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Mid-Infrared Laser Absorption Spectroscopy Measurements of Temperature, Pressure, and NO $X^2\Pi_{1/2}$ at 500 kHz in Shock-Heated Air

Morgan D. Ruesch[1], Jonathan J. Gilvey[2], Christopher S. Goldenstein[2], Kyle A. Daniel[3], Charley R. Downing[3], Kyle P. Lynch[3], Justin L. Wagner[3]

[1]School of Aeronautics and Astronautics Engineering, West Lafayette, IN

[2]School of Mechanical Engineering, Purdue University, West Lafayette, IN

[3]Engineering Sciences Center, Sandia National Laboratories, Albuquerque, NM

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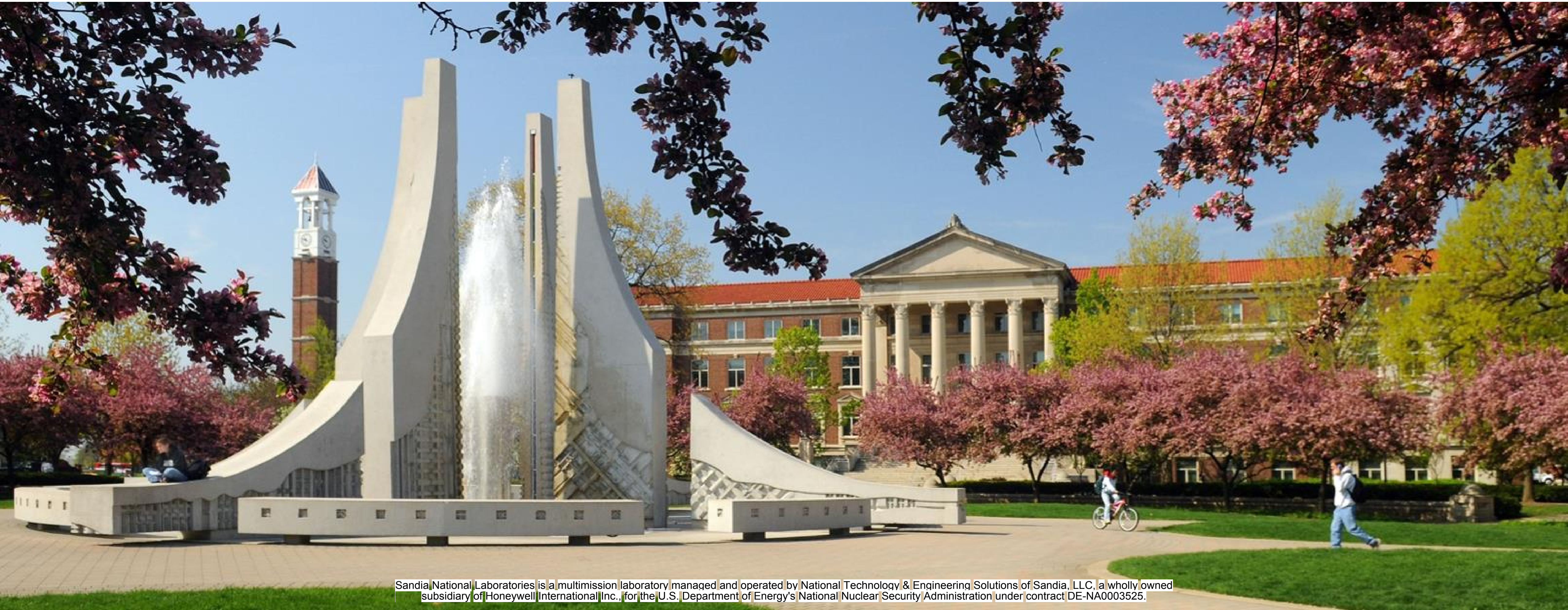

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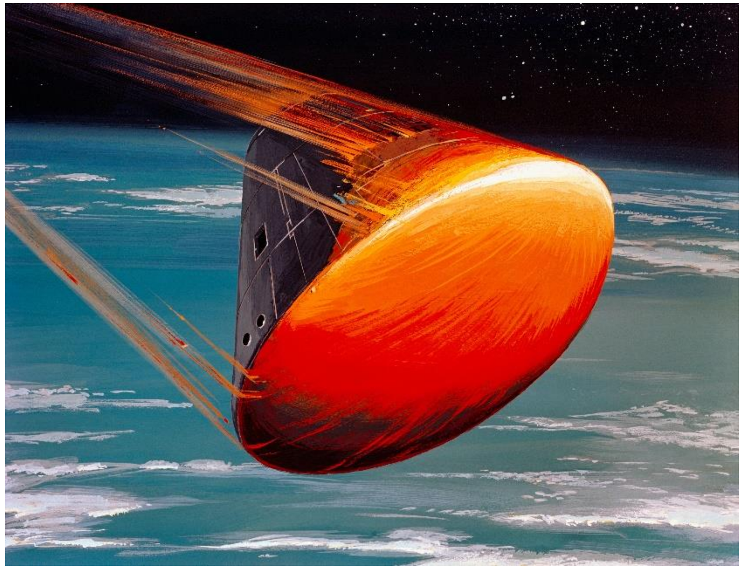
Motivation

Thermochemical process occurring in shock-heated air are poorly understood.

Understanding is critical to many applications including:
- Hypersonic vehicles
- Spacecraft re-entry
- Explosive blasts

High Temperature Shock Tube (HST) at Sandia National Laboratories:
  - Free-piston shock tube generates strong shocks for studying extreme conditions



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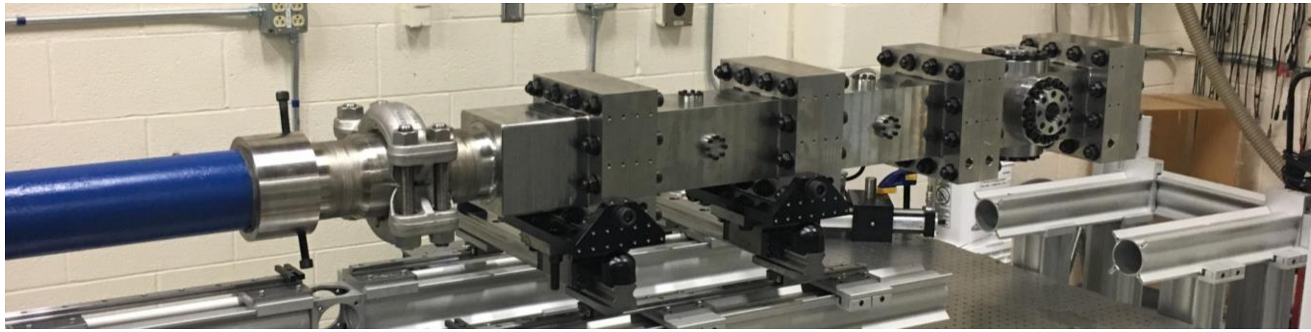

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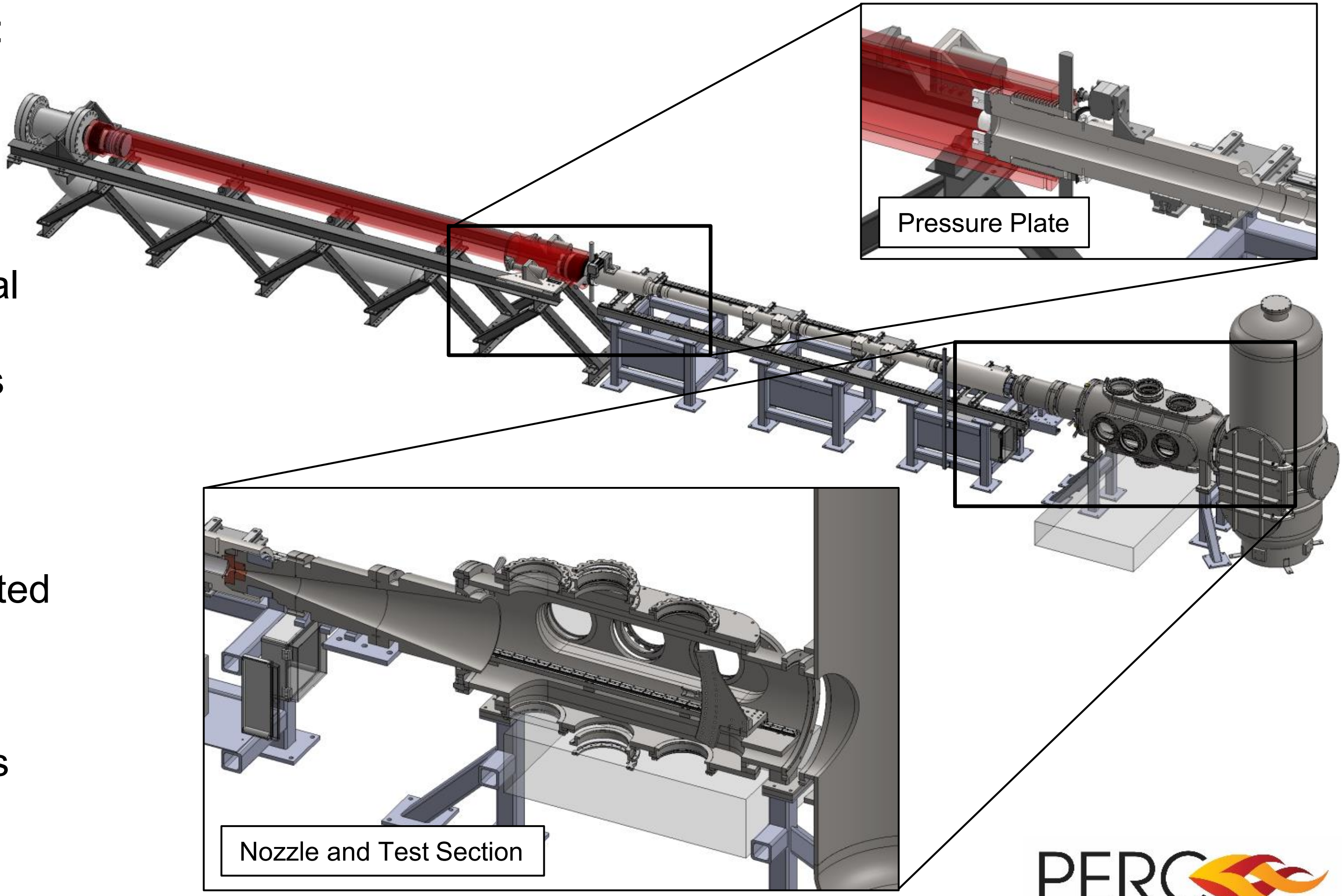
Need: diagnostics capable of characterizing shock heated air at high-T (>3000 K) with near MHz resolution

1. Characterize operation of the HST
2. Measurements in shock heated air in conditions relevant to explosive blasts

HST-R



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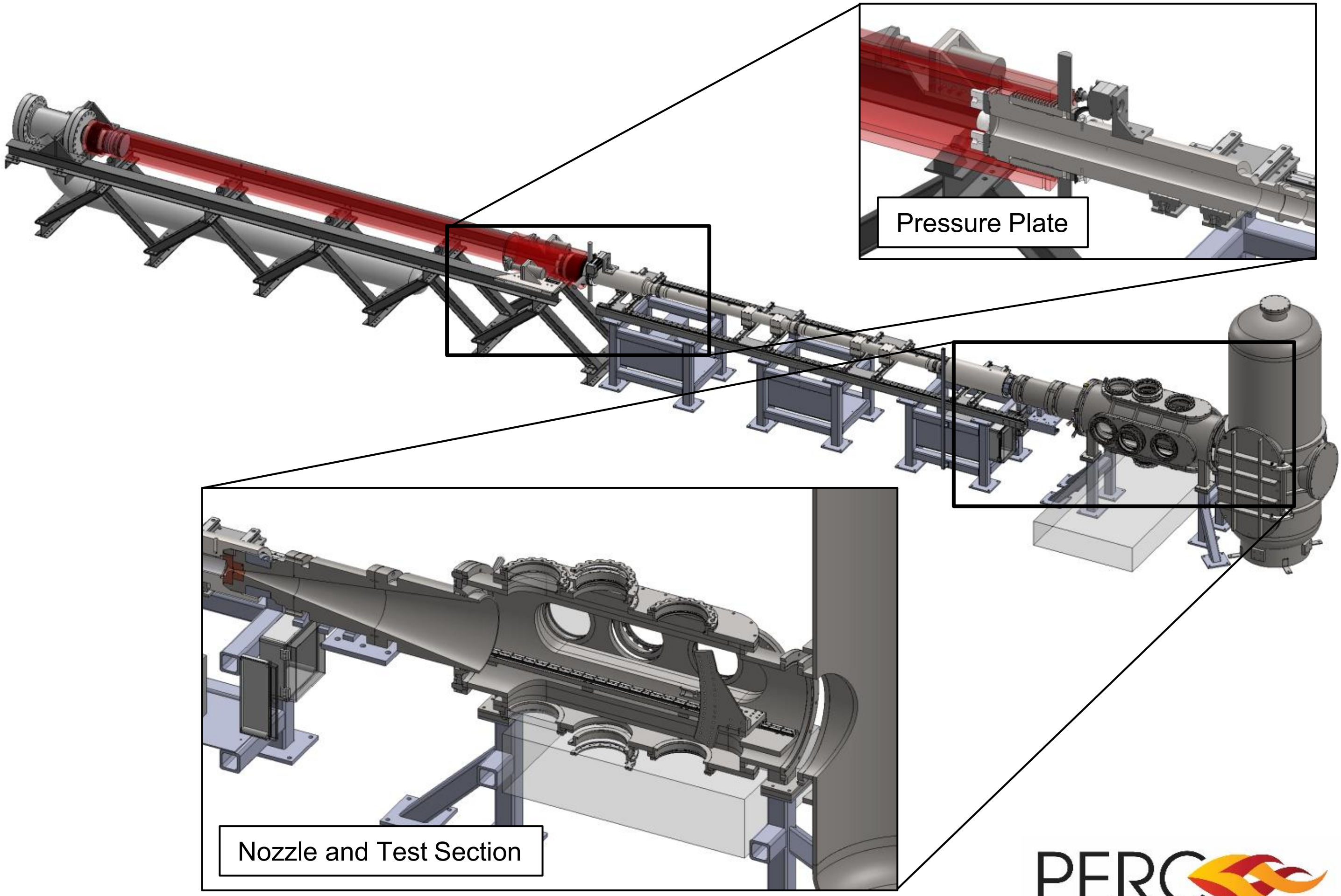
Motivation and Goal

Target Species: Nitric Oxide (NO)

Goal: Design a LAS diagnostic capable of near-MHz measurements of T, P, and NO mole fraction in shock heated air within the HST.

- Temperatures ranging from ~3000 K to 5500K
- Pressures from ~1 to 10 atm

HST-R



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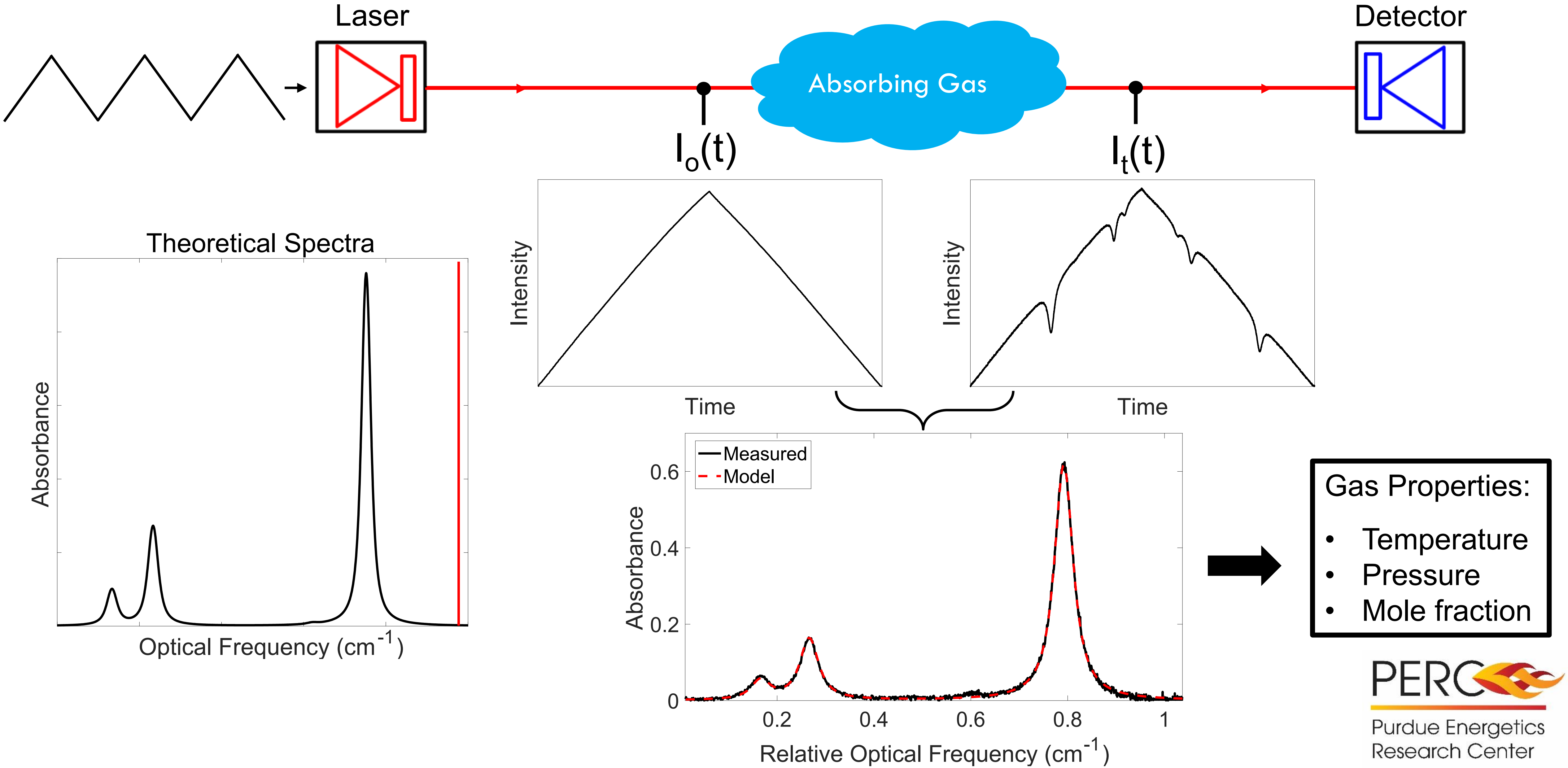
Technical Approach: Scanned-DA



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Technical Approach: m-FID

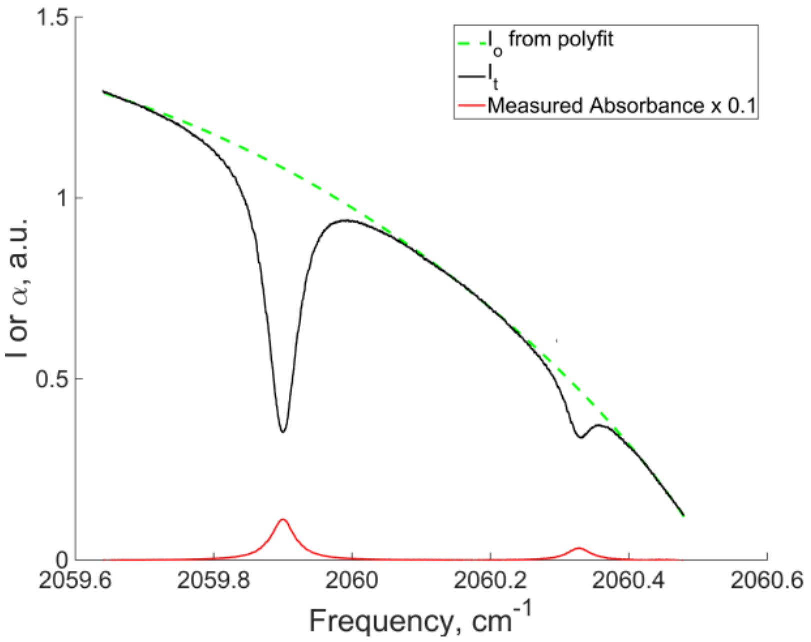
Beer-Lambert Law

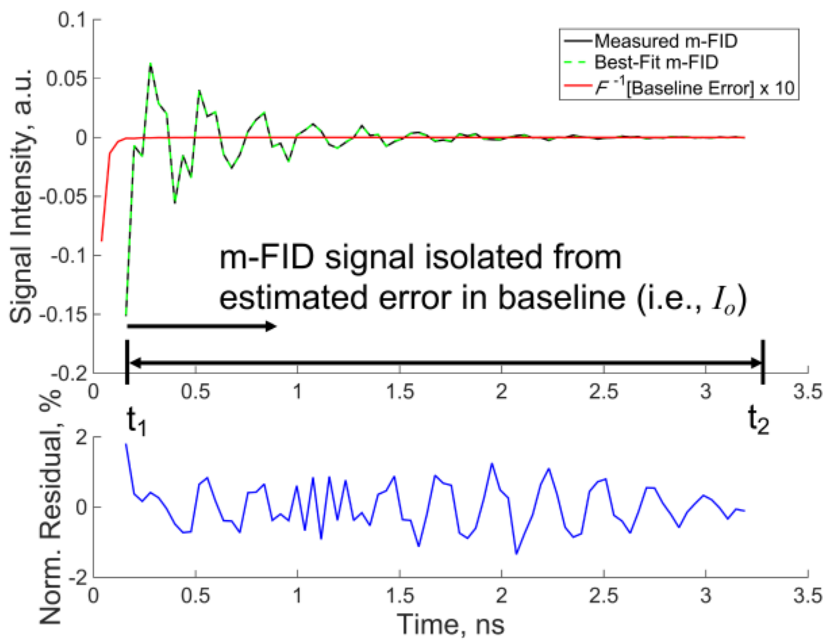
$$\frac{I_t}{I_0} = \exp(-\alpha(v))$$

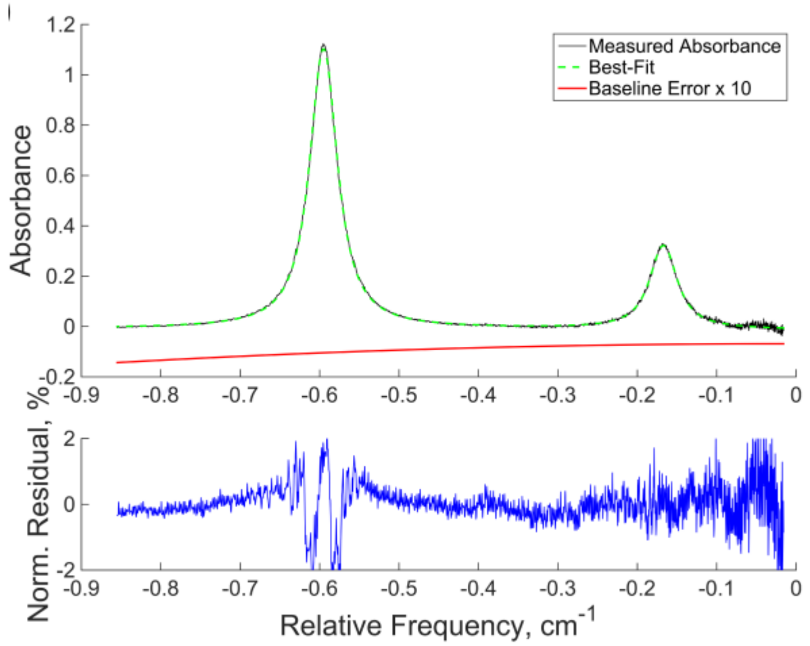
$$A(\nu) = -ln(I_t) = \alpha(\nu) - ln(I_o(\nu))$$

$$A(t) = \mathcal{F}^{-1}[A(\nu)] = \mathcal{F}^{-1}[\alpha(\nu)] + \mathcal{F}^{-1}[-ln(I_o(\nu))]$$

Modified molecular free-induction decay signal (m-FID)







Best-fit m-FID signal from I_o & simulated α → Gas Properties

Primary benefit: Insensitive to errors in the baseline

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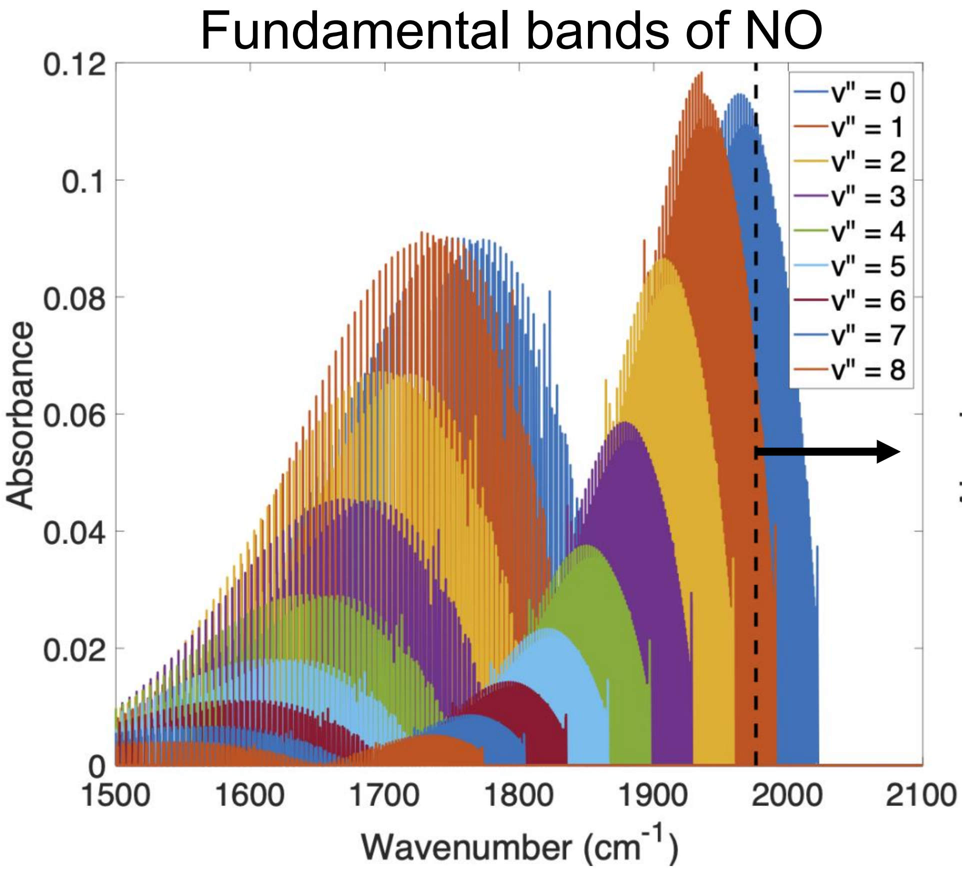
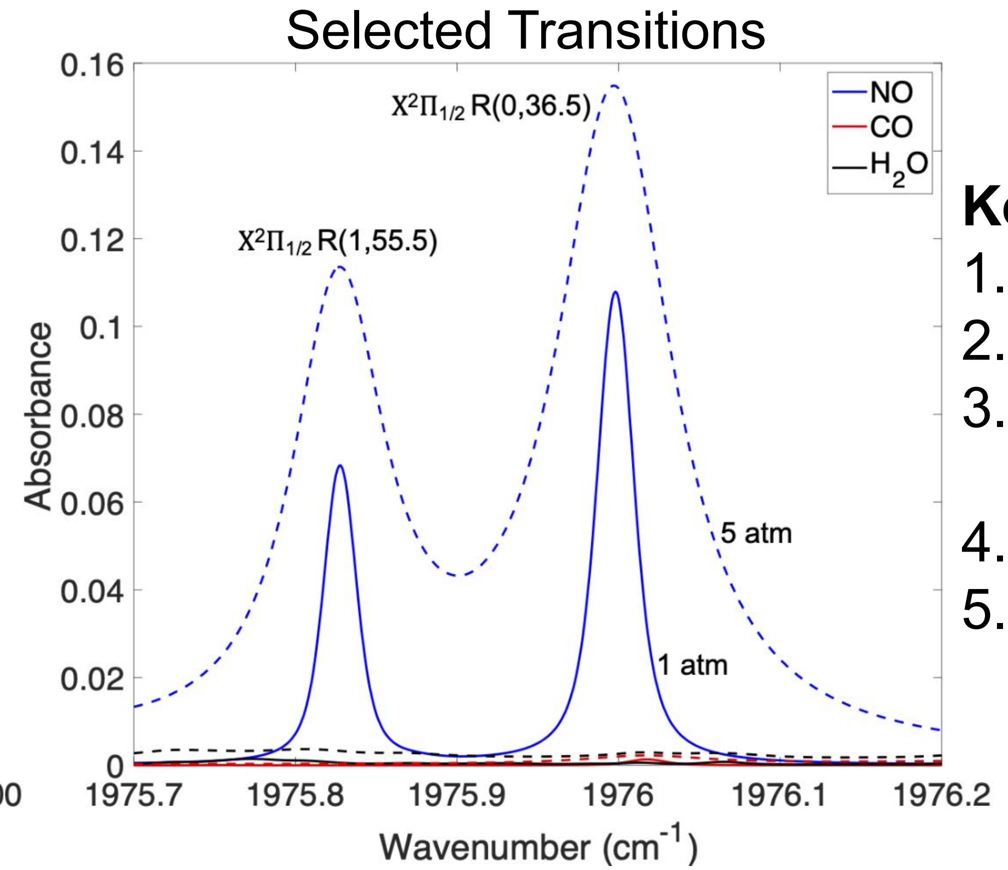
Figures: Goldenstein et al., Applied Optics, 2020

Technical Approach: Line Selection





Key Advantages:

1. Large line strengths
2. Minimal interference
3. Excellent temperature sensitivity
4. Near-optimal spacing
5. Accessible via commercial QCL with rapid tuning

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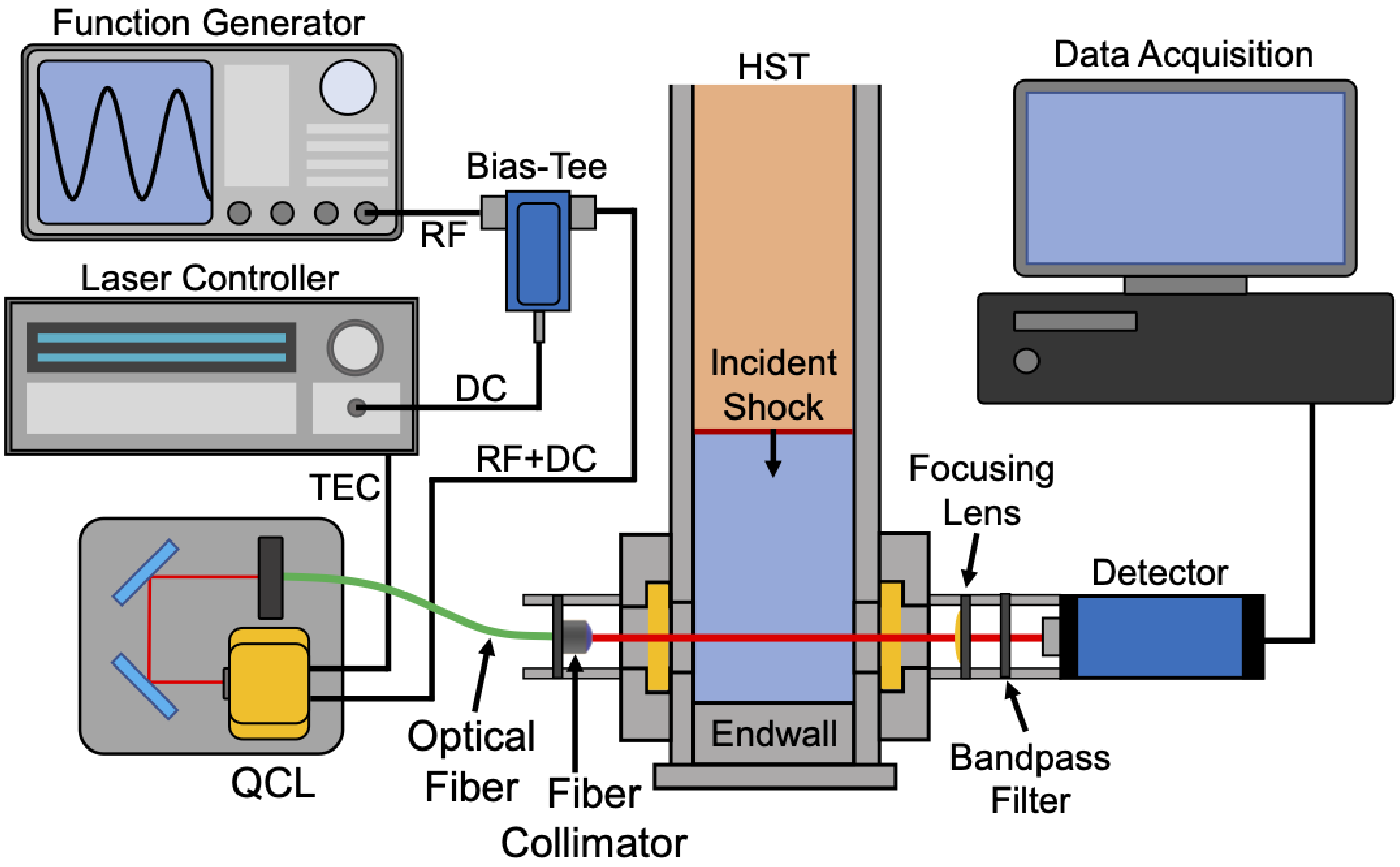
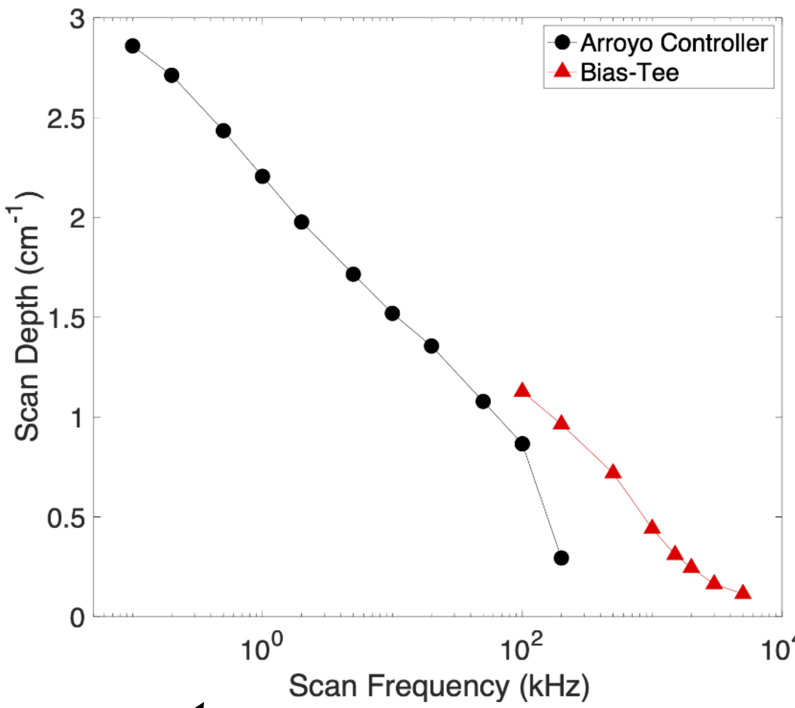
Experimental Setup



Enables 500 kHz scan frequency



Bias-tee combines DC current (from controller) with modulation (from function generator) → Overcomes bandwidth limitations of laser controller

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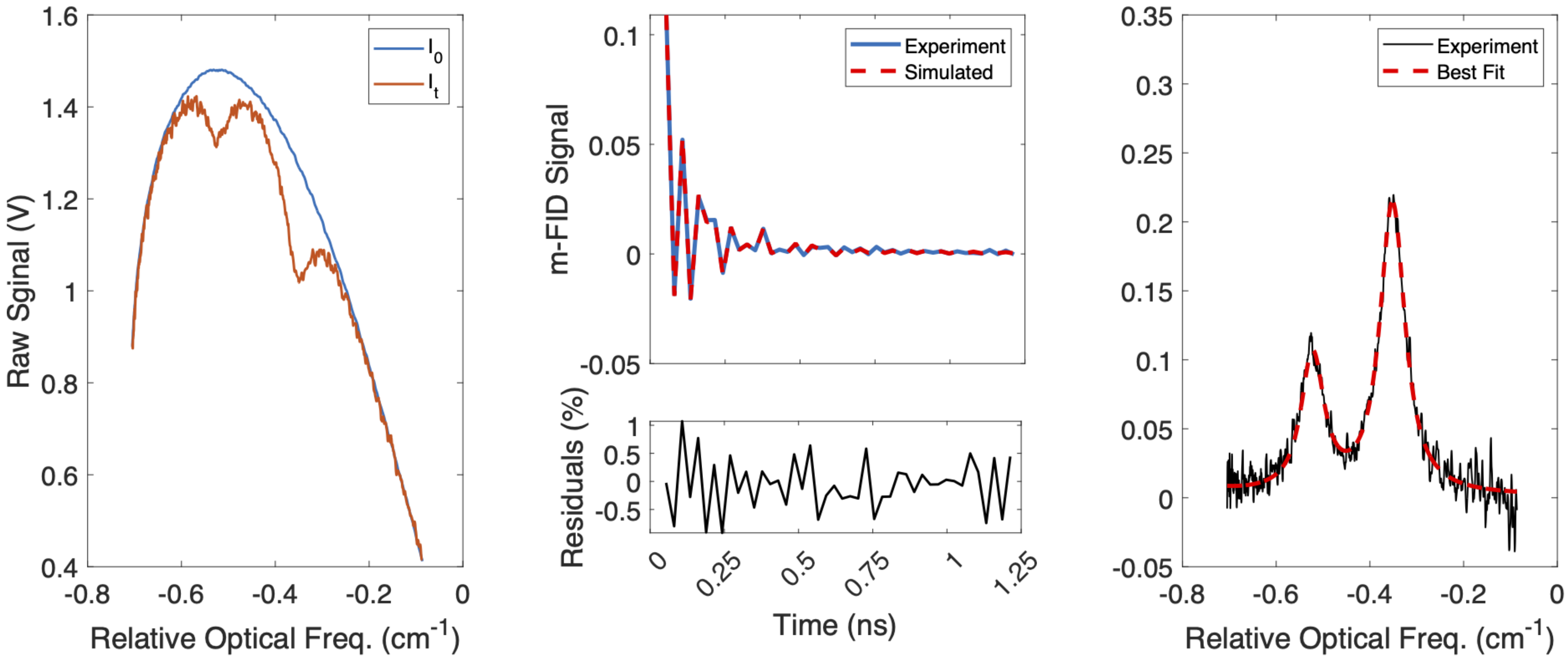
Post Processing



Fitting routine free parameters:

1. Temperature
2. Pressure
3. P_{NO}

(Pressure and P_{NO}) → X_{NO}

4-5. Line centers

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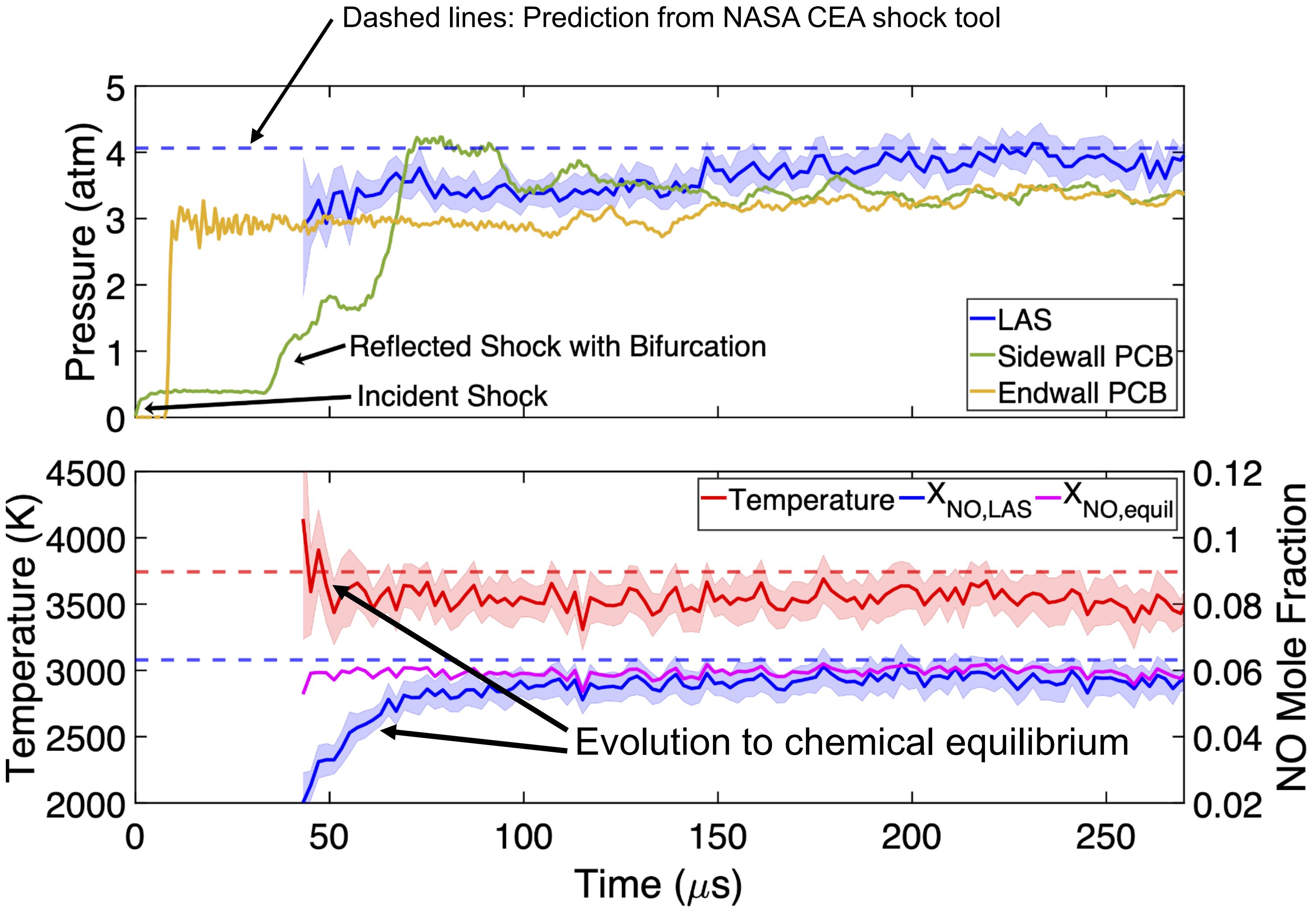
Results: Time History



Key Findings:

1. Pressure has reasonable agreement with PCBs and follows the same trend in time.
2. 500 kHz measurement rate enables observation of temporal evolution to equilibrium.
3. Temperature agrees well with NASA CEA.
4. Mole Fraction agrees well with equilibrium calculation.

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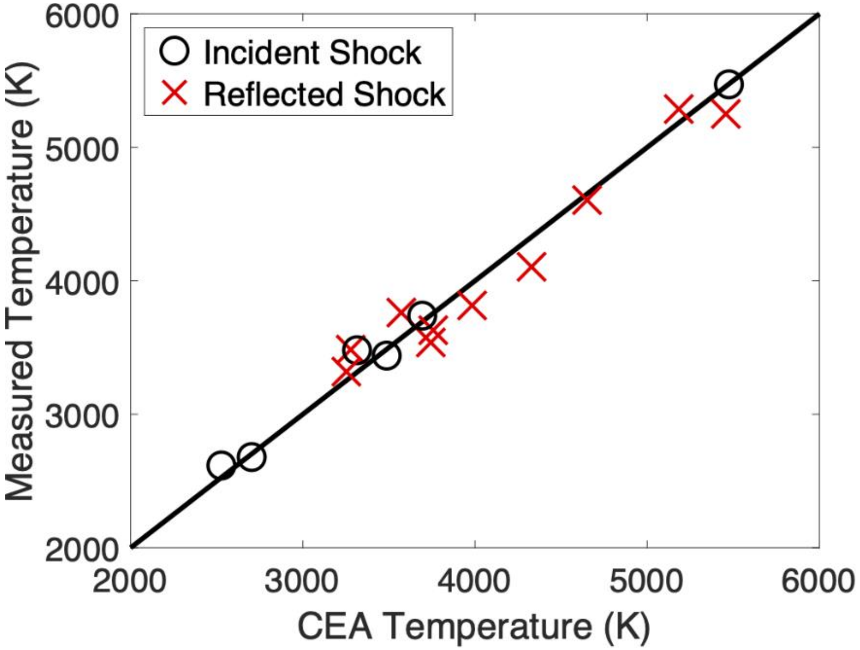
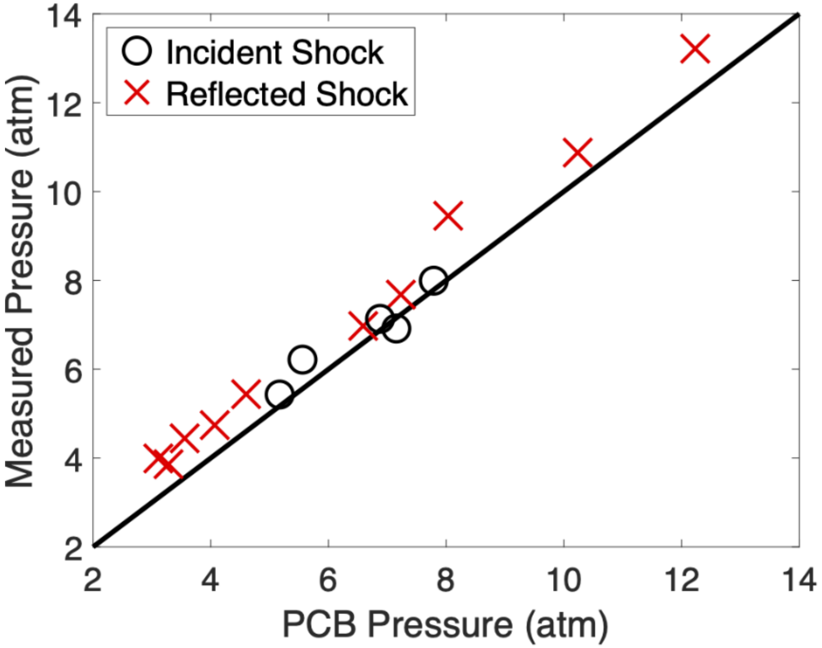
Results: Time-Averaged Values

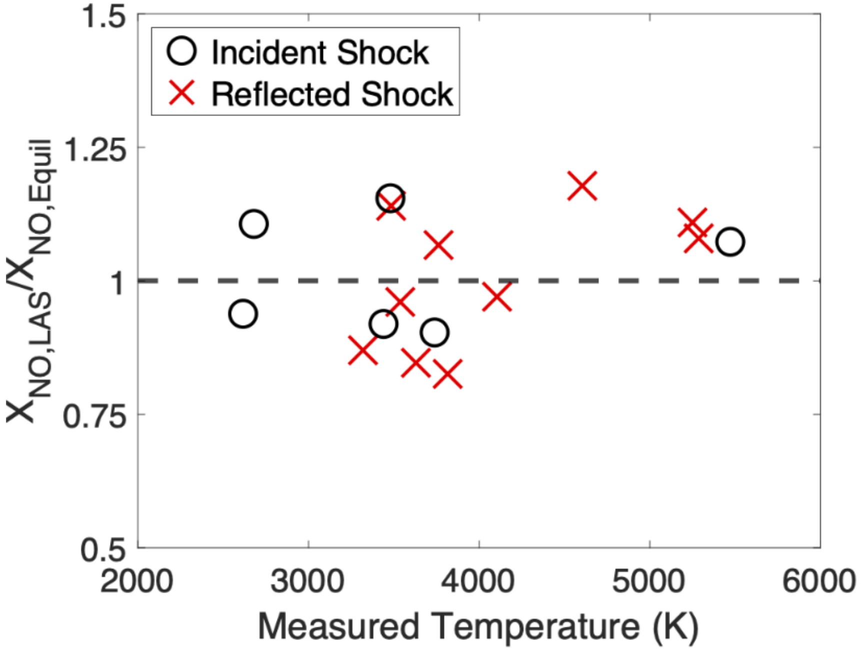
Temperature



Pressure



X_{NO}



Temperature has excellent agreement with NASA CEA predictions

Pressure in close agreement with PCBs. Differences may be due to:

- Bias in PCBs
- Error in collisional broadening model

Mole fraction of NO in good agreement with equilibrium

Differences may be due to:

- Sensitivity of equilibrium calc to T and P
- Propagating errors from measured P

Conclusion

- Designed and demonstrated a diagnostic capable of measuring temperature, pressure, and NO mole fraction at 500 kHz in shock heated air
  - Demonstrated for $T \approx 2500$ to 5500 K and $P \approx 3$ to 12 atm
- Diagnostic was able to well resolve chemical non-equilibrium behind the shock and the temporal evolution to equilibrium
- Measured gas properties generally in good agreement with other predicted/measured values (e.g., NASA CEA, PCBs, etc.)

Acknowledgements

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