SAND2022-12428C

Sandia National Laboratories

Exceptional service in the national interest

Temperature and Pressure Measurements in Hypersonic Flows: Techniques, Linewidths, and Applications

Daniel Richardson, Jon Retter, Matt Koll, Steven Beresh, Sean Kearney

ECONOS, 25-28 Sept 2022
Kiruna, Sweden

SANDXXXX-XXXXXX C

Sandia National Laboratories is a multimission 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.

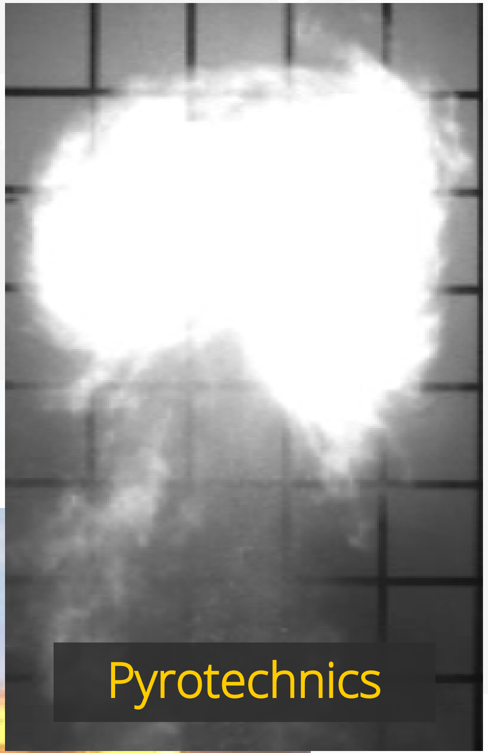
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

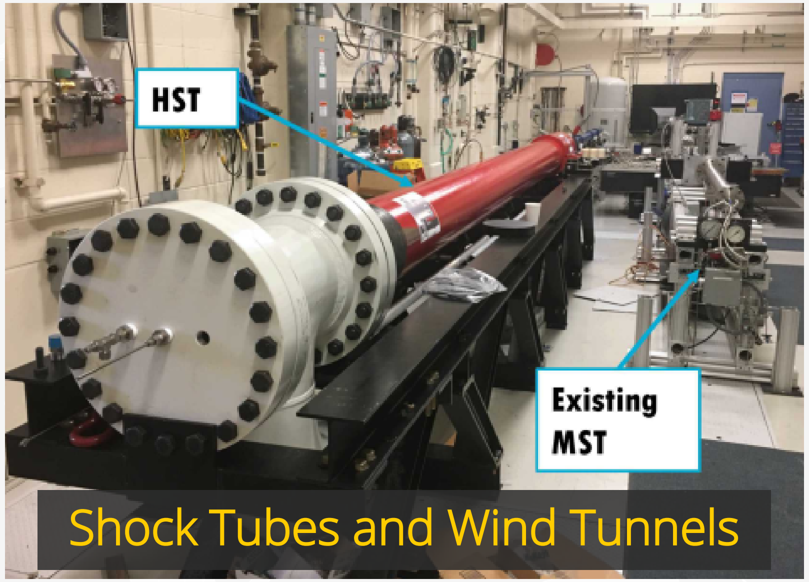
U.S. DEPARTMENT OF ENERGY

NNSA

Our Group at Sandia National Laboratories

- Sandia National Laboratories
  - Albuquerque, New Mexico
- Optical measurements:
  - Development and application
  - Challenging environments


Pyrotechnics

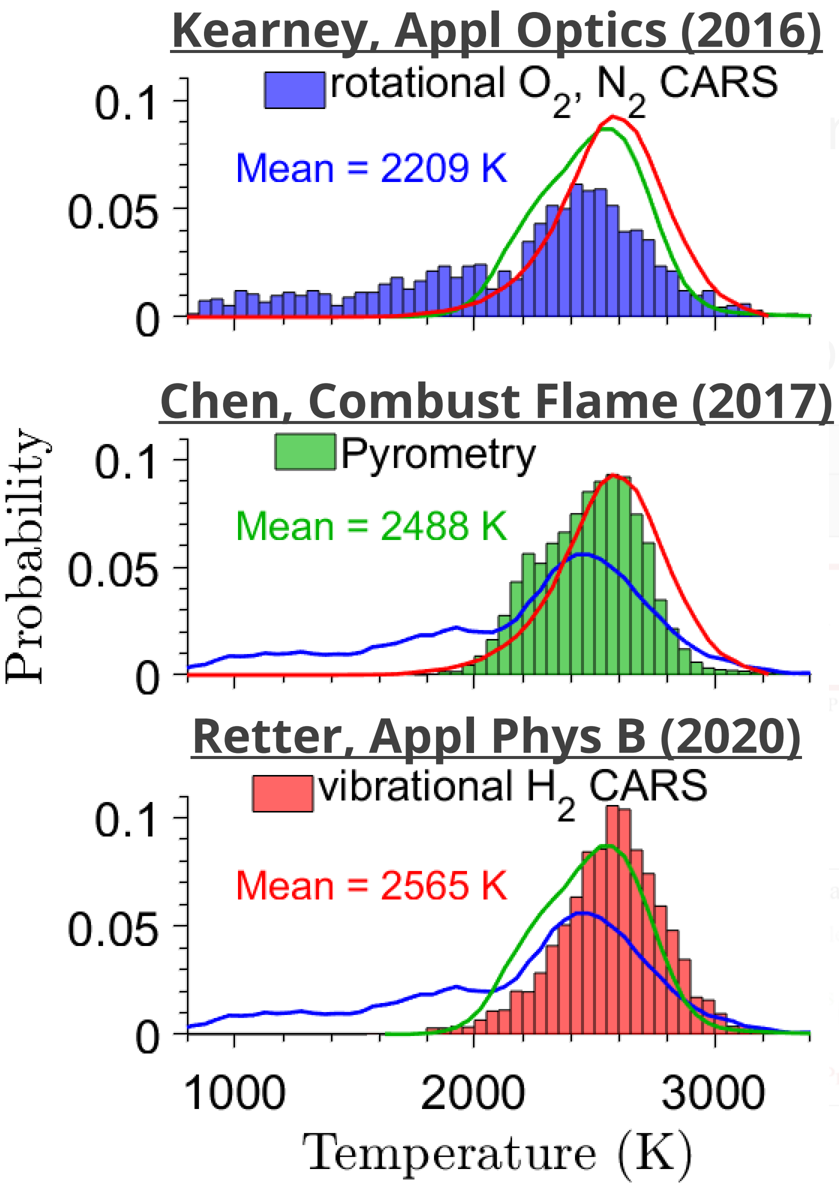


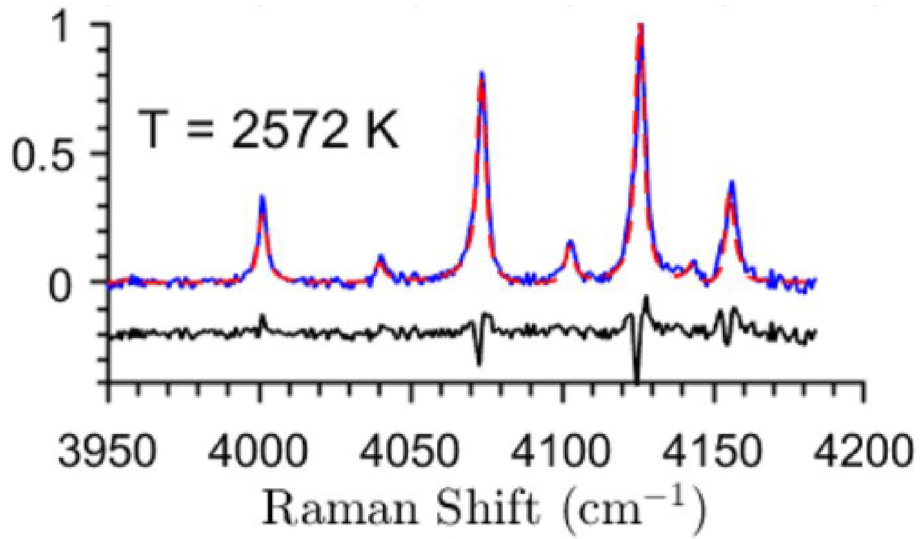
Shock Tubes and Wind Tunnels


Explosives

Pool Fires

Subsonic CARS (1 of 2): CARS Thermometry in Rocket Propellants



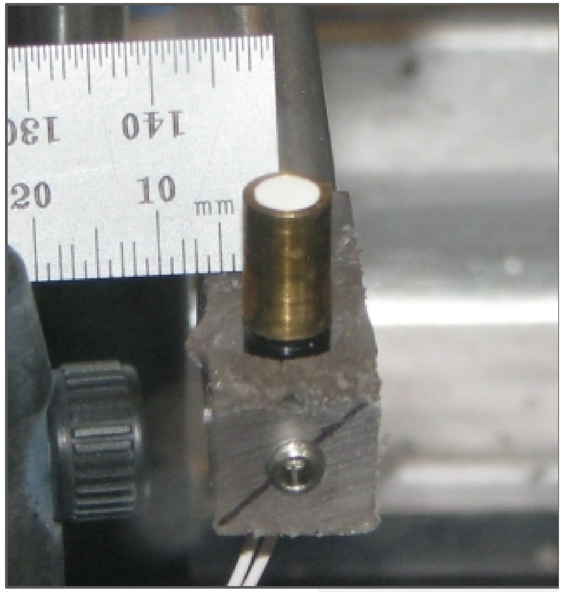


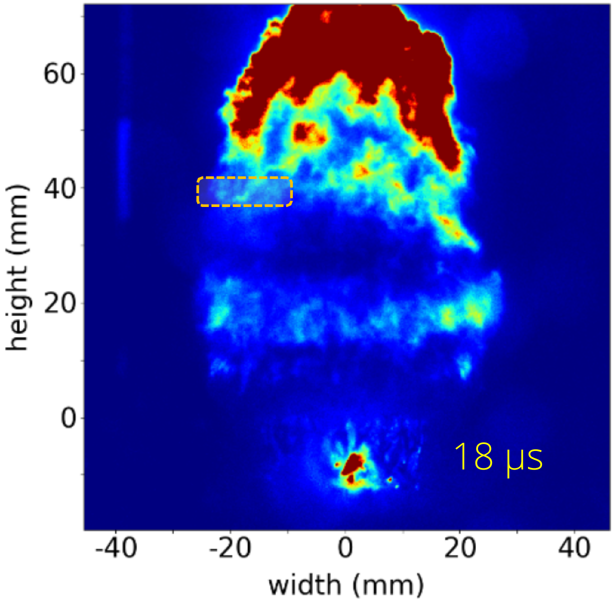
- Hydrogen CARS instrument used to measure temperature in fuel-rich plume
- Compared results to nitrogen rotational CARS and imaging pyrometry results

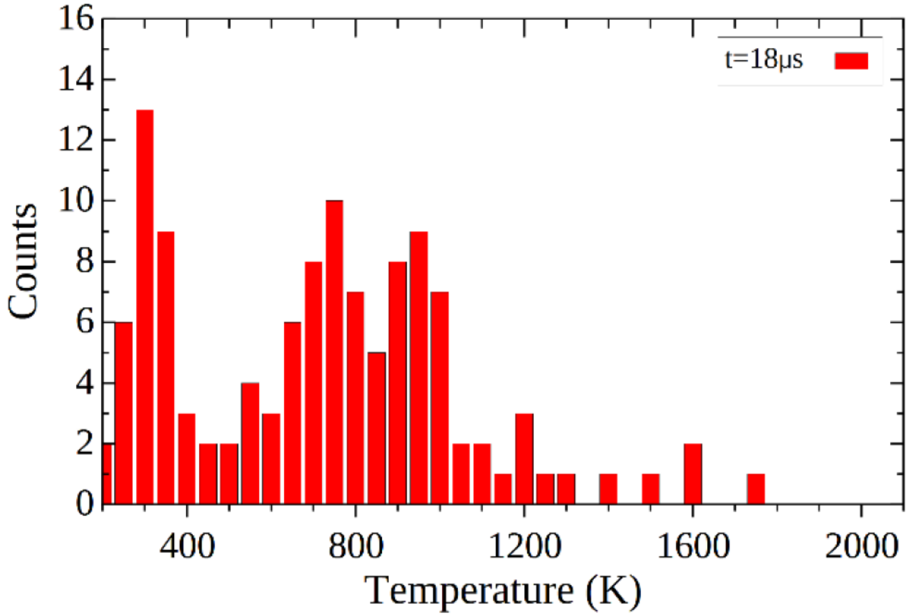
Subsonic CARS (2 of 2): CARS Thermometry in Explosive Fireballs

Detonation Fireballs

- Energetic materials are used in many industrial and military applications
- Extreme pressures and temperatures
- Fragments and debris
- 1D rotational CARS (N_2, O_2) instrument







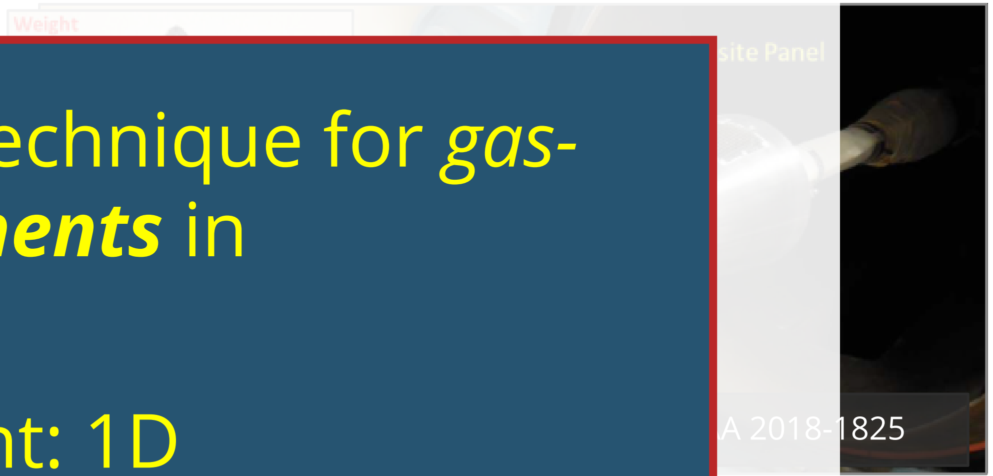
- Temporally and spatially resolved temperature measurements
- Scattered two-beam CARS signals suppressed using polarization scheme
- Measurements demonstrated at times and locations with significant mixing of detonation products with surrounding air

Introduction and Motivation

Hyp[ersonic Flow Characterization]

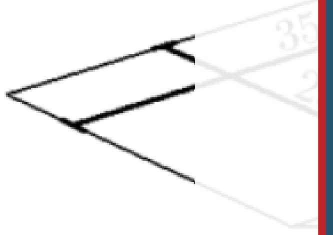
- Uncerta... conditio...
- Pressur...
  - Frees...
  - Acros...
  - Wake...
- Study fl...

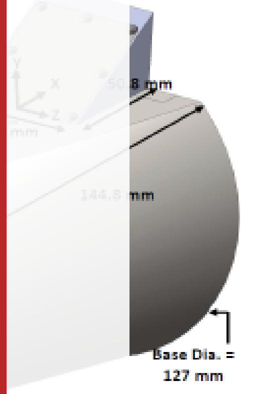
Slender Cone with Deformable Panel



A 2018-1825

Flat Plate wi... Thin Ramp





AIAA 2021-0909

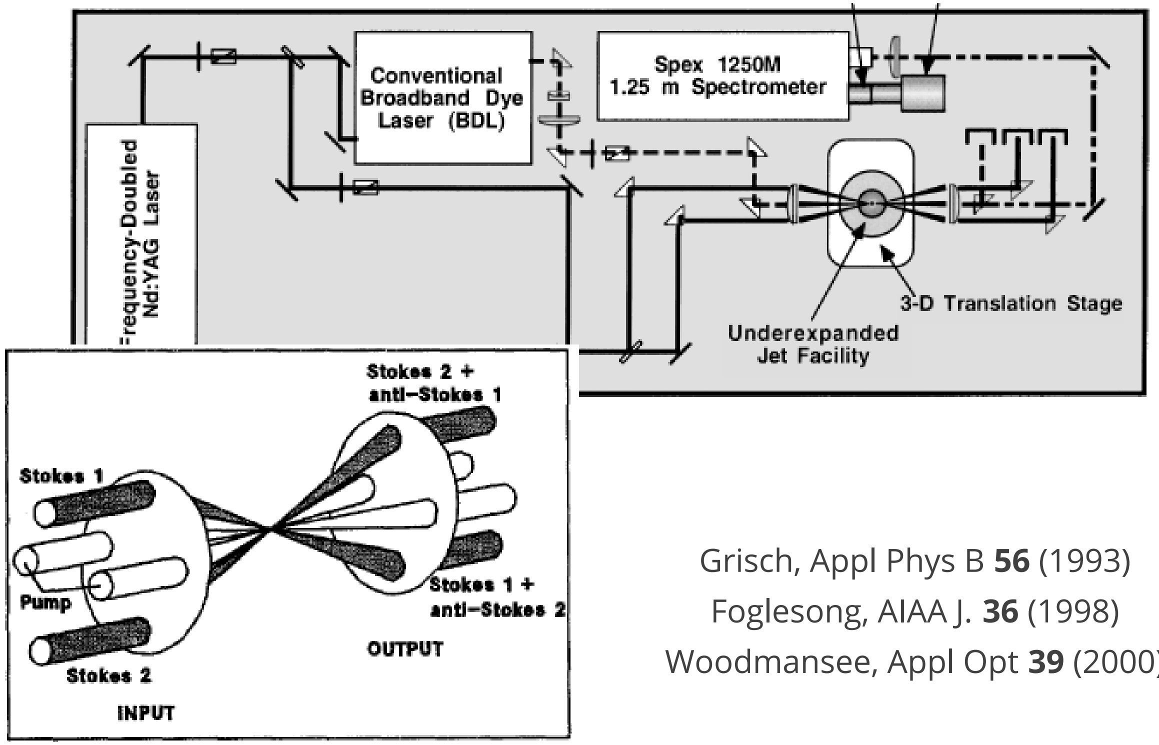
<u>Goal</u>: Develop an optical technique for *gas-phase* ***pressure measurements*** in hypersonic flows

1. Technique development: 1D measurements in bench-top jet
2. Cryogenic linewidths: required for applied measurements
3. Initial demonstrations in Sandia's cold-flow hypersonic wind tunnel

Technique Development

Previous Work: Nanosecond CARS Pressure Measurements

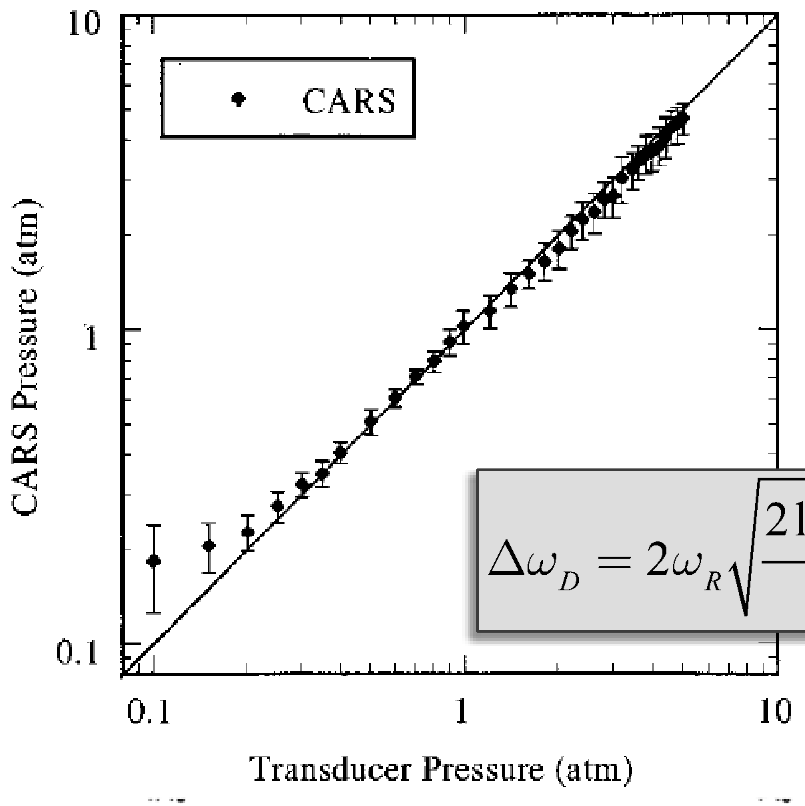
Nanosecond Coherent Anti-Stokes Raman Scattering (ns CARS)



Grisch, Appl Phys B **56** (1993)

Foglesong, AIAA J. **36** (1998)

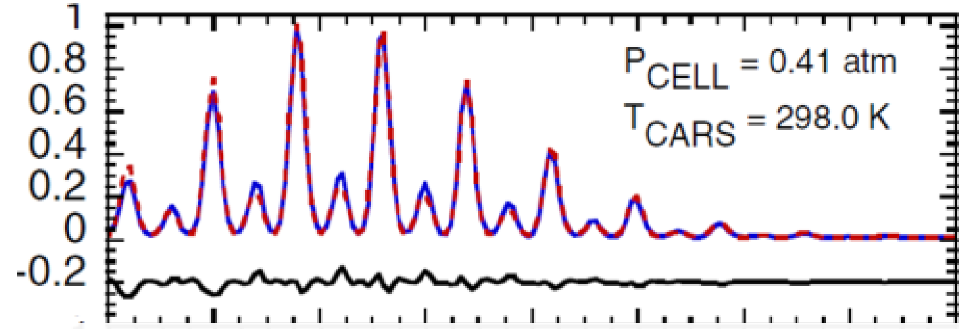
Woodmansee, Appl Opt **39** (2000)

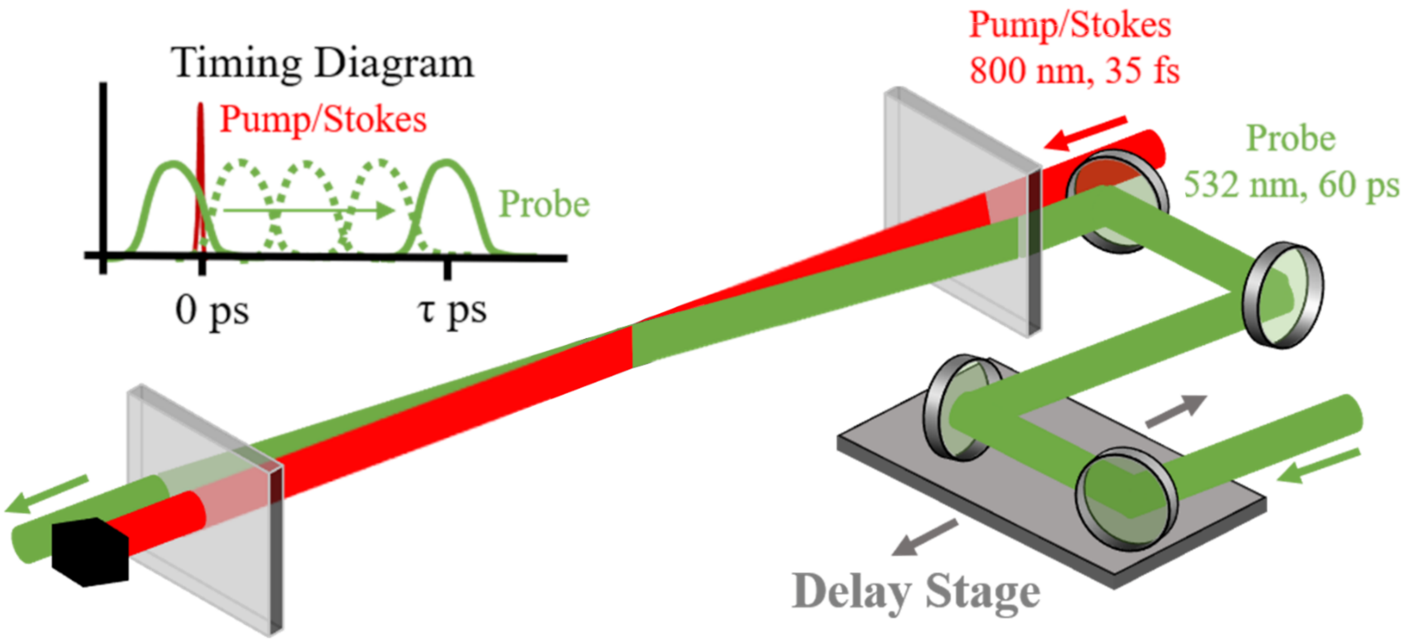


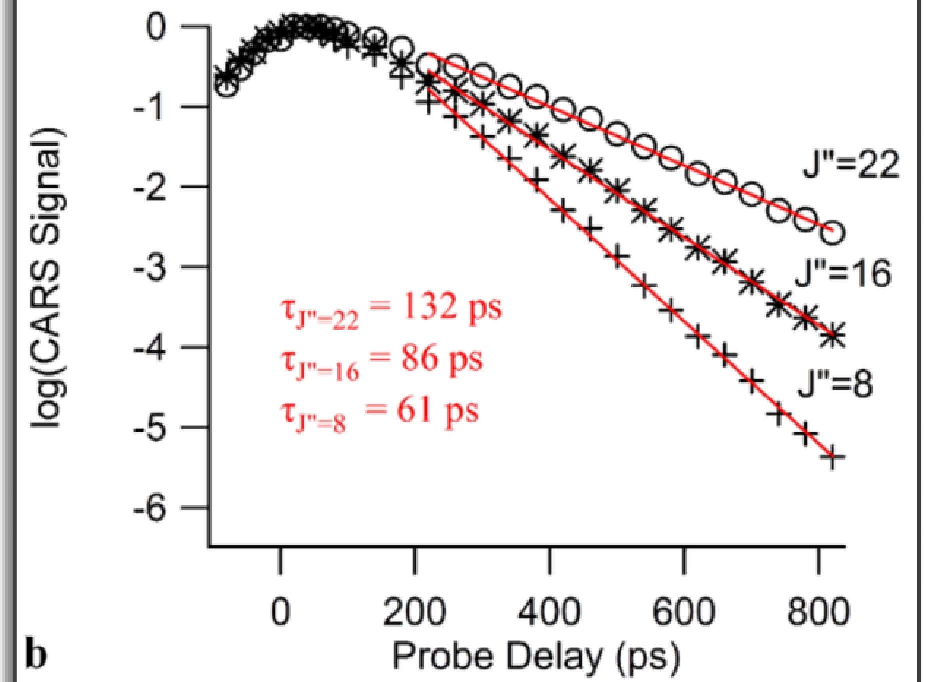
$$\Delta\omega_D = 2\omega_R\sqrt{\frac{2\log(2)kT}{m}}$$

Previous Work: Femtosecond CARS for p, T

- Broadband fs pulse excites many rotational Raman transitions
  - Each transition has a different decay rate (linewidth) from collisional dephasing
- Early probe to measure temperature
- Late probe to measure pressure



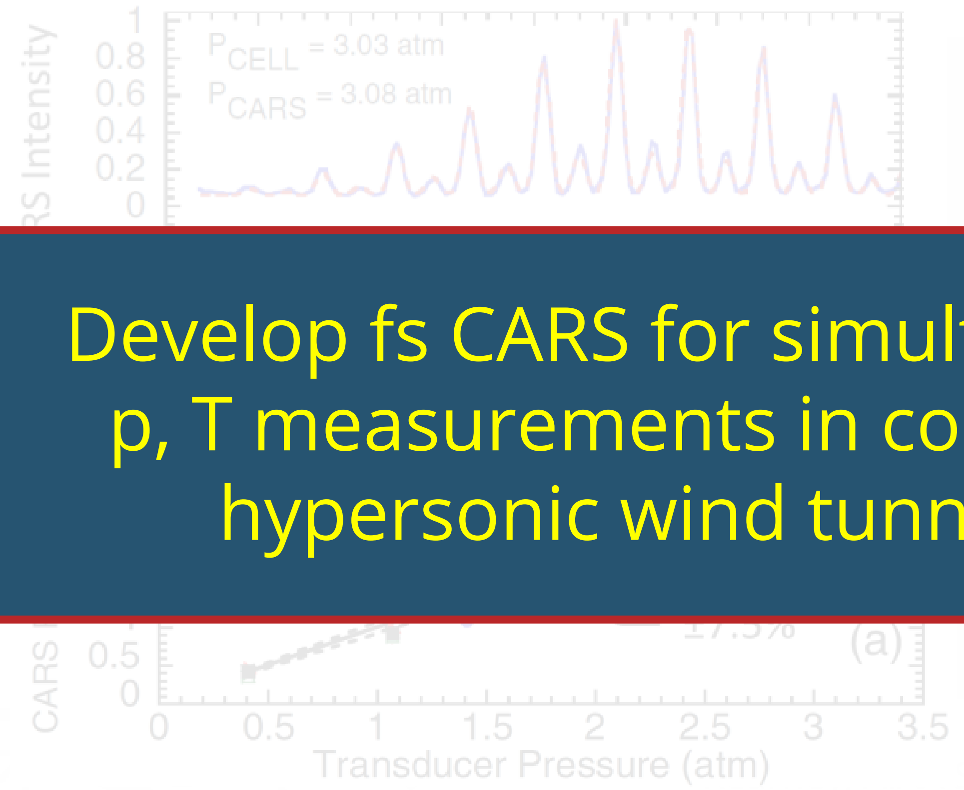




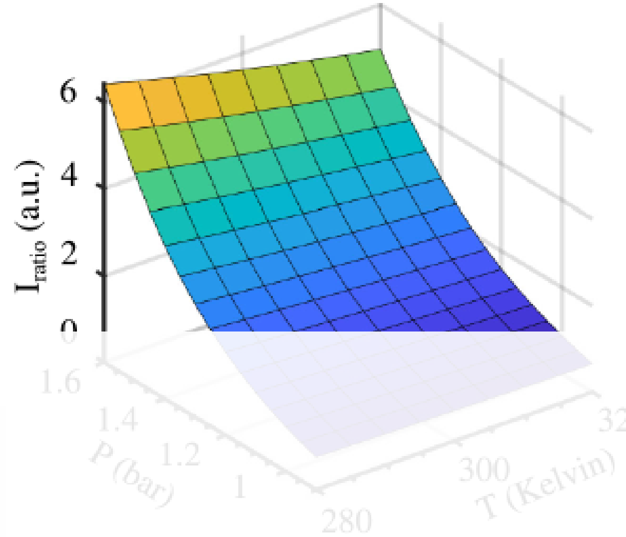
Kliewer, Appl Phys B **108** (2012)

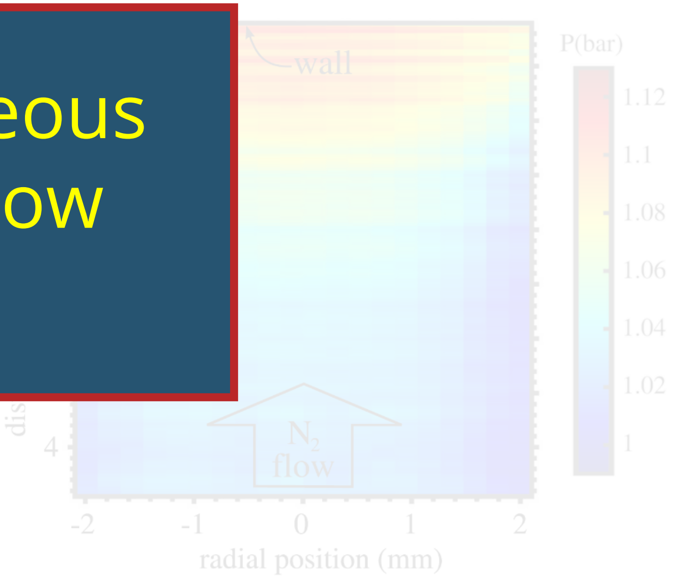
Previous Femtosecond CARS for p, T

- Single-shot measurements demonstrated with two-probe rotational CARS instruments
- Spectral fitting or ratio of intensities



Kearney, Opt. Lett. **40** (2015)

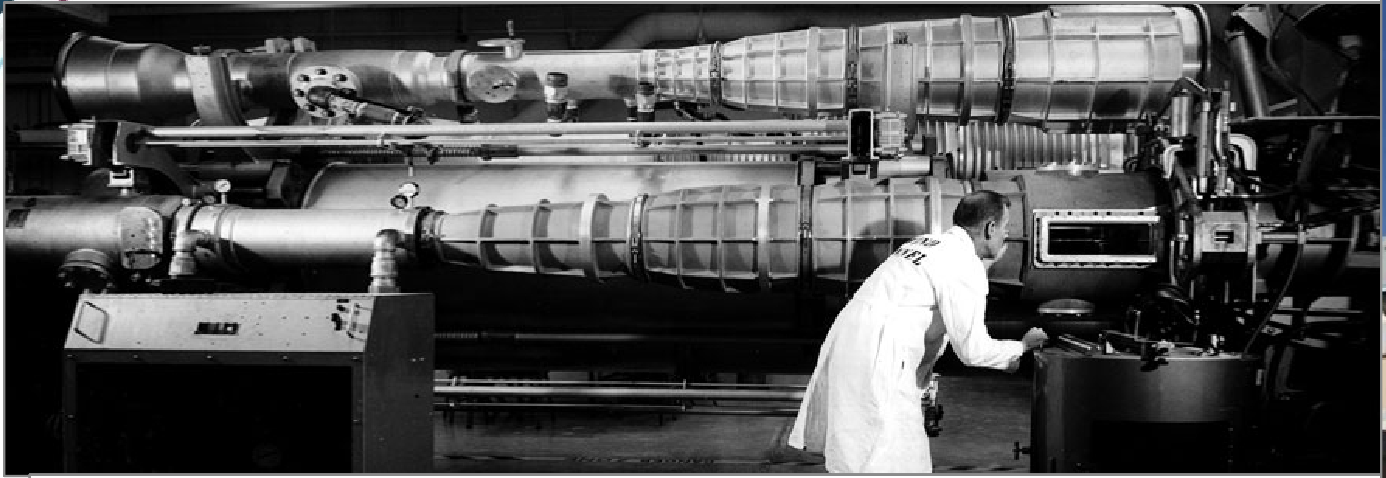


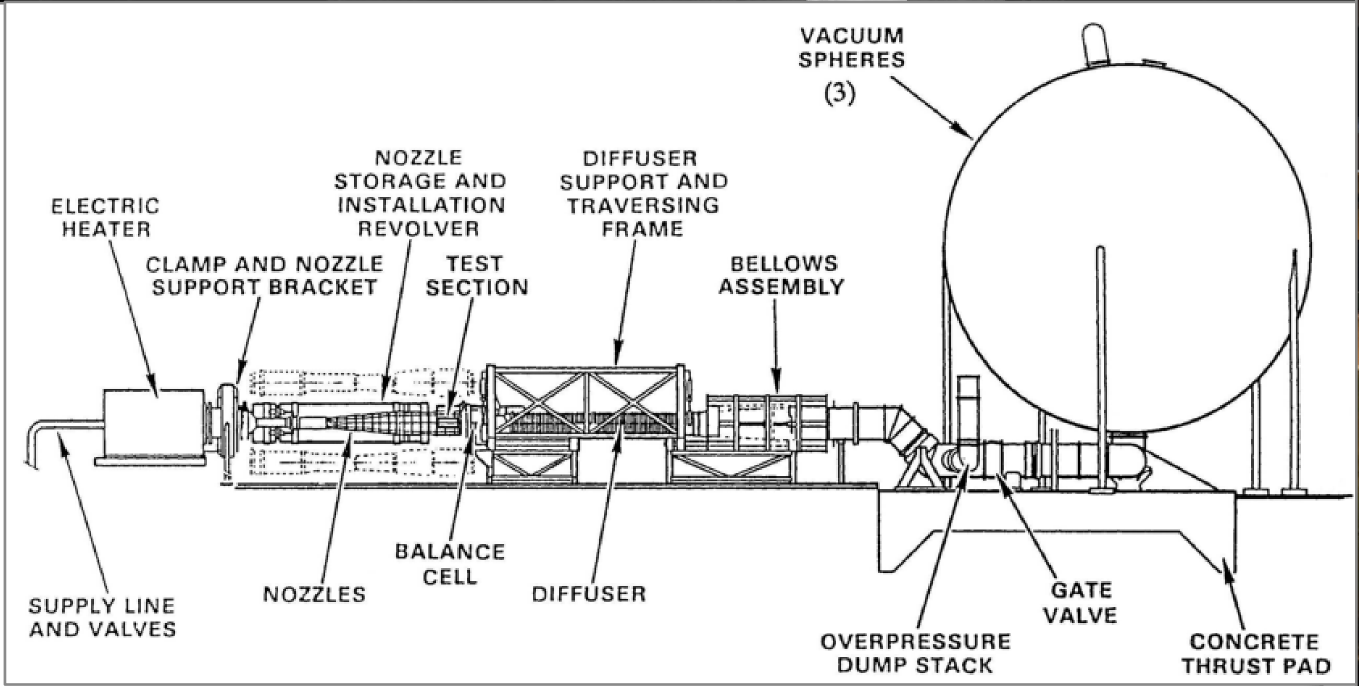


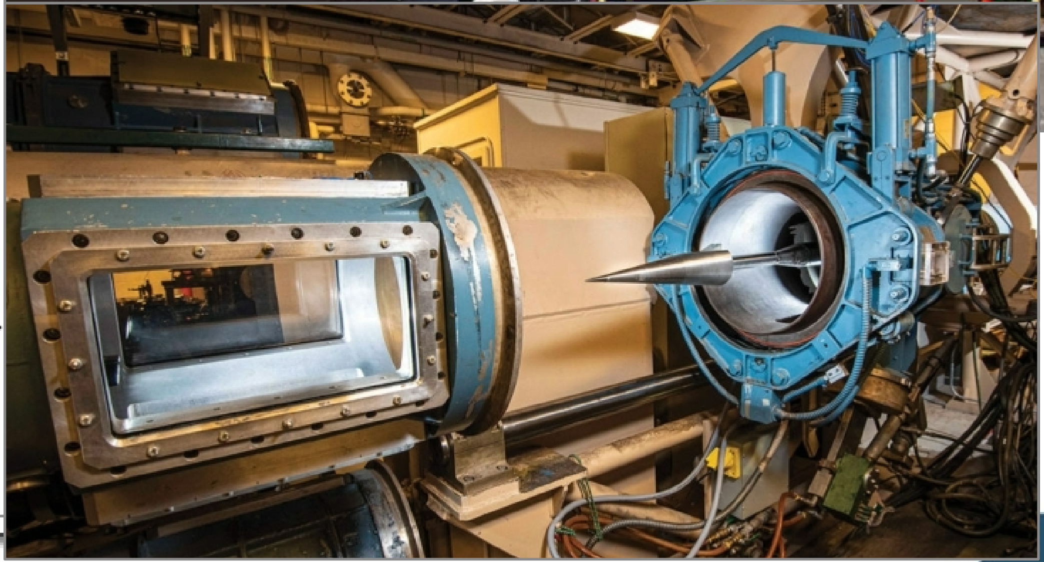
Escofet, Opt Lett **45** (2020)

Develop fs CARS for simultaneous p, T measurements in cold-flow hypersonic wind tunnels.

Sandia’s Hypersonic Wind Tunnel





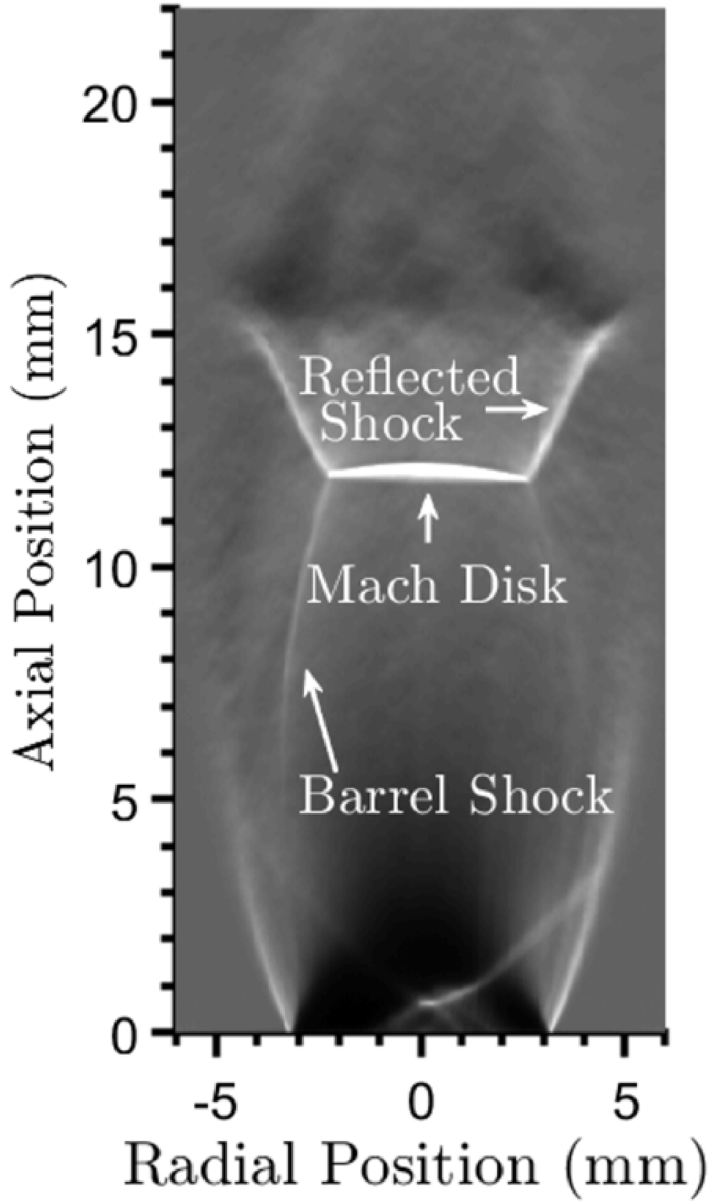


Technique Development: Extend to Low-P Hypersonic Flows

Demonstrate benchtop measurements in relevant environment….

Underexpanded sonic jet:

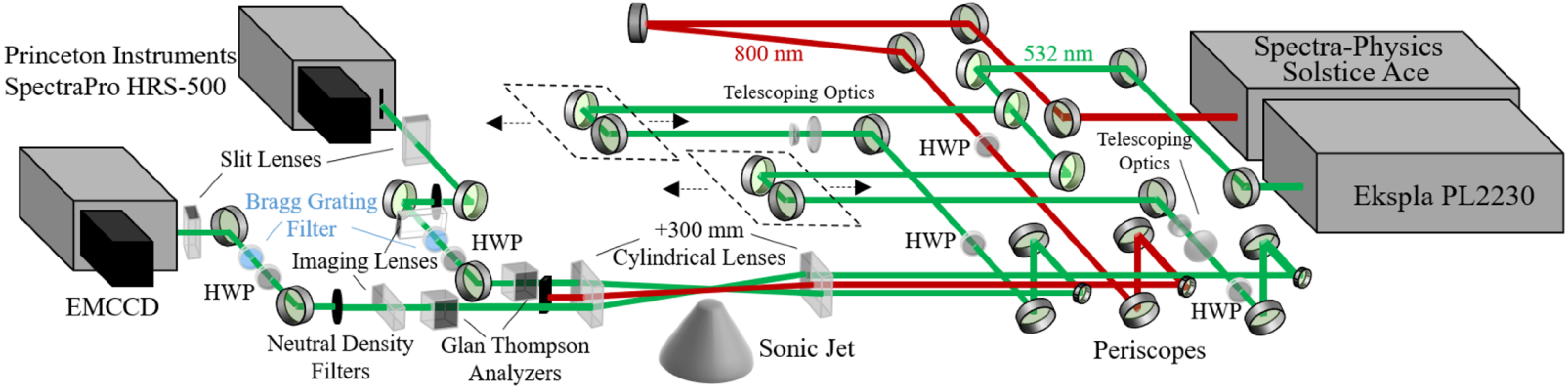
- Exit diameter of 6.35 mm
- Stagnation conditions:
  p_o = 7.62 atm, T_o = 292 K
- Flow air or nitrogen
- Isentropic expansion to Mach disk
- Wide range of static T, p in jet:
  - 3 atm → 0.1 atm
  - 240 K → 80 K
  - Conditions near Mach disk are similar to Sandia's hypersonic wind tunnel!
- Test measurement capability across shock



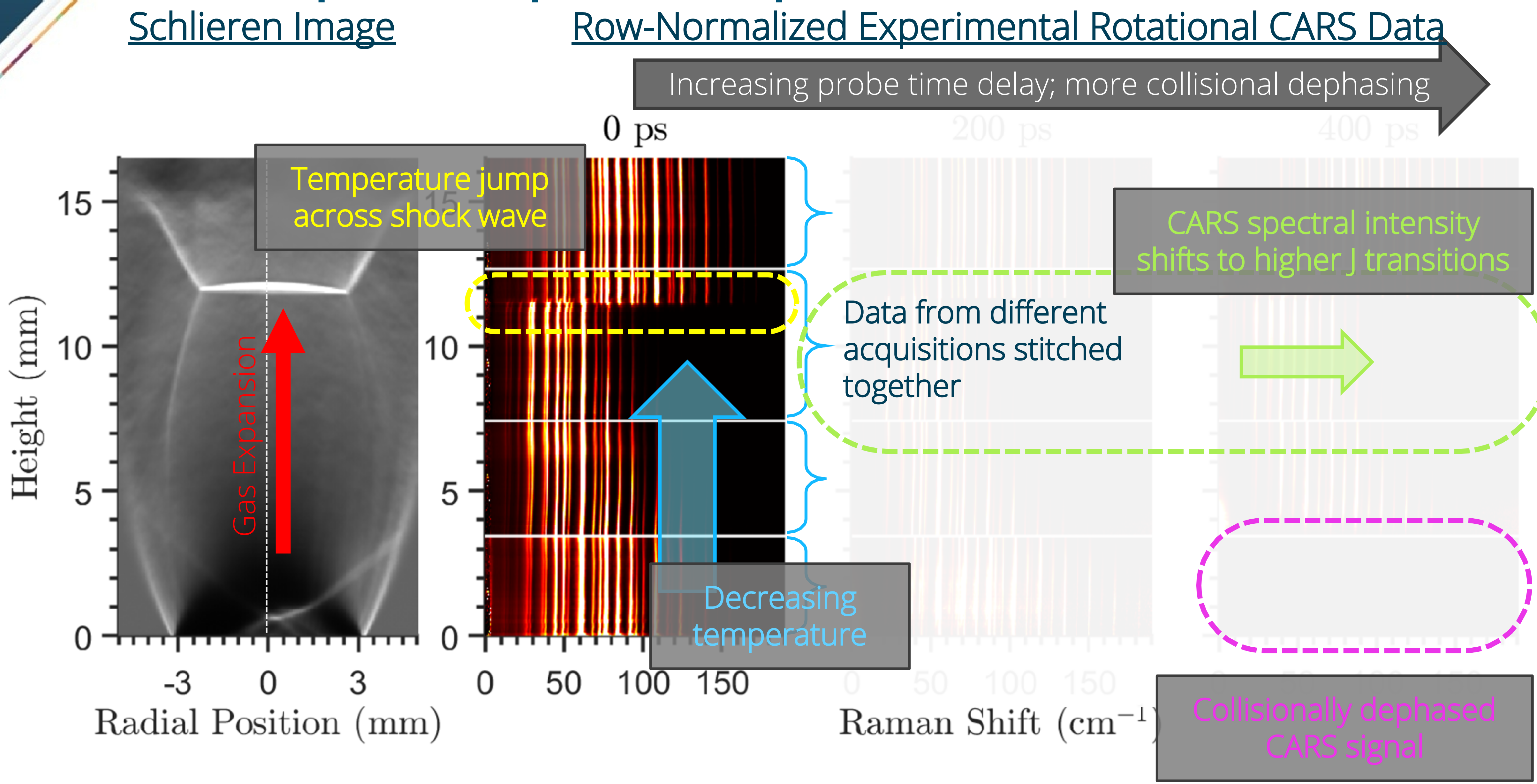
Technique Development: Extend to Low-P Hypersonic Flows

Dual-probe fs/ps rotational CARS instrument:

- 1D imaging scheme (2x) developed by Bohlin and Kliewer
- Pump: 50-fs, 4-mJ, 800-nm
- Probe: 60-ps, 50-mJ, 532-nm
- 6-mm long measurement line
- 1000 µm X 67 µm X 30 µm resolution



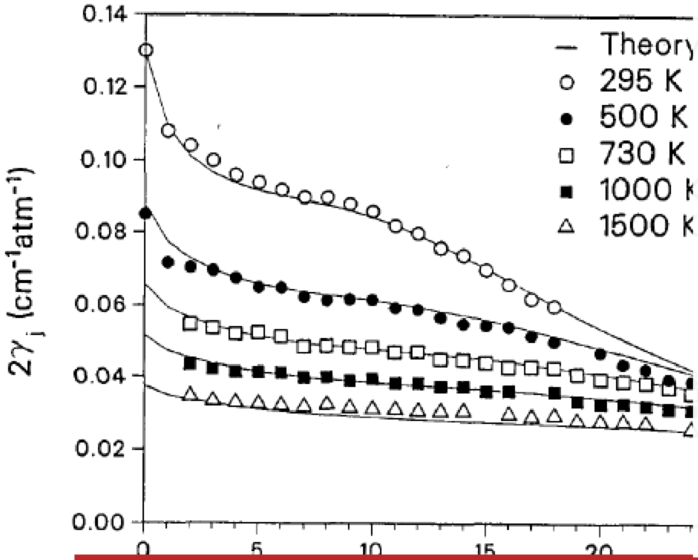
Technique Development: Sample Data



Technique Development: Need for Cryogenic Linewidths

- To determine pressure from CARS spectra, need to know accurate S-branch Raman linewidths

Q-Branch Data and MEG Model



S-Branch Data

Cryogenic S-Branch Linewidths for even J

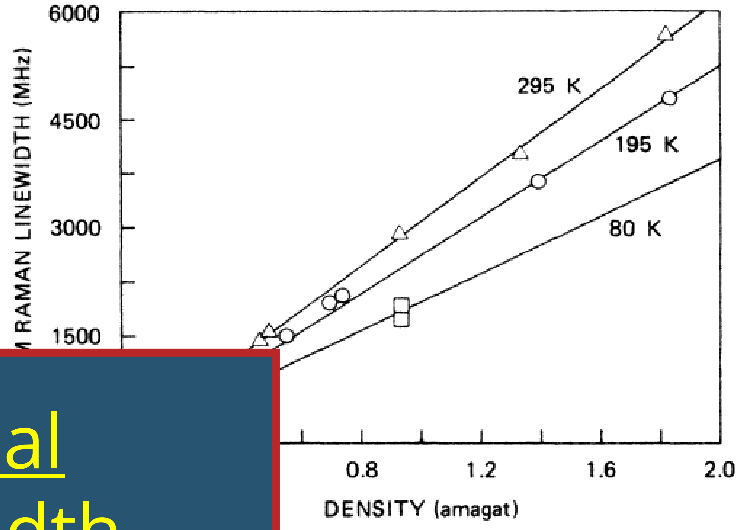


TABLE I. Temperature dependence of the self-broadening coefficients for the rotational Raman lines of N_2.

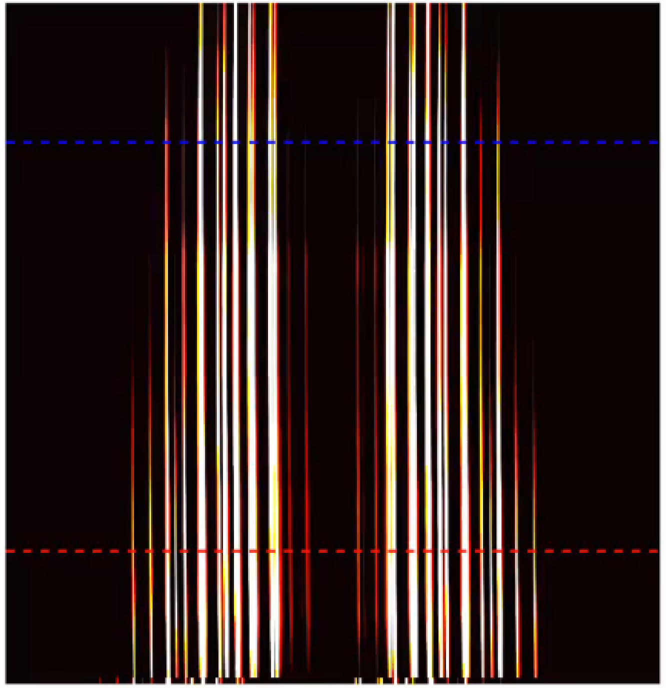
	B (MHz/amagat)		
S(*J*)	295 K	195 K	80 K
0		4730±700	3140±470
2	4160±400	3560±350	2700±270
4	3580±60	3230±320	2490±250
6	3560±30	3070±30	2520±40
8	3270±60	2860±30	2120±60
10	3060±60	2660±30	1940±40
12	2870±50	2340±260	1690±100
14	2660±270	2150±215	
16		1840±185	

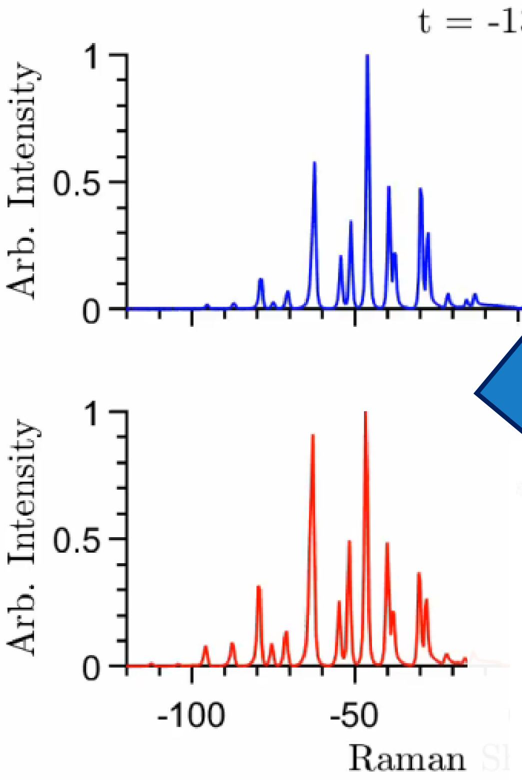
Herring, Phys. Rev. A **34** (1986)

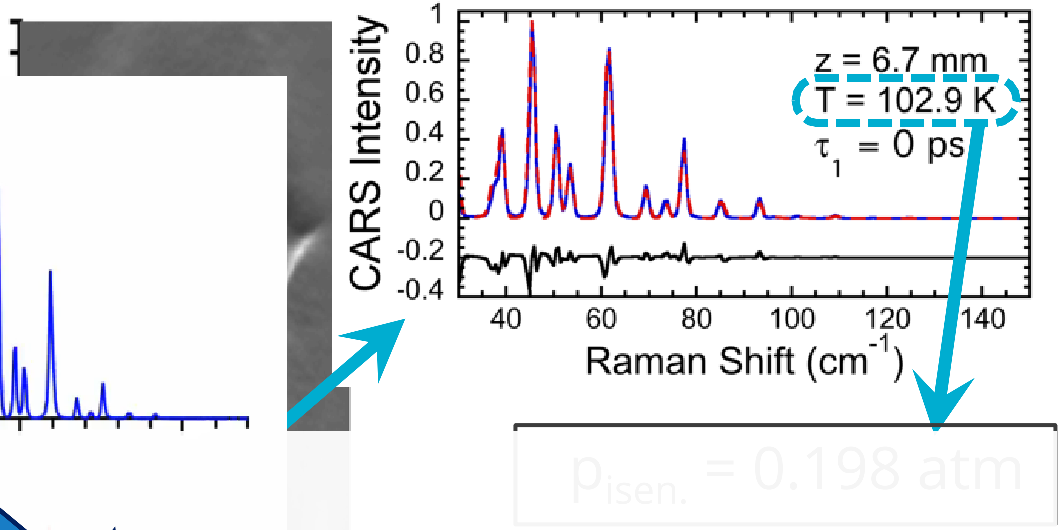
Need additional cryogenic linewidth data!

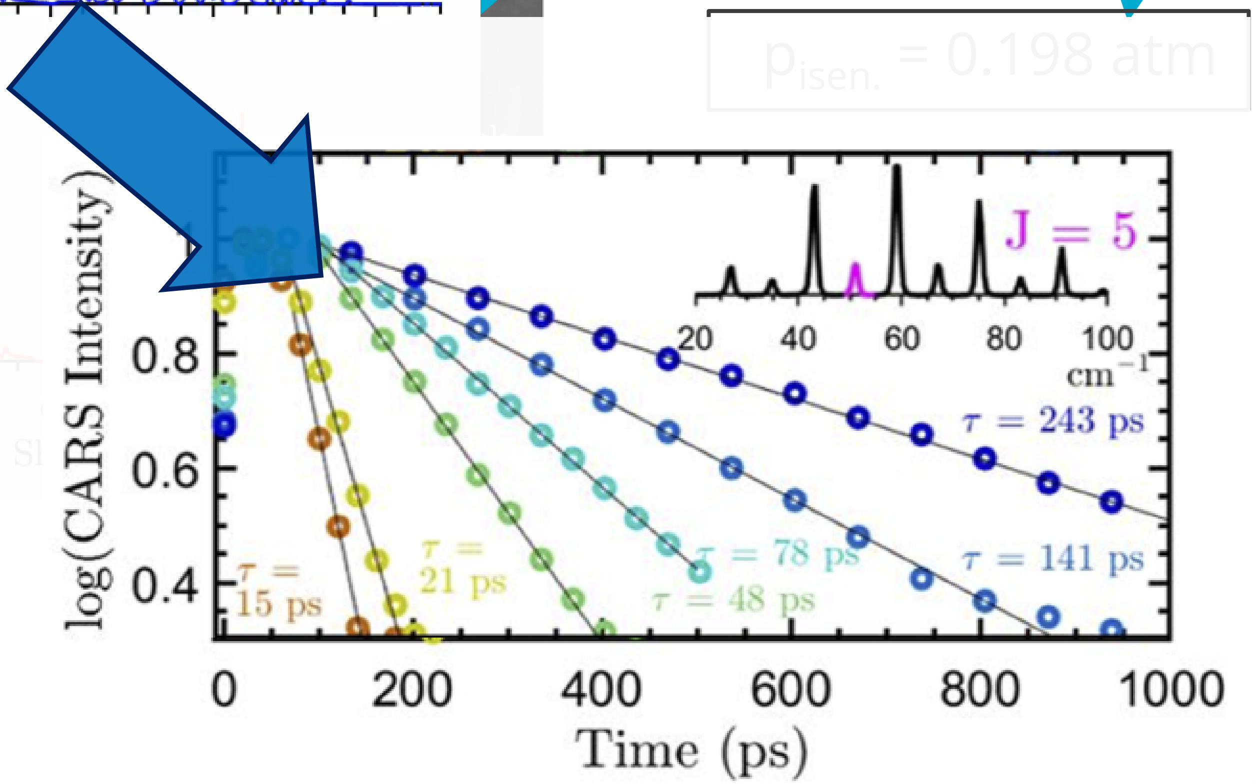
Cryogenic S-Branch Linewidths:

Cryogenic Linewidth Data: Experimental Approach









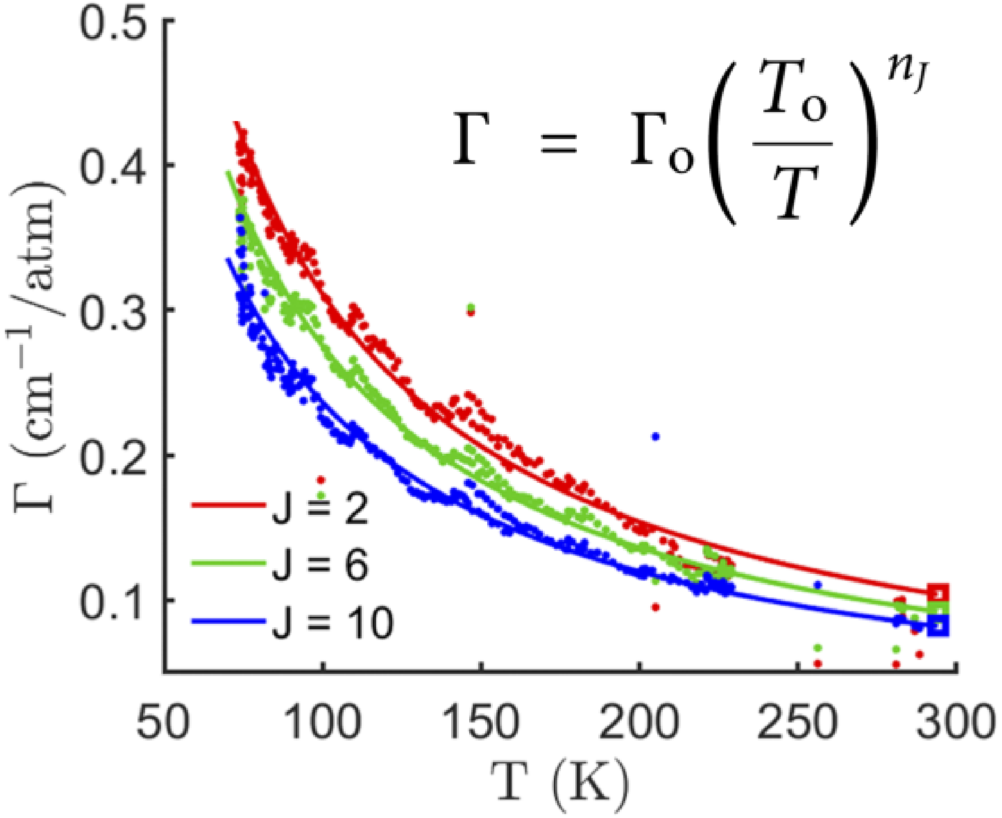
time delays

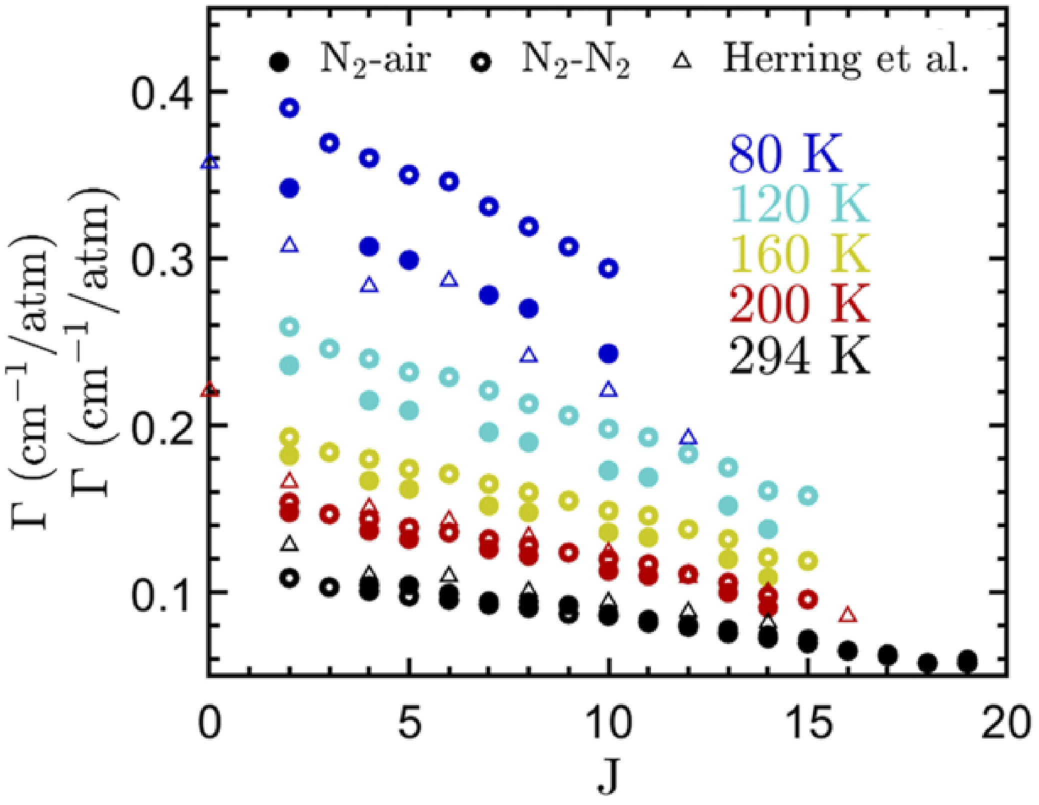
5. Compute T- and J-dependent linewidths:

$$\Gamma_J = (c\pi\tau_J)^{-1}$$

Cryogenic Linewidth Data: Experimental Approach

- Departure from MEG for low temperatures
- Experimental data fit to power law
- Cryogenic linewidths found for N_2-N_2, N_2-air, and O_2-air

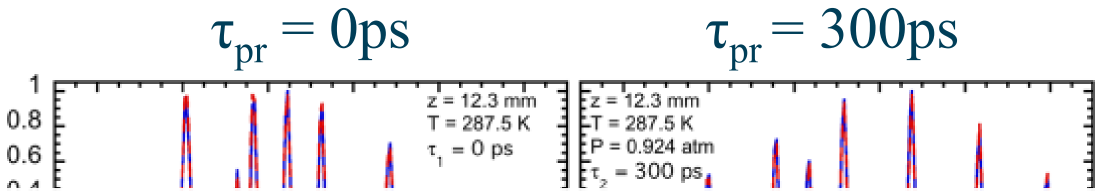


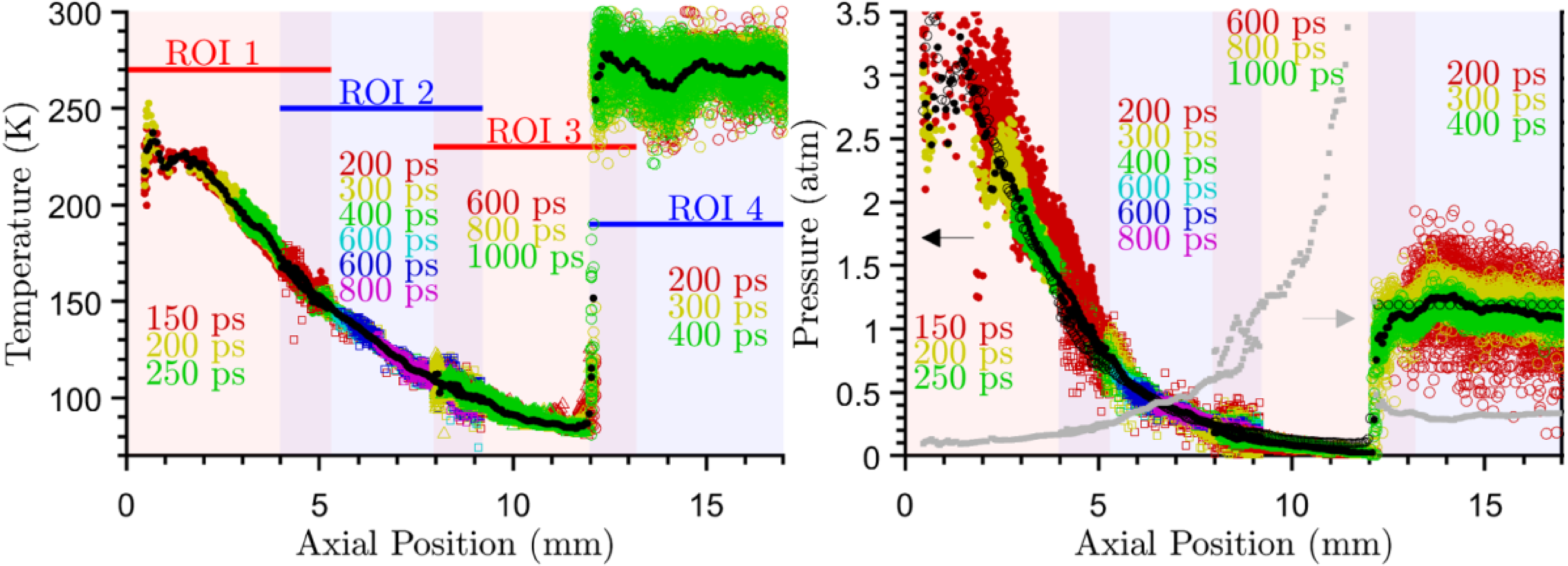


Retter, J. Chem. Phys. **156** (2022)

Cryogenic Linewidth Data: Applied to Underexpanded Jet

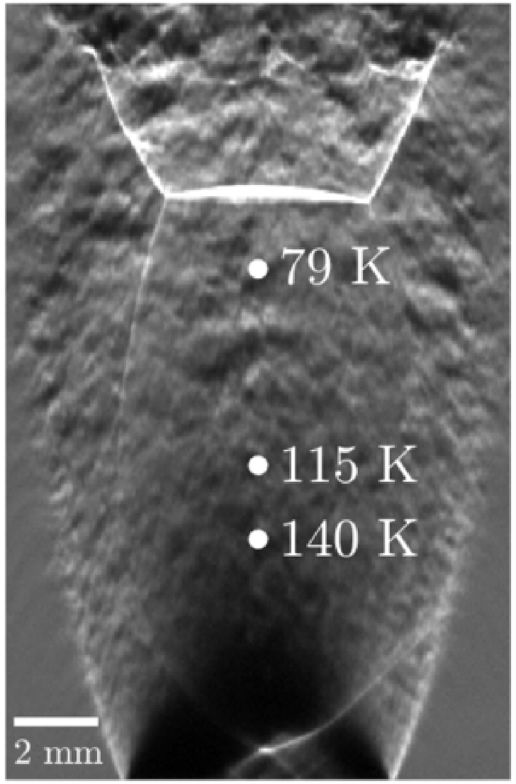
- Dual-probe RCARS spectrograms recorded
- Spectral fitting:

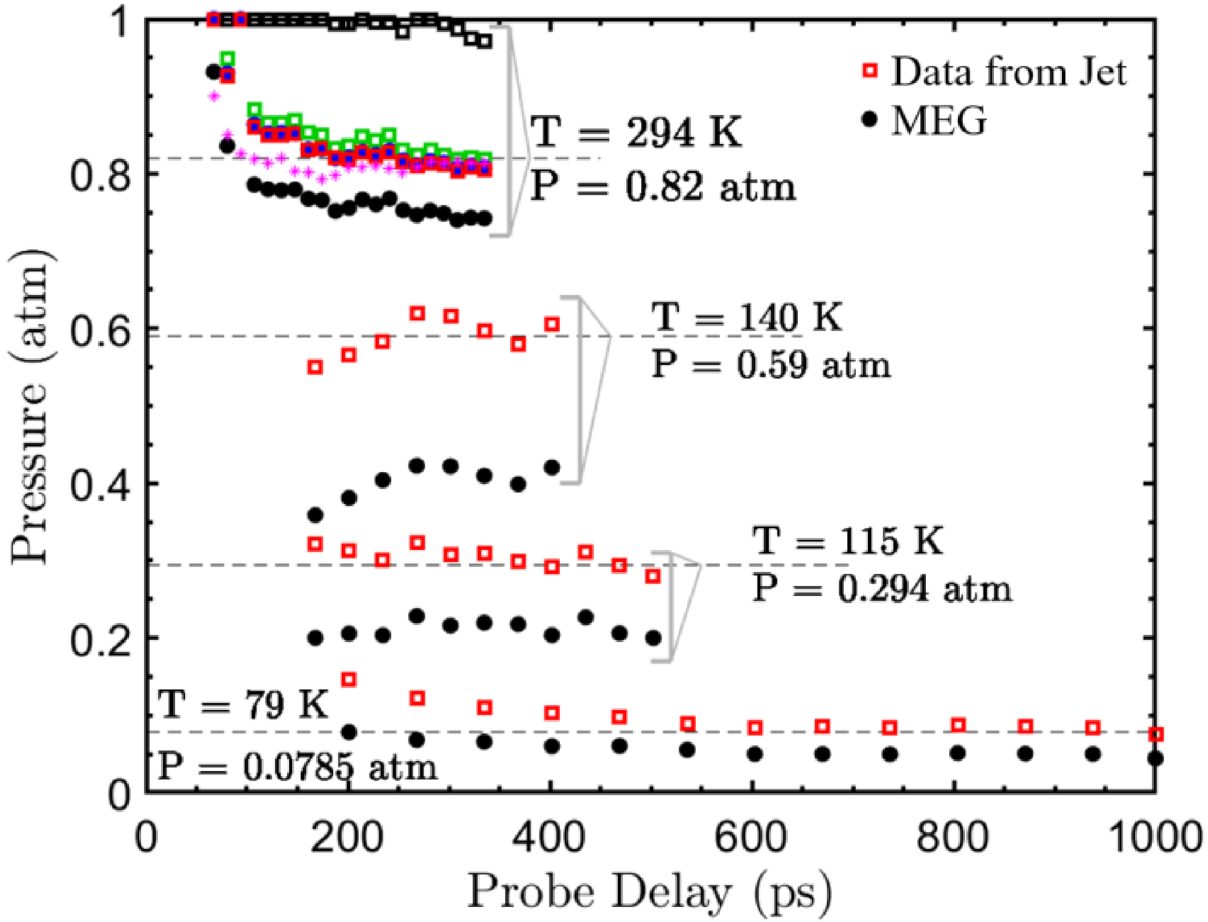




Cryogenic Linewidth Data: Impact on CARS Measurements

Extrapolation of MEG model leads to significant errors in CARS pressure measurements!

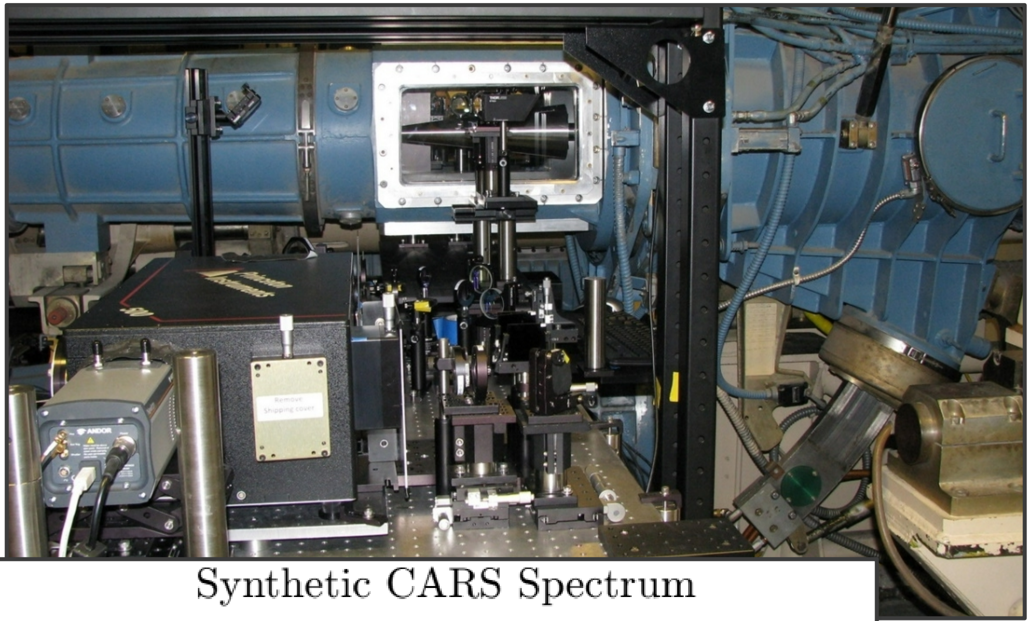


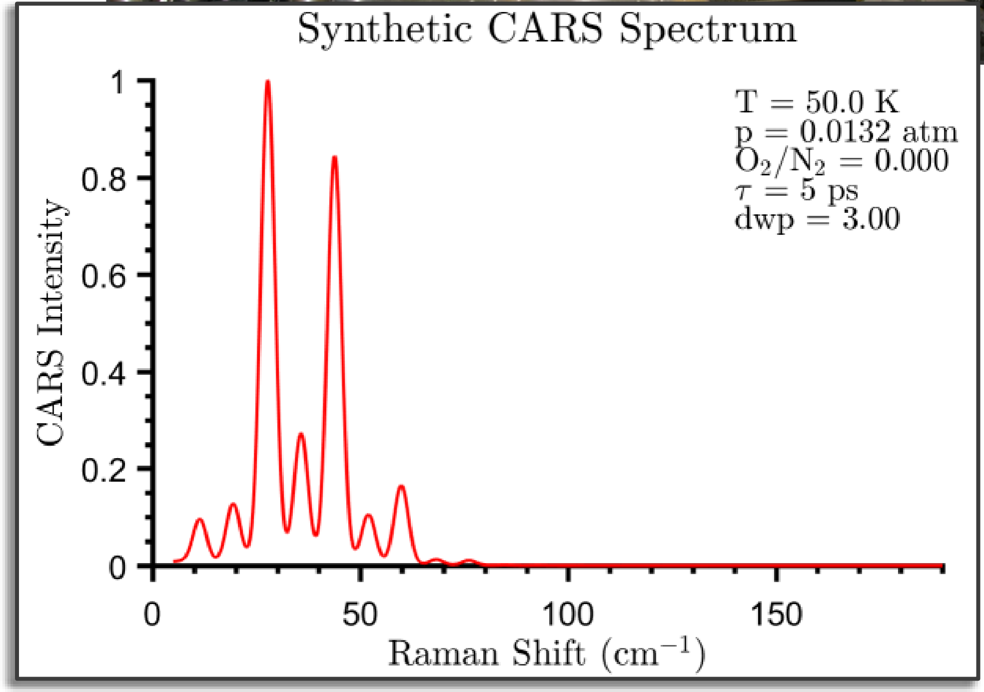


Measurements in a Hypersonic Wind Tunnel

Sandia's Hypersonic Wind Tunnel

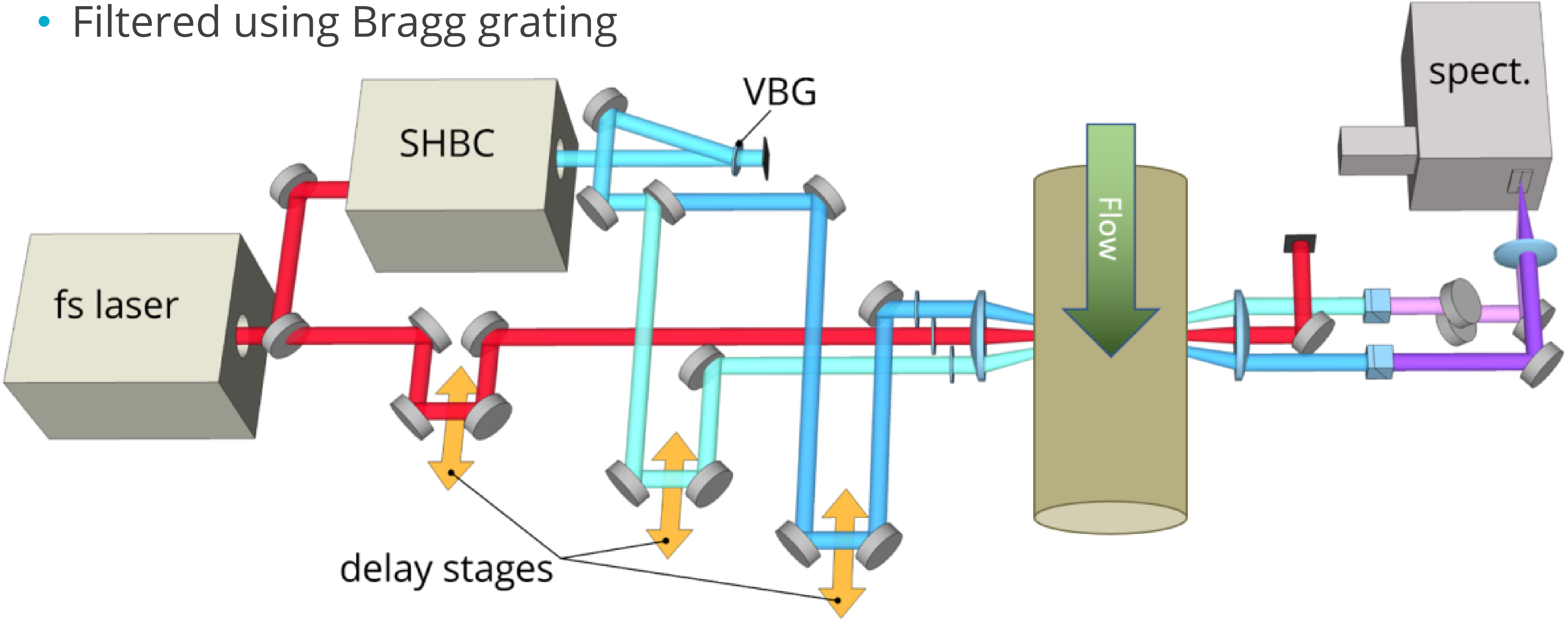
- Hypersonic wind tunnel (HWT)
  - Blowdown-to-vacuum tunnel
  - Mach 8 flow, pure N_2
  - p_o = 60 atm; T_o = 800 K
  - T_∞ ~ 50 K; p_∞ ~ 0.006 atm (5 Torr)
- Low gas density
  - ρ_∞ ~ 5% of ρ_{atm}
  - CARS signal in wind tunnel will be 0.25% of ambient CARS signal
  - Long Raman dephasing times (10 ns) → long optical delays (3 meters)
- Low gas temperatures
  - Few rotational levels populated
- Complex optical setup near large facility with limited run times





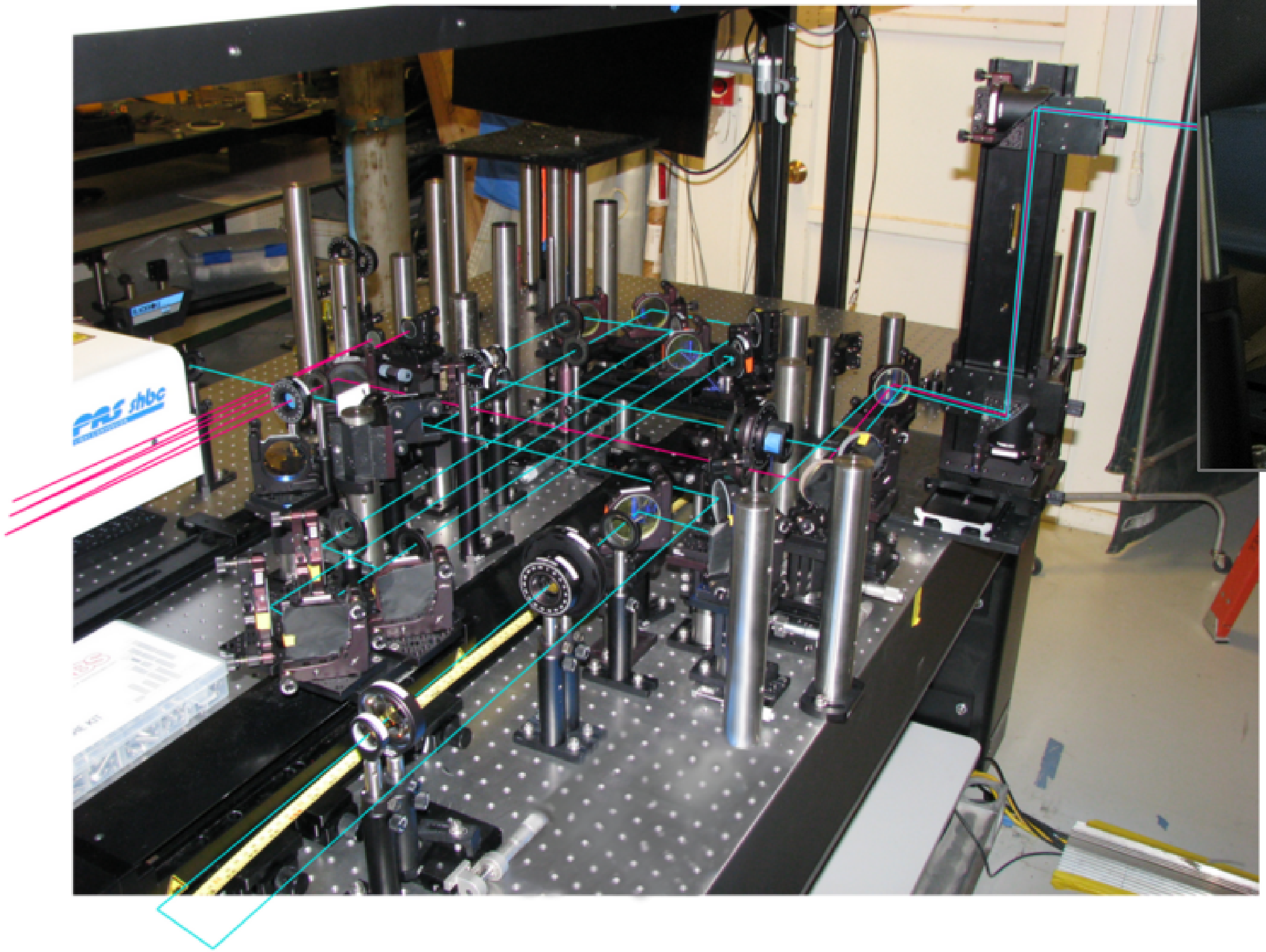
Femtosecond CARS for p, T in Hypersonic Wind Tunnel

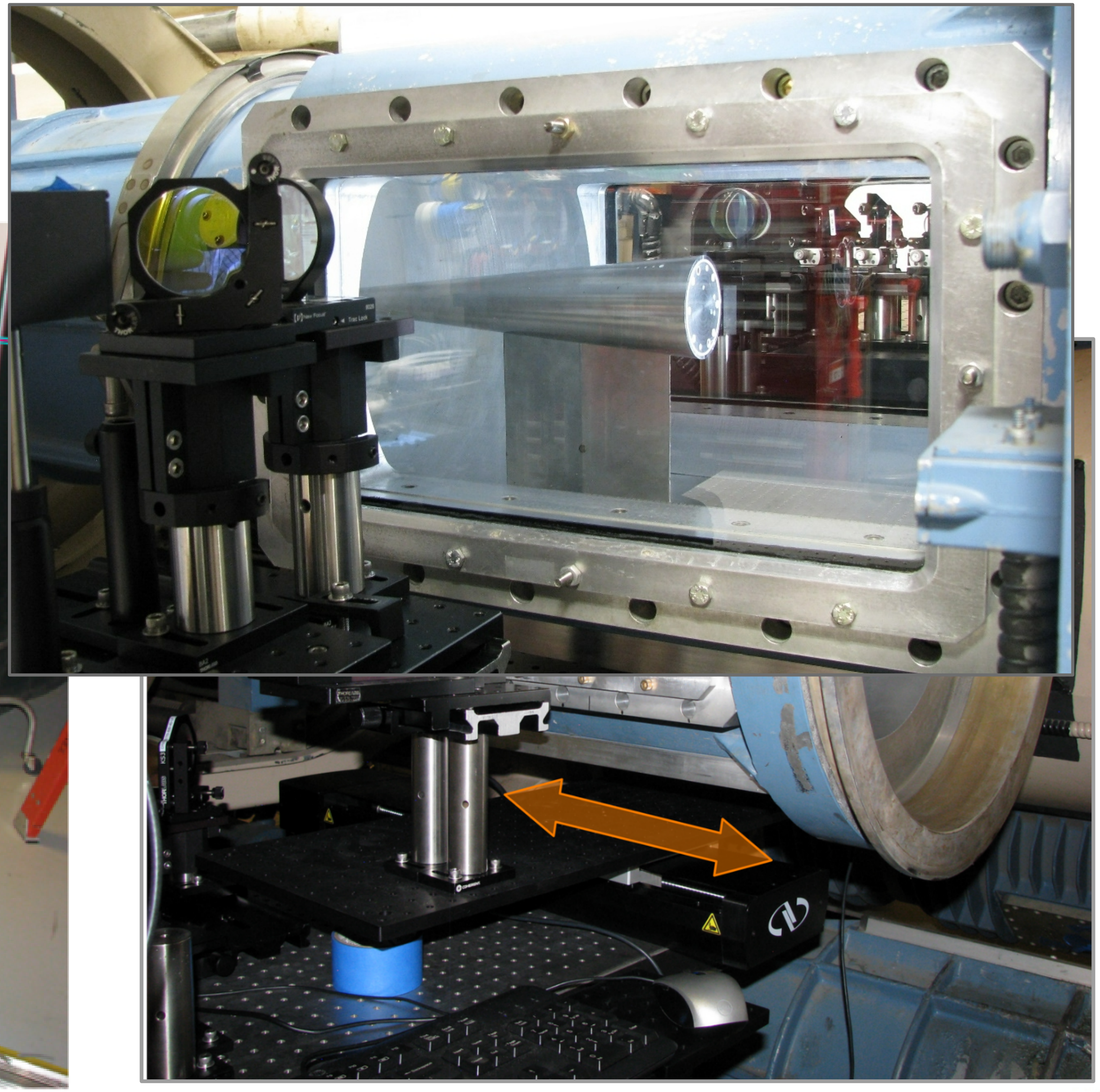
- Fs laser: 100 fs, 1 kHz, 2.5 mJ
  - Pump pulse for CARS process
  - Pumps second-harmonic bandwidth compressor (SHBC)
- SHBC probe: 6 ps, 400 μJ
  - Split to form early and late probes
  - Filtered using Bragg grating
- Polarization scheme used to reject probe from CARS signals
- CARS signals stacked vertically
  - Two single-shot spectra recorded at 1kHz on a single camera



Measurements in Hypersonic Wind Tunnel: Initial Attempts

- Dual-probe RCARS instrument setup near Sandia's HWT
- Strut-mounted, simple cone model

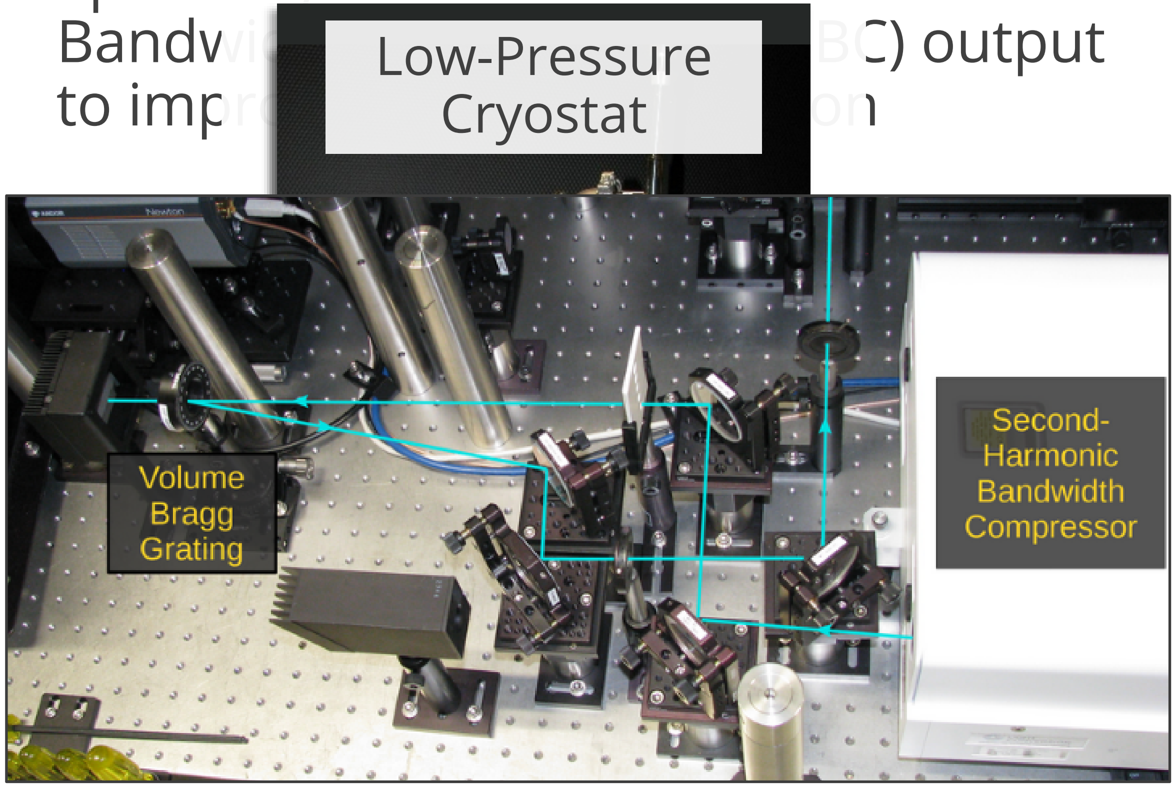


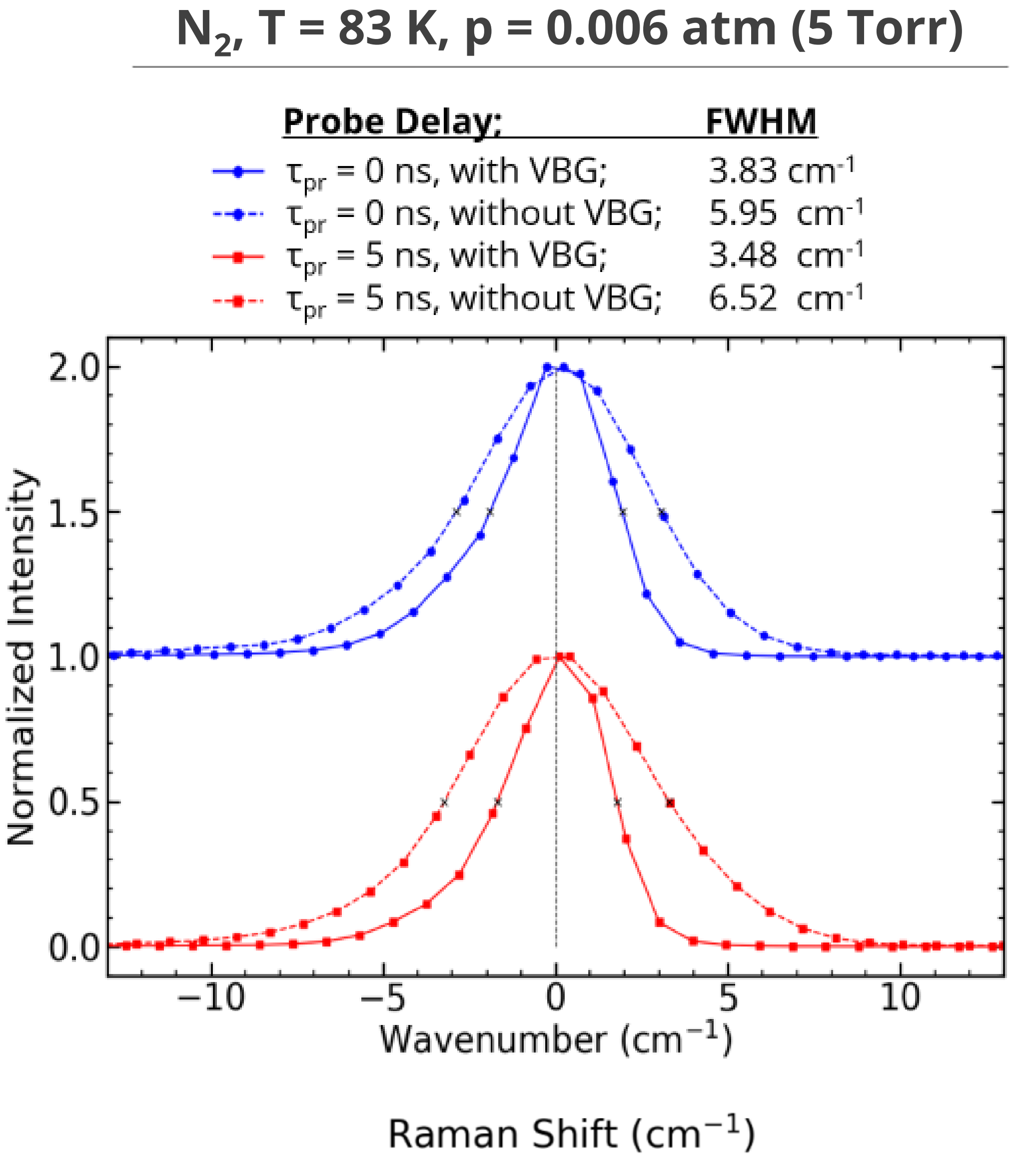


Measurements in Hypersonic Wind Tunnel: Initial Attempts

Initial attempts to apply fs/ps RCARS in the hypersonic wind tunnel led to some experimental improvements:

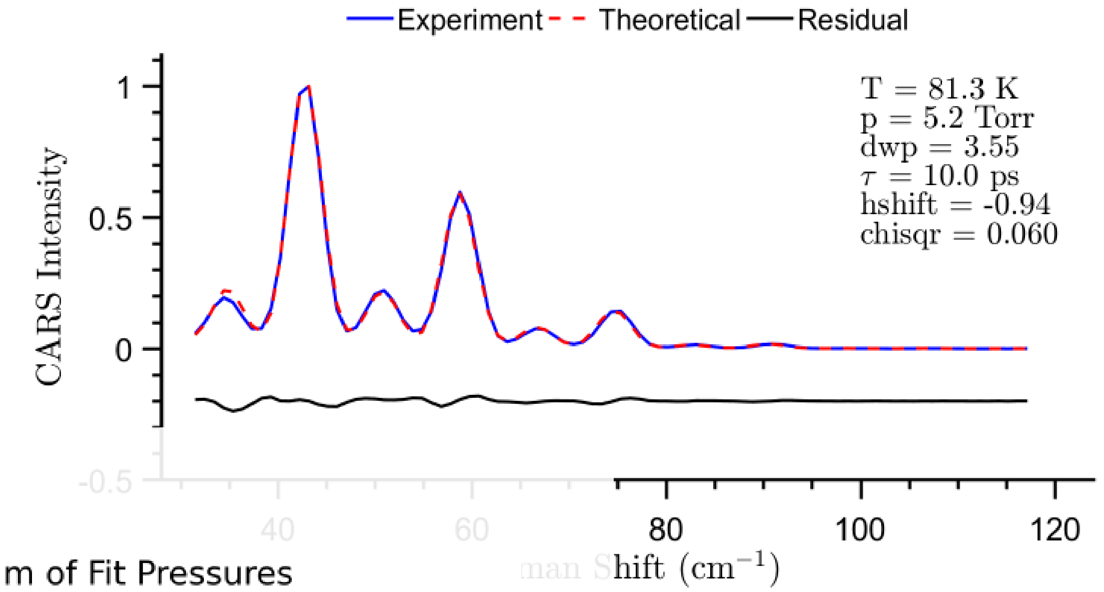
- Limit pump/Stokes pulse energy
- Spectrally filter Second-Harmonic Bandw… C) output to imp… on

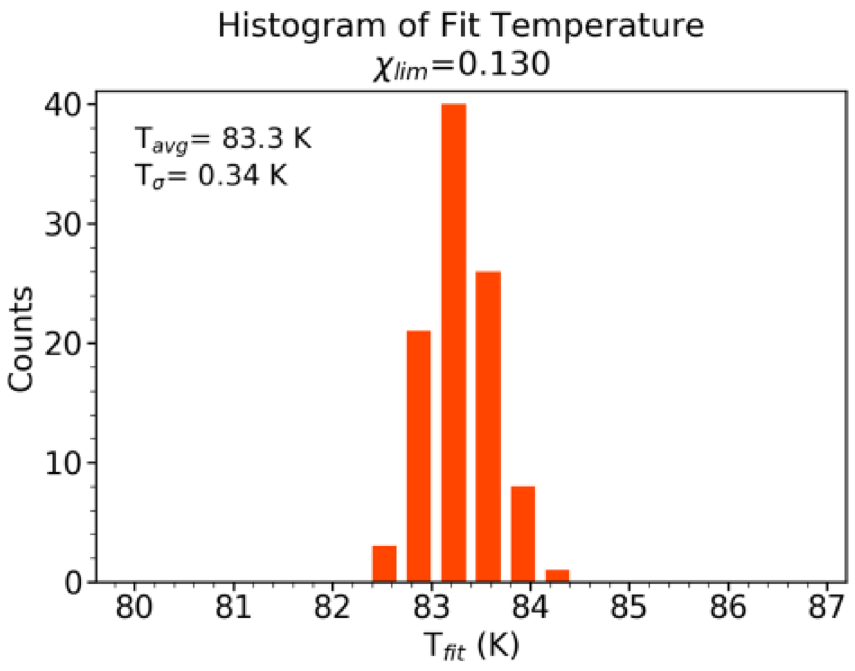


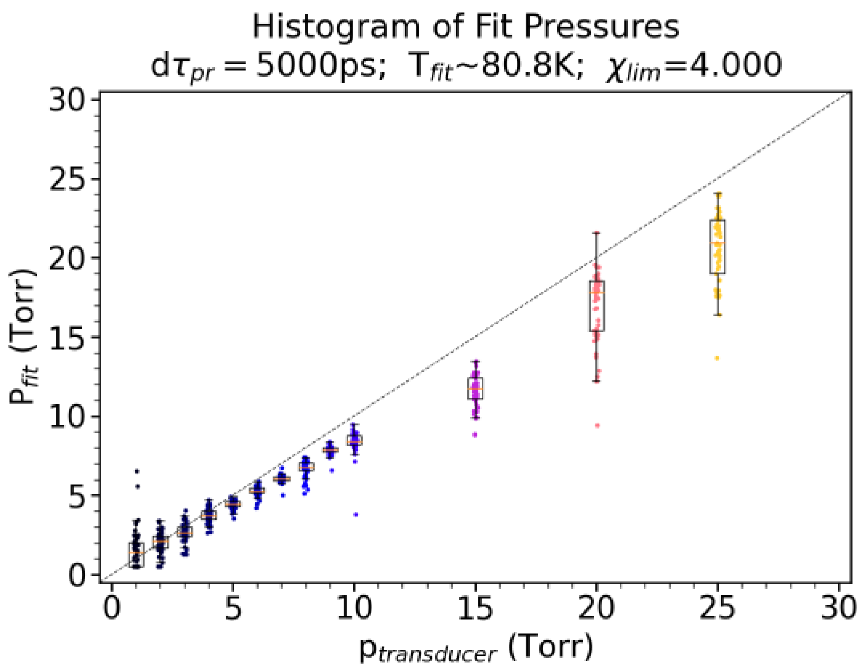


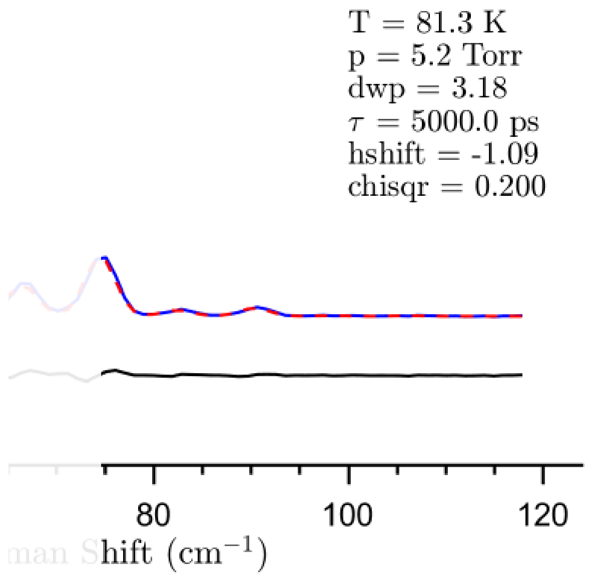
Femtosecond CARS for p, T in Low-Pressure Cryostat

- Single-shot CARS spectra recorded in cryostat and fit for T, p
- Measurement discrepancies
  - CARS pressure lower than pressure gauge
  - Result of experimental setup and placement of pressure gauges



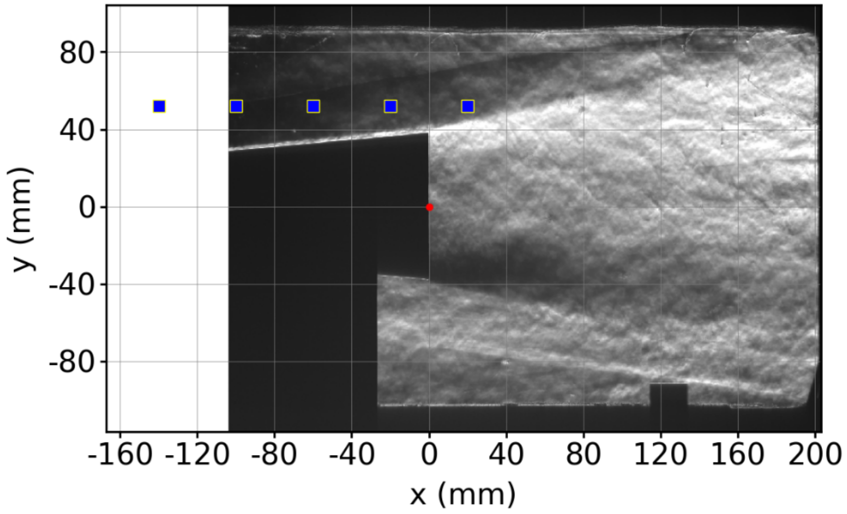


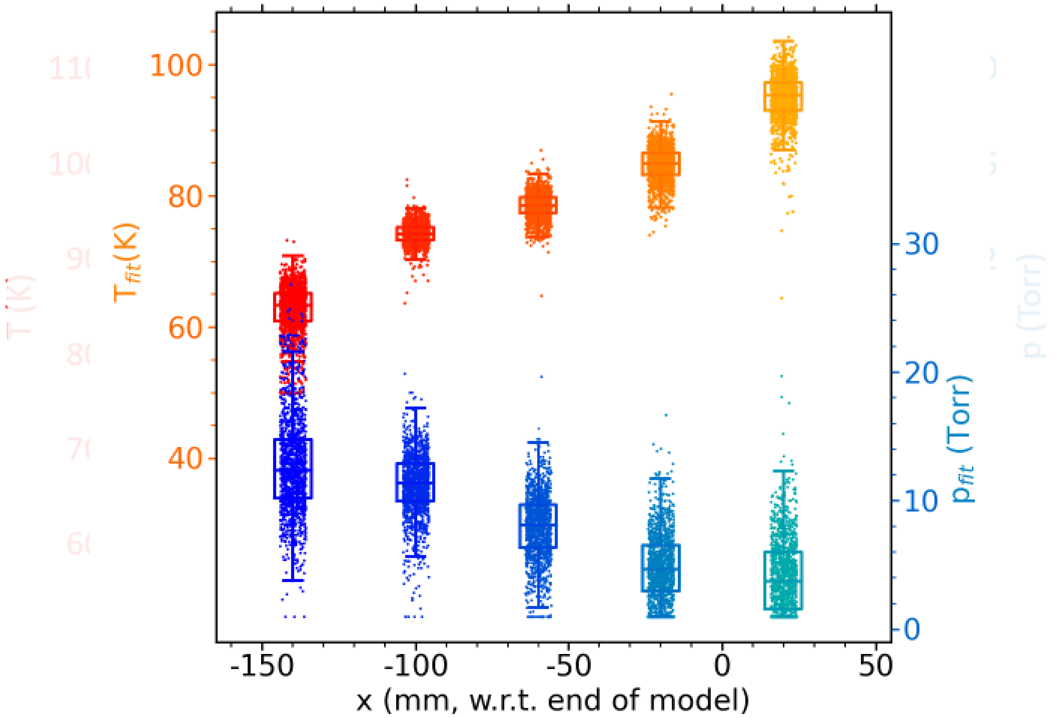


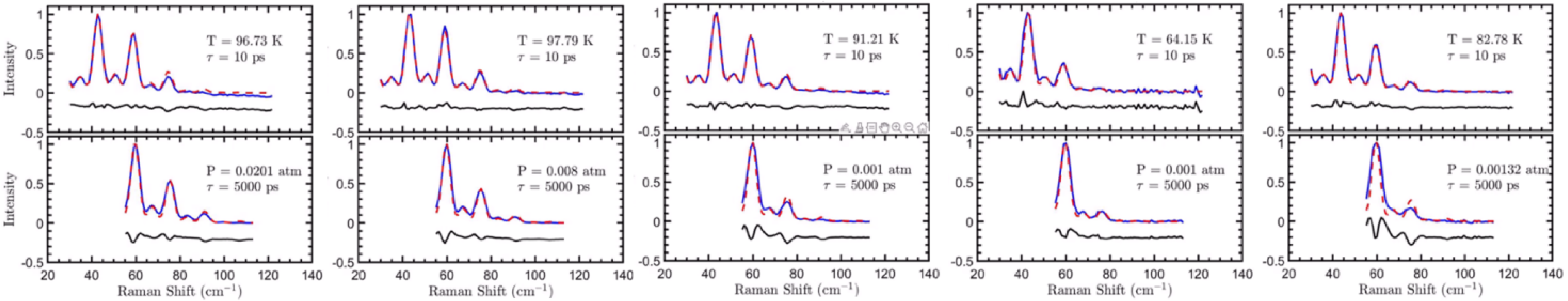


Femtosecond CARS for p, T in Hypersonic Wind Tunnel

- Single-shot CARS spectra recorded at different axial locations

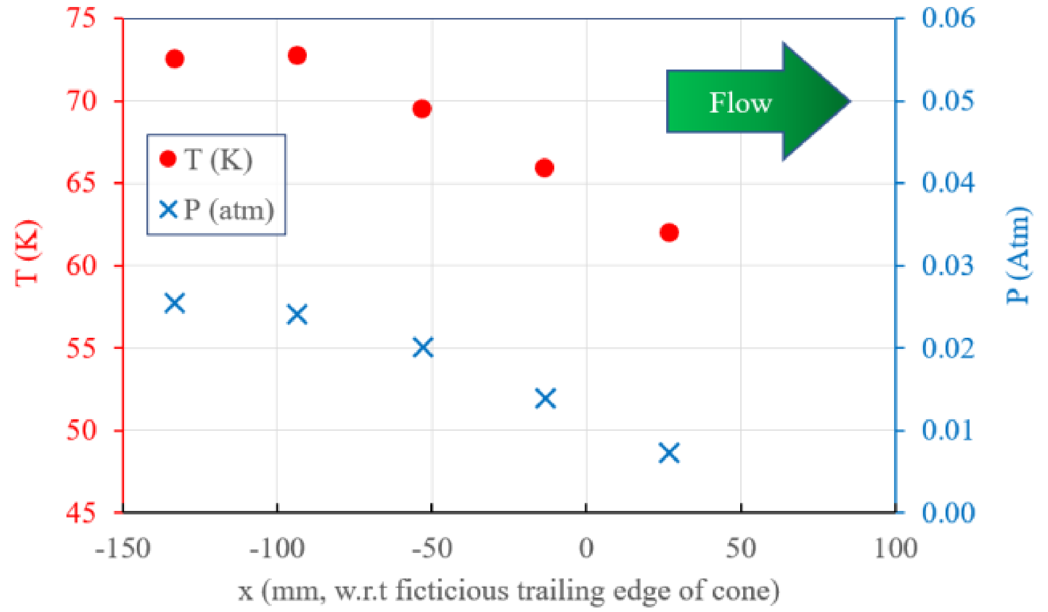


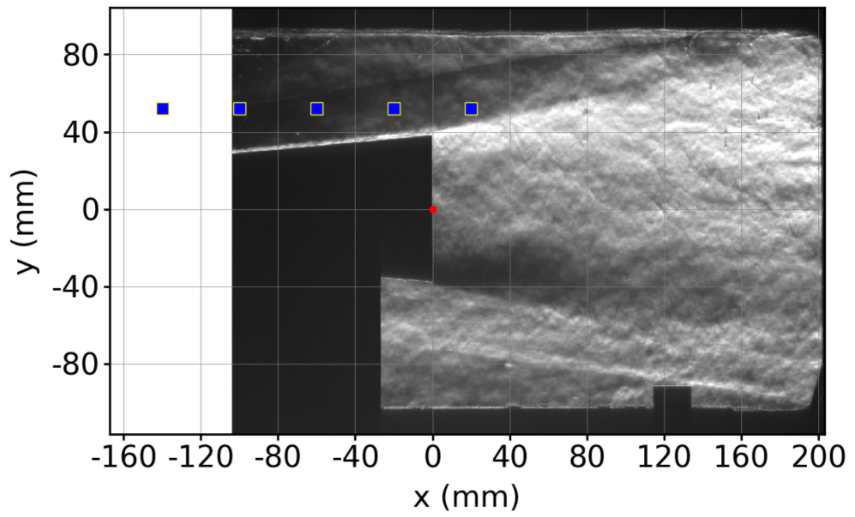




Femtosecond CARS for p, T in Hypersonic Wind Tunnel

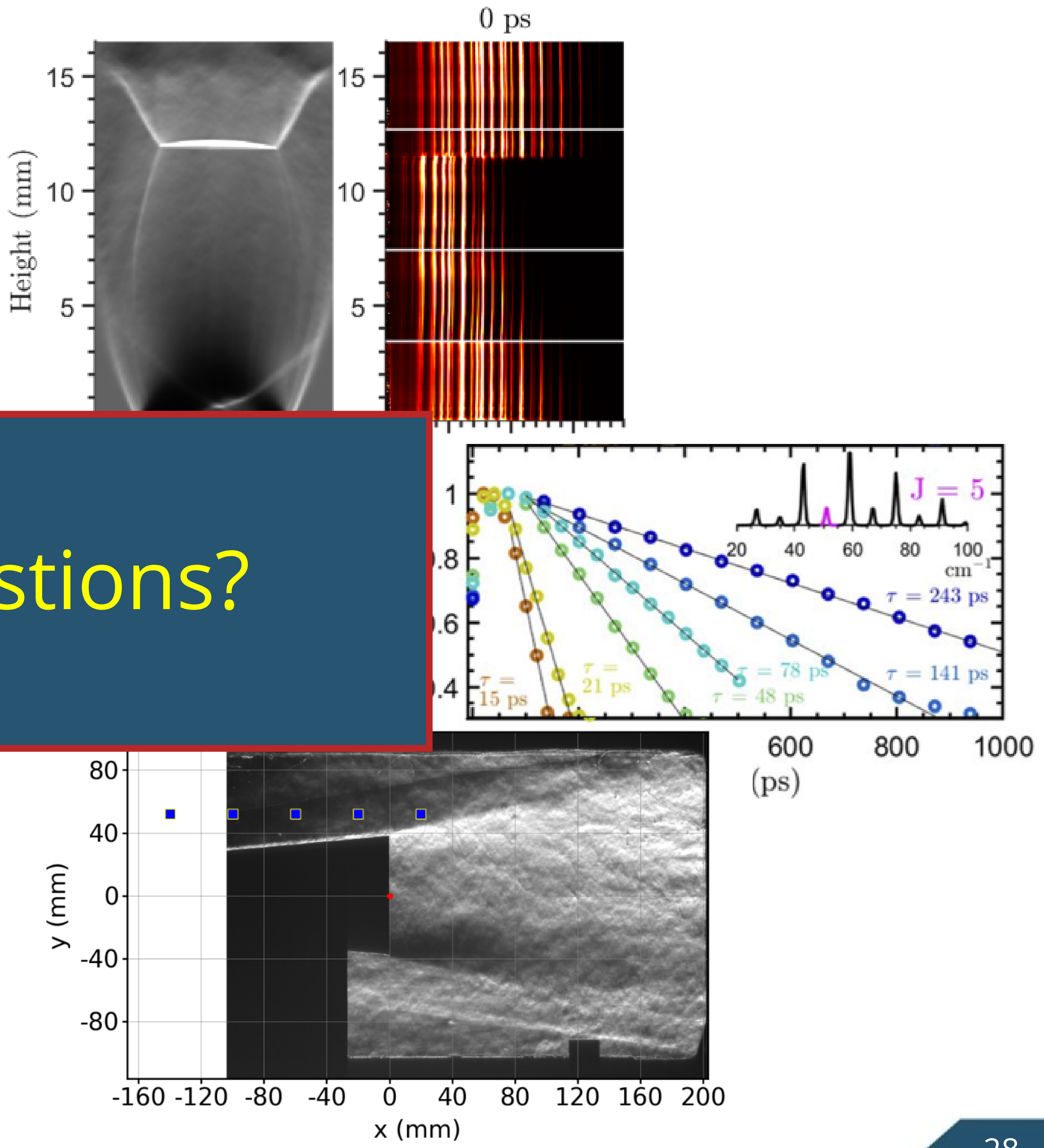
- Conical shock not readily observable
- Model removed and CARS spectra recorded in empty test section
- Possible reasons for measurement biases:
  - Position-dependent Raman excitation (nonresonant CARS spectra)
  - Changes in window birefringence between flow off and flow on (pressure loading)
  - Raman pumping from too much pump energy
  - Changes in CARS measurement location
  - Unexpected tunnel operation





Conclusion

- fs CARS is being developed for single-shot temperature and pressure measurements in hypersonic flows
- One-dimensional measurements demonstrated
  - Pressure range 0.1-2
  - Temperature range 8
- Cold (T < 295 K) S-bra linewidths measured underexpanded jet
  - N_2-N_2, N_2-air, O_2-air
- Initial measurements performed in hypersonic wind tunnel

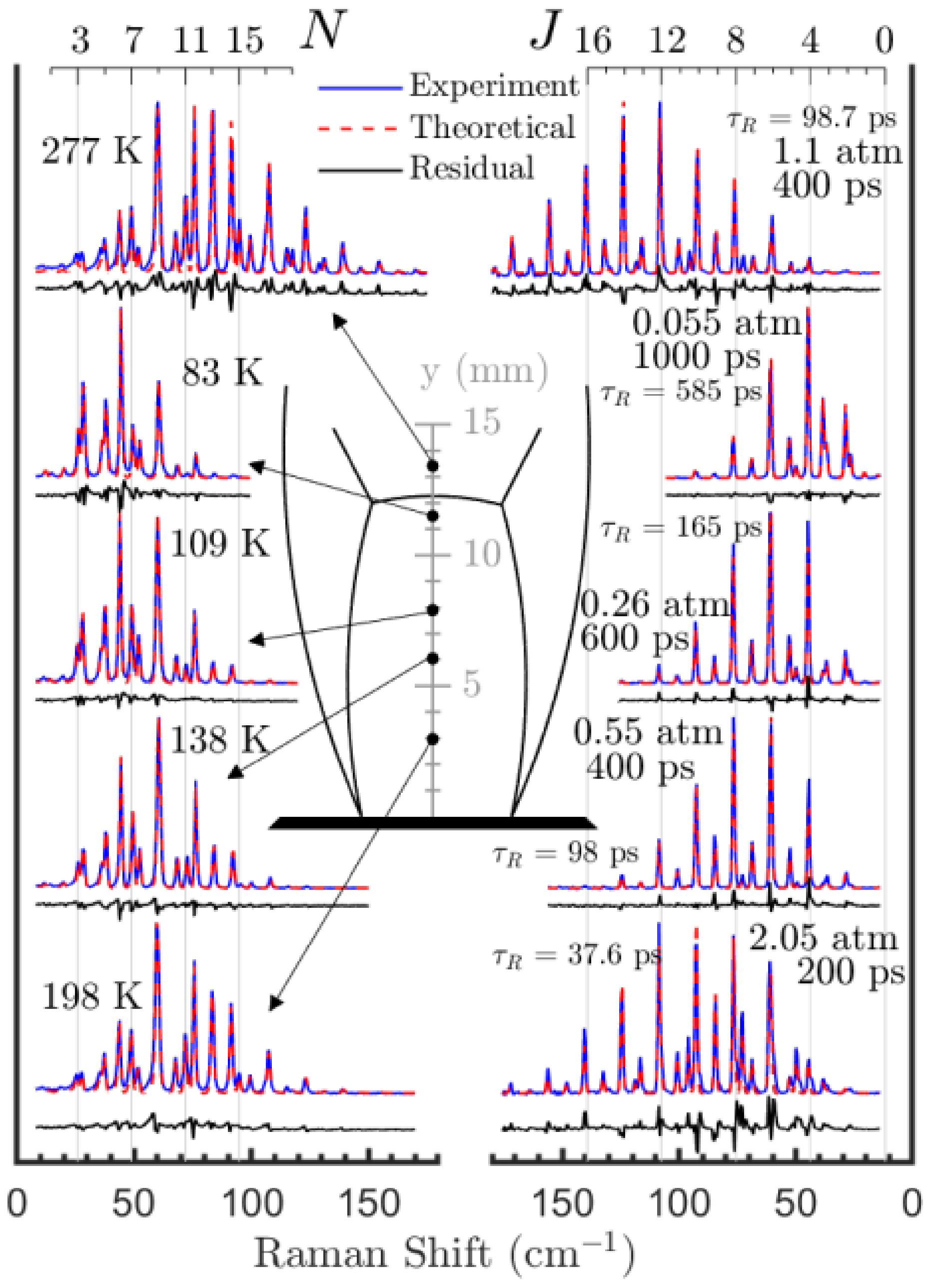


Questions?

Backup Slides

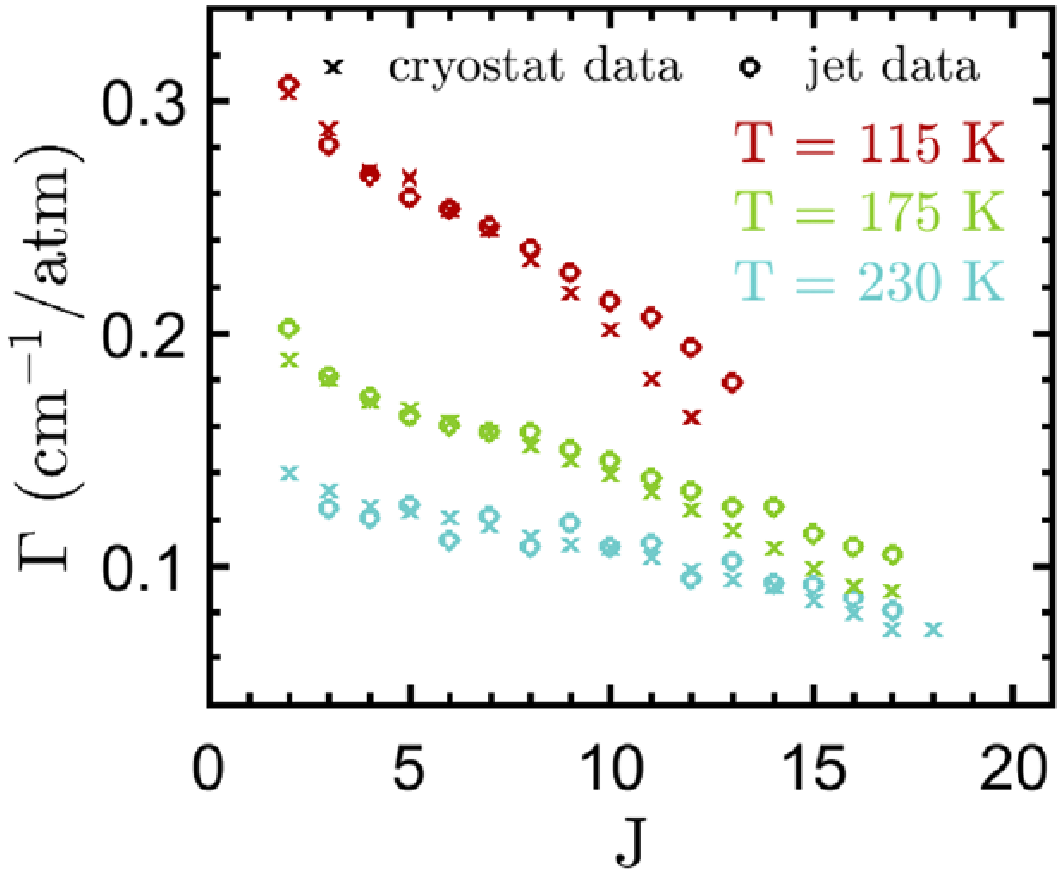
Backup

Representative single shot fits throughout the jet for both the temperature channel (left, τ = 0 ps) and the pressure channel (right, *τ* marked for each spectrum). Axial locations of the spectra proceeding downstream as marked in the figure are *y* = 2.97, 6.04, 7.9, 11.5, and 13.4 mm. Rotational transitions of O_2 (*N*) and N_2 (*J*) are marked for the temperature and pressure spectra, respectively. Raman lifetimes from Eq. (4) are listed with each pressure spectrum for *J* = 6 at the fitted temperature listed, using the low temperature S-branch linewidths.

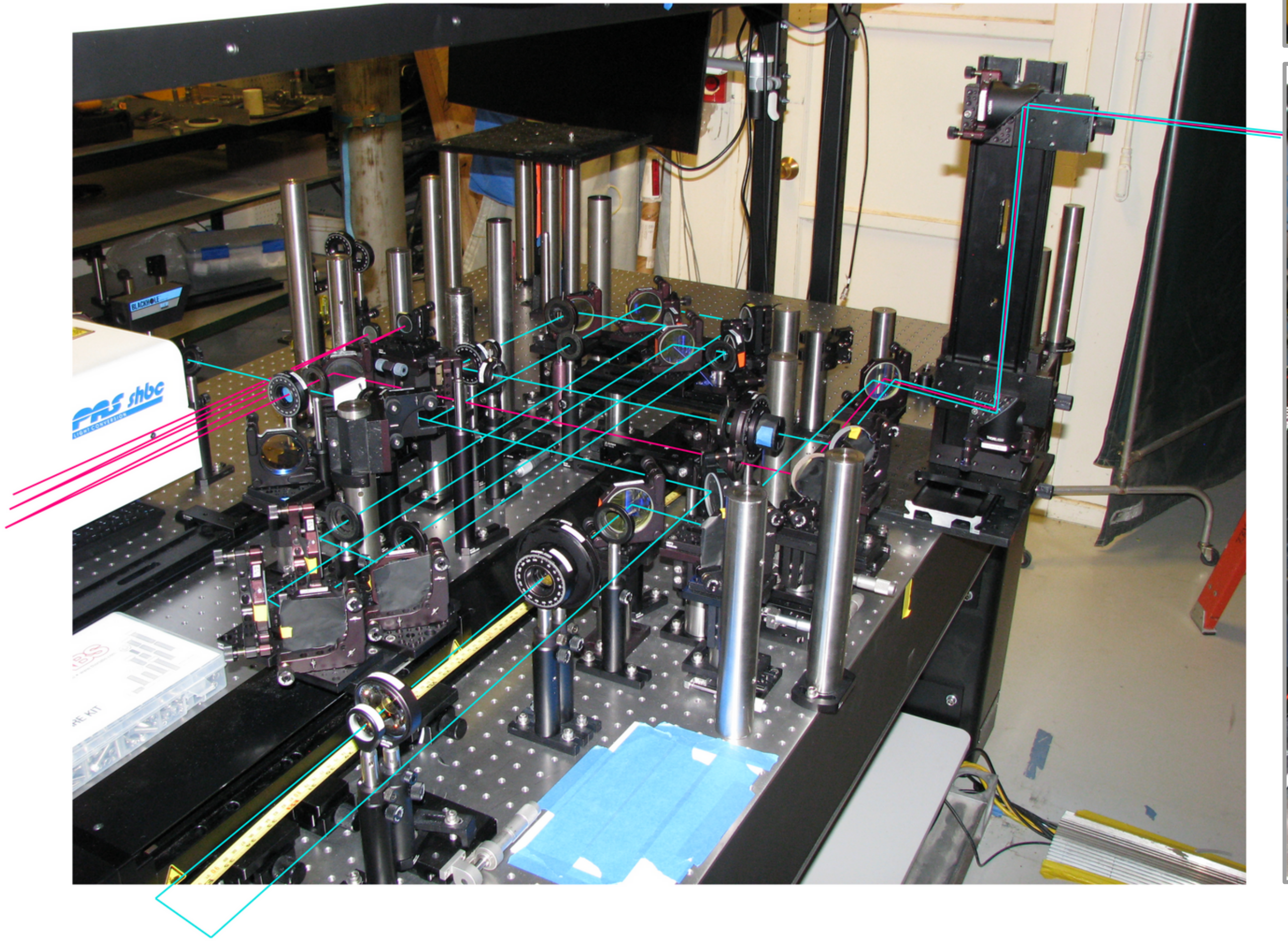


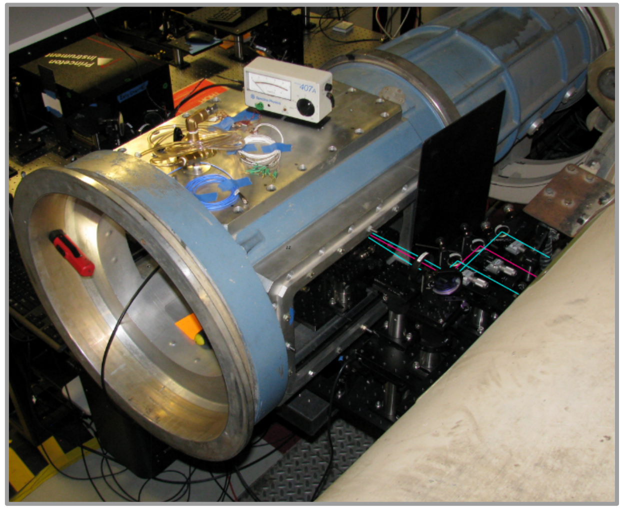
Backup

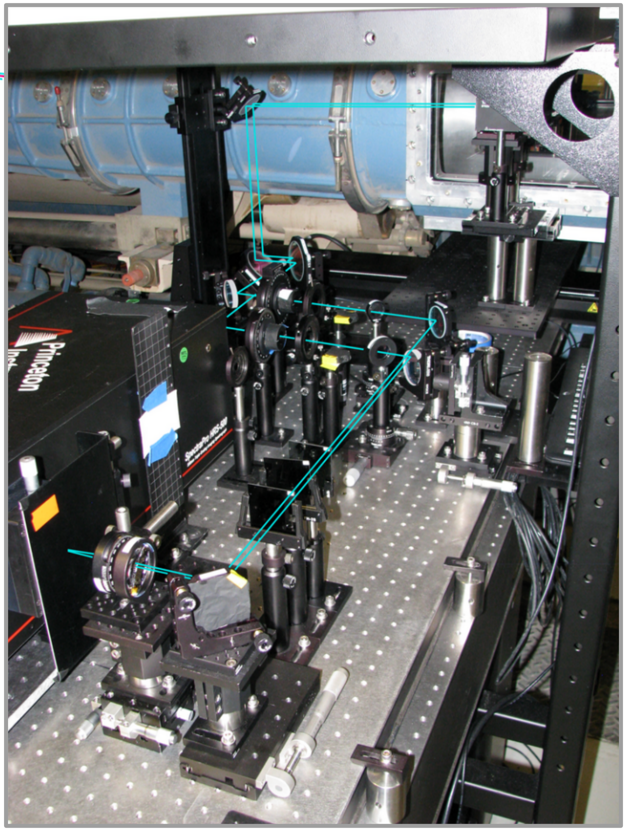
- Cryogenic N2 S-branch linewidths recorded in cryostat compared to linewidth data from underexpanded jet

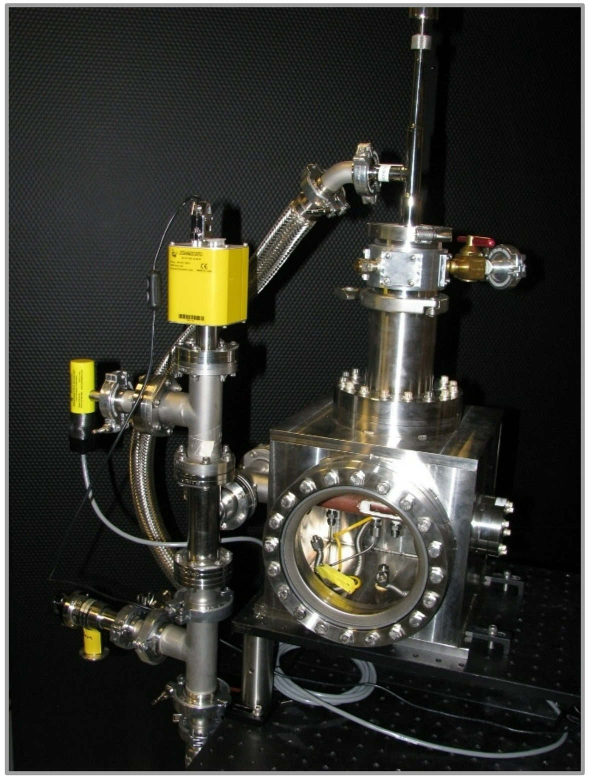


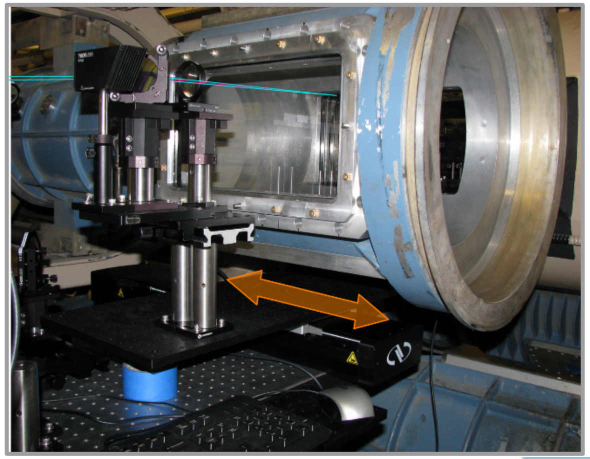
Backup











Introduction and Motivation

Hypersonic Fluid–Structure Interaction

- Fluctuations in hypersonic flows can drive surface loading on flight vehicles
- Various geometries have been studied
- Using a variety of measurement techniques:

Infrared Cameras

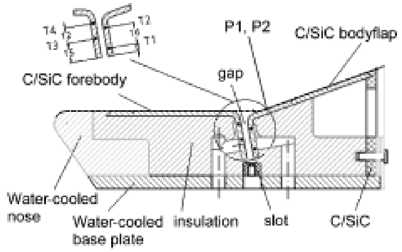
Photogrammetry

Pressure-Sensitive Paint

Accelerometers

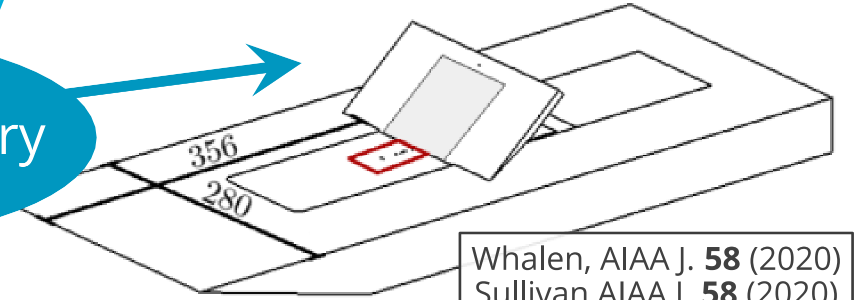
Hypersonic Gap Flows

Hinderks, AIAA 2004-2238



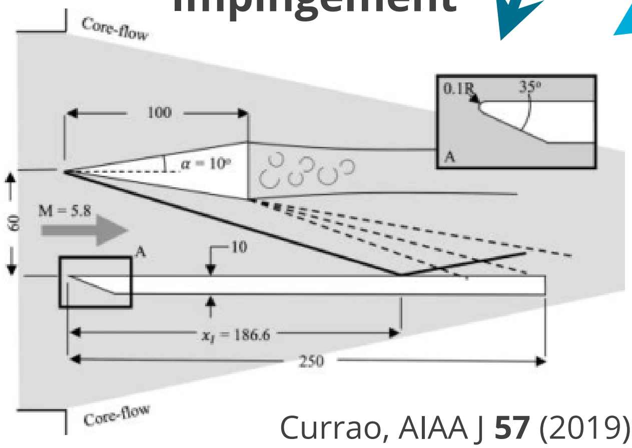
Mack, J Spacecraft Rockets **42** (2005)

Flat Plate with Thin Ramp



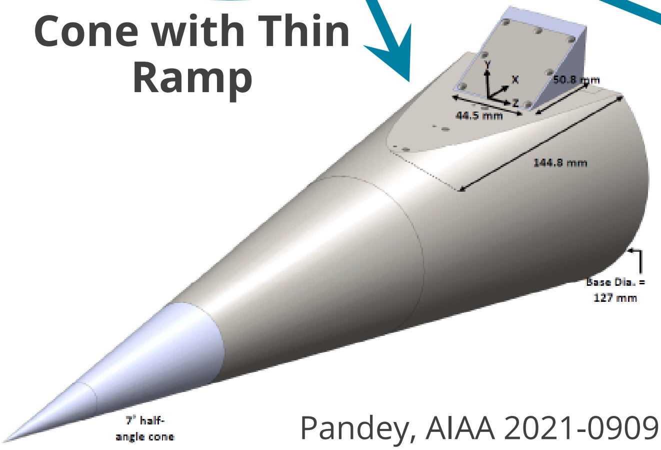
Whalen, AIAA J. **58** (2020)
Sullivan AIAA J. **58** (2020)

Cantilevered Plate with Shock Impingement



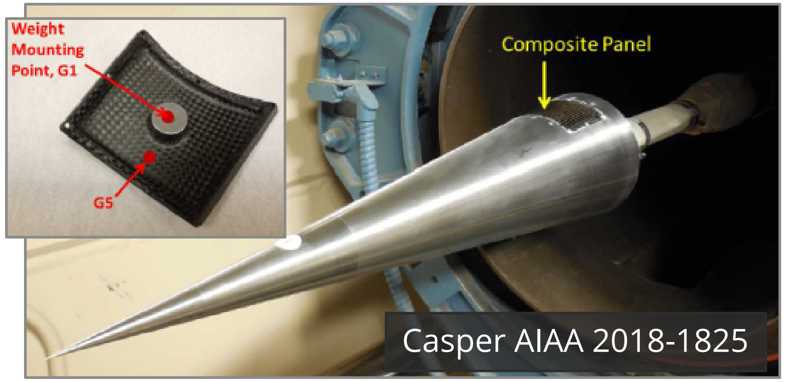
Currao, AIAA J **57** (2019)
Currao, AIAA J **58** (2020)

Cone with Thin Ramp



Pandey, AIAA 2021-0909

Slender Cone with Deformable Panel



Casper AIAA 2018-1825