The University of Texas at Austin

# Simultaneous $N_2$ and CO measurements with broadband nanosecond CARS for graphite ablation in an inductively coupled plasma torch

---

**Dan Fries**, Spenser T. Stark, John. M. Murray, Rajkumar Bhakta, Sean P. Kearney,
Noel T. Clemens, Philip L. Varghese

Gordon Research Seminar - Laser Diagnostics in Energy and Combustion Science · July 9th, 2023 · Newry, ME

ODEN INSTITUTE

PECOS
Predictive
Engineering &
Computational Science

https://pecos.oden.utexas.edu

The University of Texas at Austin
Aerospace Engineering
and Engineering Mechanics
*Cockrell School of Engineering*

# Acknowledgements

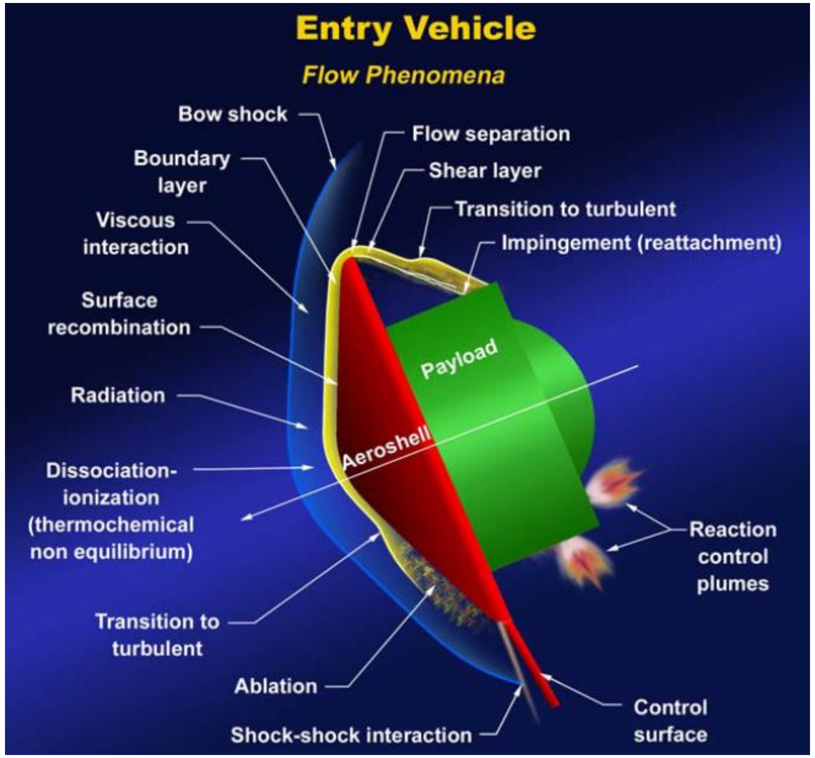
This material is based upon work supported by the Department of Energy, National Nuclear Security Administration under Award Number DE-NA0003969.

**Faculty & Staff:** Noel T. Clemens, Philip L. Varghese

**Graduate students at UT:** Spenser T. Stark, John. M. Murray

**Collaboration** with Sean P. Kearney and Rajkumar Bhakta from Sandia National Laboratories: a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

# Development of Thermal Protection Systems (TPS)



Hypersonic atmospheric re-entry: Horvath et al., *NASA Langley Tech. rep.* NASA Langley Research Center (2004)

- TPS are used for
  - spacecraft during atmospheric re-entry.
  - hypersonic aircraft during flight.
- Processes at TPS are complex multi-physics problems.
- Radiative heat load has big impact on TPS design and weight[1].
- Graphite based TPS: CN is a strong radiator.

→CN concentration influenced by reactions forming: N, O, and CO[2,3].

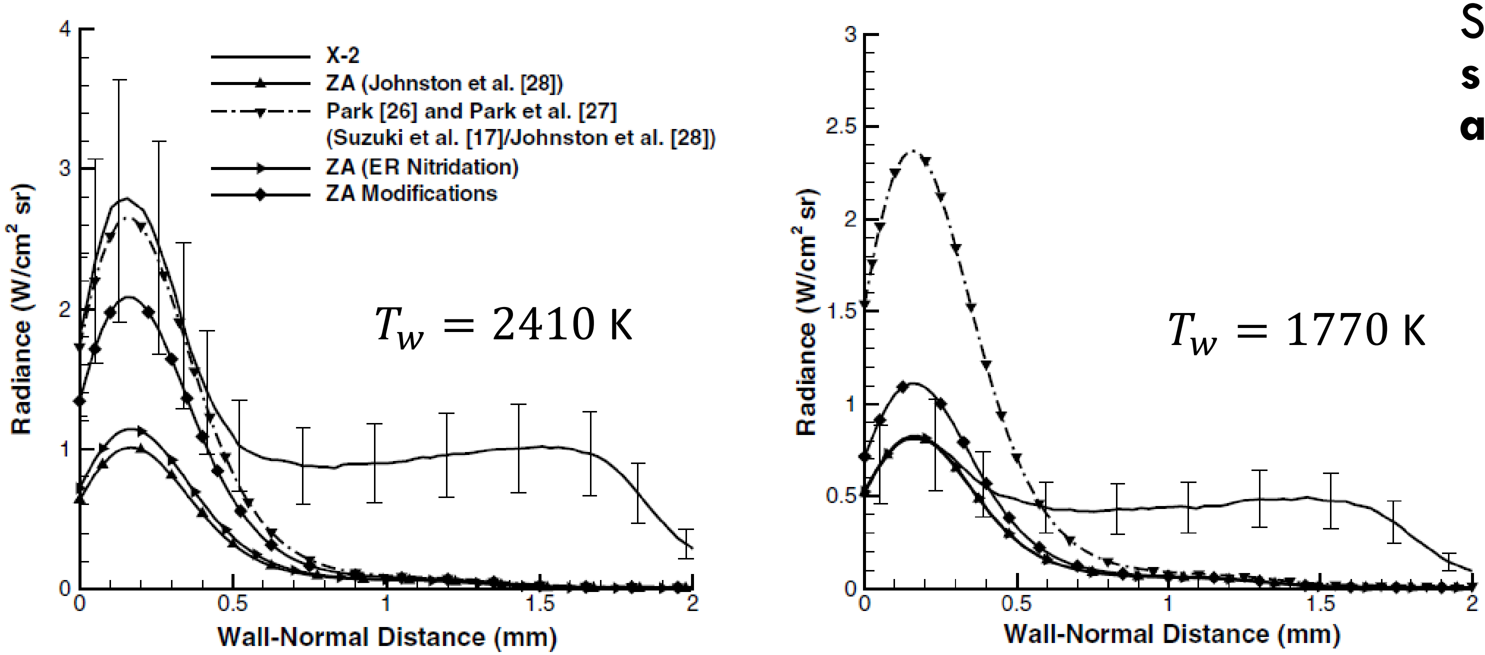
[1] Caillault et al., "Radiative heating predictions for Huygens entry". *J. of Geophys. Res.: Planet* (2006)
[2] Park et al., "Chemical-Kinetic Parameters of Hyperbolic Earth Entry". *J. Thermophys. Heat Tr.* (2001).
[3] Alba et al., "Development of a nonequilibrium finite-rate ablation model for radiating earth reentry flows". *J. Spacecraft Rocket (2016)*

# Challenges in the Development of Thermal Protection Systems

- Different models disagree with each other[1]
- Models have disagreed with experiments[2]
- More recently: new model development[3] using molecular beam experiments[4]

- Judging model accuracy requires additional experimental data
- Oxidation processes are of great interest for radiation predictions[2]

→ Utilize nanosecond multiplex Coherent Anti-Stokes Raman Scattering (CARS) to enable the **spatially resolved** simultaneous probing of **CO and N2**



Figures from Alba et al. [2], results for different wall temperatures

[1] MacLean et al., “Finite-rate surface chemistry model, II: Coupling to viscous Navier-Stokes code”. *42nd AIAA Thermophysics Conference* (2011)

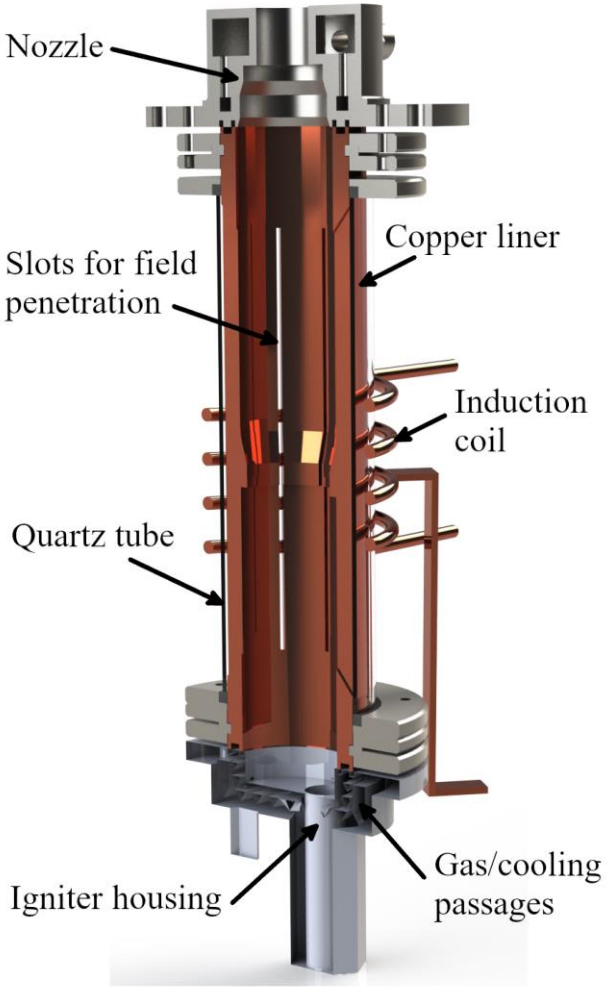
[2] Alba et al., “Development of a nonequilibrium finite-rate ablation model for radiating earth reentry flows”. *J. Spacecraft Rocket (2016)*

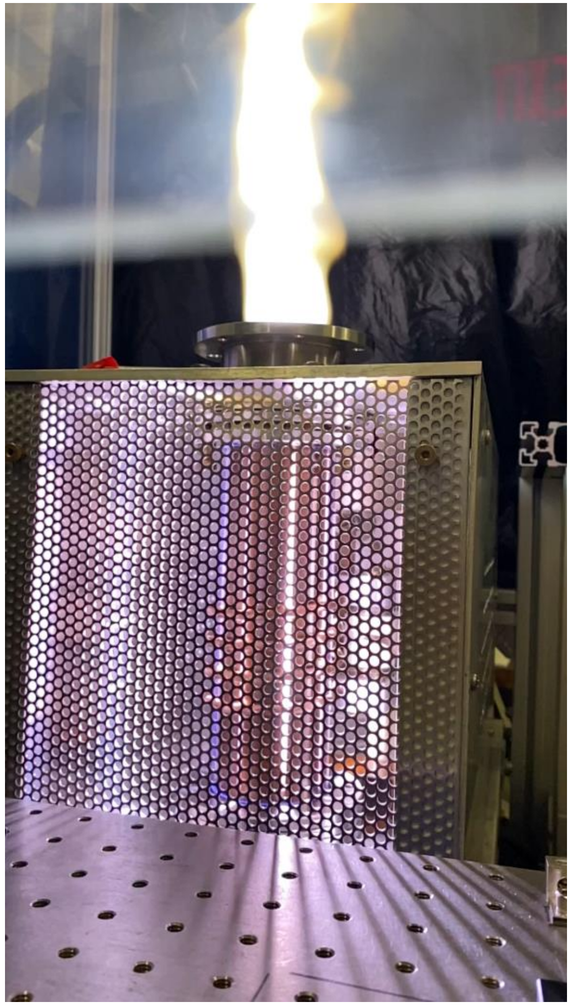
[3] Poovathingal et al., “Finite-rate oxidation model for carbon surfaces from molecular beam experiments”. *AIAA J.* (2017)

[4] Murray et al., “Inelastic and reactive scattering dynamics of hyperthermal O and O2 on hot vitreous carbon surfaces”. *J. Phys. Chem. C* (2015)

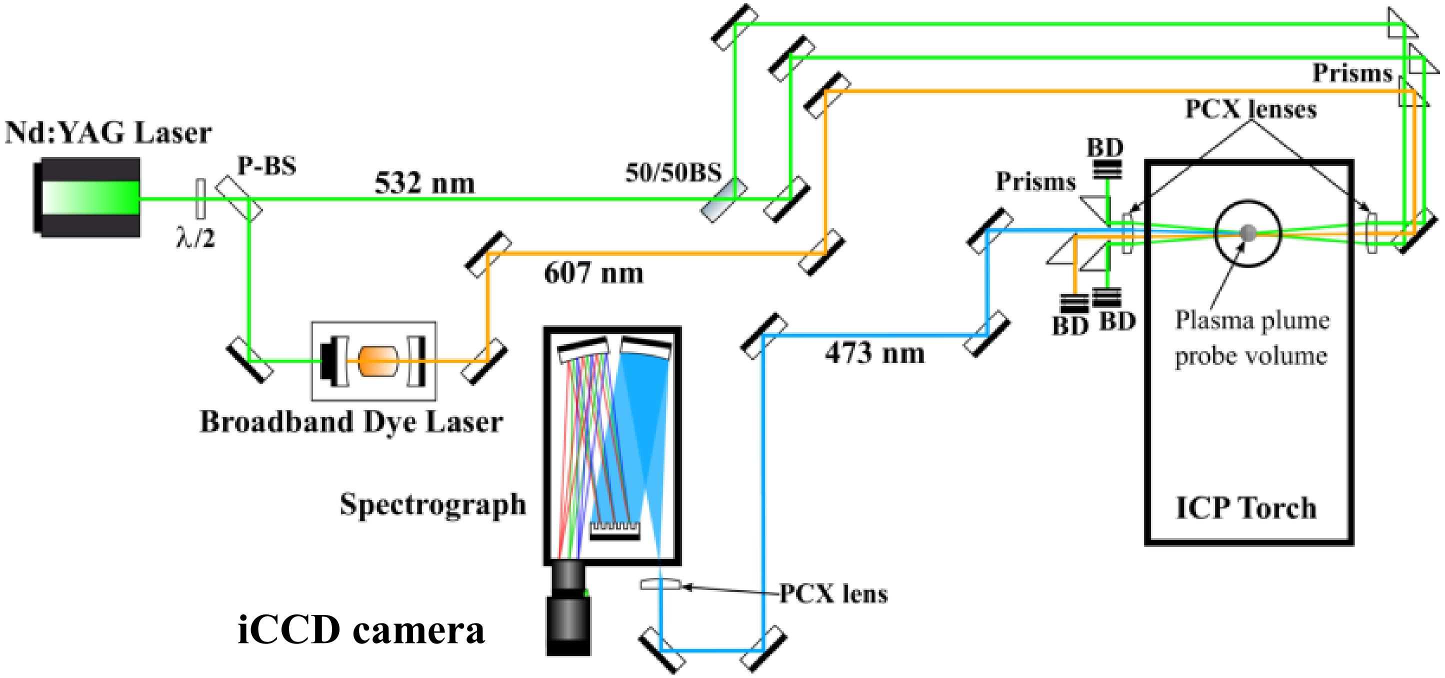
# Experimental Setup – Inductively Coupled Plasma Torch

- Atmospheric pressure
- Nozzle diameter 30 mm
- Air plasma
- Exit velocity ~15 m/s
- Exit temperature ~6000 K @ 5-20 mm from the nozzle exit
- Plume conditions near thermodynamic equilibrium

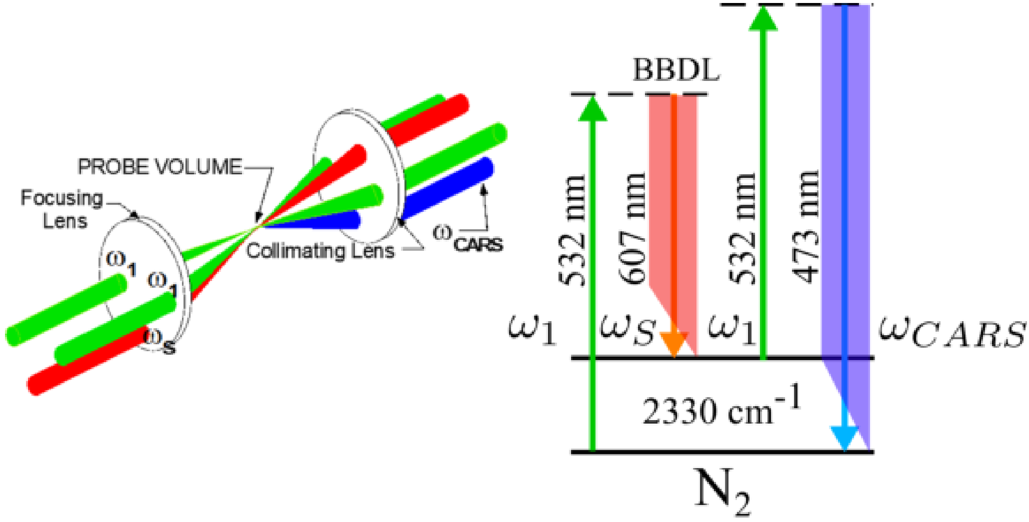


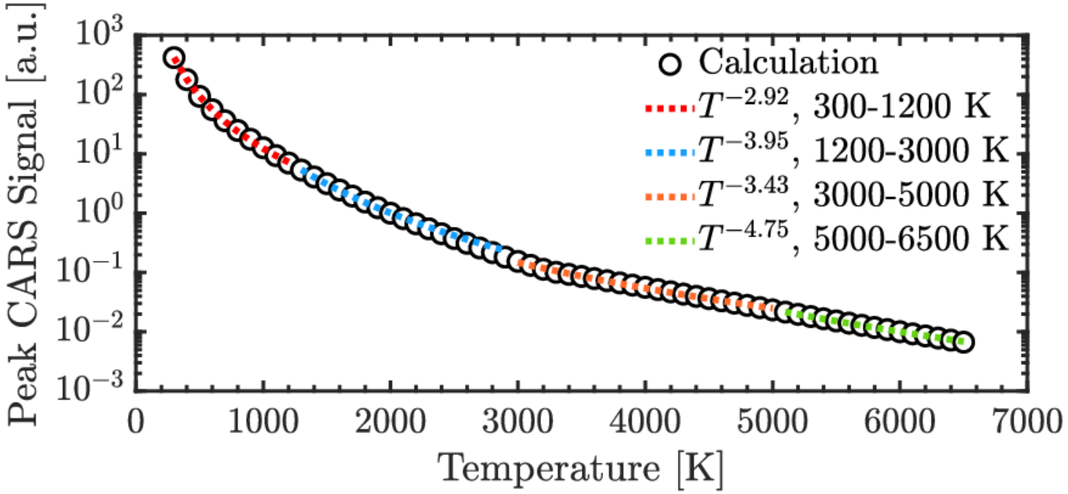


# Broadband ns Multiplex CARS – $N_2$ Thermometry

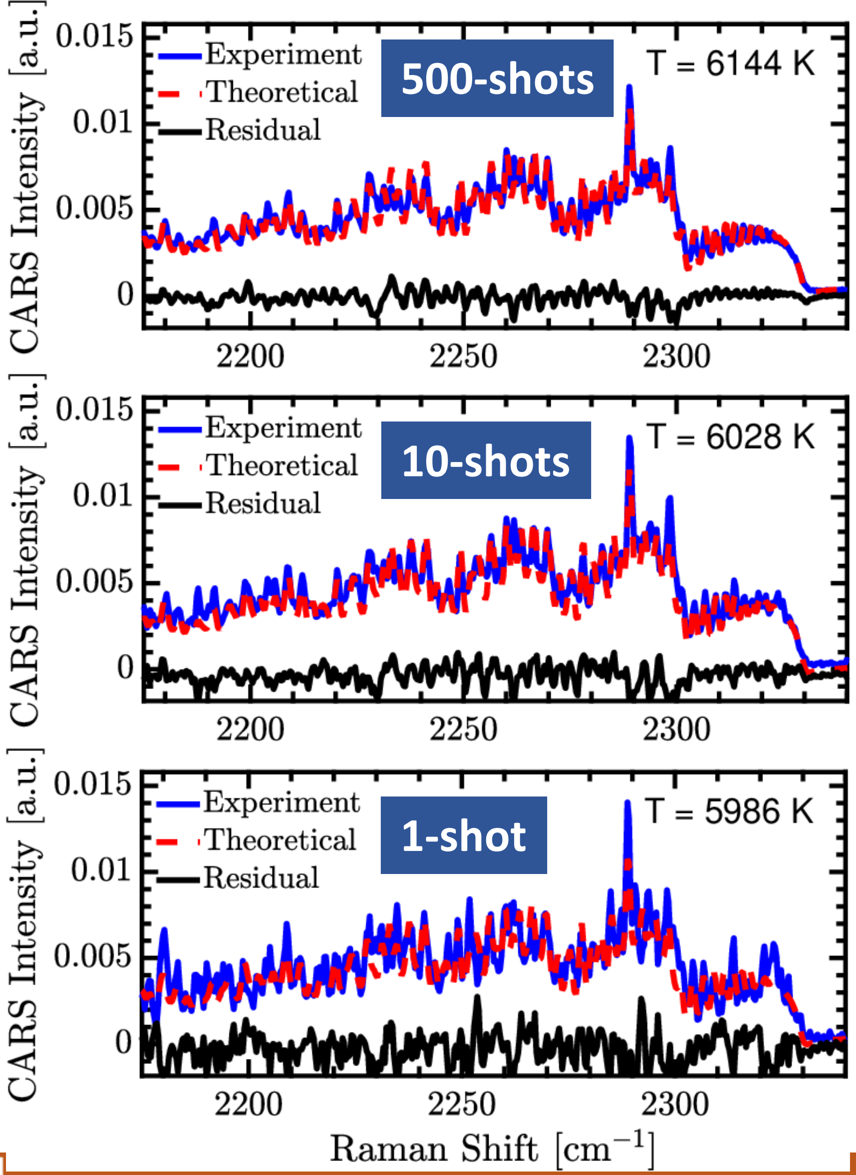


0.75 m Czerny-Turner spectrograph, 1800 g/mm grating

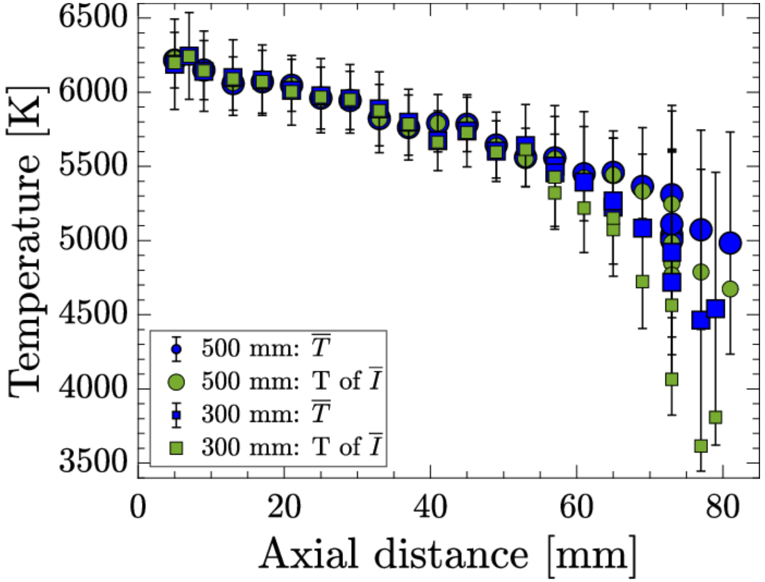




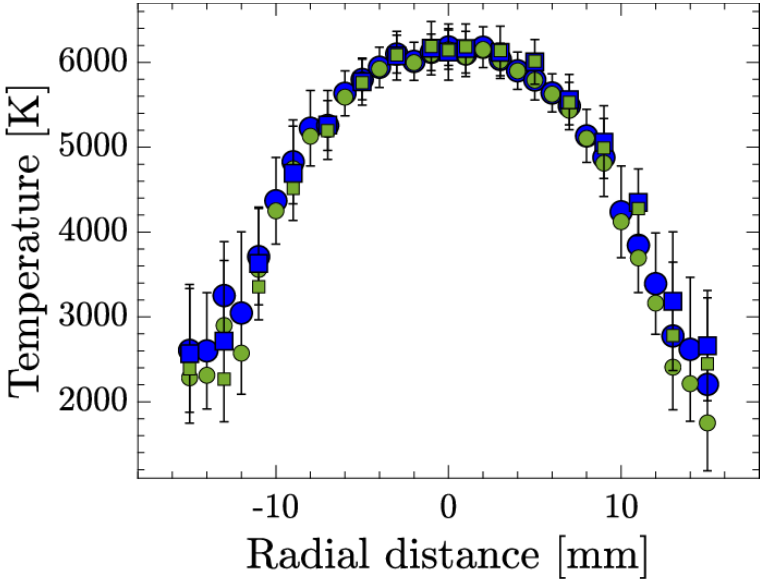
# N2 Thermometry



**On centerline**



**5 mm above nozzle**



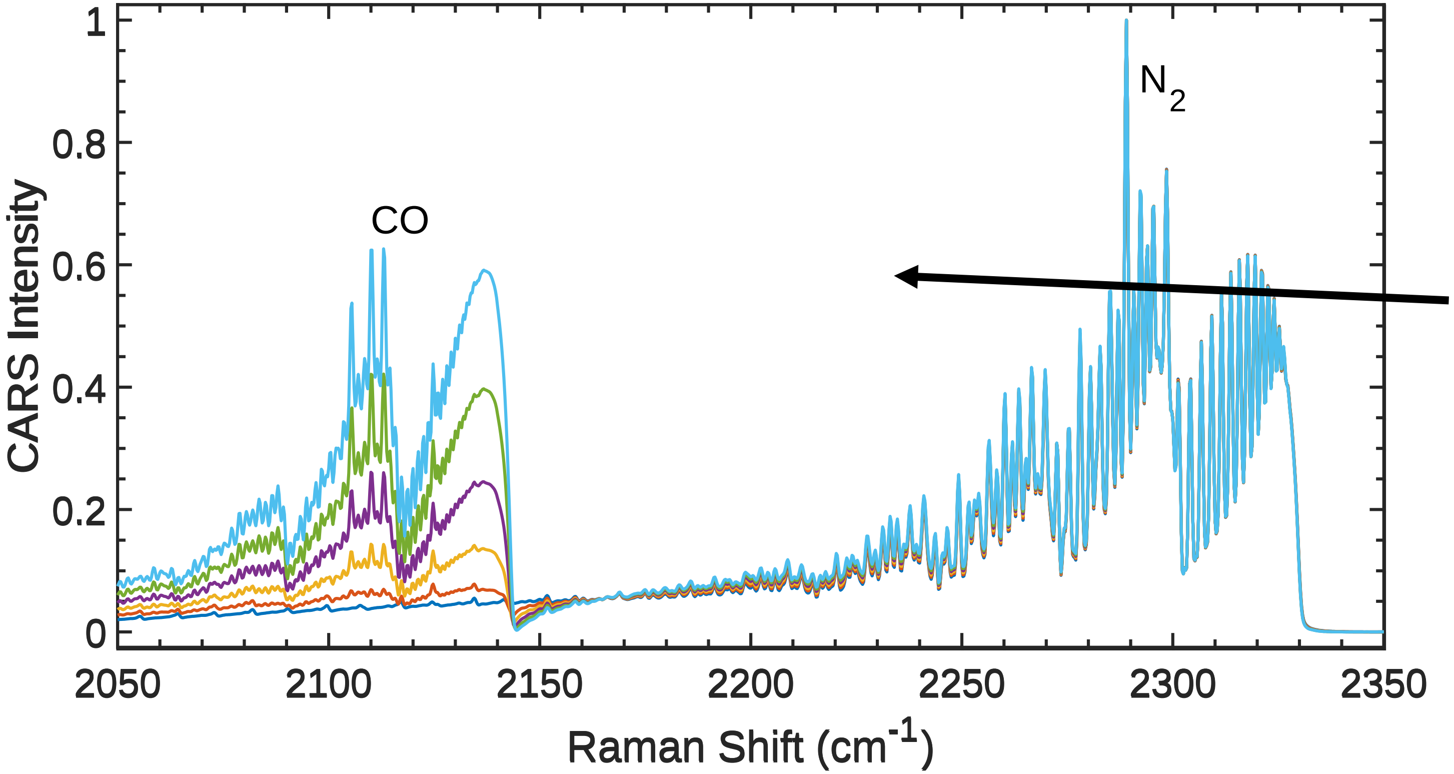
- Spectral fits with MATLAB implementation of Yuratich formalism [2]: temperature, non-resonant background.
- Temperature profiles: single shot and accumulated signal data.

[1] Fries et al., “Nitrogen Thermometry in an Inductively Coupled Plasma Torch using Broadband Nanosecond Coherent Anti-Stokes Raman Scattering”. *In preparation* (2023)
[2] Yuratich, “Effects of laser linewidth on coherent anti-Stokes Raman spectroscopy”. *Molecular Physics* (1979)

# Stokes Source Tuning and Optimization for $N_2$/CO

To probe $N_2$ and CO simultaneously:

- Need broad Stokes source spectral profile.
- Need sufficient sensitivity to relatively lower CO concentration.



**Pump CO 10-20X harder!**

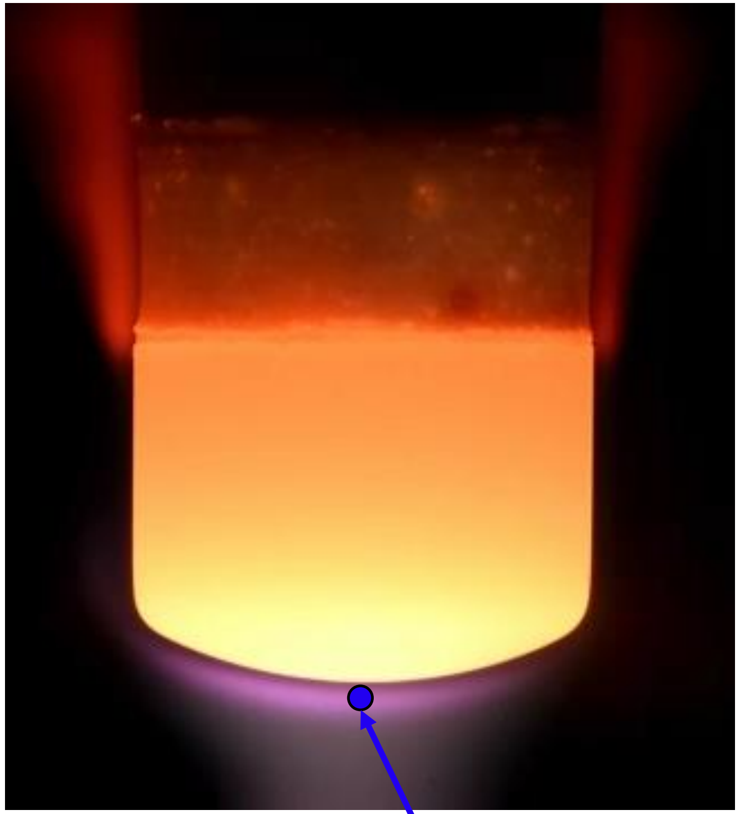
→ Rhodamine 610 and 640 to achieve $\lambda_c = 600 - 610$ nm and FWHM of 160-200 cm$^{-1}$.

# Testing of Iso-q Graphite Samples

- Iso-q graphite sample with Ø30 mm.
- CARS positional accuracy ±80 μm
- About 90 s to steady state surface temperature and recession rate.
  → ~1 mm/min

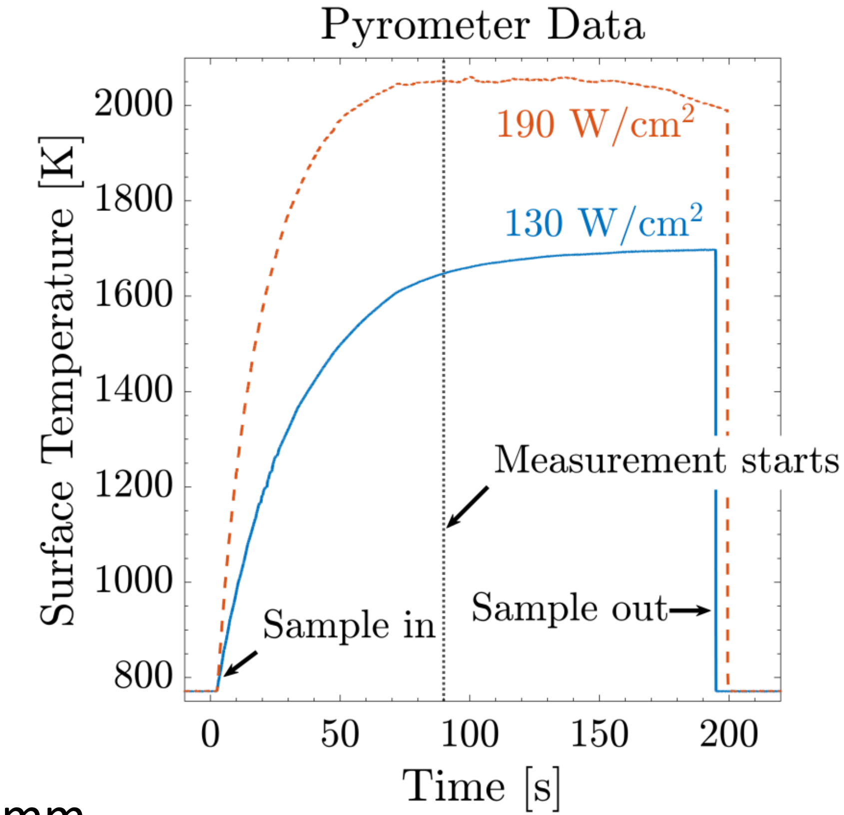
**Two test cases**

1. 10 kV anode voltage, 0.6 g/s tangential
   → ~130 W/cm$^2$, $T_s$~1700K (avg.)
2. 11.3 kV anode voltage, 0.4 g/s tangential + 0.3 g/s axial
   → ~190 W/cm$^2$, $T_s$~1980 K (avg.)



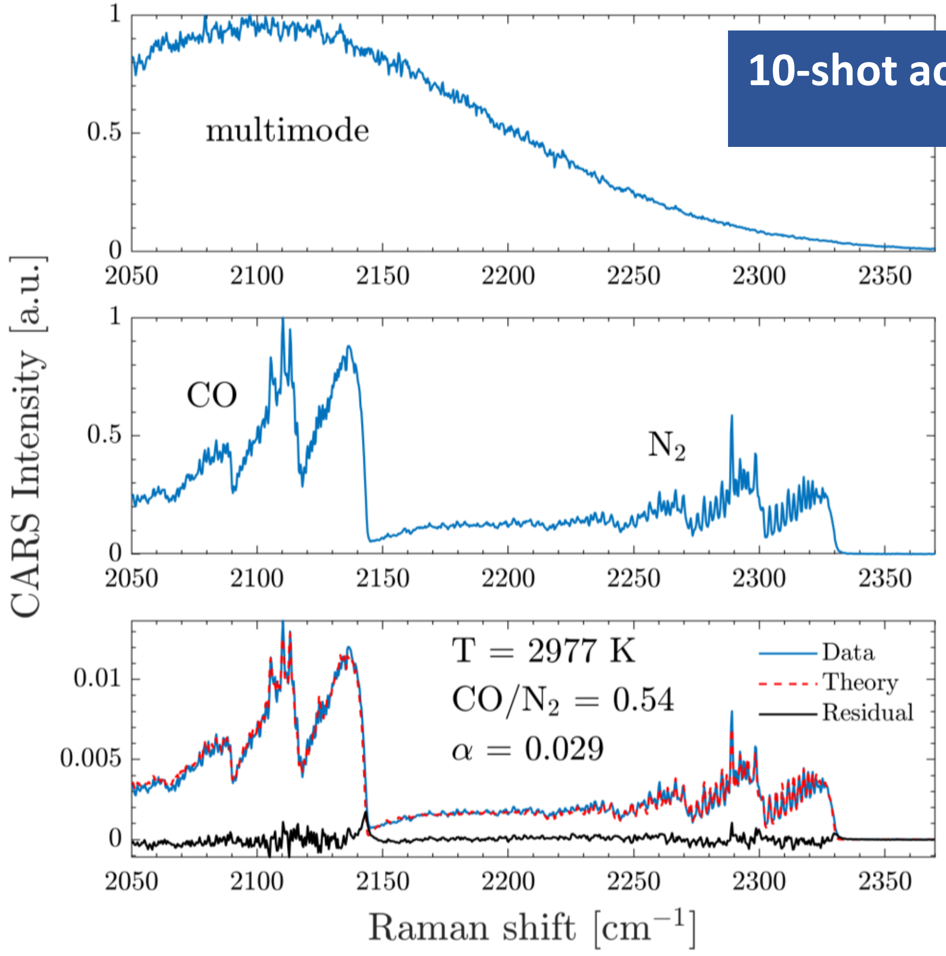
T = 6000 K approach air stream

50 μm x 4.5 mm CARS volume



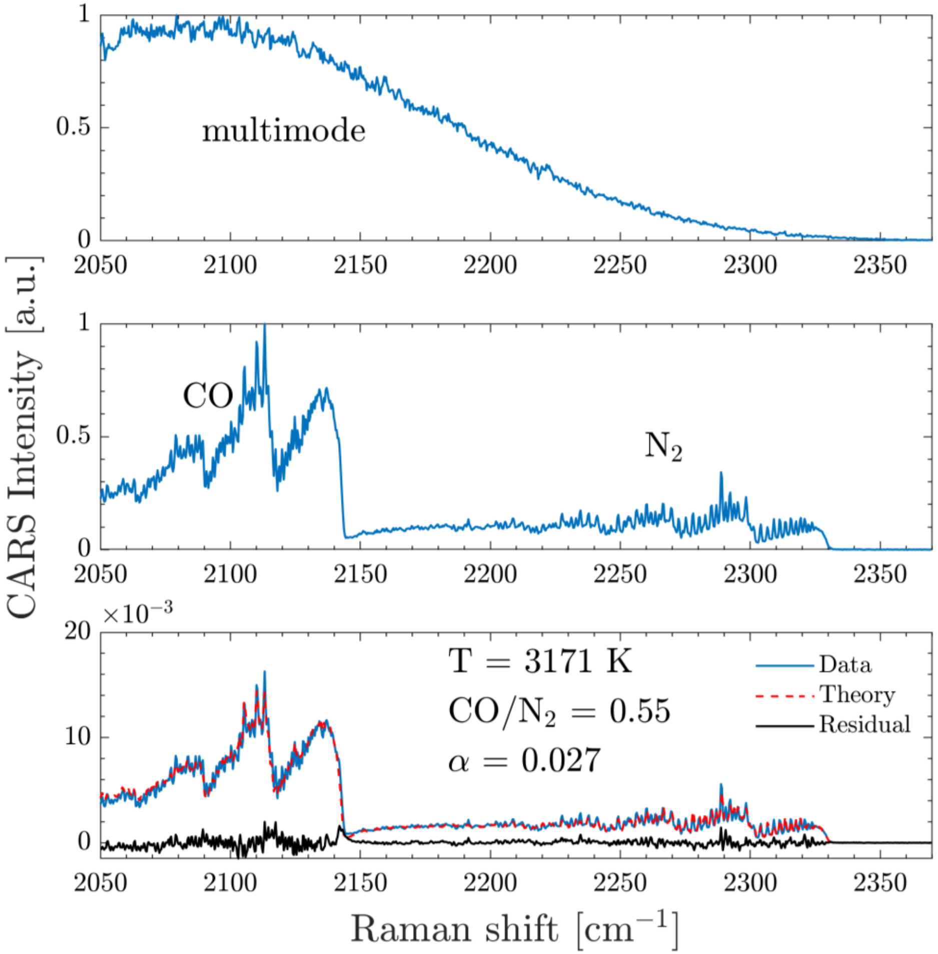
# Broadband ns CARS – Simultaneous Probing of CO and $N_2$

**Heat flux ~130 W/ cm²**



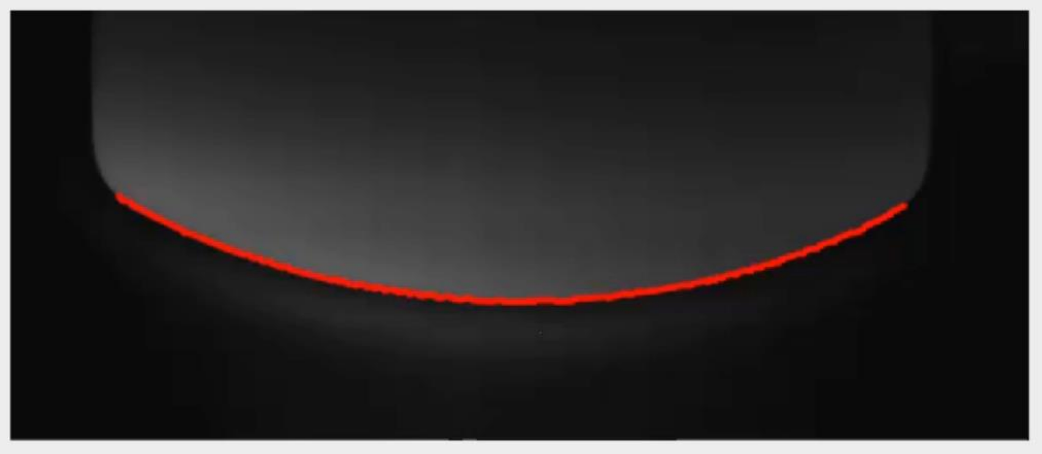
**10-shot accumulation**

**Heat flux ~190 W/cm²**

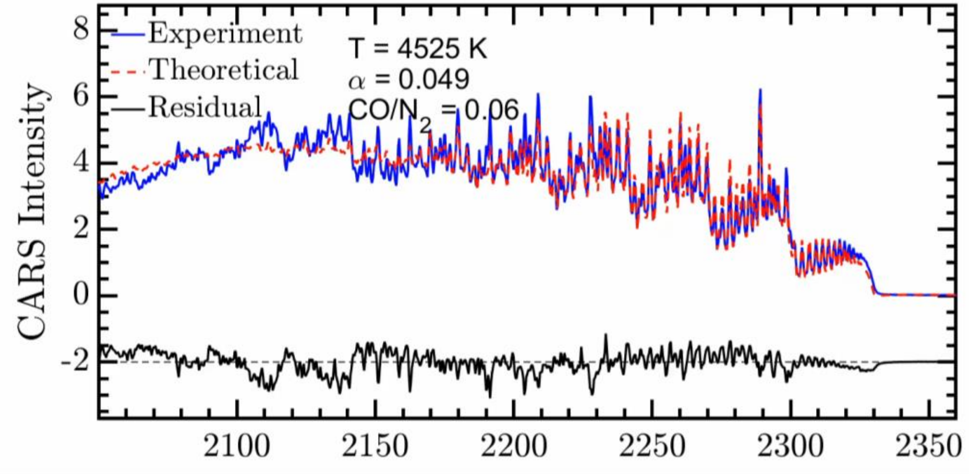


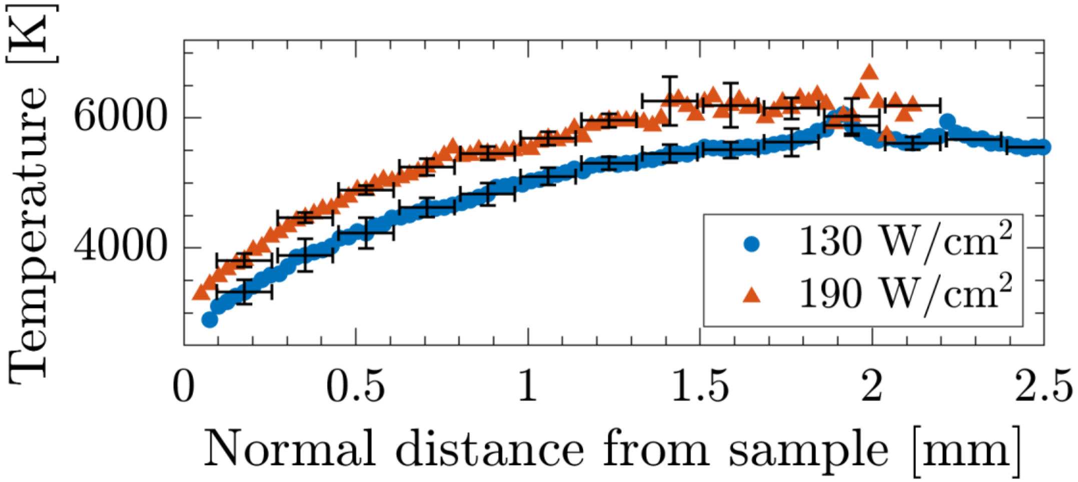
# Temperature and Relative Concentration Profiles

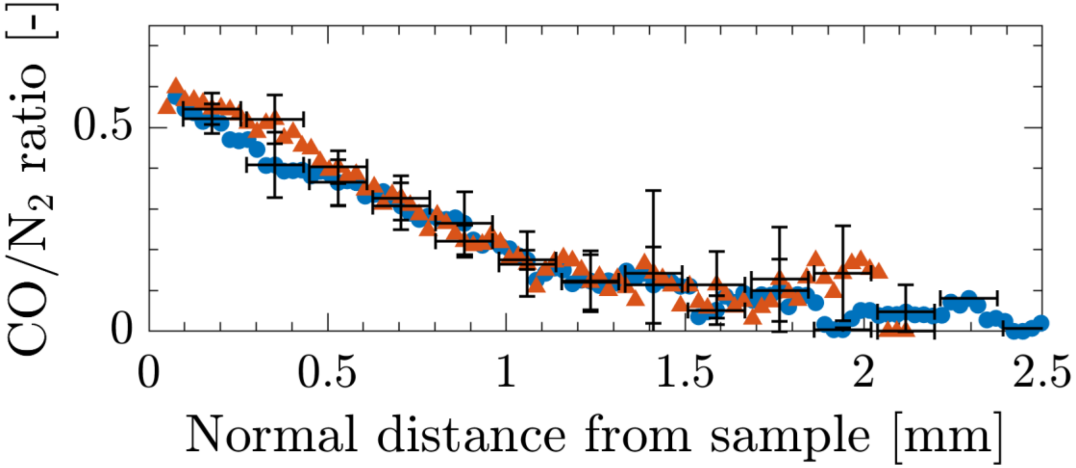
**Surface tracking**



**Spectrum evaluation**



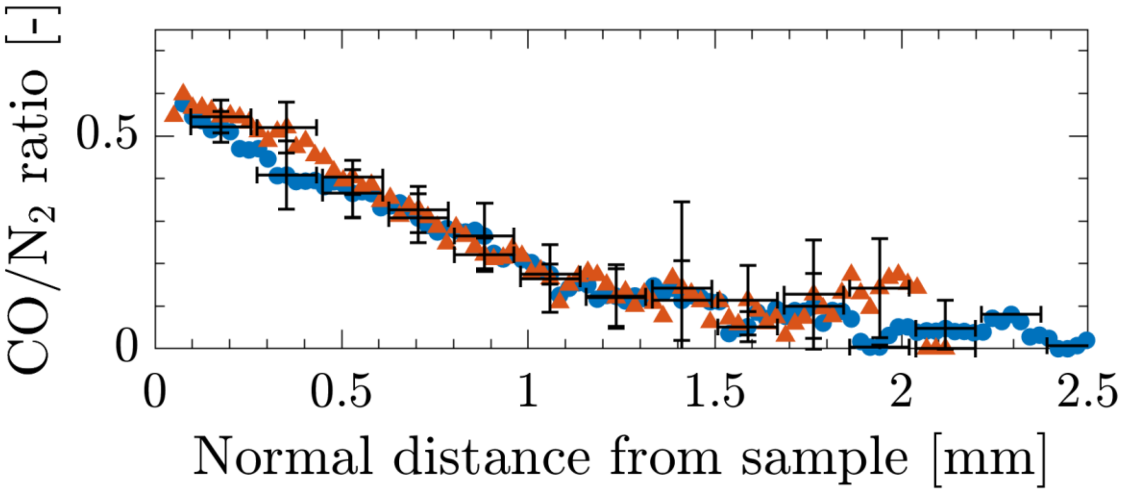




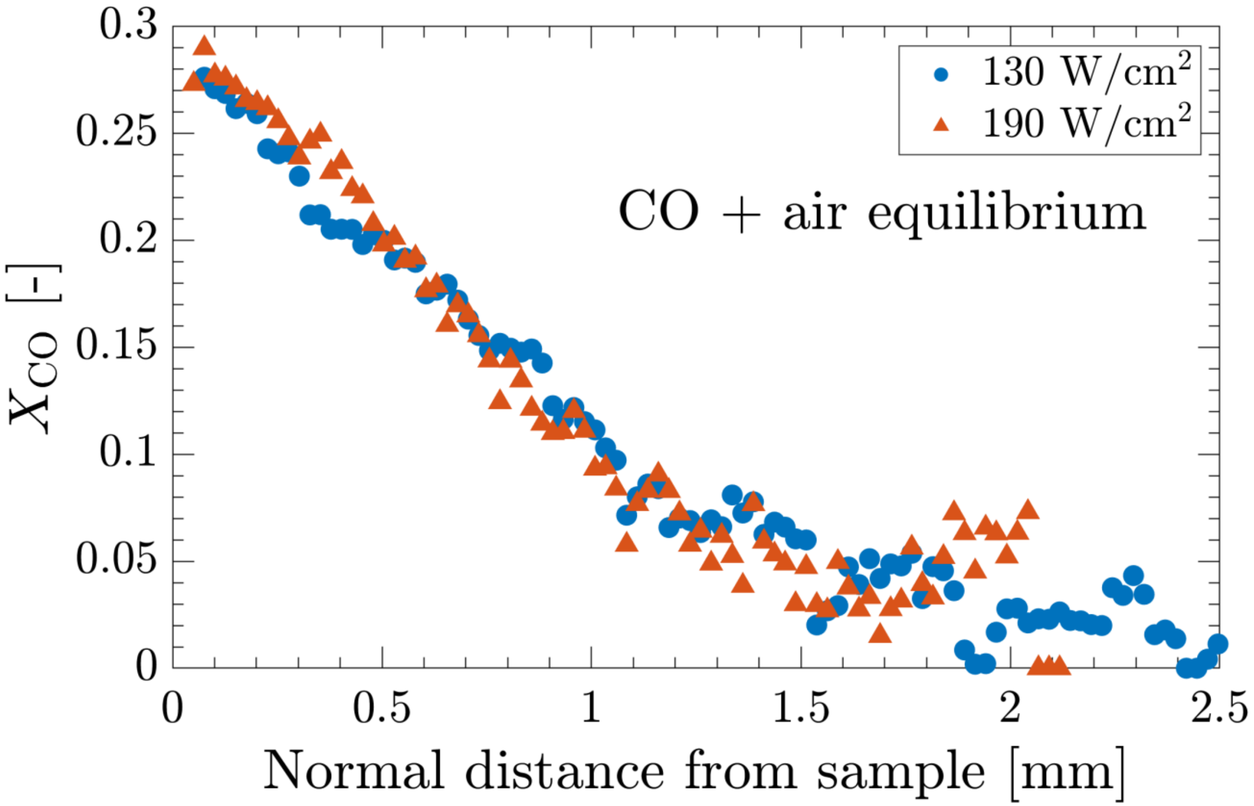
- Average of four data sets each.
- Vertical error bars represent $1\sigma$ of data series.

# Relative Concentrations and Equilibrium Estimate

**Relative CO mole fraction**



**Equilibrium CO mole fraction**



CO mole fraction determined using NASA CEA equilibrium calculations:

- CO + air.
- Get $X_{CO}$ via root finding at measured CO/N2 ratio and temperature.

# Conclusions

- Tailoring the Stokes spectral profile improves CO detectability.
- Peak CO concentration close to the sample surface:
  → ~60% of the N2 concentration .
  → mole fraction of ~28% based on equilibrium CO + air mixture.
- Similar amounts of CO close to the sample surface for both $\dot{q}''$ cases.

## Future Work

- Quantify detectability limit of CO, accuracy, and sensitivity of results to three-parameter fits.
- Compare measurements to phenomenological and finite rate graphite ablation models.

**Thank you for your attention**

**Questions?**

**Poster 45**

**Contact: dan.fries@austin.utexas.edu**

**LinkedIn: Dan Fries**