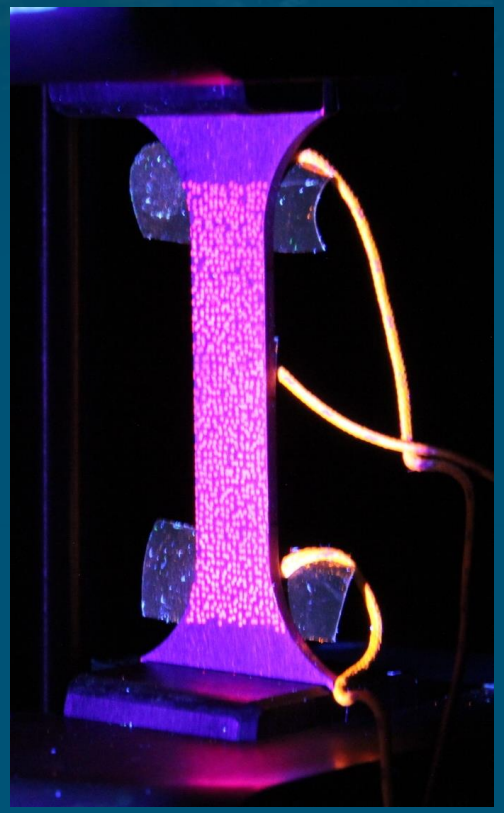
SAND2022-11711C

Sandia National Laboratories

BSSM

Thermophosphor Digital Image Correlation (TP+DIC): Simultaneous strain and temperature measurements



Elizabeth M. C. Jones, Amanda R. Jones, Caroline Winters

Sandia National Laboratories, Albuquerque, NM, USA

16th International Conference on Advances in Experimental Mechanics

7-9 September 2022

BSSM Best Paper in 'Strain' Fylde Prize for 2021

DOI: 10.1111/str.12415

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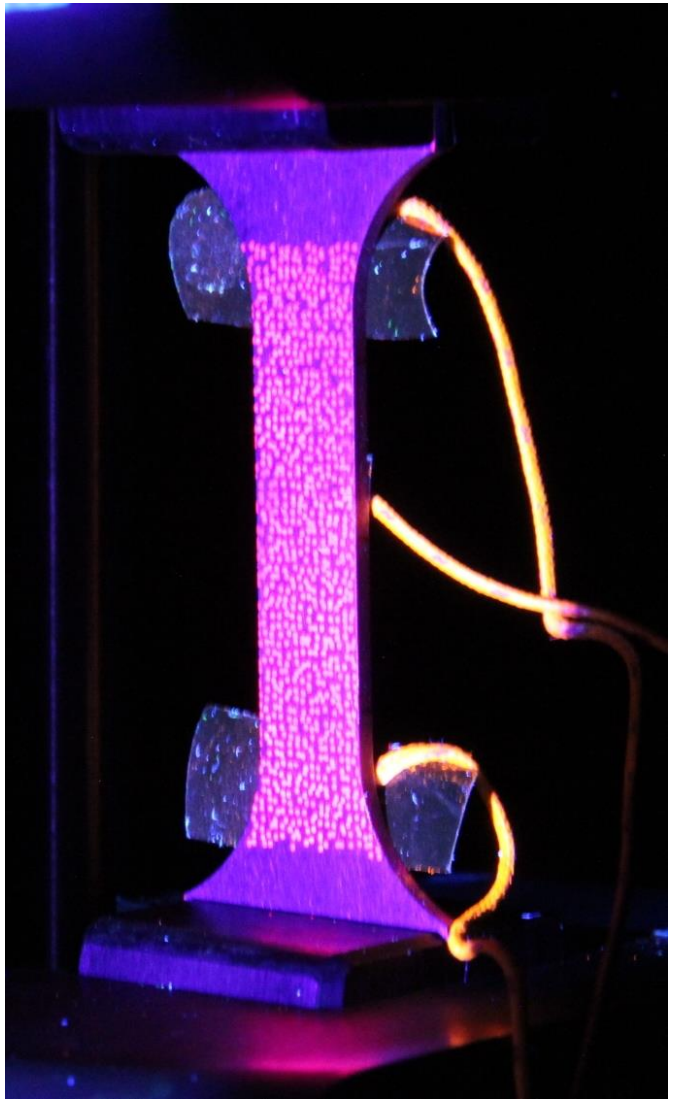
SAND2022-XXXX

Thermophosphor Digital Image Correlation (TP+DIC): Outline

Background

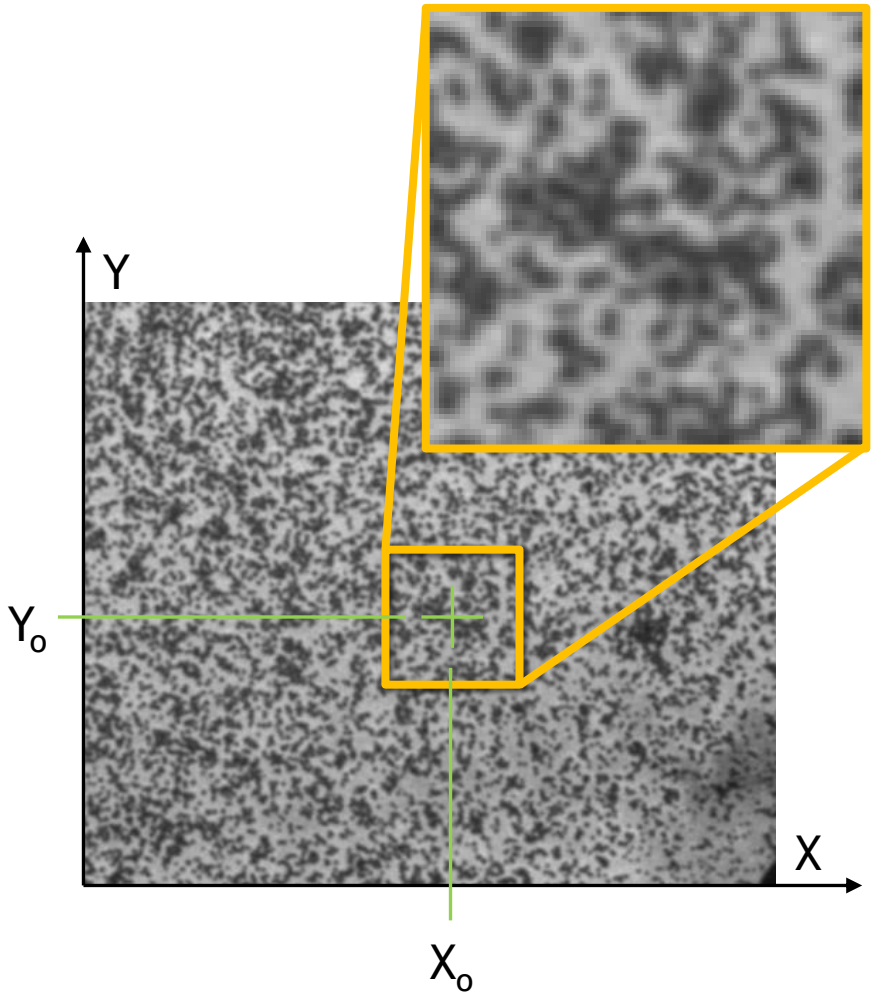


Methods and Exemplar Application

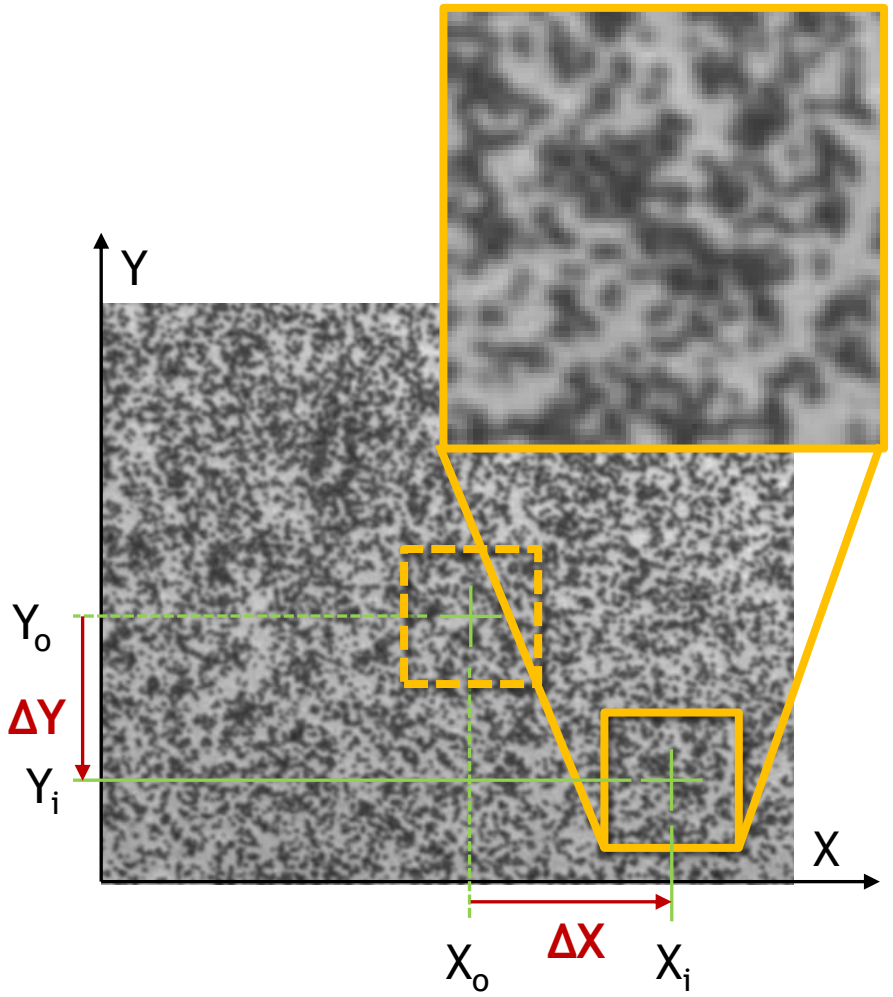
Current Developments

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

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



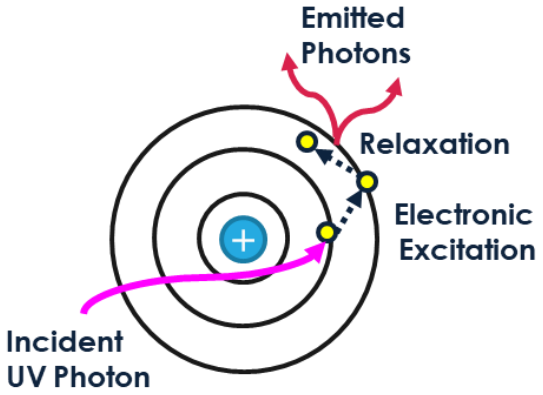
Reference (undeformed) image

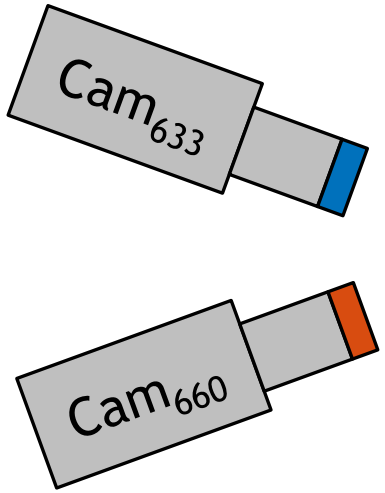


Deformed image

Phosphor emission demonstrates temperature dependence.

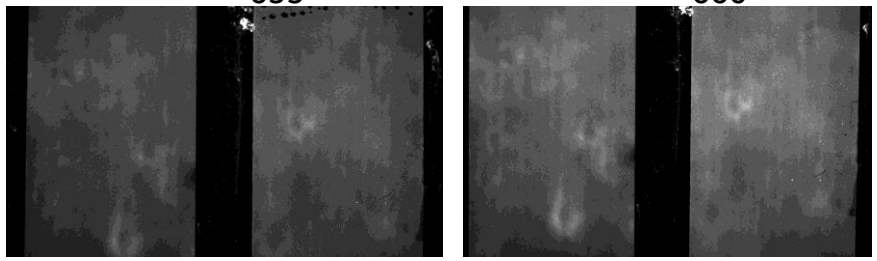
Phosphors are transition or rare earth elements doped into a ceramic material



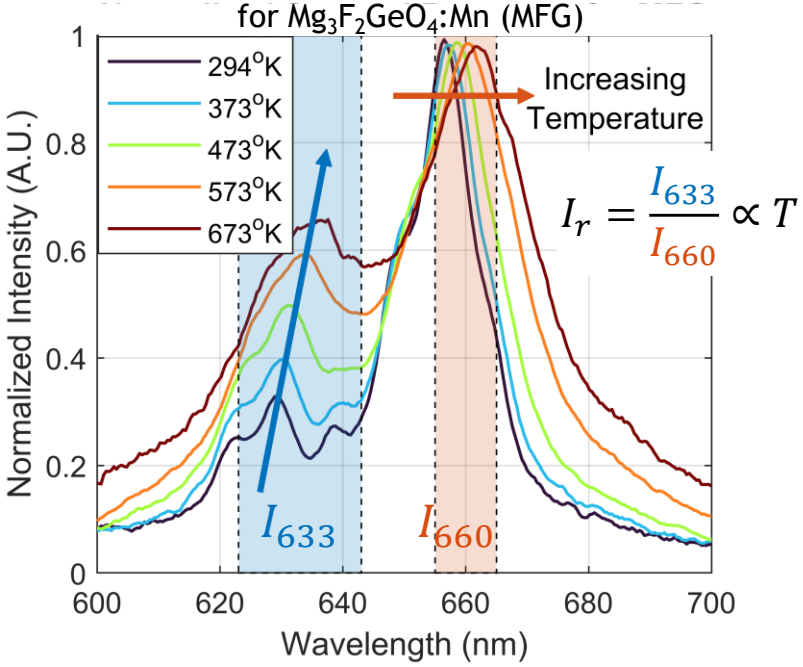


Test piece

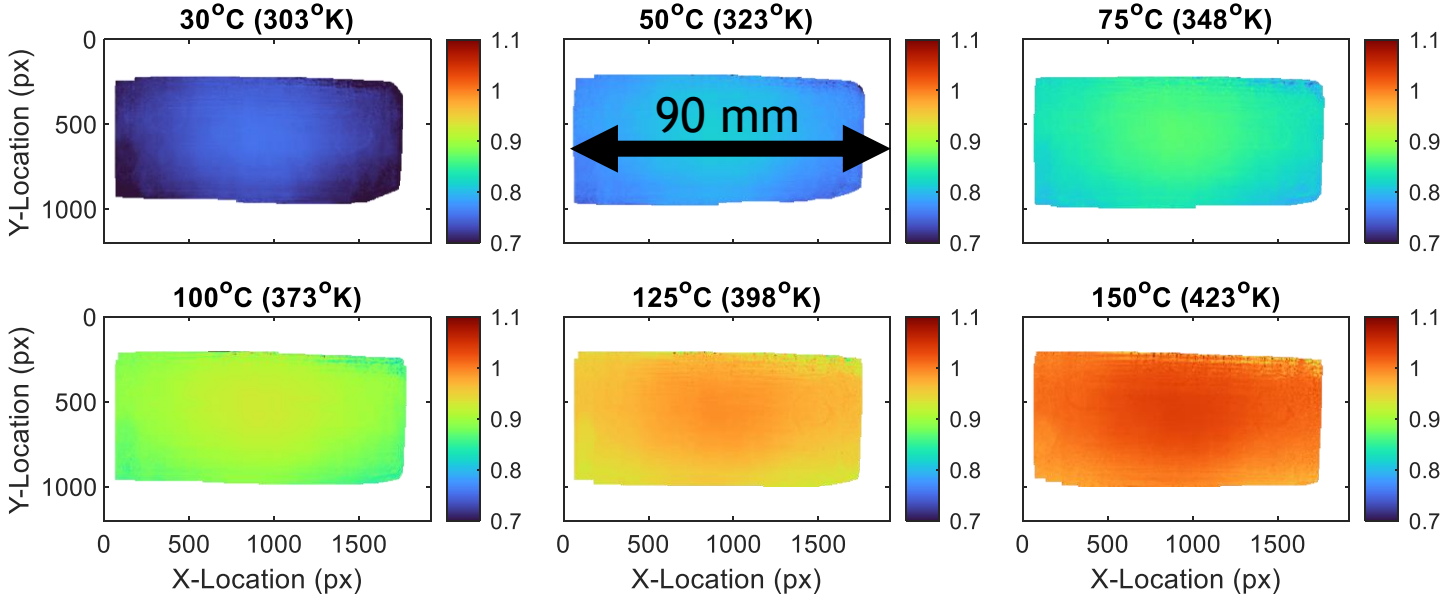
Cam633 Cam660



Normalized Spectral Response for $Mg_3F_2GeO_4$:Mn (MFG)



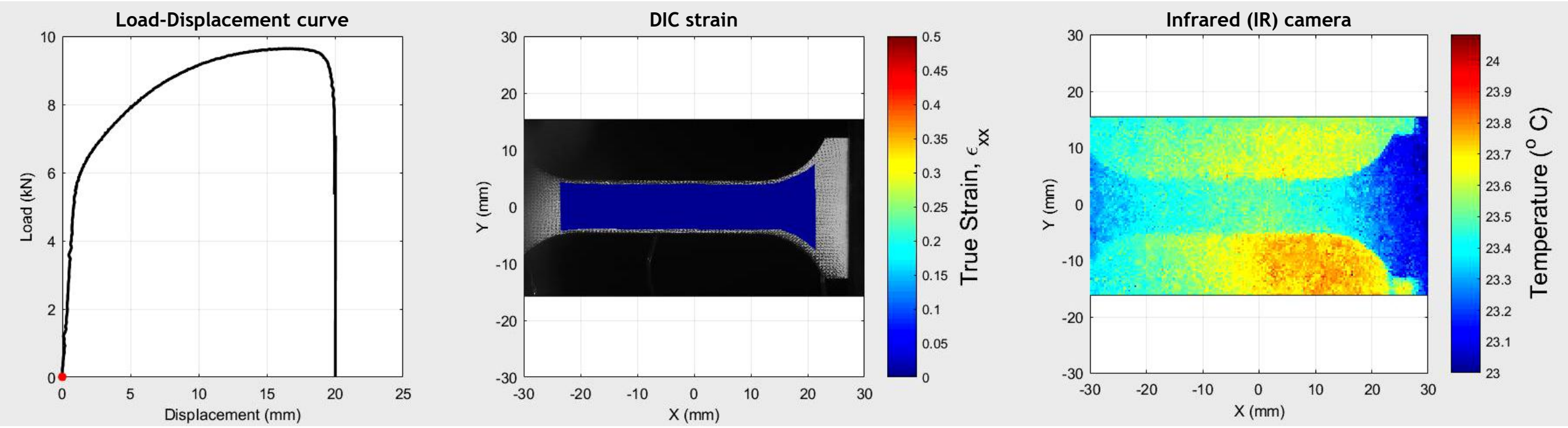
Emission Intensity Ratio: $I_r = \frac{I_{633}}{I_{660}} \propto T$



EMC Jones et al., *Meas. Sci. Tech.*, 2022

Simultaneous strain and temperature measurements are useful for many applications.

Example application: Conversion of plastic work into heat for 304L stainless steel

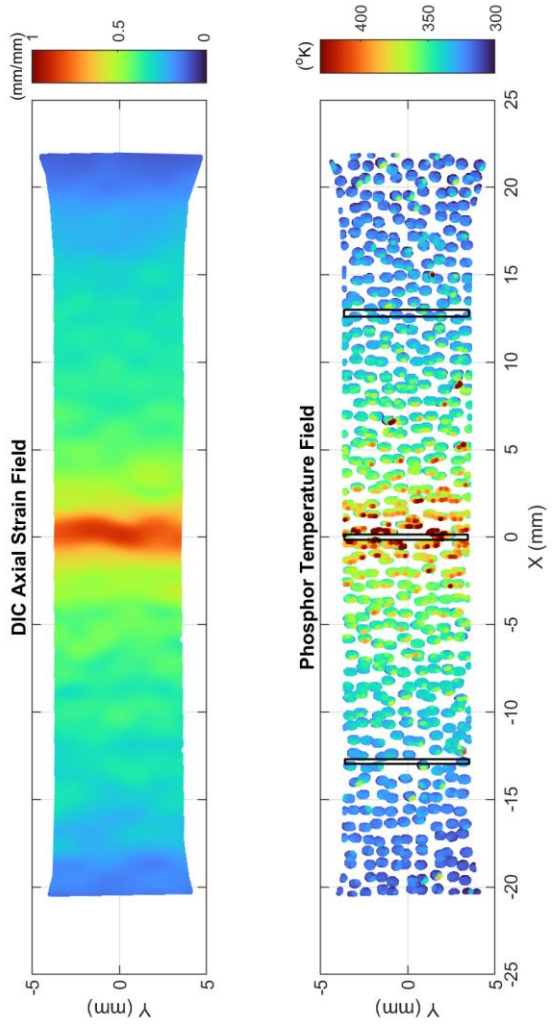


- Benefits of phosphor thermometry
  - Only need two machine vision cameras (no expensive IR camera required)
  - Strain and temperature inherently in same coordinate system (no coordinate transforms or interpolation required)
  - Optical cameras faster than IR cameras for dynamic measurements
  - Phosphors create high-contrast pattern even at >740^{o}C temperatures
  - Do not need to know sample emissivity (but do need to know phosphor emission)

Thermophosphor Digital Image Correlation (TP+DIC): Outline

Background

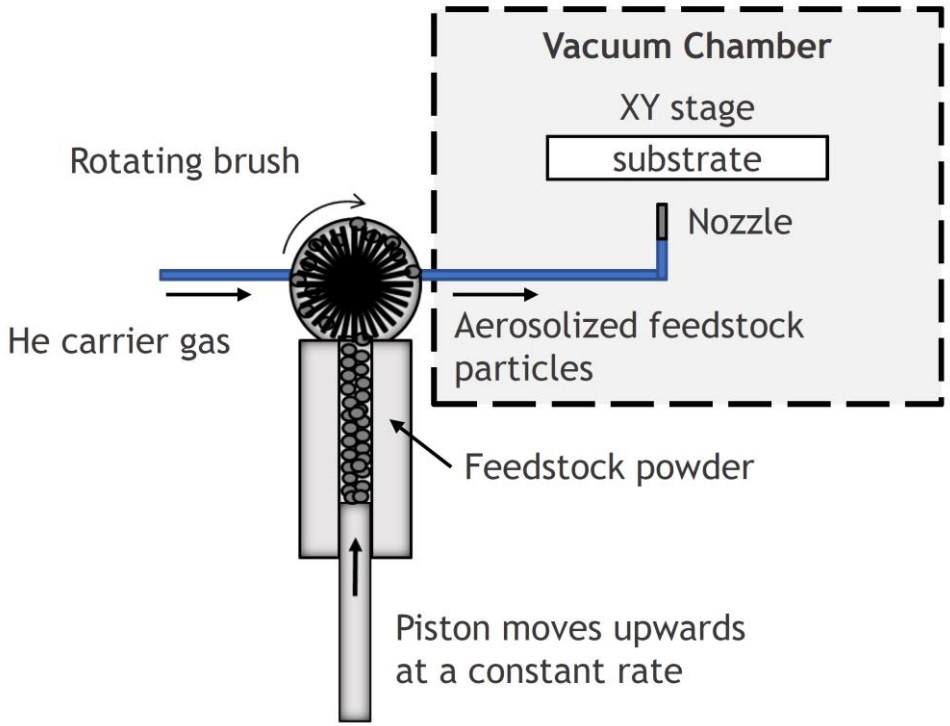
Methods and Exemplar Application



Current Developments

Robust coating of phosphors obtained by aerosol deposition (AD) through a Kapton mask.

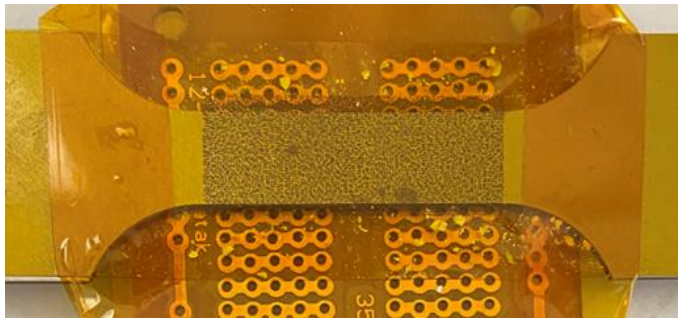
Schematic of aerosol deposition (AD) process



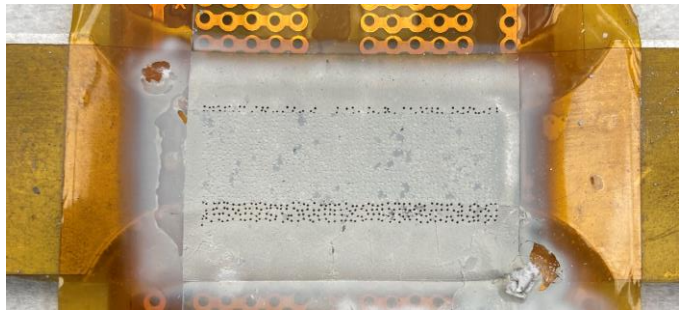
- Impact consolidation process
- Coating density > 95% base material
- Room temperature process
- Binderless coating

Kapton mask on sample

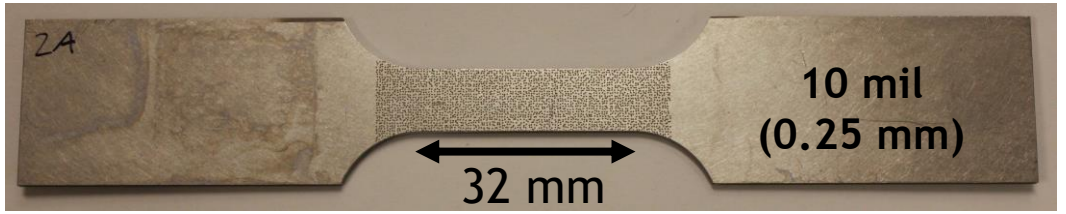
Before deposition

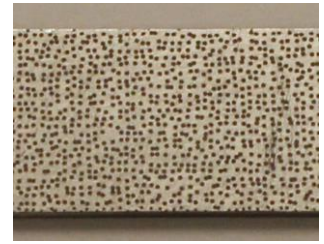


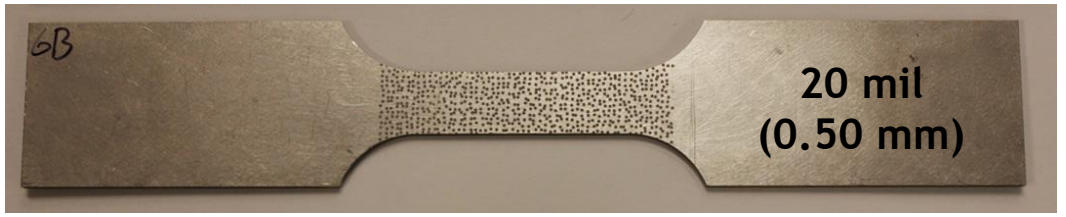
After deposition

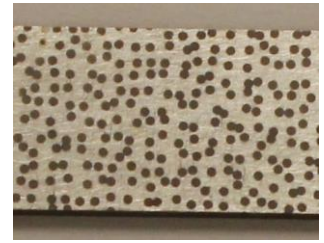


$Mg_3F_2GeO_4$:Mn (MFG) phosphor DIC patterns on 304L stainless steel dog bones





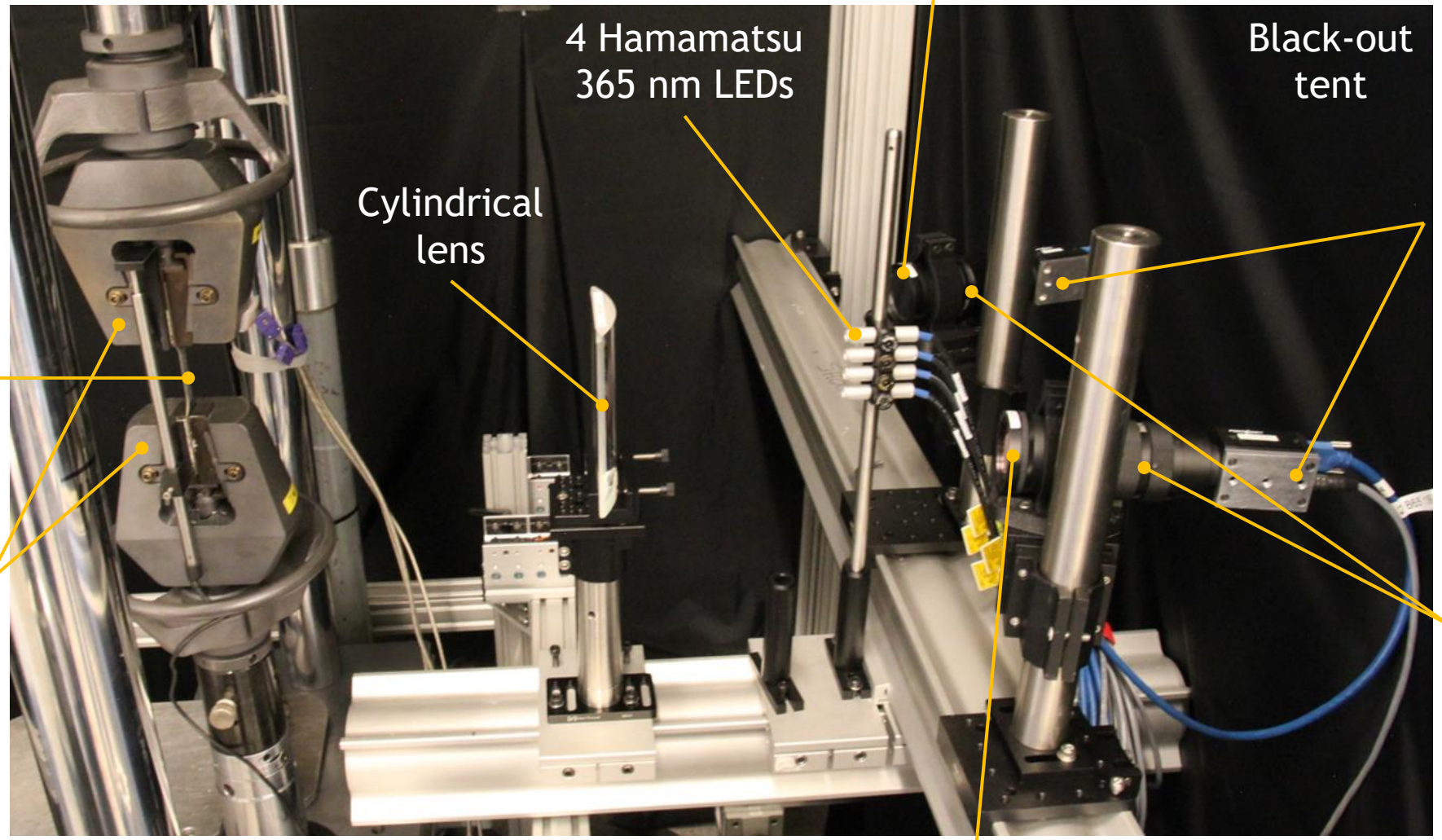




Collaborators: Adrianna Grijalva, Adrian Casias, Shannon Murray, Jake Mahaffey

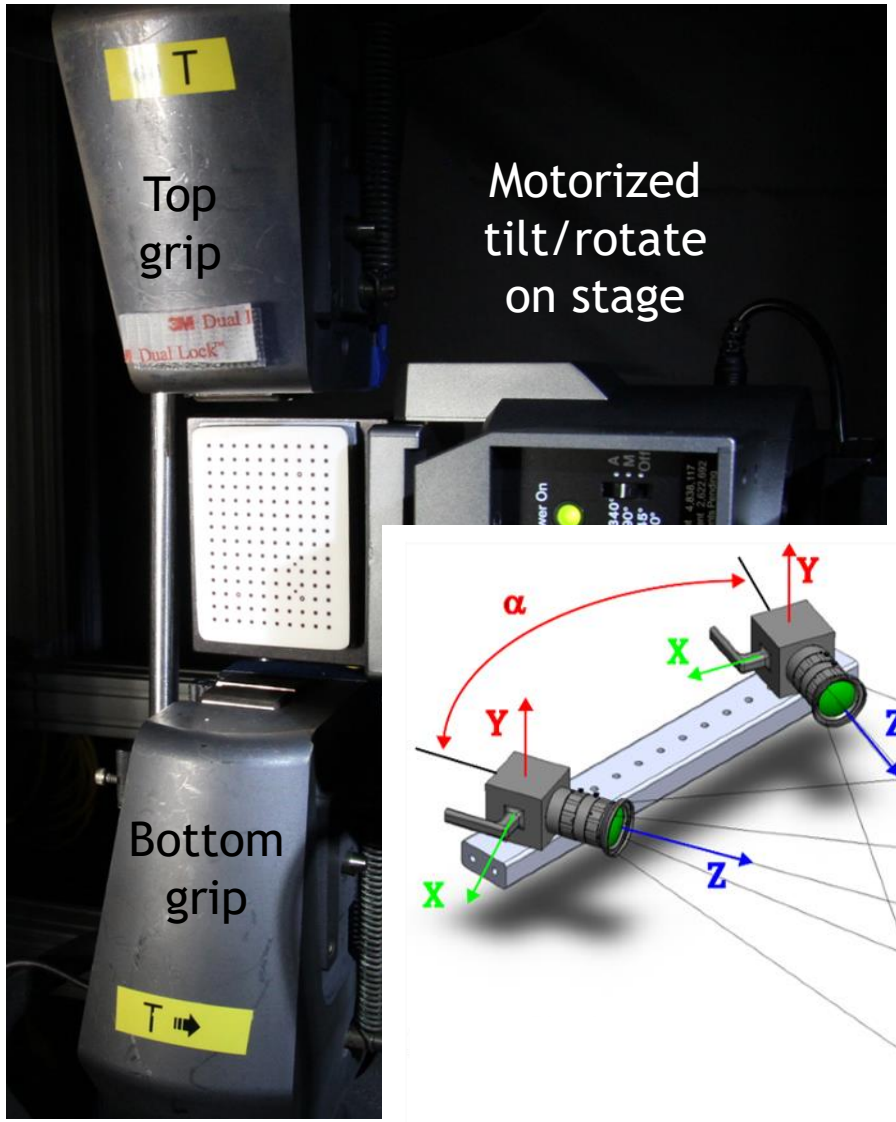
Mahaffey et al., *Proc. SPIE*, 2021
Winters et al., SAND2021-13971, 2021

Experimental Setup

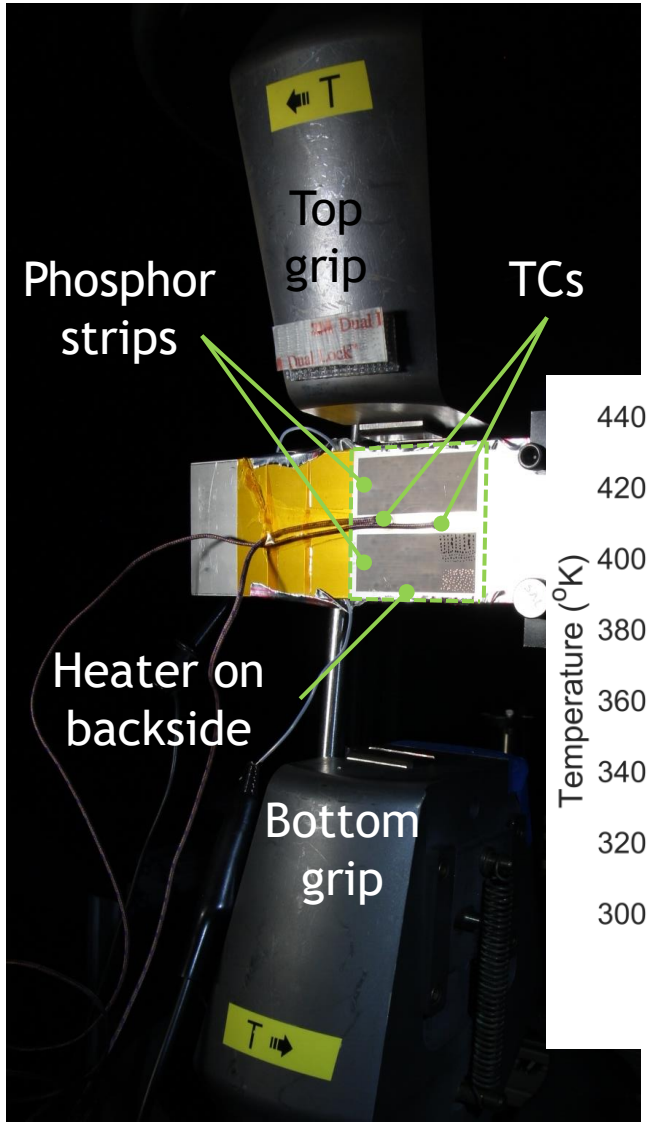


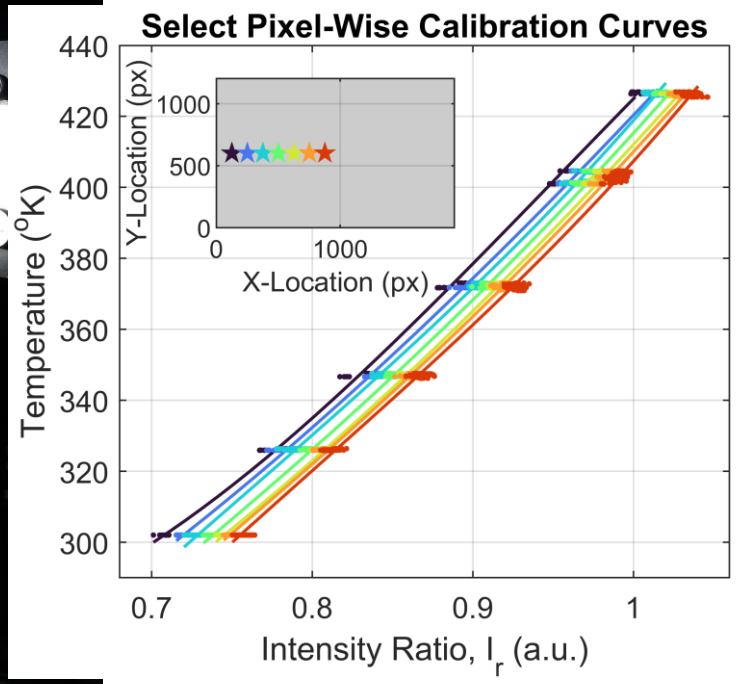
Two sequential calibrations were performed for DIC and TP.

DIC calibration



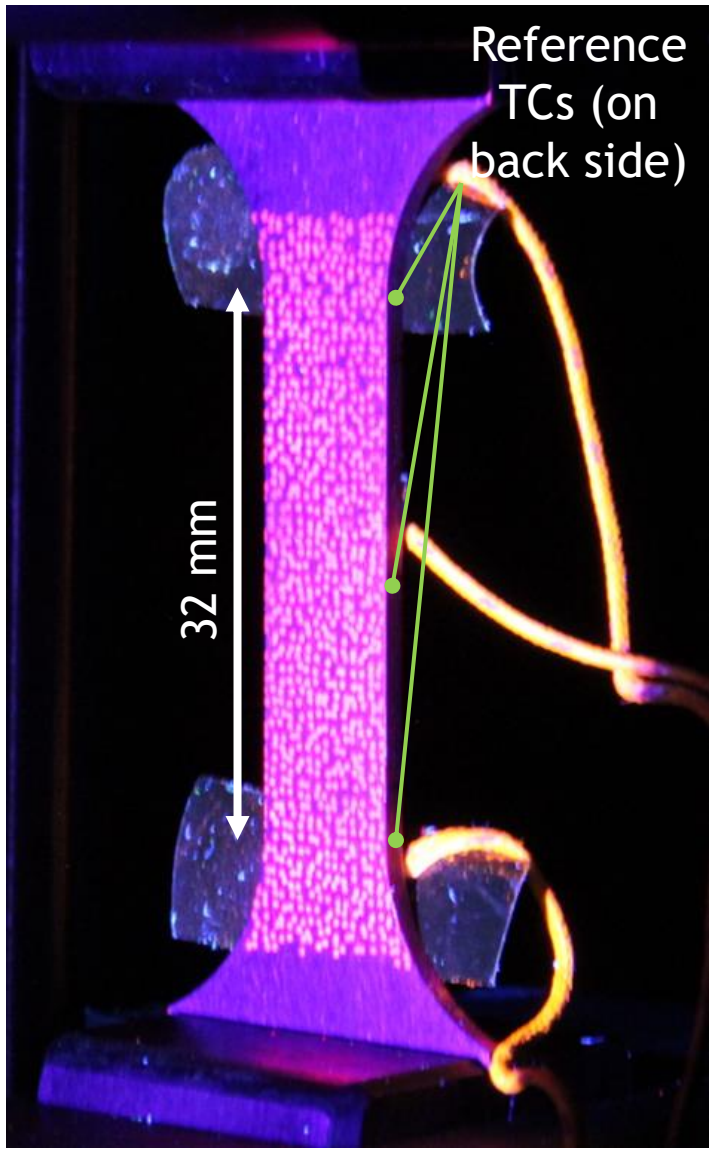
TP calibration

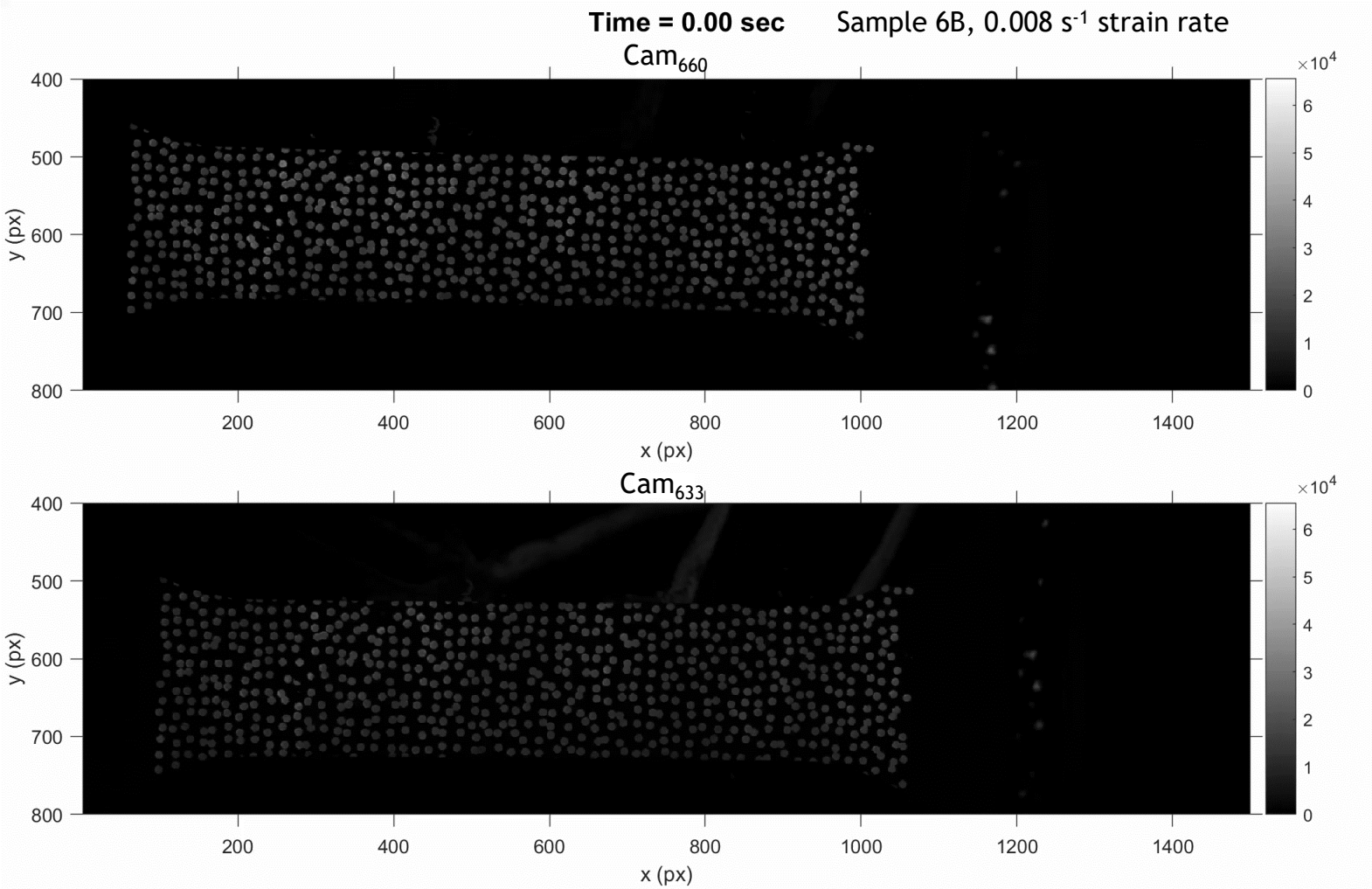




EMC Jones et al., *Meas. Sci. Tech.* (2022)

Tensile dog bones of 304L stainless steel with a phosphor DIC pattern were pulled in tension to failure at different strain rates.

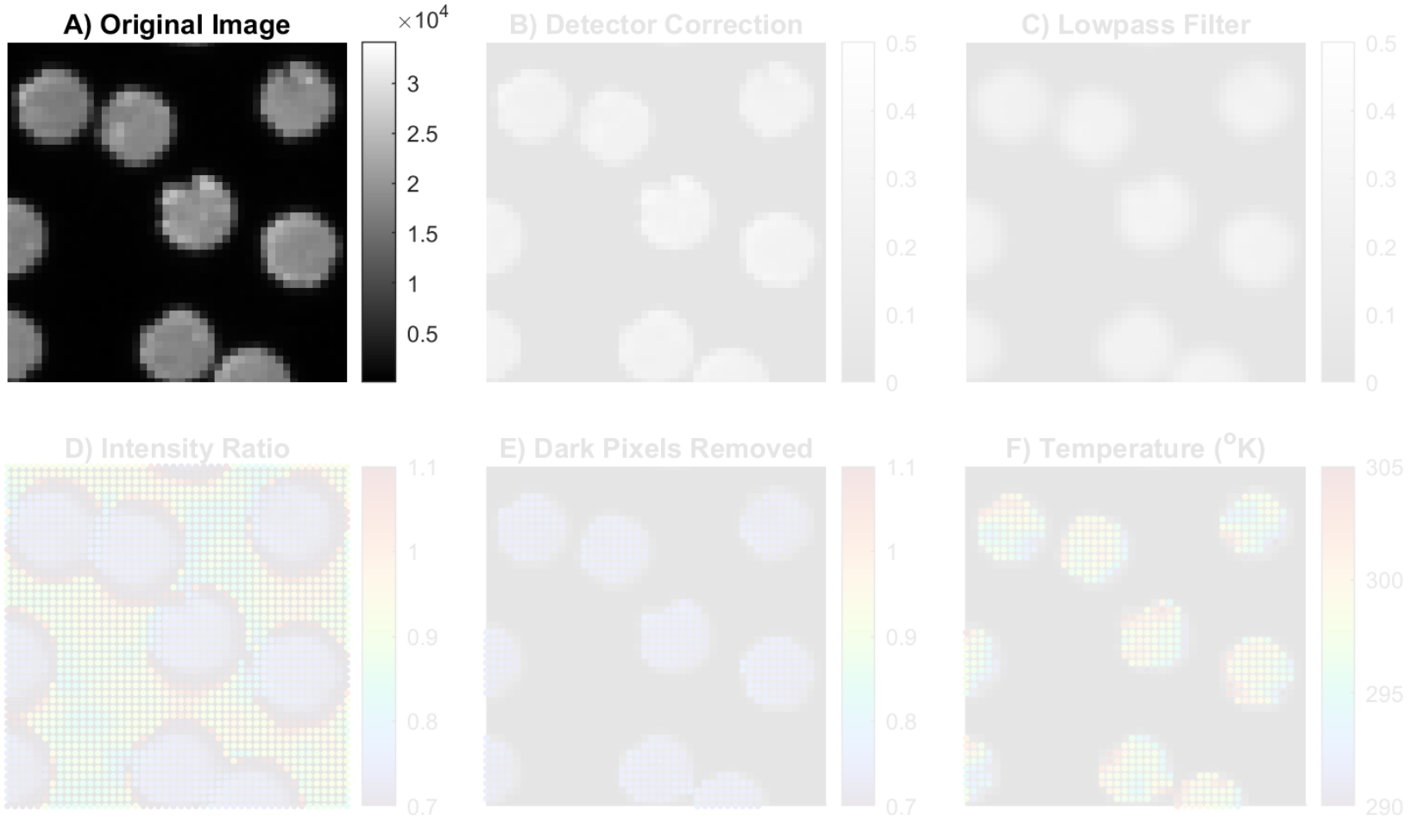




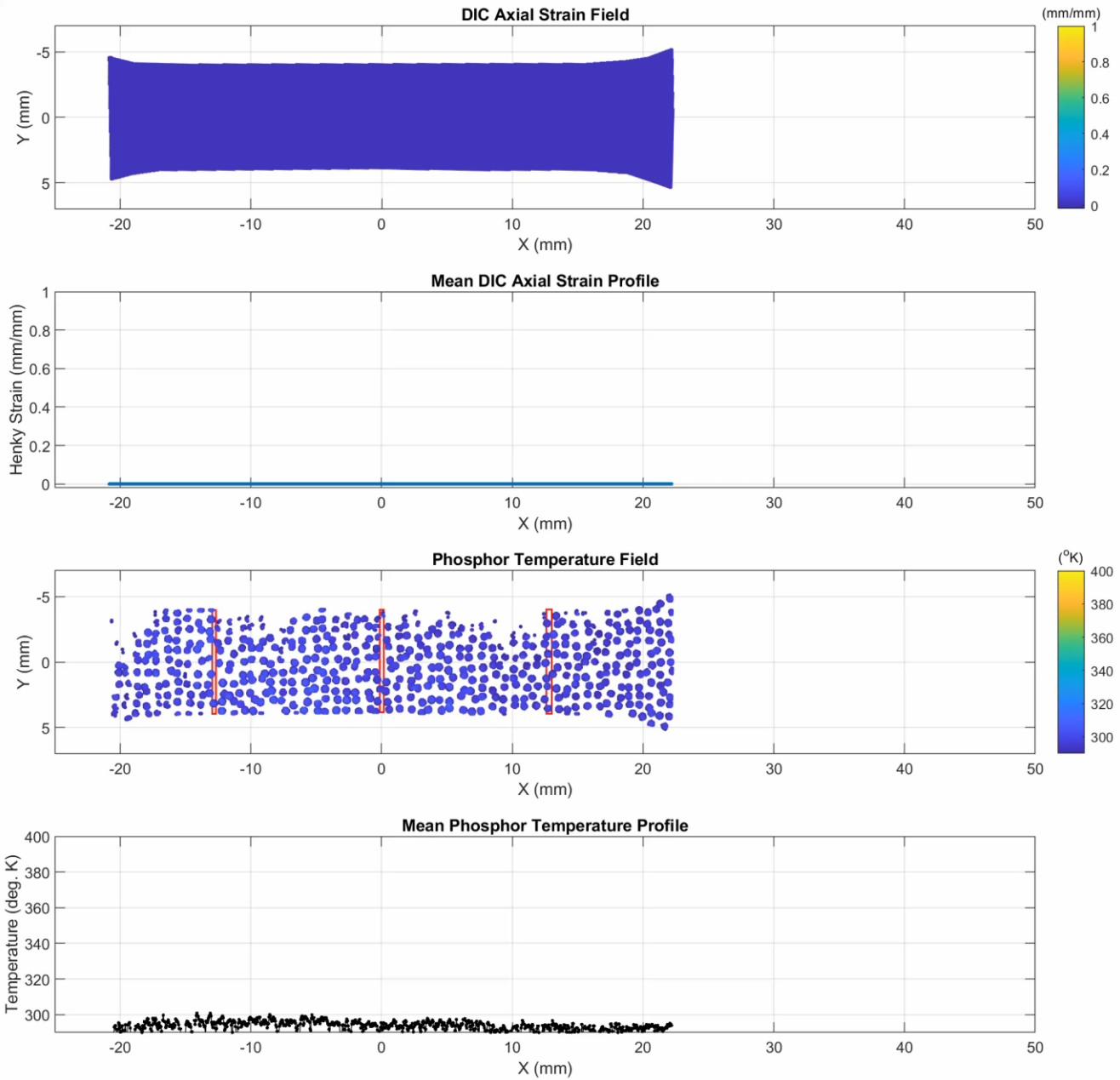
- Intensity increase in elastic and initial yield not yet fully understood.
- Phosphor dots crack as sample deforms, driving phosphor ink development.

Several steps are required to process the images to obtain temperatures.

1. Load original images
2. Apply nonlinear, heterogeneous camera detector correction
3. Low-pass filter images
4. Interpolate intensity to sub-pixel locations
5. Perform DIC to correlate points between Cam_{660} and Cam_{633}
6. Compute intensity ratio, $I_r = \frac{I_{633}}{I_{660}}$
7. Remove saturated and dark pixels
8. Compute temperature using pixel-wise calibration curves

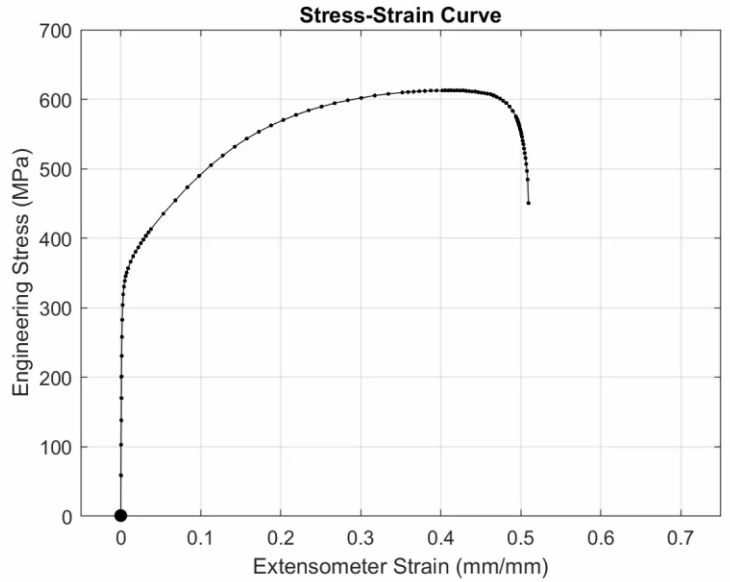


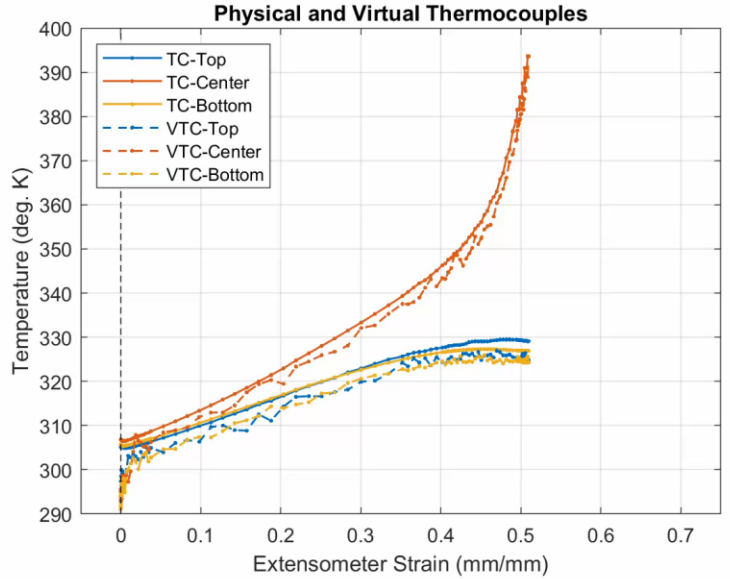
TP+DIC was successfully applied to simultaneously measure full-field strains and temperatures.



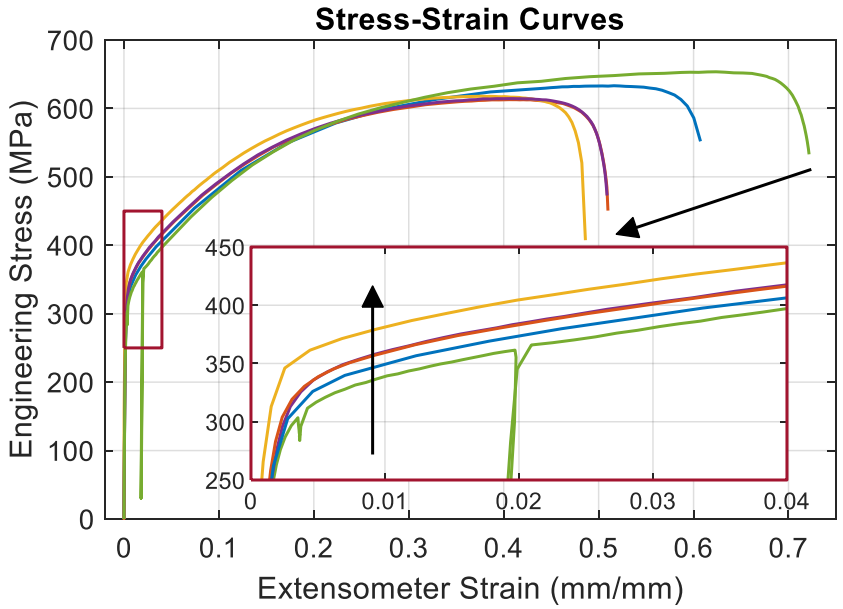
2021-04-15-Sample6B 0.008 s^{-1} strain rate

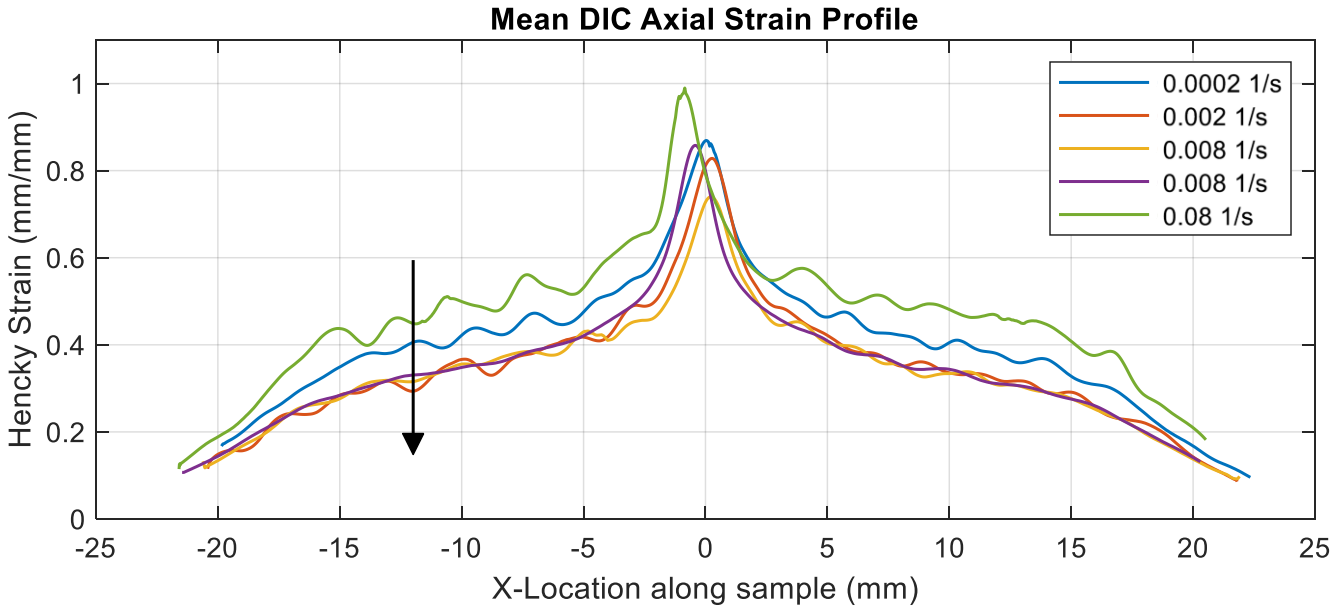
Time = 0 sec

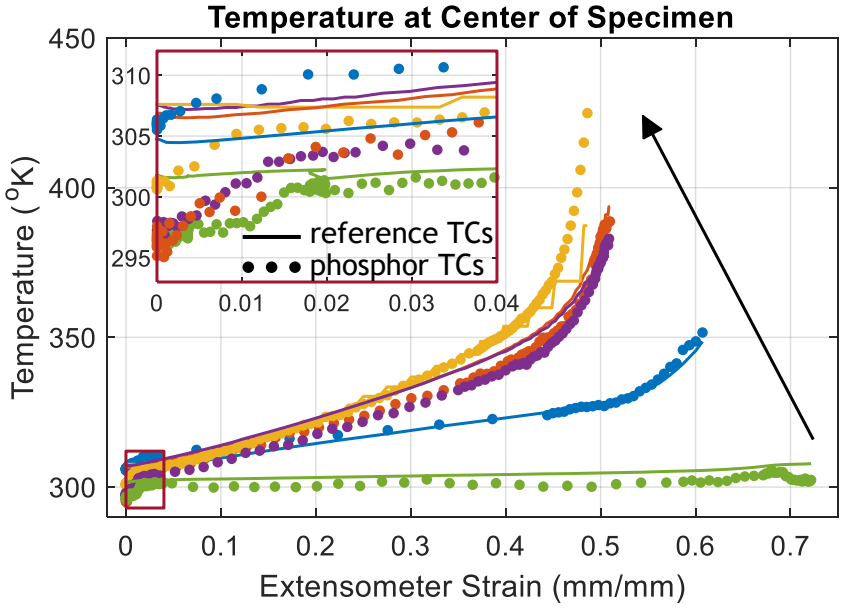


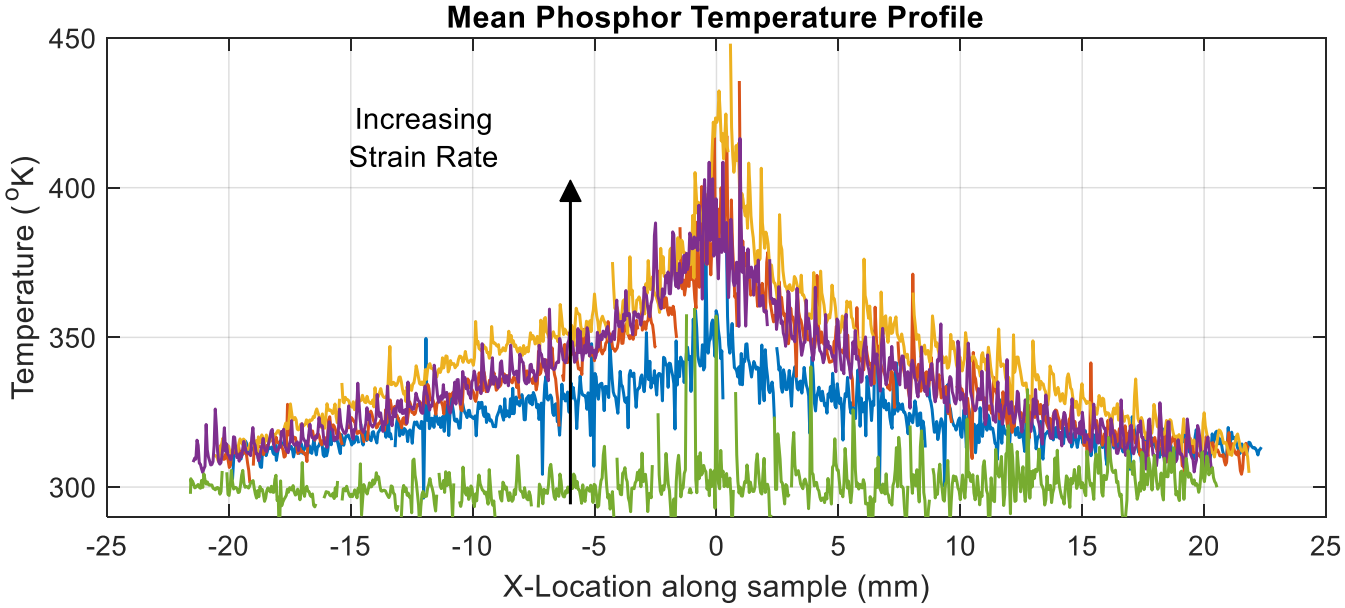


In sum, full-field strains and temperatures provide useful information for thermo-mechanical material characterization.







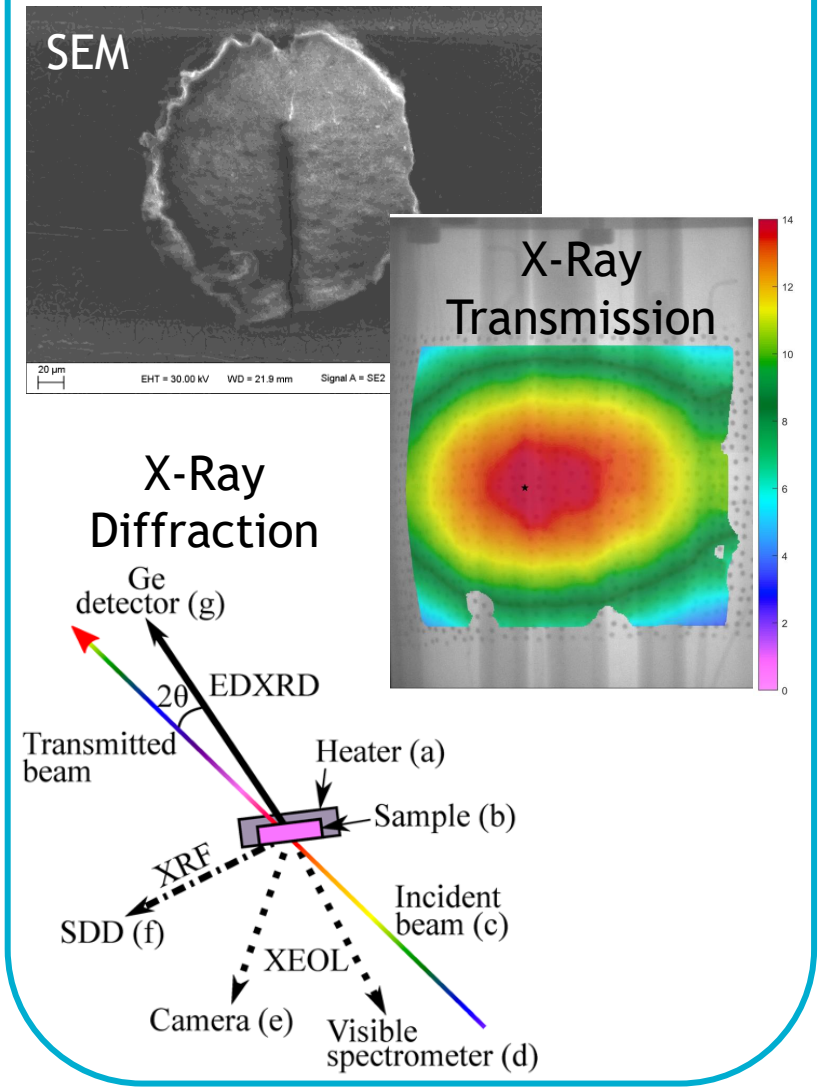


Thermophosphor Digital Image Correlation (TP+DIC): Outline

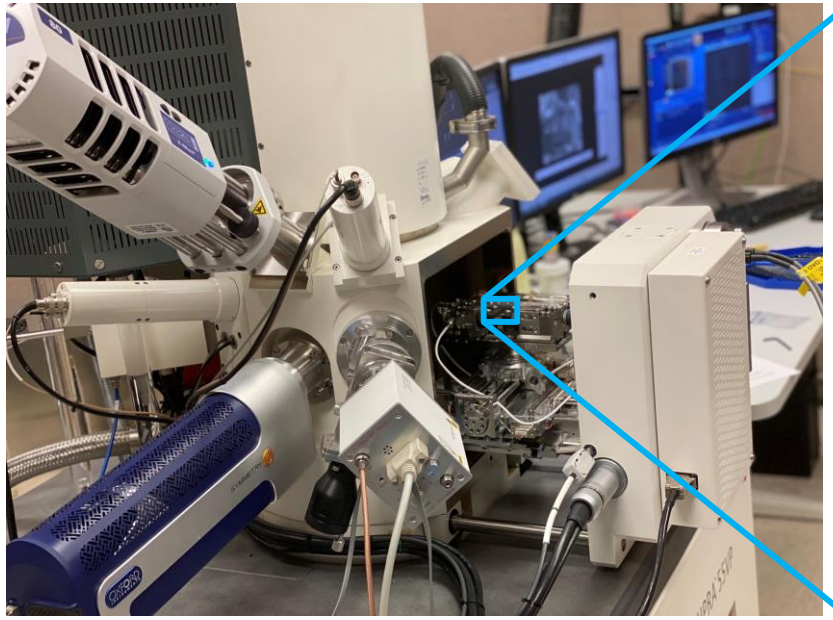
Background

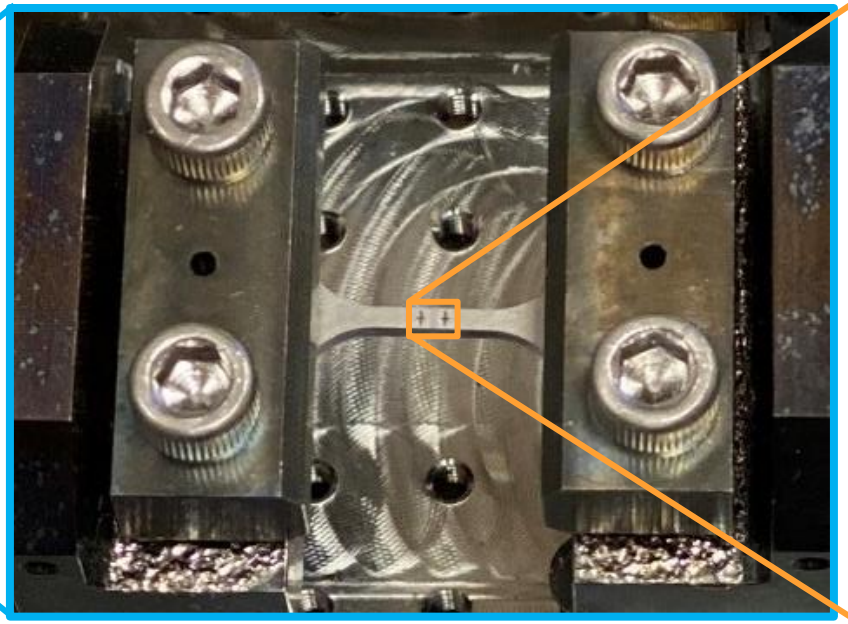
Methods and Exemplar Application

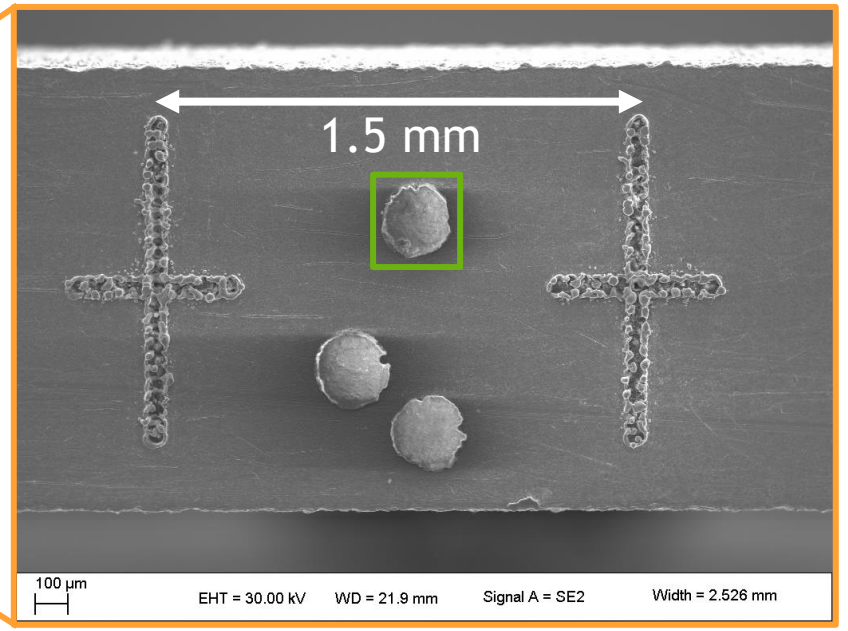
Current Developments

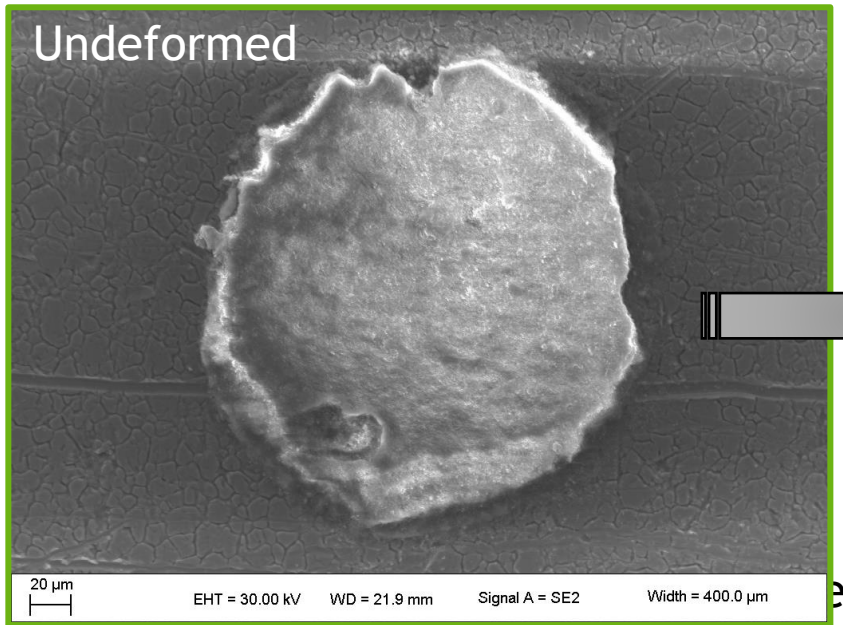


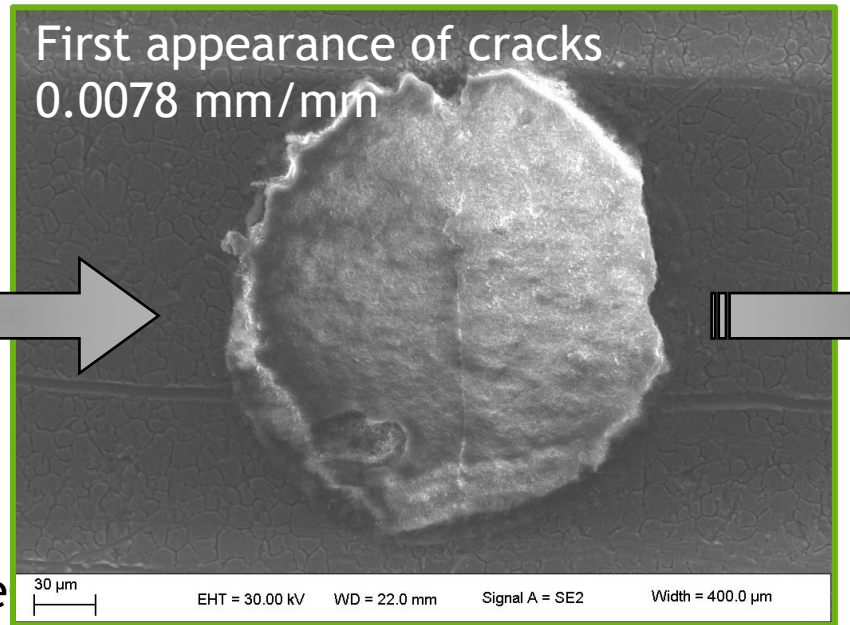
In situ tensile testing in a scanning electron microscope revealed micro-cracking and debonding.

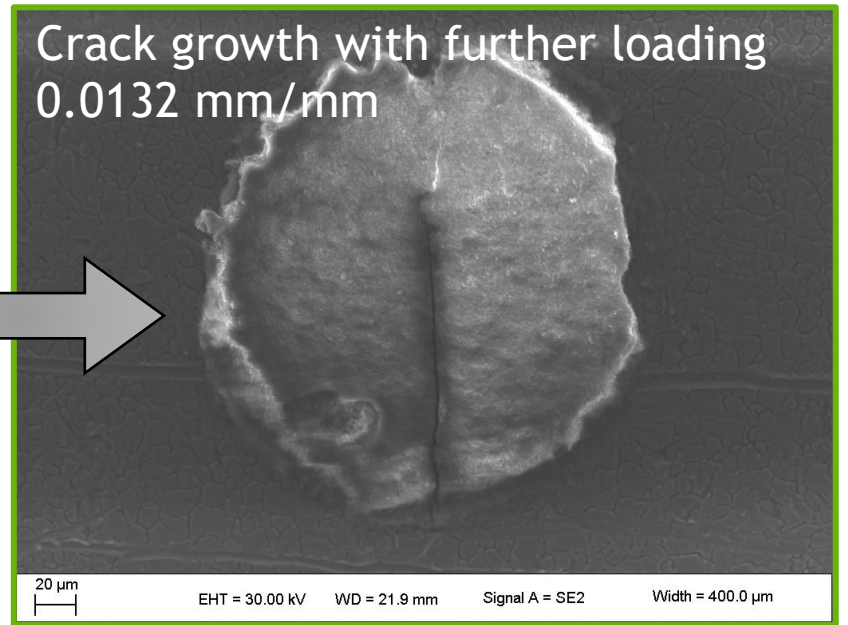






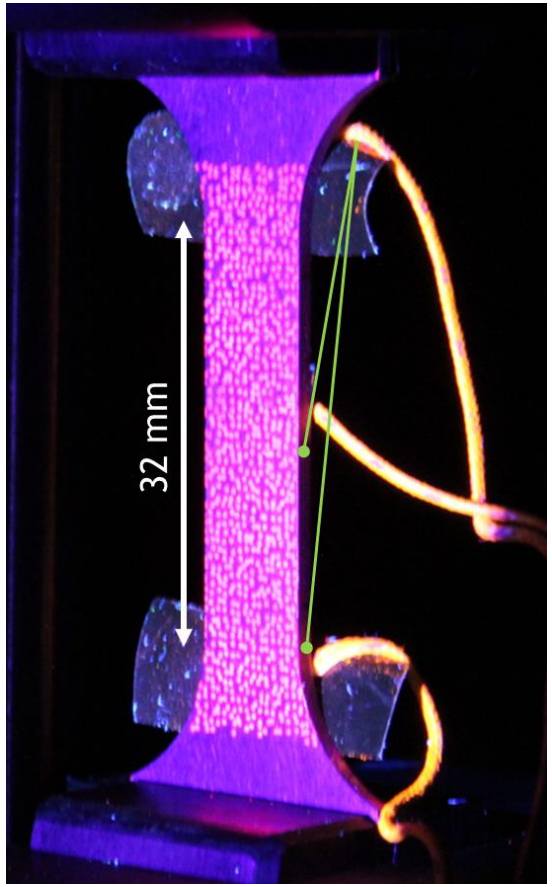


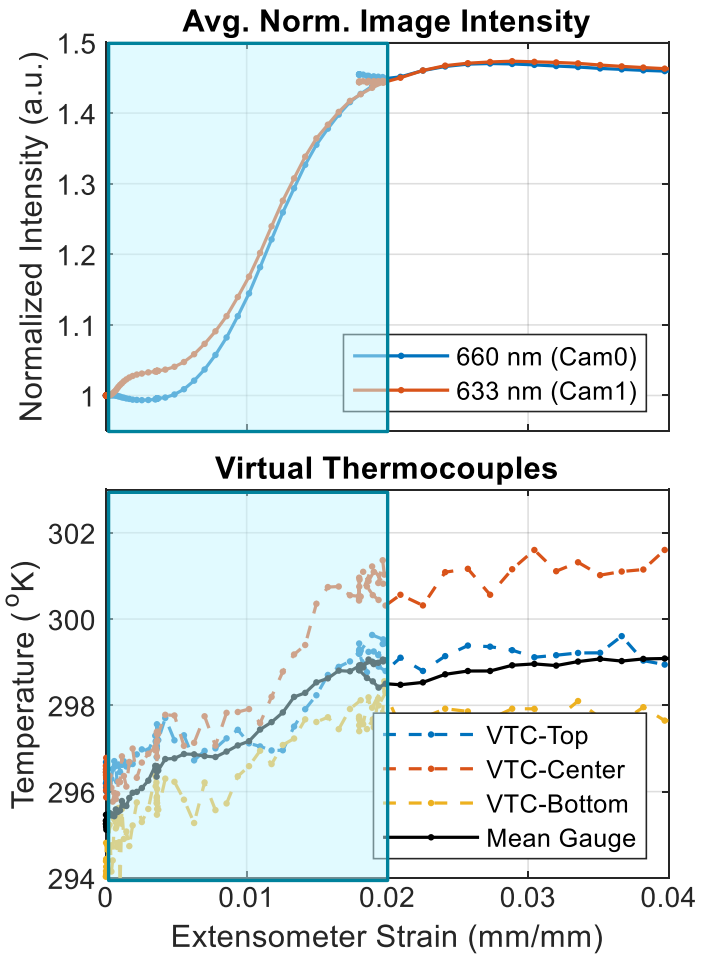




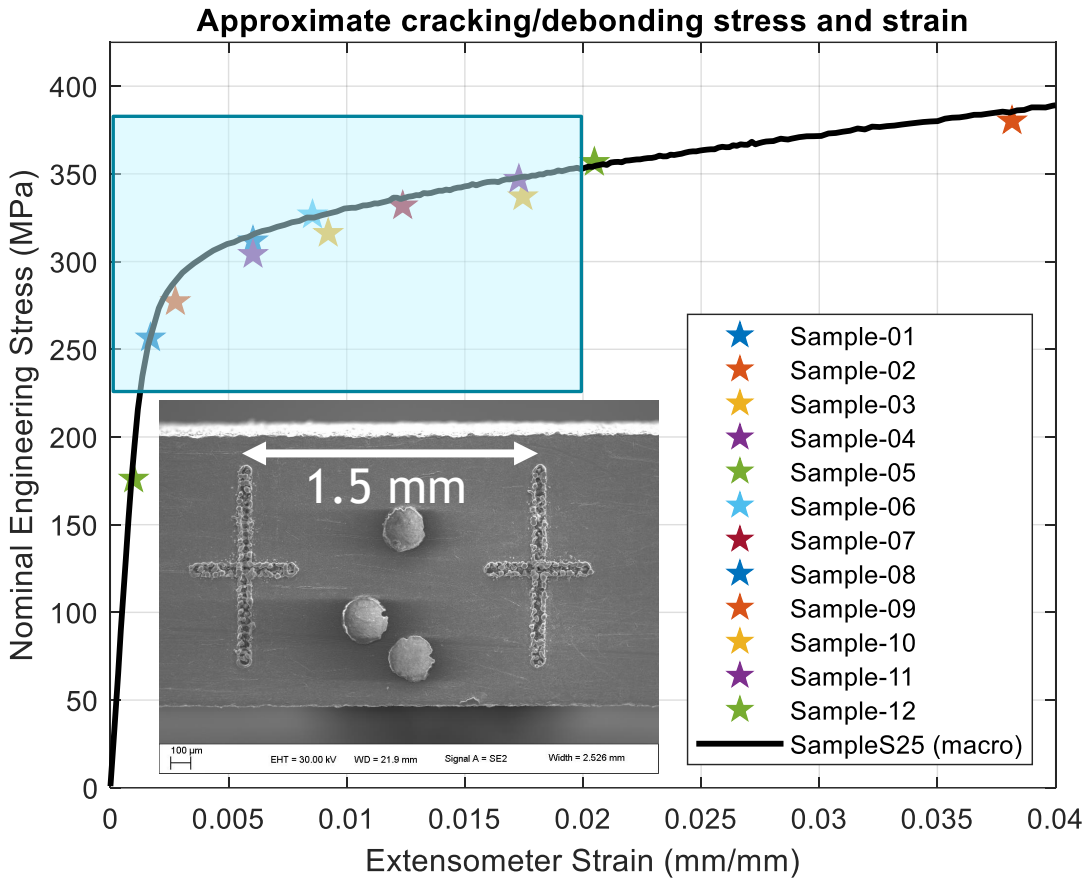
Phosphor intensity increase is correlated to micro-cracking and debonding.

Macro-scale tensile tests





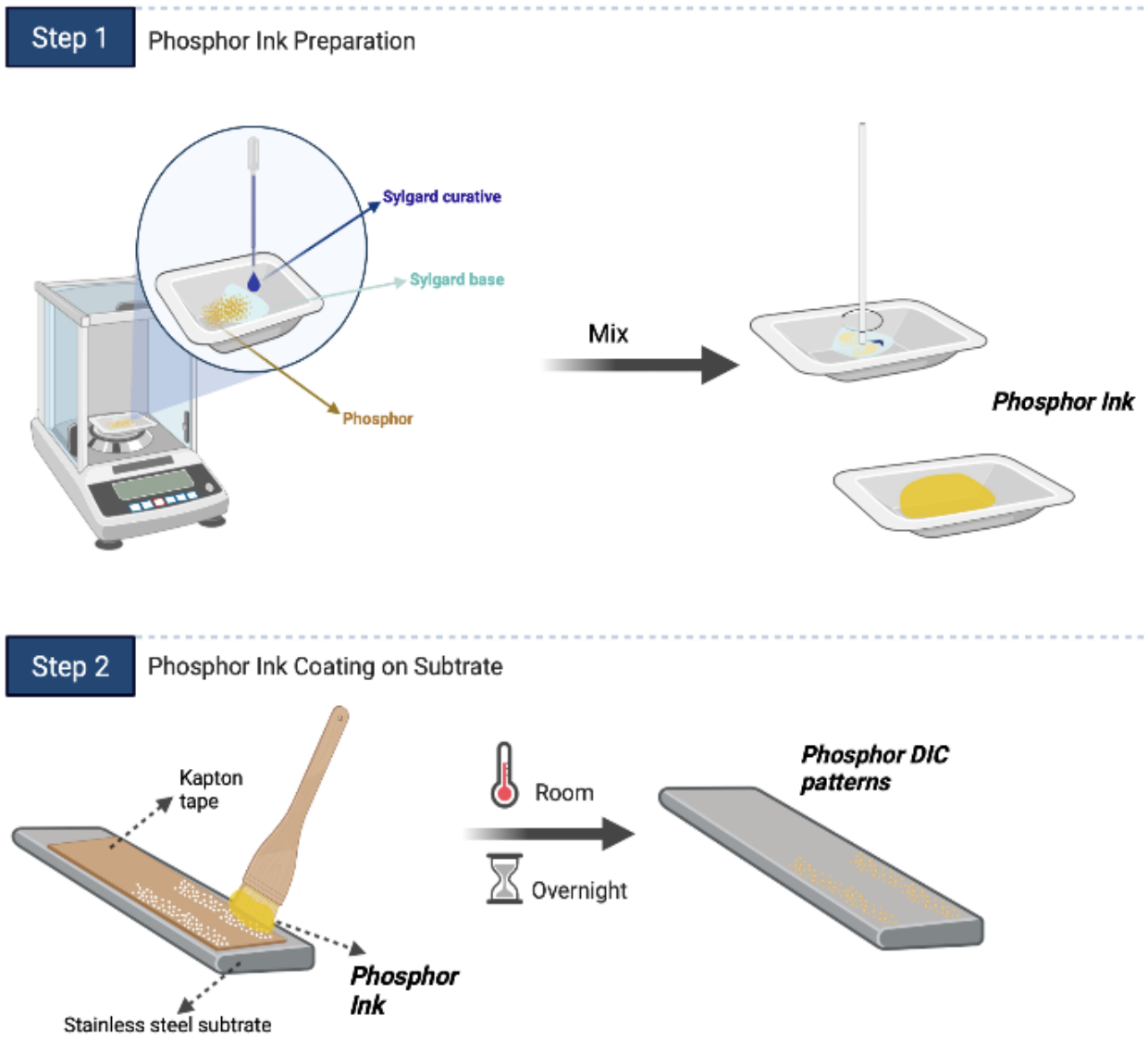
Micro-scale tensile tests

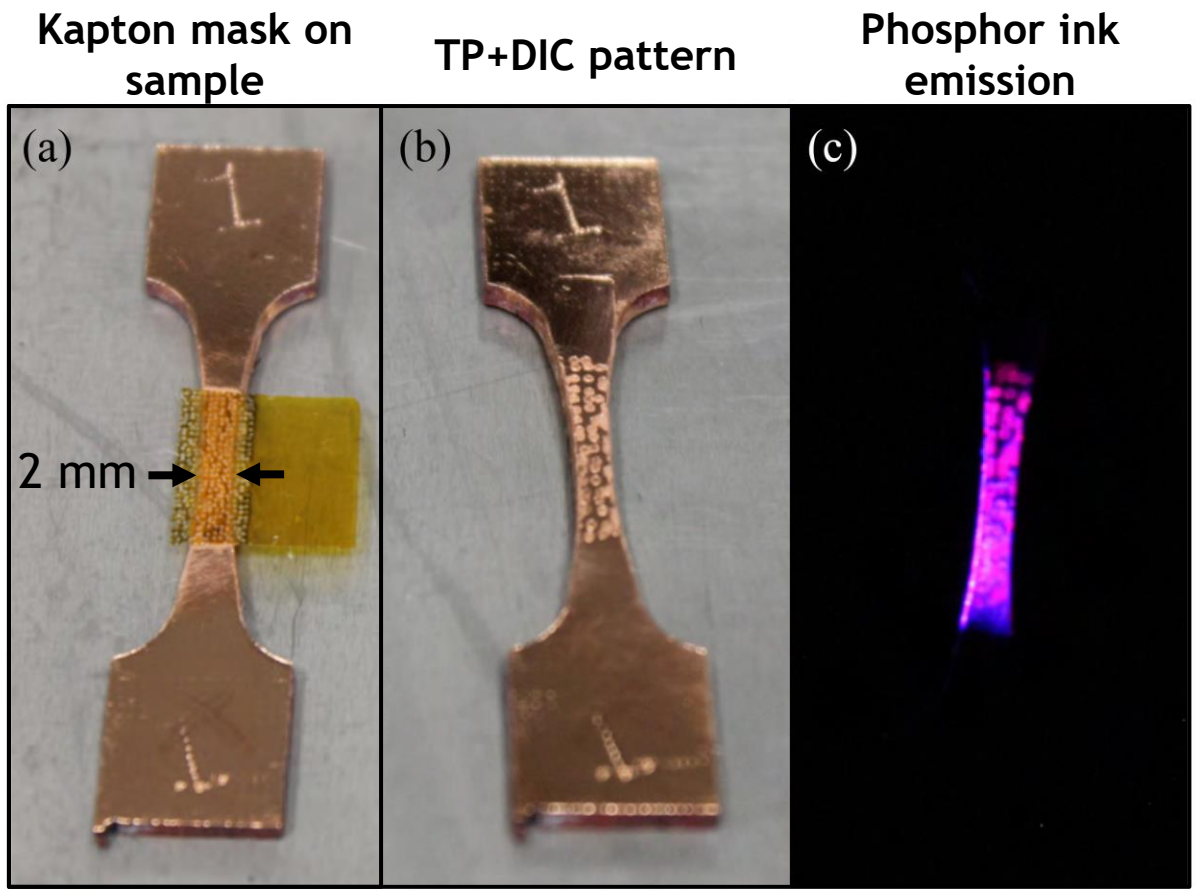


Are cracks increasing effective surface area of phosphor, and thus increasing emission intensity?

Is strain transferred to the phosphor crystals and changing the electronic bandgap, and thus the phosphorescence signature?

To tackle challenges with aerosol-deposited phosphor, a Sylgard polydimethylsiloxane (PDMS) phosphor ink was developed.



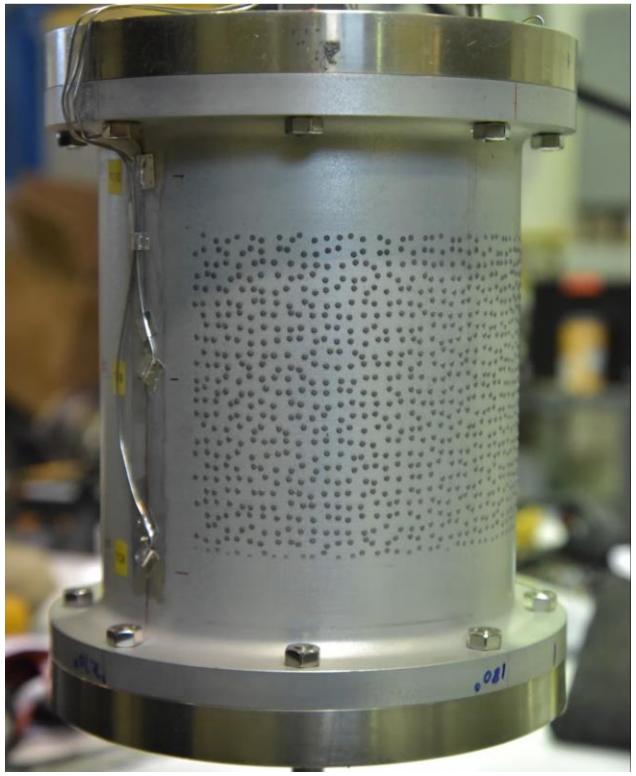


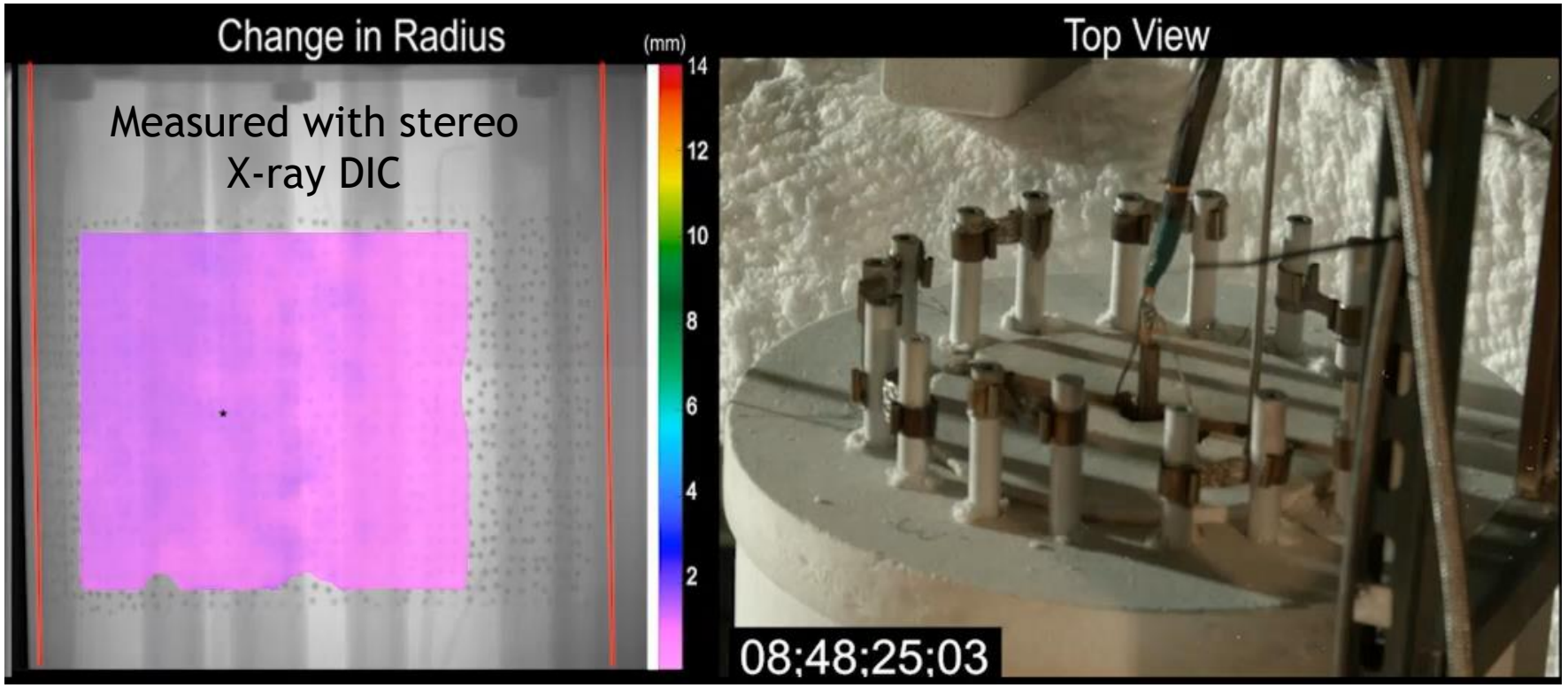
Strain effects of pattern robustness and phosphor signature still to be evaluated

Collaborators: Namir Heurtas, Linda Hansen

Beyond the visible: X-Ray based TP+DIC!

Part 1: X-ray DIC allows deformation measurements in extreme environments.





- Fiber-reinforced epoxy composite with aluminum shell
- DIC pattern fabricated from cold-sprayed tantalum

- Test article radiantly heated
- Aluminum softens and deforms while epoxy decomposes and pressurizes cylinder

- No optical access inside heater
- Flames and soot obfuscate test article
- Heat waves would bias optical DIC

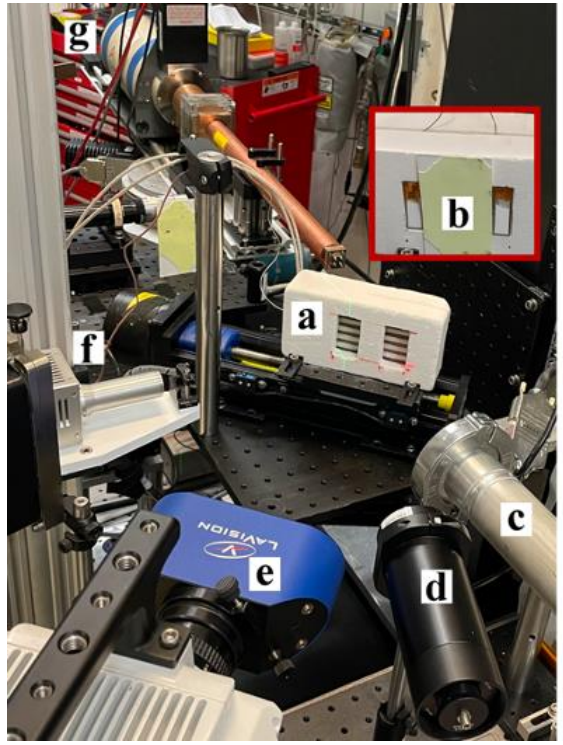
Collaborators: Brent Houchens, Alvaro Cruz-Cabera, and many more

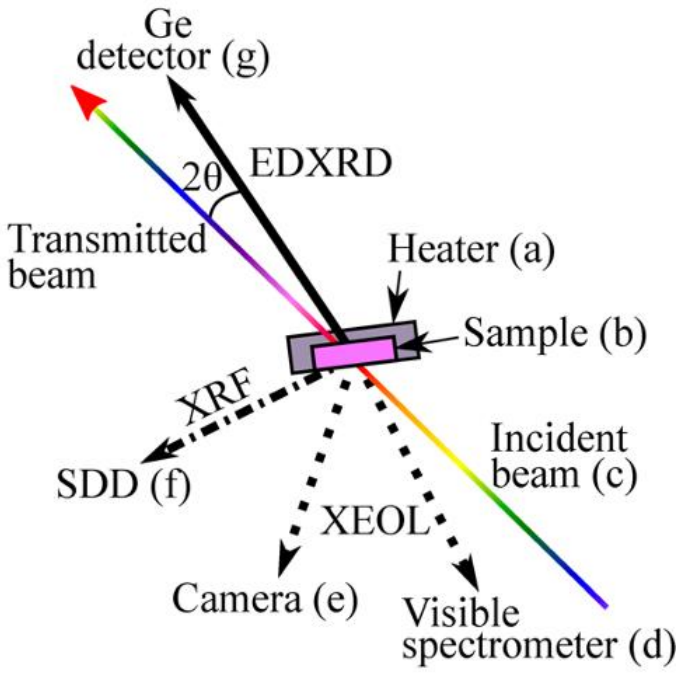
Jones, et al., *Exp. Tech.* 2020
Murphy, et al., *12th US Nat. Combust. Meeting*, 2021

Beyond the visible: X-Ray based TP+DIC!

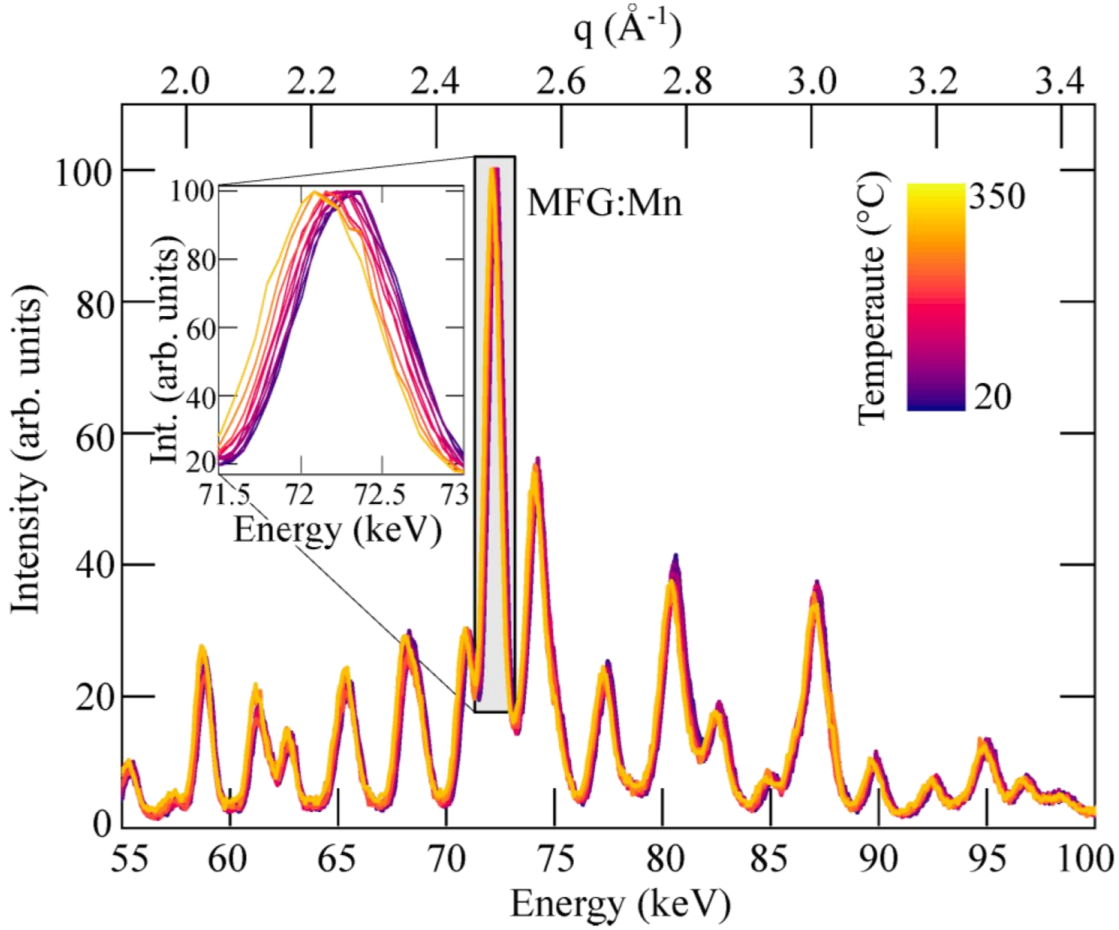
Part 2: X-ray signature of phosphor shows a thermographic response.

Experimental Setup at Argonne's Advanced Photon Source (APS)





X-ray diffraction of MFG phosphor



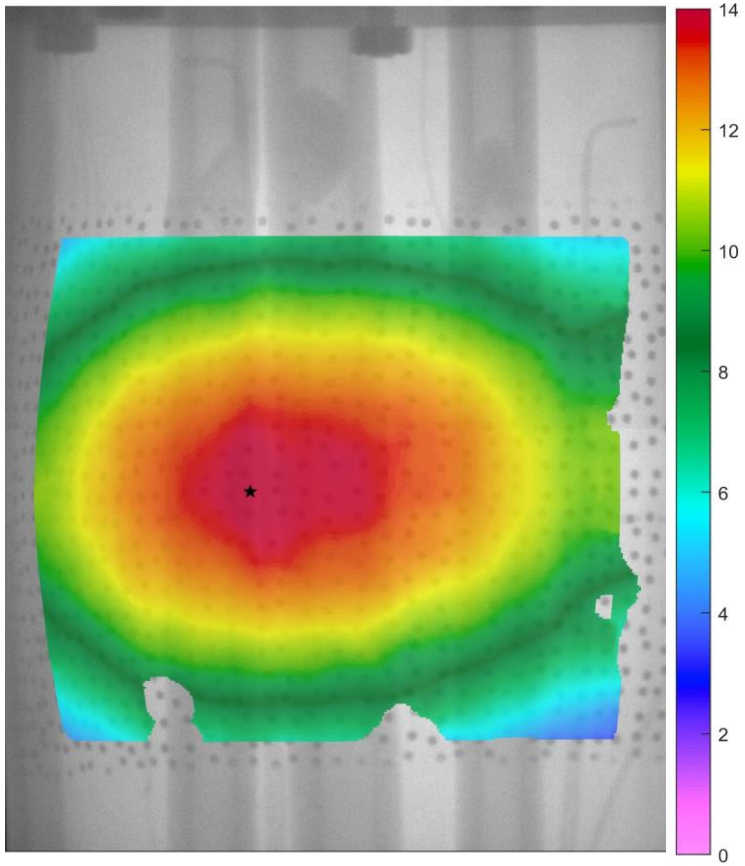
EDXRD: **Energy Dispersive X-ray Diffraction**
XRF: X-ray Fluorescence
XEOL: X-ray Excited Optical Luminescence

Collaborators: Linda Hansen, Eric Westphal, Alan Kastengren (Argonne National Labs)

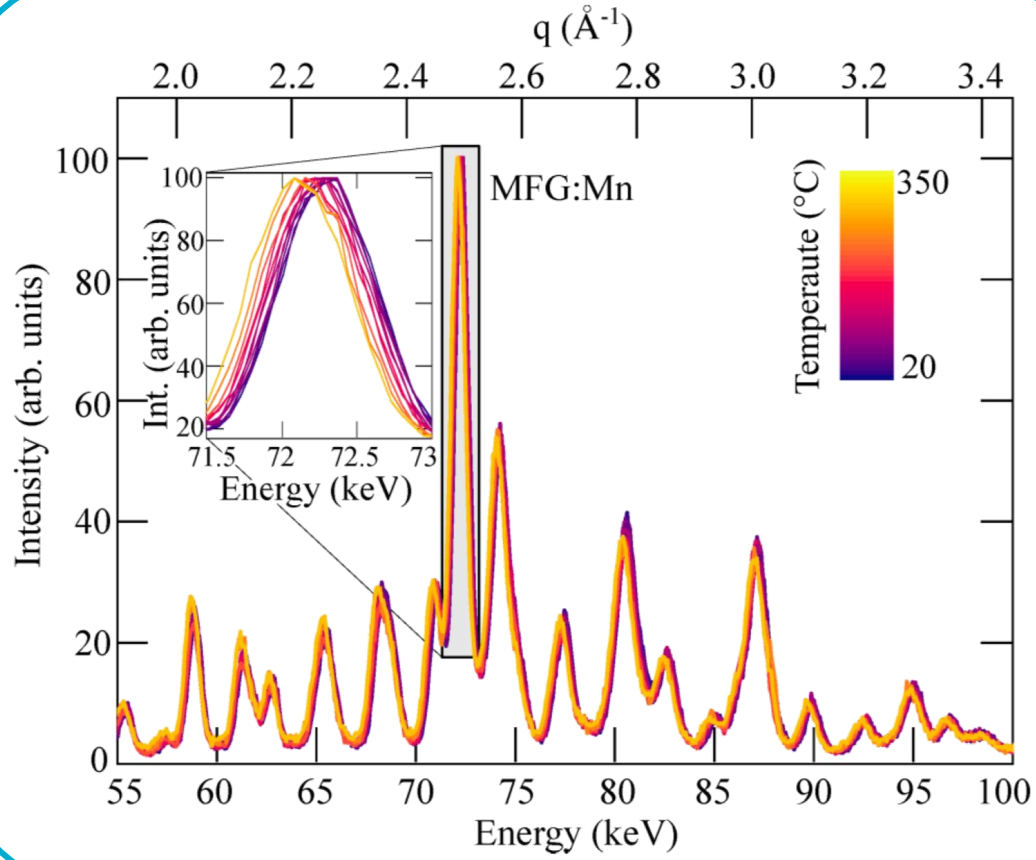
Hansen, et al., *J. Appl. Phys.*, 2022

Beyond the visible: X-Ray based TP+DIC!

Deformation



Temperature



Can we create an X-ray DIC pattern with phosphor and combine strain and temperature measurements in extreme environments?

Background

Methods and Exemplar Application

Current Developments

Thank you to BSSM and *Strain*

Elizabeth Jones
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