Simultaneous Pressure/Temperature Measurements Using Hybrid fs/ps Rotational CARS

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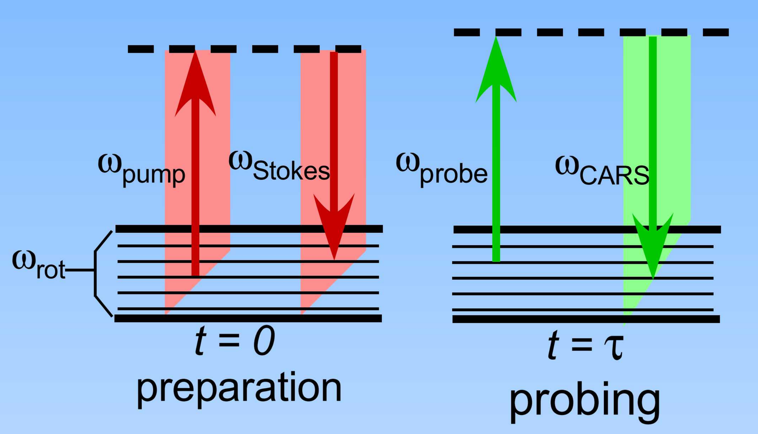
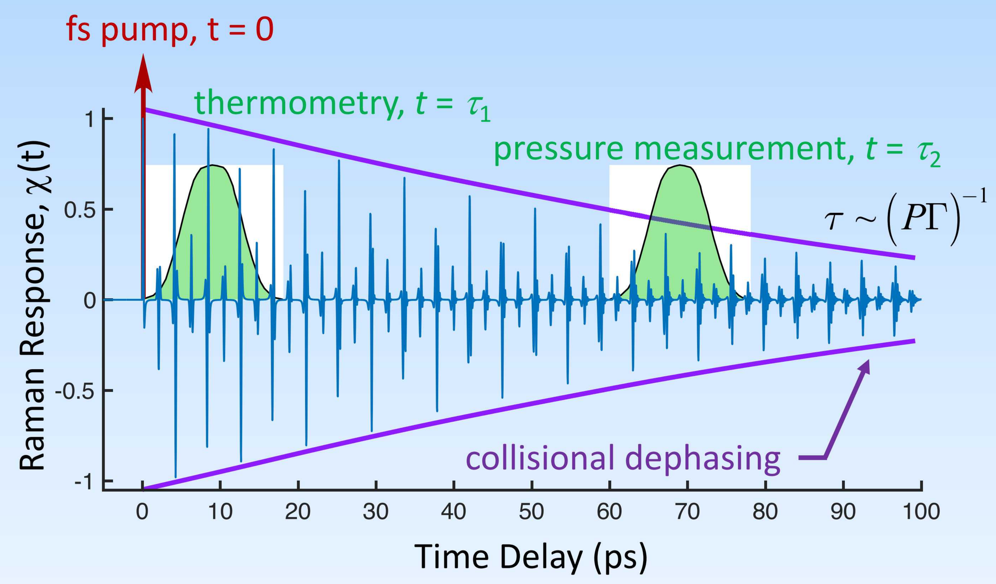
1. fs/ps CARS processes

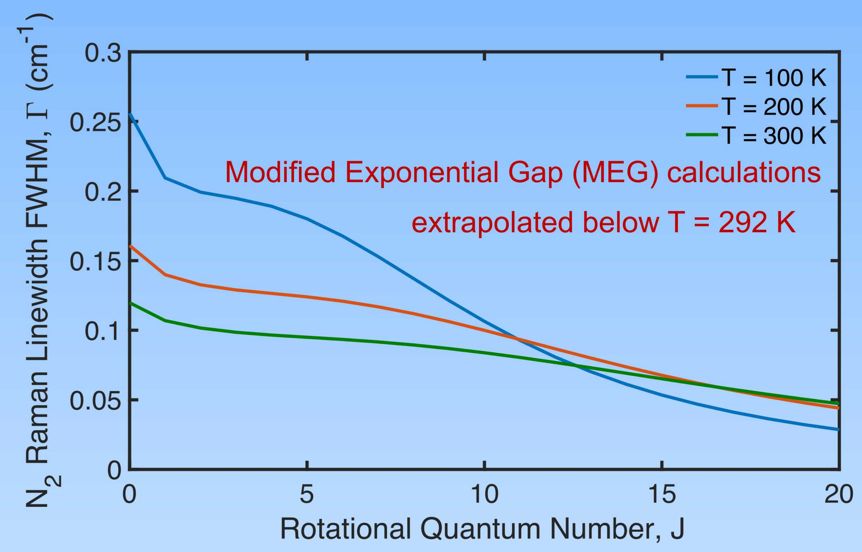


- Broadband pump prepares a Raman coherence at $t = 0$
- Coherence is probed at delay τ using a high-energy, frequency narrow picosecond pulse



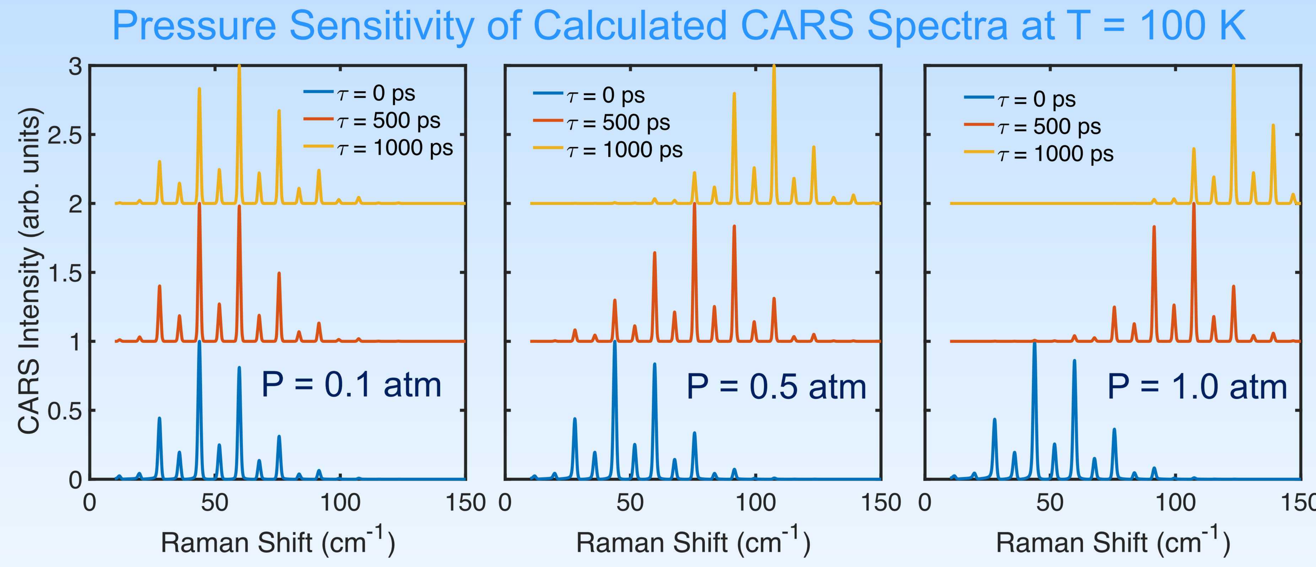
- Two probe pulses are introduced for simultaneous temperature/pressure monitoring
- Short delay ($t = \tau_1$) → minimal collisional effects → good temperature sensitivity
- Long delay ($t = \tau_2$) → sample collisions for good pressure sensitivity
- Pairs of spectra are iteratively analyzed for (T,P) determination
- Tradeoff between pressure sensitivity and signal by increasing τ_2

2. Pressure sensitivity of CARS spectra



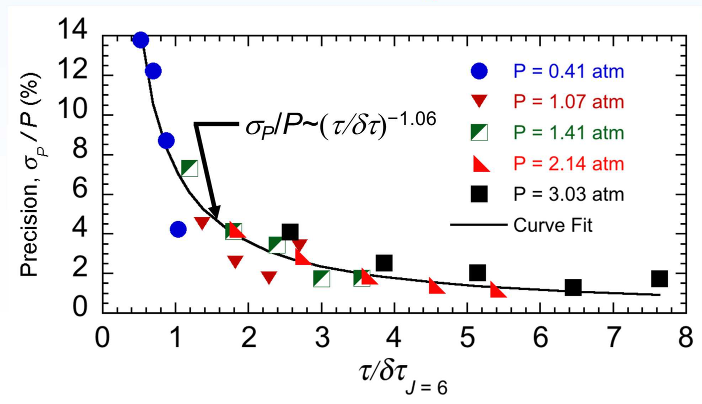
- Raman lifetime ~ $(P\Gamma_J)^{-1}$
- Intensity shifts to high J with increasing pressure or time delay
- Has the effect of making the spectrum look "hotter"
- Model constants fit to data at T = 292-2000 K
- Extrapolated to T = 75 K in this work

Pressure Sensitivity of Calculated CARS Spectra at T = 100 K

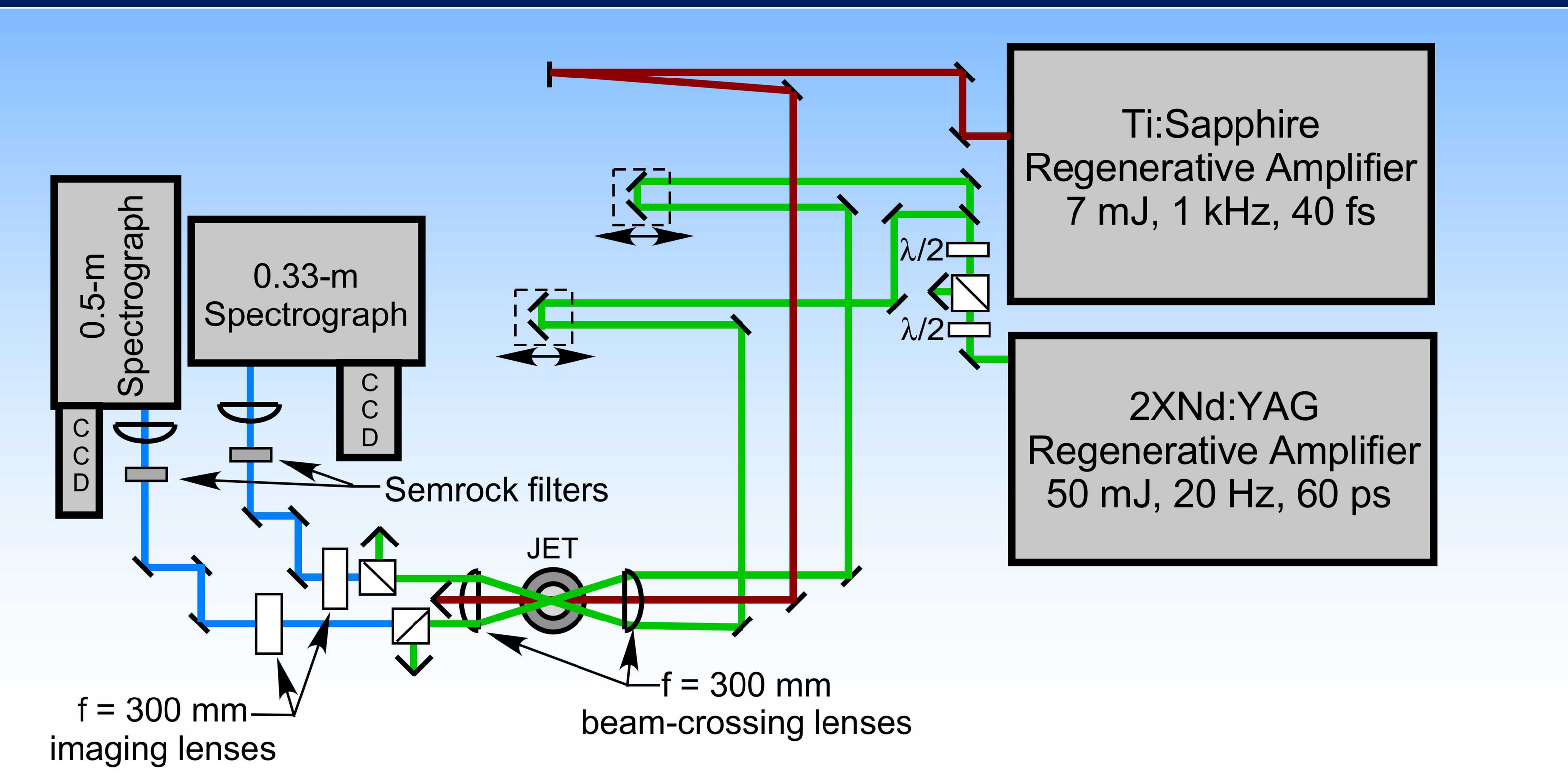


- Experiment design tradeoffs in selection of probe pulse delay, τ_2
- Pressure sensitivity increases with probe delay
- Signal and dynamic range decrease with probe delay
- Optimum delay depends upon desired pressure range

Precision of single-shot Pressure measurements in N_2 at T = 292 K



3. CARS instrument for 1-D T,P measurements



3. Time-domain rotational CARS model

- Time-dependent Raman response: $\chi(t) \sim i\sum_k \sum_{\Delta N=+2} \sum_J W_{N,J}^{(k)} \sin\left(\omega_{N,J}^{(k)} t\right) \exp\left(-P\Gamma_N^{(k)} t\right)$

$$E_{CARS}(t-\tau) = \chi(t)\sqrt{I_{pr}(t-\tau)}$$

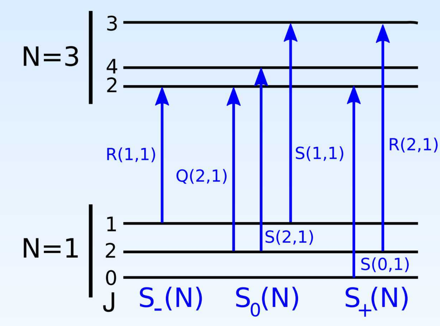
$$W_{N,J}^{(k)} = X_k \gamma_k^2 F_{N,k} \xi_{N,J,k} \frac{3(N+1)(N+2)}{2(2N+3)(2N+1)}\left(n_N^{(k)} - \frac{(2N+1)}{(2N'+1)} n_{N'}^{(k)}\right)$$

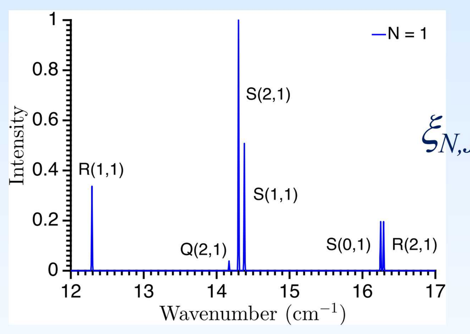
γ_k^2 = mean polarizability
$\omega_{N,J}$ = Raman frequency
P = pressure
Γ_N = Raman linewidth
n_N = Boltzmann population
X_k = mole fraction
F_N = Herman-Wallis factor
I_{pr} = probe pulse intensity

Accounts for the triplet character of the O_2 ground state

- Coupling of electron and nuclear angular momenta splits each rotational (N) line into 6 J-dependent levels

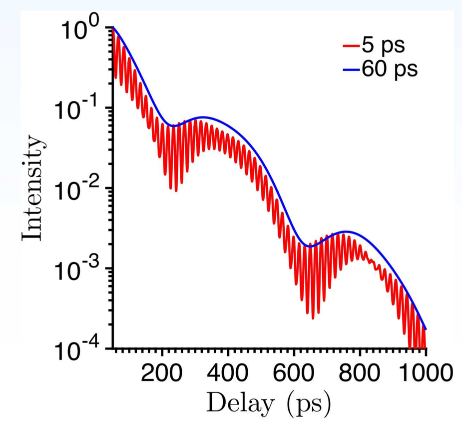
N = rotational quantum number
$J = N-1, N, N+1$, total angular momentum quantum number
$k = N_2$ and O_2

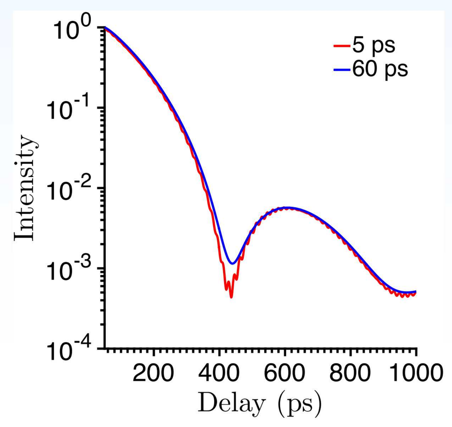




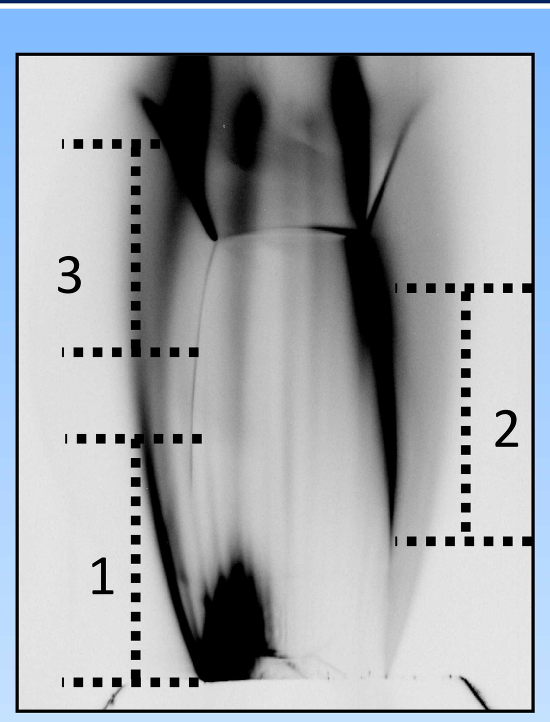
$$\xi_{N,J} = \begin{cases} 1 \text{ when } N = J, 0 \text{ otherwise for } N_2 \\ \text{Empirical values for } O_2\text{: Altmann et al. (1972), Bérard et al. (1983),} \end{cases}$$

- Decay of the O_2 Raman coherence exhibits high- and low-frequency beats
- Must be treated for pressure measurements in air at long probe delays





4. CARS spectra and temperature/pressure fit results

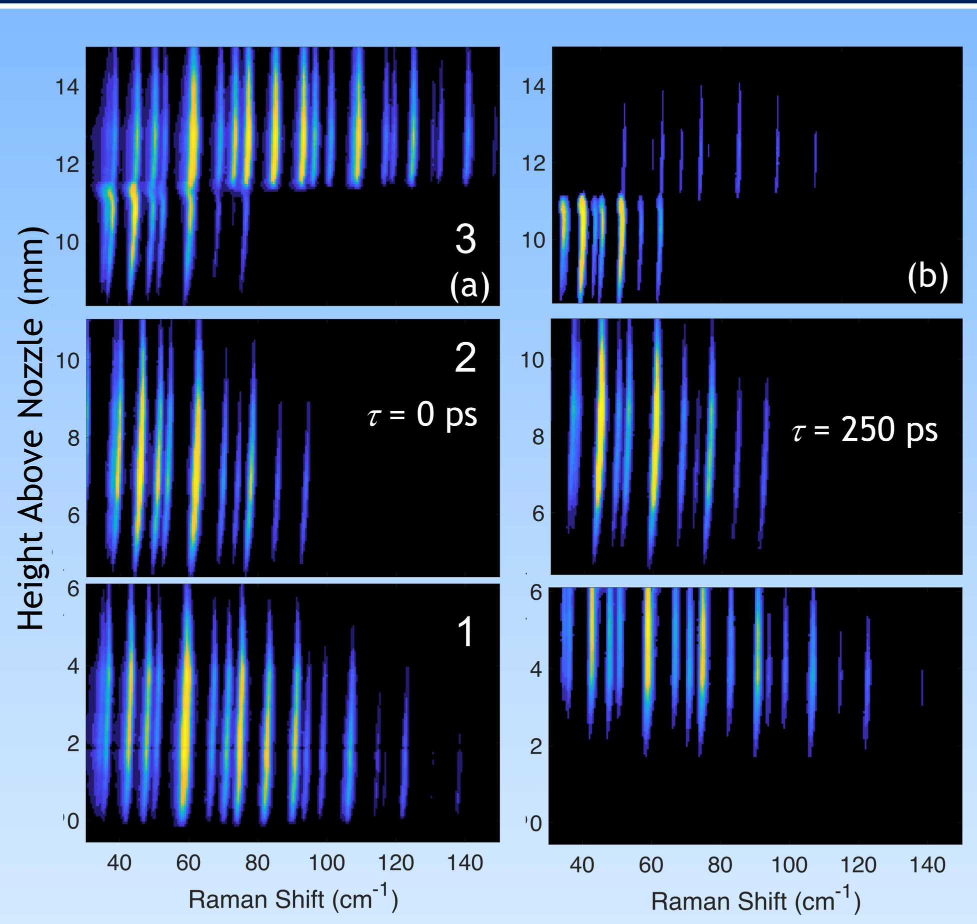


Underexpanded sonic air jet
P_o/P_a = 9.33, T_o/T_a = 1

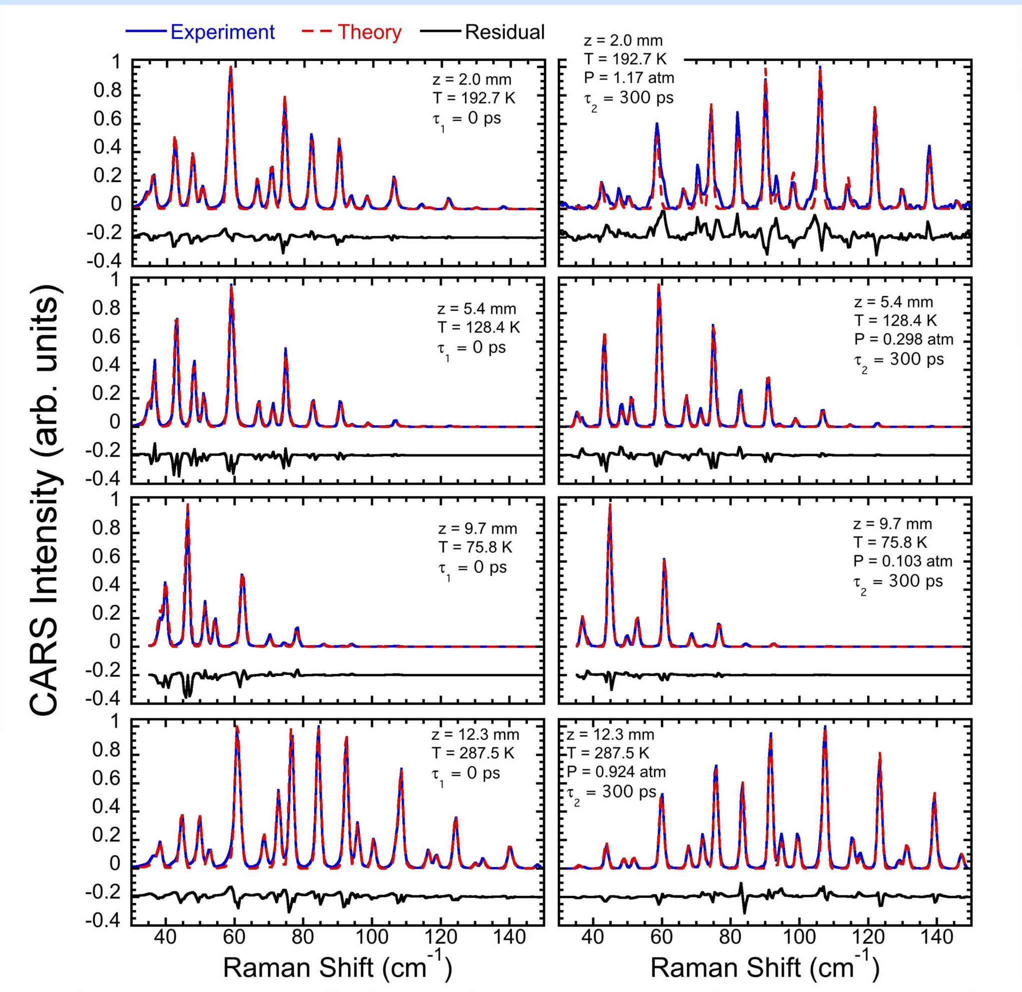
- CARS data acquired in groups of 50 single-shot spectra
- τ_1 = 0 spectra provide nearly collision free result, primarily temperature sensitive
- Time-delayed delayed spectra at τ_2 provide pressure sensitivity through the N-dependent Raman lifetime

$$\tau_R = (\pi c P \Gamma_N)^{-1}$$

- Spectra acquired along 6-mm lines in three regions of interest along the jet centerline



CARS line-imaging data along jet centerline



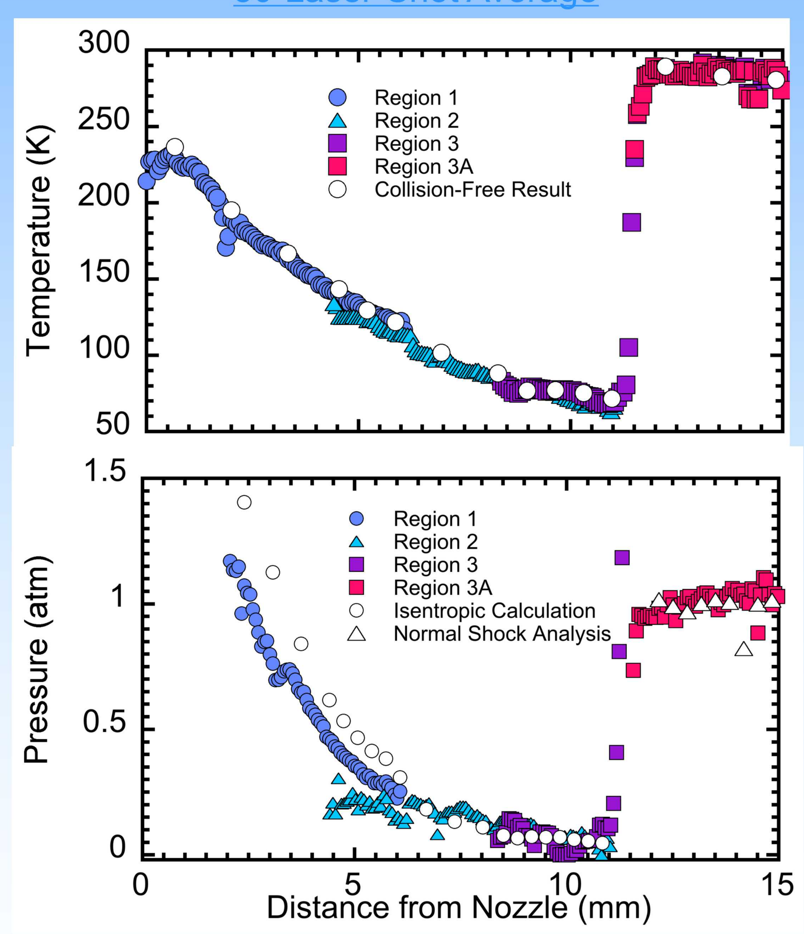
Fits for temperature (left τ = 0) and pressure (right, τ = 300 ps)

- Good temperature sensitivity and dynamic range observed throughout the jet
- Compromise between pressure sensitivity and dynamic range
- Pressure sensitivity is optimized in near-jet and post-shock regions for τ = 300 ps
- Convergence of pressure to expected values in low-pressure regions still observed

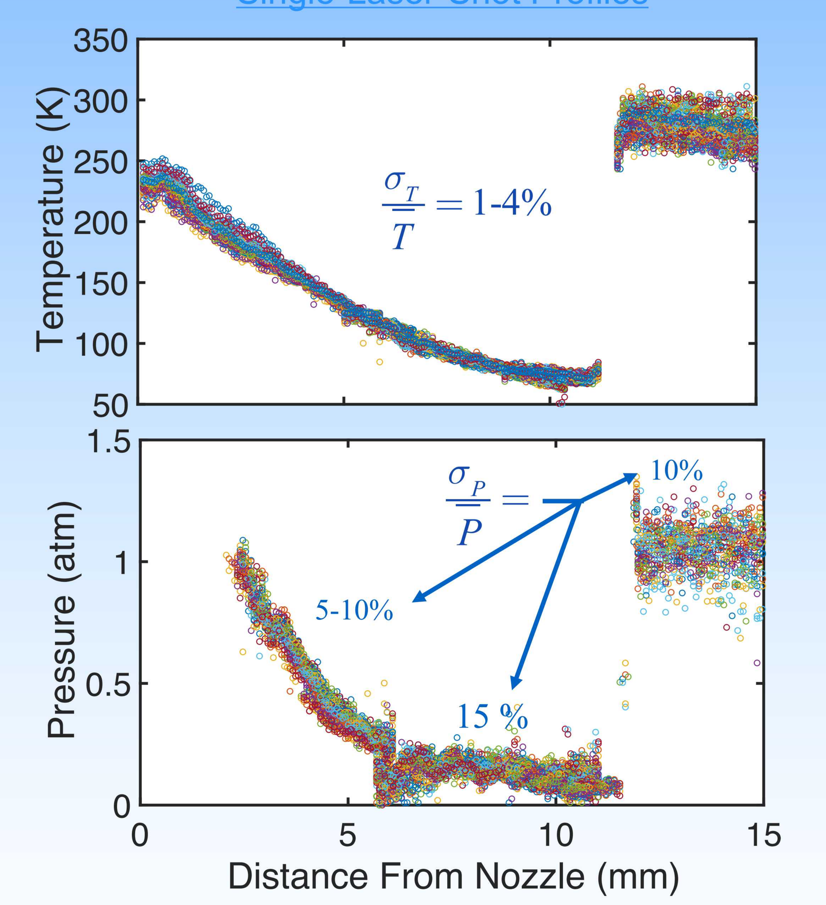
- Temperature fits performed considering impact of pressure at τ = 0 using iterative procedure
- Temperatures in good agreement with expected values at jet exit and across shock wave
- Impact of pressure on measured temperatures less than 2%
- Pressure results obtained for P ~ 1 atm and below as a result of dynamic range issues
- CARS pressures lower than isentropic predictions in near field
- Future work to examine low-pressure sensitivity for τ_2 > 1 ns

5. Jet axial profiles

50-Laser-Shot Average



Single-Laser-Shot Profiles



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