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CARS in Explosives and Pyrotechnics

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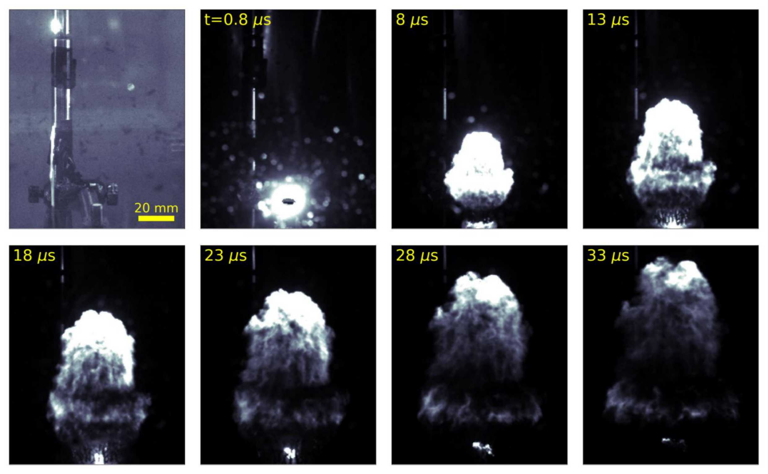
Introduction

- Detonation fireball temperatures are an important parameter to understand for safety regulations and planning, the safe destruction of chemical weapons, and for validation of explosive modeling
- Diagnostics in explosive environments are extremely challenging due to:
  - Steep temperature and pressure gradients
  - Blast wave
  - Optical density of detonator fireball
  - Short time scales
- Previous efforts to characterize detonator fireballs have focused on:
  - Emission spectroscopy:
    - Streak or high-speed cameras to capture time behavior
    - Added compounds with desirable emission properties (e.g. Ba)
  - Absorption spectroscopy with a variety of lasers including modeless dye lasers, tunable diode lasers, and quantum cascade lasers
    - Species measured: AlF, MgF, H_2O, CO, CO_2, and NO
  - Thermoluminescent particles extracted for ex-situ analysis
- In this work femtosecond/picosecond (fs/ps) rotational CARS is used for spatially and temporally resolved thermometry in detonator fireballs

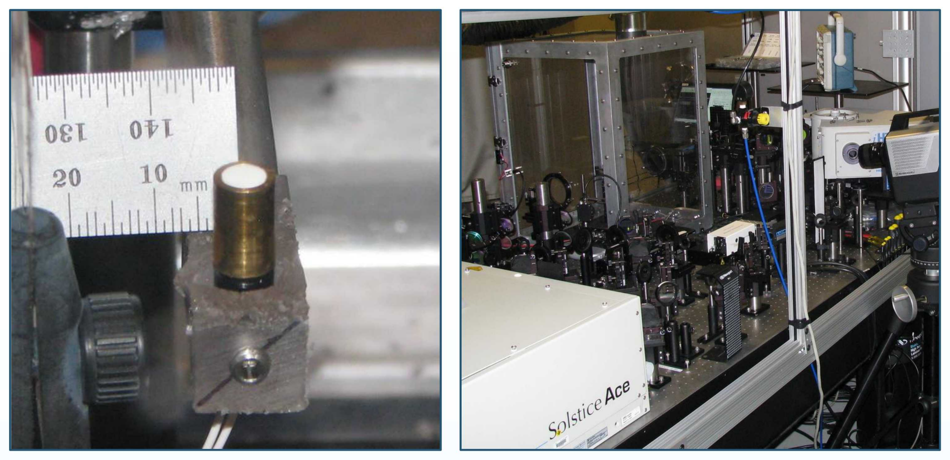


Images from 5 MHz video of detonation

Experimental Systems

Explosive Apparatus

- The detonators used were commercially available RP-80 detonators triggered by an exploding bridge wire
- A boom box with polycarbonate walls and fused silica windows was used to safely contain the explosion and allow optical access
- The detonator output forms a strong pulse of hot gases and measurements were performed at locations and times where significant mixing with ambient gases had occurred
- Measurements were performed at 18 and 28 µs after detonation and at a height of 35 mm above the top of the detonator



Photographs of RP-80 detonator (left) and experimental setup (right)

CARS Instrument

- A 1-kHz, 40-fs regeneratively amplified fs laser (Solstice Ace, Spectra Physics) was split to form the pump and Stokes with 3 mJ/pulse each
- The oscillator of a regeneratively amplified ps laser (PL2231C, Ekspla) was locked to the oscillator of the fs laser, and the narrowband, 50 mJ, 60-ps output was used as the probe pulse
- The relative timing to the pump and Stokes pulses was varied to shift the peak excitation efficiency to Raman shifts of 60–300 cm^{-1}; $\tau_{St} \sim 40$ fs
- The beams were crossed to form a 1D measurement volume:
  - The measurement volume height was 4 mm with 200 µm resolution
  - The measurement volume length was < 2 mm

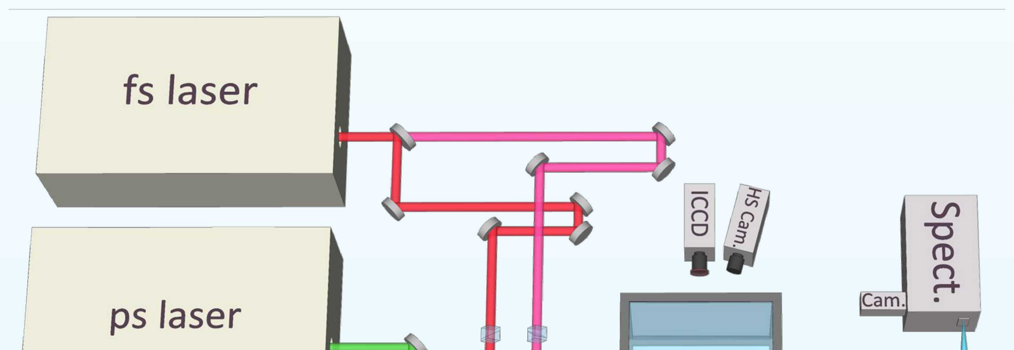


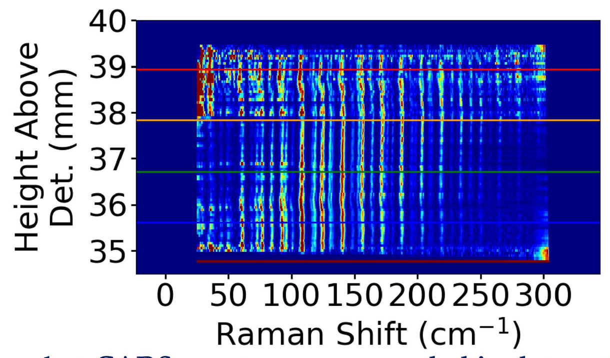
Diagram of fs/ps CARS setup with boom box to contain explosives

Imaging systems

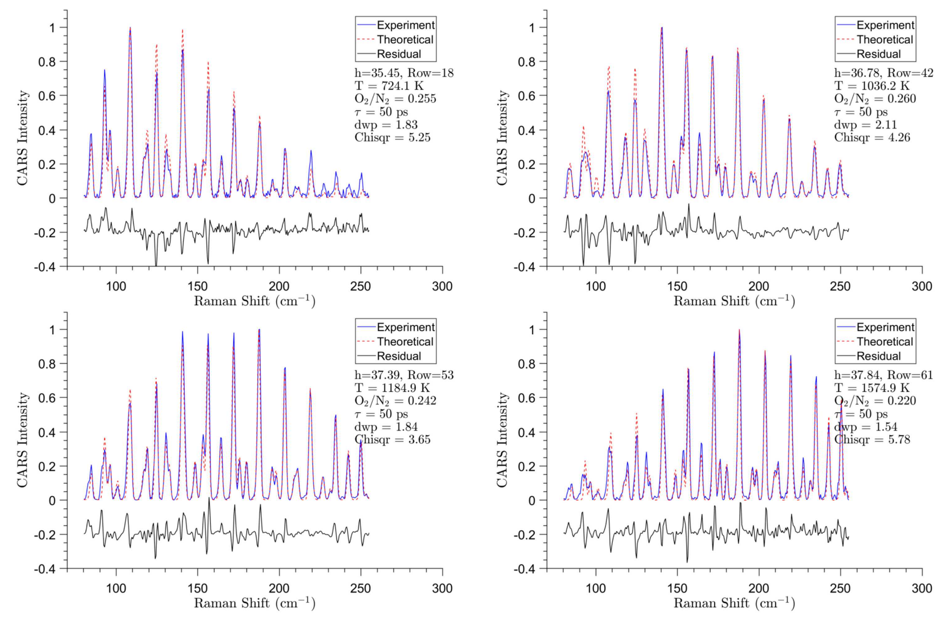
- In addition to the CARS thermometry, the explosions were monitored with two cameras
  - 5-MHz videos of the detonation reveal the fireball dynamics and show the arrival of the CARS lasers pulses
  - A 575–625 nm bandpass filter was placed in front of a gated, intensified CCD camera to record LII-like images of the fireball and show the exact location of the CARS beams (see results section)

Spectral Fitting

- Spectrograms were processed prior to spectral fitting using a dynamic background correction, and normalizing by the nonresonant background
- A library of pre-computed CARS spectra were used to fit each row of data
- An instrument function was varied as one of the fit parameters dues to distortions or beam steering in the detection optics



Single-laser shot CARS spectrogram recorded in detonation fireball



Single-laser shot CARS spectra and best-fit theoretical spectra

- A unique polarization scheme was needed to reject both two-beam CARS signals which were scattered from particulate matter during the measurement and corrupted the three-beam CARS signal

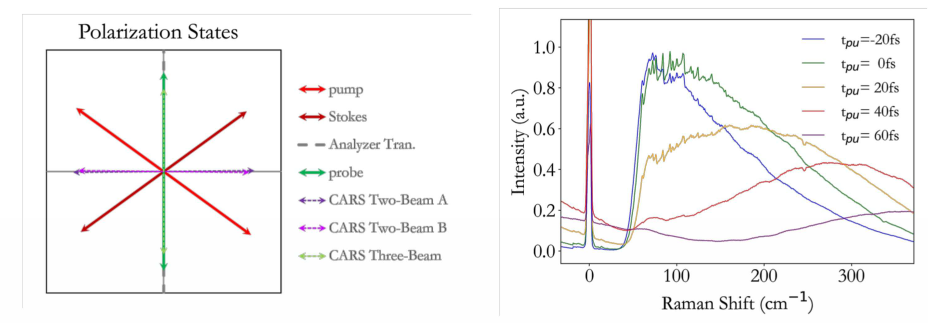
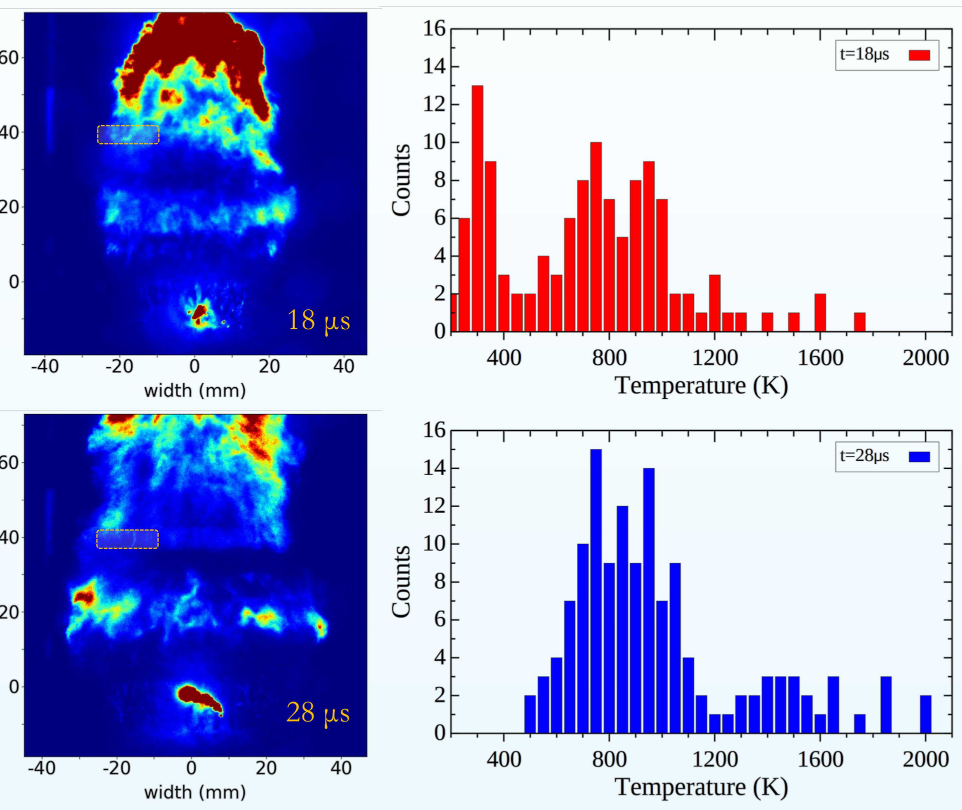


Diagram of the polarization states used in the CARS experiment (left) and plots of the nonresonant CARS spectra for various pump delays (right)

Results

- CARS data was recorded and fit at two different times after the detonation at a fixed height above the detonator
- The temperature at t=28µs is hotter than at t=18µs



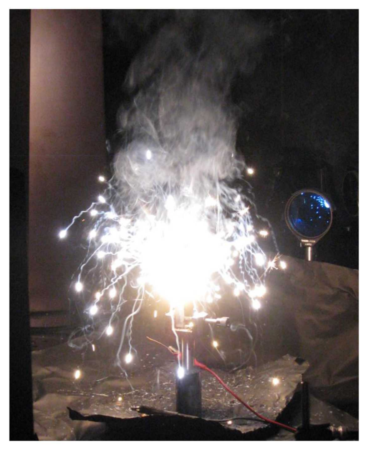
Filtered, gated images of the detonator fireball with dashed boxes indicating the CARS measurement regions (left); histograms of the measured temperatures in these regions (right)

Conclusions and Future Work

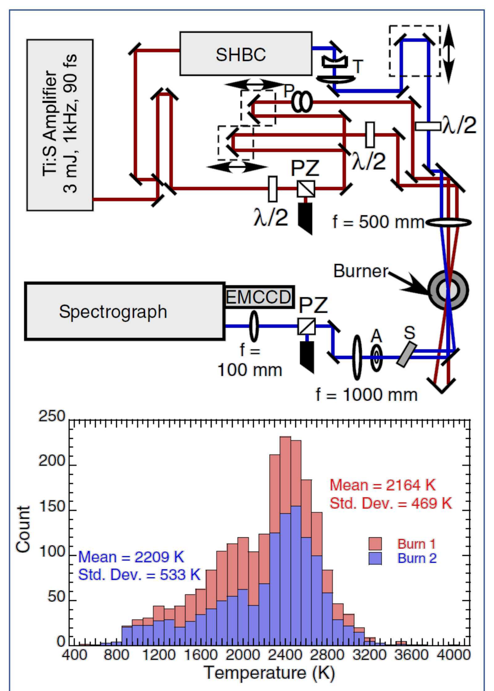
- Detonator fireball temperature measurements have been performed for laboratory-scale detonators using rotational fs/ps CARS thermometry
- The temperatures are found to be in the range 300–1800 K
- Future work may include
  - Vibrational CARS measurements of other species such as H_2 or CO
  - Determination of explosive composition on fireball temperature
  - Measurements directly before an after the detonation front

Introduction

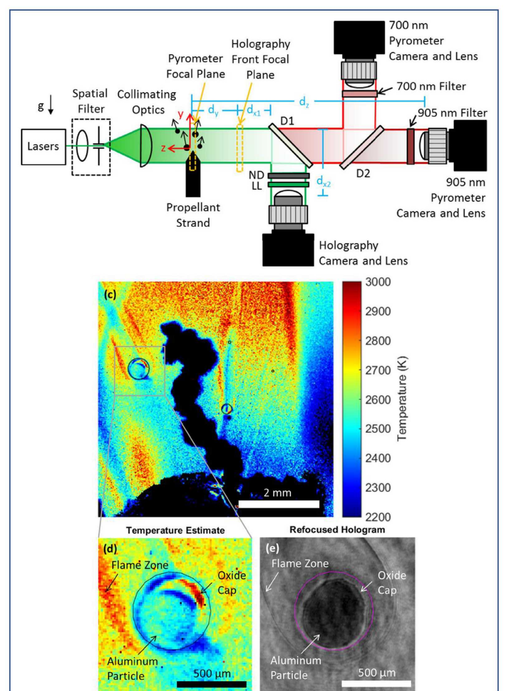
- In an accident scenario, burning solid rocket fuel can be a major hazard due to the intense thermal radiation and the harsh chemicals released
- Solid rocket fuel (propellant) flames are challenging environments for optical diagnostics and are characterized by:
  - Multi-phase plumes with burning liquid metal droplets
  - Temperatures near 3000 K
  - Corrosive chemicals such as HCl
- Previously in our laboratory these flames were studied using digital in-line holography, imaging pyrometry, and rotational N_2 CARS
- This work presents vibrational H_2 fs/ps CARS measurements to study the fuel-rich regions of the flame plume
  - These regions are primarily composed of reactants from the decomposing propellant and very little N_2
  - At distances far from the fuel source, little H_2 exists due to mixing and oxidation with the ambient gases
- The propellants studied here are aluminized ammonium perchlorate hydroxyl terminated polybutadiene (AP/HTPB)



Photograph of metalized propellant flame



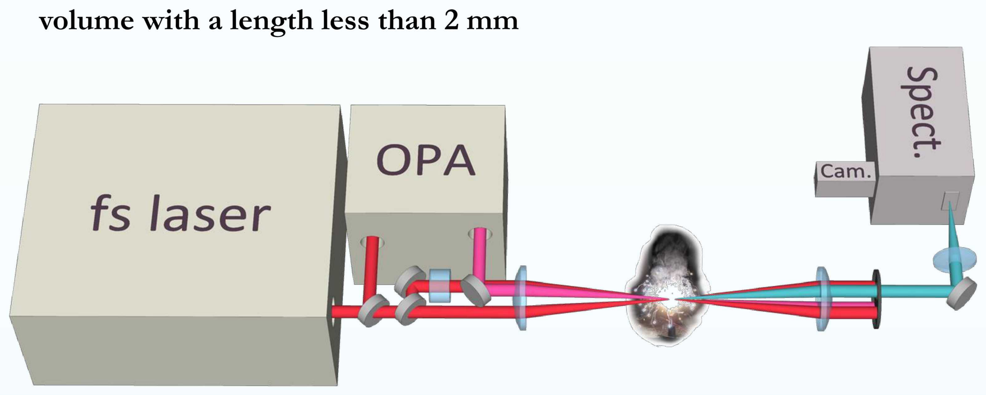
Kearney and Guildenbecher, Appl. Optics, 2016



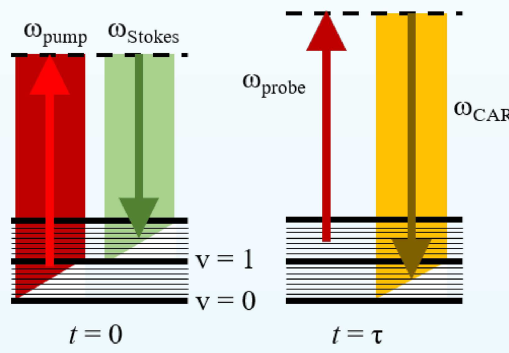
Chen, et al., Combust. Flame 2017

Measurement System

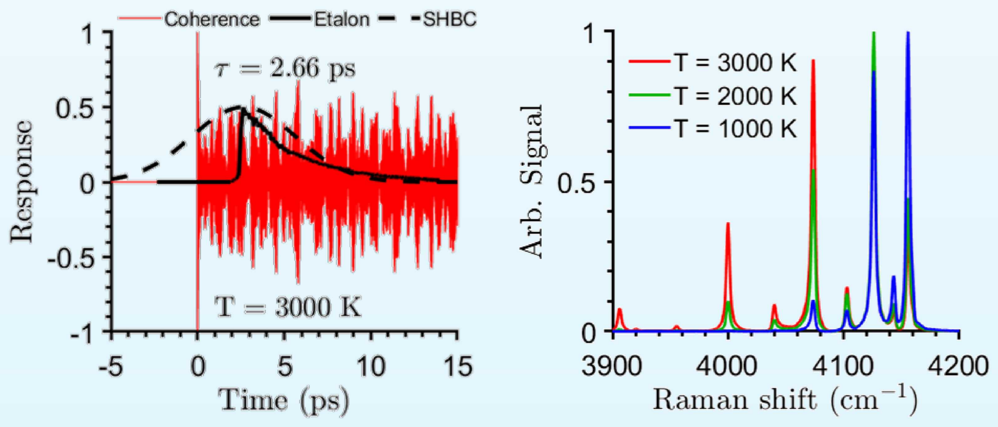
- A 1-kHz regeneratively amplified fs laser (Spitfire, Spectra Physics) was split to pump an OPA (TOPAS Prime) and to form the pump pulse
- The 80µJ output of the OPA near 1200 nm served as the Stokes pulse and the frequency difference between the pump and Stokes was tuned to excited vibrational H_2 transitions (~4000 cm^{-1})
- A portion of the remaining 800-nm radiation was passed through an etalon to form a narrowband ps-duration time-asymmetric probe pulse (15 µJ)
- The beams were crossed to form a zero-dimensional measurement volume with a length less than 2 mm



Simplified diagram of vibrational H_2 CARS setup with etalon



Energy level diagram for vibrational H_2 CARS



Time (left) and frequency (right) domain output from H_2 CARS fitting code

Results

- In these experiments a stick of metalized propellant is burned while the CARS measurement location is held fixed
  - Initially, the lasers are blocked by the unburned propellant
  - As the propellant burns downward, the location of the CARS measurement clears the burning surface and rises into the flame plume
  - Once the CARS measurement volume nears edges of the plume or the product zone, the amount of H_2 diminished and the CARS signal vanishes

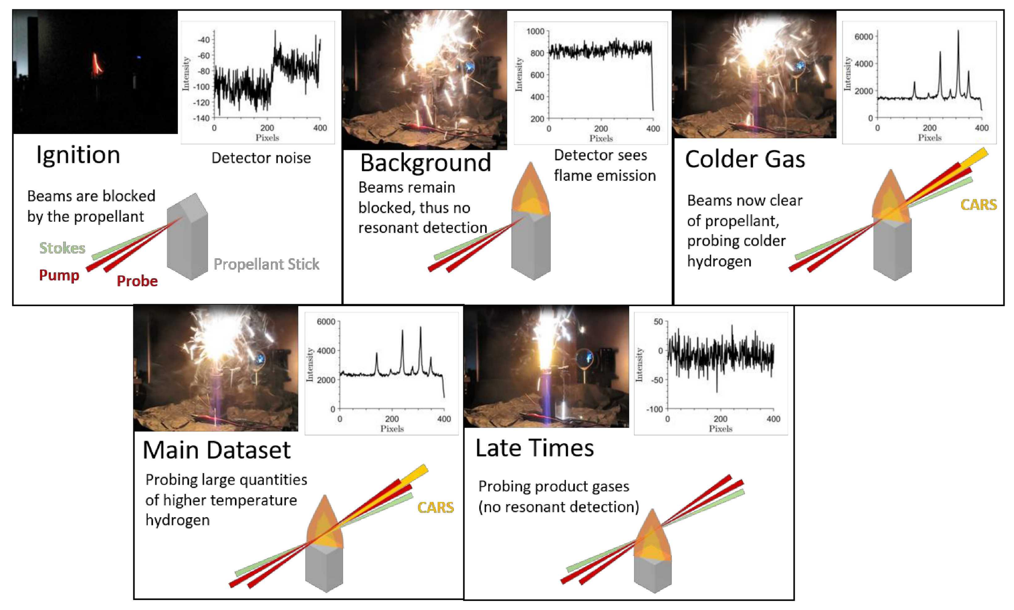
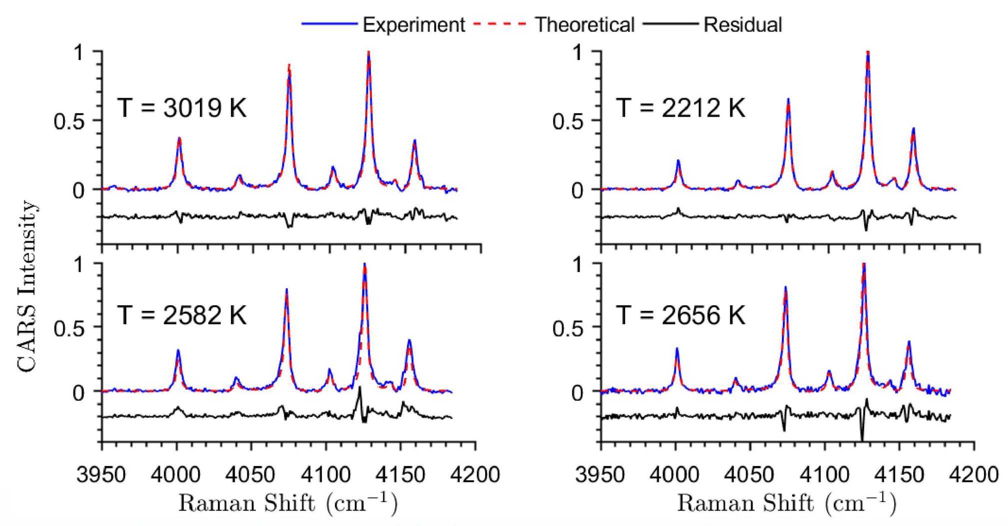
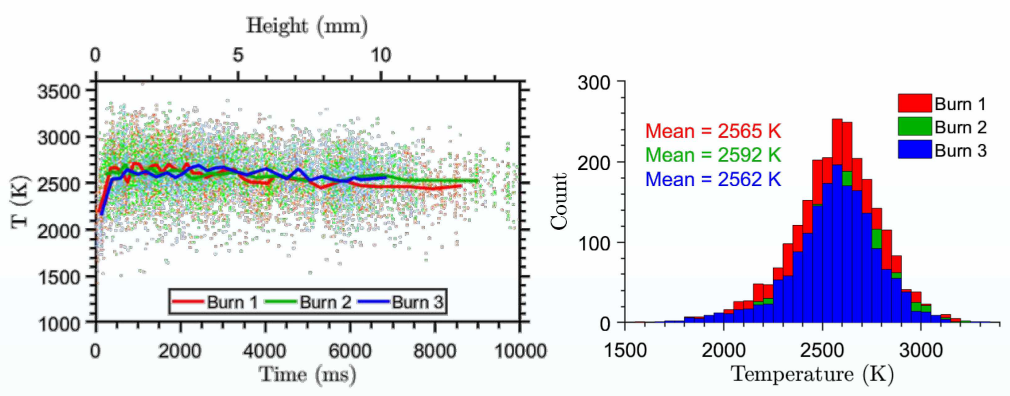


Diagram of CARS measurements in a Burning Stick of Propellant

- Data from three different propellant burns are shown below
- The measured temperatures from each burn are similar, indicating repeatability in the experiment and steady operation of the laser system
  - Measurements in a steady laboratory H_2–air flame show a measurement precision of 4%
- The location above the burning surface was estimated by measuring the duration of each burn and the length of the propellant stick



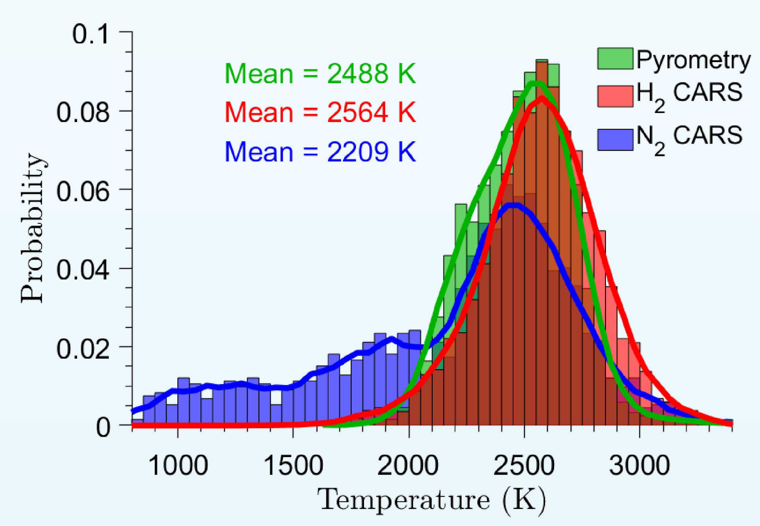
Example single-laser shot CARS spectra and best-fit theoretical spectra



Time-history of best-fit CARS temperatures (left) and histograms (right) for three different propellant burns

Conclusions and Future Work

- Vibrational H_2 CARS thermometry has been performed in the plume of a burning stick of metalized solid rocket propellant
- This data complements previous studies performed to measure the flame temperatures using rotational N2 CARS, and the temperature of liquid metal droplets using imaging pyrometry



Comparison of temperature measurements in propellant flames from vibrational H_2 CARS, rotational N_2 CARS and pyrometry

- Future work will focus on measuring other species in the flame plume to better understand the chemical kinetics in propellant decomposition and burning
- This data will be compared to flame models to understand the physical phenomena that drive heat transfer in these flames

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