Coherent Anti-Stokes Raman Scattering (CARS) for Quantitative Temperature and Concentration Measurements in a High-Pressure Gas Turbine Combustion Test Rig

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Motivation

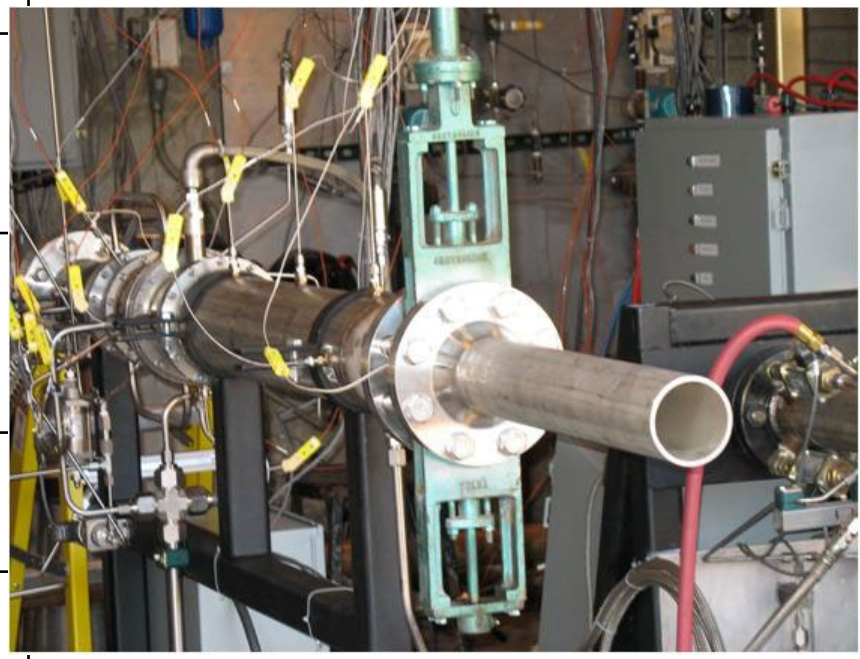
- To demonstrate dual-pump CARS measurements of CO_2, N_2 and temperature in the gas turbine combustor over a wide range of simulated supersonic flight conditions.
- To obtain high-quality data in the reacting flow field downstream of the NASA lean direct injection array for comparison with advanced computational models.

Outline of the Presentation

- Optically Accessible Gas Turbine Combustor Facility
- Dual-Pump CARS Measurements: Challenges and Optical System
- Temperature Measurements: PDFs, Mean Profiles, Standard Deviation Profiles
- Conclusions and Accomplishments
- Future Work

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 / 500 deg C
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
Cooling Water	40 gpm	400 psi



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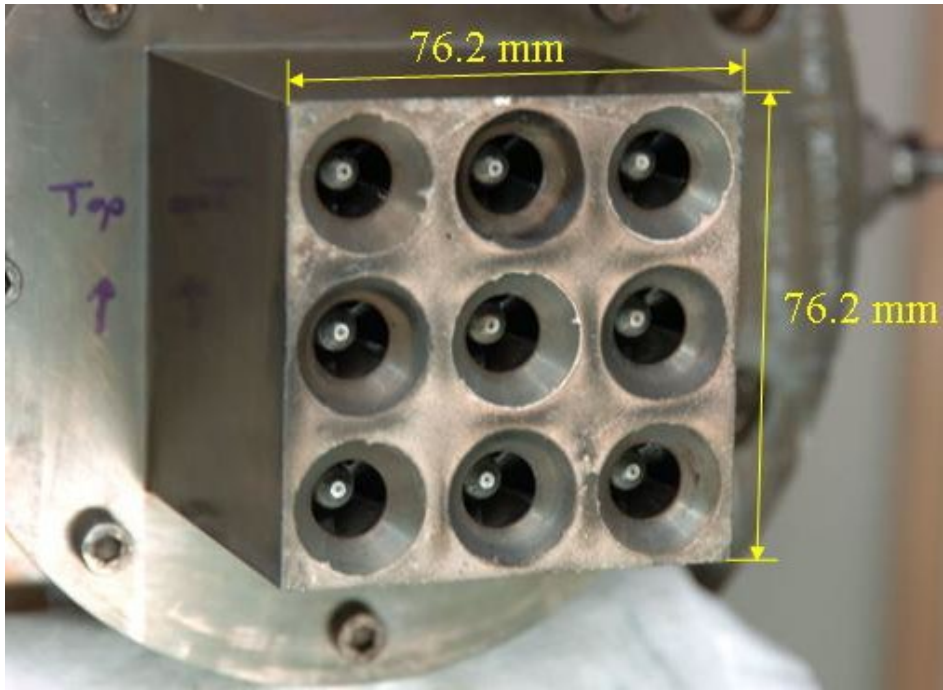
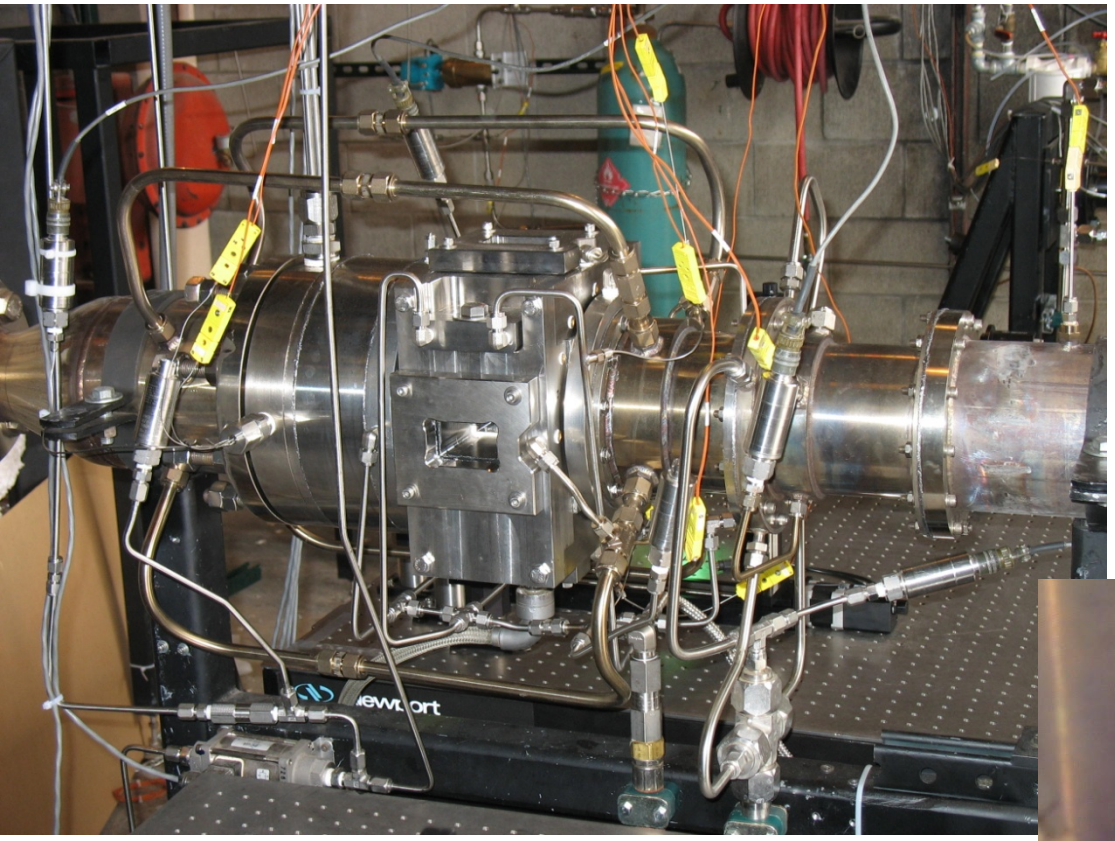
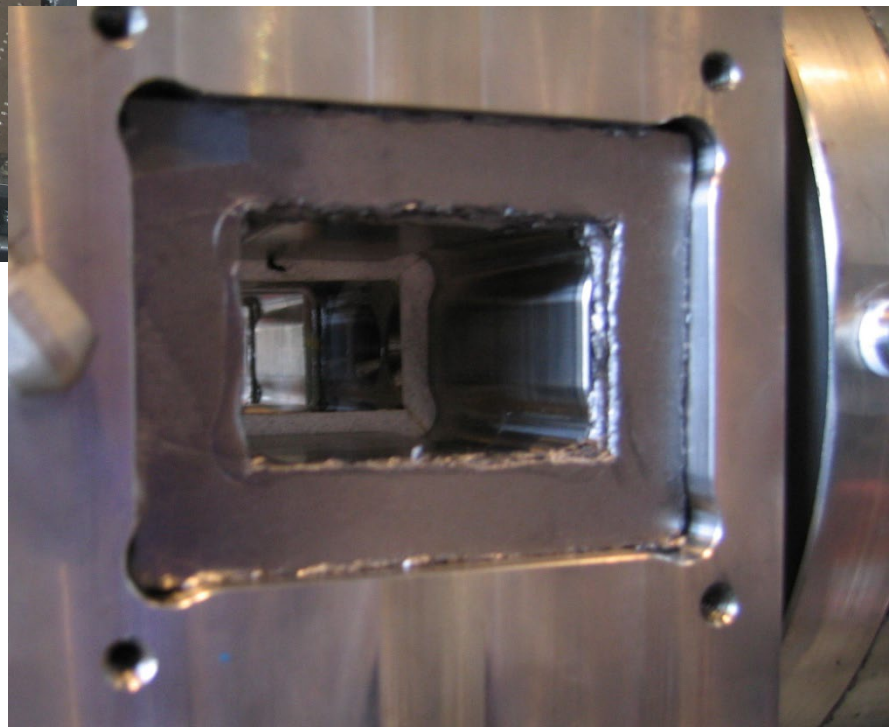
NASA 9-Point LDI Assembly (Top-Hat)

- Nine simplex injectors arranged at throats of nine converging-diverging venturis in a 3 x 3 arrangement.
- Axial swirlers with helical vanes at 60° impart swirl to incoming heated air.
- Only central injector used for testing.



Purdue GTCF – Window Assembly





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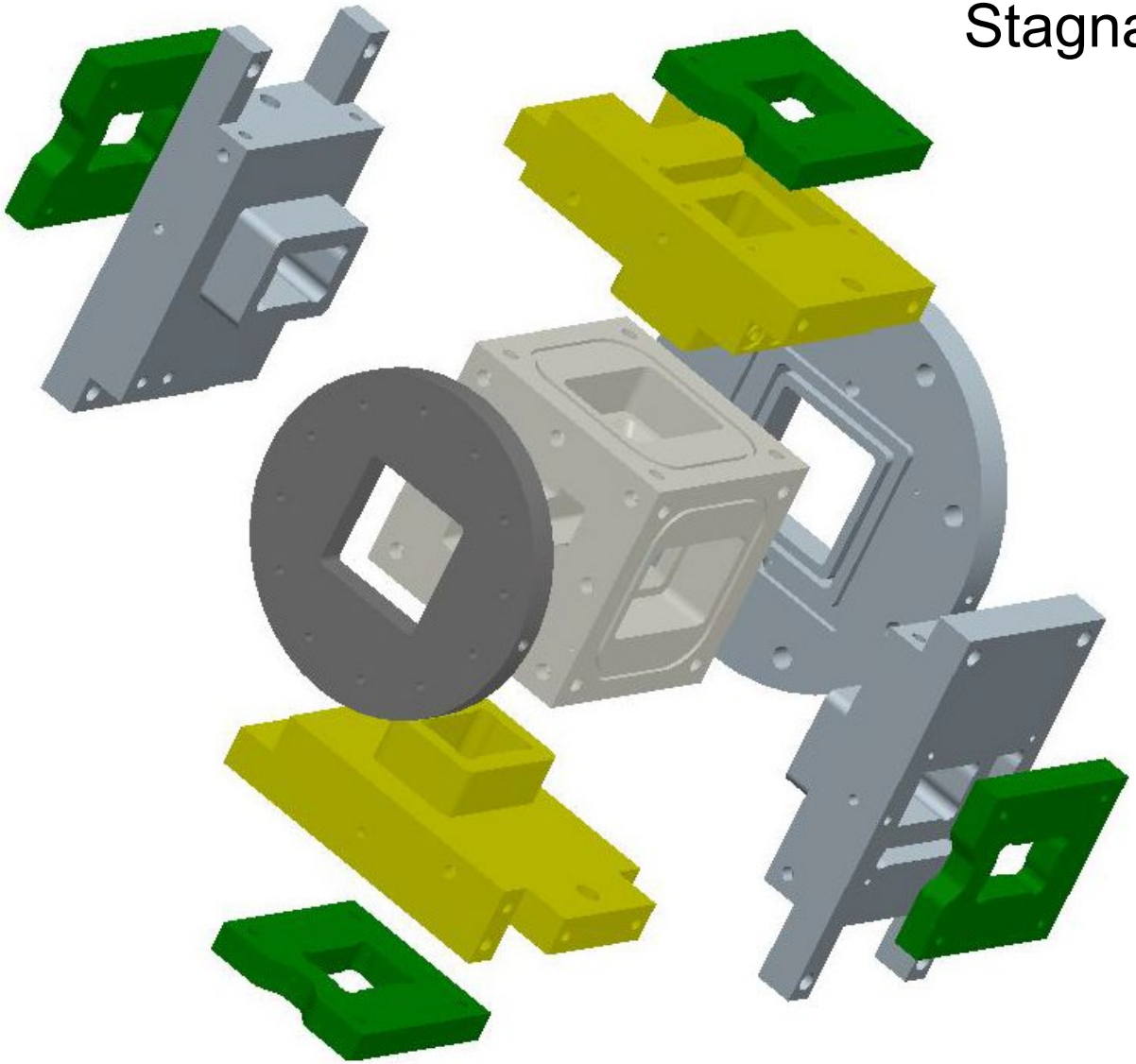
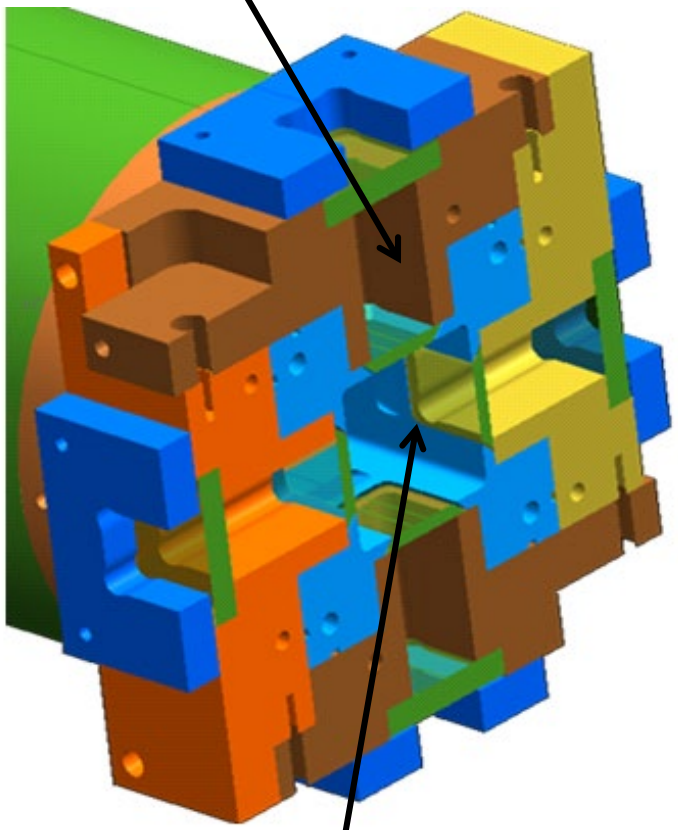
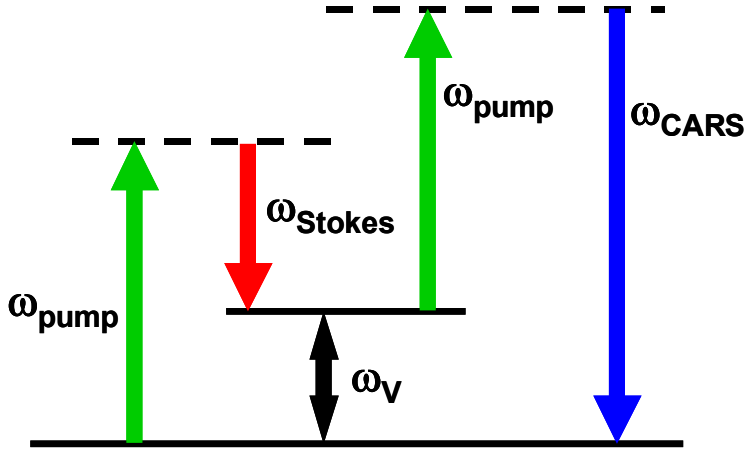
Window Assembly Details

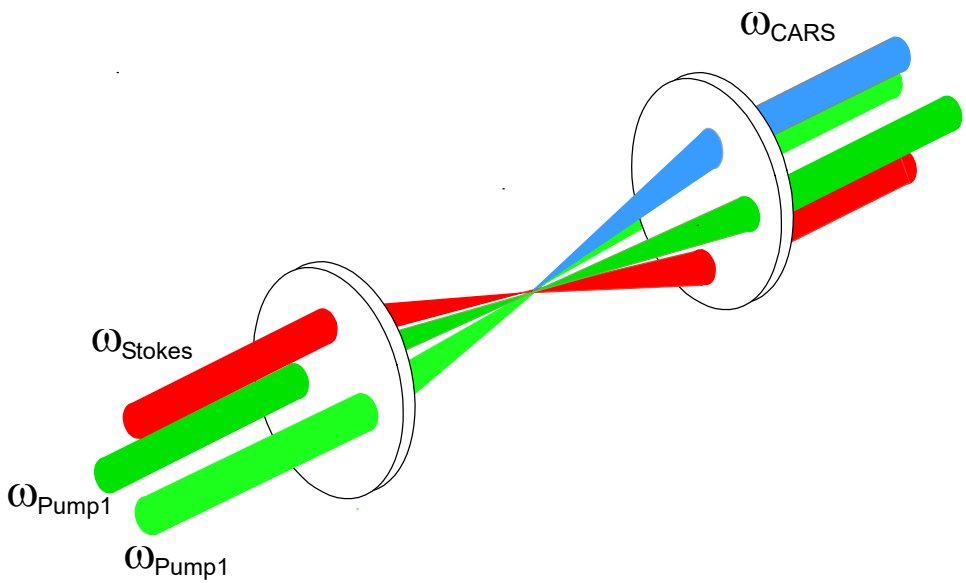




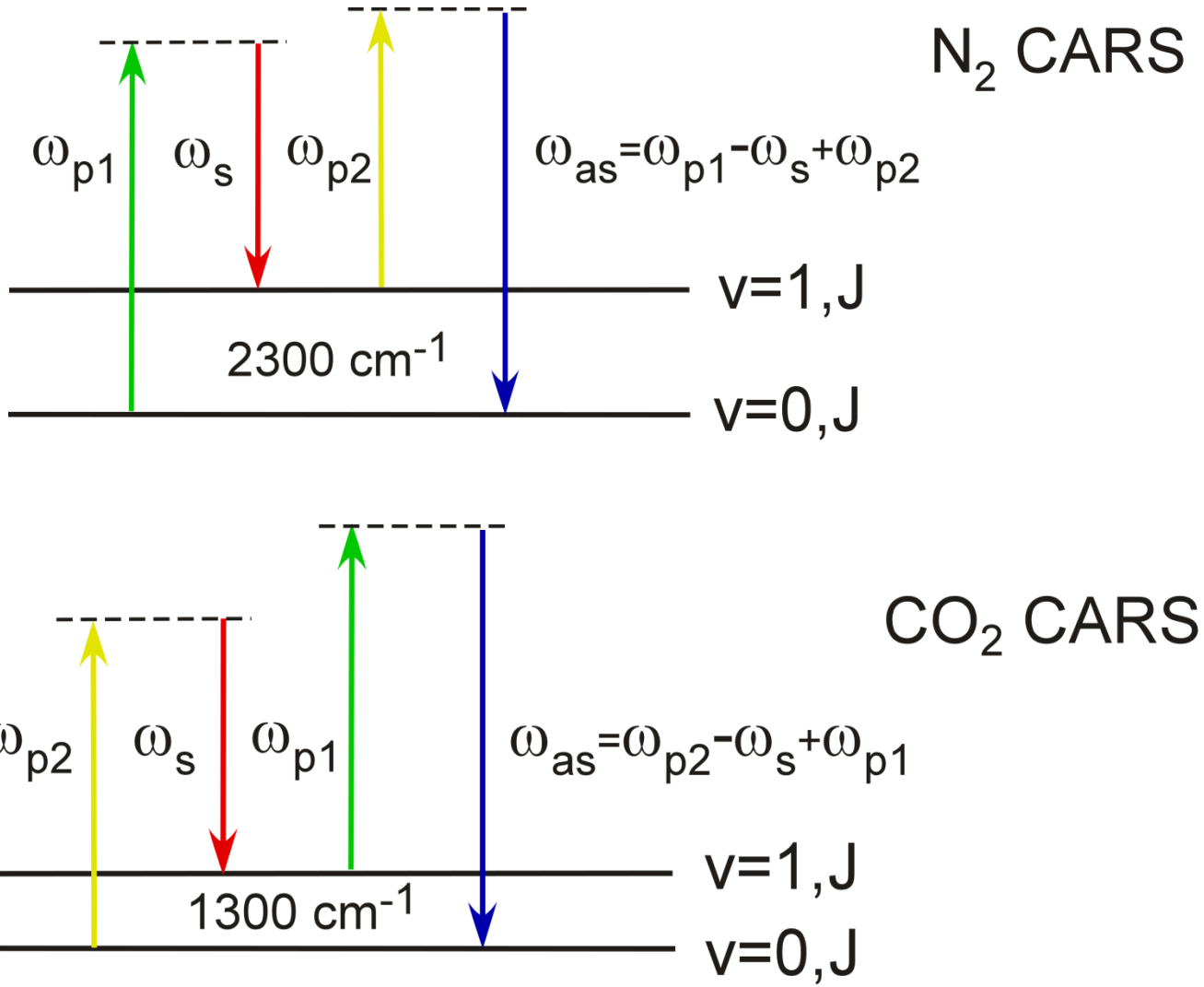
Coherent Anti-Stokes Raman Scattering (CARS)

- Conventional "Single-Pump" CARS
- Noninvasive
- Coherent Laser-Like Signal
- Spatially and Temporally Resolved
- Excellent Gas Temperature Data (especially at higher temperatures)





Dual-Pump CARS of N_2/CO_2



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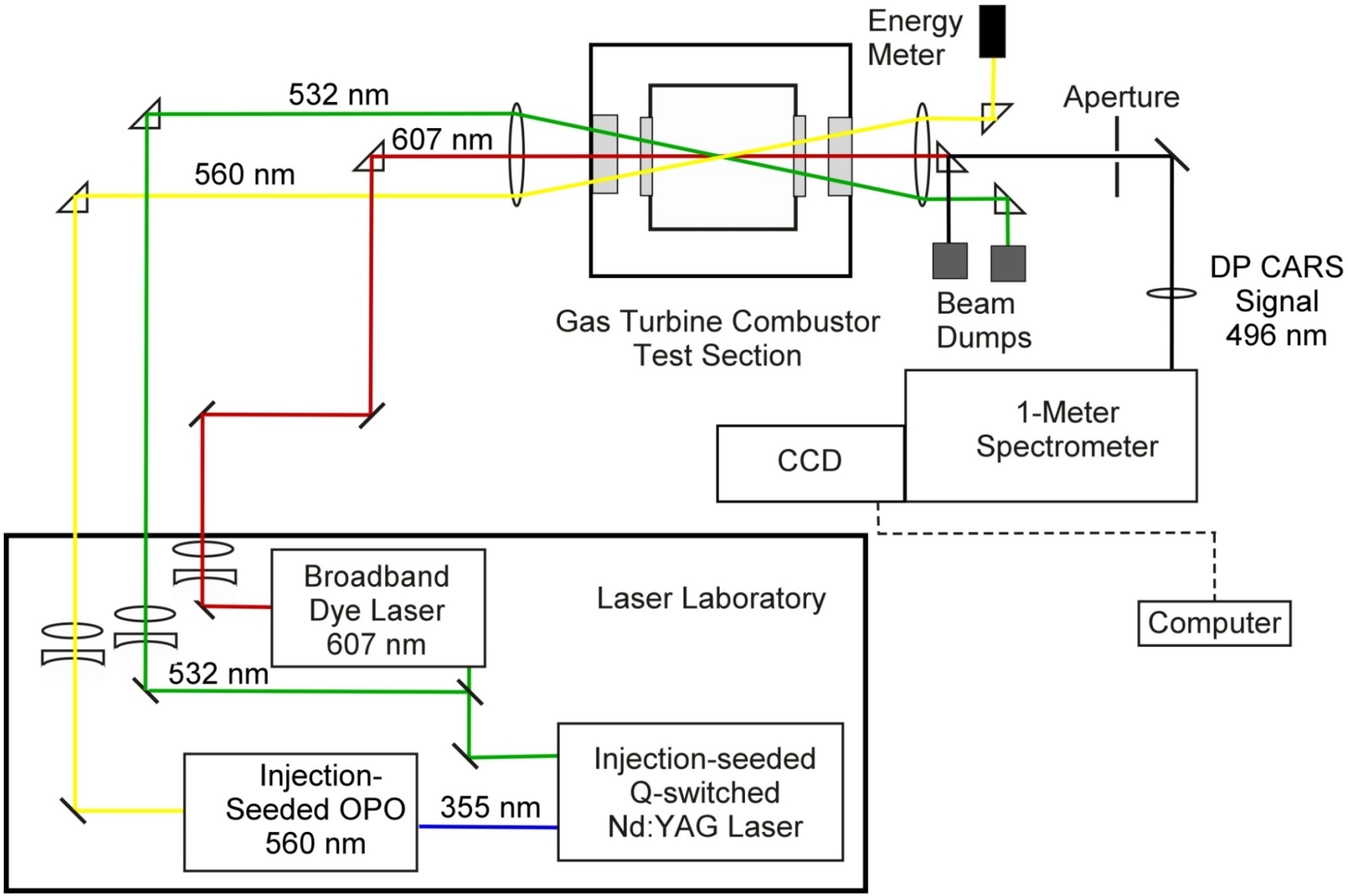
Overall Experimental System



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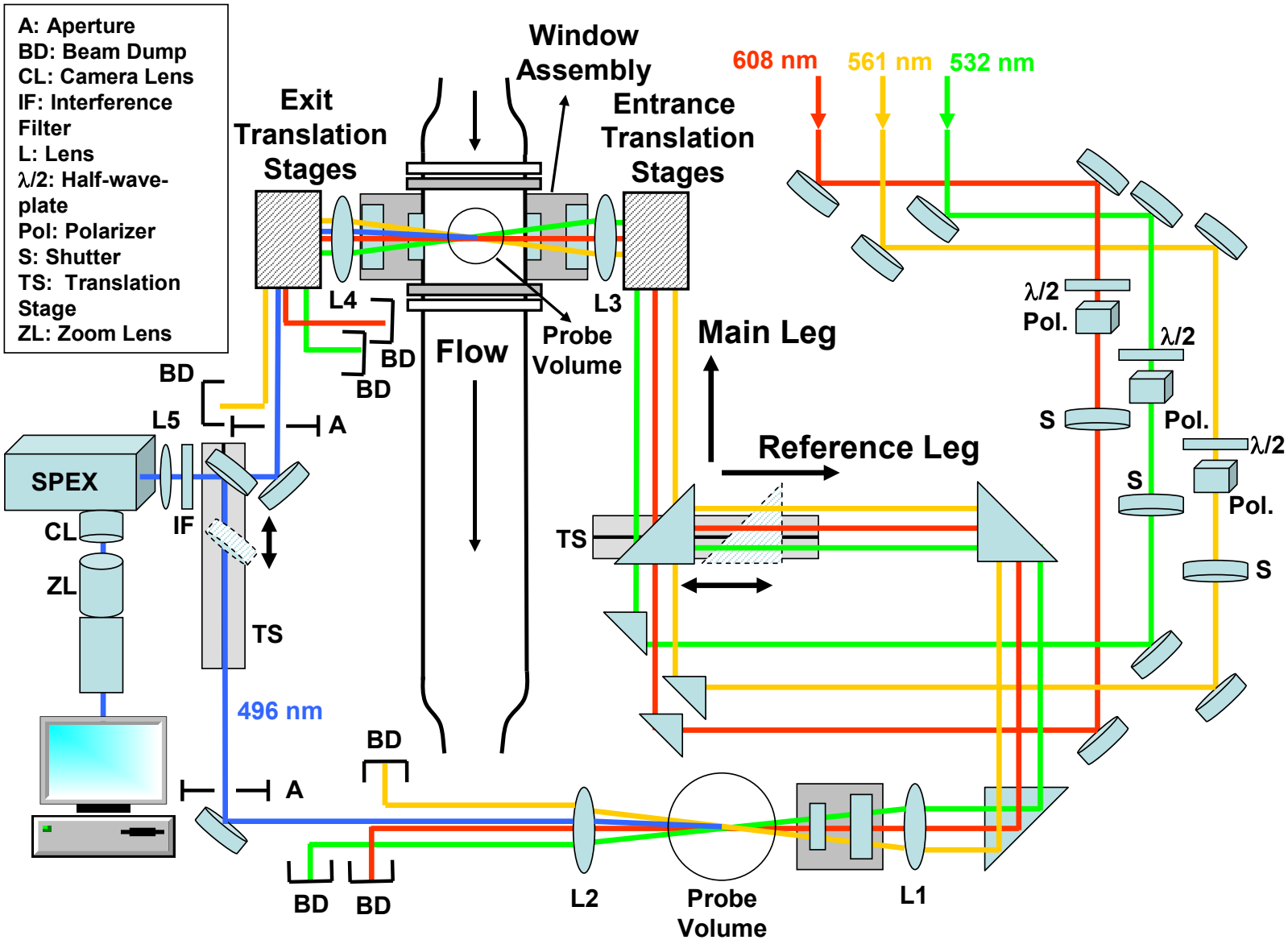
CARS System for GTCF Measurements



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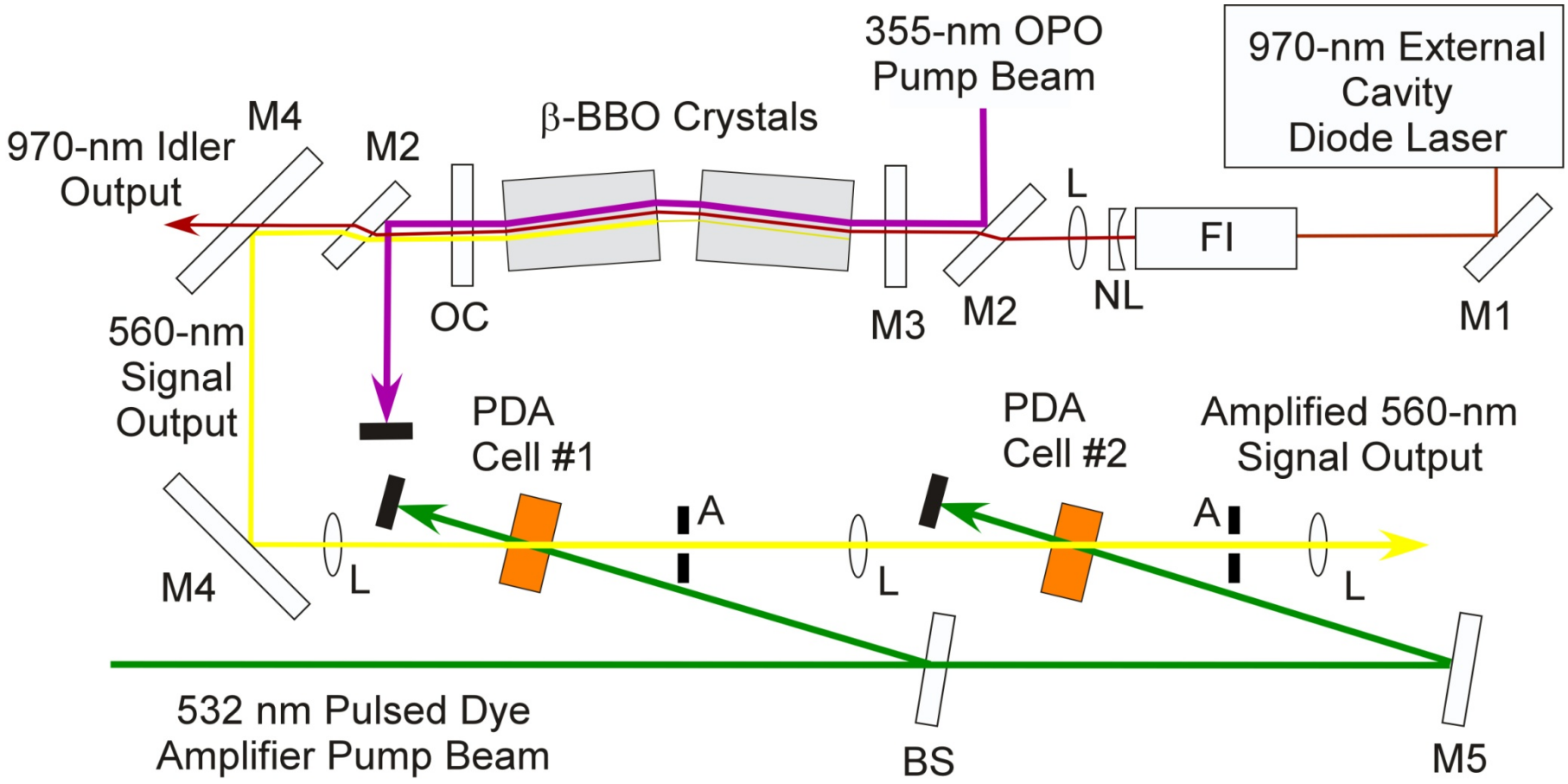
Use of Optical Parametric Oscillator/ Pulsed Dye Amplifier System



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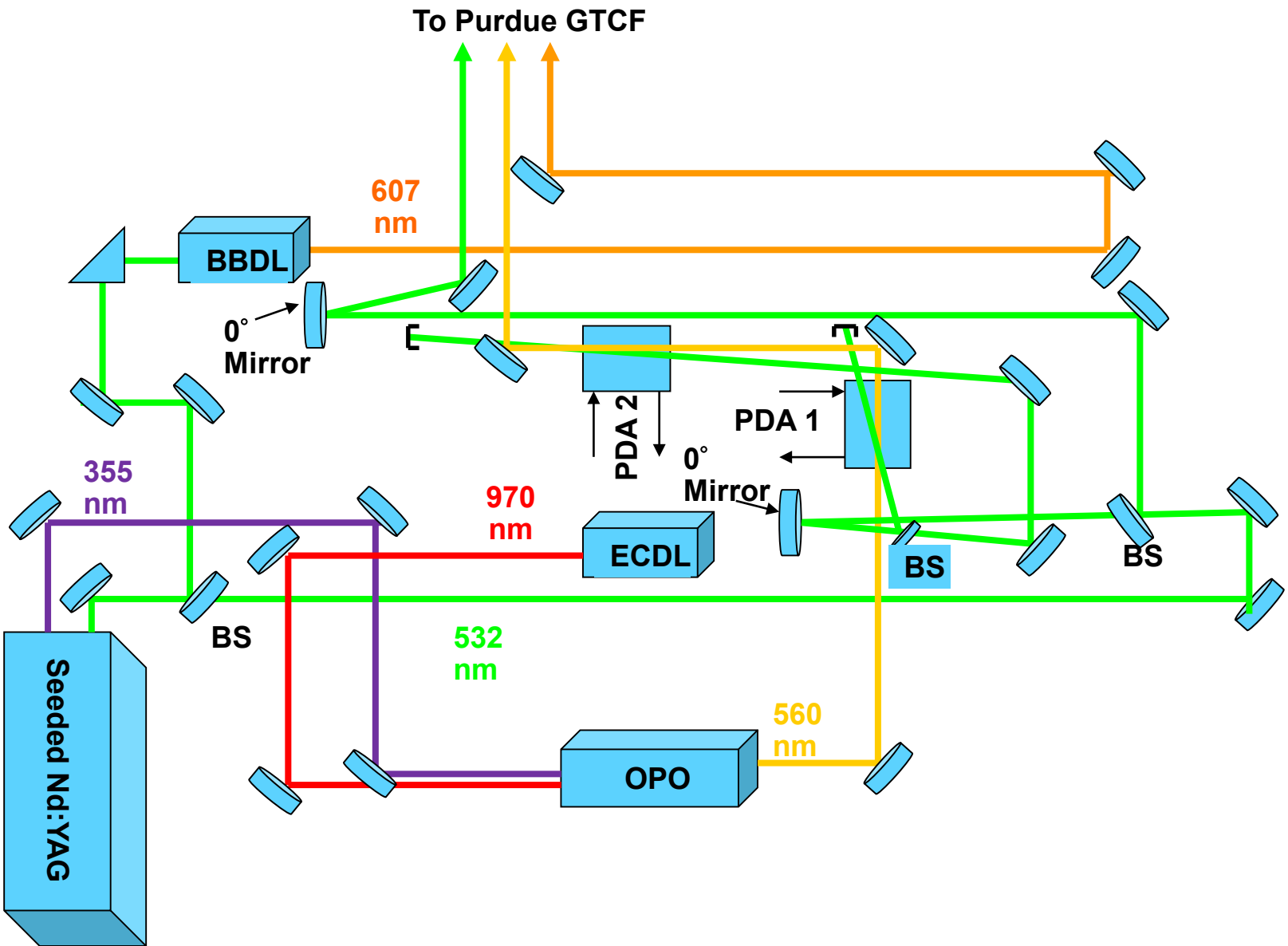
Optical Arrangement for Laser Beam Generation



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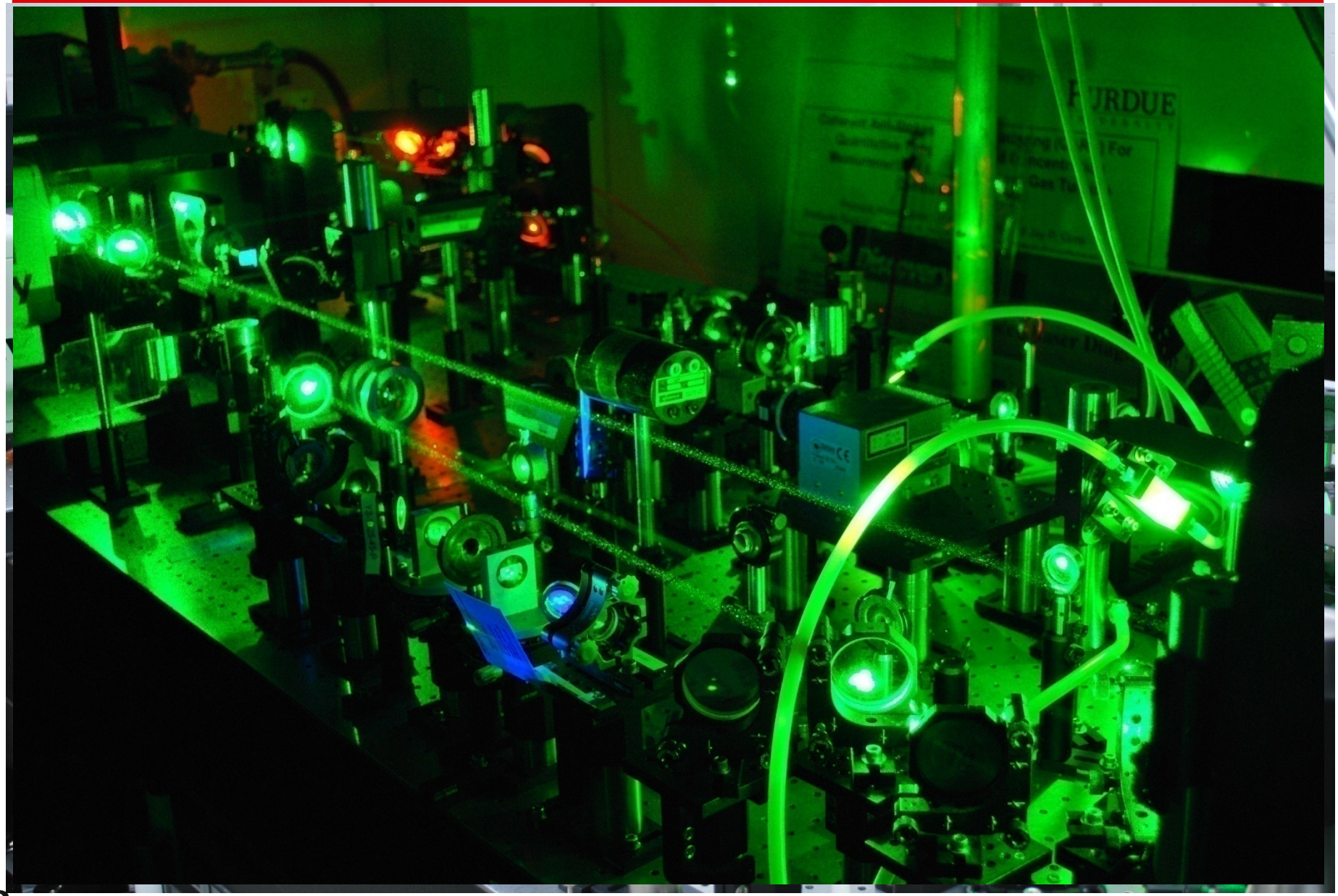
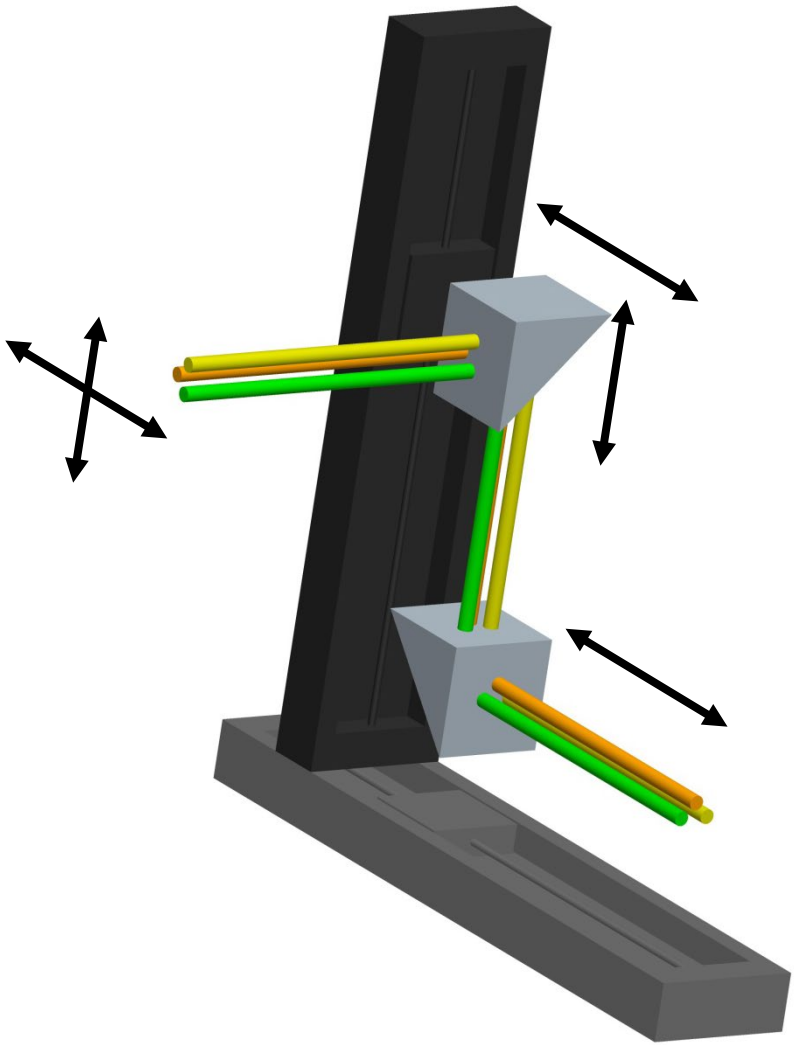
Dual-pump CARS System

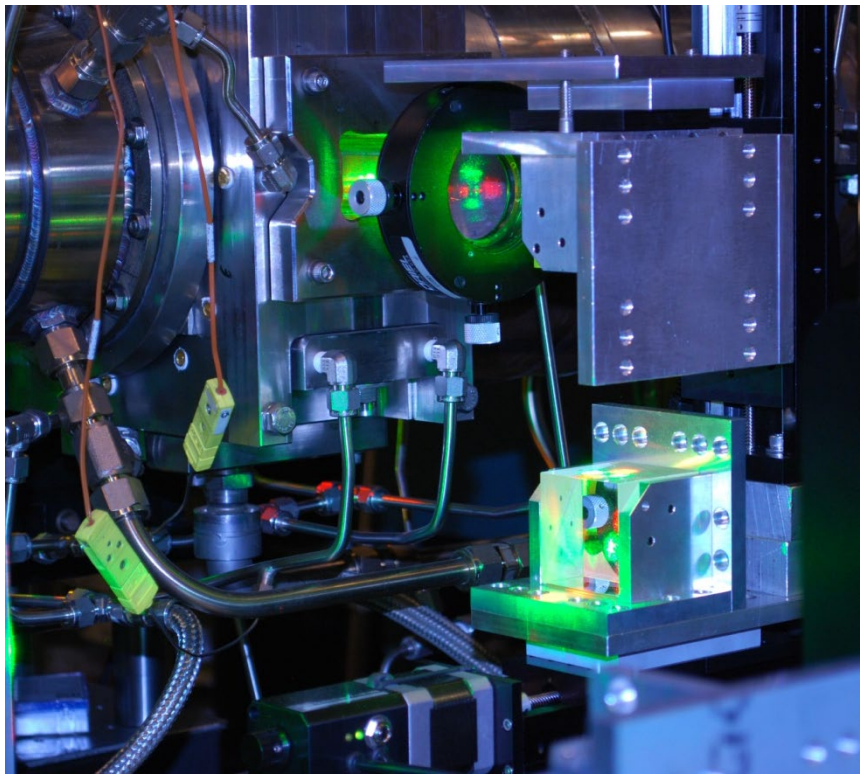


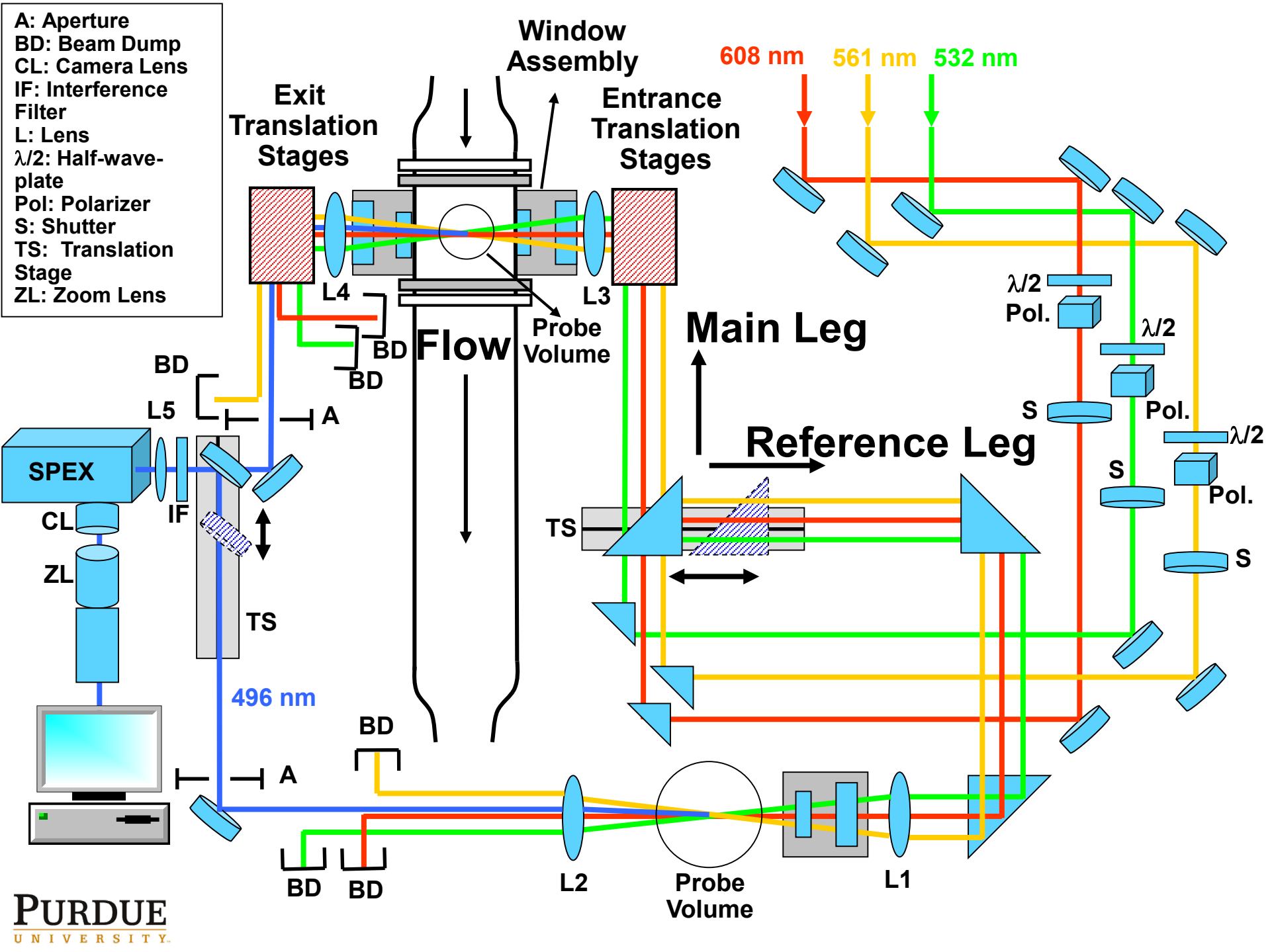
Measurement Challenges in GTCF

- Translation of probe volume inside the flame zone.
- Installation of pin-hole for spatial overlap of CARS beams not possible, must use referemce leg alignment.
- Measurement of non-resonant signal in the reference leg for spectral normalization of CARS signal.
- Safety of thin window, CARS beams are focused tightly in the middle of the test section.

CARS Probe Volume Translation






A: Aperture
BD: Beam Dump
CL: Camera Lens
IF: Interference Filter
L: Lens
λ/2: Half-wave-plate
Pol: Polarizer
S: Shutter
TS: Translation Stage
ZL: Zoom Lens
Window Assembly
608 nm
561 nm
532 nm
Exit Translation Stages
Entrance Translation Stages
L4
L3
BD
BD
BD
Flow
Probe Volume
Main Leg
λ/2
Pol.
λ/2
S
Pol.
λ/2
S
Pol.
S
Reference Leg
BD
L5
A
SPEX
IF
CL
ZL
TS
TS
496 nm
BD
A
BD
BD
L2
Probe Volume
L1
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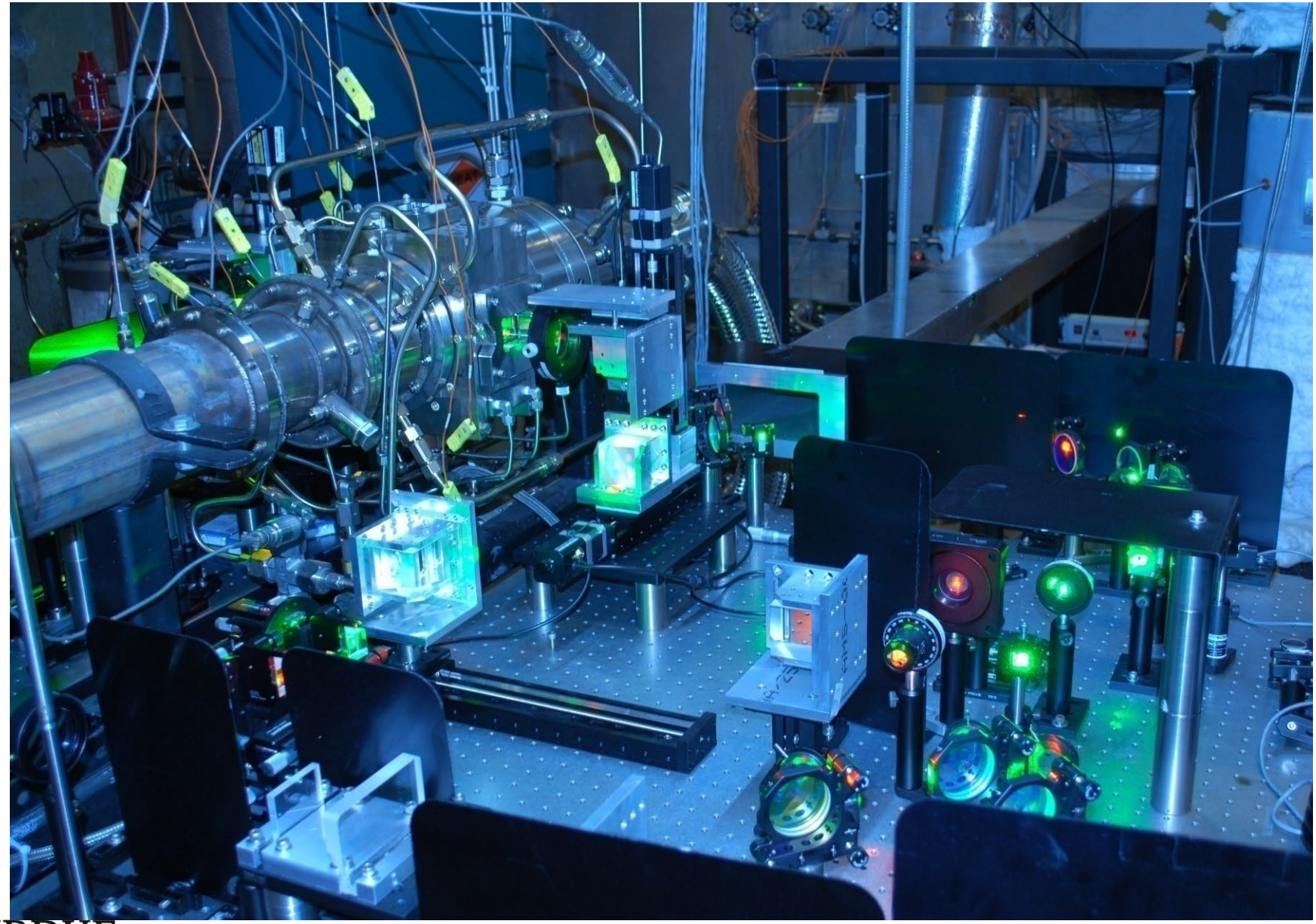
Optical System near GTCF



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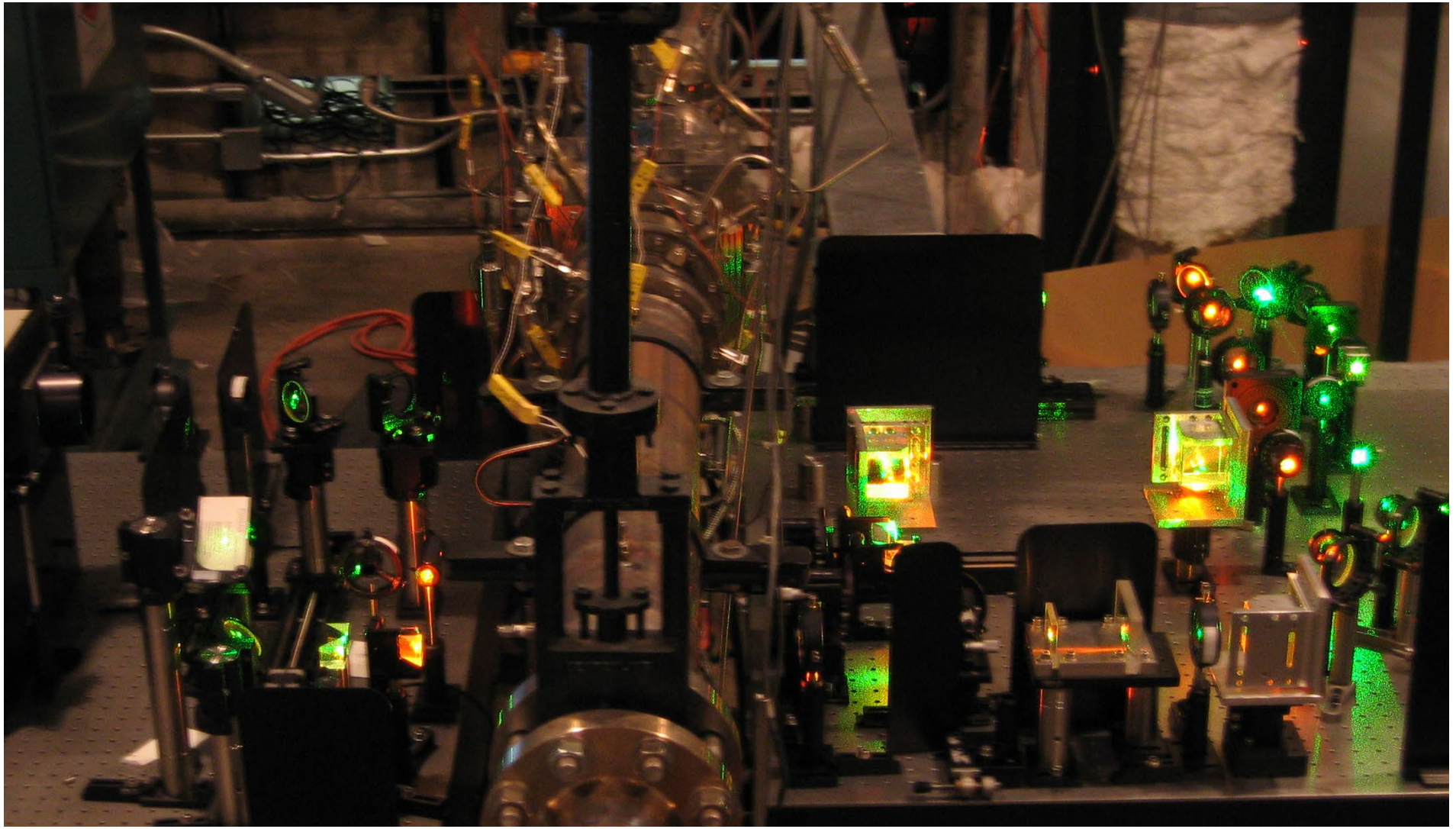
CARS System Reference Leg



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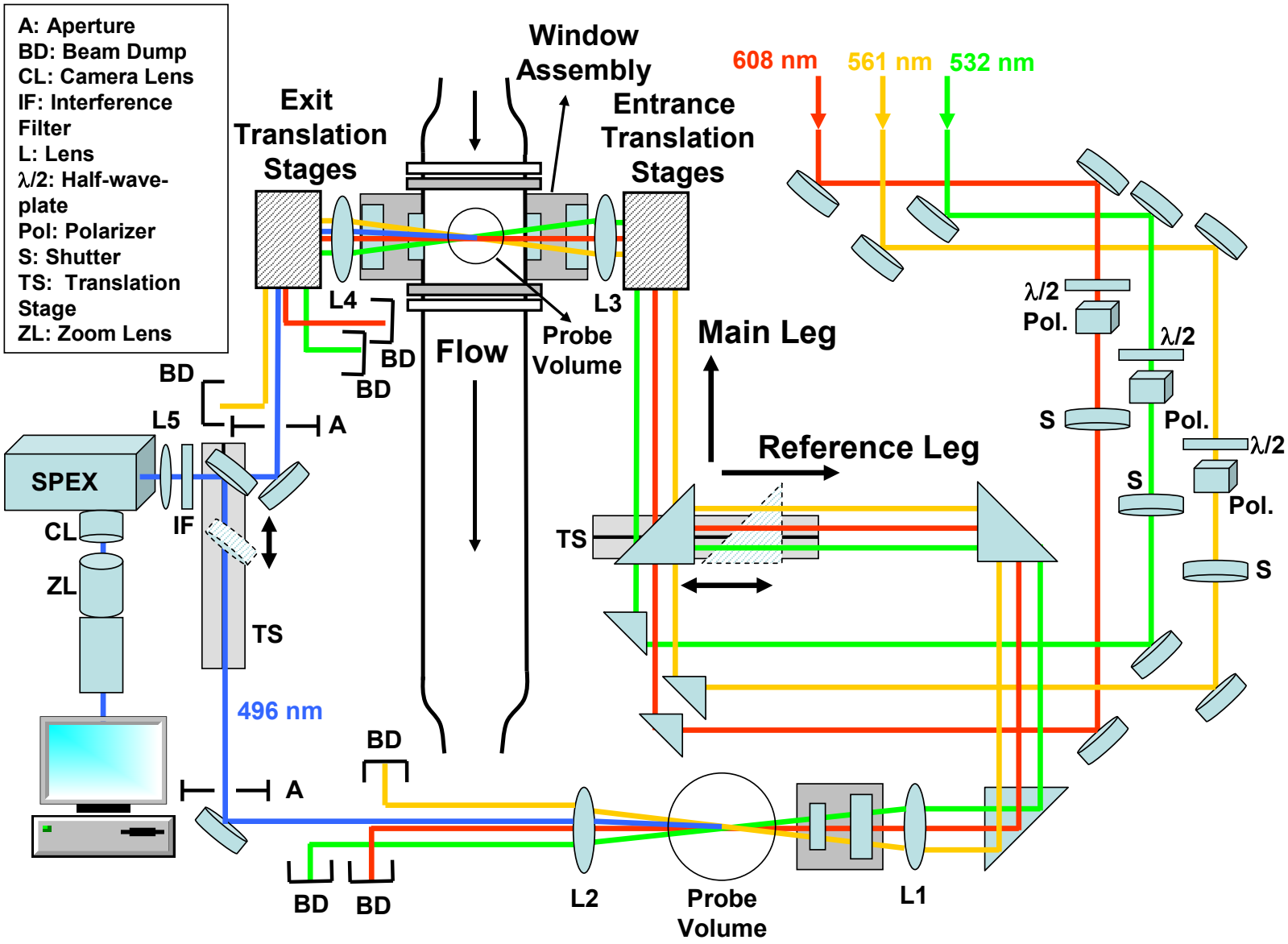
CARS System Reference Leg



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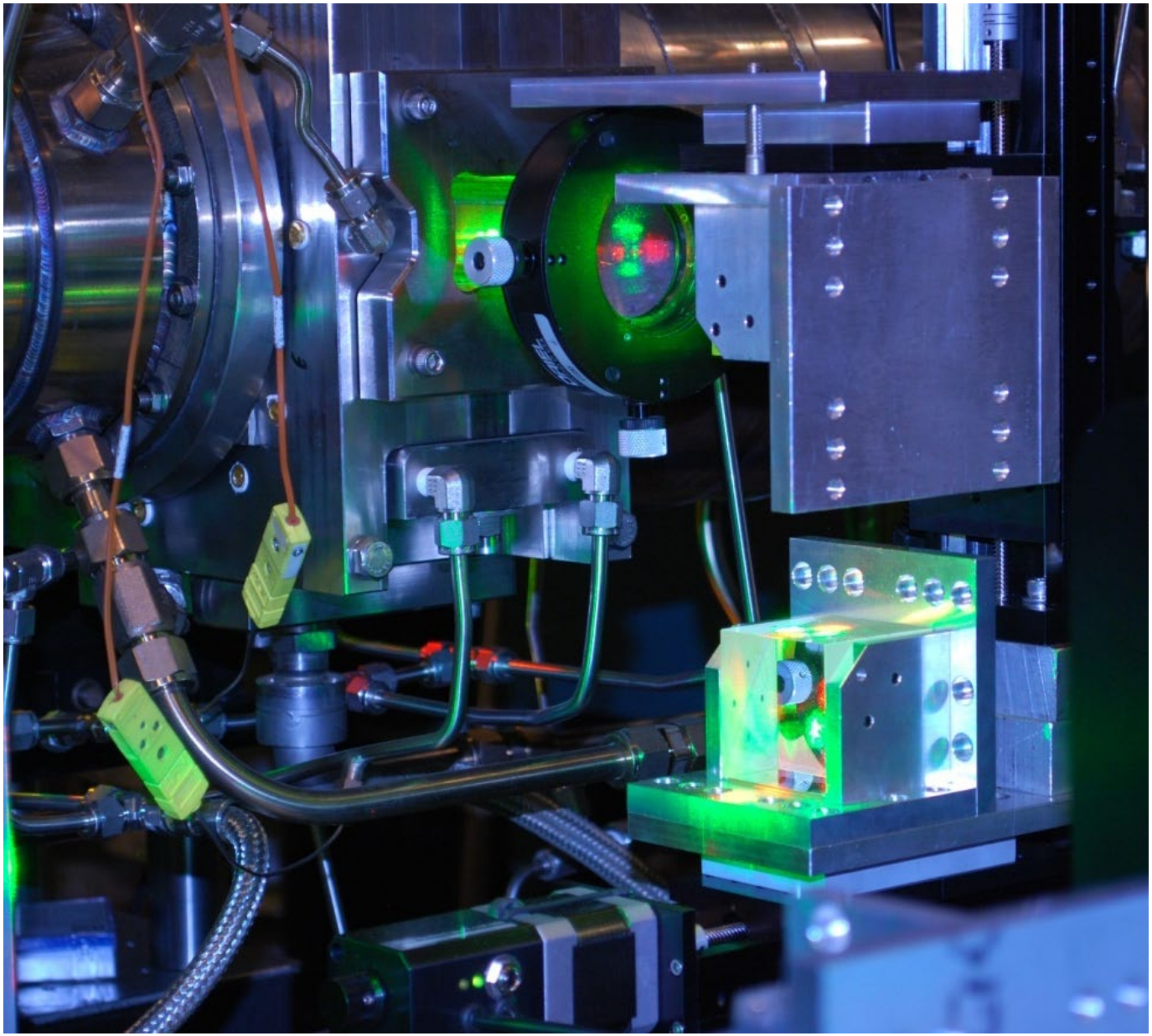
Probe Volume Translation



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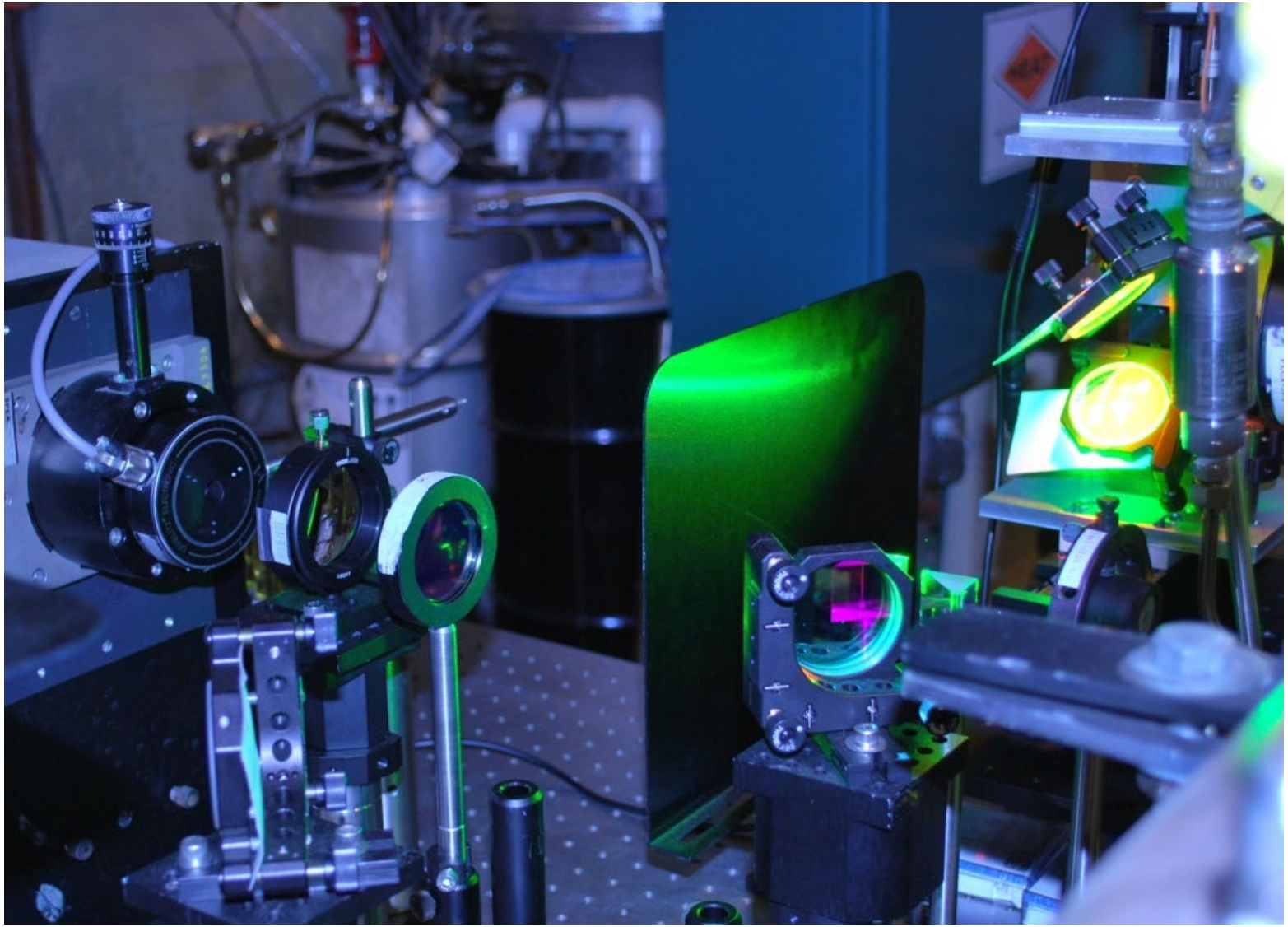
DP-CARS Detection Optics



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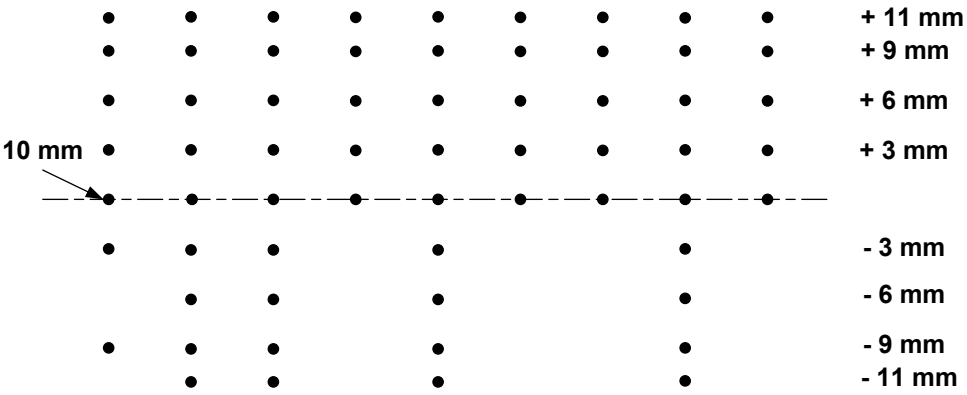
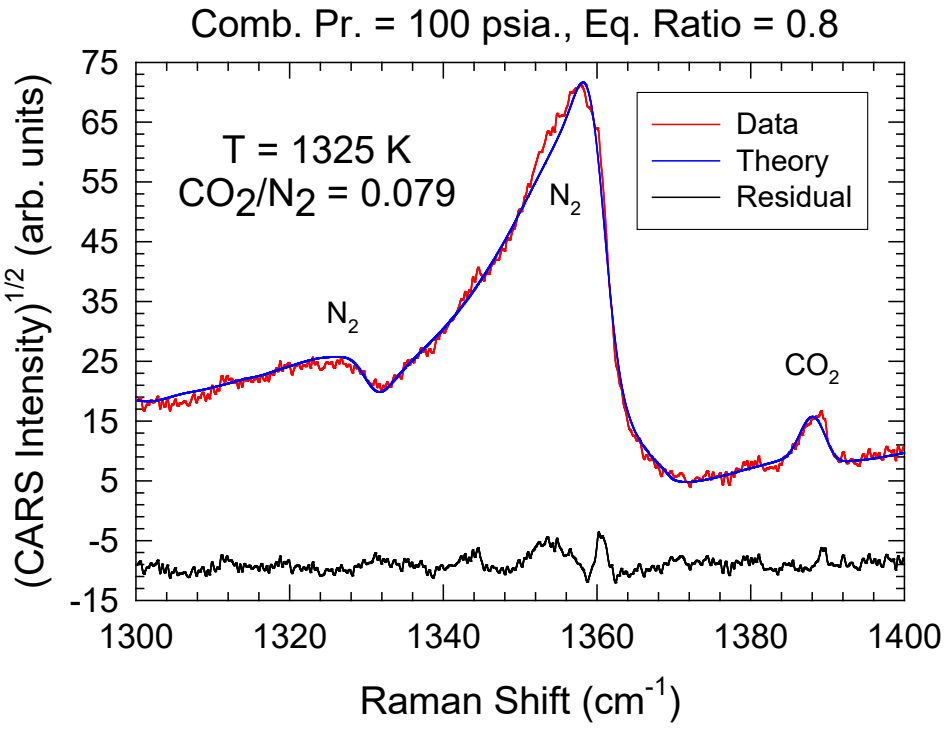
Operating Conditions, Measurement Locations and Sample DP-CARS Spectra

	Φ=0.4	Φ=0.59	Φ=0.80	Φ=1.0
100 psia *(7.0 atm.)*	■	■	■	■
125 psia *(8.5 atm.)*	■			
150 psia *(10 atm.)*	■			

- Burner Inlet Temperature: 850 ^{0}F (725 K)
- Fuel: Jet-A
- Normalized injector pressure drop = 4%

Φ = 0.6
P = 100 psi
ΔP/P = 4%
Note: Distance between points along the centerline is 5 mm





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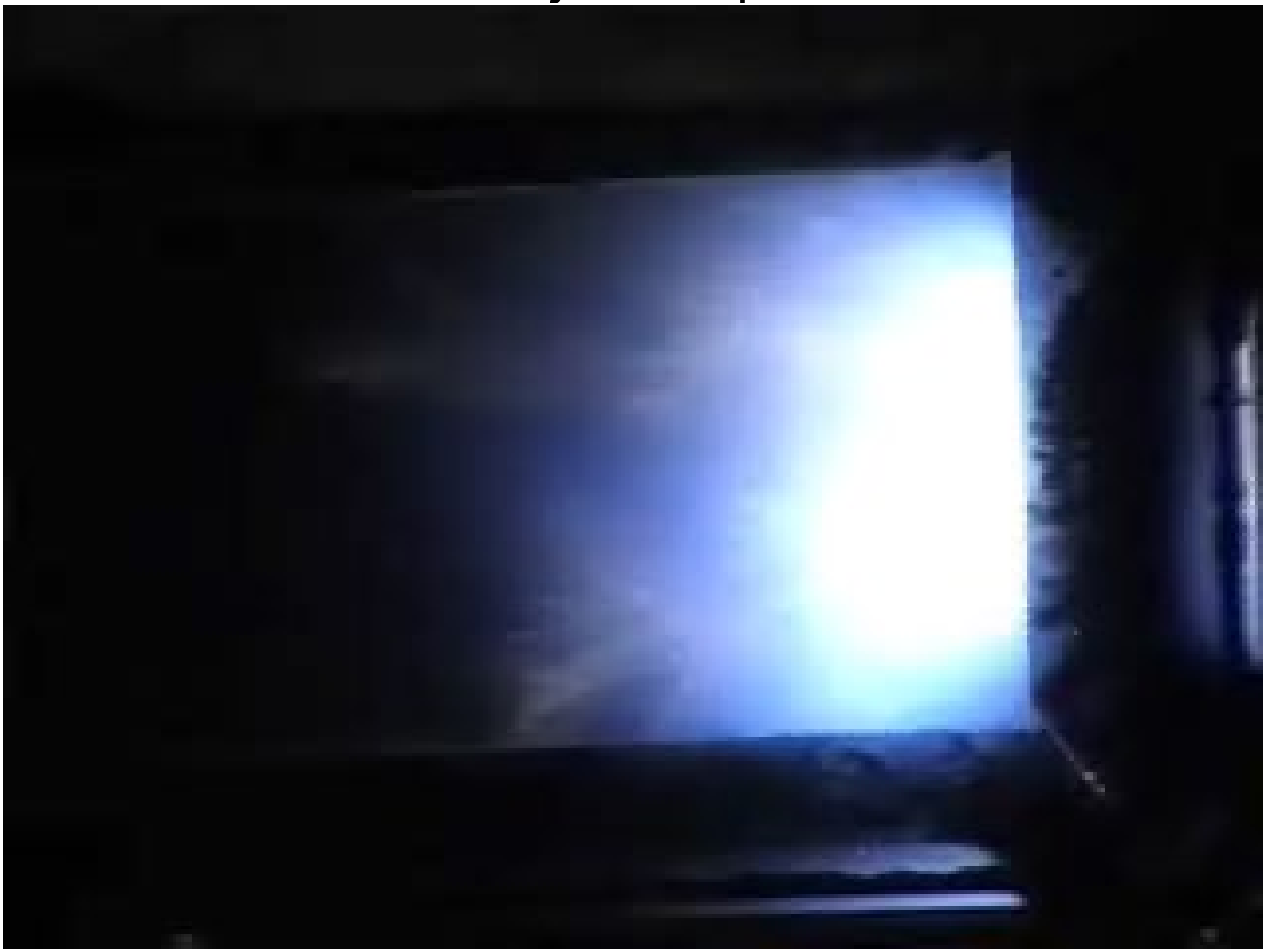
Purdue GTCF in Operation

Central injector operation



Φ= 0.45, P_{comb}= 120 psia, T_{inlet} = 780° F

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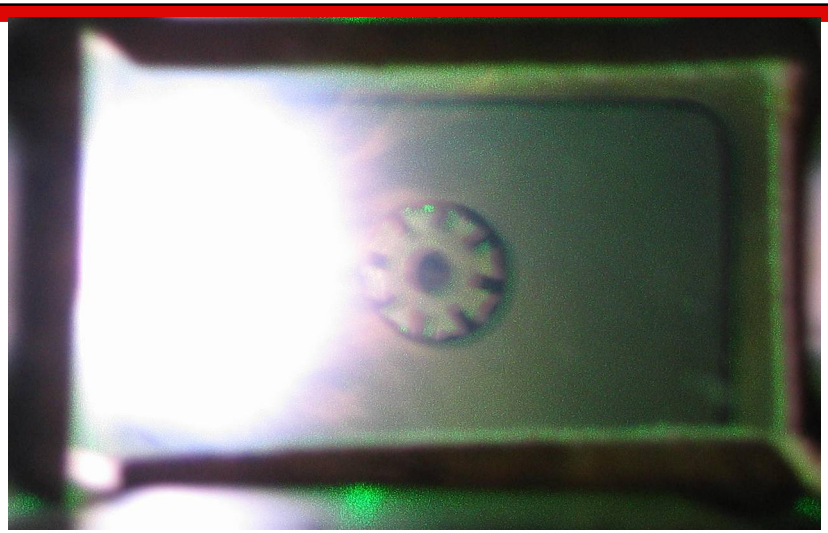
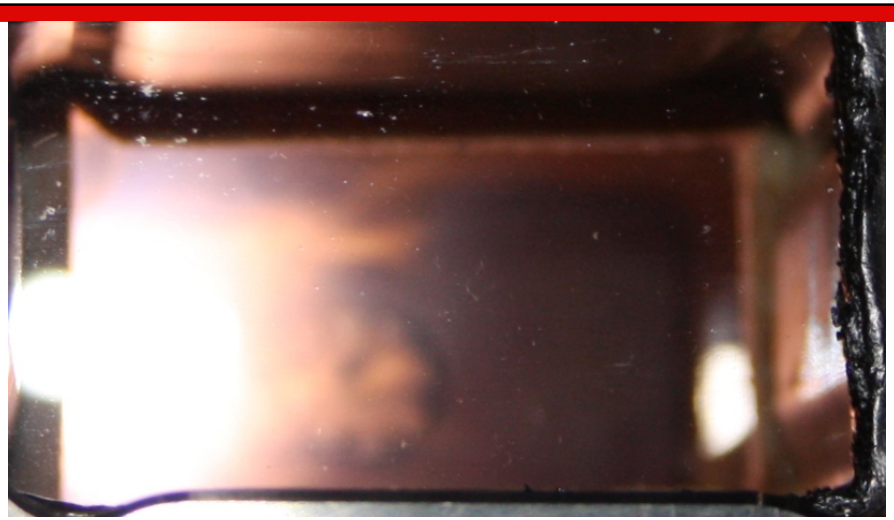
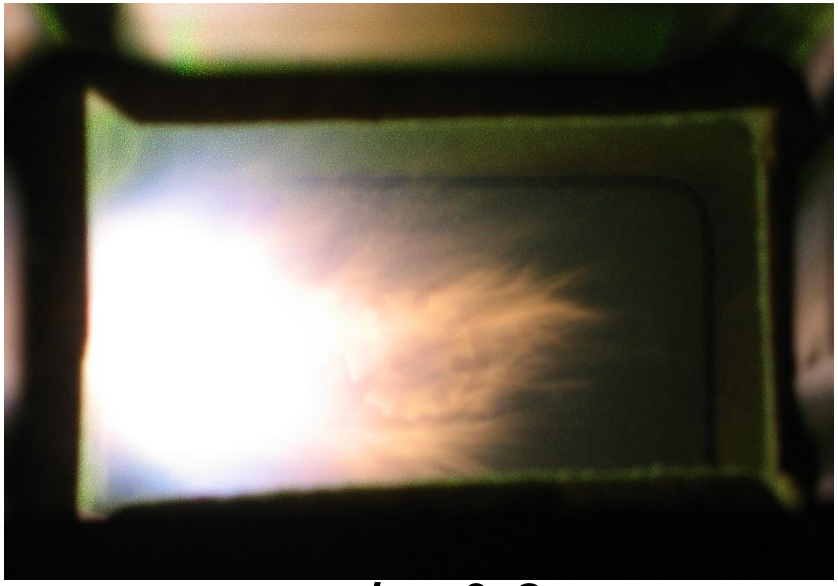
Flame Characteristics @ 100 psia



Φ =0.4



Φ =0.59



Φ =0.8

Φ =1.0

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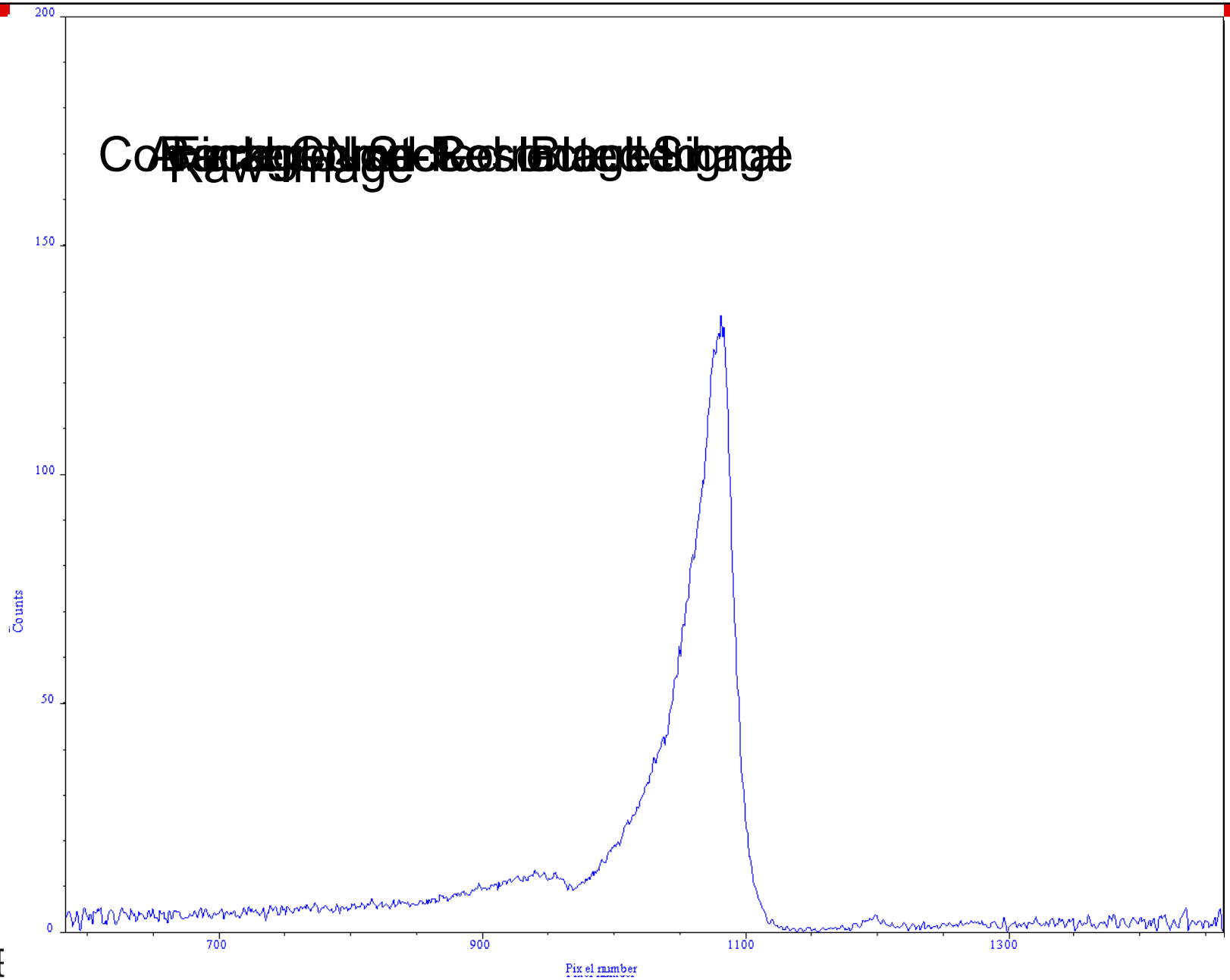
Data Analysis

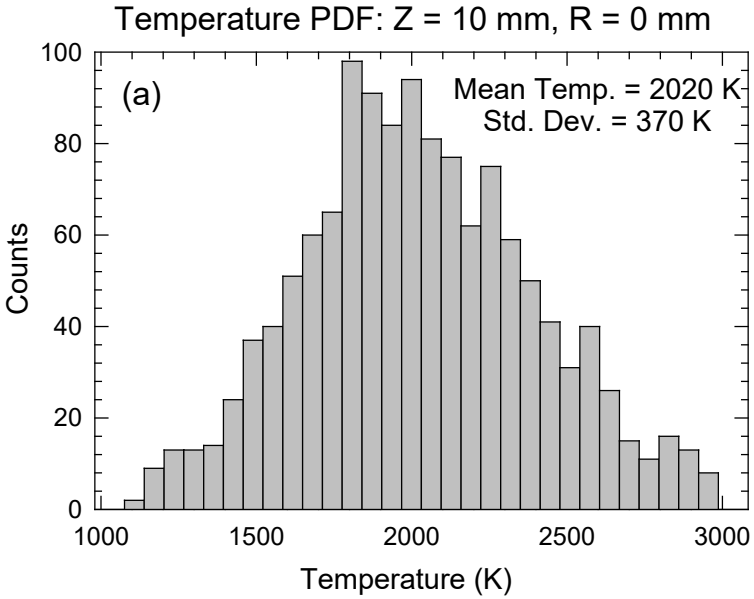
- 1000 to 2000 spectra collected at each measurement location.
- Spectra with low average N_2 signal counts and droplet interferences rejected.
- Square-root of background corrected normalized CARS spectra analyzed using Sandia CARSFT code in the batch processing mode.
- N_2 spectra analyzed for optimal temperature, horizontal and vertical shift, instrument function etc.
- Spectra with low peak CO_2 counts rejected. CO_2 part of the spectrum analyzed for CO_2/N_2 concentration ratio.

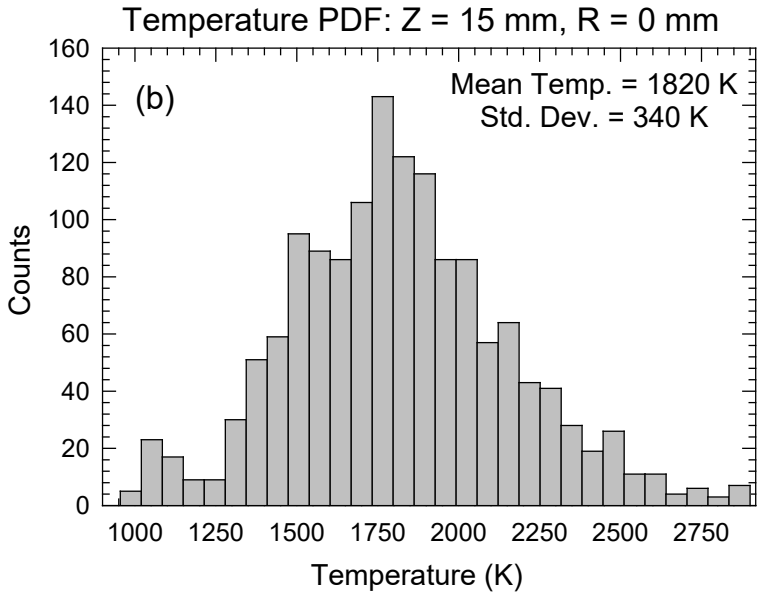
Data Processing

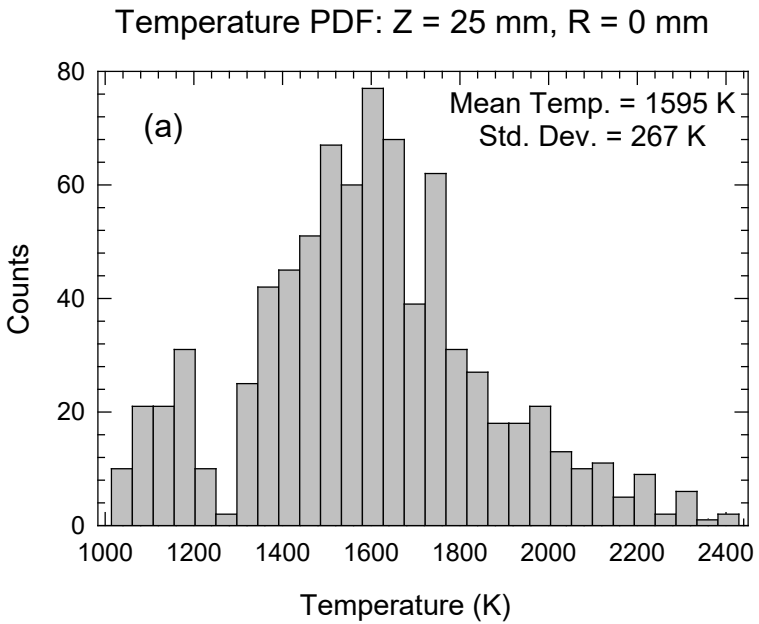


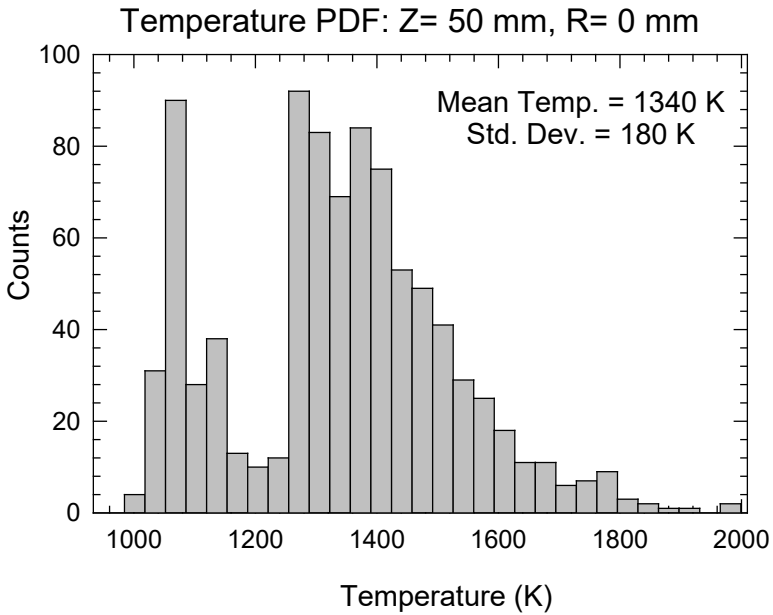
Temp PDFs Along Centerline

Combustor Pressure: 104 psia, Equivalence Ratio: 0.4









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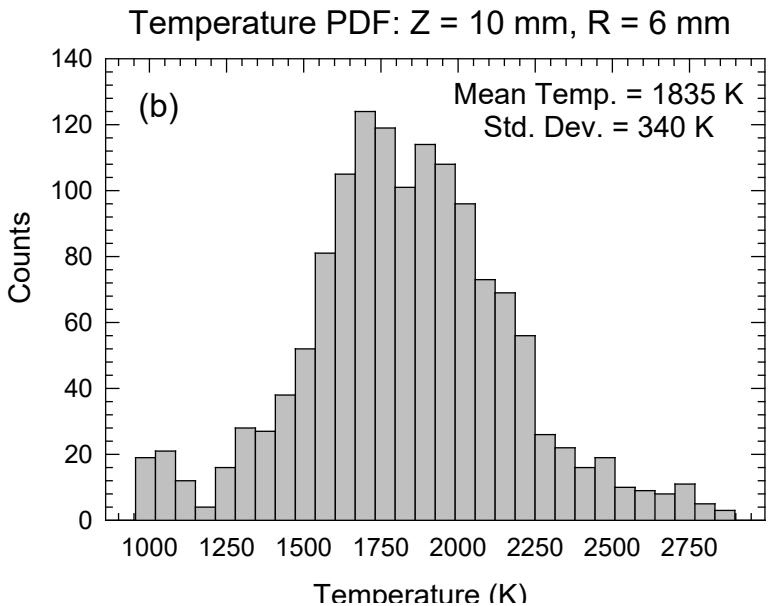
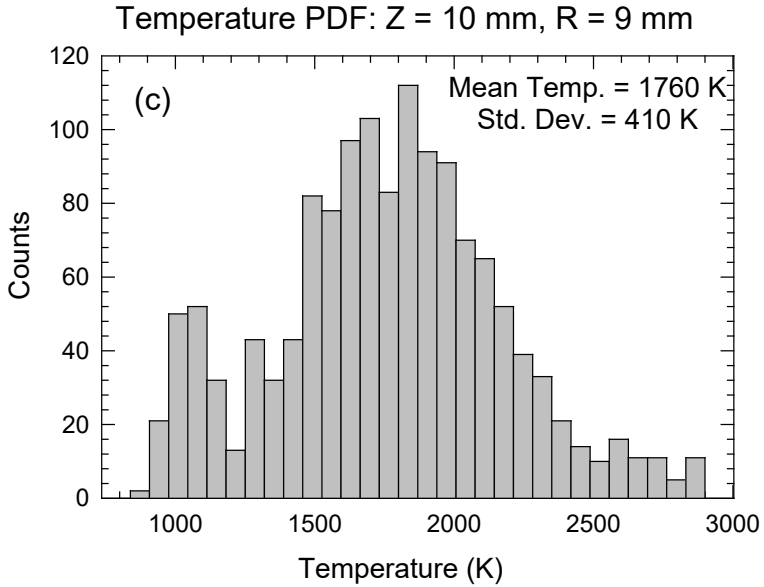
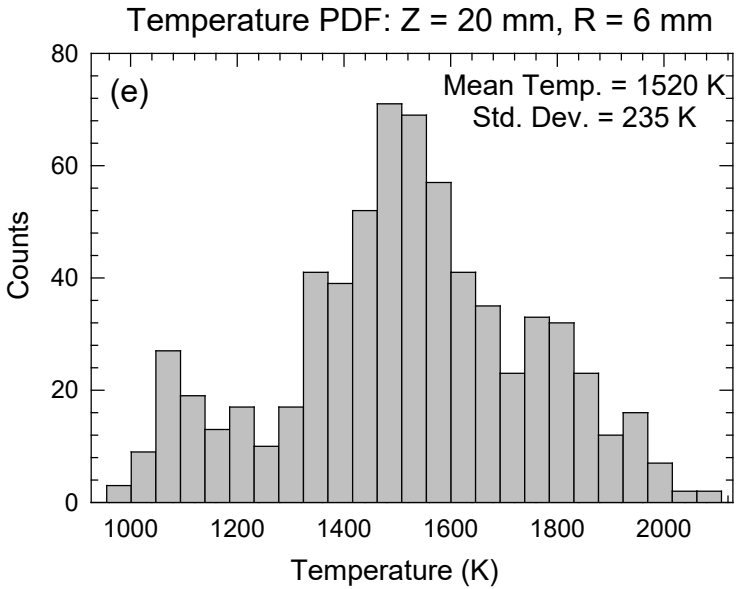
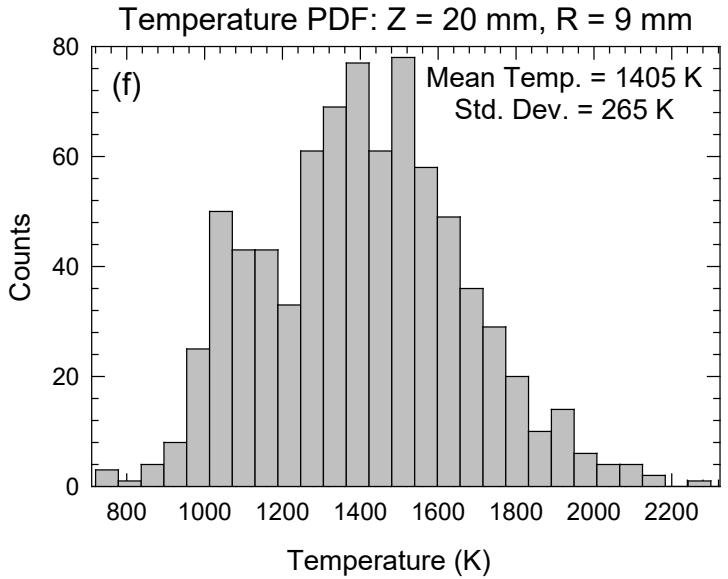
Temp PDFs at Different Locations

Combustor Pressure: 104 psia., Equivalence Ratio: 0.4









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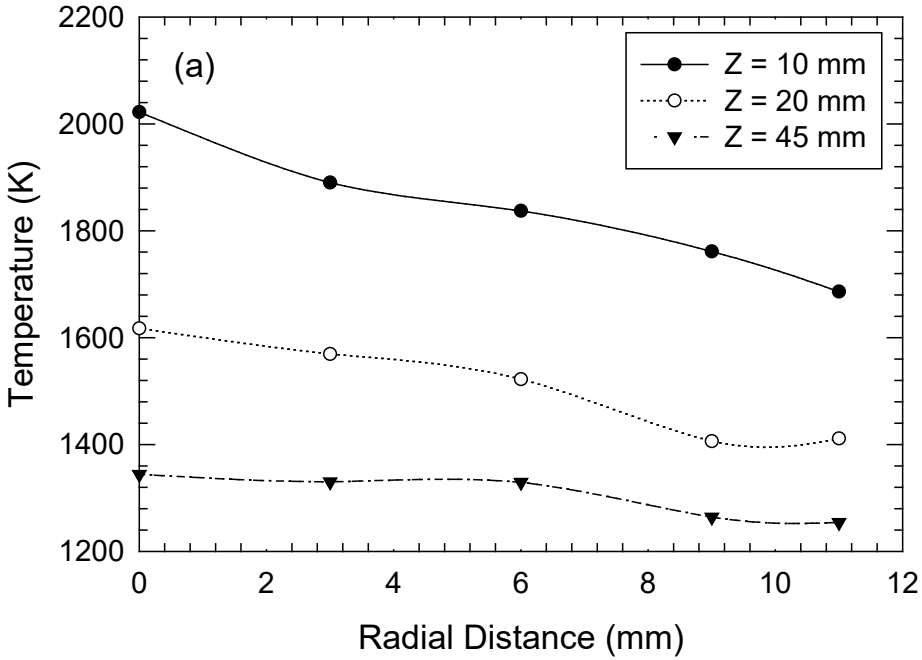
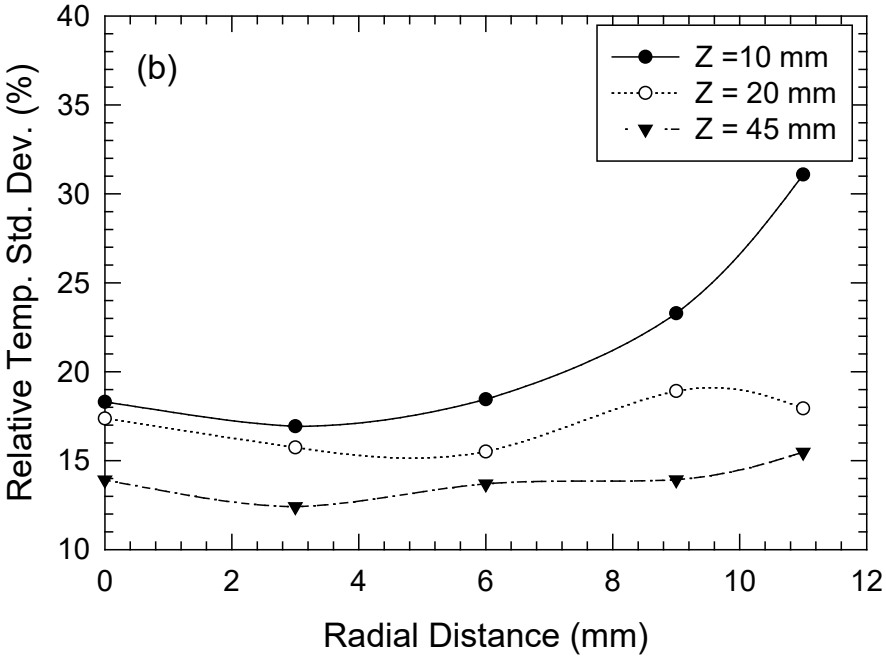
Mean Temperature & Temperature Standard Deviation Profiles



Combustor Pressure: 104 psia

Equivalence Ratio: 0.4



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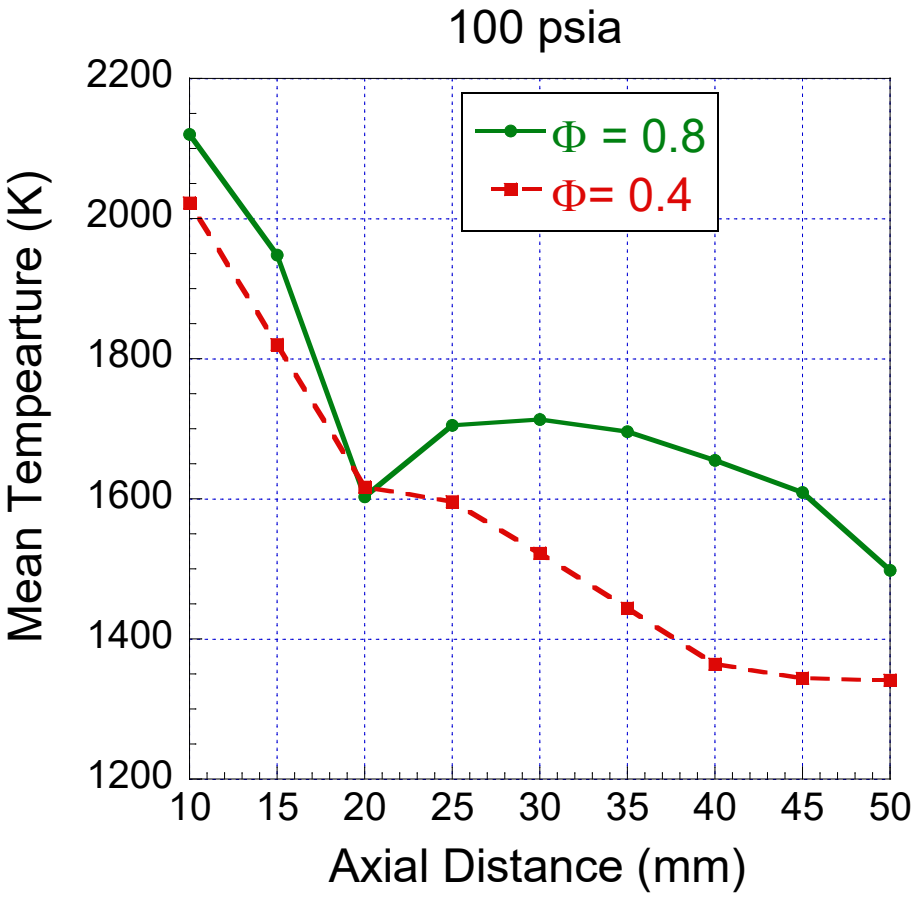
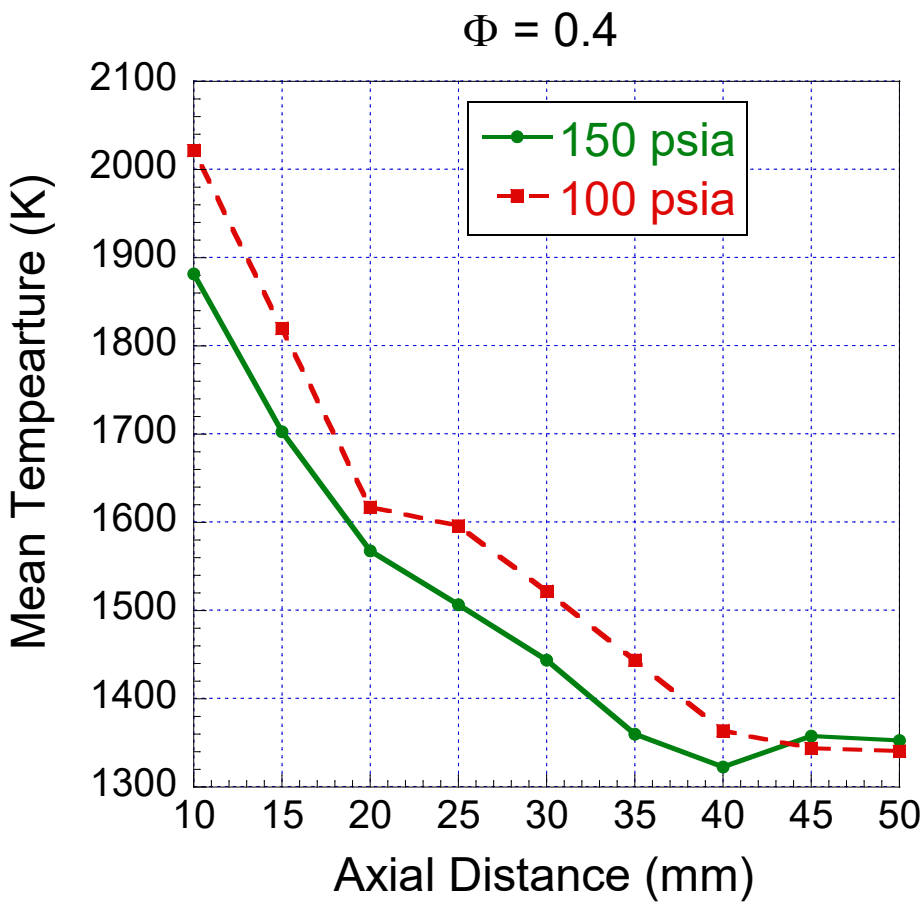
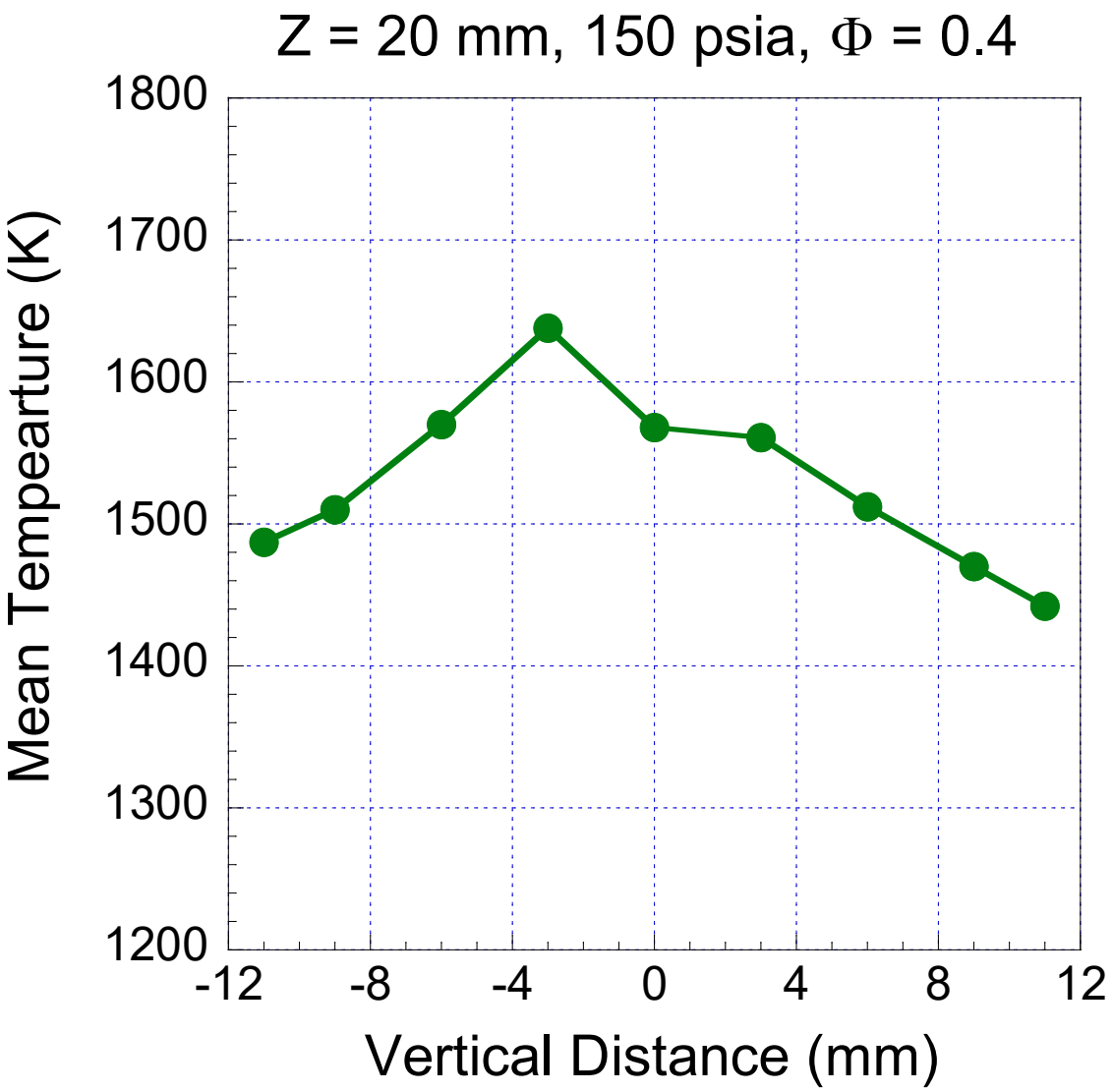
Mean Temperature Profiles



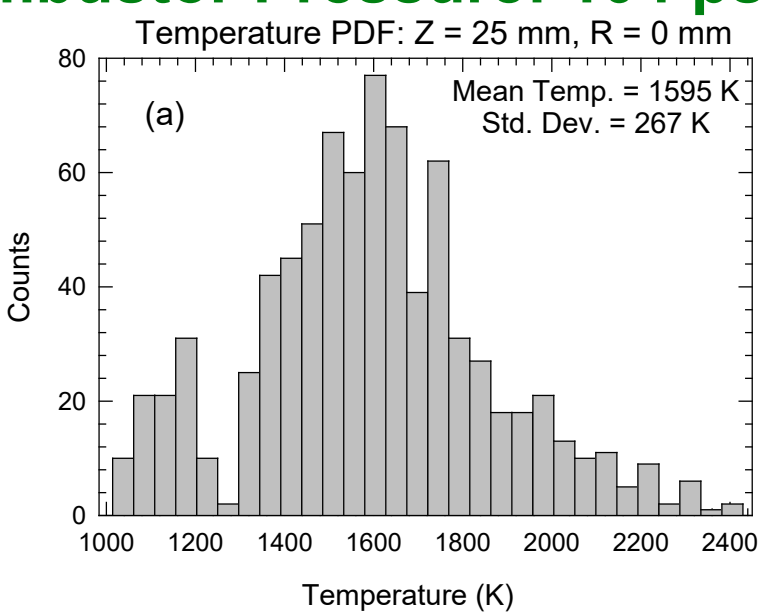


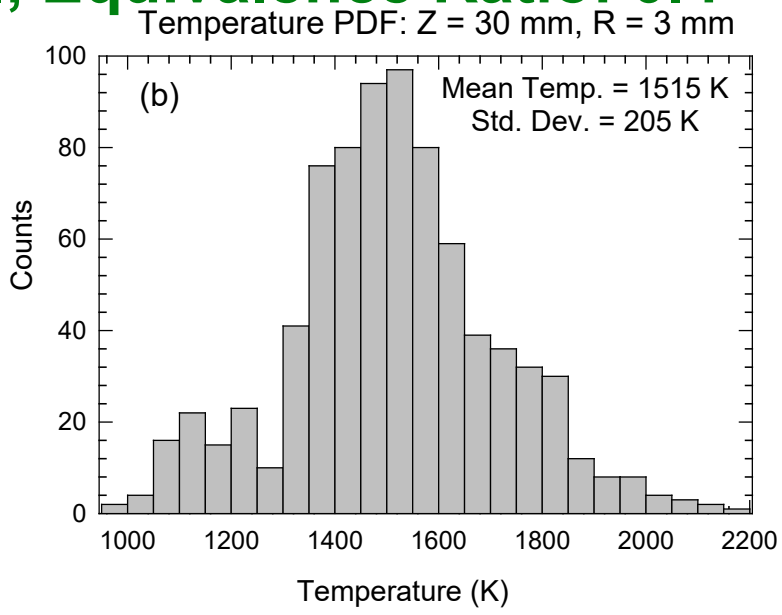
Mean Temperature Profiles

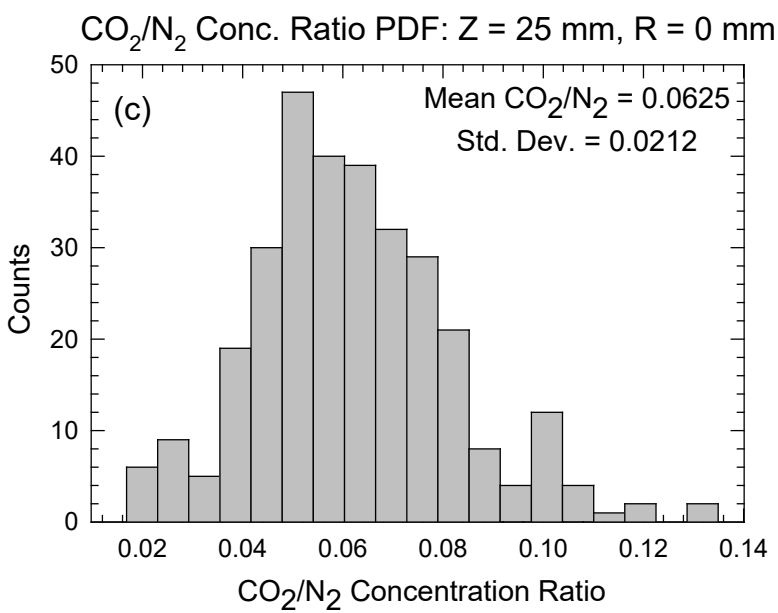


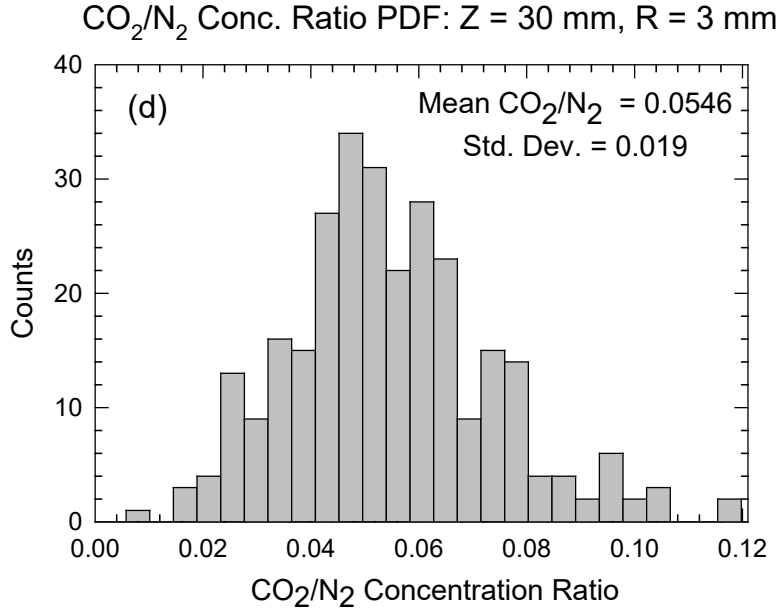
Temperature and CO_2/N_2 PDFs

Combustor Pressure: 104 psia., Equivalence Ratio: 0.4









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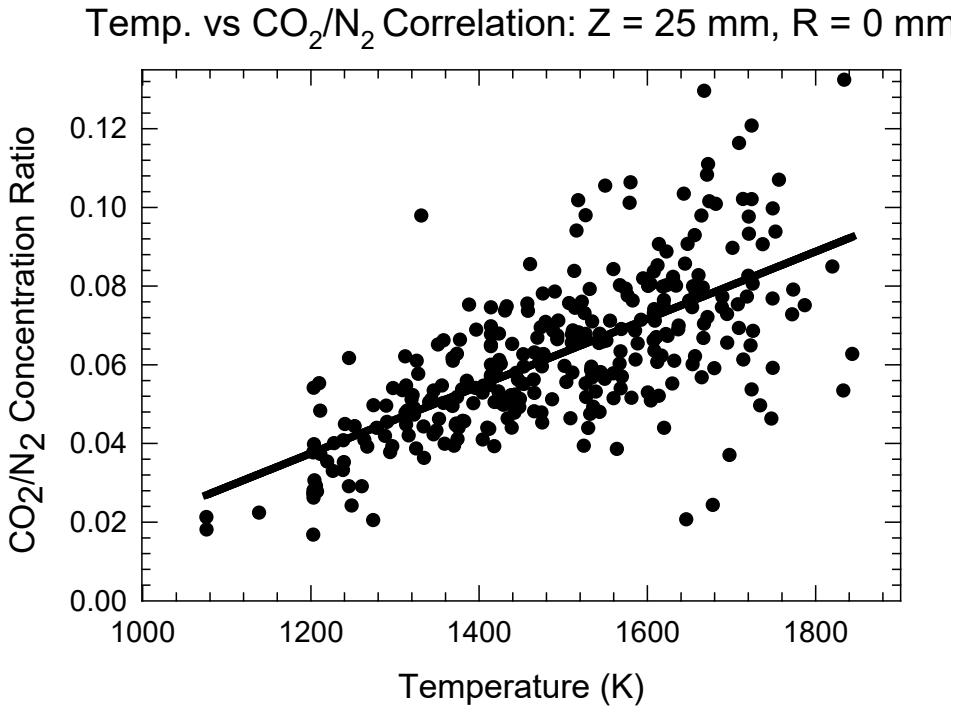
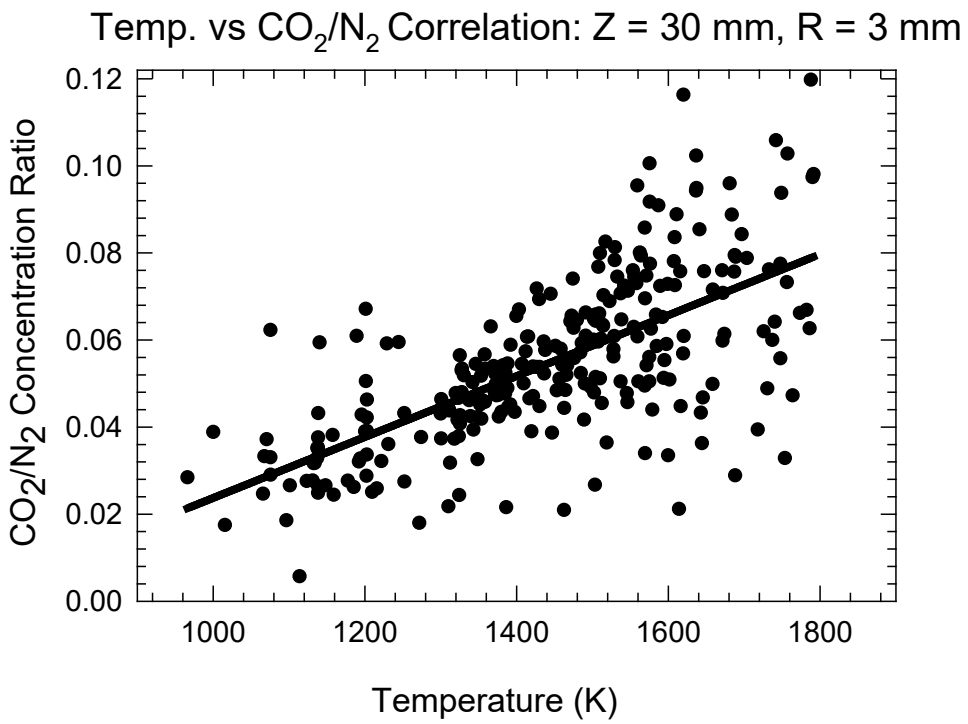
Temperature and CO_2/N_2 Scatter

Combustor Pressure: 104 psia., Equivalence Ratio: 0.4





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Accomplishments and Conclusions

- GTCF has been operated at wide range of simulated supersonic flight conditions. The optically accessible GTCF has been operated up at pressures up to150 psia, single-shot dual-pump CARS measurements obtained at all operating conditions.
- Approximately 500,000 single-shot spectra were acquired in a test campaign conducted during the summer of 2009. These spectra are being processed to obtain temperature and CO_2/N_2 concentration ratio values at various equivalence ratios at multiple axial and vertical positions downstream of the LDI injector.

Accomplishments and Conclusions

- A new OPO/PDA system was used to generate the 560-nm pump beam in the dual-pump CARS system. Considerable care in allignment was required for all beams to obtain good beam quality in the combustor test cell.
- The Zaber translation stages performed well, alignment was maintained over the entire spatial region of interest during the test.
- The reference leg was invaluable for alignment and for frequent recording of the nonresonant signal. Alignment was maintained before and after translation of the large 2-inch prisms.

Accomplishments and Conclusions

- Data analysis is still in progress. Filtering techniques to remove spectra with signals that were too low have been developed and are still being optimized. .
- Experimental results will be compared with computational results obtained from, for example, the National Combustion Code (NCC). The data will be provided in a form decided in collaboration with NASA personnel.

Accomplishments and Conclusions

- Estimated uncertainty in temperature measurements :
  - Accuracy: 1-2%
  - Precision: 2-3%
- Uncertainty in CO_2/N_2 ratio measurements :
  - Very dependent on CO2 concentration and on the temperature, approximately 10% relative standard deviation in the range of 5% CO2 concentation around 1500 K.
- Probe volume dimensions:
  - 500 μm along the laser propagation direction.
  - 50 μm perpendicular to the laser direction.

Papers and Presentations

1. Mathew P. Thariyan, Aizaz H. Bhuiyan, Sameer V. Naik, Jay P. Gore, and Robert P. Lucht, "Temperature and CO2 Concentration Measurements in a High-Pressure, Lean Direct Injector Combustor using Dual-Pump CARS," paper submitted to the 33rd Combustion Symposium.

2. Mathew P. Thariyan, Aizaz H. Bhuiyan, Scott E. Meyer, Sameer V. Naik, Jay P. Gore, and Robert P. Lucht, "Optically Accessible, High-Pressure Gas Turbine Combustion Facility and Dual-Pump CARS System," paper in preparation for submission to Measurement Science and Technology.

Papers and Presentations

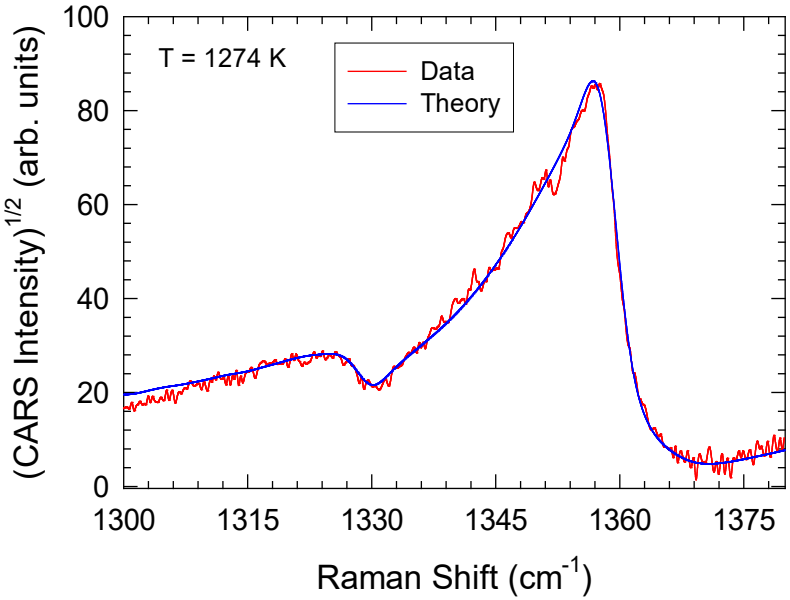
3. M. P. Thariyan, V. Ananthanarayanan, A. H. Bhuiyan, S. E. Meyer, S. V. Naik, J. P. Gore and R. P. Lucht, "Dual-Pump CARS Temperature and Major Species Concentration Measurements in Laminar Counterflow Flames and in a Gas Turbine Combustor Facility," Paper AIAA-2009-1442, presented at the 47th Aerospace Sciences Meeting, Orlando, Florida, January 5-8, 2009.

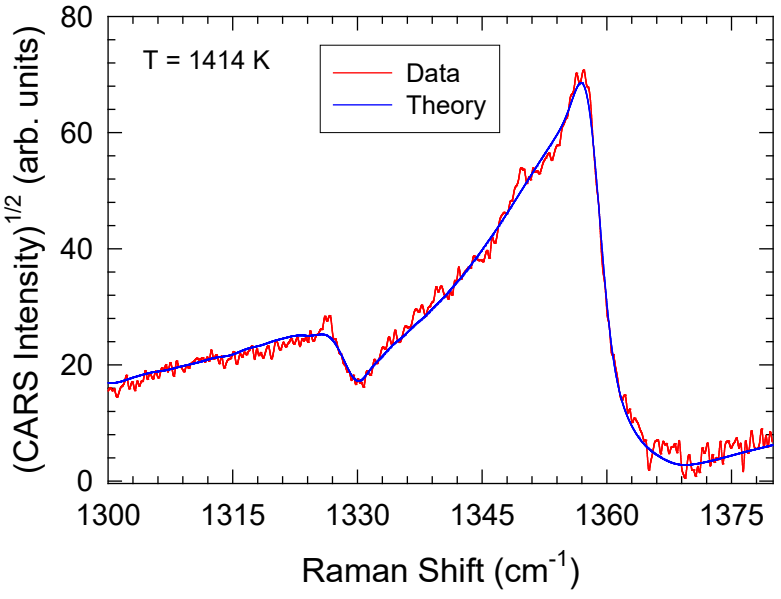
4. M. P. Thariyan, A. H. Bhuiyan, N. Chai., S. V. Naik, R. P. Lucht, and J. P. Gore, "Dual-Pump CARS Temperature and Major Species Concentration Measurements in a Gas Turbine Combustor Facility," Paper AIAA 2009-5052, 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Denver, Colorado, 2-5 August 2009.

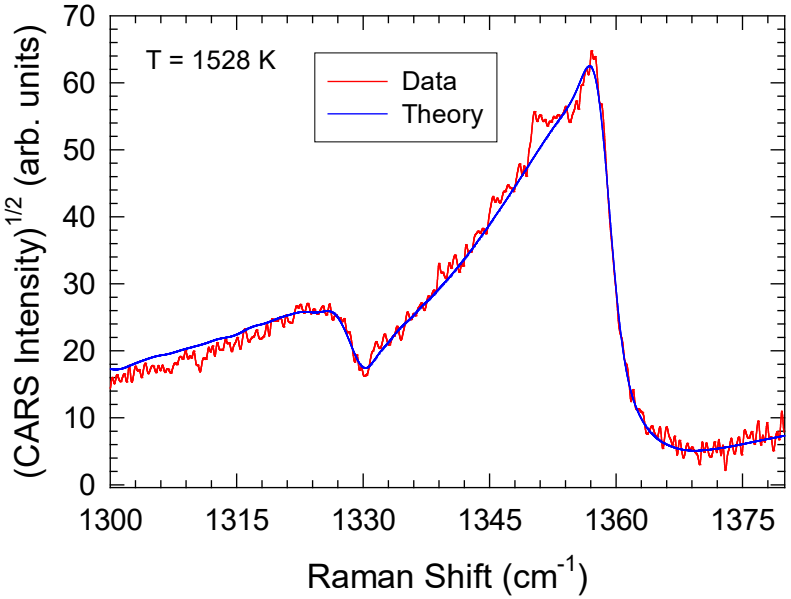
5. M. P. Thariyan, A. H. Bhuiyan, N. Chai, S. V. Naik, R. P. Lucht, and J. P. Gore, "Dual-Pump CARS Measurements in a Gas Turbine Combustor Facility Using the NASA 9-point LDI Injector," Paper AIAA-2010-1401, presented at the 48th Aerospace Sciences Meeting, Orlando, Florida, January 4-7, 2010.

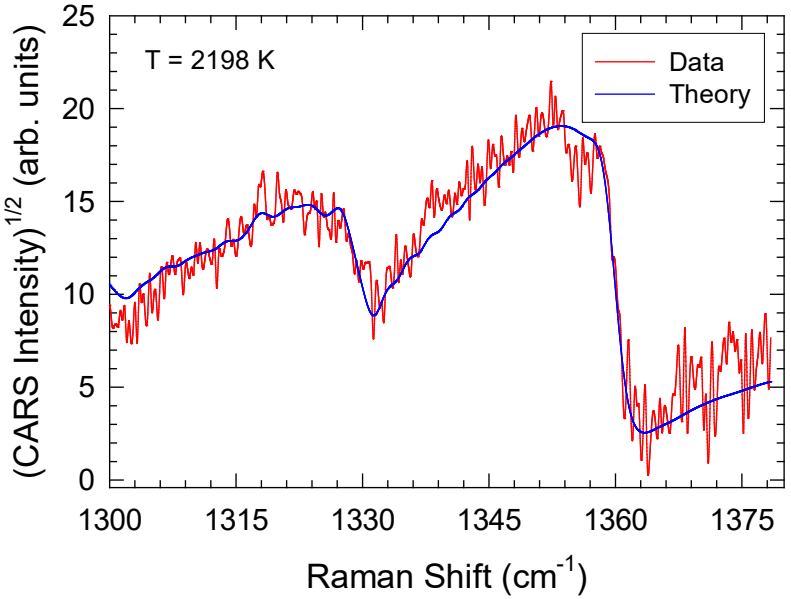
Typical Dual-Pump CARS spectra

Pressure: 100 psia. @ Φ = 1.0, 40 mm Center-line









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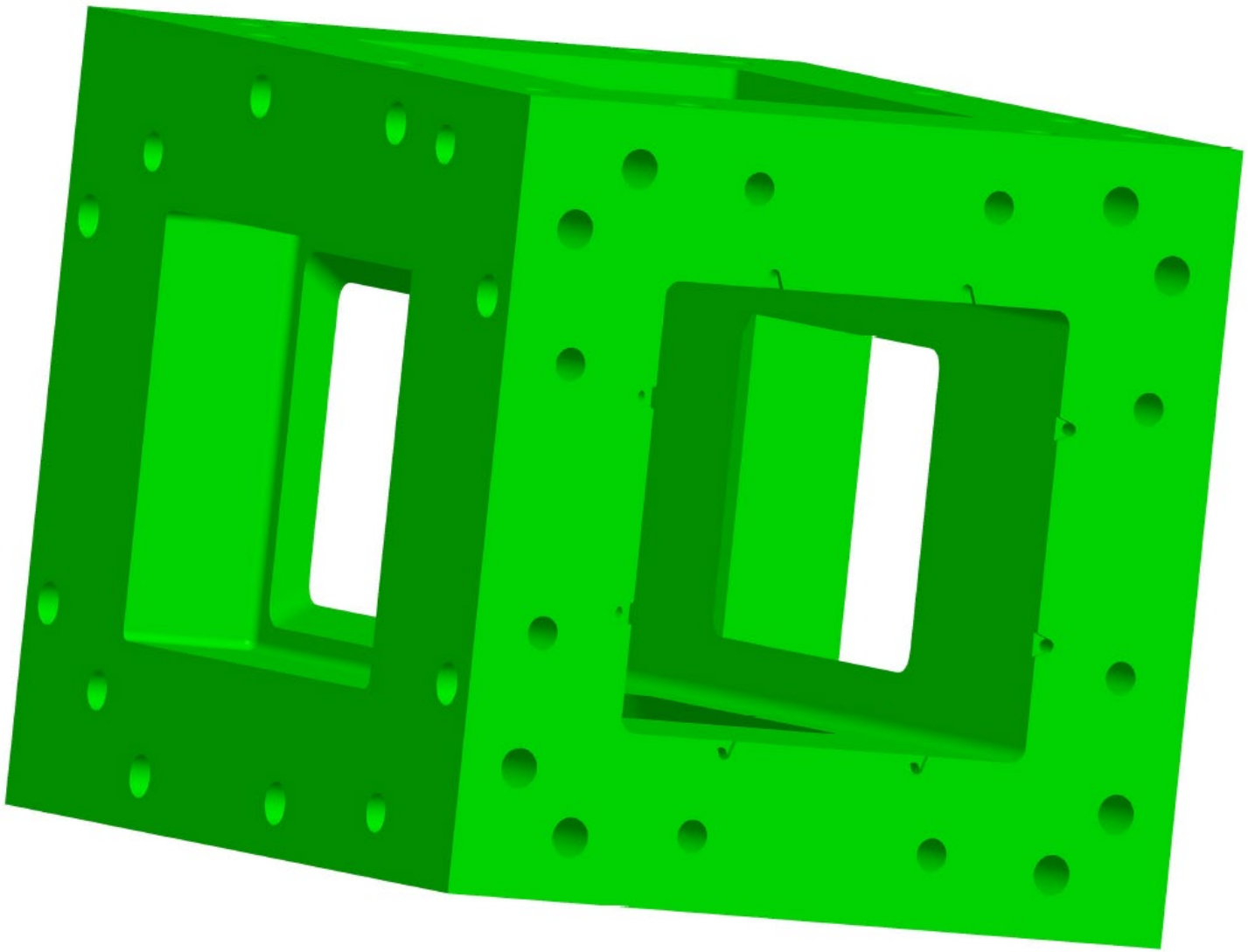
Modified Combustor Window Assembly (CWA) for RRC Injector

- Cross section increased from 3"x3“ to 4.2"x4.2". The modified CWA is fabricated from Hastelloy-X instead of stainless steel. Brazing has been eliminated. Film cooling air passages are incorporated in the injector assembly rather than in the CWA. Thermal barrier coatings are being applied to the window assembly inner surfaces.

- Upstream spool section has been redesigned to accommodate the larger injectors and to ensure uniform flow into the injector.

- Downstream spool sections redesigned for larger flow cross section.

Modified Combustor Window Assembly (CWA) for RRC Injector



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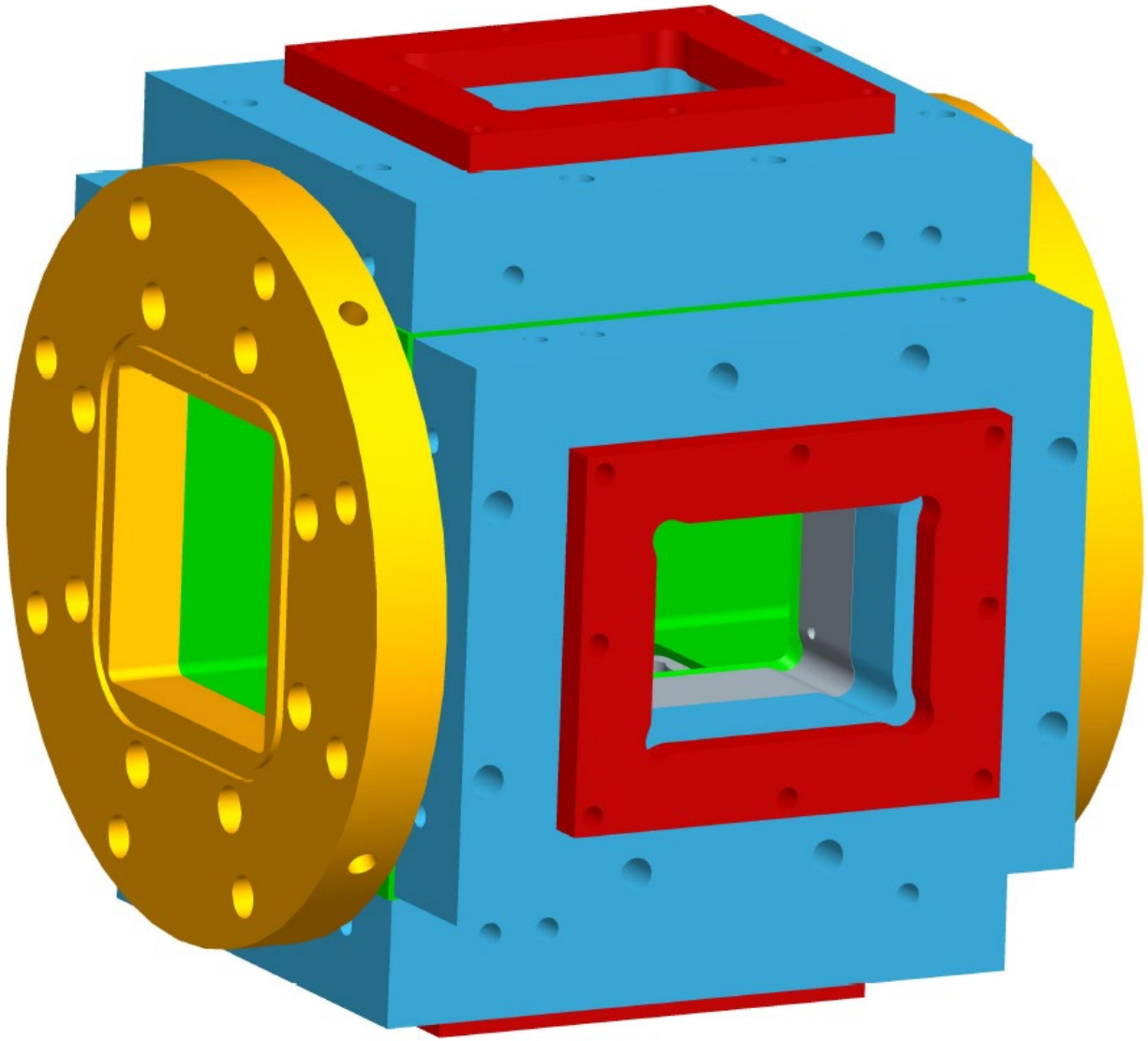
Modified Combustor Window Assembly (CWA) for RRC Injector



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