University at Buffalo
The State University of New York

Bow Shock Emission and Near-Surface Nitric Oxide Absorption Measurement Techniques for Gas/Surface Interaction Interrogation

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AFOSR Review Meeting
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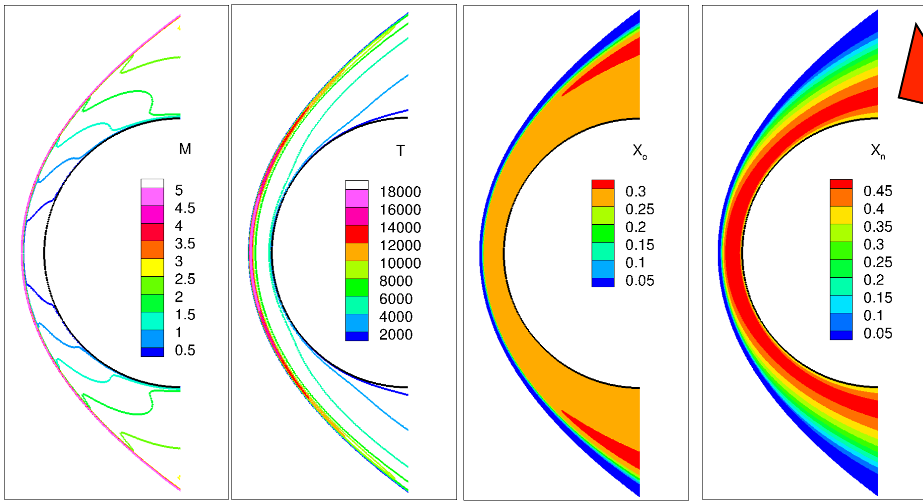
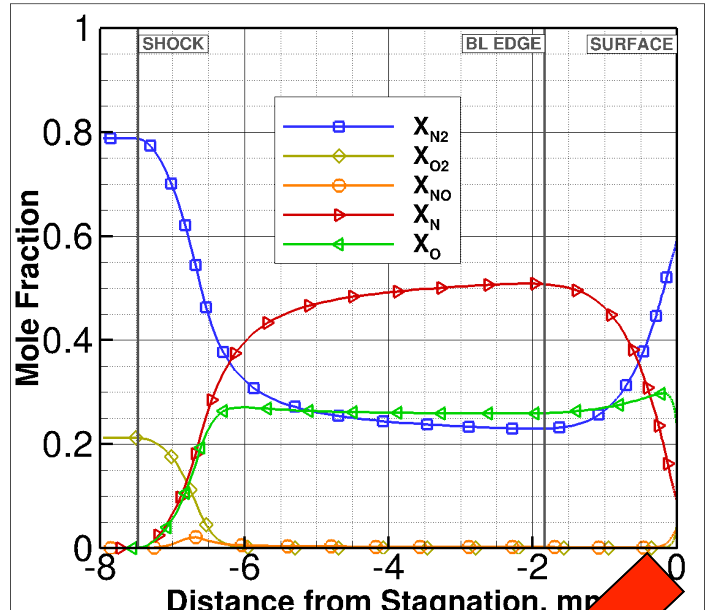
Outline

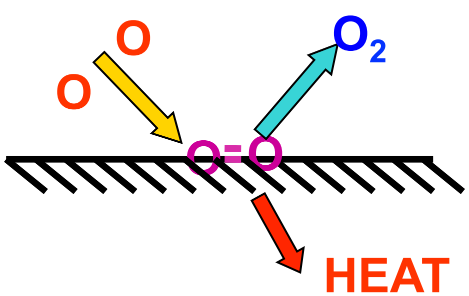
- Motivation
- CUBRC LENS-XX Facility
- Near-surface Tunable Diode Laser Absorption Spectroscopy (TDLAS)
  - Theory
  - Experimental Setup
  - Line-of-Sight Modeling
  - Results
- Bow shock Emission Spectroscopy
- Conclusions

Gas/Surface Interaction in High Enthalpy Environments

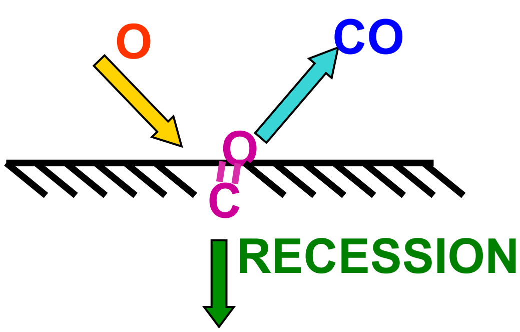


Very hot shock layer temperatures cause the gas to dissociate in a stagnation region.



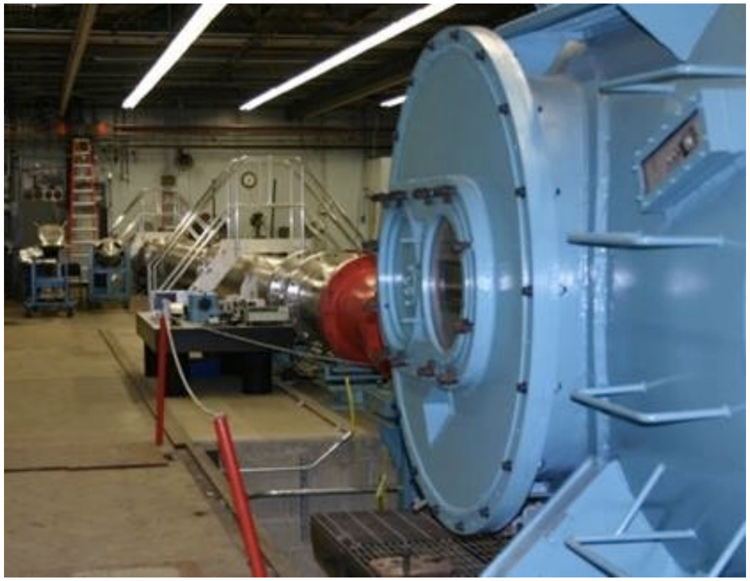


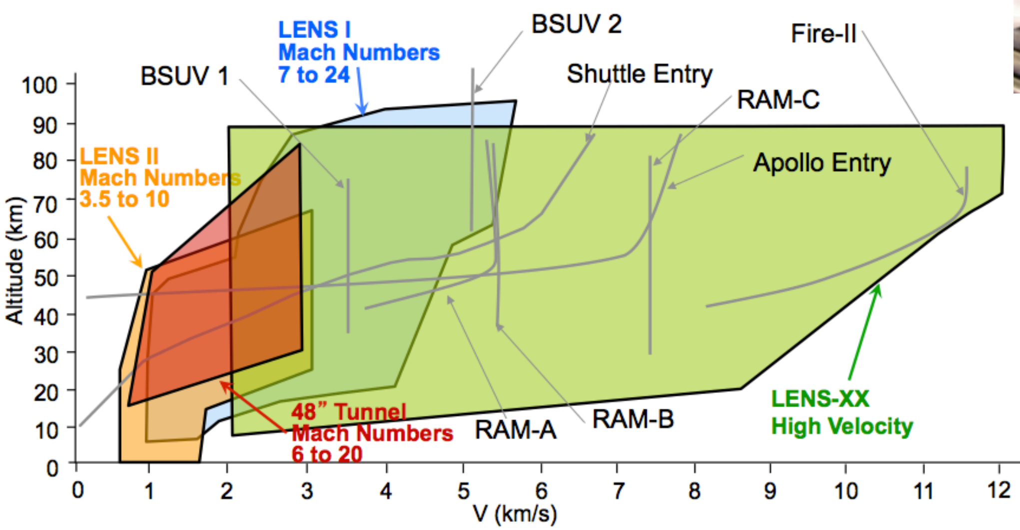
Energetic species existing in the shock layer can reach the surface and react, releasing heat and/or removing TPS.

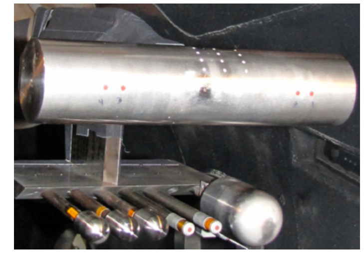


- In high enthalpy environments, it is very difficult to "measure" catalytic and ablative processes directly.
- Traditionally, must observe the "effect" by measuring the heat flux or post-test recession and inference.

LENS-XX Expansion Tunnel Facility



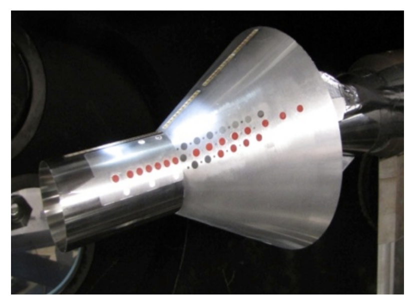




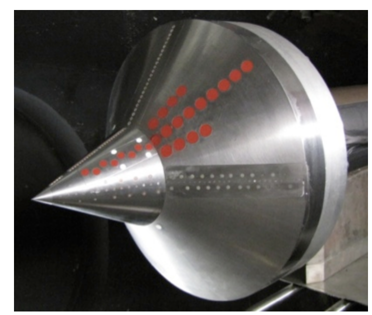
Basic shapes (hemisphere, cylinder)

Orion

MSL

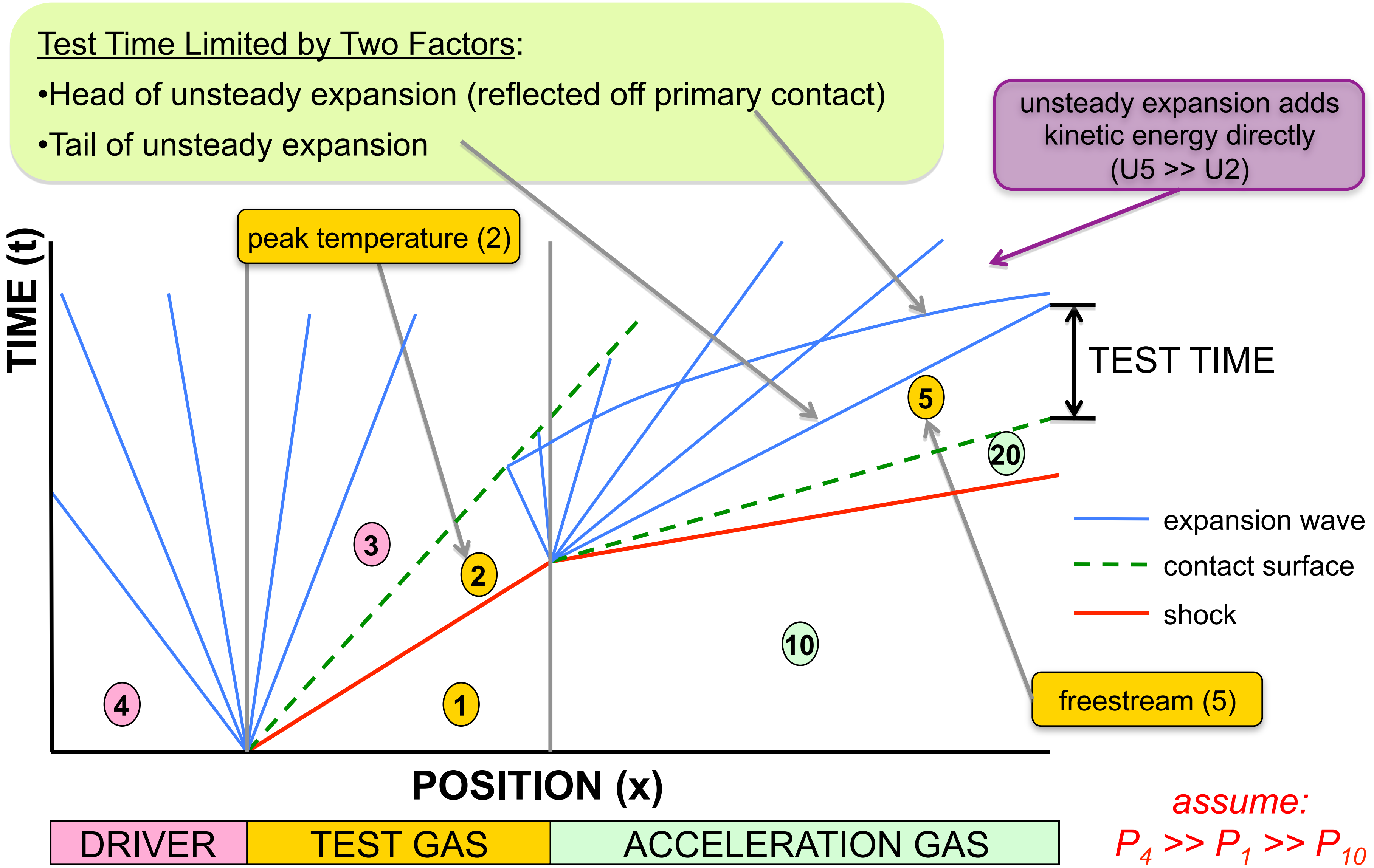


Hollow Cylinder

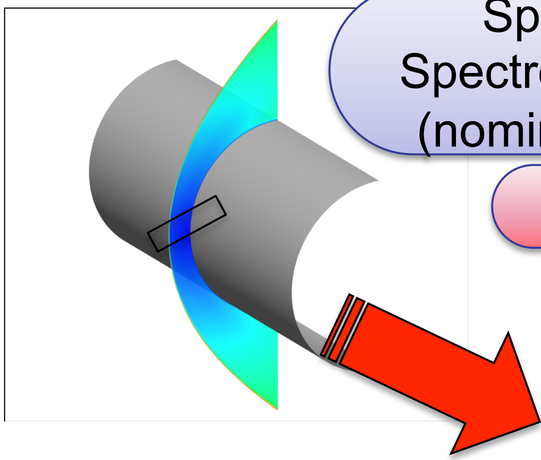


Double Cone

Wave Diagram of an Expansion Tube showing Propagation of Shocks, Expansions, and Contact Surfaces

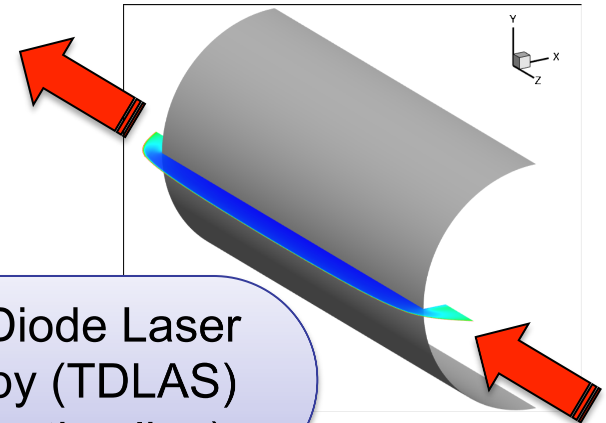


New Diagnostics for Catalytic and Ablating Flows Developed on a Cylinder Model



Spatially Resolved Emission Spectroscopy along Stagnation Line (nominally focused at centerplane)

AIAA 2013-1058



Near-Surface Tunable Diode Laser Absorption Spectroscopy (TDLAS) (integration along stagnation line)

AIAA 2013-2643

- Near-surface TDLAS with 5.44 micron QCL from Alpes Lasers targeting Nitric Oxide (NO) fundamental transition.
- Why study NO formation?
  - We already own a very expensive laser ($$$$).
  - Well-grounded cold wall (300K) surface temperature.
  - Importance of NO formation on reacting air surface catalysis demonstrated in literature.
  - Lessons learned apply directly to ablating flows later on…

Tunable Diode Laser Absorption Spectroscopy (TDLAS)

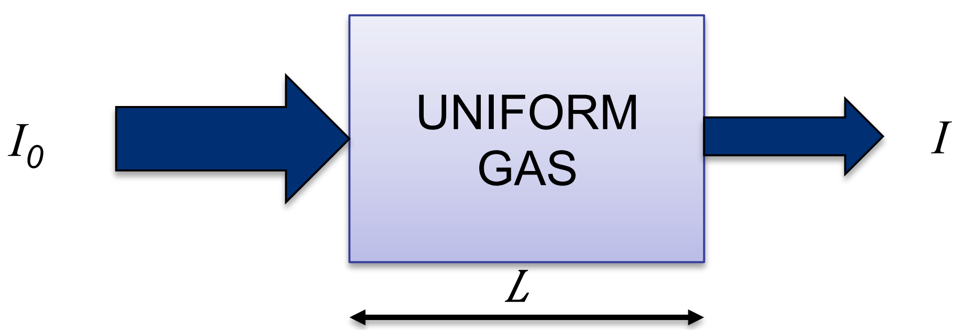
Beer-Lambert Law $\frac{I}{I_o} = exp(-k_\nu L)$ *(monochromatic absorption through a uniform gas)*

Spectral absorption coefficient $k_\nu = S_i(T)PX_j\phi_\nu$

Doppler broadening (Temperature)

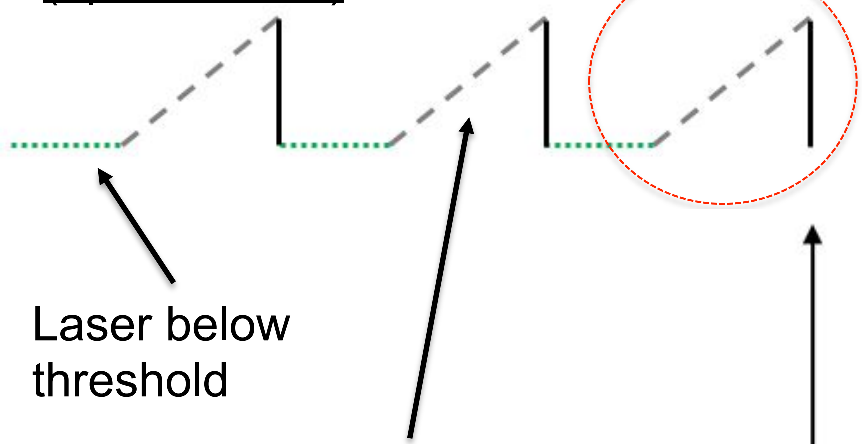
Collisional broadening (Pressure)

Gaussian + Lorentzian = Voigt convolution



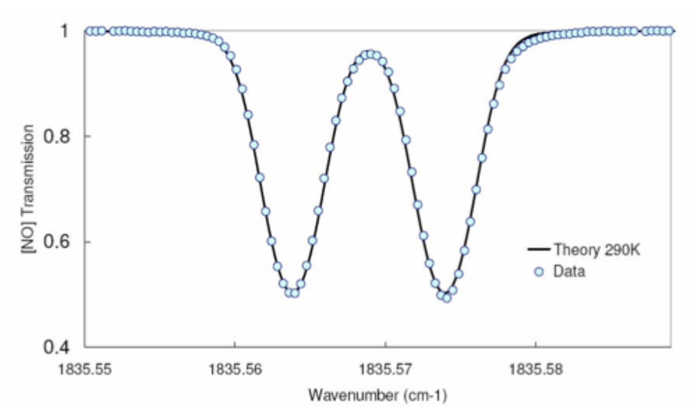
TDLAS Laser Ramp

Function Generator
(up to 10 kHz)

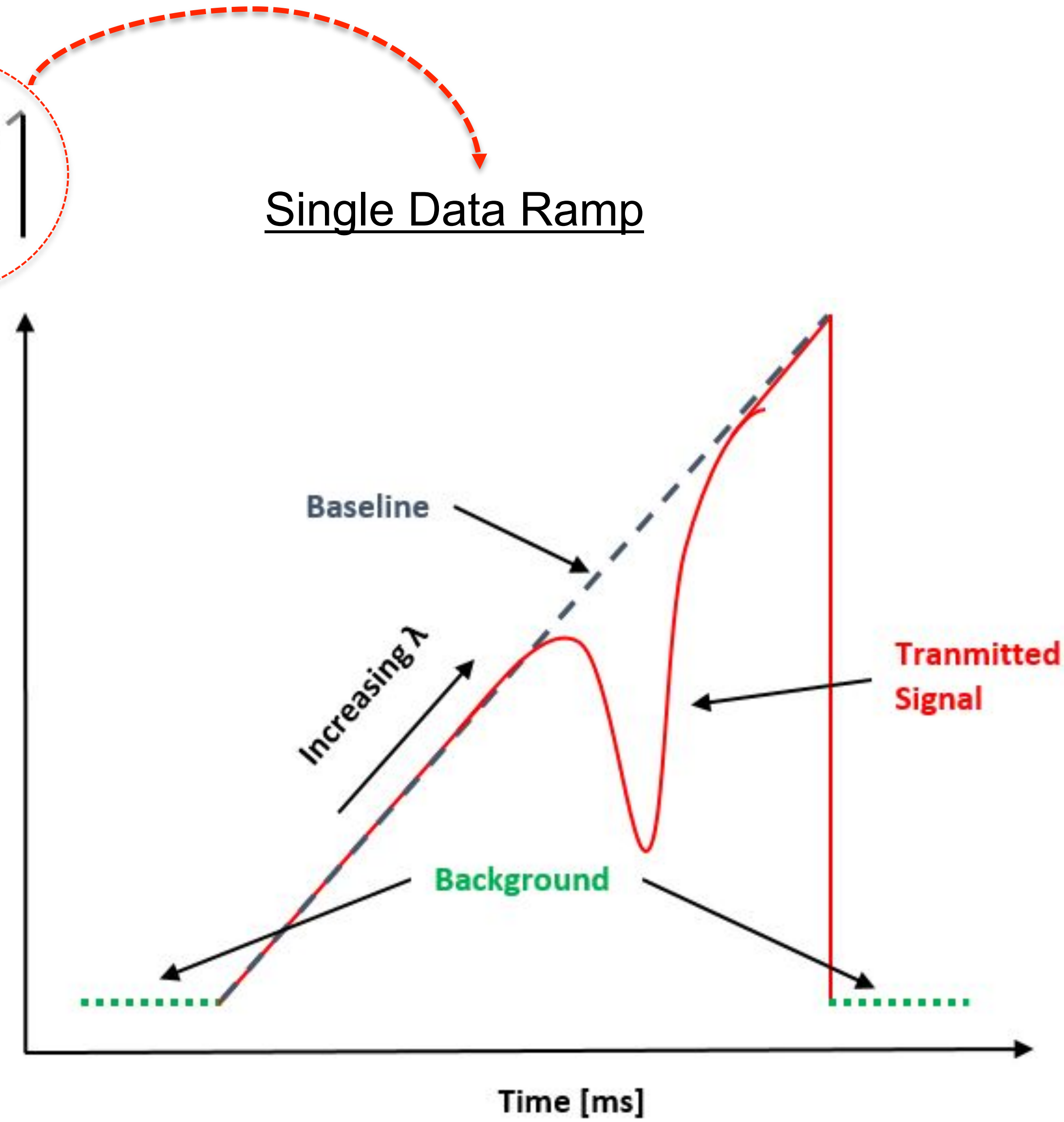


Laser below threshold

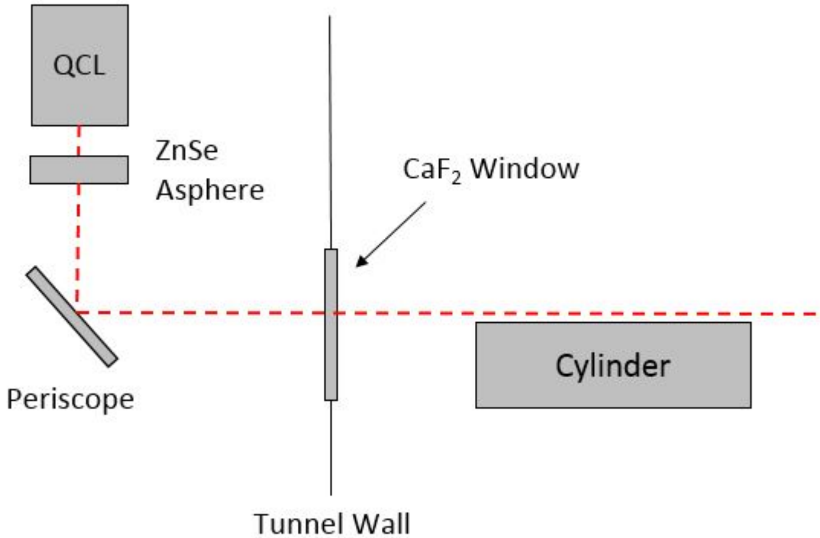
Current → Wavelength

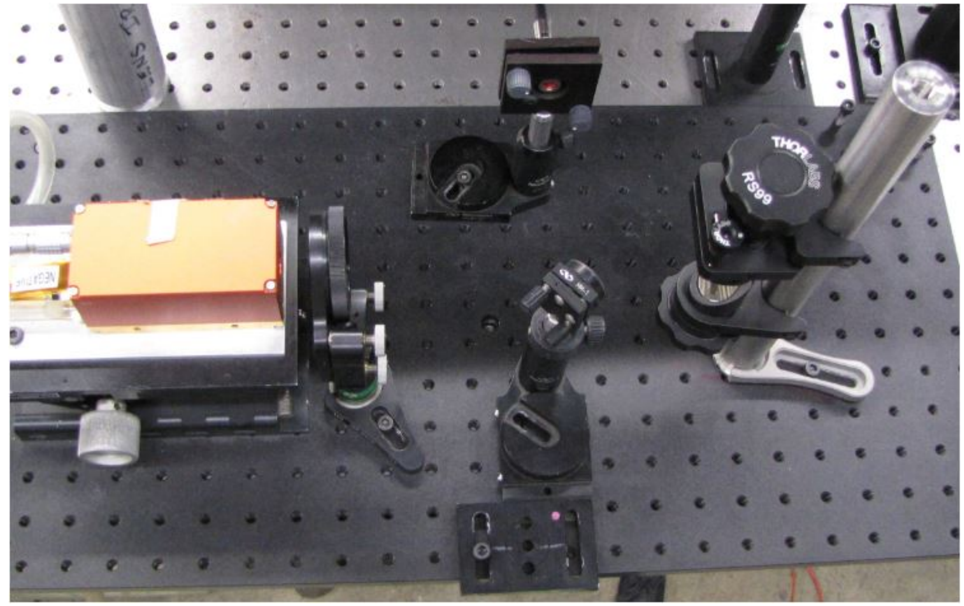


Single Data Ramp



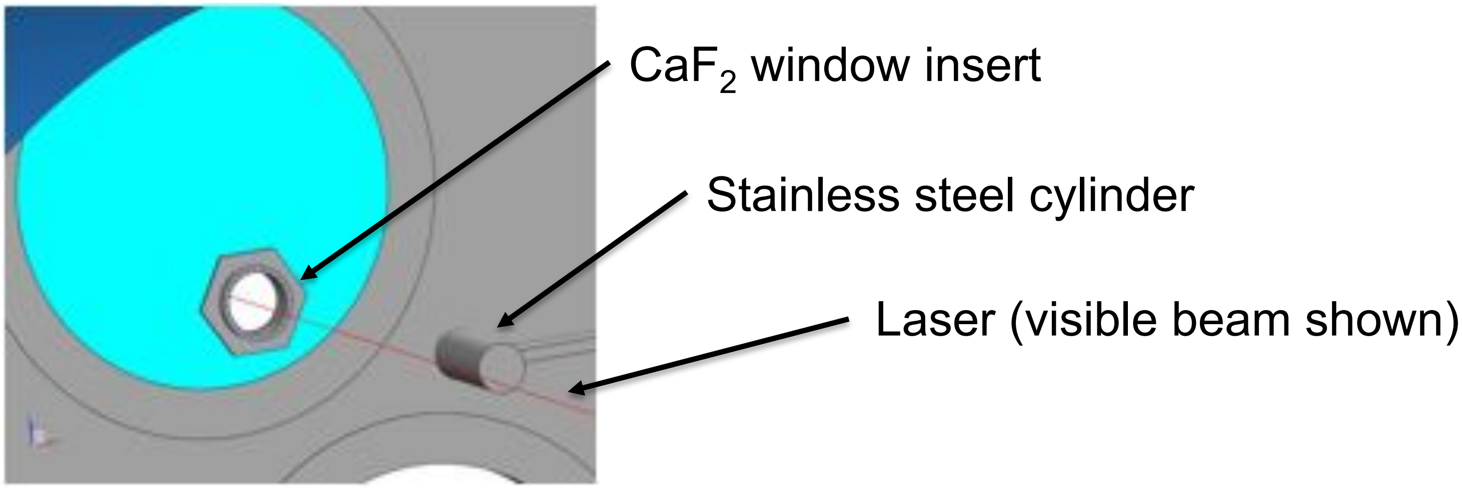
Pitch Side (Laser)

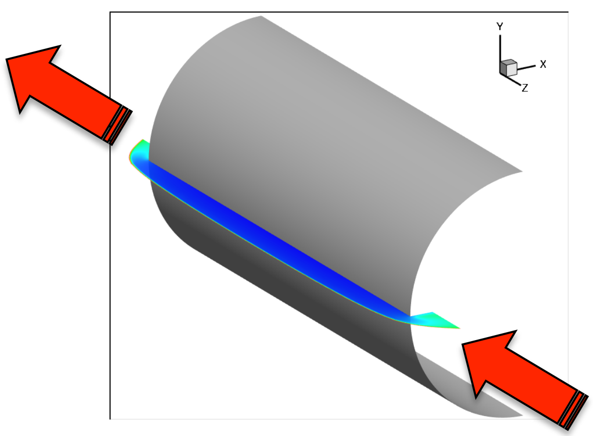


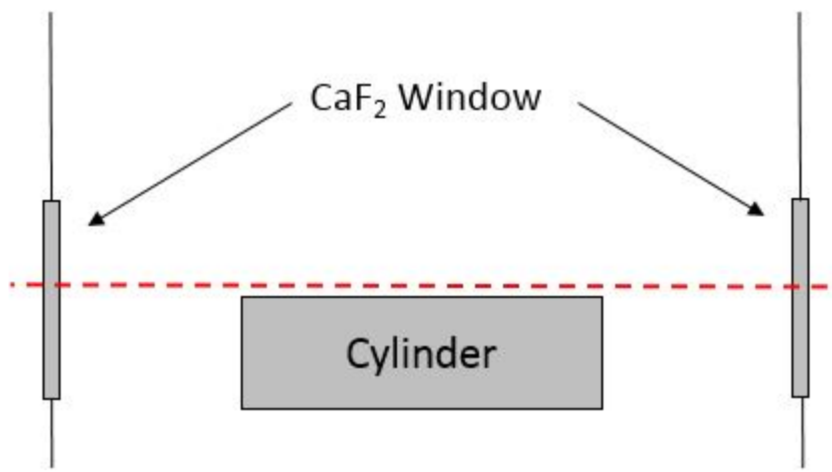


Asphere

Cylinder in Tunnel

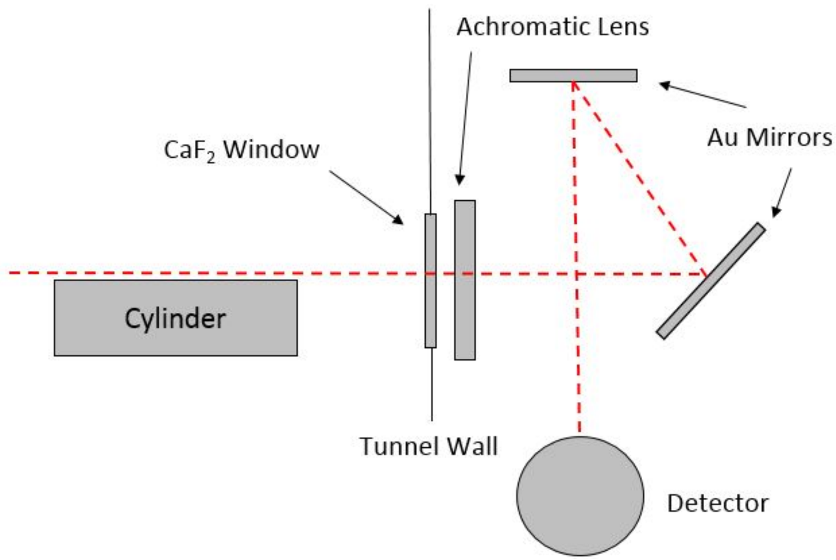


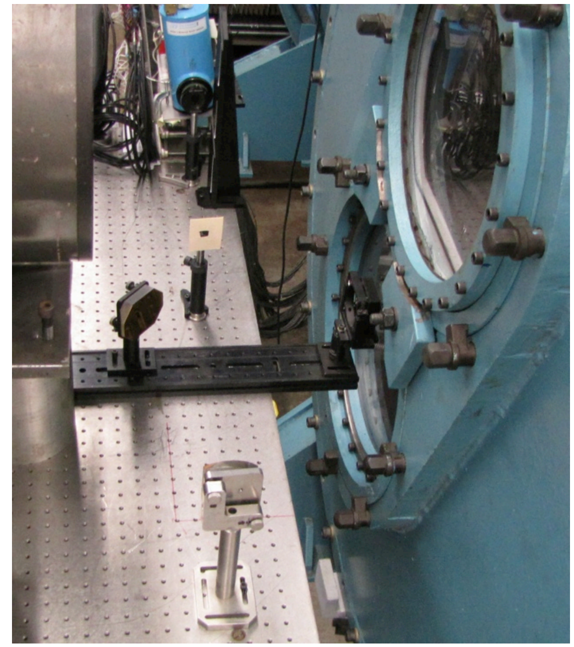




Top View

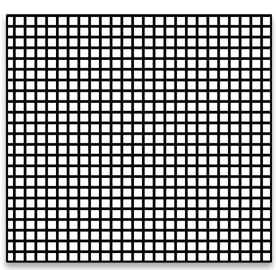
Catch Side (Detector)





Single-Element Detector

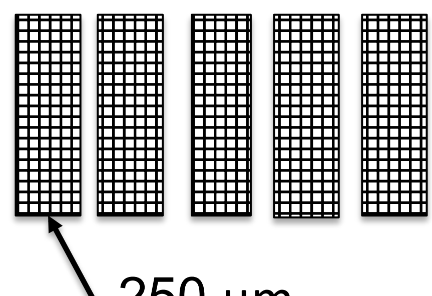
1 mm



1 mm

Linear Array Detector (32 elements)

800 μm



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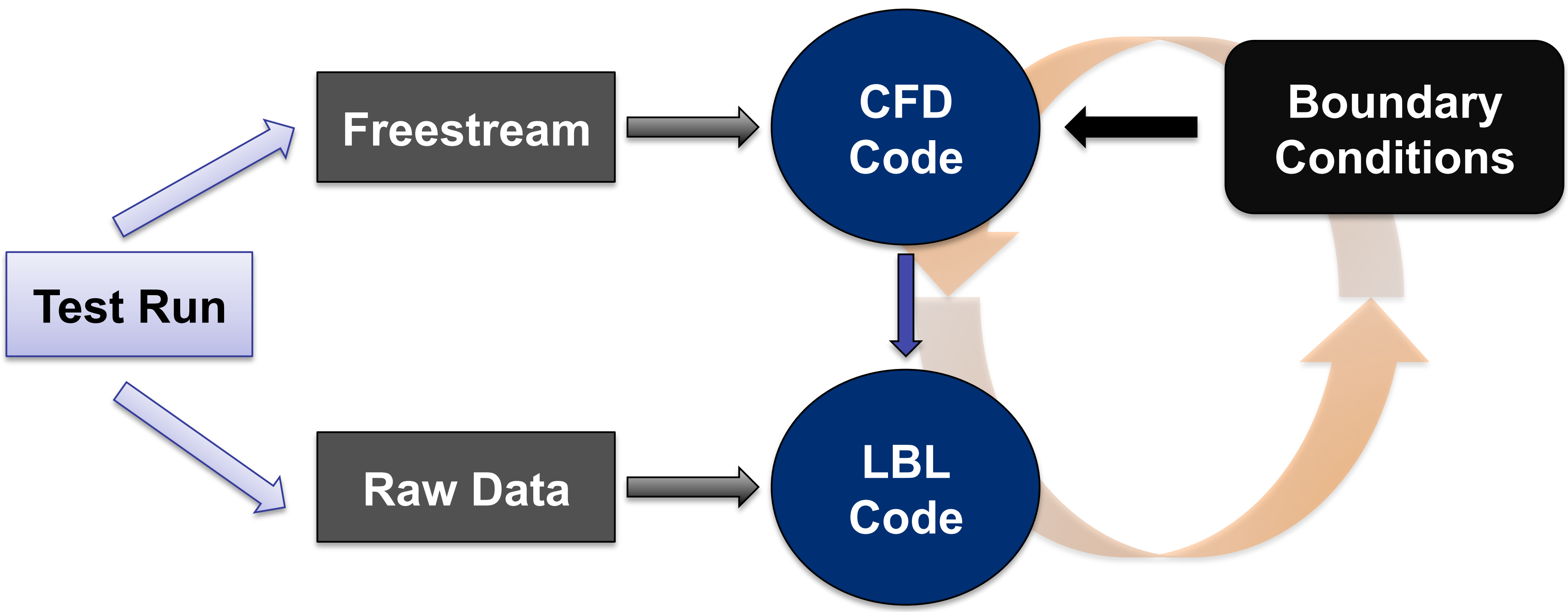
250 μm

4:1 magnification or greater possible with different optics

The Big Picture

CFD : Computational Fluid Dynamics

LBL : Line-by-Line



CFD Boundary Condition Models of Surface Catalysis

- Non-catalytic wall: no recombination occurs on the surface, which implies zero diffusion flux to surface.

$$-J_k = 0$$

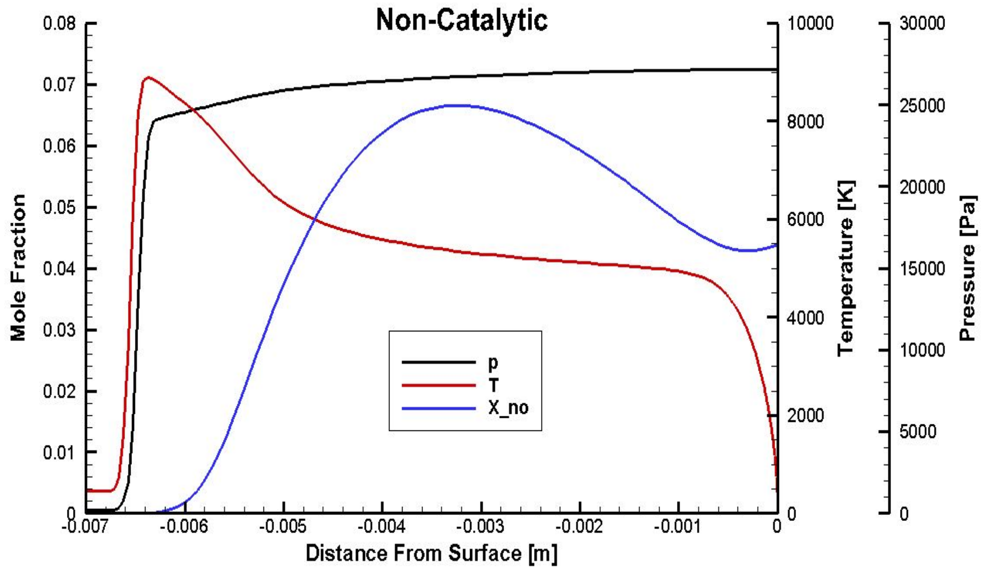
- Super-catalytic wall: Explicitly specified composition corresponding to complete recombination of energetic species into lowest energy state (N_2/O_2 for air).
- Specified reaction efficiency (SRE) catalytic wall: A percentage of reactants reaching the surface for which a reaction occurs. Controlled with a single efficiency parameter, γ, but γ has no connection to a physical process.

$$-\rho_w D_k \nabla y_k \Big|_w + \rho_w v_w y_{k,w} = \sum_r \alpha_r M_k \left(\frac{\gamma_r \rho_W c_{j(r)}}{M_{j(r)}} \sqrt{\frac{\Re T_W}{2\pi M_{j(r)}}} \right)$$

- Generalized finite rate surface chemistry (FRSC) wall: Reactions are modeled via one or more physical kinetic processes to generate production rates for each species at the surface, balanced by diffusion into the gas interior. Most physical BC, but requires a large number of parameters not easily obtainable.

$$-\rho_w D_k \nabla y_k \Big|_w + \rho_w v_w y_{k,w} = M_k \sum_{i=1}^{Nr} \left\{ \left(\nu_{ki}^{''} - \nu_{ki}^{'} \right) \left(k_{fi} \prod_{m=1}^{Ns} [X_m]^{\nu_{mi}^{'}} - k_{bi} \prod_{m=1}^{Ns} [X_m]^{\nu_{mi}^{''}} \right) \right\}$$

Computational Fluid Dynamics

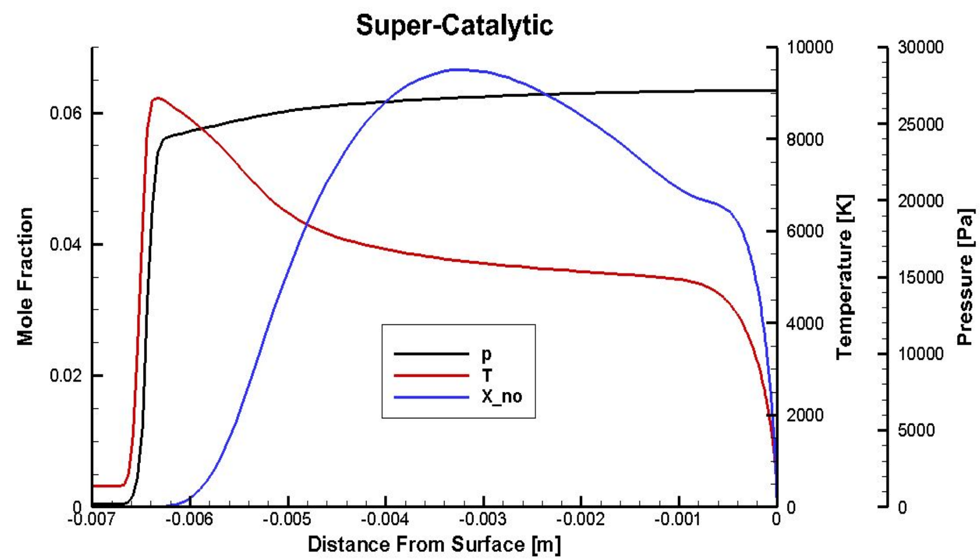


Freestream Conditions

v = 4,249 m/s

ρ = 0.00159 kg/m^3

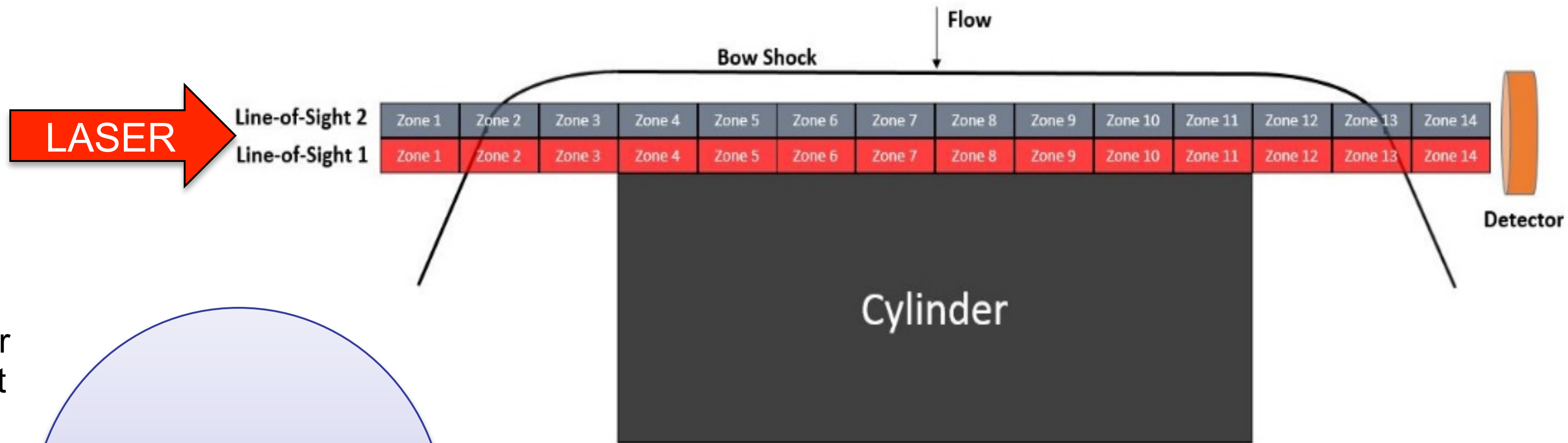
T = 457 K



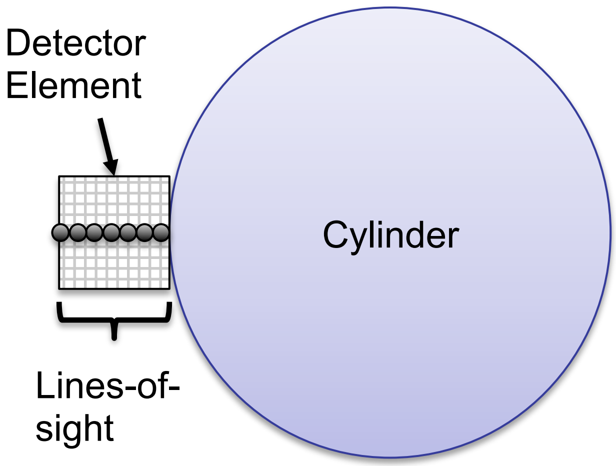
Key Difference

Concentration of NO in shock layer

Line-by-Line Spectra Calculation



Top View

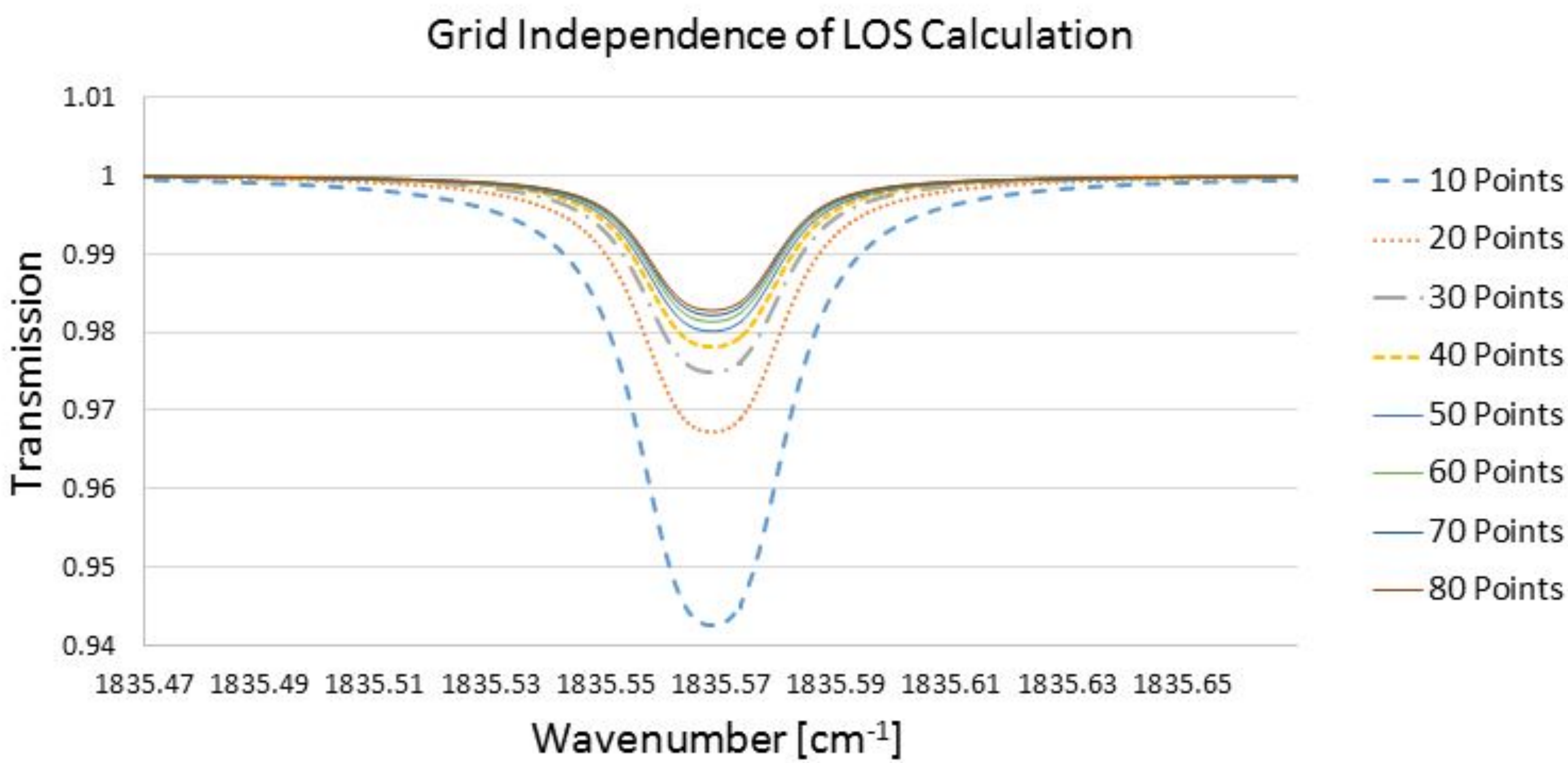


Side View

Finite detector area → Multiple lines-of-sight

Varying flow field → Multiple homogeneous zones

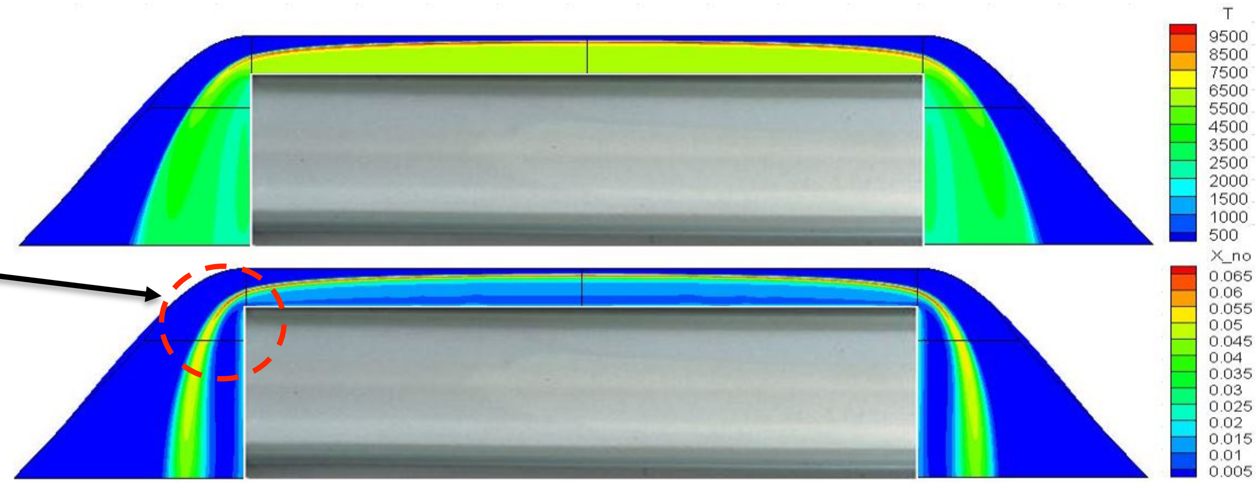
Line-of-Sight Number Independence

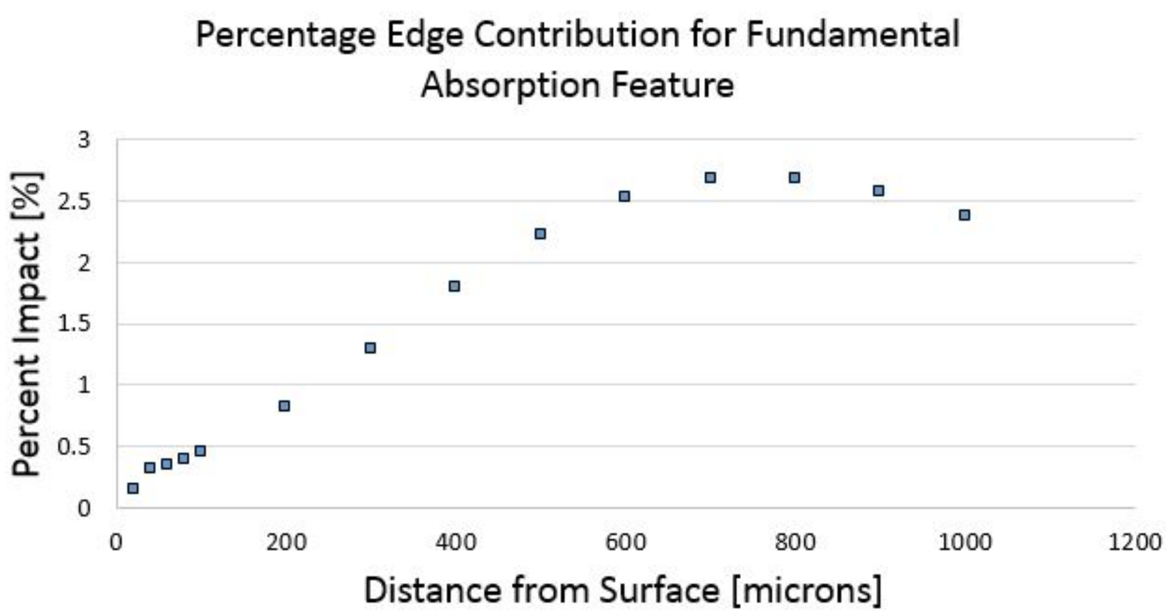


Number independence → Number of LOS > 80-100

Expanding Flow Around Edge of Cylinder

NO expanding around cylinder edge





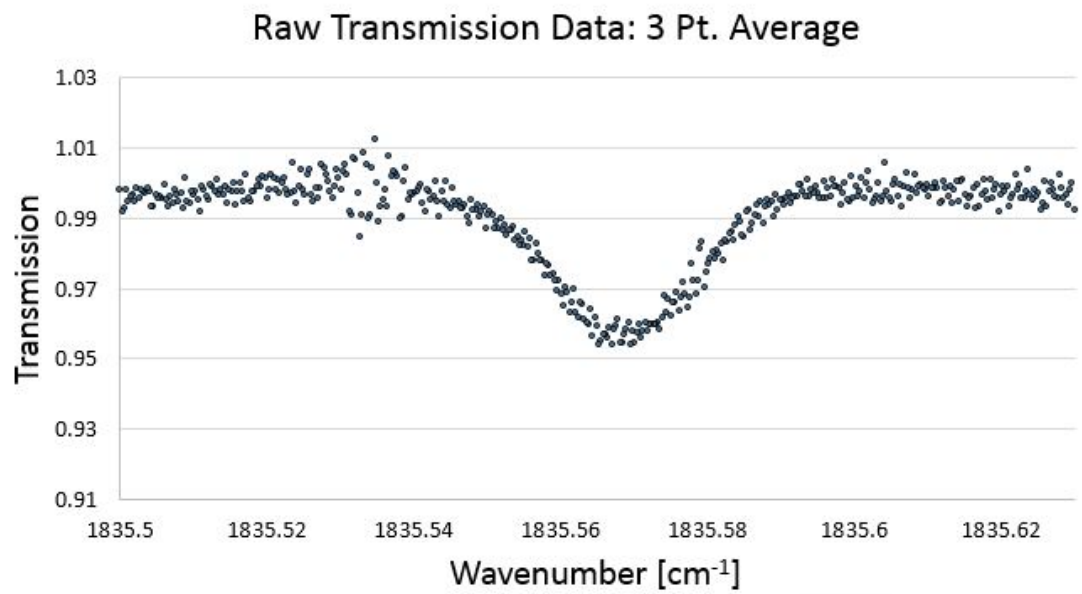
Result

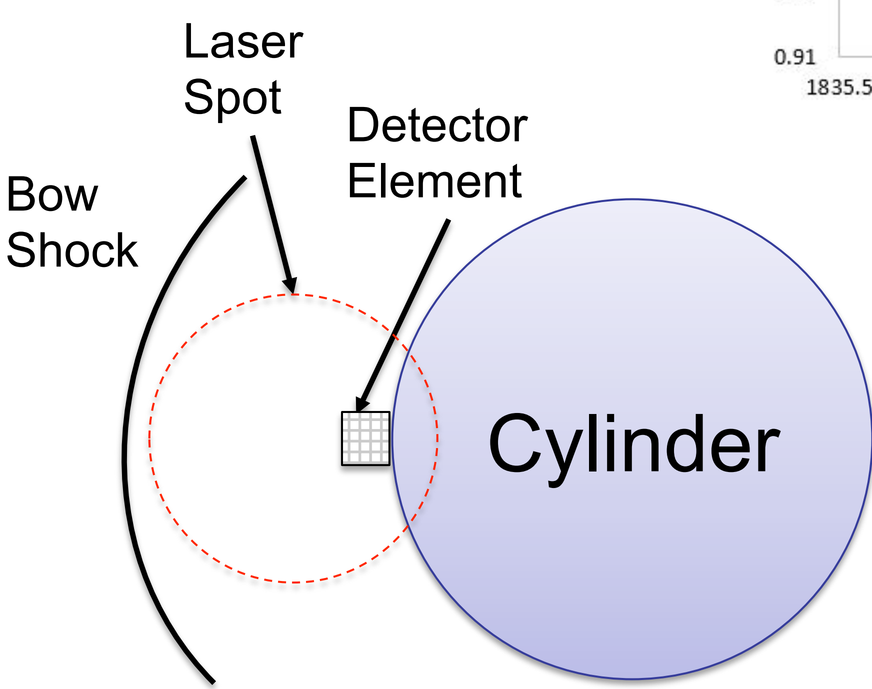
Absorption confined to width of the cylinder

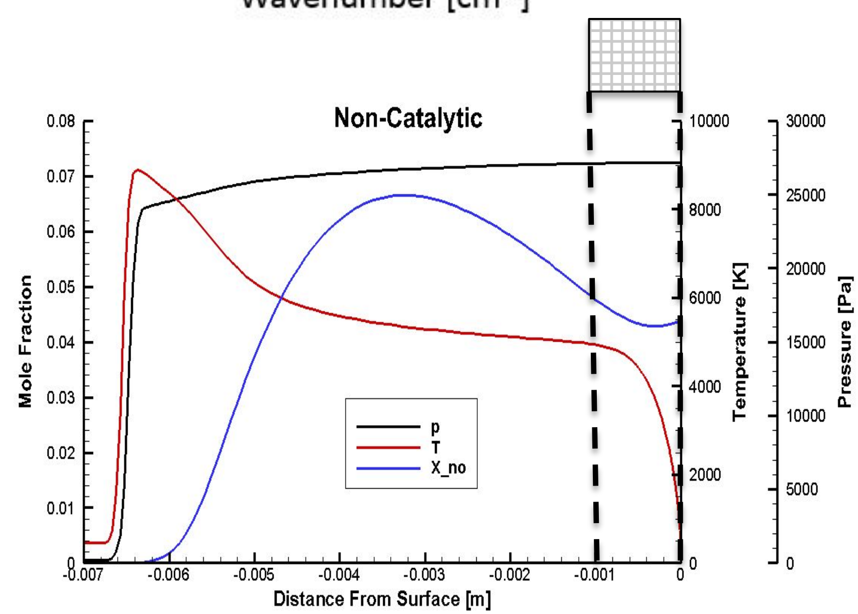
Single-Element Detector

Freestream Conditions

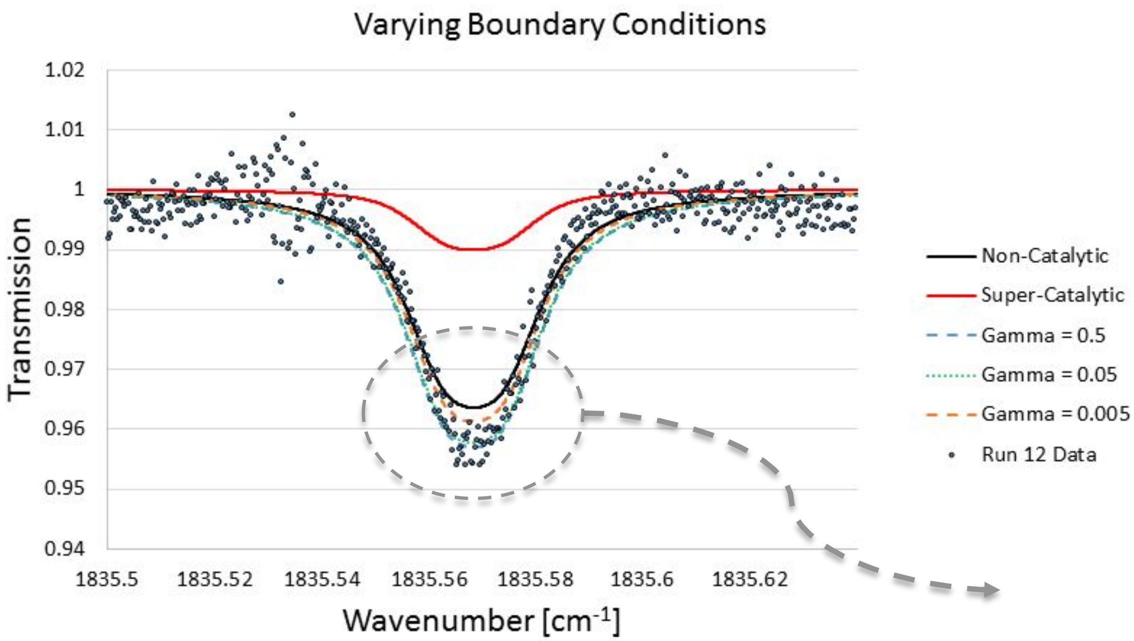
v = 4,249 m/s
$\rho = 0.00159\ kg/m^3$
T = 457 K







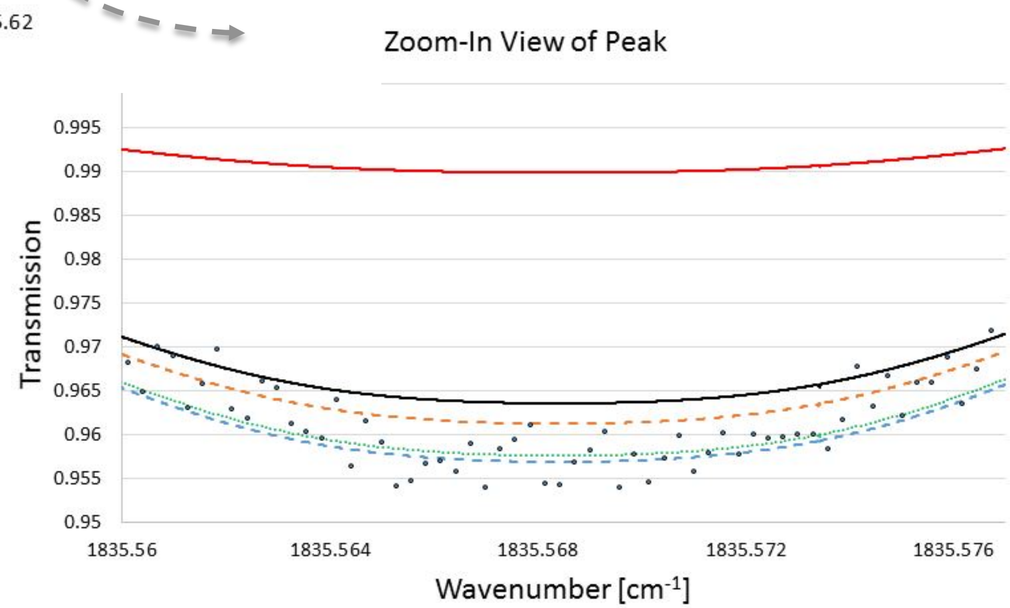
Single-Element Detector



2D CFD Solution

Line-by-Line Code

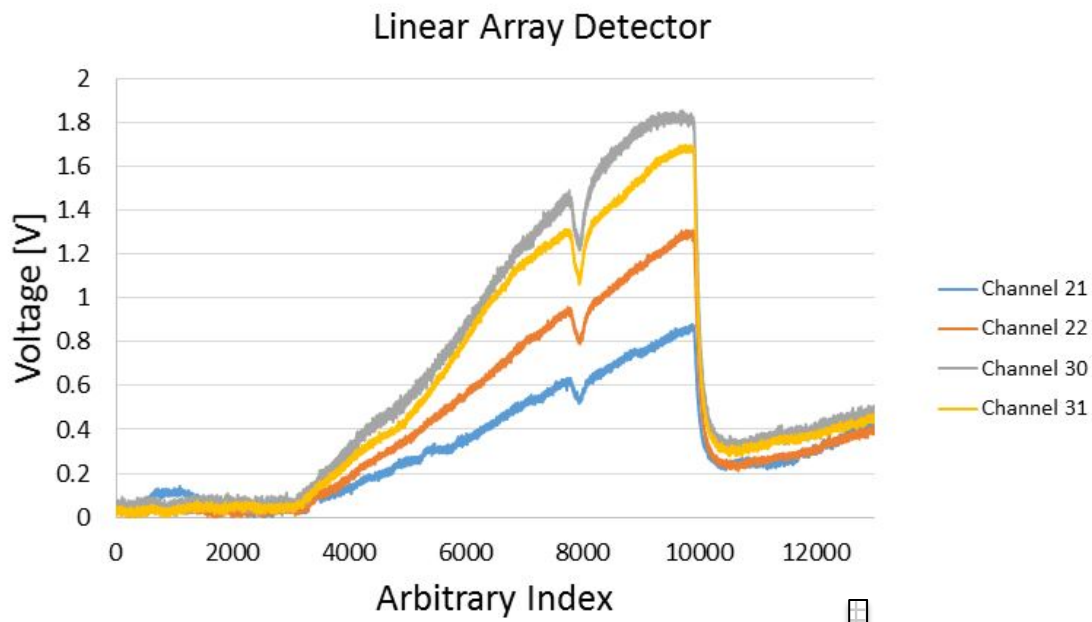
Simulated Transmission

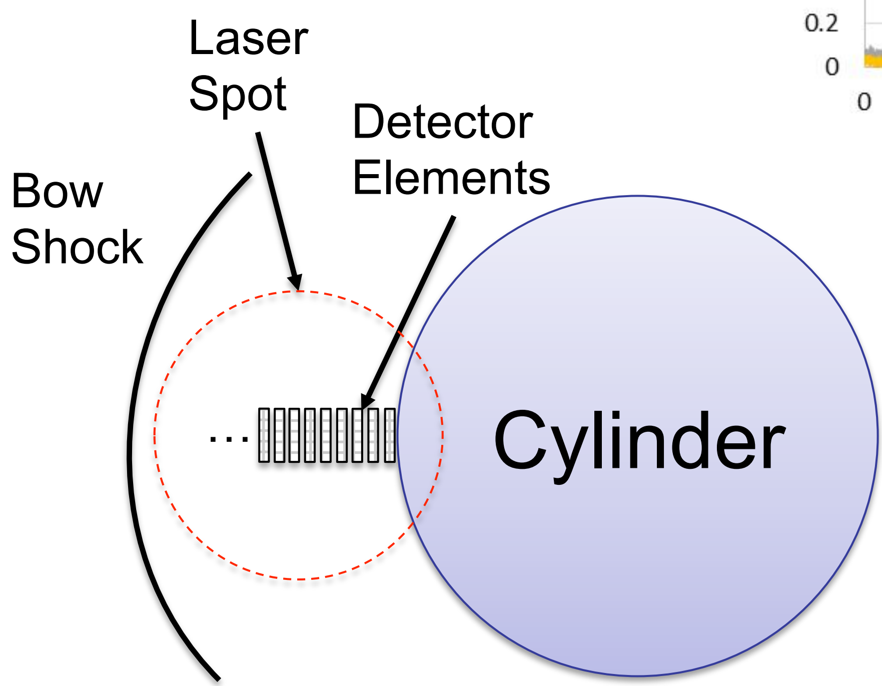


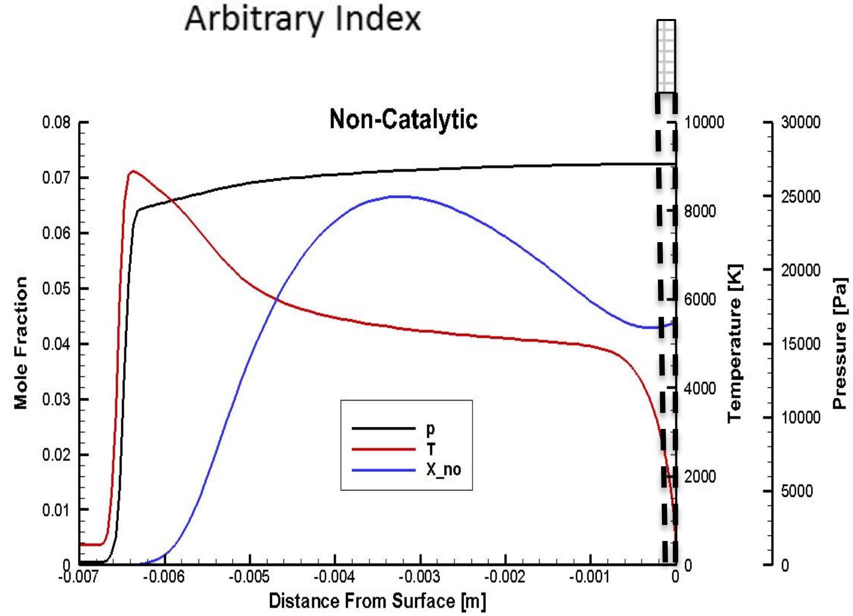
TDLAS Measurements with Linear Array Detector

Freestream Conditions

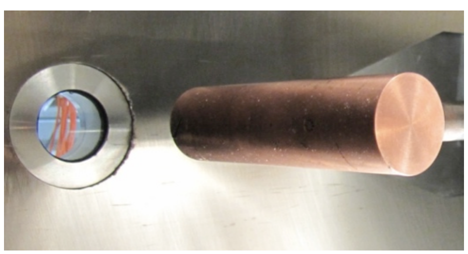
v = 5,166 m/s
ρ = 0.00317 kg/m^3
T = 215 K

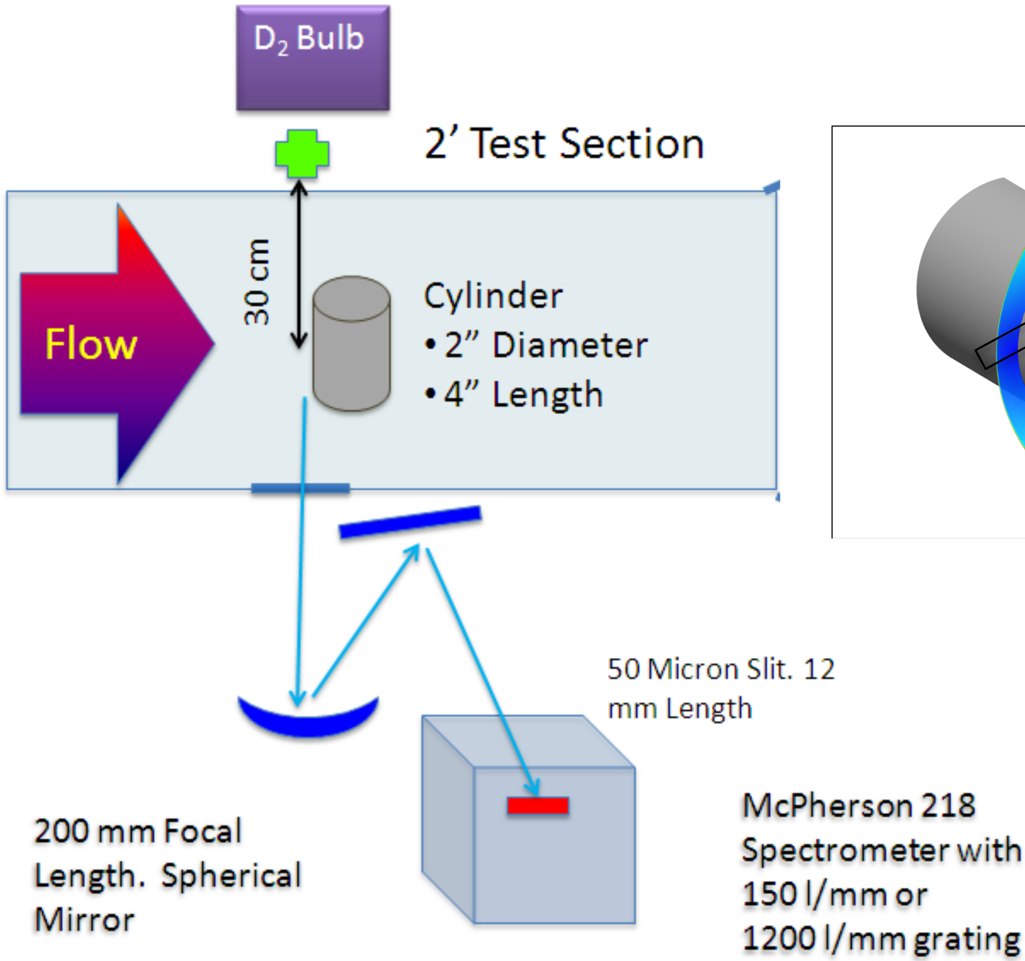


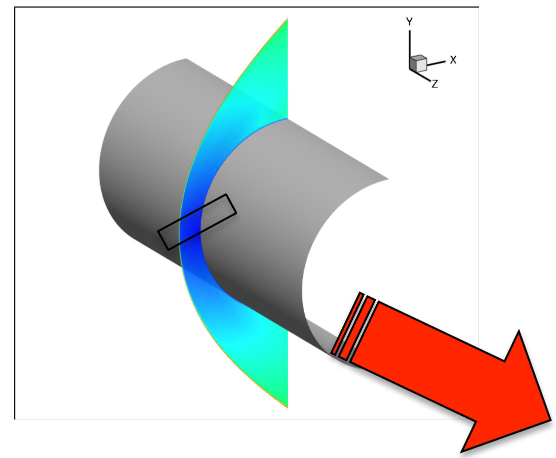




Spatially Resolved Spectral Emission Measurements in the 2 Foot Test Section

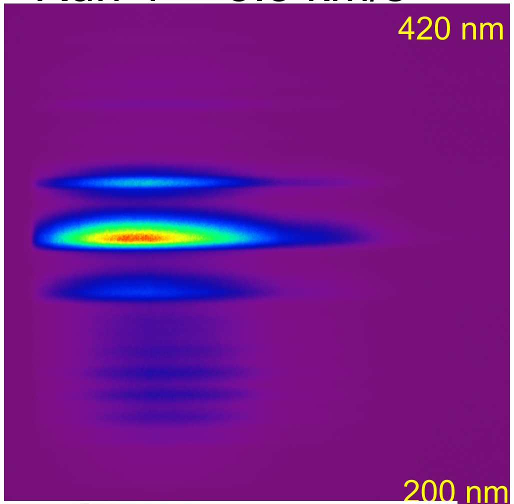




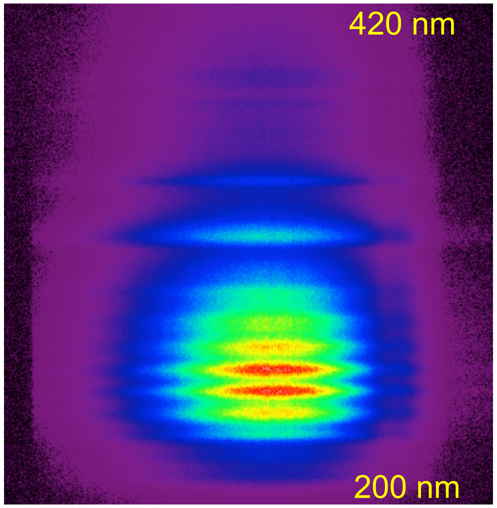


Spectral Emission Measurements for Low Density Flows from 4.7 km/s to 5.4 km/s

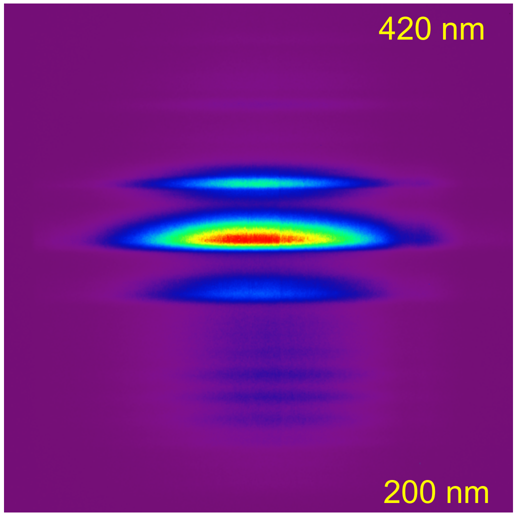
Run 4 5.3 km/s

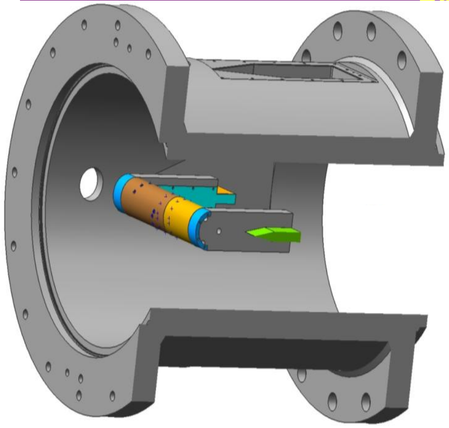


Run 5 4.8 km/s



Run 6 5.4 km/s

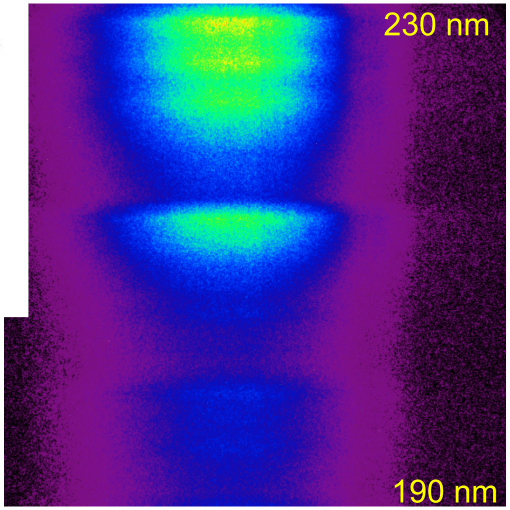


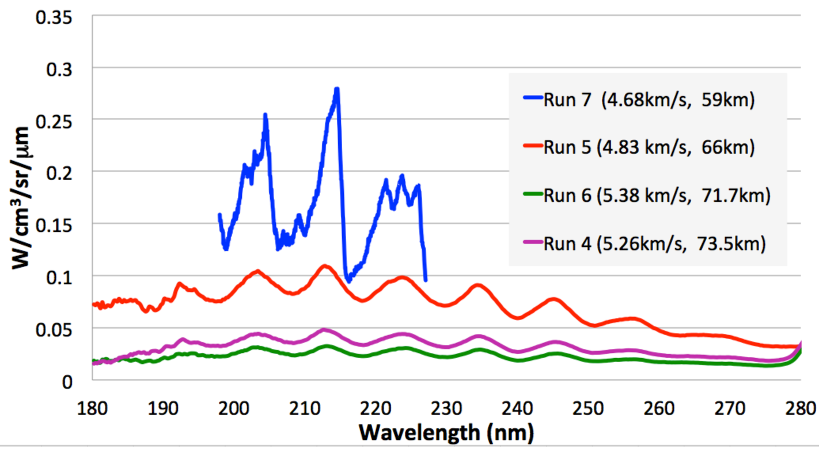


High resolution Measurement

$\Delta\lambda$ = 0.17nm

Run 7 4.7 km/s

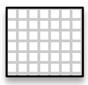




Summary and Conclusions

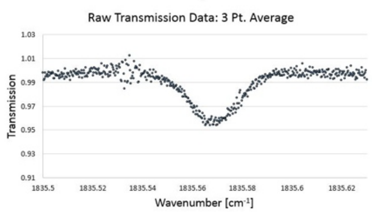
1 TDLAS NO Diagnostic

2a

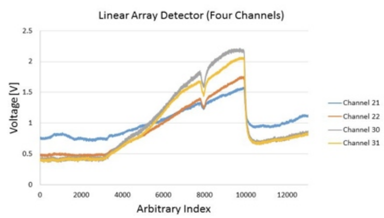


2b

3a

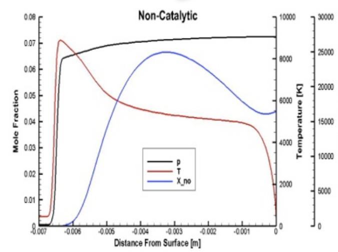


3b

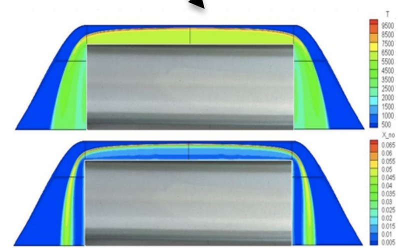


4 CFD Solutions

5a



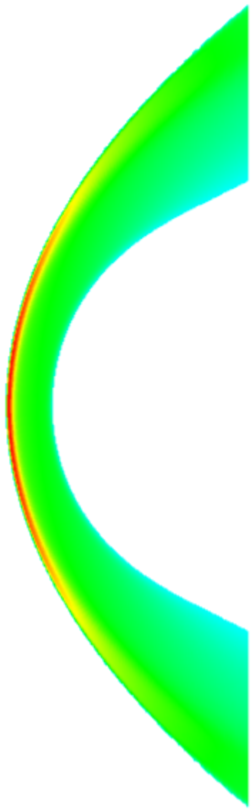
5b



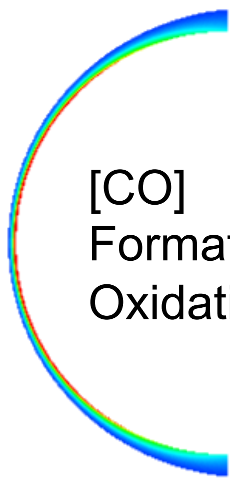
6

Analysis
Comparison
CFD Code Validation

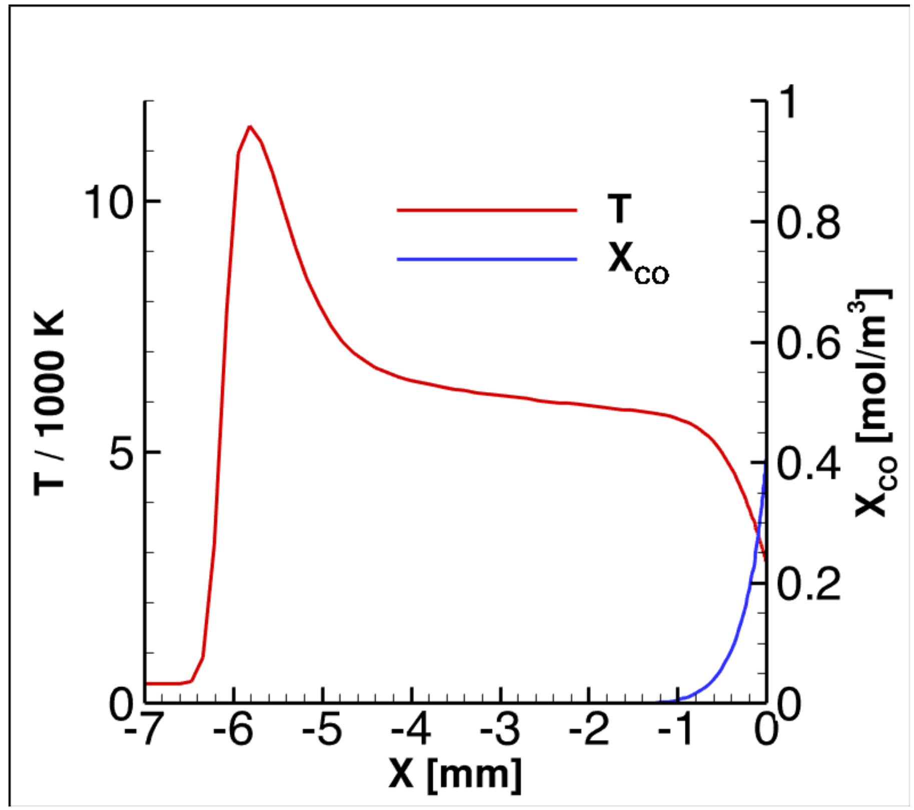
Future Directions: Modification for Ablation Surfaces



Temperature Field in Shock Layer



[CO] Formation by Oxidation



- In principle, direct substitution of TDLAS targeting CO transition possible.
- More challenging environment because of variable wall temperature
- Potentially use linear array detector to track surface recession in real-time?