# Structure and Dynamics of Fuel Jets Injected into a High-Temperature Subsonic Crossflow: High- Data-Rate Laser Diagnostic Investigation under Steady and Oscillatory Conditions

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# Acknowledgements

- PhD graduate students: Warren Lamont (now at PSM) Mario Roa, Pratikash Panda, and Chris Fugger.
- Managing Director of Zucrow Laboratories: Scott Meyer.
- DOE UTSR Project Number DE-FE0007099, Project Manager Robin Ames.

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# Outline of the Presentation

- Research Objectives
- Description of the Gas Turbine Combustion Facilities, Installation and Testing of New Window Assembly
- 5 kHz OH PLIF
- Dual-Pump CARS Measurements of Temperature and $H_2$
- Combustion Instability Rig Tests
- Summary and Planned Research

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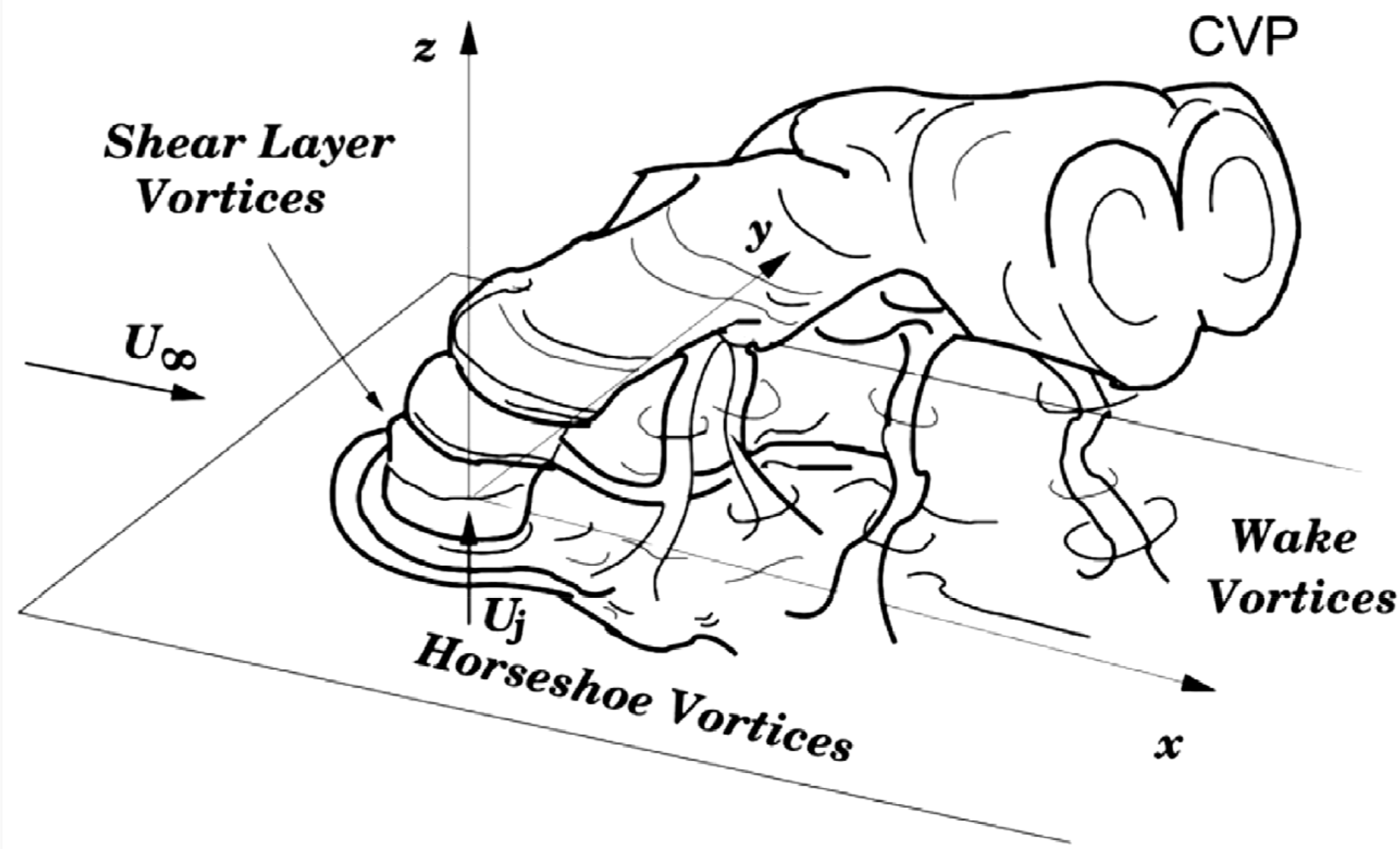
# Research Objectives

- Reacting Jet in Crossflow (RJIC) is a flow field that is of fundamental interest and practical importance.
- Primary objective is to investigate the structure and dynamics of reacting jet injected into a subsonic, high-pressure crossflow.
- High-pressure RJIC flow field will be investigated (primarily) using advanced high-data-rate (5-10 kHz) laser diagnostic methods.

# Research Objectives

- **Numerical simulation of the RJIC flow field is challenging but tractable.  Development of benchmark quality data set for comparison with numerical models will be very valuable.**
- **Mixing and flameholding are issues of critical importance for understanding the generation of pollutant species as a result of the RJIC.**
- **Interaction of RJIC and combustion instabilities is also of great interest.**

# Research Objectives



# Research Tasks

- Task 1:  Finalization of Project Management Plan.
- Task 2:  Modification and fabrication of test rig hardware.
- Task 3.1:  Development of detailed test matrix for experiments.  Jet parameters  (fuel composition, momentum flux ratio, velocity ratio…), pressure, vitiated or non-vitiated co-flow.

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# Research Tasks

- Task 3.2: Development of techniques and apparatus for high-pressure, high-data-rate PIV measurements
- Task 3.3: High-data-rate PIV measurements.
- Task 4: High-data-rate OH PLIF measurements.
- Task 5: Simultaneous high-data-rate PIV and OH PLIF measurements.

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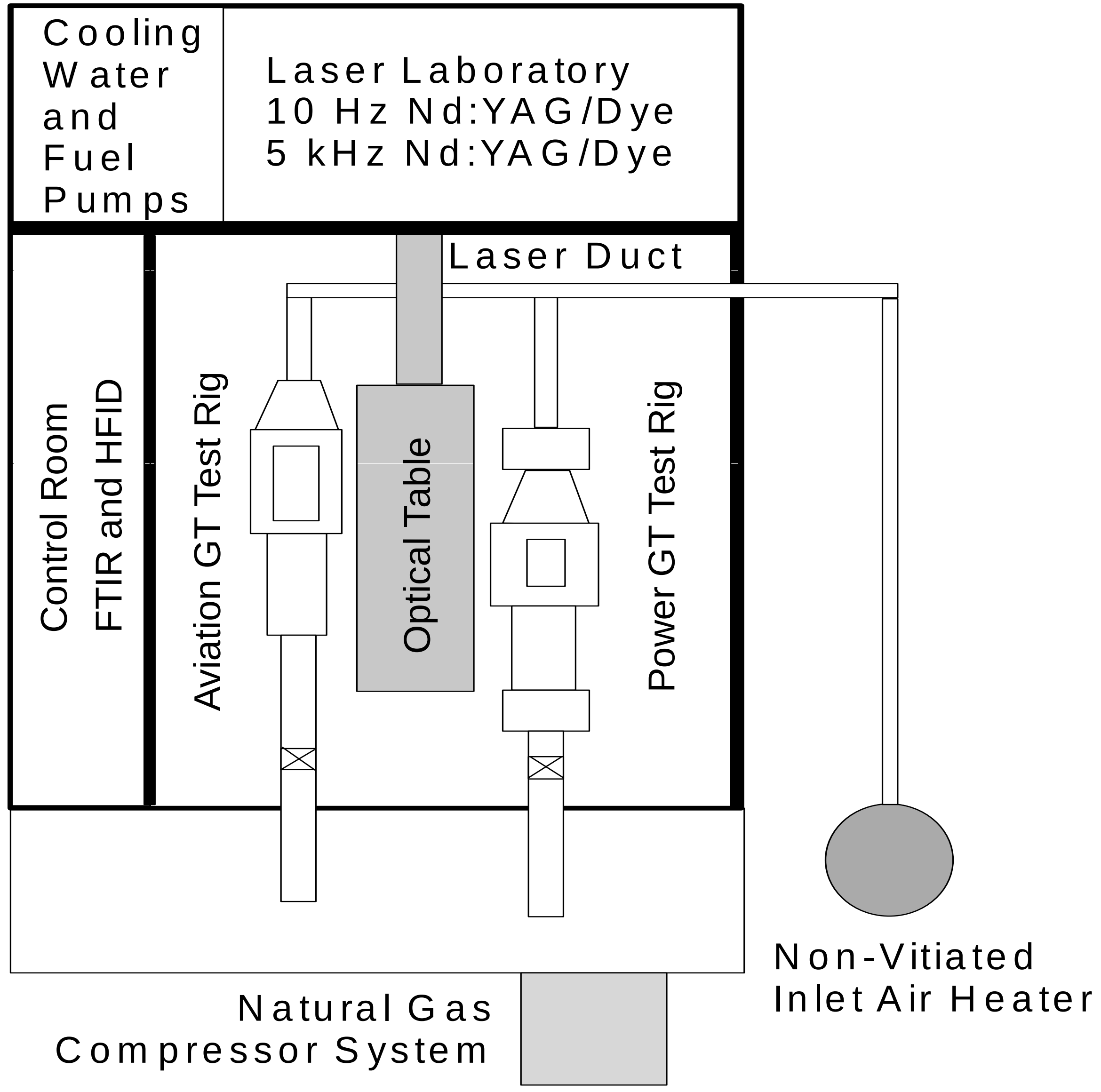
# Research Tasks

- **Task 6: Measurements under conditions with significant combustion instabilities.**
- **Task 7: Development and demonstration of high-data-rate temperature measurements using femtosecond CARS..**

# Purdue Gas Turbine Combustion Facility (GTCF)

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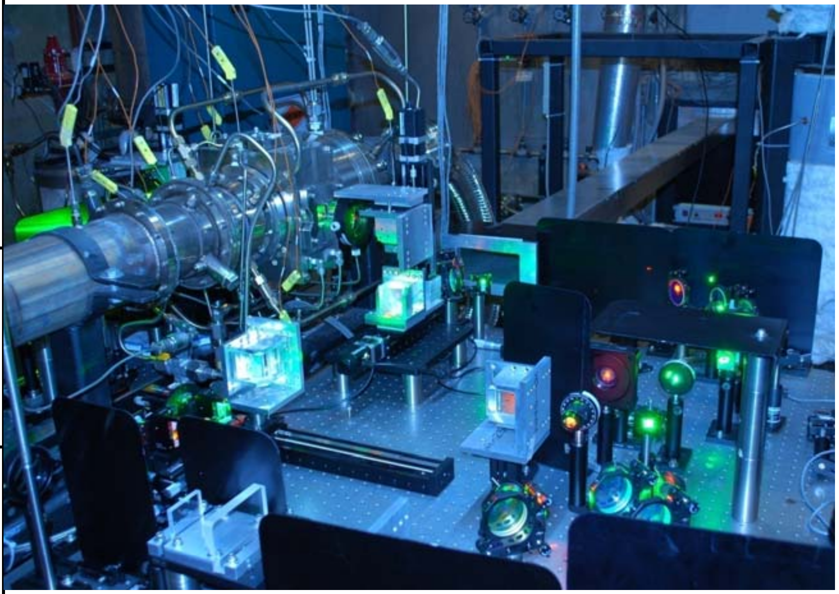
# Purdue Gas Turbine Combustion Facility (GTCF)

| High Pressure Lab System | Maximum Flow Capacity | Max Operating Condition |
|---|---|---|
| Natural Gas Heated High Pressure Air | 9 lbm/sec | 700 psi / 540 deg C 1000 deg F |
| Electric Heated Air or Nitrogen | 1 lbm/sec | 600 psi / 600 deg C |
| Nitrogen | 2 to 5 lbm/sec | 1,500 psi |
| Liquid Aviation Fuel (Kerosene) | 1 lbm/sec/tank (2 tanks) | 1,500 psi |
| Natural Gas | 1 lbm/sec | 3500 psi |



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# Natural Gas Compressor System


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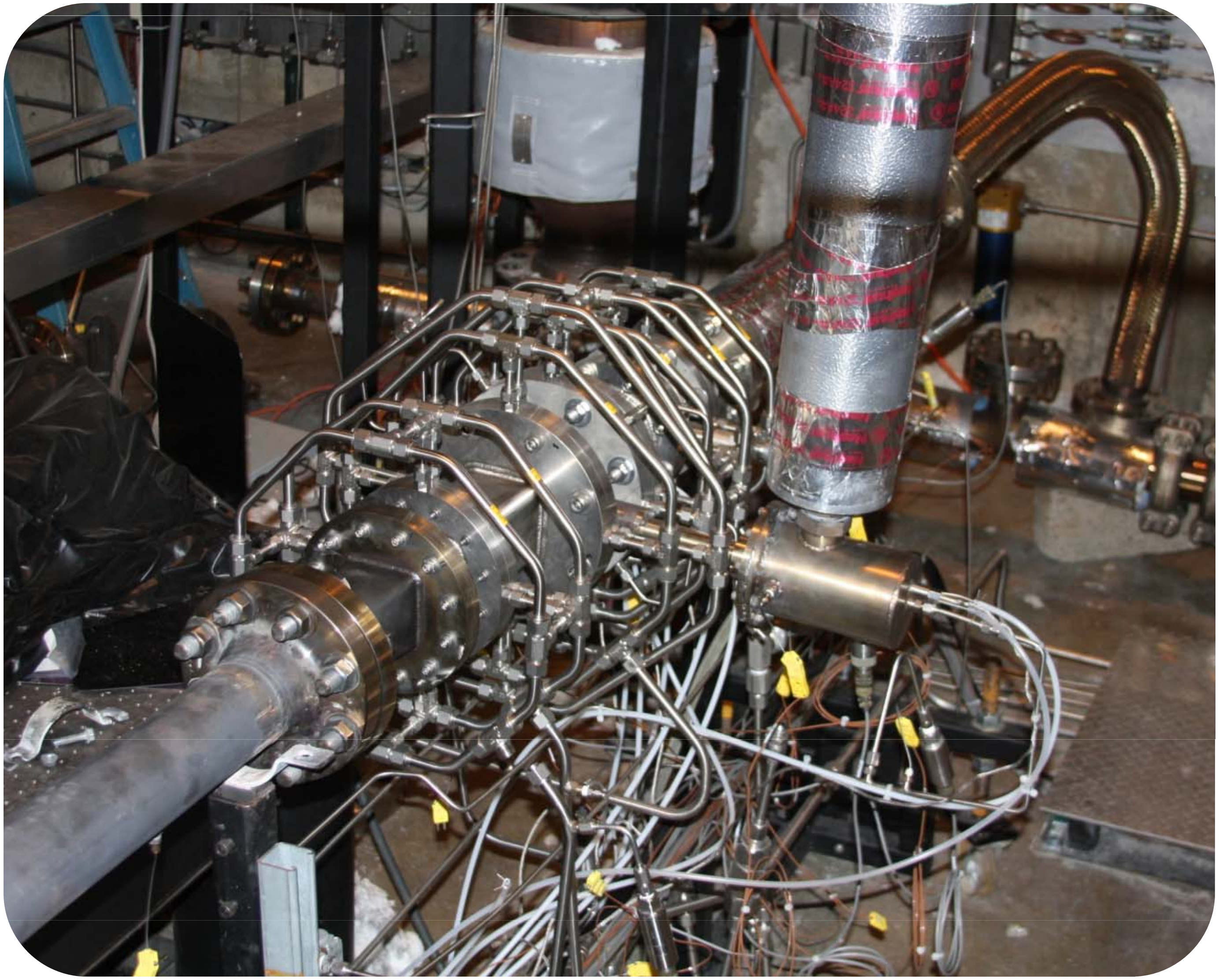
# High-Pressure RJIC Test Rig

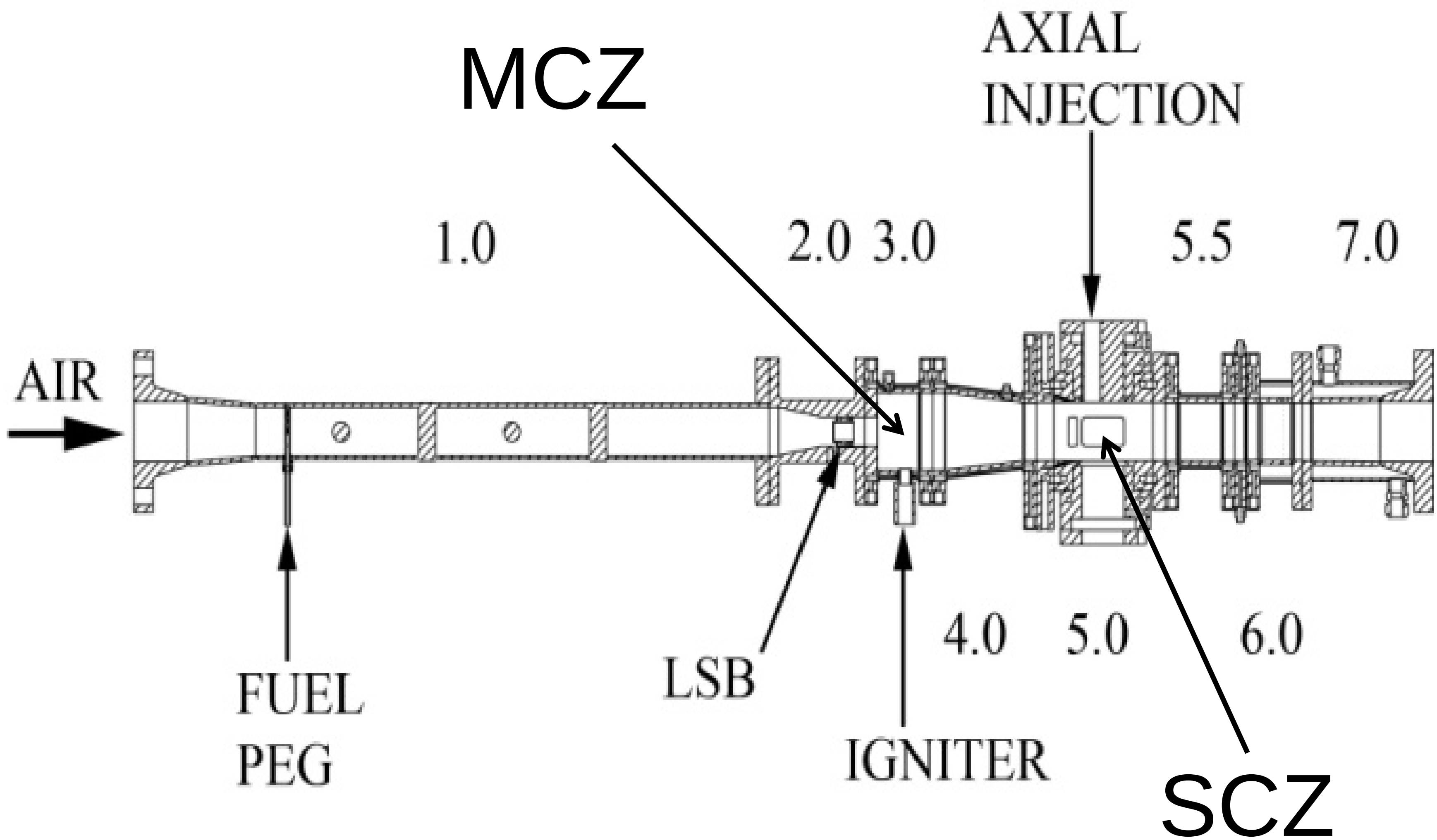


Test rig developed with funding from Siemens.

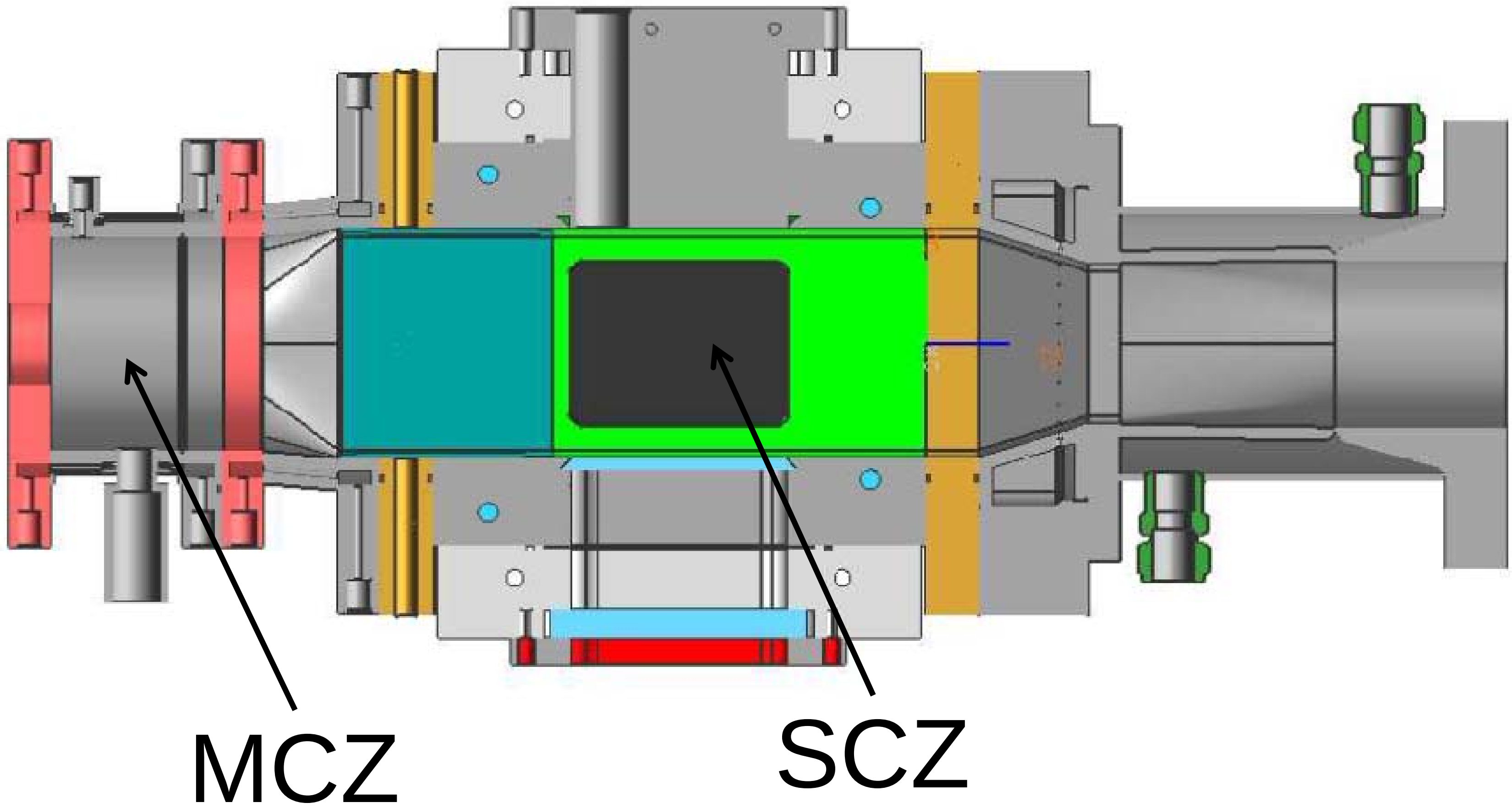
Emissions measured with FTIR system.

Window assembly for optical access.

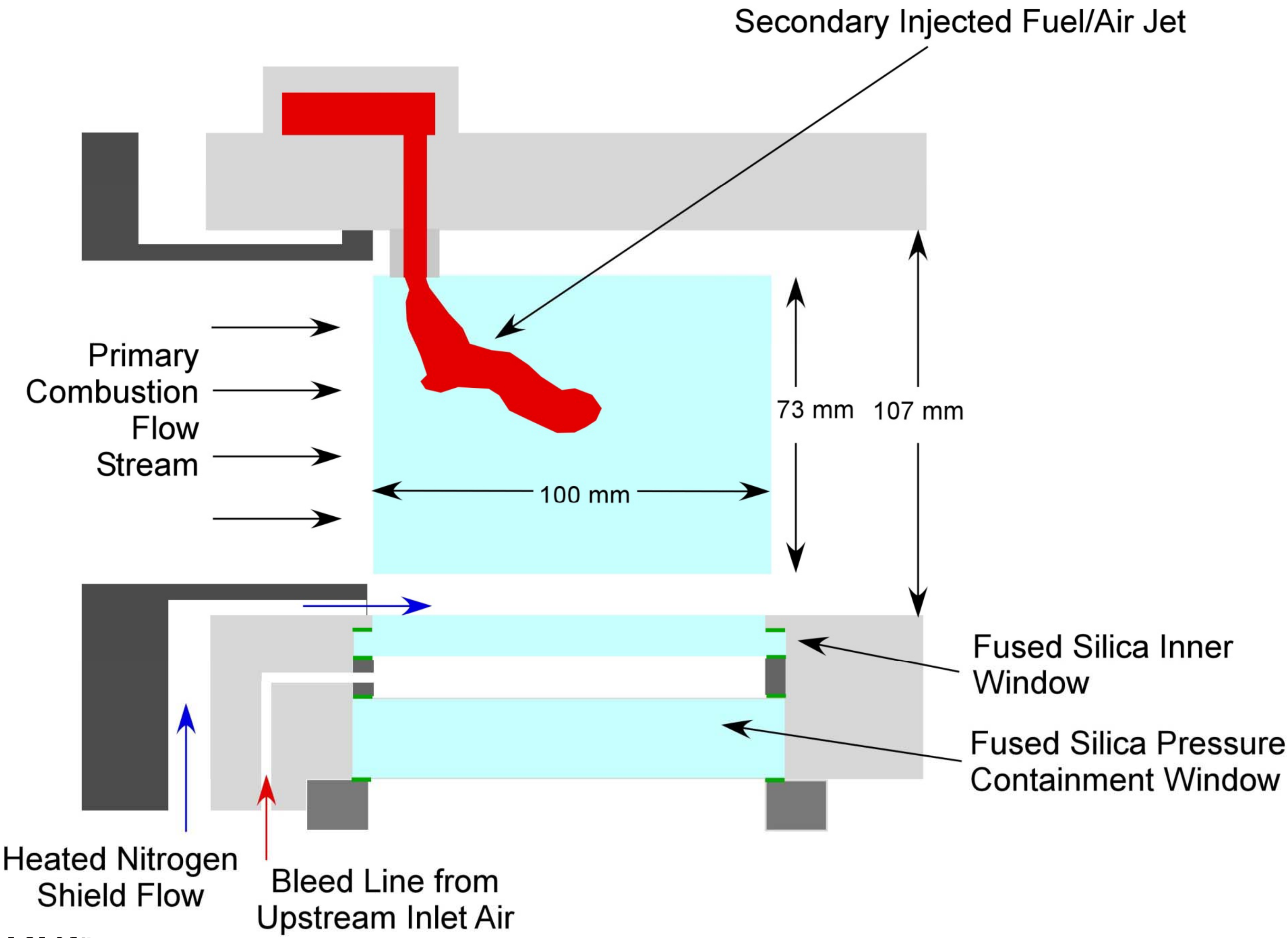
# High-Pressure RJIC Test Rig



# High-Pressure RJIC Test Rig: New Window Assembly



# High-Pressure RJIC Test Rig: Optical Access

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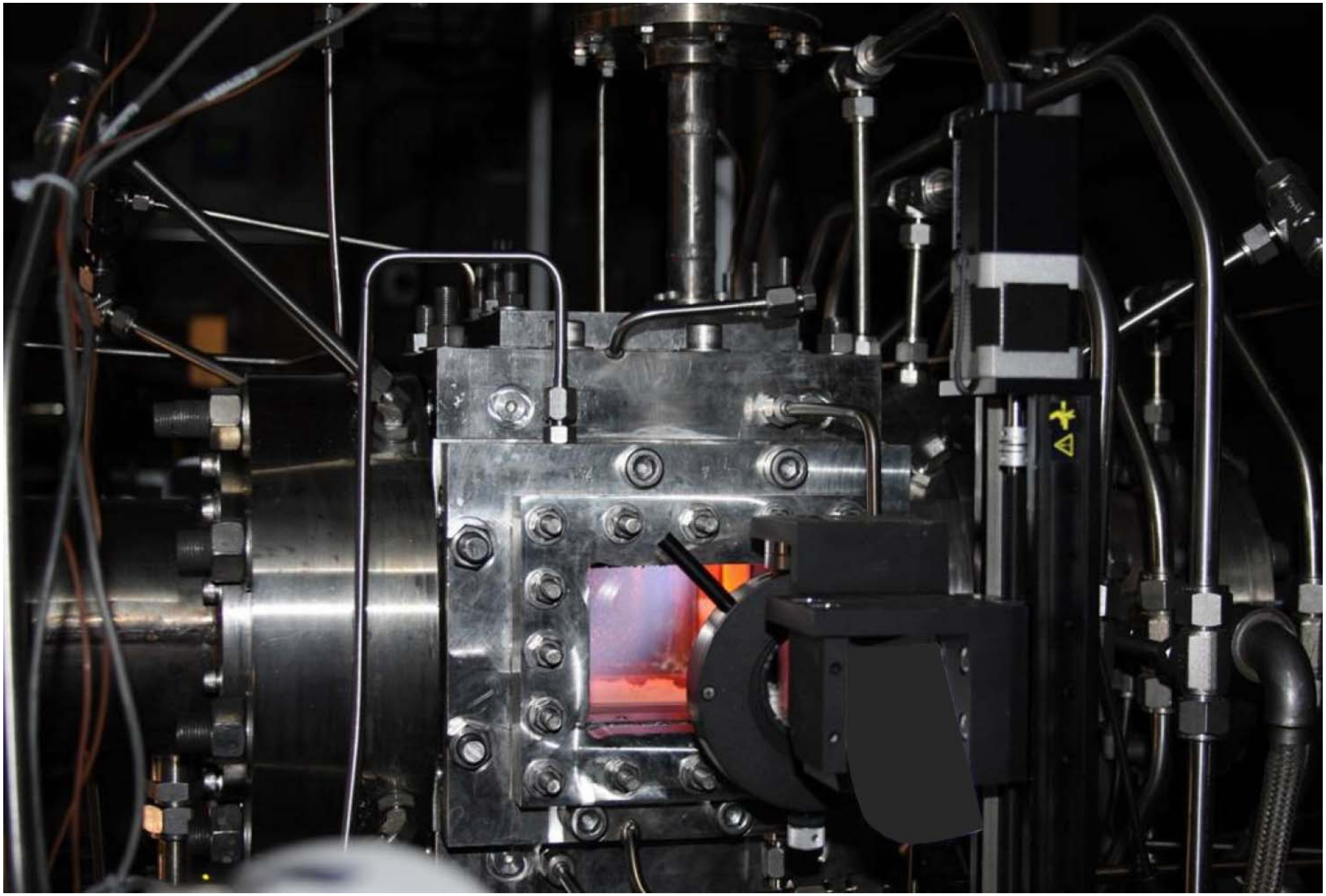
# High-Pressure RJIC Test Rig: Nominal Run Conditions

| Parameter | Symbol | SI | U.S. Customary |
|---|---|---|---|
| Static Combustion Pressure | $P_c$ | 5.57 bar | 80.8 psi |
| Inlet Air Temperature | $T_0$ | 723 K | 1301 R |
| MCZ Air Mass Flow | $\dot{m}_{air,he}$ | 0.3925 kg/s | 0.86 lbm/s |
| MCZ Fuel Mass Flow | $\dot{m}_{fu,he}$ | 0.008 – 0.017 kg/s | 0.019 – 0.038 lbm/s |
| SCZ Air Mass Flow | $\dot{m}_{air,ax}$ | 0.001 – 0.126 kg/s | 0.002 – 0.255 lbm/s |
| SCZ Fuel Mass Flow | $\dot{m}_{fu,ax}$ | $8\times10^{-5}$ – 0.010 kg/s | $2\times10^{-4}$ – 0.022 lbm/s |

# High-Pressure RJIC Test Rig in Operation



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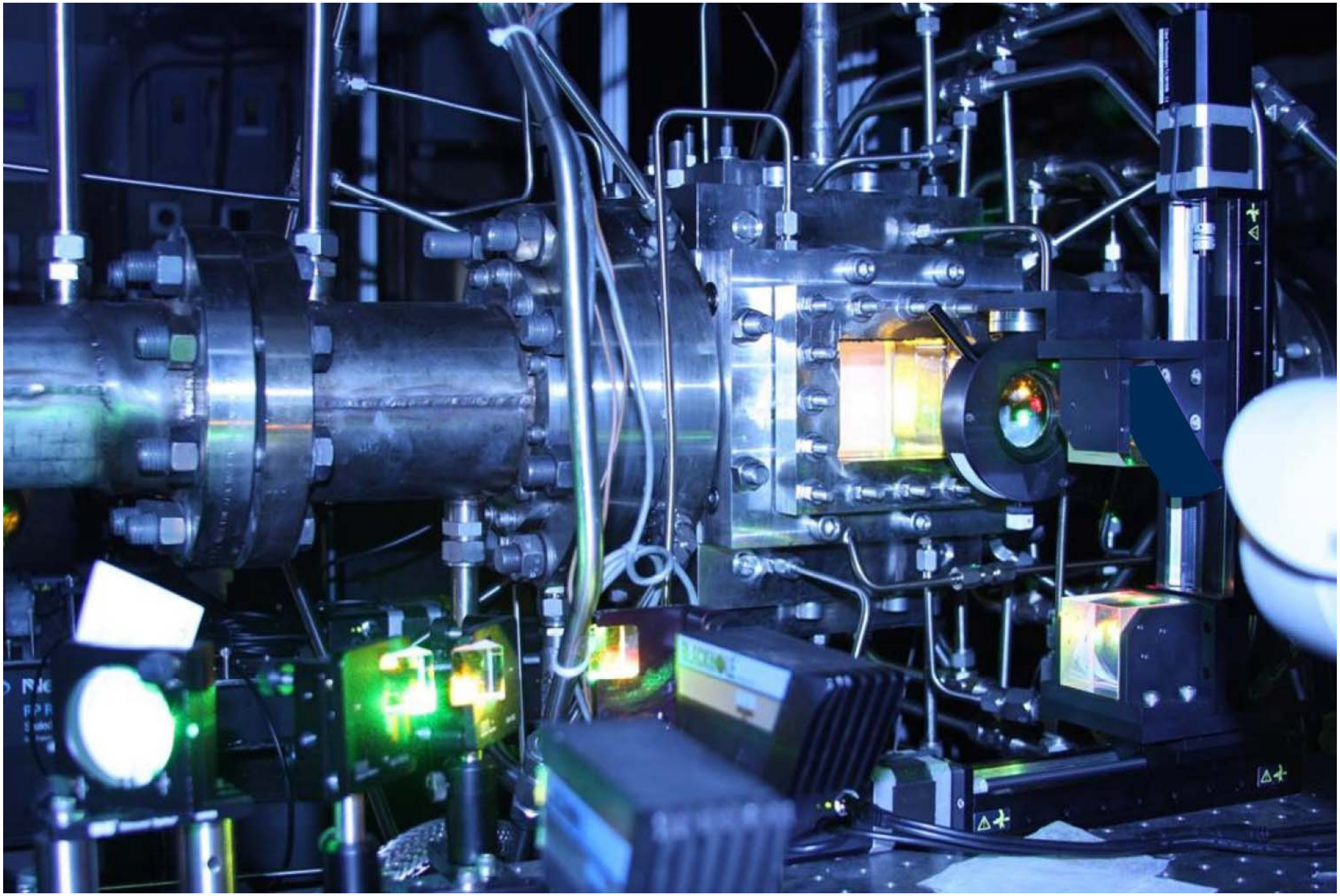
# High-Pressure RJIC Test Rig in Operation



# Laser Diagnostic Techniques

- **Much effort in the first year was expended in trying to learn how to run the test rig and to get the windows to survive. Initial tests with laser diagnostics were performed with an MCZ fueled with NG/air, $\Phi$=0.5-0.52. The SCZ jet was also NG/air in these initial tests for cost reasons.**
- **5 kHz OH PLIF – Credo dye laser pumped by the Edgewave laser.**
- **Dual-pump CARS for quantitative temperature measurements and for reaction zone location.**

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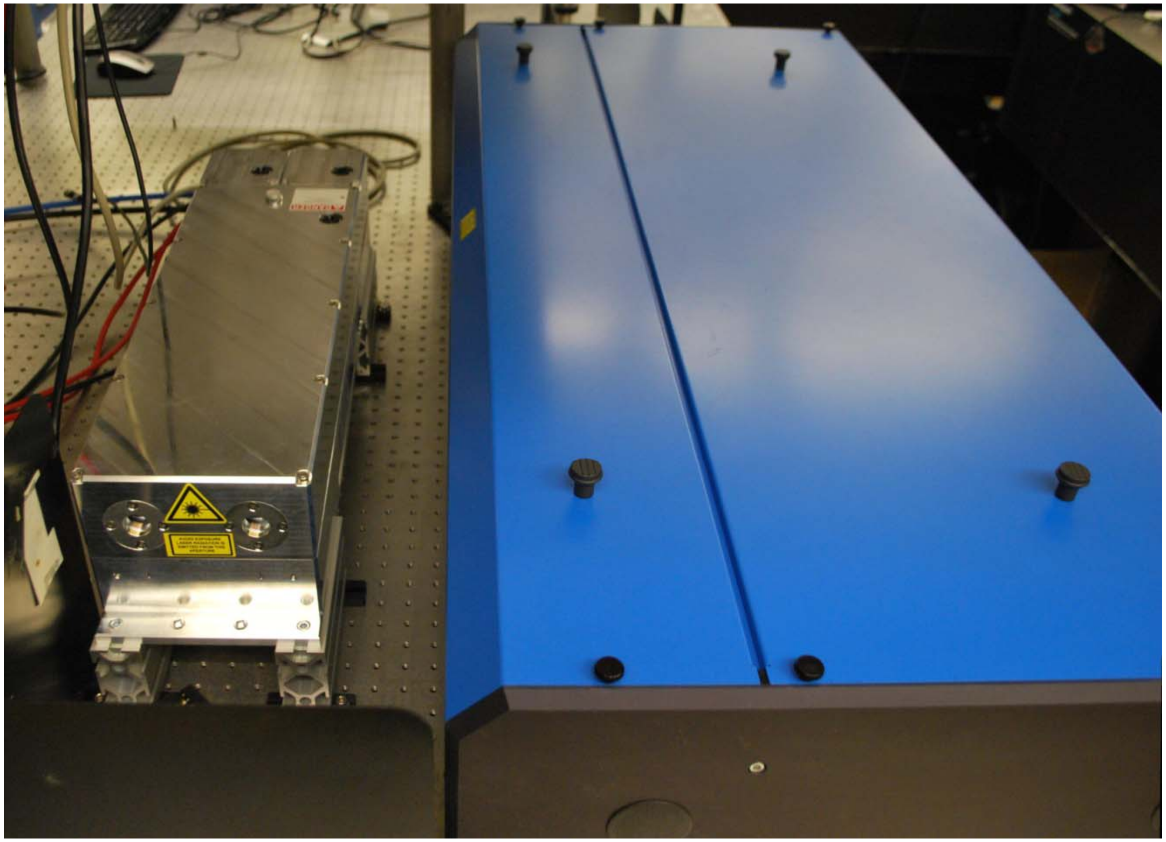
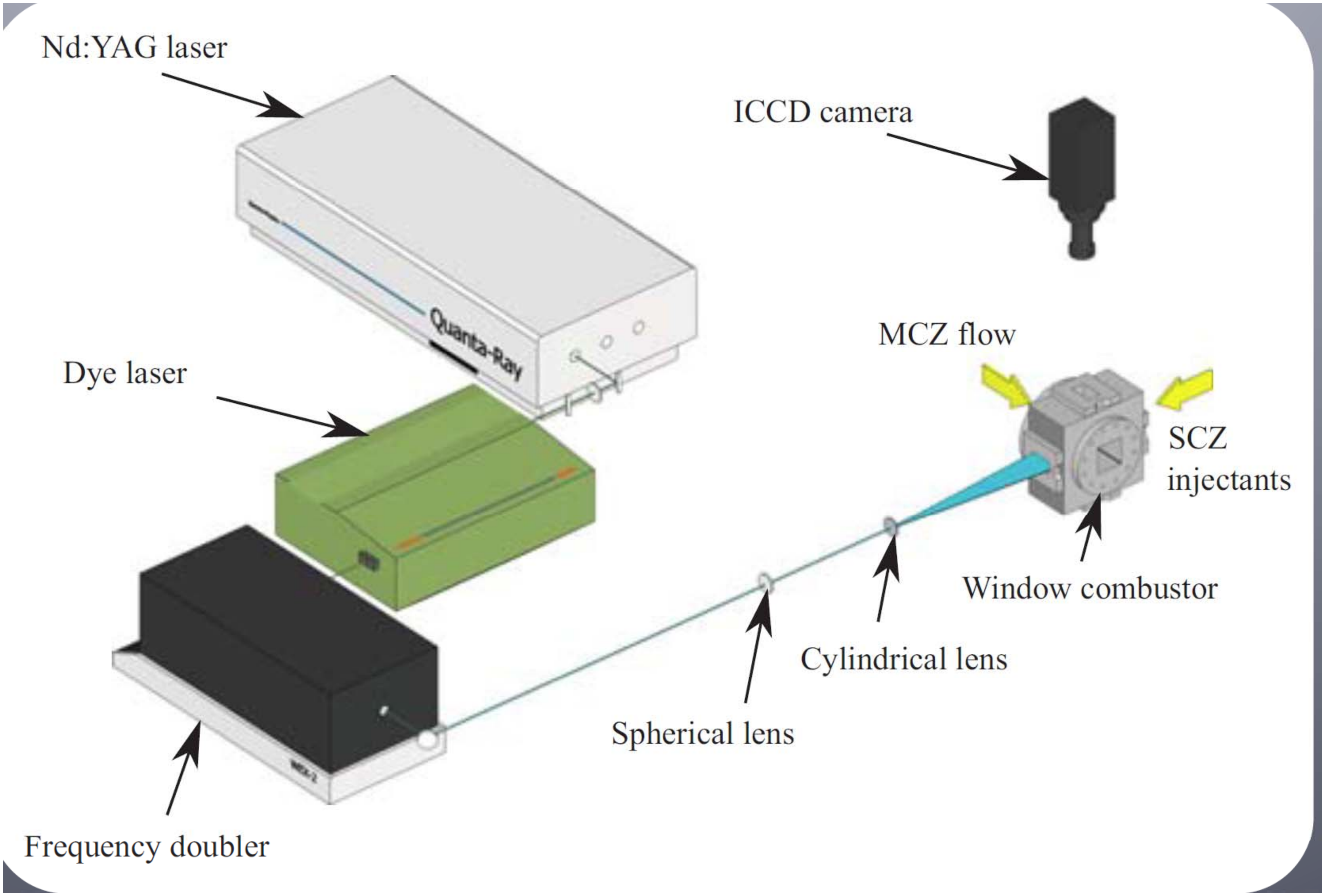
# High-Repetition-Rate Laser System



Edgewave Diode-Pumped Solid State Nd:YAG Laser:  5 kHz Rep Rate, Dual-Head, 6 mJ/Pulse at 532 nm, 7 nsec Pulses

Sirah Credo Dye Laser
5 kHz Rep Rate, 500 μJ/Pulse at 283 nm (2.5 W average power in UV)

# 0.01 kHz OH PLIF System

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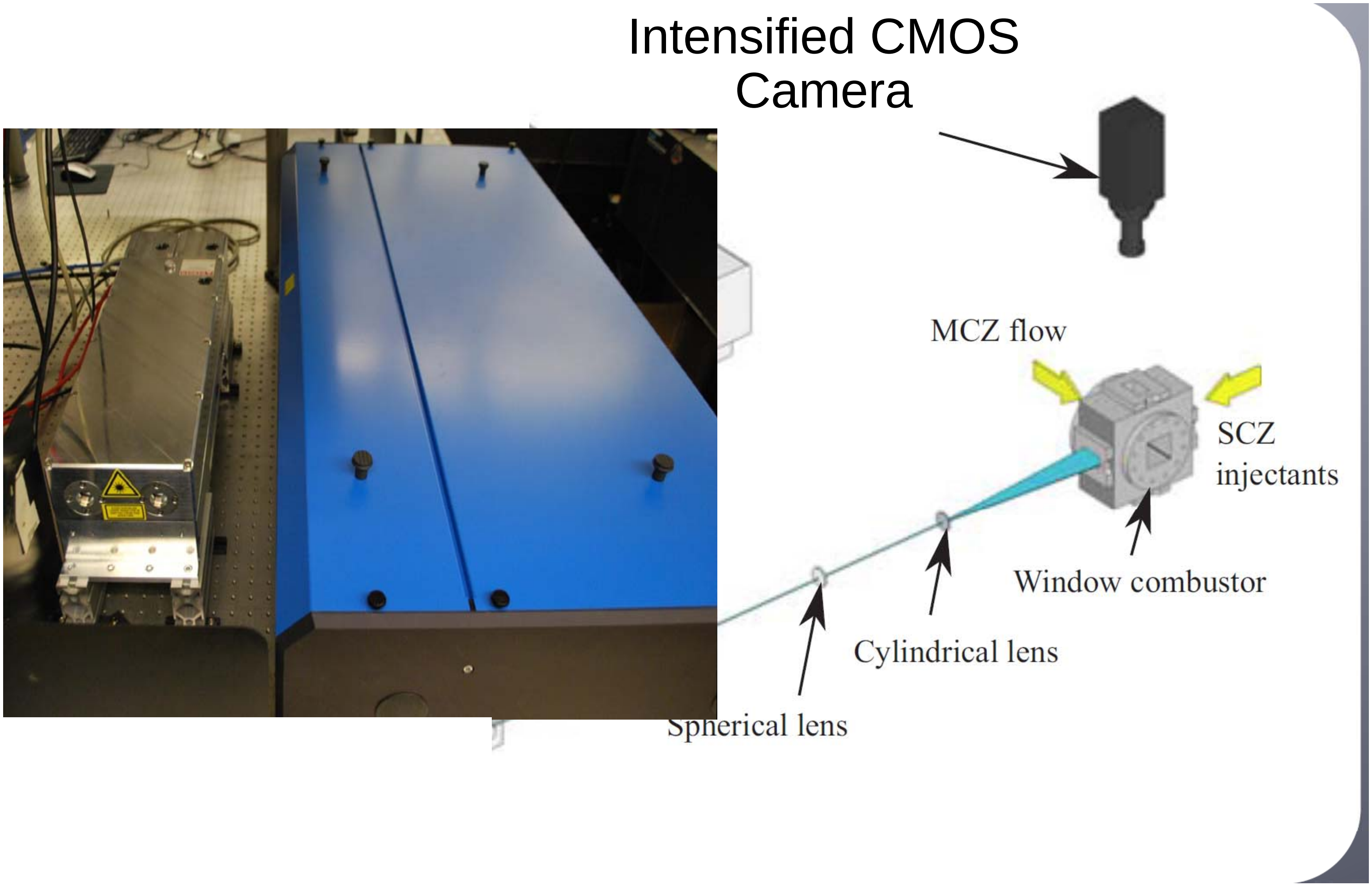
# 5 kHz OH PLIF System

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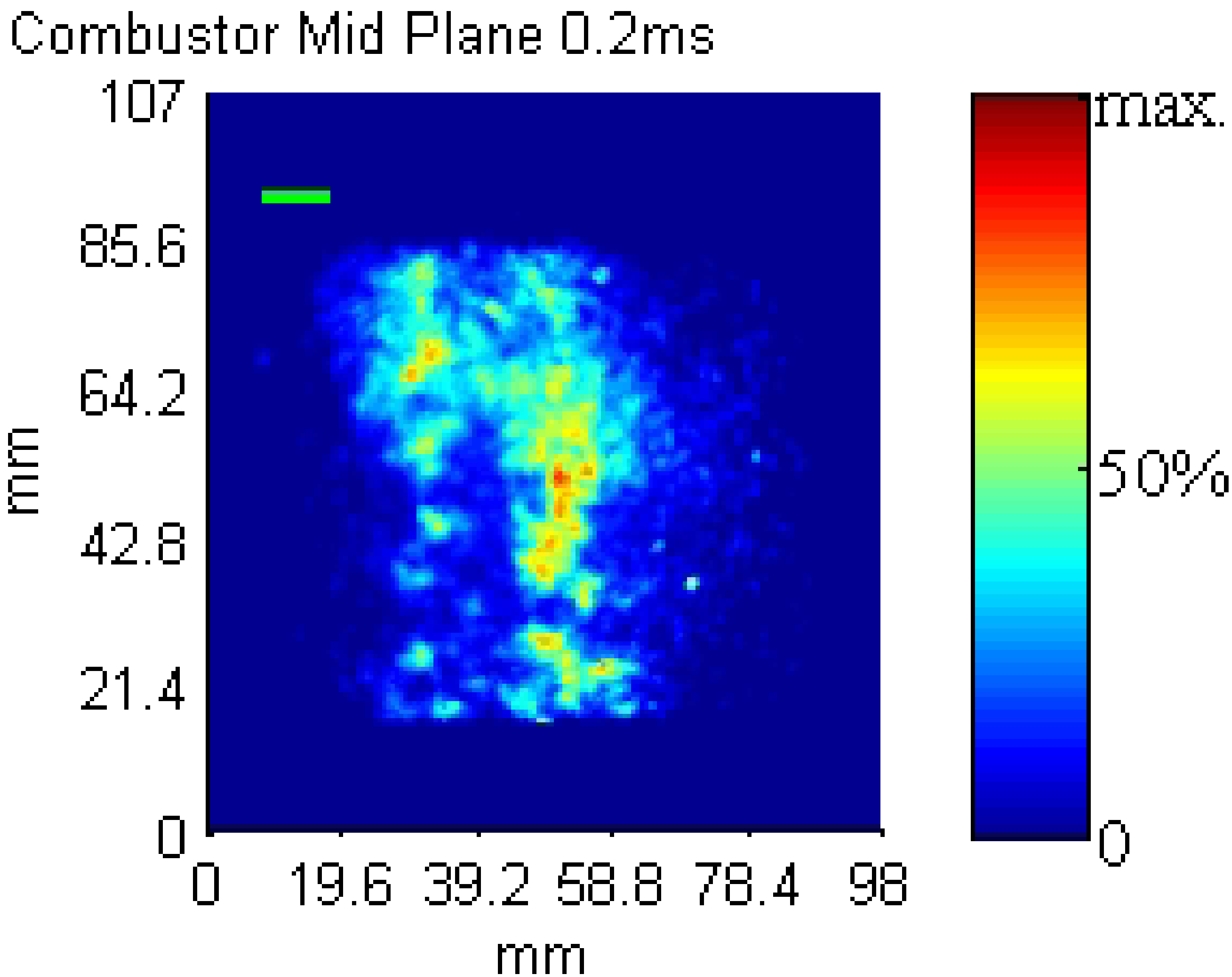
# 5 kHz OH PLIF of J=8, Rich Jet Injection

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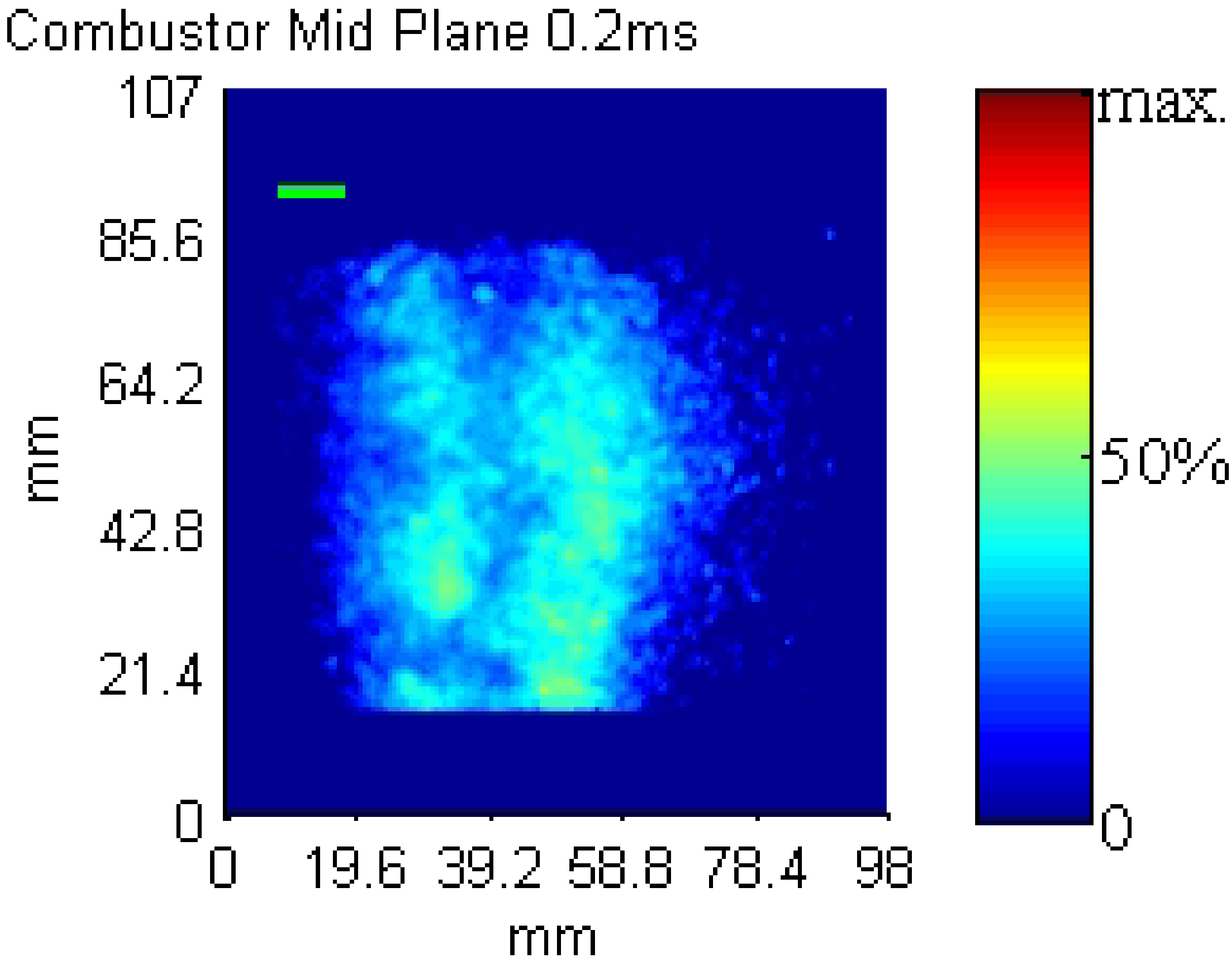
# 5 kHz OH PLIF of J=8, Lean Jet Injection

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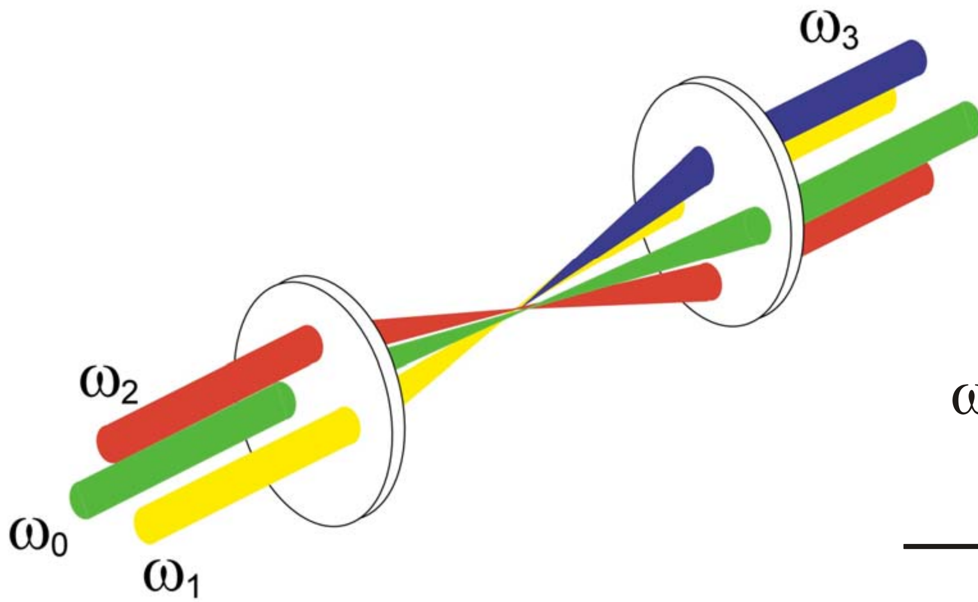
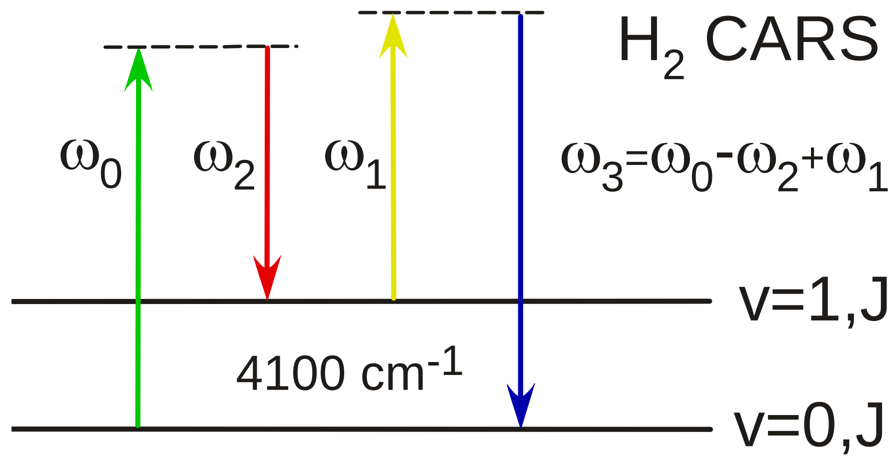
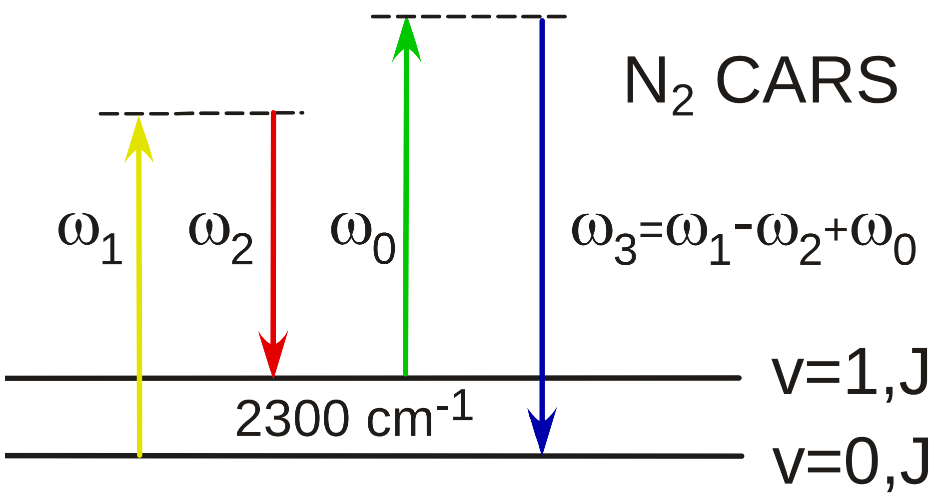
# Initial 5 kHz OH PLIF Measurements

- Signal levels are very good, even though camera was placed much too far from the test rig for the first tests.   OH PLIF signal from the vitiated stream appears to be negligible.
- Three jet conditions with different jet momentum flux ratio and/or equivalence ratio were investigated.  OH PLIF was recorded for 18 planes spaced by 3 mm across the test section for each condition.
- Sheet-forming optics were not ideal for this first test.  Also, may need to flow seeded acetone through test rig to properly normalize the images.

# Dual-Pump CARS for $H_2$ and $N_2$

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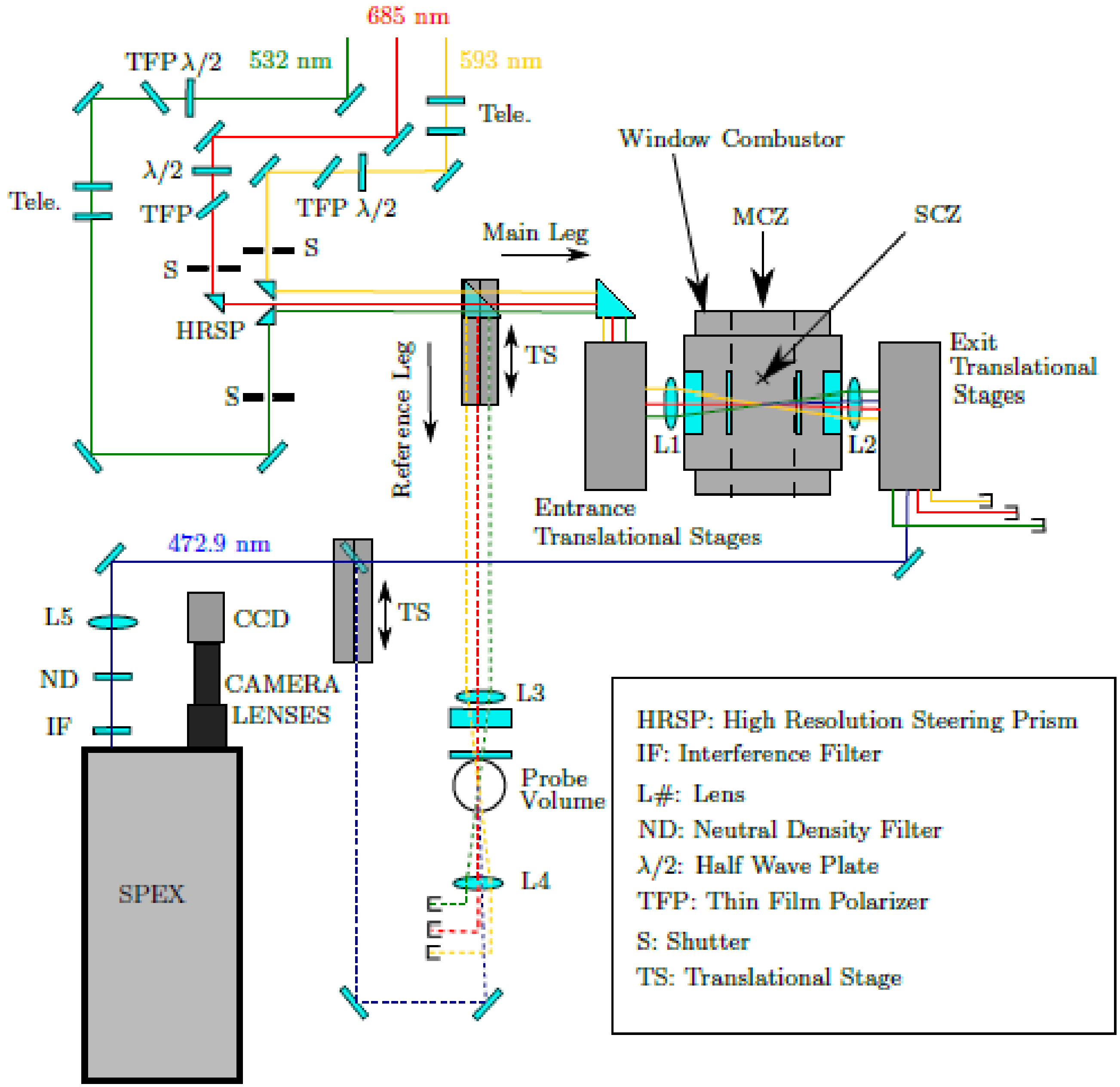


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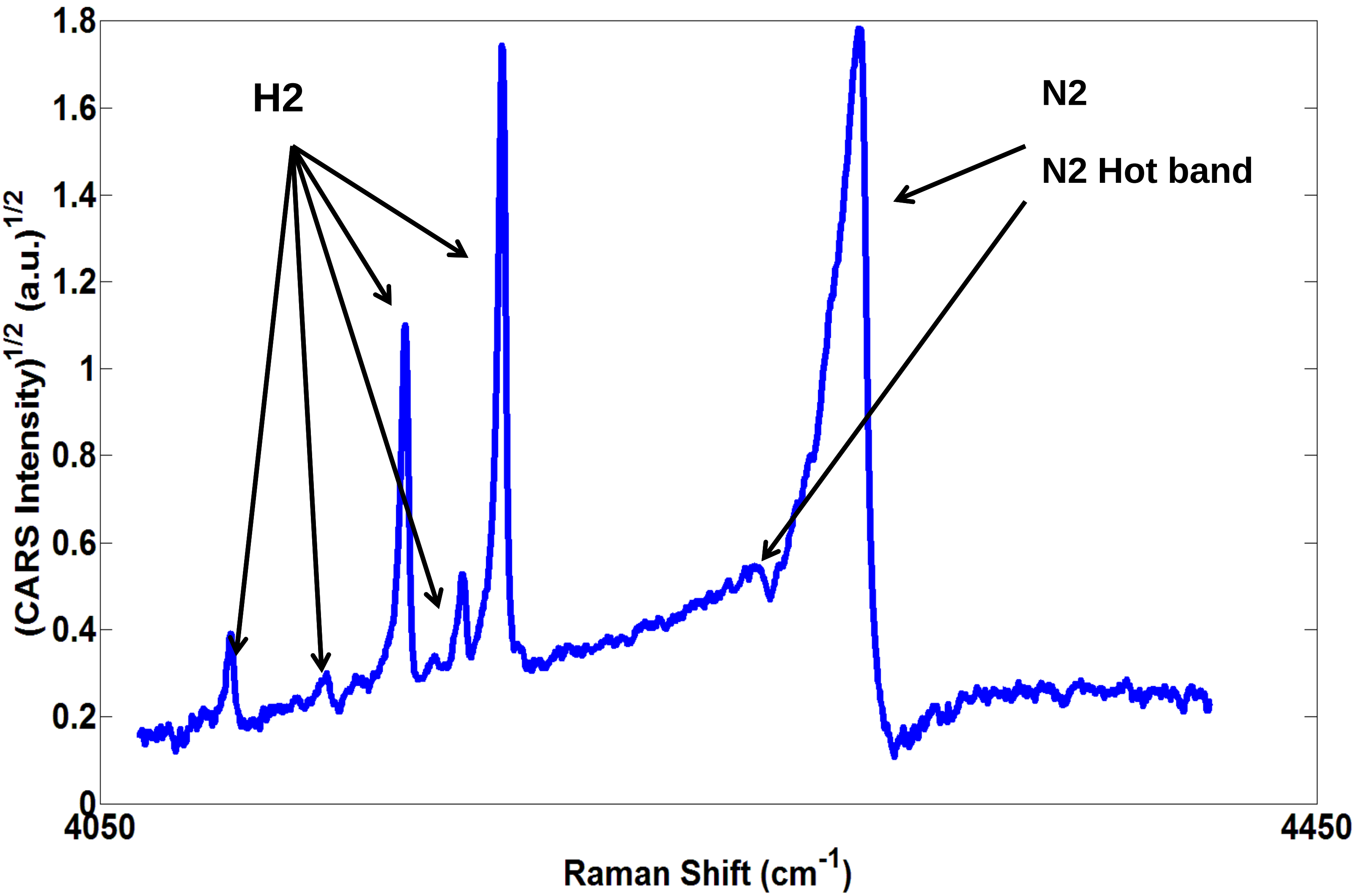
# Dual-Pump CARS for $H_2$ and $N_2$

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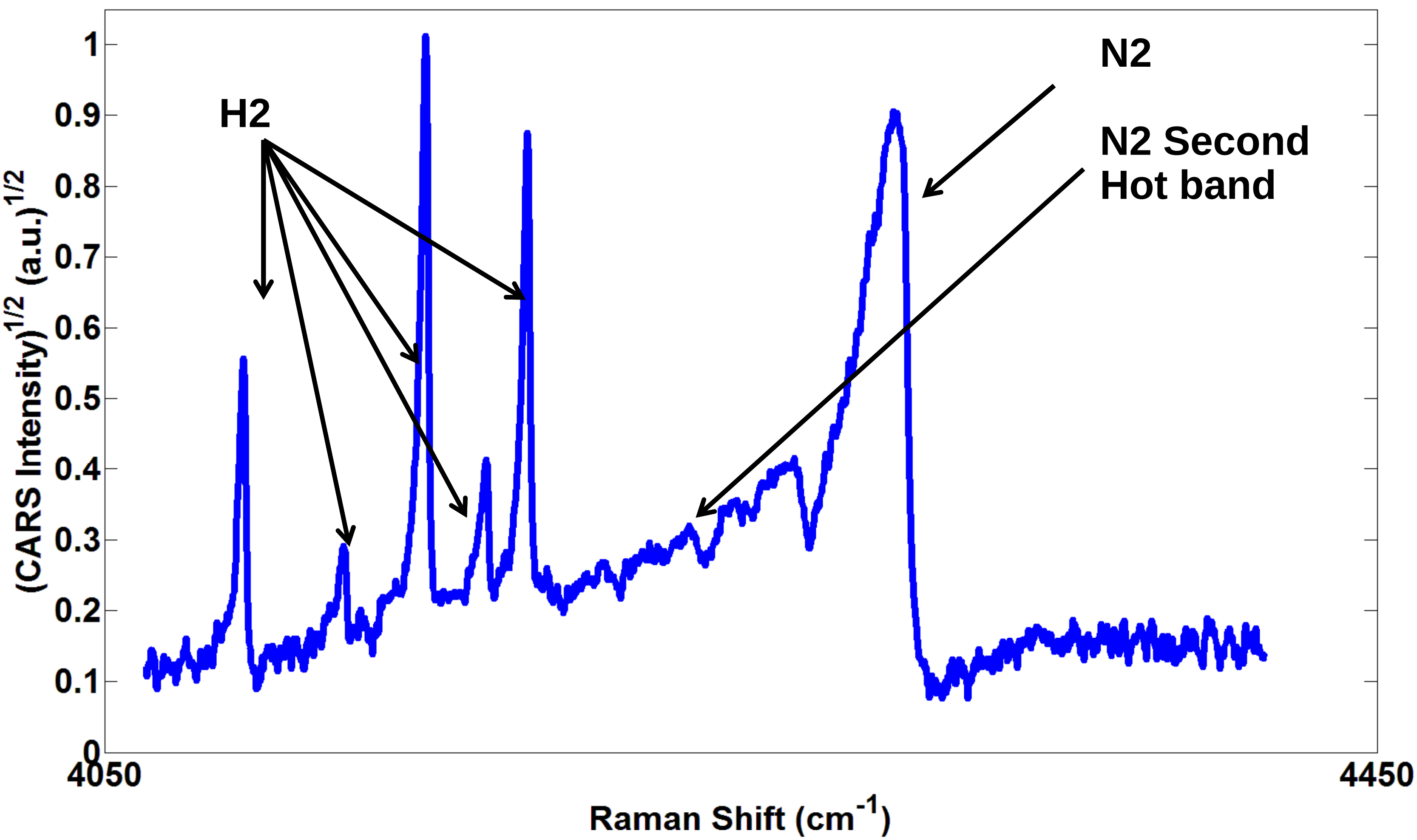
# Dual-Pump CARS for $H_2$ and $N_2$

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# Dual-Pump CARS Measurements

- Three jet conditions with different momentum flux ratio and/or equivalence ratio were investigated. Dual-pump CARS was collected from the center plane at 140 different spatial locations. 300 single-shot spectra were acquired at each spatial location.
- $H_2$ served as a marker of the reaction zone for the rich jet conditions. Little $H_2$ was observed for the lean jet conditions.
- Data processing is underway, approximately 120,000 spectra need to be analyzed.

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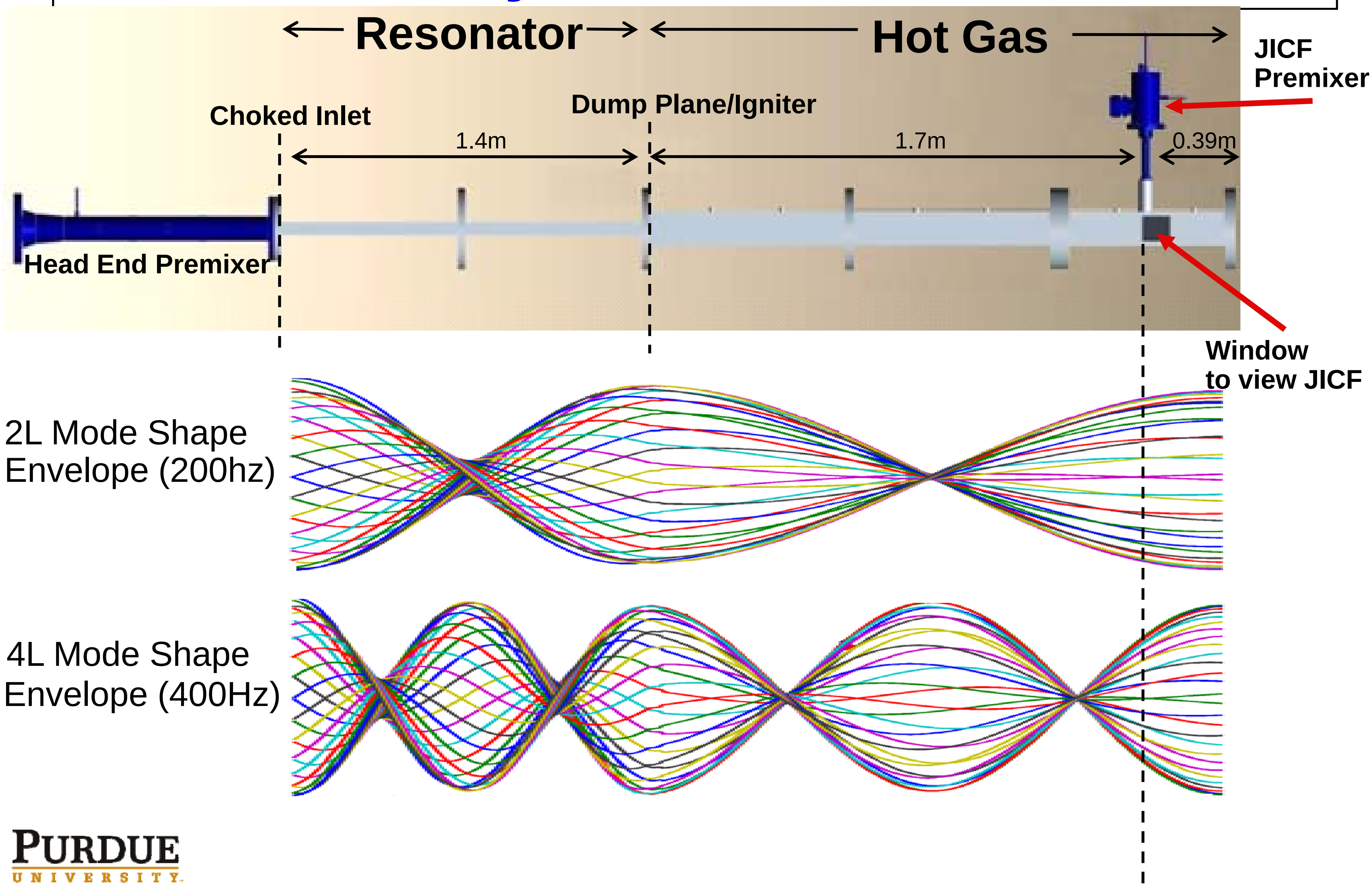
# Premixed Jet Injection in An Oscillatory Vitiated Cross Flow

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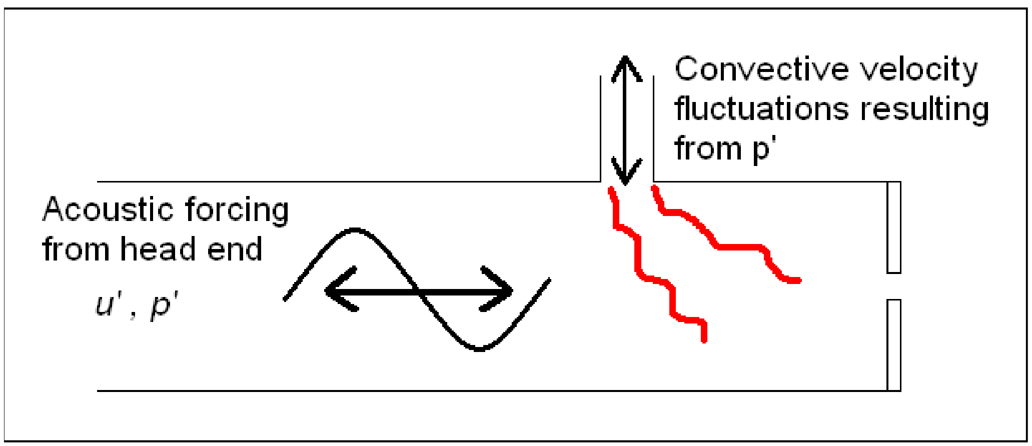
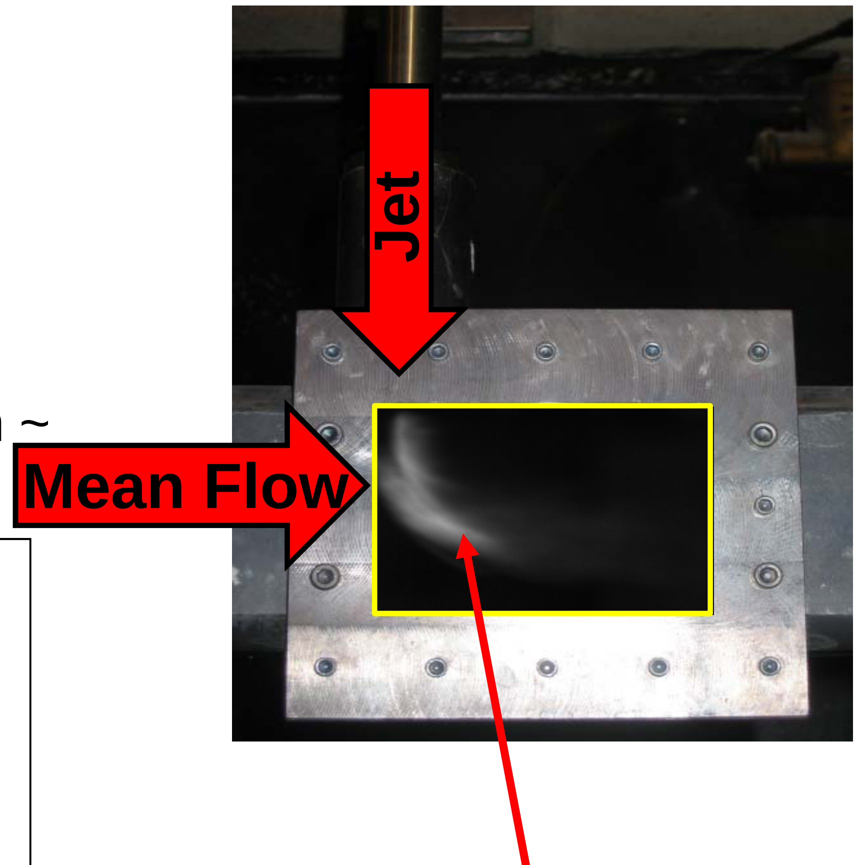
# High Speed Intensified CH* and OH* of Jet in Unstable Crossflow

- Window (4” by 3”)
- Momentum flux ratio between 3 and 8
- High speed camera and intensifier
- Pre-mixed natural gas (92 % methane)
- Mean chamber pressure 7.6 to 8.3 bars
- Jet injection velocity 65 to 85 m/s (Mach ~ 0.1)




Filtered Image of Reacting Jet

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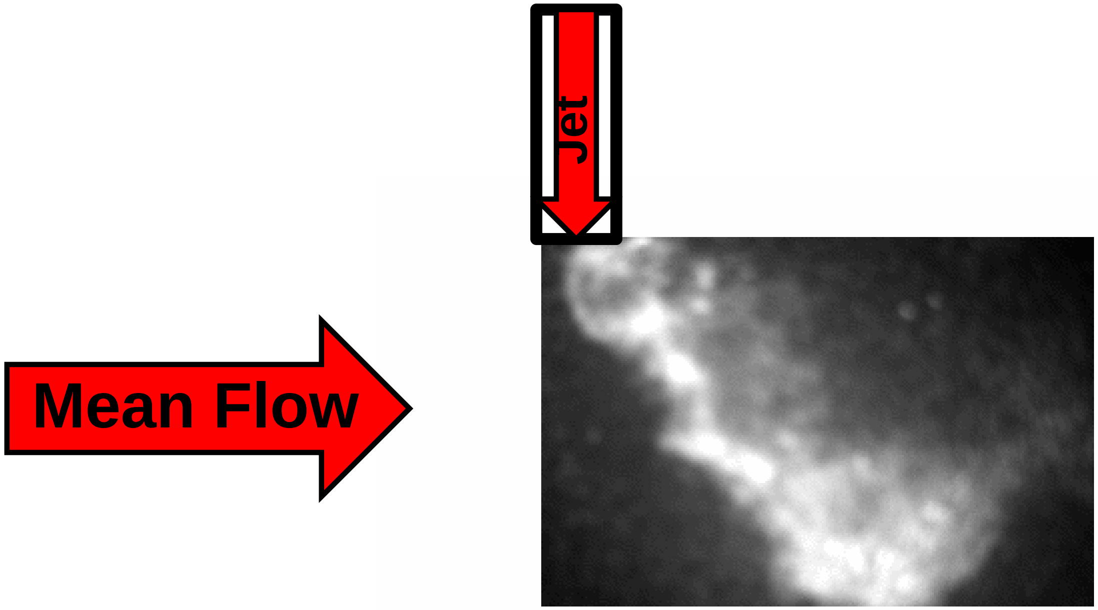
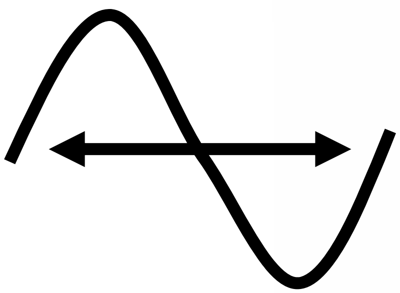
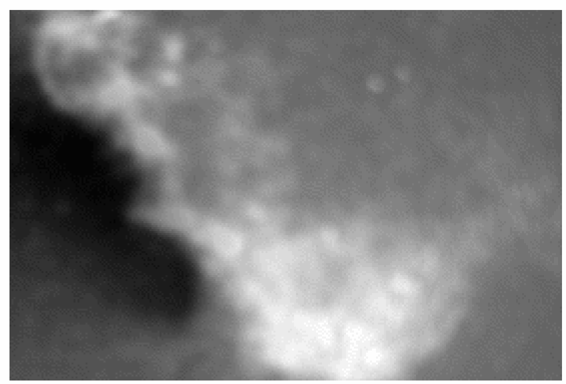
# High Speed Intensified CH* Video of JICF (J=6)




Raw Movie

Acoustic Forcing

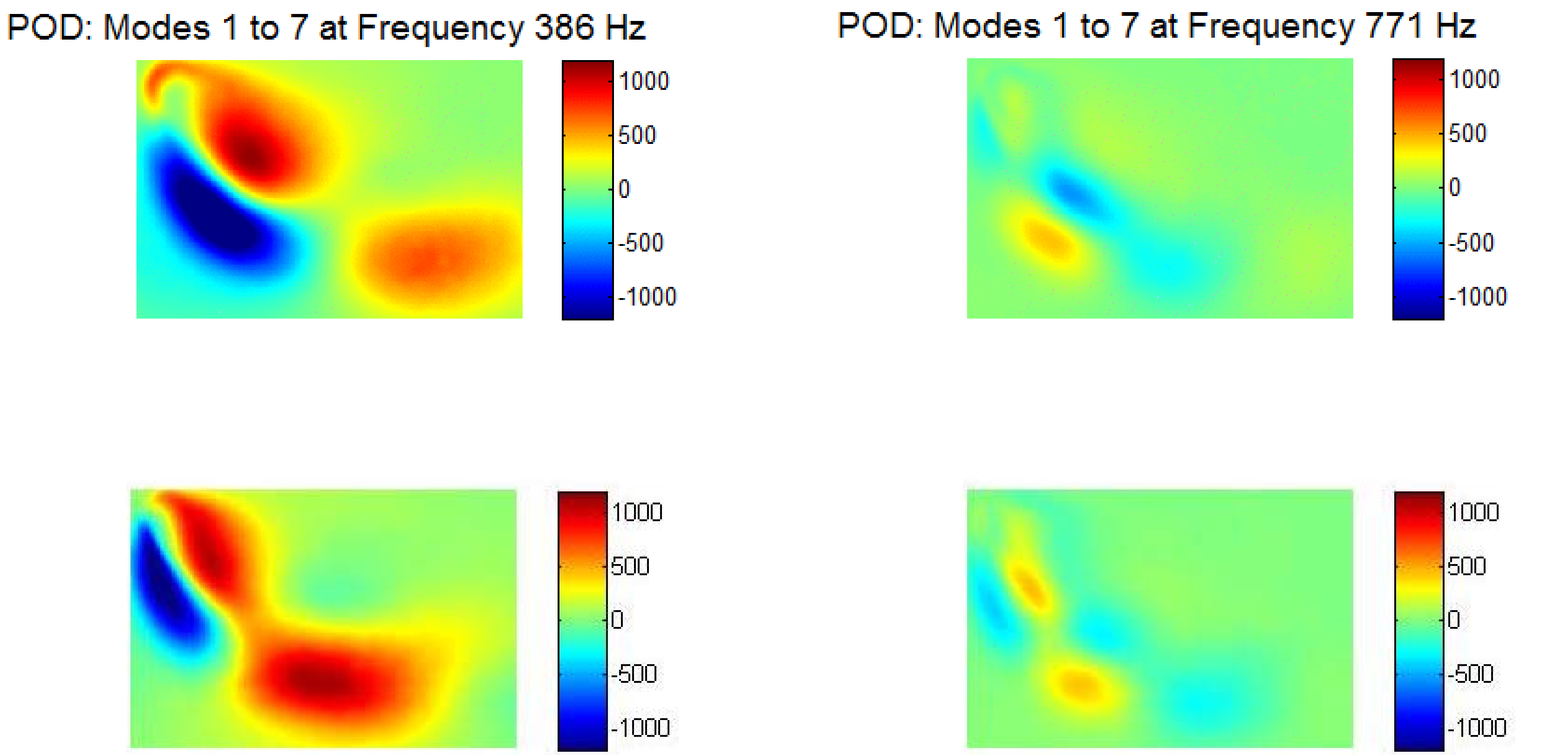




Unsteady Movie
= Raw - Mean

# Proper Orthogonal Decomposition

- Low-dimensional approximation of CH* JICF images used to identify, track, and quantify dominant JICF structures




POD isolates temporal and spatial character

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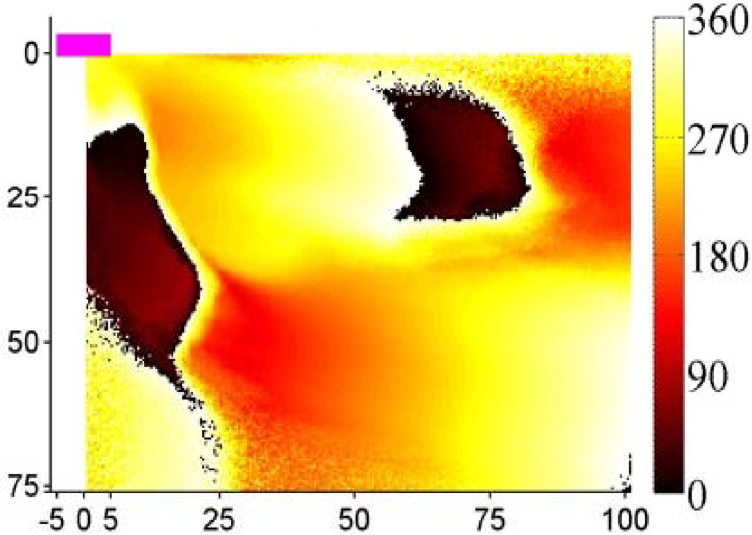
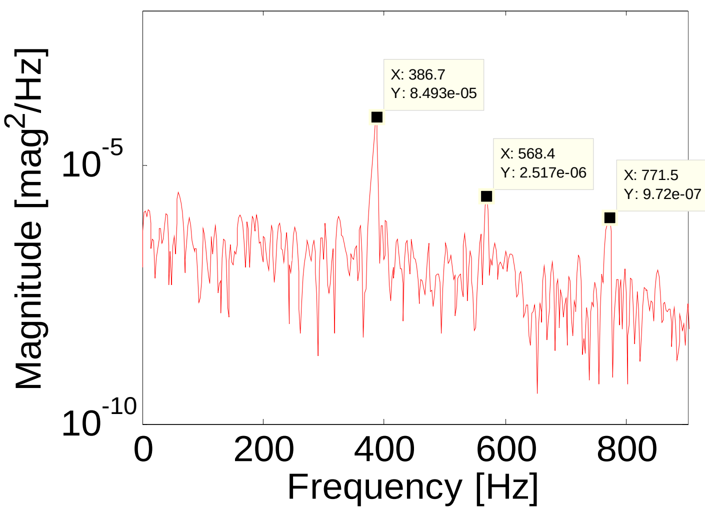
# Jet displays organization in amplitude and phase in relation to cross flow acoustics

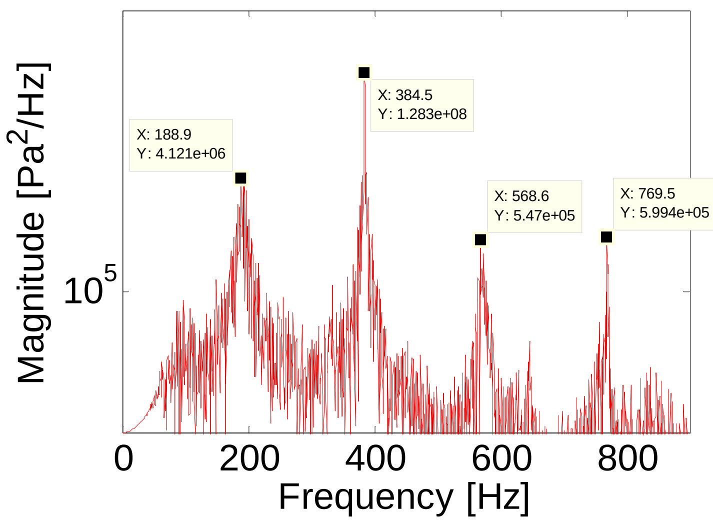
Phase at 387 Hz between cross flow u’ and CH*’




PSD of POD Temporal Mode 2




PSD of Pressure at Jet Injection

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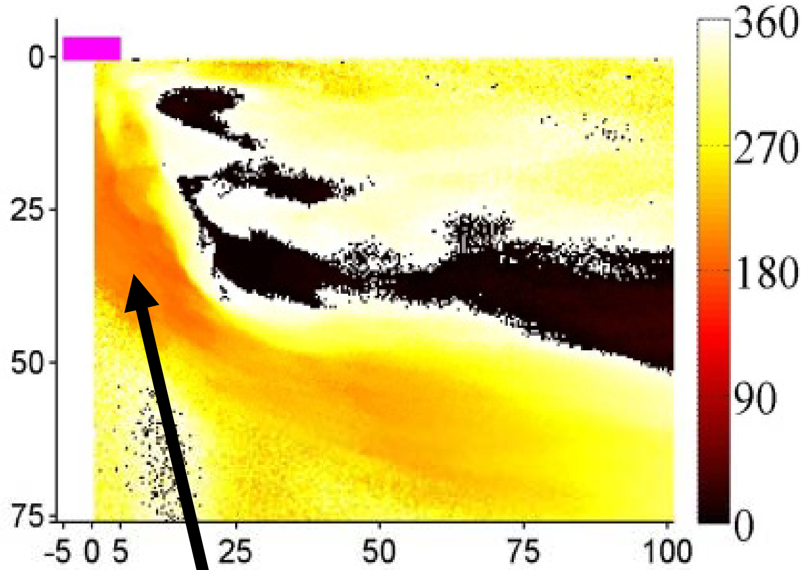
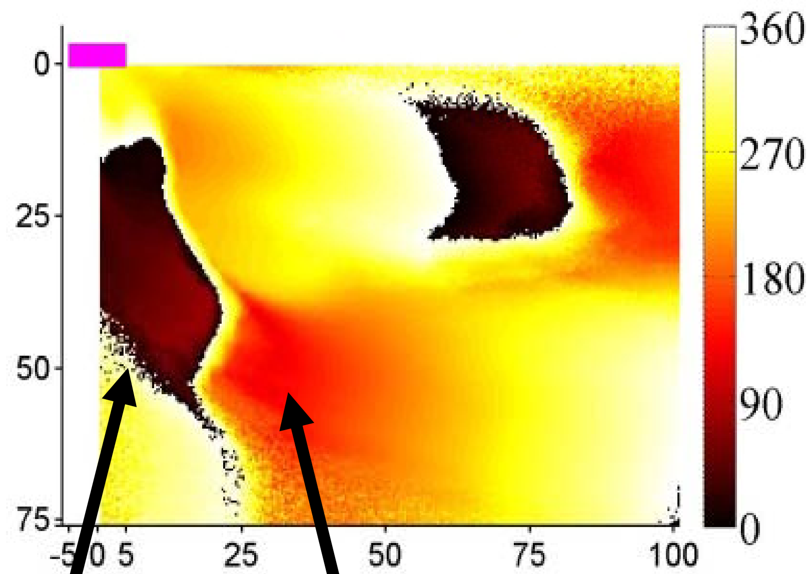
# Jet Organization in Phase Different for Fundamental and Harmonic Frequencies (J=6)

Phase at 194 Hz between cross flow u’ and CH*’




Phase at 387 Hz between cross flow u’ and CH*’




Windward side of jet in phase with downstream running compression wave

Periodic jet tip in phase with mean flow maximum (u’ with mean flow)

Windward side of jet in phase with local rarefaction

# Summary

- Facilities for high-pressure gas turbine combustion are well suited for detailed RJIC studies at realistic pressure conditions.  Shield flow control is critical for window survival for the harsh conditions in RJIC flow field.

- Dual-pump CARS measurements performed, required multiple hours per test condition to acquire the data.

- Our first 5 kHz OH PLIF performed, good signal levels observed even at the rig pressure of 5.57 bar.

- Instability measurements performed using CH chemiluminescence,  POD analysis.

# Future Work

- OH PLIF measurements will be continued in the near term.  Improved sheet optics, camera will be moved closer, normalization with acetone PLIF,  HHC fuels after experimental methods are optimized.
- High-speed PIV.
- Combined high-speed PIV/PLIF.
- CARS (5 kHz femtosecond or 0.01 kHz nanosecond) for quantitative temperature and species measurements.
- Coordination with modeling efforts at Siemens, UT Austin,…

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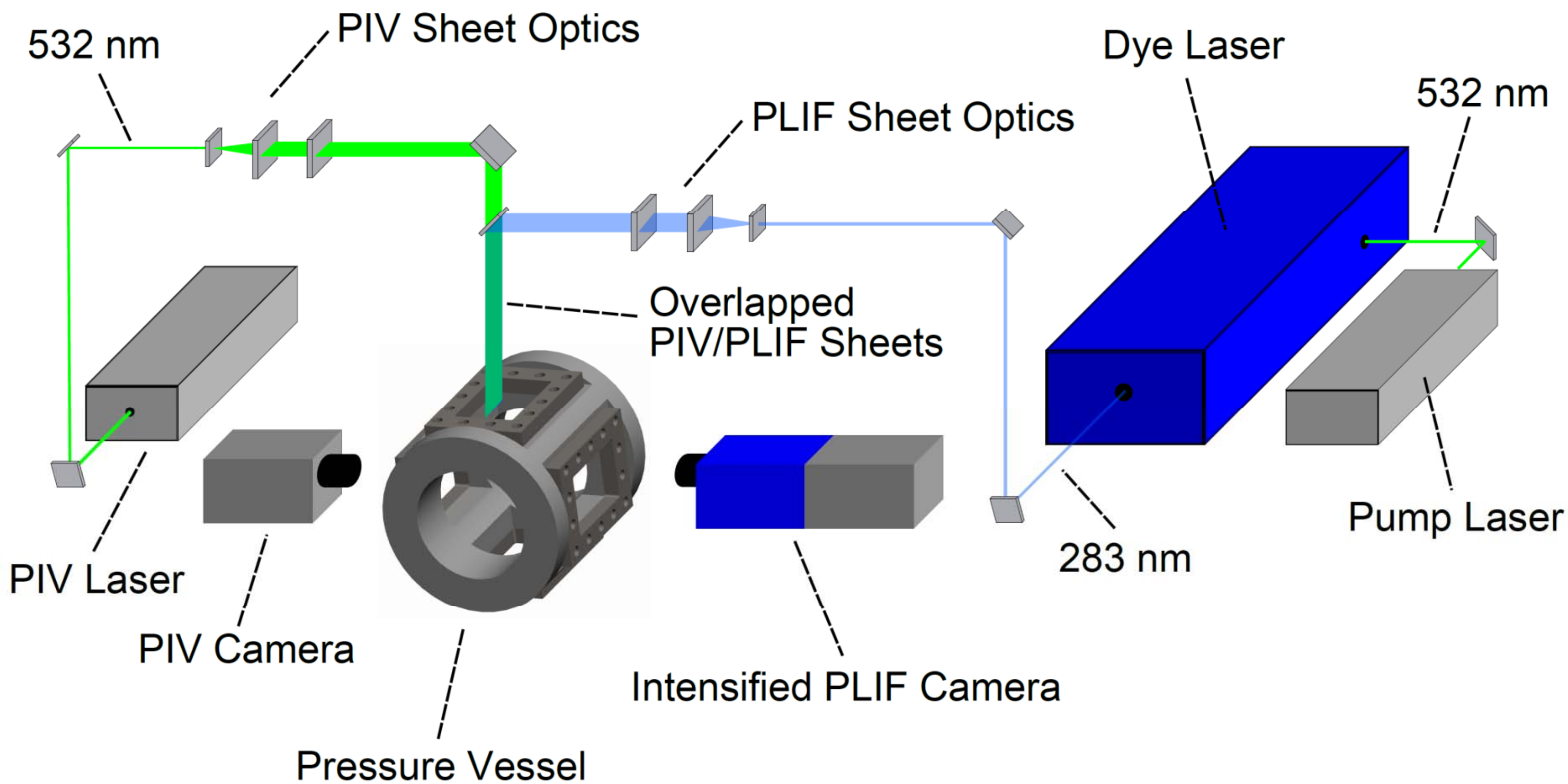
# Recent Measurements at DLR Stuttgart

3 kHz simultaneous PIV/OH PLIF in 5 bar methane/air flame in DLR test rig, measurements performed by C. Slabaugh (Purdue) and I. Boxx (DLR)

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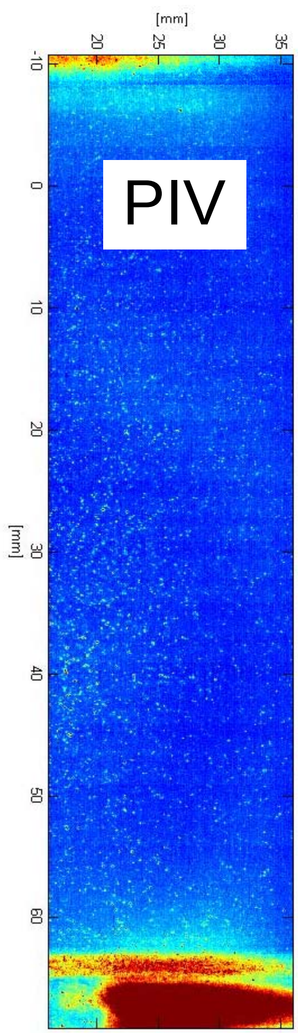


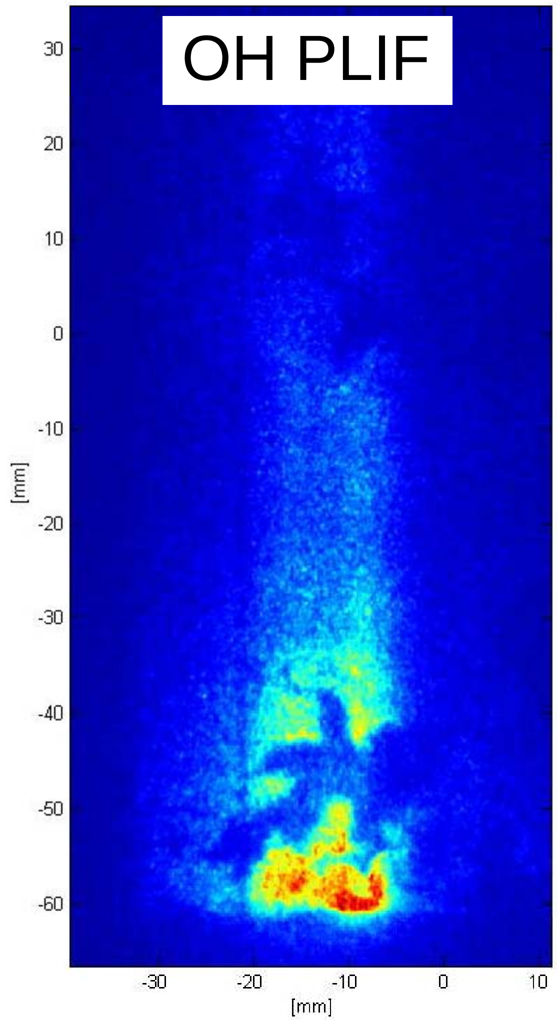


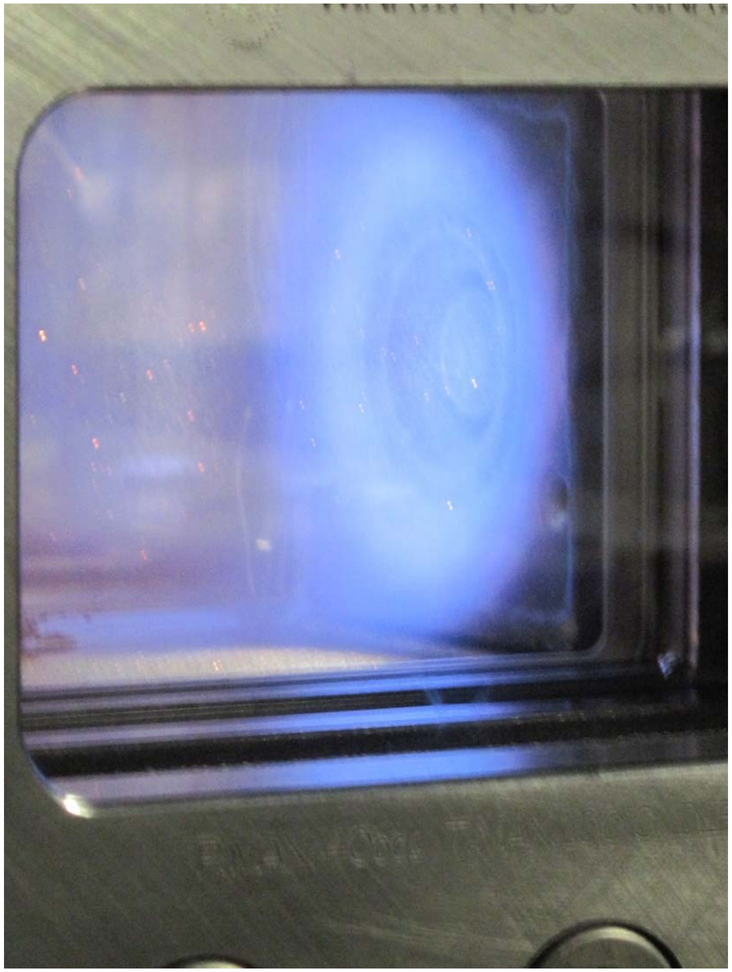

Data analysis in process

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