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CARS in an inductively coupled plasma torch, Part 2: T/CO measurements

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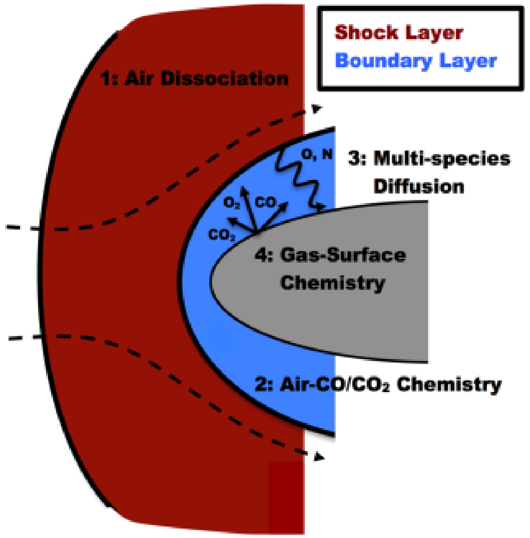
Background and Motivation

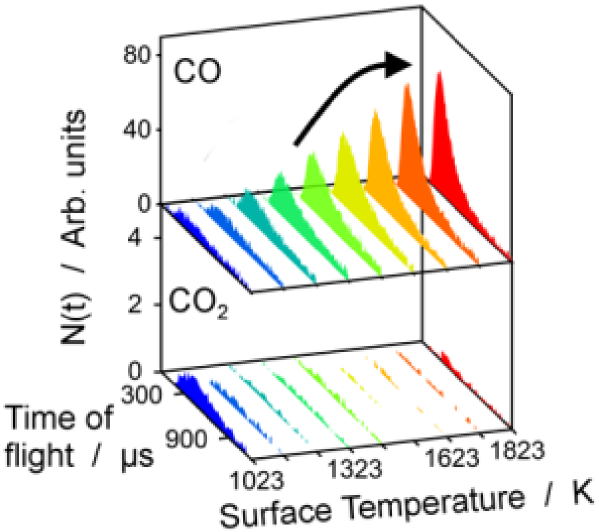
Aerothermochemistry of TPS materials is a subject of significant renewed interest



Tom Schwartzentruber, University of Minnesota

- *Oxidation* reactions are a dominant source of TPS surface recession
- *Carbon monoxide* is the dominant product of surface oxidation

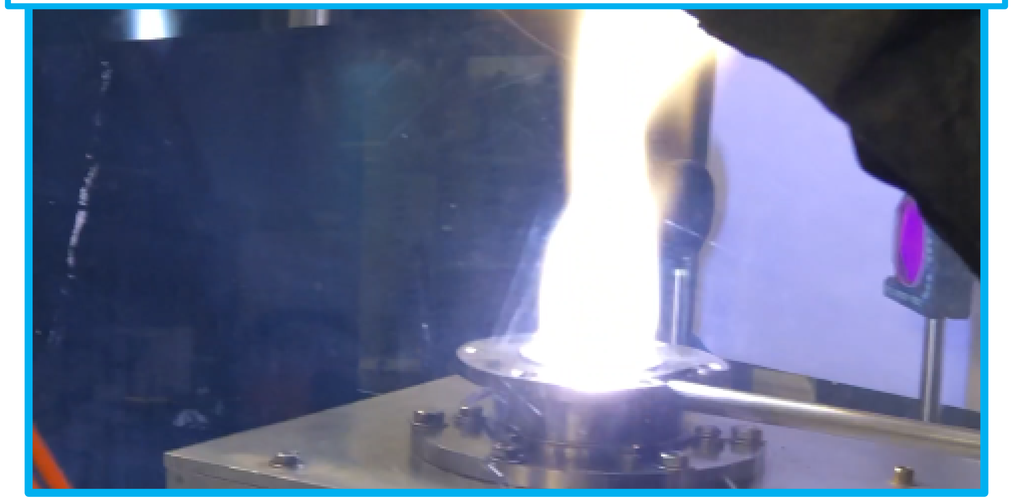
Molecular Beam Data Show Predominance of CO as product of gas-surface chemistry
Minton et al., CU-Boulder



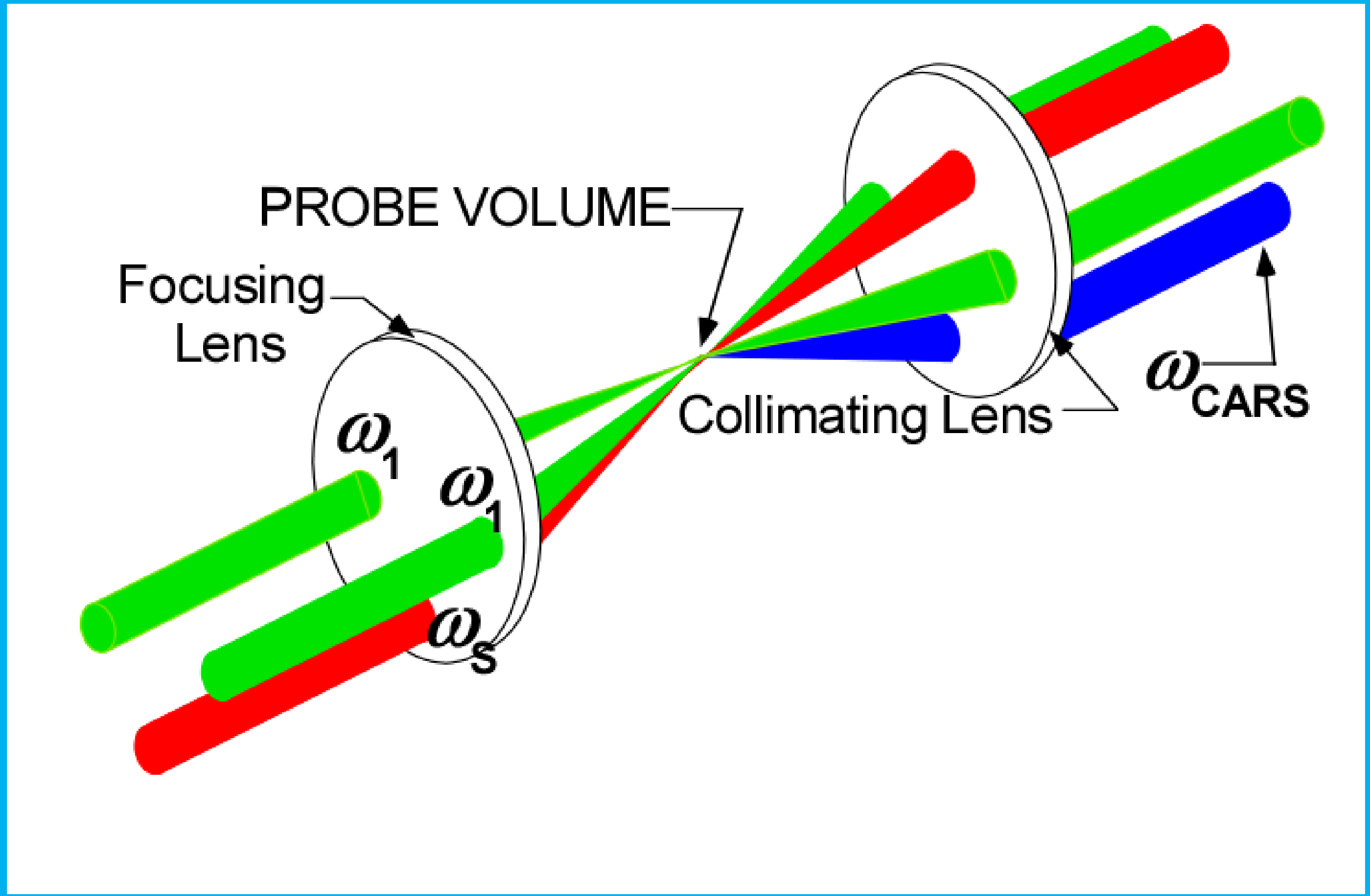
High-temperature (T = 4000–8000 K) ground-testing

- Impulsive: Shock tunnels/Expansion tubes
- Arc Jets
- *ICP torches*
  - Chemically "clean" source of extreme temperature air
  - Very low mass flow, Mach number

Inductively Coupled Plasma Torch, UT-Austin



CARS Diagnostic for Simultaneous T/CO detection



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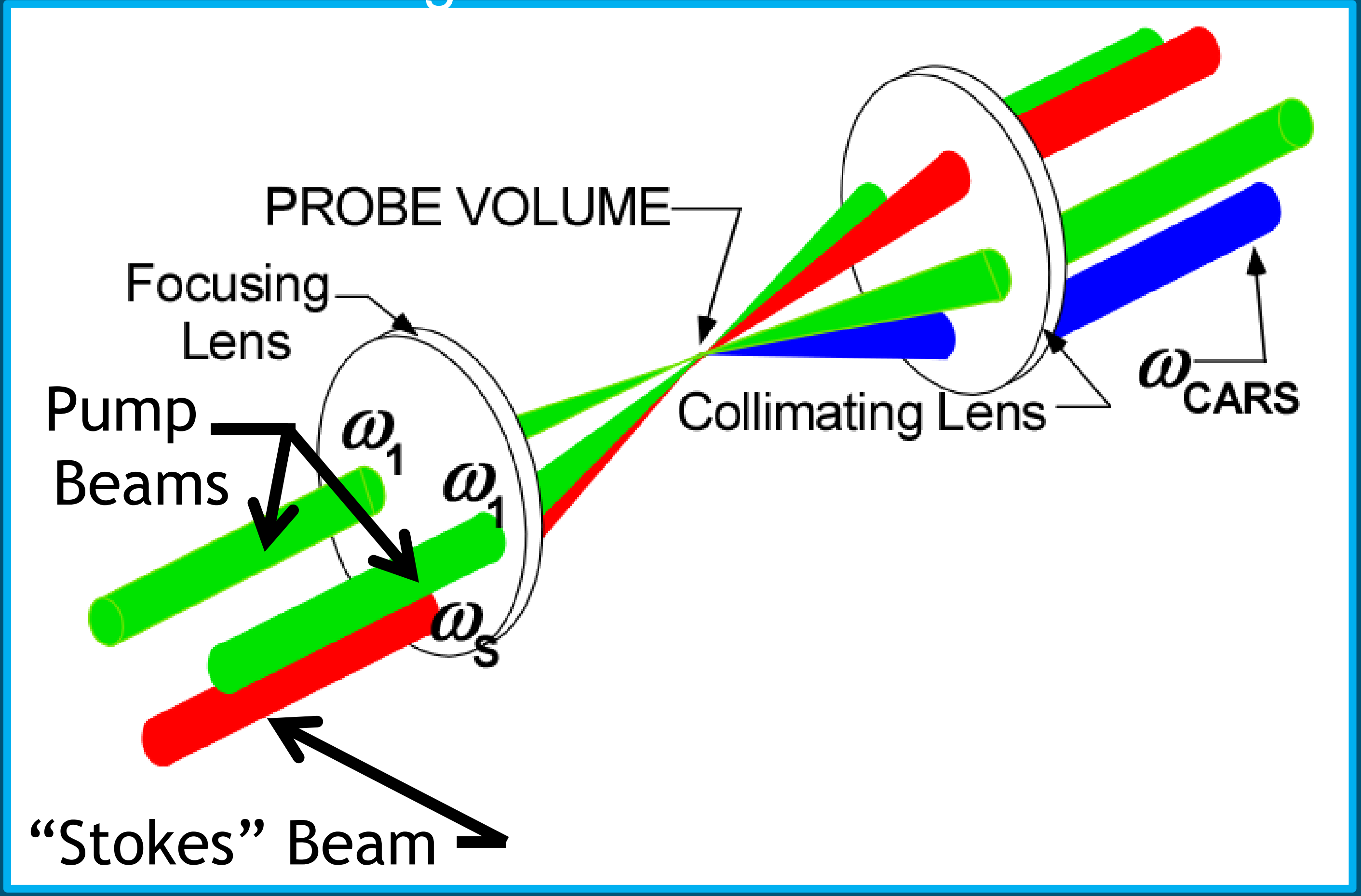
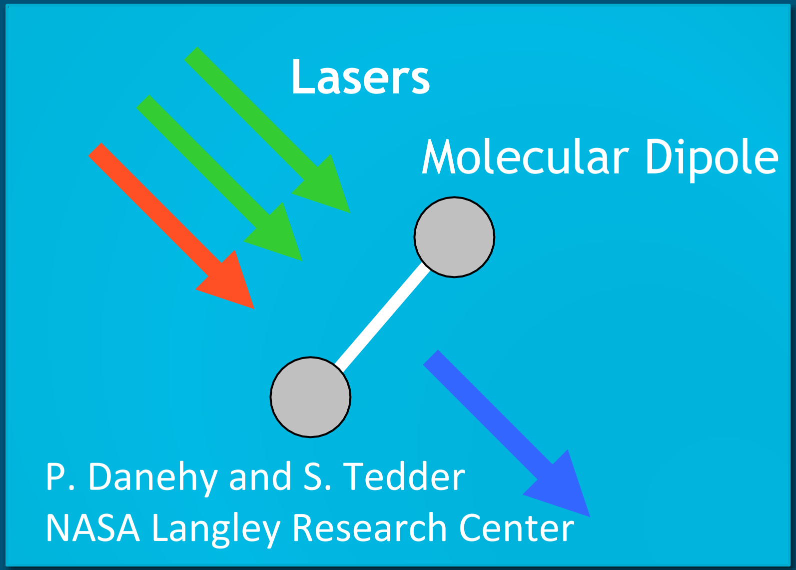
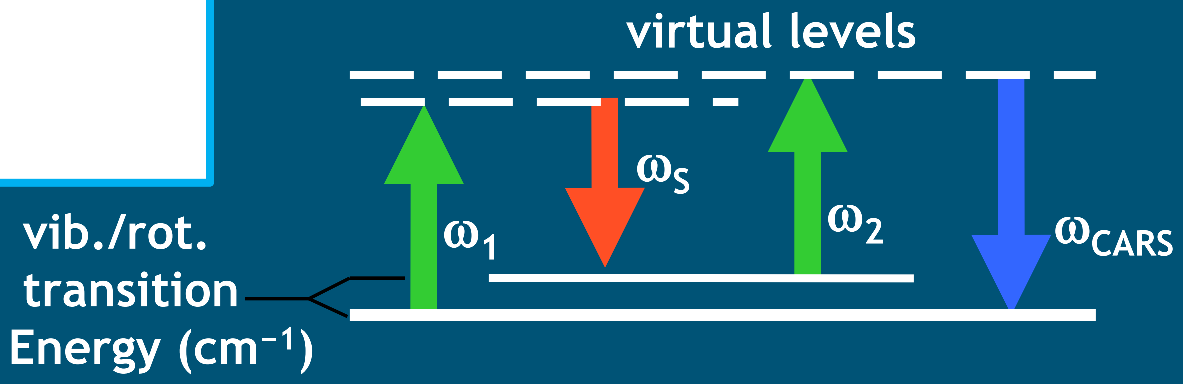
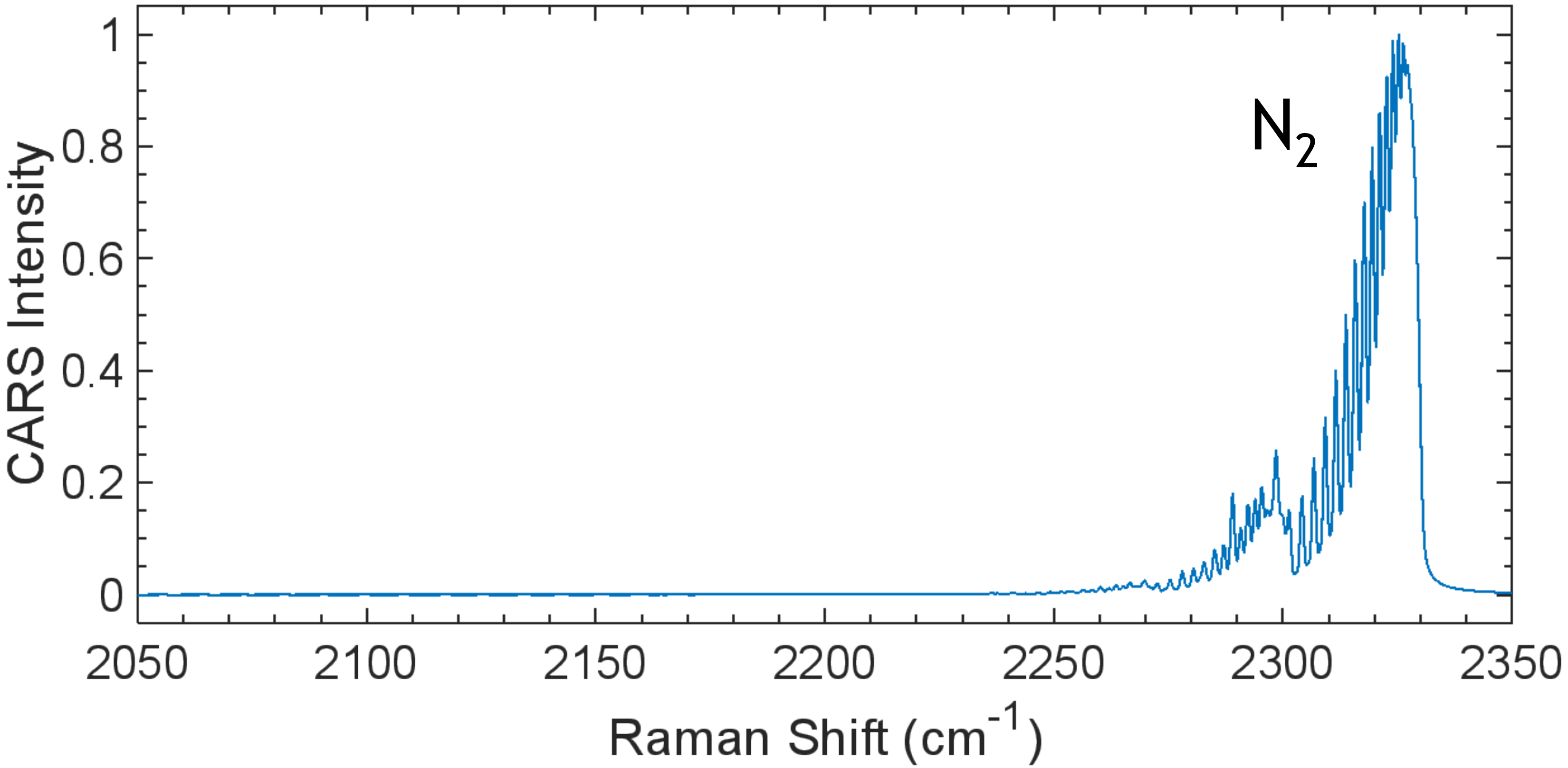




Coherent Anti-Stokes Raman



The Stokes bandwidth accesses N_2 and CO simultaneously



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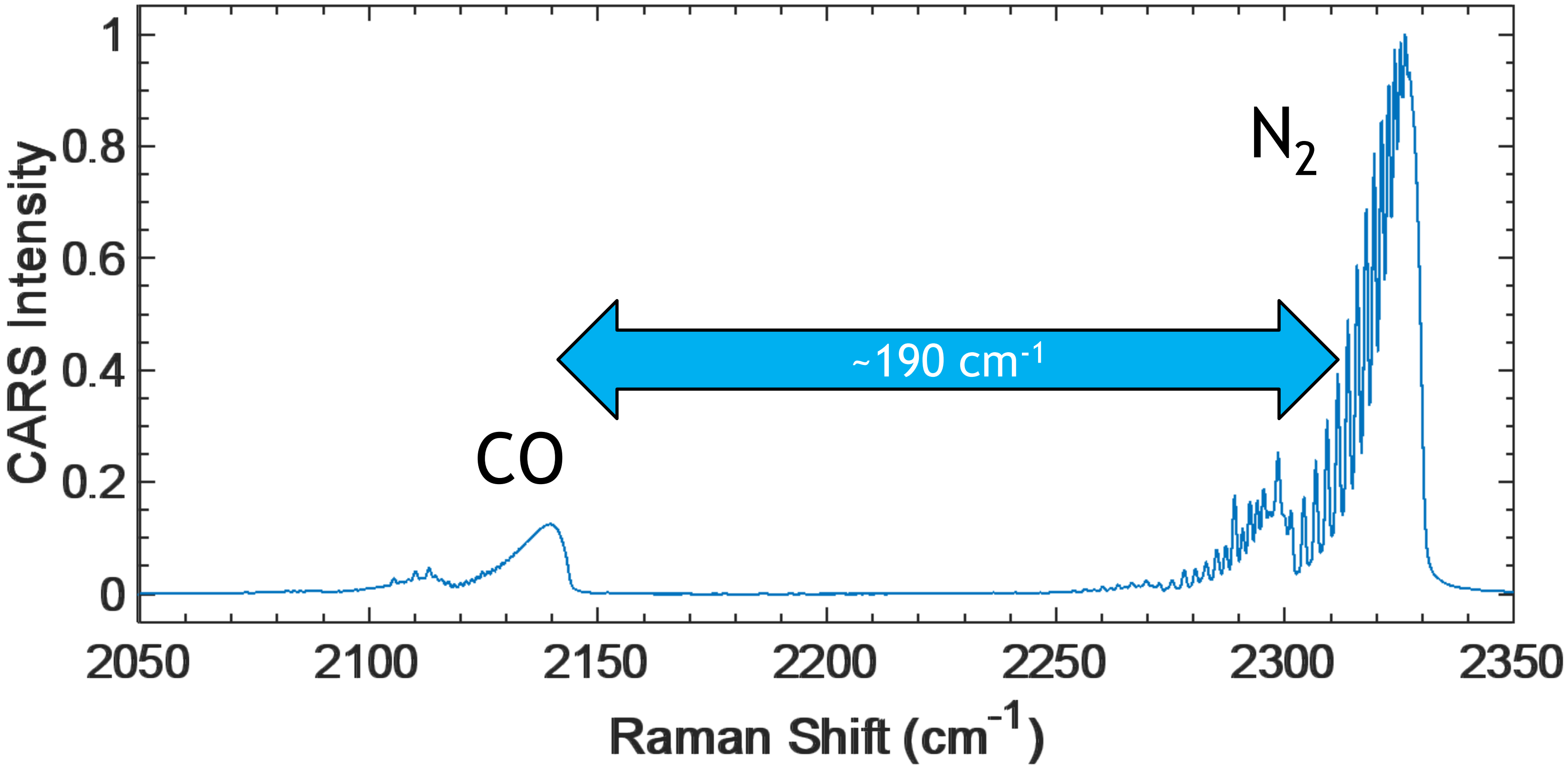

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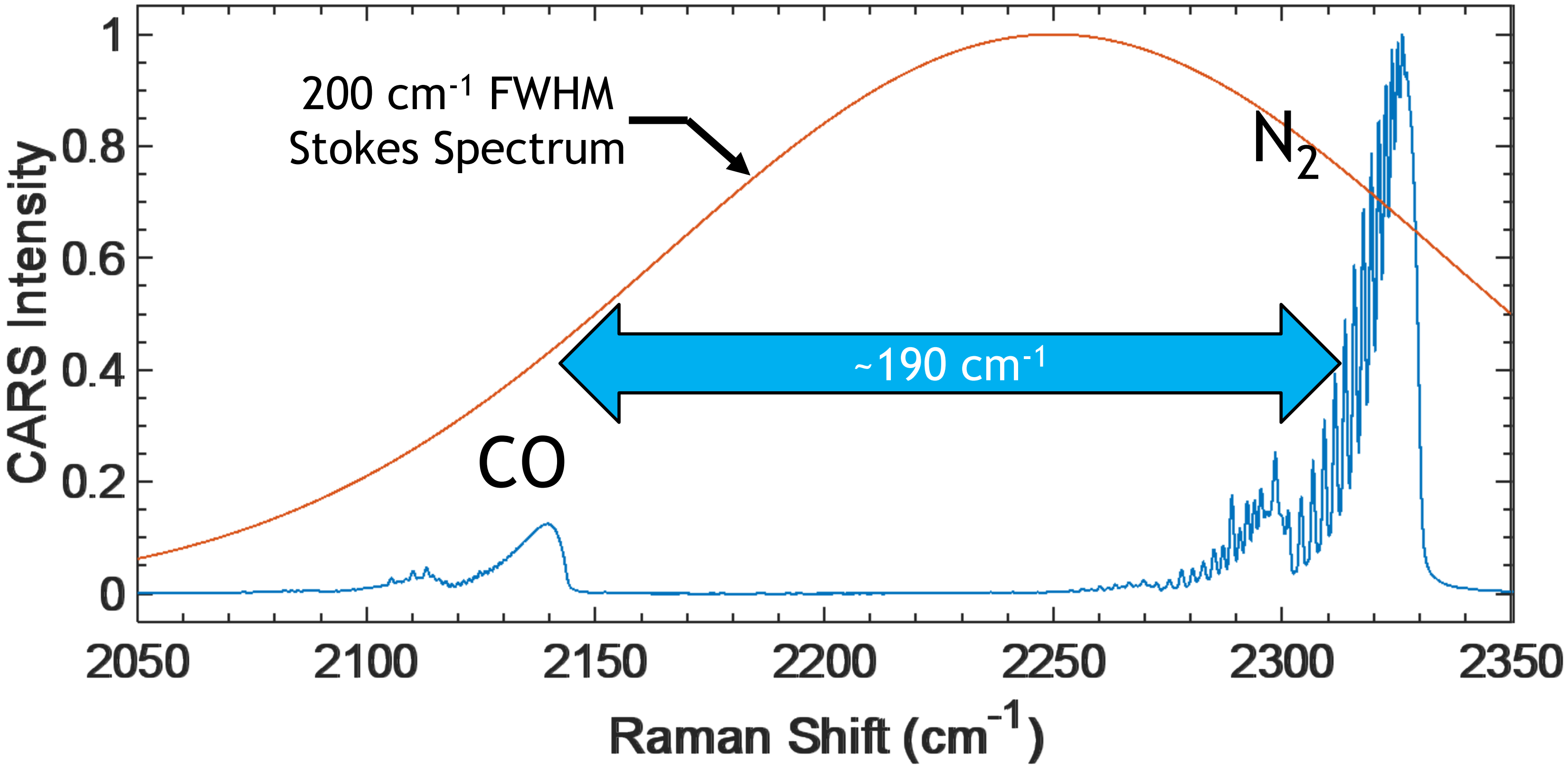
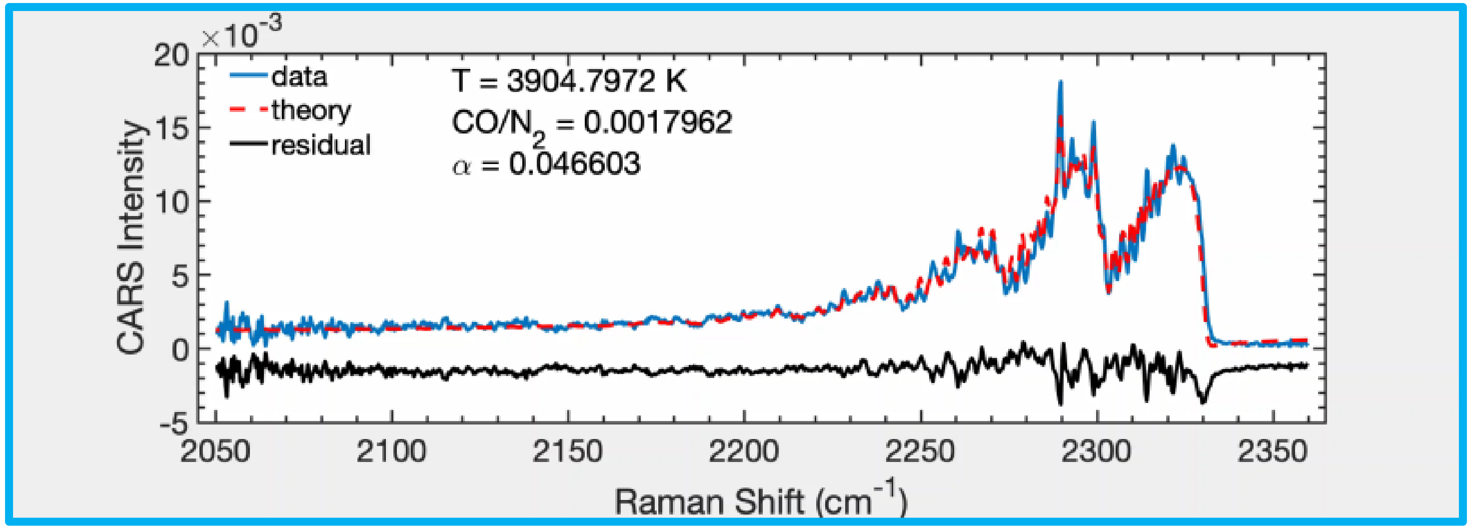


CARS measurements during graphite material sample tests

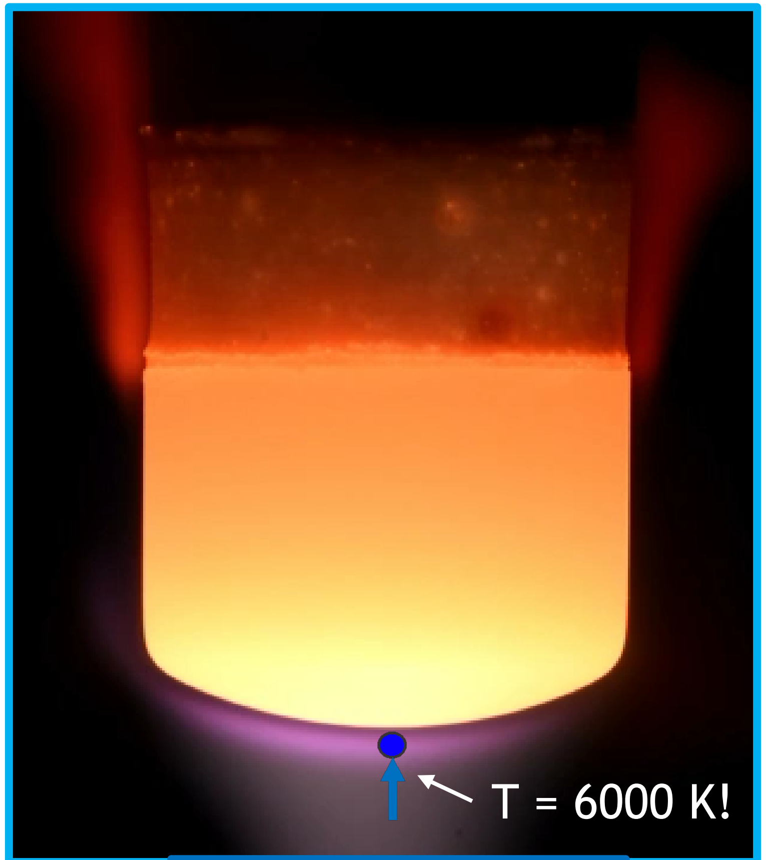
Proof-of-concept experiments

- Place CARS volume 500 μm from surface
- Move surface down (toward CARS) at 21 μm/sec
- Stop moving when CO signal is first detected
- Acquire 5-laser-shot accumulations



Fits to 5-laser-shot average CARS spectra

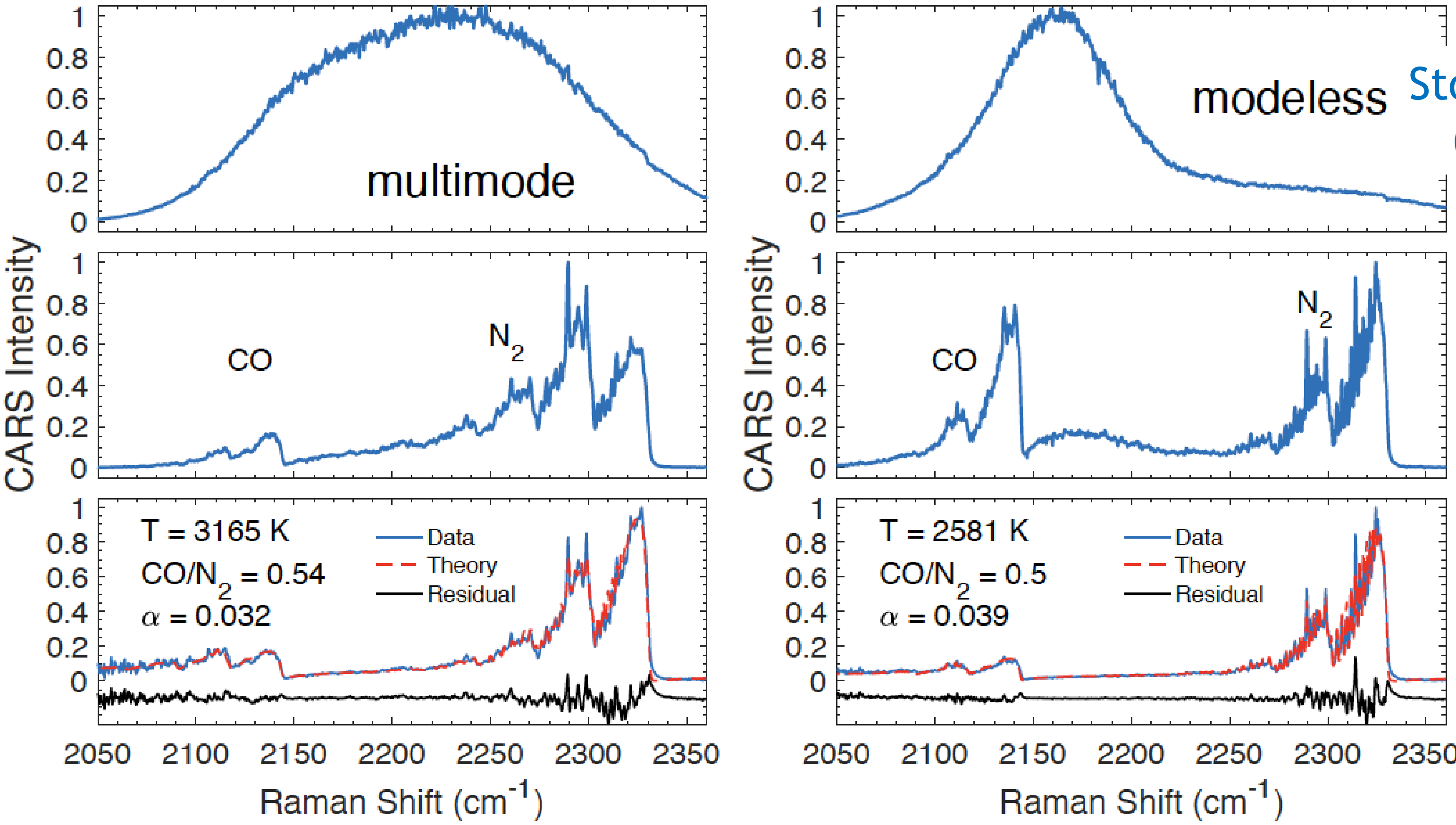
Graphite sample in torch plume



50-μm × 3-mm CARS volume

The Stokes spectrum could be optimized to enhance CO detection

- CO signal is much weaker
  - Low concentrations and N² scaling of CARS
  - Impact of Raman linewidths and spin statistics
- Modeless dye spectrum preferentially drives CO
  - Dynamic range optimization for weaker CO signal

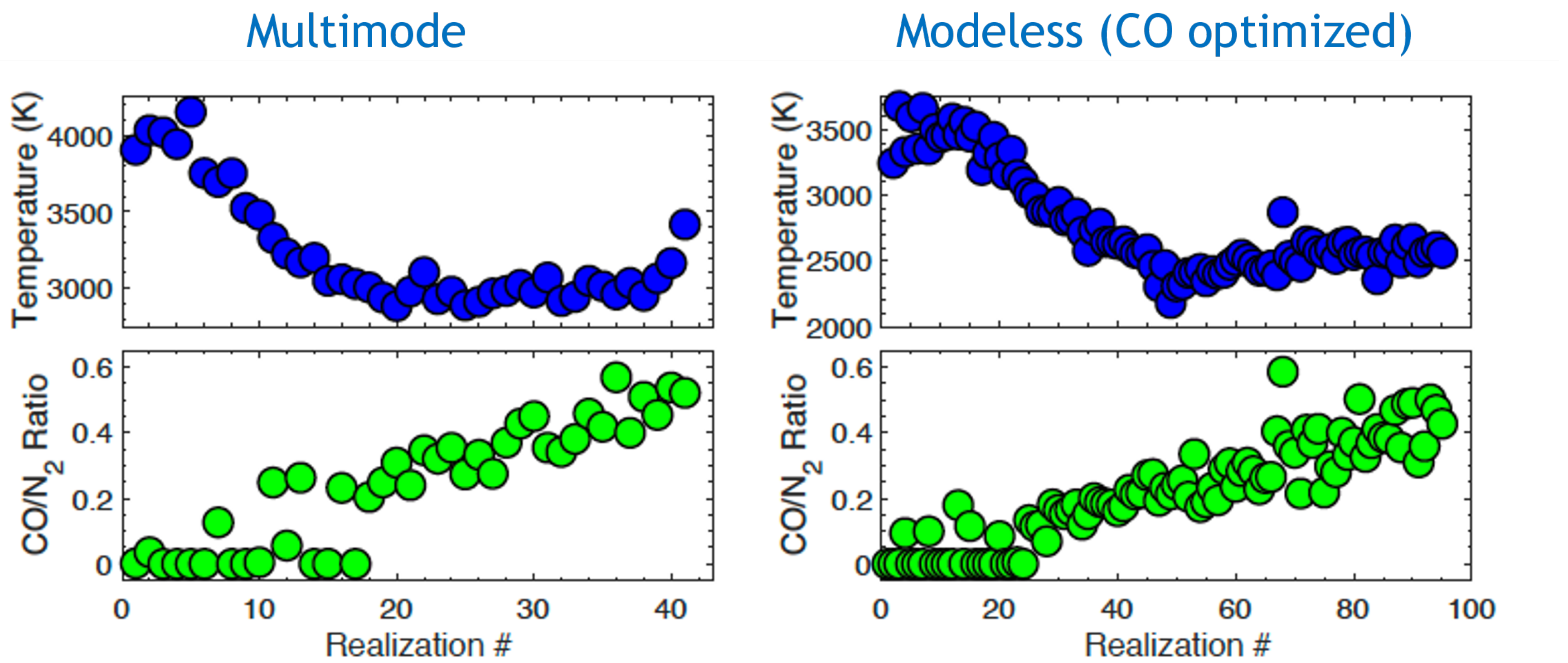


Stokes spectrum (argon CARS)

“raw” N_2, CO spectra

Normalized spectra with best-fit

Temperature/CO data



- CO/N_2 increases consistently throughout the experiment – *very high CO content in near-surface region*
- Sample is receding *away from CARS volume*
- Unsteady surface heating results in increased CO production through test
- Temperature fluctuations within about ±200 K within CO layer
- CO/N_2 scatter is larger than observed in temperature data

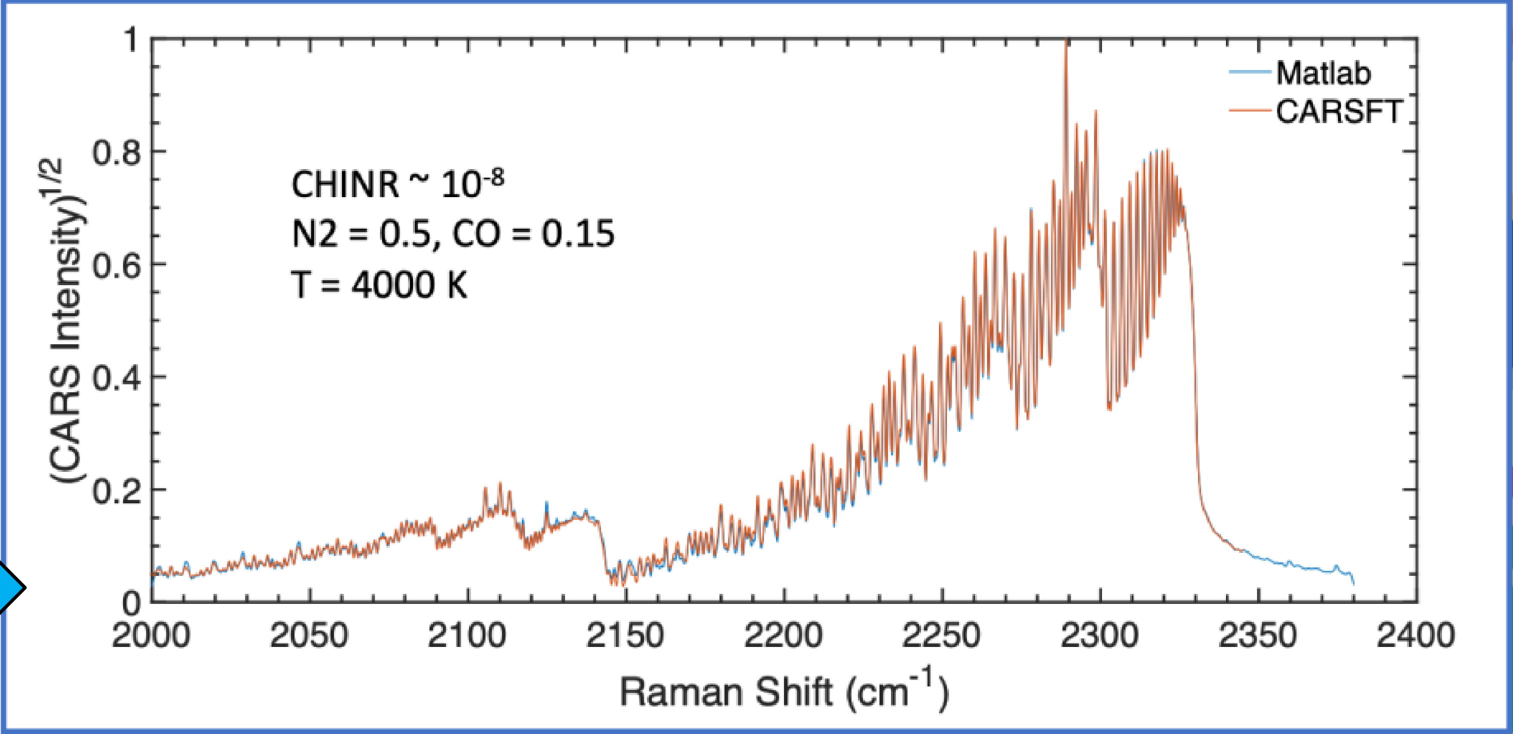
Some comments on CARS spectral modeling

- A Matlab-based code for CARS spectral modeling has been implemented
- Handles nanosecond, picosecond, and femtosecond CARS in a single *frequency domain* formulation
- Generalized Yuratich Eqaution (Marrocco et al.)

$$G(\omega;\tau)=\sum_{v,J}\Delta N_{v,J}\left(\frac{d\sigma}{d\Omega}\right)_{v,J}\int_{-\infty}^{\infty}\frac{E_3(\omega_3)e^{i\omega_3\tau}}{\left[\omega_{v,J}-(\omega_3-\omega)\right]-i\Gamma_J/2}d\omega_3$$

- Results here and in Fries et al. used collision-broadened linewidths (MEG)
- Doppler contribution is likely very significant at extreme temperatures encountered in the torch plume
- Fit T, CO/N_2, and χ_{NR} simultaneously. Uncertainty in χ_{NR} must be evaluated

Results verified against CARSFT and time-domain code for fs CARS



Summary, Conclusions, and Path Forward

- Nanosecond CARS has been demonstrated for temperature and CO detection at temperatures up to 3500-4000 K in an ICP torch environment
- CO is a dominant product of gas-surface chemistry in TPS applications
- Pointwise measurements in an unsteady thermal environment with surface recession increase uncertainties
- 1-D "line CARS" measurements can potentially yield complete profiles throughout the reaction layer on a limited number (TBD) of laser shots
- Simultaneous gas/surface measurements can provide a more complete picture of high-temperature TPS material physics