SAND2017-4069PE

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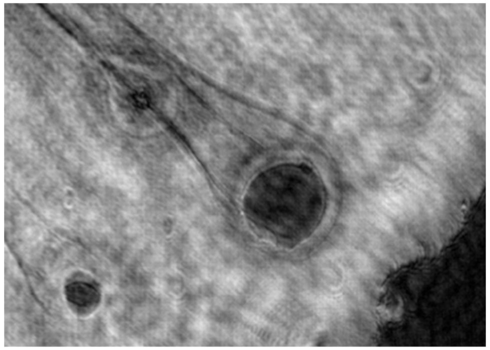

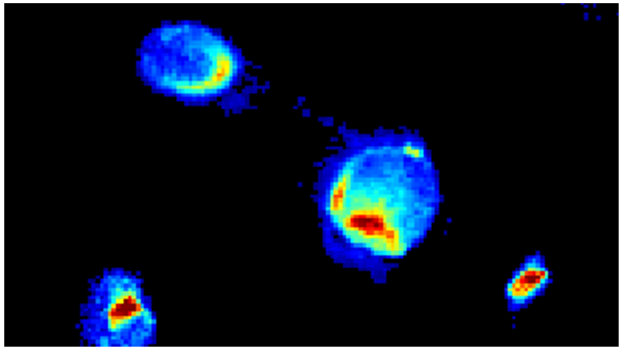

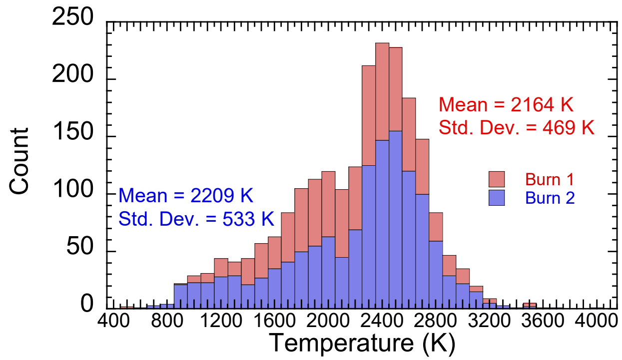

Propellant diagnostics at Sandia

Daniel R. Guildenbecher, Ellen Y. Chen, Sean P. Kearney

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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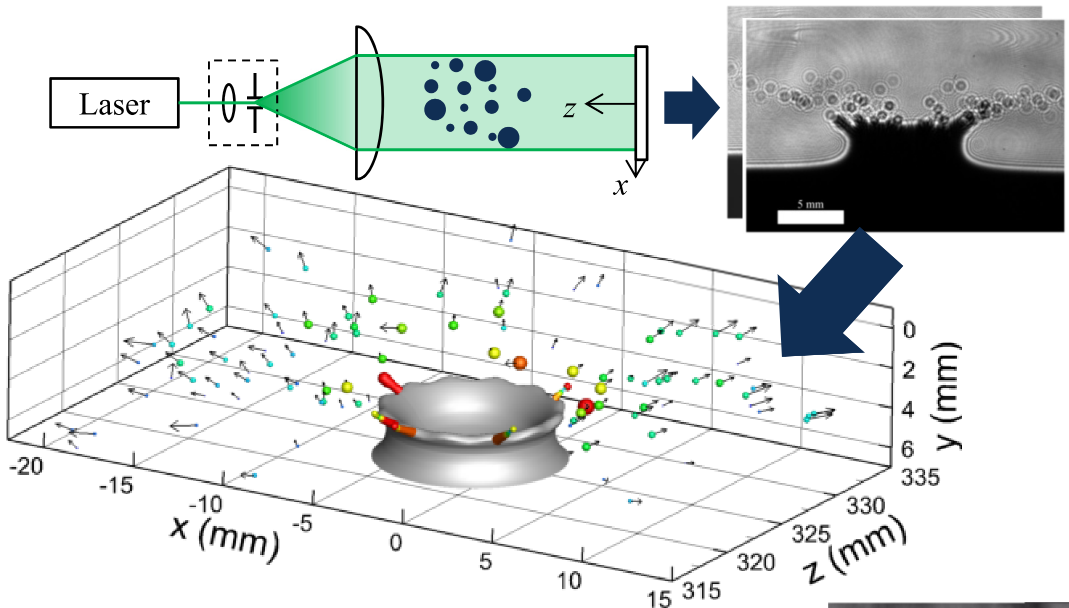
Digital in-line holography (DIH)

Daniel R. Guildenbecher

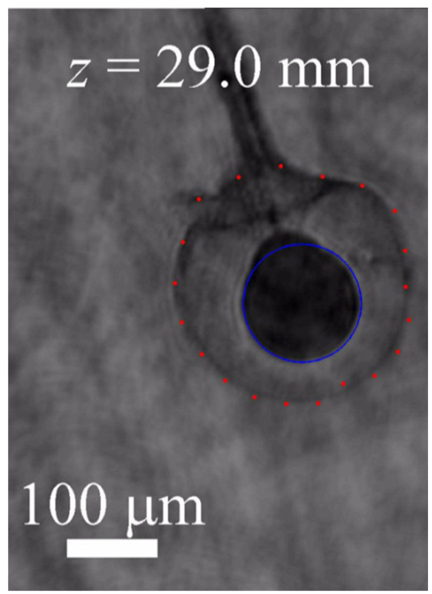


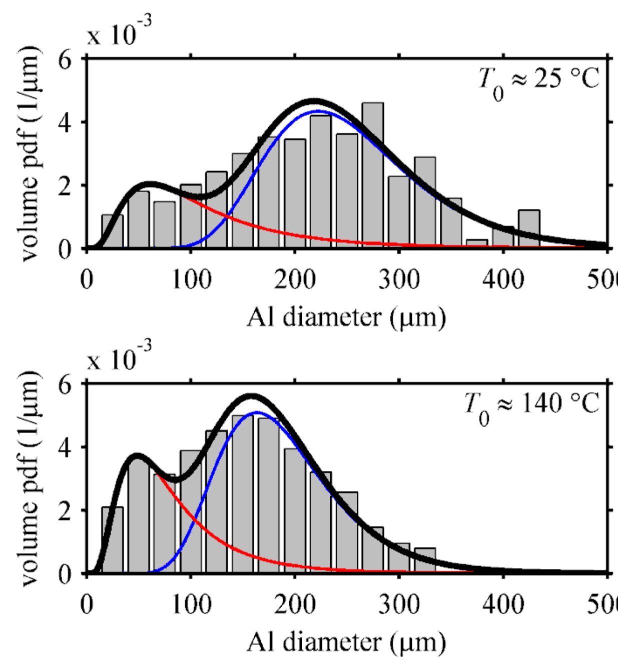
Diffraction images are numerically refocused to revel the 3D particle field

- Unique image processing automatically measures the size, 3D position, and 3C velocity of all particles within a volume
- Provides rapid quantification of size-velocity statistics

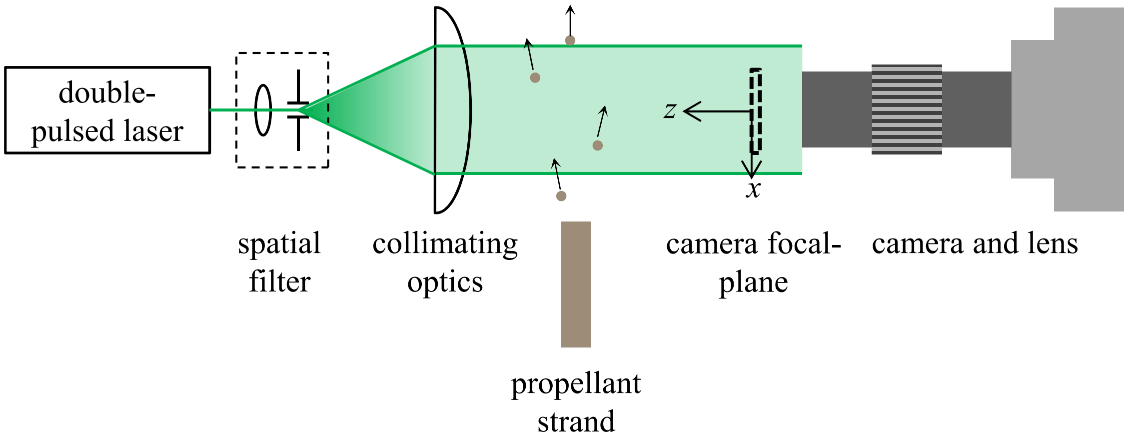
3D imaging of propellant combustion

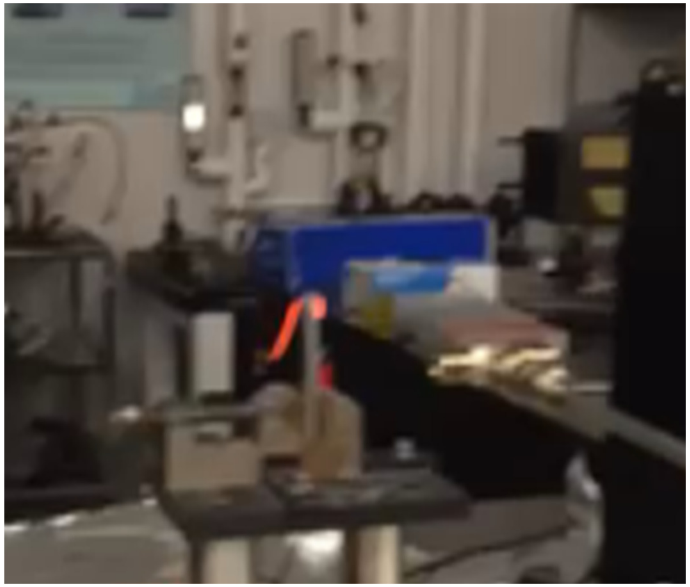
- Reveals detailed structure of aluminum combustion
- A single experiment results in 17,500 measured drops and the converged bi-modal distributions shown
- 20 kHz imaging gives size-velocity measurement of 16,000 drops from combustion of a single pencil sized strand





Aluminum drop combustion in propellants





propellant in the text fixture

Propellant: solid-rocket propellant pressed into a pencil size strand

- Combusts from the top surface down, ejecting molten aluminum particles traveling a few m/s

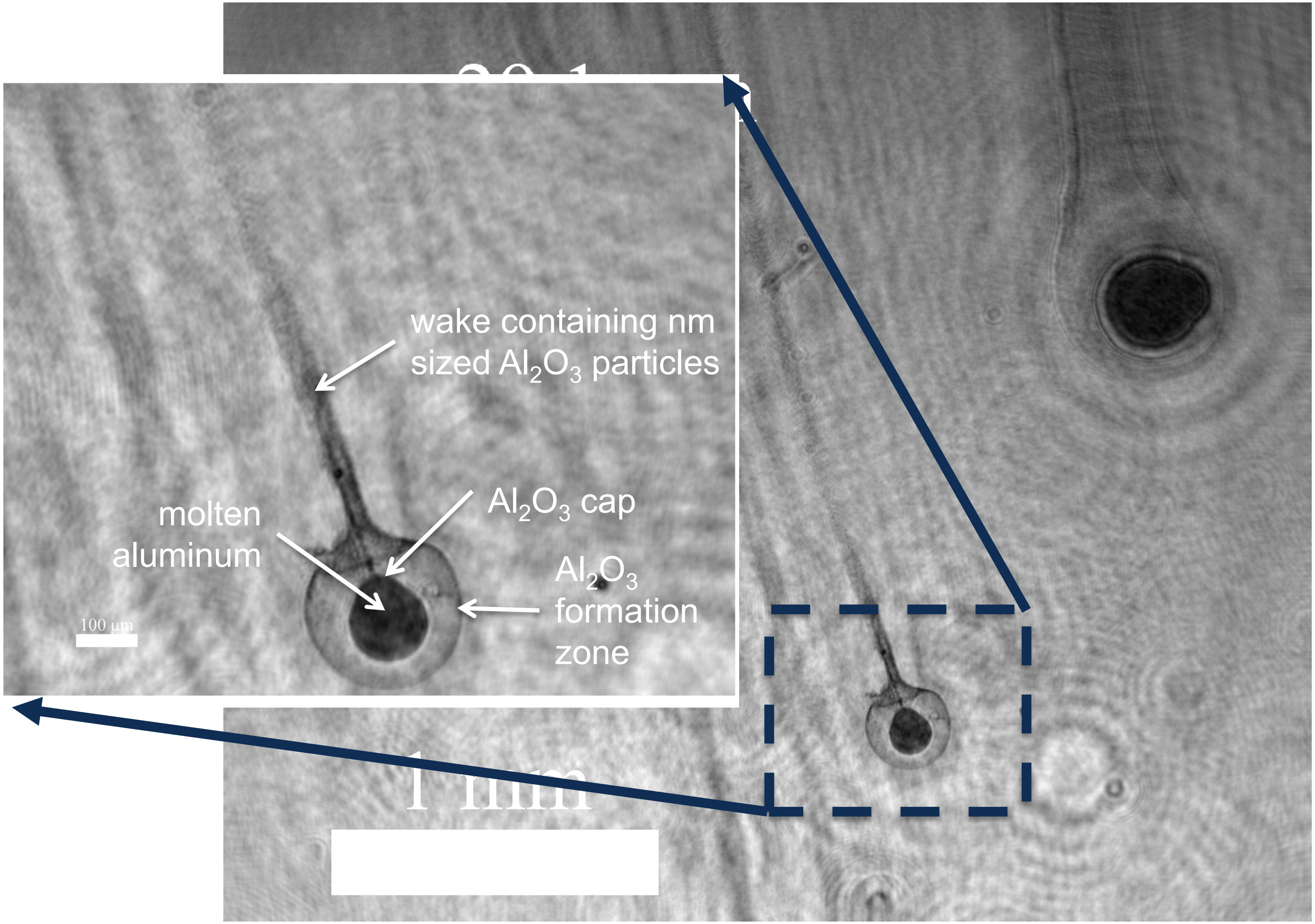
Laser: Continuum Minilite Nd:YAG, 532 nm wavelength, 5 ns pulse duration

Camera: sCMOS from LaVision at 15Hz

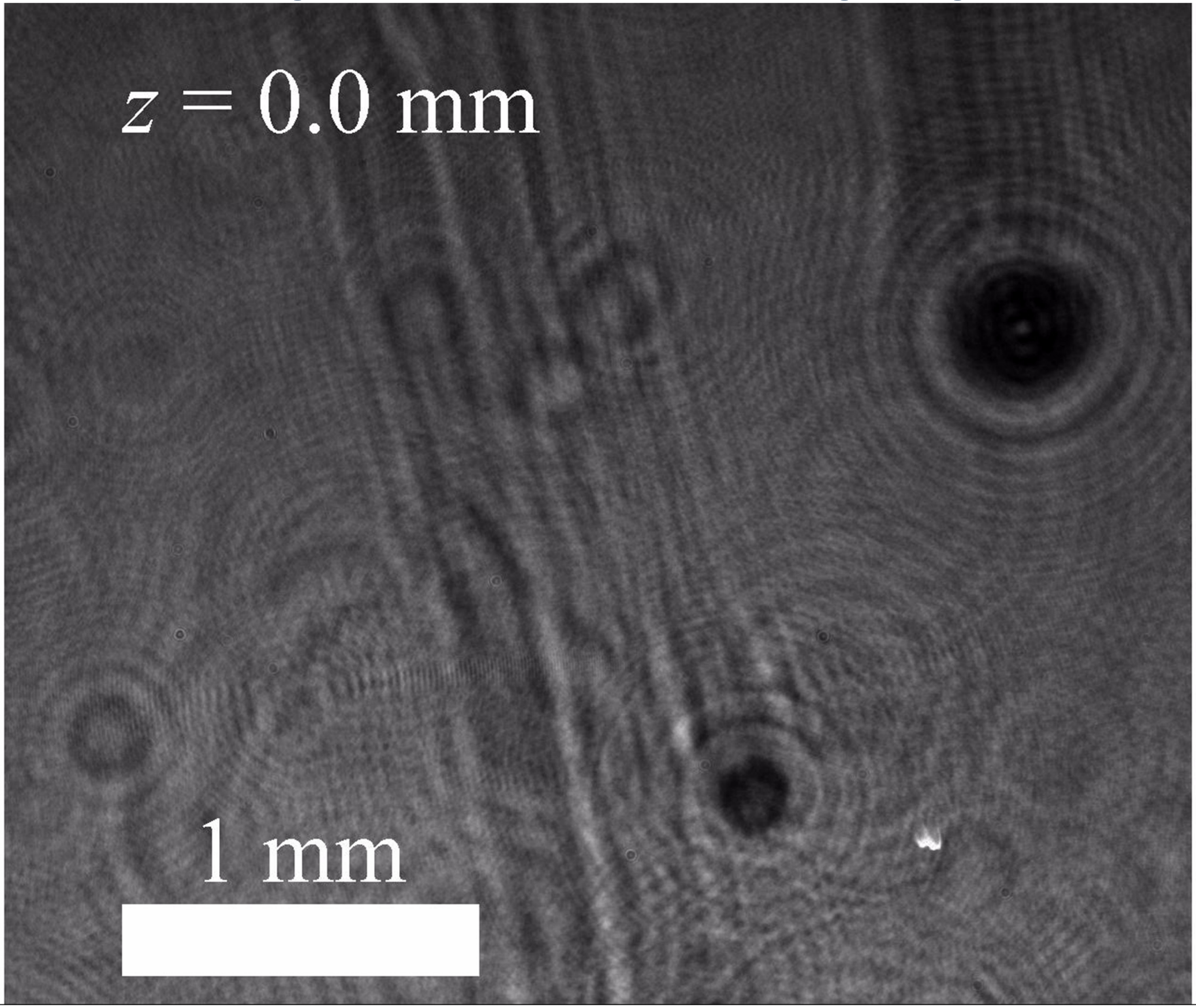
Lens: Infinity K2 long distance microscope with CF-4 objective

- ~ 6X magnification

Aluminum drop combustion in propellants



Aluminum drop combustion in propellants



Algorithms automatically measure unique features of burning aluminum

Aluminum drop combustion in propellants

Three strand burns → 5594 images and 17496 measured drops

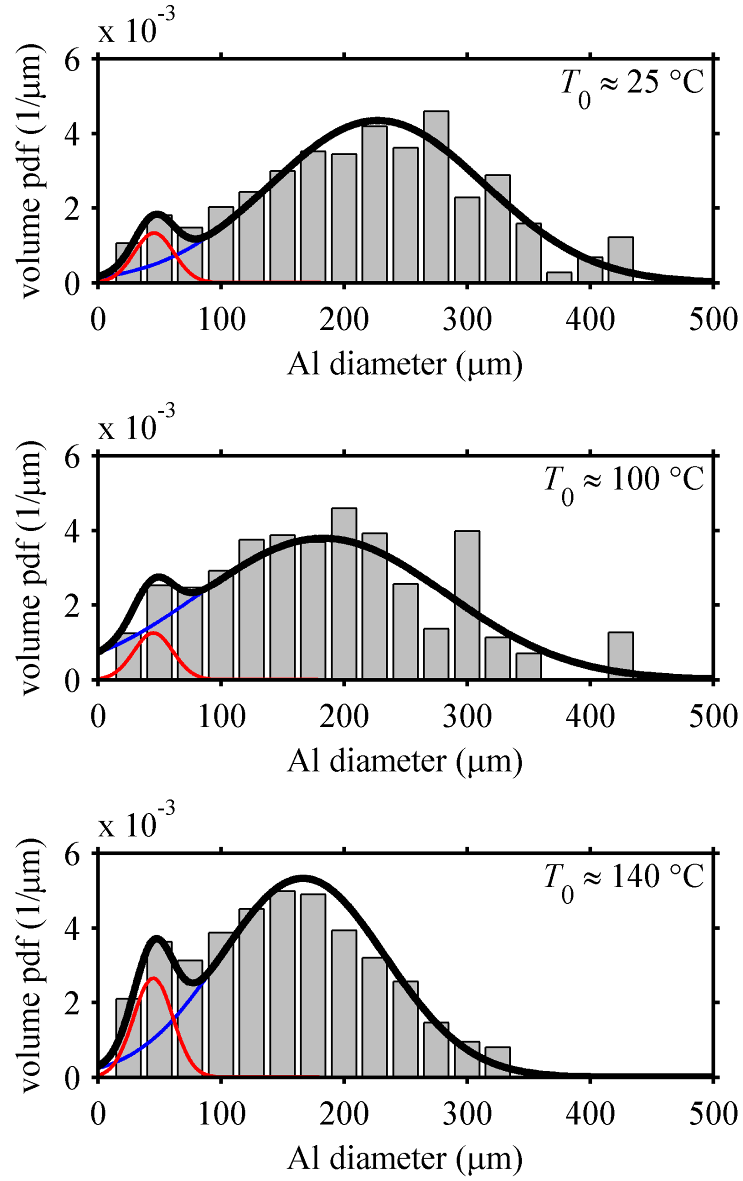
- Main peak due to agglomerated particulates
- Peak at 50 μm due to non-agglomerated particulate

Experiments repeated at higher initial temperature (faster burn rate)

- Main peak is reduced due to decreased residence time for agglomeration
- Peak at 50 μm remains

Trend is consistent at still higher initial temperatures

- Main peak reduced further
- Peak at 50 μm remains



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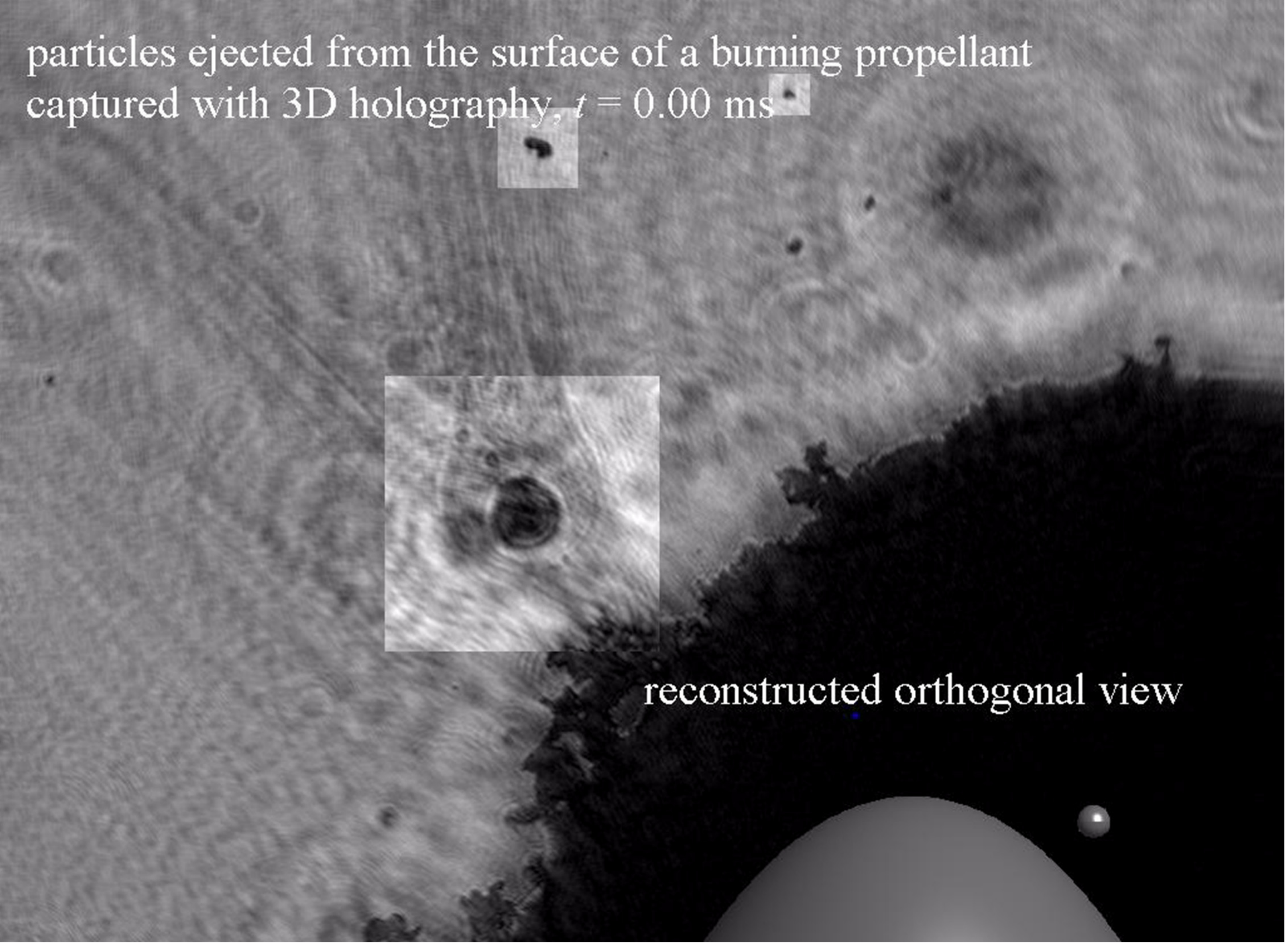
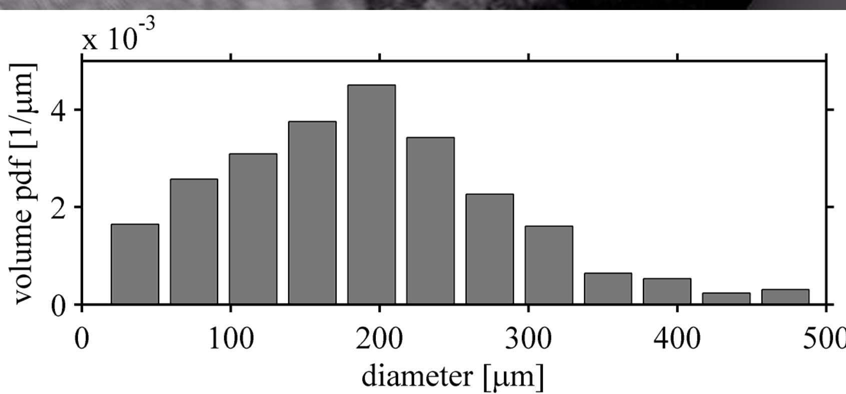


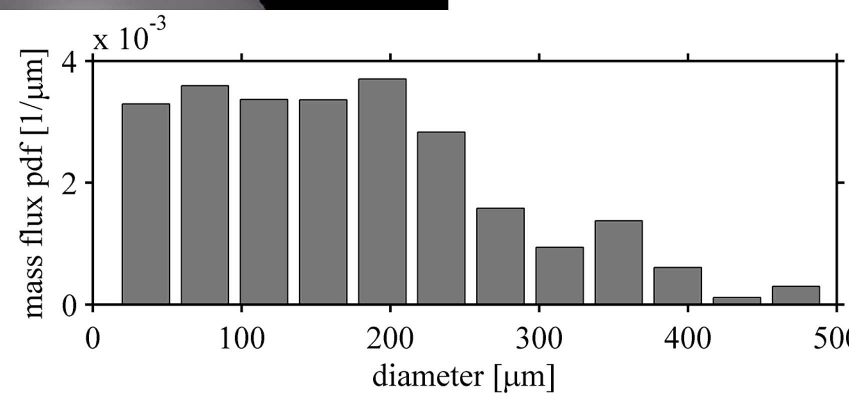
Recorded at 20,000 fps

Camera: Photron SA-Z

Laser: Coherent Verdi V6

43,684 frames → 15,991 measured drops





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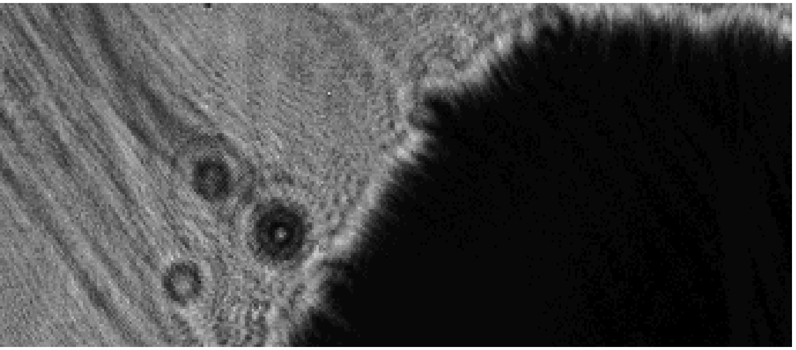
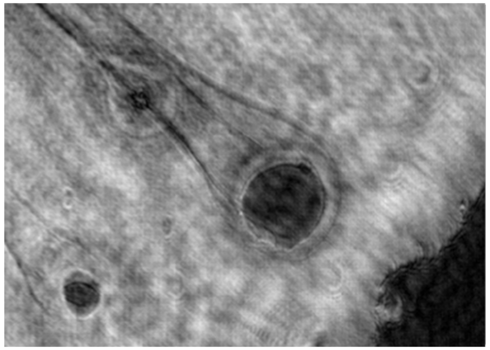
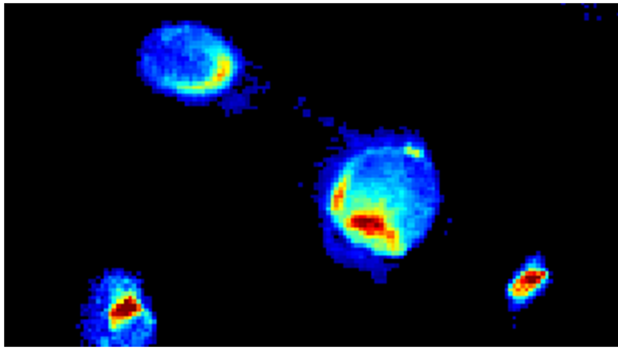

Digital Imaging Holography and Pyrometry of Aluminum Drop Combustion in Solid Propellant Plumes

Yi Chen and Daniel R. Guildenbecher

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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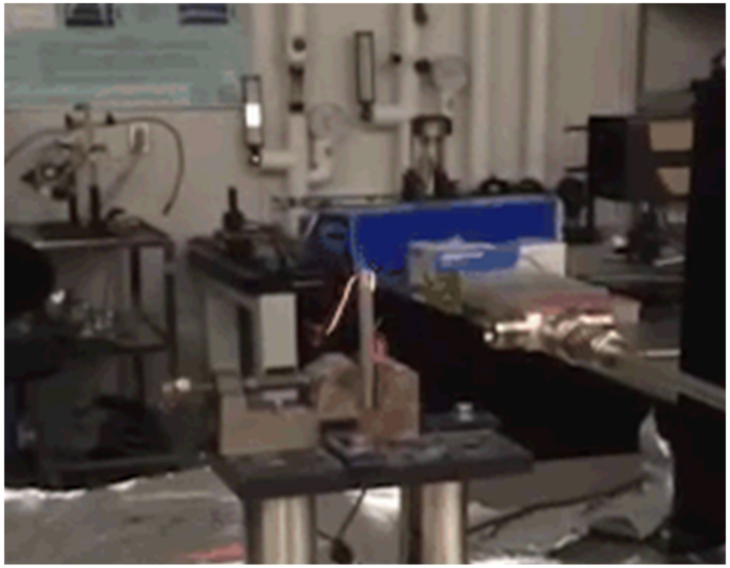
Motivation

http://www.cbsnews.com/news/rocket-crash-no-immediate-threat-to-station-but-cause-is-unknown/

Color video of burning propellant



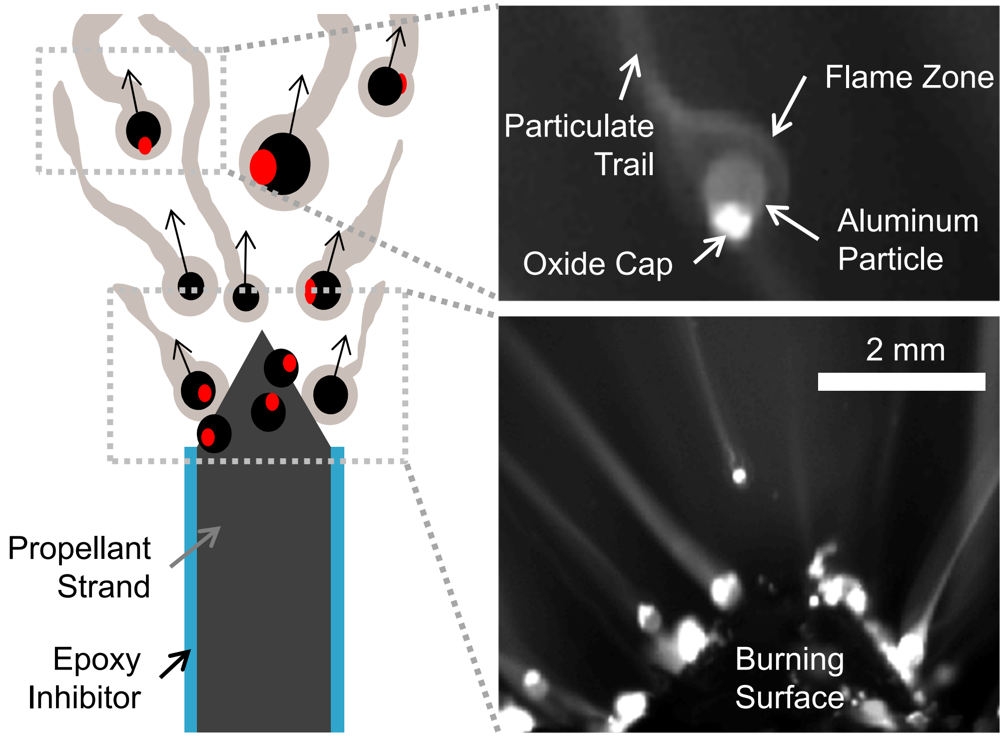
Problem:

- Rocket failures can lead to propellant fires
- Aluminum agglomeration at the surface yields large reacting drops with high damage potential
- Prediction requires knowledge of particle ***size*****,** ***position,*** **and** ***temperature***

Goals:

- Making measurements in real propellant sticks
- Measuring the size of small particles that are out-of-focus

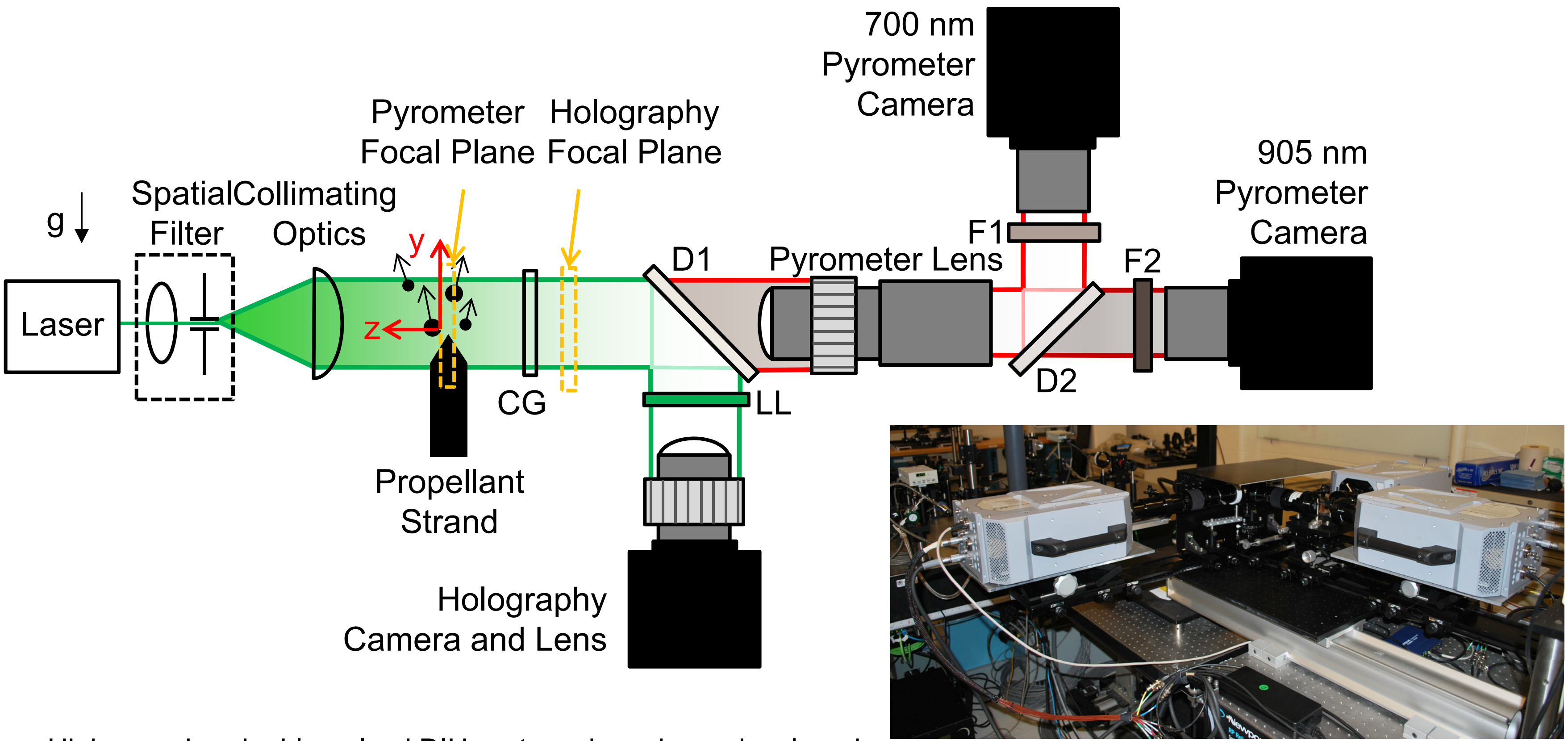
Approach



High speed video of burning propellant

Particle Size and Position?	Digital In-Line Holography (DIH)
Particle Velocity?	Double Frame DIH or High Speed DIH
Particle Temperature?	Two-Color Imaging Pyrometer
Gas Temperature and Composition?	Coherent Anti-Stokes Raman Scattering (CARS)

High Speed Pyrometry Setup



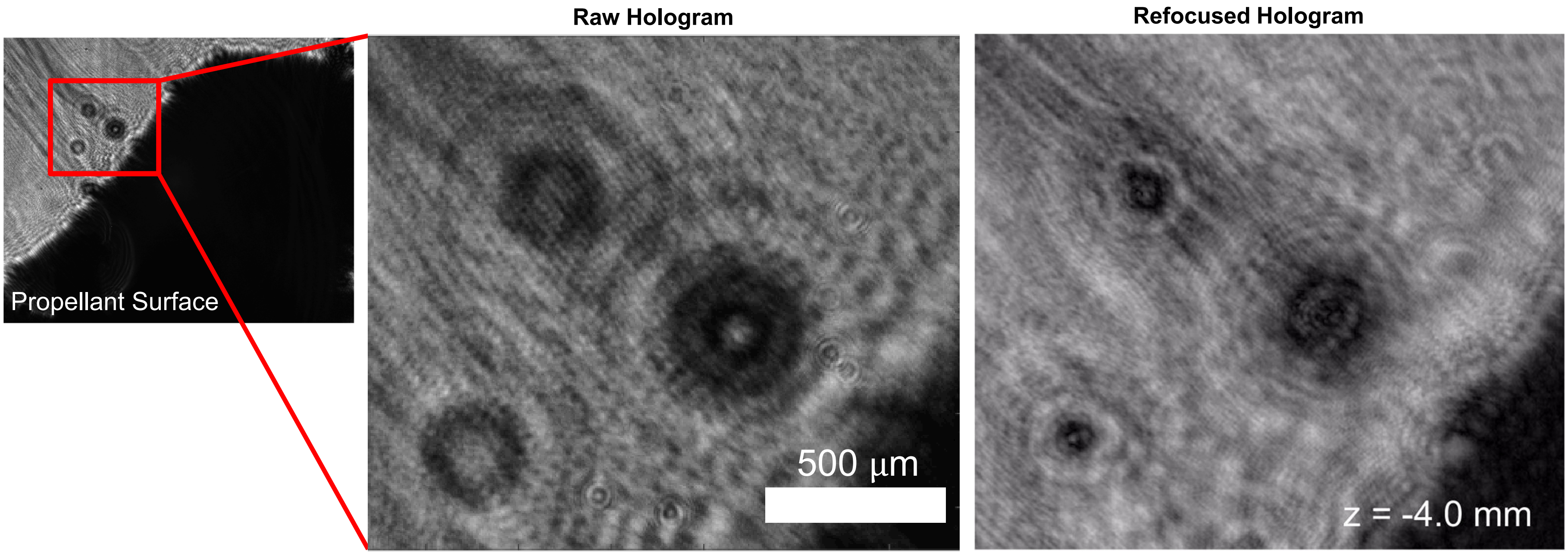
- High speed or double-pulsed DIH systems have been developed
- CW 532 nm laser for high speed system
- Three high speed Photron SA-Z cameras were used for this experiment sampling at 100 kHz
- Pyrometry cameras had exposures of 2.5 to 15 microseconds for the 700 and 905 nm cameras respectively
- LL – Laserline filter at 532 nm with bandwidth of 1 nm (Andover 532FS02-50)
- D1 – Beam splitter, reflection @ 532 nm and transmission @ 650 to 900 nm
- D2 – Beam splitter, reflection @ 650 to 750 nm and transmission @ 850 to 950 nm
- 700 and 905 nm filters with FWHM of 10 nm

Digital In-Line Holography

Light propagation is described by the diffraction integral equation:

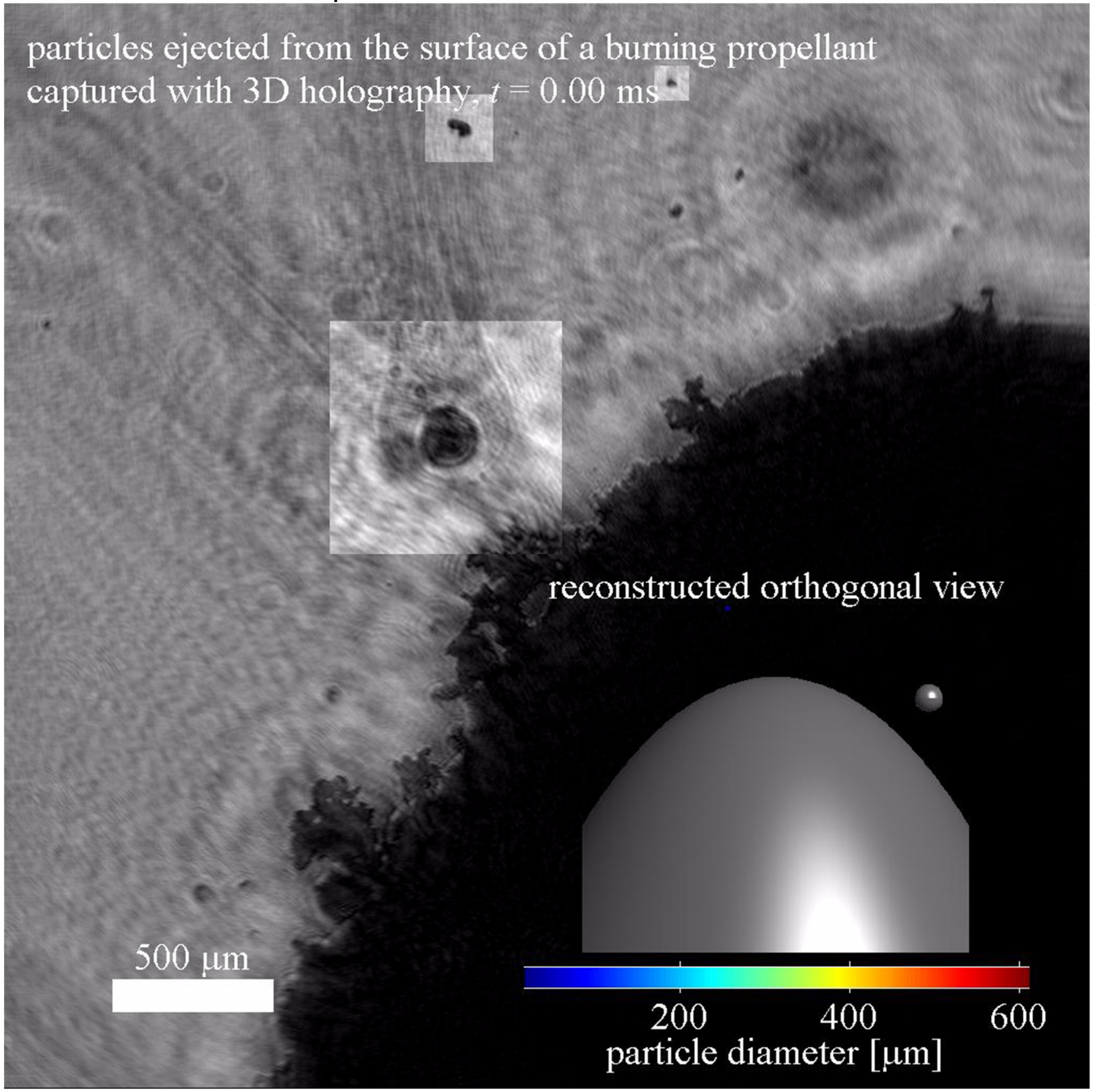
$$E(x,y,z)=\frac{1}{\lambda}\iint E(\xi,\eta,z=0)\frac{e^{-jkr}}{r}d\xi d\eta \quad \text{where: } r=\sqrt{(\xi-x)^2+(\eta-y)^2+z^2}$$

$E(x,h,0)$ ≡ complex amplitude at hologram plane = $h(x,h)\cdot E_r^*$
$E(x,y,z)$ ≡ refocused complex amplitude at optical depth z



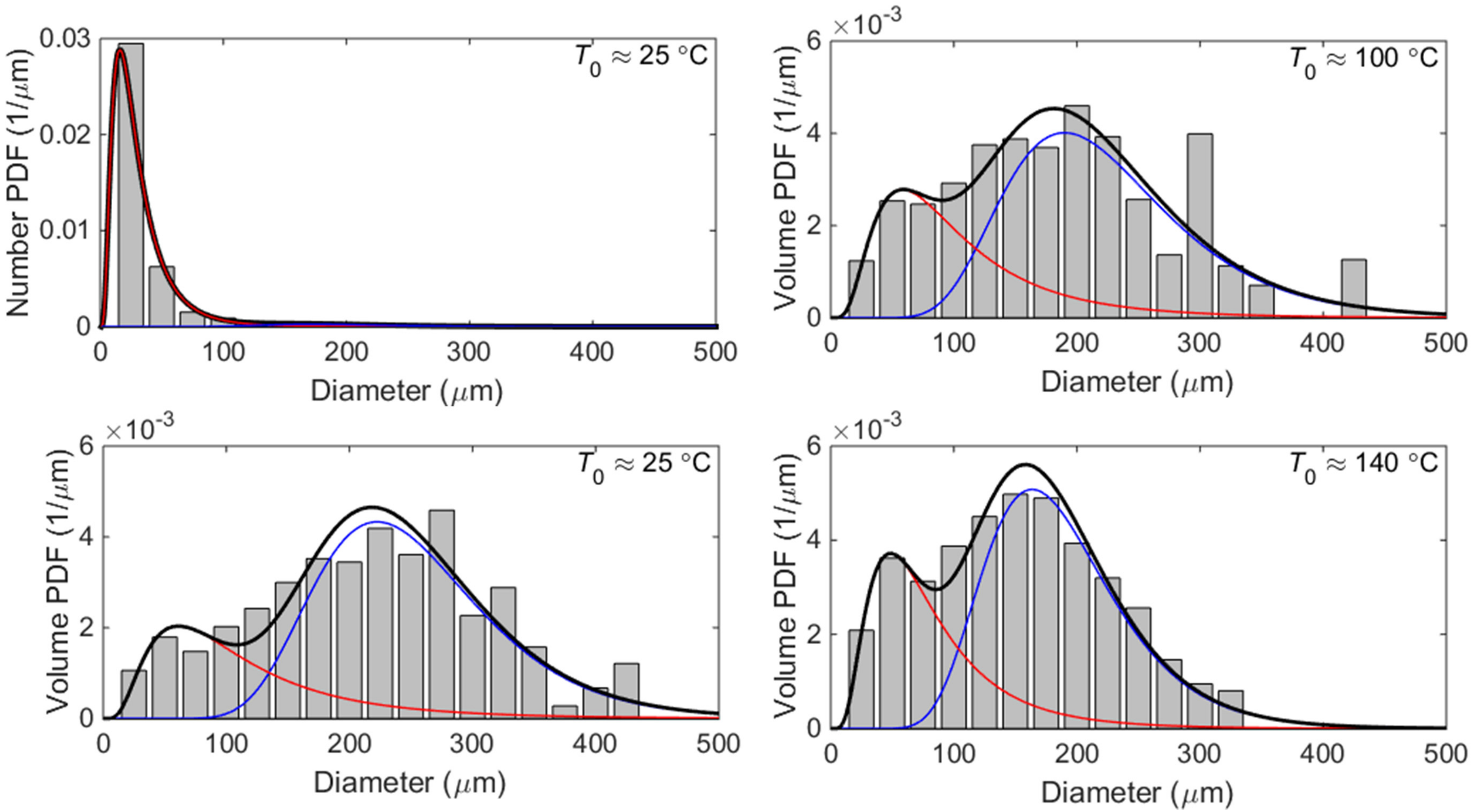
High Speed DIH

Recorded at 20,000 fps on Photron SA-Z with Coherent Verdi V6 Laser



D. Guildenbecher et. al., Applied Optics Vol. 55 (11), 2016.

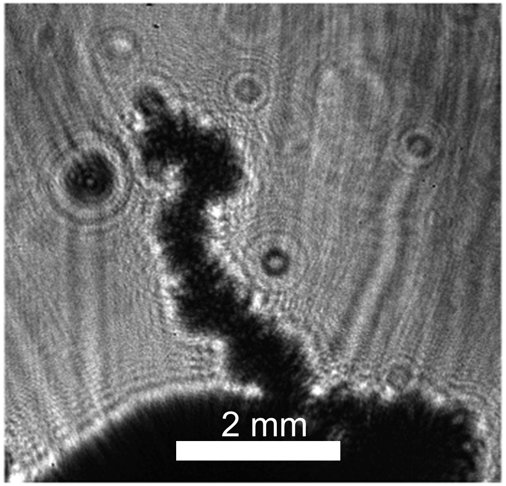
Aluminum Particle Size Statistics



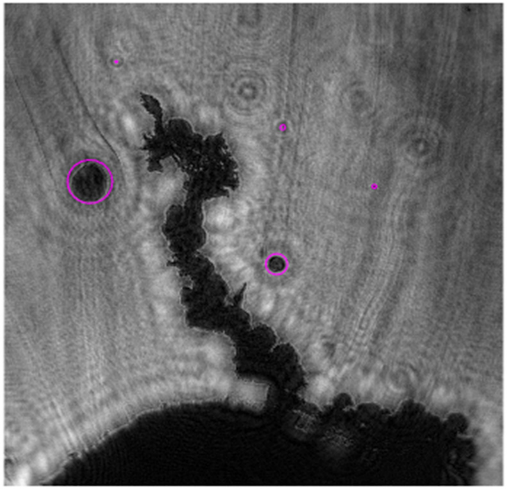
- Particle number PDFs and particle volume PDFs can be measured using DIH
- Increasing initial propellant stick temperatures can change the size distribution of agglomerated particles. Lower initial propellant stick temperatures show more agglomeration with larger particles.

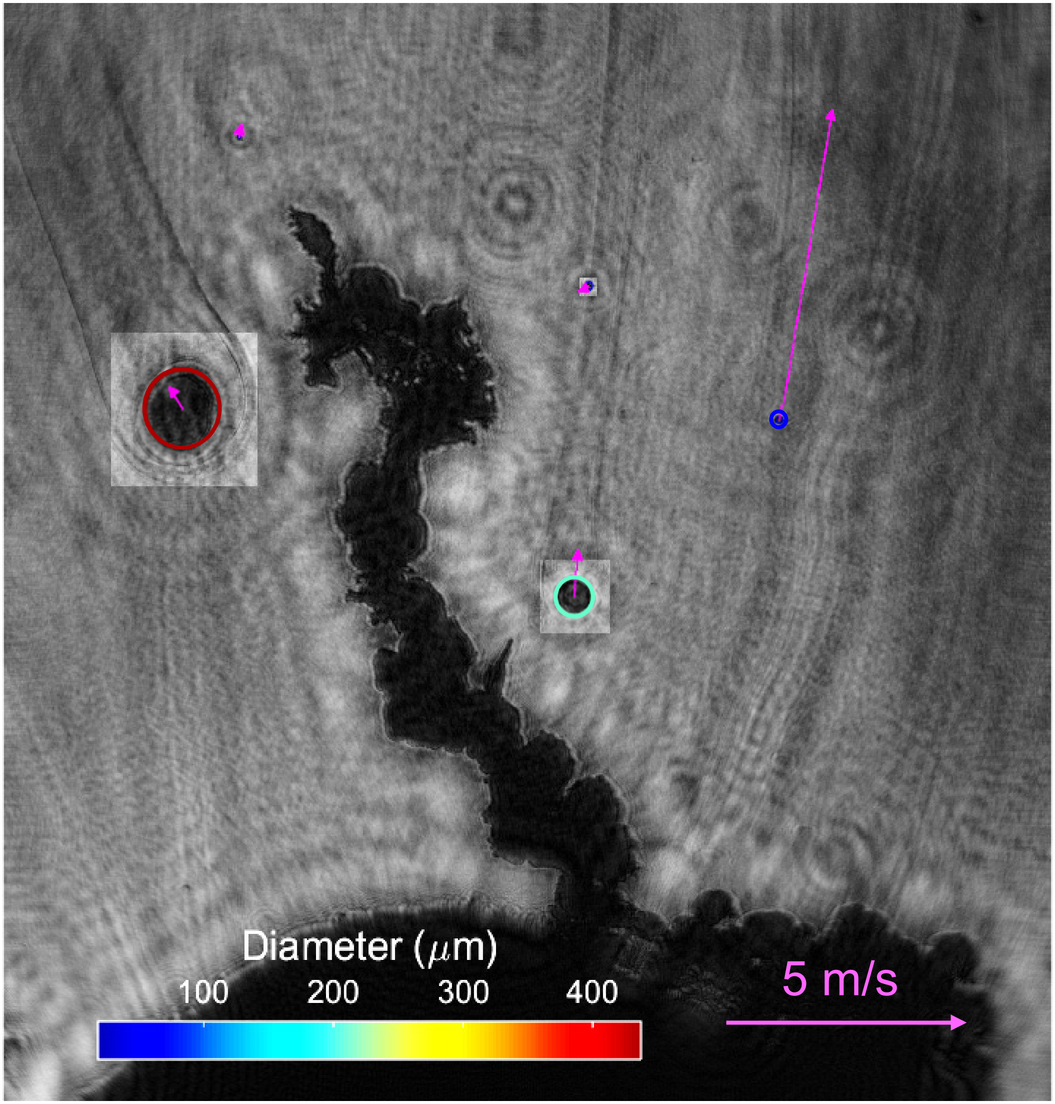
Velocity Measurement

Raw Hologram



Refocused Hologram





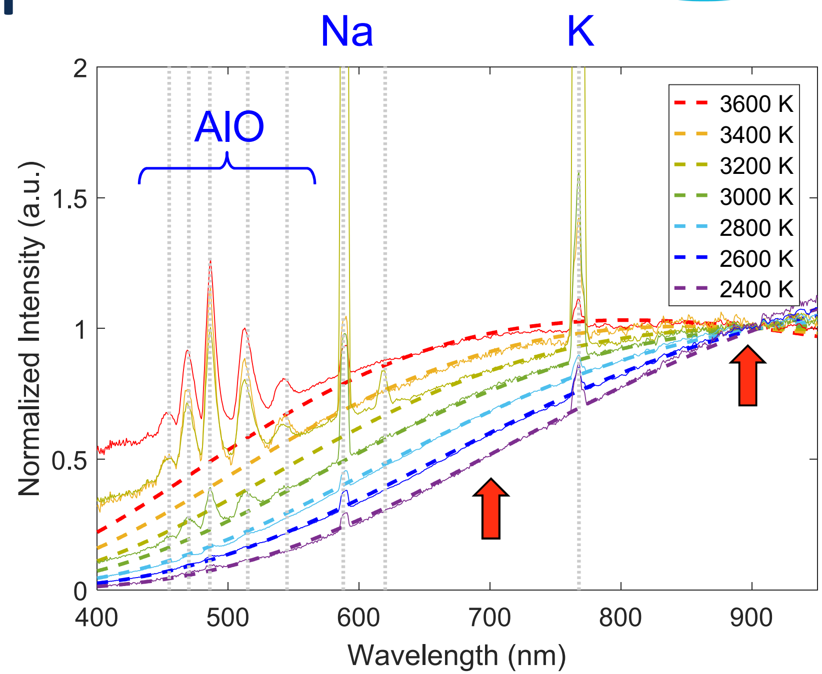
Two-Color Pyrometer

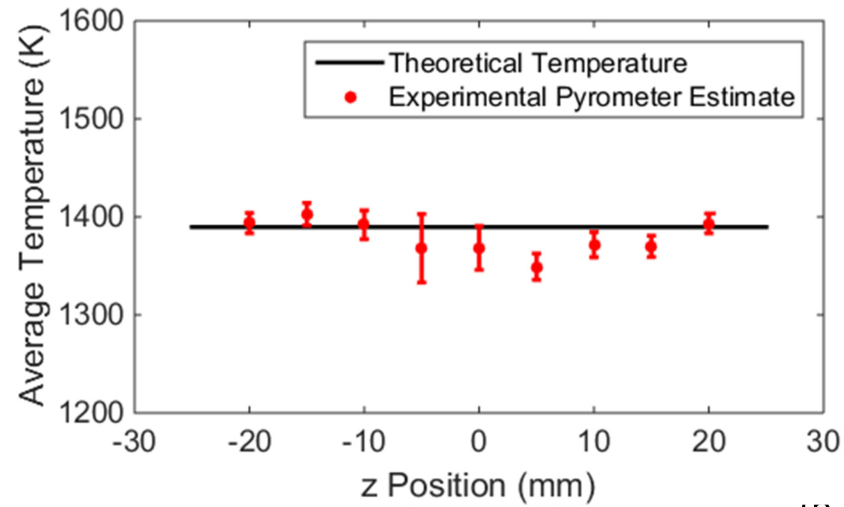
- Can use Plank's Law, assuming grey body emission
- Choose wavelengths to avoid combustion peaks
- If hc/λ >> kT, use Wein's approximation for each pixel:

$$T = \left[\frac{k}{hc}\frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1}\left(\ln(R) - 5\ln\left(\frac{\lambda_1}{\lambda_2}\right)\right)\right]^{-1}$$

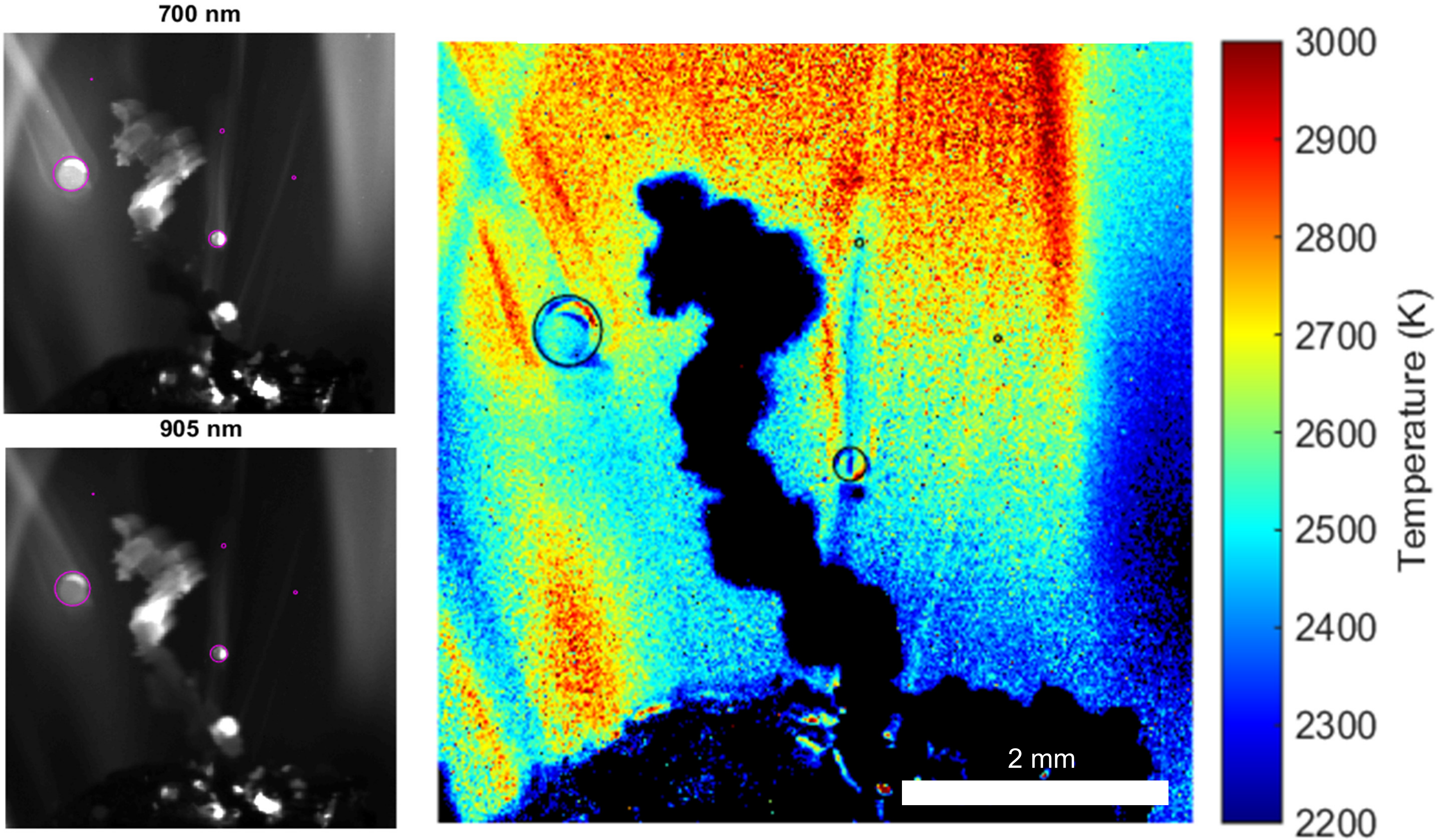
$$where\ \ R = \frac{I_2}{I_1}\frac{E_1\eta_1}{E_2\eta_2}$$

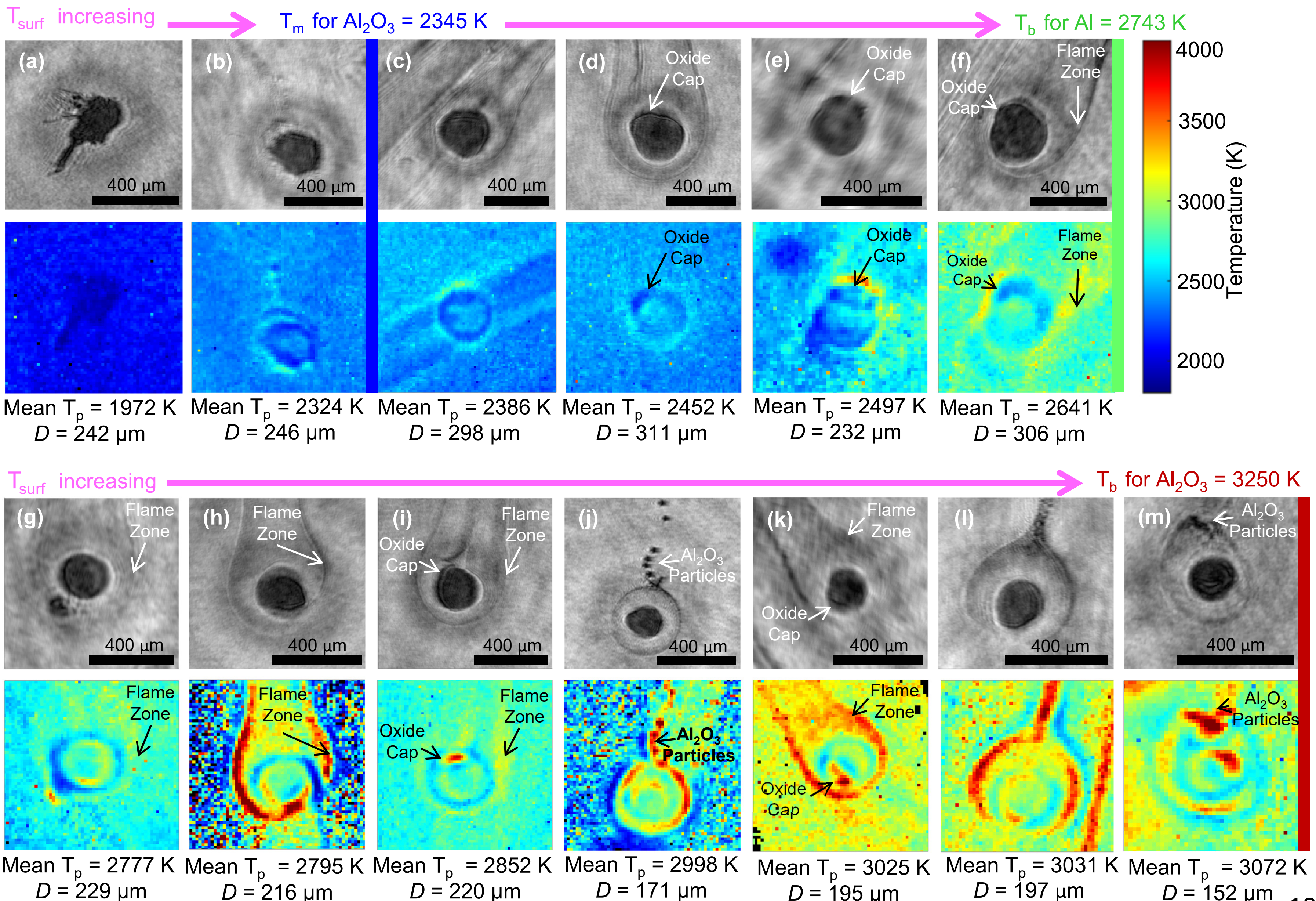
- Determine the matching pixels from DIH camera to pyrometer cameras (low intensity pixels removed)
- Calibrated against a 3200K black body source with accuracy of ±2%
- Determined the effect of focus on temperature estimate using hot nichrome wire
- Overall temperature variation over the focal range of 20 mm was ±50 K



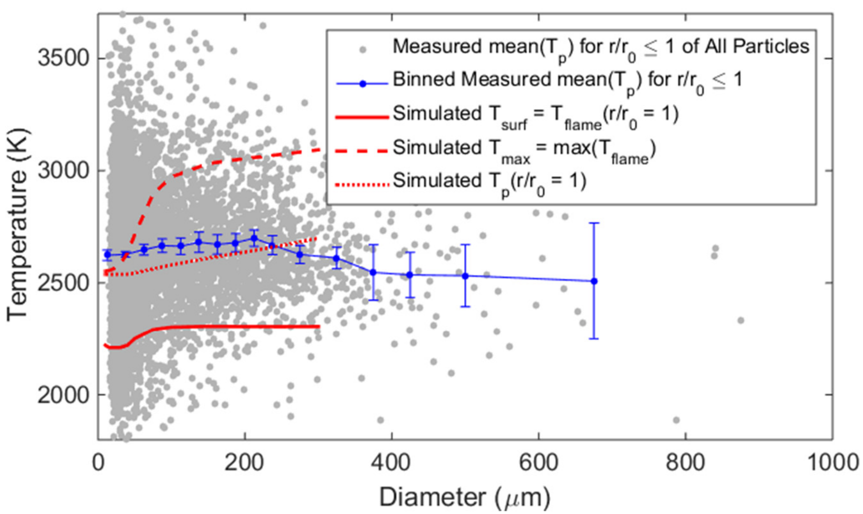


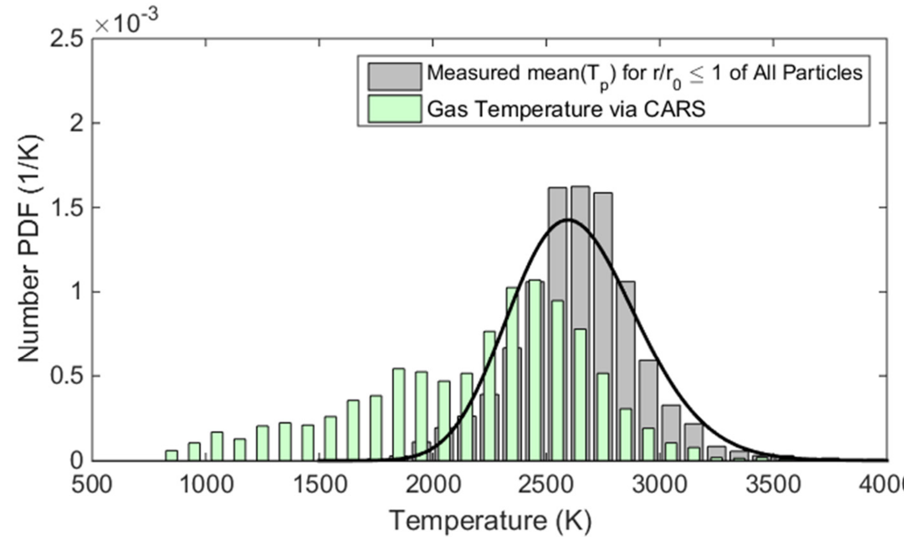
Temperature Measurement




T_surf increasing
T_m for Al2O3 = 2345 K
T_b for Al = 2743 K
(a)
(b)
(c)
(d)
Oxide Cap
(e)
Oxide Cap
(f)
Oxide Cap
Flame Zone
400 μm
Temperature (K)
4000
3500
3000
2500
2000
Mean T_p = 1972 K
D = 242 μm
Mean T_p = 2324 K
D = 246 μm
Mean T_p = 2386 K
D = 298 μm
Mean T_p = 2452 K
D = 311 μm
Mean T_p = 2497 K
D = 232 μm
Mean T_p = 2641 K
D = 306 μm
T_surf increasing
T_b for Al2O3 = 3250 K
(g)
Flame Zone
(h)
Flame Zone
(i)
Oxide Cap
Flame Zone
(j)
Al2O3 Particles
(k)
Flame Zone
Oxide Cap
(l)
(m)
Al2O3 Particles
400 μm
Mean T_p = 2777 K
D = 229 μm
Mean T_p = 2795 K
D = 216 μm
Mean T_p = 2852 K
D = 220 μm
Mean T_p = 2998 K
D = 171 μm
Mean T_p = 3025 K
D = 195 μm
Mean T_p = 3031 K
D = 197 μm
Mean T_p = 3072 K
D = 152 μm

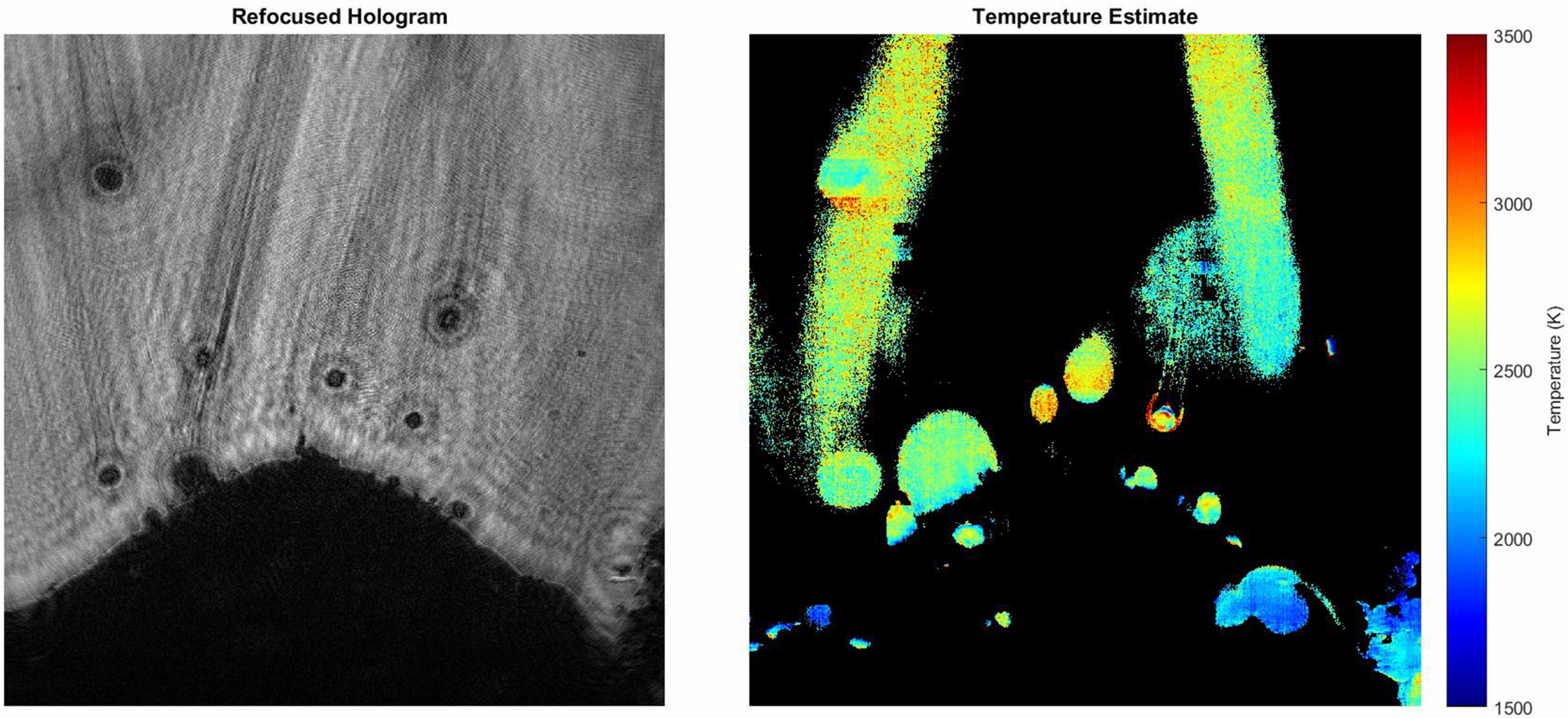
Temperature Statistics





- Pyrometry measurements can only be used to directly measure projected temperatures which include the absorption and radiation effects through hot oxide smoke clouds
- Inverse Abel transforms are difficult to apply to out-of-focus particles
- Simulation of surface temperatures are therefore corrected with a forward Abel transform to effectively capture the projection effects of absorption and radiation (similar to a model-based weighted average through the flame), thereby allowing measurements and simulations to be compared.

High Speed Pyrometry Videos



- These preliminary data show refocused DIH and calibrated (against 3200K black body) temperature estimates of the particles as they lift off the surface
- The particles on the surface can be seen getting hotter and developing oxide clouds as they leaving the surface

Acknowledgements

- The Weapons Systems Engineering Assessment Technology program
- The Laboratory Directed Research and Development program
- Howard Lee Stauffacher for his work with the propellant igniter system
- Thomas W. Grasser for his work with the optical system construction

Temperature and oxygen measurements in a metallized propellant flame by hybrid fs/ps rotational CARS

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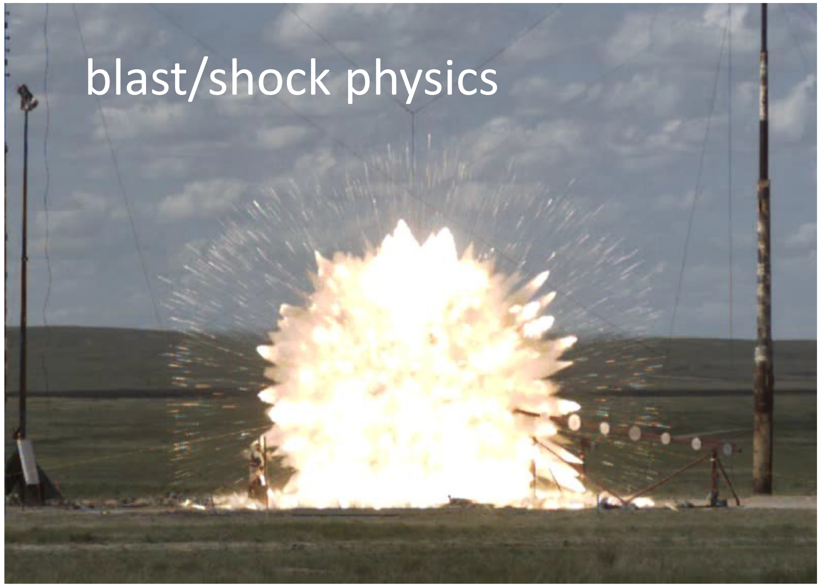
Preview

- Background
  - Sandia applications in “hostile” environments
  - Nanosecond CARS detection in particle-laden flames
- Ultrafast (fs/ps) Rotational CARS
- Successful application to metallized propellant flame
  - Propellant burn experiment
  - Behavior of CARS spectra with probe delay
  - Temperature/oxygen statistics
- Conclusion and future work

Sandia National Security Mission Space

- ***DOE strategic systems safety***
- ***DoD/WFO applications***
- ***Challenging environments***
- ***Large-scale***
- ***Heat, blast, particulate***

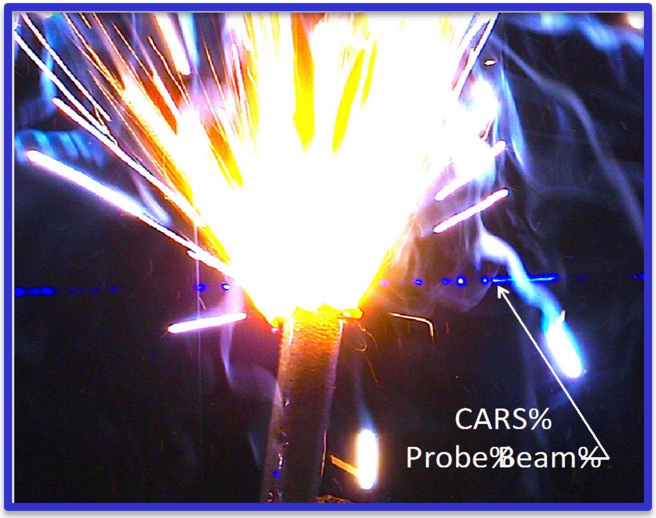
http://www.cbsnews.com/news/rocket-crash-no-immediate-threat-to-station-but-cause-is-unknown/

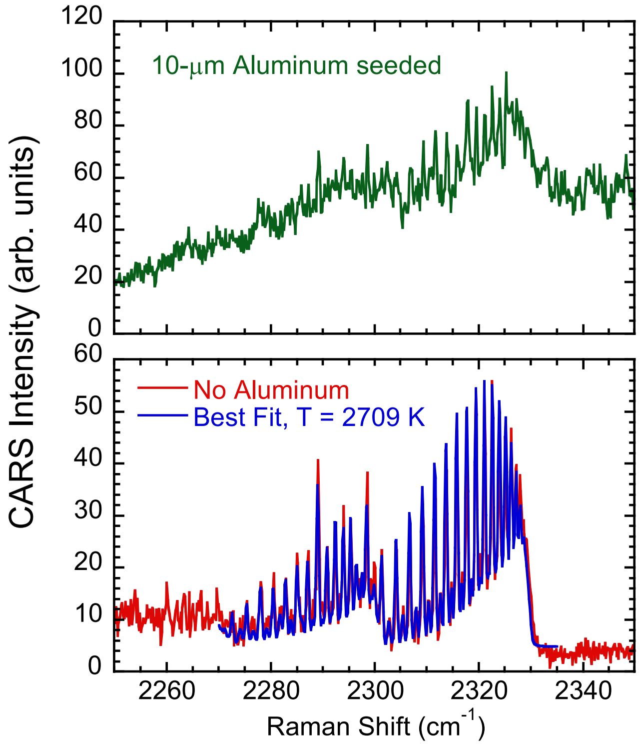


http://abcnews.go.com/Technology/Travel/wireStory?id=3529012

Metallized Propellant Combustion

- ***Metal burn represents an extraordinarily hostile environment for laser diagnostics***
  - ***Very high temperatures – T > 3000 K!***
  - ***High luminosity***
  - ***Scattering***





ns-CARS spectra with and without Al particles

- ***Previous gas-temperature measurements with ns CARS were unsuccessful***
  - ***Metal-particle-induced breakdown/plasma formation***
  - ***Disastrously high levels of nonresonant background***

Metallized Propellant Combustion

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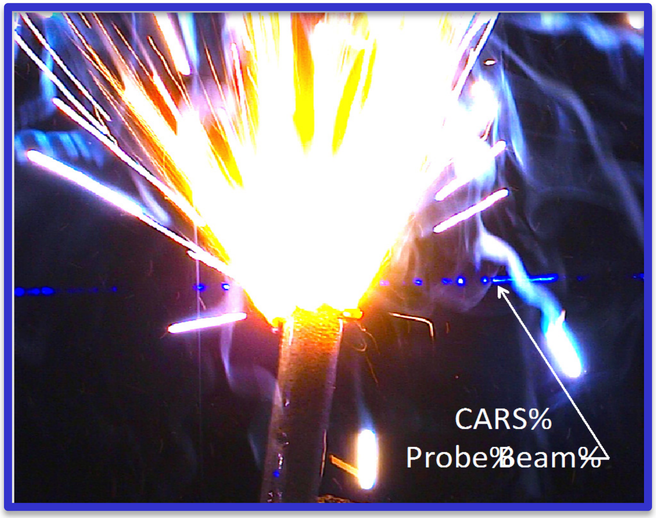
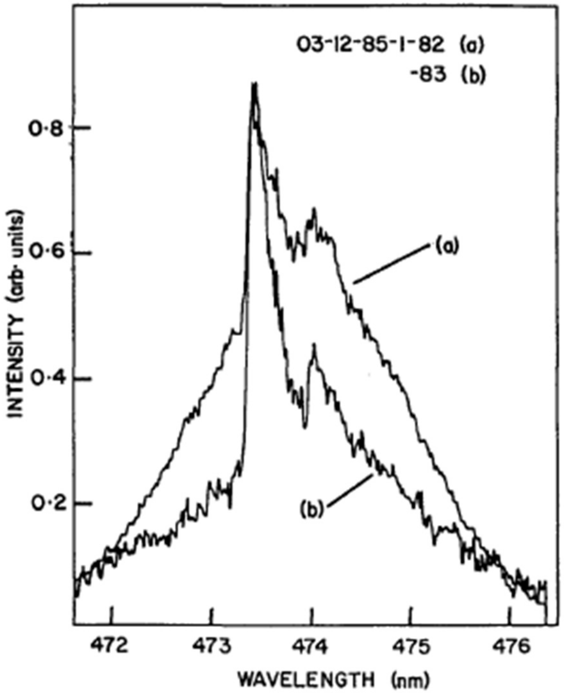
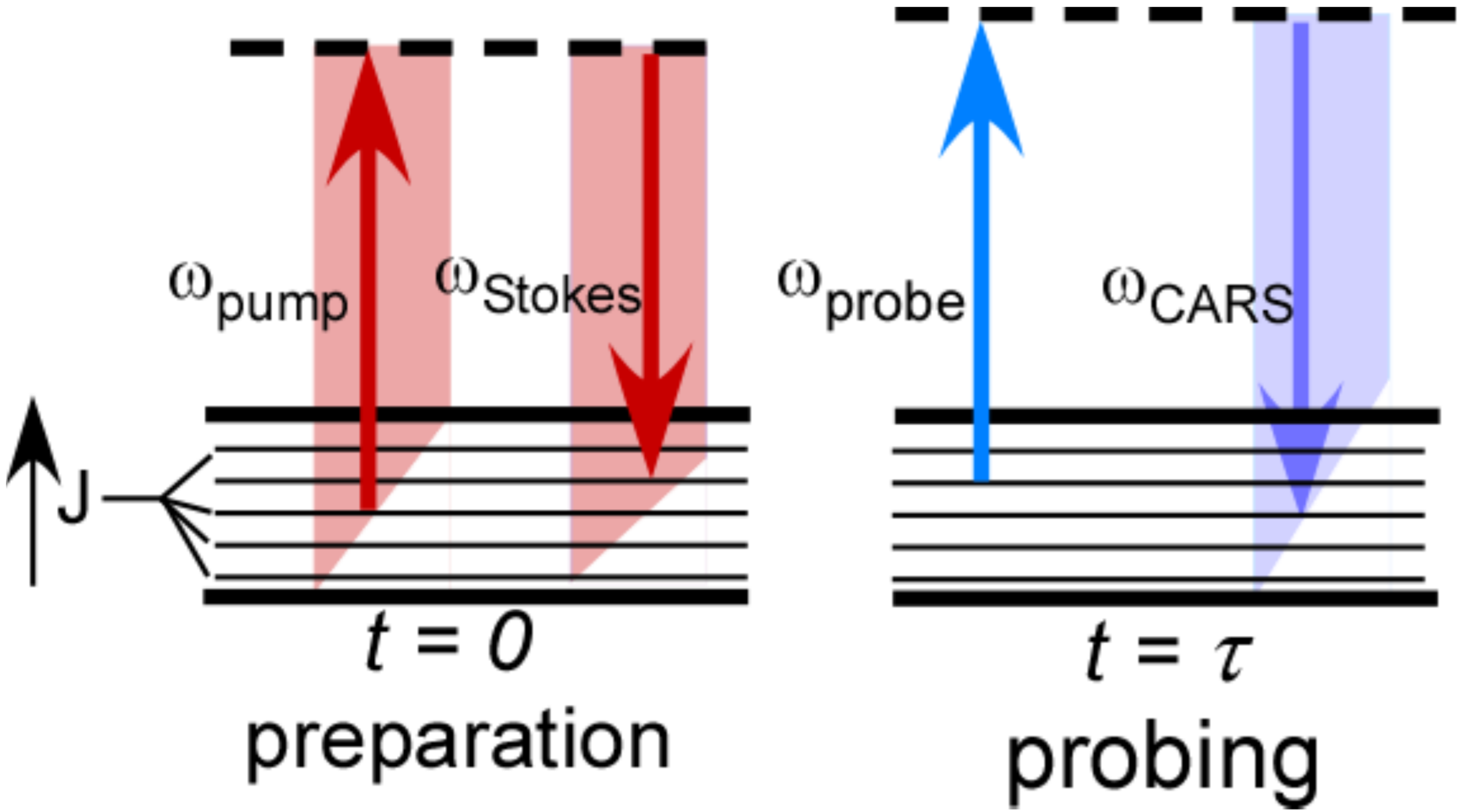




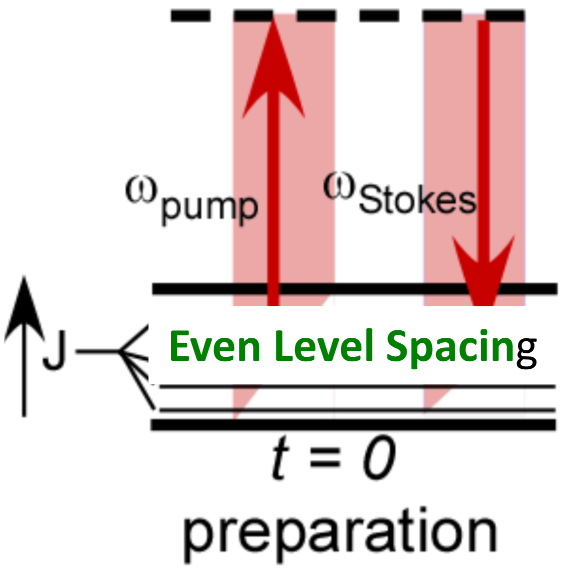
ns CARS in coal combustion (Beiting, 1985)

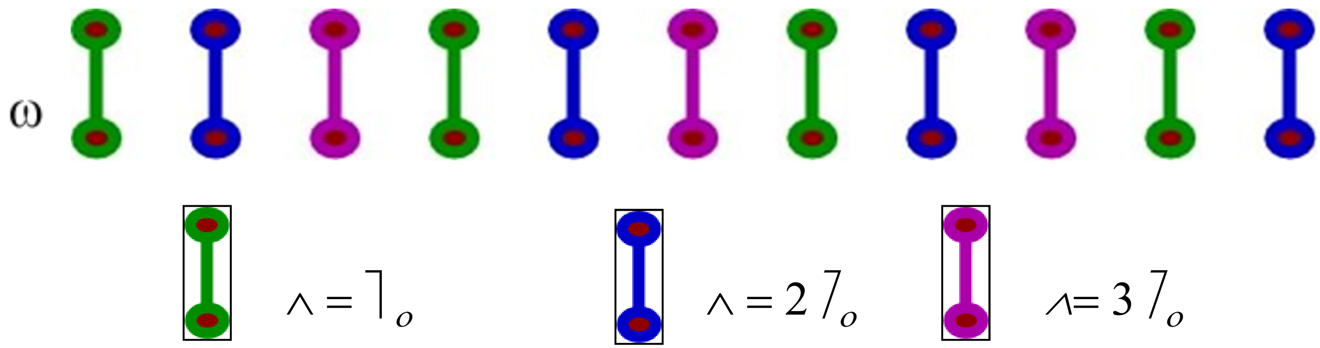
- ***Previous gas-temperature measurements with ns CARS were unsuccessful***
  - ***Metal-particle-induced breakdown/plasma formation***
  - ***Disastrously high levels of nonresonant background***
  - ***Similar to previous work in coal combustion (Beiting, 1985)***

Time-Domain Rotational Raman: $\tau_{laser} << \tau_{molecule}$

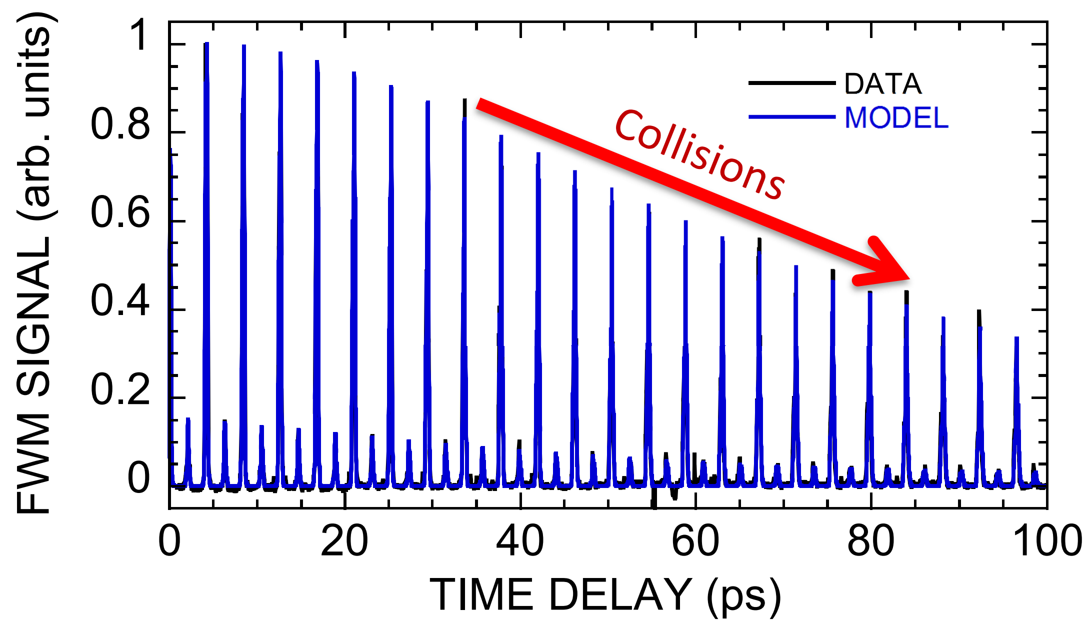


fs/ps Rotational CARS processes

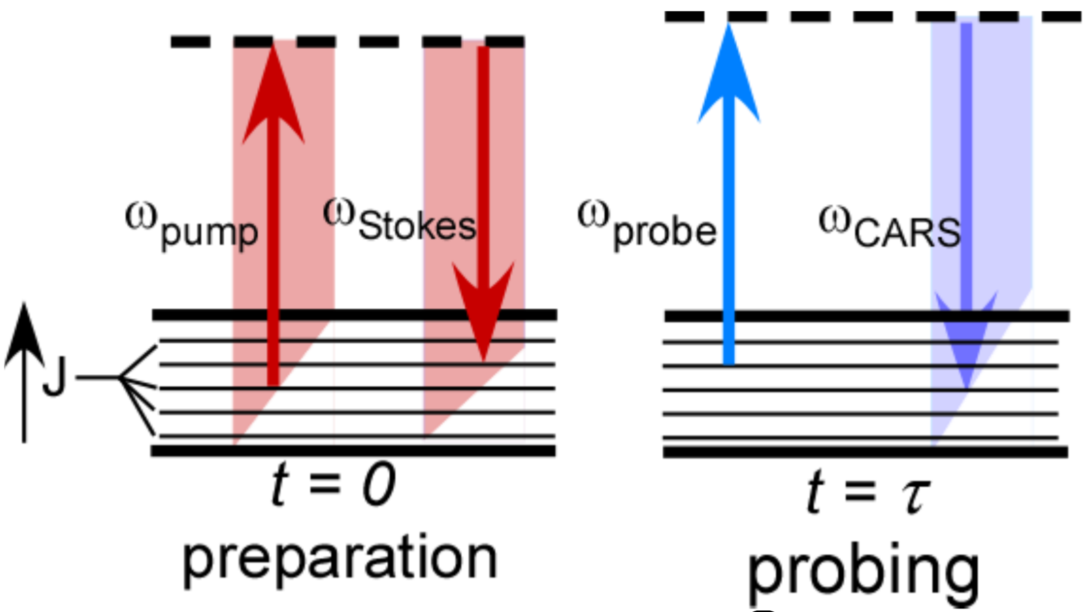


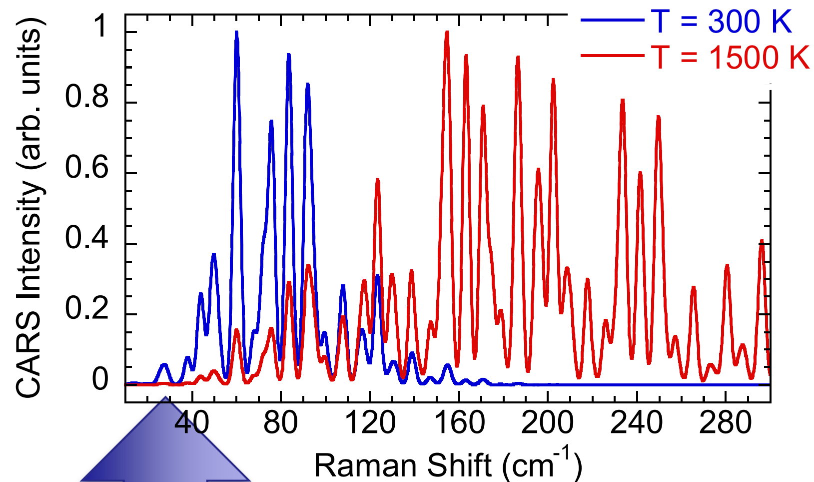


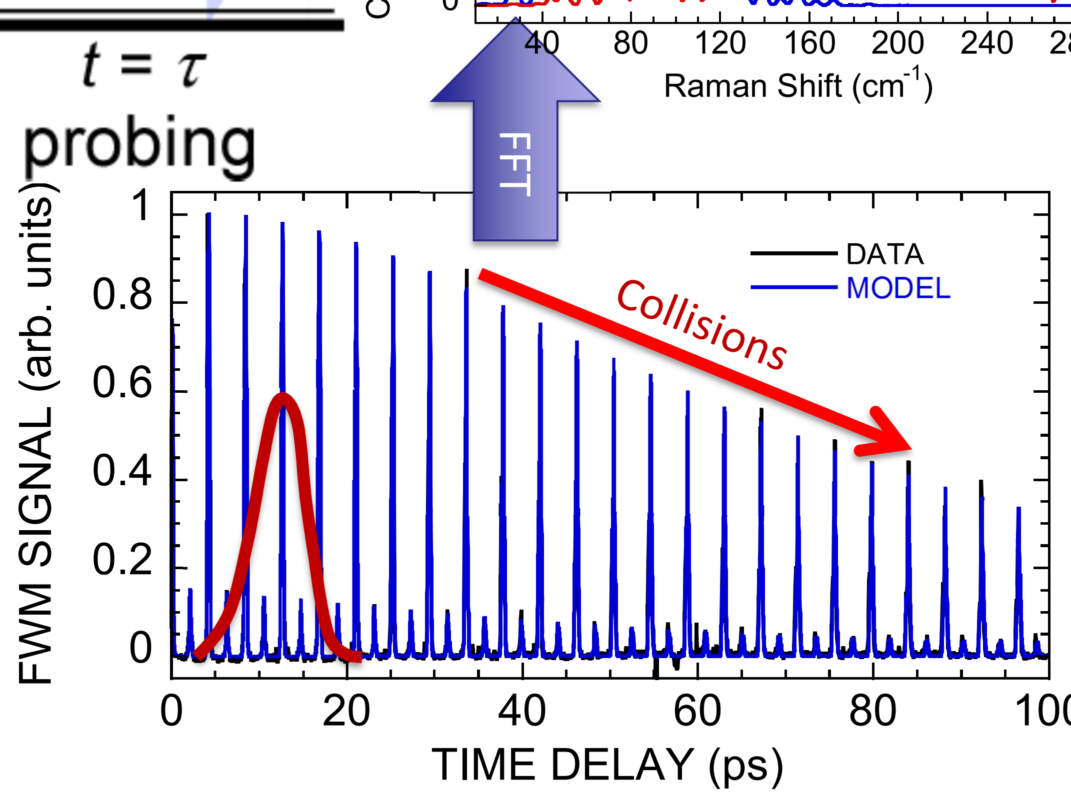
$$\chi = \sum_J W_J \exp\left(i\,\omega_J t\right)\exp\left(-\Gamma_J\, t\right)$$



fs/ps Rotational CARS processes







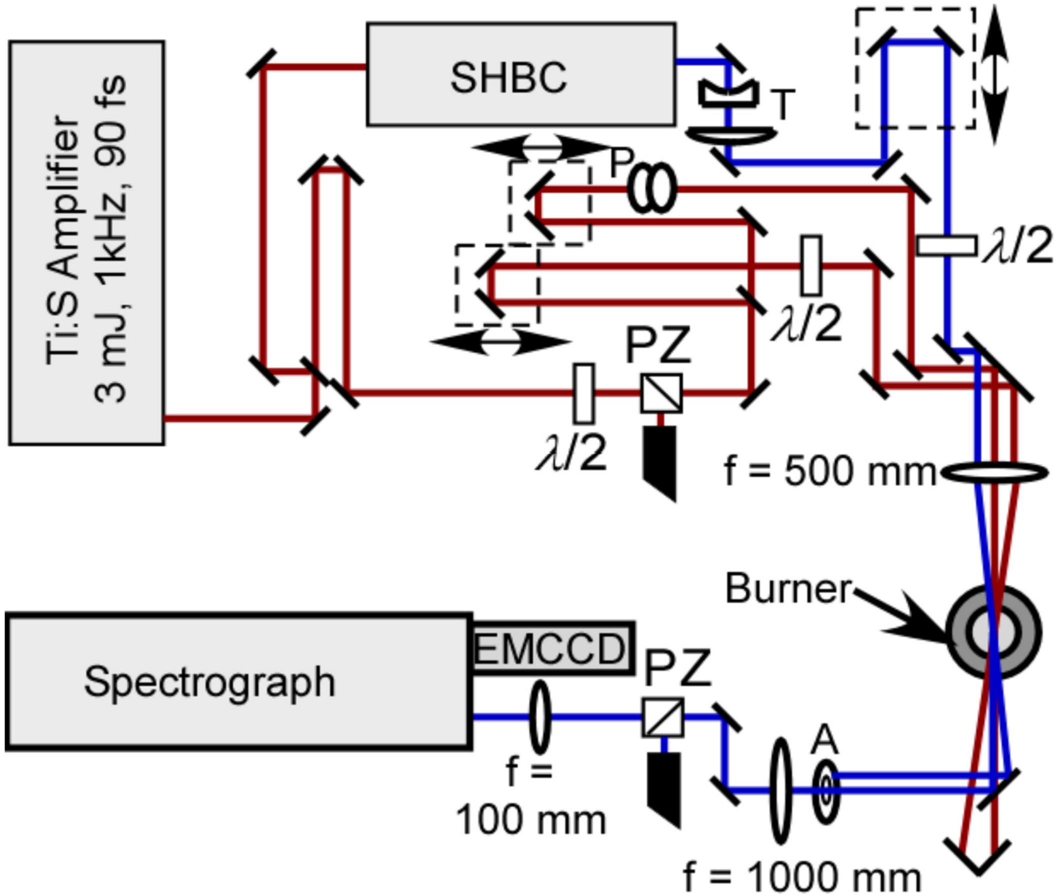
$$\chi = \sum_J W_J \exp(i\omega_J t)\exp(-\Gamma_J t)$$

$$E_{CARS}(t-\tau) = E_{probe}(t-\tau)\times\chi(t)$$

$$W_J = X\gamma^2 b_{JJ'}(N_{J'} - N_J)$$

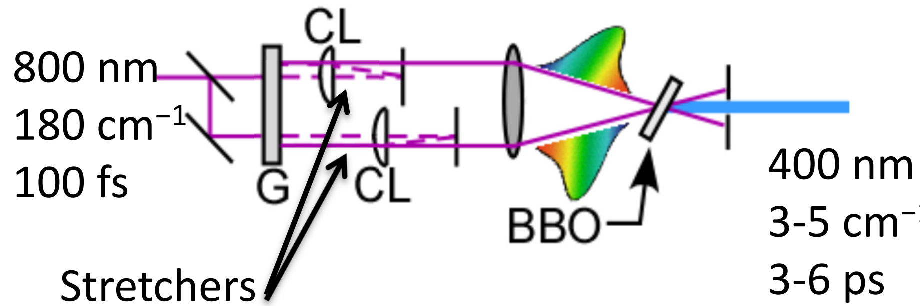
$$\frac{N_J}{N} \sim \frac{1}{T}\exp(-\varepsilon_J/kT)$$

fs/ps CARS instrument

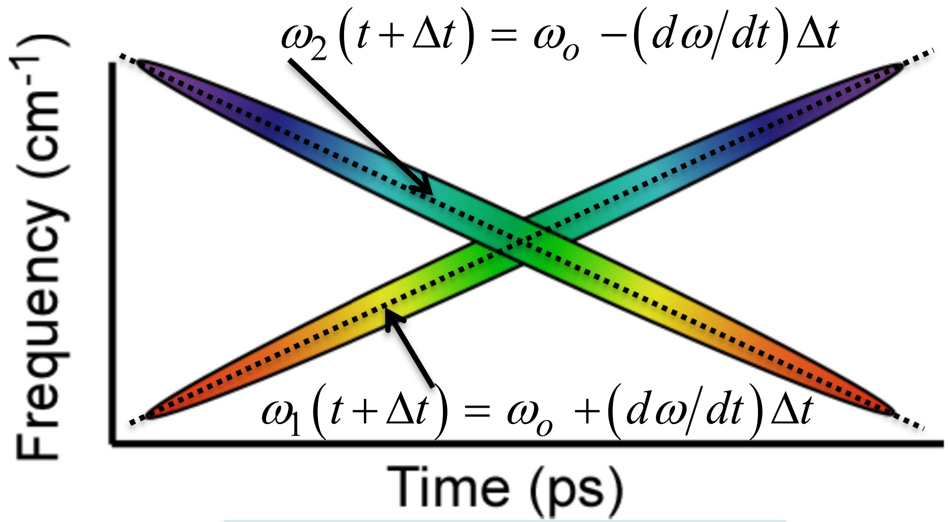


Second-Harmonic Bandwidth Compression (SHBC)

- Commercial device (Light Conversion)
- Converts fs radiation at 800 nm to ps radiation at 400 nm
- Grating pulse stretchers
- **<u>Phase-conjugate</u>** temporal chirps imparted upon broadband fs pumps
- Sum-frequency generation in BBO



$$\Delta\omega_{sfg} \sim (\Delta t)^{-1}$$

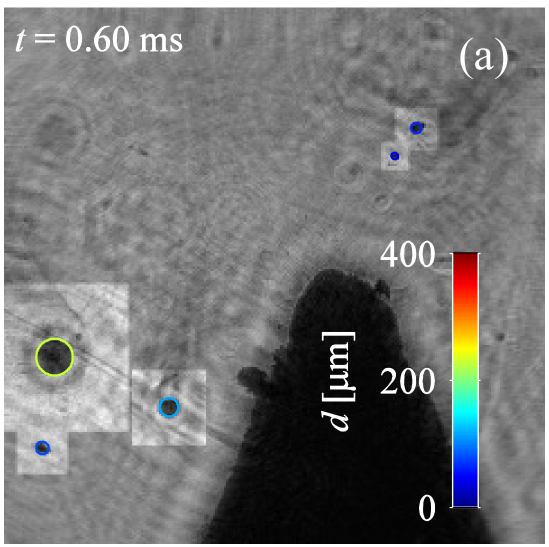


- Conversion efficiency: 35-50%!
- Output pulse energy: 1-1.4 mJ!

$$\omega_{sfg} = \omega_1 + \omega_2 = 2\omega_o$$

AP Propellant Strand Burner Experiments

- ***Aluminized ammonium-perchlorate (AP) propellant strands***
- ***Hostile environment for diagnostics***
  - ***Very high temperatures – over 3,000 K!***
  - ***Large molten-metal particles 10-100 μm***
  - ***Significant levels of smoke***
- ***Particle size distribution measured by digital inline holography (Guildenbecher, Sandia)***



Refocused DIH Hologram and Al Particle Size Distributions (Guildenbecher et al., Appl. Opt. 2016)

Video Recorded During CARS Measurements

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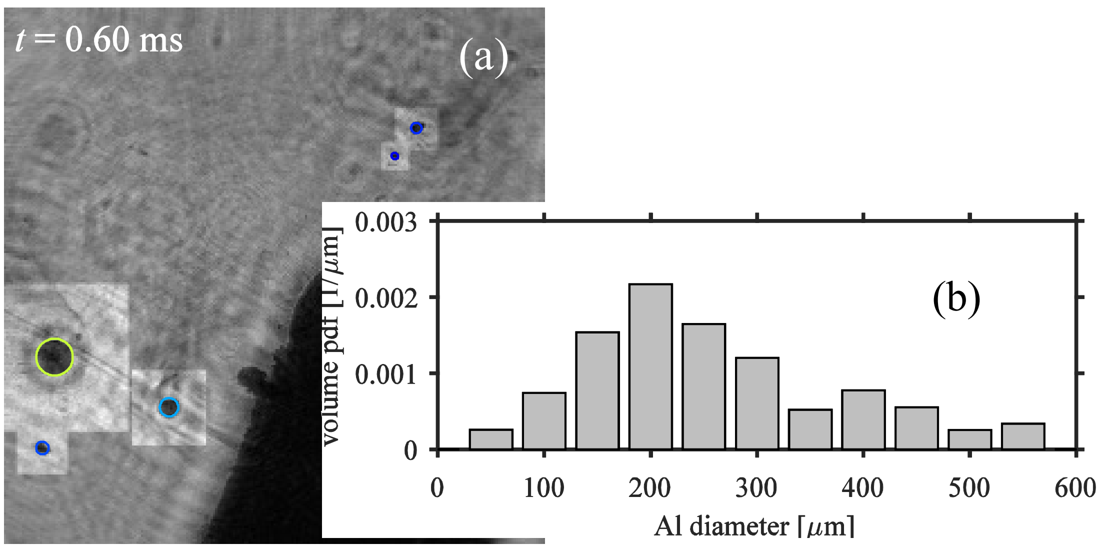

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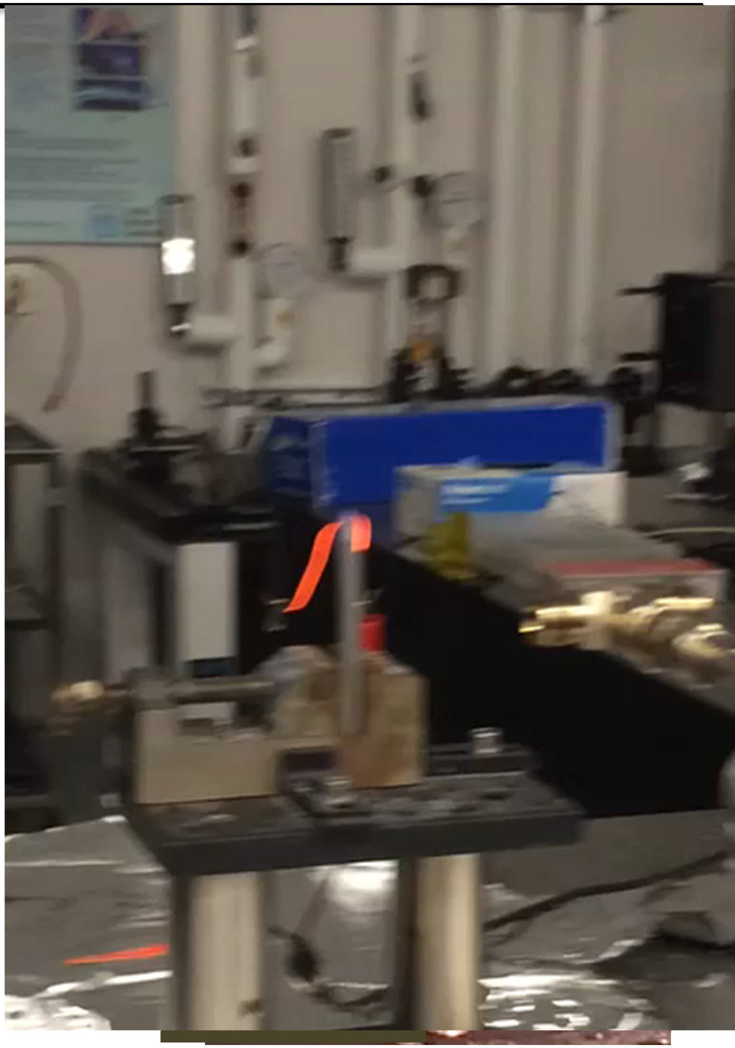
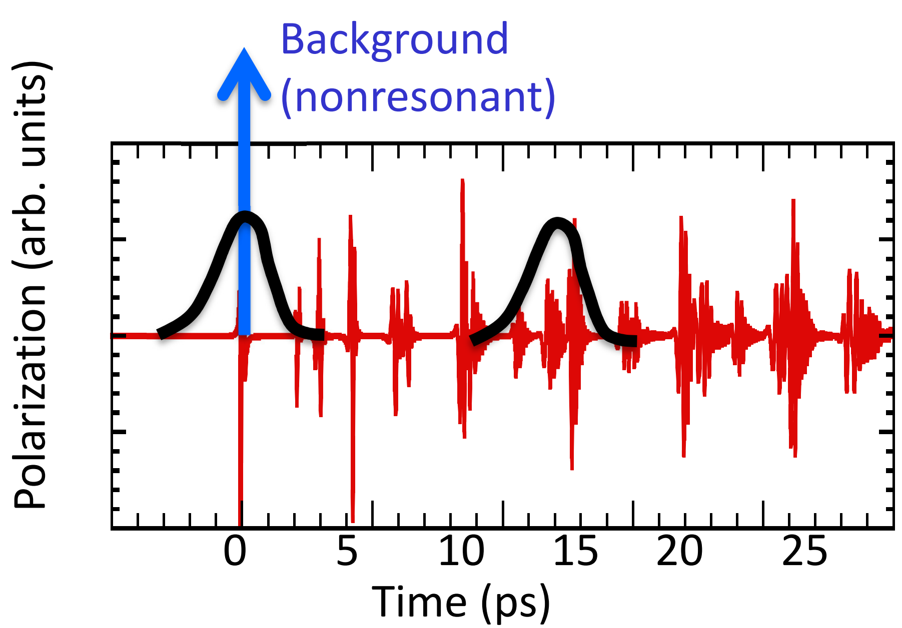
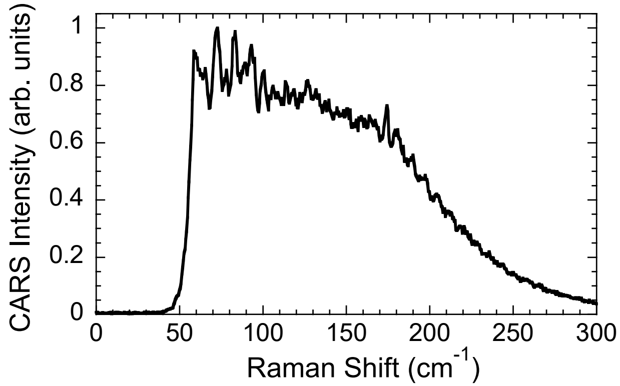


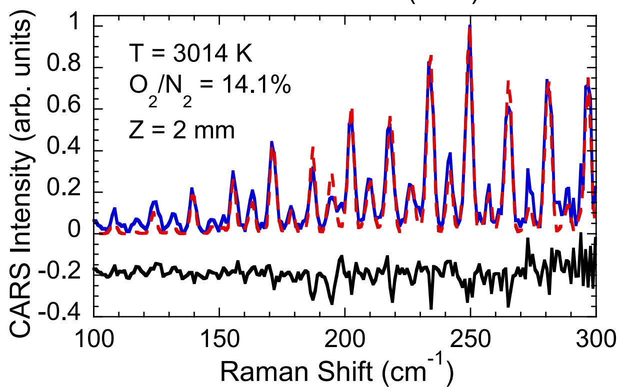
Video Recorded During CARS Measurements

Advantages of ultrafast CARS for metal-burn problems

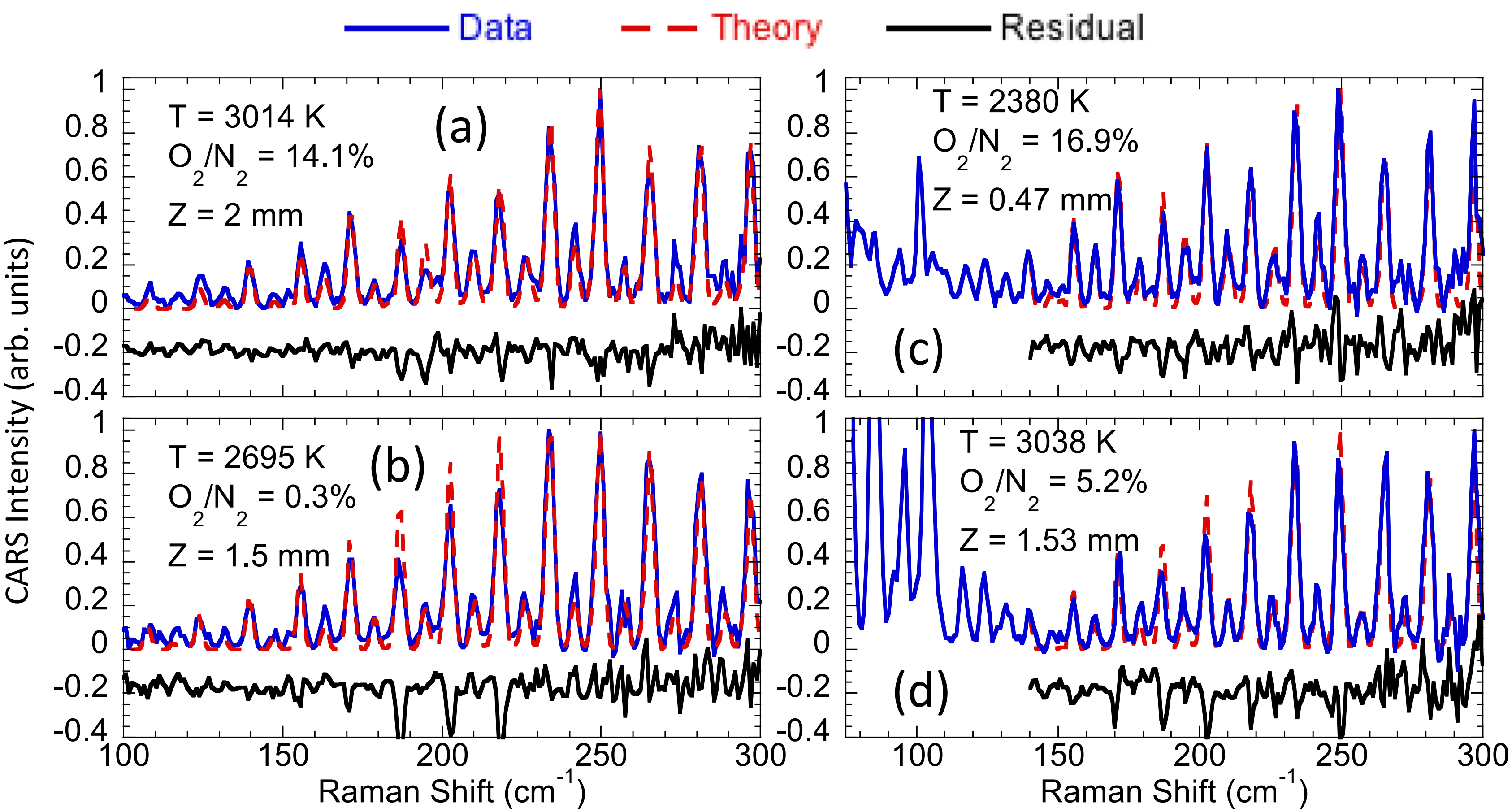
- ***Low total pulse energy***
  - ***~ 1 mJ or less***
  - ***Factor of ~40-100 lower than with ns laser pulses***
  - ***Reduces the likelihood of breakdown-type interference***
- ***Time-gate elimination of nonresonant background***
  - ***Nonresonant signal arises from response of electrons to fs forcing***
  - ***Fast decay (fs)***
- ***Raman-resonant signal results from much slower, nuclear response***





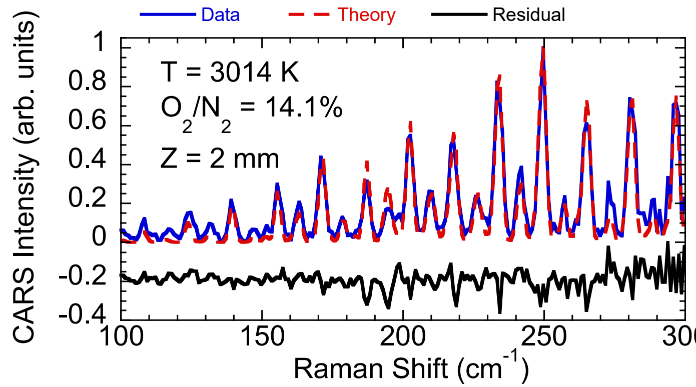


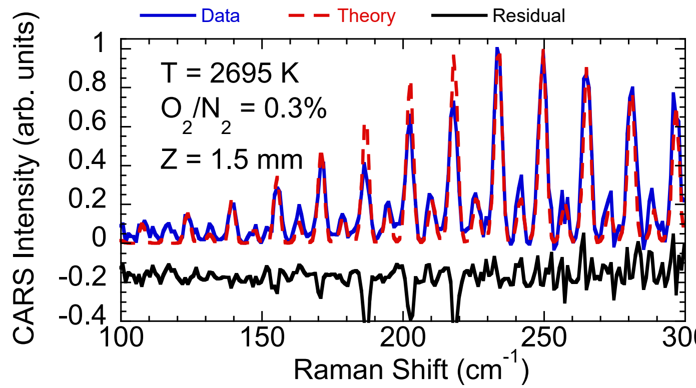
Single-laser-shot spectra

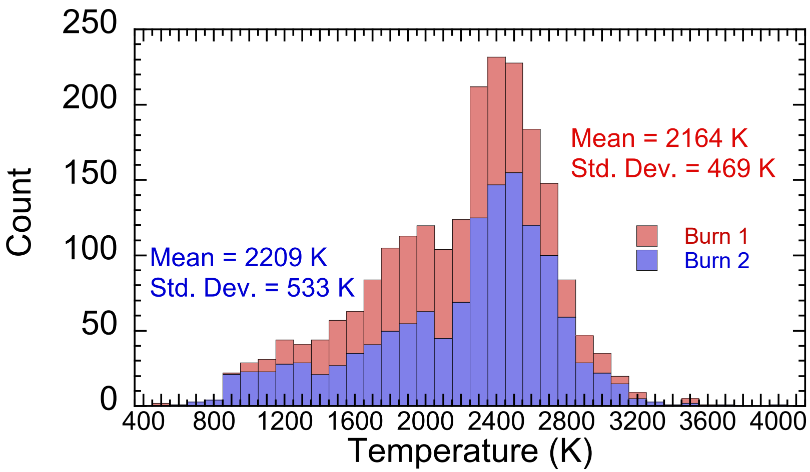


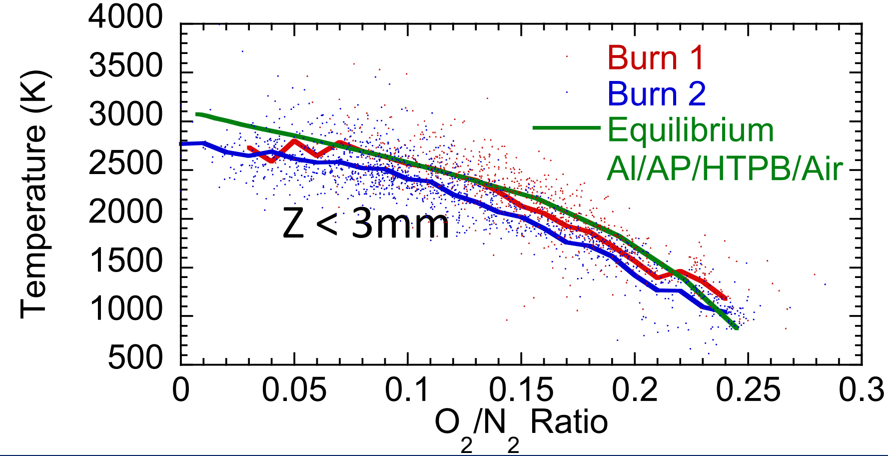
CARS Results from Propellant Burns

- ***Results for CARS measurements within 3 mm of propellant surface shown***
- ***Height estimated from 1-kHz acquisition rate and burn rate of 800 µm/sec***
- ***Spectra dominated by N_2 and O_2 contributions***
- ***Cl2; HCl; NO; NO2 also present***
- ***Switch to vibrational CARS for follow-on experiments***
- ***Decrease measurement volume length***









Conclusion and Path Forward

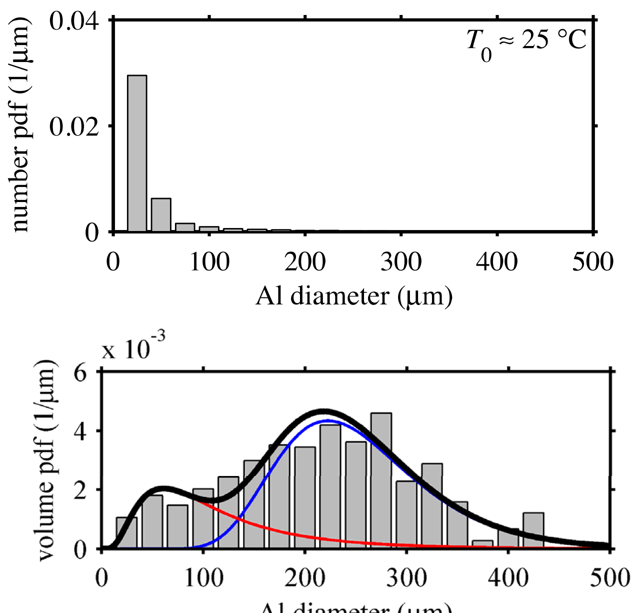
- We have successfully applied fs/ps rotational CARS in an aluminized AP propellant flame at lab scale
- Large-scale, 10-100 μm aluminum and temperatures as high as 3,000 K make this a challenging measurement environment
- Time delayed probing results in elimination of intense nonresonant background, presumably arising from particle-enhanced breakdown
- No loss of Raman-resonant signal!
- Temperature/O_2 statistics within 3-10% of adiabatic equilibrium

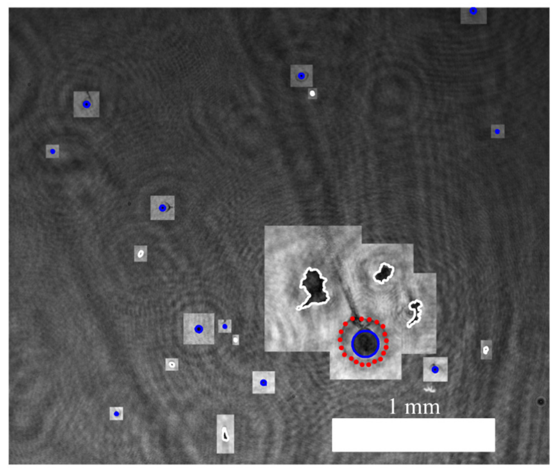
What's next?

- Switch to vibrational CARS for improved high-temperature sensitivity
- Higher signal levels
- Improved axial spatial resolution
- 1-D line imaging

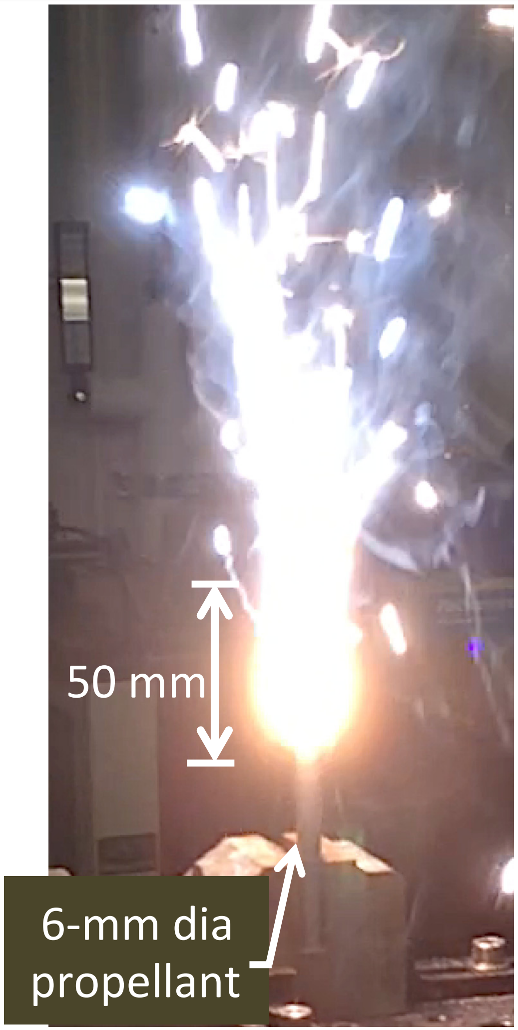
AP Propellant Strand Burner Experiments

- ***Aluminized ammonium-perchlorate (AP) propellant strands***
- ***Hostile environment for diagnostics***
  - ***Very high temperatures – fluctuations over 3,000 K!***
  - ***Dense field of large molten-metal particles 10-100 µm***
- ***Particle size distribution measured by digital inline holography (Guildenbecher, Sandia)***





(b)



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Video Recorded During CARS Measurements