Integrating a Rotating Detonation Combustor with a Power Generating Gas Turbine to Realize the Pressure Gain

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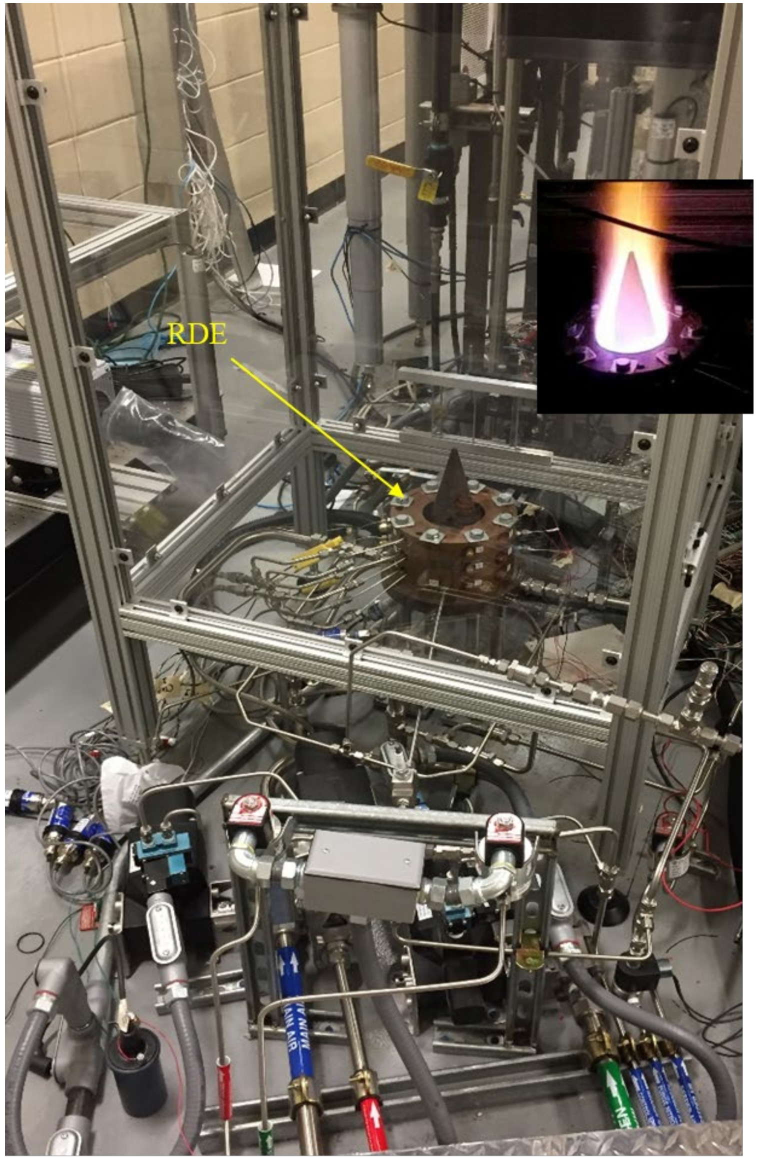
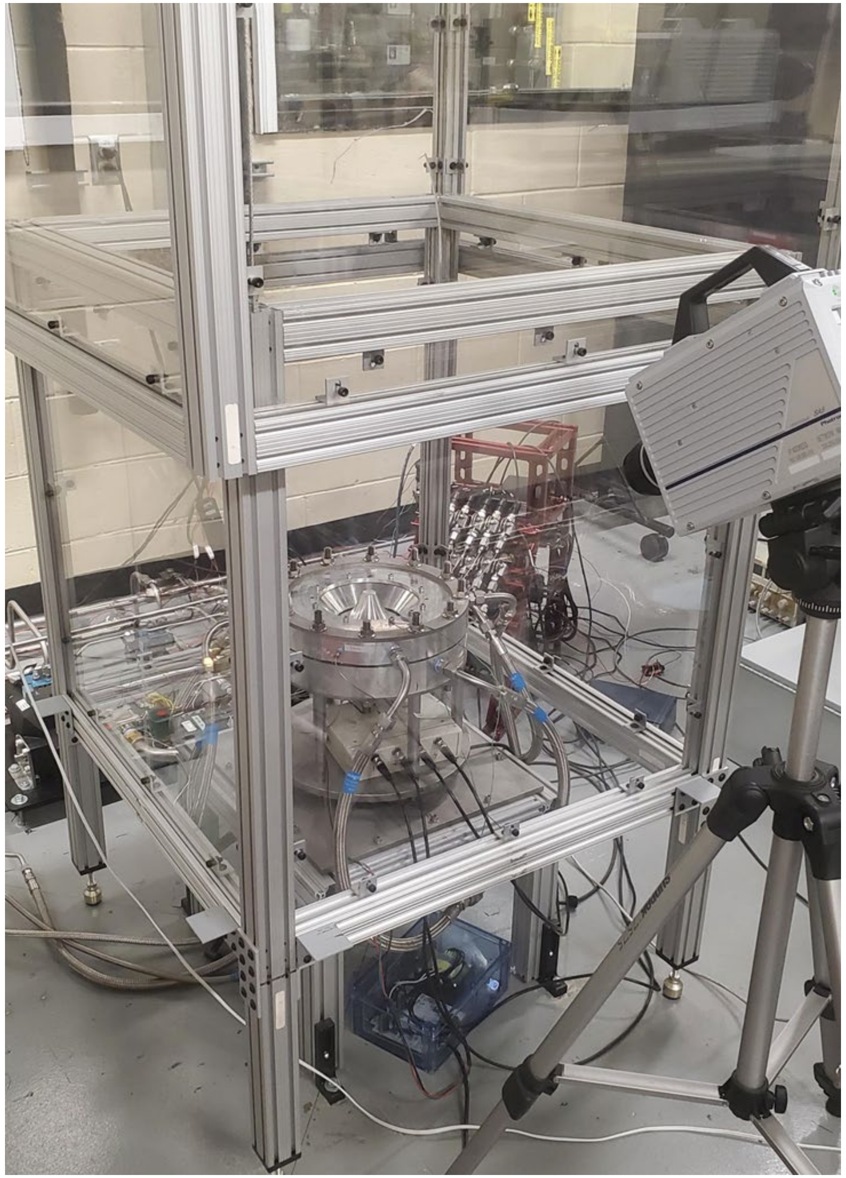
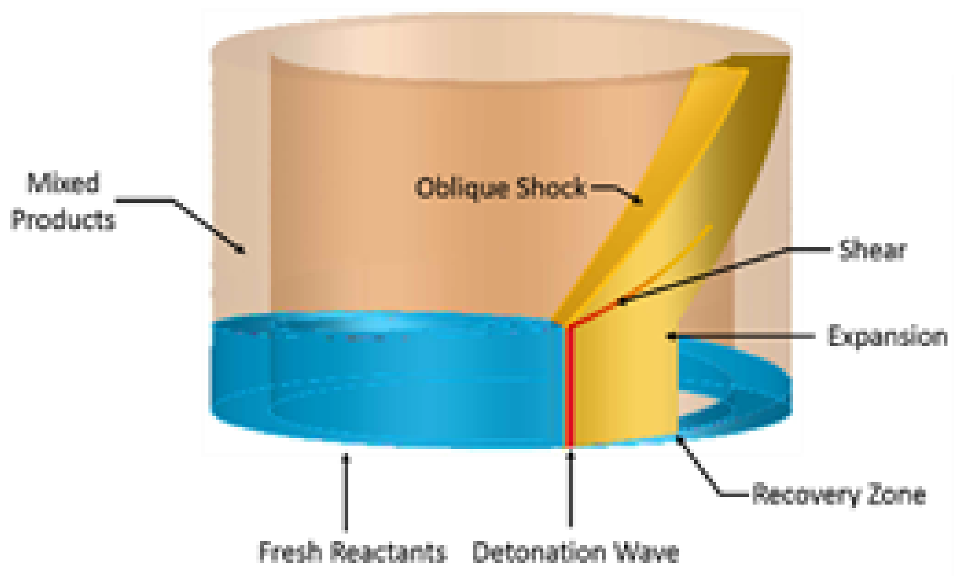
Annular (left) and radial (right) RDE facilities

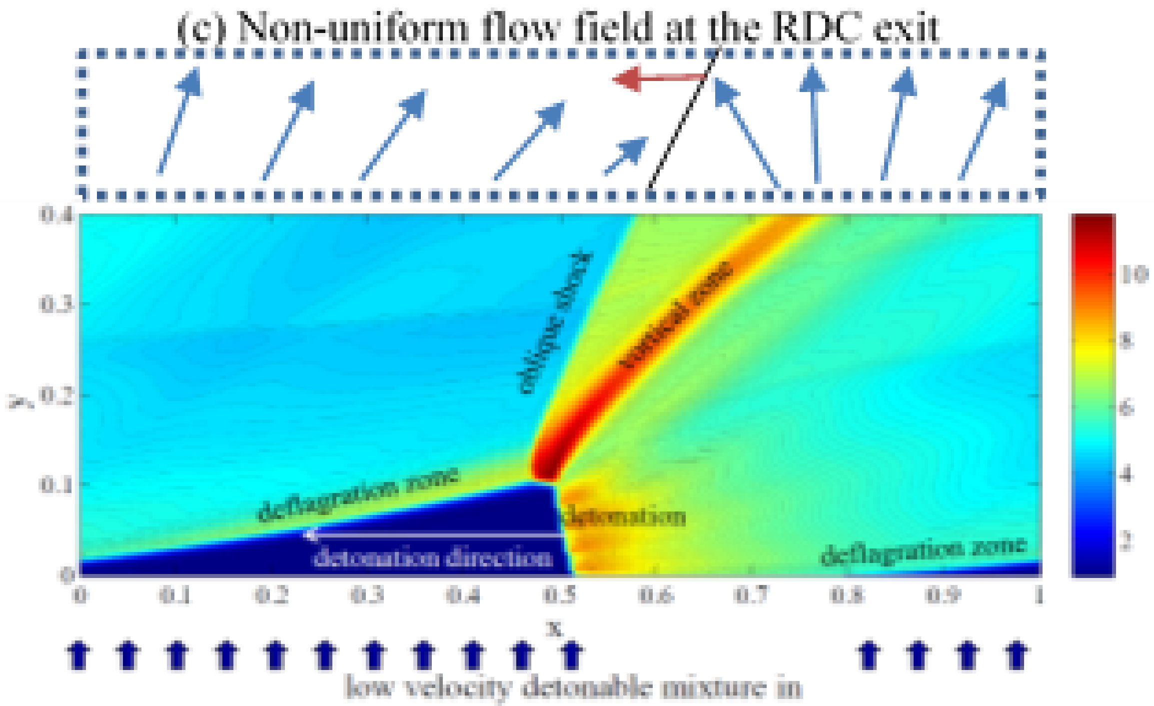




Project Background

- The shock laden Rotating detonation combustor (RDC) exit flow is inherently unsteady and spatially non-uniform (hydrodynamically and thermally) with a high degree of periodicity.
- Gas turbines are designed to operate with relatively small velocity and temperature variations at the inlet.
- RDC flow must be properly conditioned to avoid the potentially disastrous negative impacts of flow oscillations on turbine operation, and to achieve the desired performance.





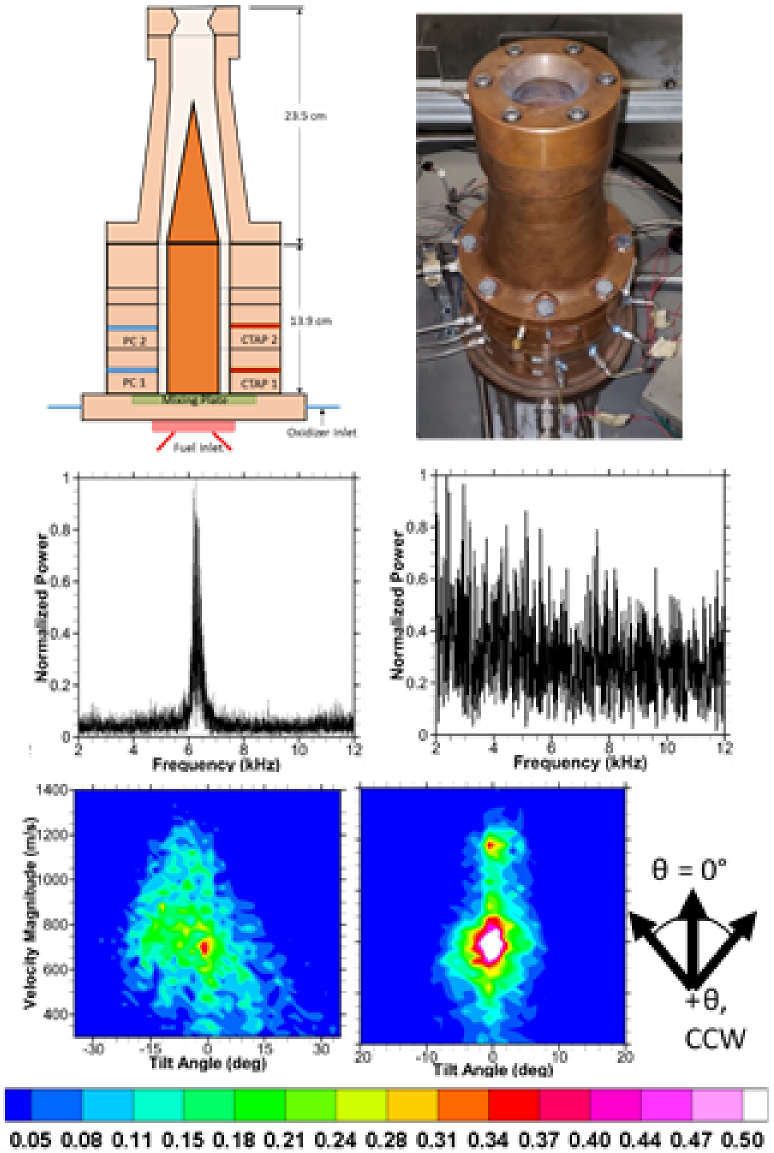


Fig. 4 Schematic (top-left) and photograph (top-right) of RDC with diffuser; FFT of axial velocity without (middle-left) and with diffuser (middle-right); 2D histogram of velocity without diffuser (bottom-left) and with diffuser (bottom-right) [20].

Background

- In our prior work with Aerojet-Rocketdyne, the RDC was integrated with a diffuser as shown.
- We employed PIV at 30 kHz to measure the flow field at the RDC exit without and with diffuser.
- The integrated RDC-diffuser system was operated at high chamber pressures of about 450 kPa.
- Diffuser eliminated the oblique shock wave and coherent flow structures and periodicity associated with it. Diffuser also reduced the circumferential flow velocities.
- However, the axial velocity varied between 300 m/s and 1,200 m/s.
- Axial flow fluctuations can be problematic to turbine operation.

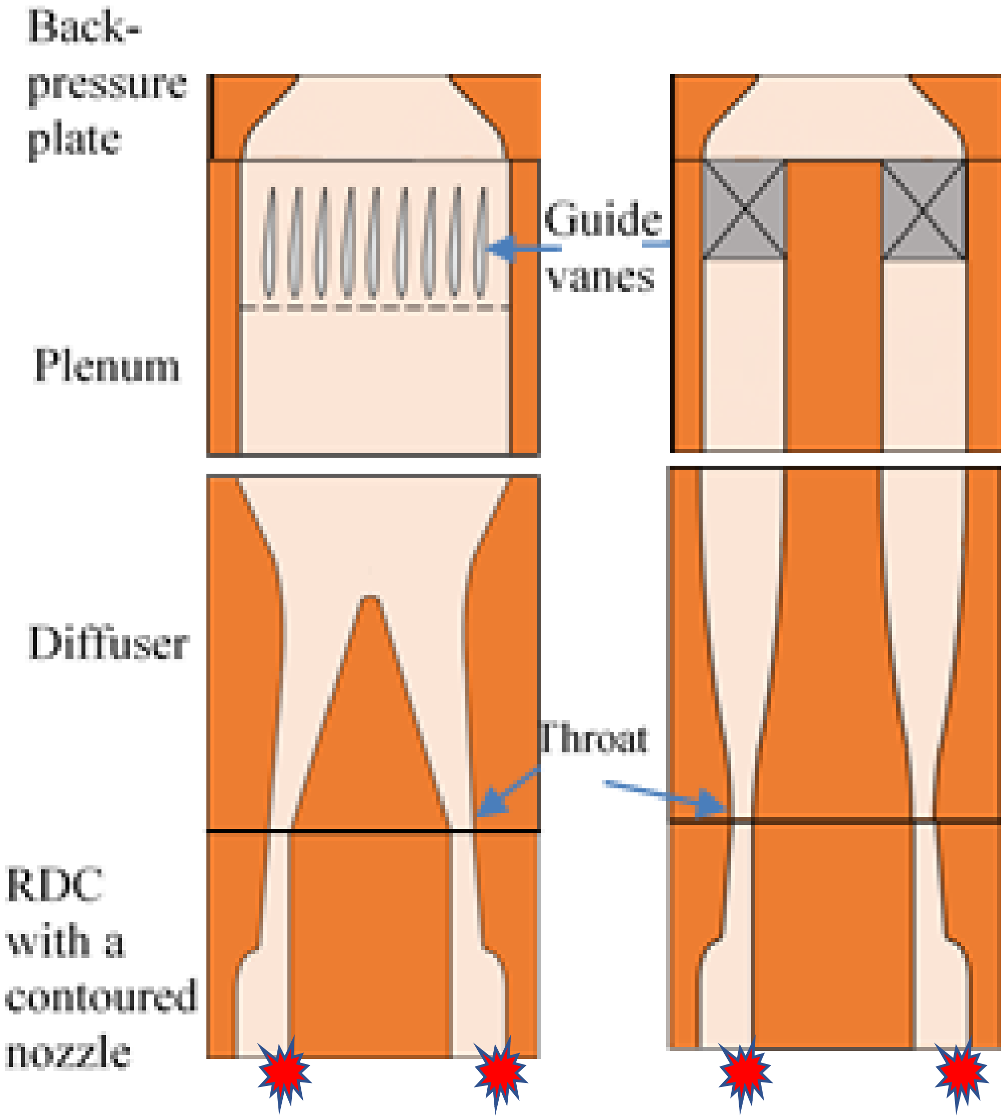


Fig. 1 Conceptual Diagram of RDC-turbine integration; F-class turbines (left) and aero-derivative turbines (right).

- In this study, we will develop robust methodology to condition the RDC flow to reduce spatial and temporal non-uniformities.

- We plan to utilize converging section with a contoured profile of the combustor channel.

- Rapid reduction in area downstream of the detonation will constrain the detonation products. This would increase detonation stability, decouple detonation from reflection waves, and constrain flow towards the axial direction.

- Rapid reduction in area is followed by gradual reduction in area of the channel.

Annular RDE Test Stand and PID of Reactant Supply System

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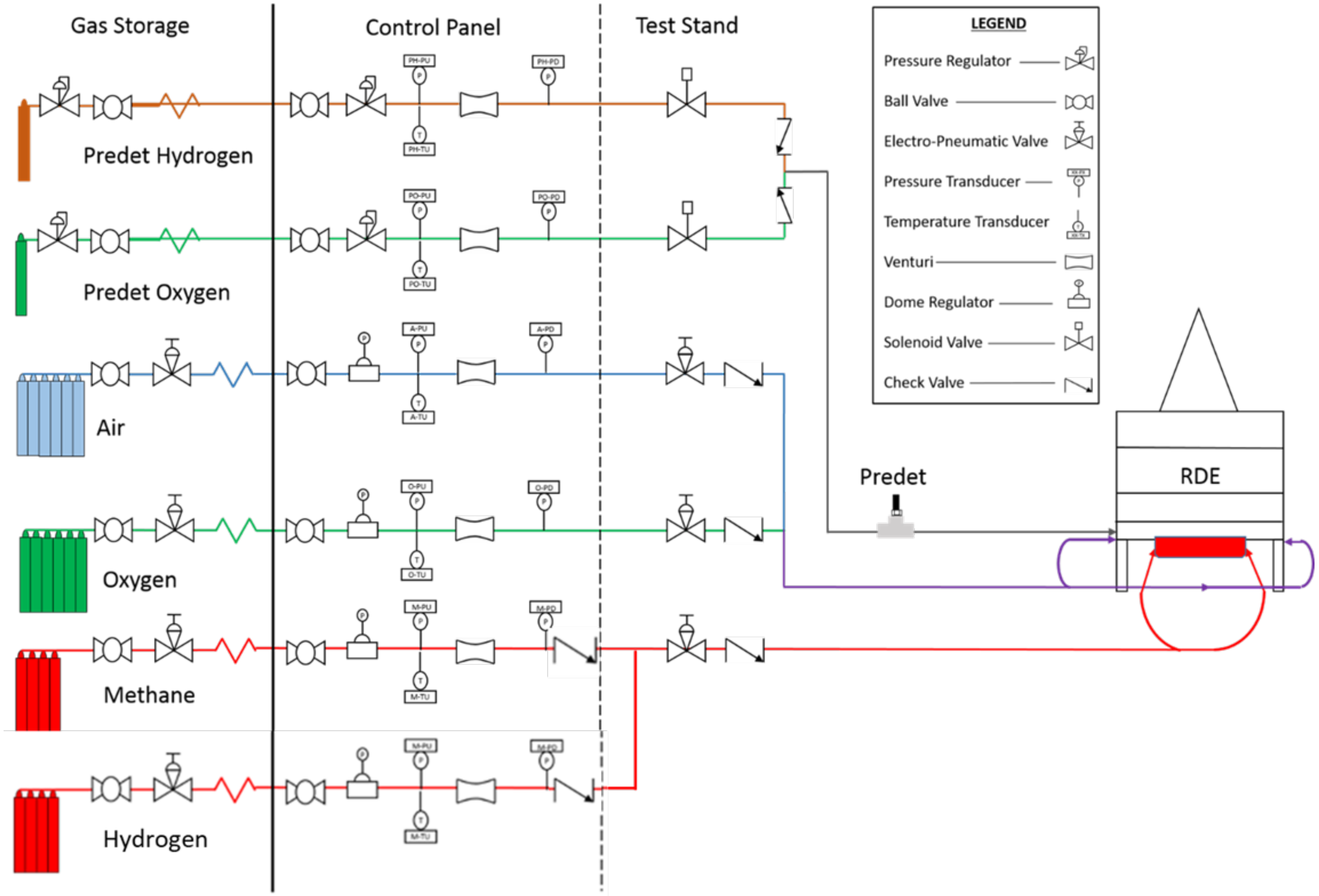
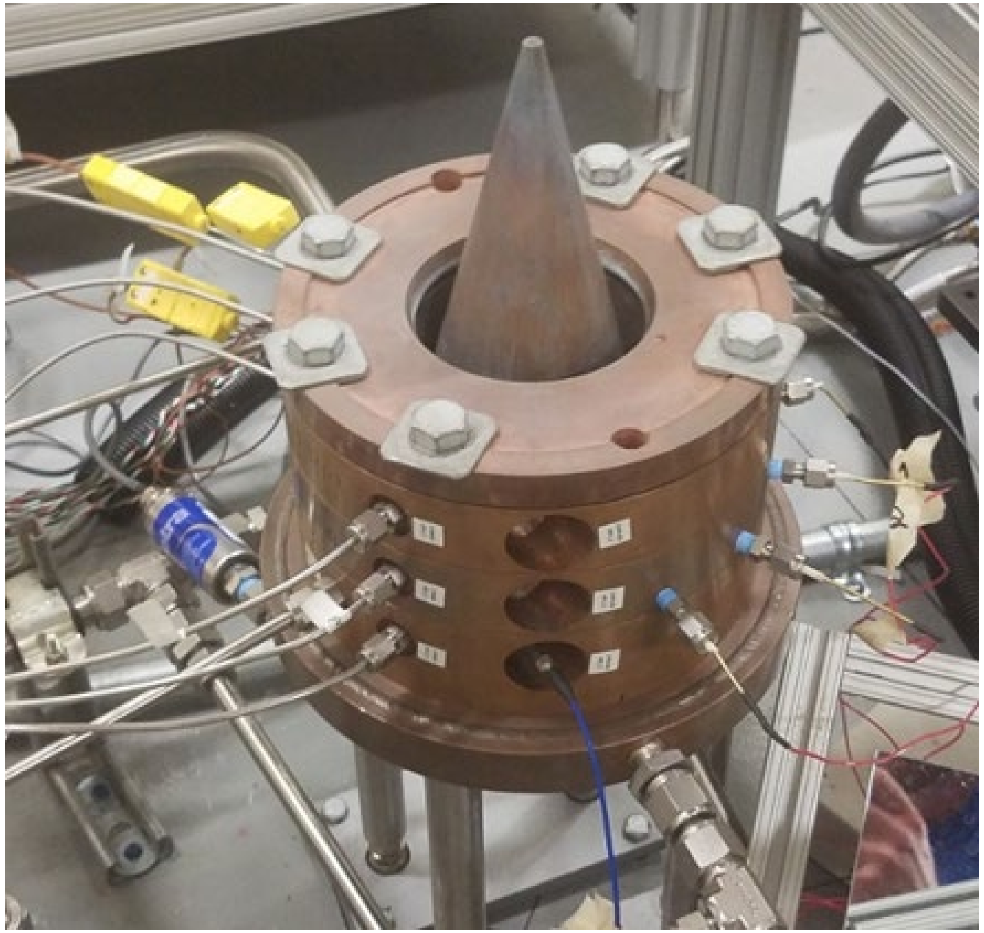


Image of the Rotating Detonation Combustor at the University of Alabama



- Wave Speed ≈ 2000 m/s, Max Flow Velocity > 1000 m/s
- 10 cm Diameter RDC ⟶ Power Output: Up to 5 MW

H_2 in Fuel Steam (Newly added to the facility)

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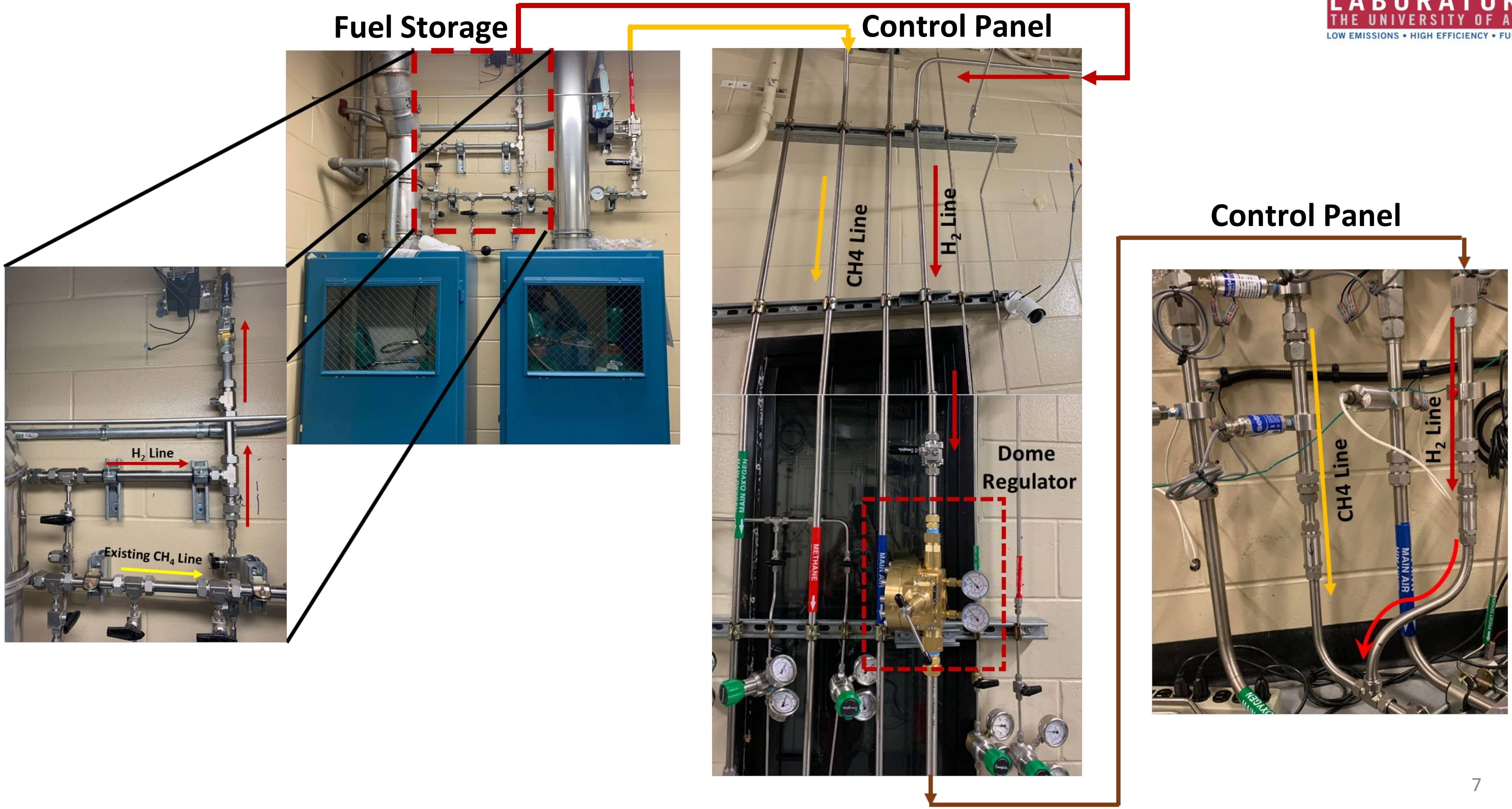
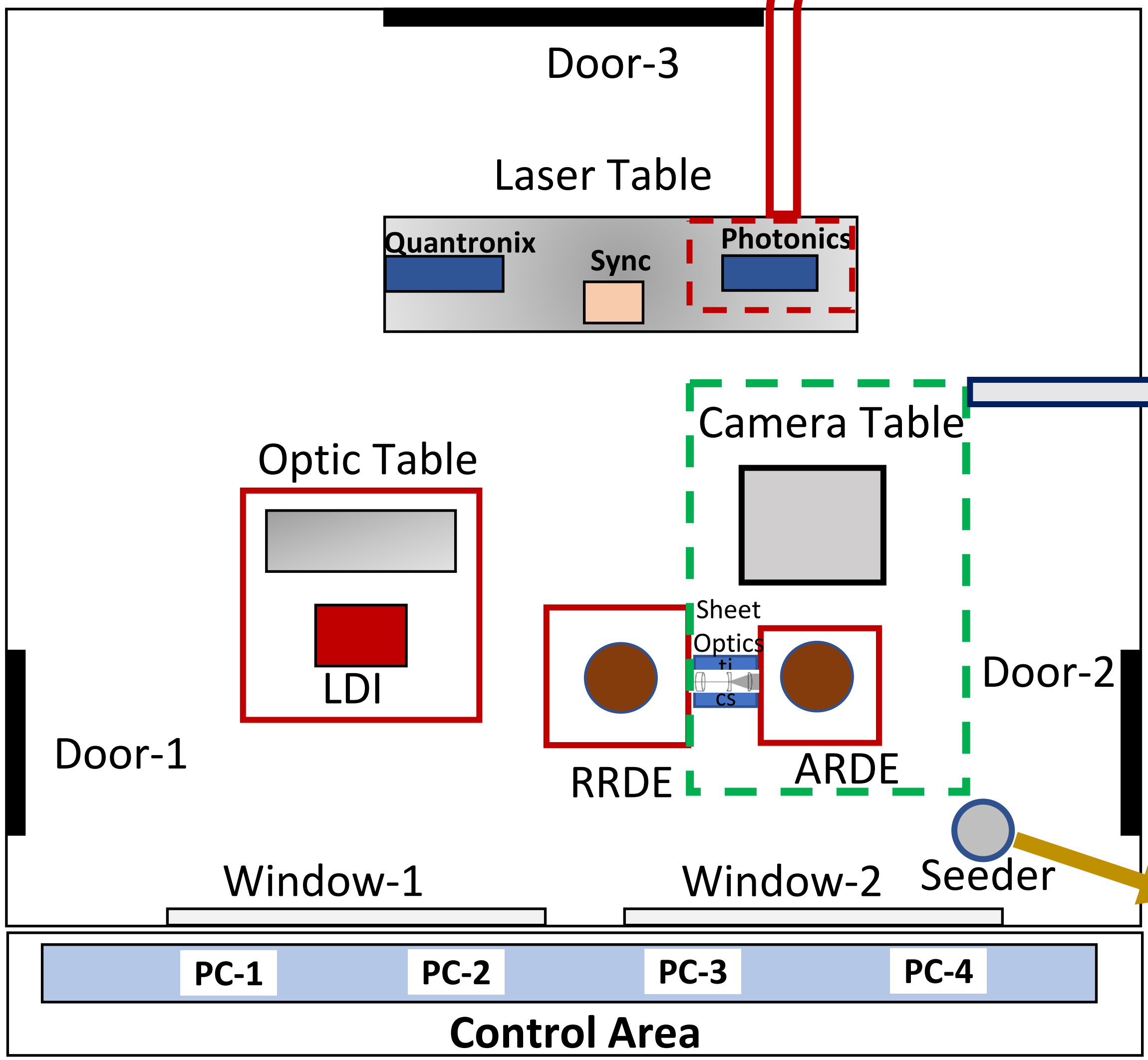


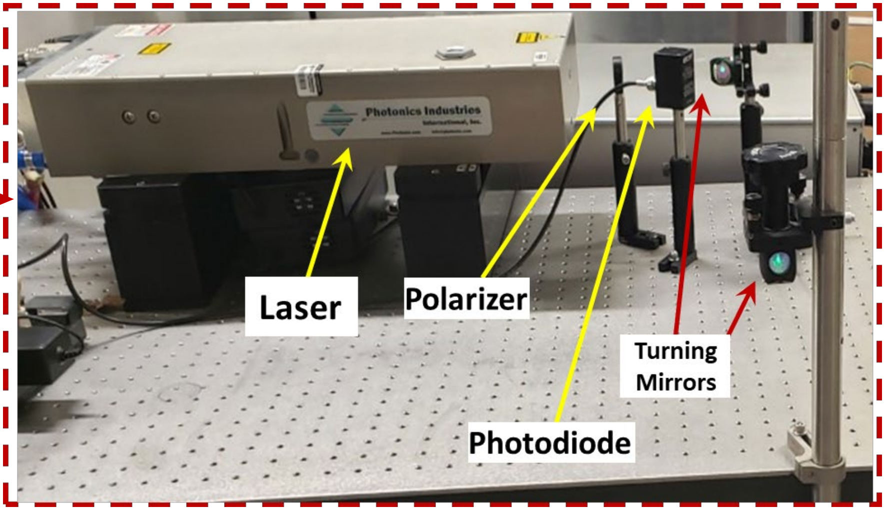
Data Acquisition Capabilities

- **Probe Measurement**
  - Pressure at upstream and downstream of sonic nozzles at 10 kHz
  - Temperature at upstream of sonic nozzle at 10 kHz
  - RDC Pressure measurement
    - Plenum Pressure (CTAP) at 10 kHz
    - Static Pressure (CTAP) at 10 kHz
    - Dynamic pressure (PCB) at 1 MHz
  - Ionization Probe Measurement at 1 MHz
- **High Speed Imaging**
- **OH*/CH* Chemiluminescence**
- **Particle Image Velocimetry (PIV) at 100 kHz**
- **Rainbow Schlieren Deflectometry (RSD) at 300 kHz**

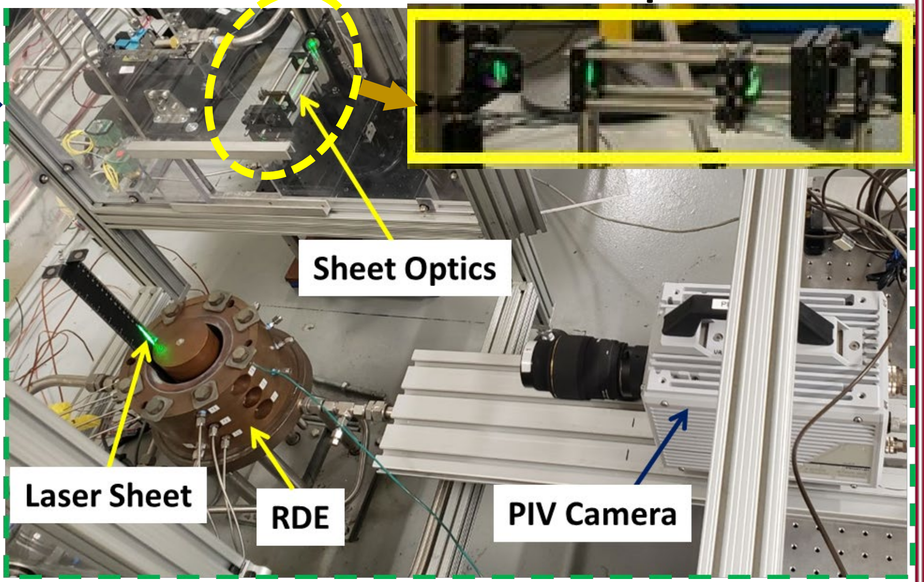
PIV Diagnostics Capabilities

Layout of Test Cell





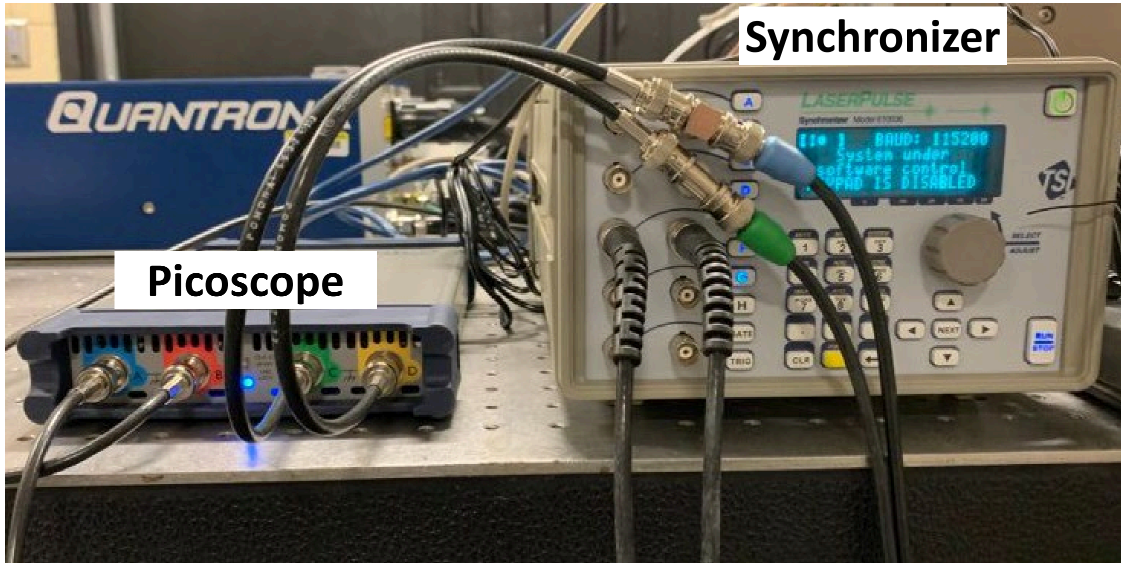
Enlarged Sheet Optics View



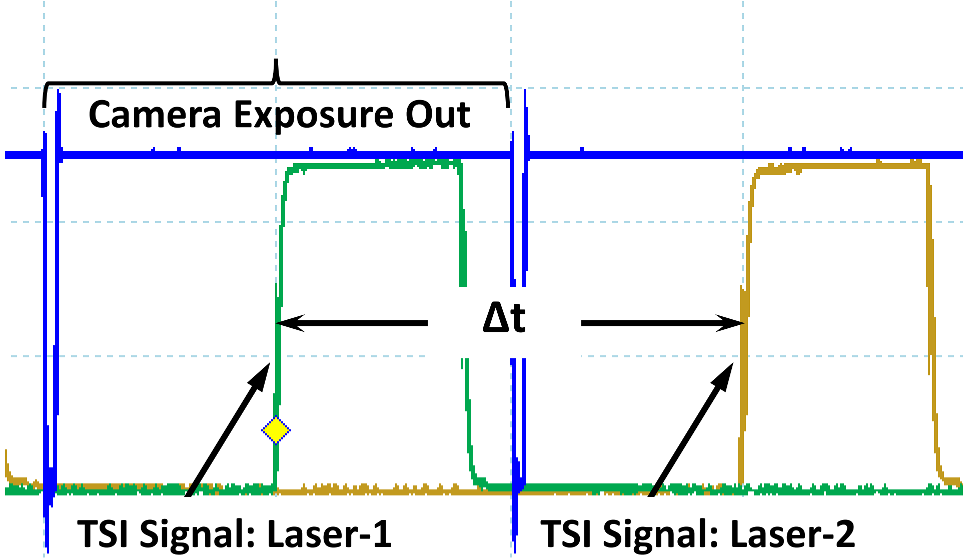
Seeder System

PIV Features

Parameter	Value
PIV Acquisition Frequency	100 kHz
Camera Framing Rate	200 kHz
Camera Exposure	5 μs
Delta T (Time lag bet^n 2 laser pulses)	500 ns
PIV ROI	192 pixel * 128 pixel
Spatial Resolution	102 micron/pixel
Seed Particle	ZrO_2 (dia. 200 nm, melting point 3000 K)
Laser Sheet Thickness at ROI	~1 mm



Output Signals in Picoscope



PIV Image Acquisition Summary

PIV image pairs/Test: ~60000

Image pairs/cycle: 14-16

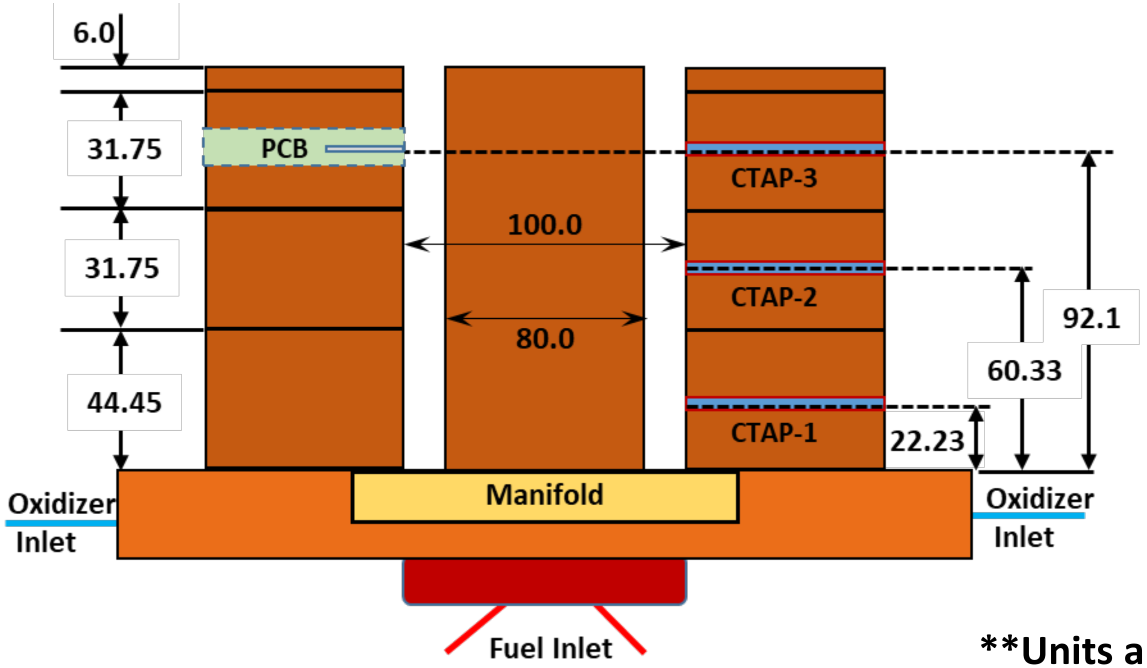
Cycles/Test: 3800-4300

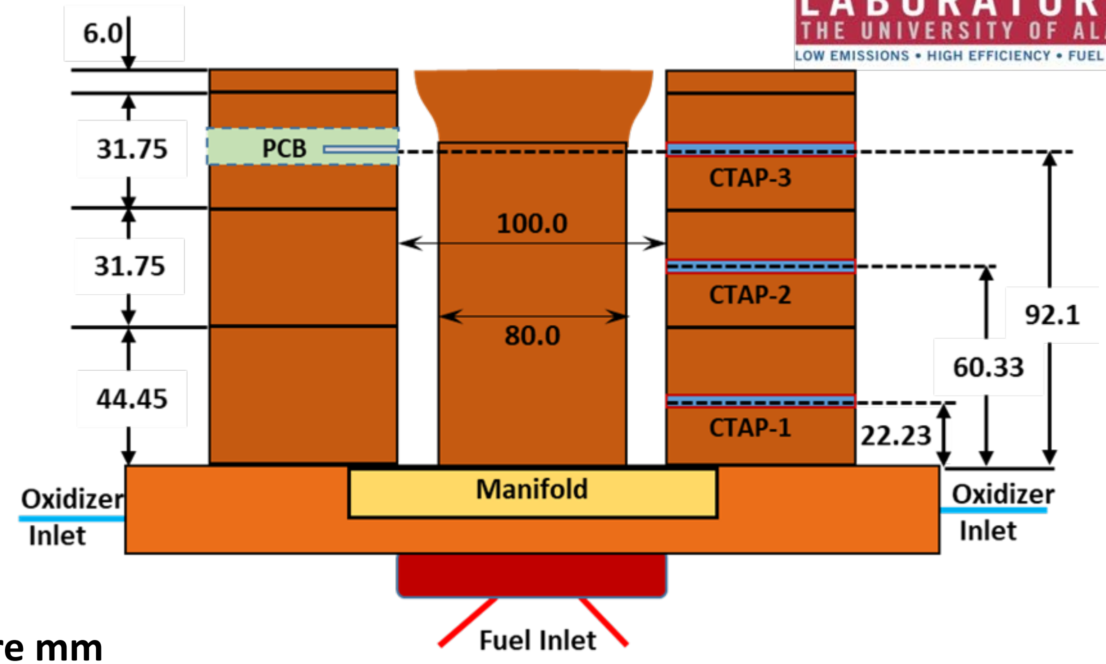
Presentation Overview

- **Convergent nozzles** with different area ratios
- Methane-hydrogen blends
- RTG profiling of the Inner wall of RDC channel
- Plenum chamber with optical access

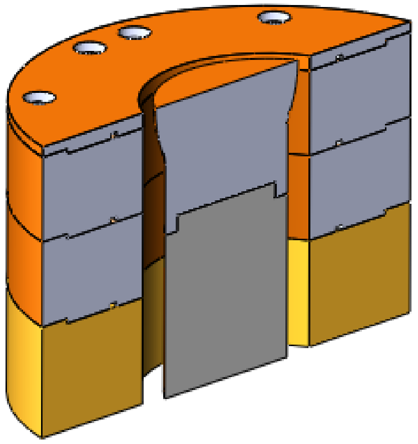
- Computational effort

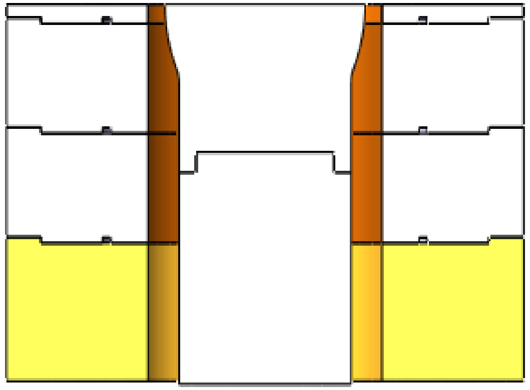
Converging Nozzle with Different Area Ratio (AR)



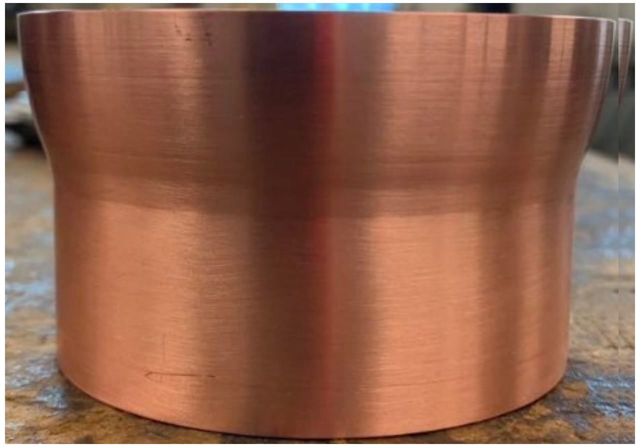


**Units are mm





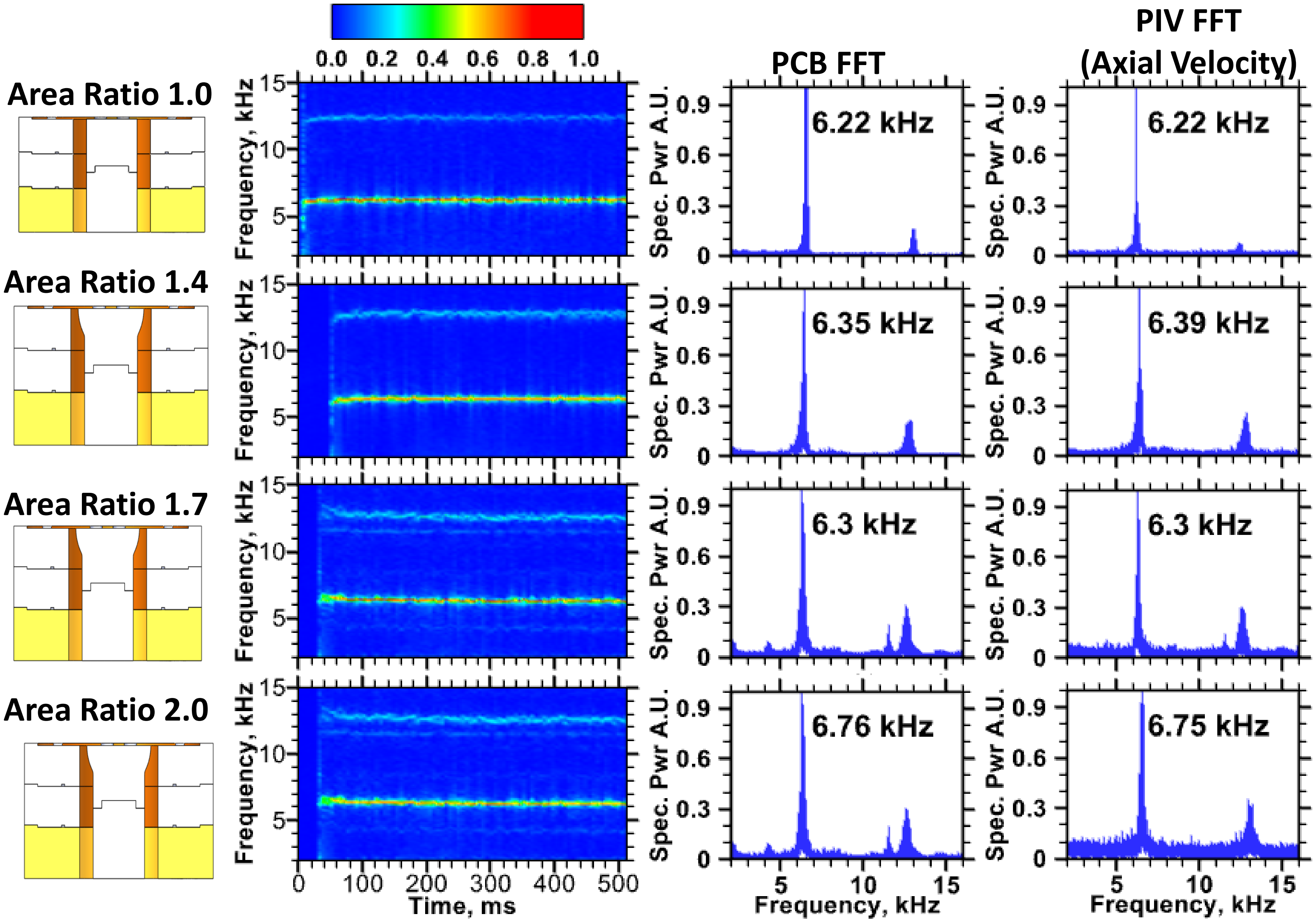
CONVERGENT NOZZLE



$$Area\ Ratio\ (AR) = \frac{Annulus\ Area}{Annulus\ Area\ at\ Nozzle\ Throat}$$

AR: 1.0, 1.4, 1.7, 2.0

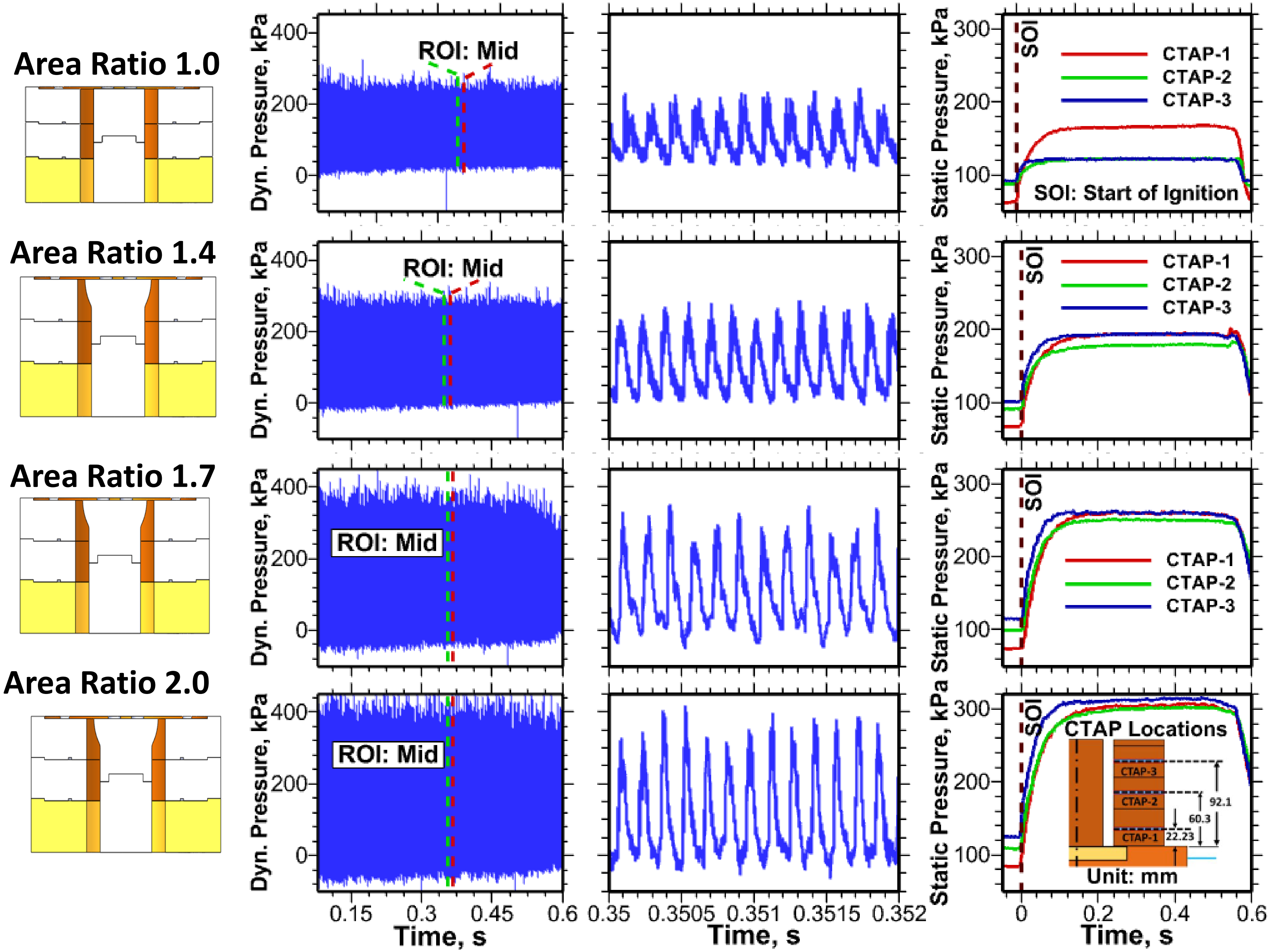
Wave Mode Analysis



Experimental Condition

- **Fuel:**
  CH_4
- **Oxidizer:**
  O_2/N_2 (66.6/33.3 %V)
- **Total Mass Flow Rate:**
  0.7 lbm/s
- **Global Equivalence Ratio:**
  1.0

Pressure Measurements



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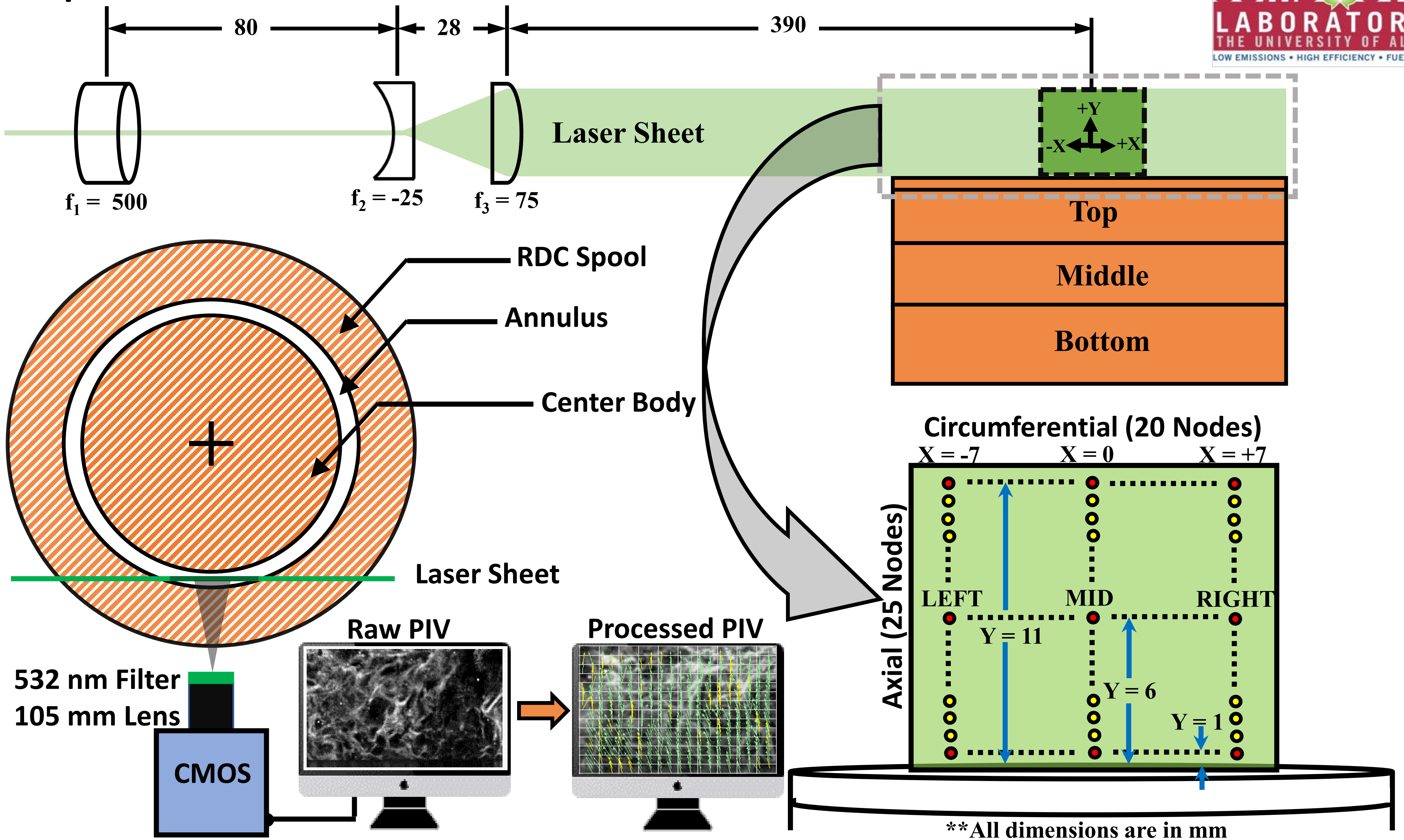
- **Total Mass Flow Rate:**
  0.7 lbm/s
- **Global Equivalence Ratio:**
  1.0

Area Ratio	Pressure fluctuations, q
1.0	0.87
1.4	0.89
1.7	0.92
2.0	0.93

$$q = \frac{P_{cycle\ maxima,mean} - P_{cycle\ minima,mean}}{p_{mean}}$$

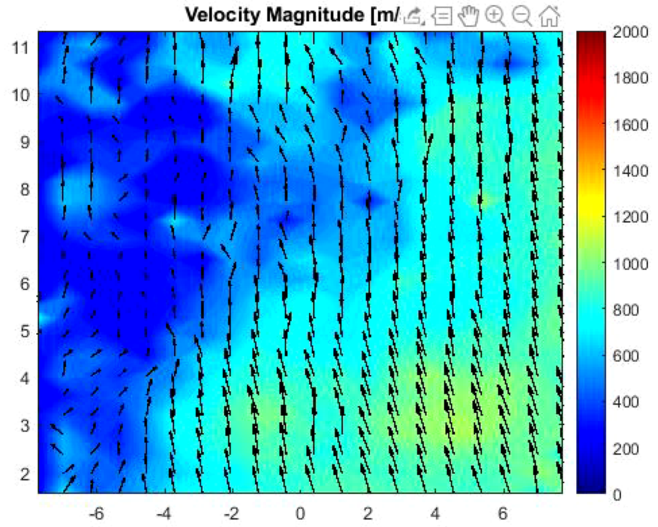
PIV Setup



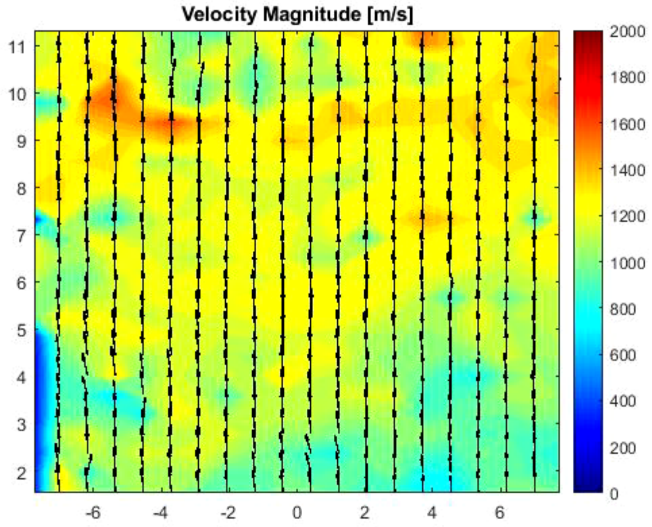
**All dimensions are in mm

Video @ Velocity Magnitude

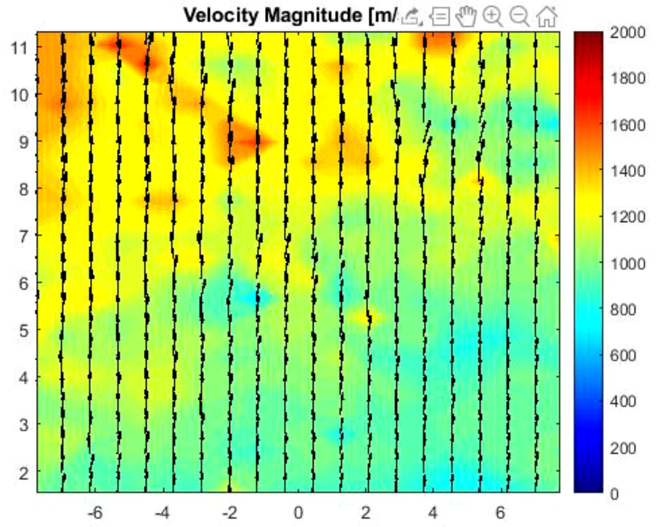
AR 1, CH4, 0.7 lbm/s



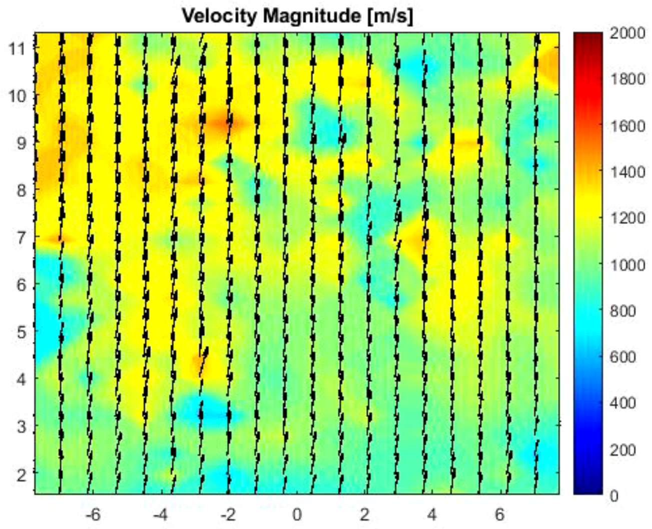
AR 1.7, CH4, 0.7 lbm/s



AR 1.4, CH4, 0.7 lbm/s



AR 2.0, CH4, 0.7 lbm/s



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Experimental Condition

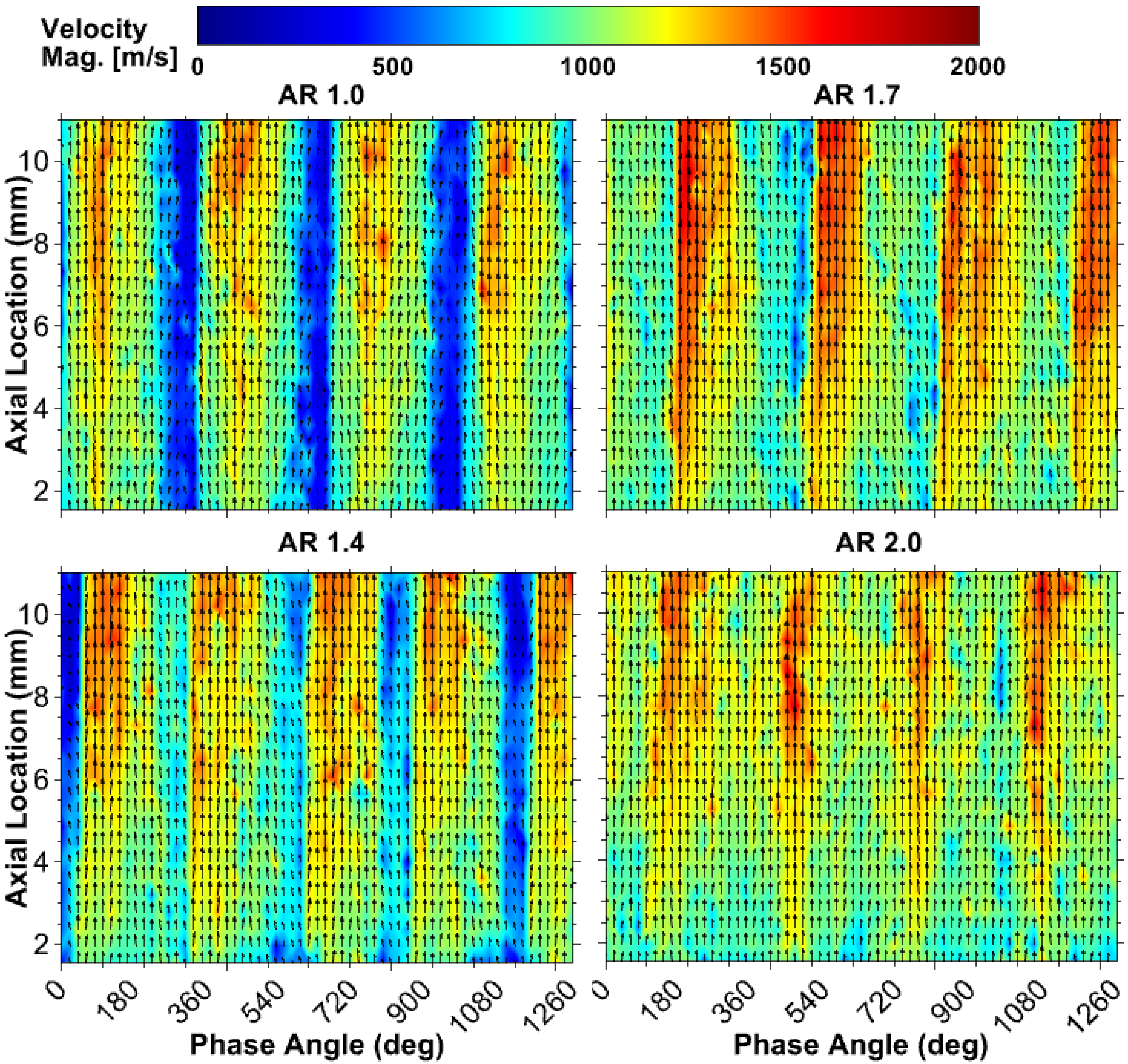
- **Fuel:**
  CH_4
- **Oxidizer:**
  O_2/N_2 (66.6/33.3 %V)
- **Total Mass Flow Rate:**
  0.7 lbm/s
- **Global Equivalence Ratio:**
  1.0

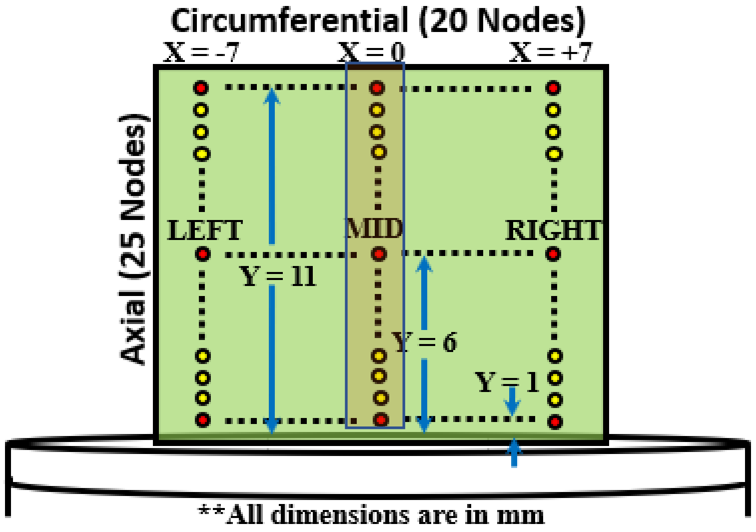
Start Time: ~105 ms after SOI

Video Duration in Actual Test: 0.6 ms

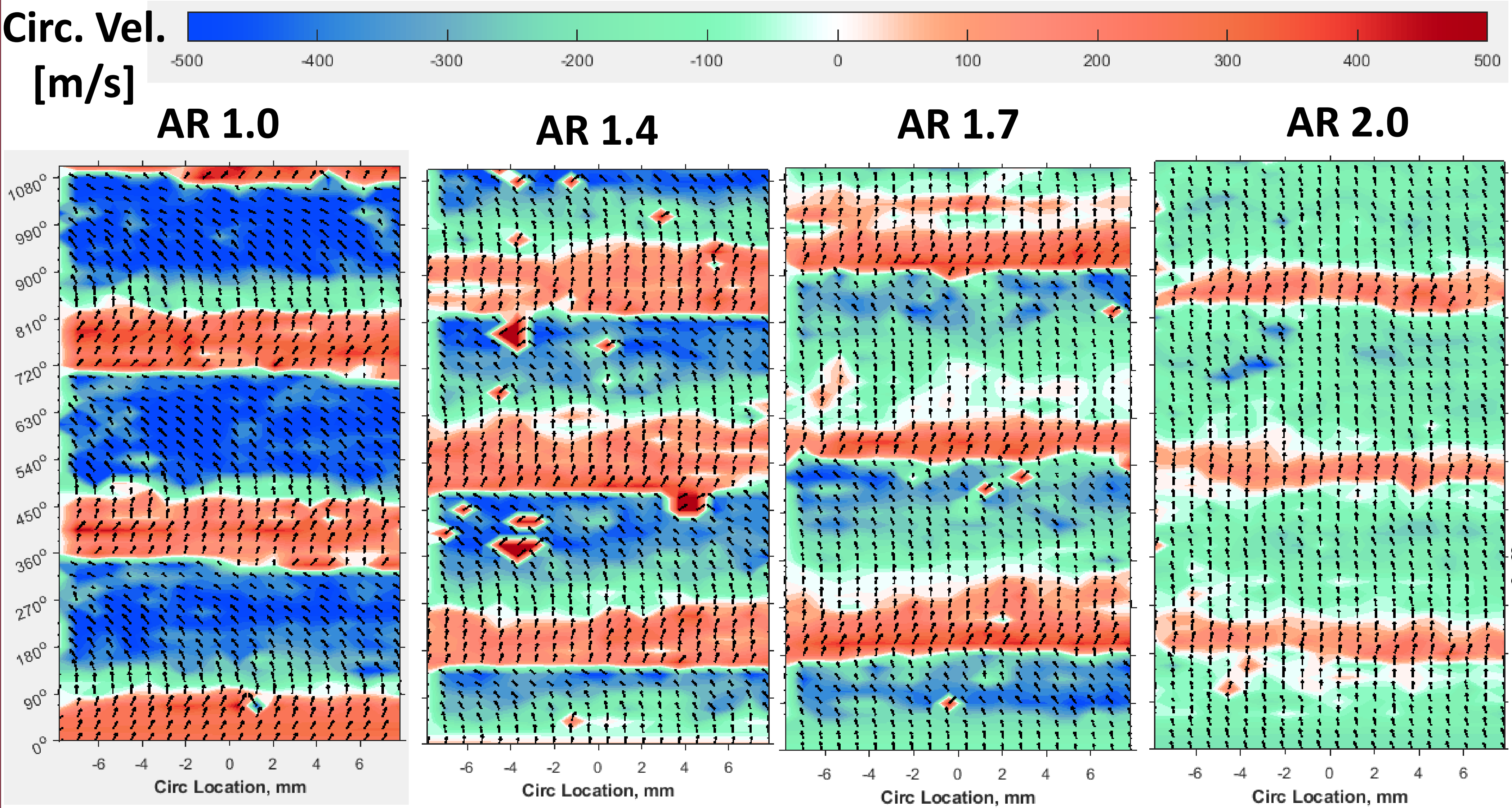
Video Frame Rate: 10 frame/s

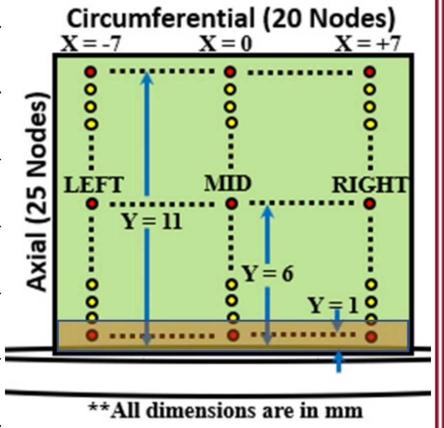
Inter Cycle Behavior

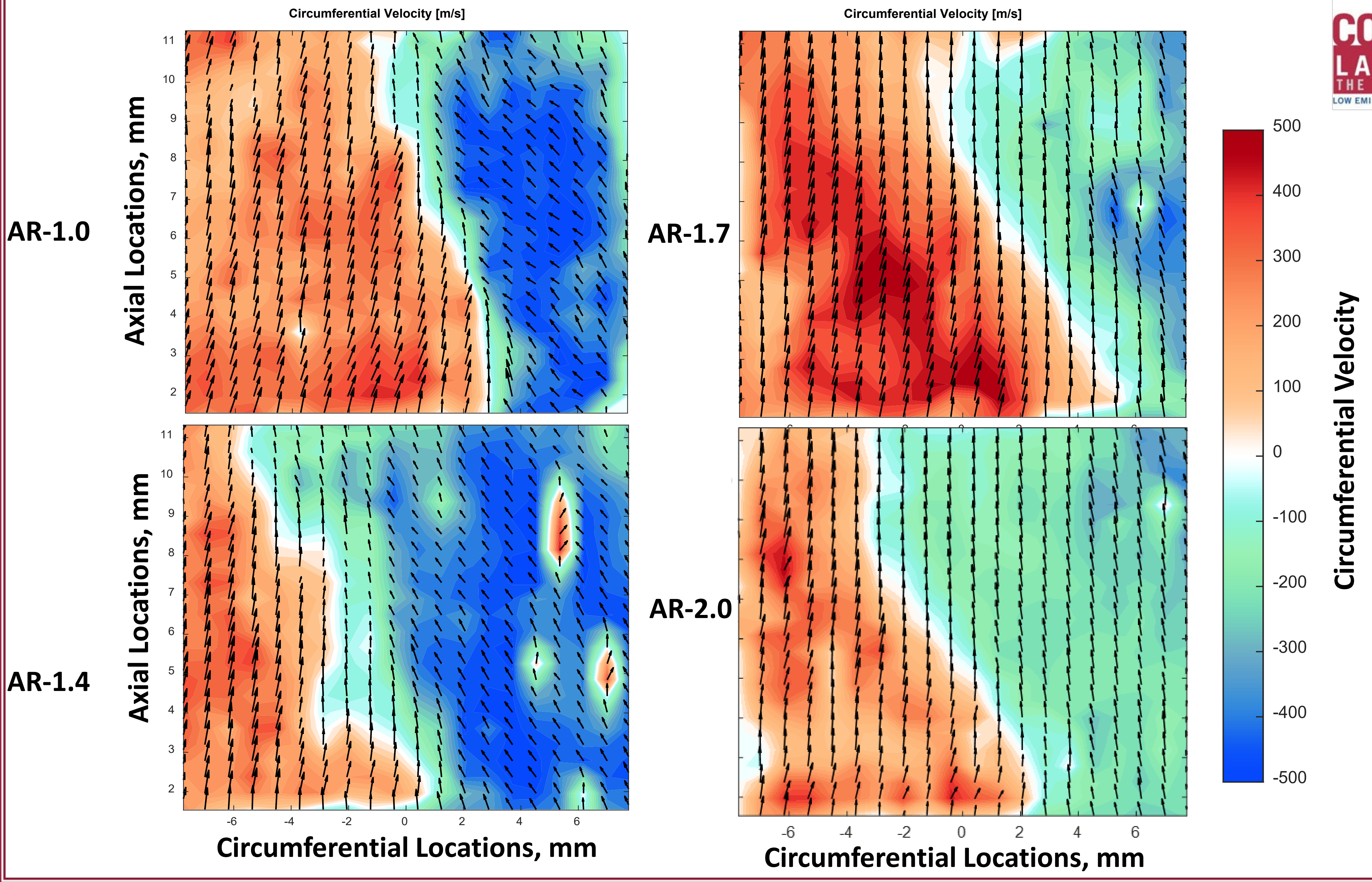




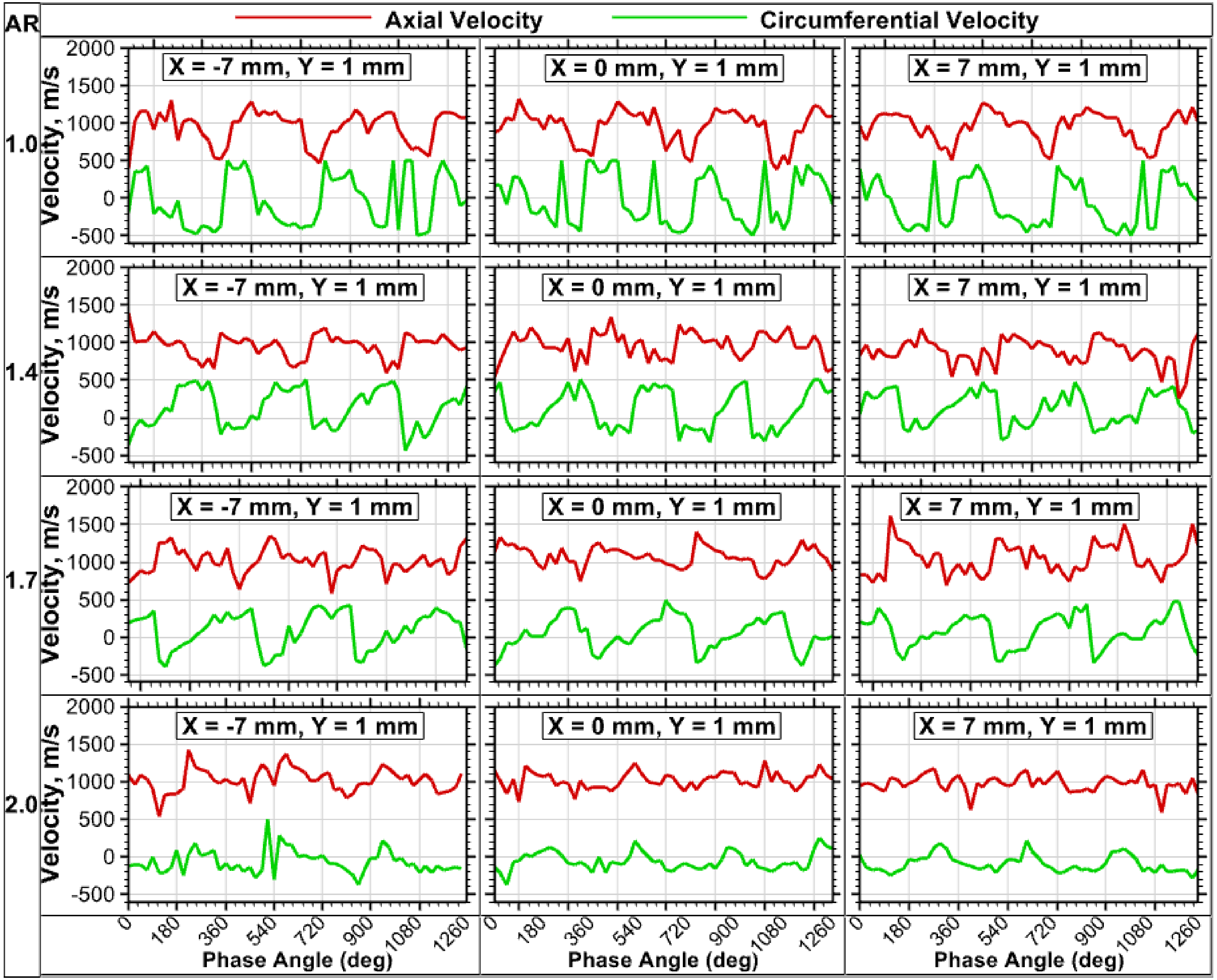
Cycle to Cycle Variation at RDC Exit



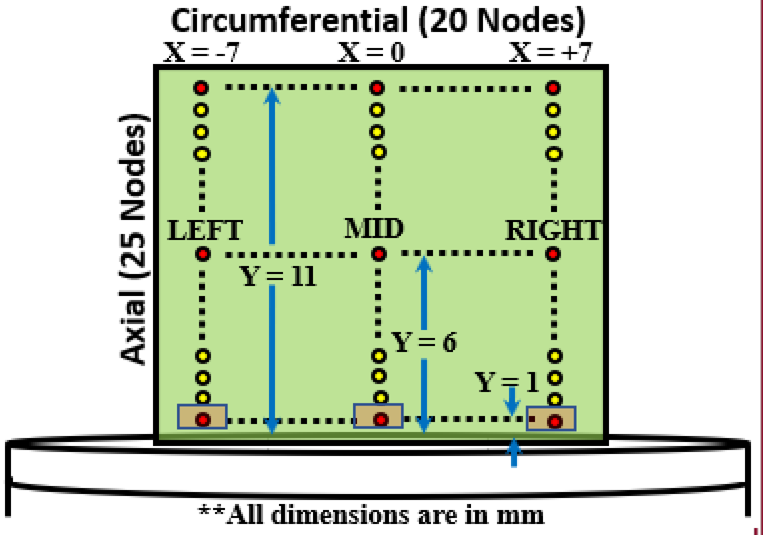




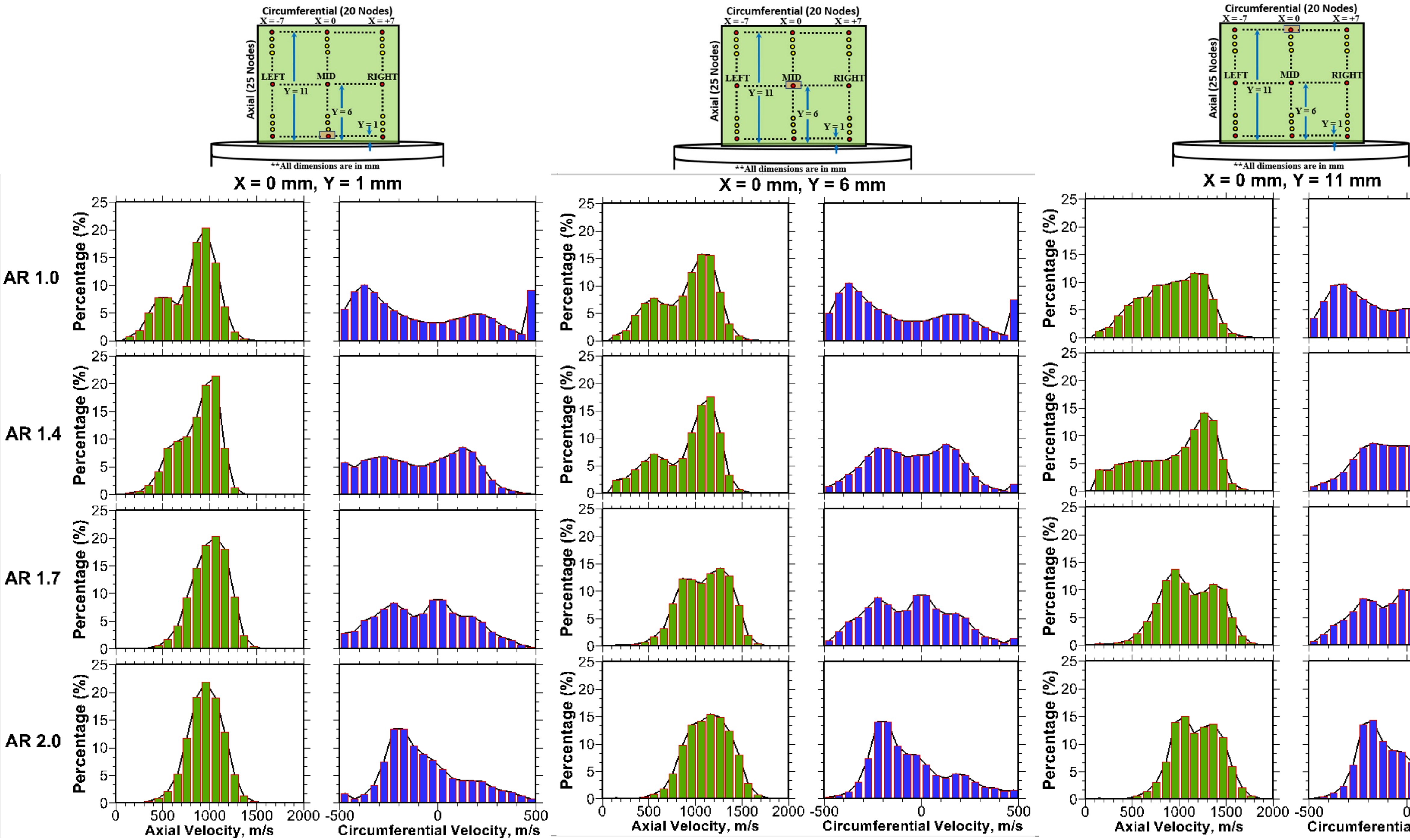
Circumferential Velocity [m/s]
Circumferential Velocity [m/s]
AR-1.0
AR-1.7
AR-1.4
AR-2.0
Axial Locations, mm
Axial Locations, mm
Circumferential Locations, mm
Circumferential Locations, mm
Circumferential Velocity
500
400
300
200
100
0
-100
-200
-300
-400
-500



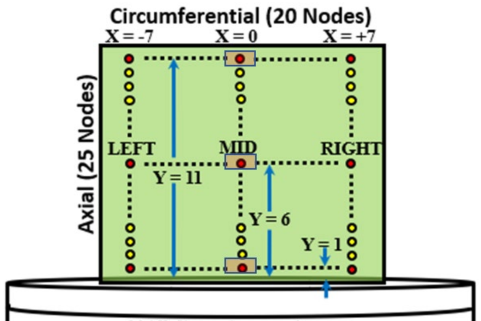
AR
Axial Velocity
Circumferential Velocity
1.0
1.4
1.7
2.0
Velocity, m/s
X = -7 mm, Y = 1 mm
X = 0 mm, Y = 1 mm
X = 7 mm, Y = 1 mm
Phase Angle (deg)



Circumferential (20 Nodes)
X = -7
X = 0
X = +7
Axial (25 Nodes)
LEFT
MID
RIGHT
Y = 11
Y = 6
Y = 1
**All dimensions are in mm



Circumferential (20 Nodes)
X = -7
X = 0
X = +7
Axial (25 Nodes)
LEFT
MID
RIGHT
Y = 11
Y = 6
Y = 1
**All dimensions are in mm
X = 0 mm, Y = 1 mm
X = 0 mm, Y = 6 mm
X = 0 mm, Y = 11 mm
AR 1.0
AR 1.4
AR 1.7
AR 2.0
Percentage (%)
Axial Velocity, m/s
Circumferential Velocity, m/s



**All dimensions are in mm

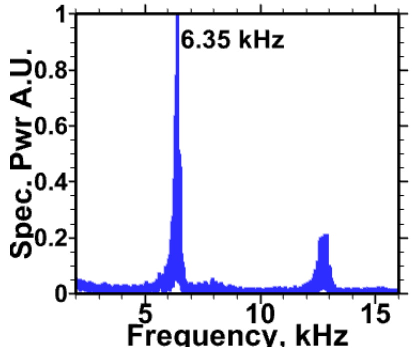
Node Location	Area Ratio	Axial Velocity				Circumferential Velocity	
		μ (m/s)	σ (m/s)	% data in μ±100m/s	% data in μ±200m/s	% data in ±200m/s	% data in ±300m/s
X = 0; Y = 1	1.0	819	246	29	56	36	55
	1.4	872	215	30	63	59	81
	1.7	995	197	38	70	63	84
	2.0	953	182	42	74	73	90
X = 0; Y = 6	1.0	899	301	20	42	39	64
	1.4	913	318	18	39	69	89
	1.7	1093	257	24	51	67	87
	2.0	1129	234	30	58	73	91
X = 0; Y = 11	1.0	921	323	20	40	47	72
	1.4	959	387	13	28	76	92
	1.7	1100	294	21	44	72	90
	2.0	1184	250	25	54	77	93

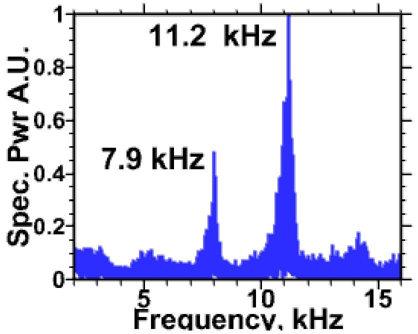
Effect on hydrogen addition

Area Ratio 1.4

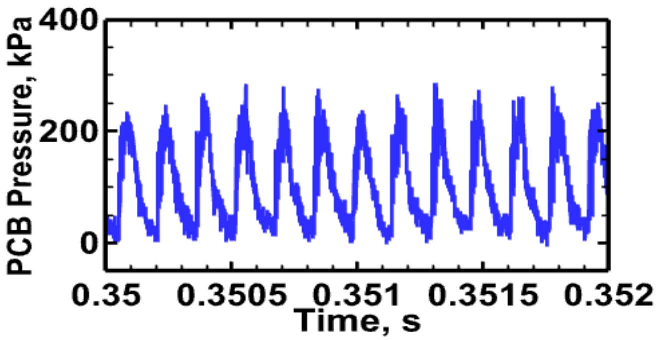
Single Wave: CH_4; 0.7 lbm/s | **More than one wave: 50/50 CH_4/H_2; 0.7 lbm/s**

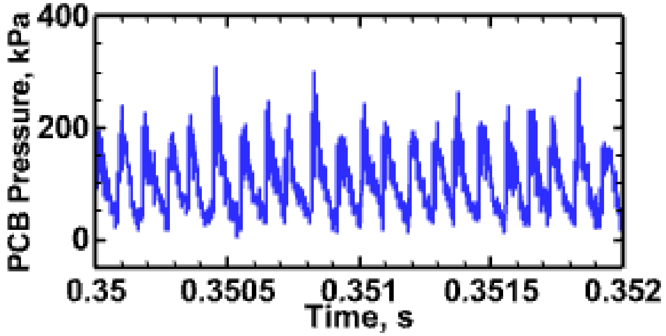
PCB FFT



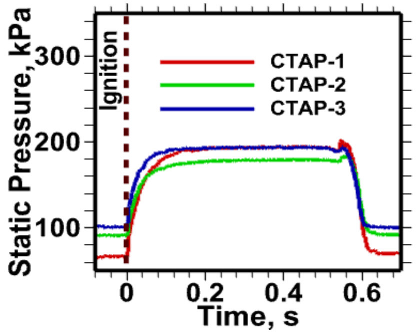


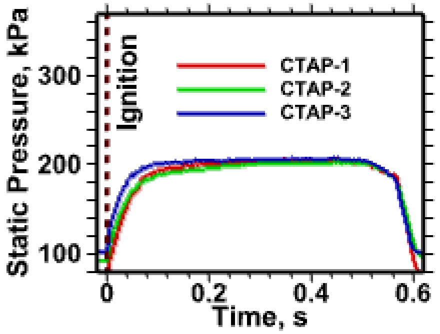
PCB Data: Dynamic Pressure





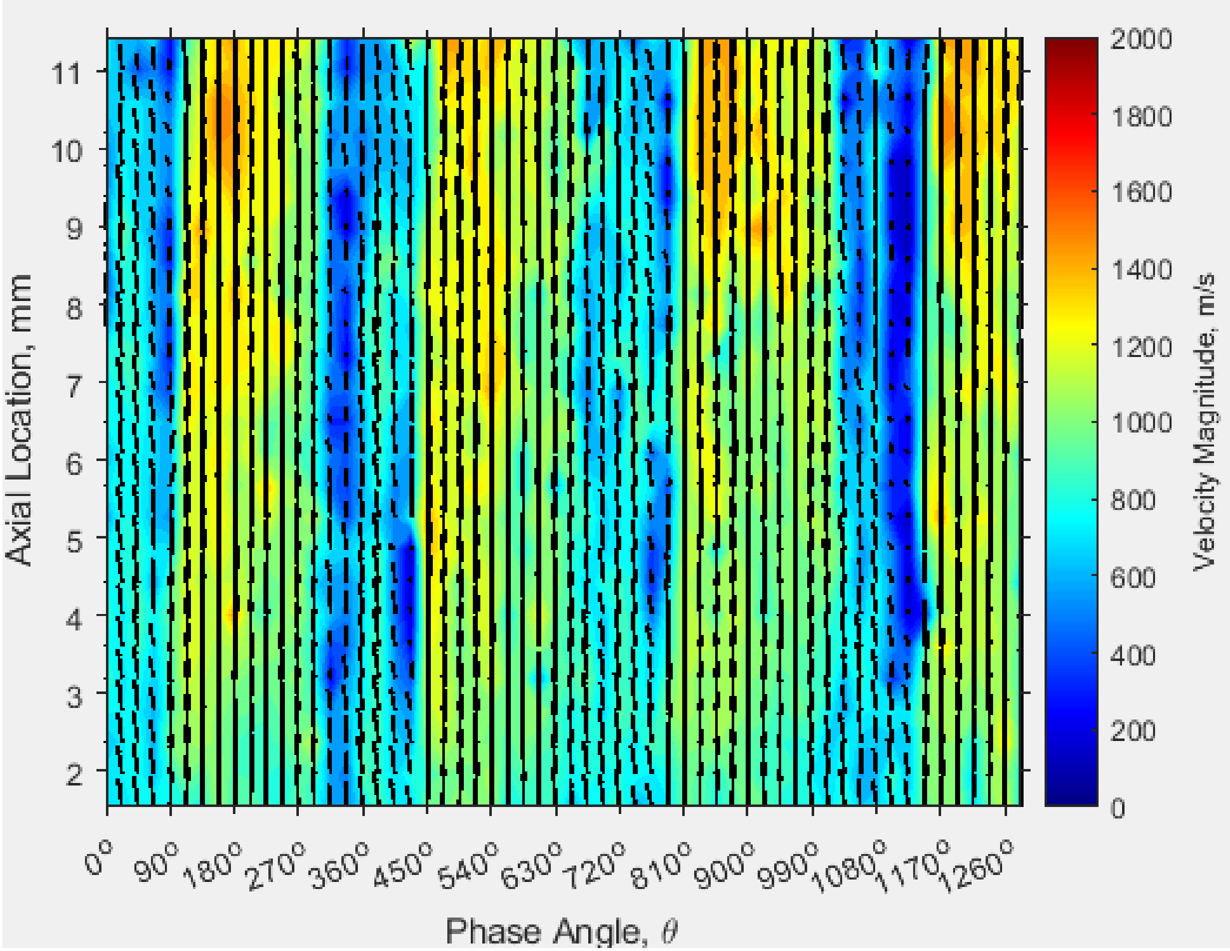
CTAP Data: Static Pressure



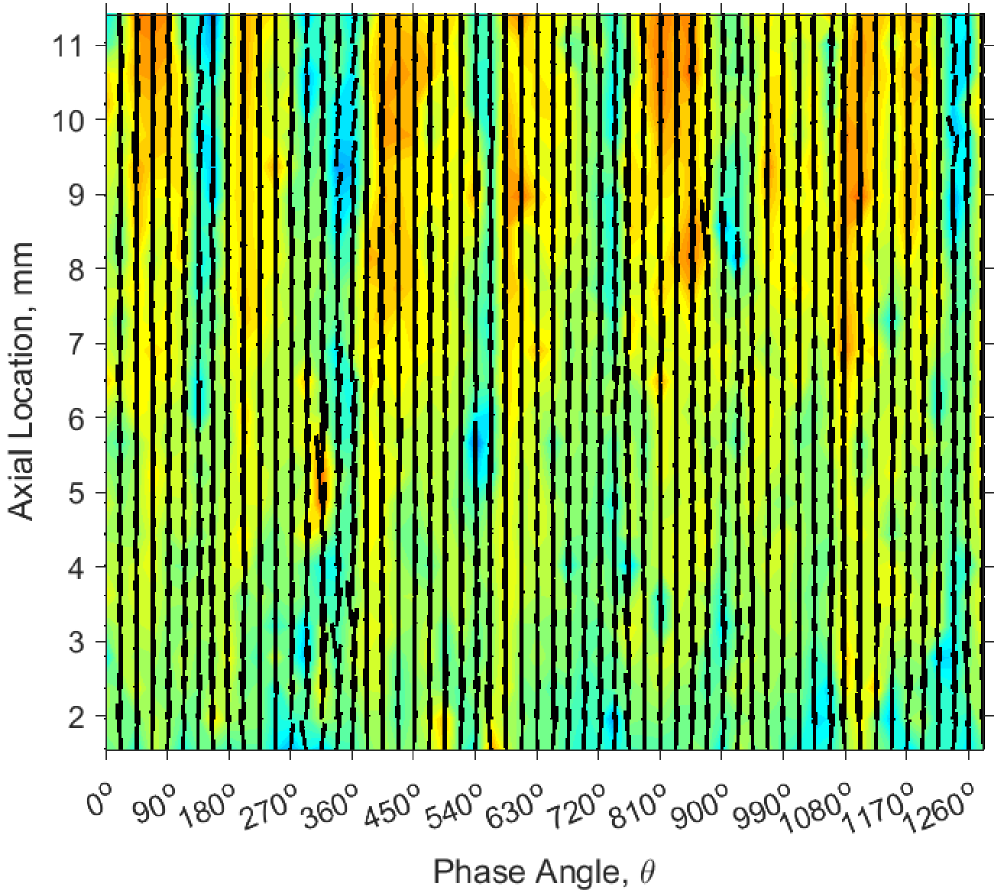


Convergent Nozzle: Area Ratio 1.4

Single Wave: CH4; 0.7 lbm/s

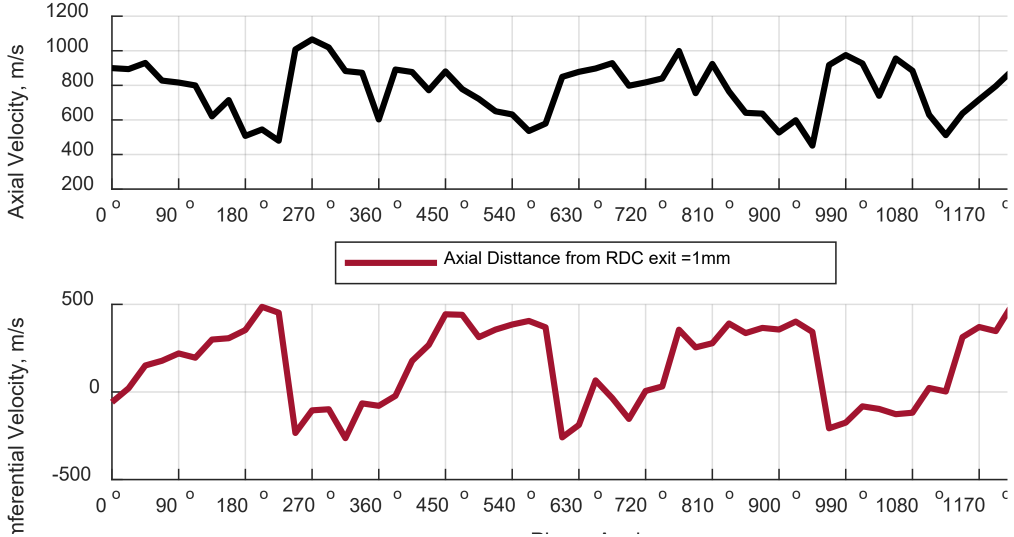


More than one wave: 50/50 CH4/H2; 0.7 lbm/s

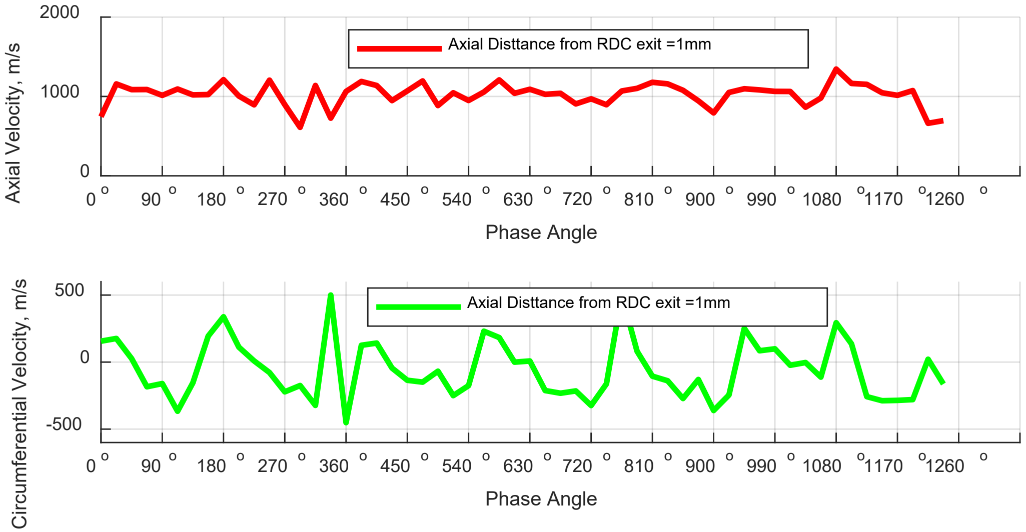


Convergent Nozzle: Area Ratio 1.4

CH4/Single Wave



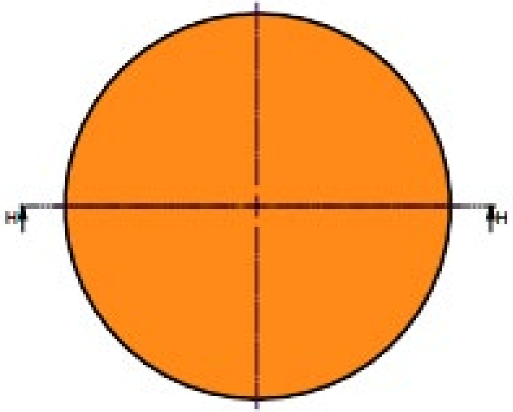
CH4/H2 Blend: Multi (two) Wave

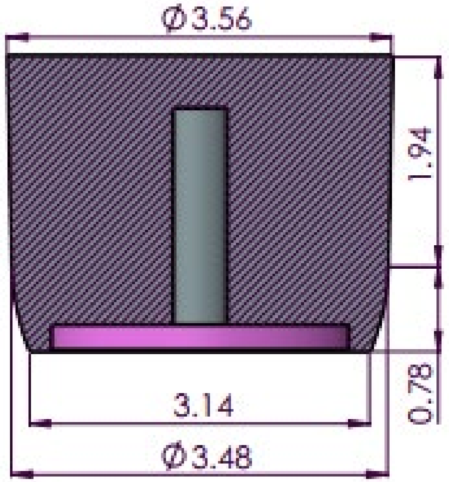


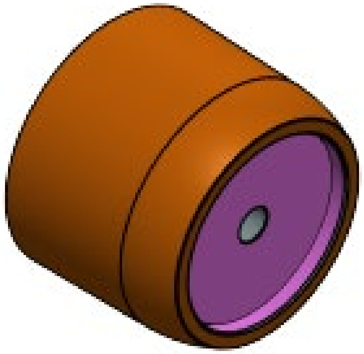
RDC Channel with Profiled Inner Wall

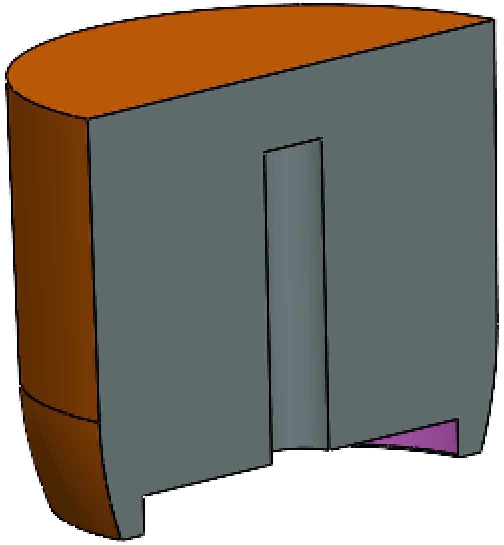
Rapid to Gradual (RTG) Profile on Inner Wall

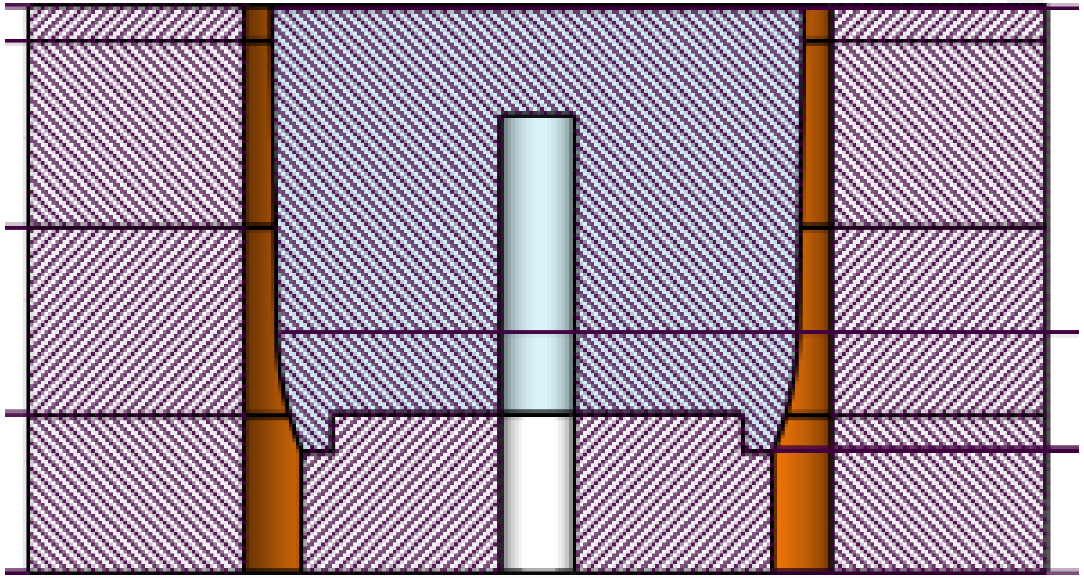
Area Ratio = 2



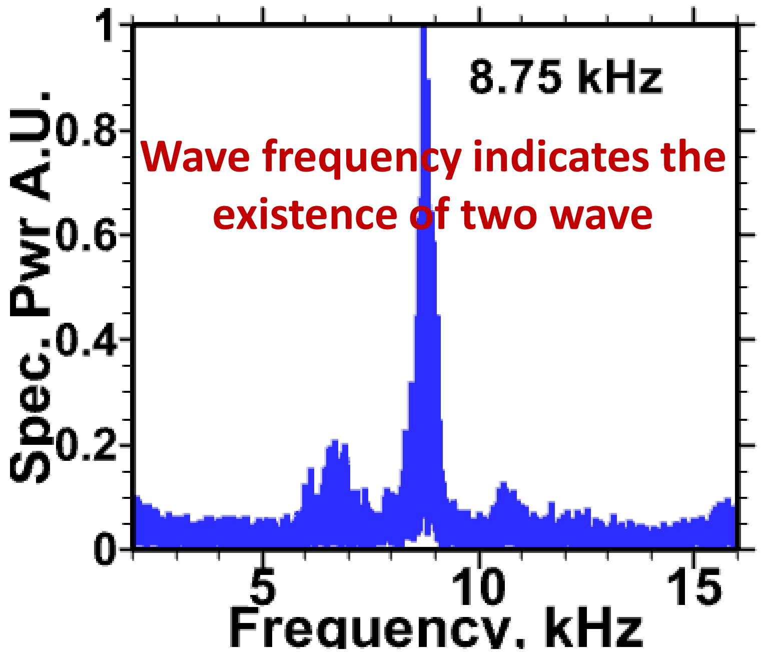


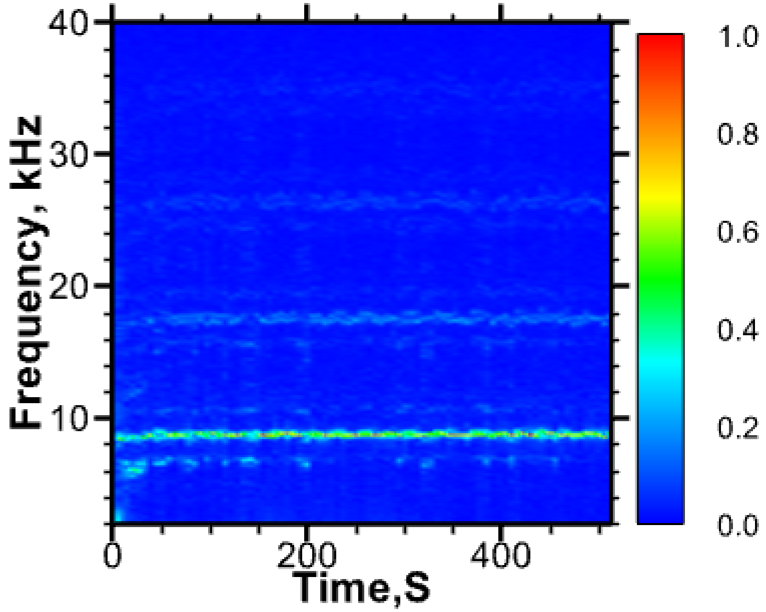


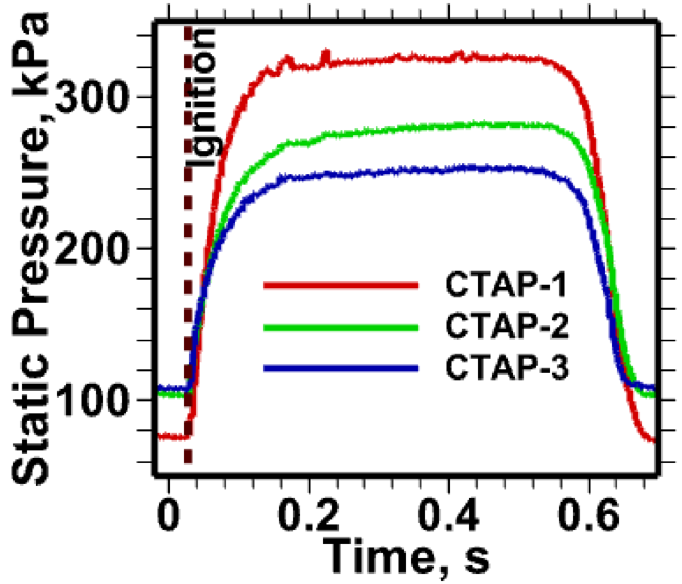


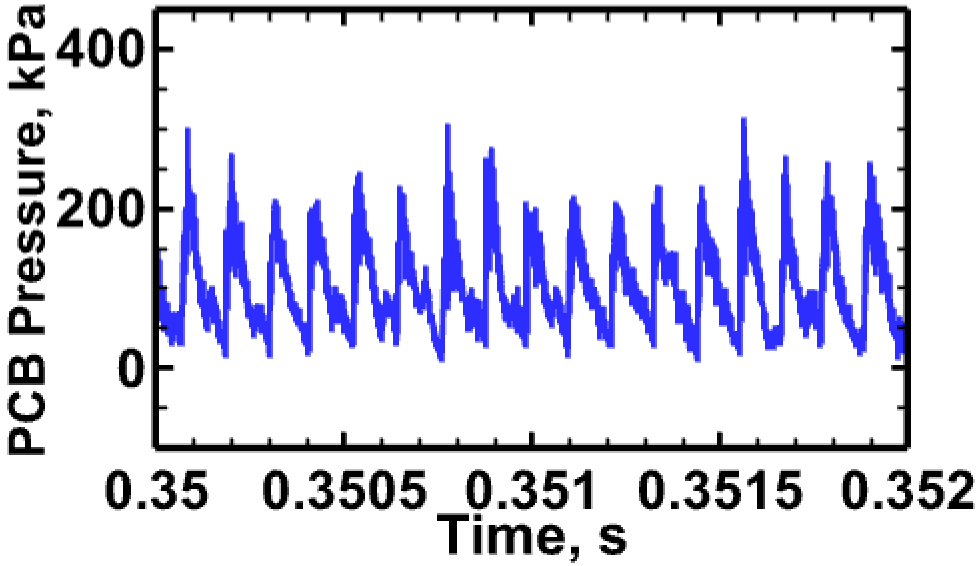


Wave Mode and Pressure Measurement









Experimental Condition

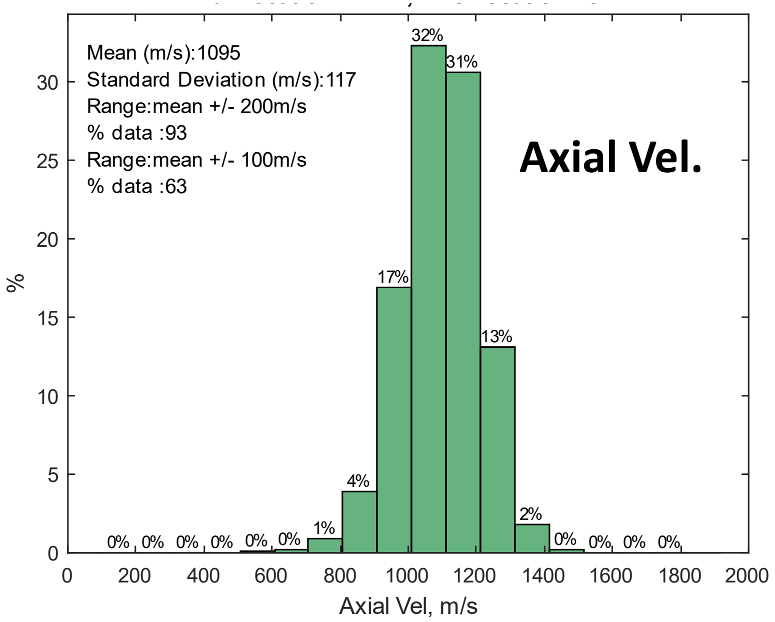
- **Fuel:**
  CH_4
- **Oxidizer:**
  O_2/N_2 (66.6/33.3 %V)
- **Total Mass Flow Rate:**
  0.7 lbm/s

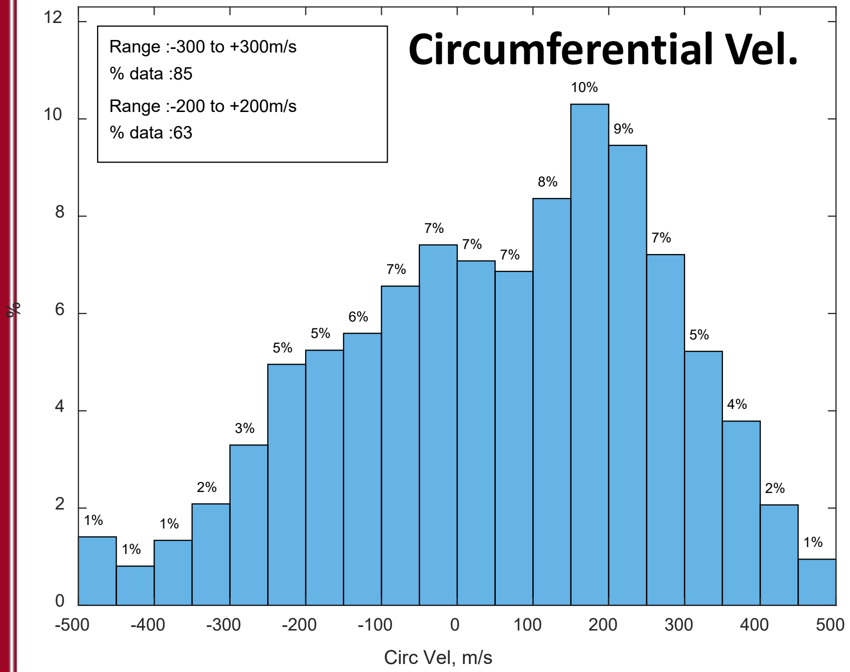
Area Ratio	Pressure fluctuations (q)
1.0	0.87
1.4	0.89
1.7	0.92
2.0	0.93
2.0 RTG	0.71

$$q = \frac{P_{cycle\ maxima,mean} - P_{cycle\ minima,mean}}{p_{mean}}$$

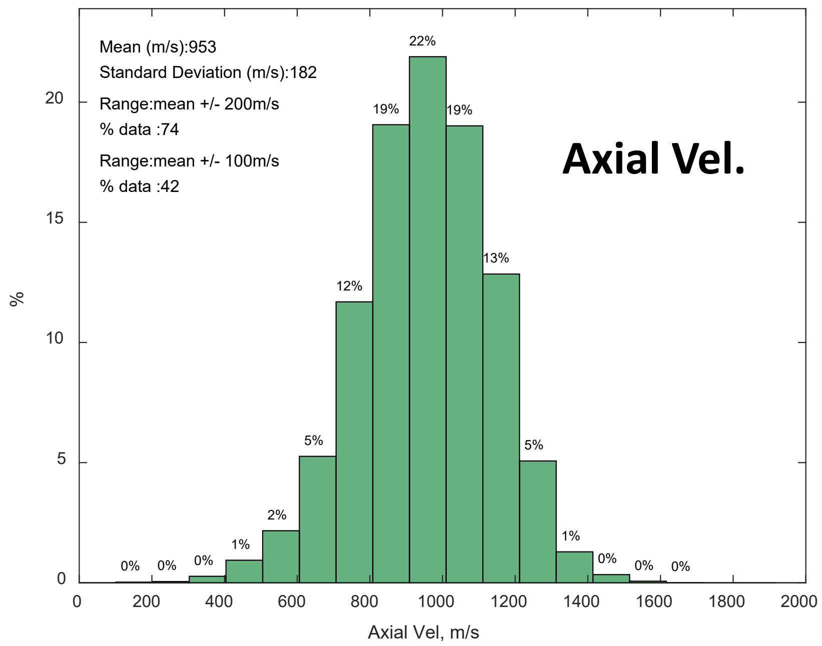
Statistical Analysis (Full Test)

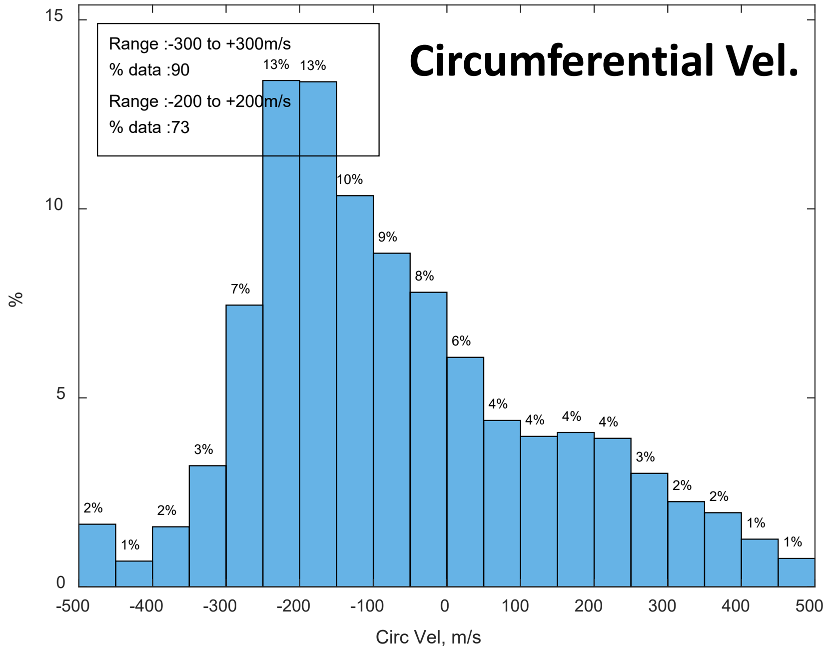
RTG AR 2.0

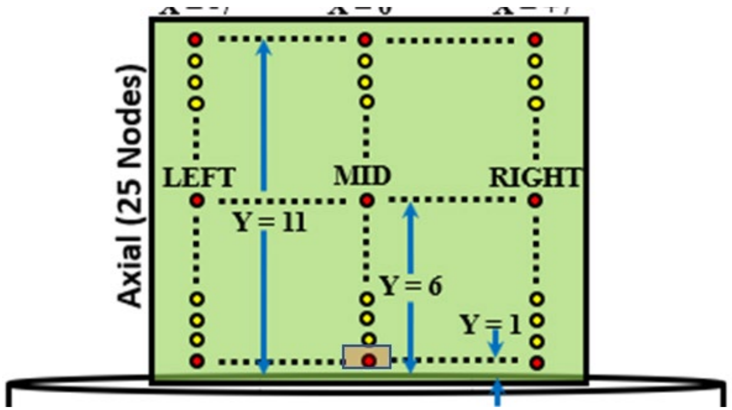




Convergent Nozzle AR 2.0

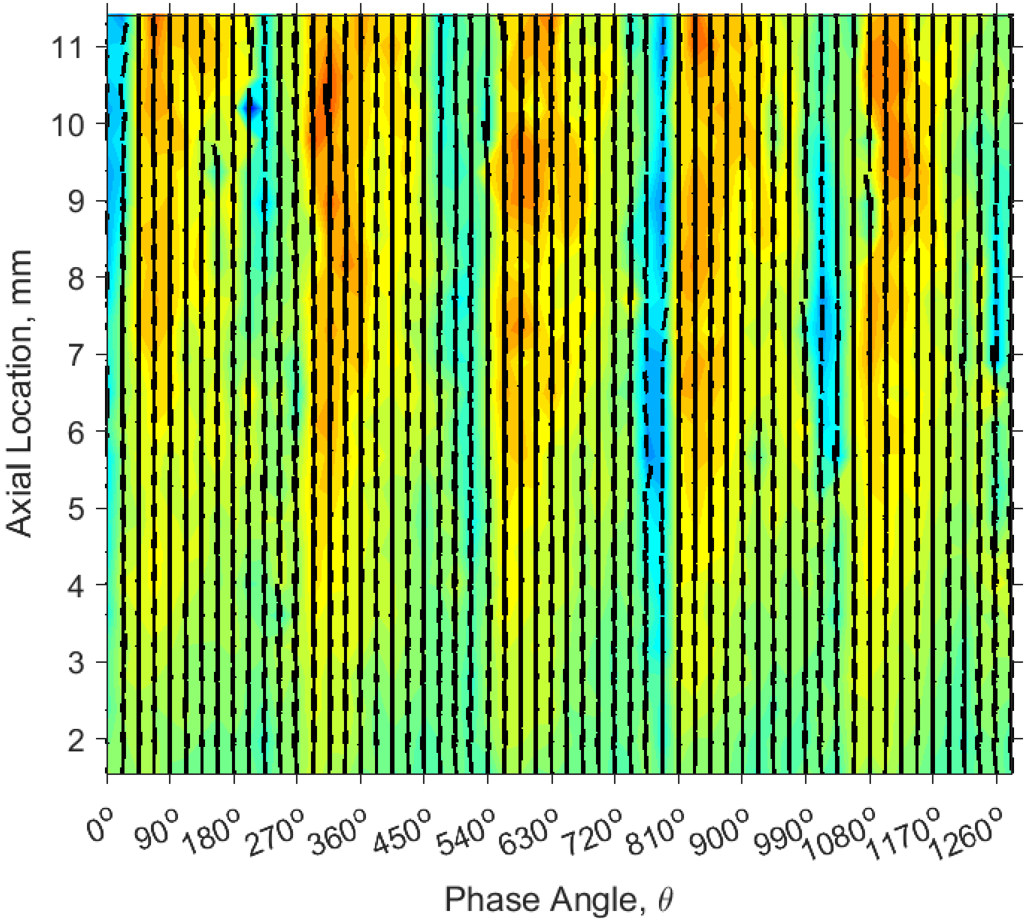




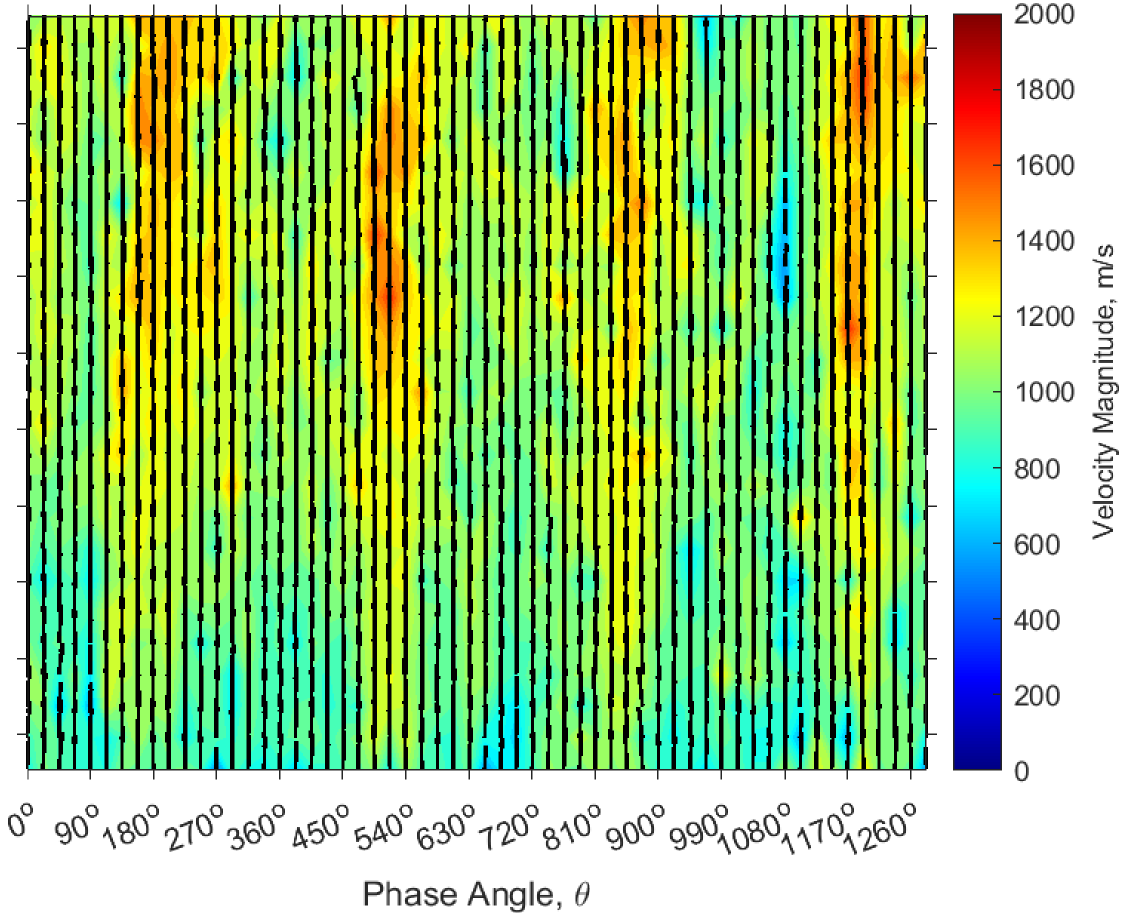


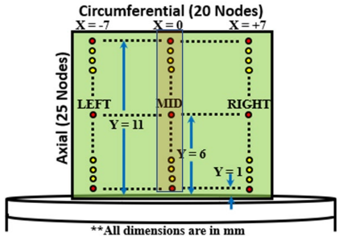
PIV Results

RTG AR 2.0



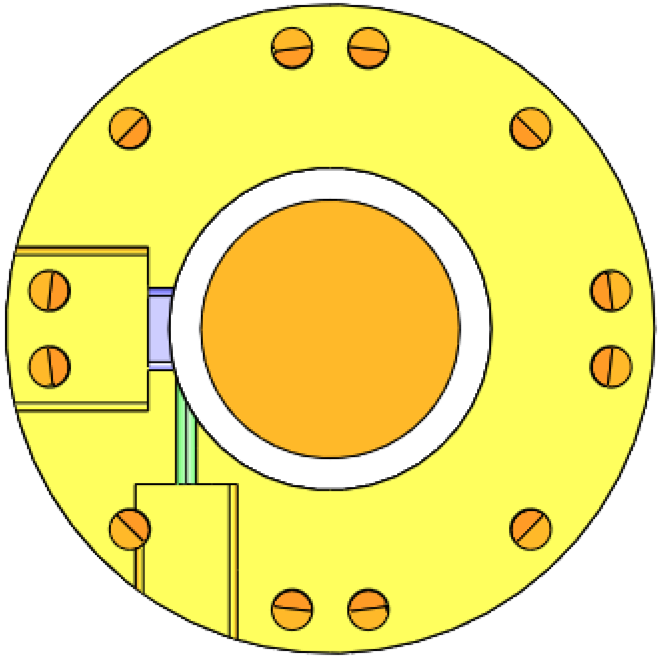
Convergent Nozzle AR 2.0

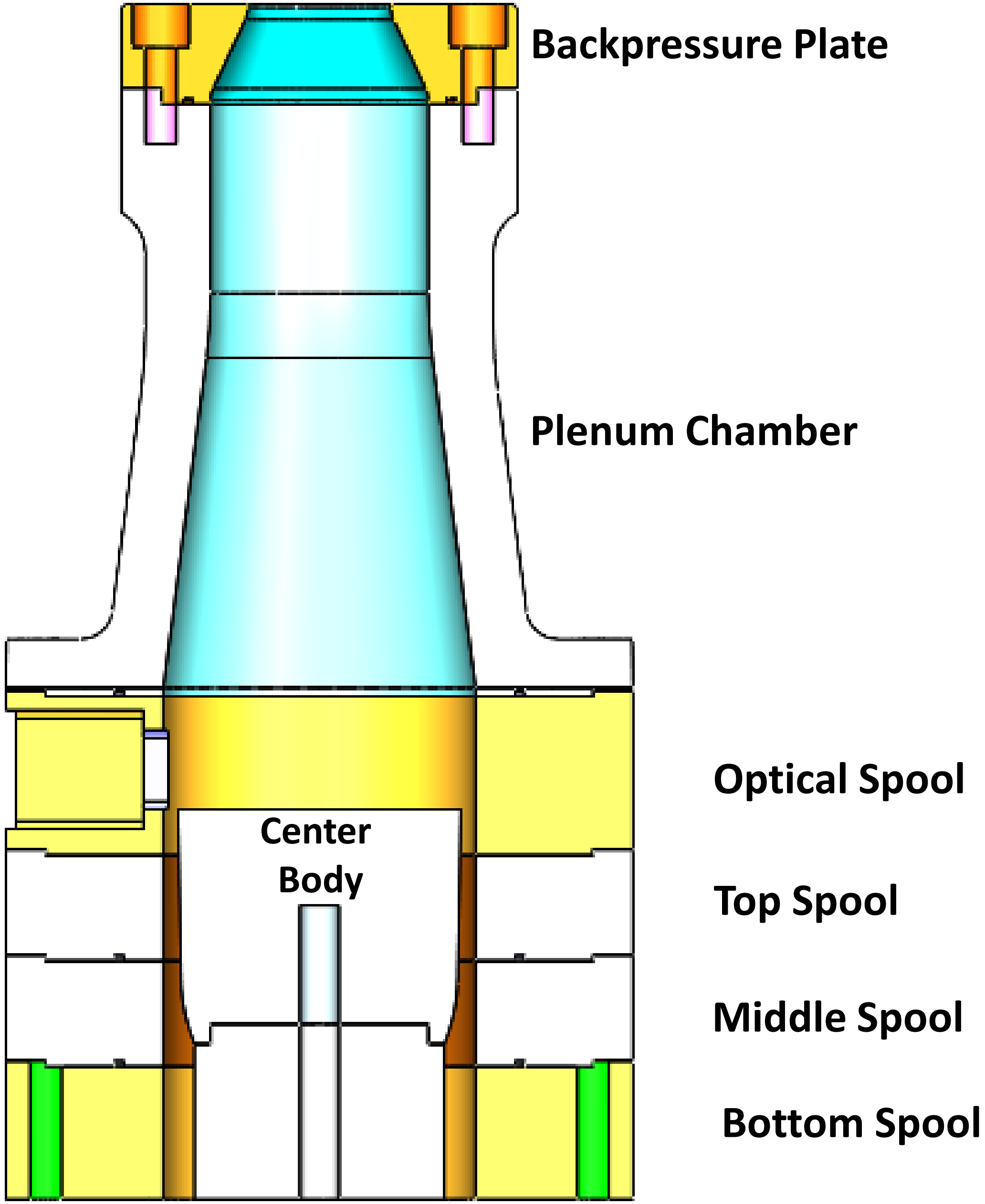




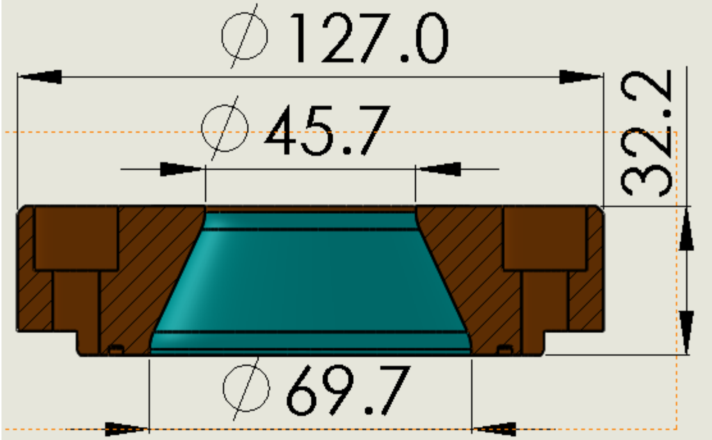
Plenum Chamber with Optical Access

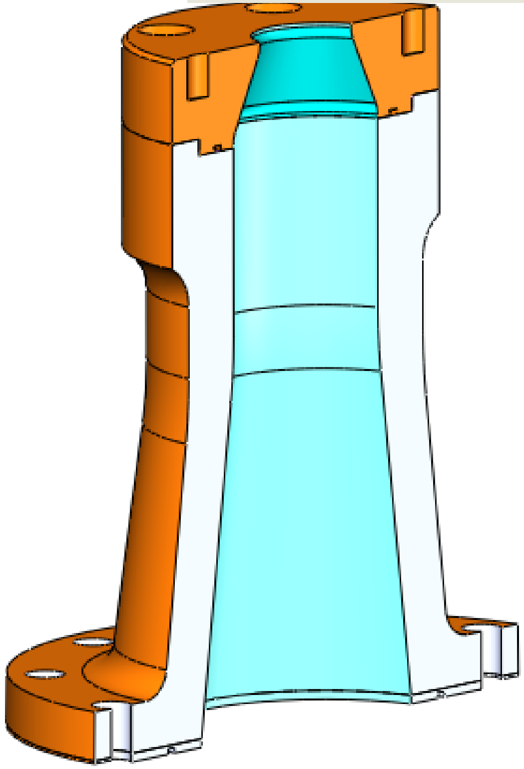
Assembly

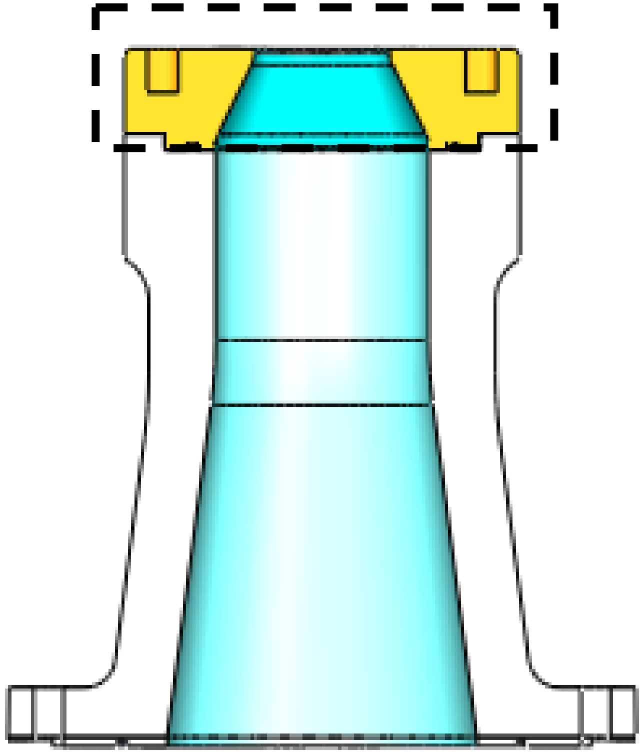


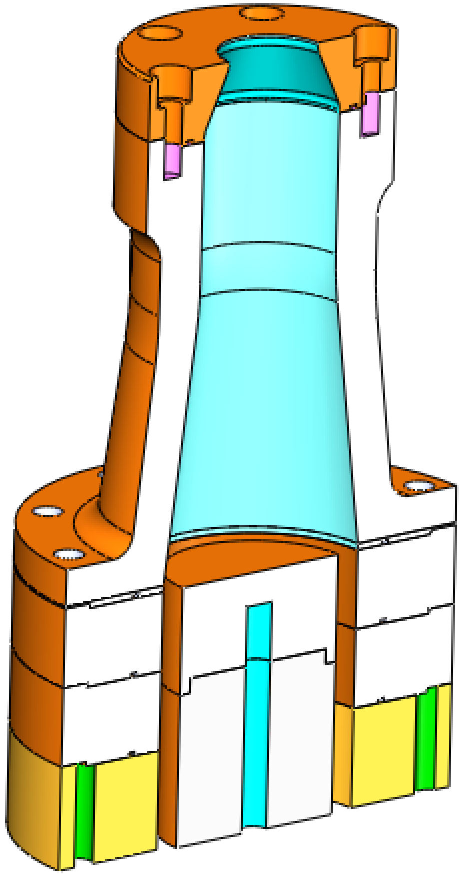

Backpressure Plate
Plenum Chamber
Optical Spool
Center Body
Top Spool
Middle Spool
Bottom Spool

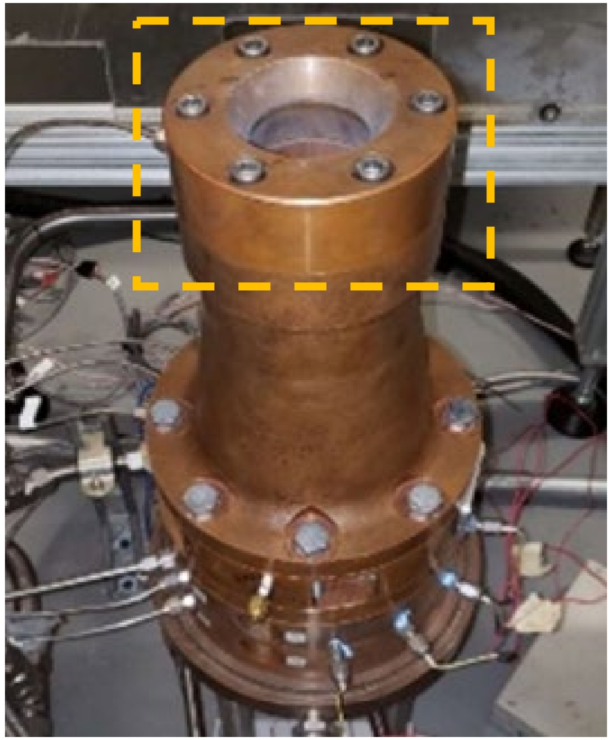
Plenum Chamber





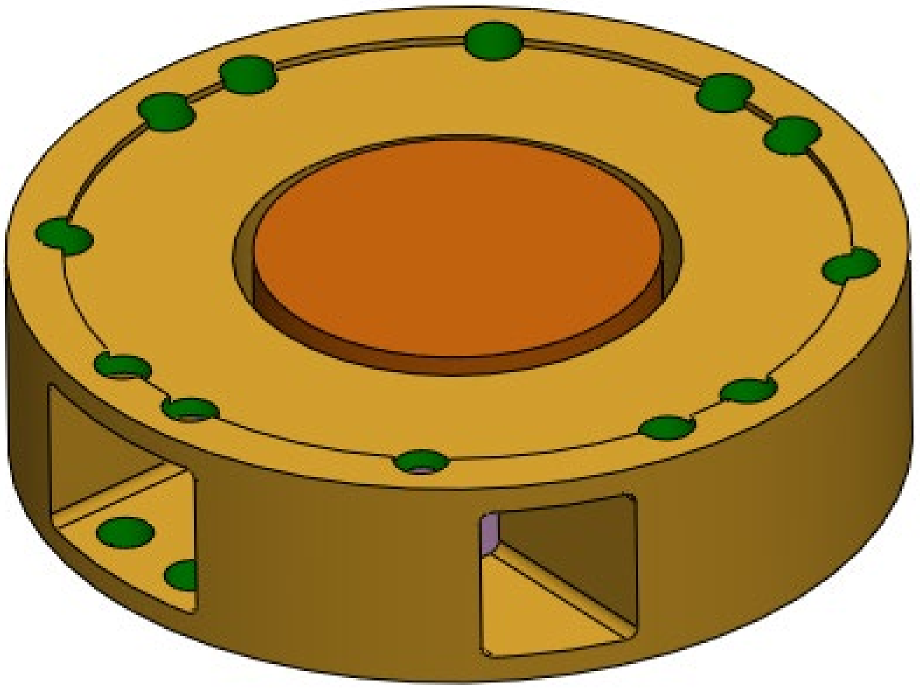


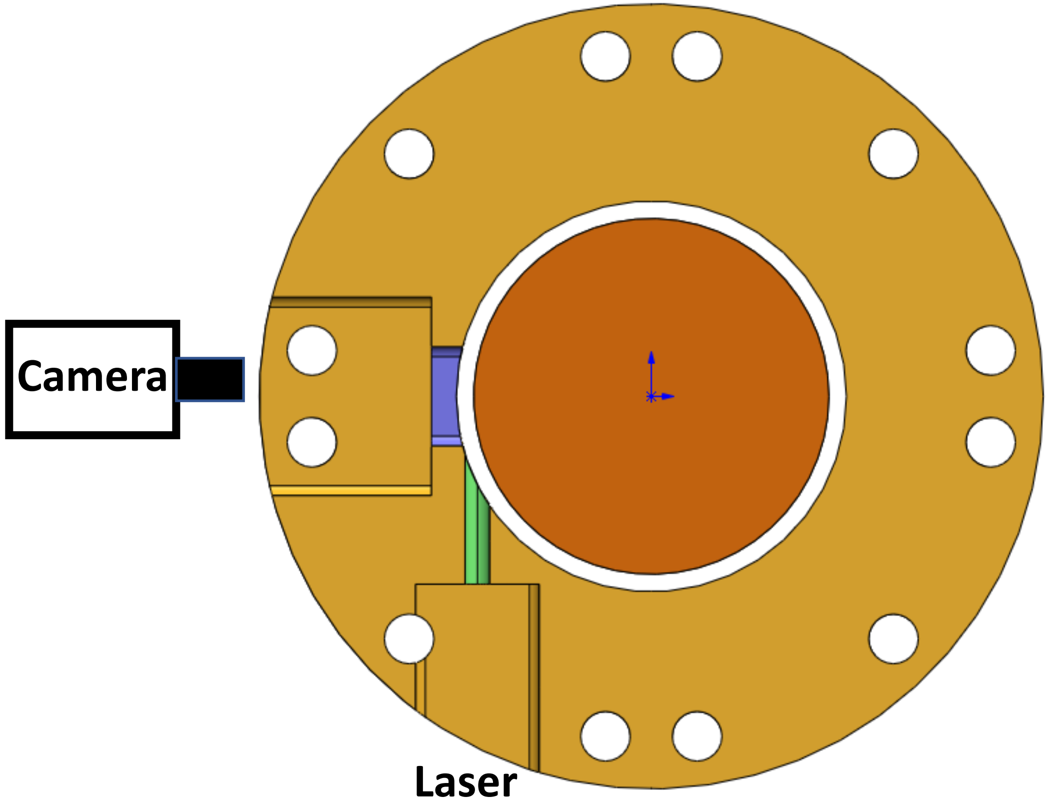




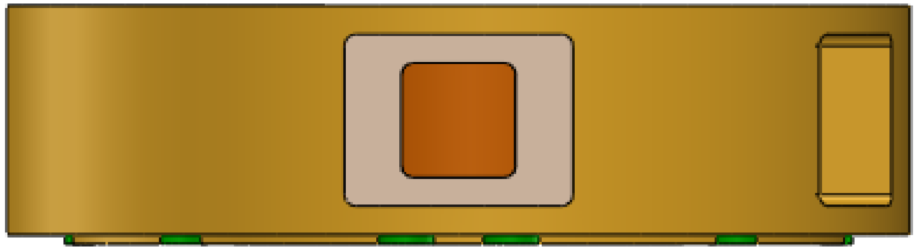
Optical Spool

COMBUSTION LABORATORIES
THE UNIVERSITY OF ALABAMA
LOW EMISSIONS • HIGH EFFICIENCY • FUEL FLEXIBILITY

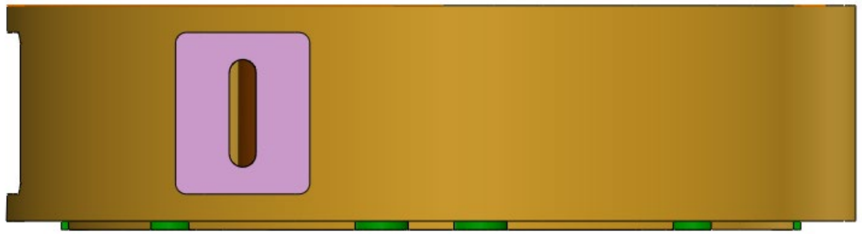




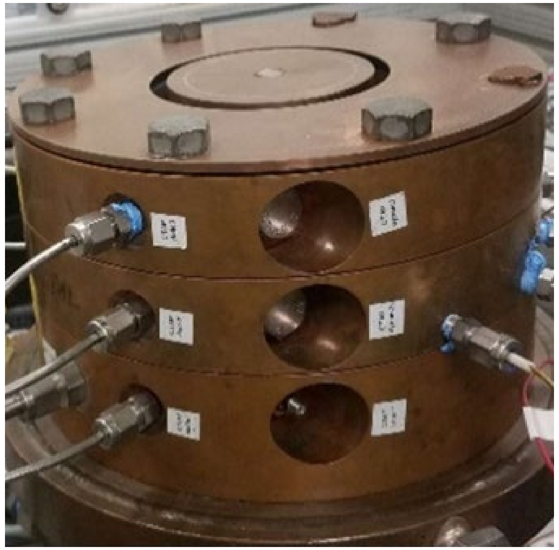
Camera Slot



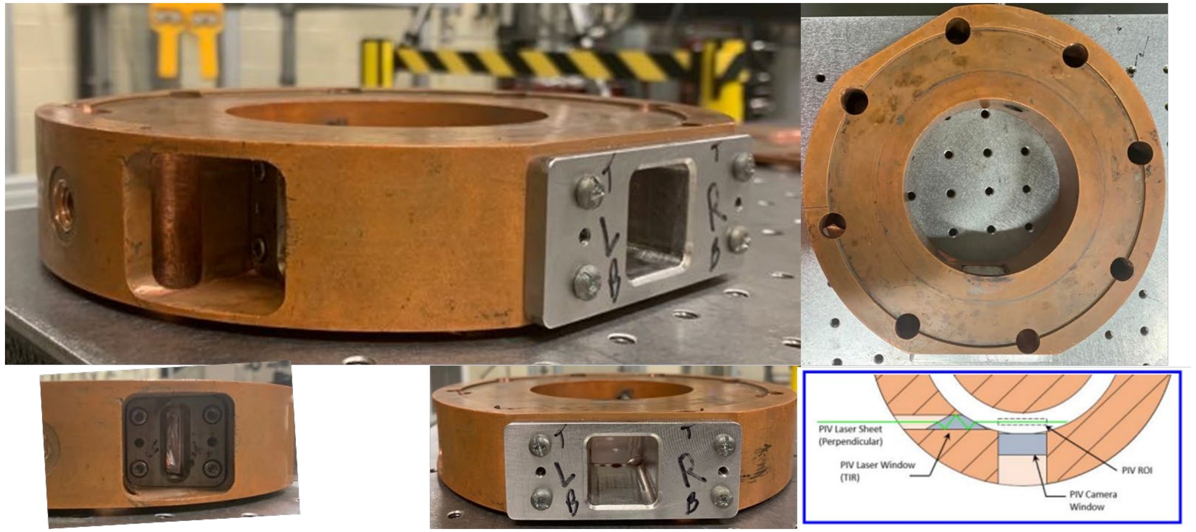
Laser Slot



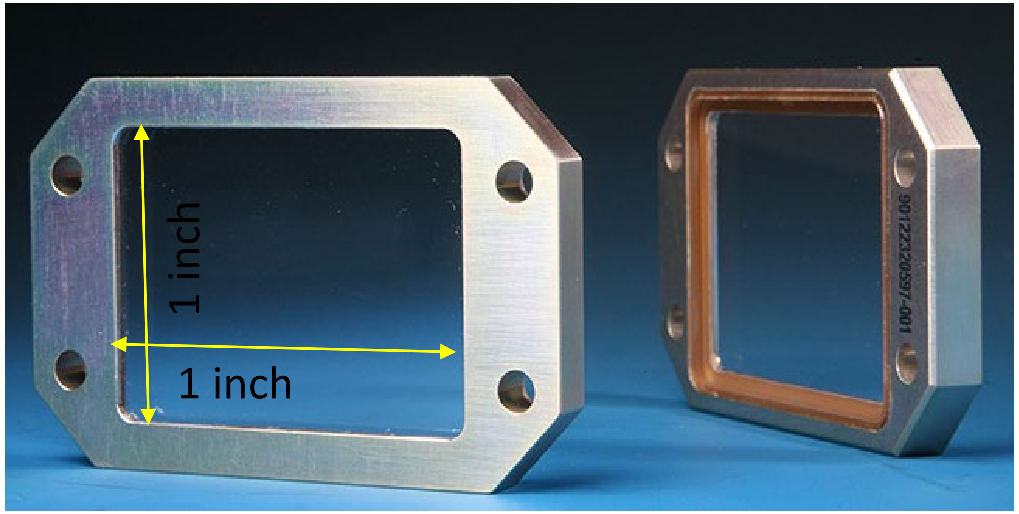
Optical Access



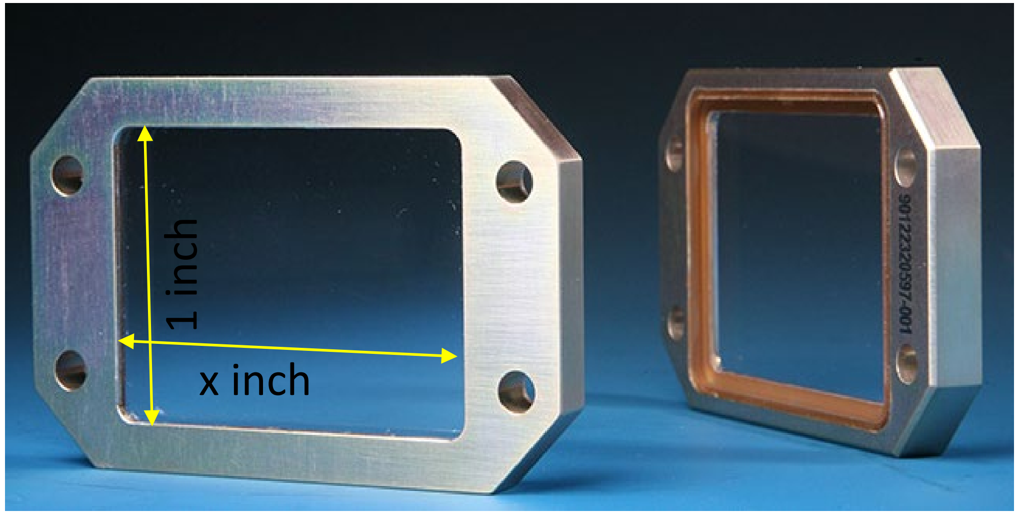
Combustion Chamber



Previously Used Optical Spool



Window for Camera Side



Window for Laser Side

Questions?