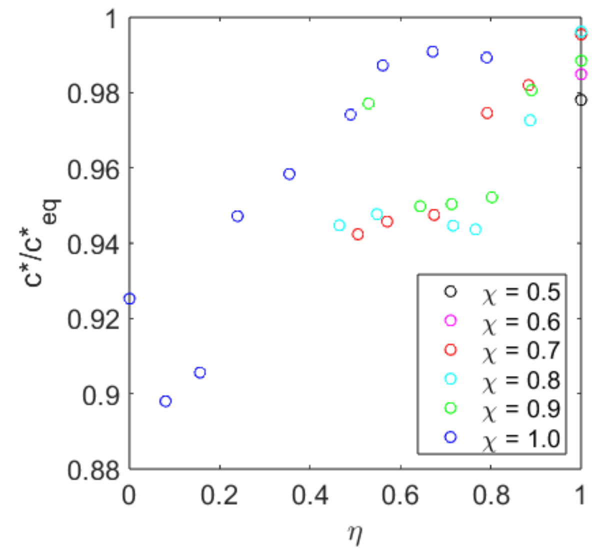
Next Steps:

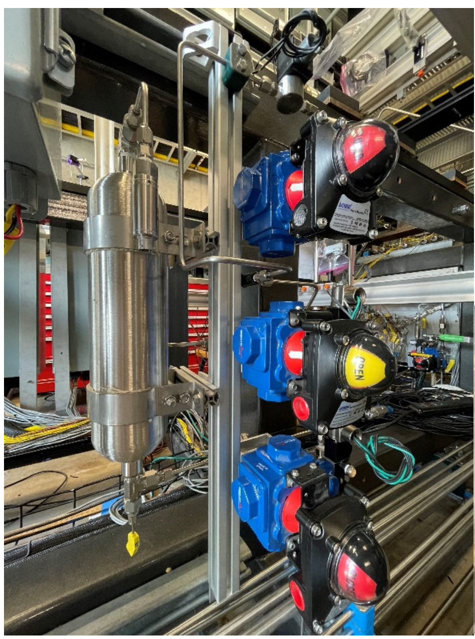
- Detailed characterization of flame structure and dynamics with application of PIV and CARS measurements
- Global emissions characterization using FTIR based extractive product gas sampling

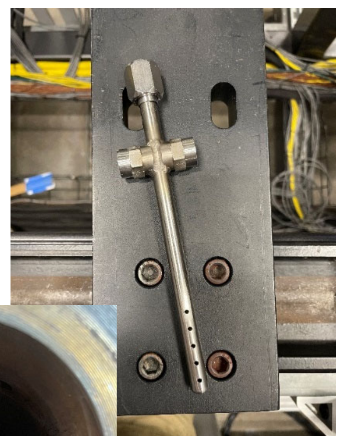


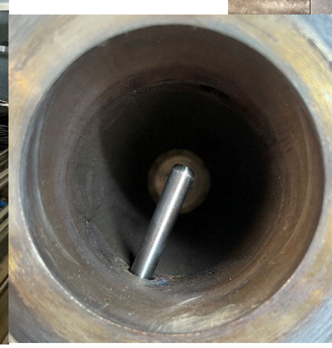
Emissions Characterization

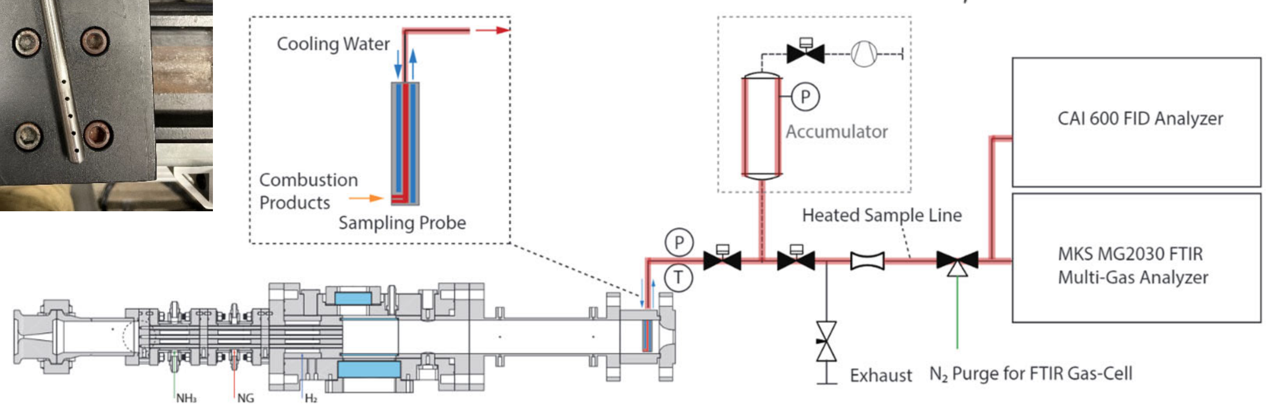
- Emissions sampling using MKS MG2030 FTIR and FID Multi-Gas Analyzer
  - Measurable species of interest include: NOx, NH3, CO, CO_2, H_2O, etc.
- Sampling system designed to provide exhaust gas at 1l/min to FTIR for >240 s
  - Achieved through filling a heated exhaust gas accumulator with steady combustion products for 0.5 seconds, and then feeding products from accumulator to FTIR in blowdown configuration





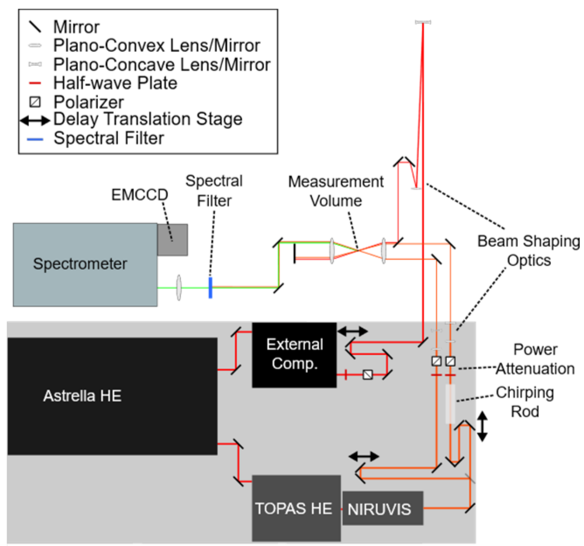


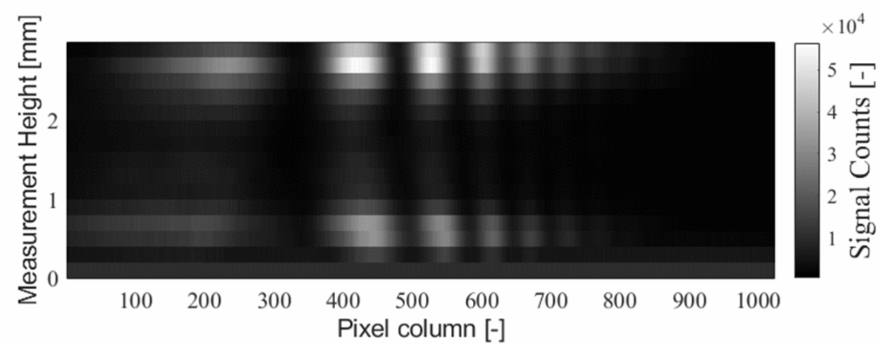


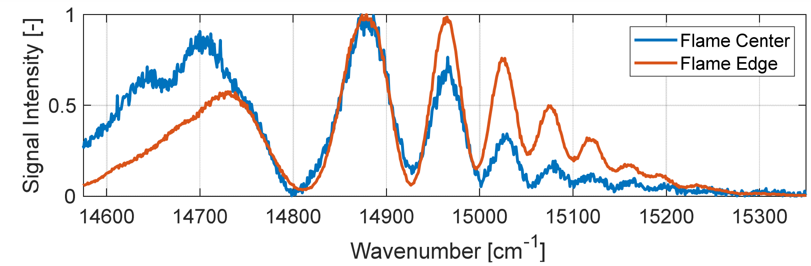


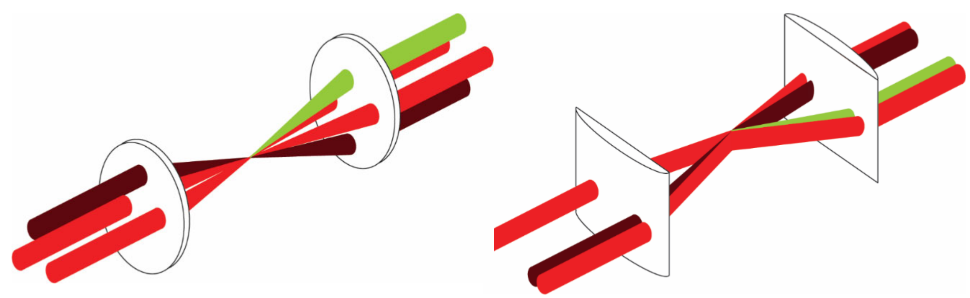
Flow field Temperature Measurements with N_2 CARS

- High-energy high-intensity ultrafast laser systems allow for 1 kHz repetition rate measurements
- N_2 chirped-probe pulse (CPP) CARS provides temporally and spatially resolved measurements of the unsteady temperature field
- Modifications of the phase matching scheme transform the probe volume from a single point to a spatially resolved line
- Preliminary measurements demonstrated in H_2/air counterflow diffusion flame across steep temperature gradient at 1kHz
  - Transition to high pressure combustor in Spring/Summer







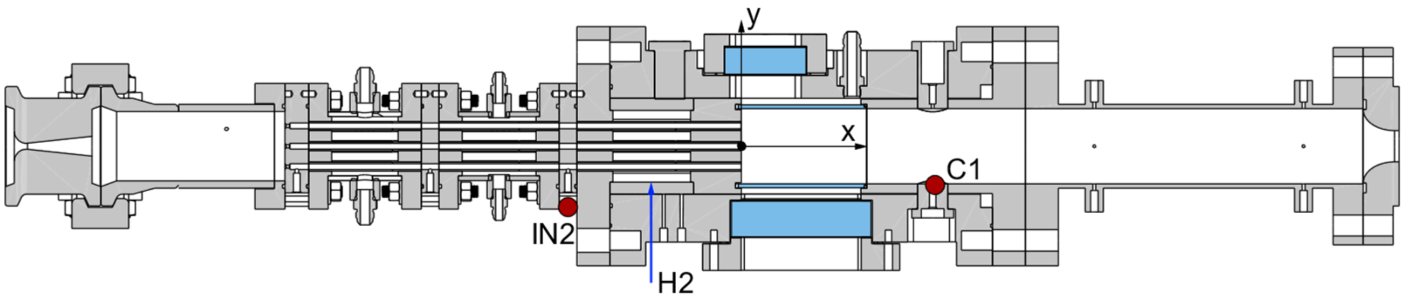


Zucrow High Speed Propulsion Labs (ZL9)

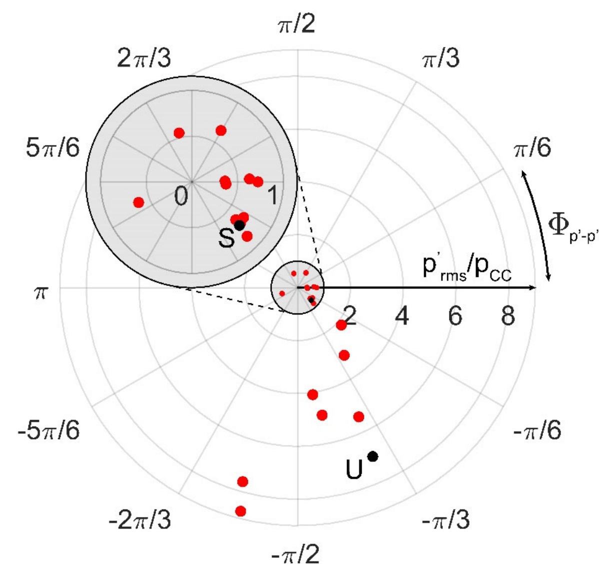
- Five propulsion test cells with bridge cranes; 30’ wide x 55’ deep x 34’ tall
- Each test cell has dedicated laser laboratories and control rooms
- New high pressure air plant will continuously produce 5 lbm/s at 3,400 psi.
- 9,000 ft^3 of air storage at 3,400 psi (150,000 lbm of air for blow-down)
- 30 lbm/sec flow rate of clean air heated to 1,500 deg F at 800 psi
- Storage volumes of oxygen, nitrogen, hydrogen, and other fuels will be increased to match (or significantly exceed) run-durations set by the air system
- Electrical infrastructure for up to 3 MW fuel heating capacity
- Electrical infrastructure for up to 3,000 HP aviation compressor & turbine testing
- Infrastructure upgrades for ZL9 are connected to improve all Zucrow facilities
- Occupancy in November 2024
- System activations through Q1 2025

The authors gratefully acknowledge the support and guidance from General Electric, Air Products and Velo3D for the project

Fuel Effects on Coupled Dynamics

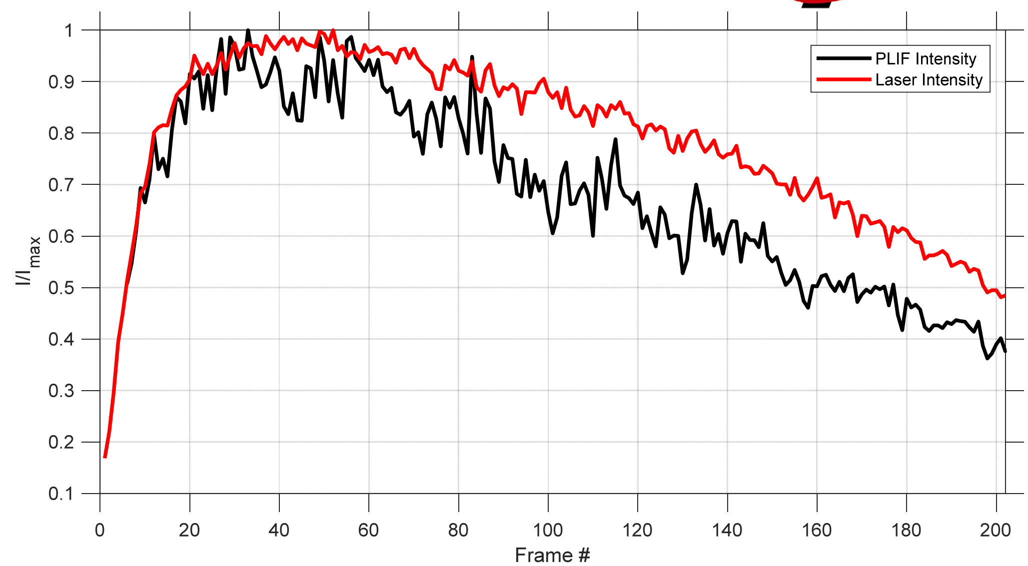


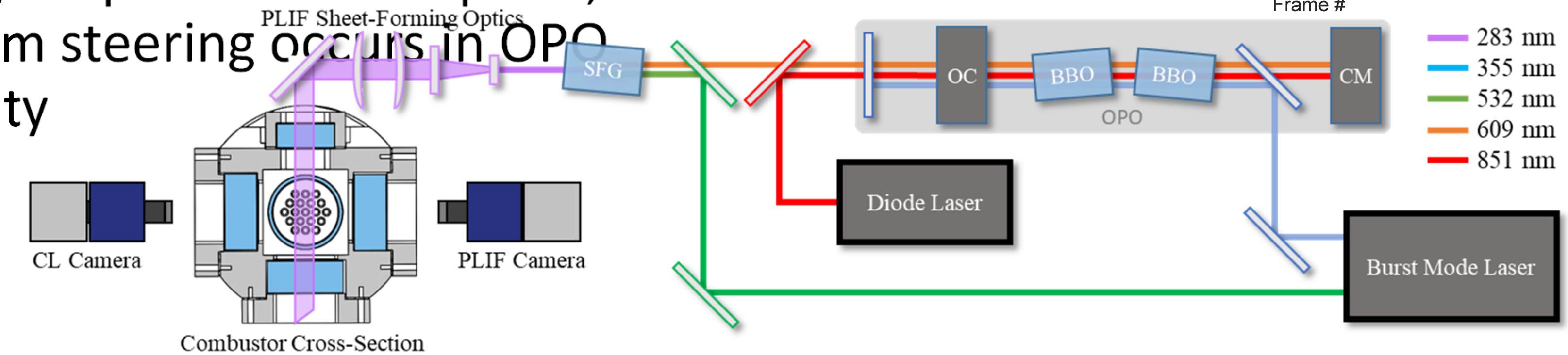
- Phase lag computed between p' measurements at IN2 and C1 $(\Phi_{p'-p'})$
- 2 major impedance sources between these locations:
  - Hydrogen premixing jet
  - Flame zone
- All unstable cases lie between $-2\pi/3 < \Phi_{p'-p'} < -\pi/6$
- Separation between stable and unstable cases observed within this band, signifying acoustic coupling between the injector and combustor as key contributor to instability growth



• PLIF Intensity Decay

- UV laser power measured proportional to photodiode response
- Integrated PLIF intensity decays proportionally to UV laser intensity
- Increasing BML amplifier voltage only helps to a certain point, beam steering occurs in OPO cavity

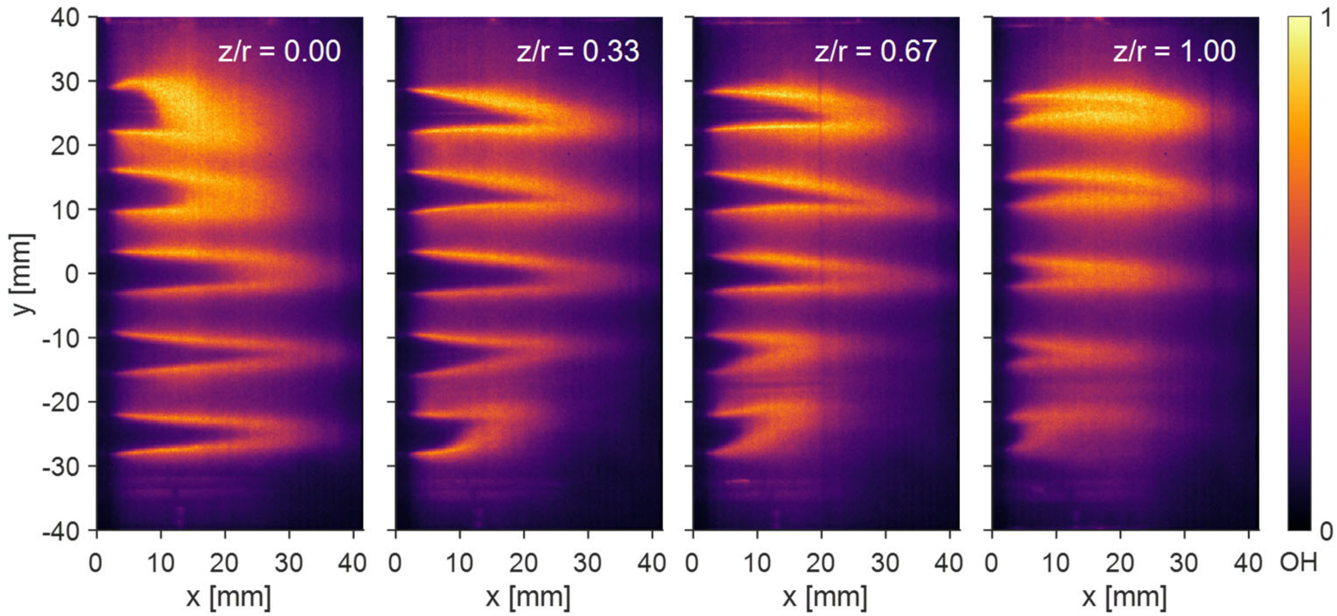




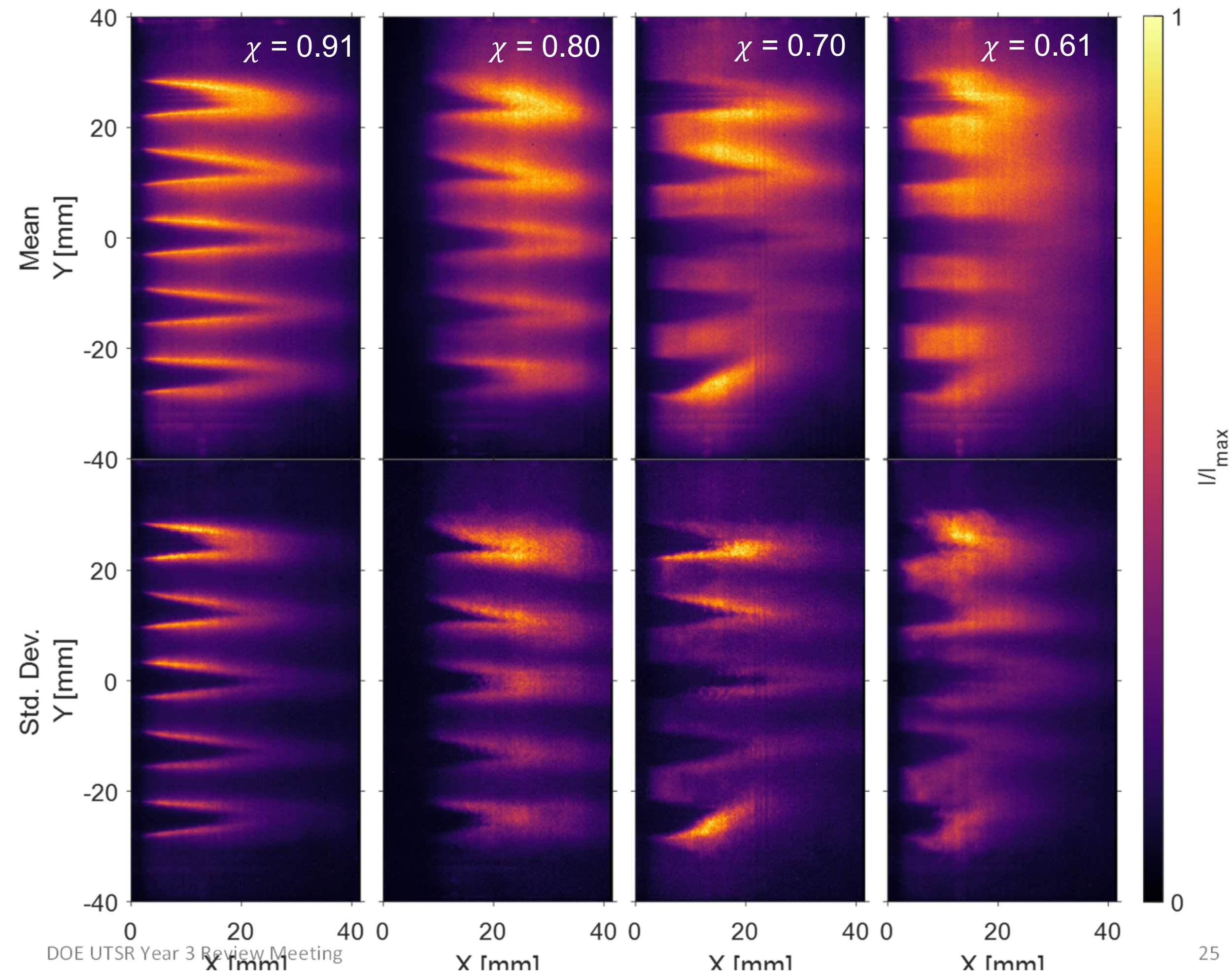
Schematic of burst mode laser and OPO for OH-PLIF measurements

• SHEET POSITION TRENDS

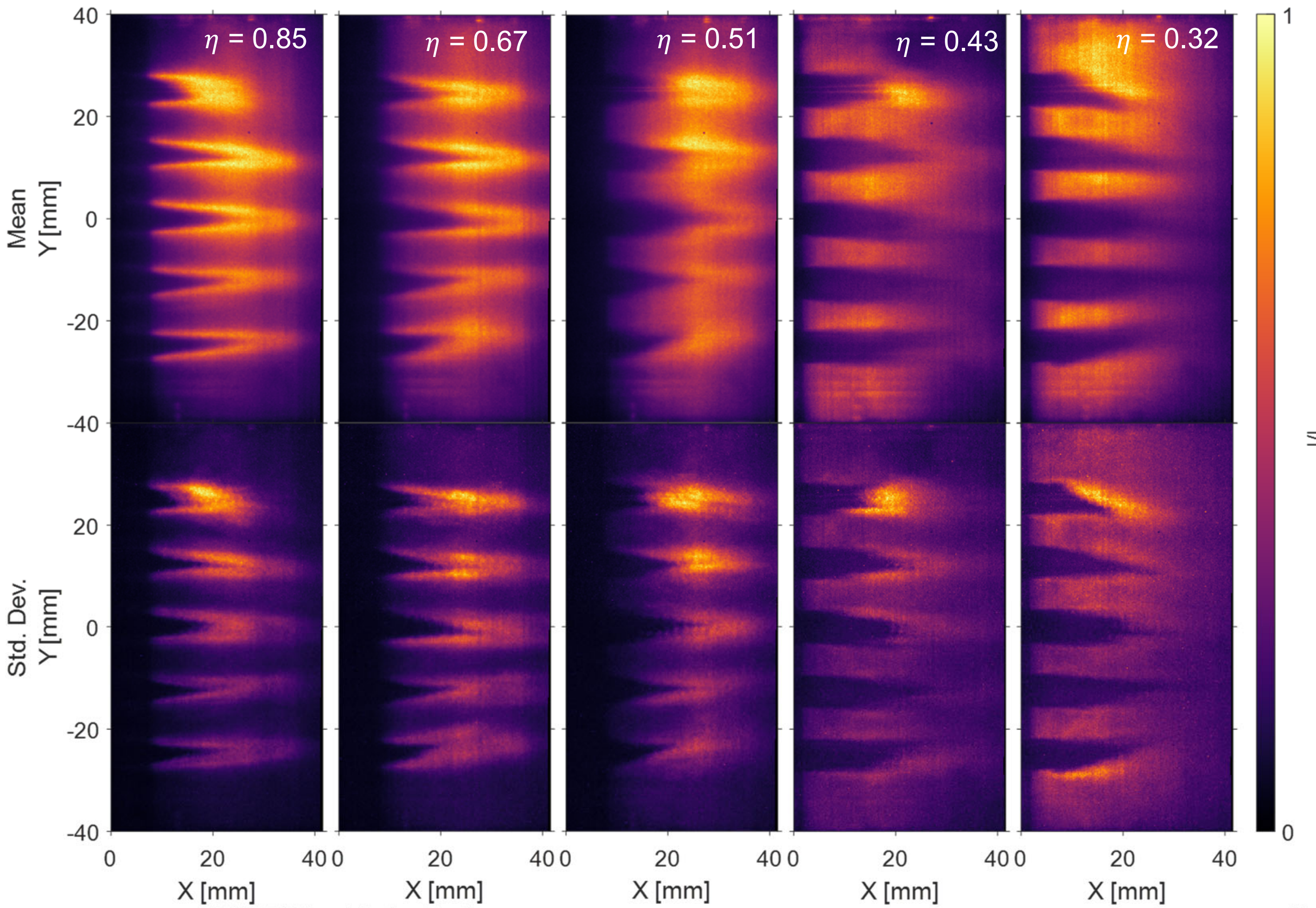
• NOTE: THIS IS A BACKUP SLIDE

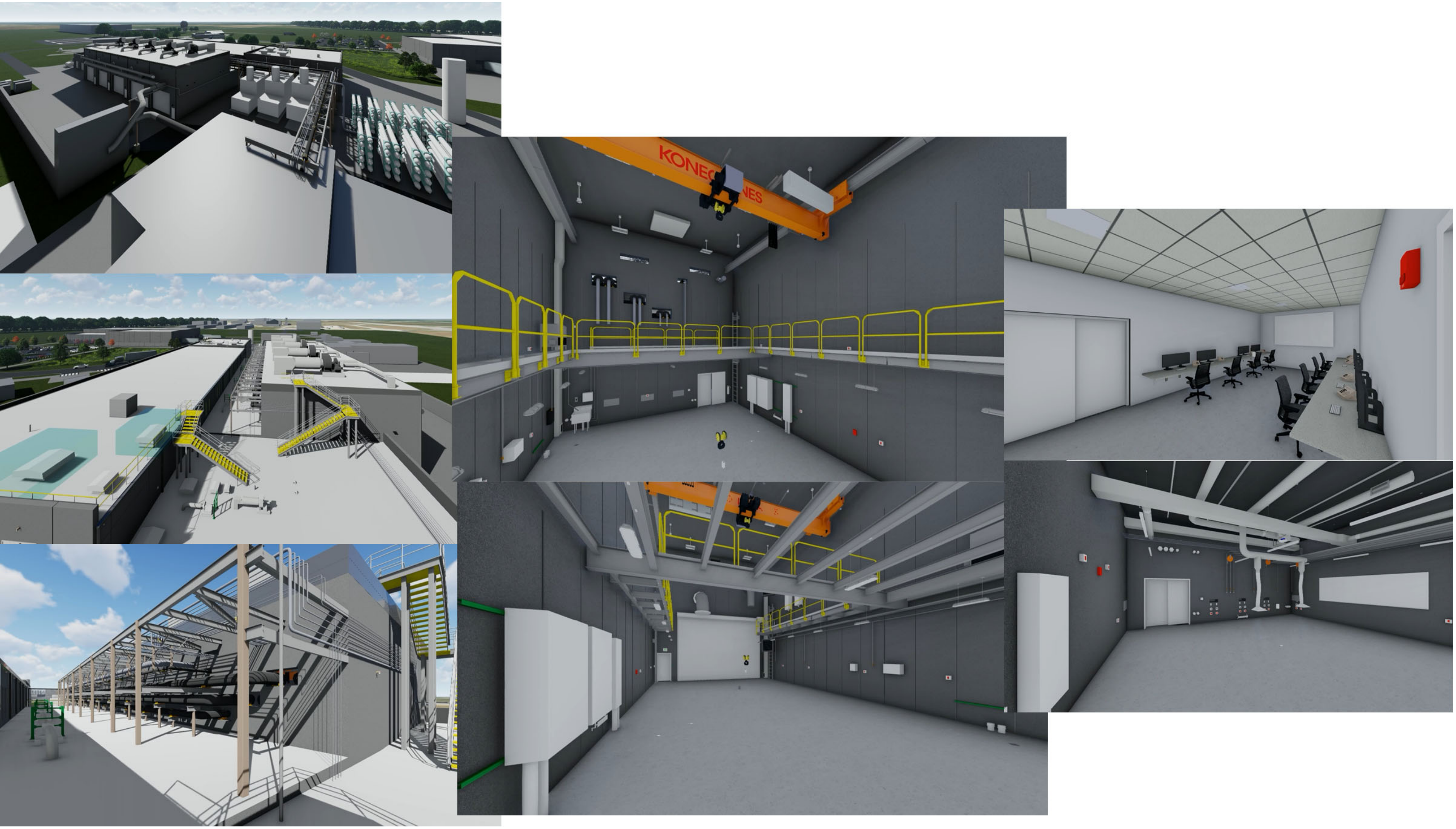


Flame Characterization- Variations in χ



Flame Characterization- Variations in η



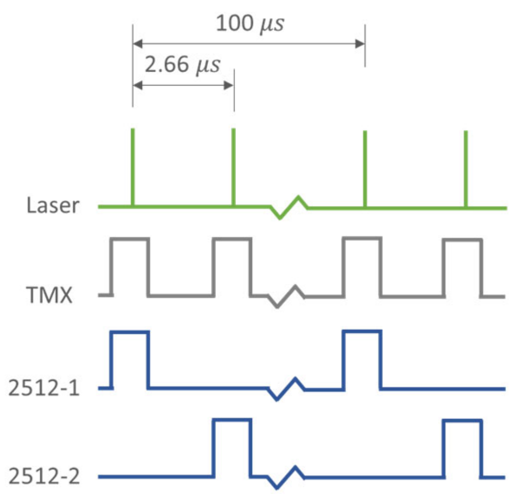


Outlook

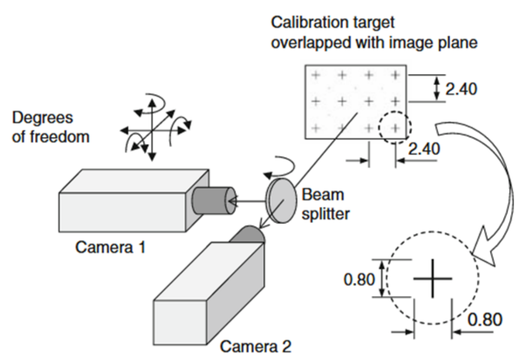
	Task	Year 1	Year 2	Year 3	Year 4
	Task 1.0 Project Management and Planning				
	Task 2.0: Reconfigure Experimental Hardware and Validate Operation				
2.1	Develop M3 Injector	04/30/2022 M1 ✓			
2.2	Develop Modular Combustion Chamber	04/30/2022 M2 ✓			
2.3	Develop High-Pressure Ammonia Supply	M3 ✓ 12/31/2021			
2.4	Complete Final Assembly, Integration, and Verification Testing	09/30/2022 M4 M5 ✓✓			
	Task 3.0: Complete Parametric Map of Global Combustion Performance				
3.1	Characterize Combustion Emissions			10/31/2024	M6
3.2	Measure Points of Lean Blowout			10/31/2024	M7
	Task 4.0: Complete Parametric Survey of Combustion Stability				
4.1	Configure Hardware for Dynamics Testing		04/30/2023 M8 ✓		
4.2	Develop Parametric Stability Map with Baseline Instrumentation		08/31/2023 M9 ✓		
	Task 5.0: Perform Advanced Diagnostics of Flow-Flame Structure and Dynamics				
5.1	Perform Simultaneous High-Speed PIV and OH PLIF Measurements			09/30/2024 M10	
5.2	Perform Ultrahigh-Speed PIV and OH-PLIF Measurements			09/30/2024 M11	
5.3	Perform NO PLIF Measurements				02/28/2025 M12
5.4	Perform NH PLIF Measurements for Fuels with Significant NH3 Fractions				02/28/2025 M13
	Task 6.0: Acquire High-Fidelity Measurements of Flow Temperature and Mixing				
6.1	Perform "Point" N_2 CARS Measurements				07/31/2025 M14
6.2	Demonstrate and Deploy N_2 "Line" CARS				07/31/2025 M15
	Task 7.0: Curate Measurement Database				
7.1	Assemble and Organize all Data, Metadata, and Processing Tools				07/31/2025 M16

Characterization of Flow-Flame Interactions

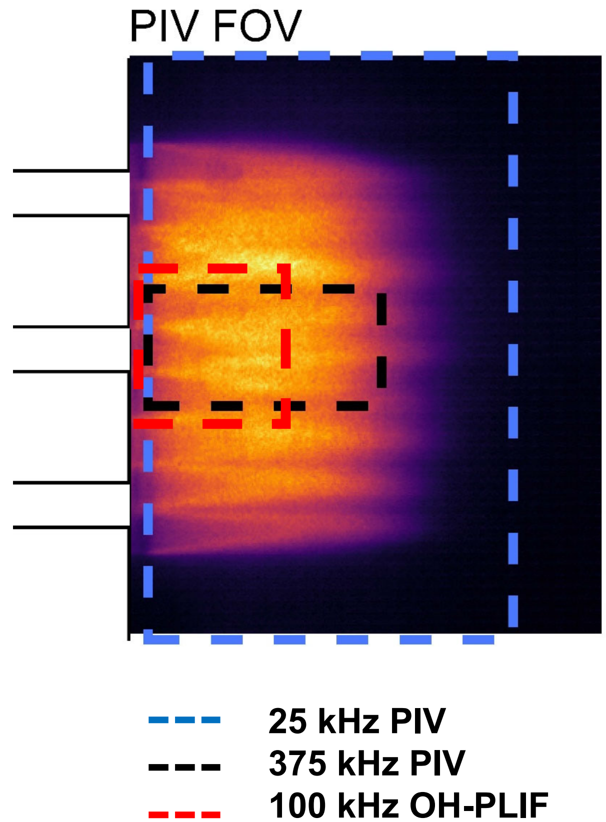
- Concurrent application of OH-PLIF and particle imaging velocimetry (PIV) to characterize flow flame interactions with changes in fuel composition
- Simultaneous 25 kHz PIV and 375 kHz PIV to improve smallest resolvable flow scales while maintaining resolution of large-scale oscillations
- Single 532 nm pulses to be generated at 375 kHz from a burst mode laser over a 10.5 ms burst duration
  - Capture 10 acoustic cycles at 2L mode and 5 cycles of the 1L mode
  - Effective pulse separation of $n * 2.66\ \mu s$, $n = 1, 2, 3, \ldots$



Multi-scale PIV timing

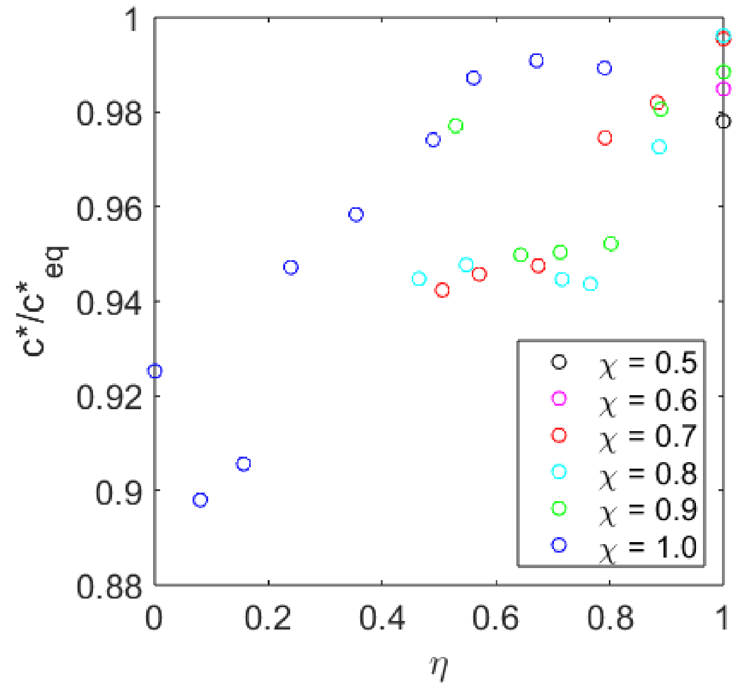


(Bian et al., 2010)



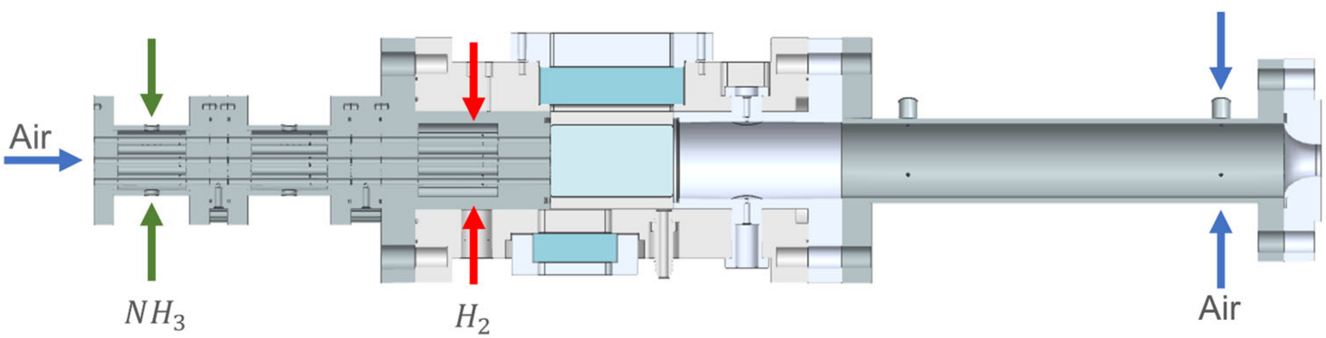
Emissions Characterization

- Characterize combustor emissions across the range of fuel mixtures previously studied
- Emissions sampling using MKS MG2030 FTIR Multi-Gas Analyzer
  - Measurable species of interest: NO_x, NH_3, CO, CO_2, H_2O, etc.
- Sampling system designed to provide exhaust gas to FTIR for over 240 seconds
  - Sampled during steady portion of test will fill heated accumulator
  - Accumulator supplies gas to FTIR system in blowdown configuration



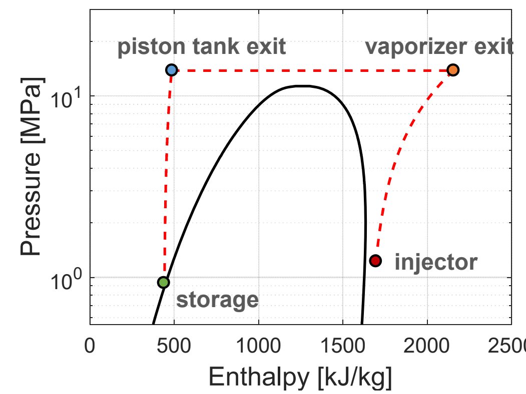
Dynamics and Emissions Optimization

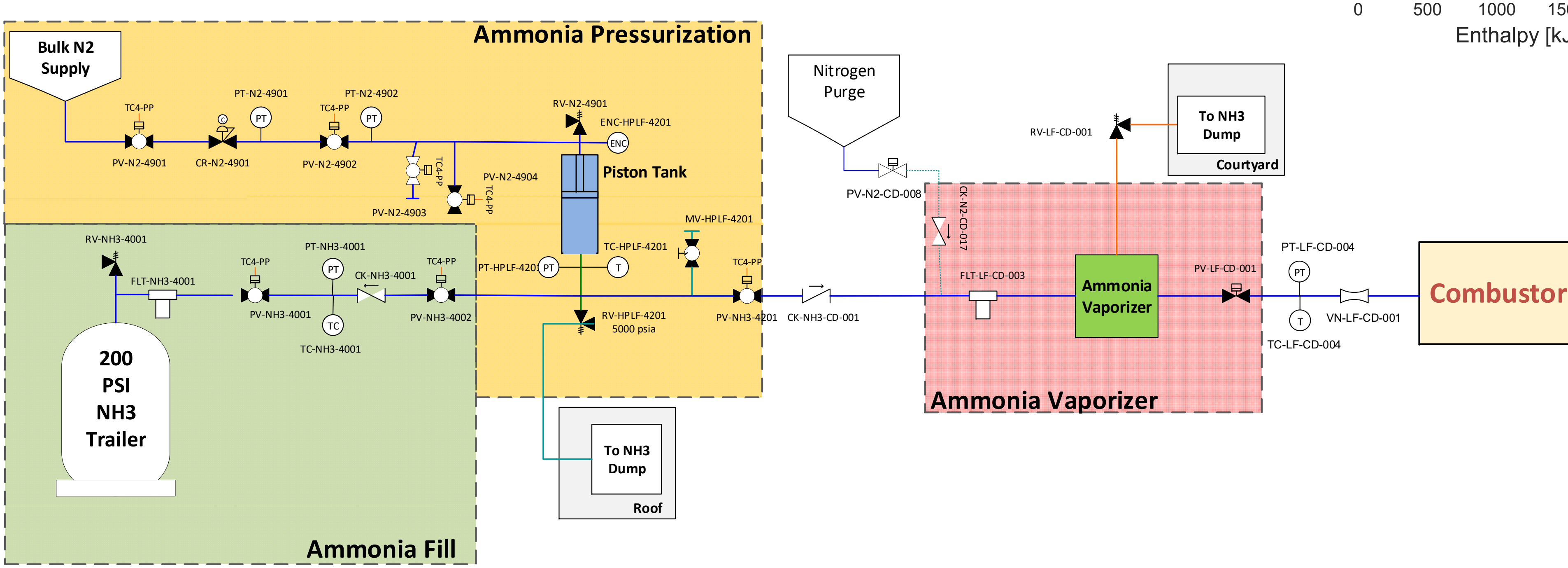
- Staged combustion of ammonia in rich-quench-lean (RQL) configuration has potential to reduce NO through additional residence time with large NH_2 radical pool
- Emissions and stability characterization required to understand sensitivities to:
  - Residence time
  - Second stage mixing
  - Flame stability
  - Ammonia-hydrogen reaction chemistry



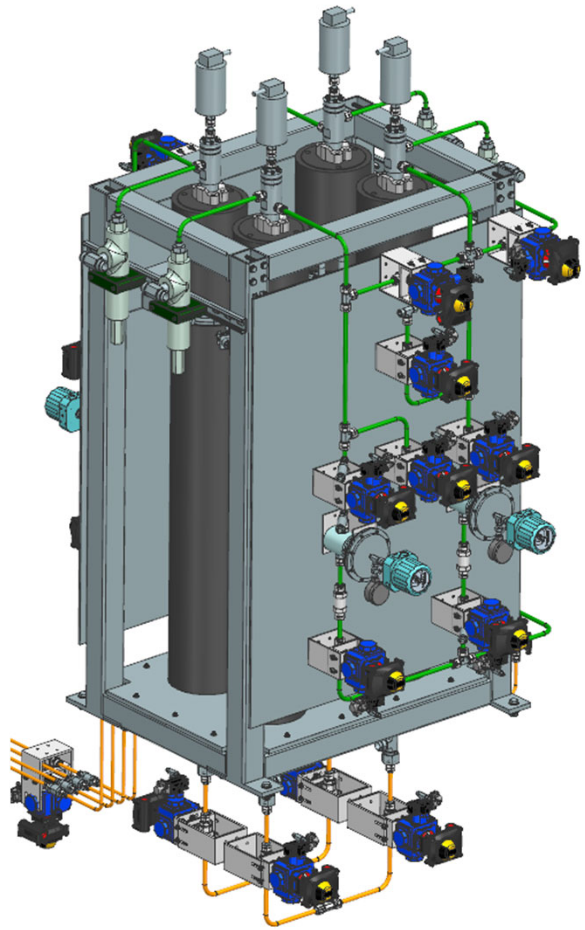
Ammonia System Design

- Ammonia filled into piston tank as saturated liquid
- Piston tank pressurized with gaseous nitrogen up to 345 bar
- Liquid ammonia delivered from piston tank to steady state vaporizer
  - Linear encoder provides position feedback from piston
- Gaseous ammonia flowrate metered using critical flow venturi nozzle





Ammonia Pressurization



Ammonia Pressurization

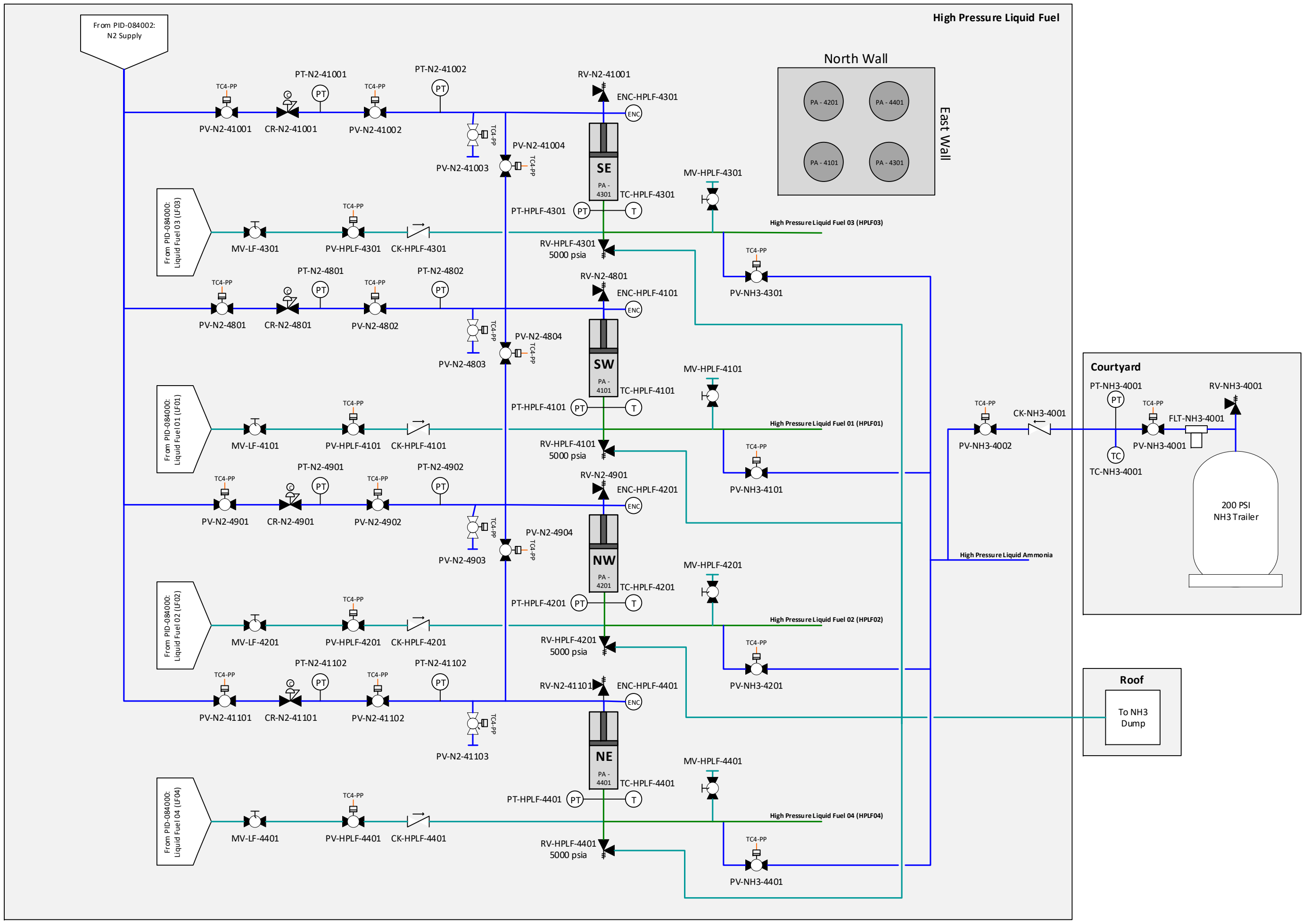
Specifications

- Up to 5,000 psi supply pressure
- 30 gallon total volume
- Capable of running tanks individually or in parallel
- Ties in to existing cell 4 liquid fuel system
- Configurable for ammonia or RP-1 operation

Ammonia Pressurization

Accumulator System P&ID

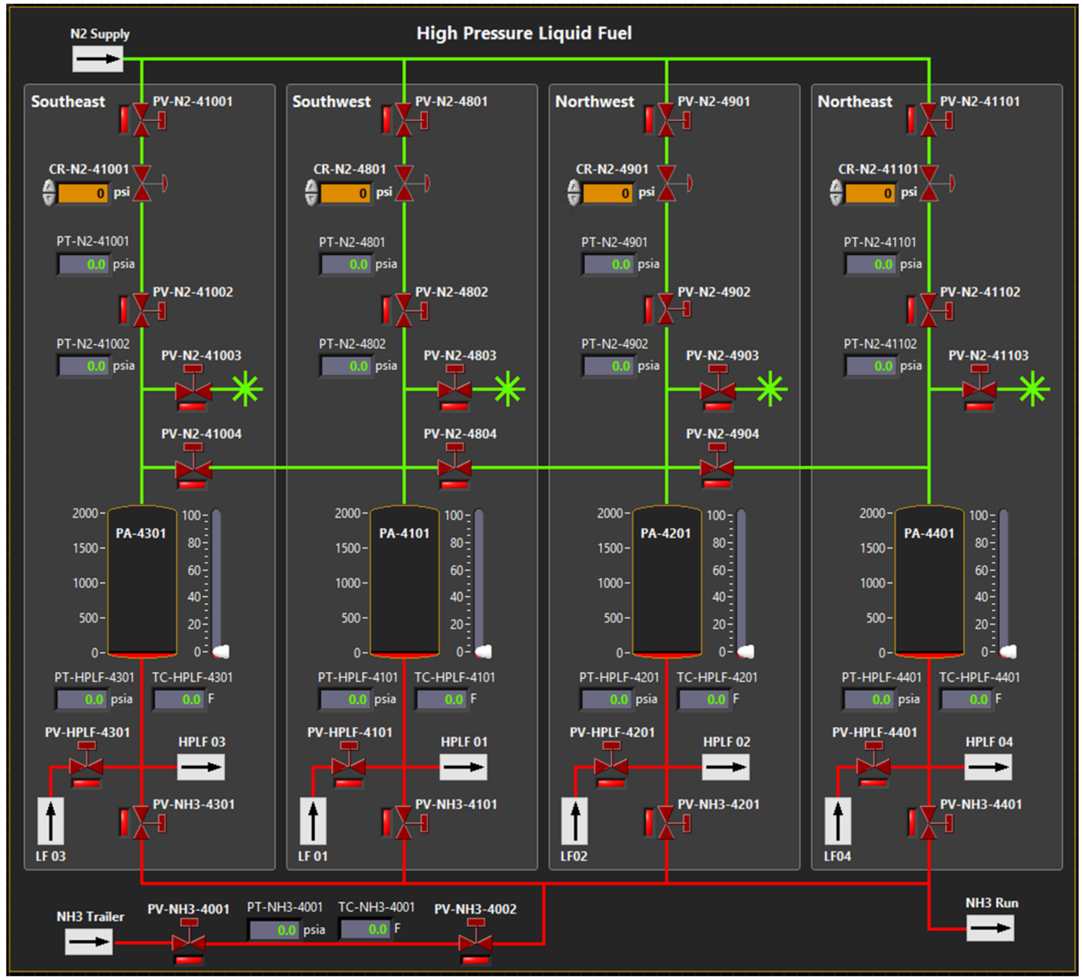
- Rated up to 5,000 psia
  - Anderson Greenwood relief valves on N2 side of tanks
  - Swagelok high pressure relief valves on liquid side route to 55 gal barrel on the roof
- Each tank holds up to 7.5 gallons
- Accumulators capable of running individually or in parallel
- Dump barrels are filled with 50/50 antifreeze-water mixture to dissolve released ammonia and prevent freezing during winter



Ammonia Pressurization

LabVIEW VI

- National Instruments LabView Software is utilized for all testing activity at Zucrow Labs
- System designed for completely remote operation



Ammonia Pressurization

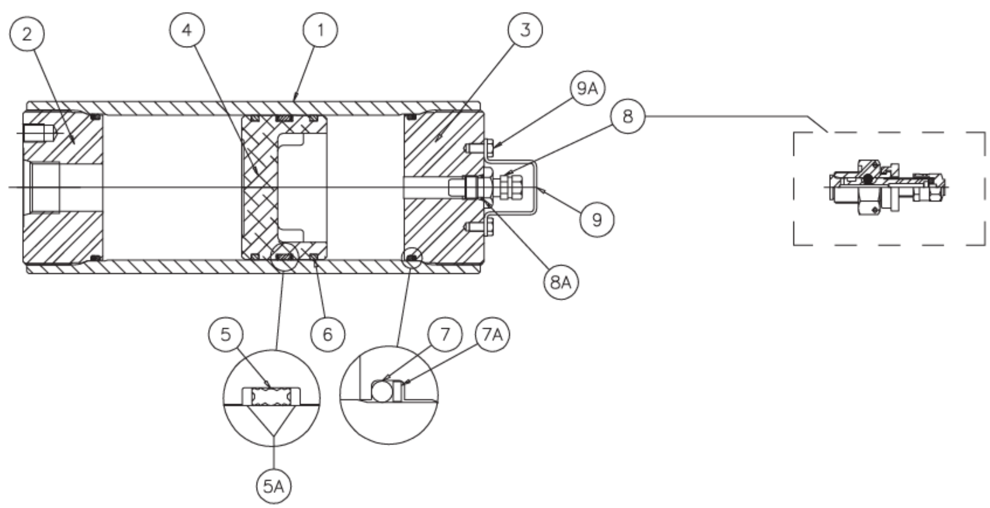
Material Compatibility

- Ethylene propylene rubber (EDPM) has excellent compatibility with ammonia and is used when elastomeric materials are required
- PTFE has excellent compatibility with anhydrous ammonia and RP-1

- Requirements for any fuel line components:
  - Use Allan Aircraft or SSP UltraFlare fittings with PTFE back-up seal
  - Use FSAE ends on all valves with the appropriate F5OX equivalent SSP/AA fitting

Seal Kits

Seal Kits are available for all piston accumulator models. When ordering seal kits, please supply the complete model and serial numbers from the name plate and specify fluid type and operating temperature.



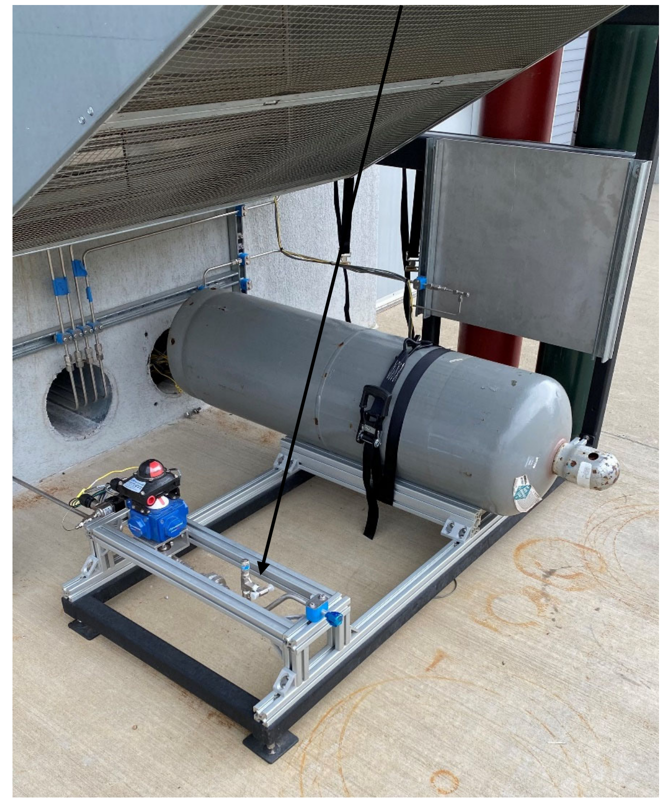
Parts List

1 Body
2 Hydraulic Cap
3 Gas Cap
4 Piston
5 V-O-ring Piston Seal
5A V-O-ring Backups
6 PTFE Glide Rings
7 O-ring
7A O-ring Backup
8 Gas Valve
8A Gas Valve O-ring
9 Gas Valve Guard
9A Screw

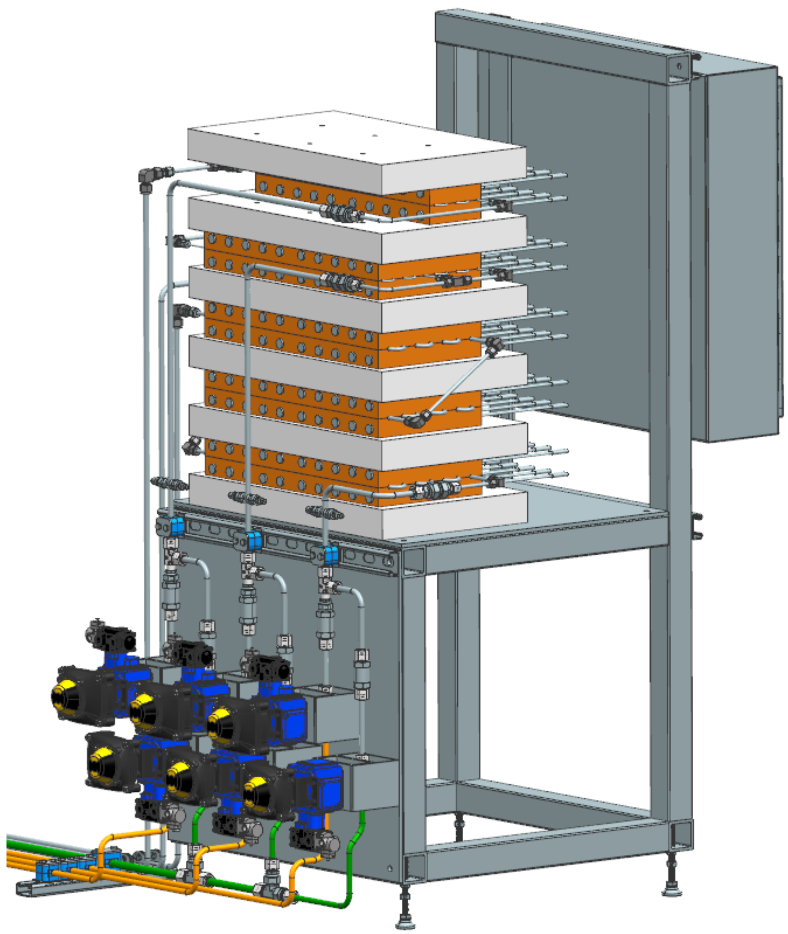
Ammonia Pressurization

Vent port uncapped

Relief valve
calibrated to 225 psia



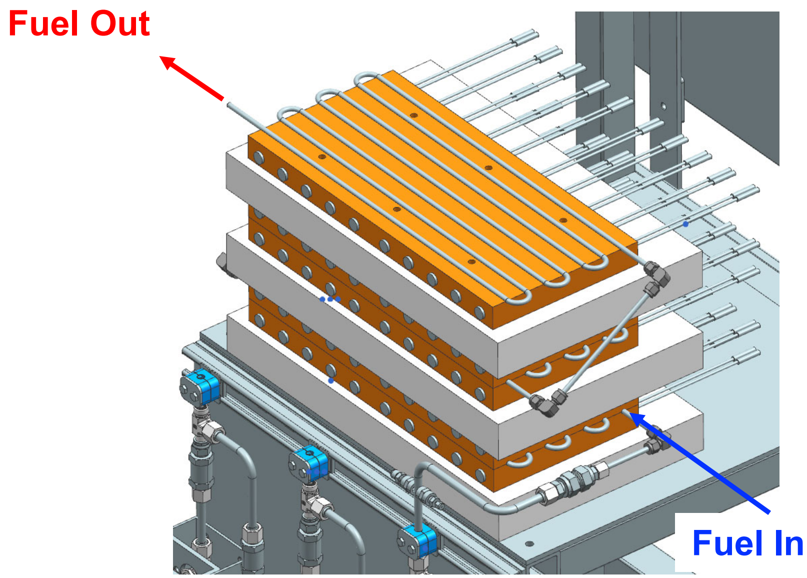
Ammonia Vaporizer



Ammonia Vaporizer

Specifications

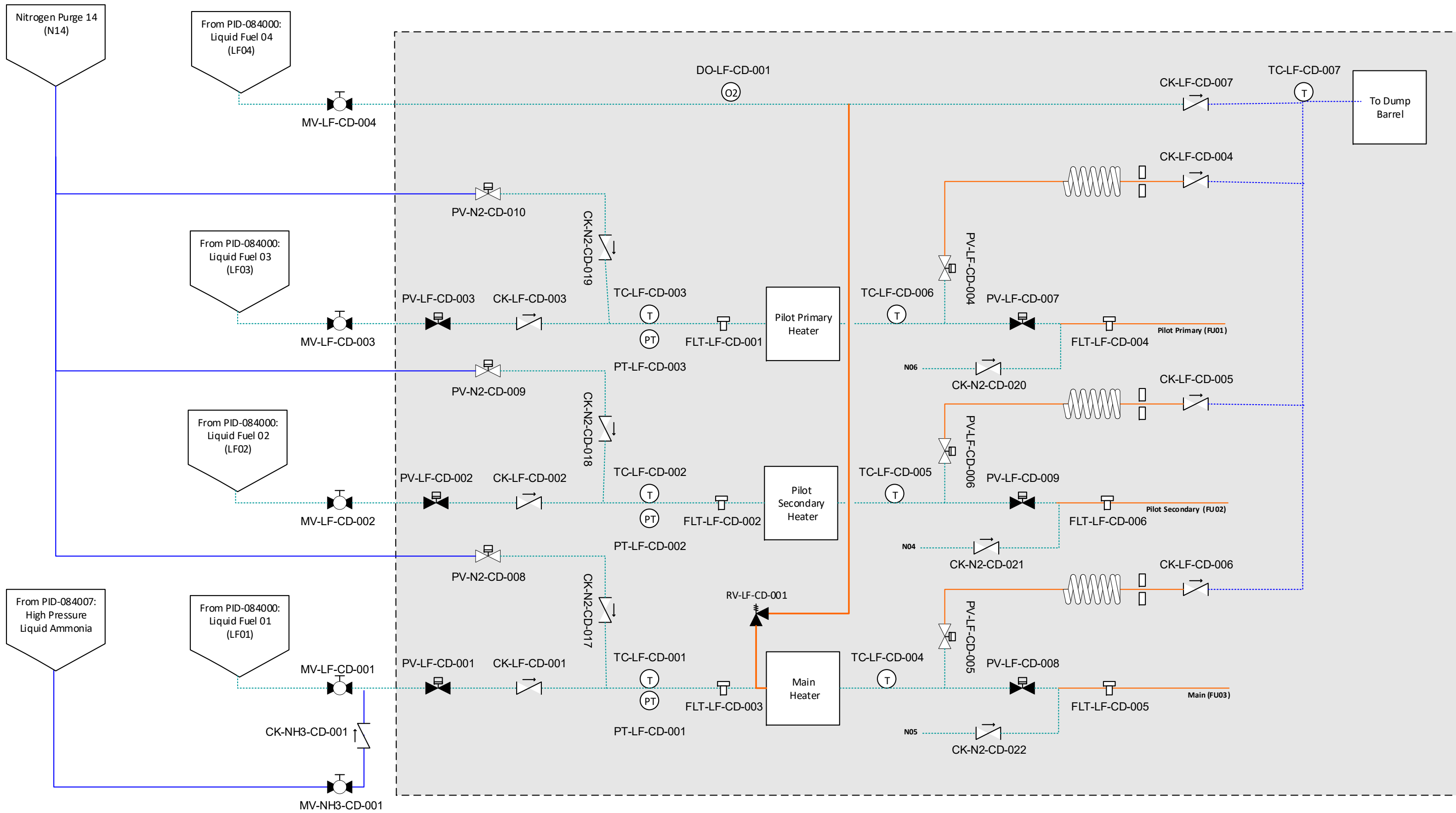
- 54 kW electrically heated ammonia vaporizer
- 480 V cartridge heaters embedded in copper blocks
- Stainless steel tubing routed through copper blocks
- Thermocouple used to monitor copper temperature and regulate power to cartridges



Ammonia Vaporizer

P&ID

- Main fuel circuit of the COMRAD fuel heater to be used for ammonia vaporization
- Seals upstream of heater swapped to PTFE for compatibility with both Jet A and ammonia
- Swagelok high pressure relief valve added to main circuit and calibrated to 4,000 psia



Gas Sensor Placement

- 4 x ammonia gas sensors (0 – 75 PPM full-scale) compatible with existing Beacon 410A controller purchased
- Locations installed
    - Above personnel door
    - Above piston accumulators
    - Below piston accumulators
    - Above fuel heater
- Currently working to integrate sensor readouts with LabVIEW VI through serial communication
- Gas detector alarm triggers test cell exhaust system

Personal Protective Equipment

- OSHA 8 hour permissible exposure limit (PEL) is 50 PPM
- NIOSH immediate danger to life and health (IDLH) condition is 300 PPM
- Primary function of PPE for splash protection and chemical burns
  - Gloves
  - Apron
  - Face Shield
  - Half mask respirator with NH3 cartridges (safe to use up to IDLH per 3M manual)
  - Rubber boots
  - 2 x ammonia detectors (0-100 PPM fullscale)

Restricted Areas During Testing

- 15 g of ammonia requires mixing in a hemisphere of air with a radius of 20 ft to bring the concentration below the OSHA PEL (50 PPM)
- Restricted areas prevent access up to 20 ft minimum