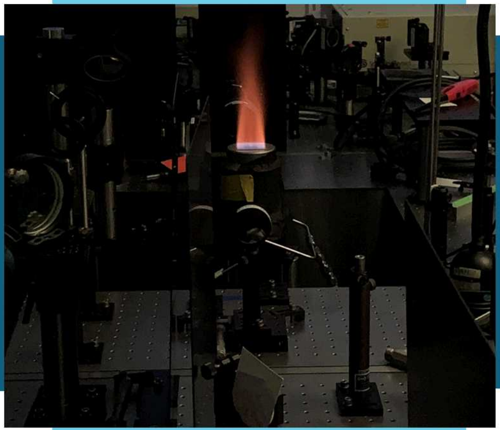
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2019-15419C

Burst-Mode Spontaneous Raman Thermometry in a Flat Flame



Caroline Winters, Timothy Haller, Sean Kearney, Philip Varghese, and Justin Wagner

January 7th, 2020; AIAA-2020-0518

AMT-06, Spectroscopic Techniques II

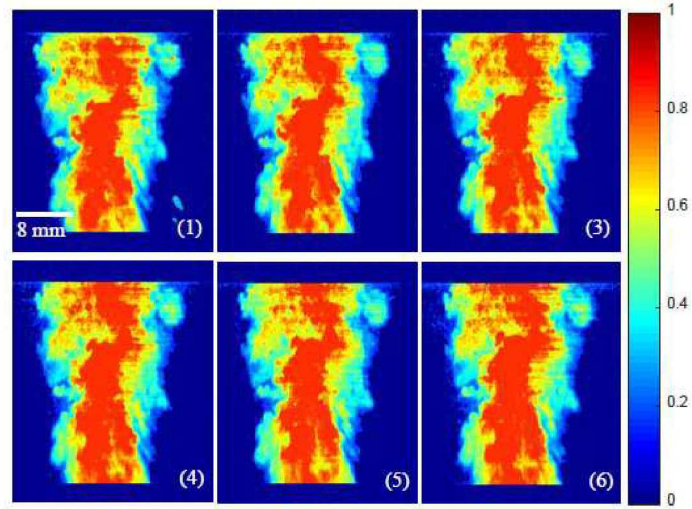
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND#

Spontaneous Raman Scattering in Flows

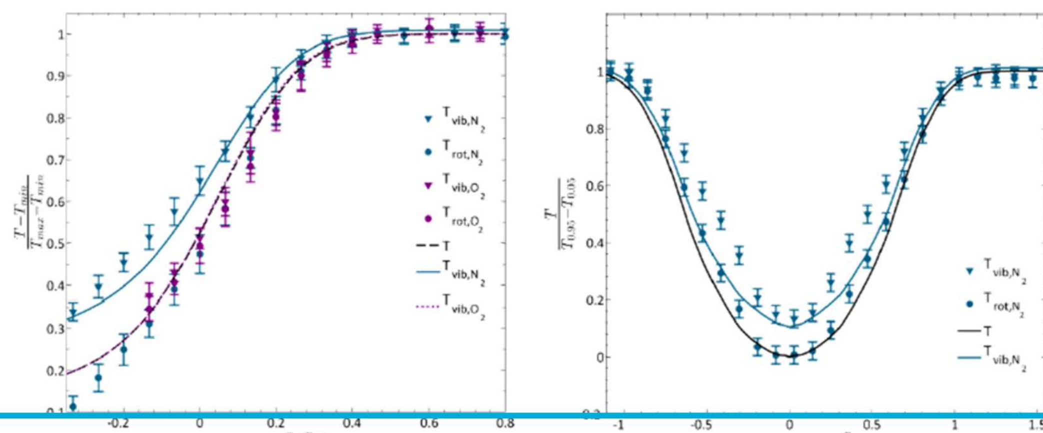
- Non-reacting flows
  - [Jiang, et al., 2018]
    - High-speed (10 kHz) 2D imaging
    - Species mixture fractions
  - [Gabet, et al., 2010]
    - 1D line imaging
    - Species mixture fractions
- Reacting flows
  - [Krishna, et al., 2019]
    - High-speed (10 kHz)
    - Thermometry from Rayleigh Scattering
- Non-equilibrium flows
  - [Reising, et.al., 2016]
    - Traditional speeds (10 Hz), time integrated
    - High-speed jets (Re_d= 27,0000 to 77,000)

CH4 mixture fraction in non-reacting jet



[Jiang, et al. 2018]

Degree of thermal non-equilibrium assessed in a jet shear layer and core



First demonstration of high-speed Raman spectroscopy for temperature

[Reising, et al., 2016]

Spontaneous Raman Spectroscopy

$$I(\lambda) = \frac{G}{T}[\nu_0 - \nu_k(v,J)]^4$$

→ Terms associated with mol fraction, *G,* number density, *1/T,* excitation frequency, ν_0, and transition frequency, ν_k

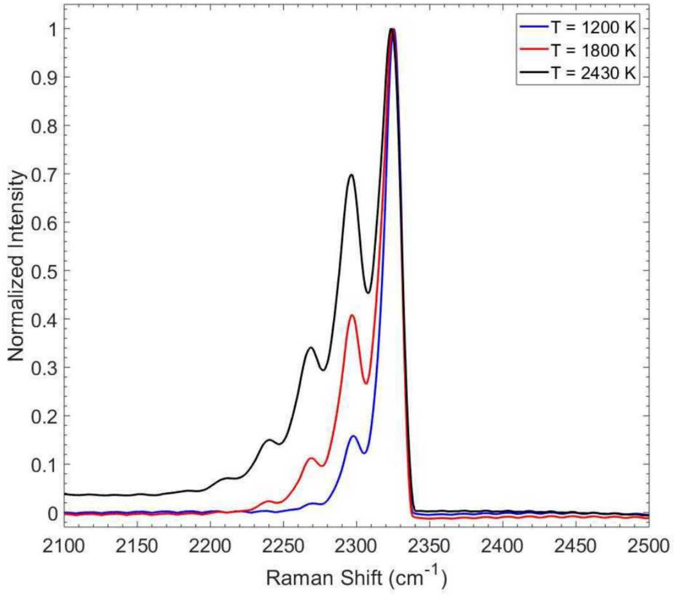
$$\times g_s(J)\frac{(2J+1)\exp\left(-\frac{hcE_v(v)}{kT}\right)\exp\left(-\frac{hcE_J(v,J)}{kT}\right)}{Q(T)}$$

→ Boltzmann factor

$$\times \Phi_x(v,J)L(\lambda;\lambda_k(v,J),b,\Delta\lambda_L,t)$$

→ ∝ (space-avg. polarizability tensor)^2 and Lineshape function: Lorentzian ⊗ Trapezoid

Simulated Raman Spectra

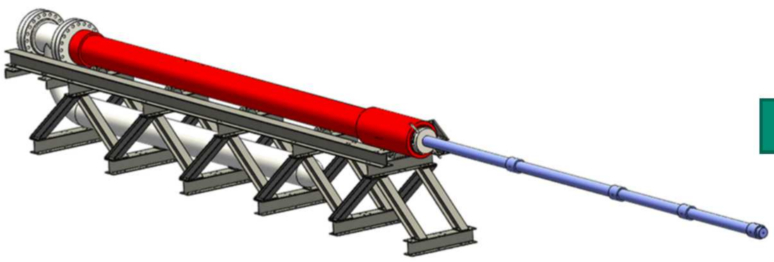


- Q-branch transitions resolved in this work
- Peak signal ratios between vibrational bands is temperature dependent
- $S_R \propto P_{Laser} \times number\ density$

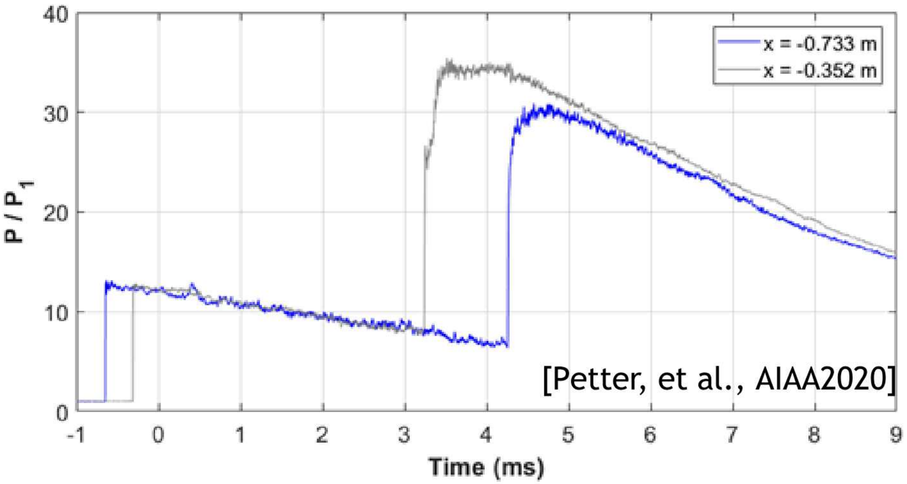
[Ustav, et al., 2013]

What Drives the Need for Fast Diagnostics?

High Temperature Shock Tube



Test Section Pressure Data



❖ Spontaneous Raman Scattering has been demonstrated in NASA's Electric Arc Shock Tube

[Sharma, et al., 1993]

Sandia's High Temperature Shock Tube is a high-speed, impulsive facility

❖ Longer laser pulses allow more energy to be coupled for each measurement

❖ **The pulse-burst duration is on the order of transient air-shock interactions**

❖ High burst rate can provide multiple pulses per camera exposure

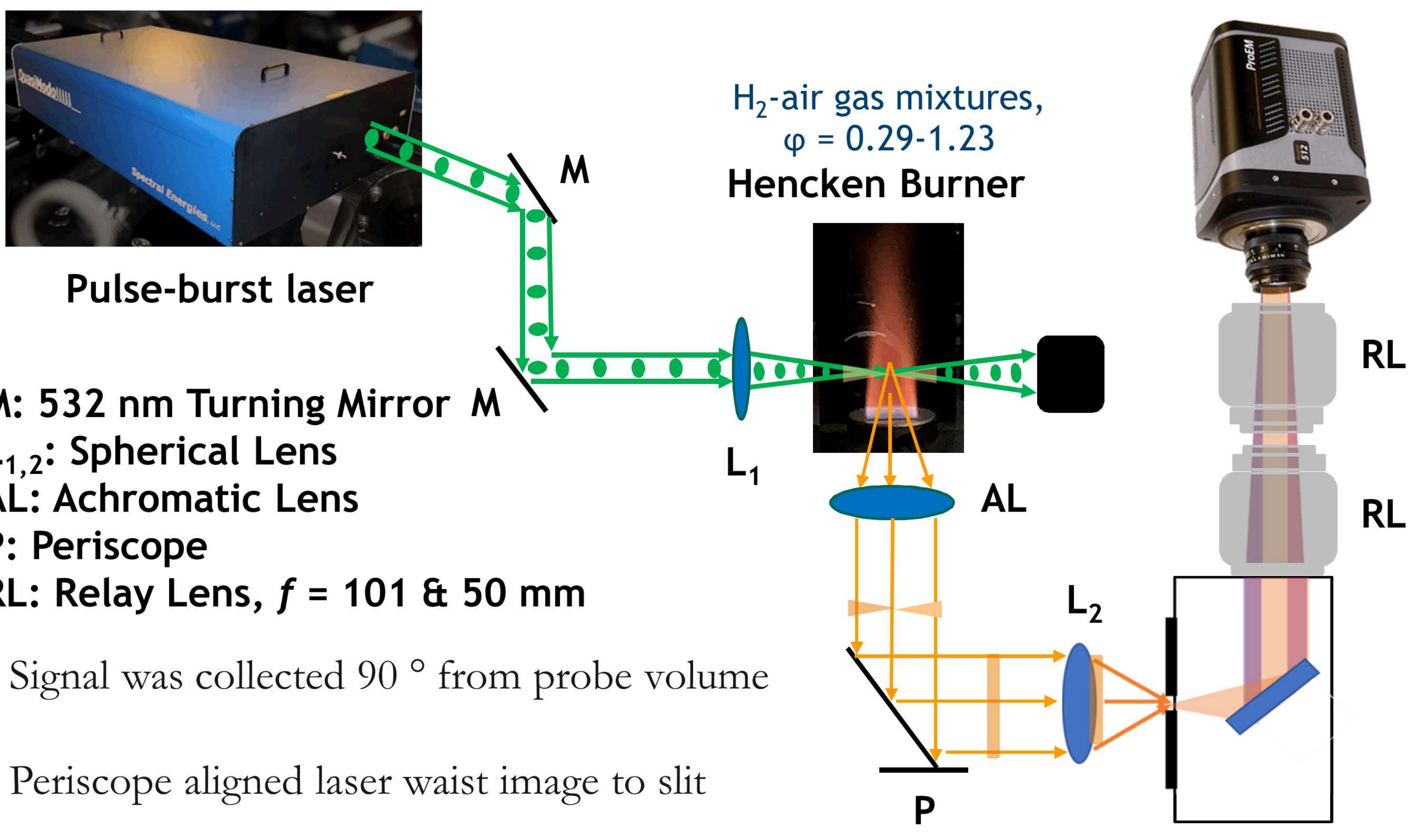
❖ Temporal resolution is set by laser pulse duration, $\boldsymbol{\tau}$ **~ 3-200 ns**

Burst-mode Raman thermometry provides high repetition rate measurements with nanosecond temporal resolution

Benchtop Experimental Design

Burst rate: 10 kHz, Burst duration: 2.5 ms
$t_{laser} \approx 200$ ns, $E_{laser} \approx 13$ J

Max. frame rate: 5 kHz
Test time: 1.4 ms, "*Kinetics Mode*"



M: 532 nm Turning Mirror
$L_{1,2}$: Spherical Lens
AL: Achromatic Lens
P: Periscope
RL: Relay Lens, *f* = 101 & 50 mm

- Signal was collected 90 ° from probe volume
- Periscope aligned laser waist image to slit
- Image was compressed by 2x using Relay Lens pair

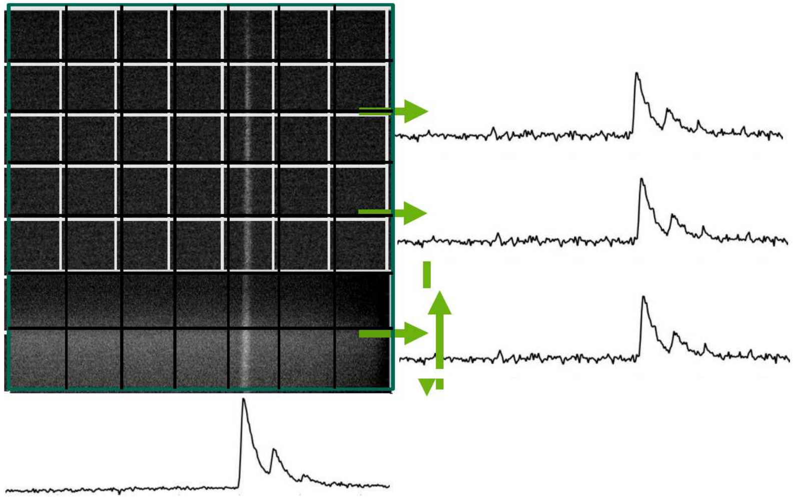
Detector Architecture

❖ Full-burst signal was collected in "Frame Transfer" mode → Full Chip

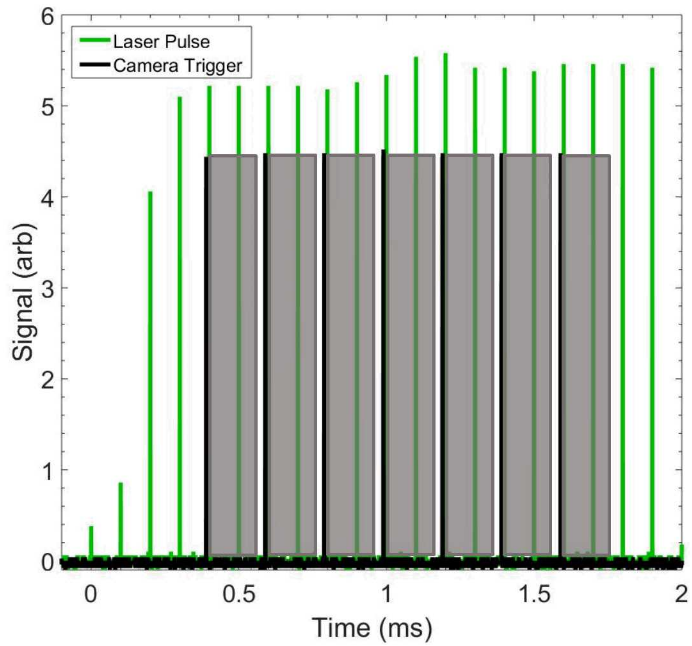
❖ Pulse-burst signal was collected in "Kinetics" mode→ 280 row illumination at 5 kHz

❖ Chip is always exposed as rows are shifted → stray light mitigation critical

Single Exposure / Burst Exposure



10 kHz pulse train with camera gate



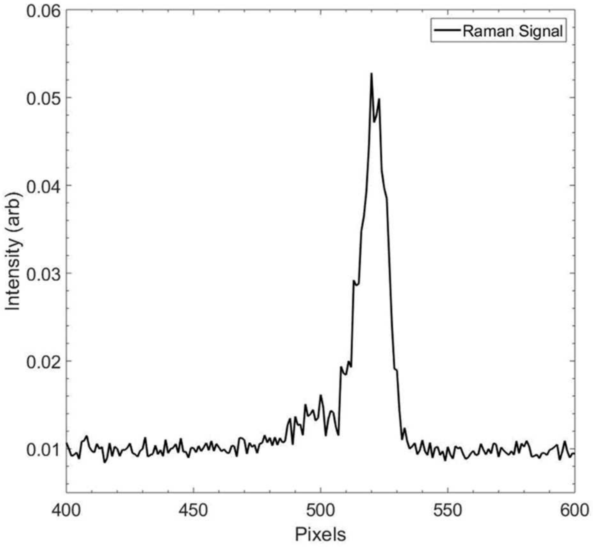
❖ Pulse train intensity stabilizes after 5 pulses

❖ First pulse-burst frame collected four pulses of Raman signal

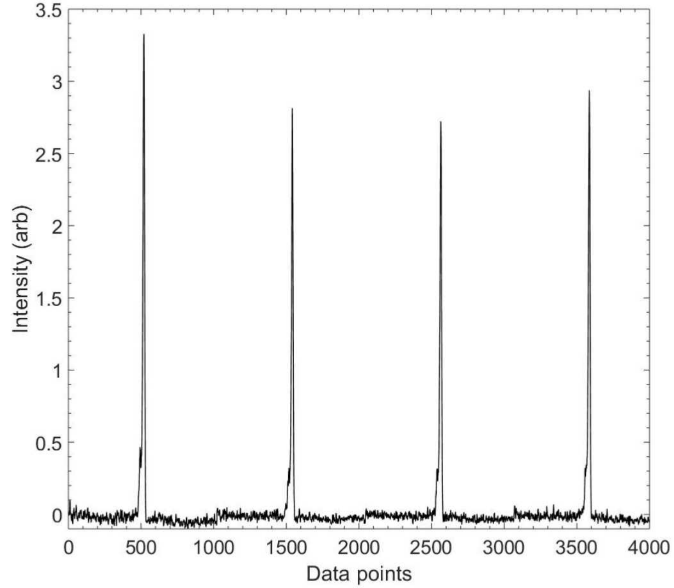
❖ Test time limited by number of frames
  - Frames set by number of rows illuminated

Pulse-burst (5 kHz) Raman Signal at φ = 0.29

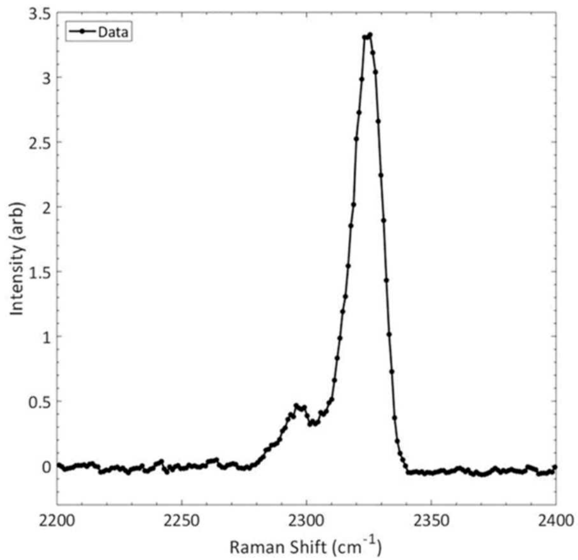
Raw Signal



Pulse-burst Data Frames



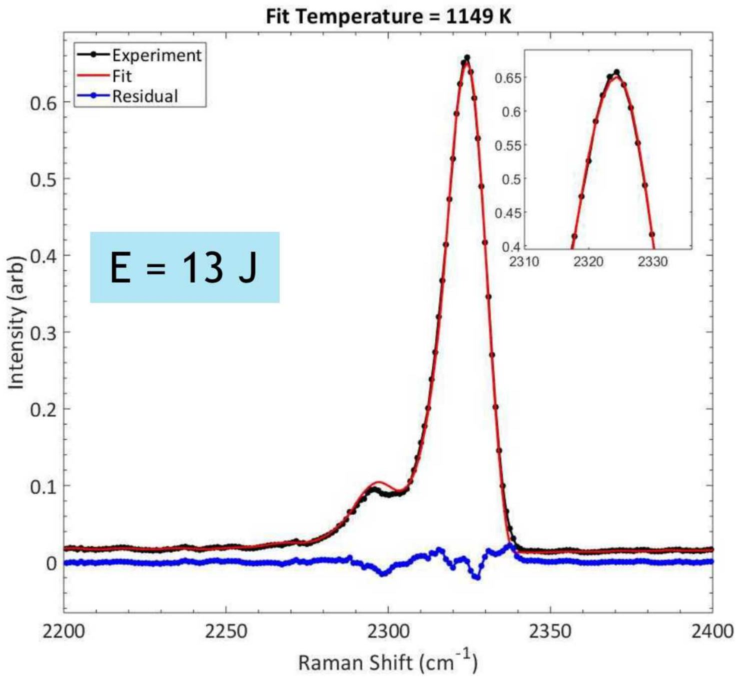
Binned Spectra



- Frame exposure = 150 μs
  - Integrated over two pulses
  - Limited row illumination decreased Raman signal
- Binning the data resulted in a decrease in spectral resolution, but an increase in peak signal
- Raman is a linear technique
  - ↑ flame temperature → ↓ number density →↓ S_R

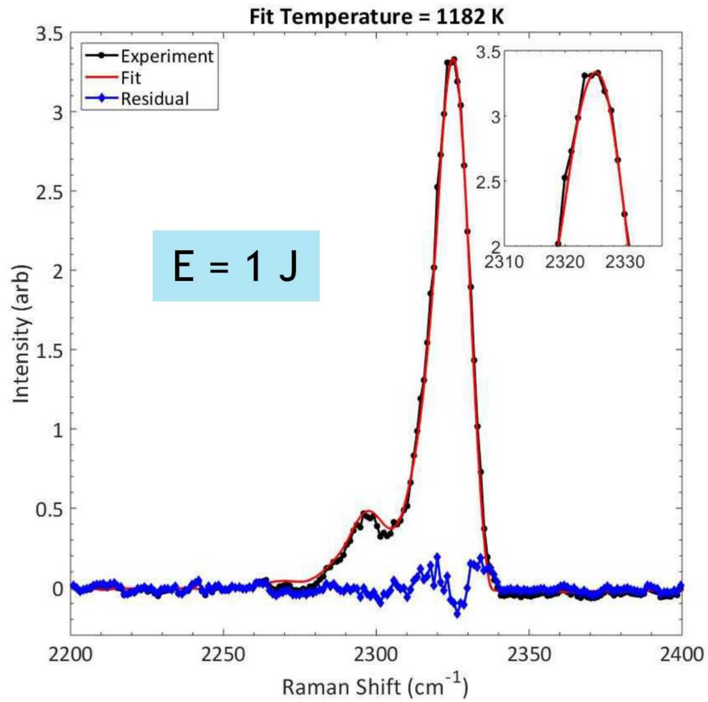
Temperature Inference from Spectral Fits

Burst-Int. Raman Spectra, Φ = 0.29



Tmean = 1148 ± 8.7 K

5 kHz Raman Spectra, Φ = 0.29

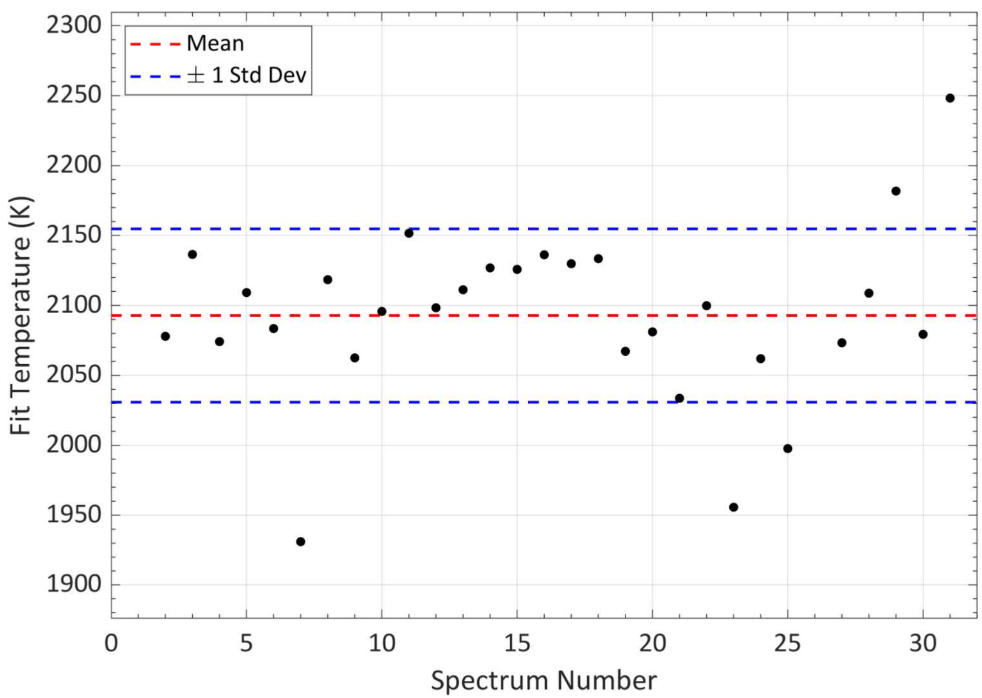


Tmean = 1160 ± 23 K

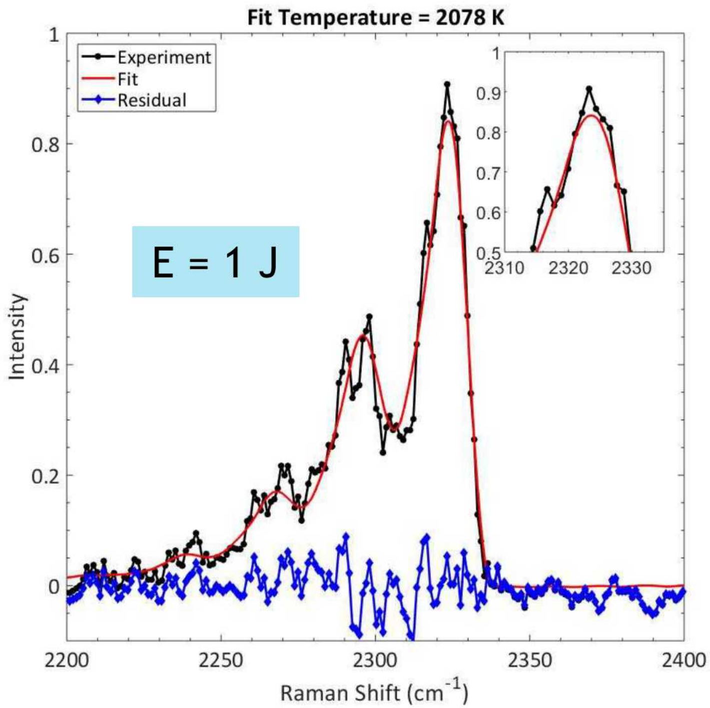
- Precision of inferred temperatures from five full-burst spectra = ± 8.7 K
- Precision of a single burst = ± 27 K
- Precision from 5 bursts = ± 23 K

Temperature Inference from Spectral Fits

Inferred Temperatures from Bursts



Pulse-Burst Raman Spectra, Φ = 0.79



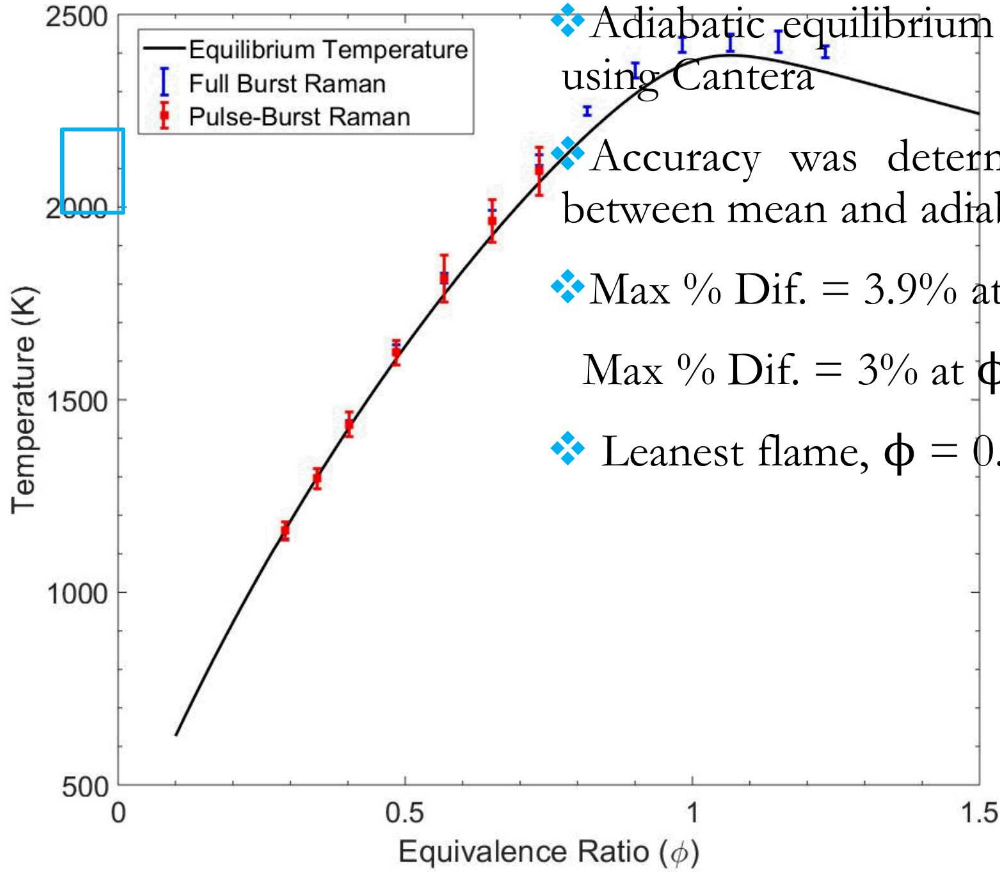
Tmean = 2093 ± 62 K

- SNR defined as the ratio of the peak signal to the RMS baseline fluctuations
- Operational range of Raman was set when SNR ≤ 5, $\phi = 0.73$

Precision is always within 3% of the measured temperatures

Quantifying Measurement Accuracy

Flame Temperature Map Across Equivalence Ratios



- Adiabatic equilibrium temperatures calculated using Cantera
- Accuracy was determined by % difference between mean and adiabatic temperatures
- Max % Dif. = 3.9% at ϕ = 0.73 → Full Burst

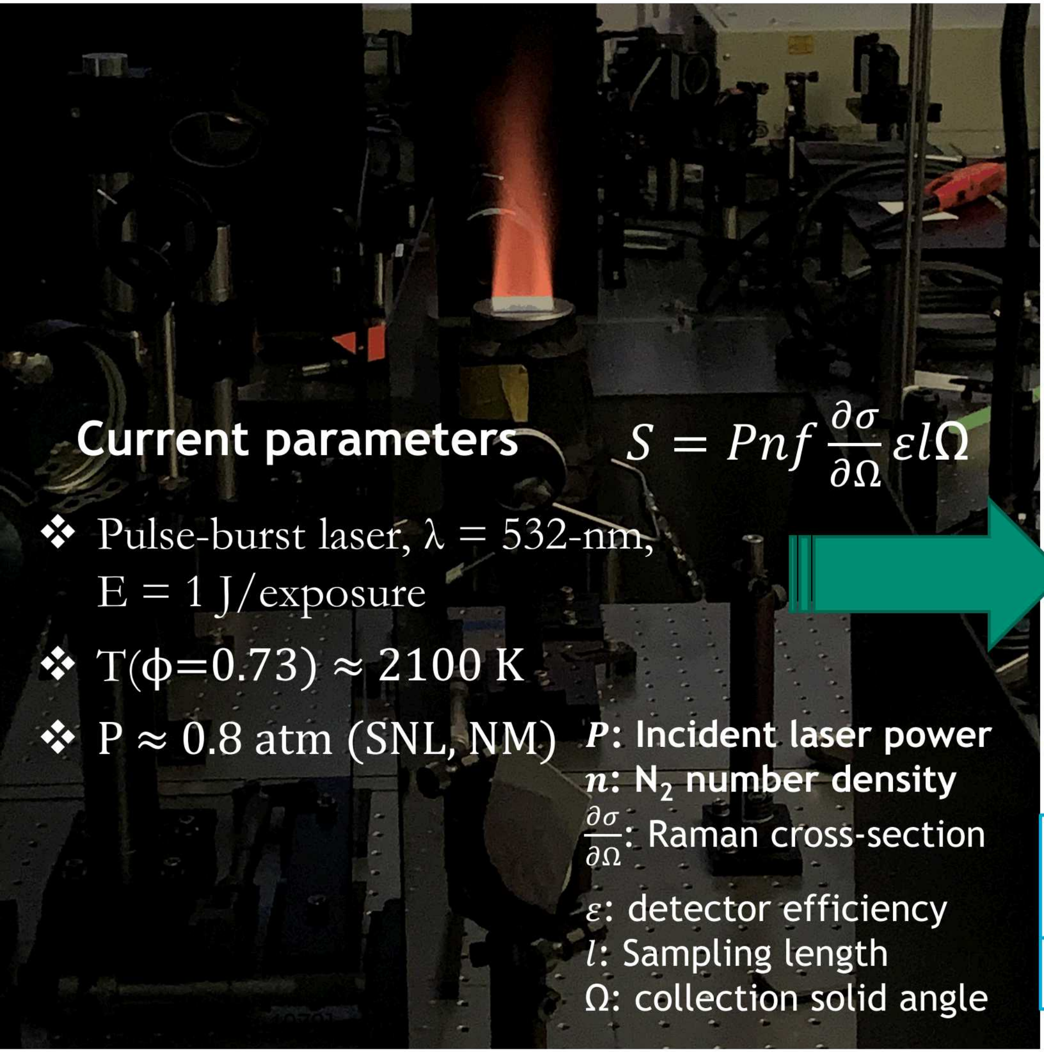
  Max % Dif. = 3% at ϕ = 0.73 → Pulse- Burst
- Leanest flame, ϕ = 0.29, % Dif. < 1%

- Accuracy improved in lean flames due to improved signal-to-noise
- Full-burst temperatures were systematically higher at of ϕ > 0.5

Pulse-burst Raman thermometry was precise and accurate within 3% in lean H_2-air flames

Next Steps: High Temperature Shock Tube

HST provides a facility to study dynamics of particle curtains and kinetics of shock-heated gas mixtures

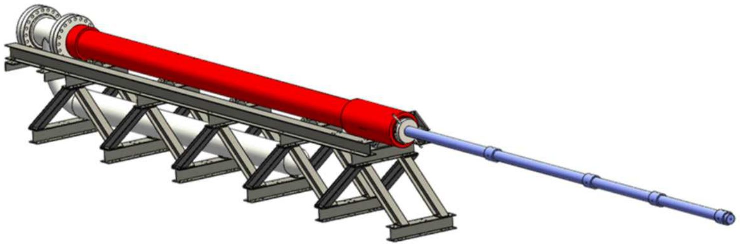


Current parameters

$$S = Pnf\frac{\partial\sigma}{\partial\Omega}\varepsilon l\Omega$$

- Pulse-burst laser, λ = 532-nm, E = 1 J/exposure
- T(ϕ=0.73) ≈ 2100 K
- P ≈ 0.8 atm (SNL, NM)

P: Incident laser power
n: N_2 number density
$\frac{\partial\sigma}{\partial\Omega}$: Raman cross-section
ε: detector efficiency
l: Sampling length
Ω: collection solid angle



Predicted parameters

- Energy/exposure remains constant
- Estimated from current HST testing
  - $T_{post\text{-}shock}$ = 2100 K
  - $P_{post\text{-}shock}$ = 30 atm

Raman signal in shock tube is expected to be a factor of 38 greater than flame

Data acquisition rates ≥ 5 kHz

Next Steps: High Temperature Shock Tube

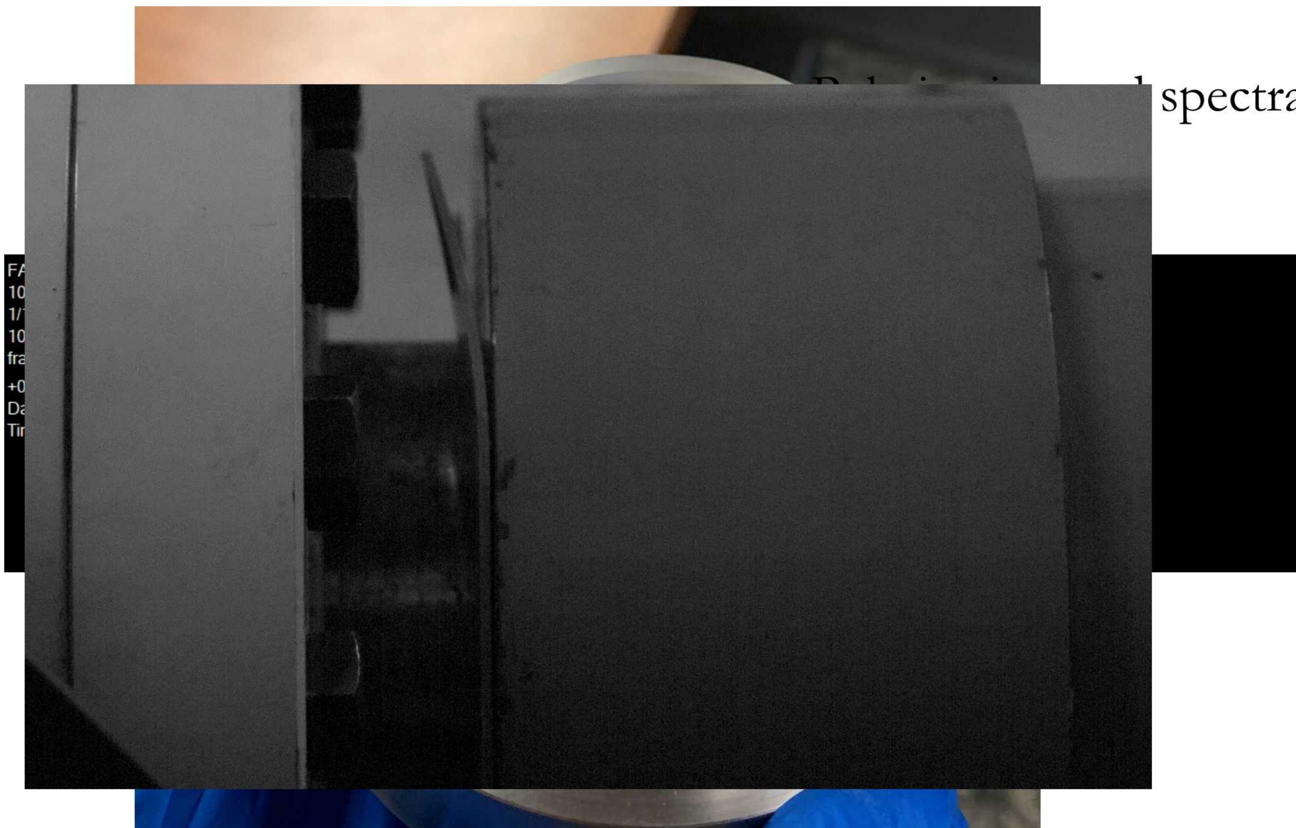
Challenge

Shock Tube Moves During Testing

Consideration

Image Relay Optics (IRO) provide time gating around laser pulse

spectral filtering



Summary and conclusions

- Spectrally-resolved Raman thermometry has been assessed in a stabilized near-adiabatic flat-flame burner to gauge its accuracy and precision as a temperature measurement technique.

- Full-burst spectra utilizing the entire 13 J of burst energy served as a baseline over an equivalence ratio range of 0.29 – 1.23.

- Measurements were demonstrated at 5 kHz by integrating two pulses onto a high-speed, back-illuminated EMCCD detector over an equivalence ratio range of 0.29 – 0.73.

- The standard deviation of the 5-kHz Raman thermometry was 2 – 3% of the measured temperature, dependent on SNR

- The accuracy of the burst-mode measurement was at worst 3%, indicating that this simple, robust configuration can potentially offer high-speed measurements with high accuracy

Acknowledgements

We gratefully acknowledge Sandia National Laboratories and the Laboratory Directed Research and Development (LDRD) program for funding this research

Great thanks for the support and advice from:

- **Tom Grasser**
- **Kate Hoffmeister**