DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

UTSR
University Turbine Systems Research

2019 ANNUAL PROJECT REVIEW MEETING FOR CROSSCUTTING, RARE EARTH ELEMENTS, GASIFICATION AND TRANSFORMATIVE POWER GENERATION

ADVANCED INSTRUMENTATION

IN-SITU OPTICAL MONITORING OF GAS TURBINE BLADE COATINGS UNDER OPERATIONAL EXTREME ENVIRONMENTS (DE-FE00312282)

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CATER

University of Central Florida

IN-SITU OPTICAL MONITORING OF GAS TURBINE BLADE COATINGS UNDER OPERATIONAL EXTREME ENVIRONMENTS

Overall 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).

Specific goals are to improve the accuracy and effectiveness of temperature and strain measurements made on high temperature gas turbine blades.

Project Objectives

- Achieve intelligent sensing that leverages intrinsic properties of coatings and dopants through optical emission and absorption characteristics while ensuring coating integrity and durability goals are concurrently met.
- Achieve accurate diagnostics of turbine blade coatings under operating environments through calibration and correlation of measurements with direct and indirect parameters.
- Achieve advances in benchmarked optical measurement technologies of infrared imaging (IR) measurements and digital image correlation (DIC) in existing laboratory replicated environments.

Project Tasks

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

Outline

- **Background and motivation**
- **Modeling phosphor luminescence for phosphor thermometry**
- **Coating characterization by synchrotron XRD measurements**
- **Instrumentation for phosphor thermometry and initial measurements**
- **Summary and Future work**

Background & Motivations

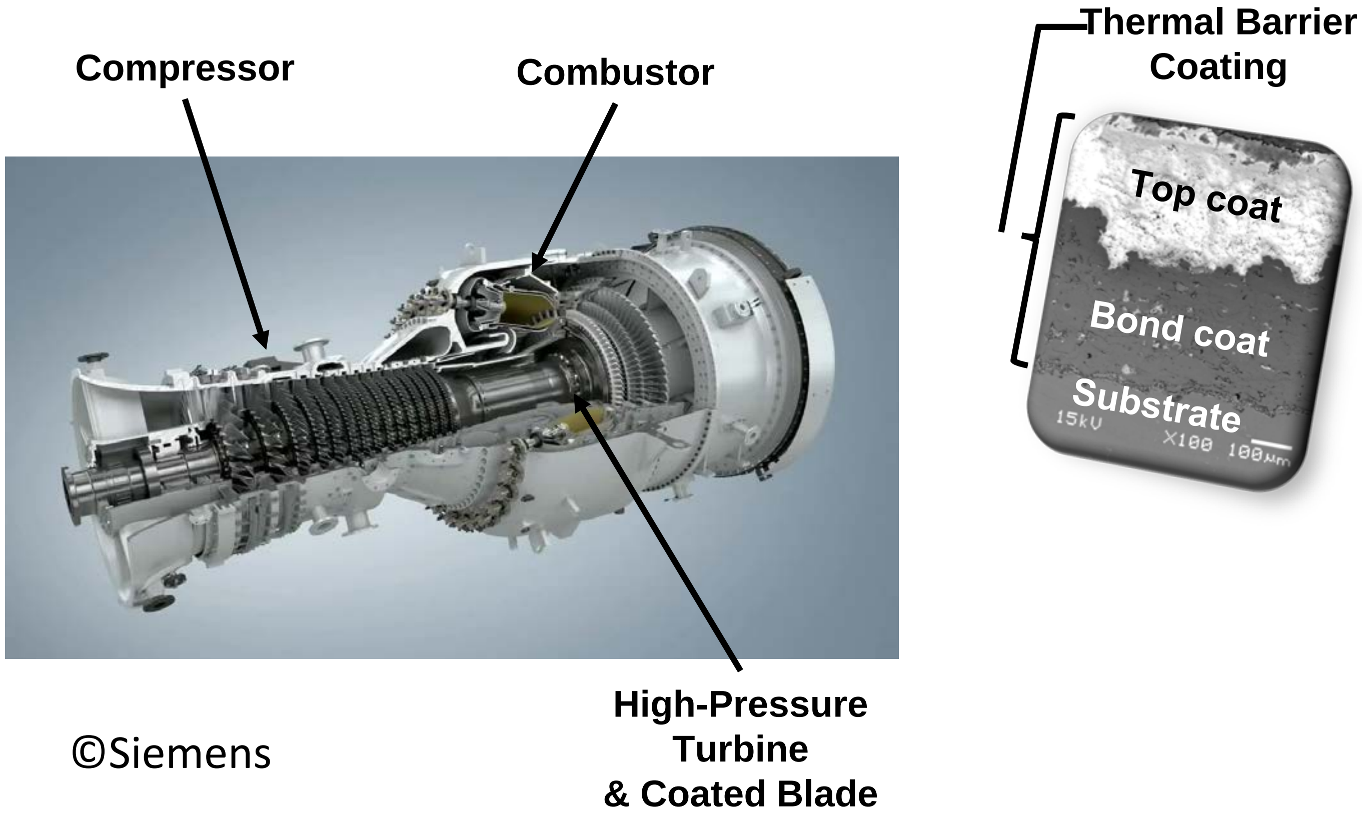
Background - Thermal Barrier Coatings (TBCs)

- **Thermal barrier coatings (TBCs)** used to protect metal substrates from extreme temperatures (1300 - 1600°C).
- **Temperature gradients:** Temp decreased by ≈ 150°C across the top coat.
- **TBC structure:**

Top coat	**YSZ**
TGO	**Alumina**
Bond coat	**NiCoCrAlY, Pt-aluminide**
Substrate	**Inconel, SX-superalloys**

- **Major applications:**
  - Power generation engines, Aeroengines
- Gas turbine systems work under the Brayton cycle:

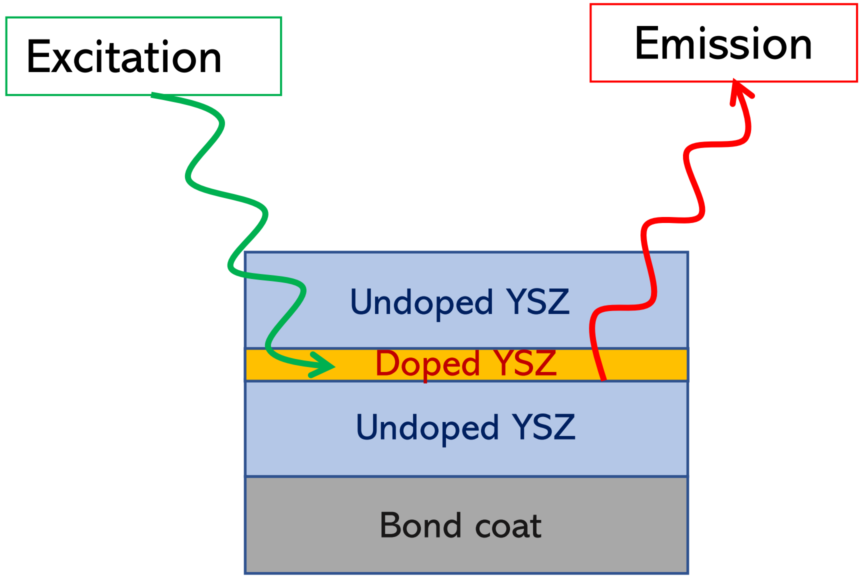
$$\boldsymbol{\eta = 1 - \frac{1}{Temp\ Ratio}}$$



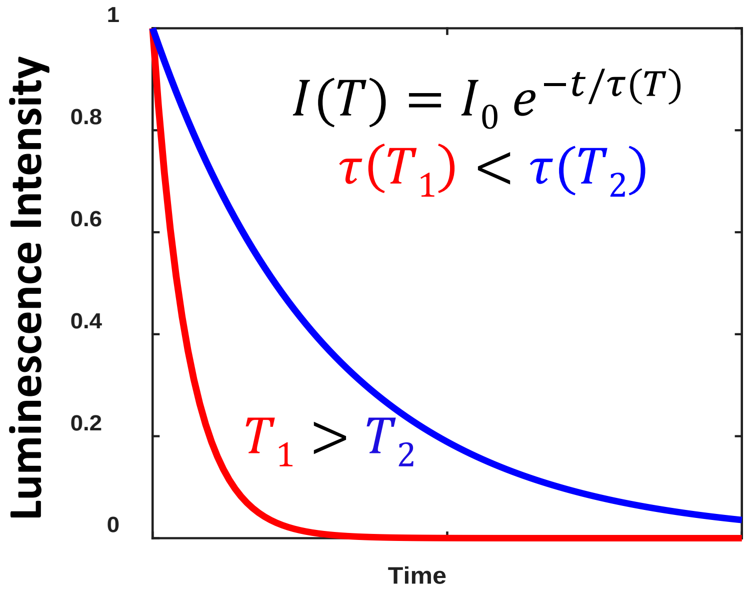
Cutaway view of a power generation SGT-800 industrial gas turbine [©Siemens] and a scanning electron microscope (SEM) image of a cross-section of a TBC

Temperature sensing TBCs for Phosphor Thermometry

- Embedded doped layer in a TBC enables temperature measurement “beneath the coating”
- Typical dopants are rare-earth elements (Dy, Eu, Er, etc.)
- The time dependent intensity is measured following the excitation pulse to determine the temperature dependent decay constant $\tau(T)$.



Configuration of TBC including a doped layer for Phosphor Thermometry



Schematic of Normalized intensity vs. time

Task 2: Define and manufacture sensor configuration

Modeling Luminescence of Rare earth doped TBC configurations for Phosphor Thermometry

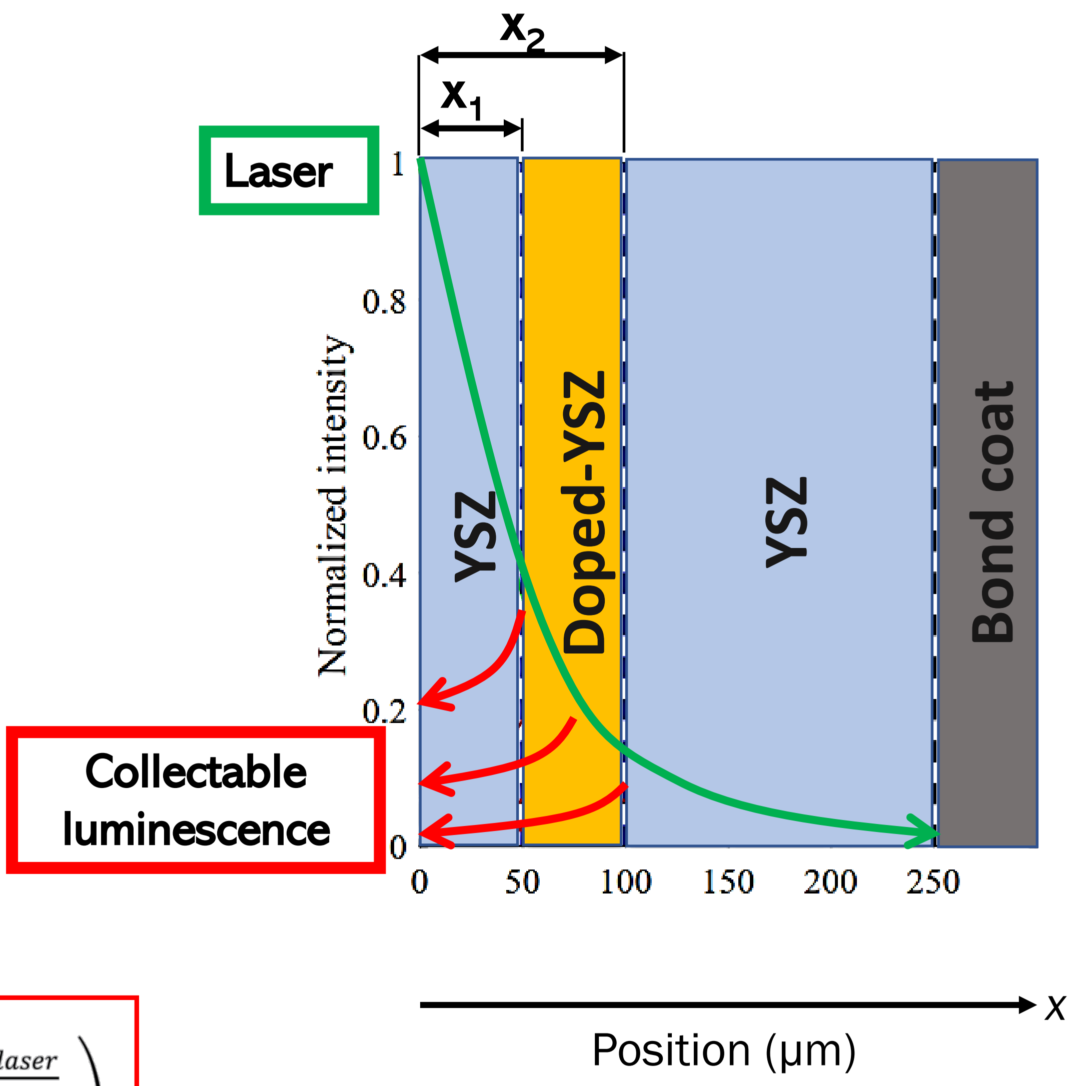
Modeling Luminescence

Four-flux Kubelka-Munk model

$$\begin{Bmatrix} I'_{laser} \\ J'_{laser} \end{Bmatrix} = \begin{bmatrix} -(K_{laser} + S_{laser}) & S_{laser} \\ -S_{laser} & K_{laser} + S_{laser} \end{bmatrix} \begin{Bmatrix} I_{laser} \\ J_{laser} \end{Bmatrix}$$

I_{laser} : intensity of laser traveling towards bond coat
J_{laser} : intensity of laser traveling towards top surface
I_{lum} : intensity of the luminescence traveling towards bond coat
J_{lum} : intensity of the luminescence traveling towards top surface

$$\begin{Bmatrix} I'_{lum} \\ J'_{lum} \end{Bmatrix} = \begin{bmatrix} -(K_{lum} + S_{lum}) & S_{lum} \\ -S_{lum} & K_{lum} + S_{lum} \end{bmatrix} \begin{Bmatrix} I_{lum} \\ J_{lum} \end{Bmatrix} + \begin{bmatrix} \frac{qK_{laser}}{2} & \frac{qK_{laser}}{2} \\ -\frac{qK_{laser}}{2} & -\frac{qK_{laser}}{2} \end{bmatrix} \begin{Bmatrix} I_{laser} \\ J_{laser} \end{Bmatrix}$$



$$S \equiv 2s$$

$$K \equiv 2k.$$

s: scattering coefficient
k: absorption coefficient

$$\boxed{Q = \begin{pmatrix} \frac{qK_{laser}}{2} & \frac{qK_{laser}}{2} \\ -\frac{qK_{laser}}{2} & -\frac{qK_{laser}}{2} \end{pmatrix}}$$

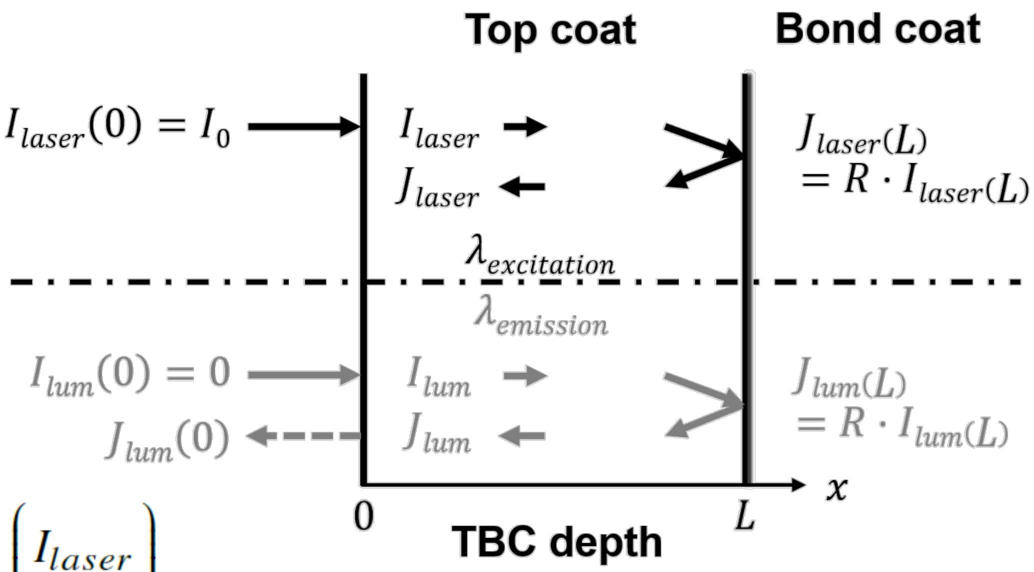
Phosphor Luminescence production coefficient

Modeling Luminescence

Four-flux Kubelka-Munk model

$$\begin{Bmatrix} I'_{laser} \\ J'_{laser} \end{Bmatrix} = \begin{bmatrix} -(K_{laser}+S_{laser}) & S_{laser} \\ -S_{laser} & K_{laser}+S_{laser} \end{bmatrix} \begin{Bmatrix} I_{laser} \\ J_{laser} \end{Bmatrix}$$

$$\begin{Bmatrix} I'_{lum} \\ J'_{lum} \end{Bmatrix} = \begin{bmatrix} -(K_{lum}+S_{lum}) & S_{lum} \\ -S_{lum} & K_{lum}+S_{lum} \end{bmatrix} \begin{Bmatrix} I_{lum} \\ J_{lum} \end{Bmatrix} + \begin{bmatrix} \frac{qK_{laser}}{2} & \frac{qK_{laser}}{2} \\ -\frac{qK_{laser}}{2} & -\frac{qK_{laser}}{2} \end{bmatrix} \begin{Bmatrix} I_{laser} \\ J_{laser} \end{Bmatrix}$$



Boundary conditions used for the model

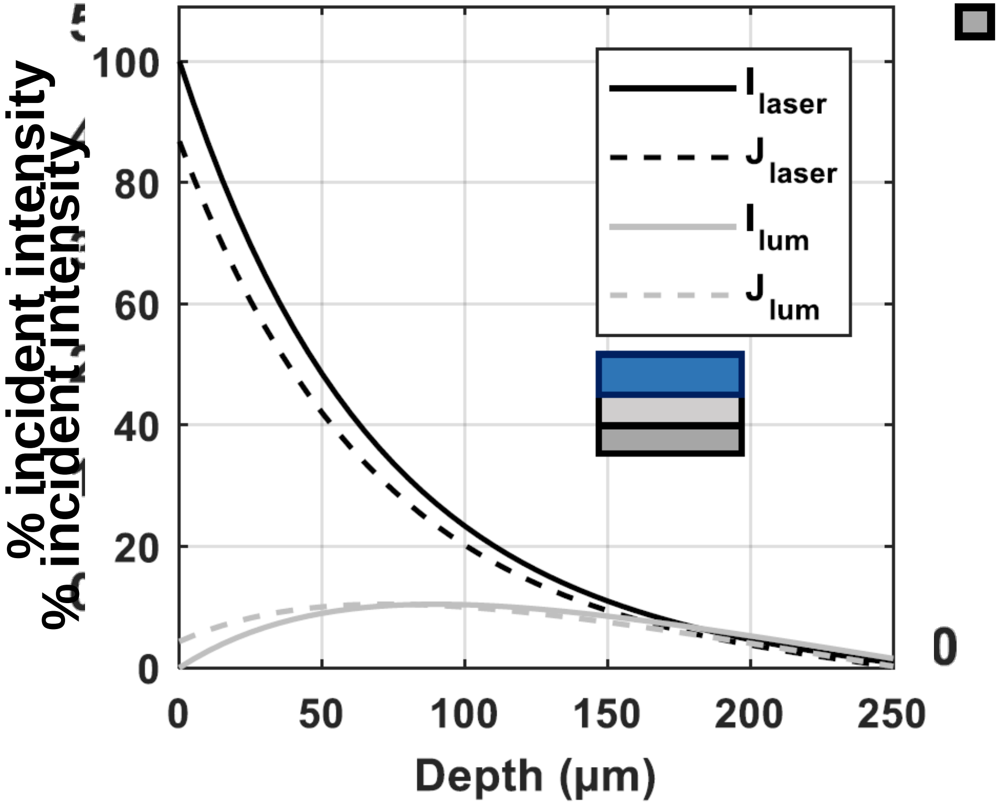
Material	λ (nm)	scattering coefficient s (m^{-1})	absorption coefficient k (m^{-1})
Excitation properties			
YSZ:Dy	355	50866	511
YSZ:Er / YSZ:Sm	532	33026	111
Emission properties			
YSZ:Dy	590	29585	95
YSZ:Er	545	32113	107
YSZ:Sm	619	28490	88

Input properties (Stuke, 2012)

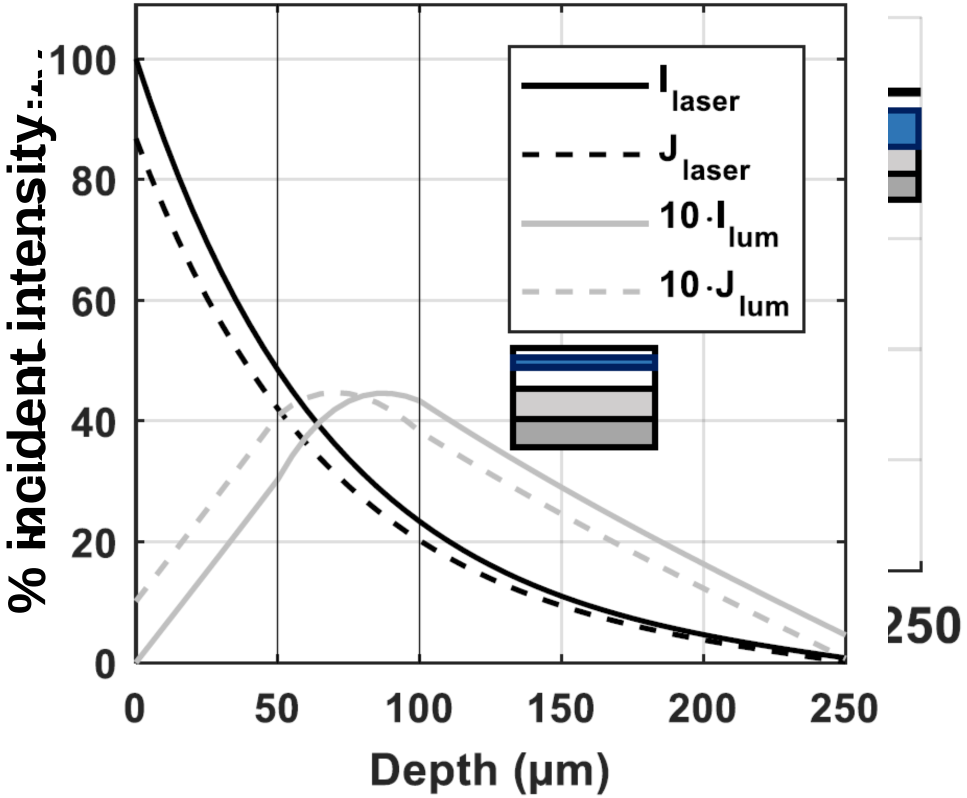
A. Stuke, Int. J. Appl. Ceram. Technol. 9: 561–574, 2012

Modeling Luminescence Intensities – Results of Kubelka-Munk model

🟦 Doped top coat
☐ Undoped top coat
▨ Bond coat
■ Substrate



- Intensity is higher when the doped layer is positioned at the top and decreases with position at depth

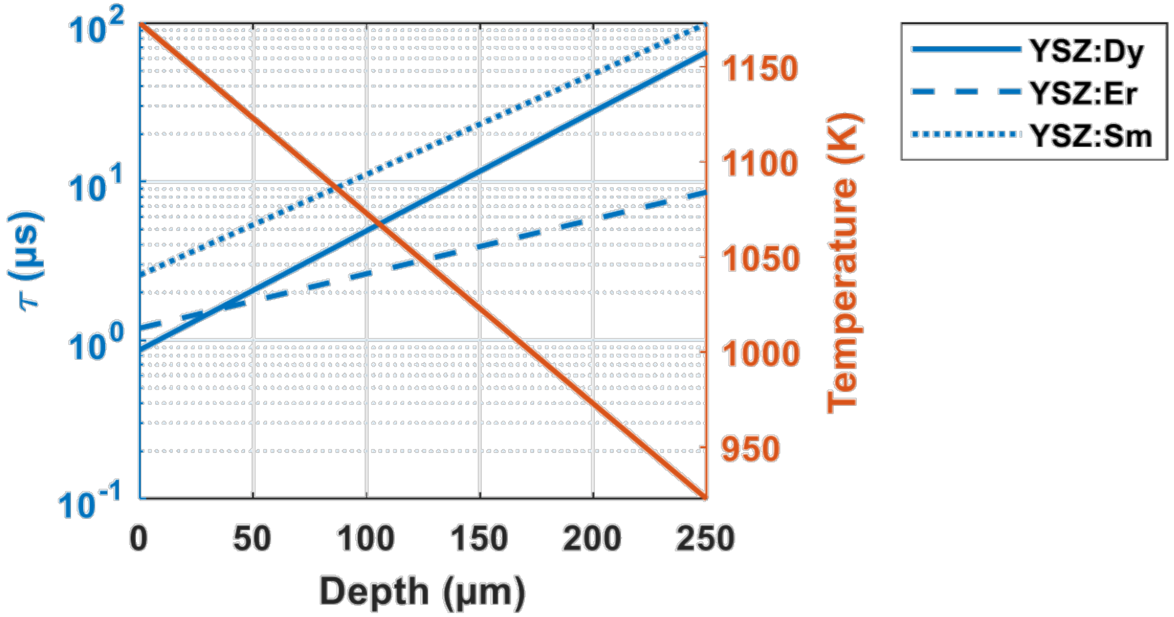


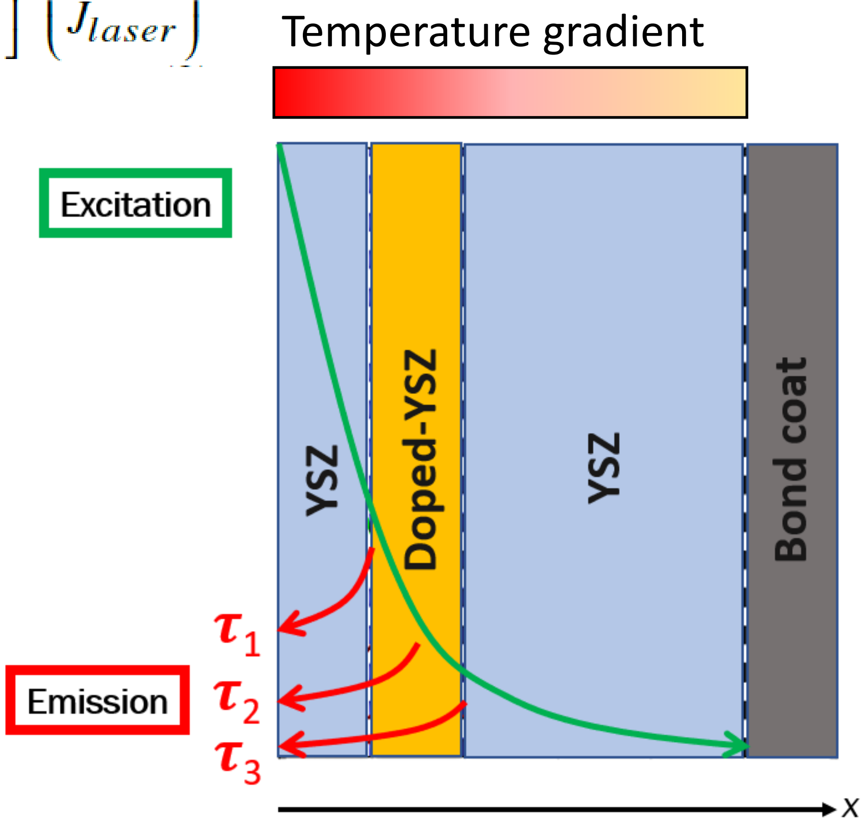
- Increase in the thickness of the doped layer results in an increase in collectible intensity up to a limit

Decay time of luminescence in TBC configurations

$$\begin{Bmatrix} I'_{lum} \\ J'_{lum} \end{Bmatrix} = \begin{bmatrix} -(K_{lum}+S_{lum}) & S_{lum} \\ -S_{lum} & K_{lum}+S_{lum} \end{bmatrix} \begin{Bmatrix} I_{lum} \\ J_{lum} \end{Bmatrix} + \boxed{\phi(x,t)} \begin{bmatrix} \frac{qK_{laser}}{2} & \frac{qK_{laser}}{2} \\ -\frac{qK_{laser}}{2} & -\frac{qK_{laser}}{2} \end{bmatrix} \begin{Bmatrix} I_{laser} \\ J_{laser} \end{Bmatrix}$$

$$\boxed{\phi(x,t) = e^{-t/\tau(x)}}$$

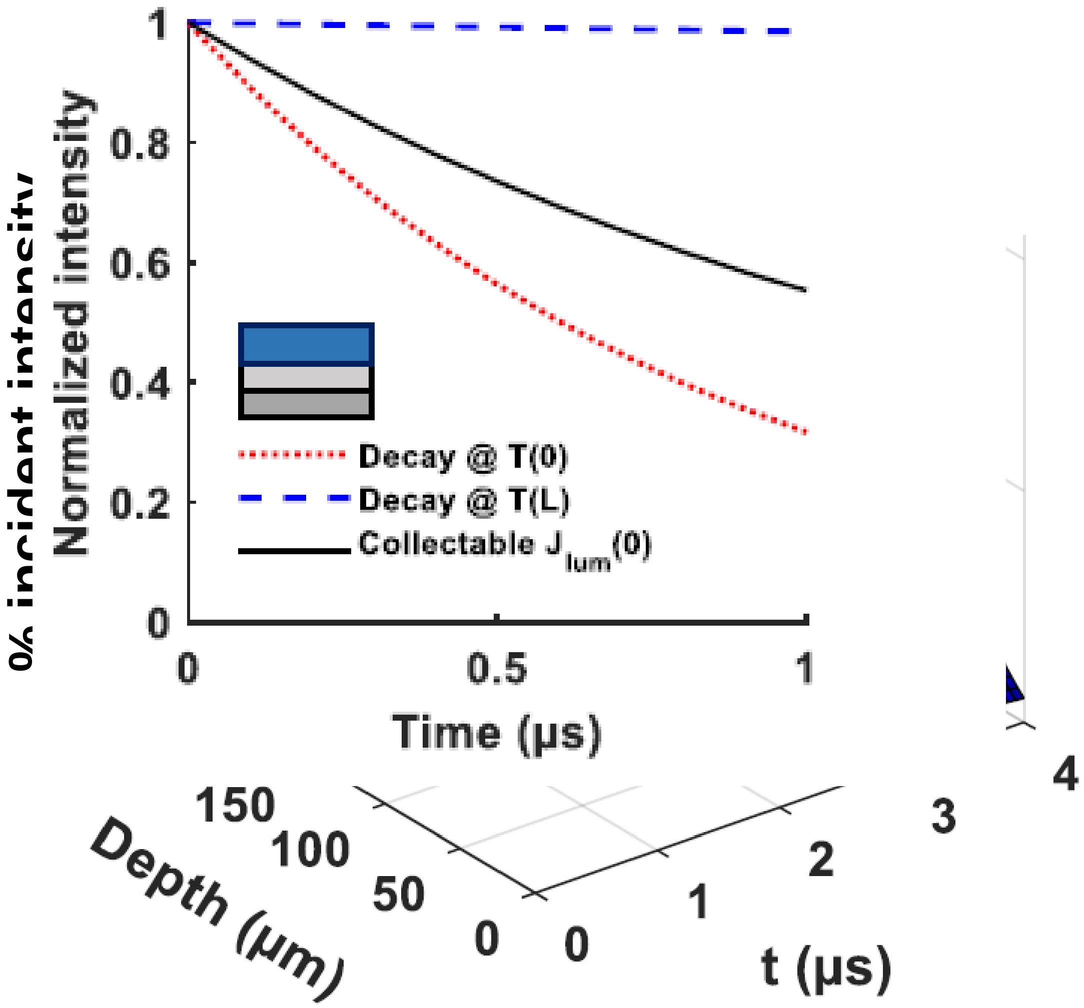


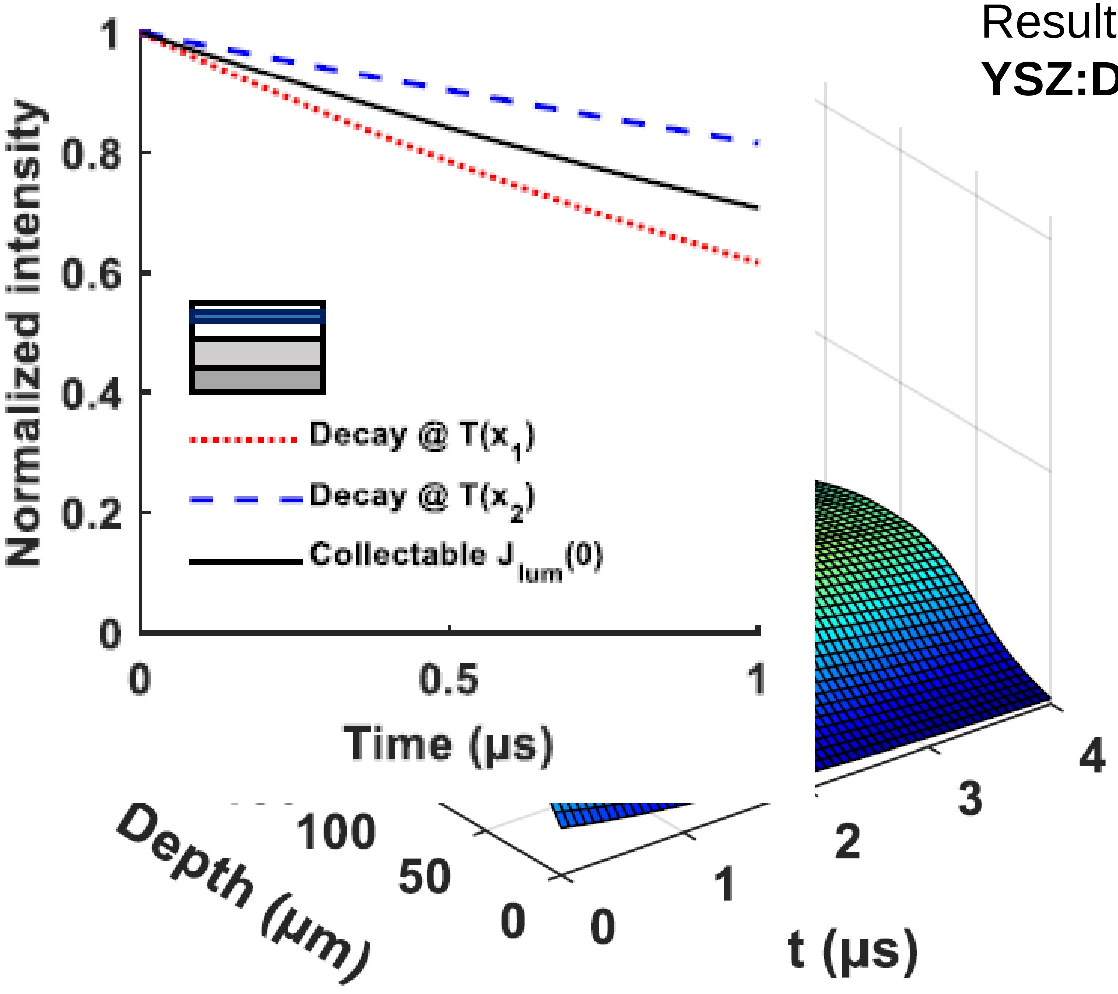


- Decay time of the luminescence depends on position due to gradients in temperature.
- Decay time of collectable luminescence is contribution of luminescence from different positions into the doped layer.

Decay time of luminescence in TBC configurations

Results for
YSZ:Dy

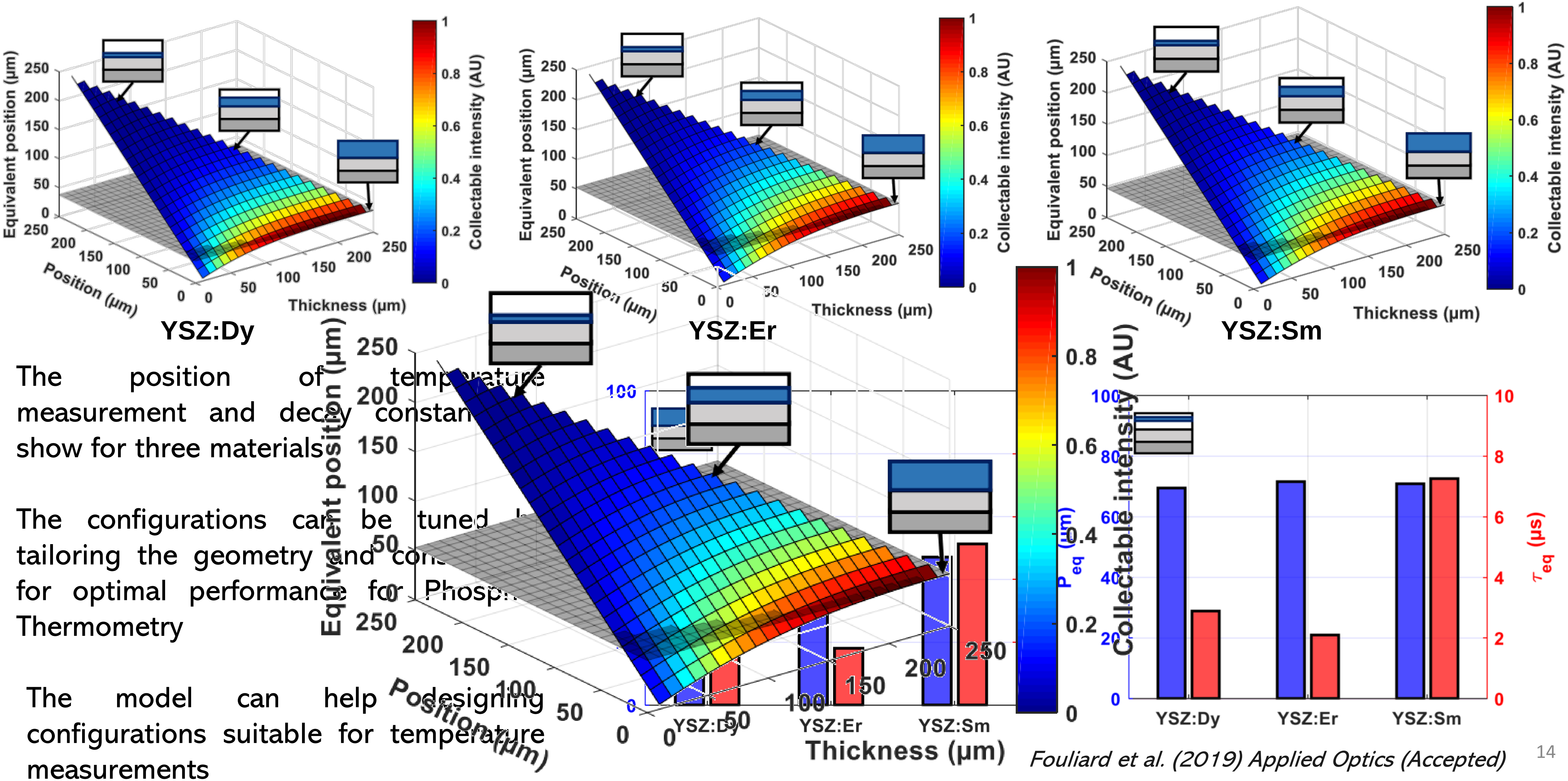




- The decay constant of the collected luminescence can be associated with a particular position of the top coating
- The temperature measurements then can be mapped to the position

Luminescence decay behavior in doped TBC configurations

Extension of Kubelka-Munk model - Results

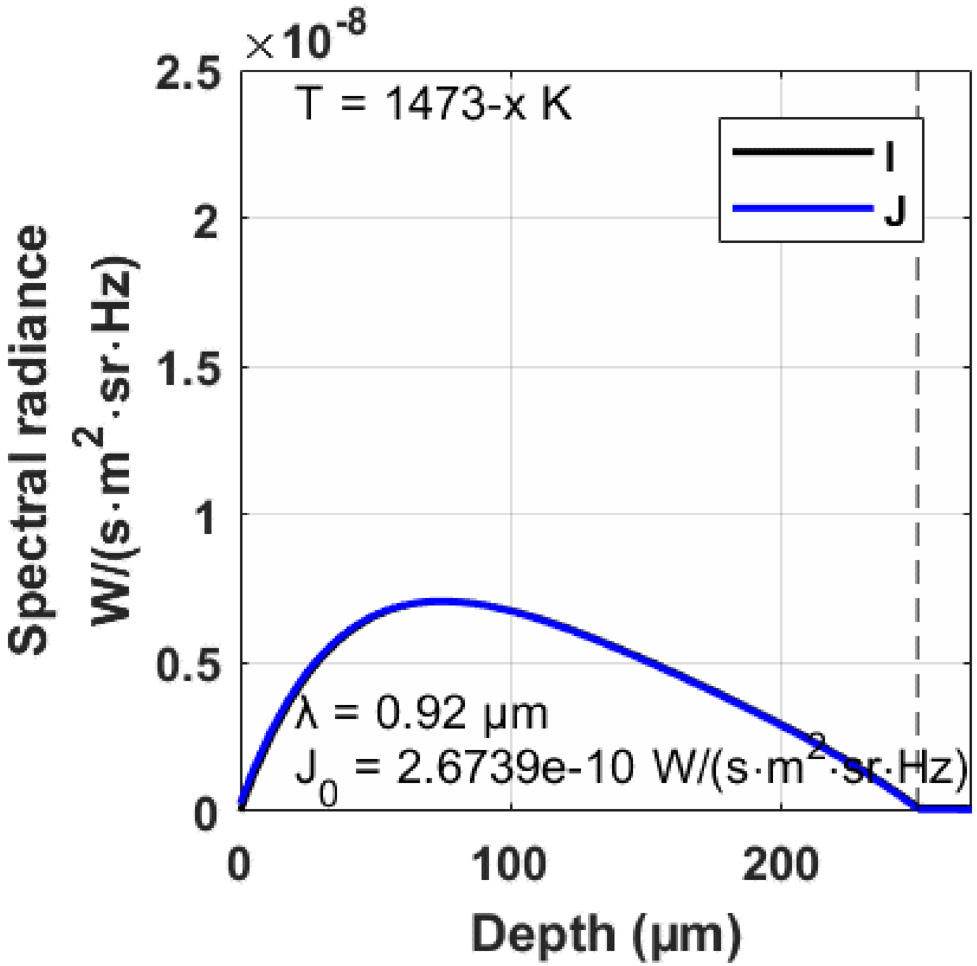


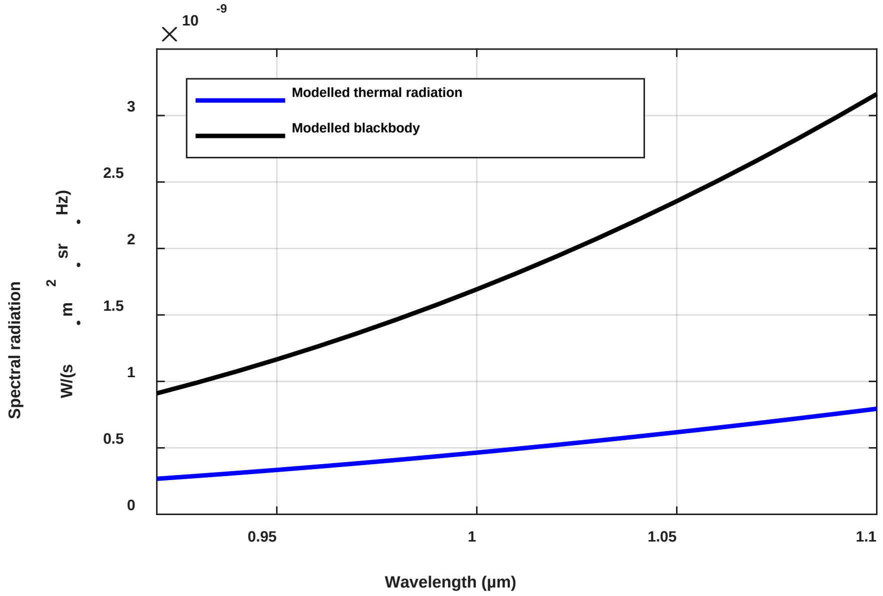
- The position of temperature measurement and decay constan show for three materials
- The configurations can be tuned b tailoring the geometry and con for optimal performance for Phosp Thermometry
- The model can help designing configurations suitable for temperature measurements

Fouliard et al. (2019) Applied Optics (Accepted)

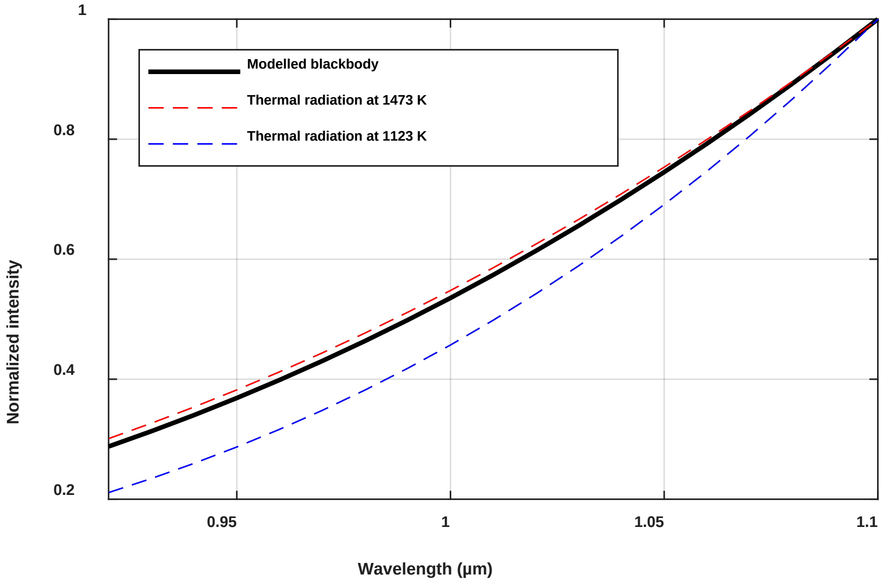
Model provides the expected emissivity spectra of EB-PVD YSZ TBC

Varying wavelength: distribution of intensities throughout the coating





Comparison of total intensities emitted by painted (blackbody e≈ 1) and unpainted TBC



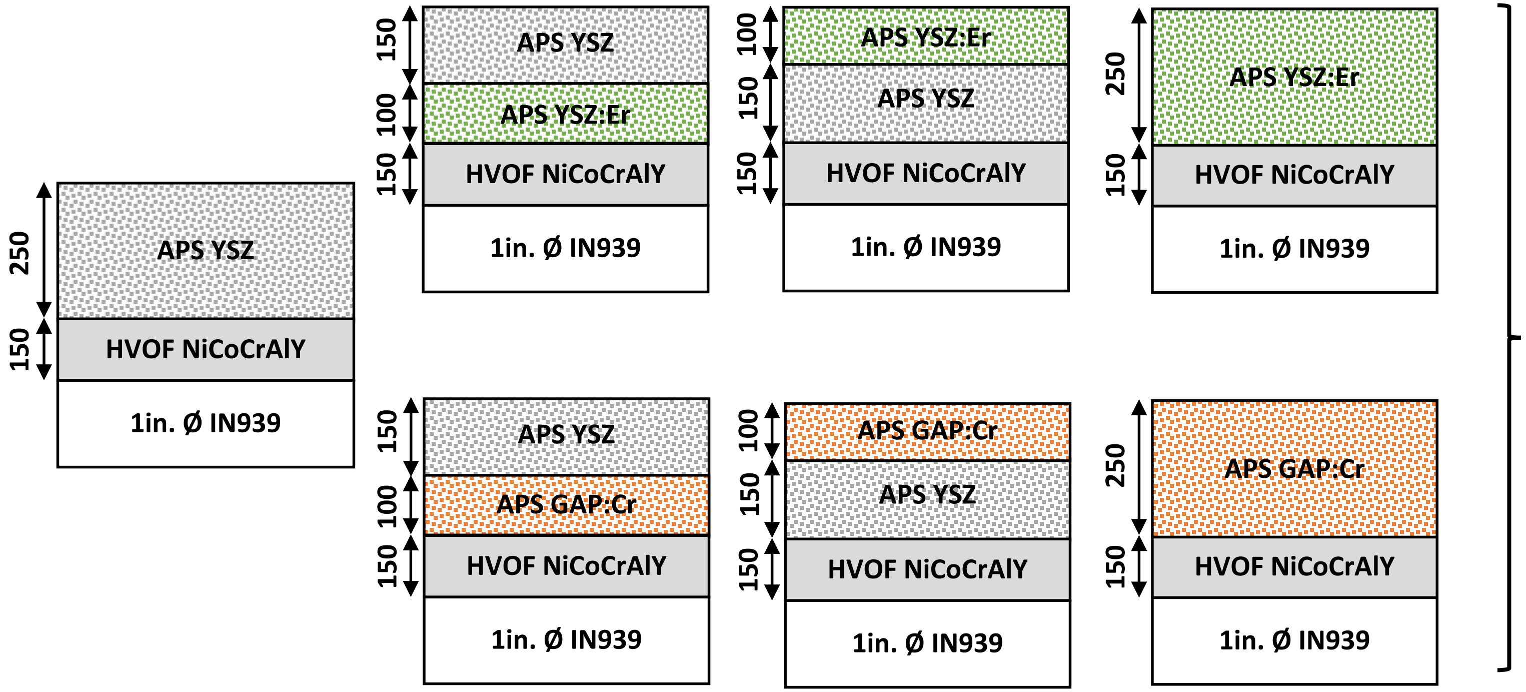
Data collected by the IR camera is mainly represented by radiation from the surface but measures a slightly smaller temperature

Defining sensor configurations

(thicknesses are in µm)

Compositions	
YSZ	8% at. Y_2O_3 , 92% at. Zr_2O_3
YSZ:Er	98.5% at. YSZ, 1.5% at. Er_2O_3
GAP:Cr	99.8% at. $GdAlO_3$, 0.2% at. Cr_2O_3

Number of specimens	21
Coupon dimensions	25.6mm ø x 3mm (height)
Ref samples must use same spray parameters	



(3 specimens for each configuration)

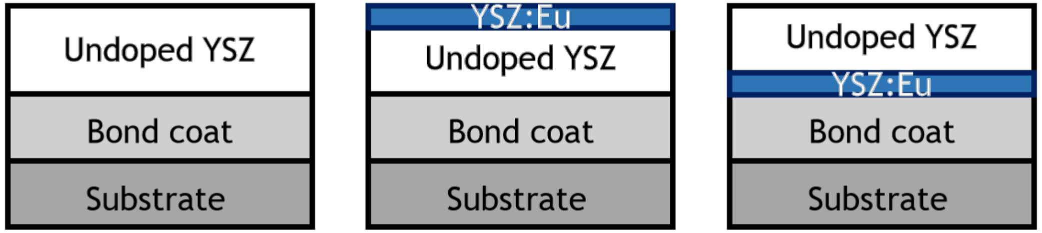
- Plan of sample fabrication for the APS TBCs

Task 3: Establish Sensing Properties and Characterize Coating Response for Luminescence Based Sensor

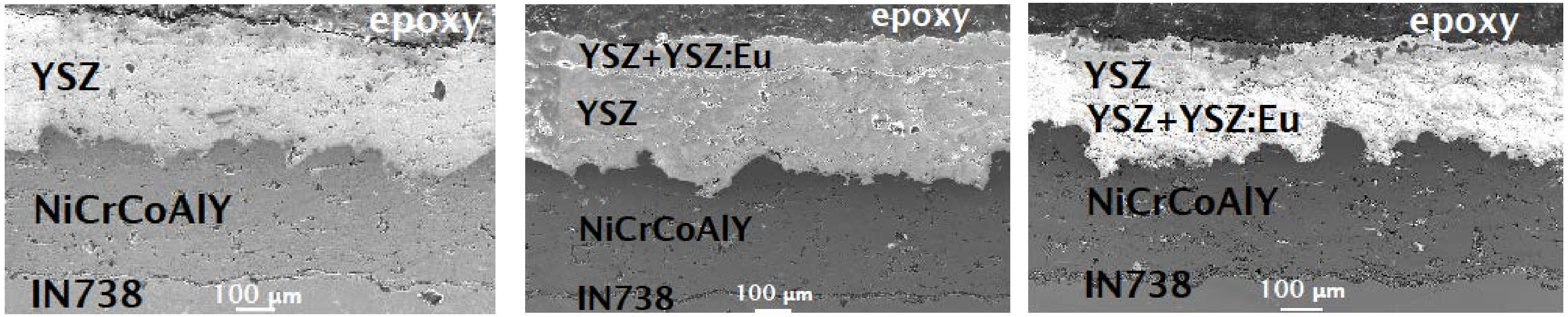
Synchrotron Characterization of TBC configurations with Rare Earth dopants

TBCs by Air Plasma Spray (APS)

Parameter	Spray distance (cm)	Current (A)	Voltage (V)	Ar (SLM)	He (SLM)
Value	10	900	43.9	54	44



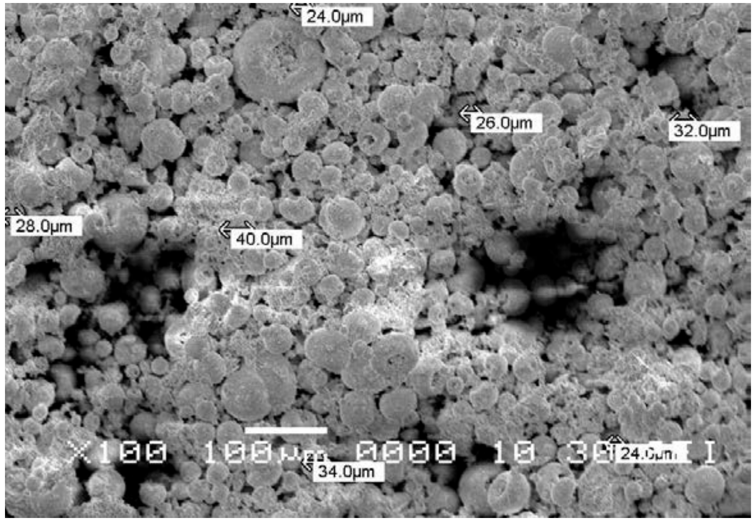
(C) (T) (B)



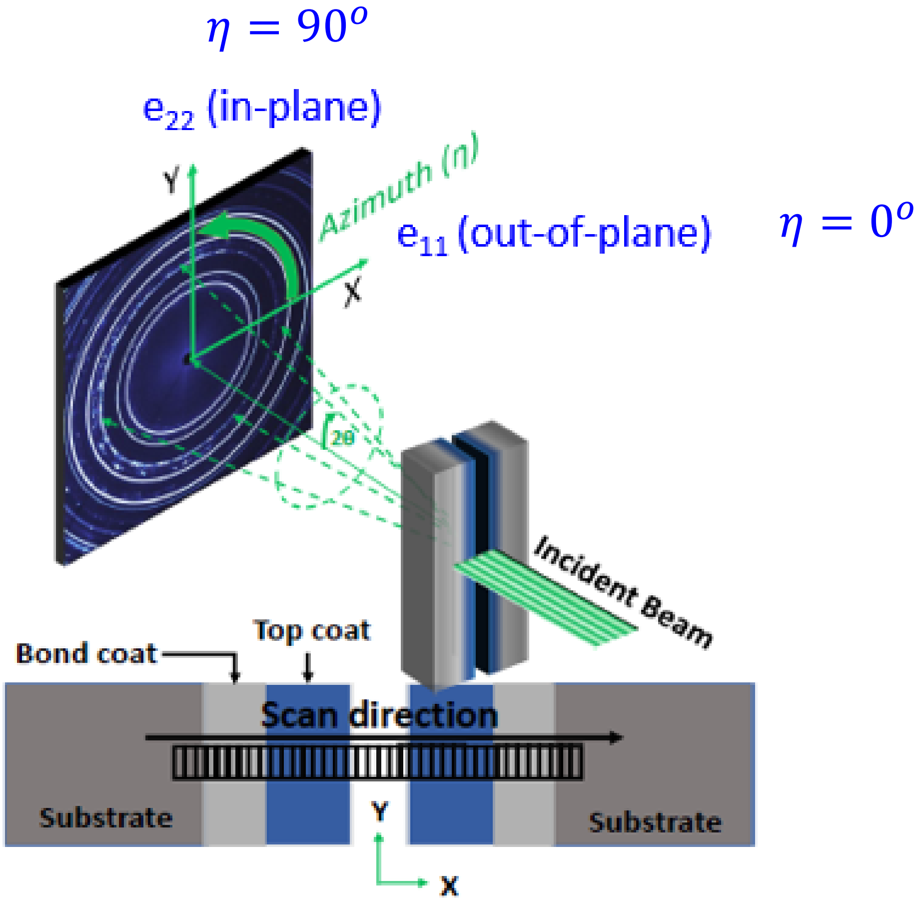
Configuration	Layer	Thickness	Hardness	Porosity
Regular (C)	BC	312 ± 33 μm	711.47 ± 268.80	
	TC	330 ± 22 μm	1037.89 ± 358.30	5.76 %
Doped layer at bottom (B)	BC	329 ± 29 μm	682.98 ± 125.10	
	TC-YSZ+YSZ:Eu	75 ± 12 μm	1220.30 ± 344.32	12.23 %
	TC-YSZ	247 ± 18 μm	1013.84 ± 323.45	9.22 %
Doped layer at top (T)	BC	323.60 ± 27.21 μm	670.07 ± 150.56	
	TC - YSZ	346 ± 25 μm	848.83 ± 64.21	6.36 %
	TC - YSZ+YSZ:Eu	75 ± 12 μm	996.07 ± 272.84	12.07 %

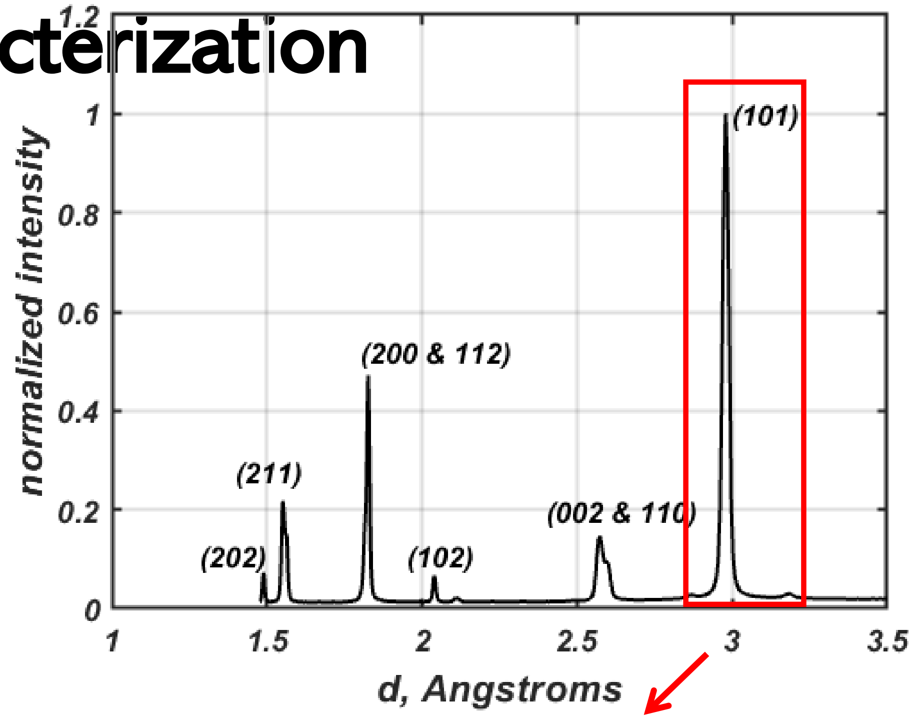
Doped layer: Mixture YSZ+YSZ:Eu [2:1 wt%]

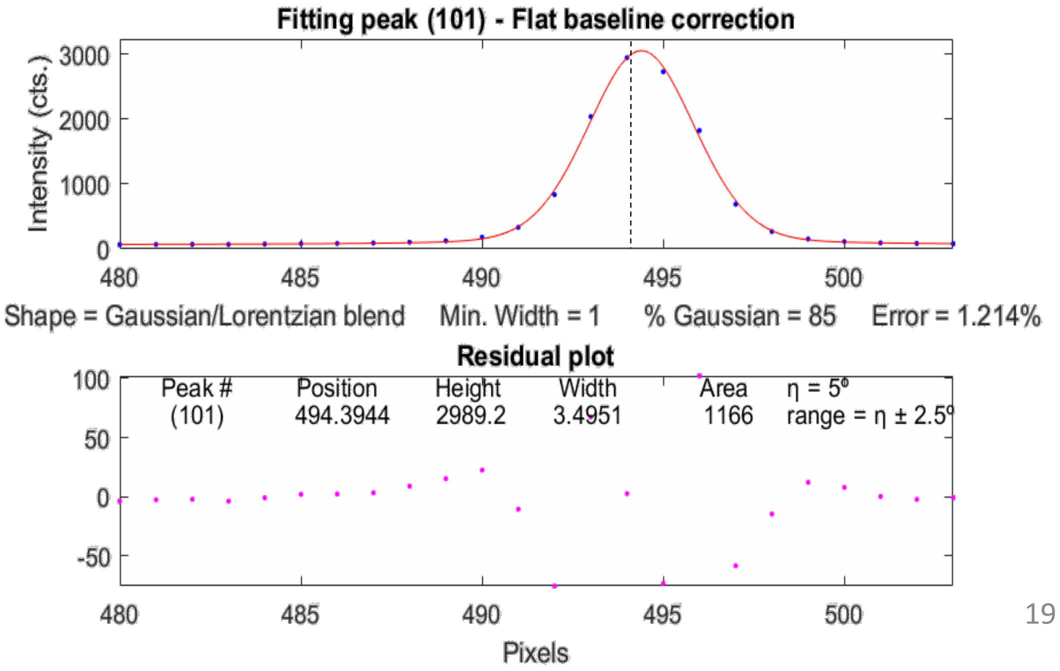
- Sprayable YSZ acts as a carrier



Synchrotron experiments for coating characterization






Fitting peak (101) - Flat baseline correction

Shape = Gaussian/Lorentzian blend   Min. Width = 1   % Gaussian = 85   Error = 1.214%

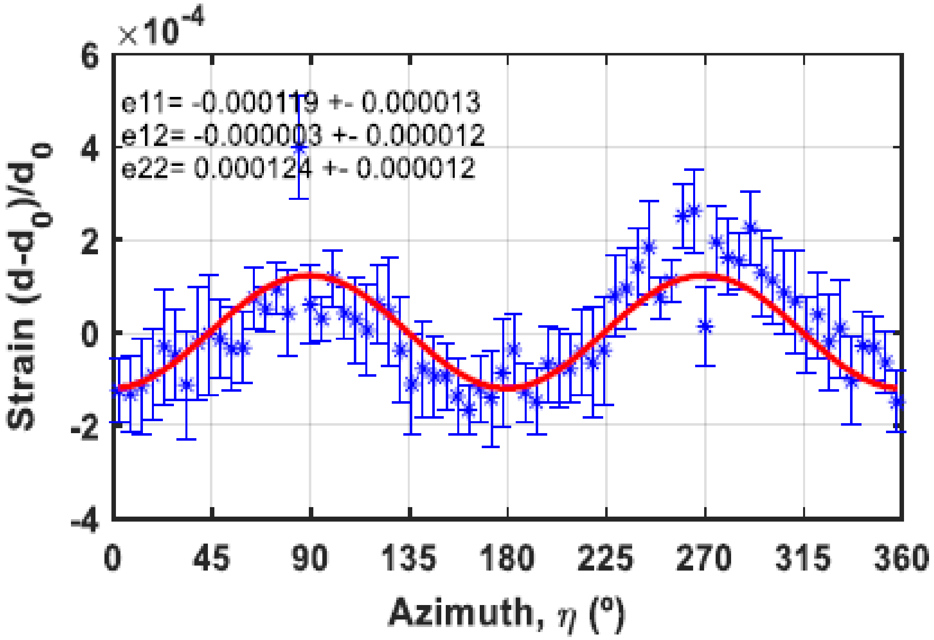
Residual plot

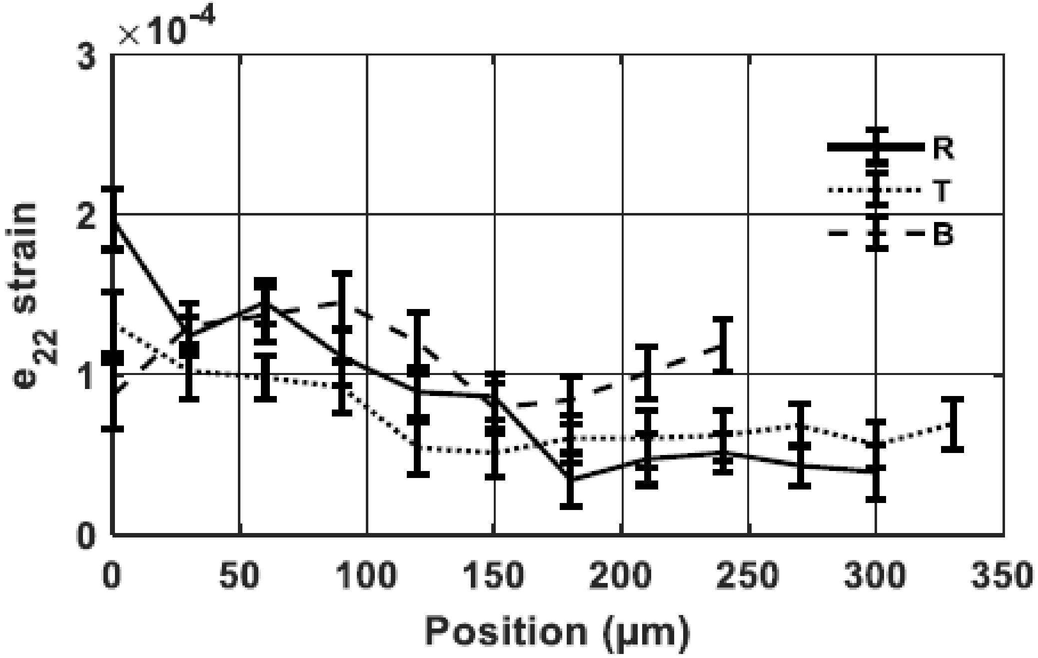
Peak #	Position	Height	Width	Area	η = 5°
(101)	494.3944	2989.2	3.4951	1166	range = η ± 2.5°

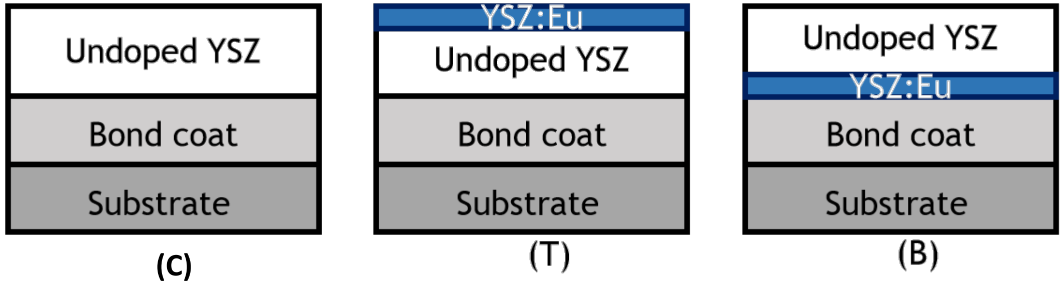
X-ray diffraction measurements have been performed in synchrotron at Argonne National Laboratory.

- Measurement of residual strain
- Coefficient of Thermal Expansion

XRD results – Residual strain







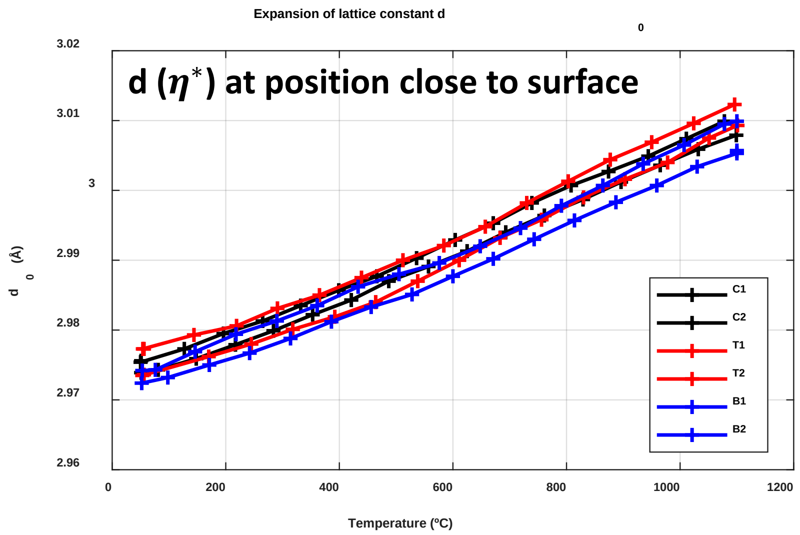
$$\epsilon(\eta) = \frac{d(\eta) - d_0(\eta^*)}{d_0(\eta^*)} \qquad \eta^*(101) = 44.33^o$$

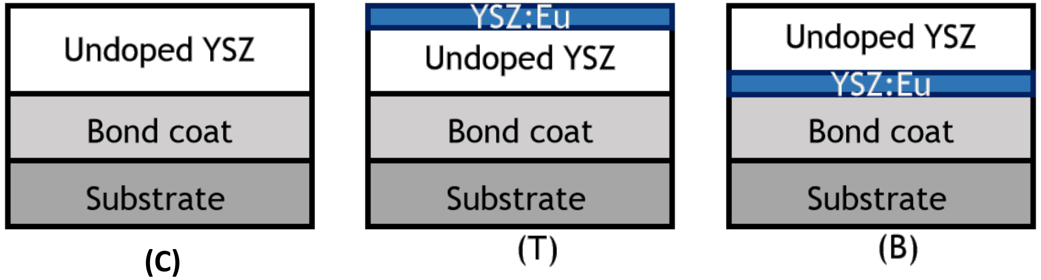
η^*: Strain free azimuth

- Depends on the peak
- To be calculated from single crystal elastic properties along with a grain interaction model

- The YSZ layer is found to be under in-plane tensile strain (e_{22})
- The strains are in the order of 10^{-4} that is close to experimental limit
- Overall mechanical integrity is not harmed by the multi-layered configuration

Coefficient of Thermal Expansion (CTE) of top coat




Undoped YSZ
Bond coat
Substrate
(C)

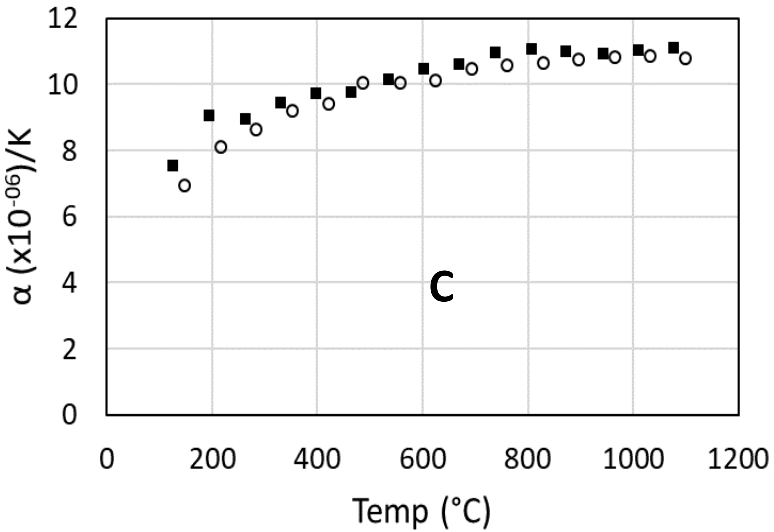
YSZ:Eu
Undoped YSZ
Bond coat
Substrate
(T)

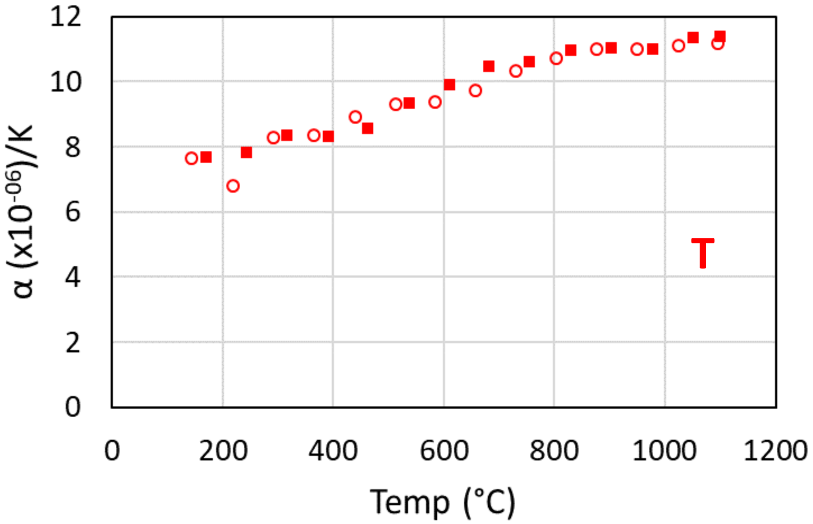
Undoped YSZ
YSZ:Eu
Bond coat
Substrate
(B)

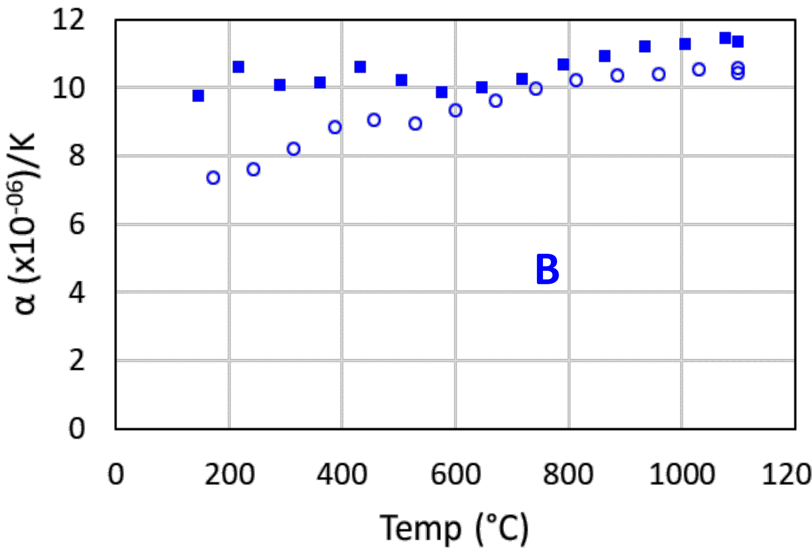
$$\alpha = {}^{dl}/_{l.dT}$$

$$\alpha_{low\ Temp} = 8x10^{-6} - 10x10^{-6}/K$$

$$\alpha_{high\ Temp} = 10x10^{-6} - 12x10^{-6}/K$$







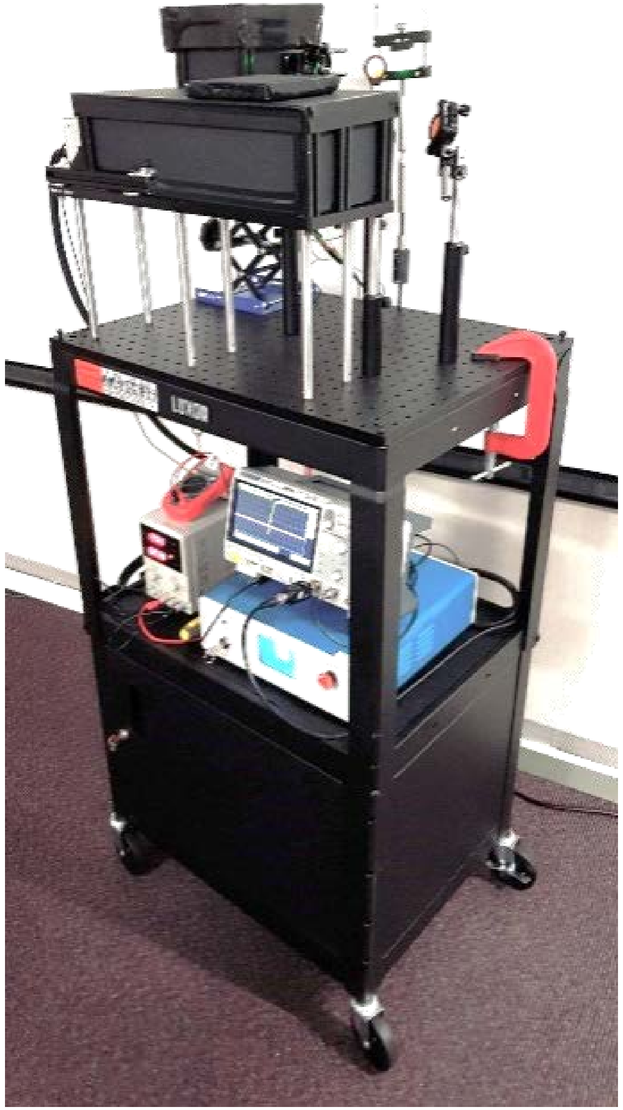
- The CTE increases with temperature
- The values of CTE are similar to reported values in literature
- The TBC configuration does not alter the thermal expansion behavior

Hayashi et al, Solid State Ionics, 176(5-6), 2005

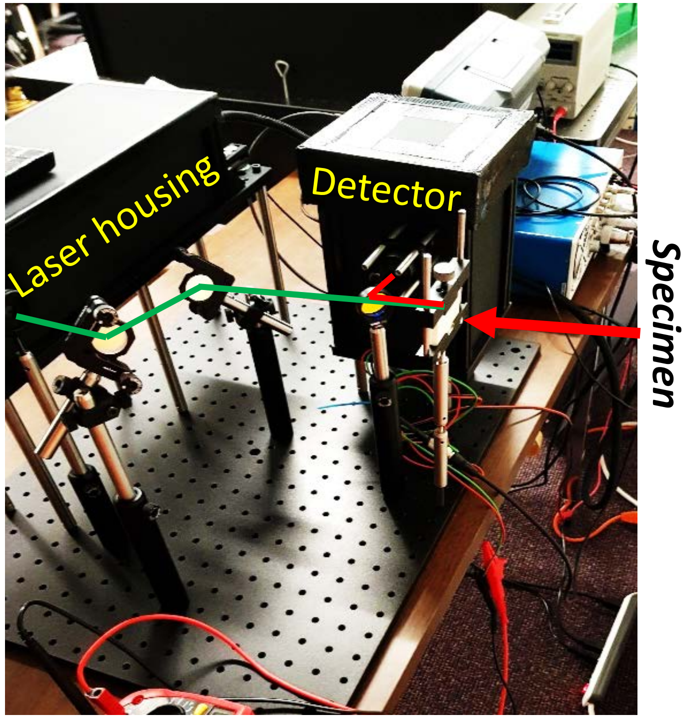
Task 5: Develop and Test Laboratory Scale Sensor Instrumentation Package

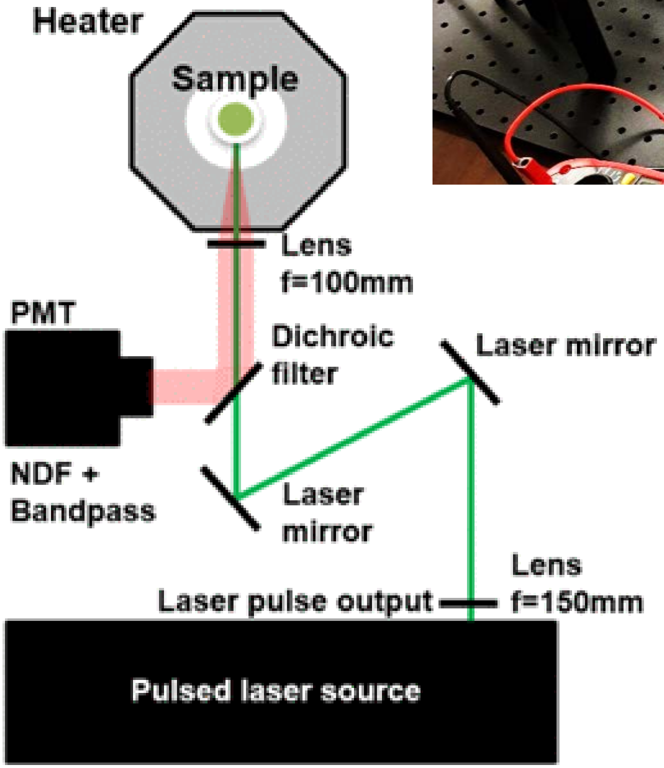
Instrumentation for Phosphor Thermometry

Instrumentation for luminescence decay method

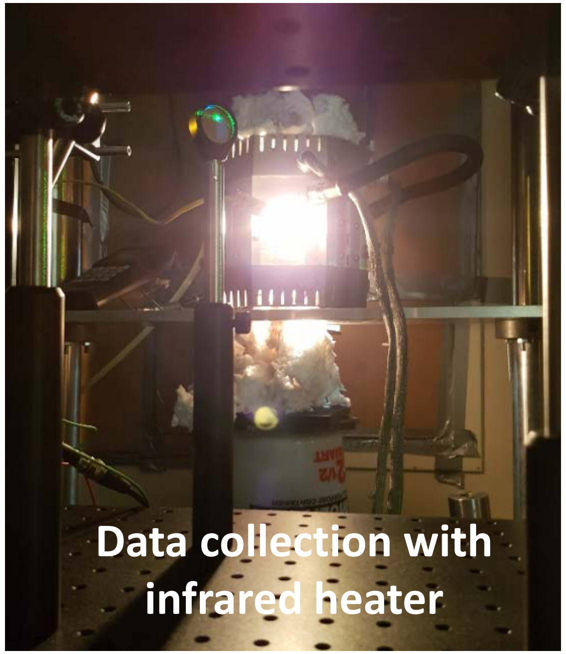


- Low power Pulsed-laser:
  - Nd:YAG laser: 355 nm / 532 nm
  - 1 mJ pulse energy, 10 ns excitation, 10 Hz
- Fast PMT:
  - Neutral density filter and bandpass filters
  - Combination of PMTs is under development for synchronized decay fitting
- Data acquisition system using LabVIEW

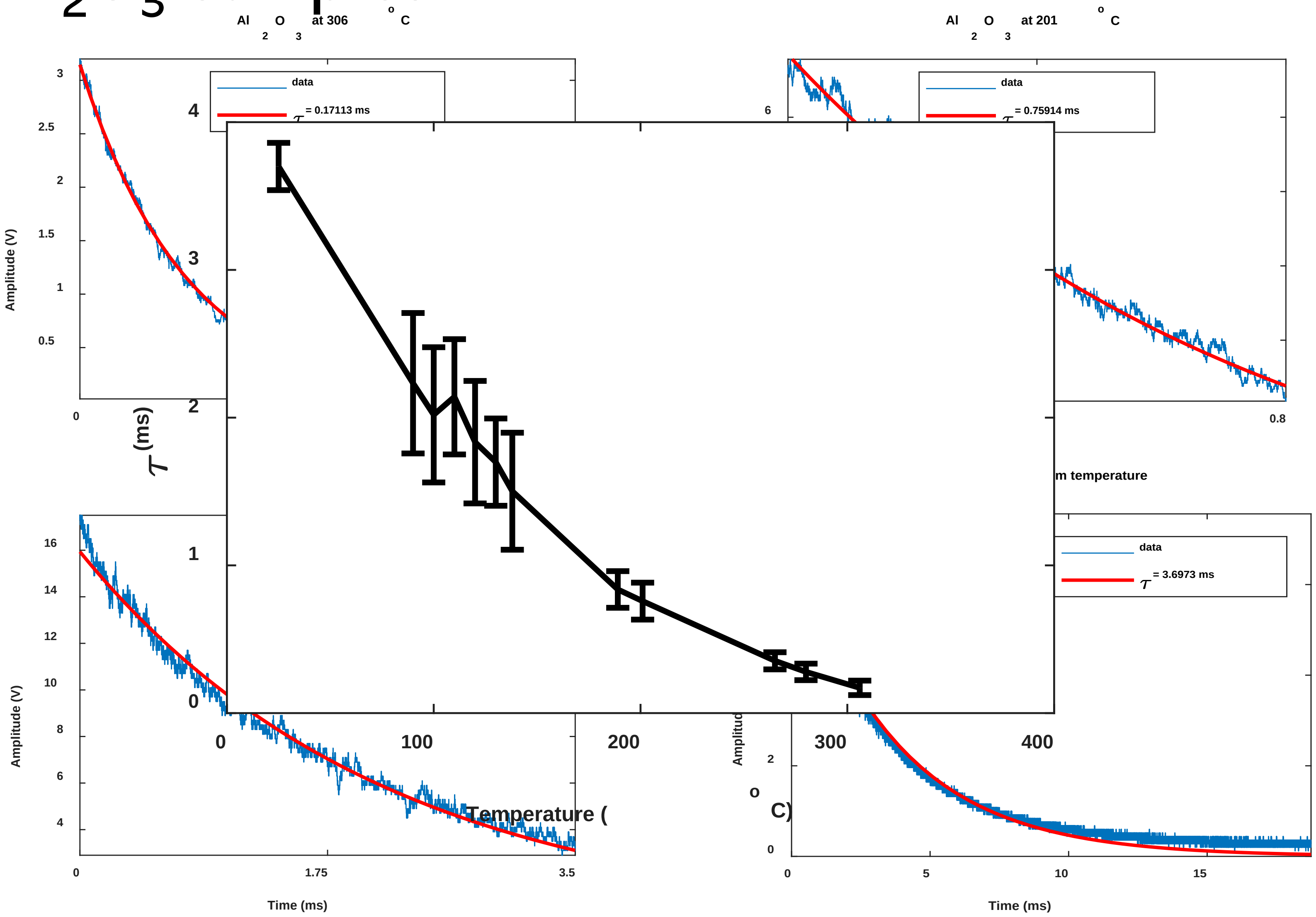




Experiments with Al_2O_3 samples



Data collection with infrared heater



$$I(t) = I_0 e^{-t/\tau}$$

- Initial measurements using a Al_2O_3 sample was performed
- Temperature was recorded using a K type thermocouple
- The decay constants are similar to those reported in literature

Seat and Sharp, IEEE Tran. on Instr and Meas, 53.1 (2004): 140-154.

Summary and Conclusions

Task 2 - Modeling

- A modeling framework was developed to predict the luminescence behavior for Phosphor Thermometry considering different TBC configurations and dopants
- The model provides insight to tailor the doped TBC configuration for phosphor thermometry
- The model can be applied to study the microstructures of TBC (e.g. graded TBC), emissivity of the coating,

Task 3 - Coating characterization

- Eu doped TBC coupons have been fabricated by APS method
- The TBC coupons were characterized by high energy XRD at synchrotron
- The in-plane tensile residual strain was measured that resulted due to tensile quenching
- It was observed that over mechanical integrity and residual strain distribution was not altered due to doped layer

Task 4 – Benchmark measurements

- Instrumentation for Digital Image Correlation (DIC) at high temp
- IR thermometry for temperature measurements

Task 5 – Instrumentation for Temperature measurement by Phosphor Thermometry

- Instrumentation for the Phosphor Thermometry has been developed
- Initial temperature measurements of Al_2O_3 using the Instrument have been presented

Future Work

Task -3

- Characterization of the effectiveness of sensing TBCs (YSZ:Er & GAP:Cr) by Phosphor Thermometry and verification of the mechanical integrity using transmission XRD.

Task -4

- Benchmark measurements:
    - IR thermometry considering tailoring the emissivity of the coating
    - DIC for benchmark measurements for strain measurements

Task -5

- Laboratory scale sensor Instrumentation:
    - Temperature measurements at high temperature with doped TBC coupons
    - Further improvements in the Phosphor Thermometry instrument

Publications

- Q. Fouliard, S. Haldar, R. Ghosh, S. Raghavan (2019) Modeling Luminescence Behavior for Phosphor Thermometry Applied to Doped Thermal Barrier Coating Configurations, *Accepted in Applied Optics*

- P. Warren, S. Haldar, S. Raghavan, R. Ghosh (2019) Modeling Thermally Grown Oxides in Thermal Barrier Coatings using Fractal Patterns, *Accepted in ASME Turbo Expo 2019, , Phoenix, AZ*

- S. Haldar, P.Warren, Q. Fouliard, D. Moreno, M. McCay, J.S. Park, P. Kenesei, J. Almer, R. Ghosh, S. Raghavan (2019) Synchrotron XRD Measurements of Thermal Barrier Coating Configurations with Rare Earth Elements for Phosphor Thermometry, *Accepted in ASME Turbo Expo 2019, Phoenix, AZ*

- Q. Fouliard, S.A. Jahan, L. Rossmann, P. Warren, R. Ghosh, S. Raghavan (2018) Configurations for Temperature Sensing of Thermal Barrier Coatings", *International Conference on Phosphor Thermometry, 25-27 July, 2018, Glasgow, UK*

Thank you for your attention

Questions ?

Dr. Seetha Raghavan - Associate Professor
Dr. Ranajay Ghosh - Assistant Professor
Dr. Sandip Haldar – Postdoctoral Fellow
Quentin Fouliard – Graduate Research Assistant
Peter Warren – Graduate Research Assistant