Structure and Dynamics of Fuel Jets Injected into a High-Temperature Subsonic Crossflow: High- Data-Rate Laser Diagnostic Investigation under Steady and Oscillatory Conditions: DOE UTSR DE-FE0007099

Robert P. Lucht and William E. Anderson

Purdue University

West Lafayette, Indiana

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Outline of the Presentation

- Research Objectives
- Gas Turbine Combustion Test Rigs
- Laser Diagnostic Techniques
- Experimental Results
- Summary and Future Work

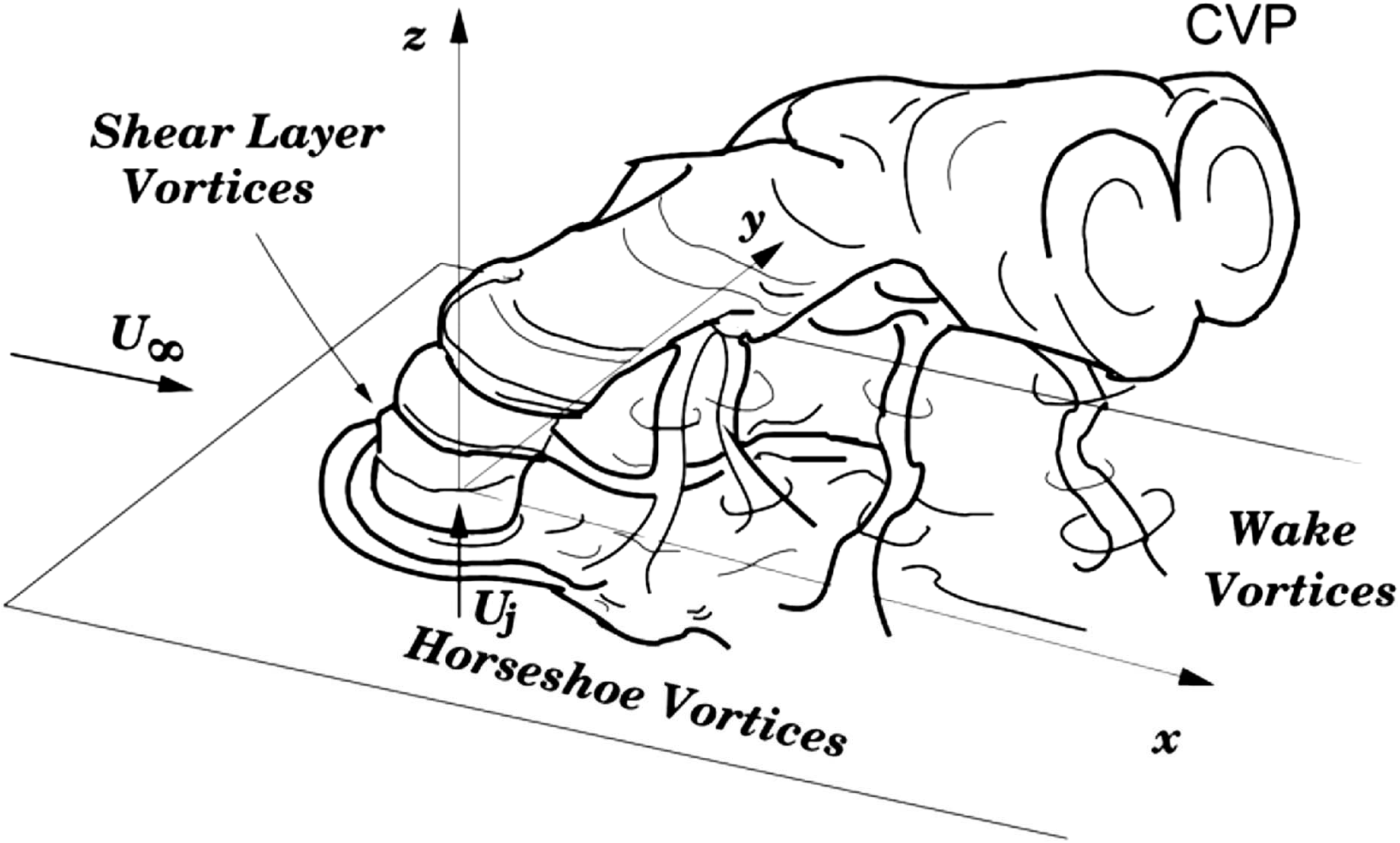
Research Objectives

- 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 fields investigated using advanced, high-data-rate (5-10 kHz) laser diagnostic methods.

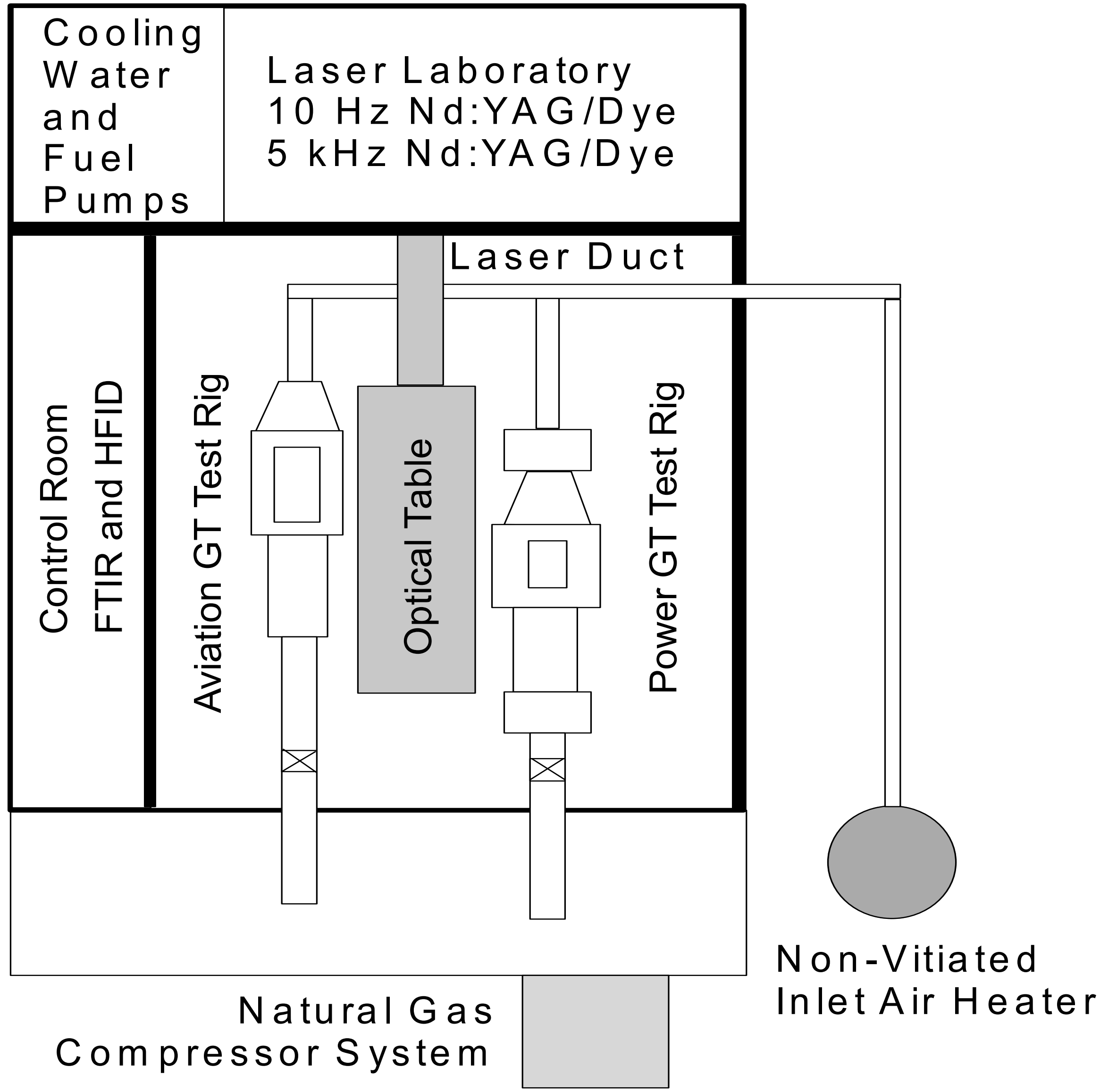
Research Objectives

- 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.
- Effect of the RJIC on combustion instabilities is also being investigated.

Research Objectives

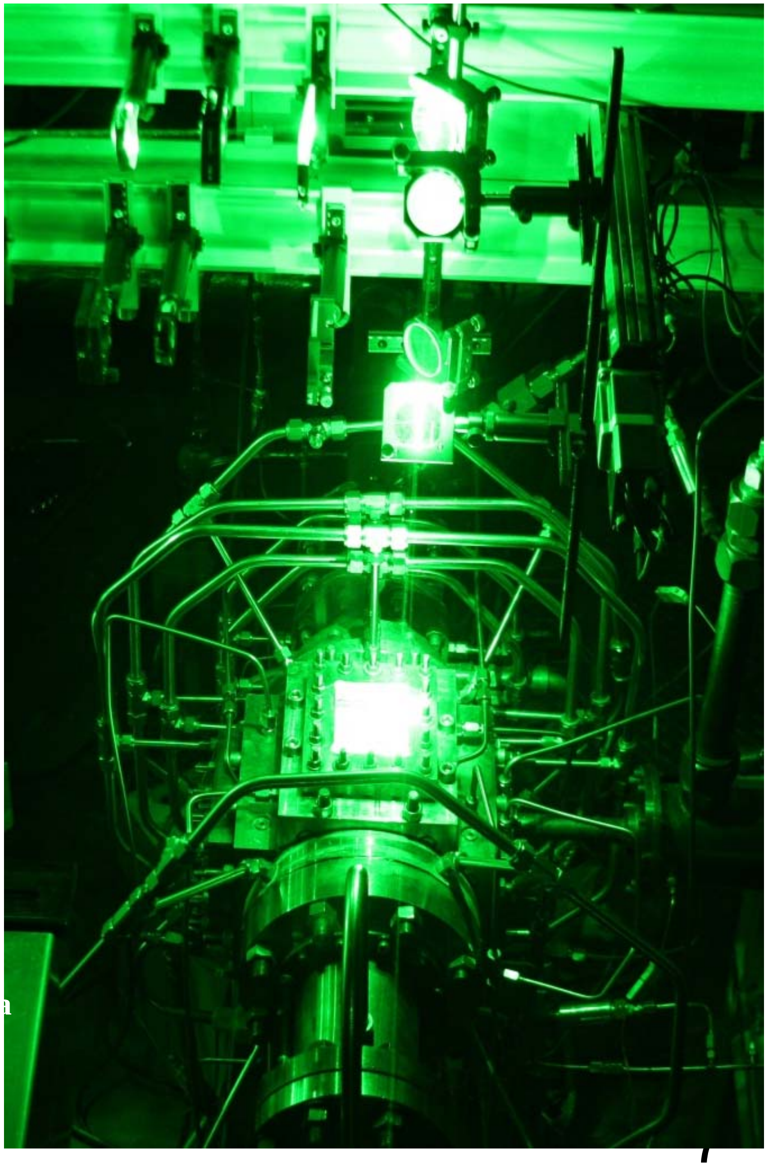


Purdue Gas Turbine Combustion Facility (GTCF)



Purdue Gas Turbine Combustion Facility (GTCF)

High Pressure Lab System	Maximum Flow Capacity	Max Operating Condition
Natural Gas Heated High Pressure Air	9 lbm/s 4 kg/s	700 psi / 1000 F 1400 F in 2015
Electric Heated Air or Nitrogen	1 lbm/s 0.5 kg/s	600 psi / 1000 F
Nitrogen	5 lbm/s 2 kg/s	1,500 psi
Liquid Aviation Fuel (Kerosene)	1 lbm/s 0.5 kg/s	1,500 psi
Natural Gas	1 lbm/sec 0.5 kg/s	3500 psi



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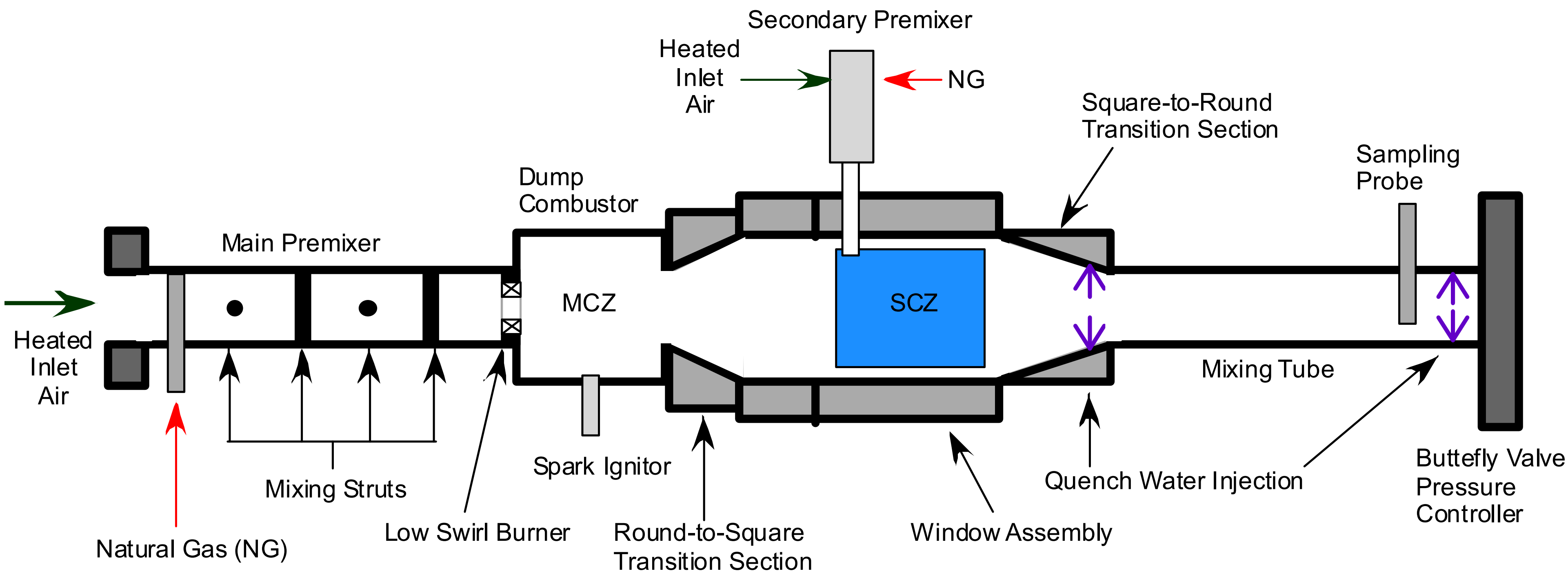
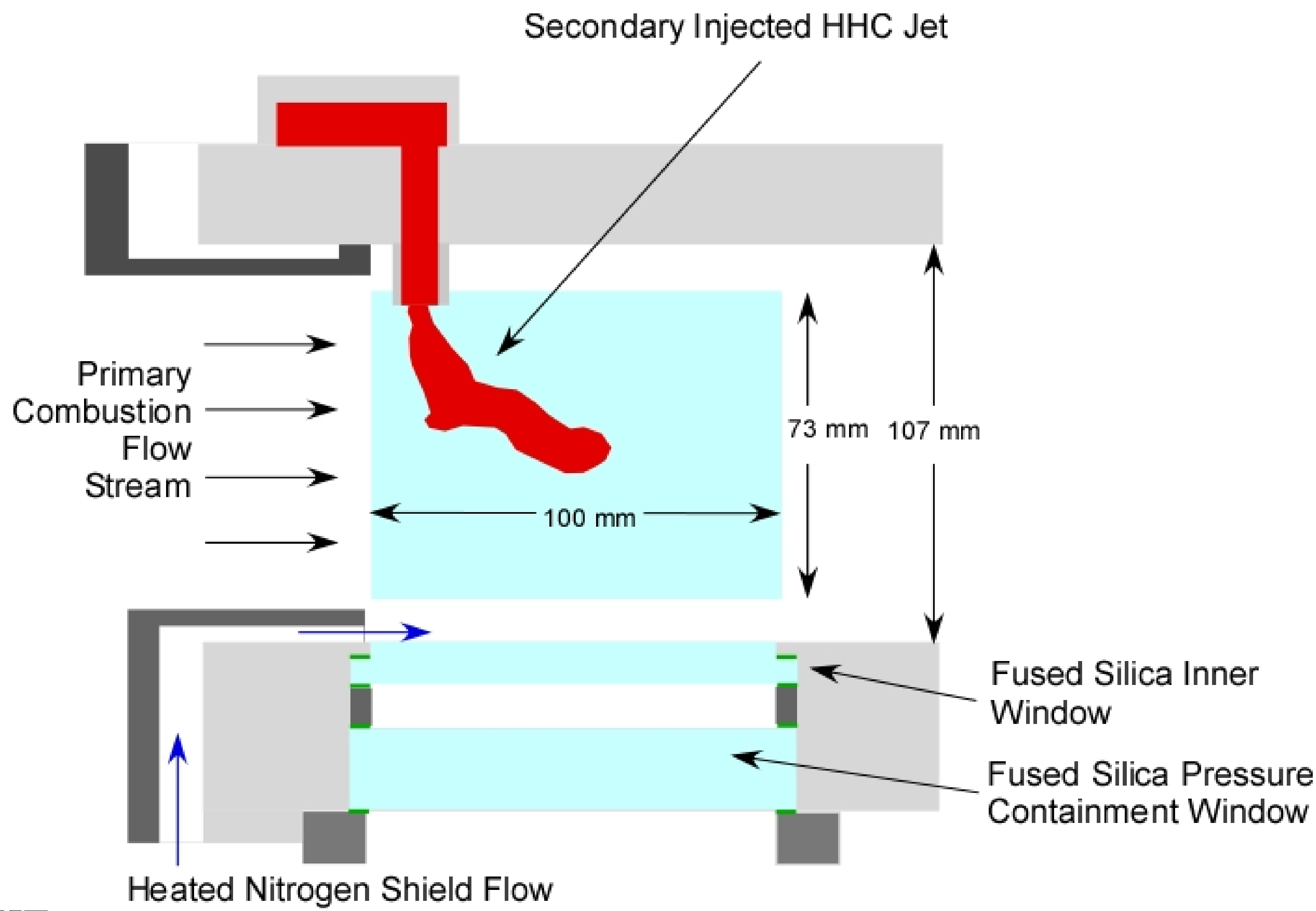
High-Pressure RJIC Emissions Test Rig: Present Configuration



High-Pressure RJIC Test Rig: Present Configuration



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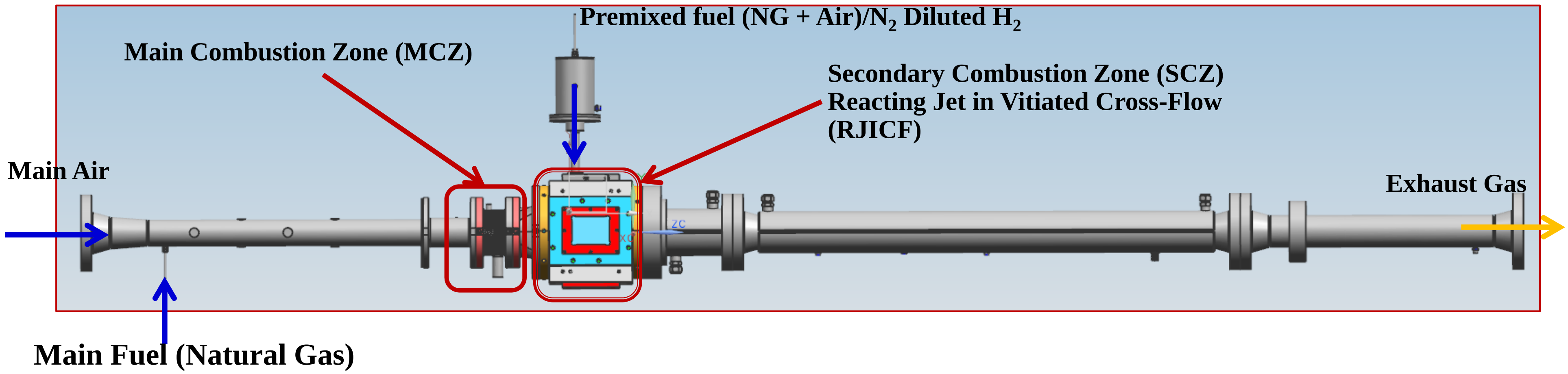
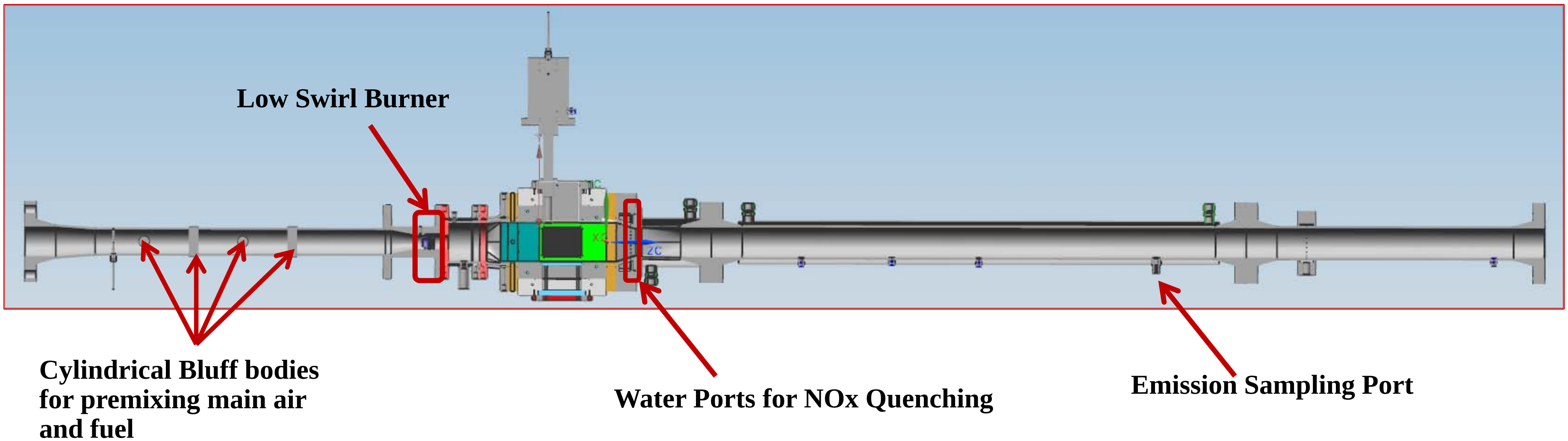
High-Pressure Distributed Combustion System (DCS)





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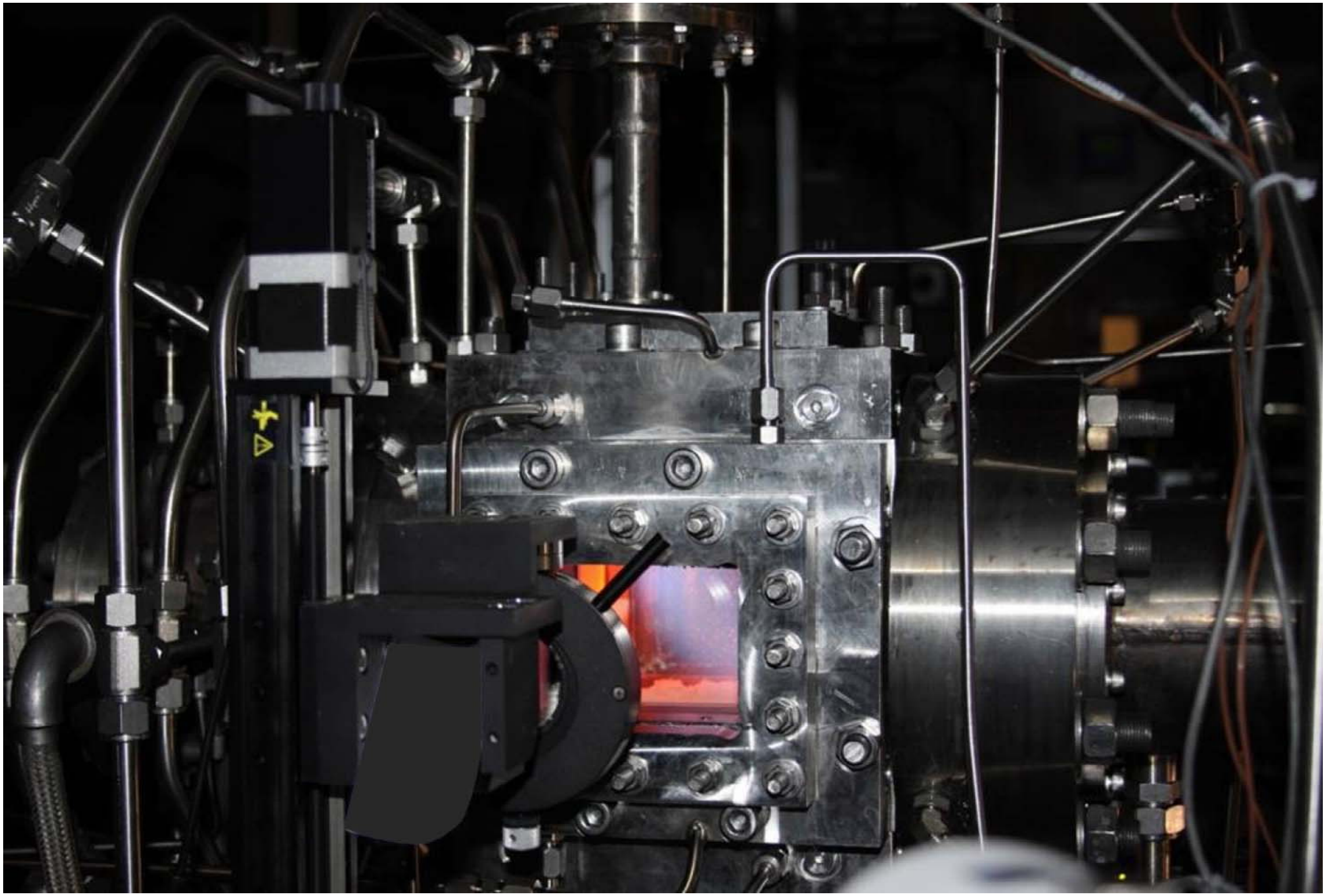
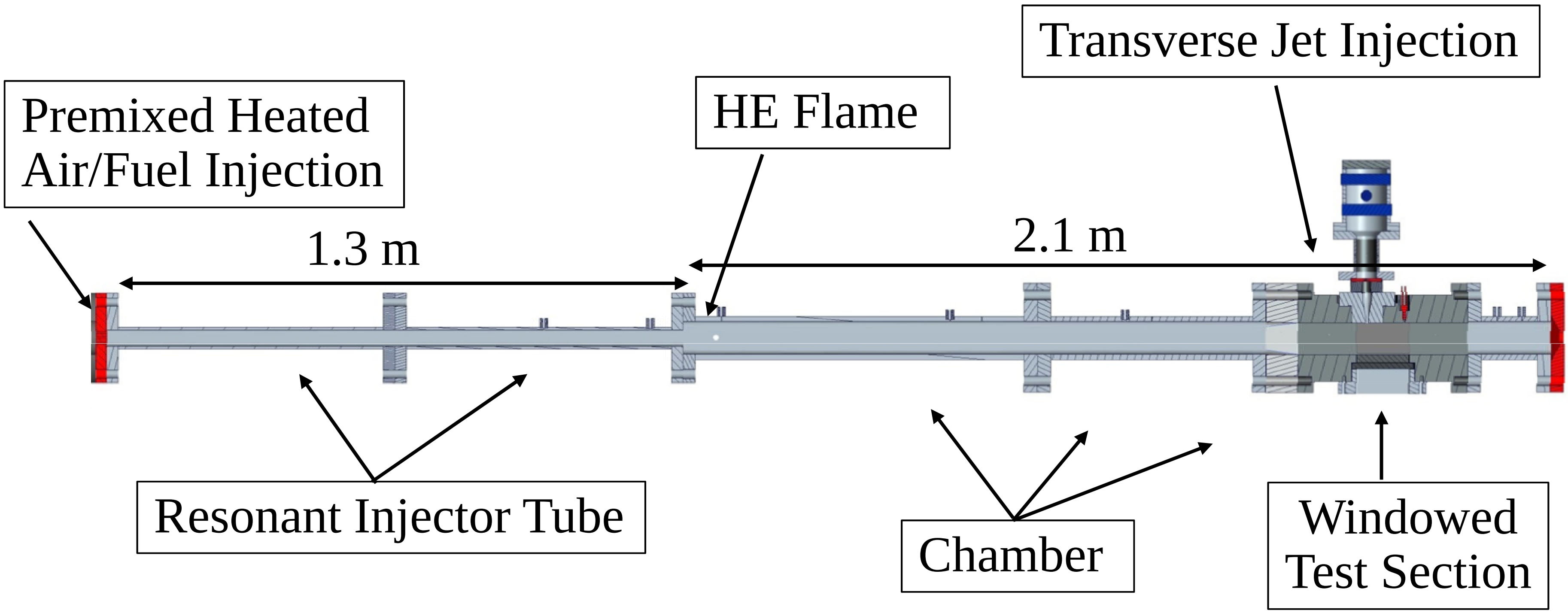
High-Pressure RJIC Test Rig in Operation



Purdue Instability Test Rig



- $P_{chamber}$ ~ 0.7-1.1 MPa
- Preheat Air Temp ~ 400C
- Air mdot ~ 0.41 kg/s
- Natural gas fuel for HE flame

Cross Flow Mode	**1L**	**2L**	**3L**	**4L**	**5L**
Freq [Hz]	100	195	299	389	498

Test rig provides acoustic environment for transverse jet injection

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High-Repetition-Rate Diagnostic Techniques: Current Capabilities

- 5-10 kHz PIV – dual-head Edgewave laser, 30 W per head at 532 nm

- 5-10 kHz OH PLIF – Credo dye laser pumped by a 90 W Edgewave laser up to 7W of ultraviolet (1.4 mJ/pulse at 5 kHz)

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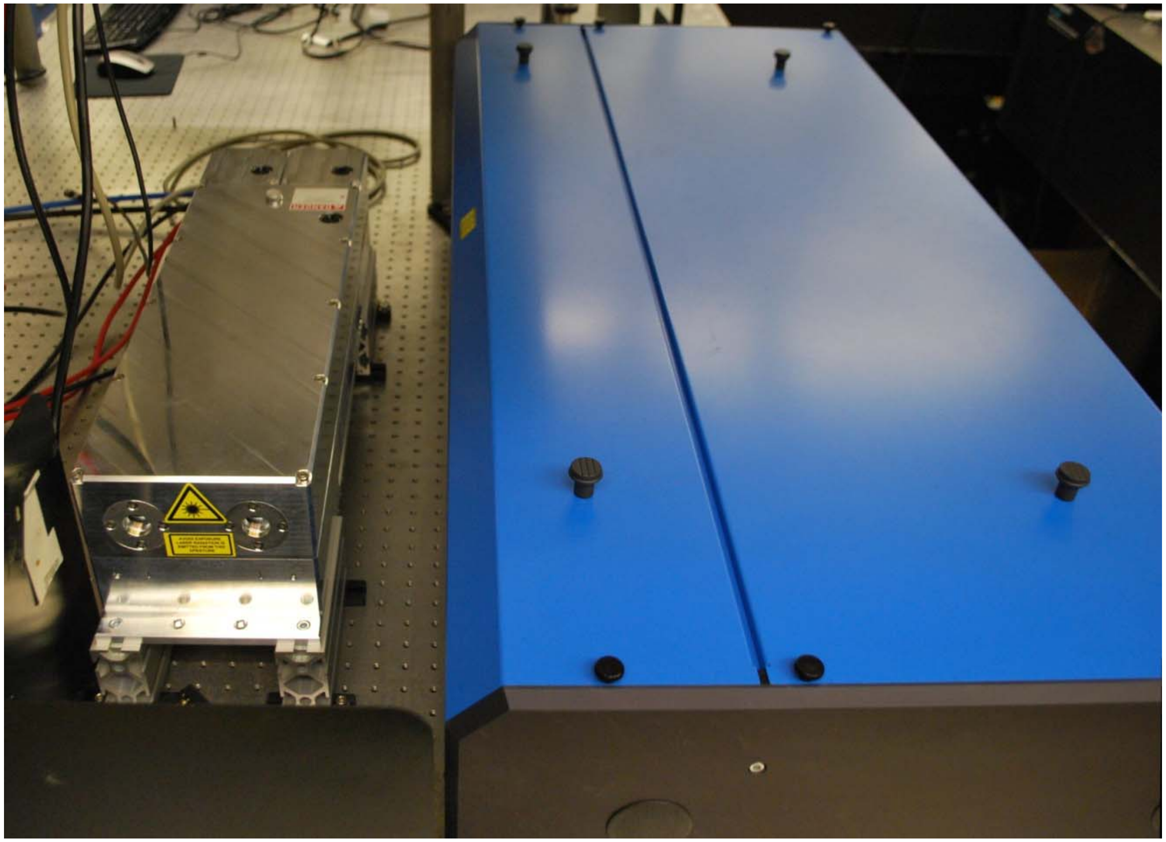
Current High-Repetition-Rate Laser System

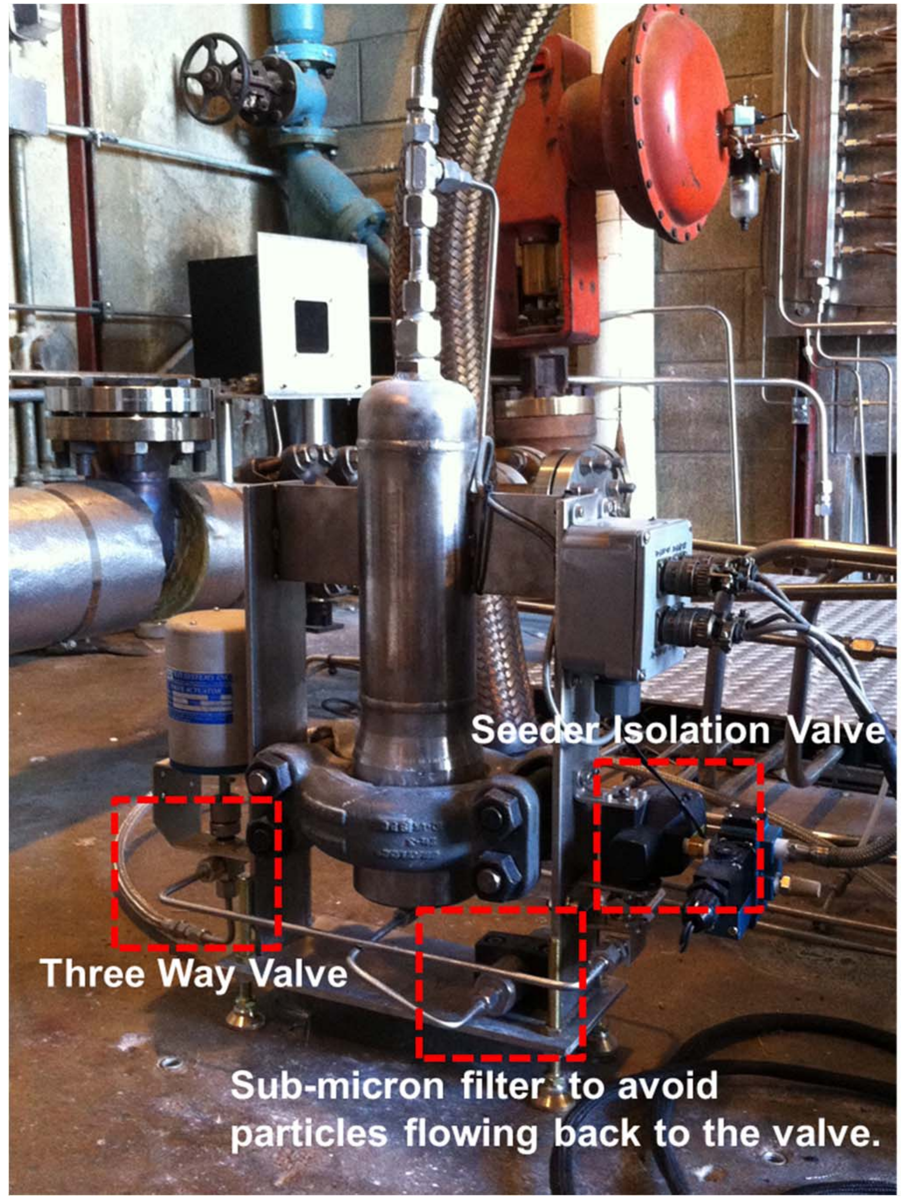


Edgewave Diode-Pumped Solid State Nd:YAG Laser: 5 kHz Rep Rate, Dual-Head, 6 mJ/Pulse at 532 nm, 7 nsec Pulses

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

Seeding for High-Speed PIV

- High-speed PIV offers possibility of acquiring significant PIV data sets even in high-pressure systems with windows.
- Particle seeding turned on and off, synchronized with PIV data acquisition.
- Dynamics of seeder must be tuned by trial and error for good signal, maximum run time.



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Experiment Operating Condition: Test Matrix

Cross Flow Operating Condition						
Operating Pressure (atm)					**5.5**	
Operating Temperature (K)					**723**	
MCZ Air Flow Rate (kg/s)					**0.39**	
MCZ Equivalence Ratio, ϕ_{main}					**0.5**	
Main Flow Reynolds Number(NR), Re_{main}					**105000**	
Main Flow Reynolds Number(R), Re_{main}					**61000**	
Non-Reacting Jet in Cross Flow						
JET	**Temperature (K)**	**Momentum Flux Ratio, J**	**Density Ratio, S**	**Jet Reynolds Number, Re_{jet}**		
Hot Air	400	3	1	16900		
Hot Air	400	8	1	27600		
RJICF Conditions						
FUEL JET	**Temperature (K)**	**Momentum Flux Ratio, J**	**Density Ratio, S**	**Jet Reynolds Number, Re_{jet}**	ϕ_{jet} =0.9	ϕ_{jet} = 3.0
Premixed NG	400	3	2.5	27500	ΔT = 36 K	ΔT = 145
	400	8	2.5	45000	ΔT = 52 K	ΔT = 212
					40%/60%	**50%/50%**
H_2/N_2	280	3	4.25	72000	ΔT = 28 K	ΔT = 131
	280	8	4.25	118000	ΔT = 64 K	ΔT = 182

- **The NR jets and premixed NG jets are preheated to T = 400K. (After mixing with particle carrying cold air)**
- **The H_2/N_2 jets are at ambient temperature.**

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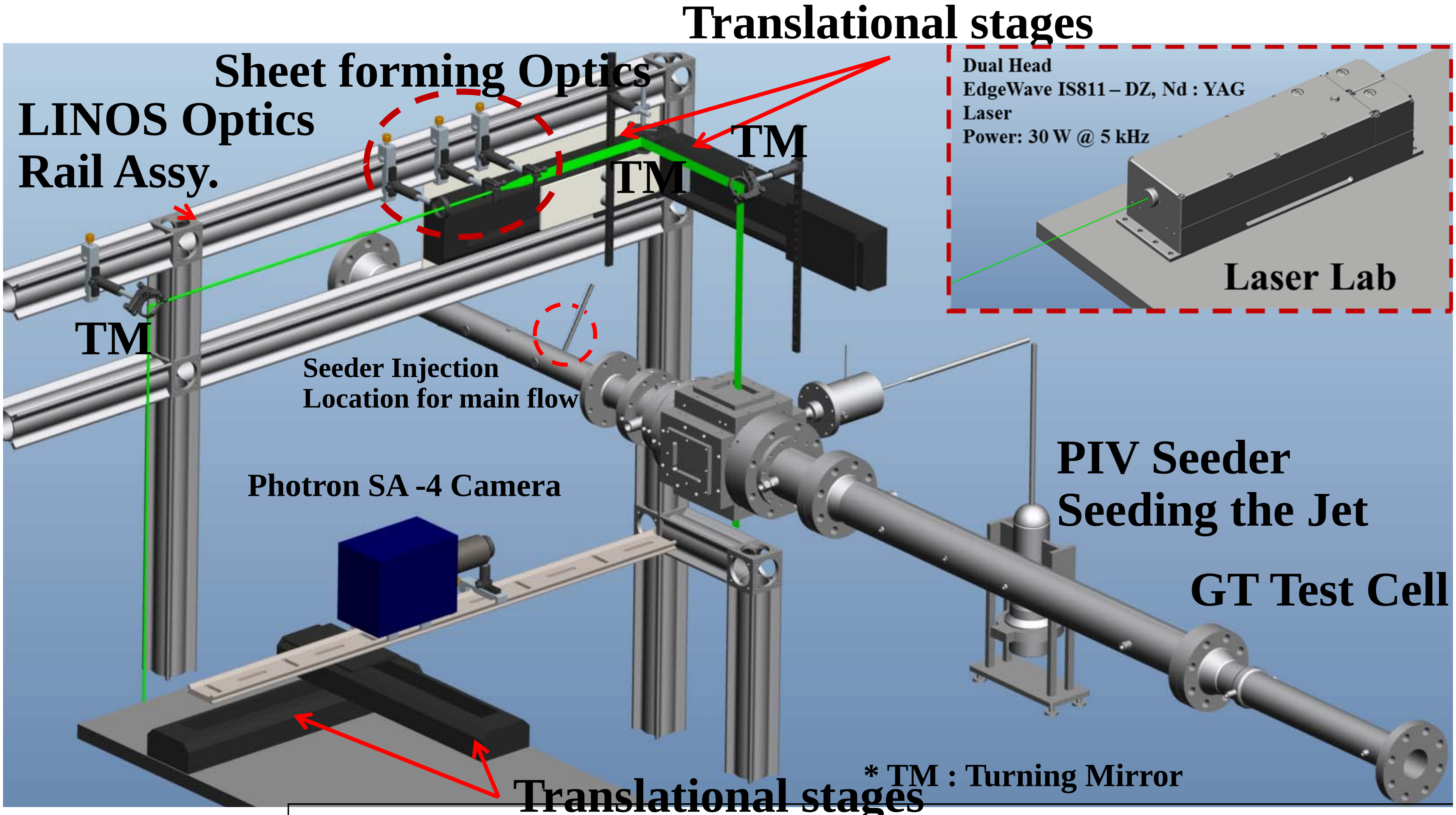
CAD Representation of the PIV Experimental System

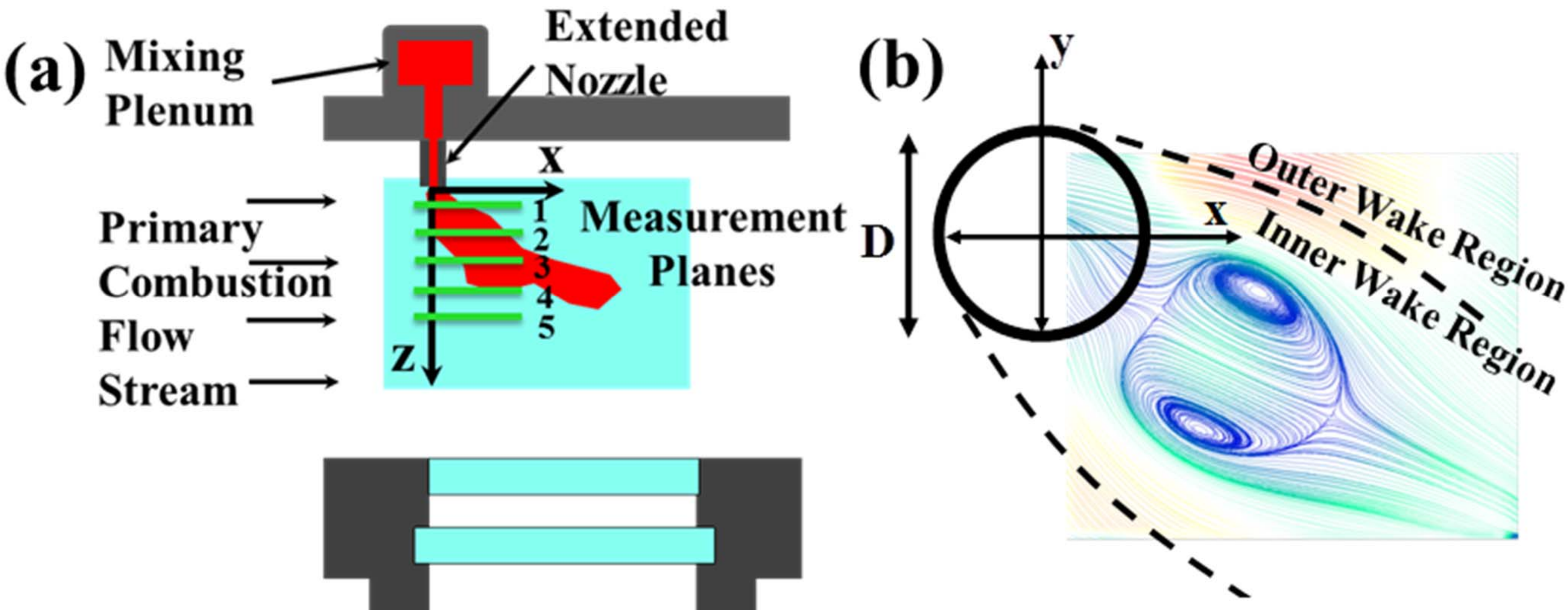


The rig has two locations for injecting PIV seed:

i) Upstream of the LSB.

ii) Seeding the jet.

RJICF Schematic : PIV Measurement Planes



5 measurement planes selected to acquire a three-dimensional picture of the flow field.

Raw Particle Images

Conditions : J = 3 Φ_{jet}= 3.0
Plane : z/d = 5mm

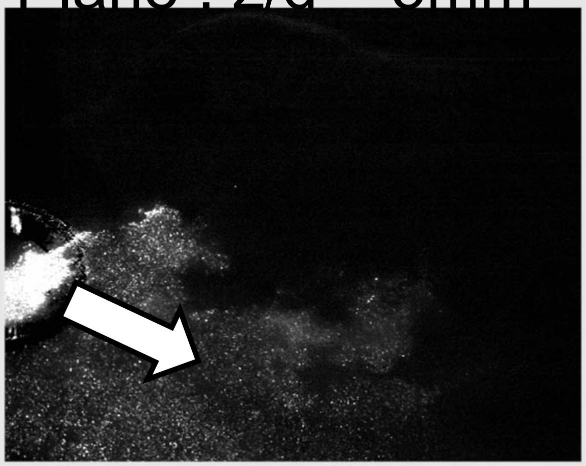


Image showing the seeded jet with a net downward direction indicated by the arrow due to the swirling crossflow.

Conditions : J = 3 Φ_{jet} = 3.0
Plane : z/d = 48mm

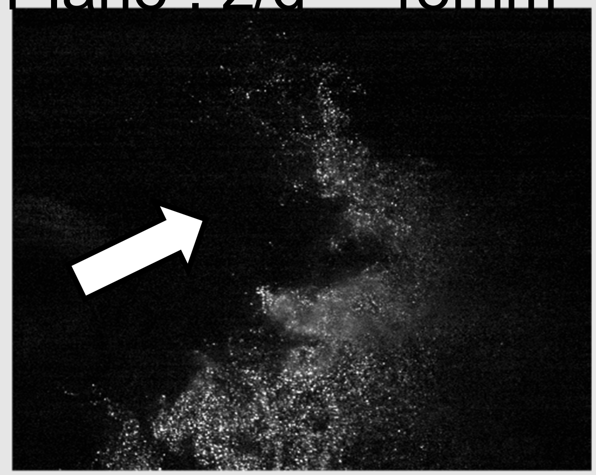
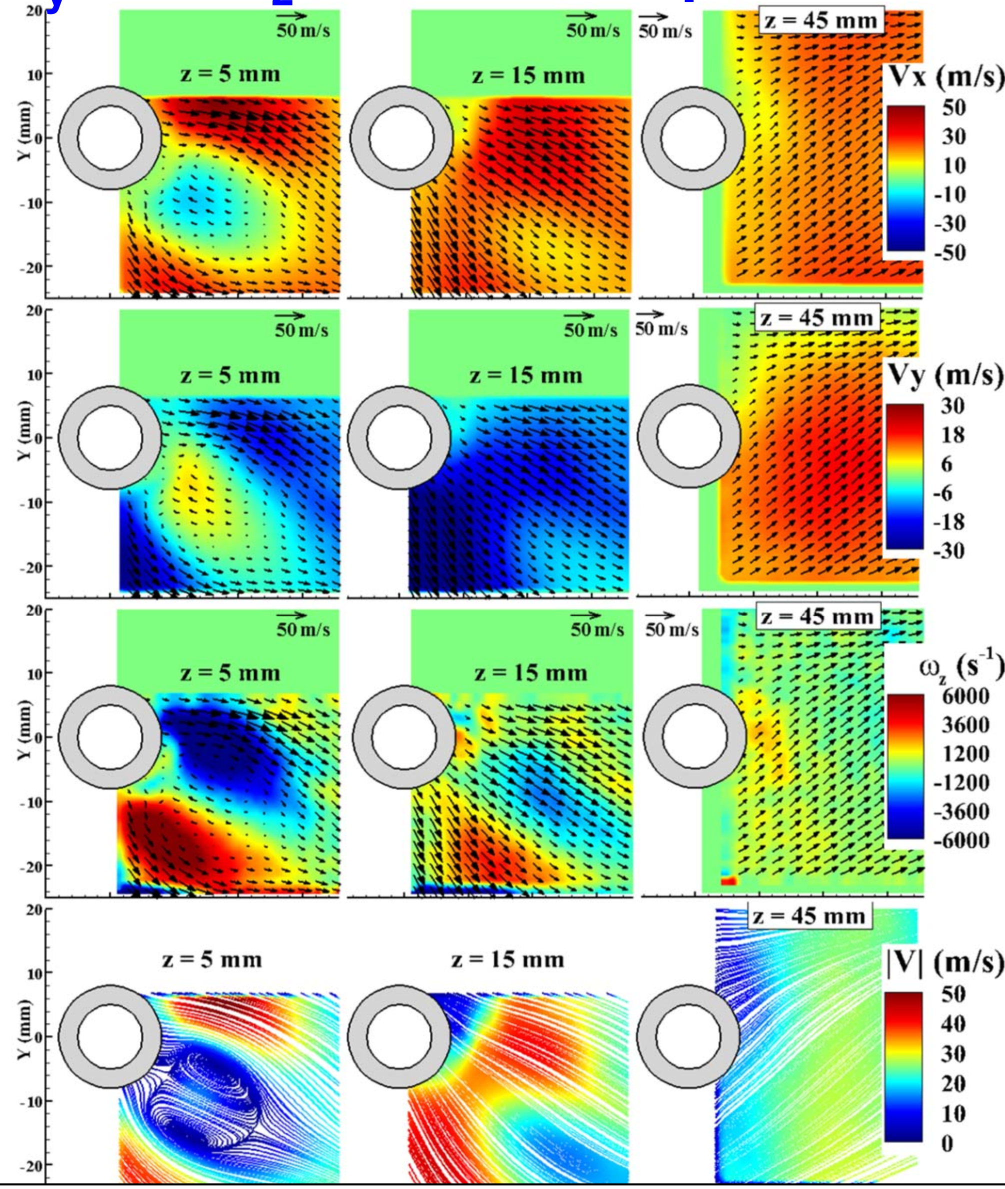


Image showing the seeded jet with a net upward direction indicated by the arrow due to the swirling crossflow.

3777 image pairs captured in order to obtain good turbulence statistics

Reacting Jet in Swirling Crossflow: Variation of time averaged V_x, V_y and ω_z at various z planes for J=3 Φ=3



Time averaged flow field indicating the effect of swirling crossflow on the reacting jet. Steady wake vortices captured at z=5mm

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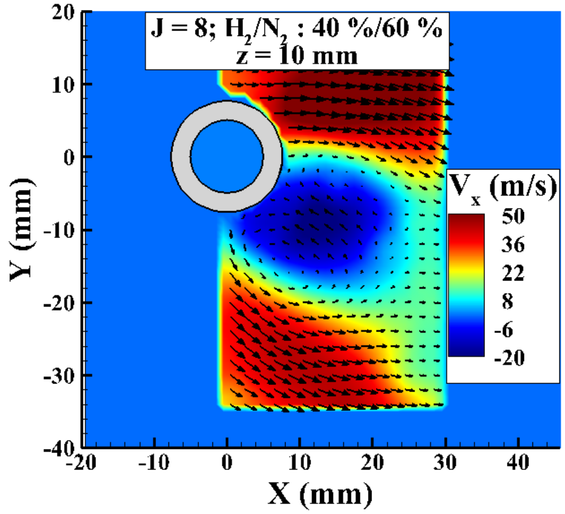
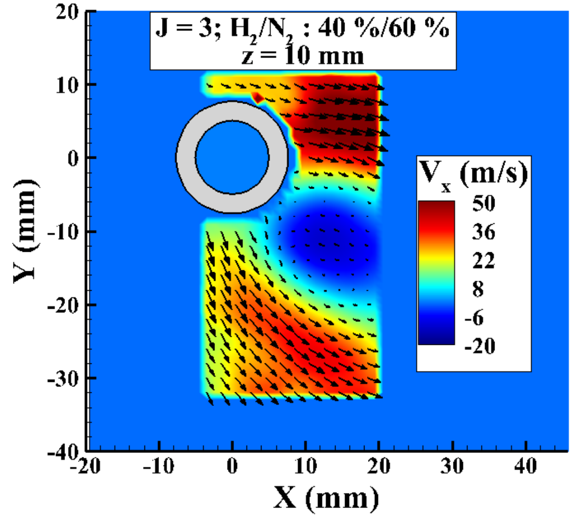
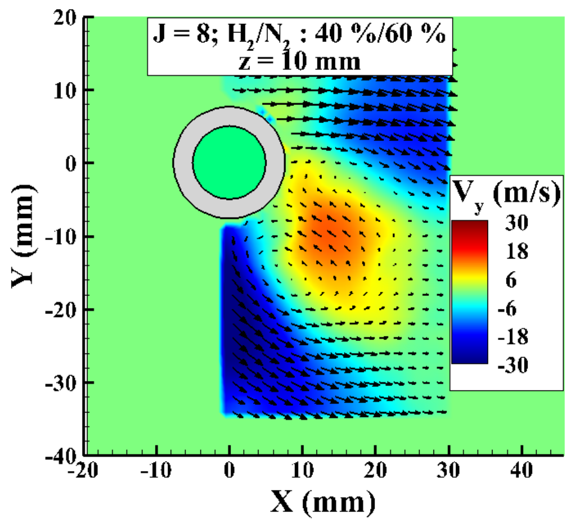
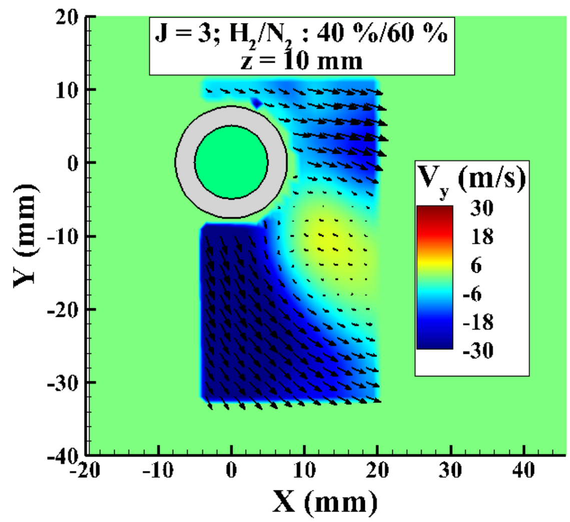
Reacting Jet in Swirling Crossflow: Time-Averaged V_x and V_y for H_2/N_2 Jets with J = 8 and 3









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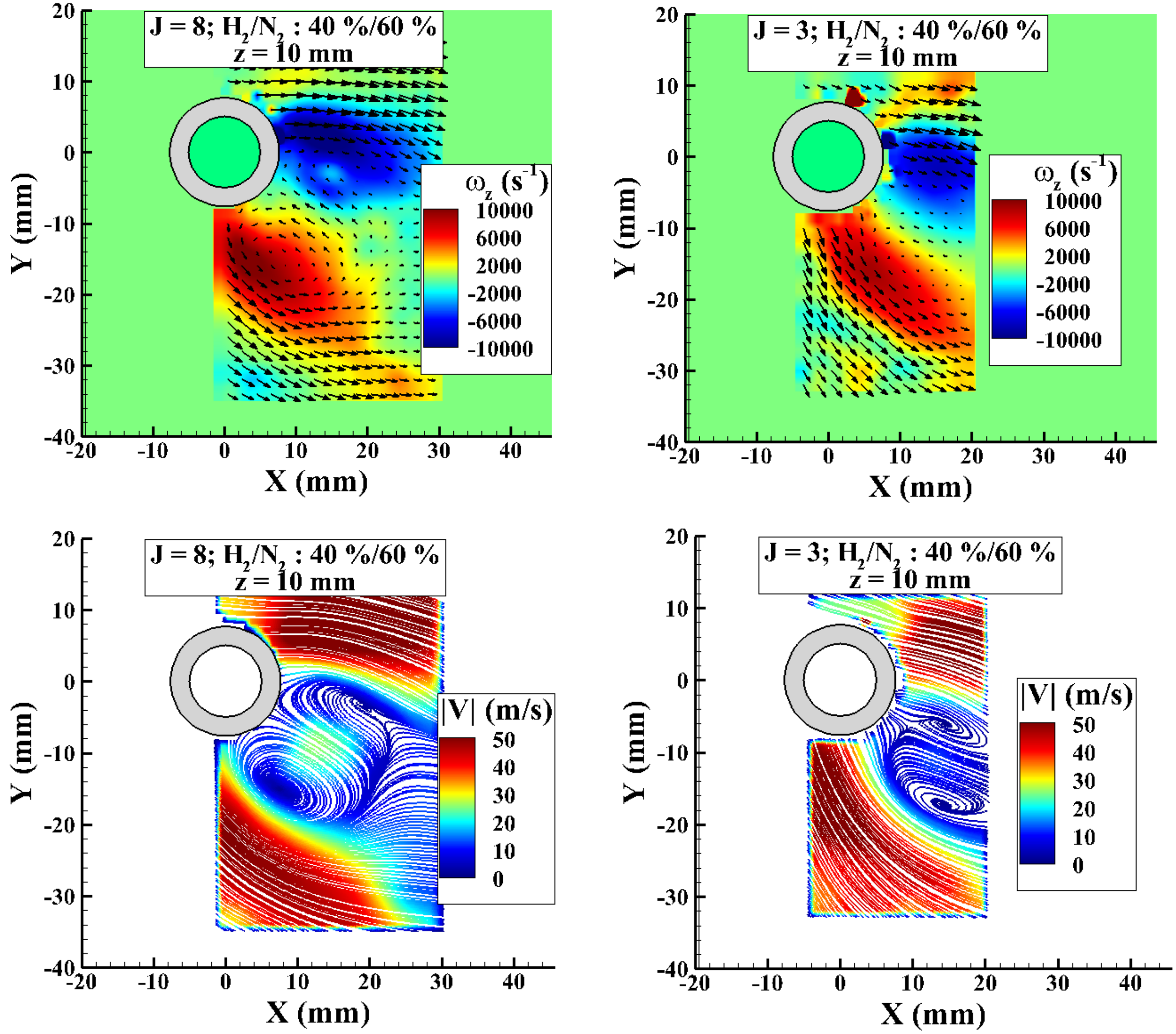
Reacting Jet in Swirling Crossflow: Time-Averaged Vorticity and Streamlines for H_2/N_2 Jets with J = 8 and 3



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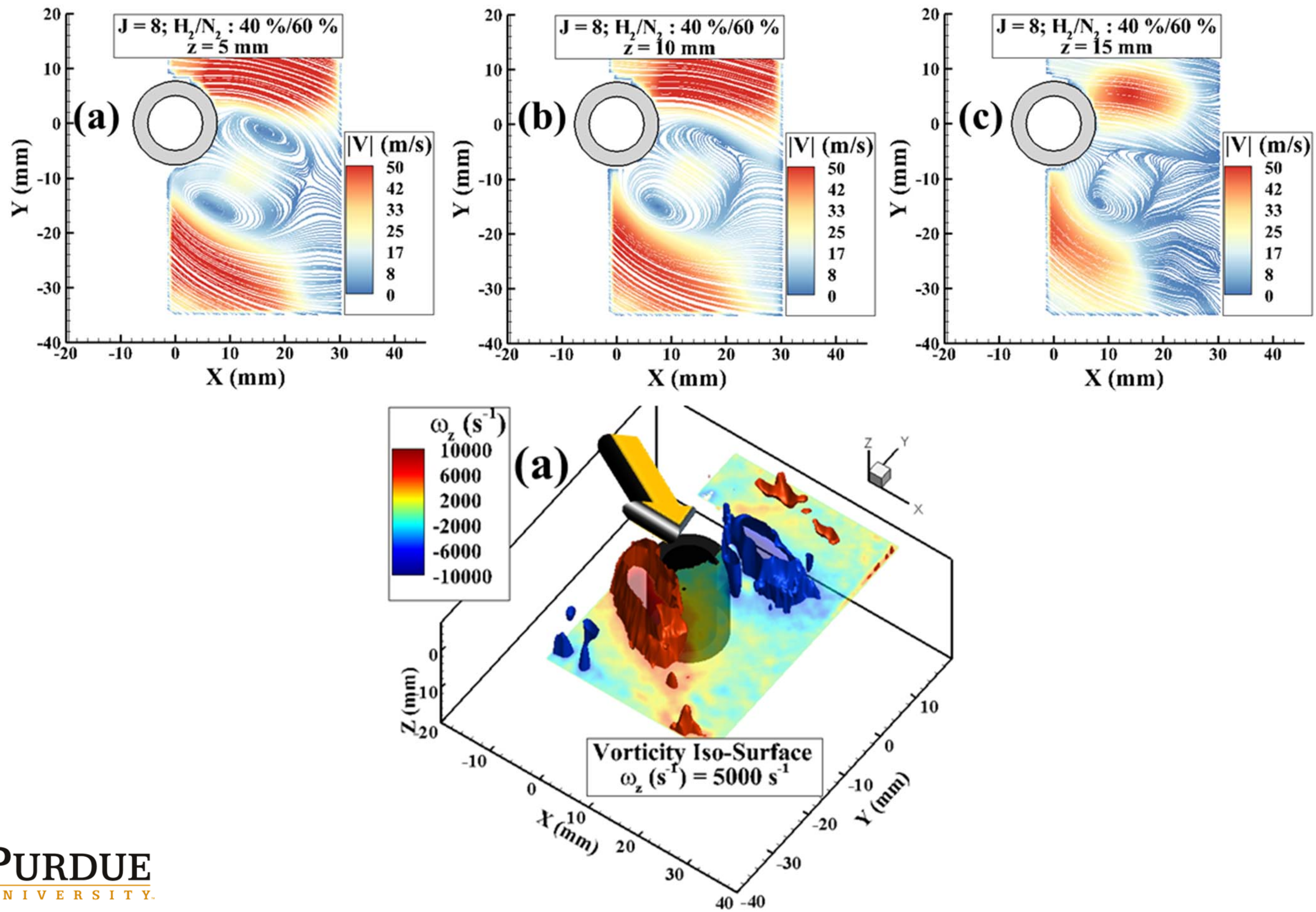
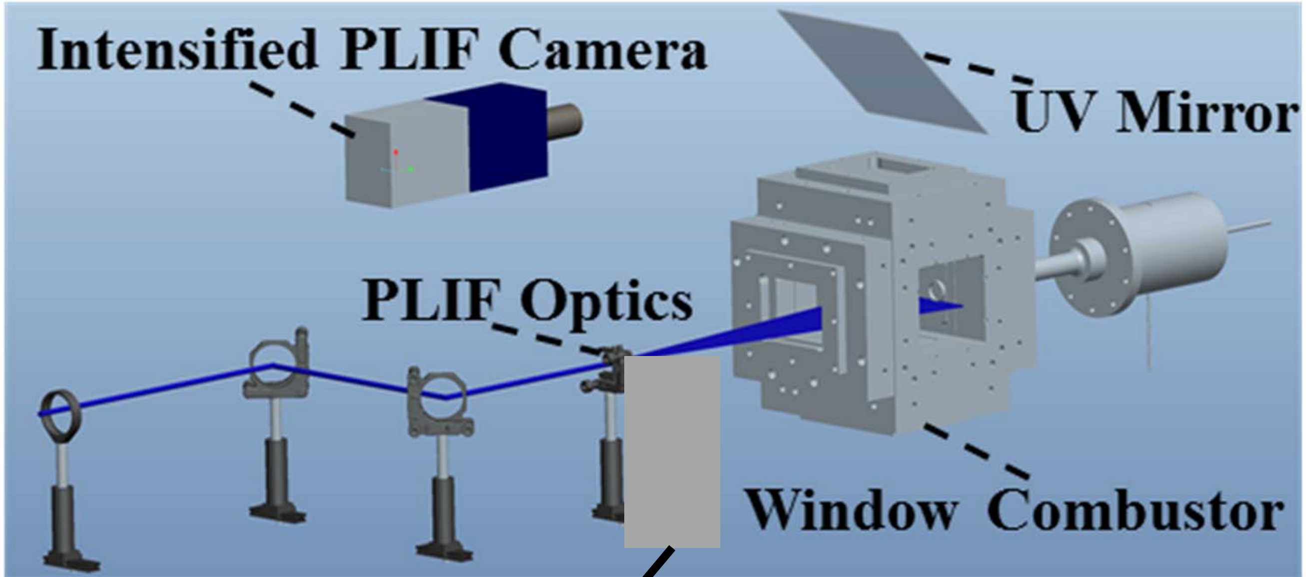
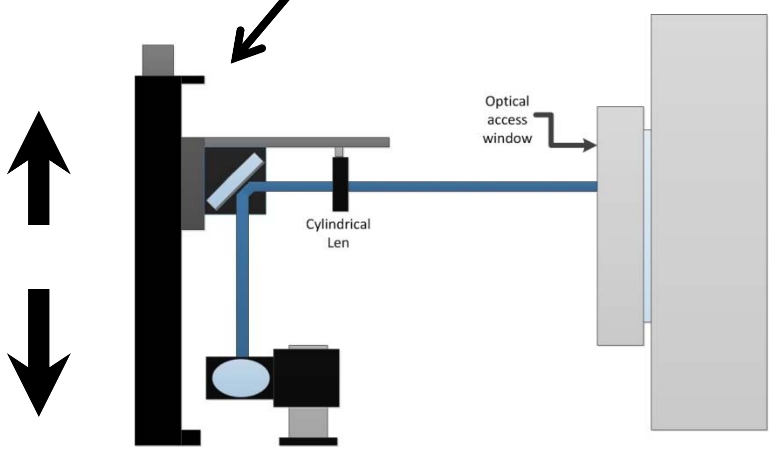
Time Averaged three dimensional wake structure of the RJICF



CAD Representation of the OH-PLIF Experimental System

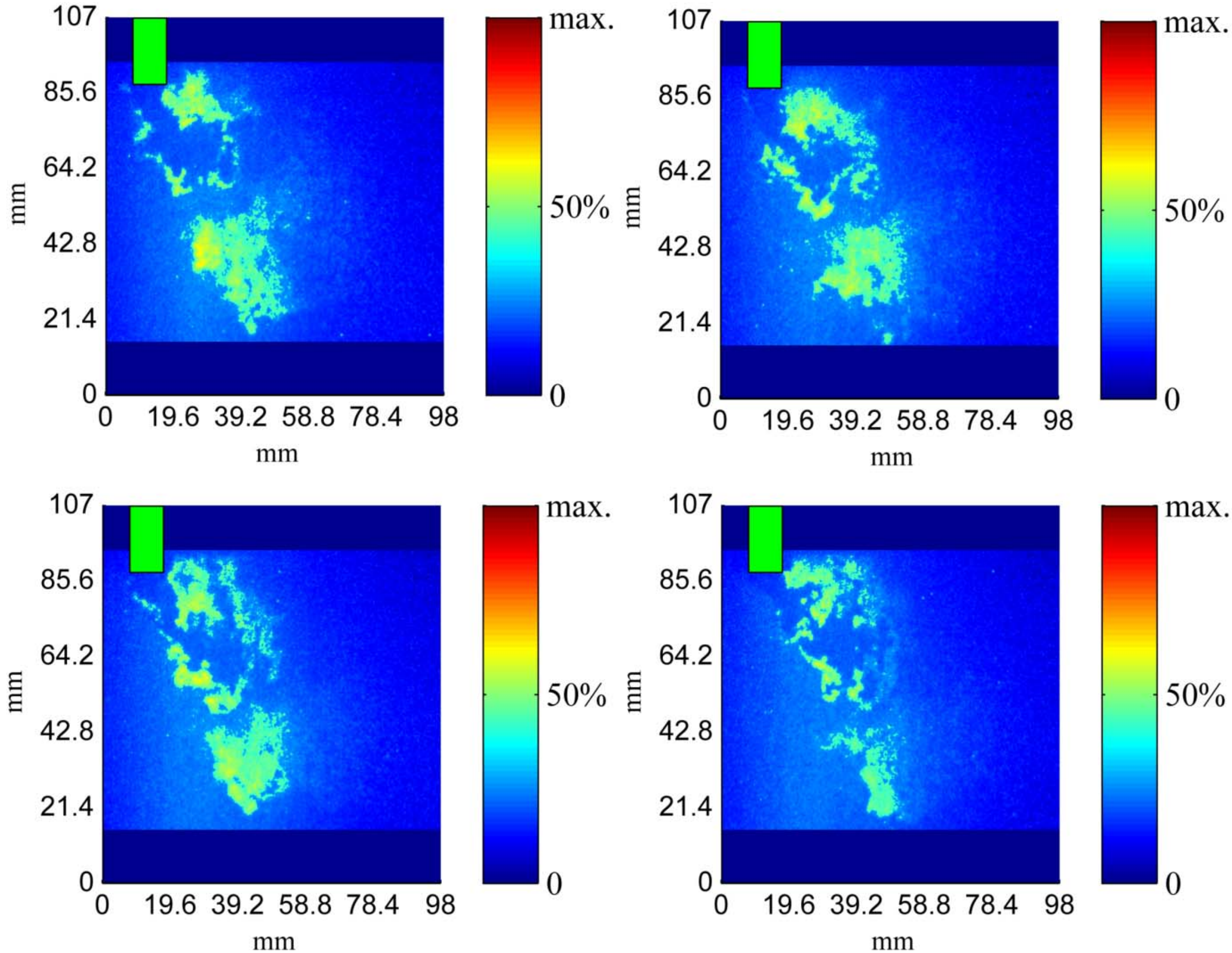


Translation Stage

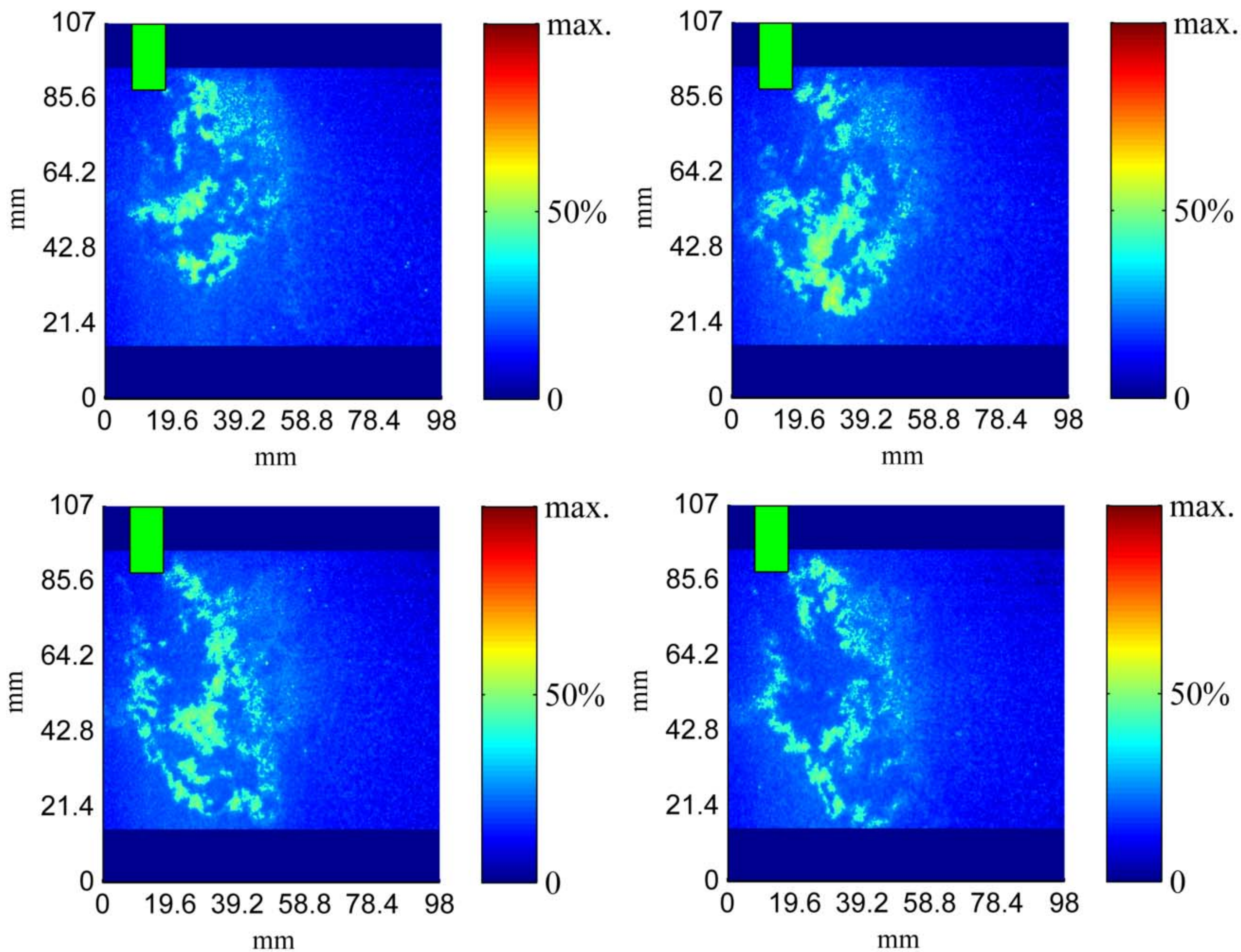


The laser sheet is traversed to visualize the jet flame at 19 different planes to obtain 3-dimensional information on the flame structure

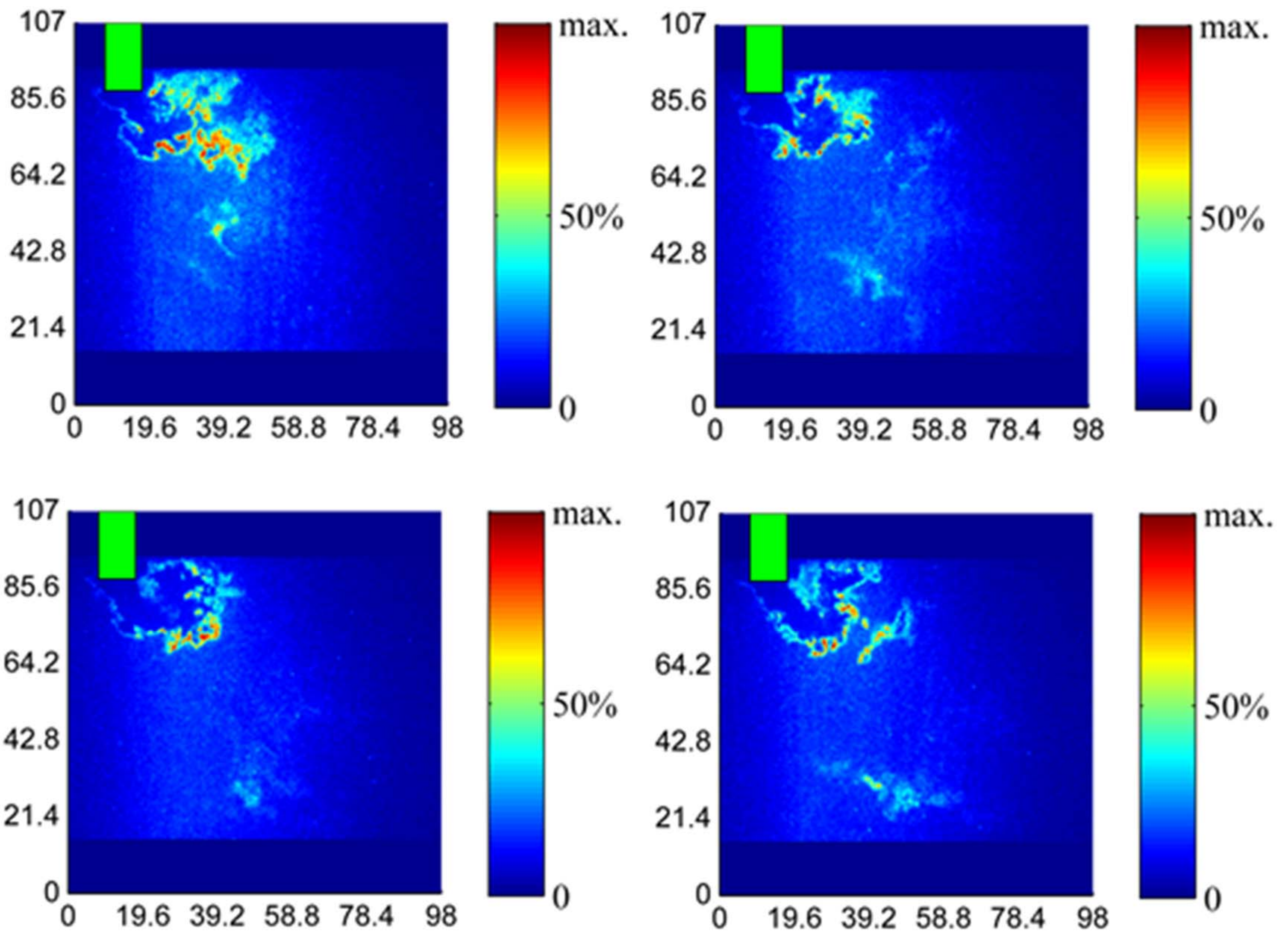
Sequence of single-shot OH-PLIF images: J =3, fuel is premixed natural gas, ϕ_{jet} = 3, measurement plane z = 38.1 mm



Sequence of single-shot OH-PLIF images of J =8 fuel is premixed natural gas, ϕ_{jet} = 3, measurement plane Z = 38.1 mm



Sequence of single-shot OH-PLIF images: J =8, fuel is 40% H_2 and 60% N_2, measurement plane z = 38.1 mm.



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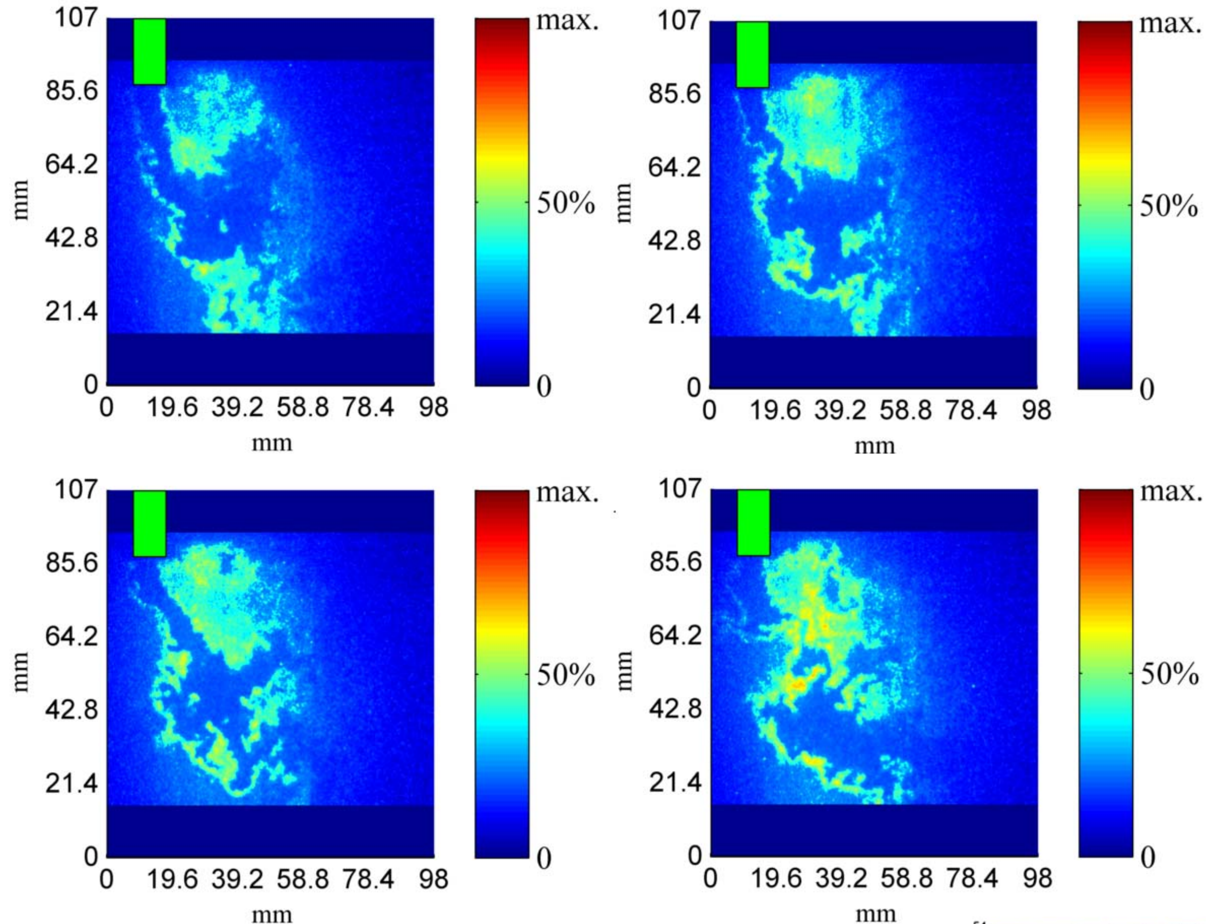
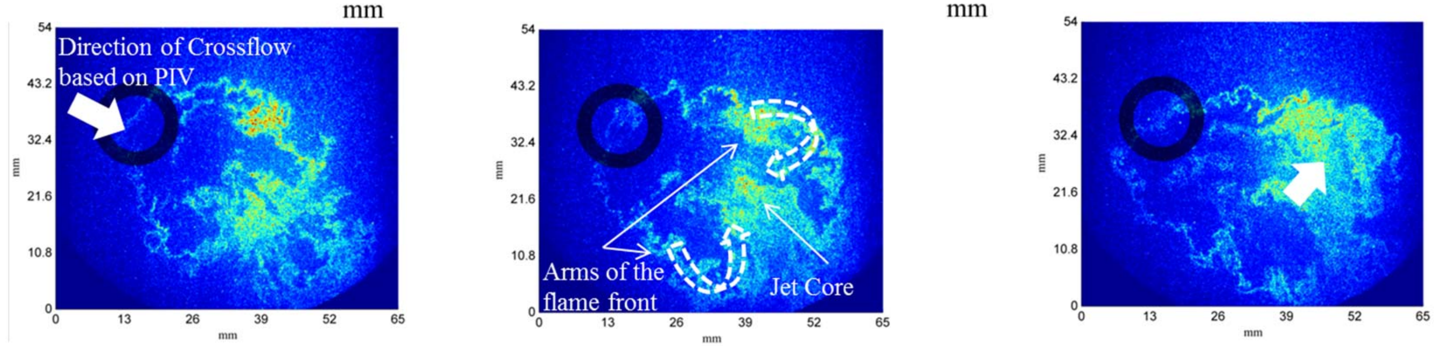
Sequence of single-shot OH-PLIF images: J =8, fuel is 40% H_2 and 60% N_2, measurement plane z = 42.5 mm.





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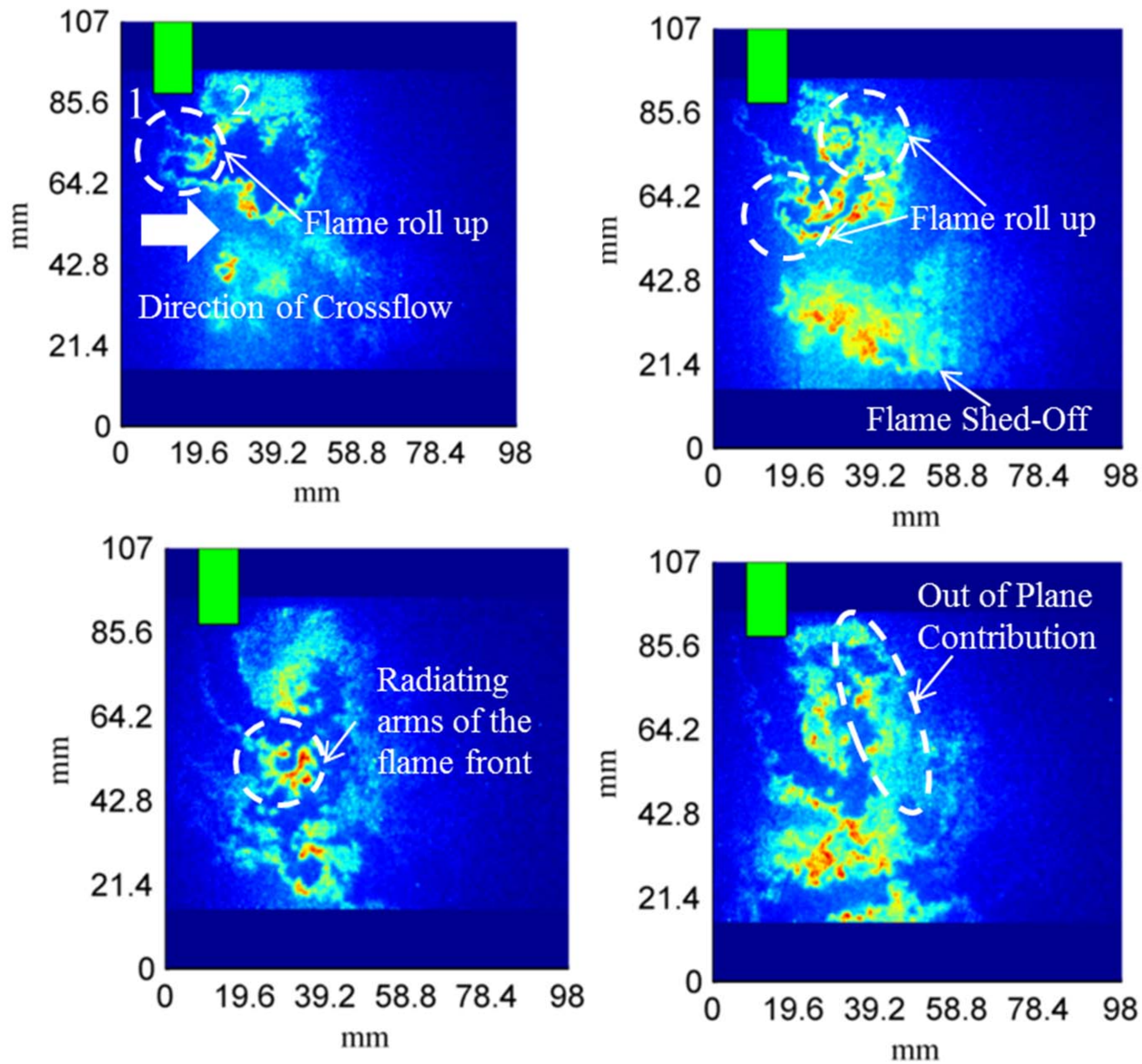
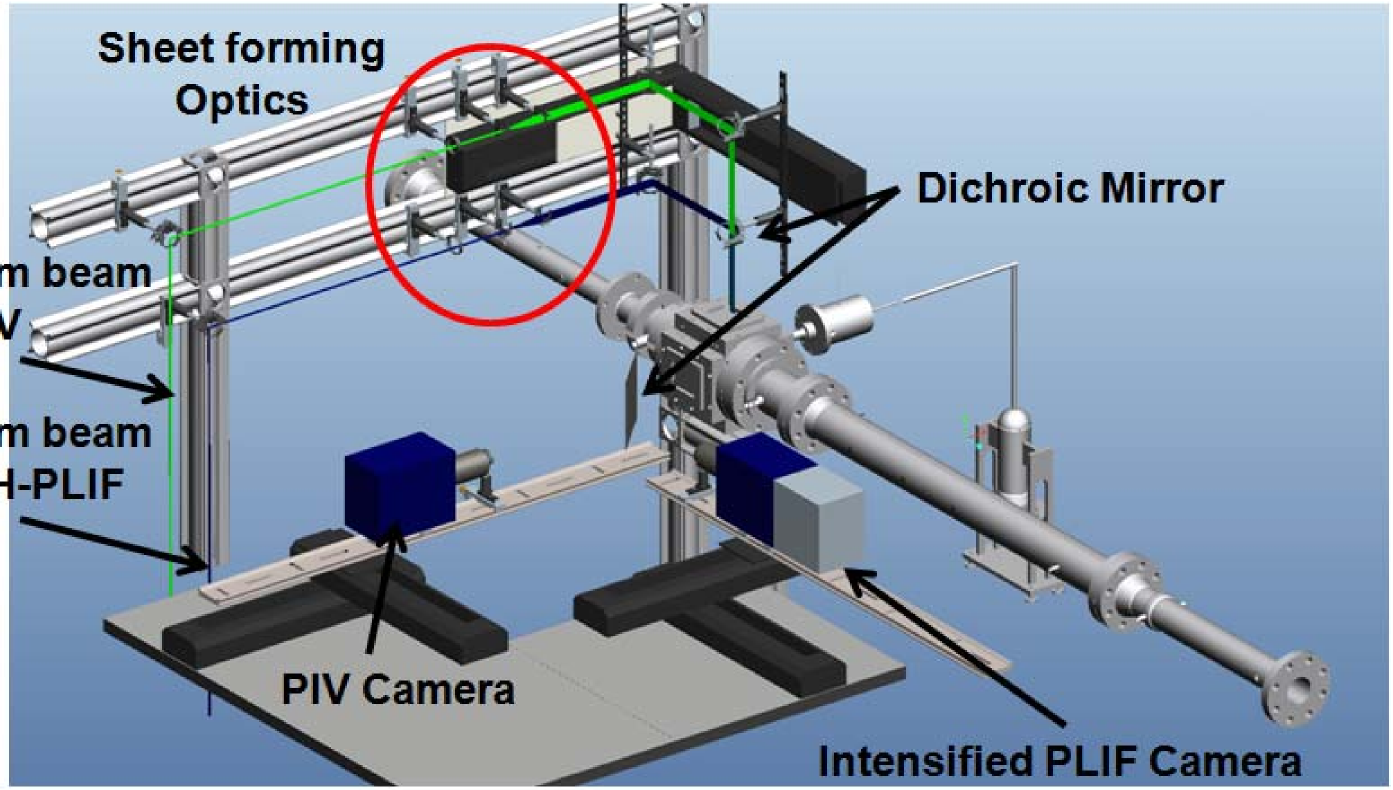
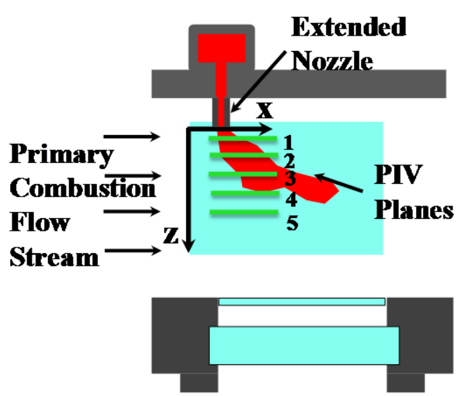
OH PLIF single-shot images for the 40% H_2/60% N_2, J=3 case acquired at the midplane. Two significant events are highlighted in the two images, (a) flame roll-up and (b) flame shedding.



Schematic Diagram of Simultaneous PIV/OH-PLIF Experimental System





Simultaneous PIV/OH-PLIF Measurement Planes

1. Z = 5 mm
2. Z = 10 mm
3. Z = 15 mm

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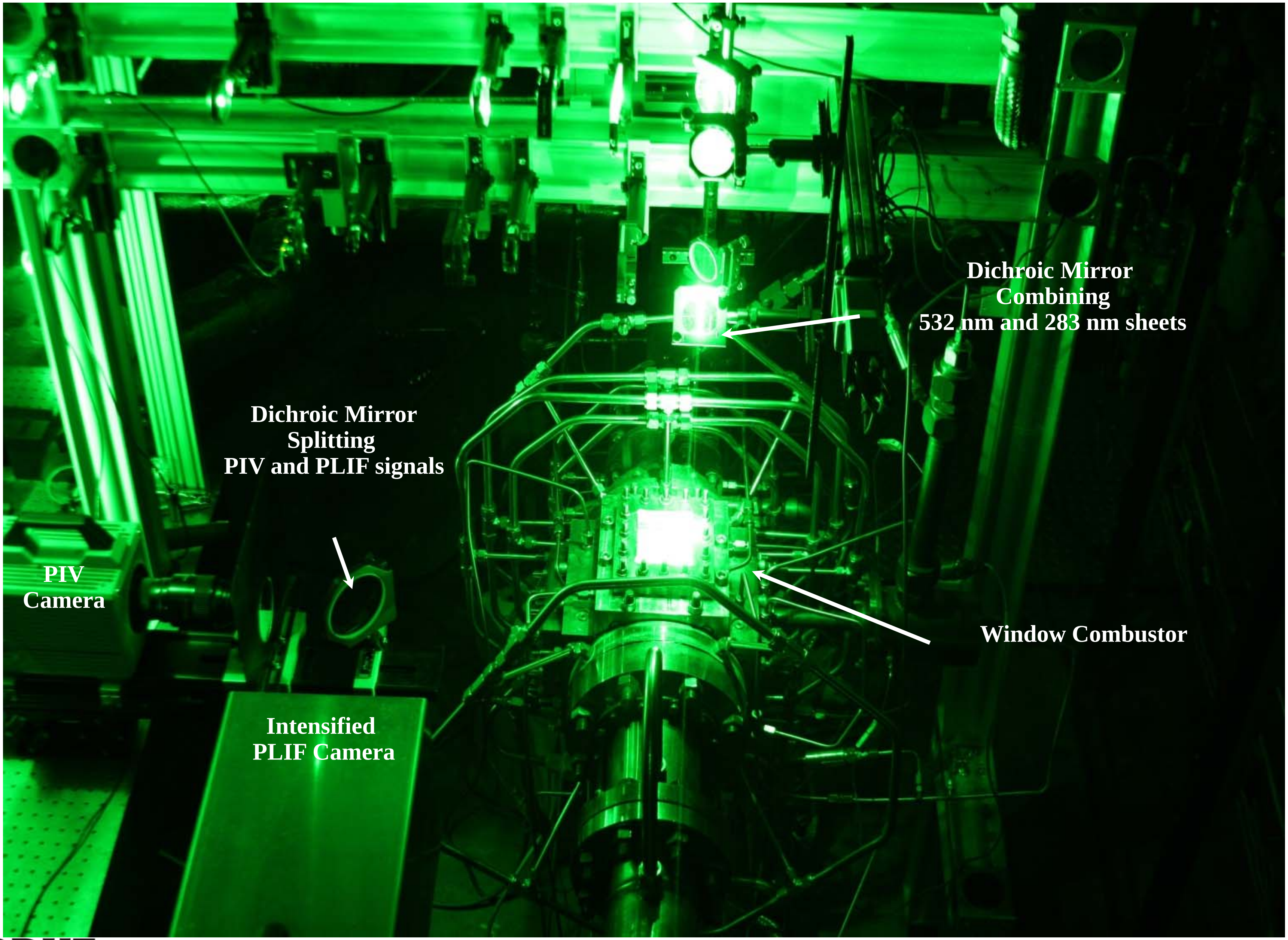

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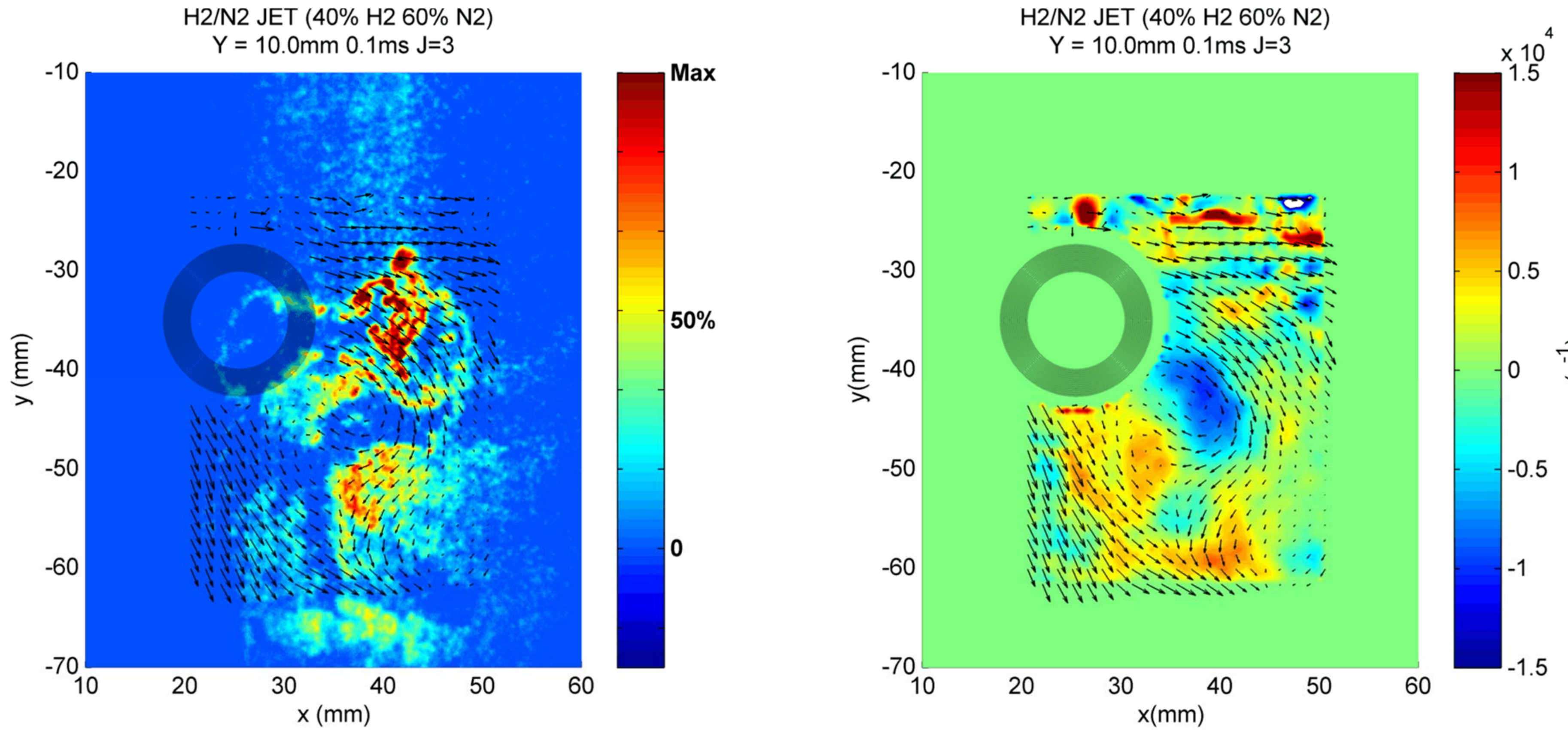
Instantaneous velocity vector fields overlapped on OH PLIF and vorticity magnitude: J=3 H_2/N_2 40%/60% z = 10 mm

Repetition Rate : 10 kHz



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Instantaneous velocity vector fields overlaid on OH PLIF and vorticity magnitude: J=8, H_2/N_2 40%/60%, z = 10 mm

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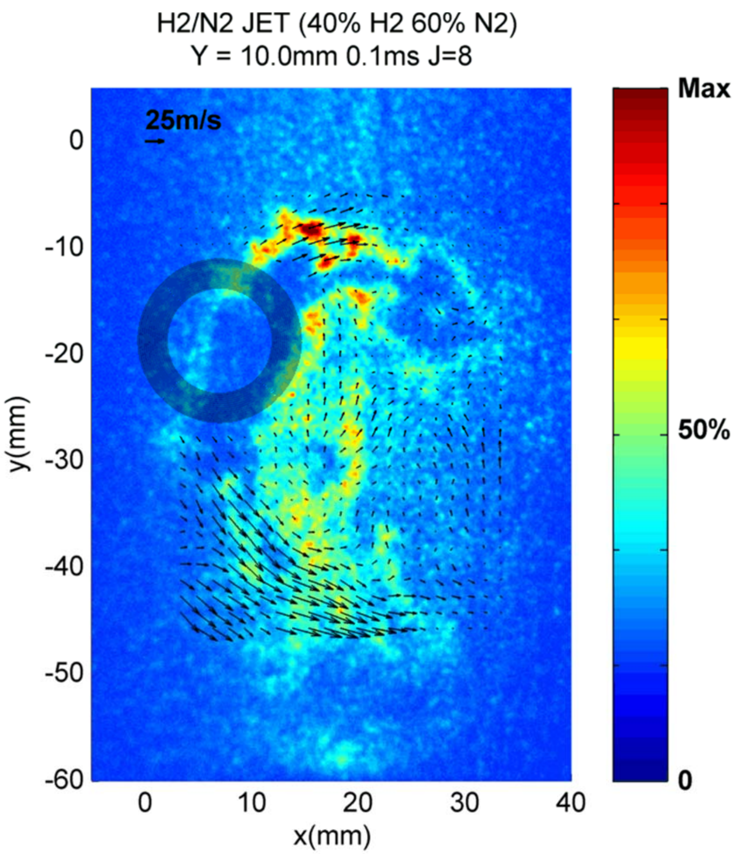

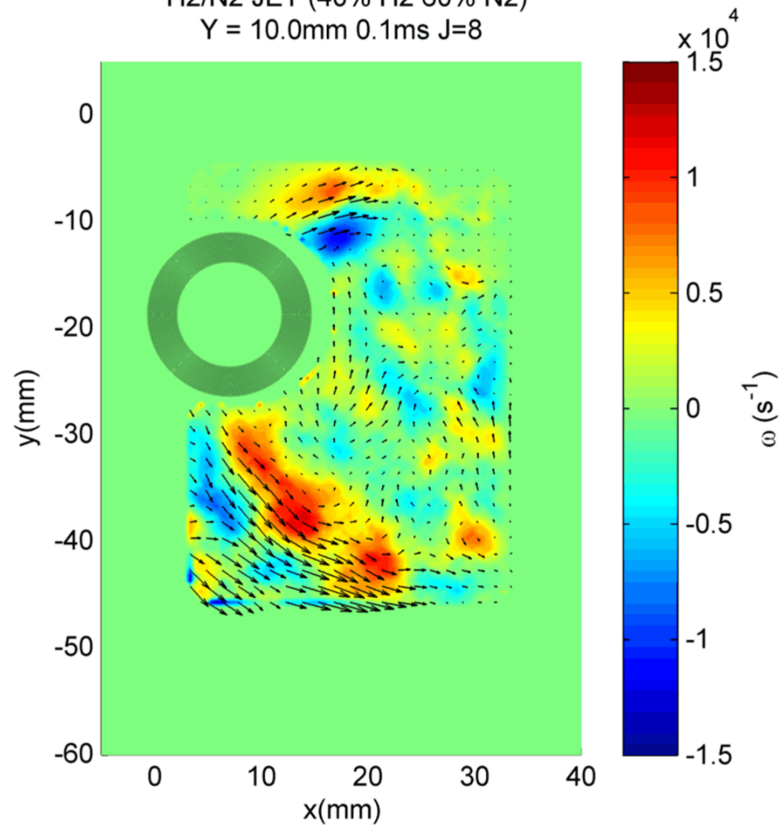

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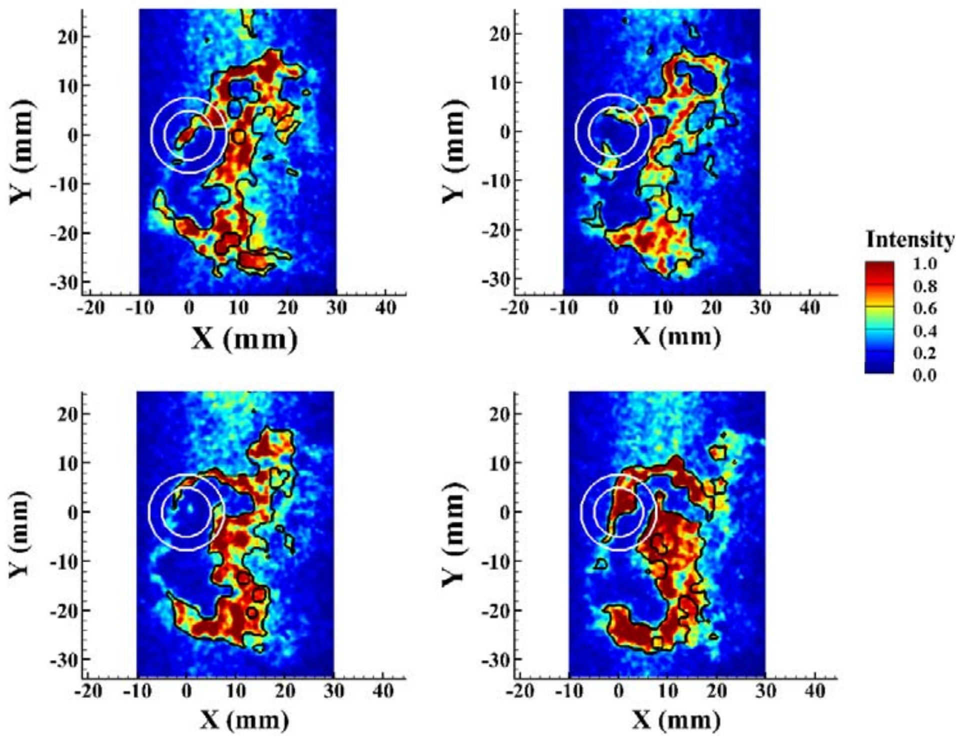
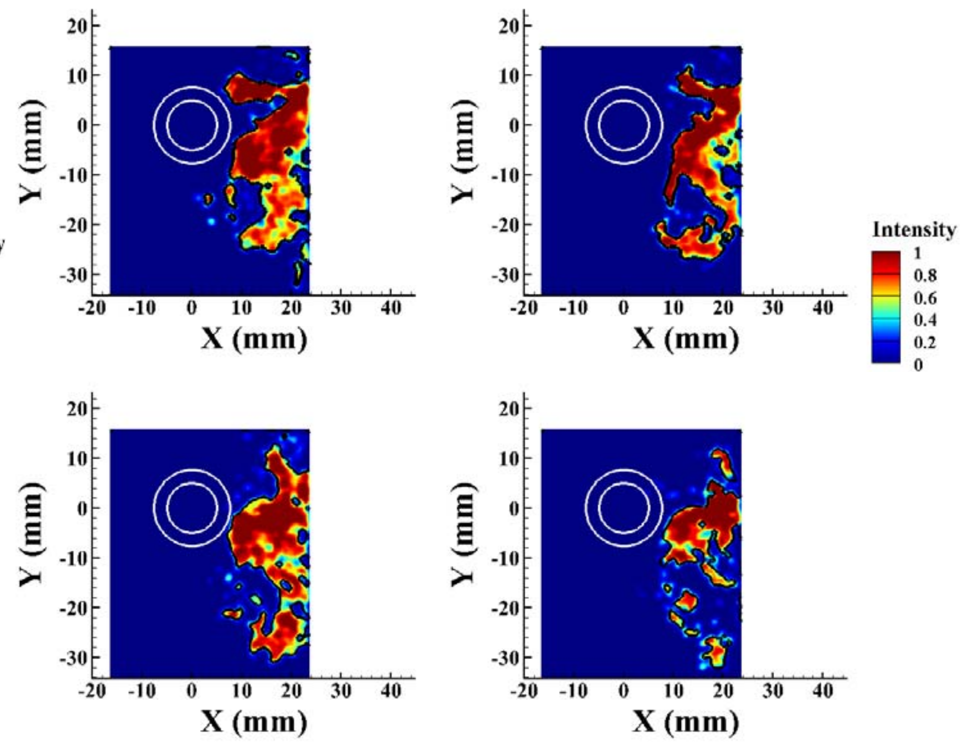
Sequence of OH-PLIF images measured at z = 10 mm

J = 8, H_2/N_2:40%/60%



J = 8, Premixed NG : $\phi = 0.9$



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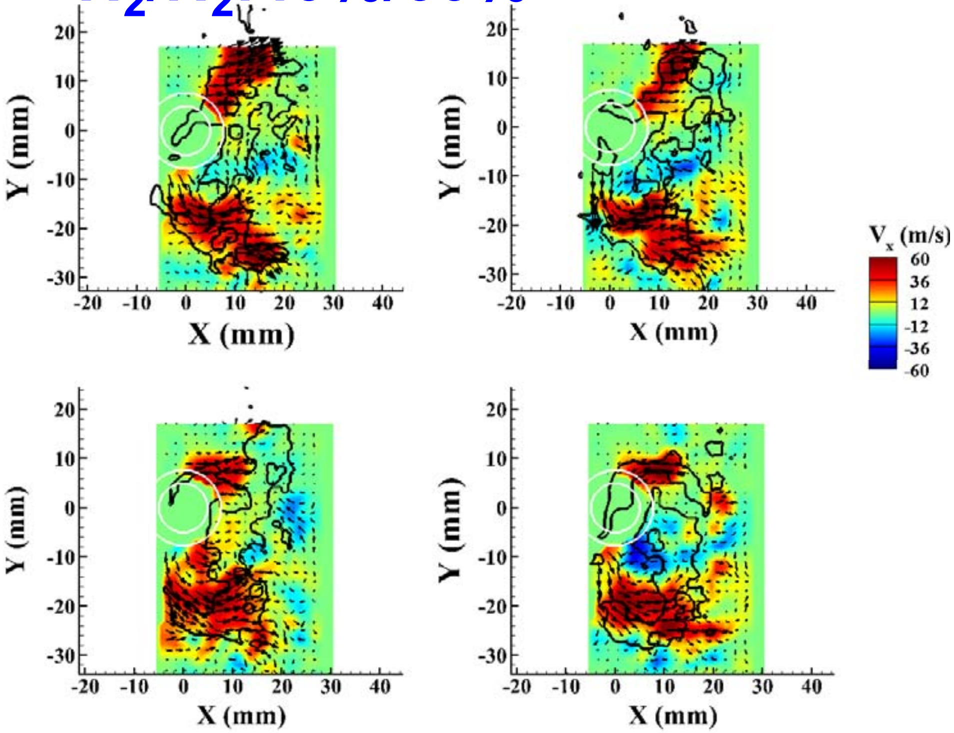
Sequence of velocity vectors and flame front edges overlaid on x-velocity magnitude measured at z = 10 mm

CASE : J = 8, H_2/N_2:40%/60%



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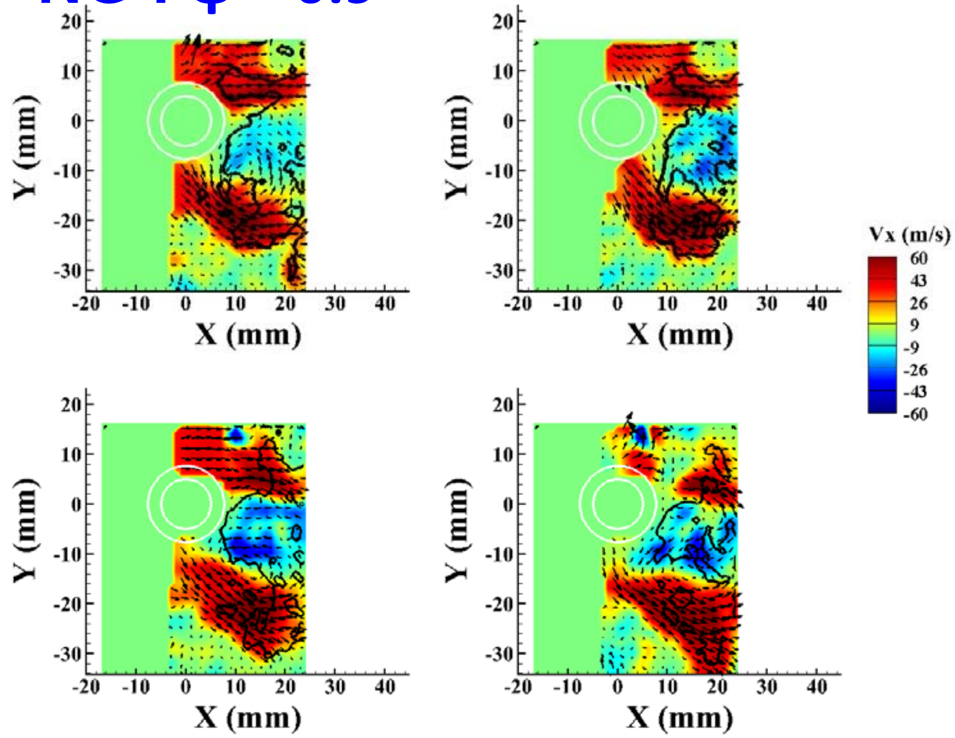

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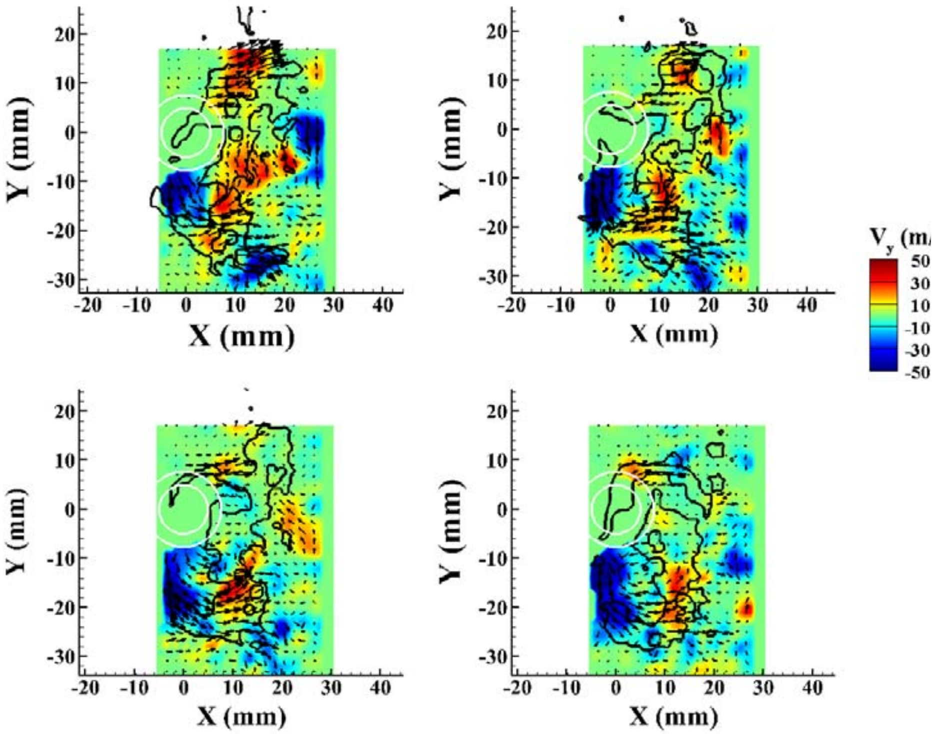
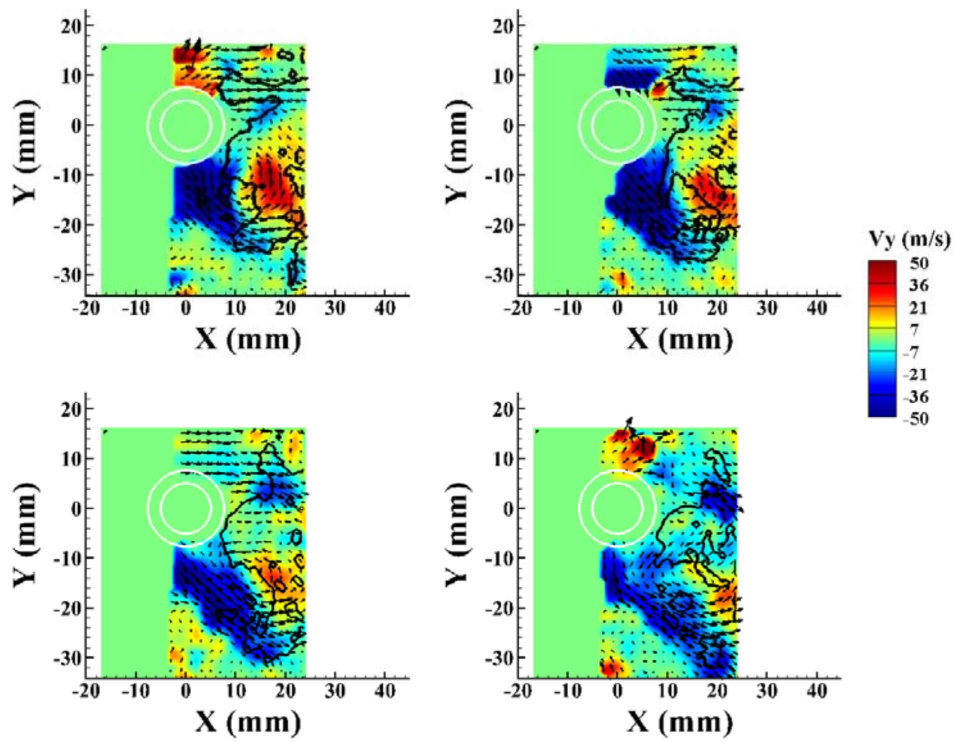
Sequence of Velocity vectors and flame front edge overlaid on y-velocity magnitude measured at z = 10 mm

J = 8, H_2/N_2:40%/60%

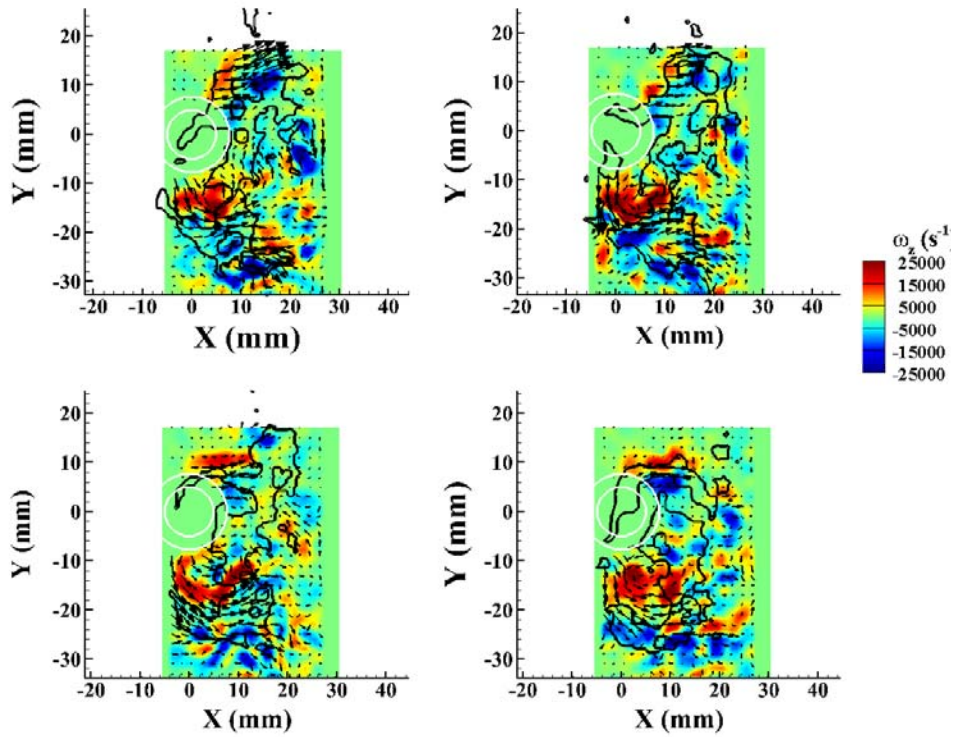


J = 8, Premixed NG, ϕ = 0.9

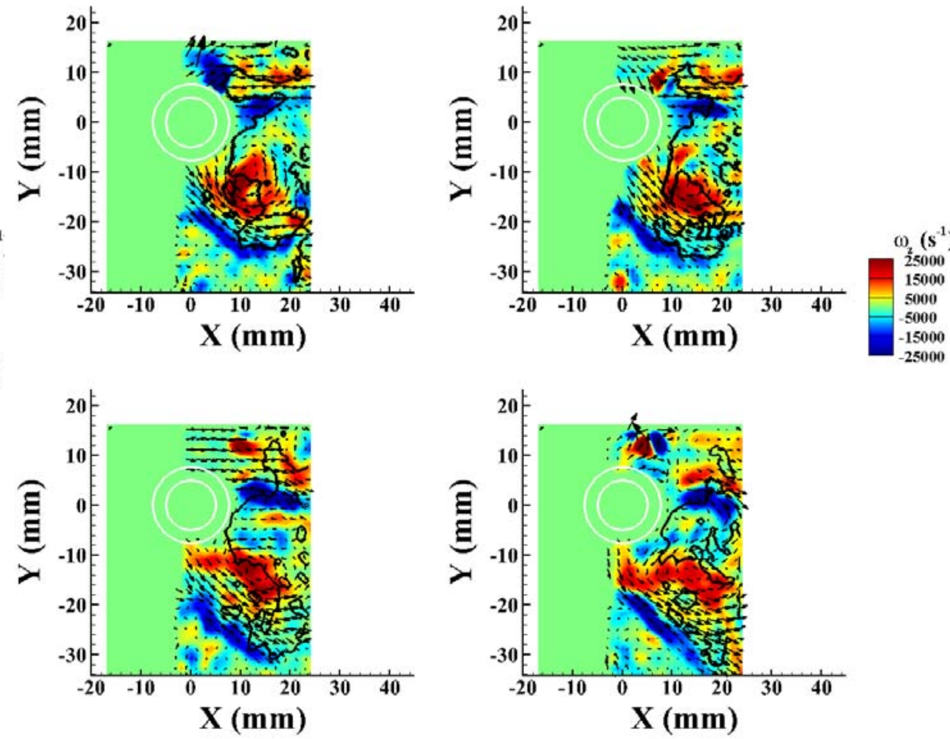


Sequence of velocity vectors and flame front edges overlaid on z-vorticity magnitude, measurement plane z = 10 mm

J = 8, H_2/N_2:40%/60%



J = 8, Premixed NG, ϕ = 0.9



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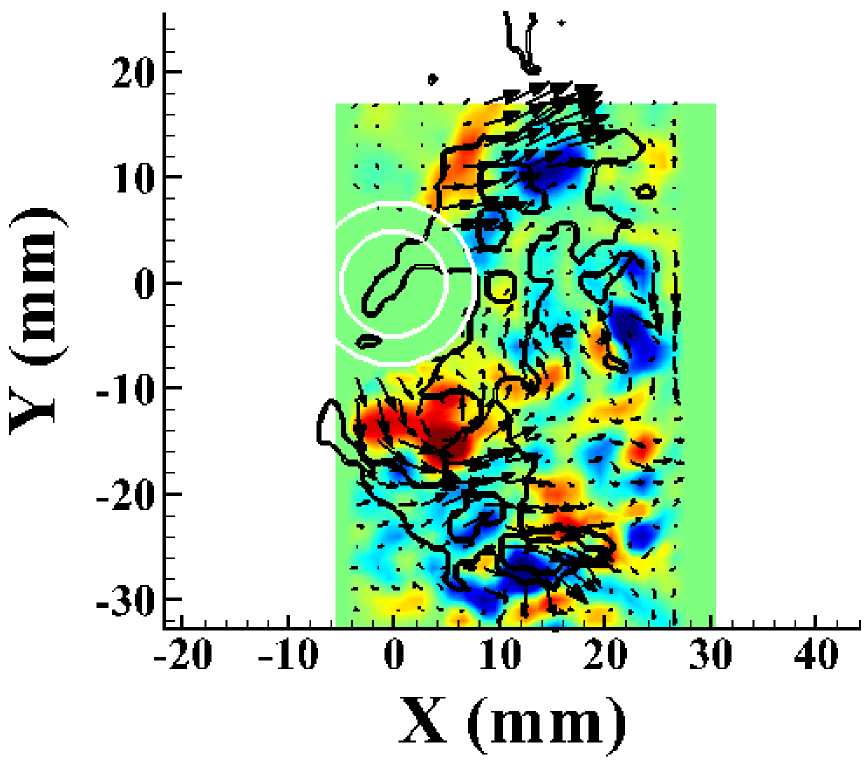
Sequence of velocity vectors and flame front edges overlaid on z-vorticity magnitude, measurement plane z = 10 mm

J = 8, H_2/N_2:40%/60%



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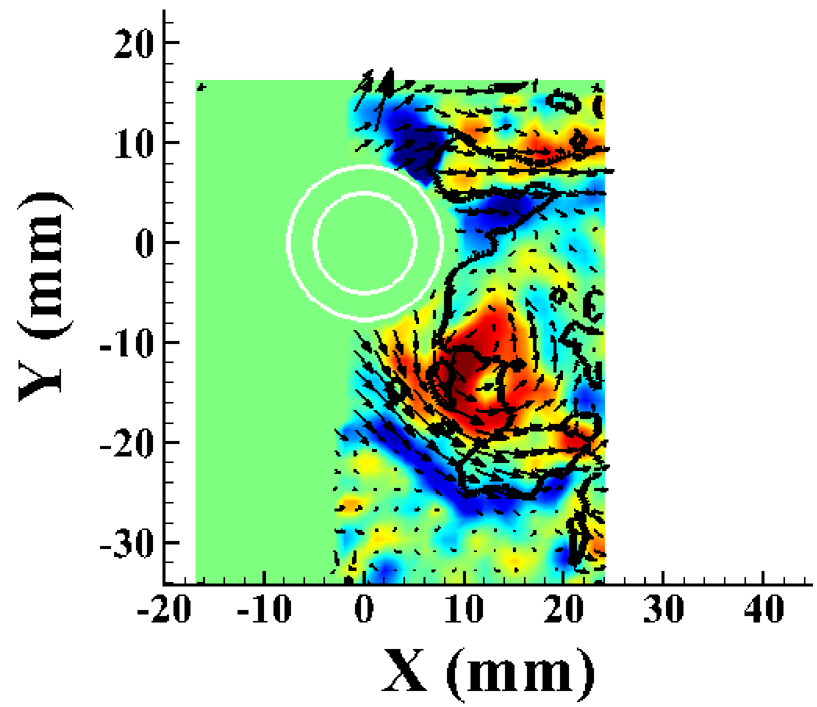

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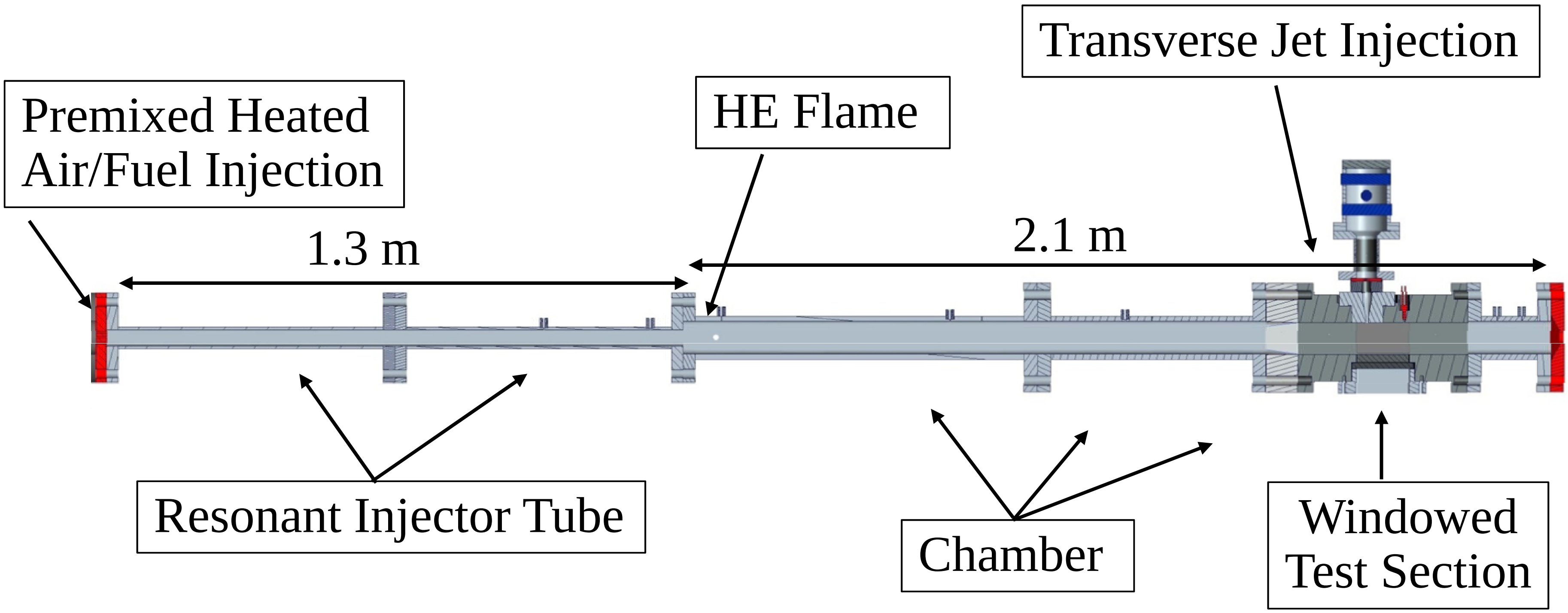
Purdue Instability Test Rig



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- Air mdot ~ 0.41 kg/s
- Natural gas fuel for HE flame

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Freq [Hz]	100	195	299	389	498

Test rig provides acoustic environment for transverse jet injection

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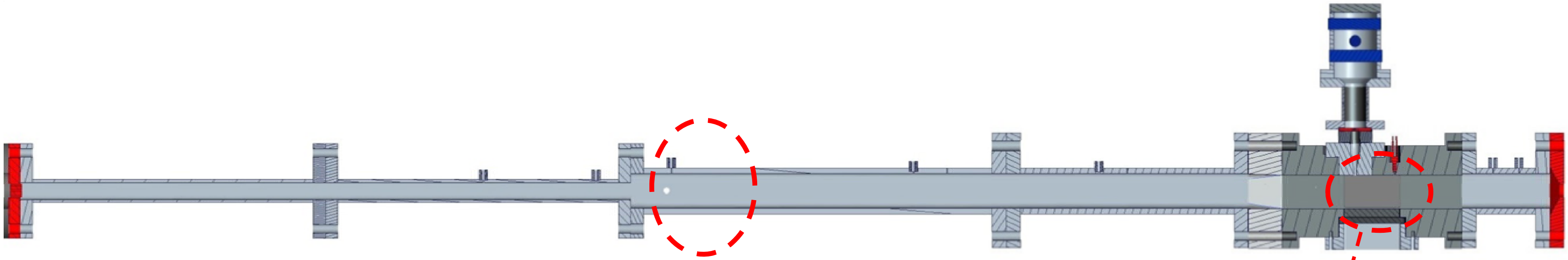
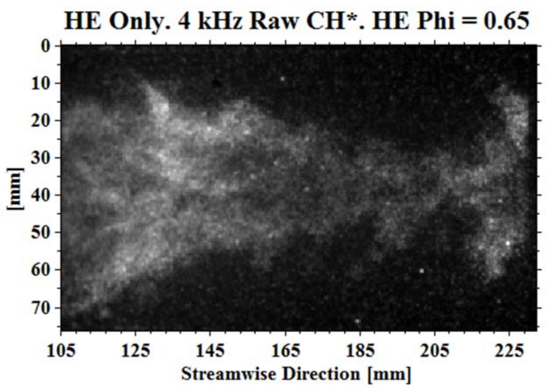
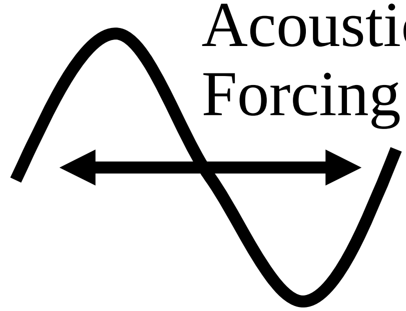
4kHz Intensified Chemiluminescence Imaging of Dump Flame and Injected Transverse Jet. 432nm (+/-8 nm) (CH^*/CO_2^*).

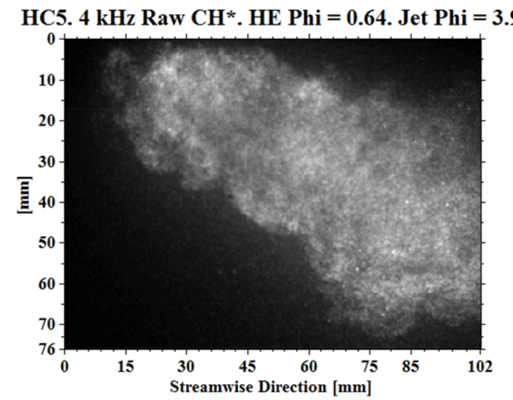




Dump Stabilized Flame
Sustains Longitudinal Acoustics



Acoustic
Forcing



Transverse Jet Injected
Into Oscillating Vitiated
Cross Flow

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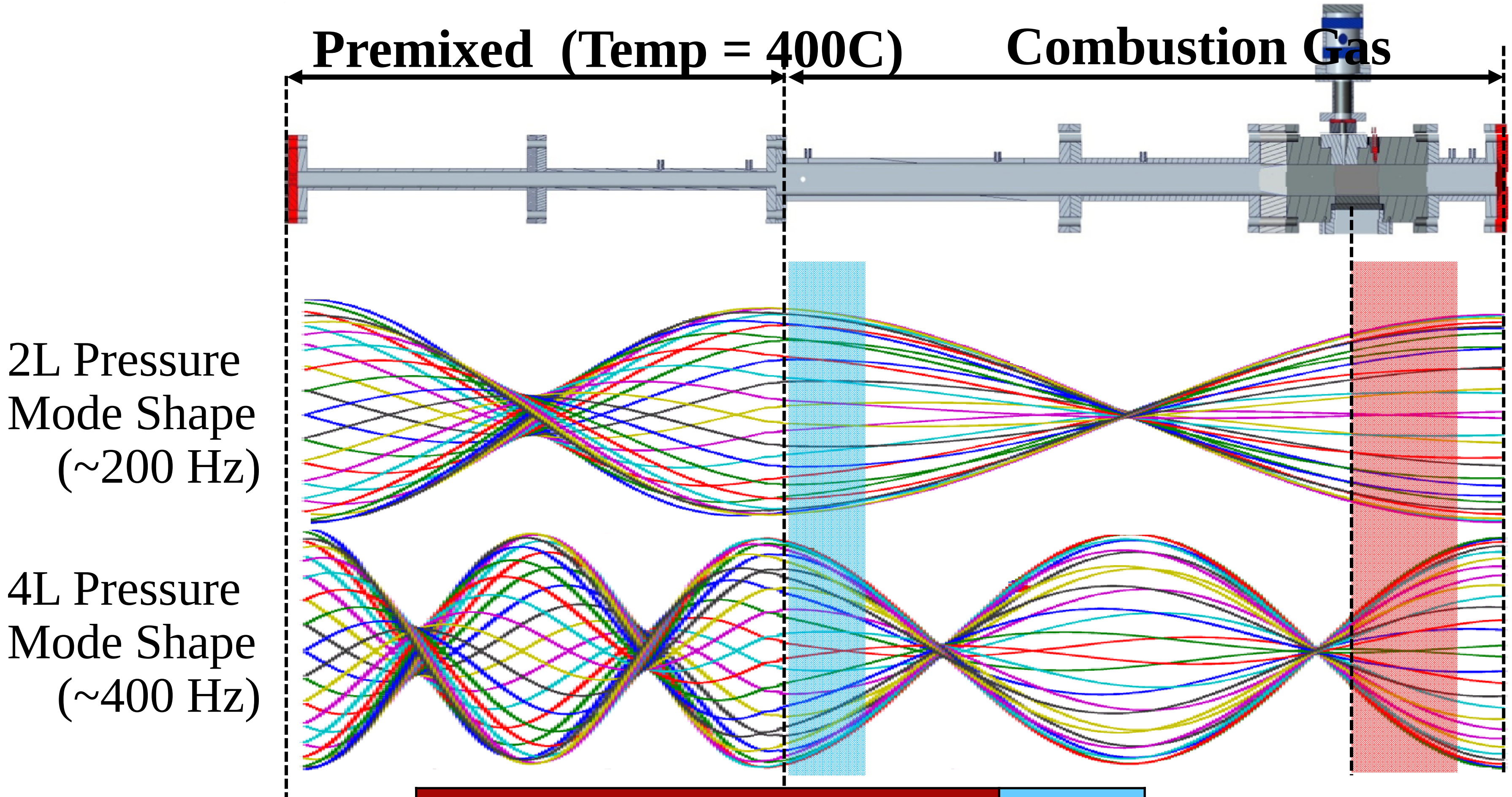
Chamber Acoustic Mode Shapes

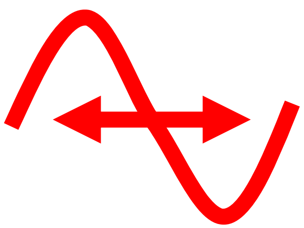


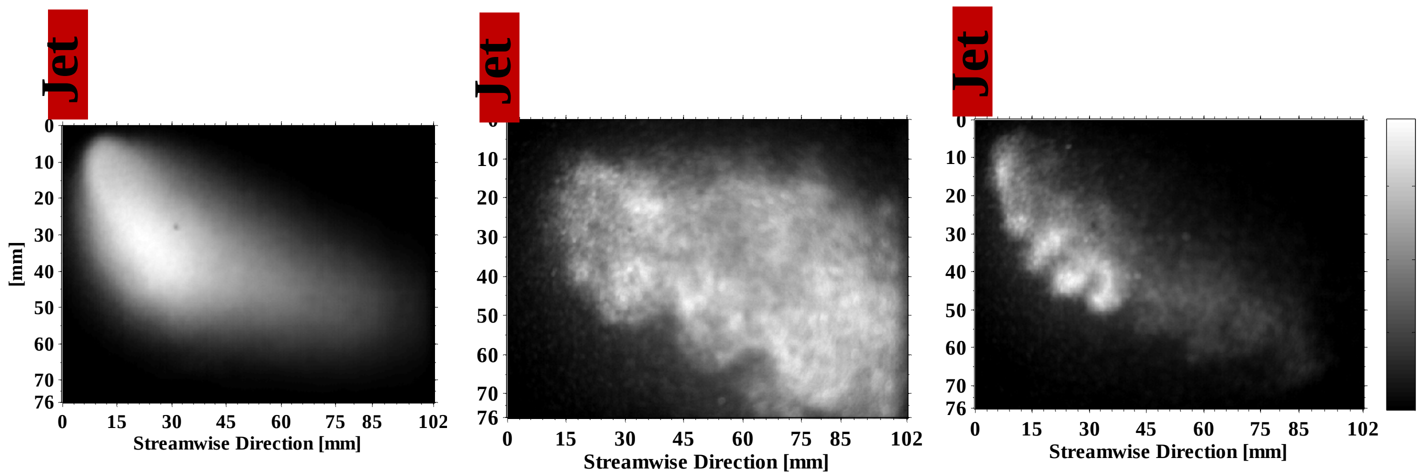
Dump Flame Heat Input	
Transverse Jet Heat Input	

Have generated 2L and 4L peak-to-peak p’ ~ 0 to 140 kPa individually

Physics of Heat Release Coupling With Unsteady Crossflow

Crossflow Forcing





Ensemble Average	Instantaneous 400 Hz	Instantaneous 600 Hz

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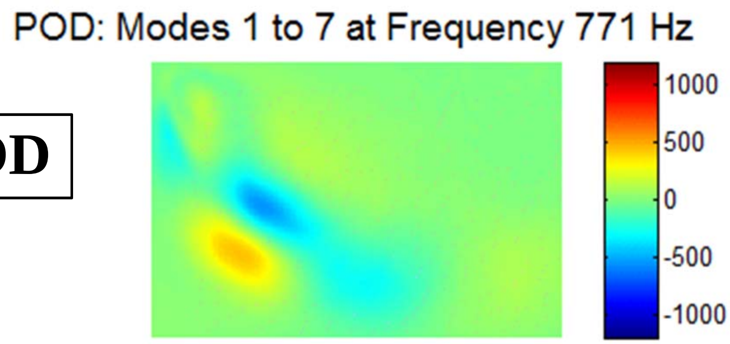
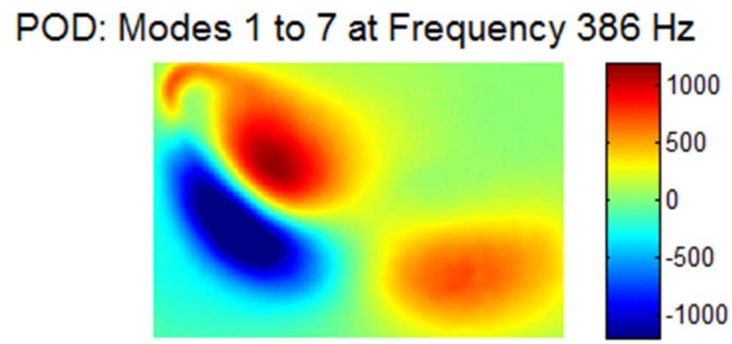
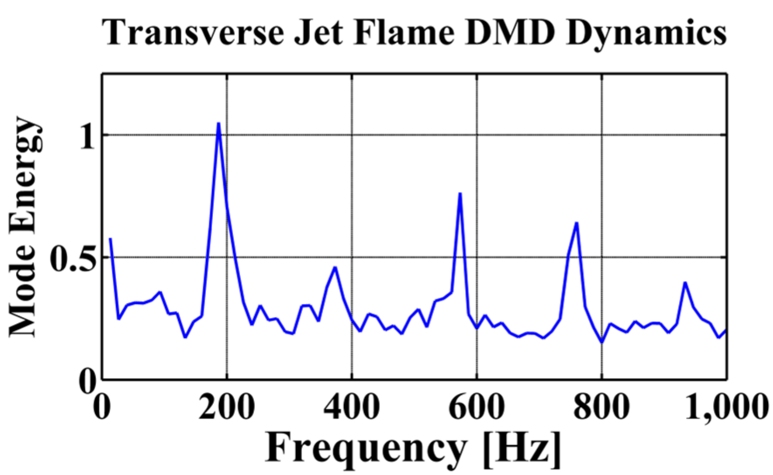
POD and DMD used as low dimensional approximations to identify, track, quantify dominant coupling structures

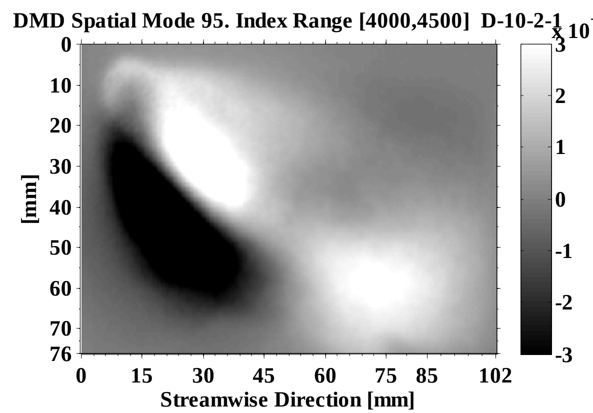
POD





DMD





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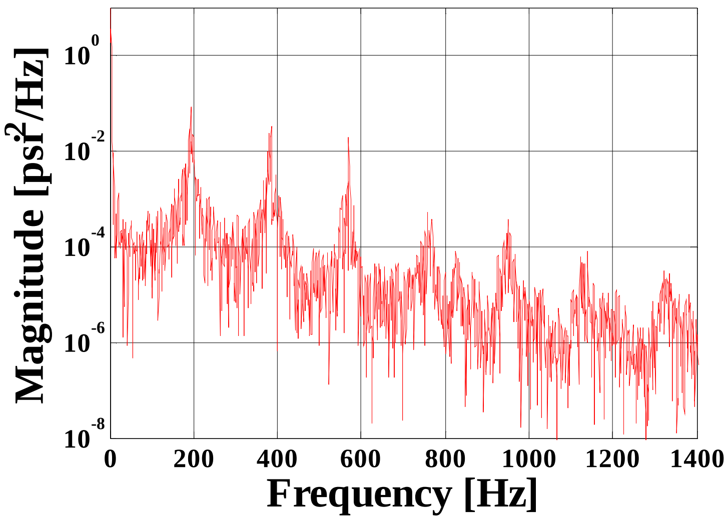
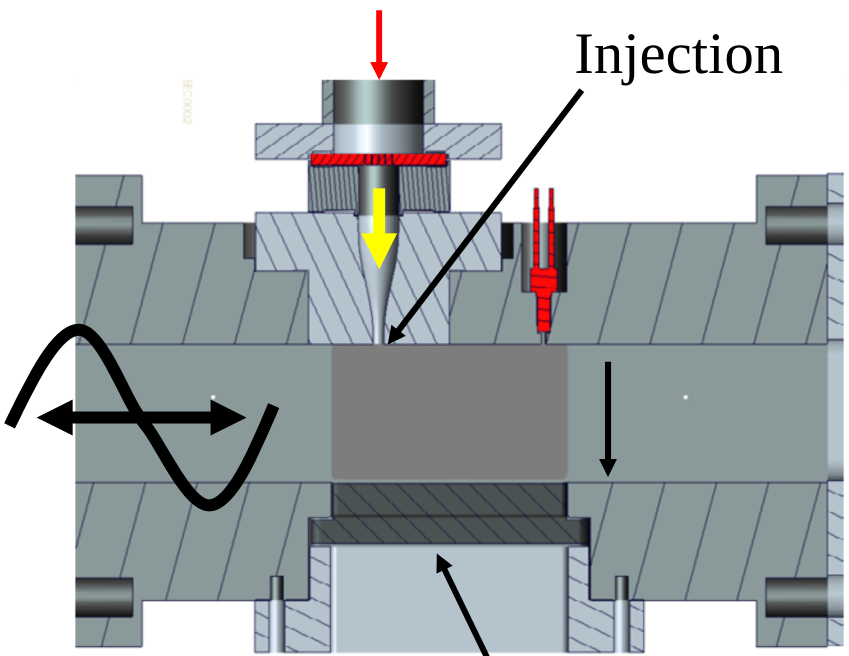
60/40 H2/N2 Transverse Jet Injection

PSD Crossflow Raw Pressure





<u>JICF Parameters:</u>
Jet Exit = 5.8 mm
Momentum Flux Ratio J=6
Jet Re = 30k

Currently setting up for OH-PLIF and PIV for this configuration

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High-Repetition-Rate PIV/OH PLIF Measurements: Summary

- 5 and 10 kHz PIV and OH PLIF measurements were performed for the reacting jet in a swirling vitiated crossflow with the extended nozzle configuration, with the jet being seeded with the TiO_2 particles.
- The mean flow field shows the strong influence of a counter-rotating vortex pair in the planes close to the nozzle.
- The swirling crossflow is found to affect the jet, with its impact being felt significantly in the planes closest and farthest from the nozzle.
- Flame structure is very different for H_2/N_2 and NG/air jets. Momentum flux ratio J also has a significant effect.

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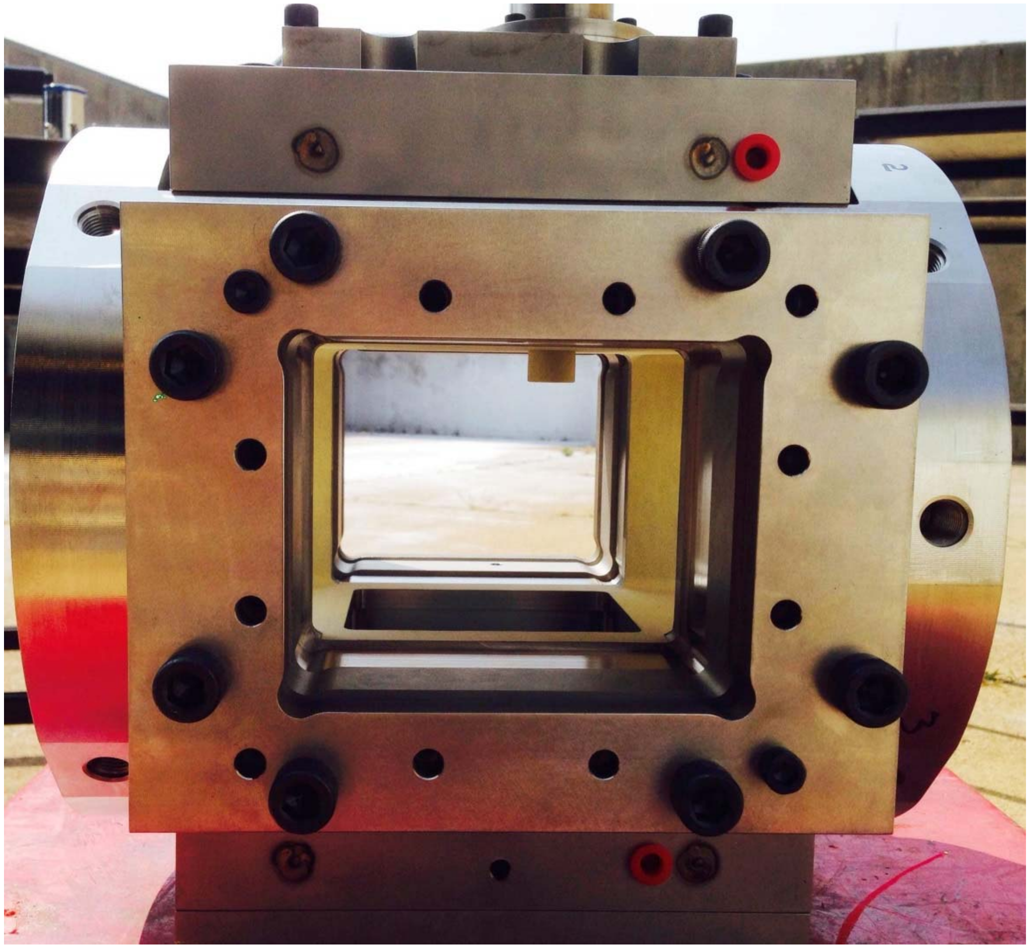
Future Research

- PIV/OH PLIF Measurements in Combustion Instability Test Rig
- PIV/OH PLIF Measurements in Water-Cooled Combustion Test Rig with Enhanced Optical Access



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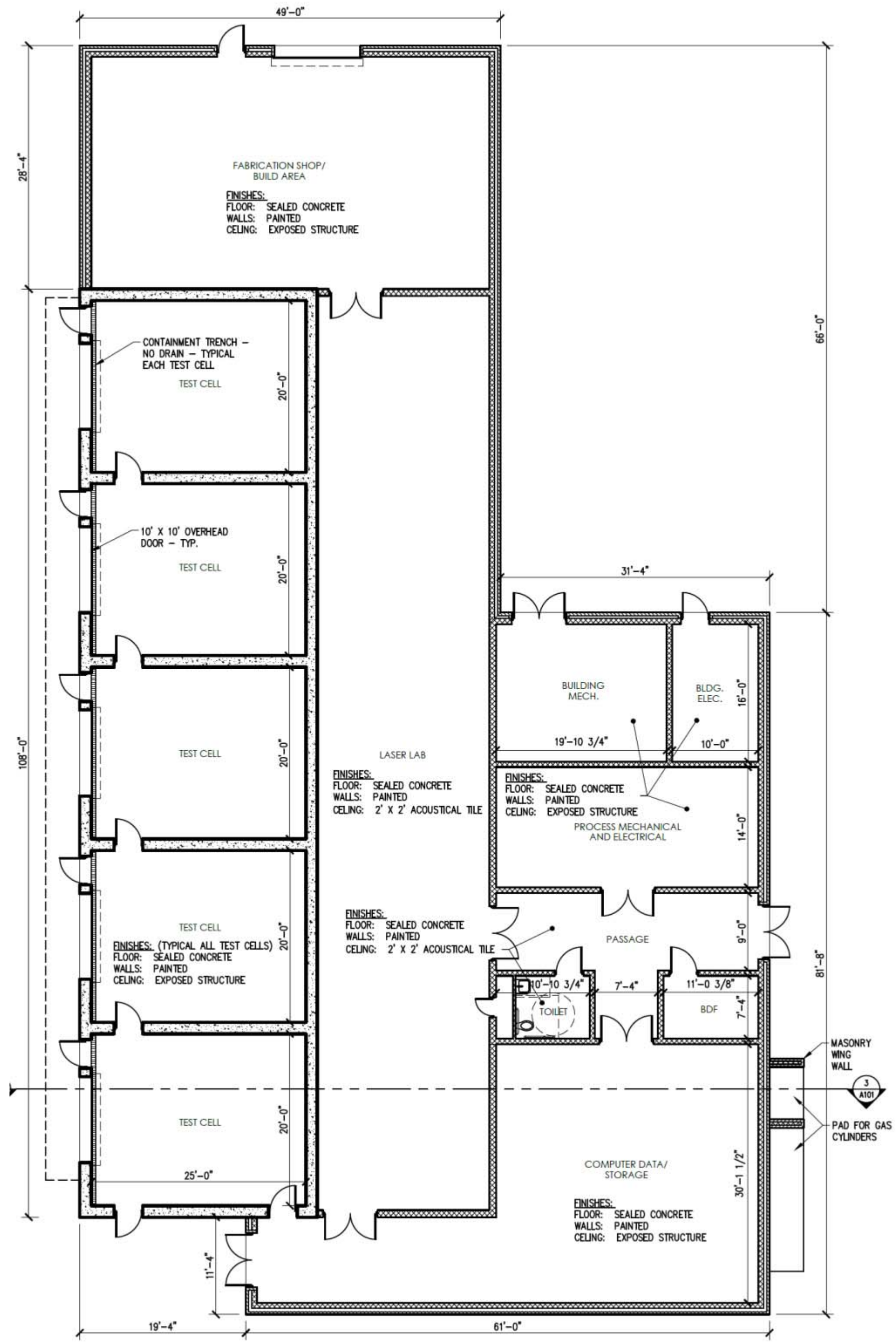
New Gas Turbine Test Rig Facility in Design Phase

- Will include five new 500 square-foot test cells and a 2000 square-foot laser laboratory with excellent temperature and humidity control.   Groundbreaking is scheduled for early next year, completion in CY2015.
- A new air heater with the capability of 4 kg/s at 40 bar and 1100 K (1500°F) has been ordered and will be installed next year.

New Gas Turbine Test Rig Facility in Design Phase



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- Managing Director of Zucrow Laboratories: Scott Meyer.

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