National Aeronautics and Space Administration

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SPACE LAUNCH SYSTEM

Date: 1/4/2016

Base Heating Test:
Tunable Diode Laser Absorption Spectroscopy

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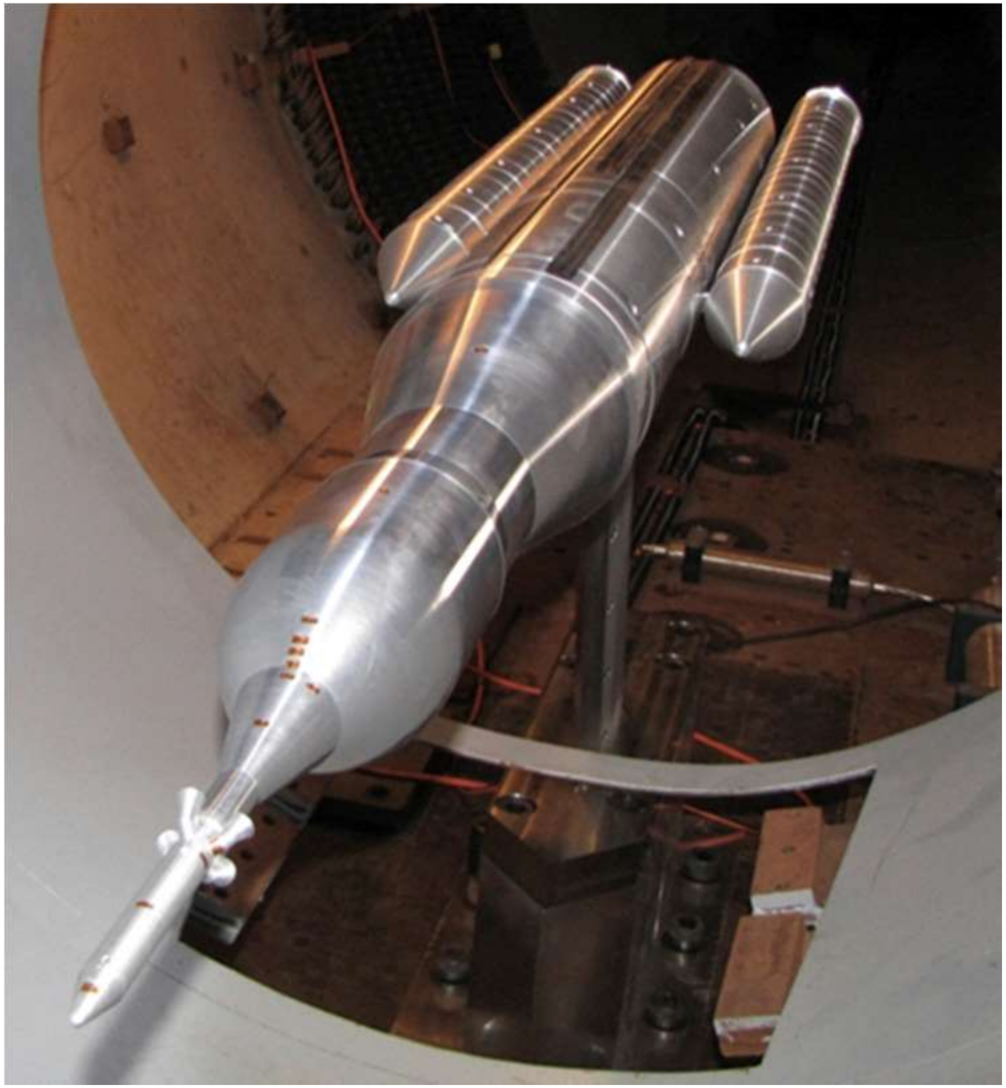
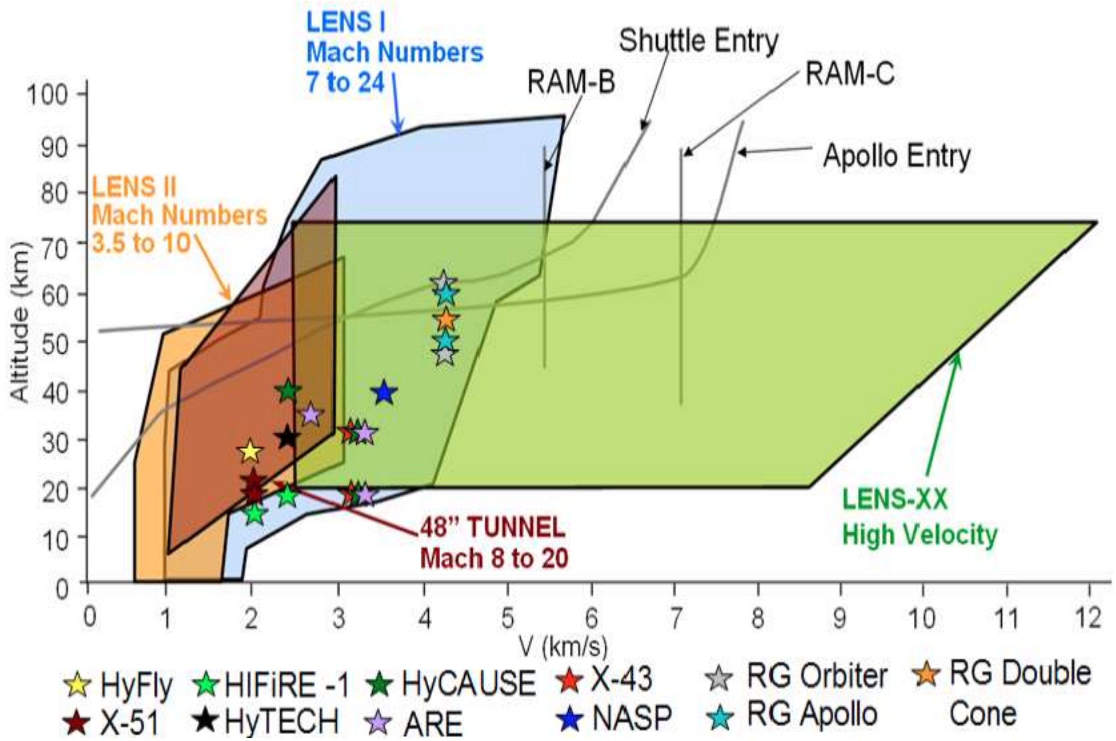
NASA Marshall Space Flight Center

- **Outline**



▪ **LENS FACILITIES**



NASA Space Launch System (SLS)

CUBRC
Advantage through technology

- **Designed to take NASA beyond low-earth-orbit for the first time in over forty years**

- **Geometry and rocket motors are significantly different than previously-flown systems**
  - four RS-25D LOX/LH_2 rocket engines in the core stage
  - two 5-segment solid rocket motors in the booster stage

- **Characterization of the base heating environment to reduce design risk is an important concern**

Objective, Motivation, and Approach

Objective

- Design measurement of gas temperature in the base region of a sub-scale hot-fire model rocket
- A technique that is non-intrusive with relatively low uncertainties is desirable

Motivation

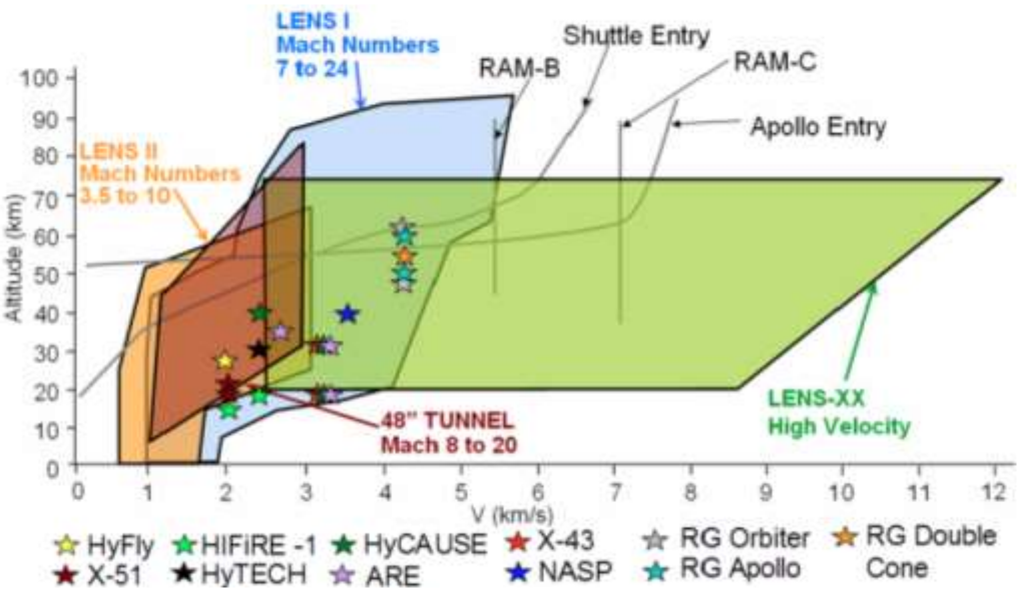
- Base-region heating is of critical design importance for rocket-propelled launch vehicles
- Gas temperature can be used to infer full-scale base heat transfer from sub-scale measurements
- Legacy launch vehicle design programs reported large uncertainties in sub-scale base gas temperature measurement

Approach

- Explore tunable diode laser absorption spectroscopy (TDLAS) to achieve objectives using H_2O as a tracer species
- Verify TDLAS sensitivity at predicted conditions of temperature, pressure and H_2O concentration
- Implement measurement during testing of SLS vehicle in CUBRC's LENS II facility

CUBRC's LENS II Facility

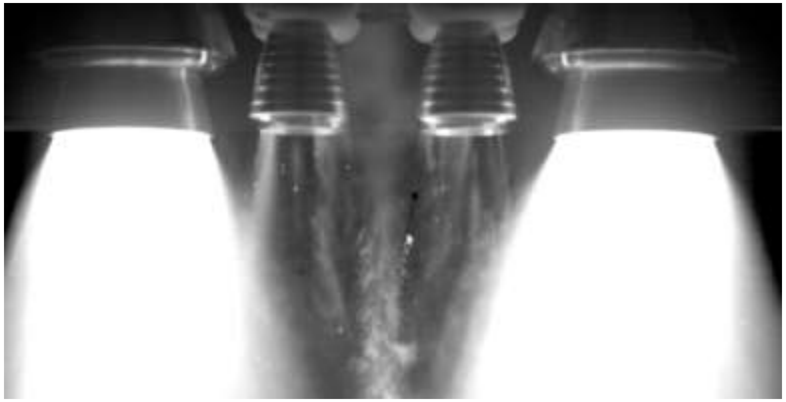
- Can be operated as reflected shock tunnel or Ludwieg tube
- Test section: 8 ft diameter, 30 ft long
- Mach range: $2.7 \leq M_\infty \leq 9.25$
- Pressure altitudes of sea-level ≤ H ≤ 200kft



2%-Scale SLS Base Heating Model

- A 2%-scale hot-fire model of SLS designed for testing in LENS II facility
- Ground experiments at near flight-scale chamber pressures with flight-like propellant
- Duplicated flight conditions preserve the plume expansion and interaction region which has a first-order effect on base heating levels
- Program primarily consists of heat transfer measurement with fast-response thin-film heat transfer gauges or thermocouples

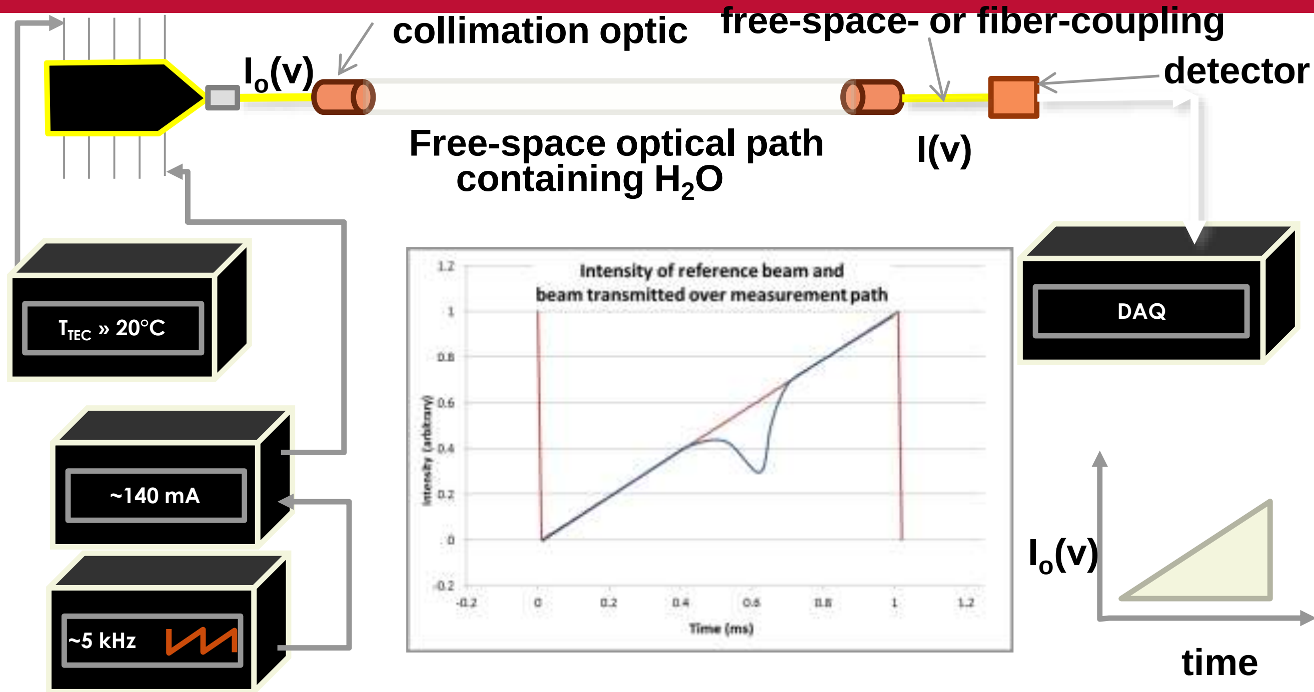
2%-scale SLS model installed in LENS II



Tunable Diode Laser Absorption Spectroscopy (TDLAS)

TDLAS

- Laser diode emission is modulated by increasing current across diode.
- Laser wavelength increases with increasing current.
- Very high resolution scan (<0.1 nm) of a molecular absorption feature.
- The magnitude and shape of two features can be used in conjunction with HITRAN to extract properties of the gas



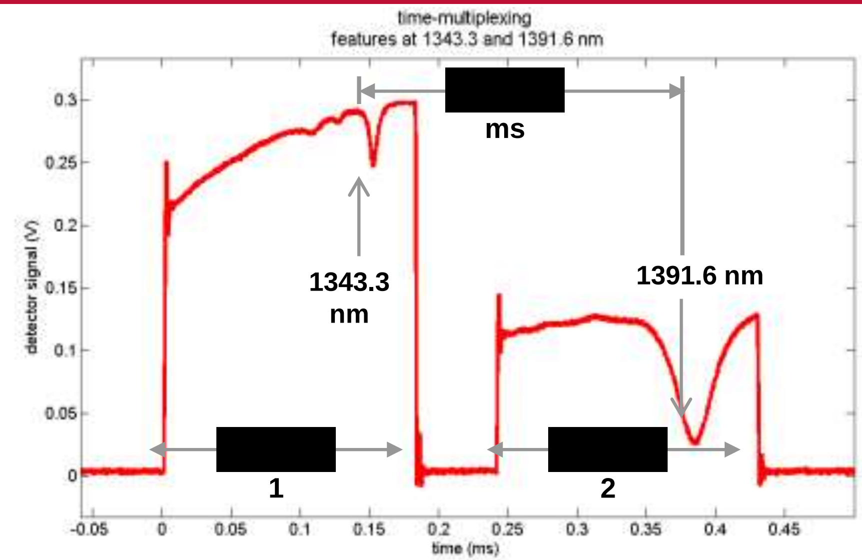
TDLAS will be used to measure the path averaged temperature and concentration in the base heating region of the SLS model during duplicated flight conditions in LENS II.

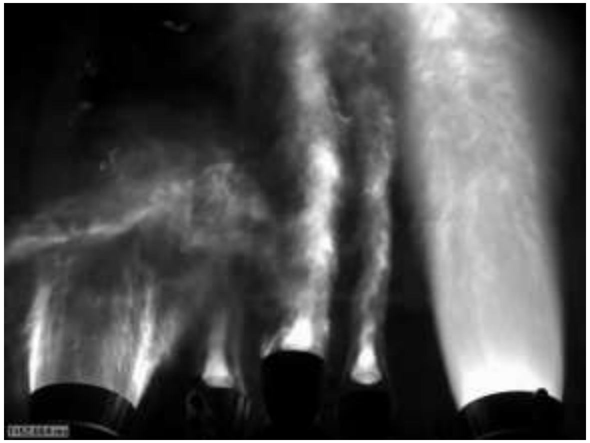
Preliminary testing was performed to characterize the aero-optic environment, verify the operation of the laser, and characterize signals for CFD-predicted conditions.

$$R = \frac{S_{12}(T_o, \nu_o^1)}{S_{12}(T_o, \nu_o^2)} \exp\left(-\frac{hc}{K}(E''_1 - E''_2)\left(\frac{1}{T} - \frac{1}{T_o}\right)\right)$$

Initial Testing: Pathfinder Program

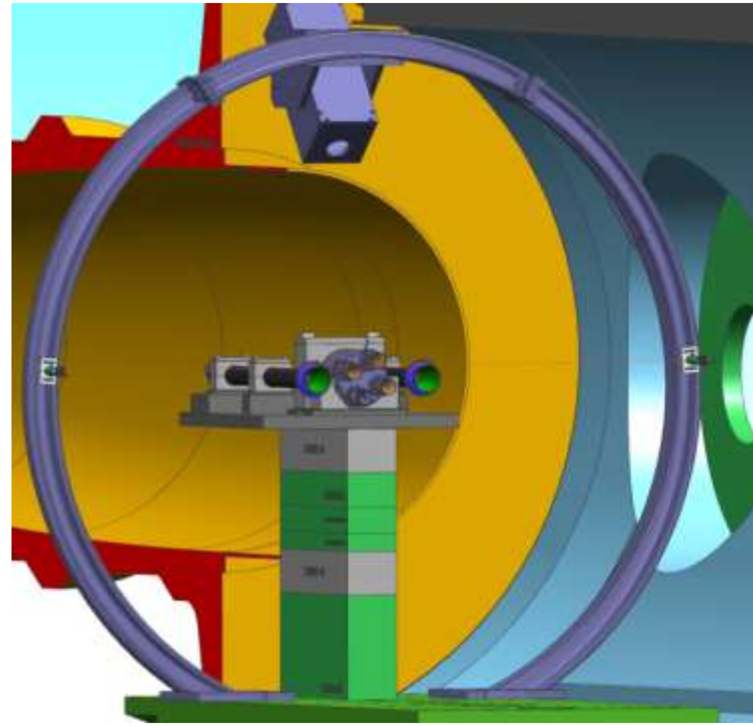
- **TDLAS with pre-packaged Zolo TRACK system – designed for measurements in scramjet flowpaths**
- **Time multiplexed using two lasers tuned to absorption features at 1343.3nm and 1391.6 nm**

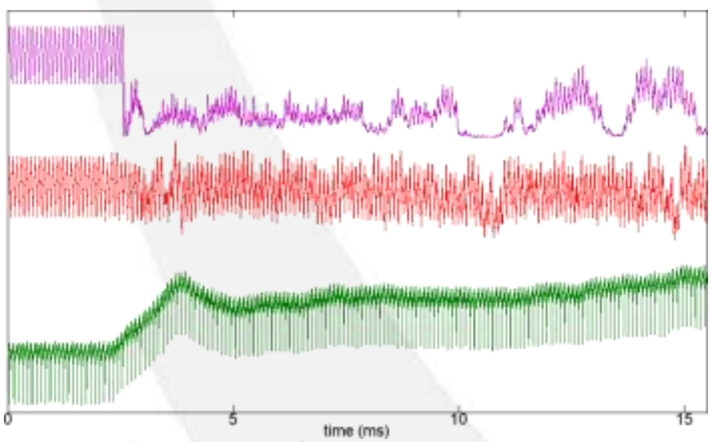




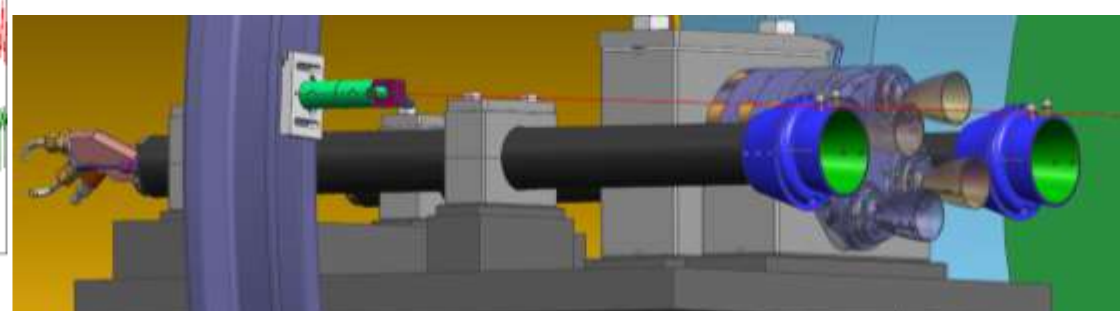
Initial Testing: Pathfinder Program

- Aero-optic effects encountered, particularly for measurements made at atmosphere
- Initial pathfinder testing indicated that a fiber-based system not viable





- Completely fiber-based
- 1mm detector (in-situ)
- 5mm detector (in-situ)

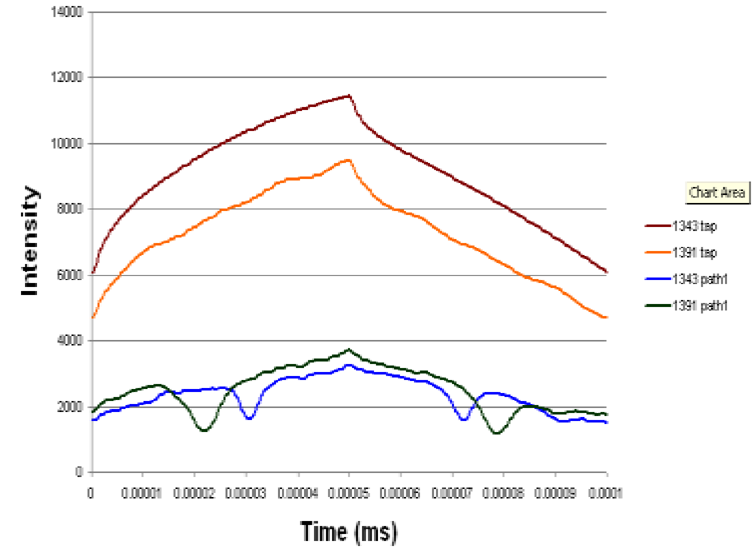


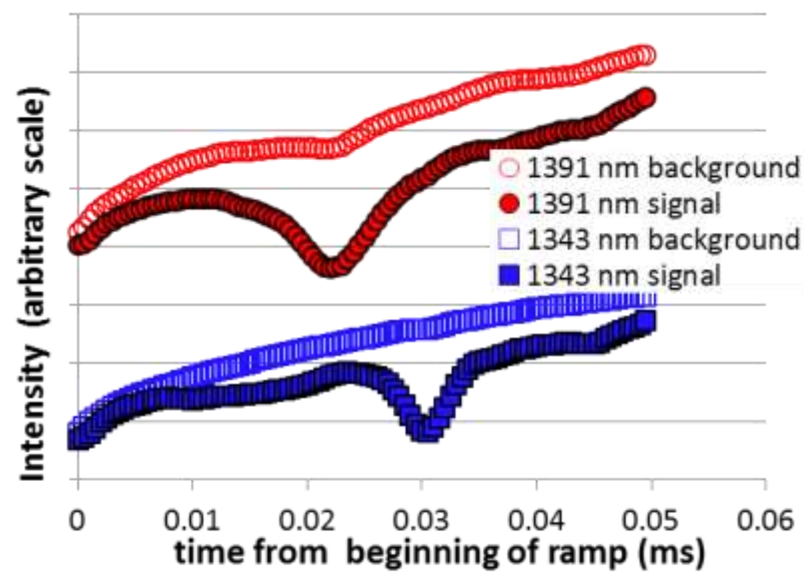
Initial Testing: Pathfinder Program

CUBRC
Advantage through technology

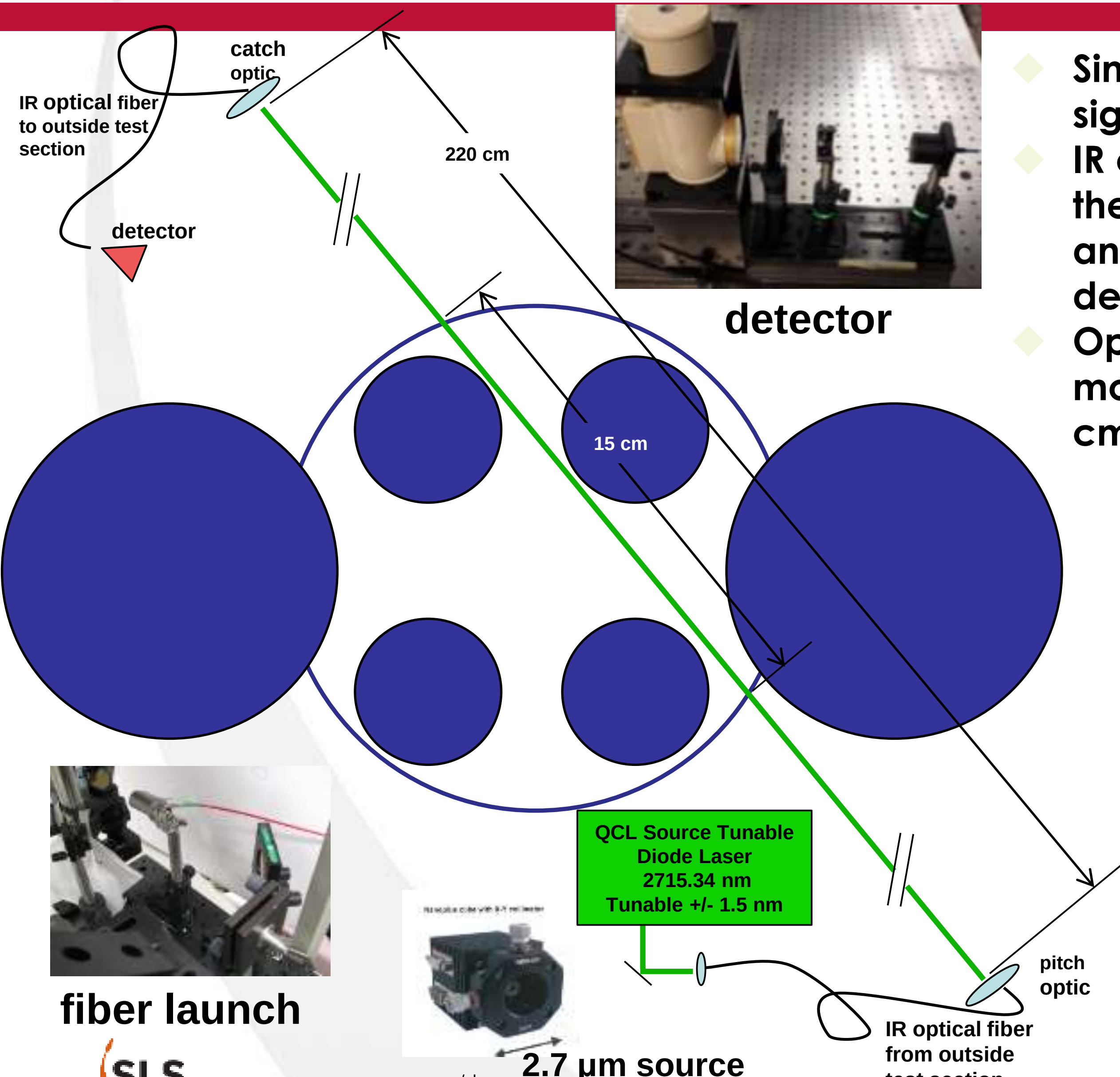
- Measurement made through SRM plume using a 5 mm detector inside the tunnel
- Aero-optic effects were insignificant compared to tests at atmosphere, fiber-based pitch-catch setup possible
- The absorbance-wavelength curve is integrated over each absorption feature
- The value from the integration of pre-run data is subtracted
- The ratio is formed

ratio = 0.89



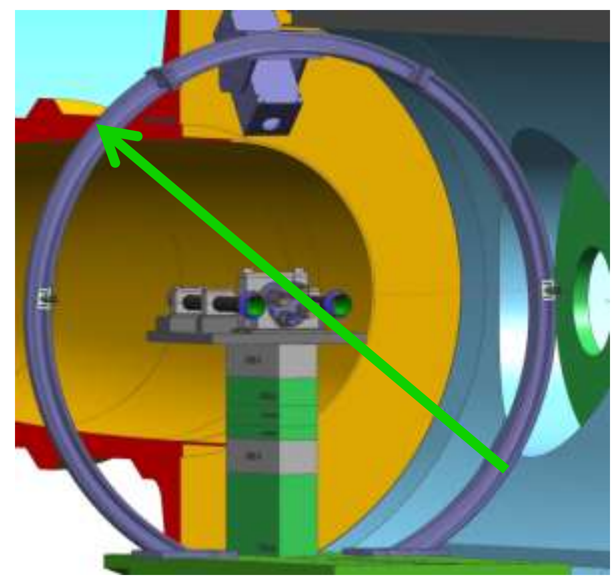


Redesign of TDLAS System



detector

- Single TDLAS path along line of sight shown
- IR optical fiber brings light into the test section from the source and out of the test section to a detector
- Optics inside test section mounted on large ring with 220 cm diameter

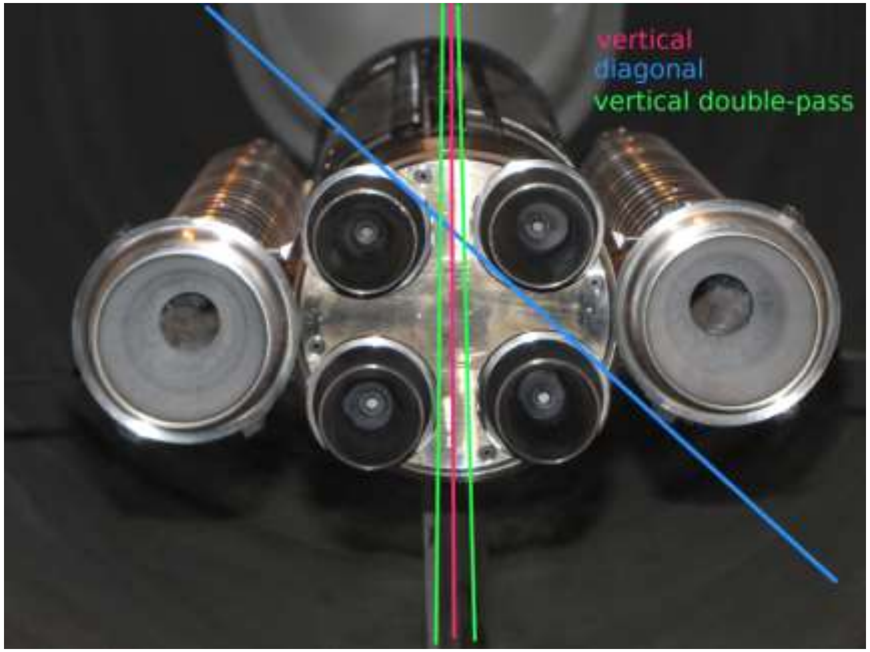


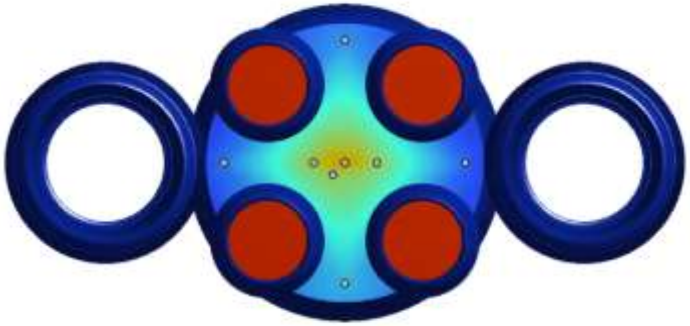
fiber launch

2.7 µm source

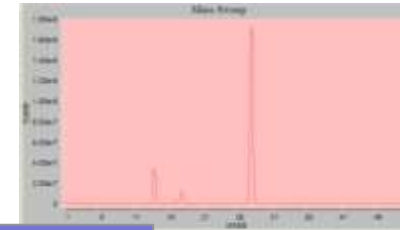
Redesign of TDLAS System

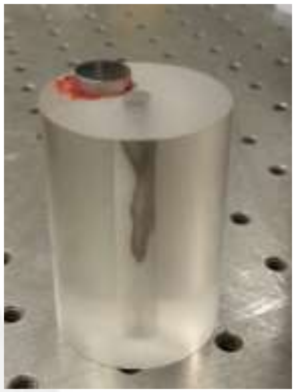
- Diagonal and vertical paths tested
- Typical distribution shows higher heat transfer near center of base region, falling off toward the periphery
- Diagonal path should result in lower temperatures because path does not traverse hottest part of base region

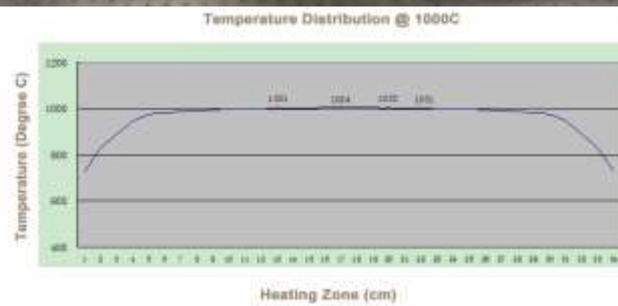


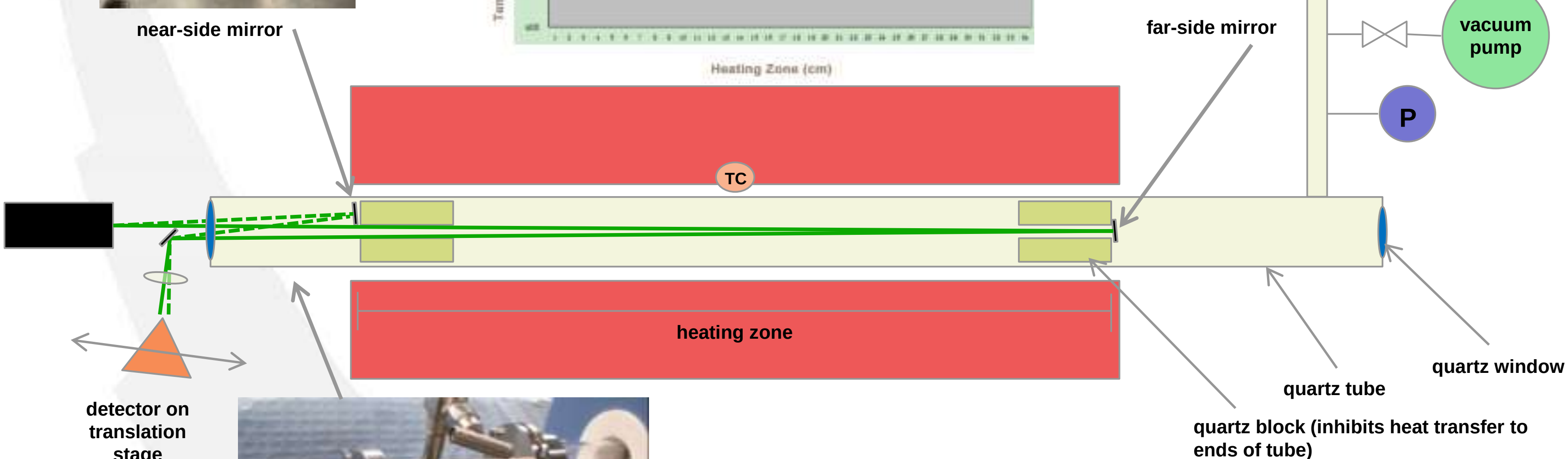


Vacuum Furnace Test Cell Setup

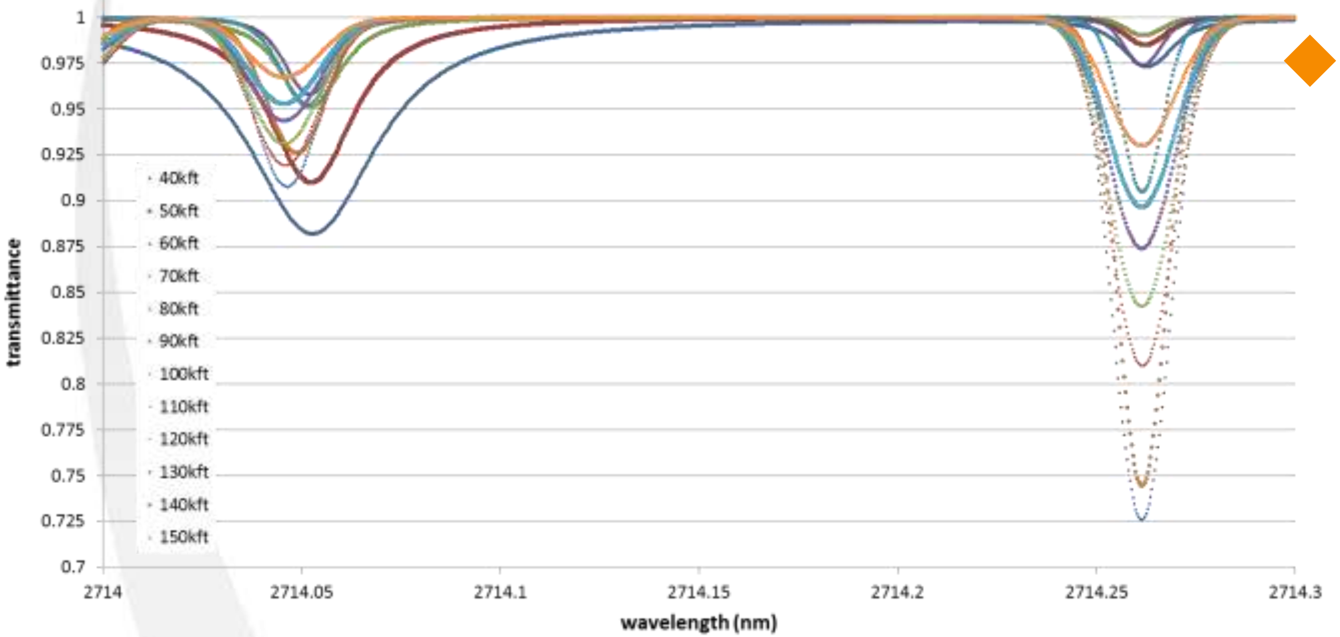






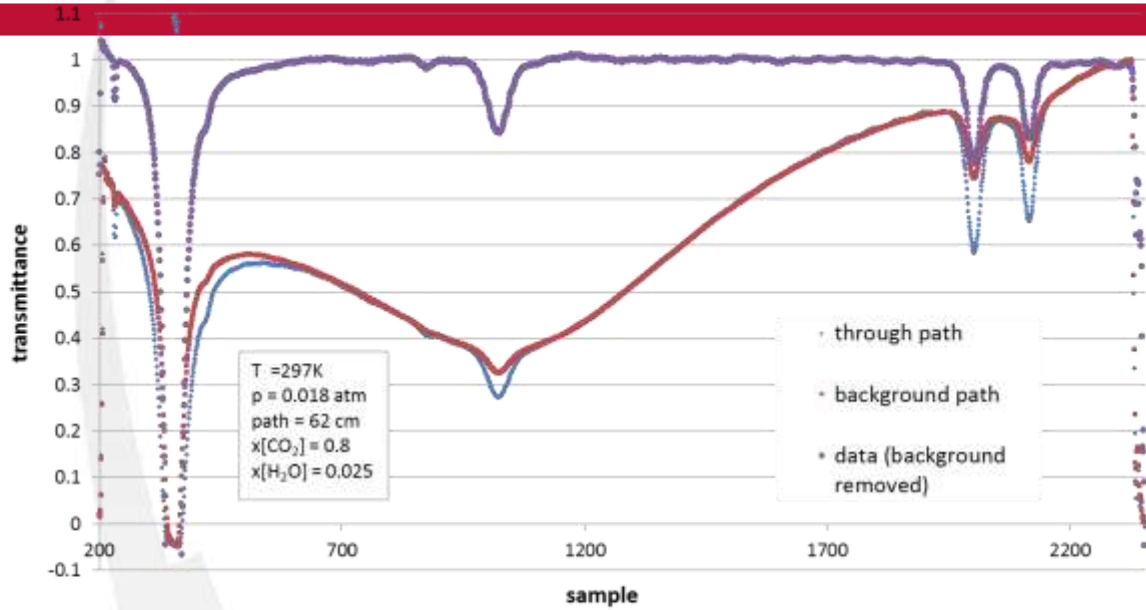


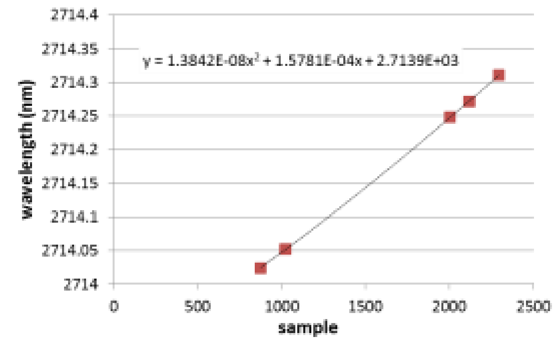
Absorption at CFD-Predicted Conditions

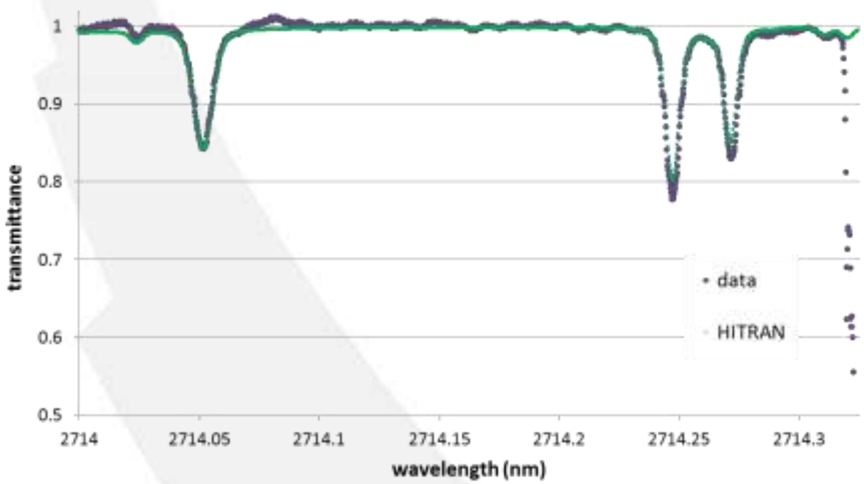


- Predicted conditions yield measureable absorption features at CFD-predicted conditions
- Absorption feature pair has good temperature sensitivity

Wavelength Calibration using CO_2



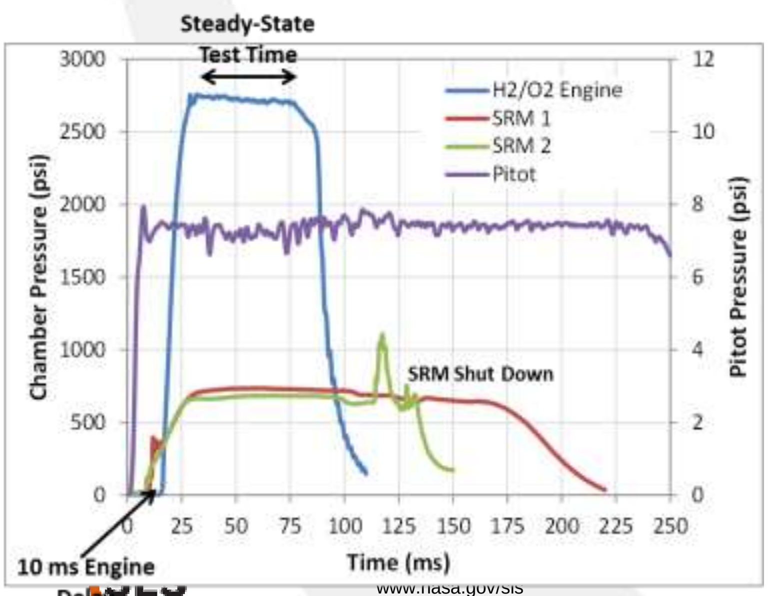




- Many CO_2 absorption features in the scan range of the laser give more points for wavelength calibration
- Operation of the laser is consistent from day-to-day

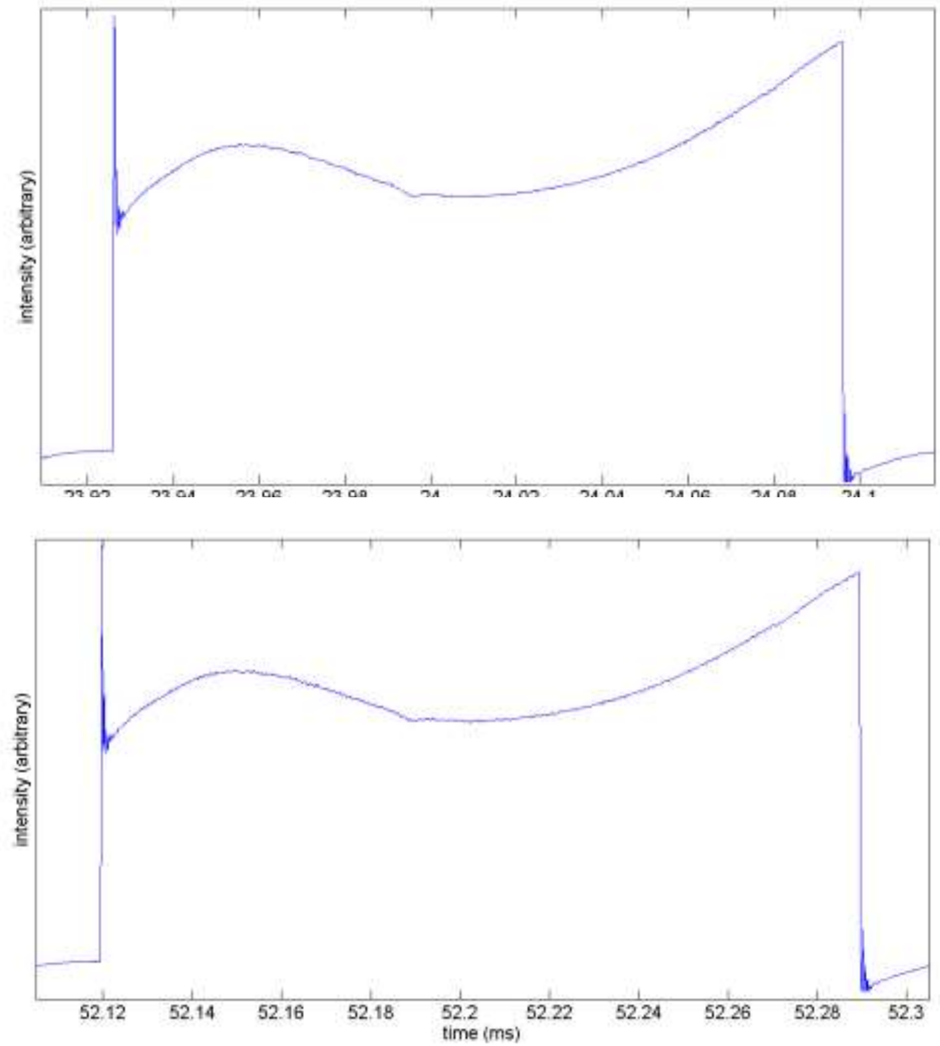
Base Heating Testing in LENS II

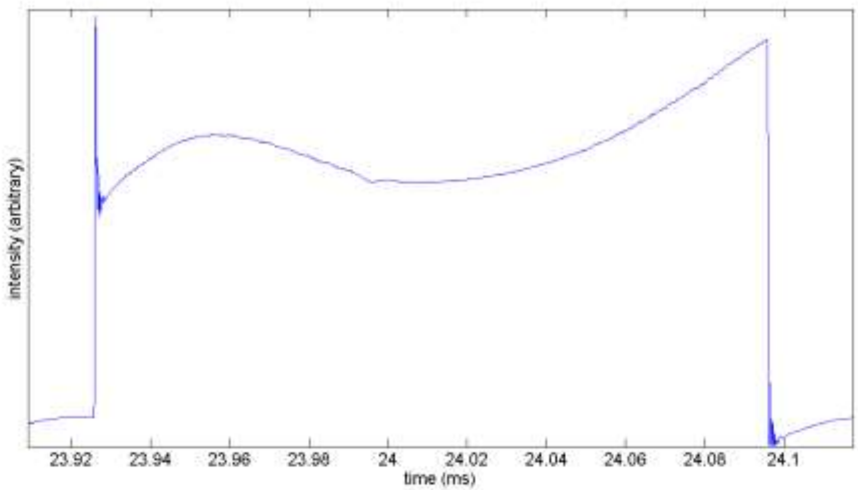
- Reusability of hardware made possible by short-duration testing
- SRMs and core stage start up just as flow becomes steady – ignition timed to maximize steady period
- Approximately 50 ms of steady test time
- Tunnel operates for between 20 and 300 ms depending on velocity
- TDLAS measurements made using 5 kHz wavelength modulation, sampling at 100 MHz for 180 ms
- All TDLAS measurements for M = 0 condition

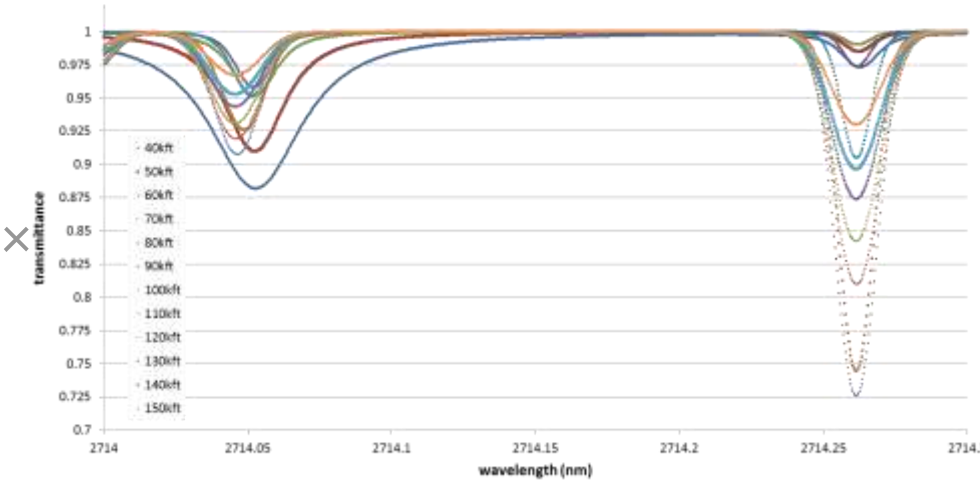


Results: Background Characterization

- For the Run 12 condition the part of the path that is not in the base (measurement) region is characterized
- A changing background would need to be accounted for
- Little change outside the base region for this condition – should repeat this for each condition





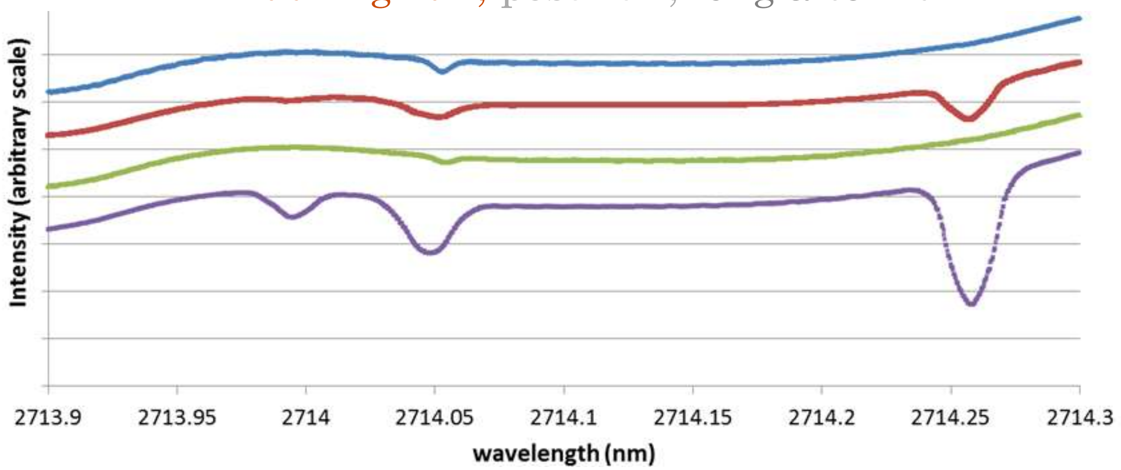


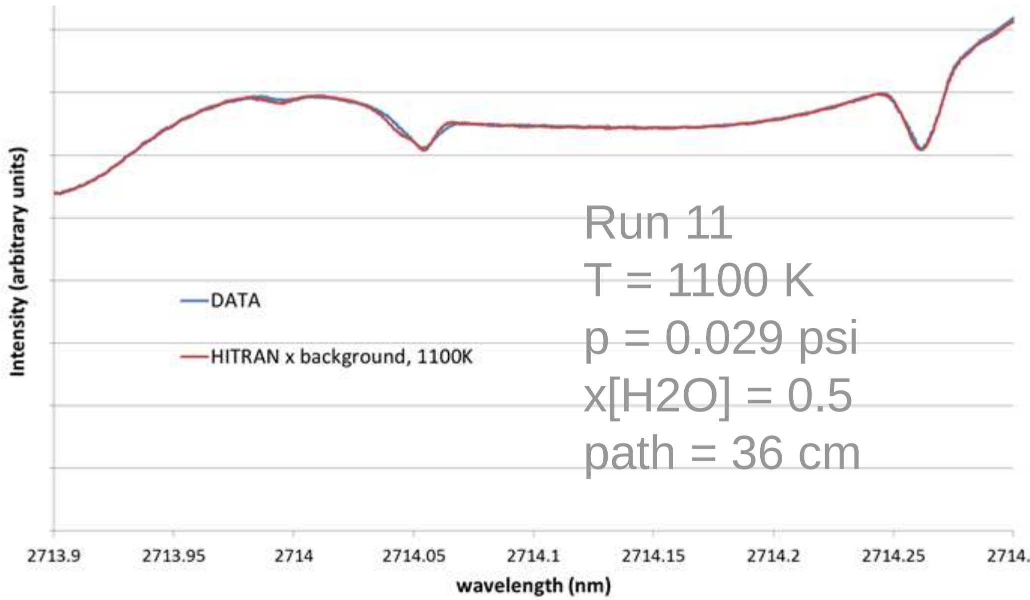
- Unchanging background is normalized an multiplied by spectra computed using HITRAN and line-by-line code
- The result is compared to the measurement
- Parameters (temperature, pressure, and concentration) are changed and the spectra is recomputed until a match is attained
- Simultaneous use of ratio technique and line shape analysis for all absorption features in laser scan range
- Temperature is determined, and pressure and concentration can be estimated although more information (e.g. a base pressure measurement) would allow better determination of those parameters

Results: Temperature Results

- ± 50 K uncertainty estimated
- Able to achieve very good match to background-multiplied HITRAN data
- some differences between the curves attributed to small changes in background

during run, post-run, long after run

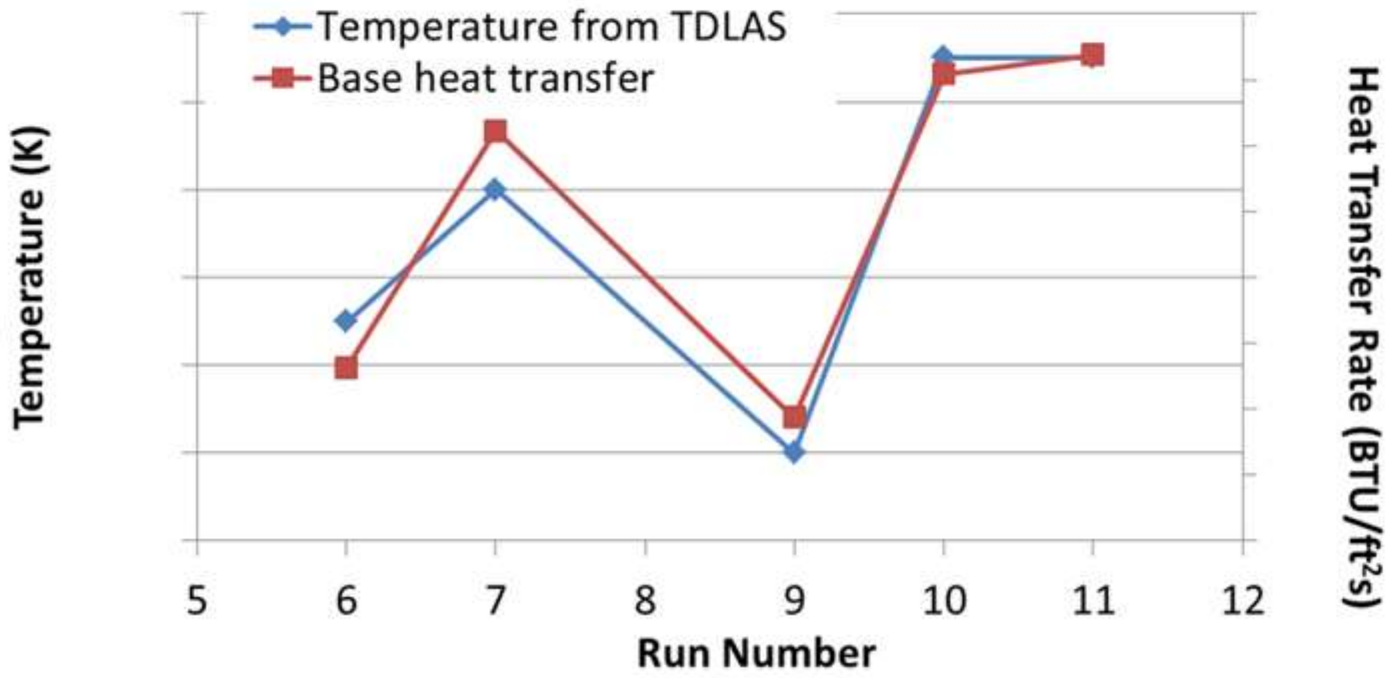




Run 11
T = 1100 K
p = 0.029 psi
x[H2O] = 0.5
path = 36 cm

Results: Comparison with Base Heat Transfer Measurements

- Base temperature is not the only factor in base heat transfer but it is the most significant
- Heat transfer measurements are made using thin-film heat transfer gages



Conclusions and Future Work

CUBRC Advantage through technology

<u>Conclusions</u>

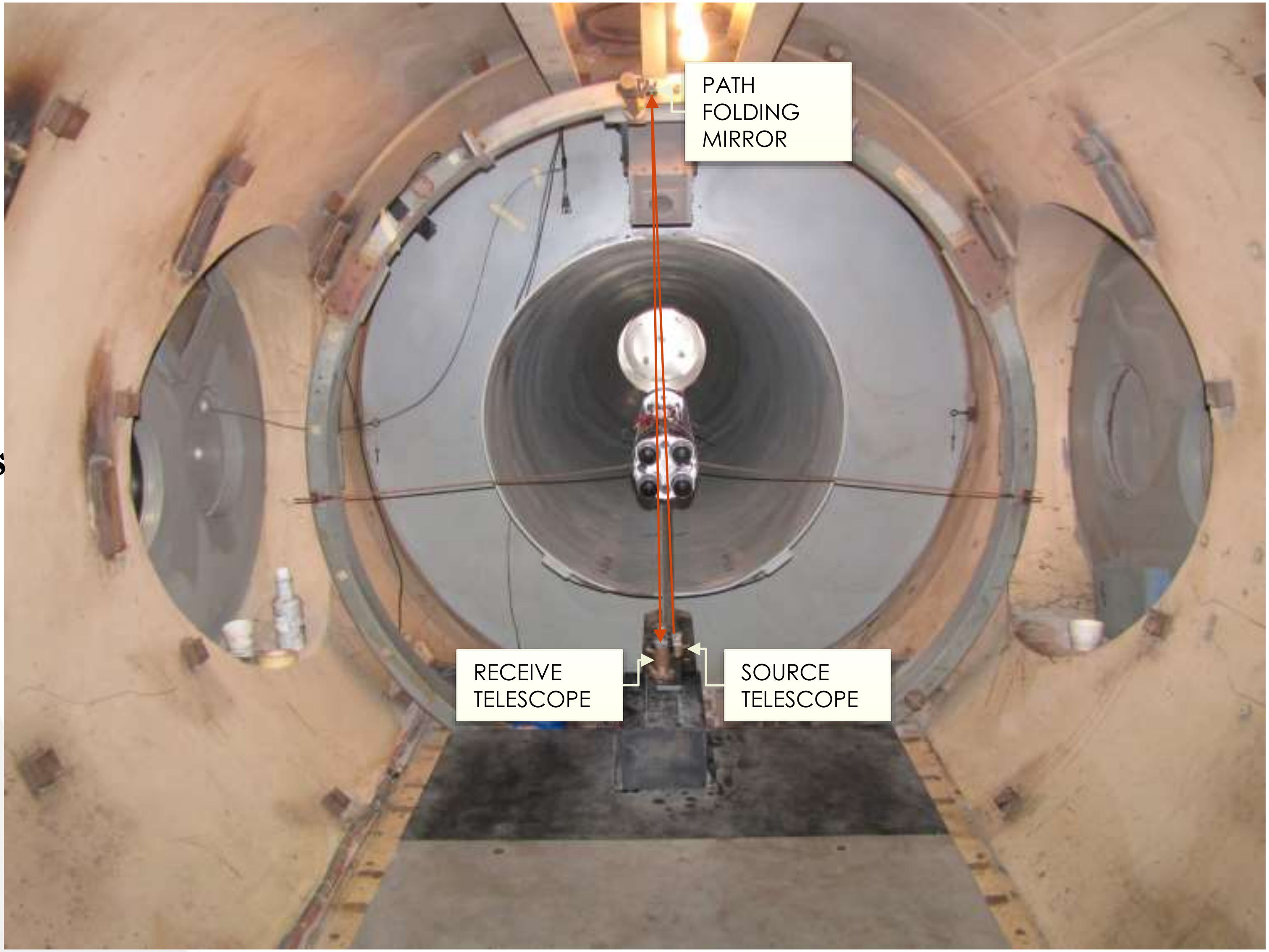
- A 2% scale hot-fire SLS model was tested in CUBRC's LENS II facility to characterize the base heating environment
- A TDLAS instrument was developed to measure path-integrated temperature
- Base gas temperatures from TDLAS agree qualitatively with the base heat transfer trends
- Measured temperatures from TDLAS are generally lower than CFD predictions

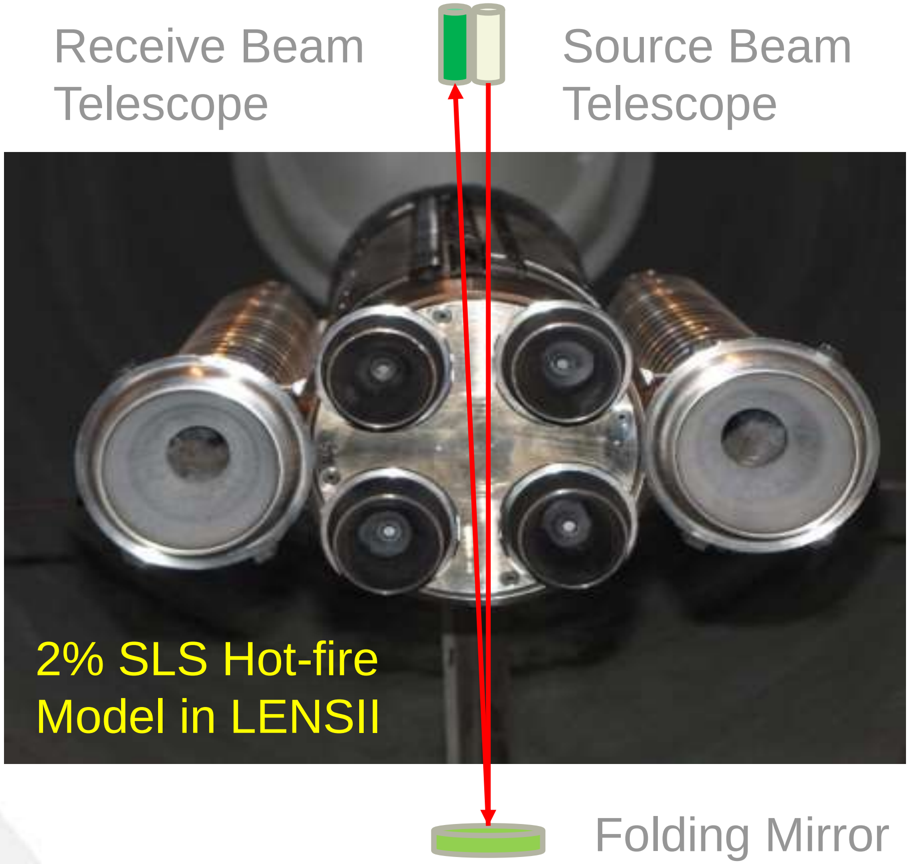
<u>Future Work</u>

- Better characterize portion of path outside base region
- Improvement of data analysis through automation and optimization
- Make measurements with flow
- Use pressure data to improve measurement
- Make quantitative comparison to other measurements

SLS - TDLAS OPTICAL BEAM

Optical path is folded to increase the absorption signal. The beam fluctuation during flow is only about 10%. Beam steering is minimal.




Receive Beam Telescope
Source Beam Telescope
2% SLS Hot-fire Model in LENSII
Folding Mirror