In-situ Optical Monitoring of Operating Gas Turbine Blade Coatings Under Extreme Environments

DE-FE0031282

Fossil Energy Sensor & Control Project Review Meeting

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https://aerostructures.cecs.ucf.edu/

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Key goals

- Develop and demonstrate at the laboratory scale an advanced optical suite of instrumentation technologies for enhanced monitoring of gas turbine thermal barrier coatings (TBCs)
- **1.5-year extension assigned for the demonstration of surface temperature measurement capability and deployment of the instrumentation on an engine rig for in-situ phosphor thermometry**

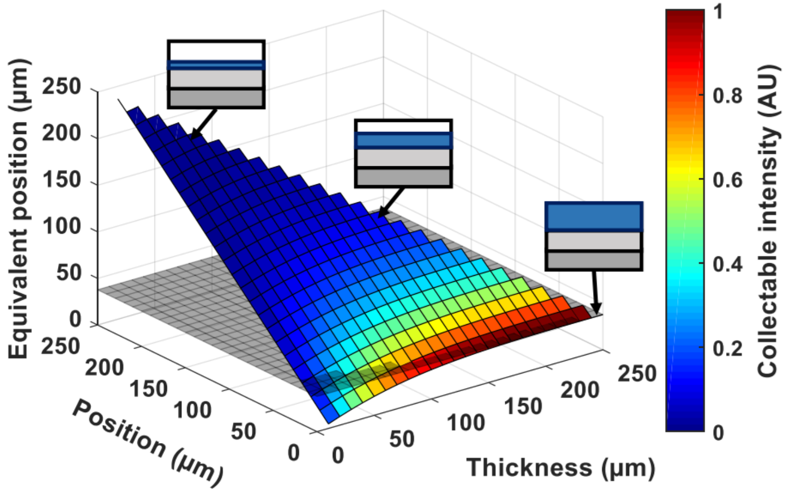
Project Tasks (Tasks 1-5: Oct 2017 – Oct 2020, + Task 6: Oct 2020 – Sep 2022)

Task 1: Project Management & Planning
Task 2: Define and manufacture sensor configuration
Task 3: Establish Sensing Properties and Characterize Coating Response for Luminescence Based Sensor
Task 4: Perform Non-Intrusive Benchmarking Measurements of Surface Temperature and Strain
Task 5: Develop and Test Laboratory Scale Sensor Instrumentation Package
Task 6: Instrumentation adaptation to engine rig + surface measurements

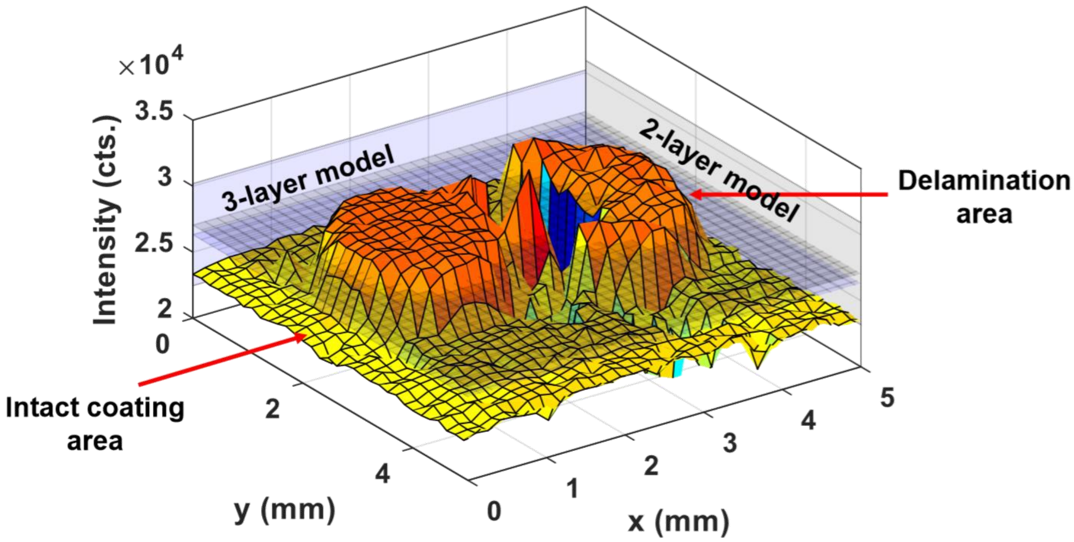
Previous achievements on the project

- **4 patents on novel instrumentation, methodologies and materials** developed for improved temperature accuracy.

- Publications in:
  - **Applied Optics (2019)** for the prediction models for the selection of sensor coating configurations.
  - **Measurement Science Technology (2020)** for the design and demonstration of phosphor thermometry system.
  - **Surface and Coatings Technology (2020,2022)** for delamination monitoring using embedded luminescence sensors and for the determination of phosphor coating thermomechanical integrity .
  - **AIAA Scitech (2020, 2021, 2022)**
  - **ASME Turbo Expo (2019, 2021)**
  - **ICPT (2018, 2020)**



Fouliard et al., *Applied optics* 58.13 (2019): D68-D75.



Fouliard et al., *Surface and Coatings Technology*, 2020

Overview of the presentation

- **Background, Motivations & Objectives**
  - Thermal Barrier Coatings and their benefits
  - Challenges for in-situ monitoring and potential benefits

- **Research effort during this last project period was focused on providing solutions to the following:**
  - **Higher accuracy of temperature measurements (part A)**
    - **Phosphor Thermometry experimentation / adaptation to engine rig (Task 6)**
  - **Improving methods for coating early damage monitoring – quantifying stress in sensor coatings (part B) - Coating stress monitoring (additional results for Task 4)**

- **Conclusions and perspectives**

Background, Motivations & Objectives

Thermal Barrier Coatings (TBCs)

- **Thermal barrier coatings (TBCs)** used in combination with air cooling to protect metal substrates from extreme temperatures in the high-pressure turbine (1300 to 1600°C)

  Clarke, D (2012). *MRS Bulletin*, 37(10), 891-898

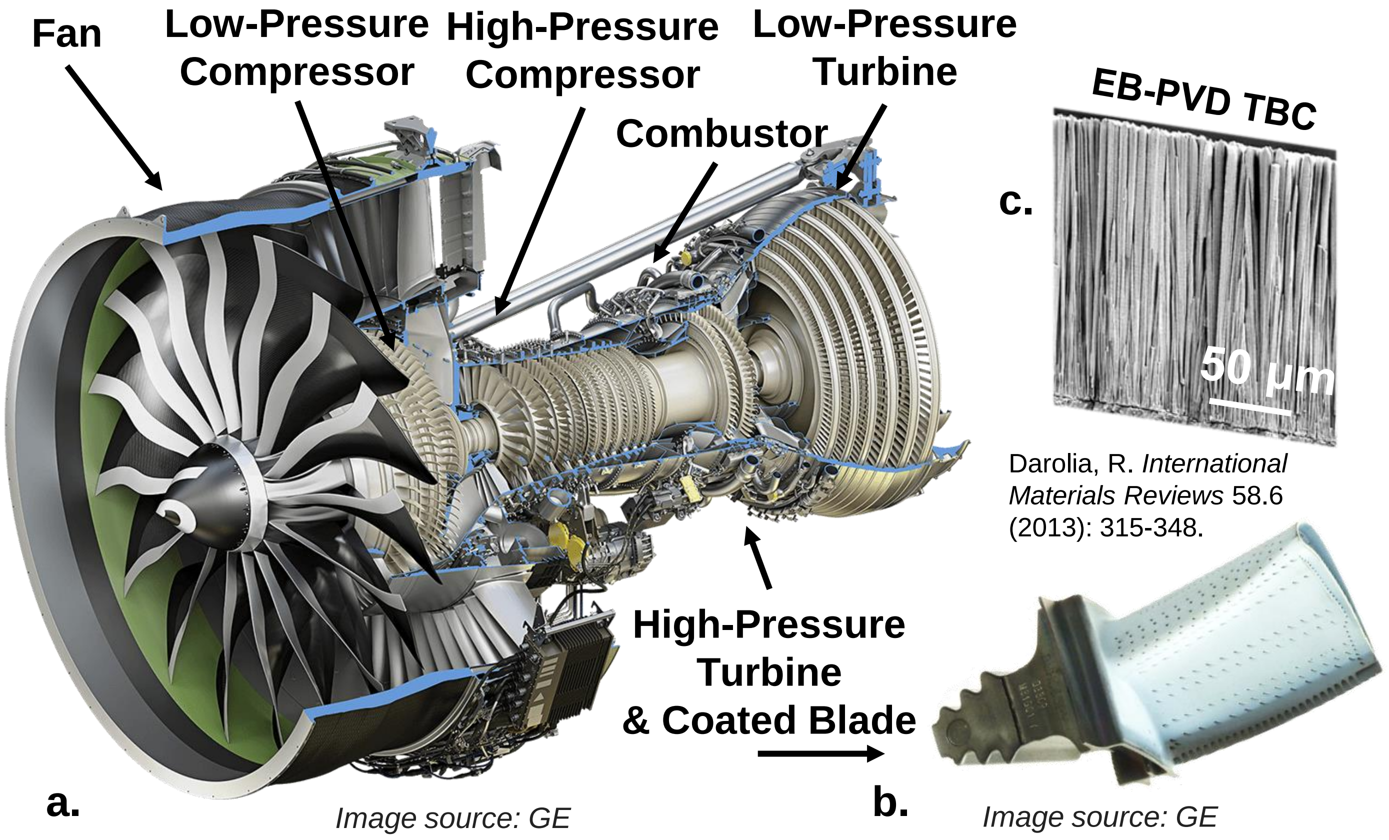
  - Air film cooling: ΔT= -100 to -400°C

  Kotowicz, J, et al. *Archives of Thermodynamics* 37.4 (2016): 19-35

  - **TBC: ΔT= -150 to -200°C**

  Sobhanverdi, R. and Alireza A. *Ceramics International* 41.10 (2015): 14517-14528.
  Bacos, M. P., et al. *Review of ONERA Activities* (2011).
  Darolia, R. *International Materials Reviews* 58.6 (2013): 315-348.
  Xu, Li, et al. *Procedia Engineering* 99 (2015): 1482-1491.

- **Major applications:**
  - Aeroengines
  - Power generation engines

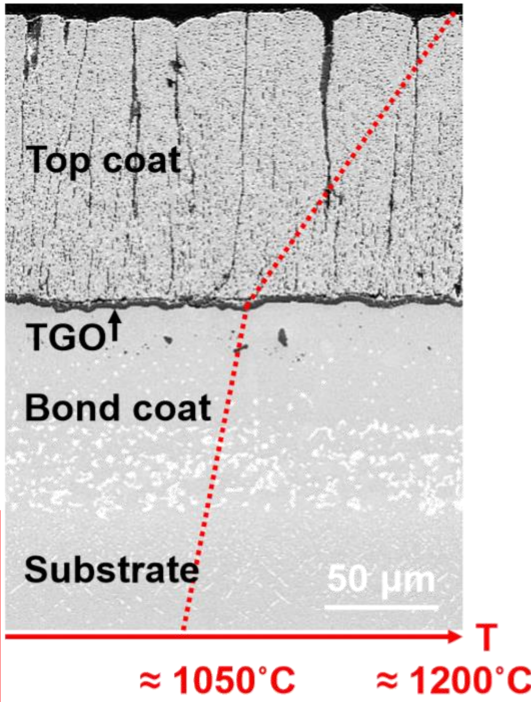


a) Cutaway view of the new GE9X aircraft engine
b) Photograph of a turbine blade coated with TBC
c) SEM micrograph of an EB-PVD TBC top coat

Review of TBC materials properties

TBC layer Typical composition	**Top coat** **7-8wt.%YSZ**	**TGO** Al_2O_3	**Bond coat** **NiCrAlY / PtAl**
Thermal conductivity λ at 1100°C (W/(m·K))	**1-3** [1,2,4,5]	**5-6** [4,6]	**34** [5]
Coefficient of thermal expansion α ($\times 10^{-6}$ K^{-1})	**11-13** [3,4,7,8]	**7-10** [3,7,8,9]	**13-16** [3,7,8,9]
Elastic modulus (GPa)	**0-100** [13]	**320-434** [3,7,8,9]	**110-240** [3,7,9]
Toughness K (MPa· √m)	**0.7-2.2** [7,10]	**2.8-3.2** [7,11]	**>20** [7]
Poisson's ratio ν	**0.2** [8]	**0.2-0.25** [8,9]	**0.3-0.33** [8,9]
Oxygen diffusivity at 1000°C (m^2/s)	$\mathbf{10^{-11}}$ [4]	$\mathbf{10^{-19}}$-$\mathbf{10^{-21}}$ [4,6]	-
Crystal microstructure (phase) Stable up to	*t'* **1200°C** [12]	α **1750°C**	β, γ **1050°C**

[14]



[1] Dinwiddie, Ralph B., et al. No. CONF-9606158-1. Oak Ridge National Lab., TN, USA, 1996
[2] Nicholls, John R., et al. *Surface and Coatings Technology* 151 (2002): 383-391.
[3] Liu, Jing., *PhD dissertation University of Central Florida* (2007).
[4] Lee, Woo Y., et al. *Journal of the American Ceramic Society* 79.12 (1996): 3003-3012.
[5] Lim, Geunsik, and Aravinda Kar. *Journal of Physics D: Applied Physics* 42.15 (2009): 155412.
[6] Steenbakker, Remy. *PhD dissertation Cranfield University*, (2008).
[7] Rabiei, et al. *Acta materialia* 48.15 (2000): 3963-3976.
[8] Yang, Lixia, et al. *Surface and Coatings Technology* 251 (2014): 98-105.
[9] Busso, E., et al. *Acta materialia* 55.5 (2007): 1491-1503.
[10] Liu, Y. et al. *Surface and Coatings Technology* 313 (2017): 417-424.
[11] Petit, J. *PhD dissertation University Pierre été Marie Curie – Paris VI* (2006).
[12] Witz, G., et al. *Advanced Ceramic Coatings and Interfaces II: Ceramic and Engineering Science Proceedings, Volume 28, Issue 3* (2007): 39-51.
[13] Renusch, D., et al. *Materials and corrosion* 59.7 (2008): 547-555.
[14] Fouliard, Q. *PhD dissertation University of Central Florida* (2019).

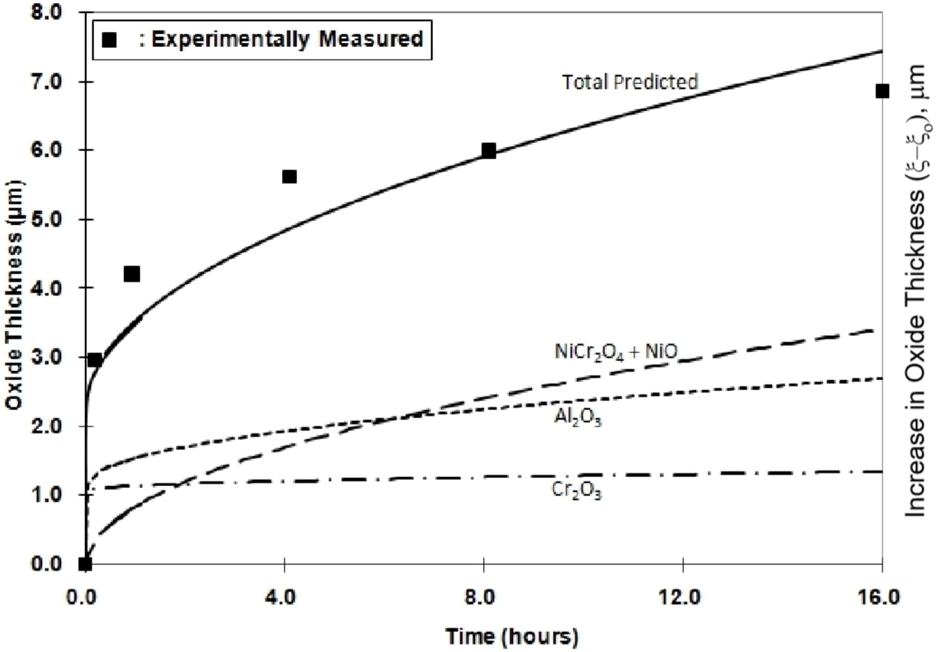
Thermally grown oxide (TGO) formation in TBCs

Importance of controlling the operating temperature

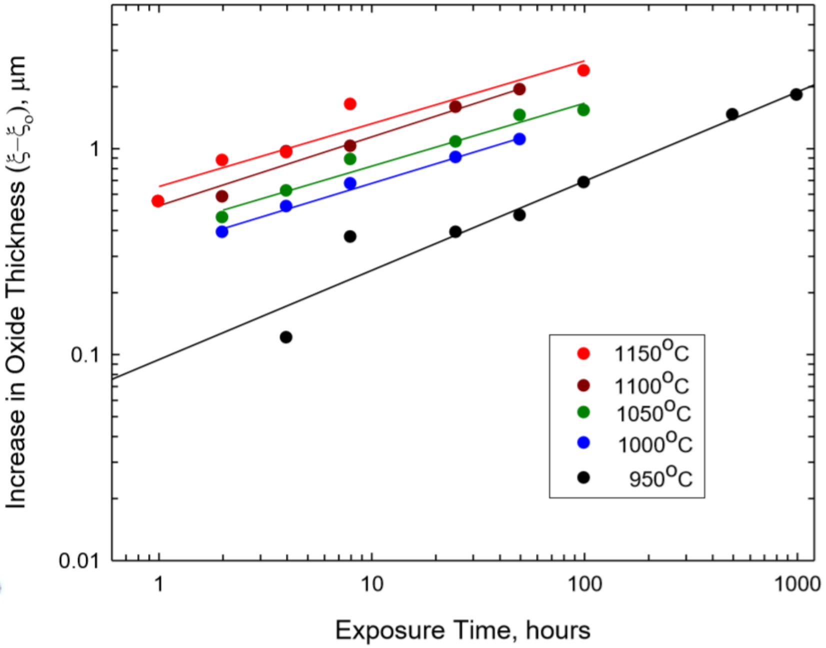
- **Logarithmic growth limited by the low oxygen diffusivity through the TGO:**

$$3\beta NiAl + \frac{3}{2}O_2 \rightarrow \gamma' Ni_3Al + \alpha Al_2O_3$$

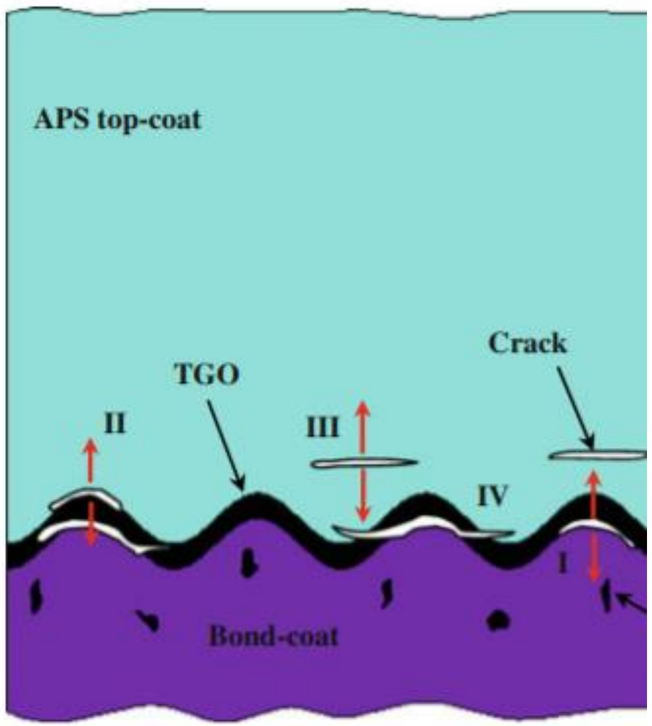
Liu, Y. Z., et al. *Journal of the European Ceramic Society* 36.7 (2016): 1765-1774.
Bernard, B., *PhD dissertation, Université de Lorraine* (2016)



Wu, B, et al. *Journal of the American Ceramic Society* 72.2 (1989): 212-218.



Jackson, R, *PhD dissertation University of Birmingham* (2009)



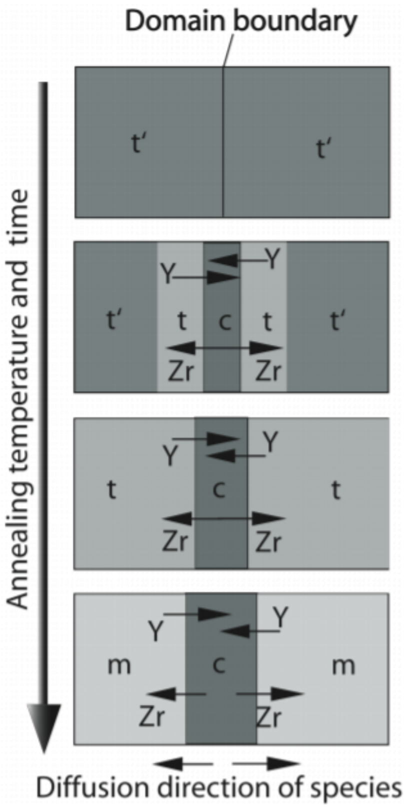
Wang, L., et al *Journal of thermal spray technology* 23.3 (2014): 431-446.

Temperature drives oxide growth in TBCs and is a key factor in coating failure

Phase stability in Thermal Barrier Coatings (TBCs)

Importance of controlling the operating temperature

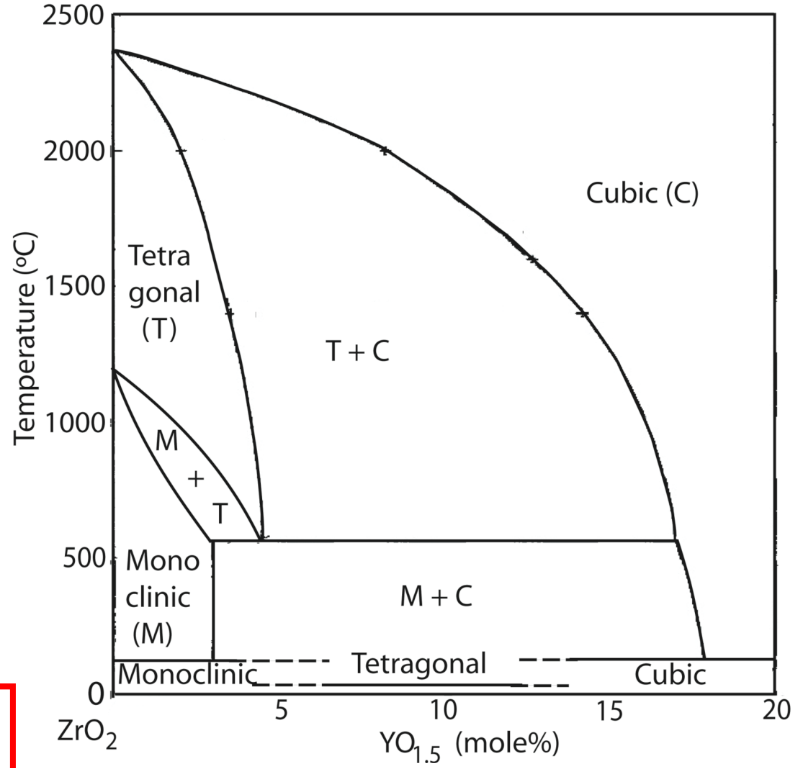
- **Standard top coat material**: 7-8wt.% (4-4.5 mol.%) YSZ optimal for resistance to spallation and thermal stability Patnaik, P. et al, National Research Council Of Canada Ottawa, Ontario (2006)
  - **Y^{3+} introduces oxygen vacancies that stabilizes t'**



Witz, G., et al. *Advanced Ceramic Coatings and Interfaces II: Ceramic and Engineering Science Proceedings, Volume 28, Issue 3* (2007): 39-51.

- **High temperature sintering of t'-YSZ:**
  - **Pore coarsening → thermal conductivity increase** Guignard, A. *Vol. 141. Forschungszentrum*, Jülich, (2012).
  - **Crack forming**
- **t' phase stable up to 1200°C:**
- $t' \xrightarrow{1200°C} t + c \xrightarrow[\Delta V = +4\%]{600°C} m + c$

Accurate control of TBC operating temperature is needed to control degradation of coatings.



Witz, G., et al. *Advanced Ceramic Coatings and Interfaces II: Ceramic and Engineering Science Proceedings, Volume 28, Issue 3* (2007): 39-51.

Significance of TBC temperature measurements

- State-of-the-art TBCs are not being used to their highest potential because of uncertainties in temperature measurements at high-temperature.
    - Safety margins as high as 200°C are used.

Steenbakker, R, (2009) *Journal of Engineering for Gas Turbine and Power*, 131-4 p 041301

- Ideal Brayton cycle efficiency: $\eta = 1 - \frac{T_c}{T_t}$

η: cycle efficiency, $\frac{T_c}{T_t}$: temperature ratio compressor exit / turbine inlet.

- 1% efficiency improvement can save $20m in fuel over the combined-cycle plant life.

- A 130°C increase leads to a 4% increase in engine efficiency.

Ruud, J, (2003). *Performance of the Third*, 50 pp 950-4.

- Failure mechanisms are driven by temperature conditions in the depth of the TBC.

Problem statement:

Accurate determination of thermal gradients in Thermal Barrier Coatings (TBCs) is critical for the safe and efficient operation of gas turbine engines.
Failure mechanisms are thermally activated during engine operation, uncertainty in temperature measurements contribute significantly to lifetime uncertainty.

Measurement techniques for *in-situ* temperature evaluation of TBCs

	Thermocouples (TCs) - RF	Infrared Thermometry	Phosphor Thermometry
Operational temperature range (˚C)	-250 to 2320 (TCs)	-50 to 2000	-250 to 1700
Advantages	- Inexpensive - Wide temperature range	- Wide temperature range - Non-contact method - Fast response time	- **Non-contact method** - **High sensitivity at high temperatures** - **Fast response time** - **Usable on rotating parts** - **Low sensitivity to turbine environment (aging and contamination)**
Drawbacks	- Intrusive probe - Disrupts flow patterns - Not chemically stable in all environments - Low accuracy (TCs) - Unusable on rotating surfaces (TCs)	- Optical access required - Sensitive to stray light (flames) - Sensitive to emissivity variations	- Optical access required - Signal weakening at high temperatures

Gas turbine efficiency

Components lifetime

Proposed solutions & key objectives

- **Better temperature control in gas turbine engines is needed to improve engine efficiency and reduce maintenance and operation costs (part A)**

→ Implementation of phosphor thermometry instrumentation and adaptation of setup to engine rig starting with demonstrating surface temperature capabilities using high-speed camera

- **Integrity and suitability of sensor TBCs is unknown (part B)**

→ Quantification of stresses in sensor coatings using synchrotron X-ray diffraction and luminescence spectra

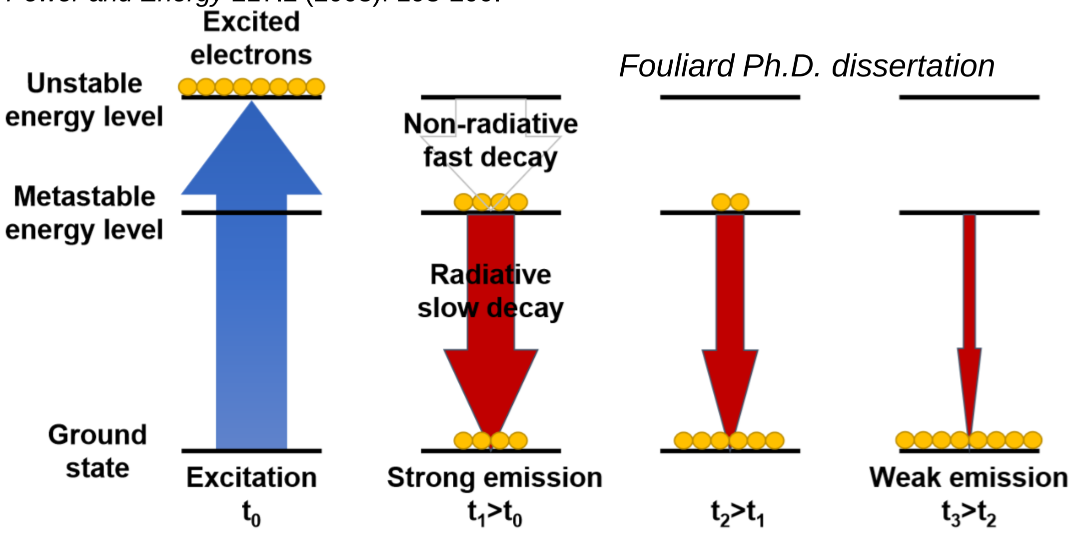
Part A: Phosphor thermometry instrument adaptation

Part of task 6

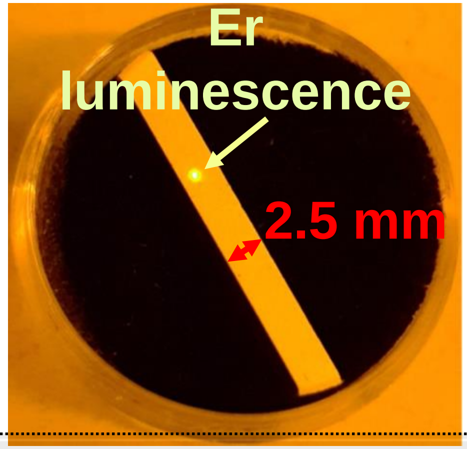
Phosphor Thermometry – fundamentals

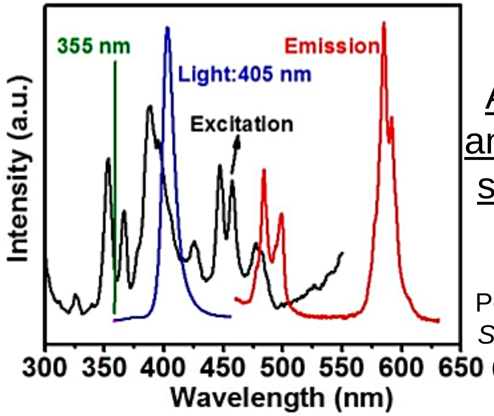
- Typical dopants are rare-earth elements and transition metals.
- Electronic configuration determines the usable excitation wavelength.
- Emission wavelength is generally longer than excitation wavelength.

Brübach et al., *Progress in Energy and Combustion Science (*2013) 39(1), pp. 37-60
Chambers, M., and Clarke, D. *Annual Review of Materials Research* 39 (2009): 325-359.
Allison, S. and Gillies, G. *Review of Scientific Instruments* 68.7 (1997): 2615-2650.
Feist, J., et al. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 217.2 (2003): 193-200.



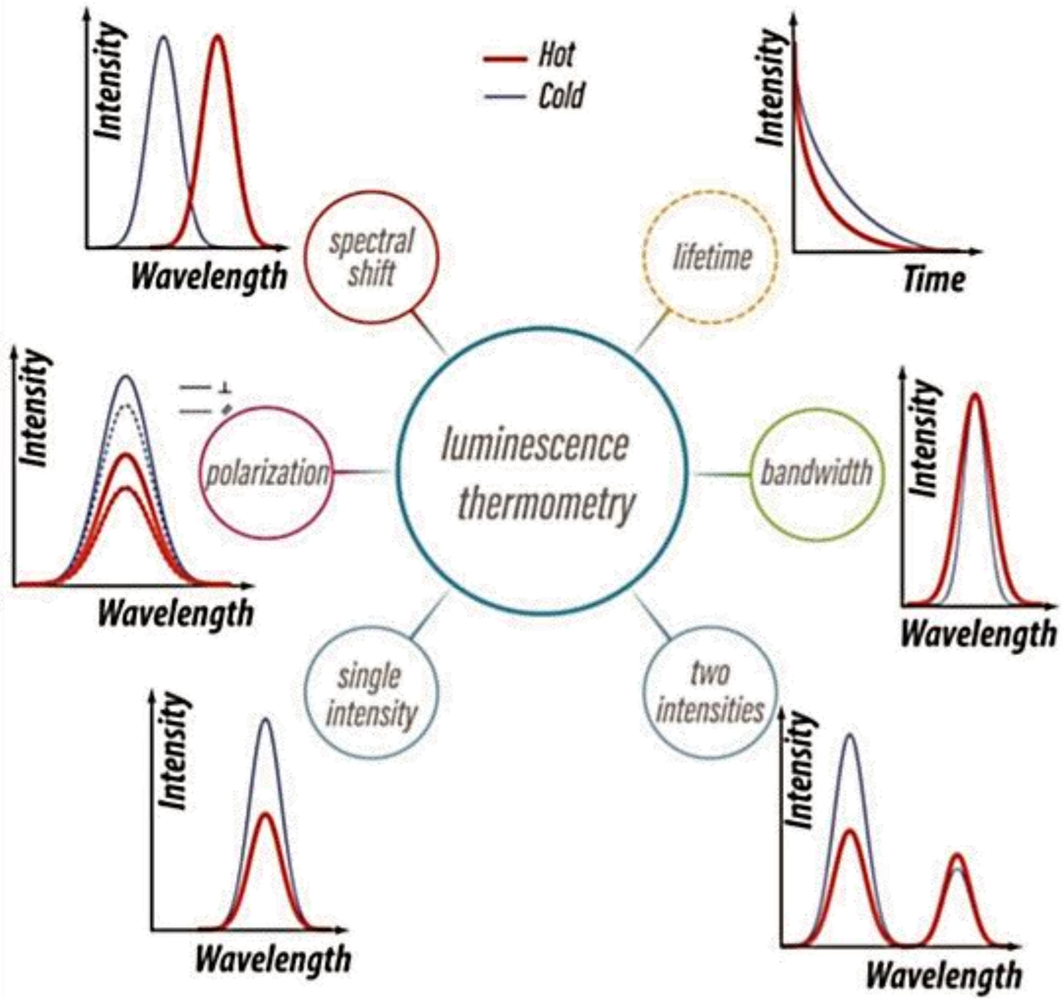
Fouliard Ph.D. dissertation





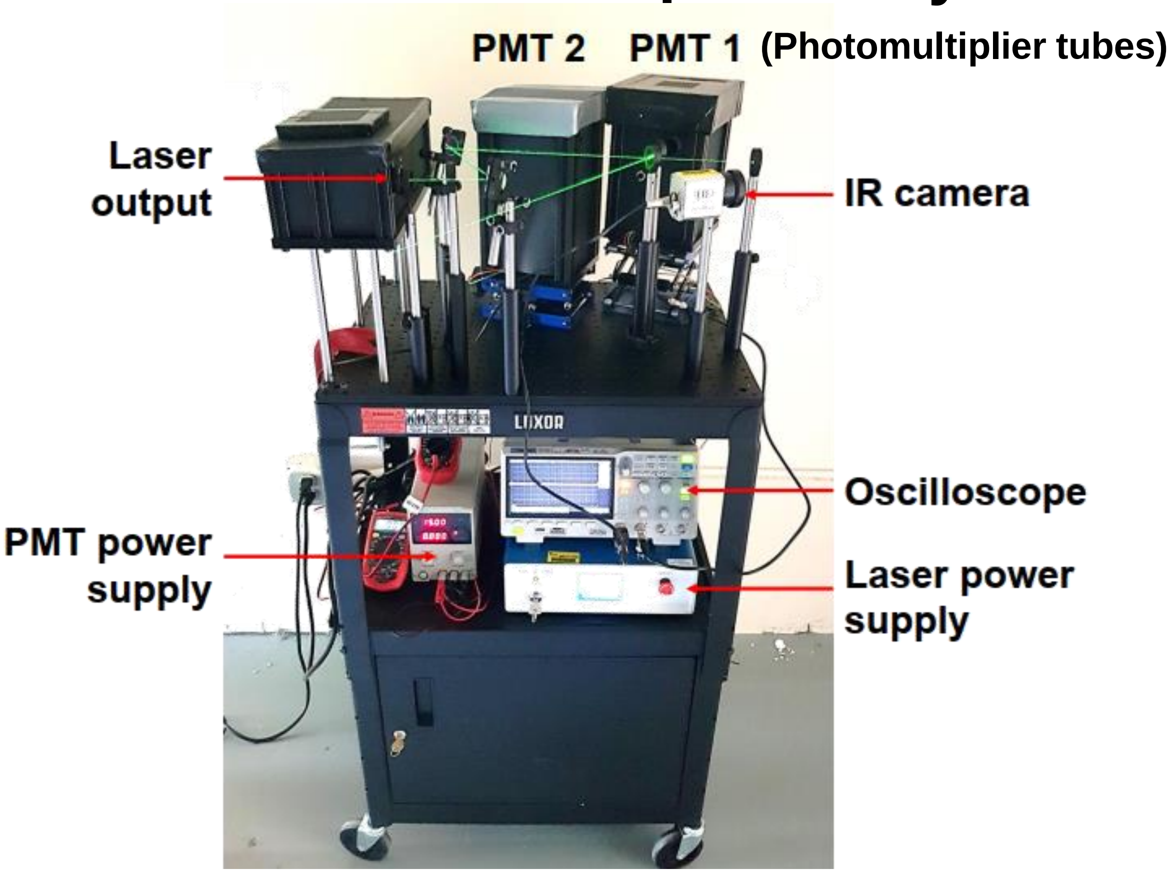
Absorption and emission spectrum of YSZ:Dy

Peng, Di, et al. *Sensors* 16.10 (2016): 1490.

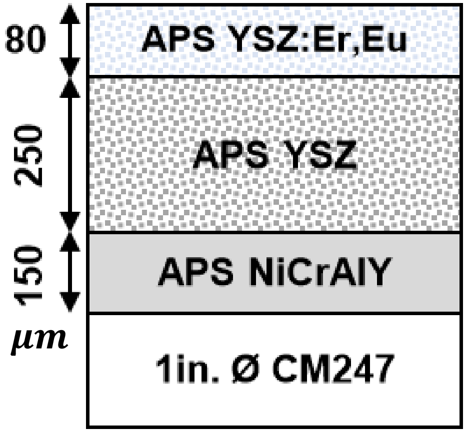


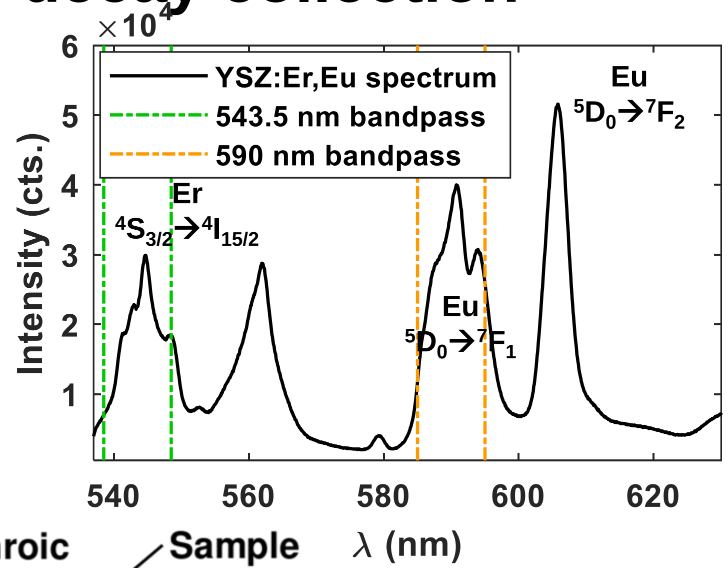
Brites, Carlos DS, Sangeetha Balabhadra, and Luís D. Carlos. "Lanthanide-based thermometers: at the cutting-edge of luminescence thermometry." *Advanced Optical Materials* 7.5 (2019): 1801239.

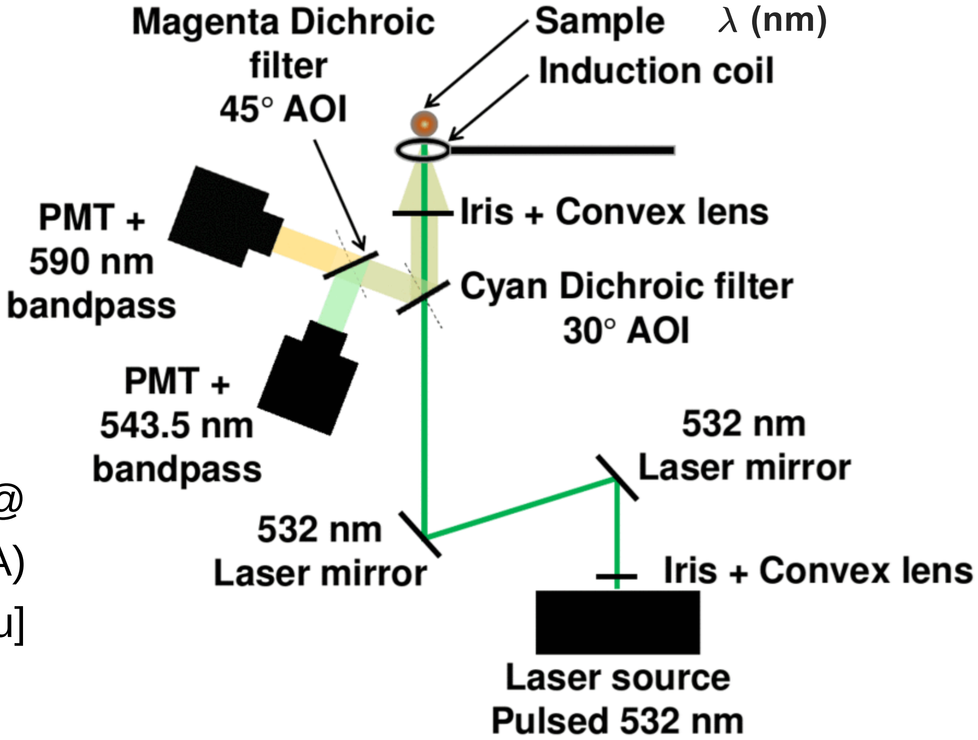
Instrumentation developed for synchronized luminescence decay collection



Fouliard et al., *Measurement Science & Technology*, 2020







Parameters:

Nd:YAG 532 nm

0.5 mJ pulse

10 Hz

20 ns pulse duration

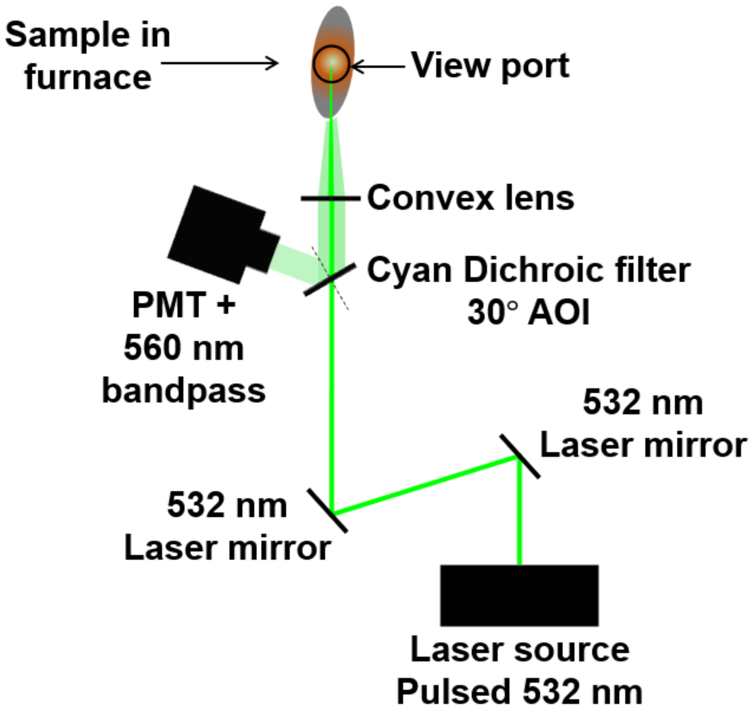
Sample:

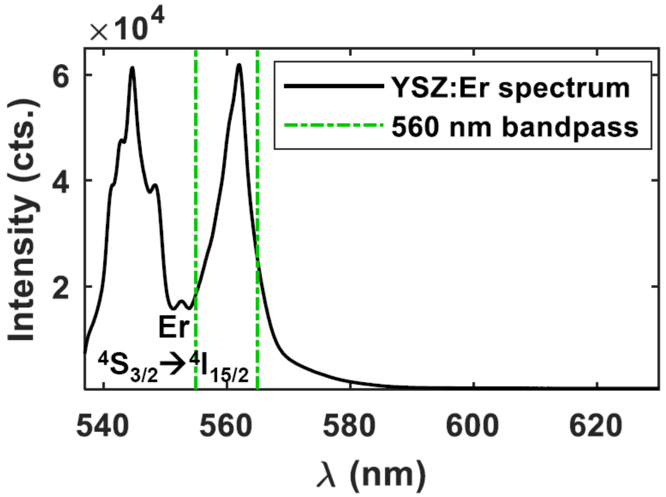
Air Plasma Spray (UCF team @ FIT, Melbourne, FL, USA)

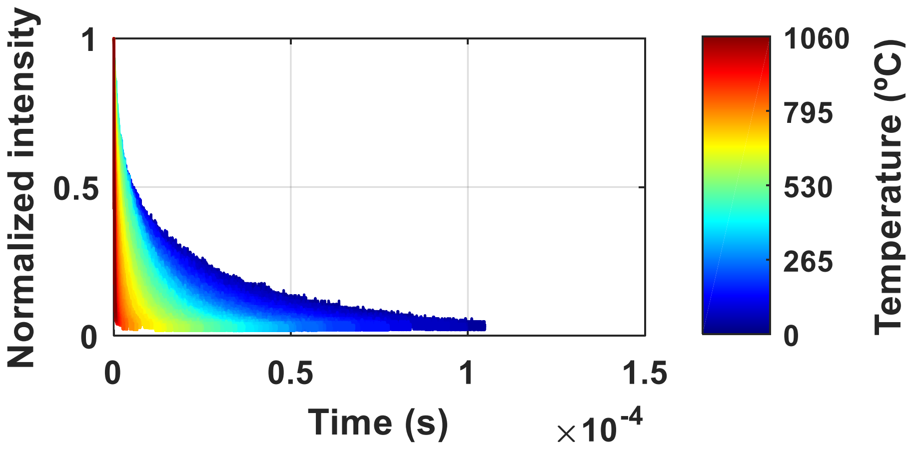
YSZ:Er,Eu [1.5% Er, 3% Eu] (Phosphor Technology, UK)

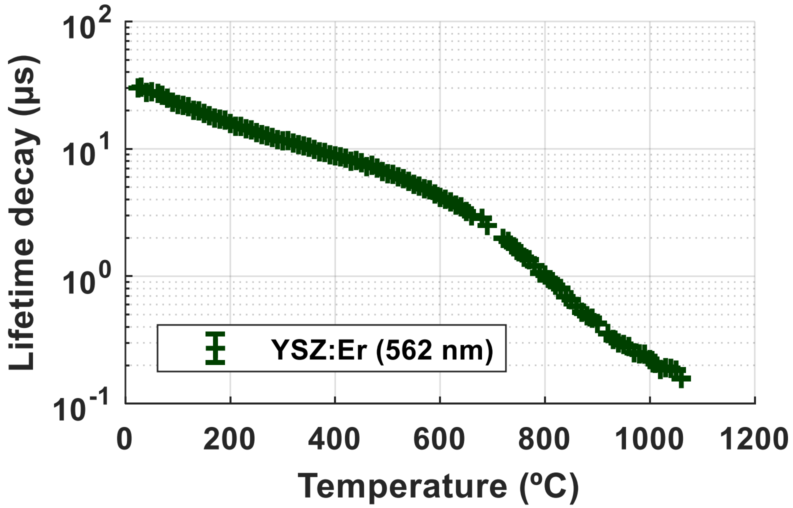
Annealed 2h @ 800˚C

Phosphor thermometry calibration and adaptation to engine setup

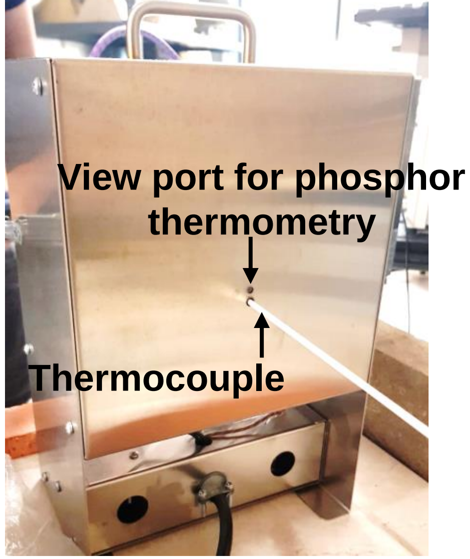






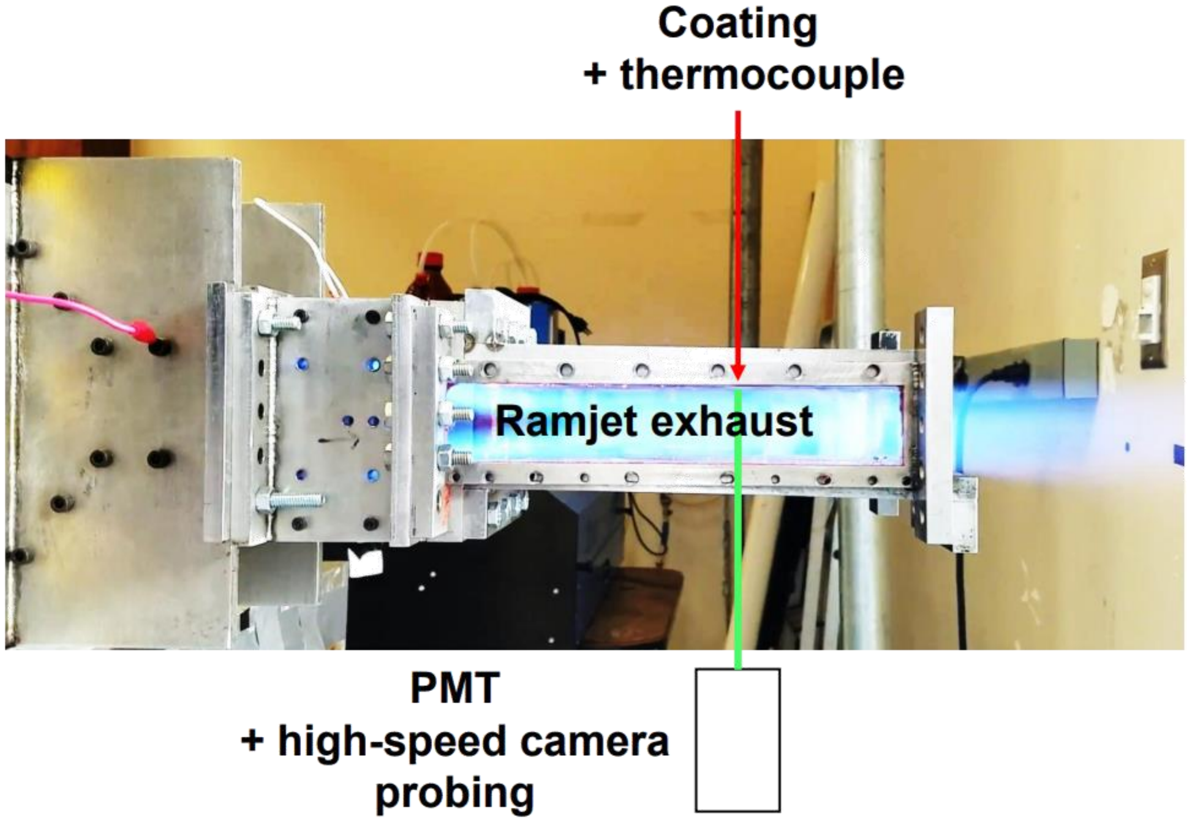


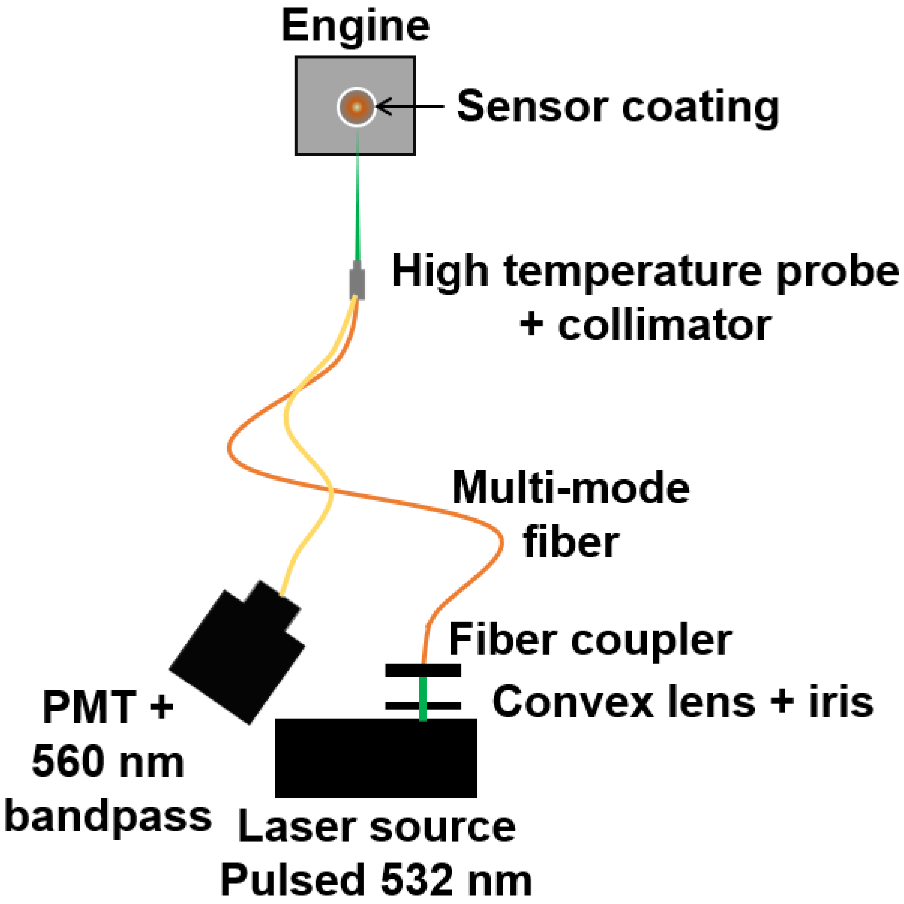
Phosphor calibration furnace



- Temperature calibration was achieved in a muffle furnace for the sample that will be integrated to the engine setup.

Integration of the phosphor thermometry system for surface temperature monitoring of ramjet exhaust

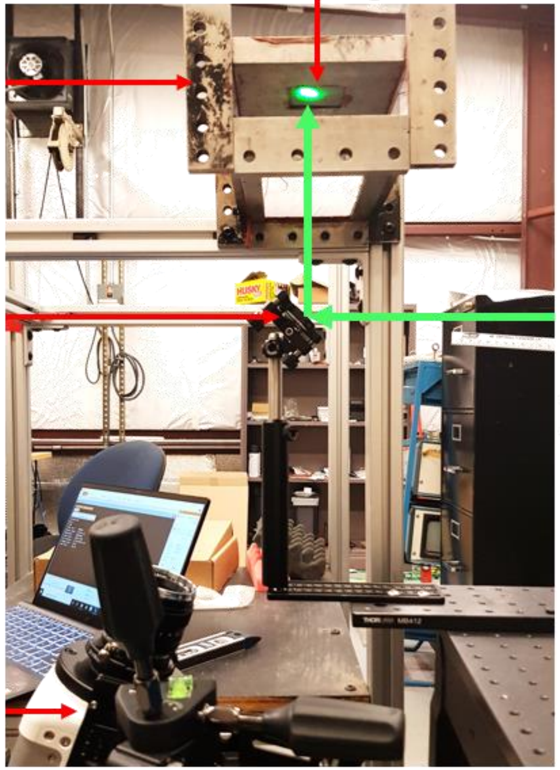




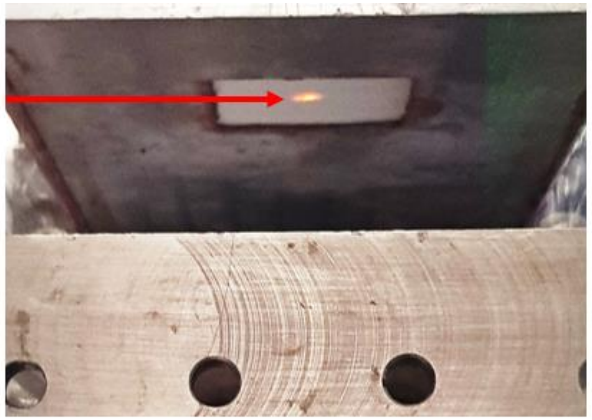
- Integration of the phosphor thermometry system on ramjet exhaust
- Implementation of high-speed camera for surface coating temperature

Setup of temperature monitoring on ramjet exhaust

Coating
Ramjet exhaust
Laser mirror
High-speed camera

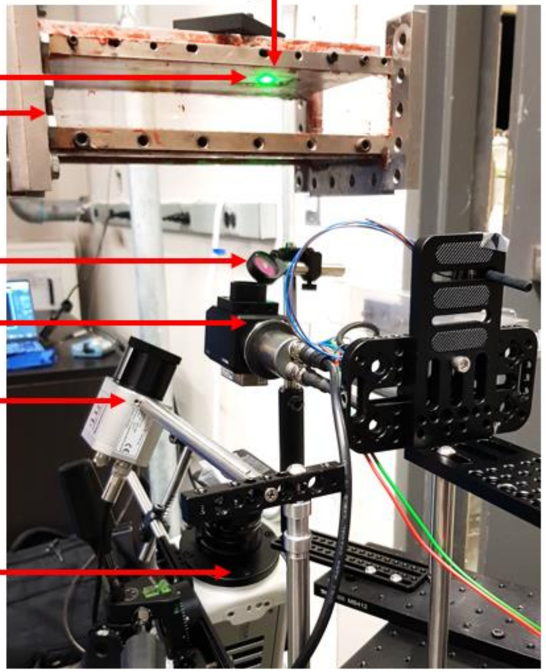


YSZ:Eu luminescence



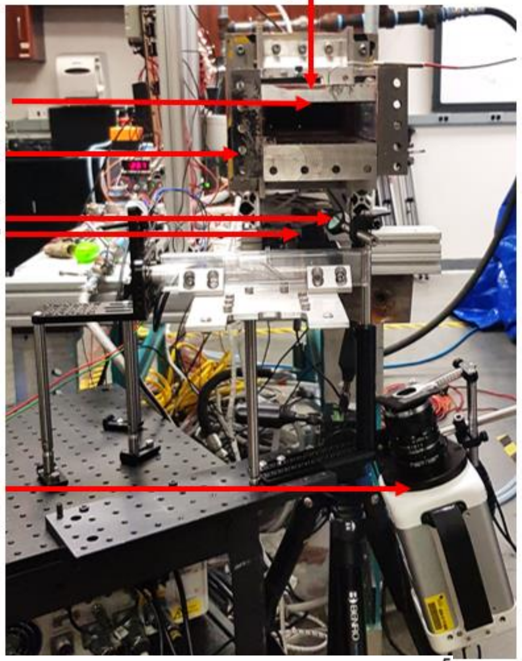
(side view)

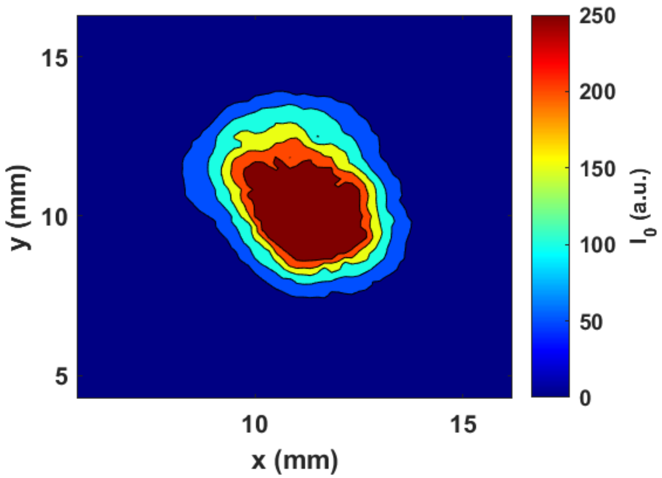
Coating
Probed area
Ramjet exhaust
Laser source
Laser mirror
PMT + bandpass
IR camera
High-speed camera

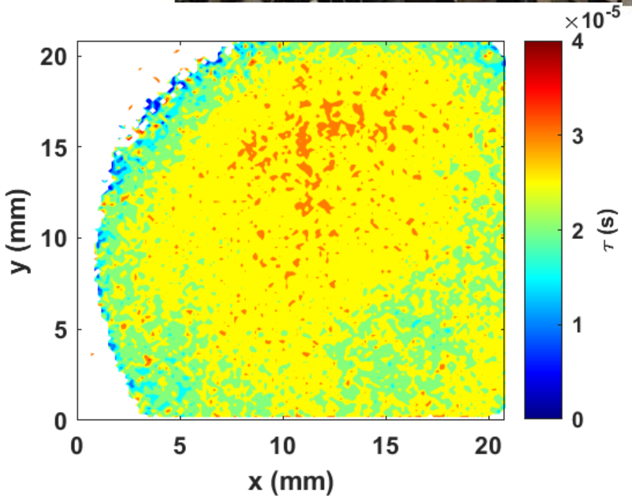


(front view)

Coating
Probed area
Ramjet exhaust
Laser mirror
PMT + bandpass
High-speed camera





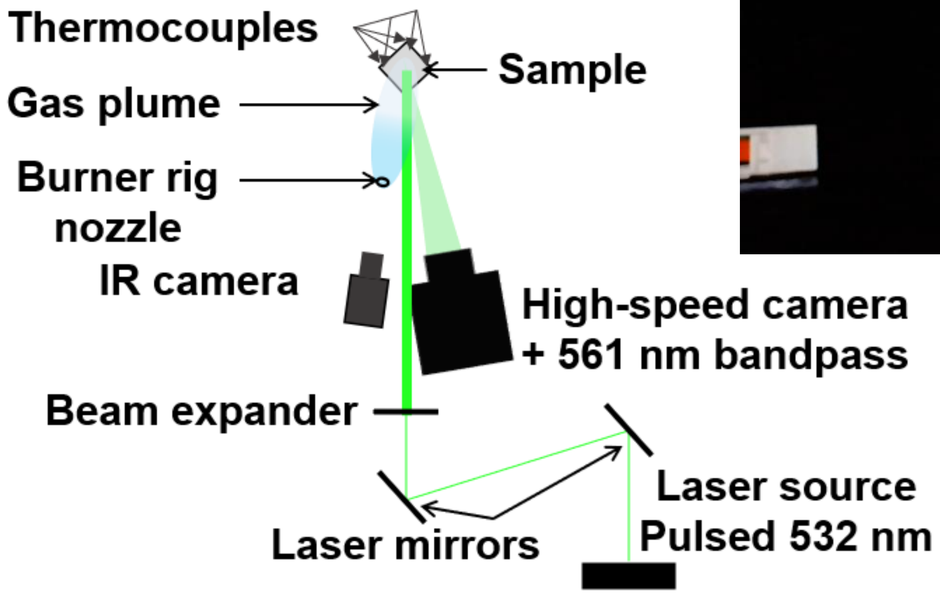


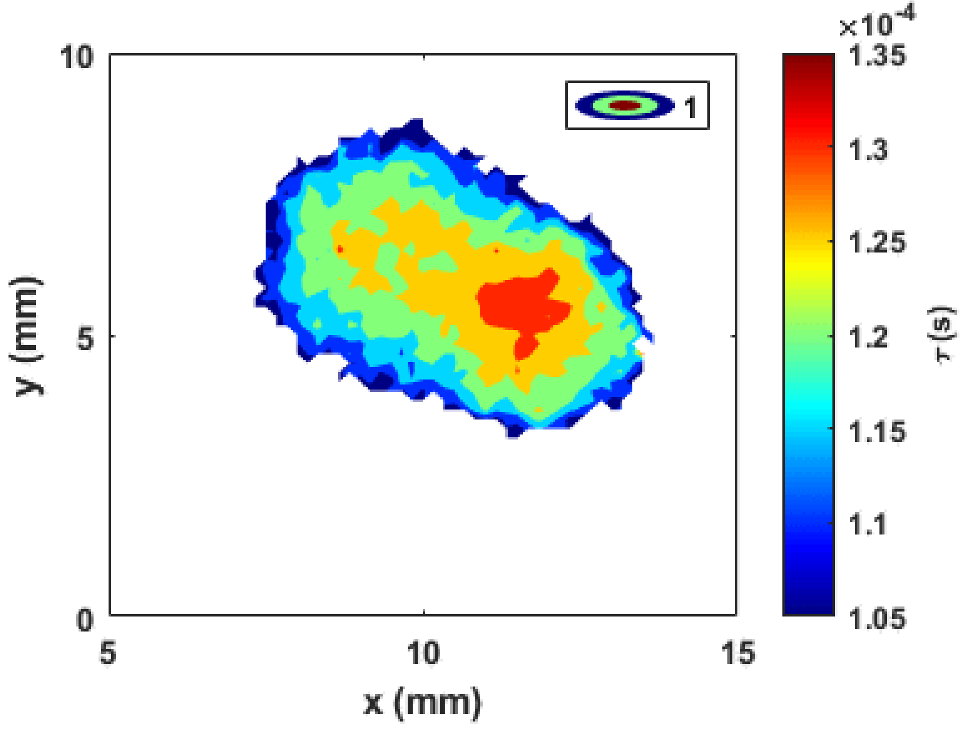
High-speed camera setup and coating surface temperature measurements

A first step towards the upgrade/conversion of the setup for engine rig testing was to enable surface measurement:

→ Completed successfully with:

- High-speed camera (Photron Nova S6):
    - 160k frames/s
    - 64x128 pixel resolution
    - ISO 64,000
- Infrared camera (TIM450) – reference meas.:
    - Longwave (7.5-13 microns)
    - Emissivity set to 0.93





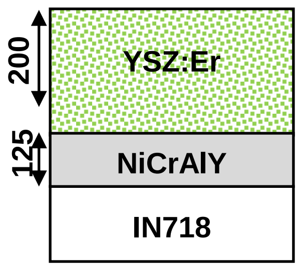
- Successfully measured surface temperature variation during engine run
- Lifetime decay needs to be calibrated for each pixel for high temperature measurements and quantifying temperature gradients on coating surface

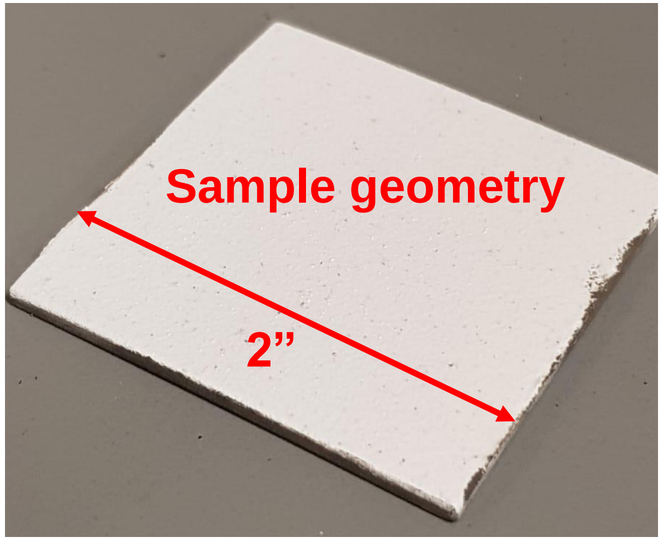
Part B: Coating stress monitoring

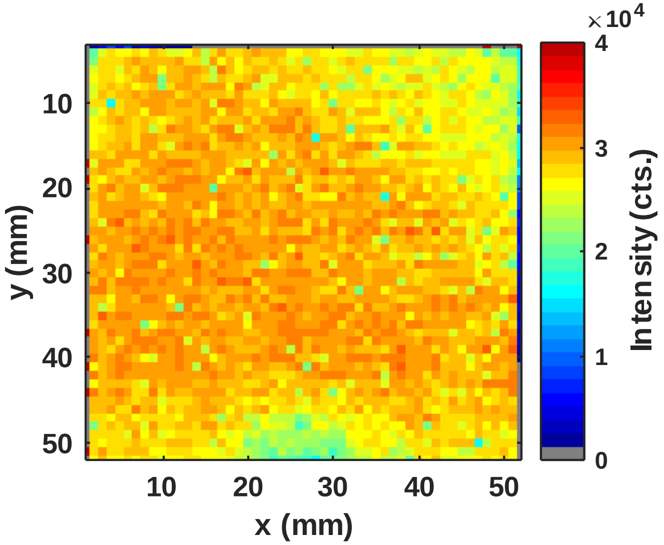
Part of task 4 – additional outcomes to the project

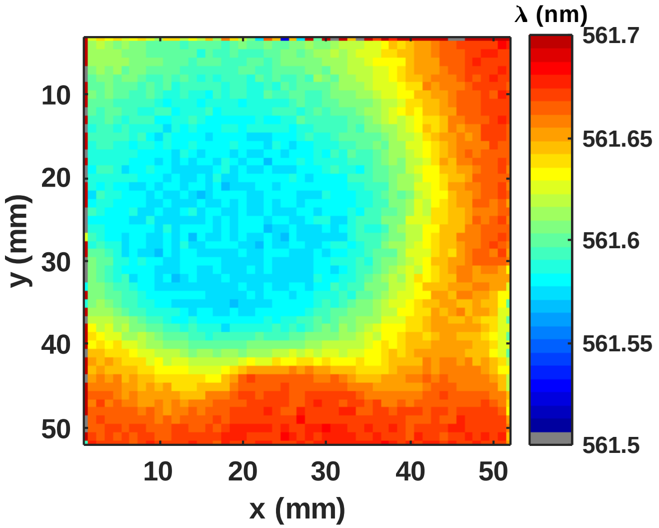
Potential for measuring stress using phosphor properties

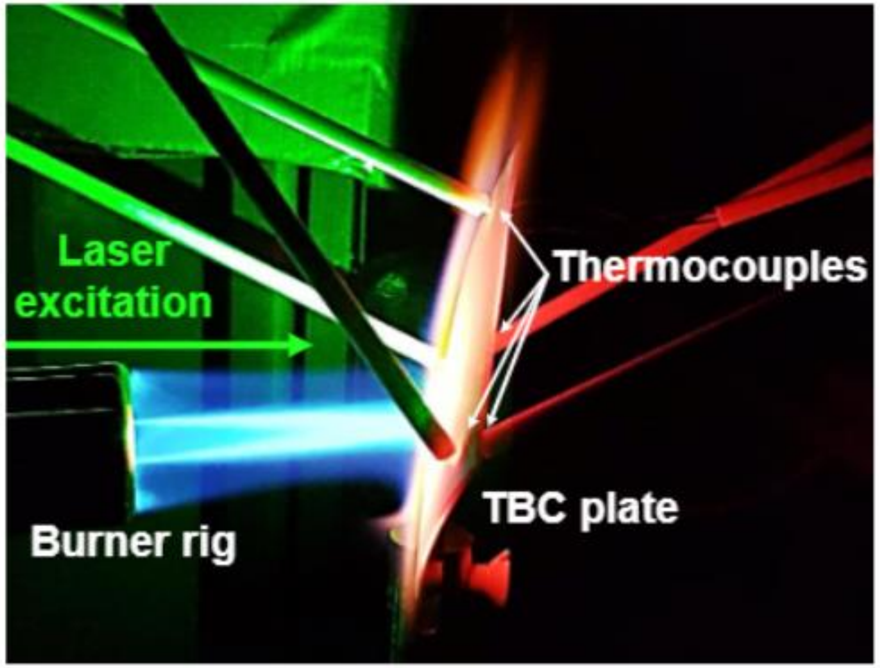
T-Er-1

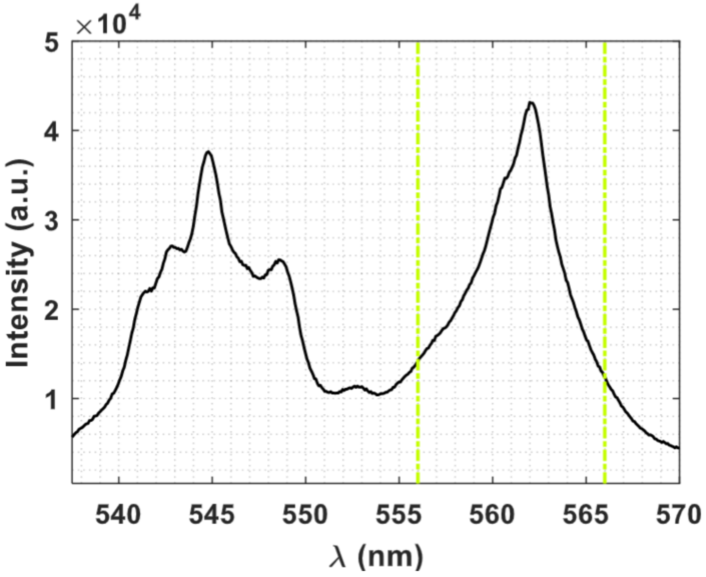


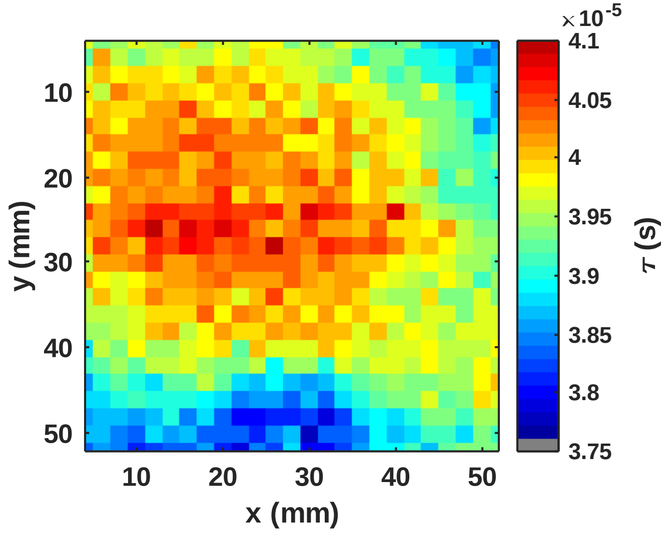




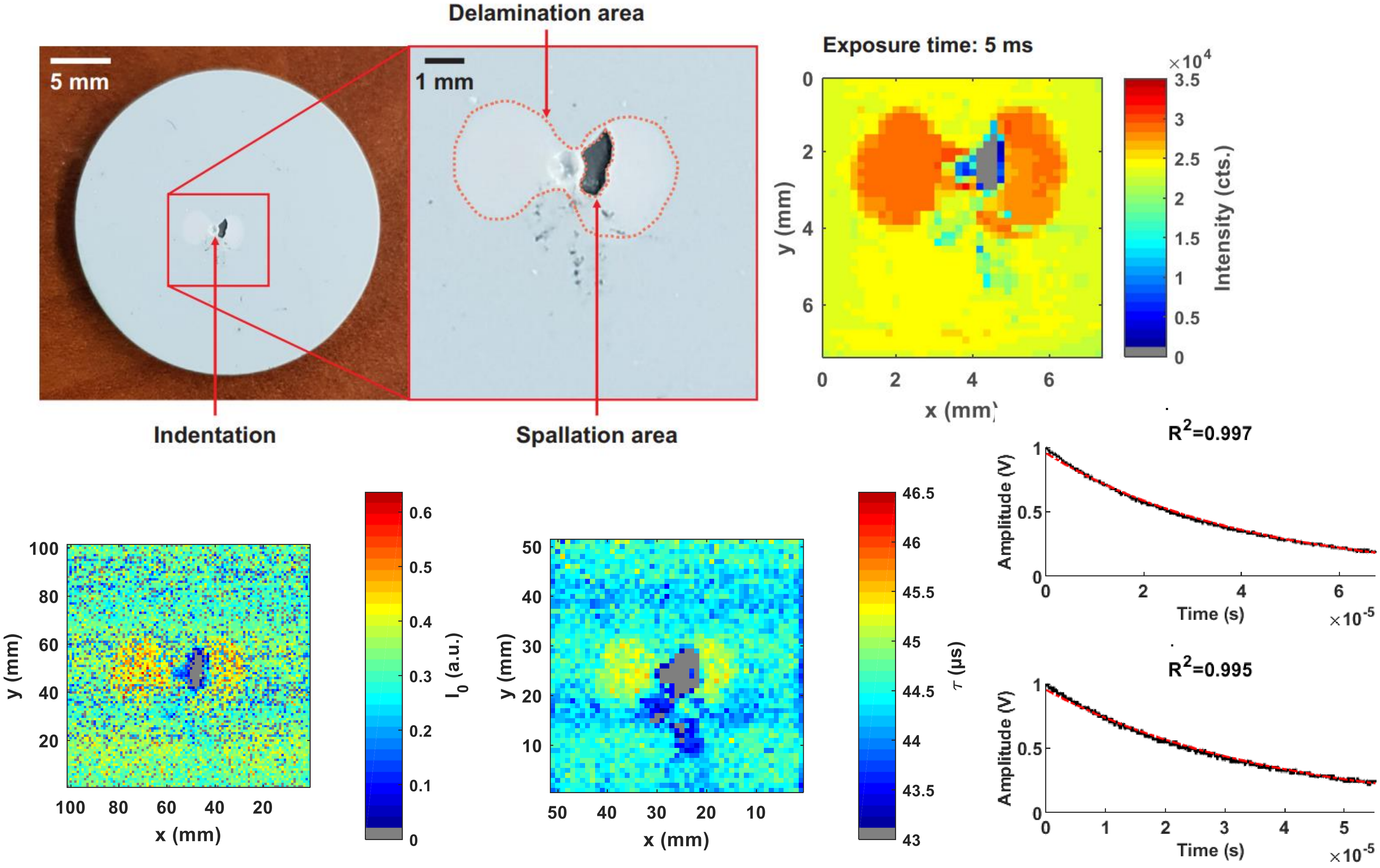






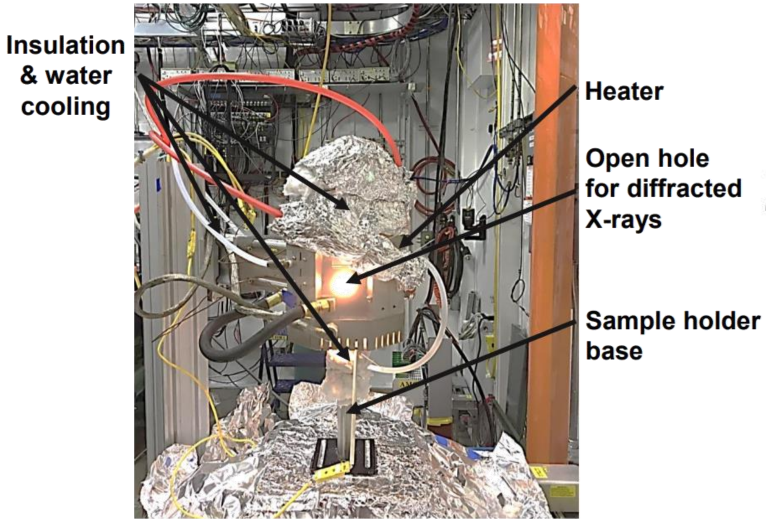


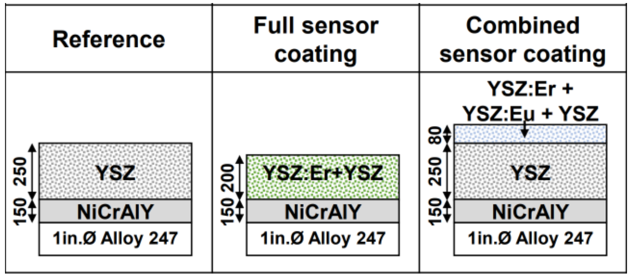
Potential for measuring stress using phosphor properties

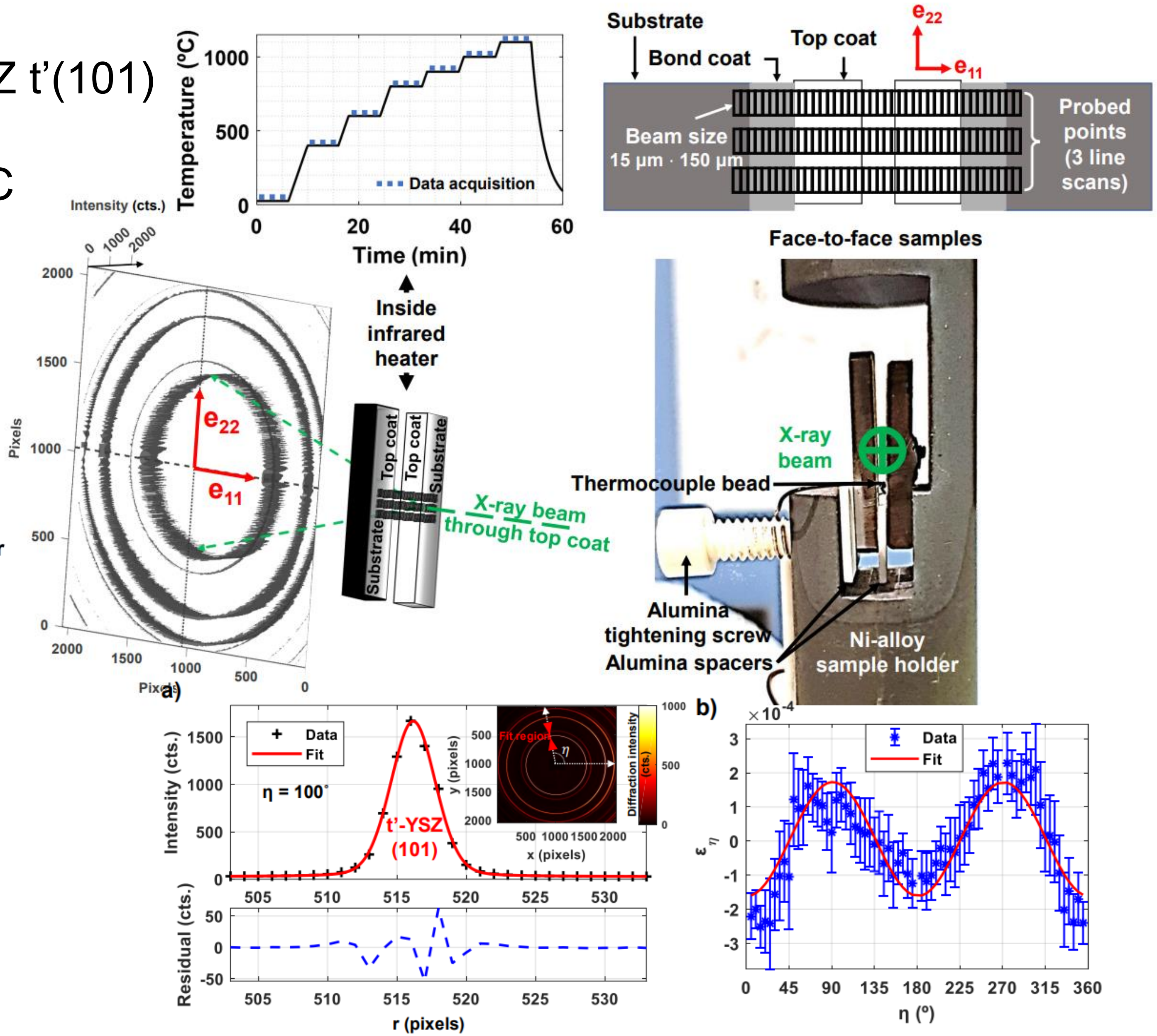


Synchrotron work to determine suitability of sensor coatings

- Analysis using diffraction peak YSZ t’(101)
- In-situ measurements up to 1100˚C







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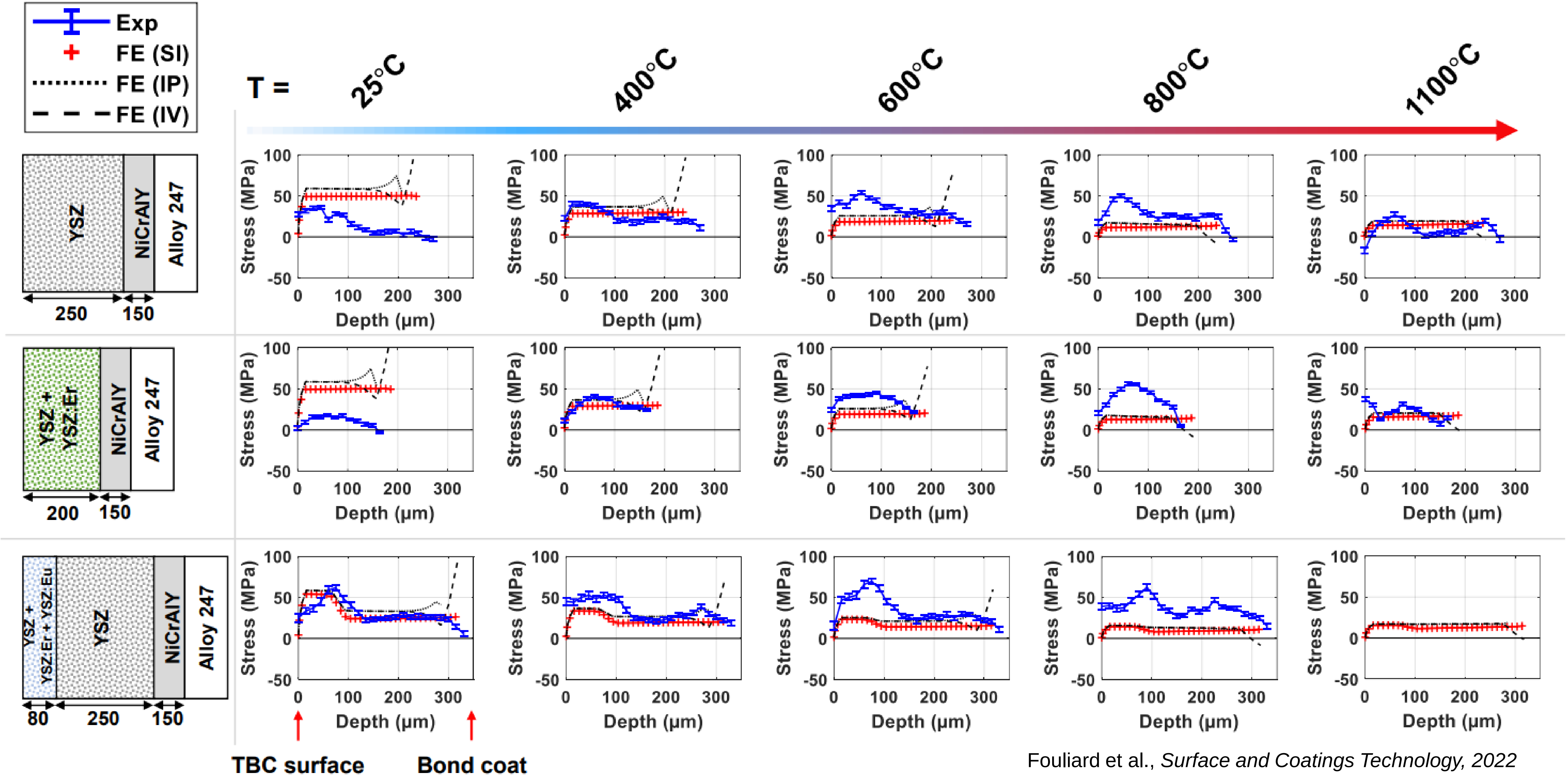
Calculation of in-plane stress for coating comparison



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Conclusions & Perspectives

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Conclusions

- Precise determination of temperatures in TBCs can result in large benefits in terms of fuel savings, reduction of emission, as well as better monitoring of TBC lifetime
- Enabled the extension of the range of measurable temperatures using phosphor thermometry with higher sensitivity by capturing simultaneously luminescence decays and intensities using a co-doped YSZ:Er,Eu sensor TBC.
- Demonstrated surface temperature measurement capabilities using a the phosphor thermometry system with a high-speed camera setup for in-situ engine measurements.
- Quantified stress in sensor coatings through synchrotron X-ray diffraction.

Future work

- Efforts will be focused on condensing data for publication.

- Additional work on phosphor thermometry high-temperature measurements will be performed as to complete Task 6 including experimentation with high-speed camera for surface and through-depth temperature measurements.

Patents

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THANK YOU FOR YOUR ATTENTION

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