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Study of Titanium Potassium Perchlorate Combustion using Electric Field Holography and Imaging Pyrometry

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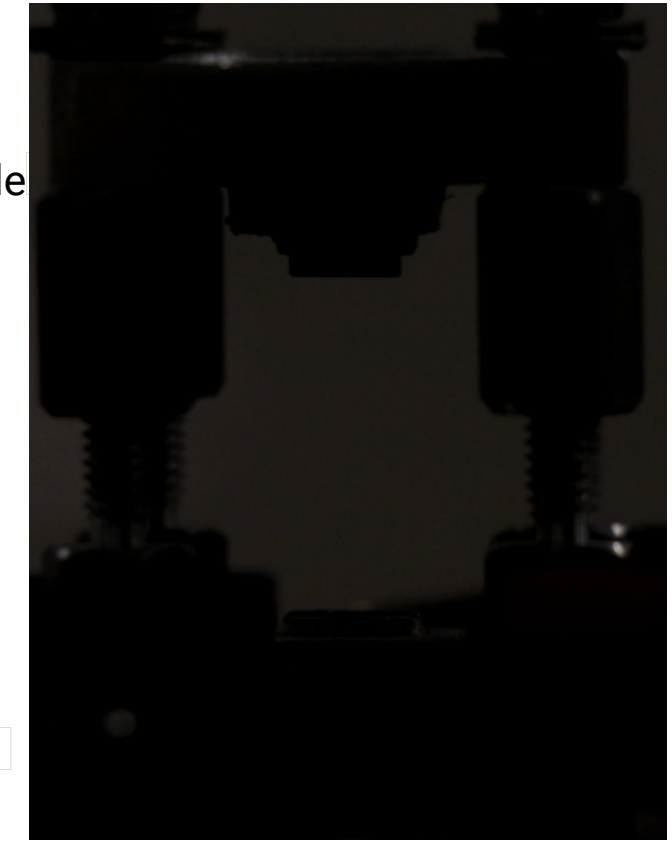
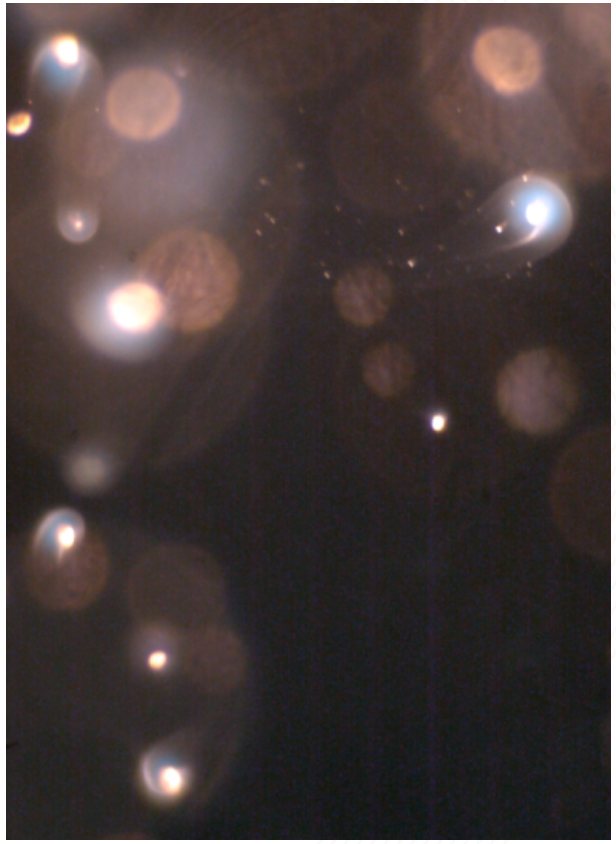
Introduction

- Titanium particles are a common component of pyrotechnic, explosive, and other energetic mixtures
- Most previous studies have focused on analysis of a single controlled combusting titanium particle
- We investigate *in-situ* titanium particle combustion statistics from an uncapped pyrotechnic igniter
- Spatial measurement were made using electric field propagation holography (EFP)
- Projected surface temperature measurements were made using split-image two color pyrometry

$Ti/KClO_4$ Ignition of a Thermal Pellet



$Ti/KClO_4$ Combustion



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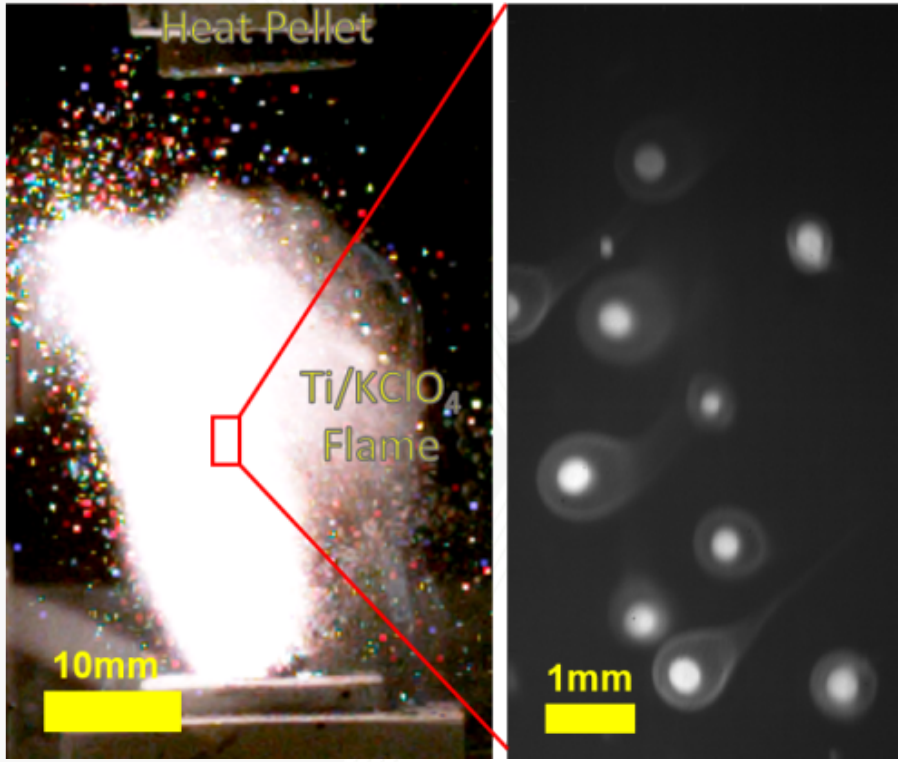
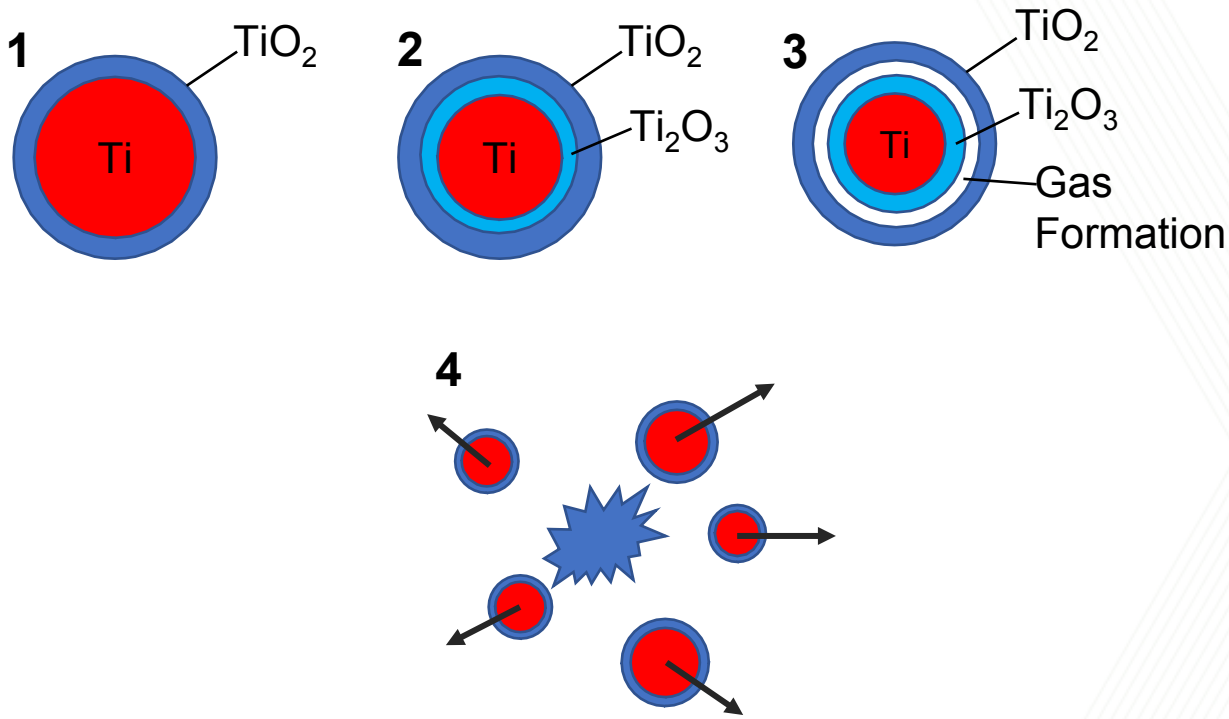
Titanium Particle Morphology





- The surface morphology of titanium particles are homogenous without any oxide caps
- The formation of gas from the boiling Ti interior and the cooling of the TiO_2 results in particle fragmentation
- In these experiments, particle fragmentation does not occur till very late in the process

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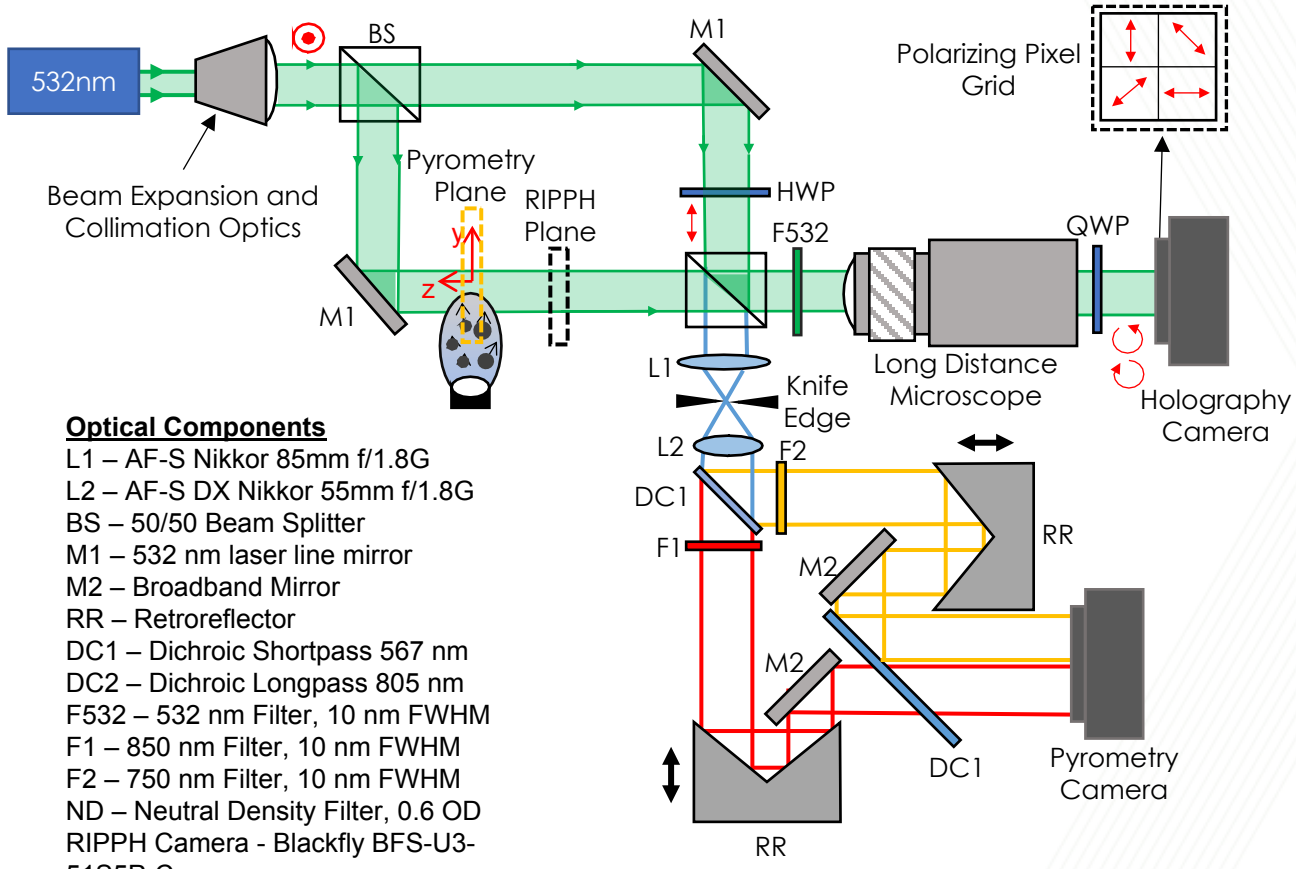
Experimental Setup

- 30 mg samples of stoichiometric Ti/$KClO_4$ (32% Ti, 68% $KClO_4$) were ignited using a tungsten wire in an uncapped configuration

- Electric field propagation holography is used to capture 3D spatial information on the titanium particles
  - Thermal gradients cause distortions that need to be removed with special holography techniques
  - A specialized camera with a polarizing pixel grid is necessary for this diagnostic

- Two color imaging pyrometry captures temperature maps
  - When matched with the spatial information from holography, particle temperatures can be extracted from calculated temperature maps
  - By splitting the camera sensor in half, both pyrometry images were captured on a single sensor



Optical Components

L1 – AF-S Nikkor 85mm f/1.8G
L2 – AF-S DX Nikkor 55mm f/1.8G
BS – 50/50 Beam Splitter
M1 – 532 nm laser line mirror
M2 – Broadband Mirror
RR – Retroreflector
DC1 – Dichroic Shortpass 567 nm
DC2 – Dichroic Longpass 805 nm
F532 – 532 nm Filter, 10 nm FWHM
F1 – 850 nm Filter, 10 nm FWHM
F2 – 750 nm Filter, 10 nm FWHM
ND – Neutral Density Filter, 0.6 OD
RIPPH Camera - Blackfly BFS-U3-51S5P-C
Pyrometry Camera – Photron SA 1.1

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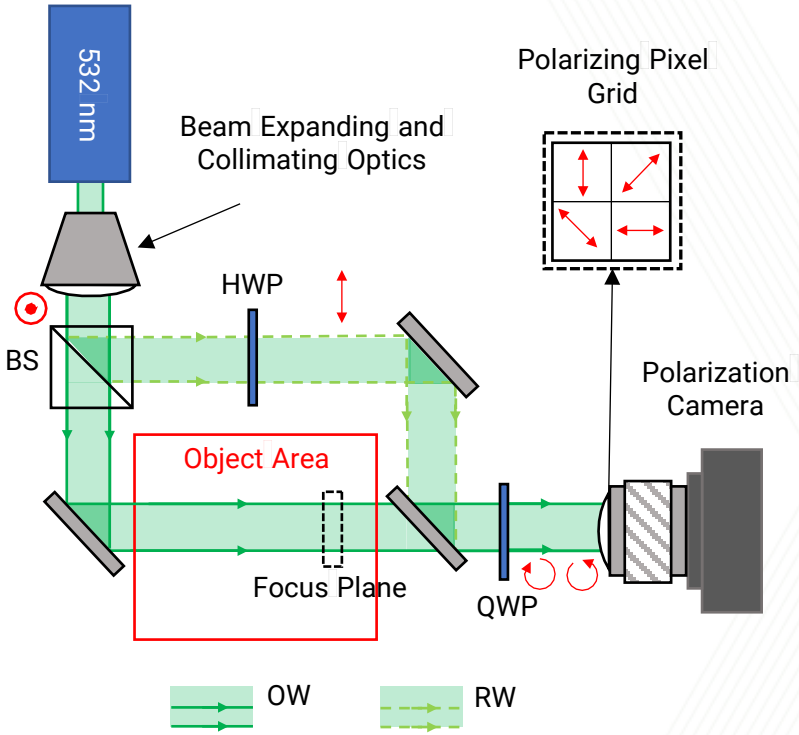
Electric Field Holography

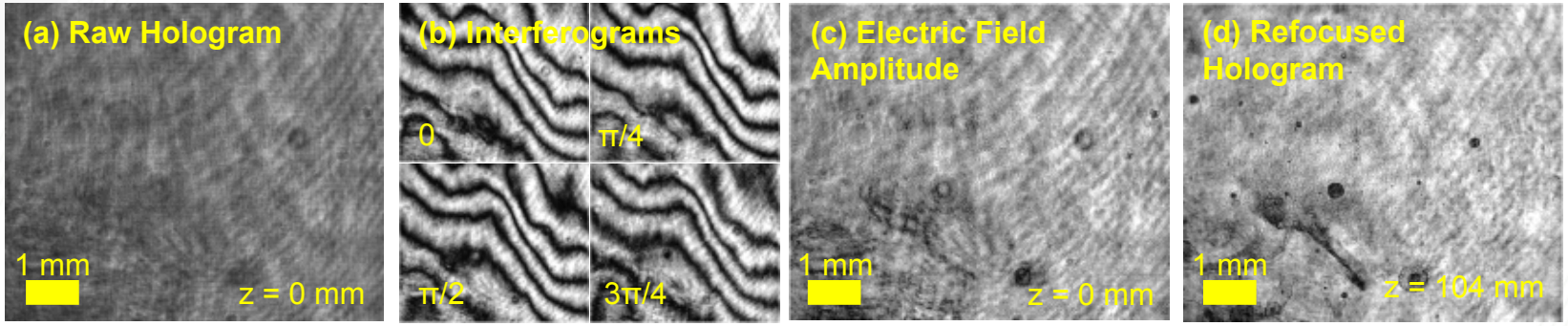
- Holography records the full field information (amplitude and phase), proposed by D. Gabor in 1948
- In tradition digital inline holography (DIH) only intensity information is recorded
- Electric field propagation (EFP) utilizes a reference beam to reconstruct an electric field containing both amplitude and phase information from four $\pi/2$ shifted interferograms using:

$$OB = (I_0 - I_\pi) - i * (I_{\pi/2} - I_{3\pi/2})$$

- The hologram can then be refocused using the Fresnel diffraction equation and processed with DIH algorithms



EFP Reconstruction



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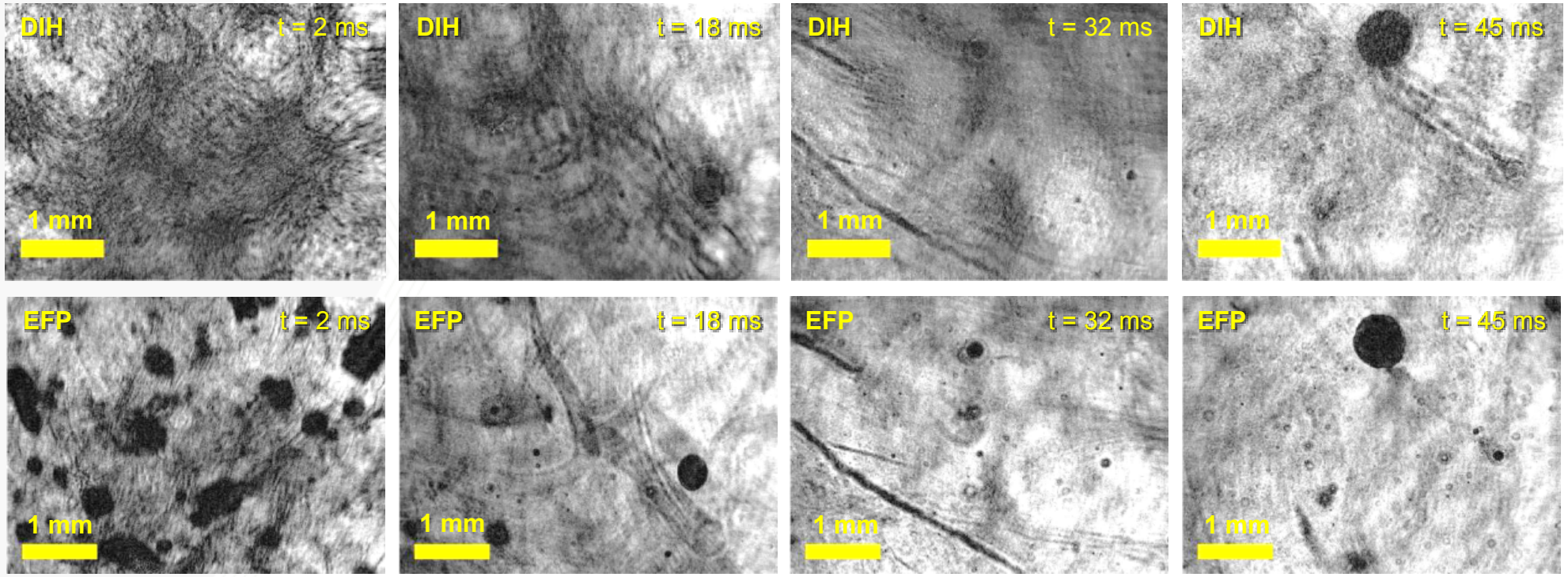
DIH vs. EFP

Comparison of DIH to EFP



- DIH is susceptible to phase distortions from index of refraction gradients since only the intensity is recorded
- Index of refraction gradients can be caused by compressed gas, discrete shocks, thermal gradients, and flame zones
- Since EFP retrieves the phase information of the hologram, distortions are minimal and can be cancelled

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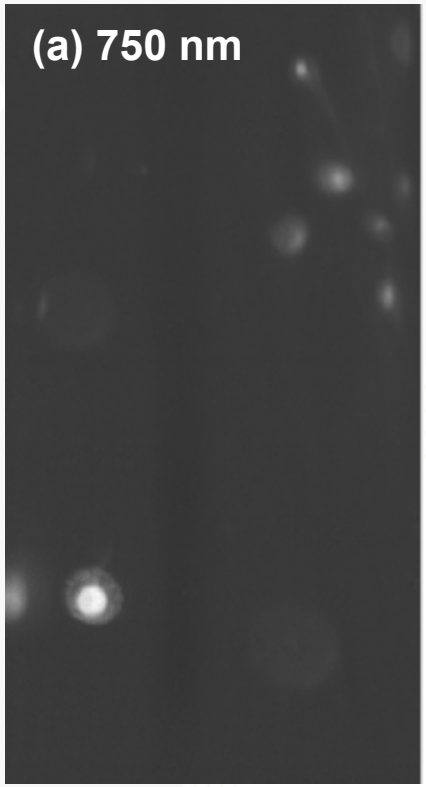
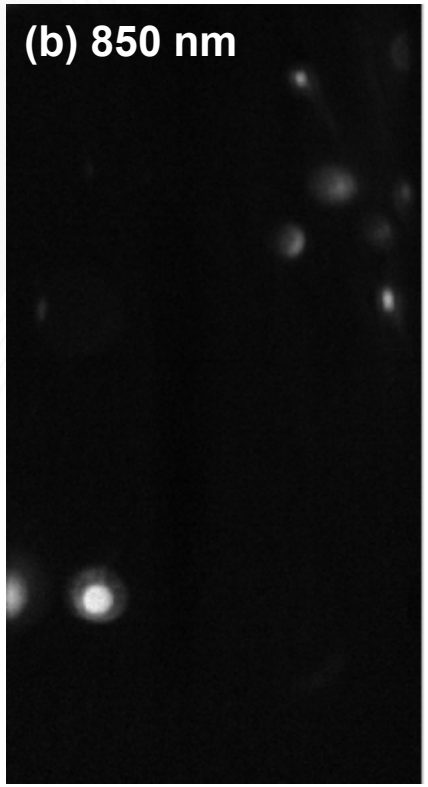
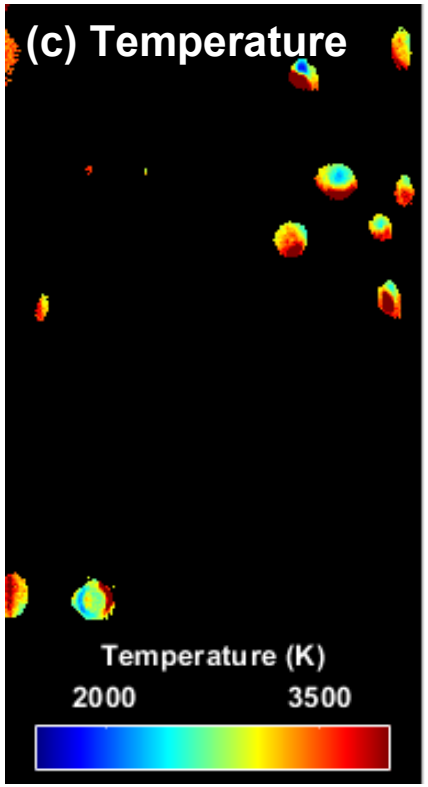
Pyrometry

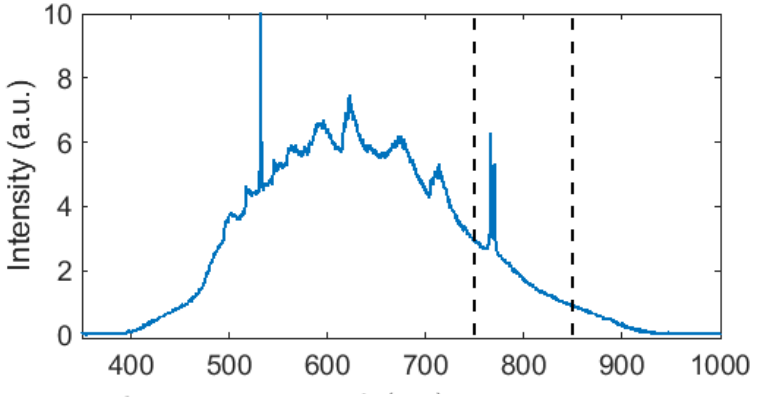
- Selected wavelengths at 750 and 850 nm to avoid emission peaks
- By assuming gray body emission, the temperature can be derived as a function the emitted intensities (I) and quantum efficiencies (η)

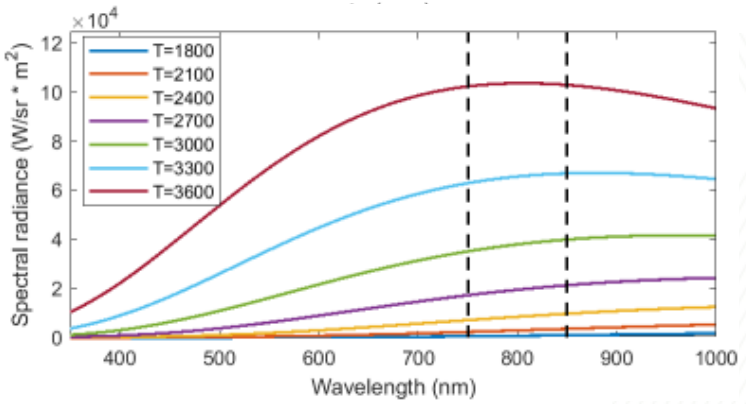
$$T = \left[\frac{k}{hc}\frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1}\left(\ln\left(\frac{I_2}{I_1}\frac{\eta_1}{\eta_2}\right) - 5\ln\left(\frac{\lambda_1}{\lambda_2}\right)\right)\right]^{-1}$$

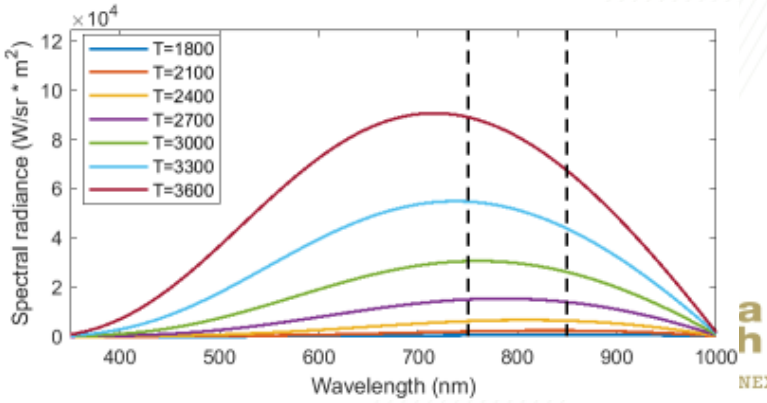




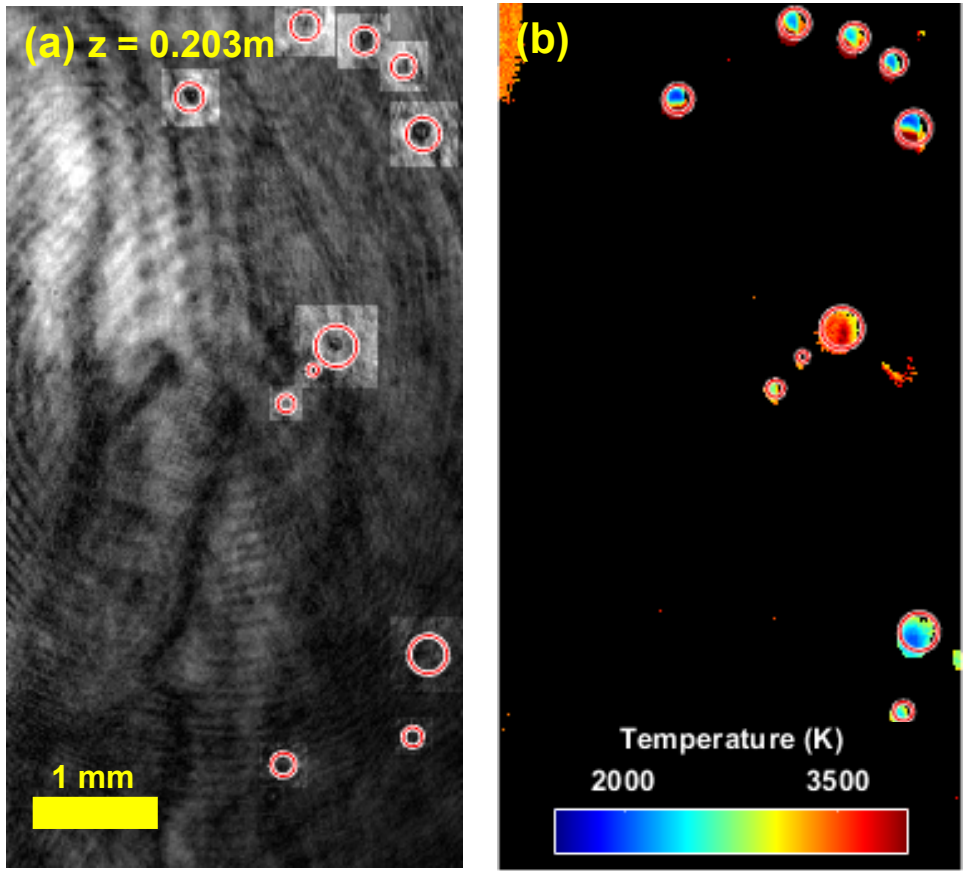








Simultaneous Holography and Pyrometry

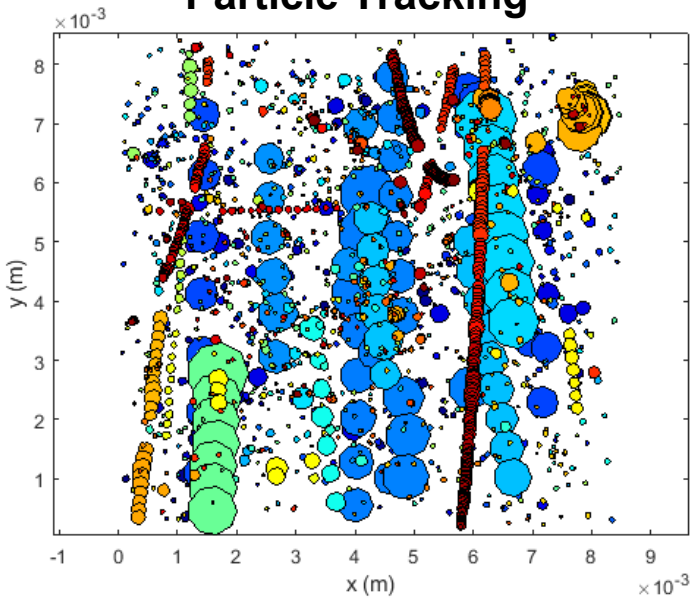


- Identified about 500 particles per experiments over four runs (~2000 total particles)
- A large number of particles allows for statistical analysis of size, velocity, and temperature statistics

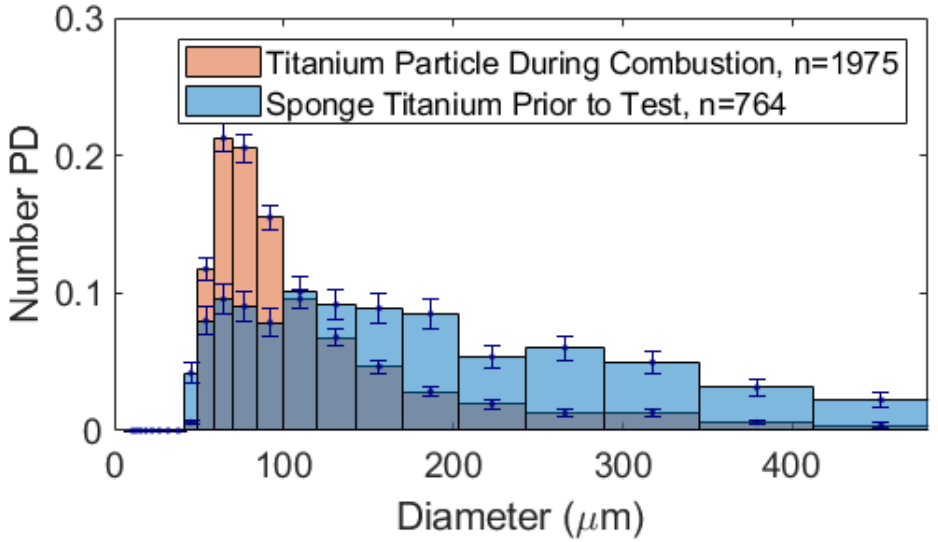
Spatial Statistics

- Size distribution shows that the particle size is larger prior to combustion.
- Since the combustion process is fast, there is not enough time for significant agglomeration to occur between the titanium particles
- Smaller particles are on average ejected at much higher velocities

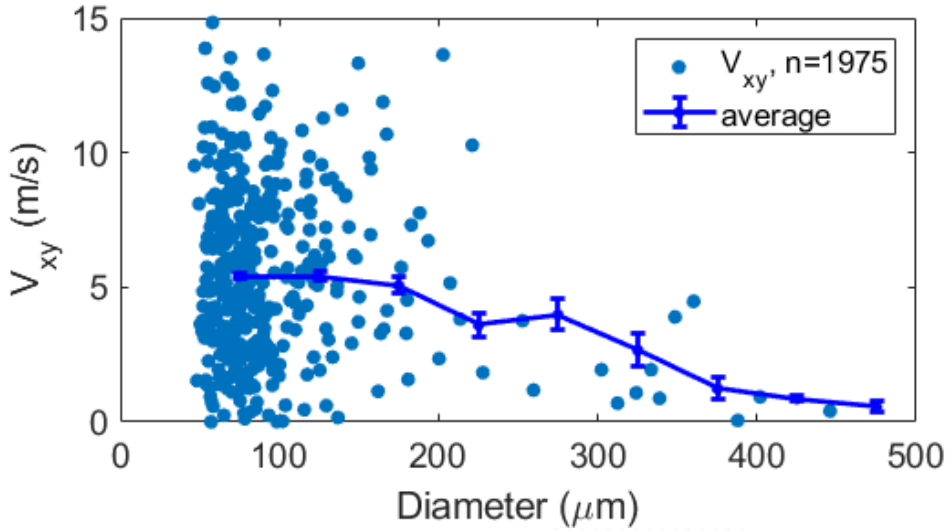
Particle Tracking



Size Distribution

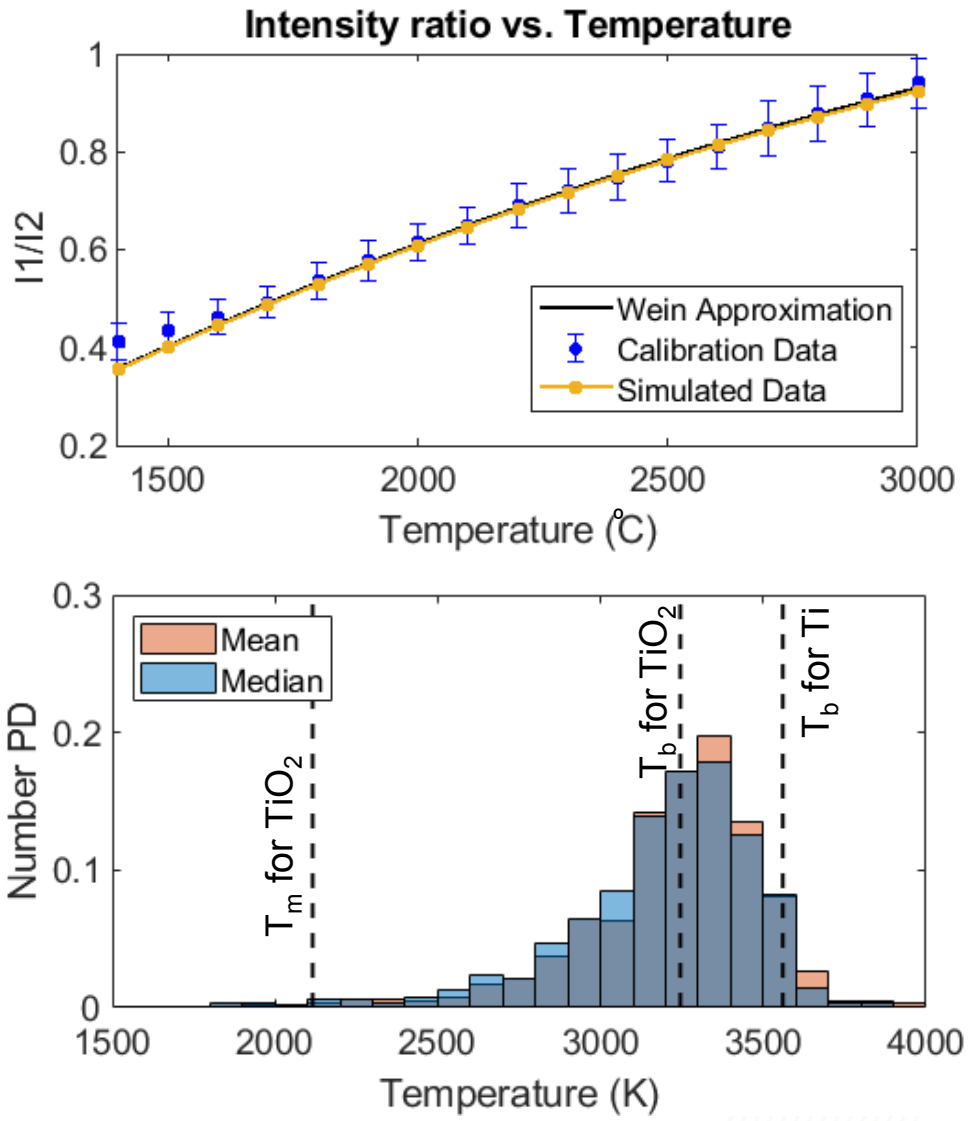


Velocity Distribution



Temperature Distribution

- Calibrated the imaging pyrometer using a tungsten lamp and measured the temperature using a commercial 2-color single point pyrometer (Metis M311)
- Majority of particle temperatures fall between the melting point of TiO_2 and the boiling temperature of Ti and TiO_2
- Edges of particles appear hotter due to sub-pixel misalignment and slightly bias the mean temperature estimates to higher temperatures
- Additional work is needed to quantify uncertainties and validate results



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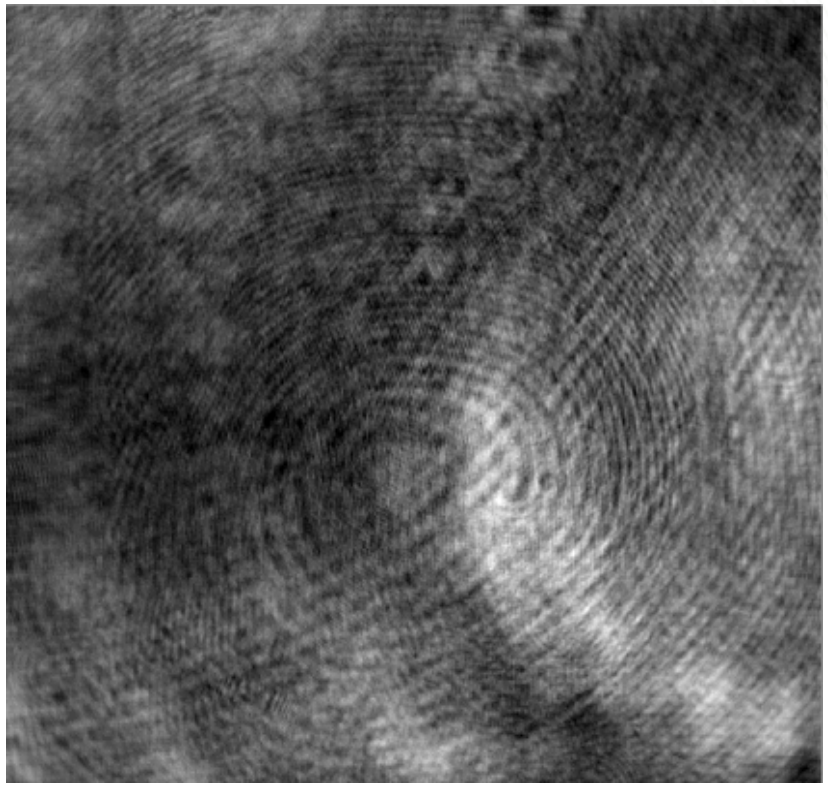
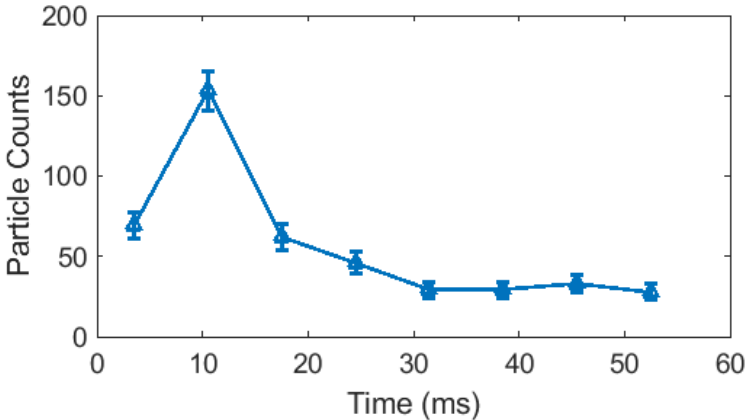
Capped Ignition of $Ti/KClO_4$

- When capping the $Ti/KClO_4$ igniter, an initial fast burst of small particles leads the main particle front that contains larger, slower moving particles

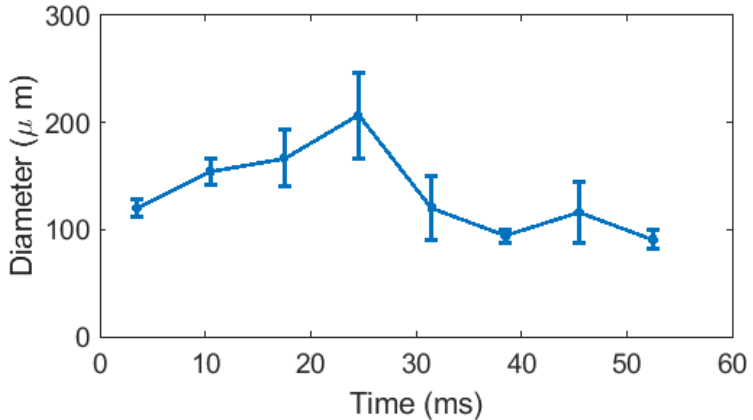
- The main particle front is followed by slower moving particles



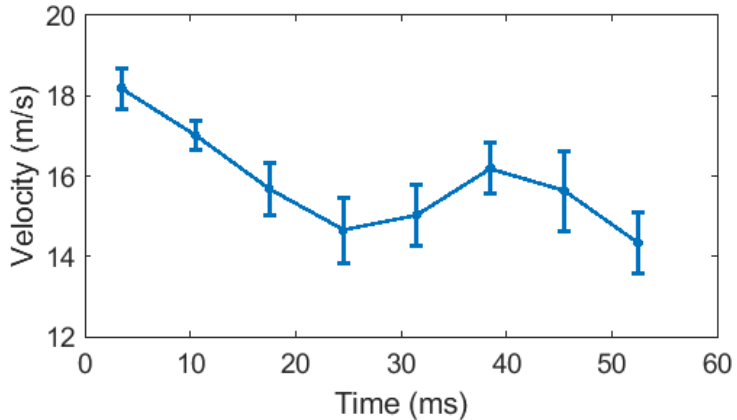
Particle counts



Particle Diameters

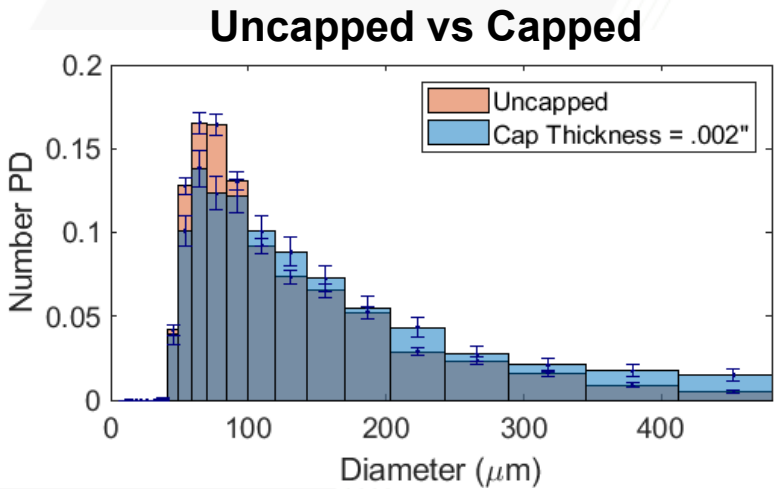


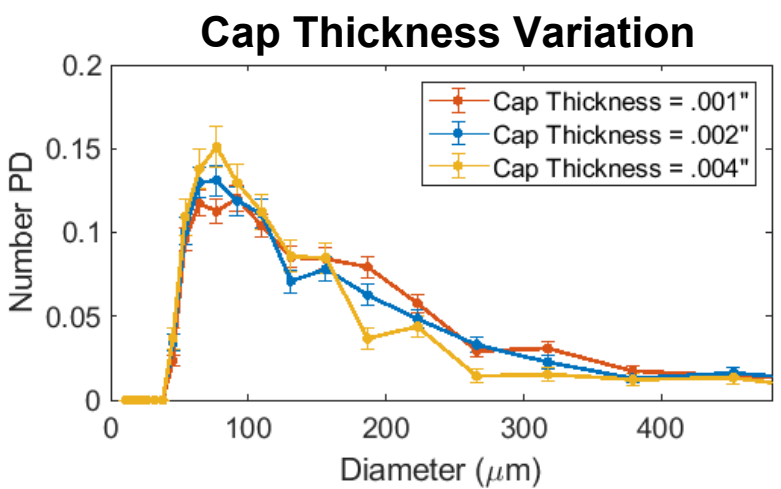
Particle Velocities

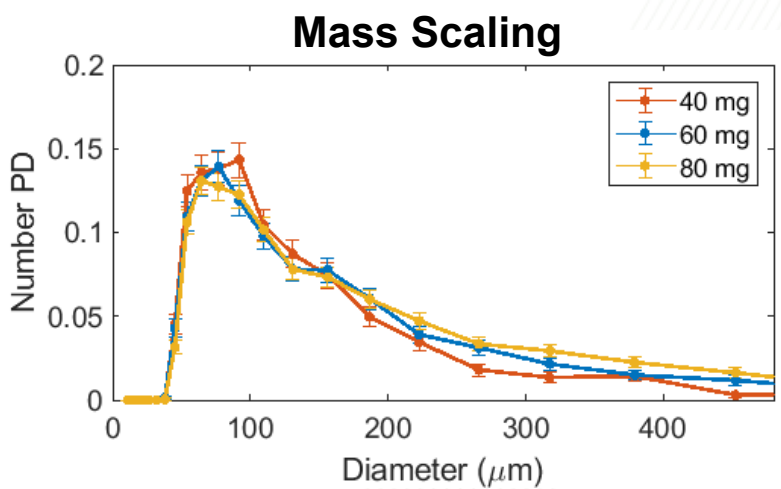


Mass Scaling and Cap Thickness Effects

- Increased residency durations cause larger particle agglomerates to form when ignitor is capped versus uncapped.
- Cap thickness, which controls the peak pressure inside the ignitor, plays a larger role in changing the particle size distribution.
- When scaling the mass of the Ti/$KClO_4$ sample, the size distribution did notvary significantly since the igniter pressure was the same for all three samples



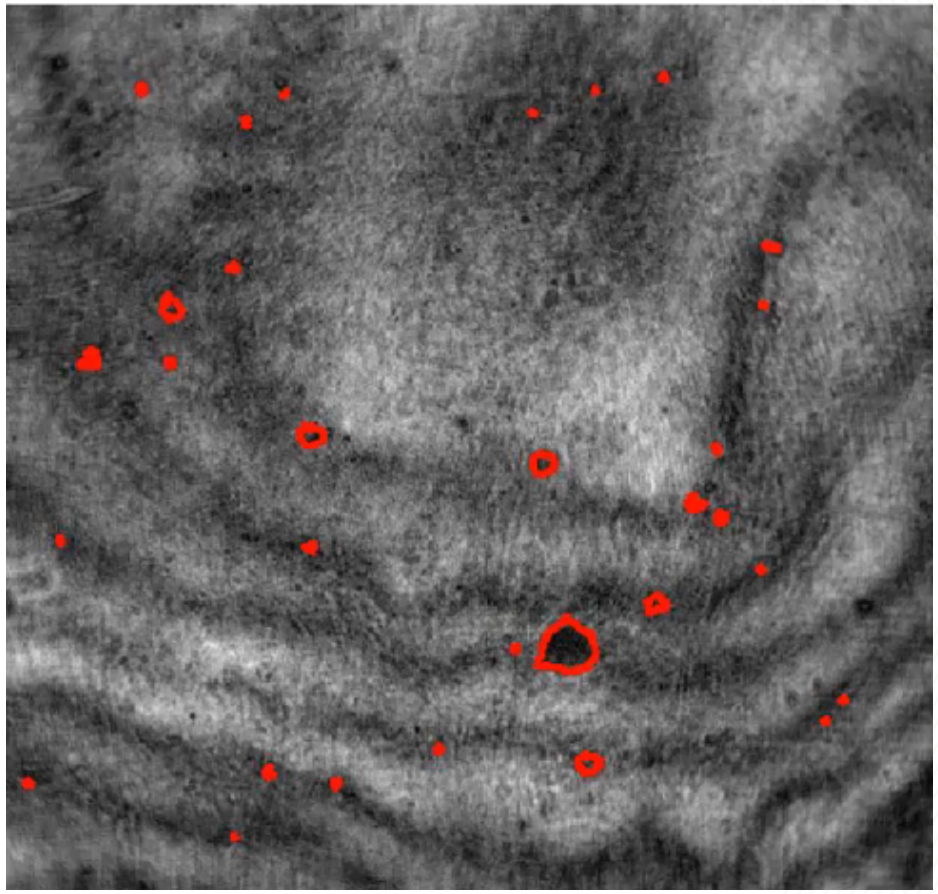




Conclusion

- Titanium particles are a common component in pyrotechnics and explosives
- Spatial and temperature measurements are necessary to understanding systems that utilize Ti particles to promote combustion
- We use simultaneous electric field holography and imaging pyrometry to measure joint size, velocity, and temperature information
- A statistically significant sample size was captured for statistical analysis

Holography Particle Tracking



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Acknowledgements

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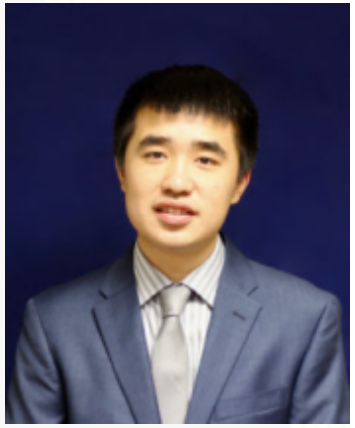

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