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Dynamic Simultaneous Strain and Thermometry using Thermophosphor Digital Image Correlation (TP+DIC)

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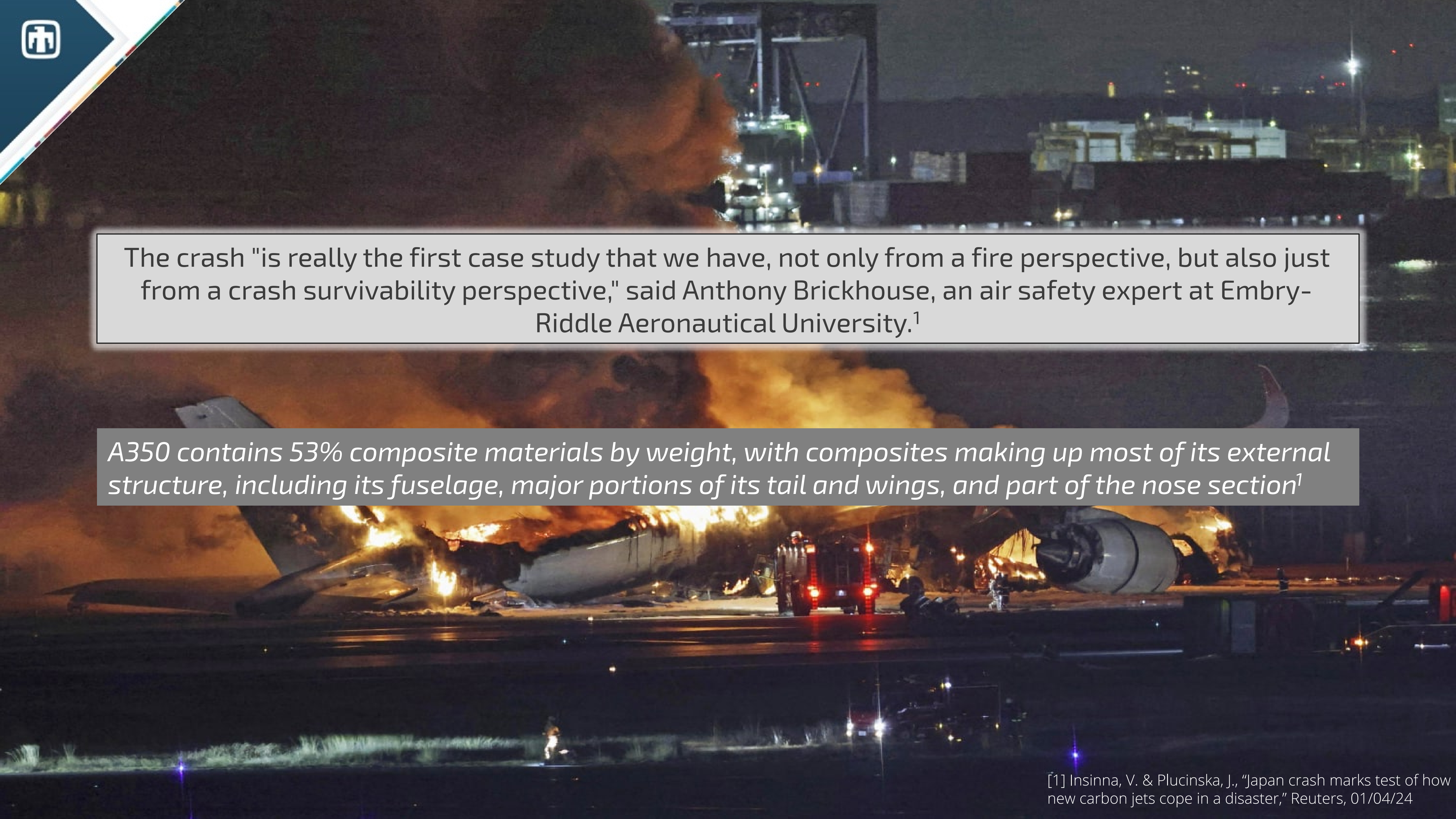
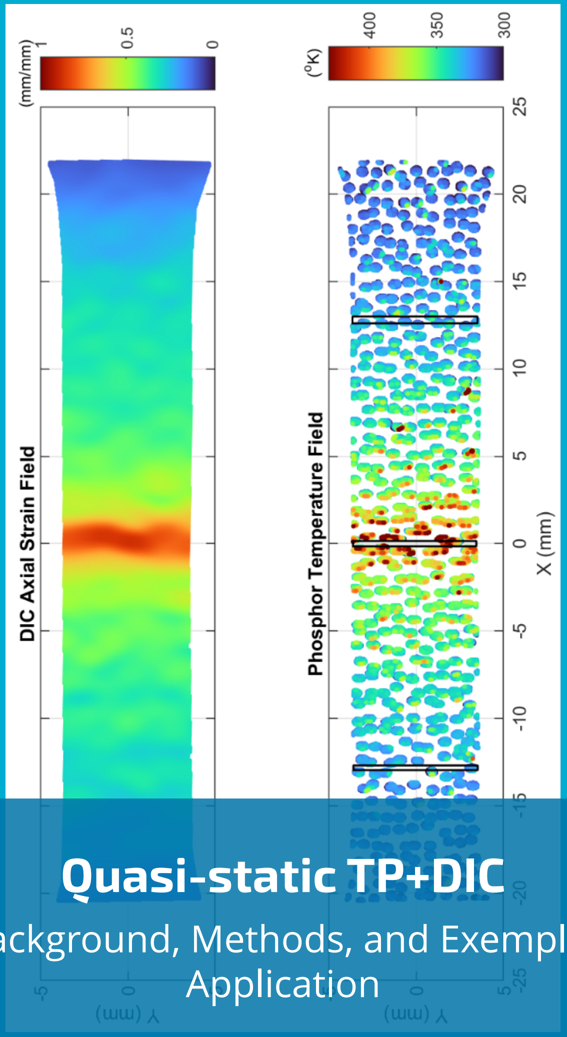


The crash "is really the first case study that we have, not only from a fire perspective, but also just from a crash survivability perspective," said Anthony Brickhouse, an air safety expert at Embry-Riddle Aeronautical University.[1]

A350 contains 53% composite materials by weight, with composites making up most of its external structure, including its fuselage, major portions of its tail and wings, and part of the nose section[1]

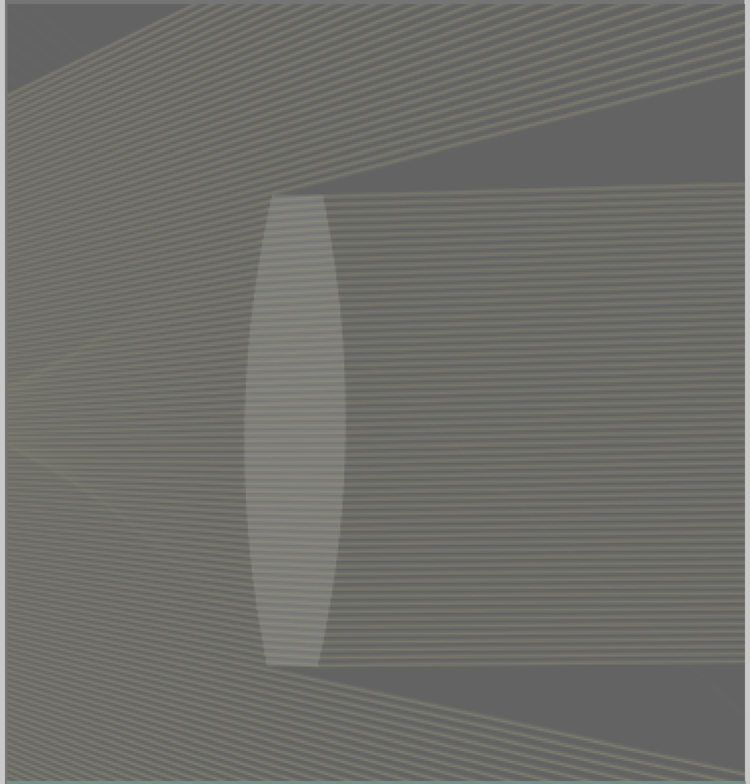
[1] Insinna, V. & Plucinska, J., "Japan crash marks test of how new carbon jets cope in a disaster," Reuters, 01/04/24

Outline

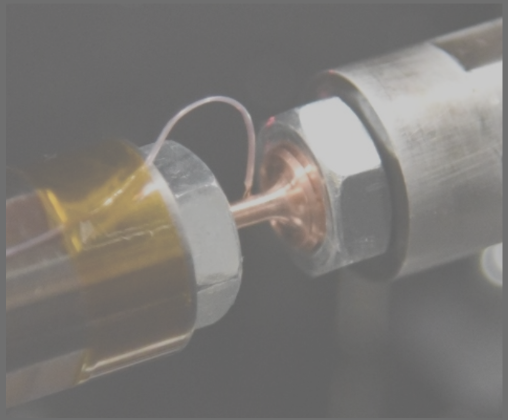


Quasi-static TP+DIC

Background, Methods, and Exemplar Application



Geometry-agnostic Calibration

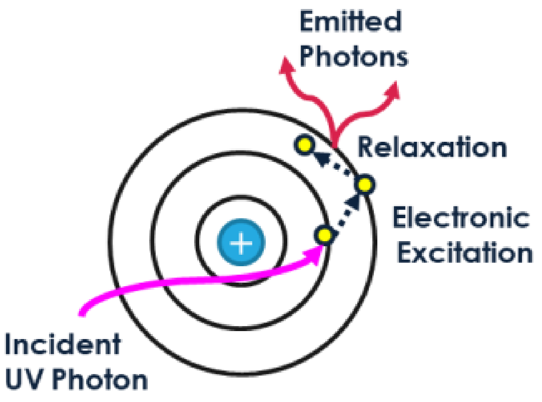


Dynamic Testing

Preliminary set-up and considerations for high strain rate testing

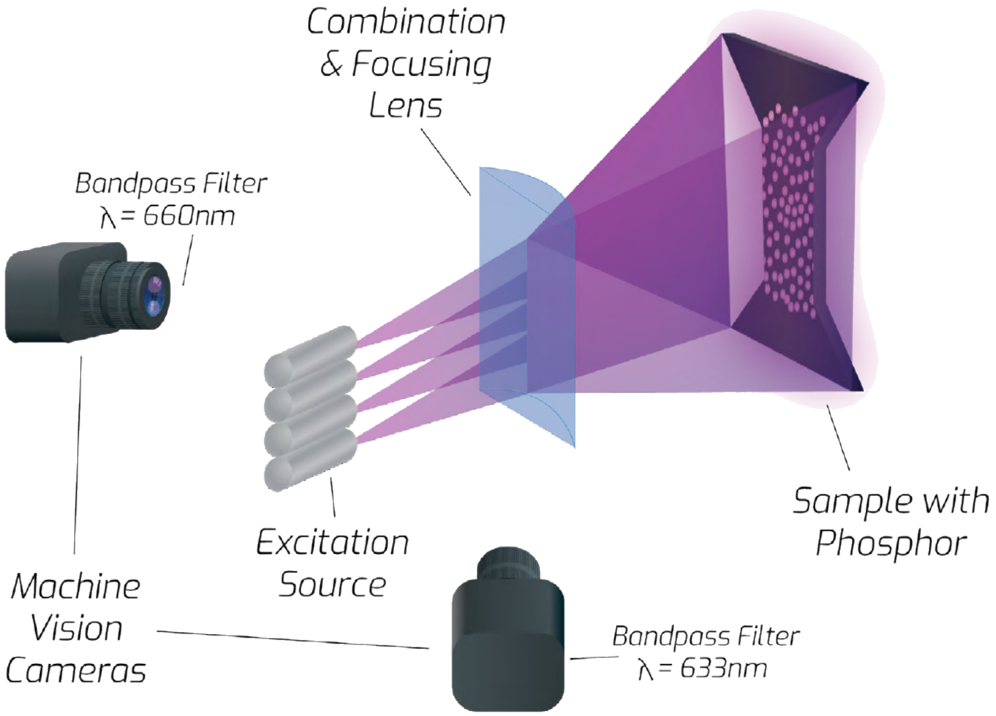
Phosphors are inorganic ceramics that can sense temperature changes ranging from cryogenic (approximately -260°C) to flames (approximately 1000°C).

Physics of phosphor emission



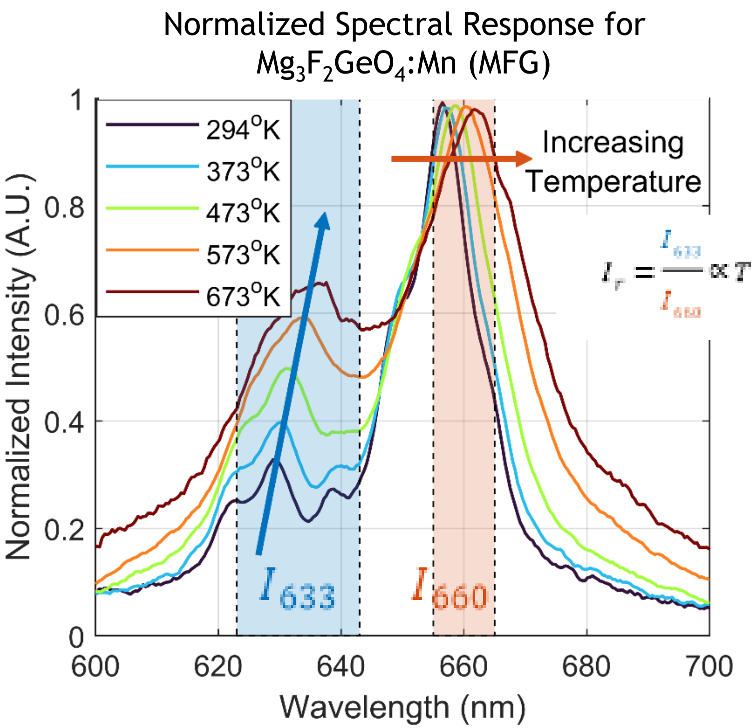
Phosphors are transition or rare earth elements doped into a ceramic material

Experimental Set-up



Cameras image a sample that is 'excited' with UV light

Spectral Data



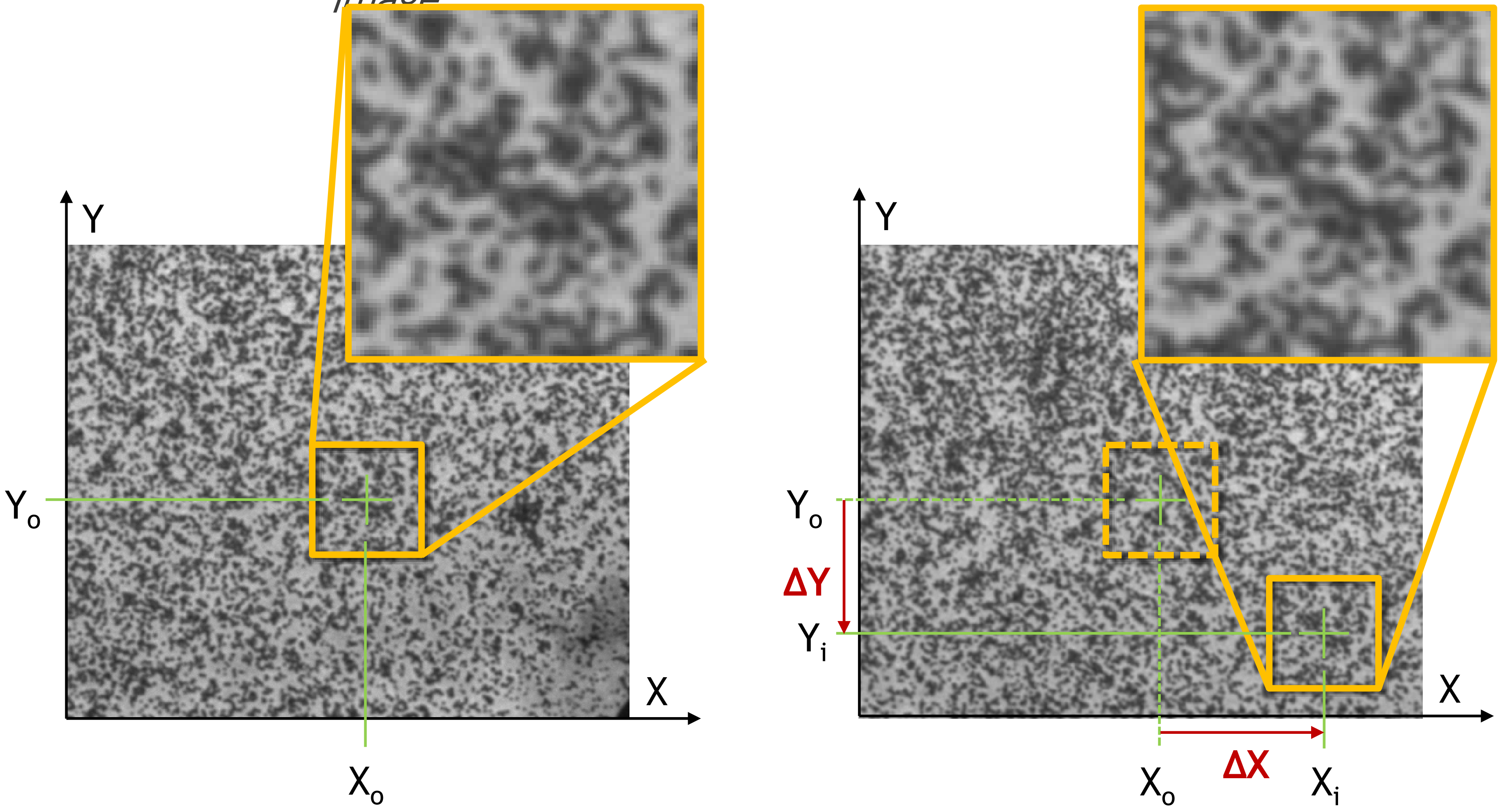
Phosphors produce light with temperature-dependent color

Digital Image Correlation (DIC) provides full-field measurements of strain and other kinematic quantities.

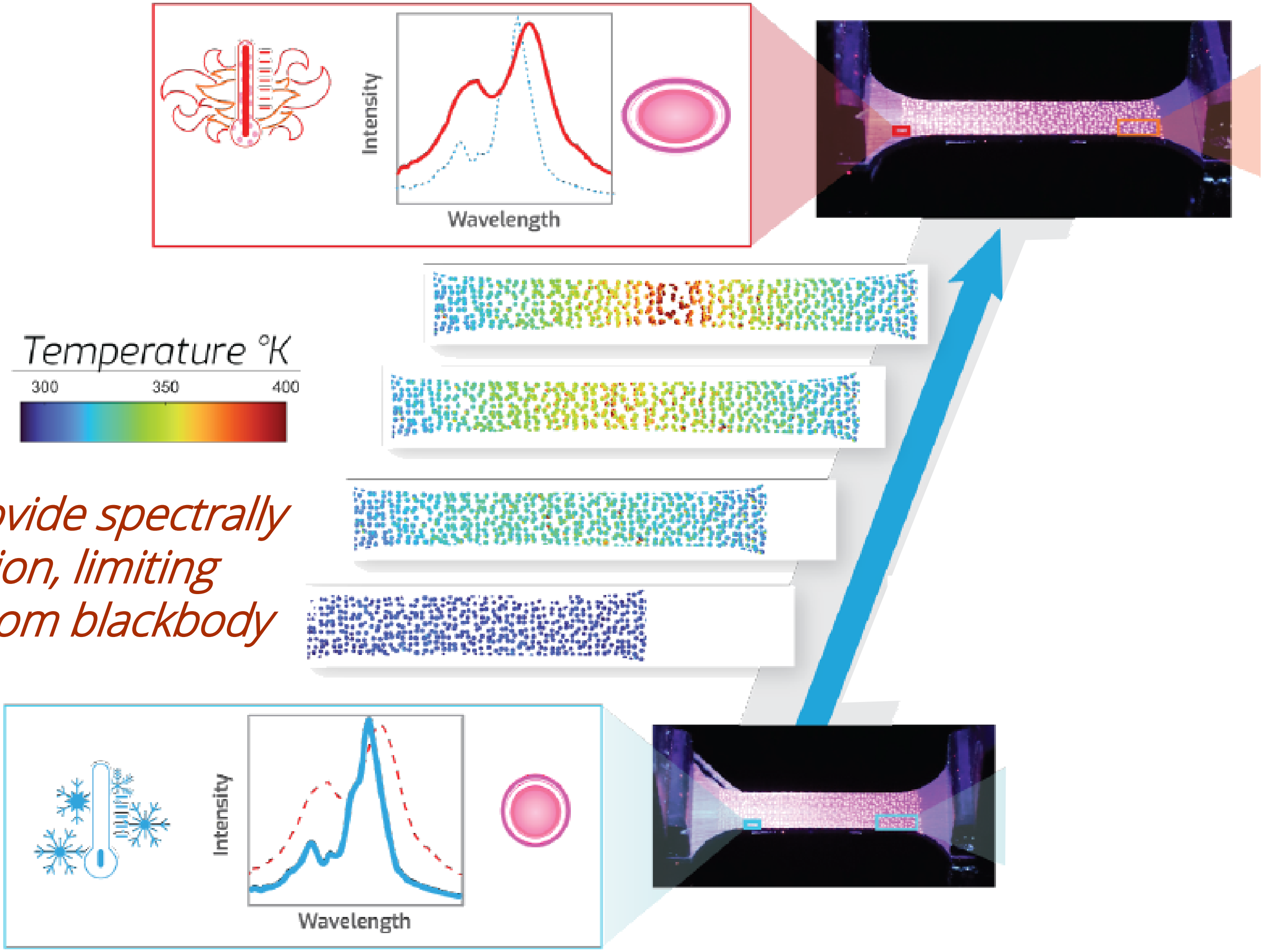
"Keep the dots in the box" (Prof. Samantha Daly)

Reference (undeformed) image

Deformed image



Thermographic Phosphor Digital Image Correlation (TP+DIC) is a synergistic elevation of the two optical diagnostics[2,3].

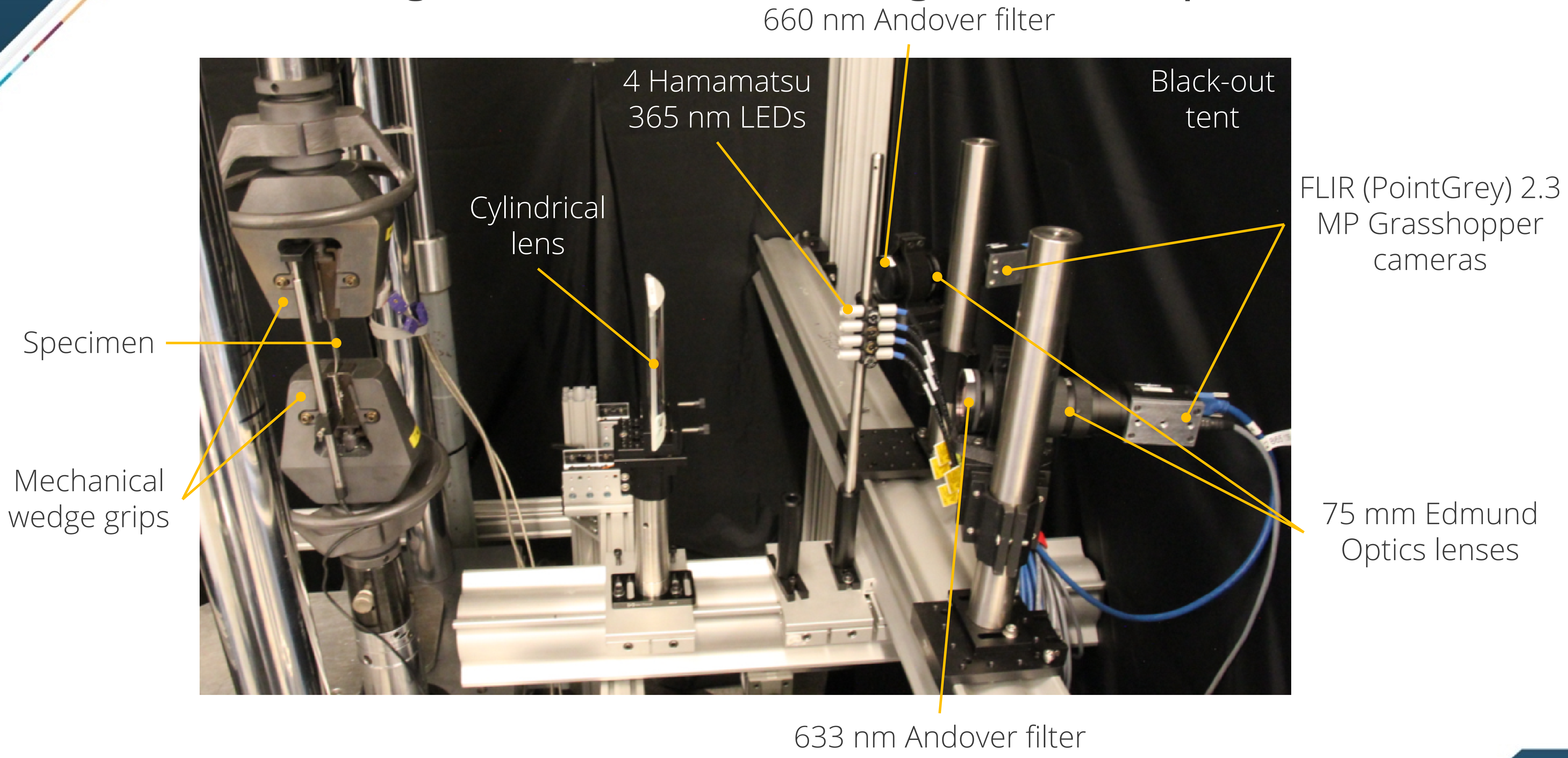


Phosphors provide spectrally isolated emission, limiting interference from blackbody radiation

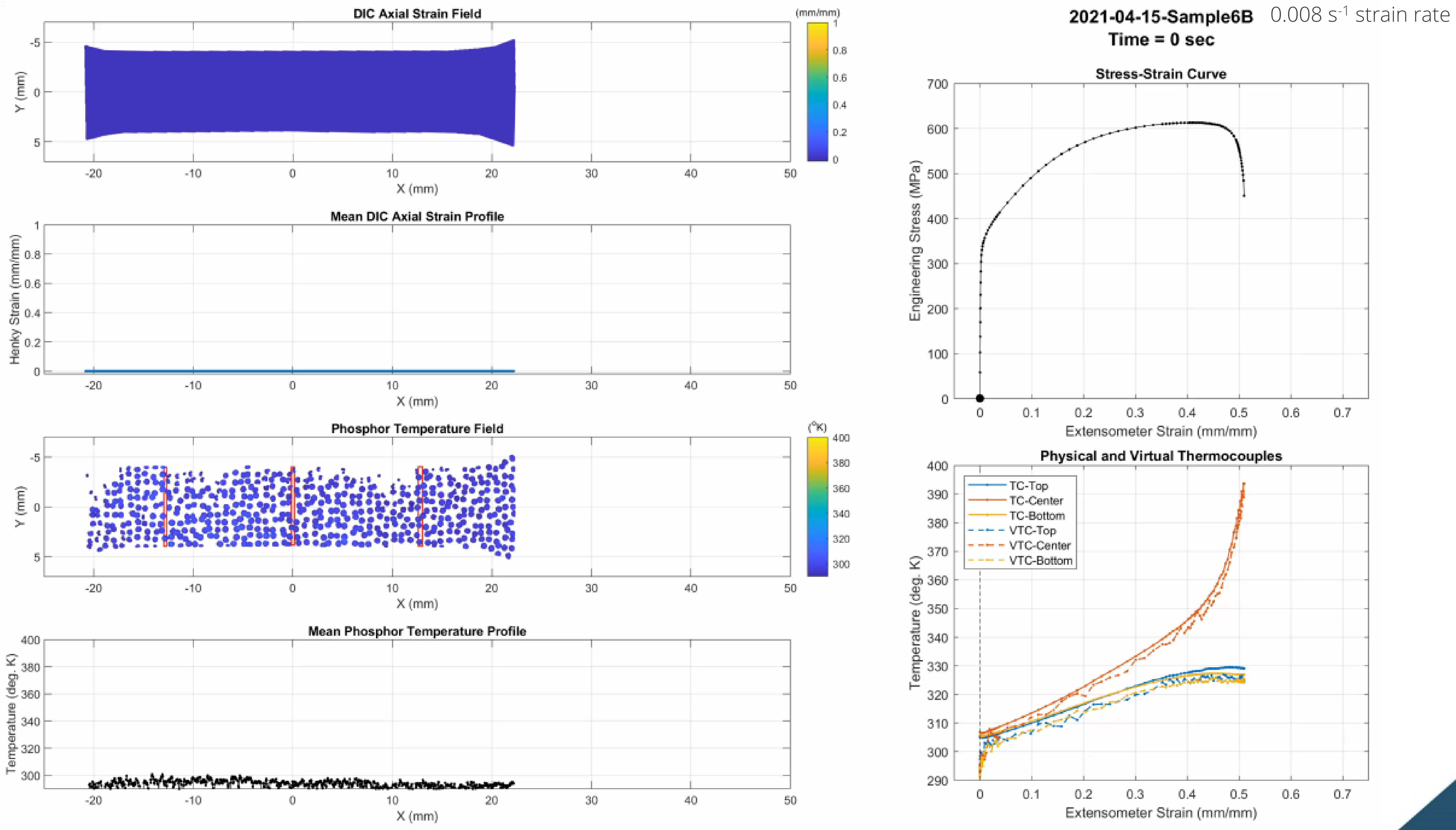
DIC algorithms provide sub-pixel image registration, greatly reducing uncertainty

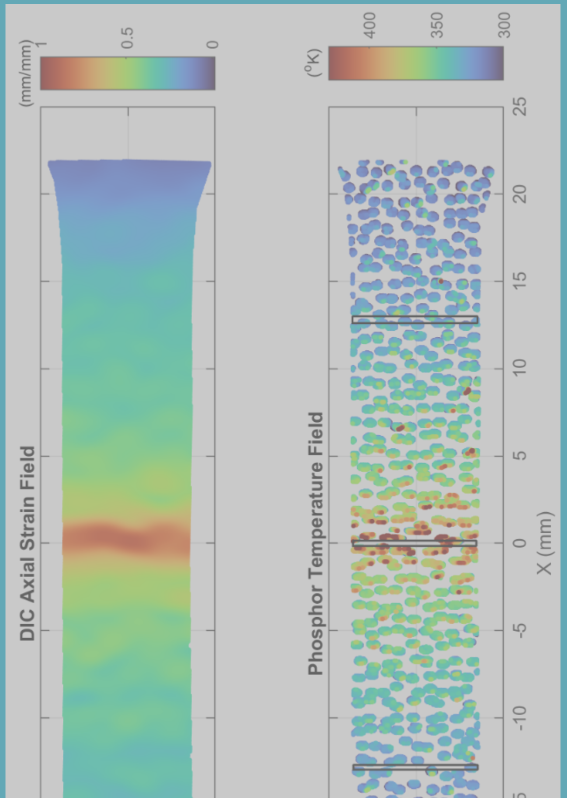
[2] EMC Jones et al., Meas. Sci. Tech., 2022
[3] EMC Jones et al., Strain, 2022

Quasi-static TP+DIC leveraged two machine vision cameras and four UV LEDs to image a stainless steel 304L dogbone tensile specimen.



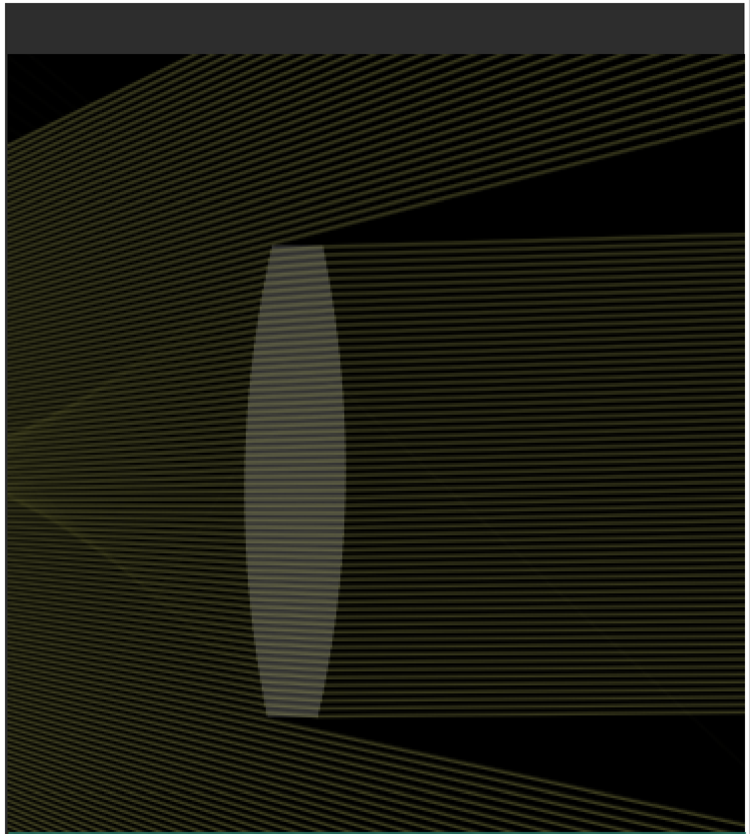
TP+DIC was successfully applied to simultaneously measure full-field strains and temperatures.



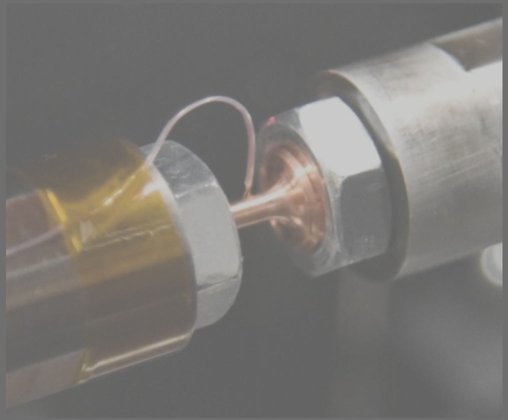


Static TP+DIC

Background, Methods, and Exemplar Application



Geometry-agnostic Calibration

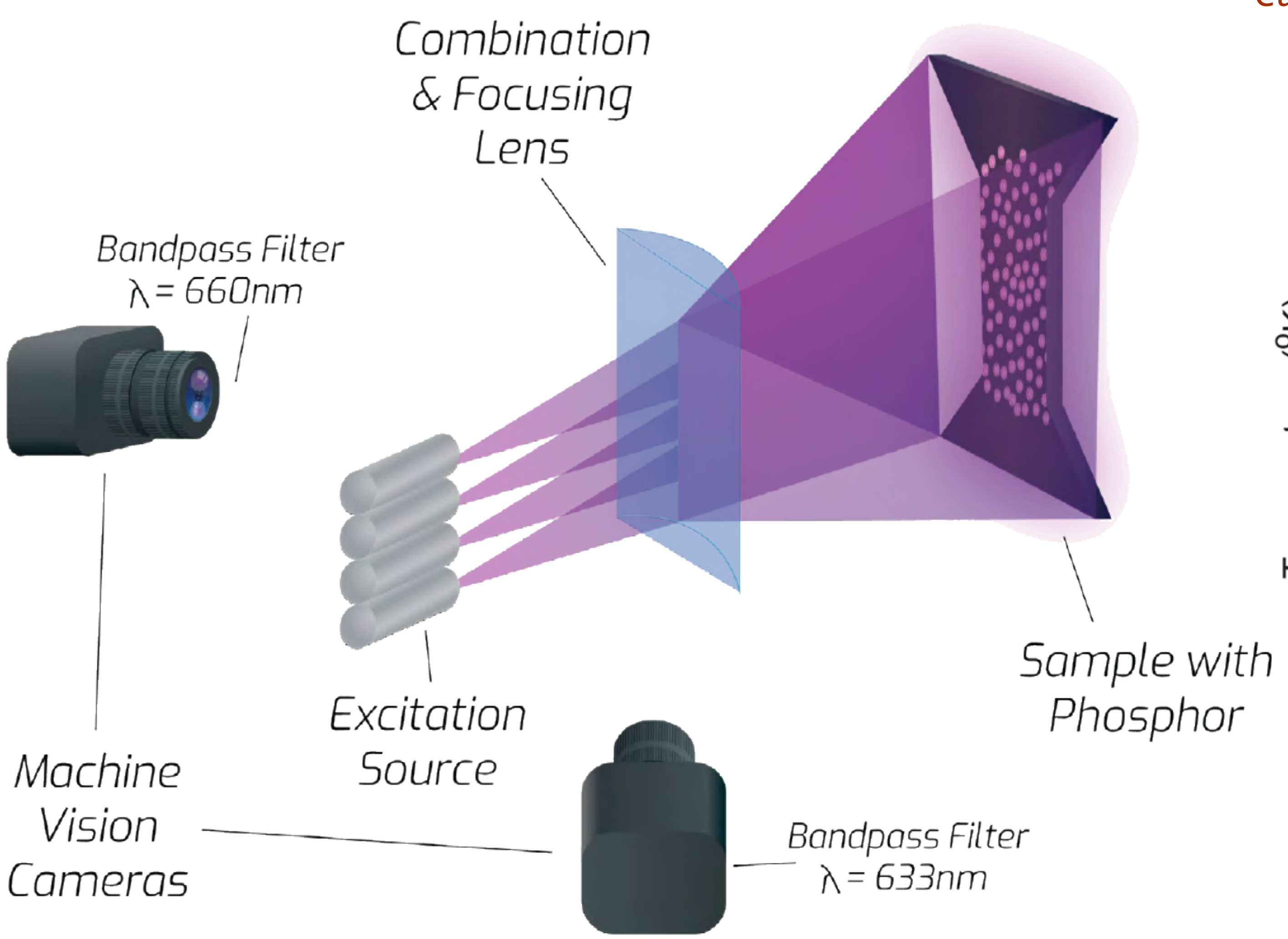


Dynamic Testing

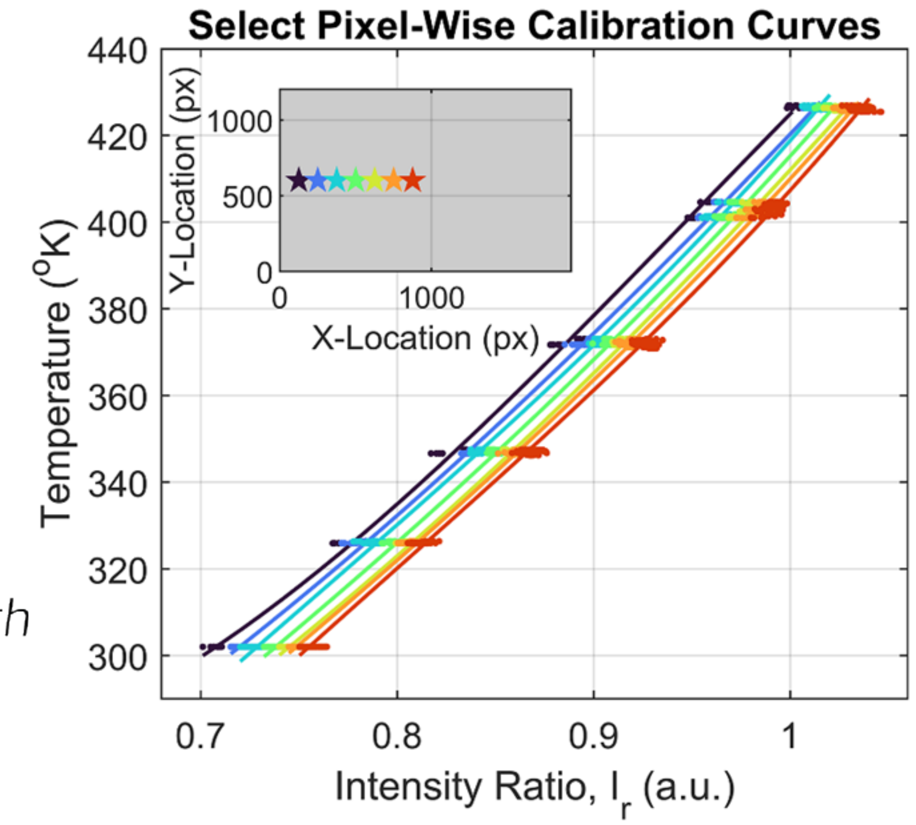
Preliminary set-up and considerations for high strain rate testing

The relationship between the intensity ratio and the temperature depends on the geometry of the imaging equipment.

Representation of Experiment

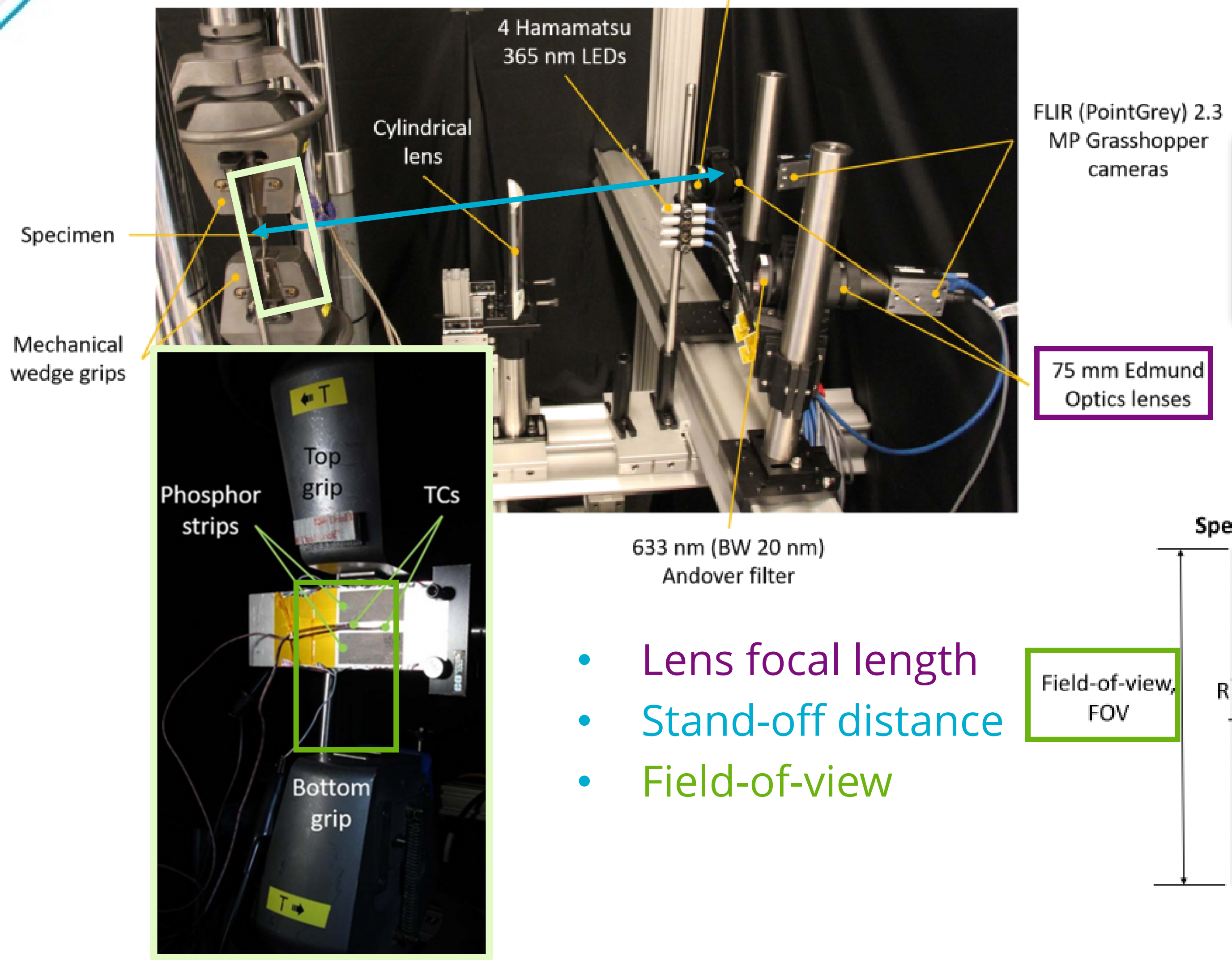


Current procedure requires a 4 hour in-situ phosphor temperature calibration



The relationship between the intensity ratio and the temperature depends on the geometry of the imaging equipment.

Real Experiment

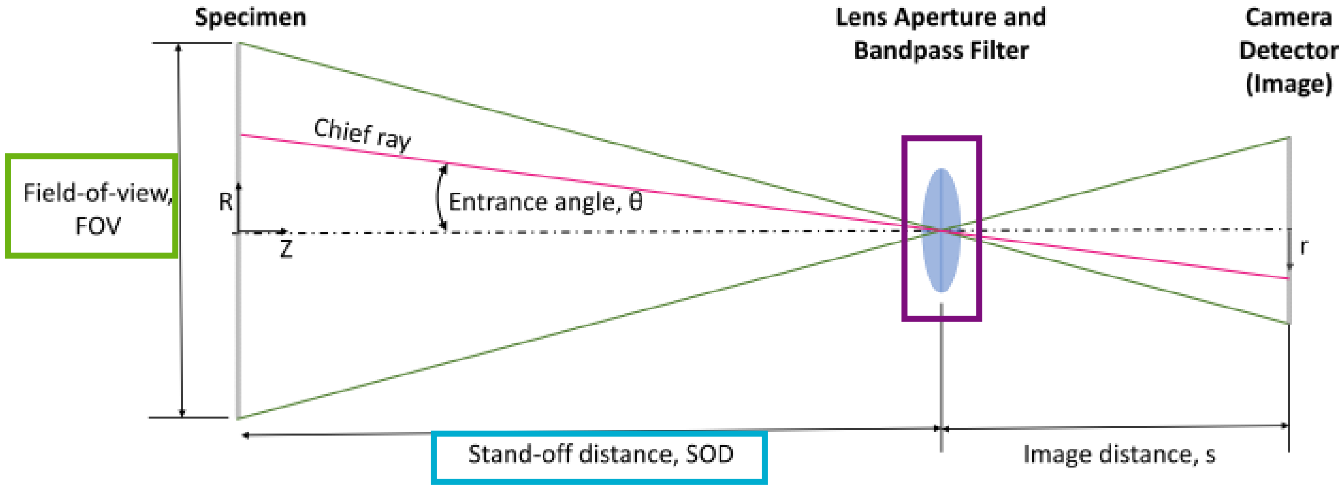


Current procedure requires a 4 hour in-situ phosphor temperature calibration

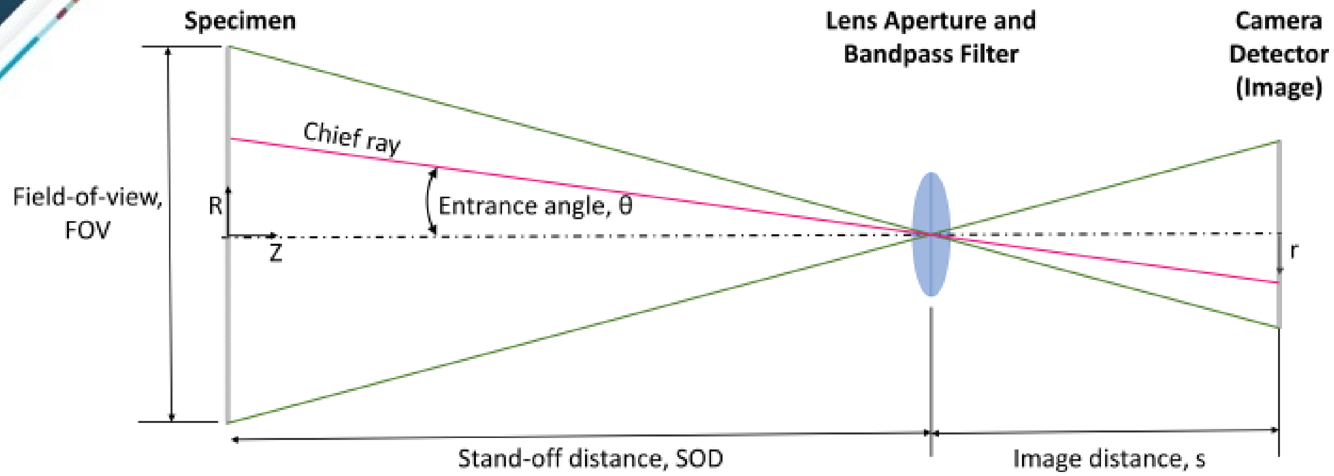
Increasing efficiency of calibration will mature the TP+DIC technology and facilitate broader adoption of TP+DIC diagnostic.

- Lens focal length
- Stand-off distance
- Field-of-view

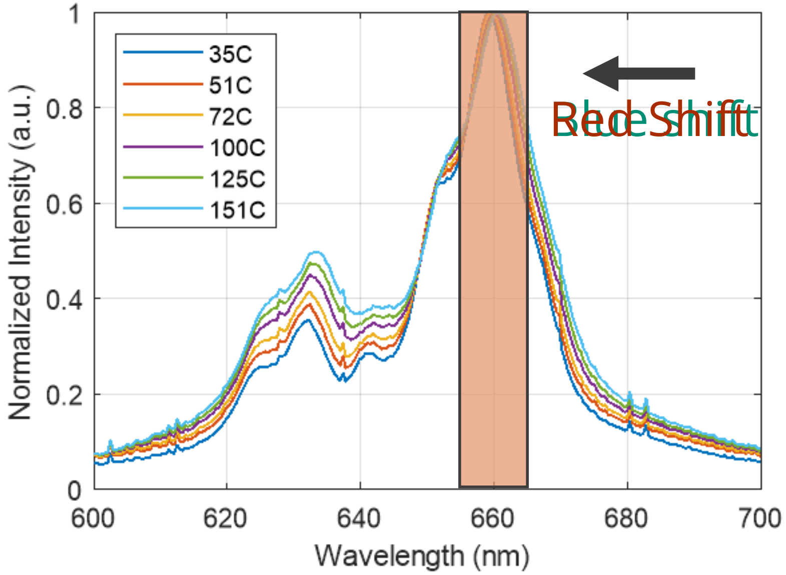
Geometry of imaging system



Development of an imaging model to account for the geometry of the equipment and the blue-shift effect of interference bandpass filters



Spectrally-resolved phosphorescent signal



- If light isn't perfectly normal to the filter, it will be non-linearly transformed. *Blue Shift [4]*

$$\lambda_\theta = \lambda_0\left[1 - \left({}^{N_E}/_{N^*}\right)^2 \sin\theta^2\right]^{1/2}$$

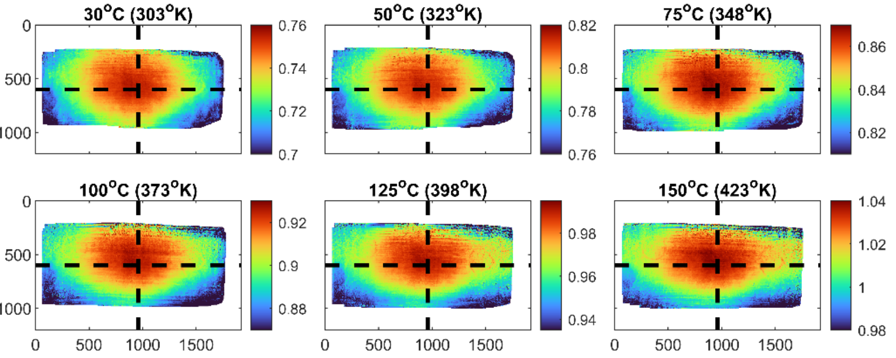
λ_θ : **blue-shifted wavelength [nm]**
λ_0 : **wavelength at normal incidence [nm]**
N_E : **environmental refractive index (e.g. of air)**
N^* : **effective refractive index of the filter**
θ : **entrance angle [rad]**

- This shift changes amount of light collected for each camera image as a function of position in the image and of temperature of the sample
- Our model takes known geometric parameters (FOV, SOD) and spectrally-resolved phosphorescent signal to compute the geometric effects on the intensity ratio

[4] andovercorp.com/technical/bandpass-filter-fundamentals/

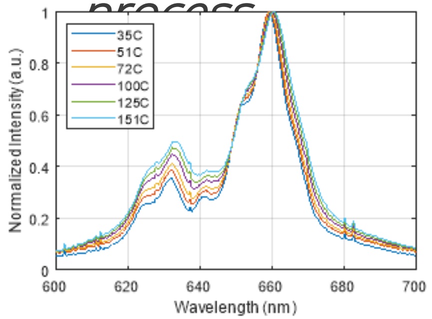
This model greatly reduces the time required to generate phosphor calibration curves, increasing overall efficiency and applicability of TP+DIC.

Original in situ *calibration process*

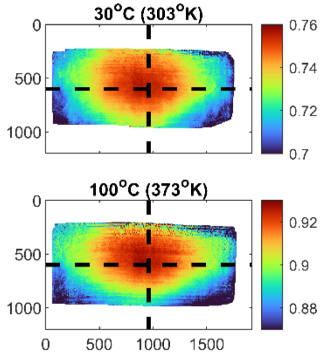


- Phosphor calibration coupon heated to 6 individual temperatures and imaged *in situ*
- ~ 4 hours to complete

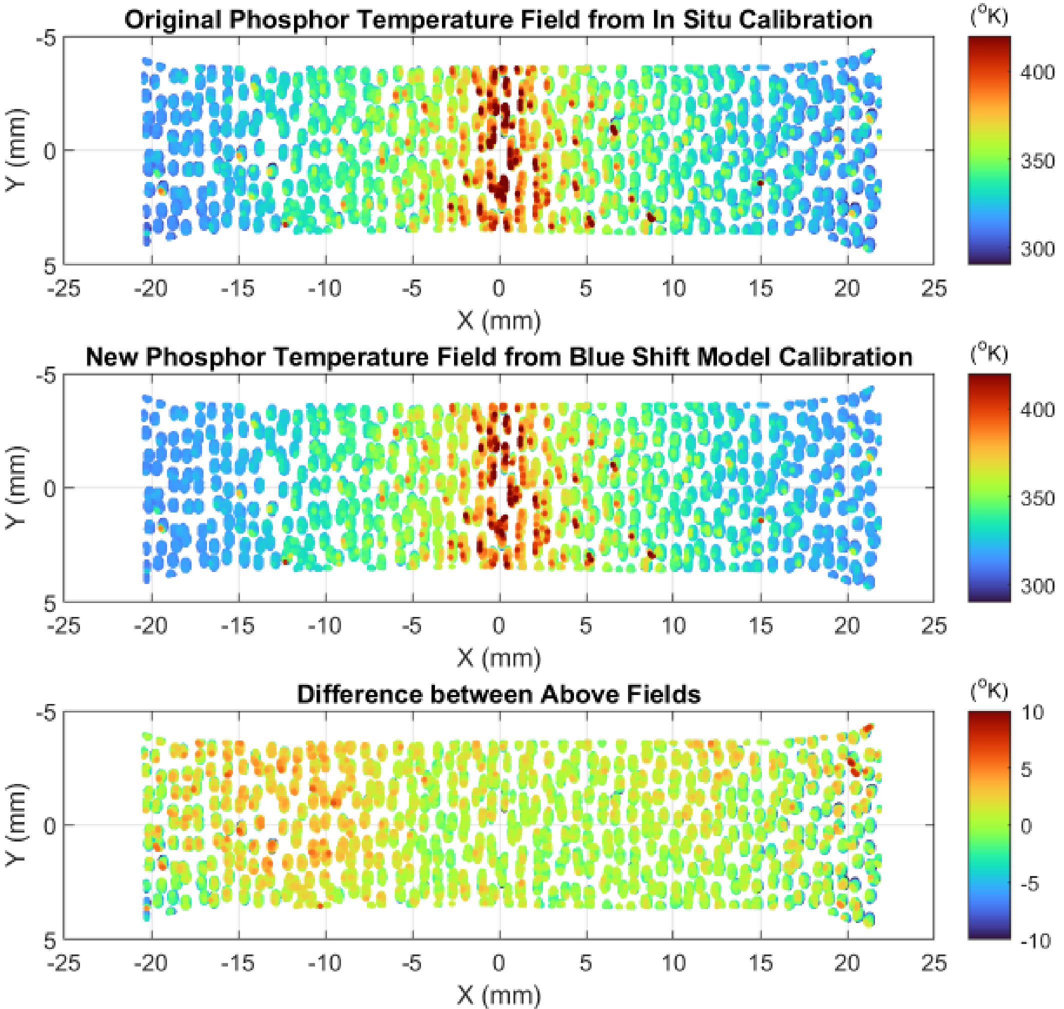
Improved blue-shift model calibration process



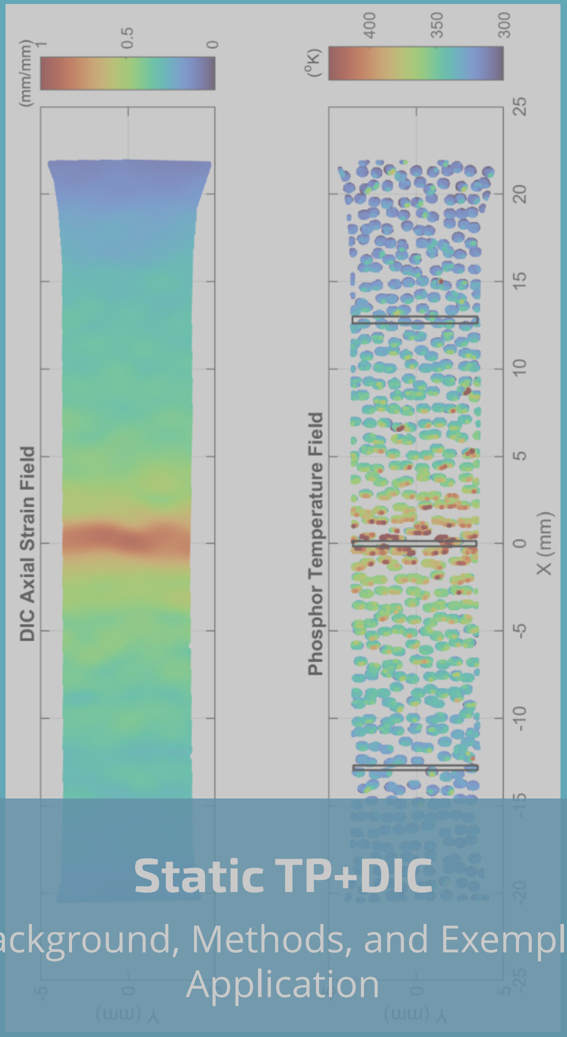
$$\lambda_\theta = \lambda_0\left[1-\left({}^{N_E}/_{N^*}\right)^2\sin\theta^2\right]^{1/2}$$



- Spectral response characterized **a single time** per phosphor
- Phosphor calibration coupon image *in situ* at room temperature and <u>**1**</u> elevated temperature

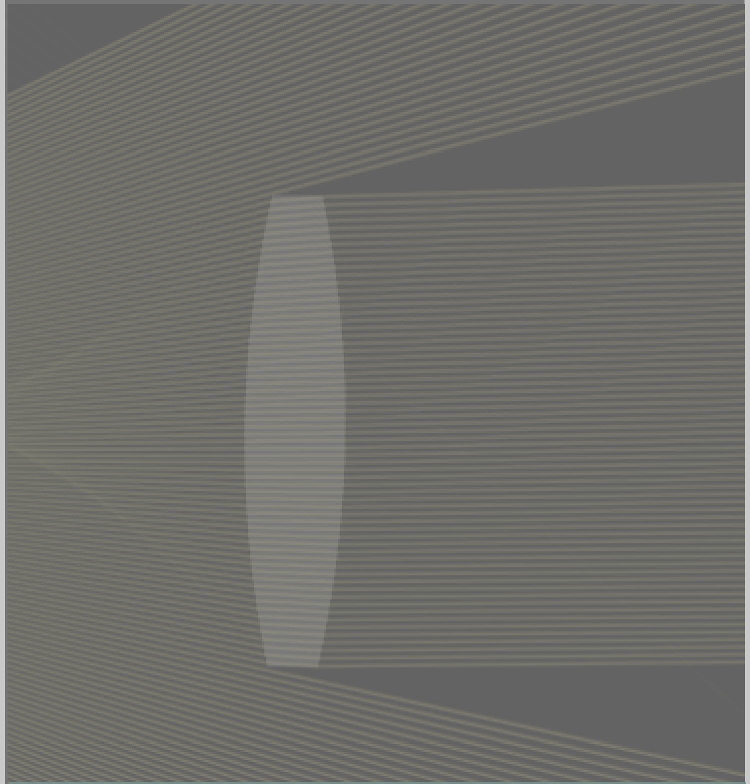


Preliminary results of temperature rise in a mechanically-deformed tensile dog bone show good agreement between the two calibration processes. Agreement will be improved with tuning of the blue shift model parameters



Static TP+DIC

Background, Methods, and Exemplar Application



Geometry-agnostic Calibration

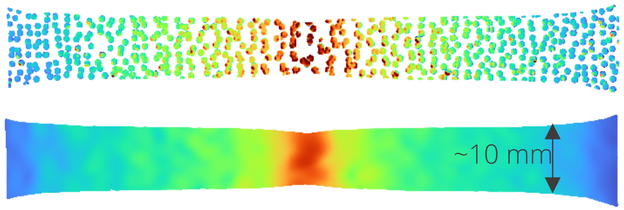
Dynamic Testing

Preliminary set-up and considerations for high strain rate testing

Maturing TP+DIC to dynamic testing will broaden applicability

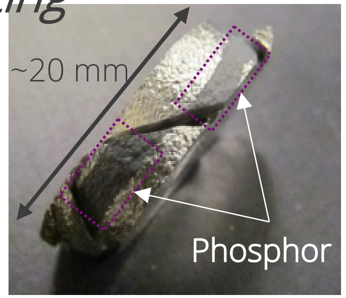
All samples were sprayed with Aerosol Deposition → binderless coating

Quasi-static testing



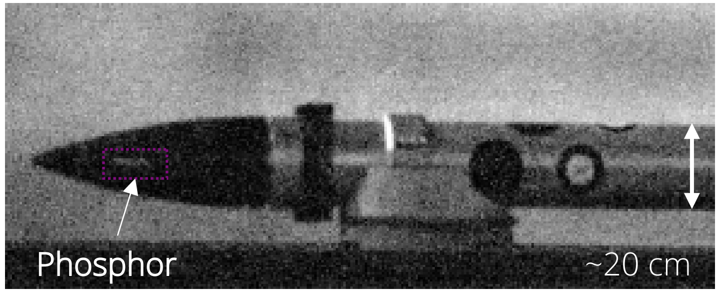
Surface maps of specimen response to tensile loading, at the moment before fracture

Moderate Dynamic Testing



Phosphor remained adhered to metal coupon after Hopkinson bar testing

Extreme Dynamic Testing



Thermo-phosphors patterned on a rocket nosecone were trackable during a sled track test

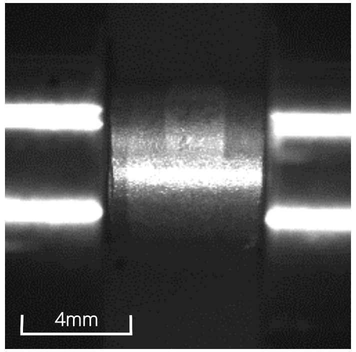
	Current Status	Next Steps
Strain Rates (s^{-1})	0.08 (quasi-static)	5×10^2 - 3×10^3 (moderate dynamic)
Temperature (˚C)	150	250-1000
Data Acquisition Rate (Hz)	24	10,000 – 500,000

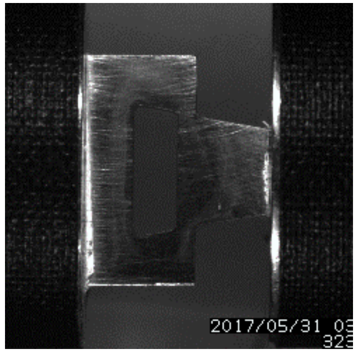
Dynamic testing advances diagnostics in a controlled laboratory

Experimental Impact Mechanics Lab

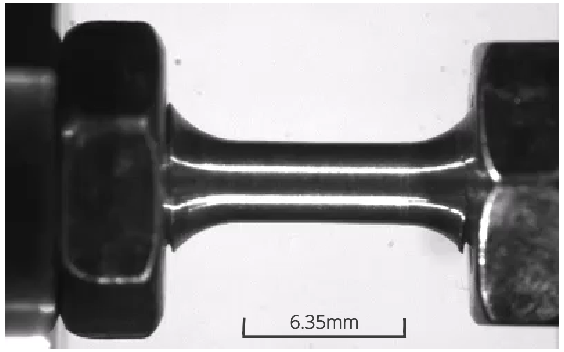
Capabilities:
- Strain rates ranging from 100s^{-1} to 5000s^{-1}
- Loading durations up to ~1ms
- Various stress states including compression, tension, torsion, shear, etc.
- Extreme temperatures ranging from -200°C to 2000 °C
- In-situ DIC
- In-situ IR Temperature Measurement

Dynamic Compression



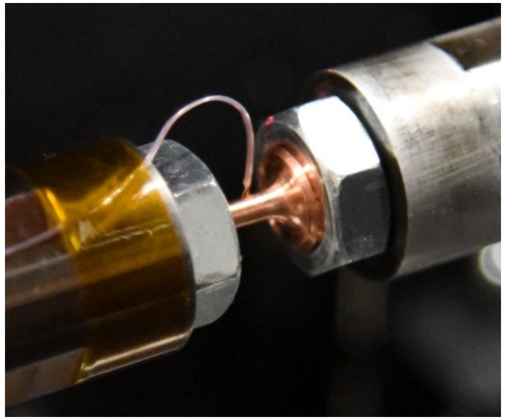


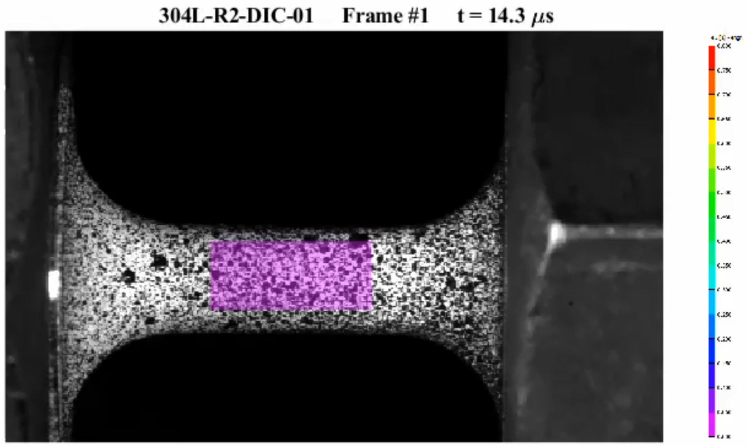
Dynamic Tension



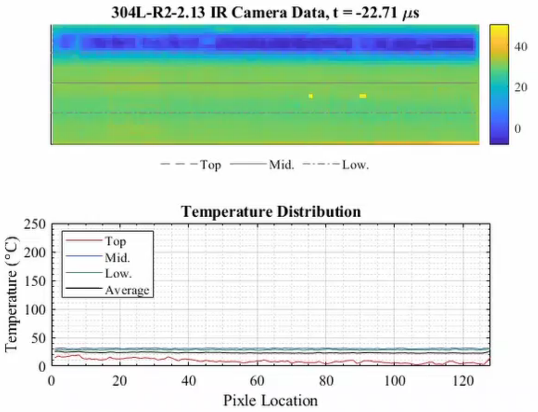
ca. 600μs loading duration

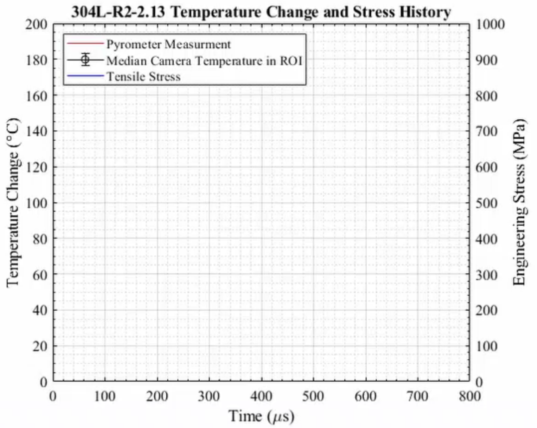
In-situ DIC





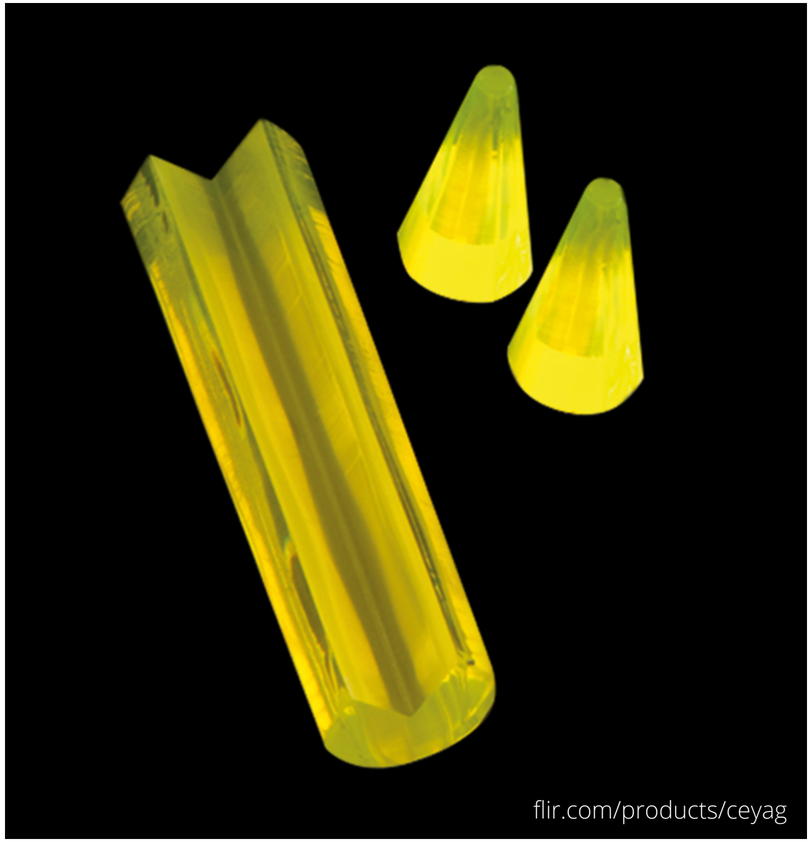
In-situ Temperature Measurement





High-speed phosphor selection must consider four factors.

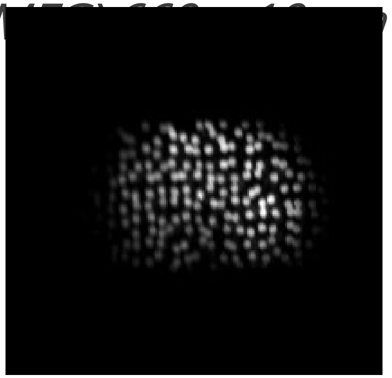
Temperature Sensitivity 300 – 600 K



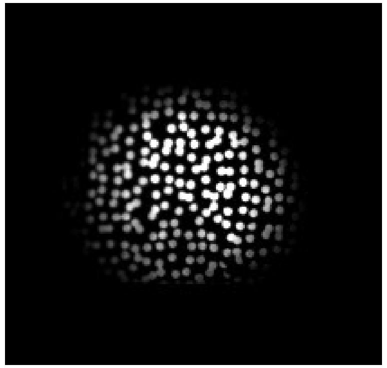
Phosphors must thermally respond faster than the image capture time, remain temperature sensitive, and produce high quality images.

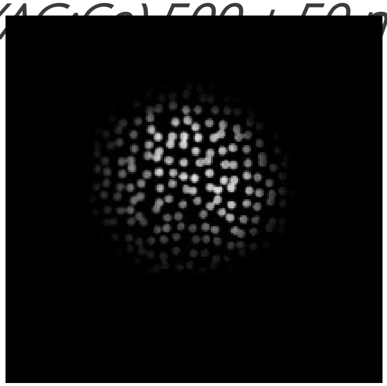
- All samples were sprayed with Aerosol Deposition → binderless coating
- Magnesium Fluorogermanate (MFG) is used as a benchmark

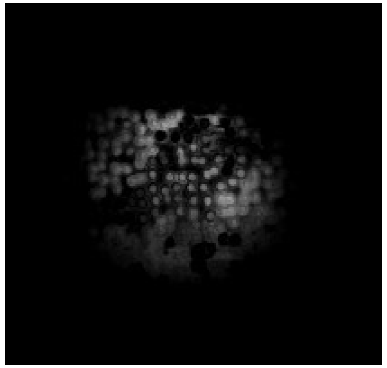
Magnesium Fluorogermanate (MFG) 660 ± 10 nm



Cerium doped Yttrium Aluminum Garnet (YAG:Ce) 500 ± 50 nm







E = 280 μJ/pulse
Exposure Time = 3300 μs
Thickness = 5-10 μm

E = 100 μJ/pulse

E = 50 μJ/pulse

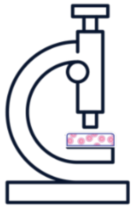
Exp. Time = 0.87 μs

Thickness = 4 μm

Thickness = ~80 μm

Sufficient signal from YAG:Ce was generated using a nanosecond laser pulse.
Insufficient signal was generated using continuous UV LEDs.
Next steps – finalizing excitation and installation into Hopkinson Bar Lab

How can we use TP+DIC to assess structural integrity for safety engineering?



10s of Microns

LABORATORY TESTING

Small-scale material characterization

How does work convert to heat?

MODEL CALIBRATION

Plastic-work-to-heat conversion added to models

Rich and reliable data sets reduce uncertainty

COMP/SIM DESIGN

Physically-sound models simulate new design response

PRODUCTION TESTING

Individual pieces can be tested in accident scenarios

Do predictions account for thermal and solid mechanics effects?

FULL-SCALE TESTING

Test the safety and response of an entire aircraft to an accident

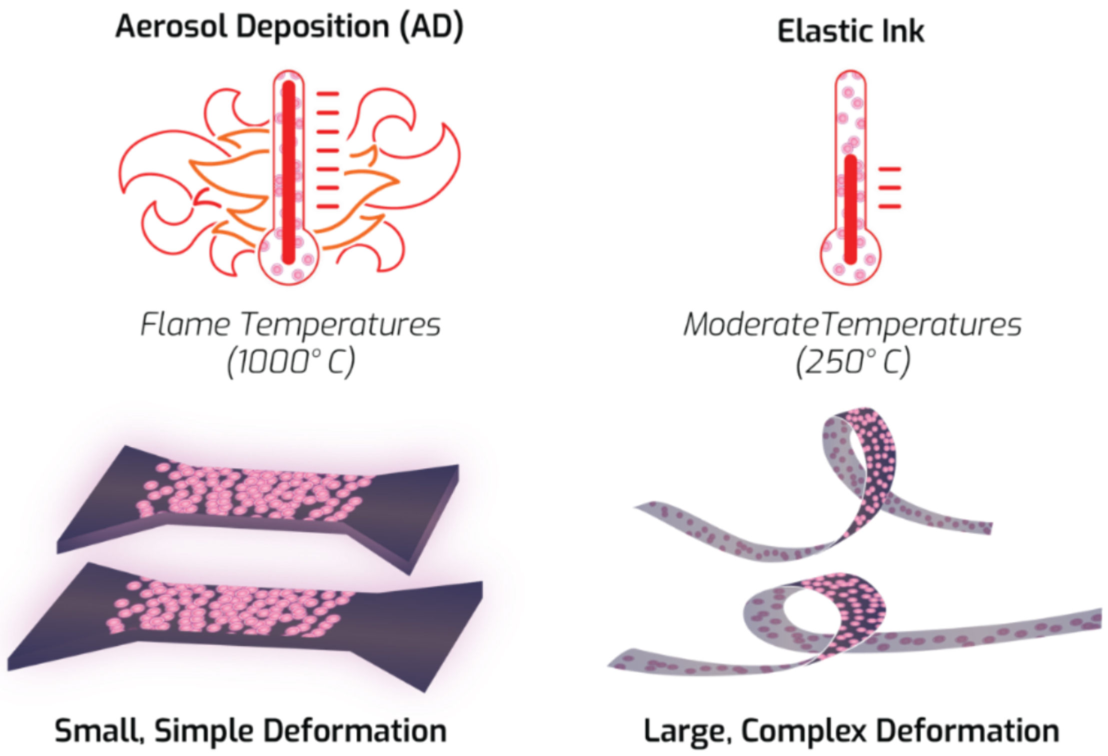
10s of Meters

This work was funded by Sandia's Laboratory Directed Research and Development Program & NNSA's Technology Maturation Portfolio

Questions?

Additional Slides

Evaluate phosphor-ink under large deformations



Multiple patterning techniques extend the usability of TP+DIC

- Patterning can be tailored to the environment
- Aerosol deposition – a binderless, impact consolidation coating – can resolve flame temperatures in reacting environments but only small deformations (left).
- Elastic ink with embedded thermo-phosphors can resolve and large deformations but only at moderate temperatures (right).