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# Aluminum Combustion in a Shock Tube at High Pressure

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U.S. DEPARTMENT OF ENERGY

NNSA

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# Background: Aluminum Combustion

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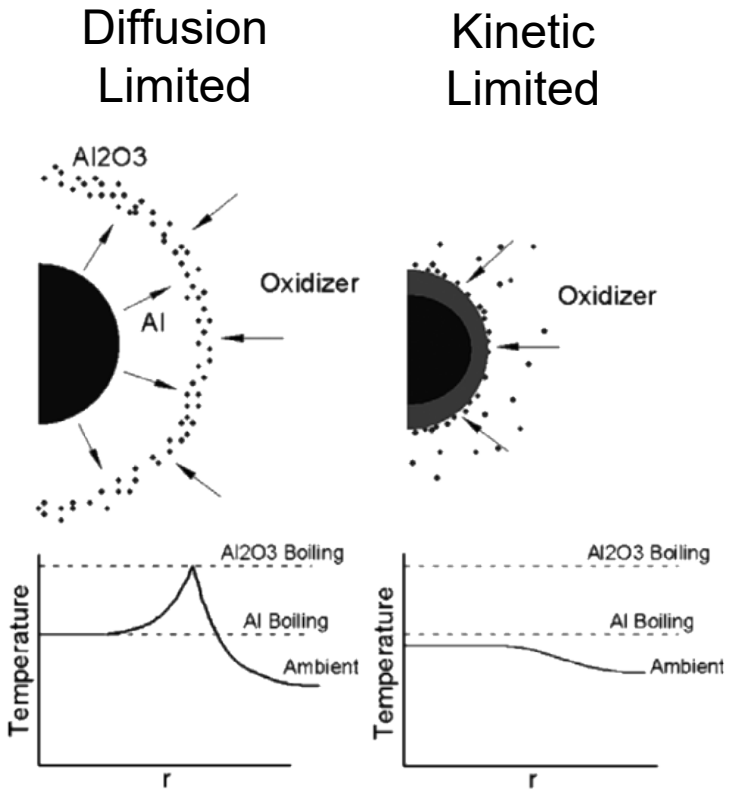
## Combustion Regimes:




Bazyn et al. 2006

### Diffusion:

- AlO burning in flame surrounding particle
- Peak temperature far above ambient
- Large particles $d > 10\mu m$

### Kinetic:

- Surface Burning
- Peak temperature similar to ambient
- Small particles $d < 10\mu m$

## Gaps in Understanding:

**High Pressure Combustion:**

- As pressure increases, $Al_2O_3$ boiling temperature increases
- Combustion at high pressures may become kinetic limited (Glumac et al. 2007)

## Combustion Diagnostics:

**Absorption spectroscopy**

- Pressure broadening
- Lack of lasers in visible wavelengths

**Emission Spectroscopy**

- May become optically thick
- Spatial uncertainty due to scattering

Need for robust suite of diagnostics to probe high pressure combustion

# Aluminum Combustion Diagnostics

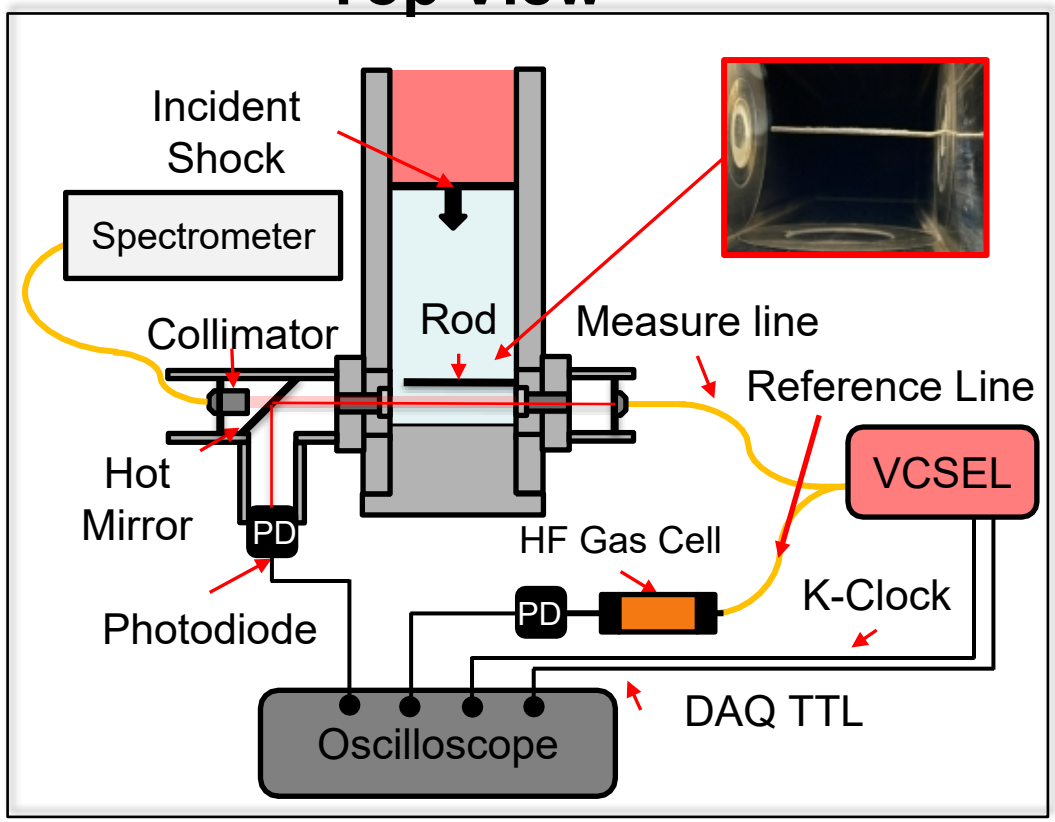
**LAS**
- AlO Absorption
- $f_s = 100\ kHz$

**Emission**
- AlO Emission
- $f_s = 11\ kHz$

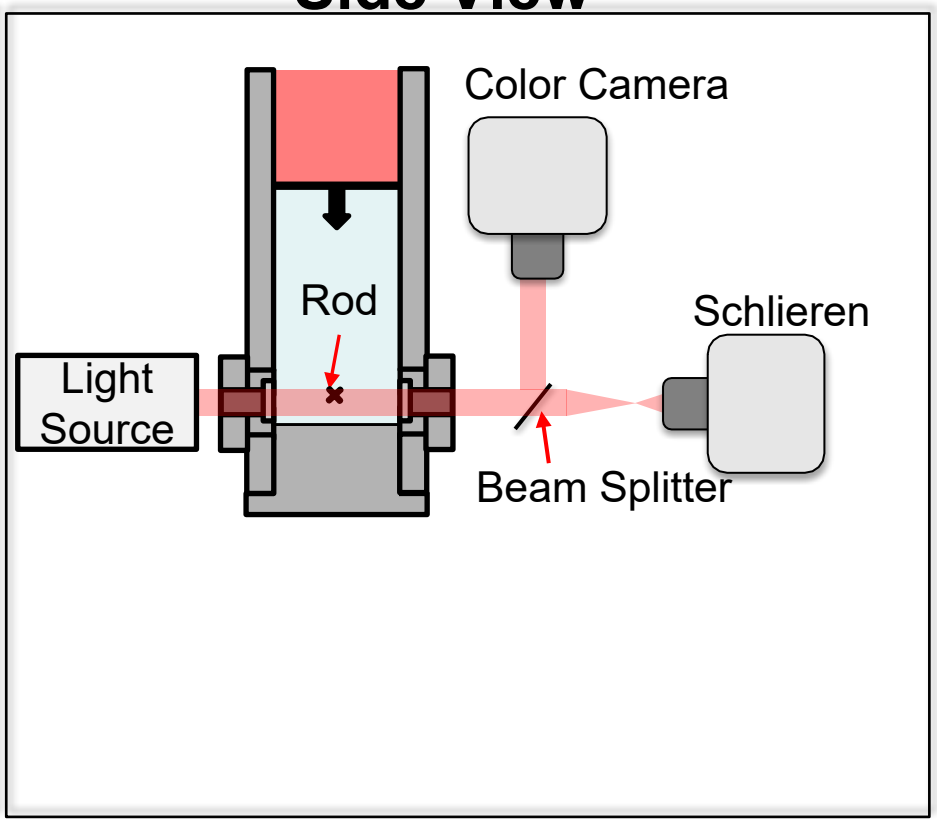
**High-speed Color Video**
- Monitor combustion
- $f_s = 100\ kHz$

**High-speed Schlieren**
- Observe Al dispersal
- $f_s = 450\ kHz$

## Top View




## Side View



# Schlieren & Color Imaging

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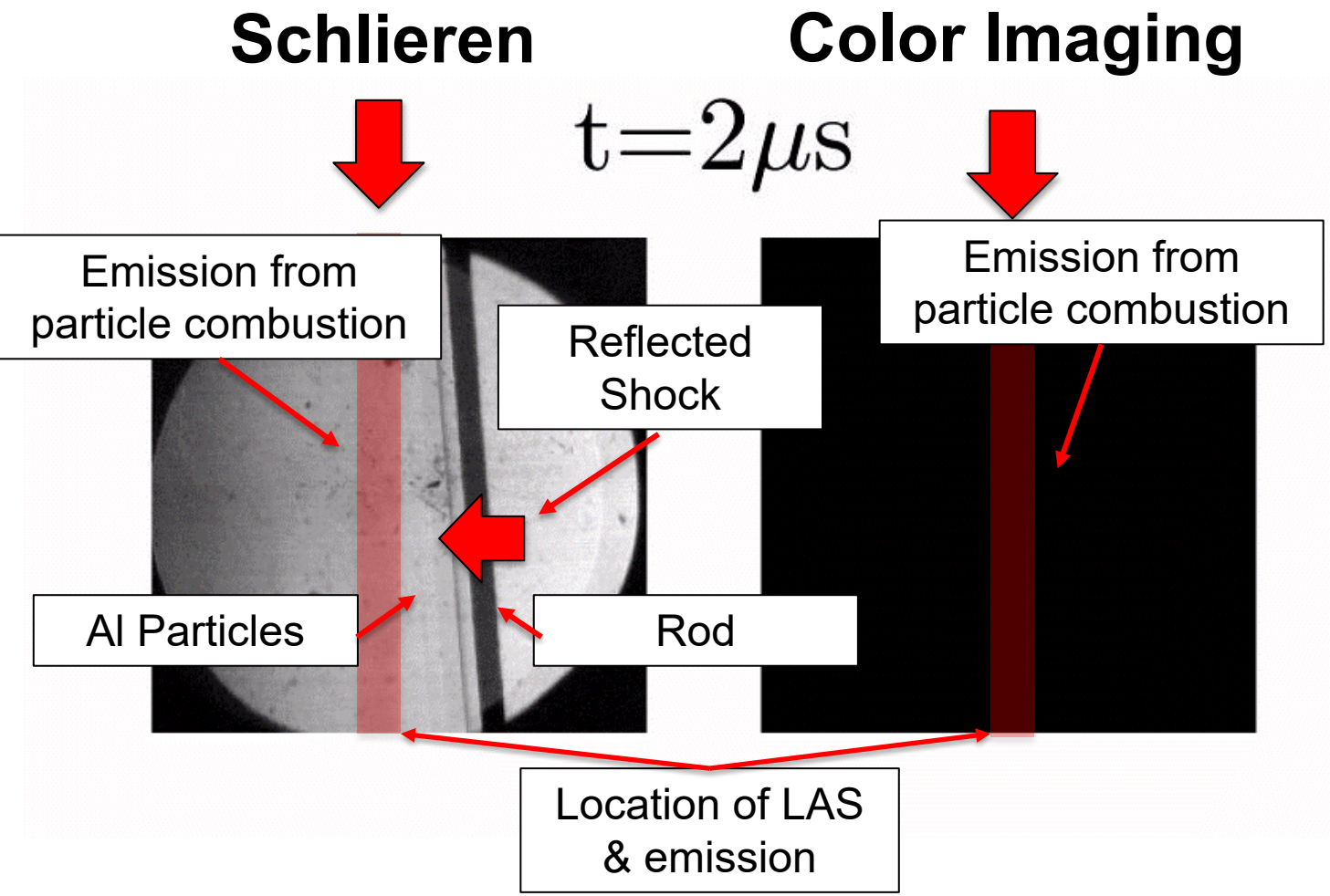
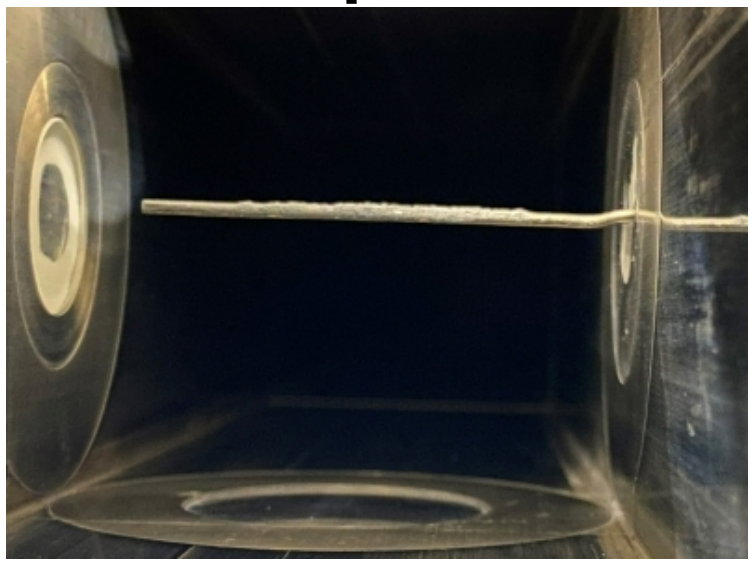



**Aluminum Loading Rod**

- 10 $\mu m$ particles
- Pulls off rod somewhat uniformily
- Schlieren & color images indicated particle position

## Example Rod

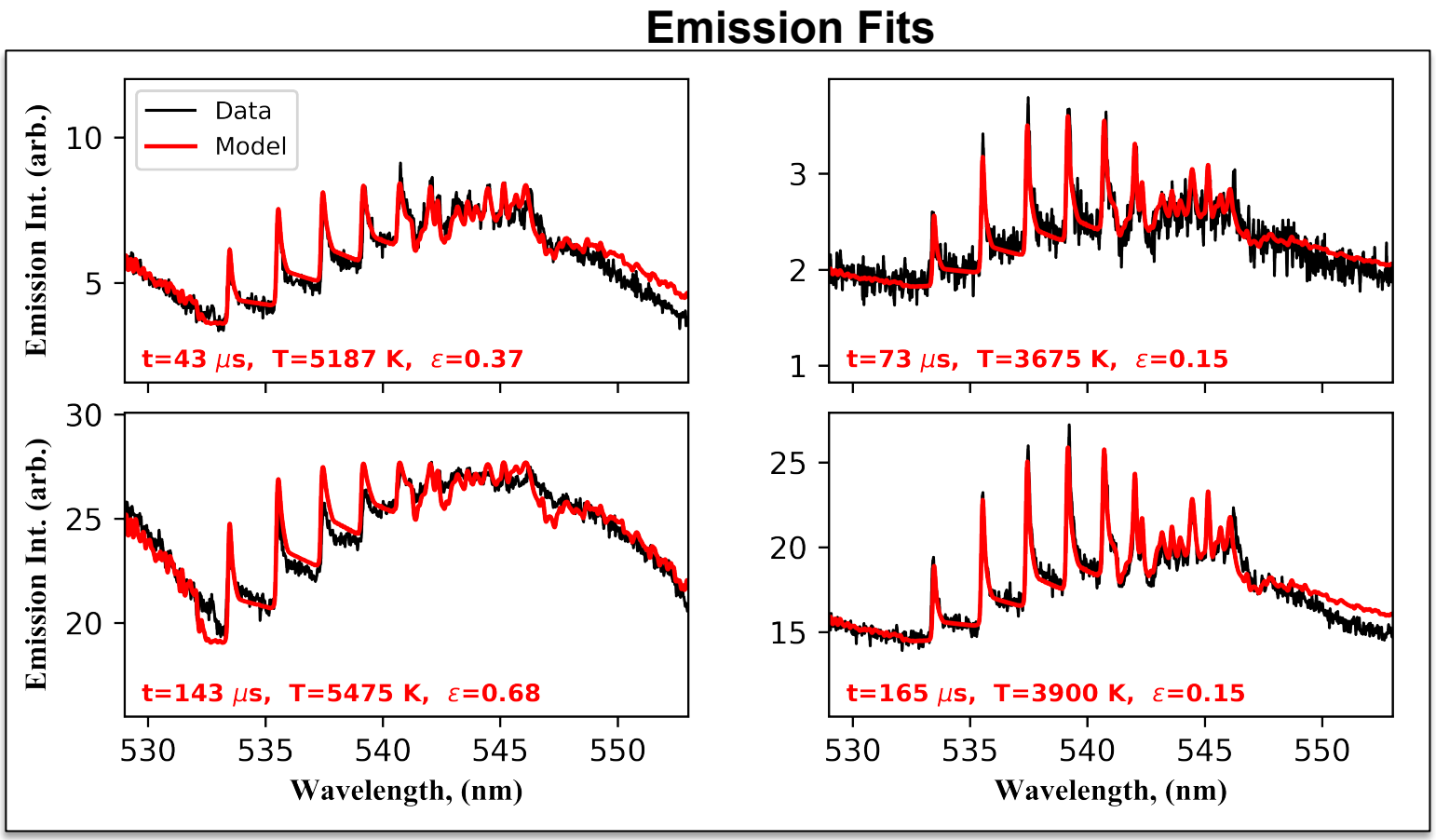


Schlieren & Color imaging indicate position of burning Al relative to Emission & LAS

# High Pressure Diagnostics: Emission

## Emission

- Frequency: 11 kHz
- AlO $B^2\Sigma^+ - X^2\Sigma^+$, band ($\Delta v = -2$)
- Fitting:
  - LUT of AlO cross section
  - Include condensed phase emission
  - Uncertainty ~250 K



# High Pressure Diagnostics: Absorption

Laser:
- MEMS-VSCEL
- Scanning Range: 7400-7900 $cm^{-1}$ at 100kHz

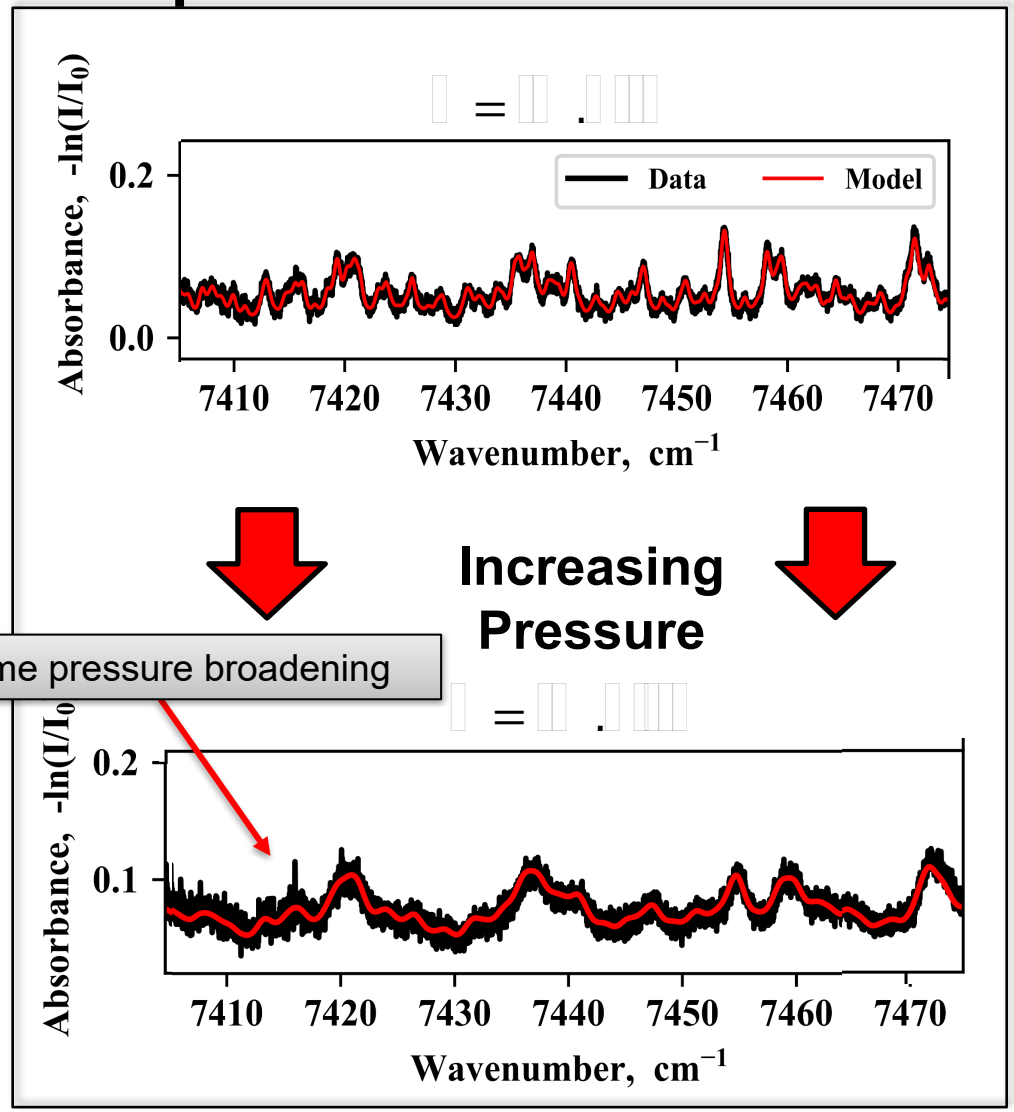
Measured Bands:
- AlO $A^2\Pi_i - X^2\Sigma^+$ band
- Atomic Aluminum

## Results:

**Fitting**
- LAS fits both pressure environments extremely well
- Fits for $T$, Column density

**How do temperature estimates compare to emission fits & $T_5$?**

## Absorption Fits:



# Absorption Spectrograms

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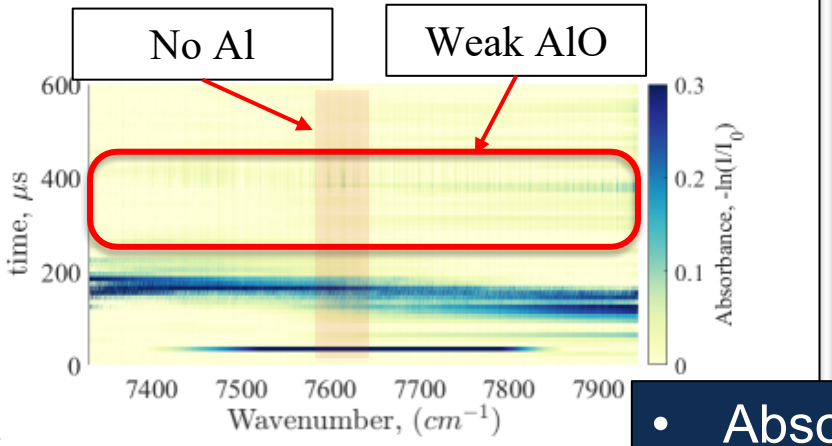
## Case 1:

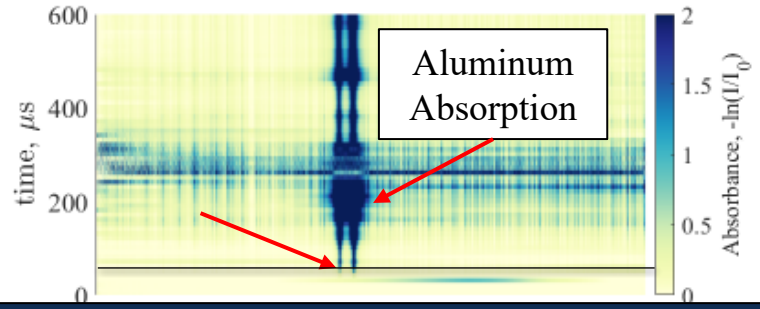
$T_5 = 3200K, P_5 = 9.2\ Bar$




- No Al & small of AlO abso
- Ignition delay~200 $\mu s$
- Similar to Servaites et al. (2001)

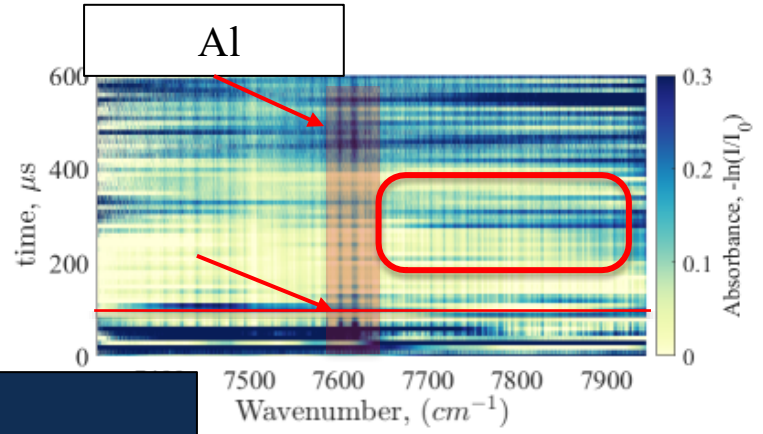
## Case 2:

$T_5 = 4690K, P_5 = 11.2\ Bar$




## Case 3:

$T_5 = 4060K, P_5 = 63.8\ Bar$




- r Al compared to case 2
- AlO from pressure broadening.
- Ignition delay ~100$\mu s$

- Absorption identifies Al & AlO
- 100 kHz time resolution can be used for ignition delay & burn time

**Temperature Trends:**

- Increase in Al vapor with increased $T_5$
- Decrease in ignition delay with increased $T_5$

**Physical Interpretation:**

- Suggests change in combustion behavior
- Complicated by $T_5 > Al_2O_3$ volatilization temperature.

# Temperature Fits

## Fits of Emission & Absorption

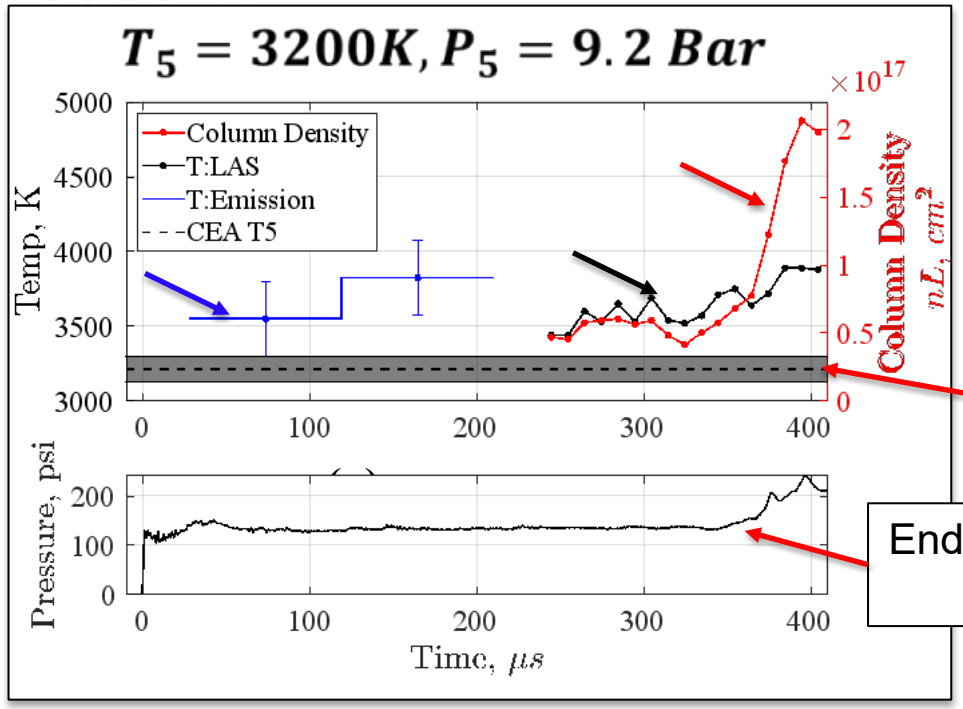
- Absorption: AlO column density and temperature
- Emission: AlO Temperature
- Compared to reflected shock temperature $T_5$
- Test time determined by endwall pressure

## Emission & Absorption

- Agree when emission uncertainty taken into account
- Fits estimate $T > T_5$

AlO temperatures above $T_5$ indicated diffusion limited combustion

## Case 1:




Uncertainty from shock speed

Endwall Pressure Trace

# Temperature Fits

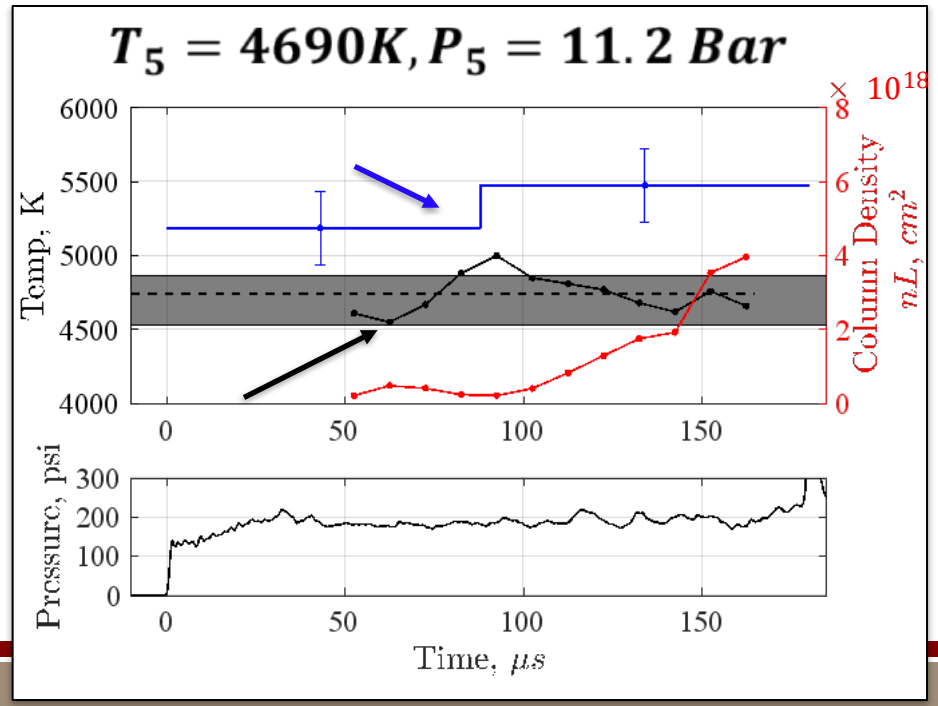
## Emission
- Optically thick
- Fits give artificially high temperature

## Absorption:
- Temperature fit matches CEA
- Column density variations associated movement of particles into FOV

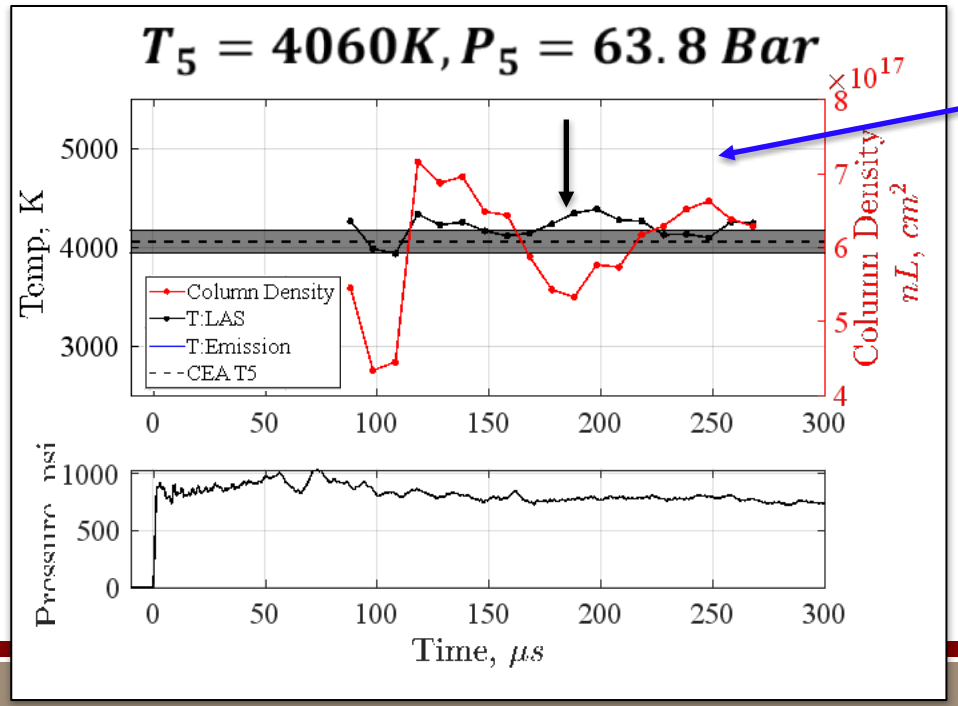
## Physical Interpretation:
- $T_5 >$ volatilization temperature of $Al_2O_3$
- Max temperature of system is $T_5$

- Absorption correctly measures temperature in environments where emission fails
- Can measure temperature in cases with $P > 60\ Bar$!!

## Case 2:




## Case 3:




Unable to fit emission

# Conclusion

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- **Suite of diagnostics applied to Al combustion in the HST**
  - Absorption: AlO & Al
  - Emission: AlO
  - Schlieren & Color Imaging

- **Measurements made in high temperature & pressure environments ($T_5$>4000K, $P_5$>60 Bar)**
  - Absorption indicates decrease in ignition time and increase of Al vapor with temperature
  - Emission & absorption agree for $T_5$=3100K case
  - Absorption shows at $T_5 > 4000$, AlO vapor teperature is equal to the ambient

Absorption diagnostic has potential for future physics focused experiments, particularly at high pressure conditions where gaps in the fundamental understanding of particle combustion remain

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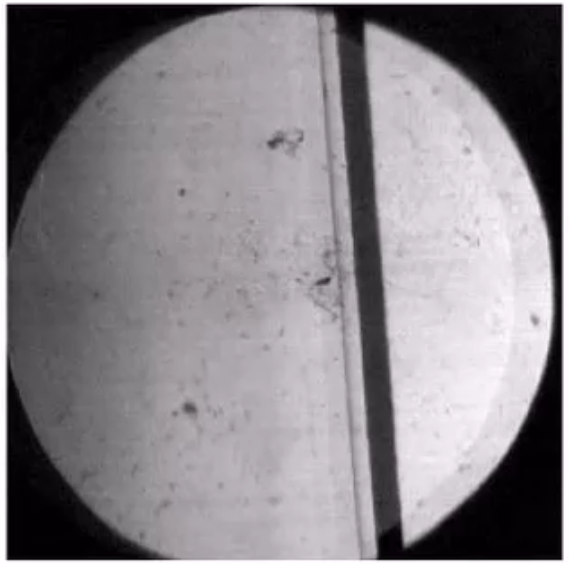
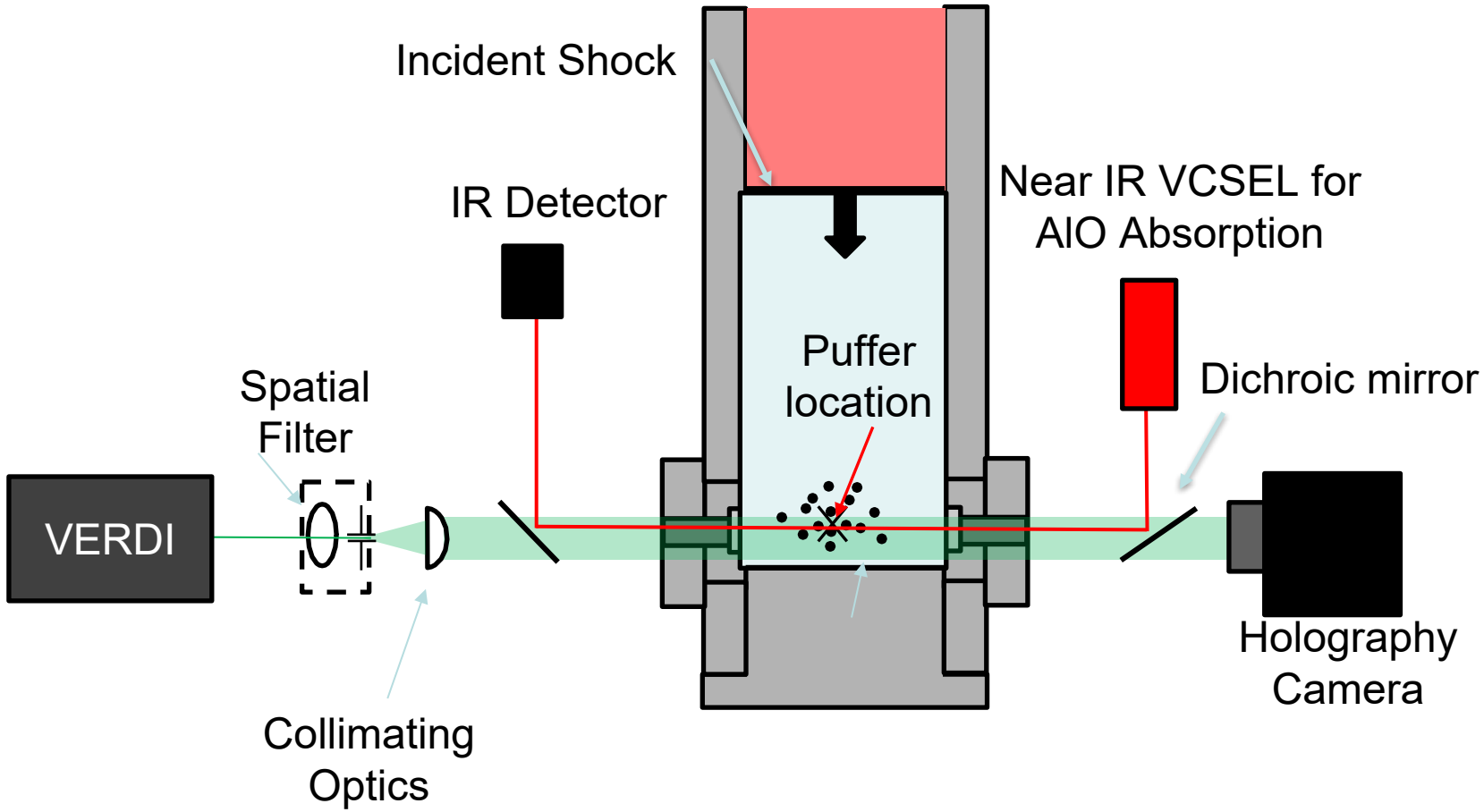
# Questions?



# Next Steps: Characterize Particle loading




- **Characterize particle loading in situ with digital in line holography**
  - Measure number of particles in laser for each test
  - Enables comparing AlO measurements between runs