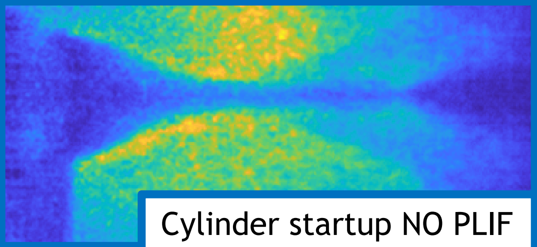
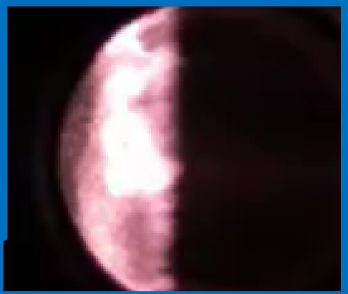
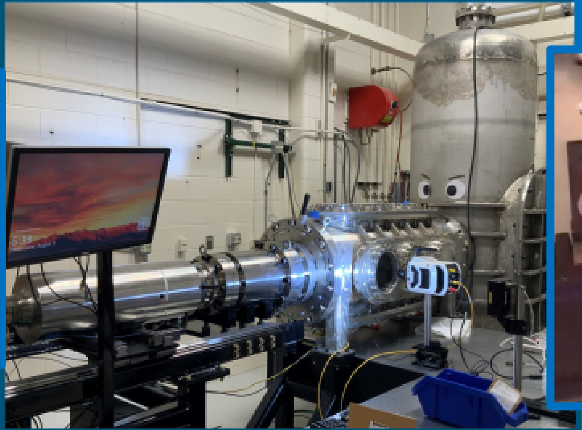
SAND2022-16407C

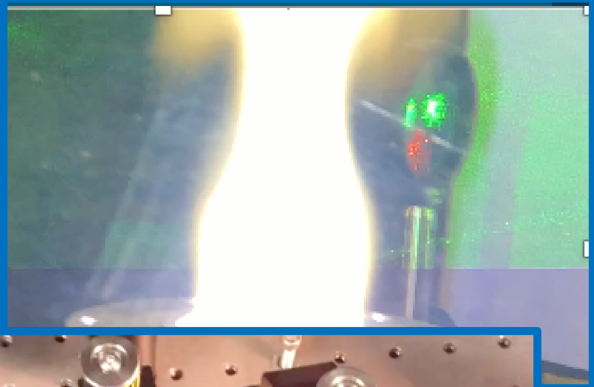
Sandia National Laboratories

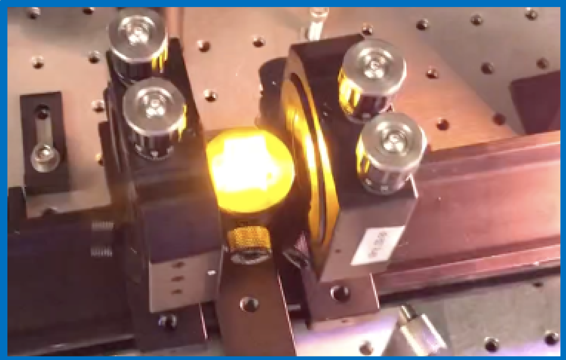
High-speed measurements in the Sandia free-piston shock tunnel


Cylinder startup NO PLIF









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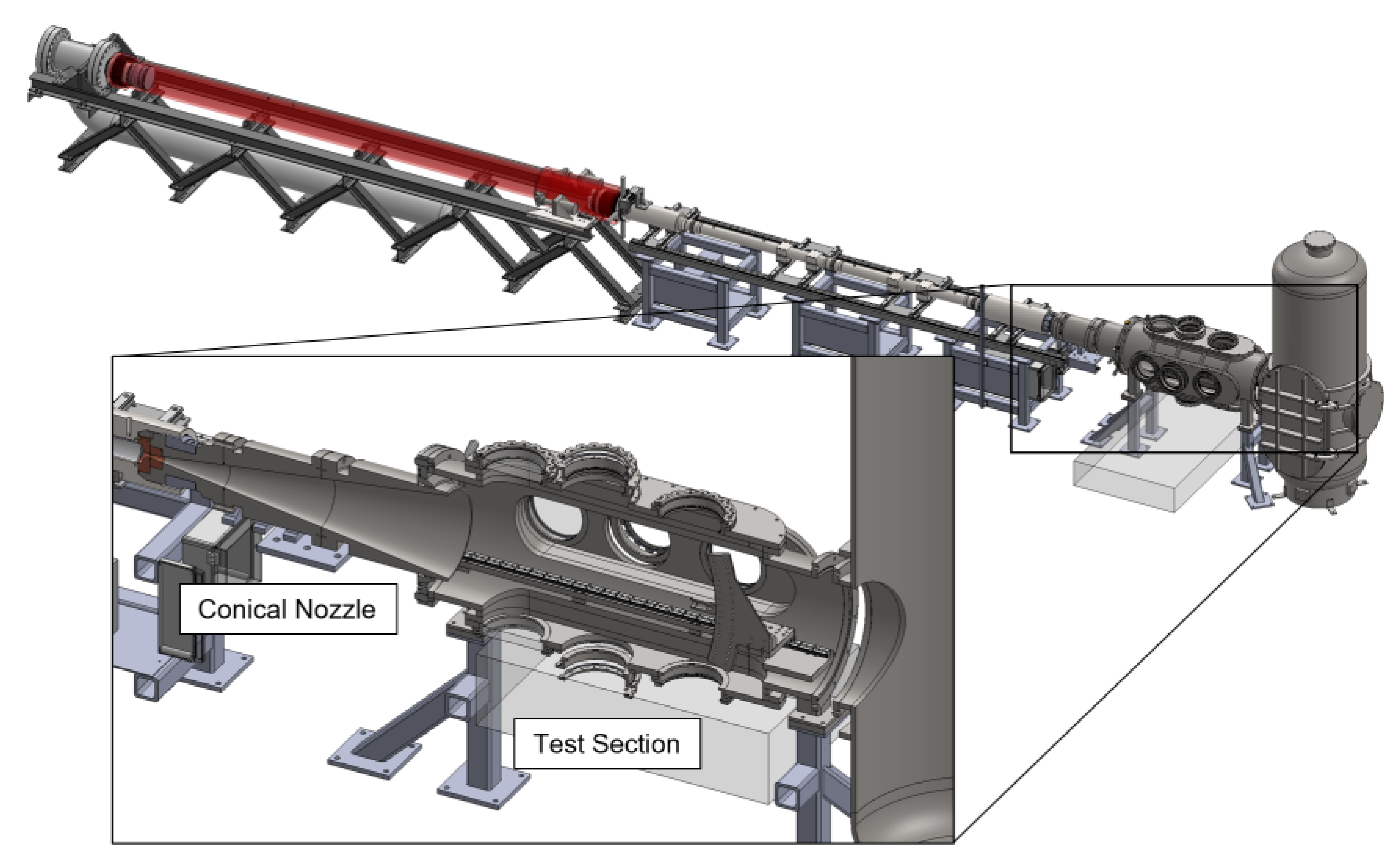
Sandia Free-Piston Hypersonic Shock Tunnel (HST)



Tunnel Specifications

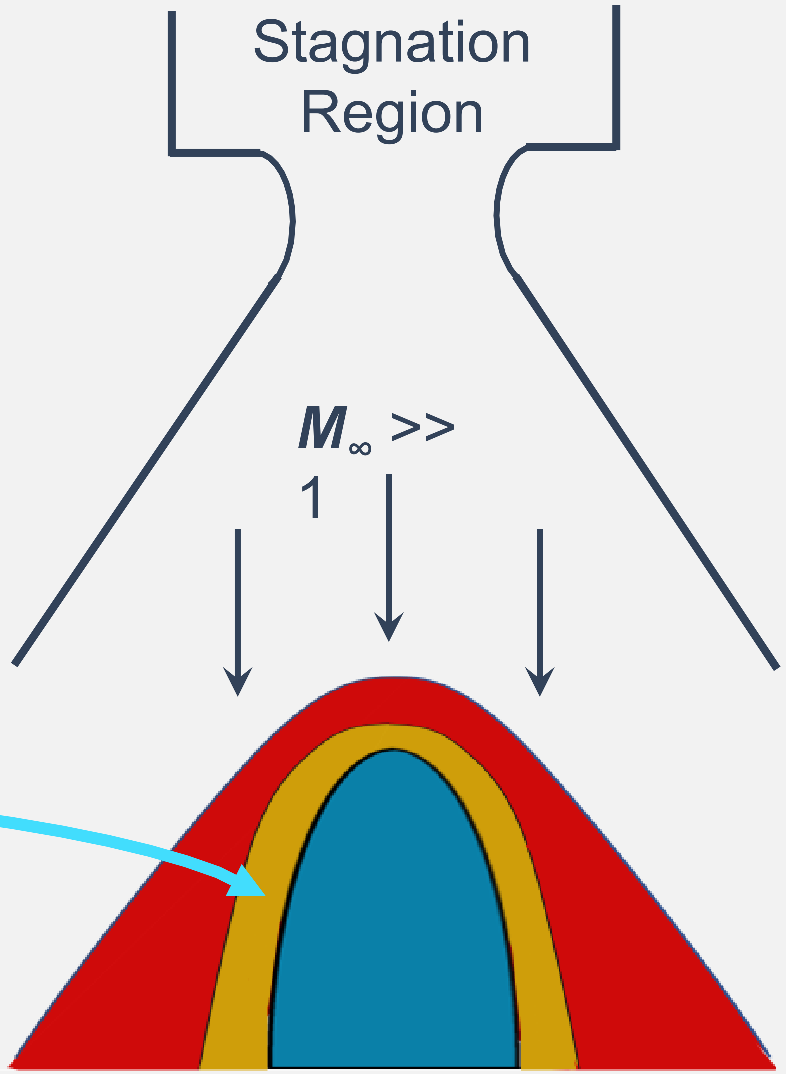
- Nozzle Exit Dia. = 0.36 m
- Test section diameter 0.5 m
- Run times of 1-2 milliseconds

U_∞ (m/s)	H_0 (MJ/kg)	T_0 (K)	P_0 (MPa)
2850	4.6	3400	12
4060	9	6000	17

Target applications include high-temperature surface chemistry and hypersonic thermochemistry.

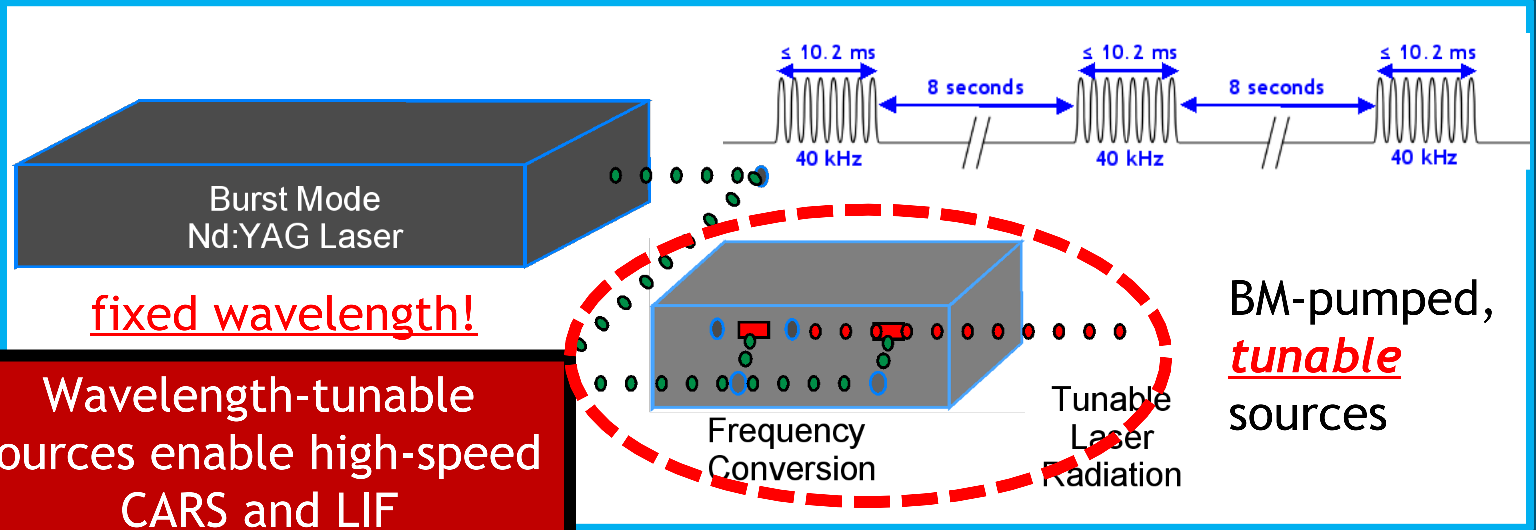
Survey of Upcoming Experiments in HST

- **HST introduces flow complexities**
  - Stagnation region gases react
  - Gas rapidly expanded through nozzle
  - Result: thermal non-eq., NO addition
- **Free-stream characterization necessary**
  - Temperature: CARS for heteronuclear molecules
  - Velocity: NO LIF
  - 100-kHz data with <u>*pulse-burst laser!*</u>
- **Examine boundary layer products**
  - Speciation/temperature of CO
    - Laser absorption
    - CARS (Coherent Anti-Raman Stokes Raman Scattering)

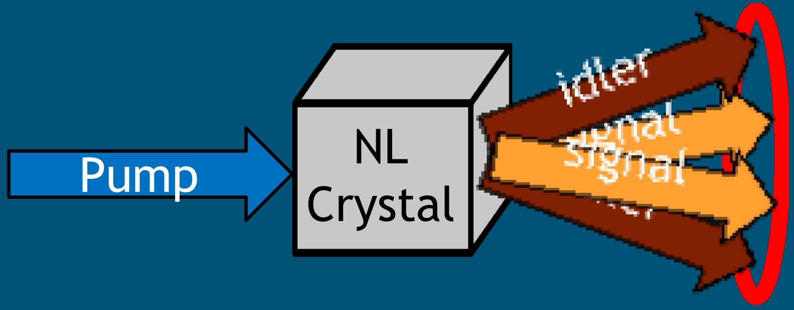


Pulse-burst laser for 100-kHz laser diagnostics

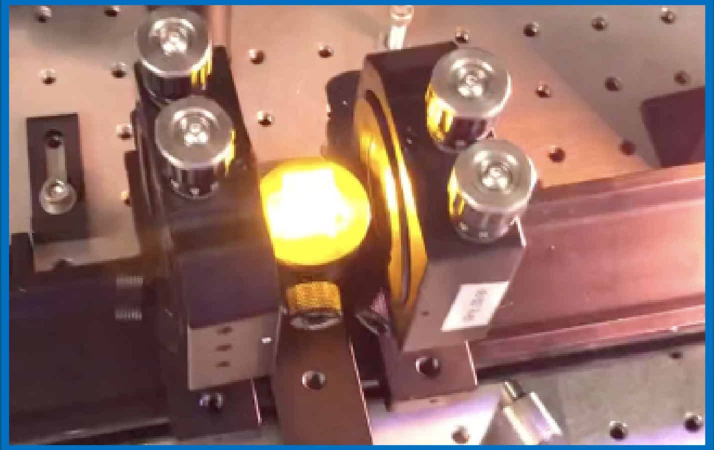
- Burst-mode lasers have allowed experimentalists to access high-speeds (10s to 100s of kHz)
- While powerful, these systems are not wavelength tunable—this prohibits application of ***chemically specific*** imaging and spectroscopic tools



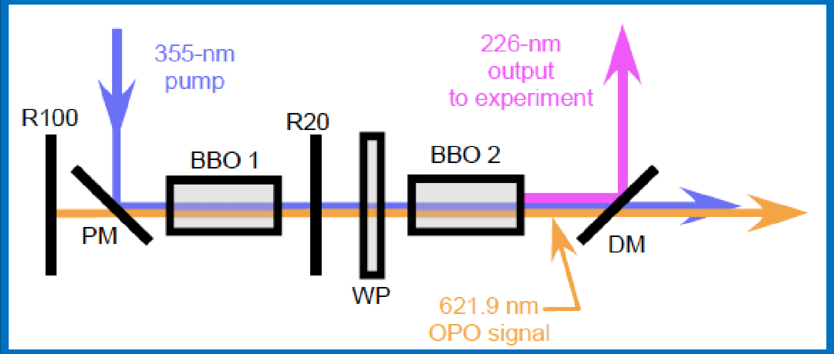
Wavelength-tunable sources enable high-speed CARS and LIF



Picosecond Optical Parametric Generation

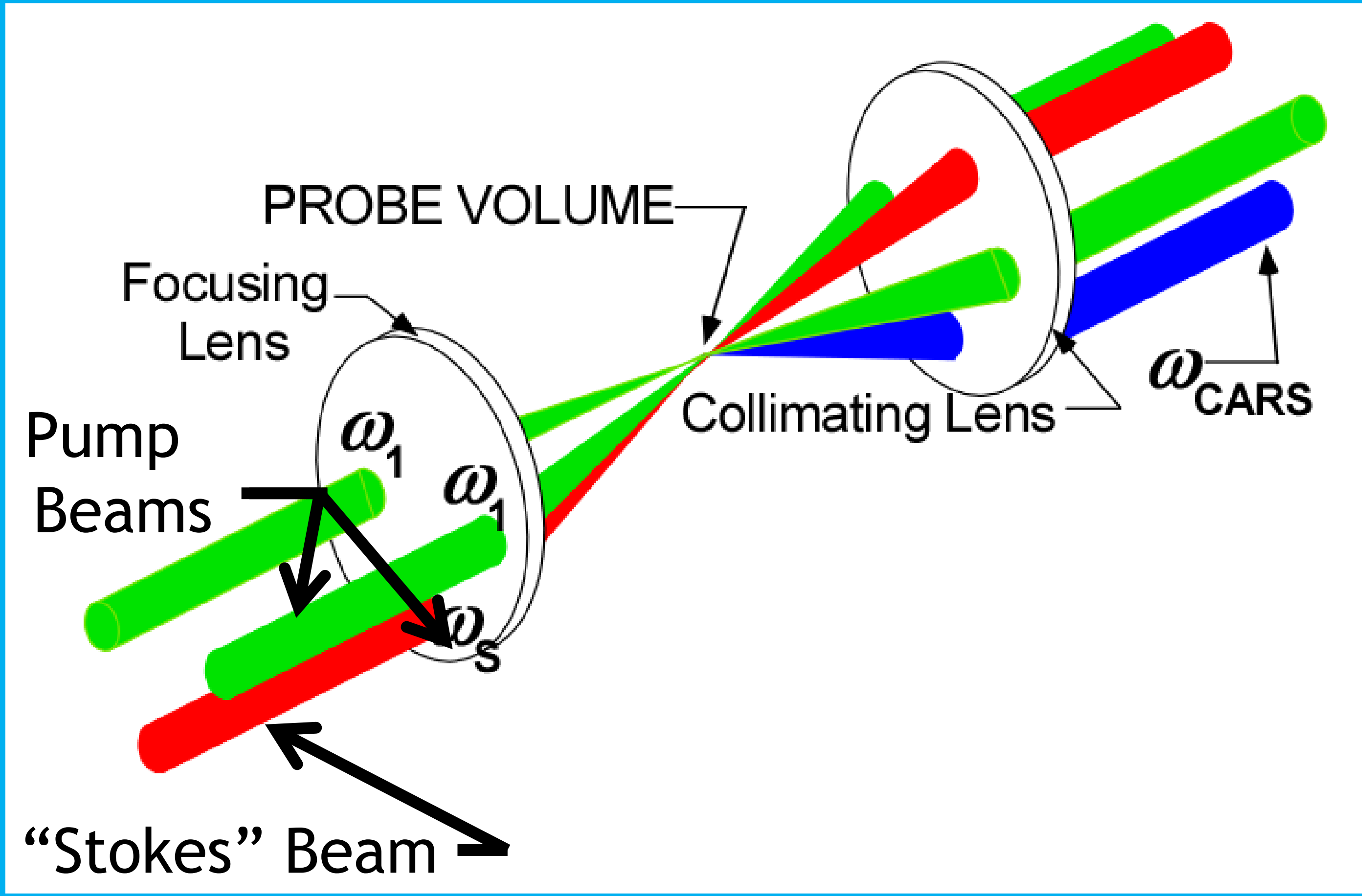


Optical Parametric Oscillator (nanosecond)

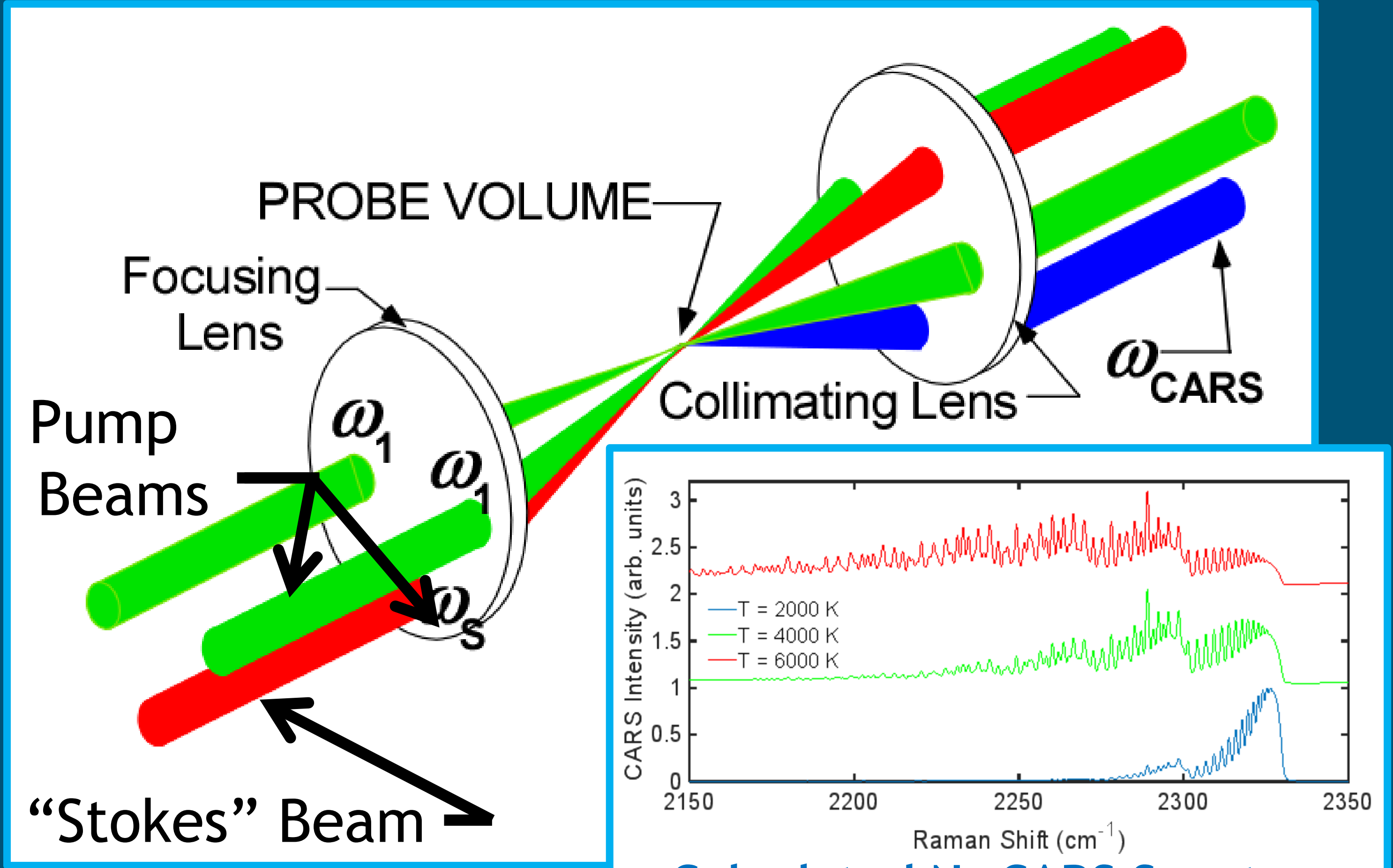


UV Generation for NO PLIF

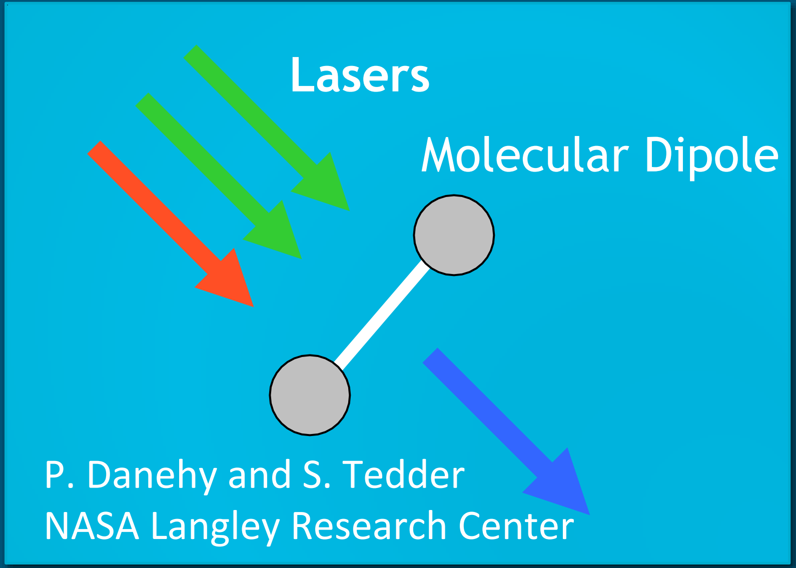
Coherent anti-Stokes Raman scattering (CARS)



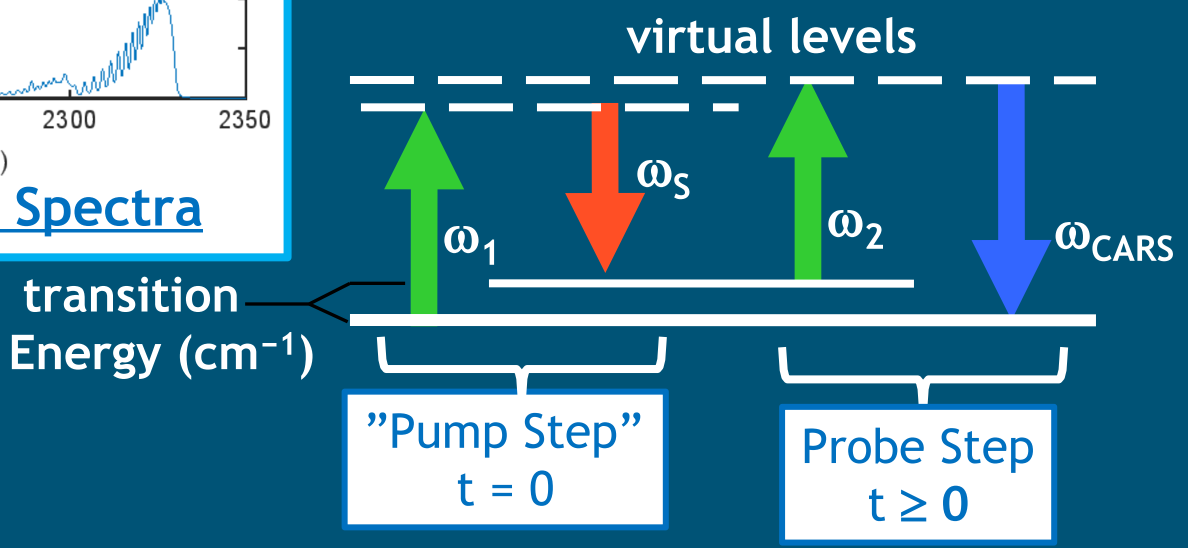
Coherent anti-Stokes Raman scattering (CARS)



Calculated N_2 CARS Spectra

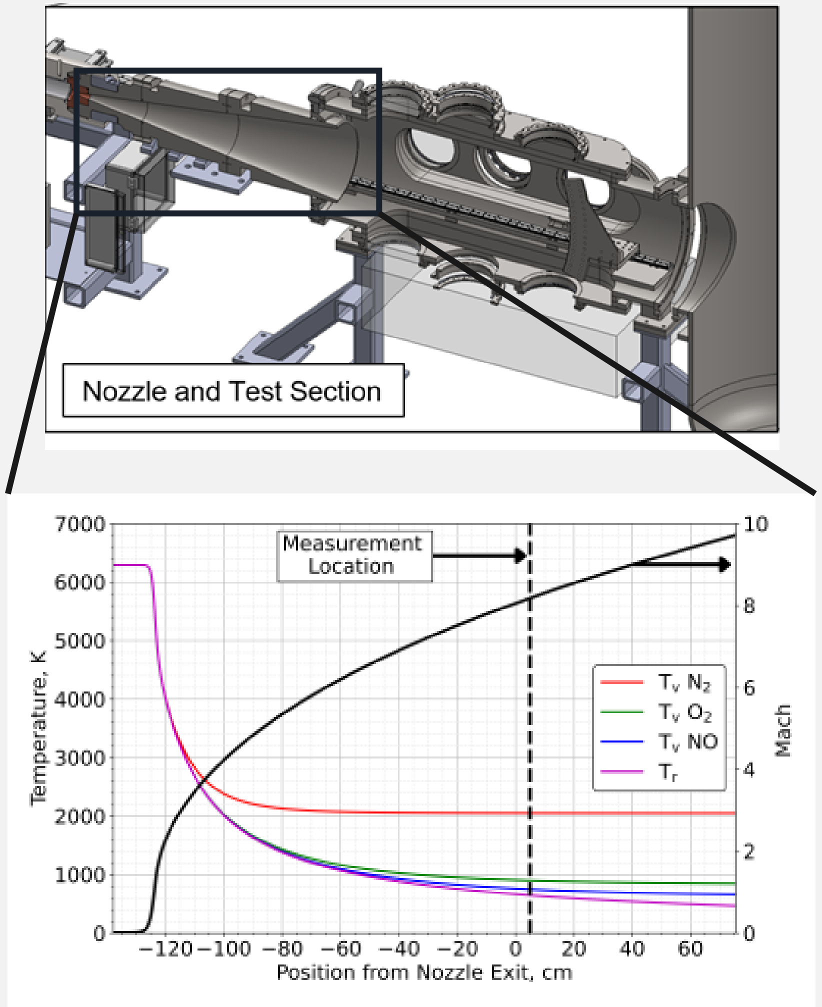


Coherent Anti-Stokes Raman



Free-Stream Characterization: Temperature

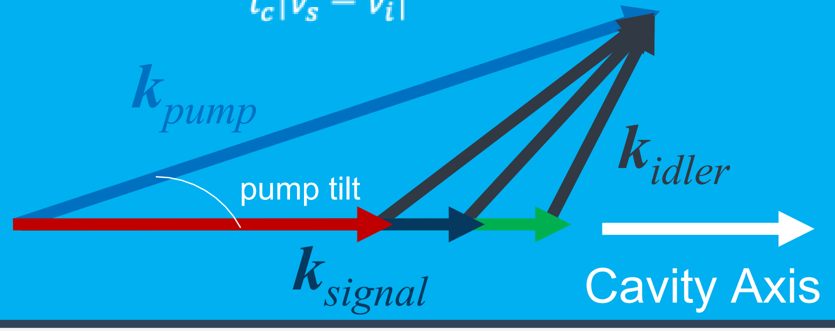
- **Free-stream conditions**
  - Major source of uncertainty in shock tunnels
  - Temperature non-eq. in nozzle is expected
- **Simulation of nozzle temperatures**
  - Significant T_v differences between species
  - N_2 has highest degree of non-eq
- **Characterizing temperature non-eq. in HST**
  - Use CARS to measure T_{vib}, T_{rot} for N_2
  - Further improvement needed for T_{rot}
  - Next: O_2 CARS temp. measurements

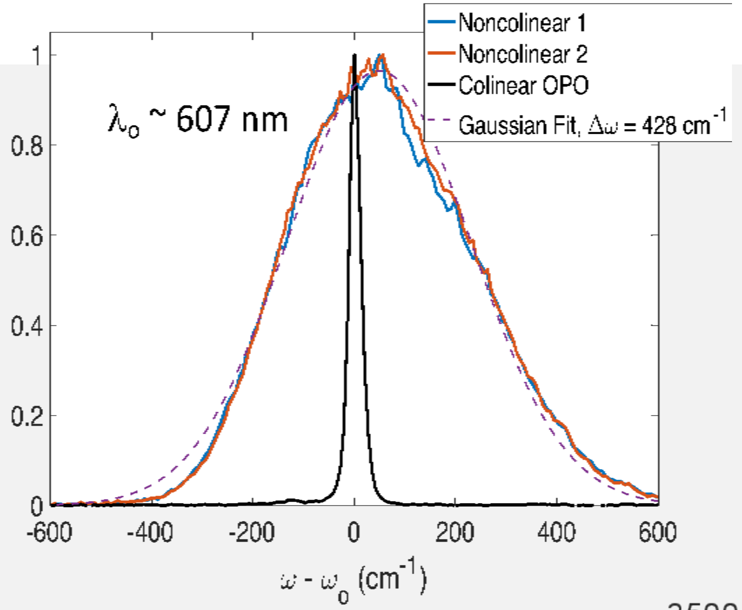


100-kHz *nanosecond* CARS for HST free-stream

Noncolinear OPO produces wide spectral bandwidth for CARS detection

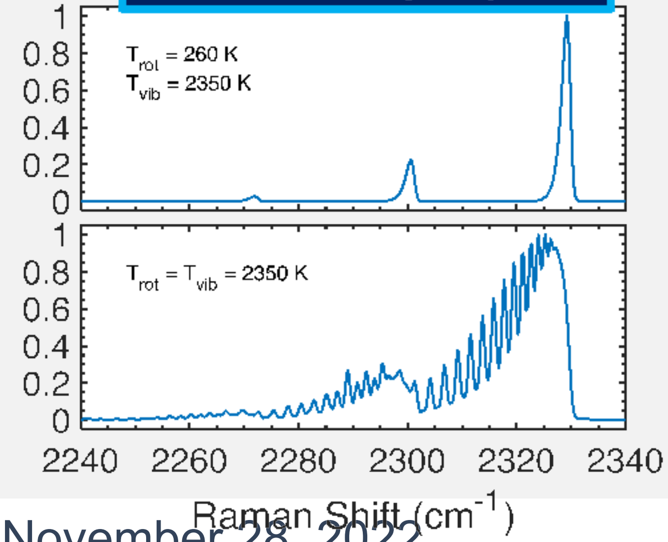
$$FWHM_{OPO} = \frac{c}{l_c |\nu_s - \nu_i|}$$

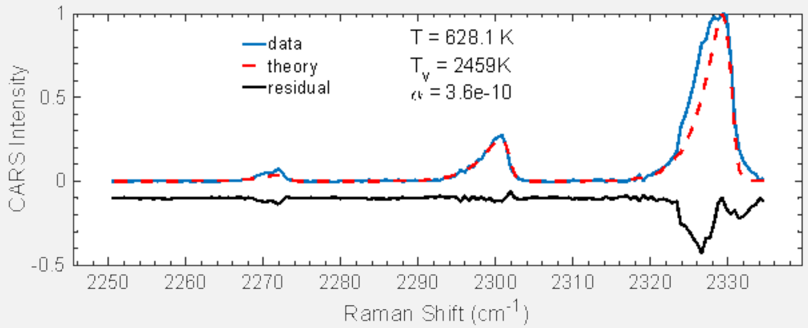


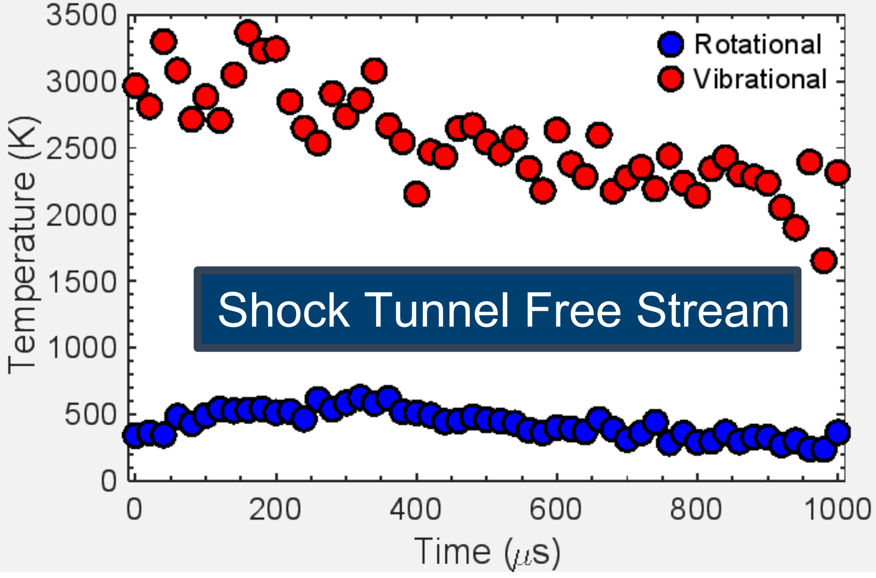


- 2X reduction in measurement uncertainty re: picosecond CARS
- Good sensitivity to thermodynamic nonequilibrium
- Improve sensitivity to Trot
- O_2 measurements

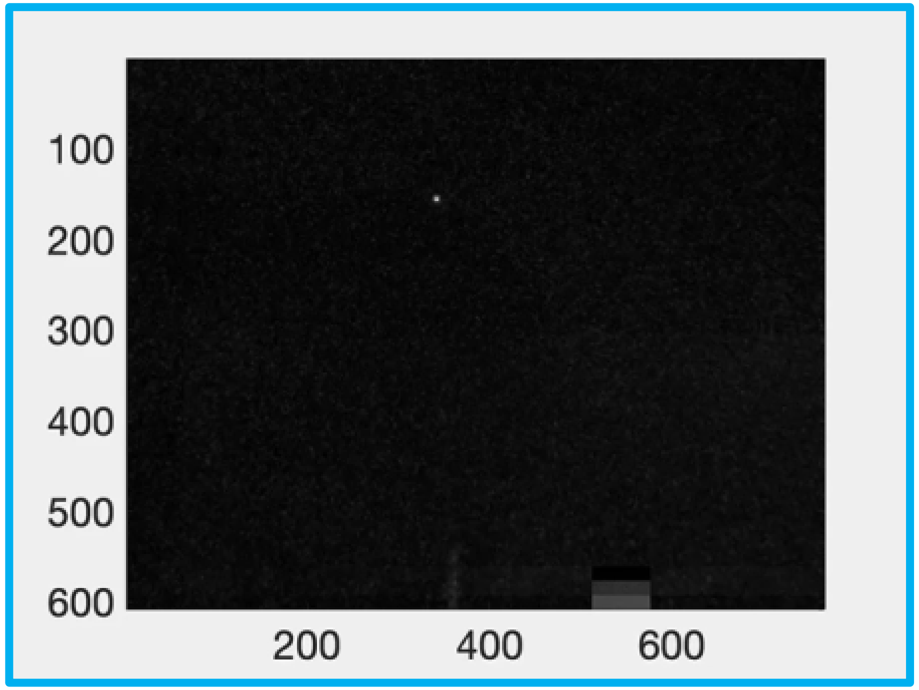
CARS spectra can reveal *nonequilibrium* conditions in N_2 and O_2



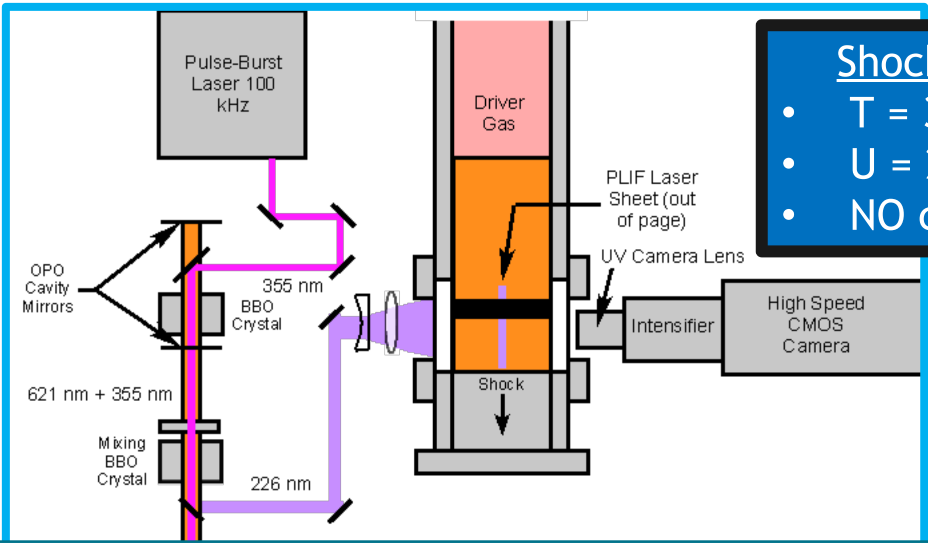




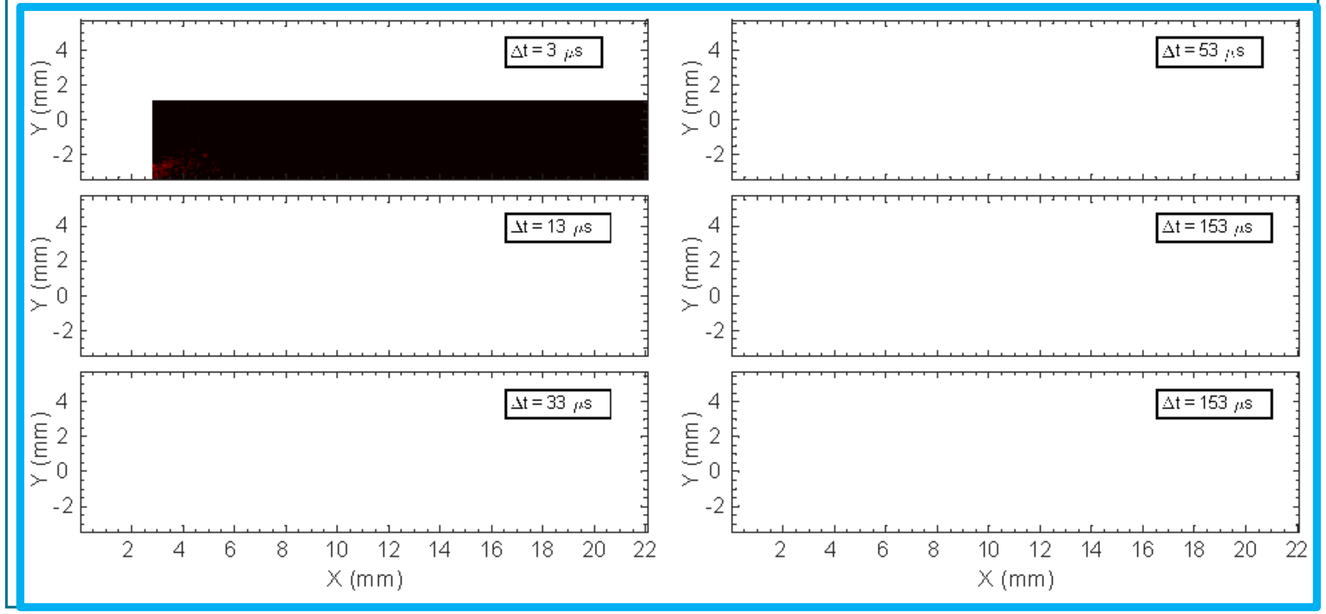
100-kHz nitric oxide LIF imaging of transient flows



- M = 9 flight condition at ~130 kft
- Enthalpy ~ 5 MJ/kg
- NO PLIF Visualization over large, 70-mm field of view



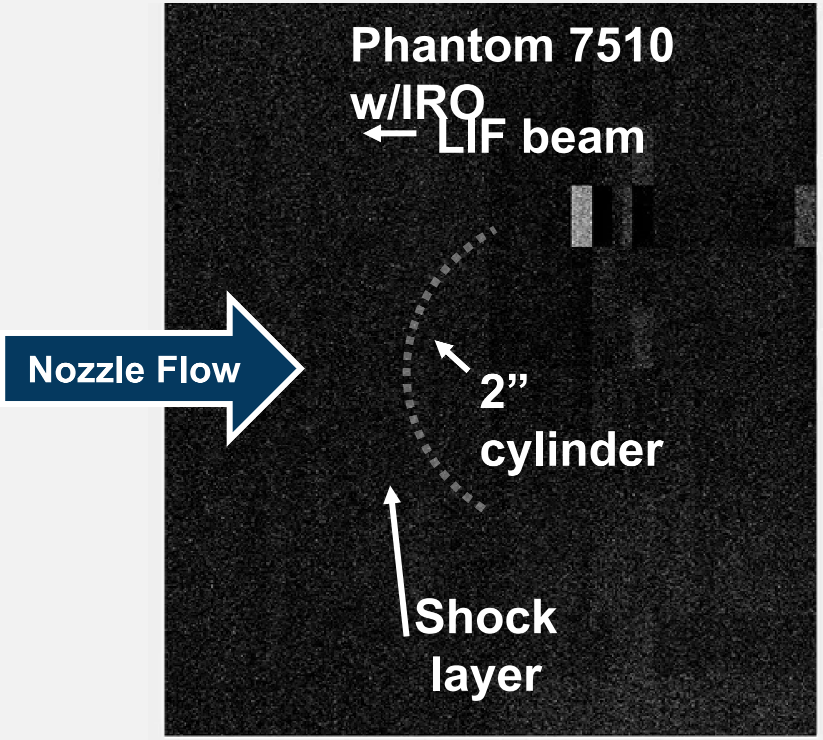
Shock Tube Experiment
- T = 3000 K
- U = 2.5 km/s
- NO concentration ~4%

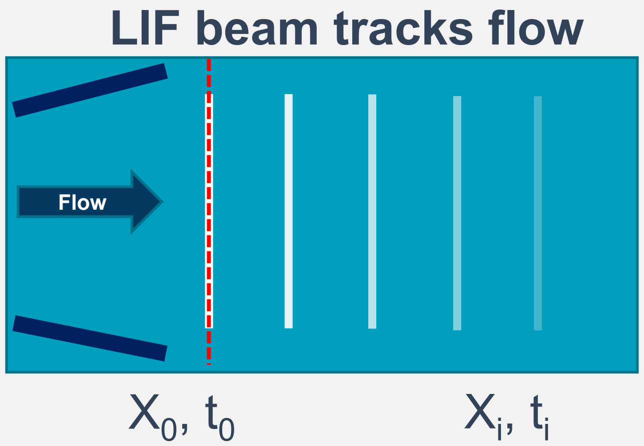


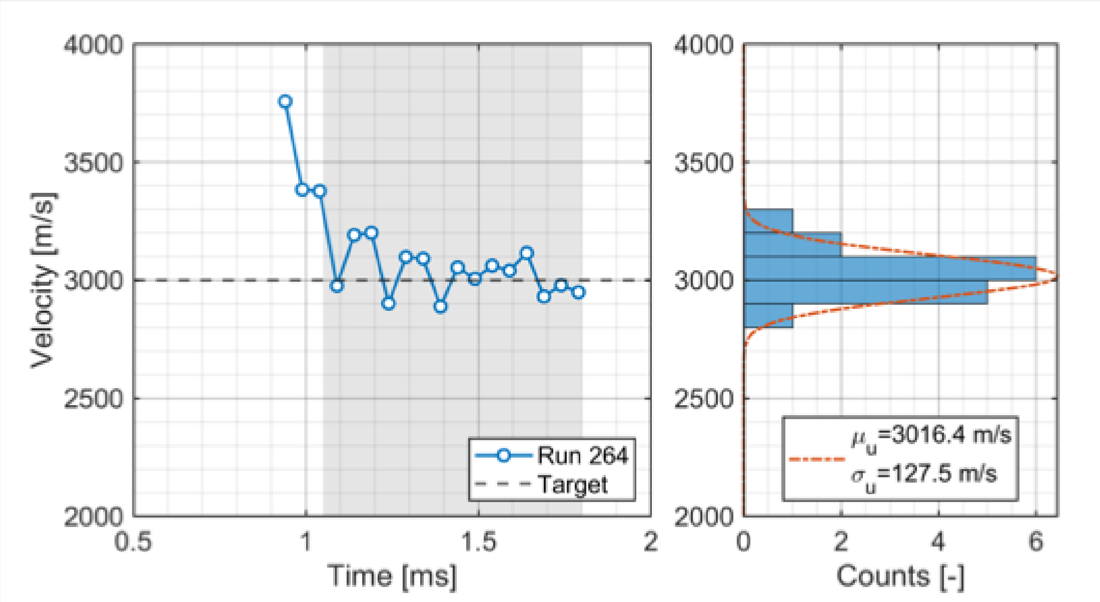
100-kHz NO PLIF Imaging of Cylinder wake startup: U = 2.5 km/s, T = 3000 K

Free-Stream Characterization: Velocity

- NO is present in shock tunnel flow (X_{NO}~4-5%)
- Tracer for flow visualization
- Nitric Oxide Tagging Velocimetry
- Long fluorescence lifetime, >100 ns
  - U_∞=3 km/s = 3 μm/ns, Δt~100 ns → Δx~300 μm
  - Track NO fluorescence at high image magnification



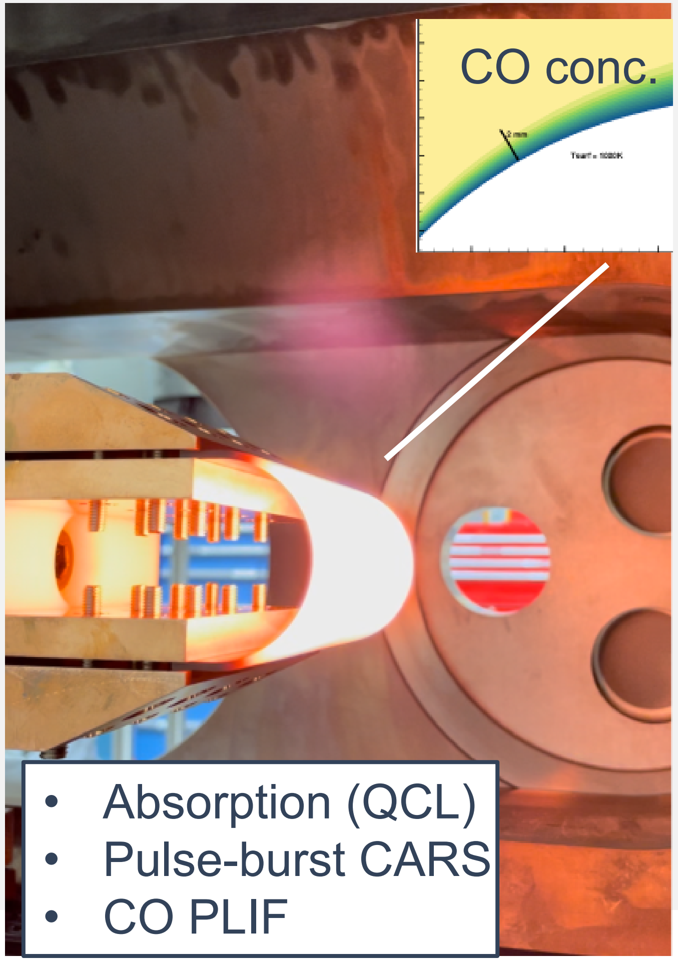




TEMPERATURE/SPECIES MEASUREMENTS IN TPS BOUNDARY LAYERS

Shock Tunnel—Resistively Heated Models

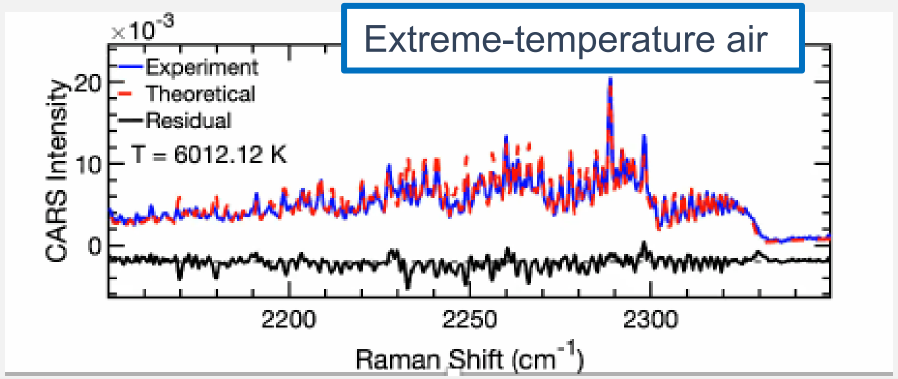
- Impulse facility – insufficient test time
- Graphite coupons as TPS surrogate



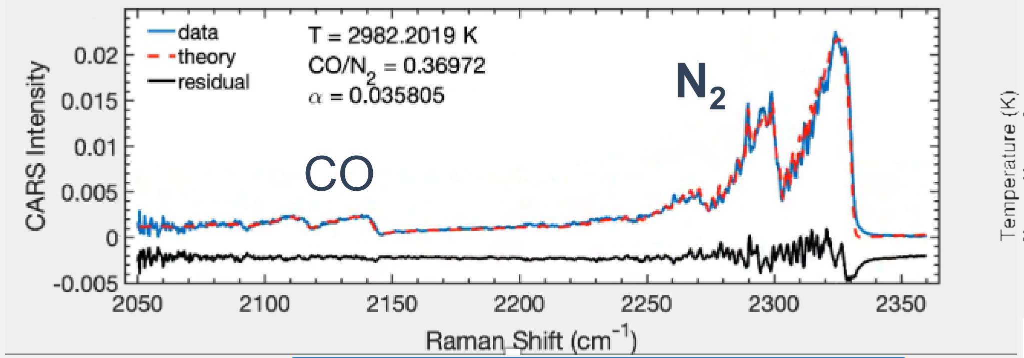
- Absorption (QCL)
- Pulse-burst CARS
- CO PLIF

IC Plasma Torch Environment

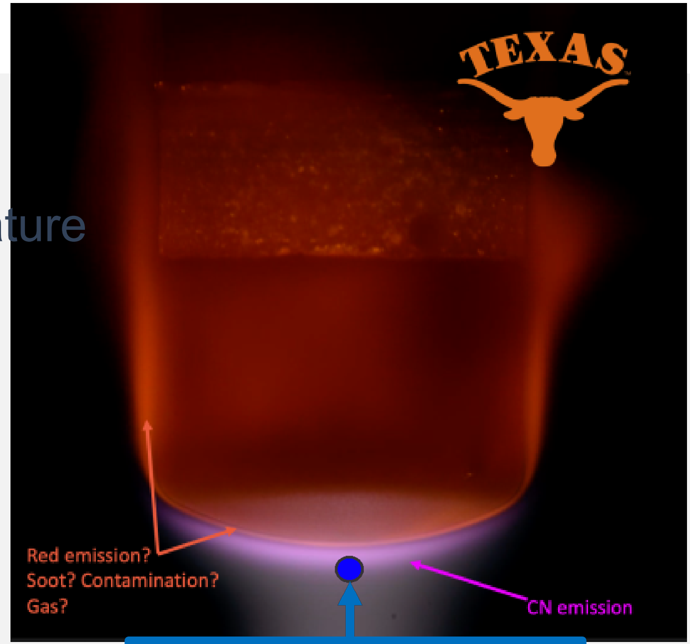
- Long test duration (minutes)
- Low velocity but relevant temperature



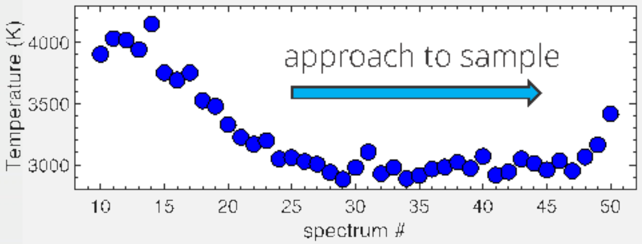
Extreme-temperature air

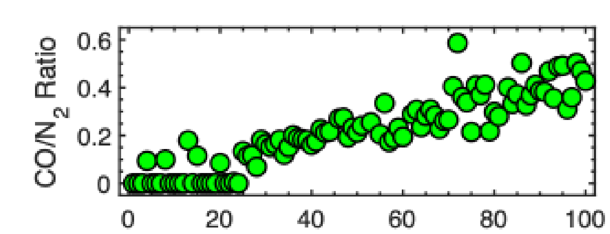


Simultaneous T/CO measurement



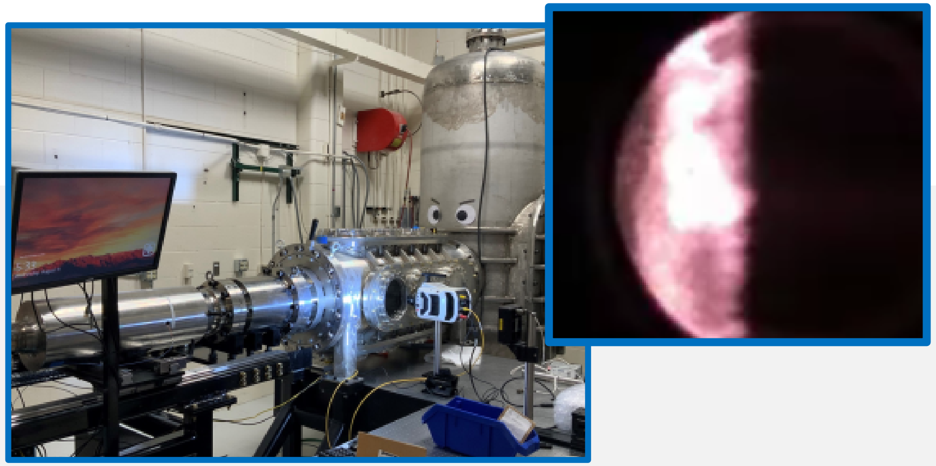
50-μm × 3-mm CARS volume

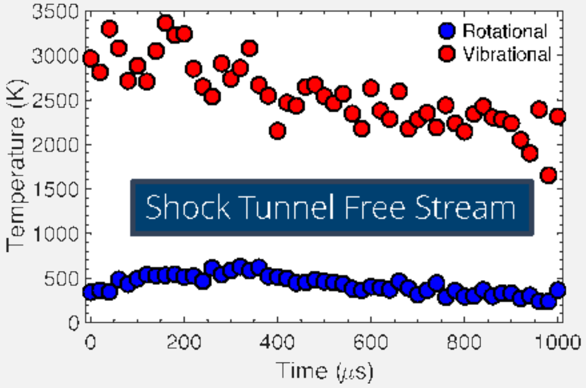


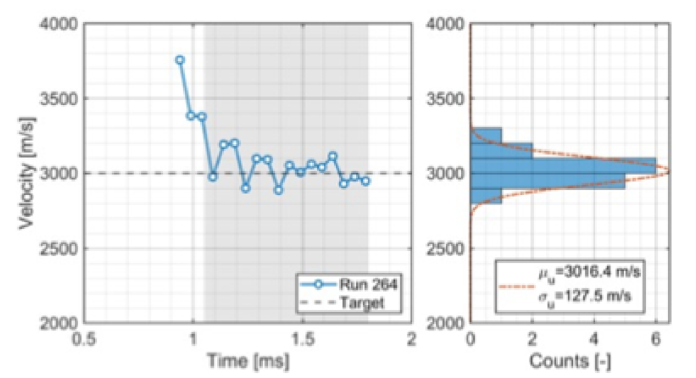


Summary and Conclusions

- Sandia relies heavily on laser diagnostics for high-speed measurements in it's free-piston hypersonic facility
  - Short-duration, impulsive experiments
  - Thermal and chemical nonequilibrium
  - Free-stream and near-surface data



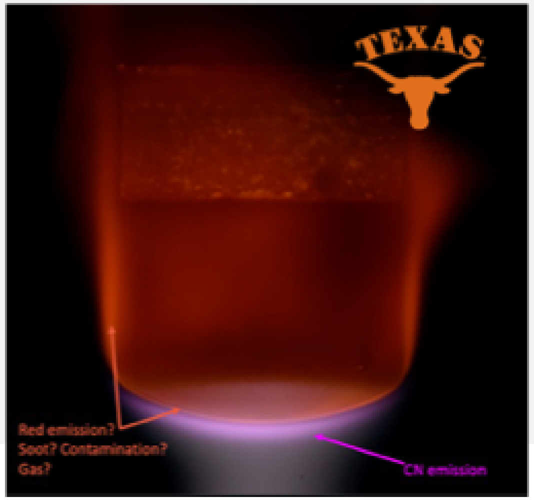


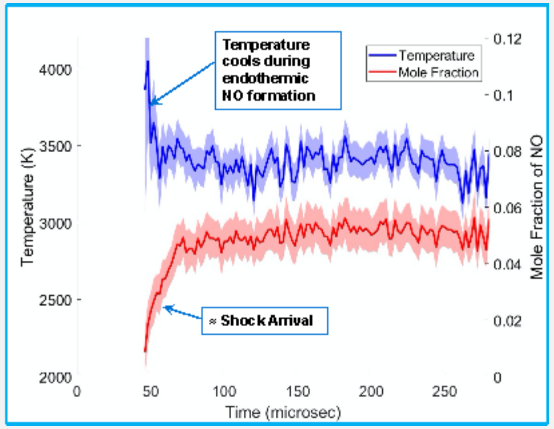


- Pulse-burst lasers can be adapted for CARS thermometry!
- Pulse-burst PLIF has been applied for flowfield imaging and *velocimetry* – 4-5% NO!

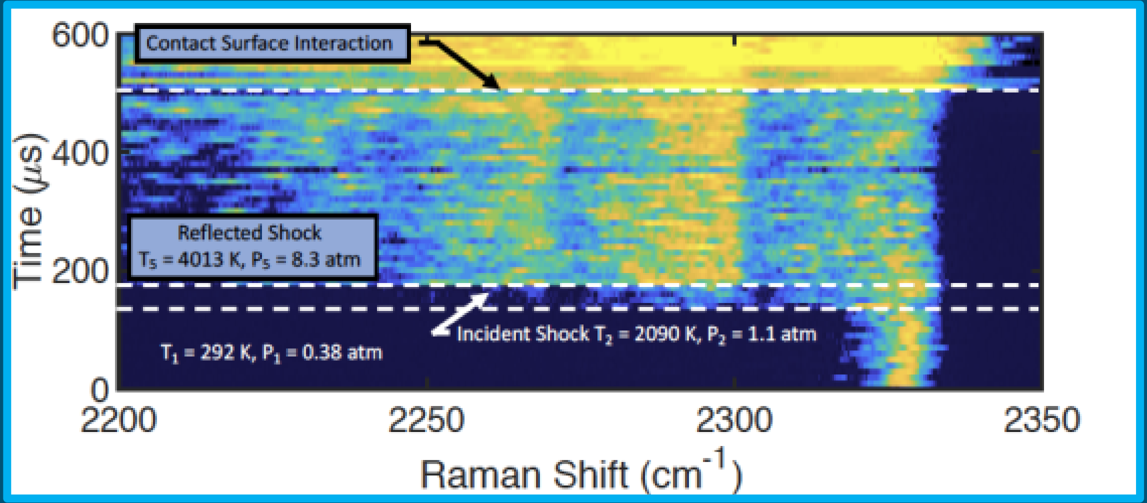
- Complementary measurement in ICP torch environment

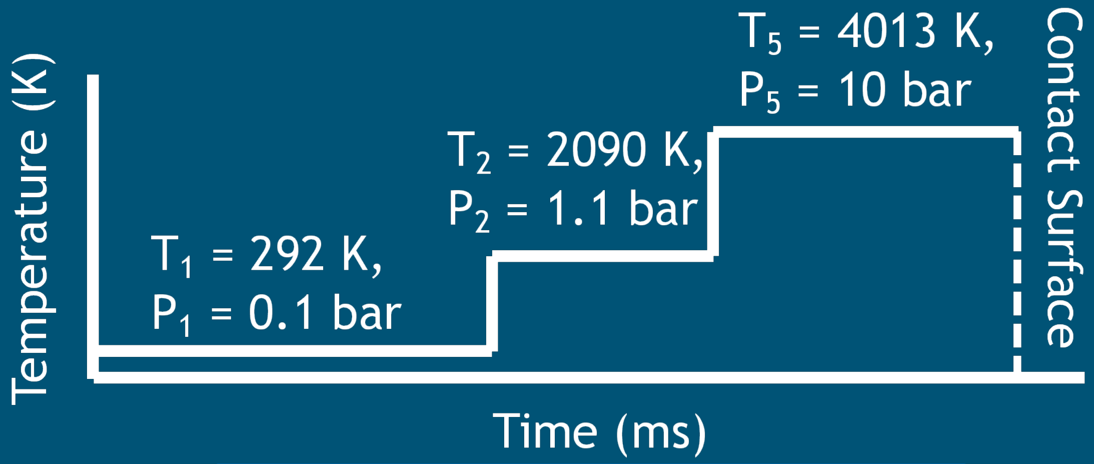
- Additional laser-based methods include:
  - Laser absorption: QCL, VCSEL
  - Emission spectroscopy





100-kHz Pulse-Burst CARS in the Sandia Free-Piston Shock Tube





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