Temperature Mapping at the Thermal Barrier Coating/Bond Coat Interface by Luminescence Lifetime Imaging Using Integrated Erbium-Doped Sublayers

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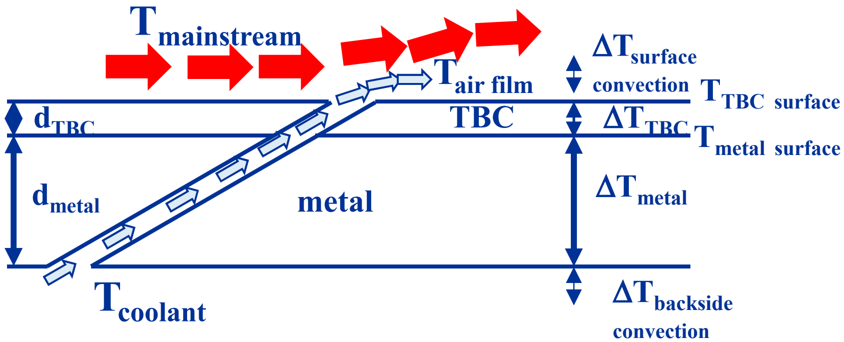
Background

- Temperature mapping is typically performed for TBC surfaces even though it is the temperature *below* the TBC that is critical to thermal protection.



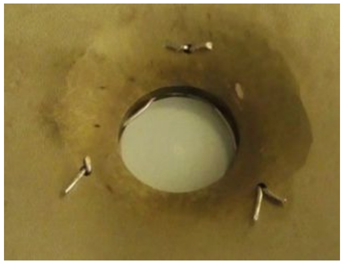
Objectives

- Develop luminescence-based diagnostics for temperature mapping and damage monitoring below TBC for turbine engine components.
  - Extend surface temperature mapping to subsurface (at TBC/bond coat interface) temperature mapping.
  - Extend room temperature damage (delamination/erosion) monitoring to engine temperatures.
  - Combine delamination/erosion monitoring and subsurface temperature mapping.
    - Evaluate degradation of thermal protection associated with TBC damage.

Approach

- Select thermographic phosphor with temperature sensitivity to 1200 °C that overcomes challenges of temperature sensing by luminescence lifetime imaging from the TBC/bond coat interface:
  - Sufficient high temperature emission intensity after attenuation from overlying TBC.
  - Nonintrusive integration into TBC at the TBC/bond coat interface.
  - YSZ:Er(0.8%) meets requirement of nonintrusive integration into bottom of YSZ TBC.
  - Hypersensitive excitation at 517 nm provides necessary high emission intensity.
- Intentional localized delamination produced by scratch test.
- Intentional localized erosion produced by alumina particle bombardment.
- TBC-coated superalloy button specimens tested in NASA GRC high heat flux laser for simultaneous temperature monitoring and damage detection.
- TBC-coated superalloy plates with cooling holes tested in NASA GRC Mach 0.3 burner rig to compare air film cooling effectiveness above and below TBC.

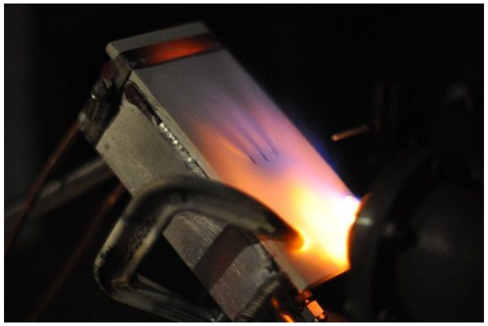
High heat flux laser testing



CO_2 laser off

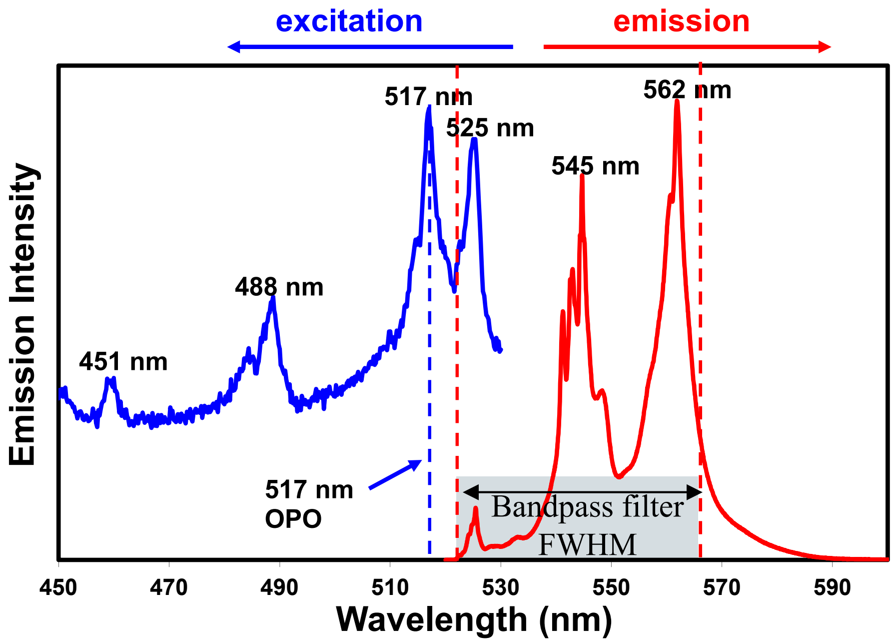
CO_2 laser on

Air film-cooling in burner rig



YSZ:Er^{3+} Energy Level Diagram
Visible Luminescence

Extremely high luminescence emission intensity achieved by utilizing Er^{3+} hypersensitive transition at 517 nm for excitation.



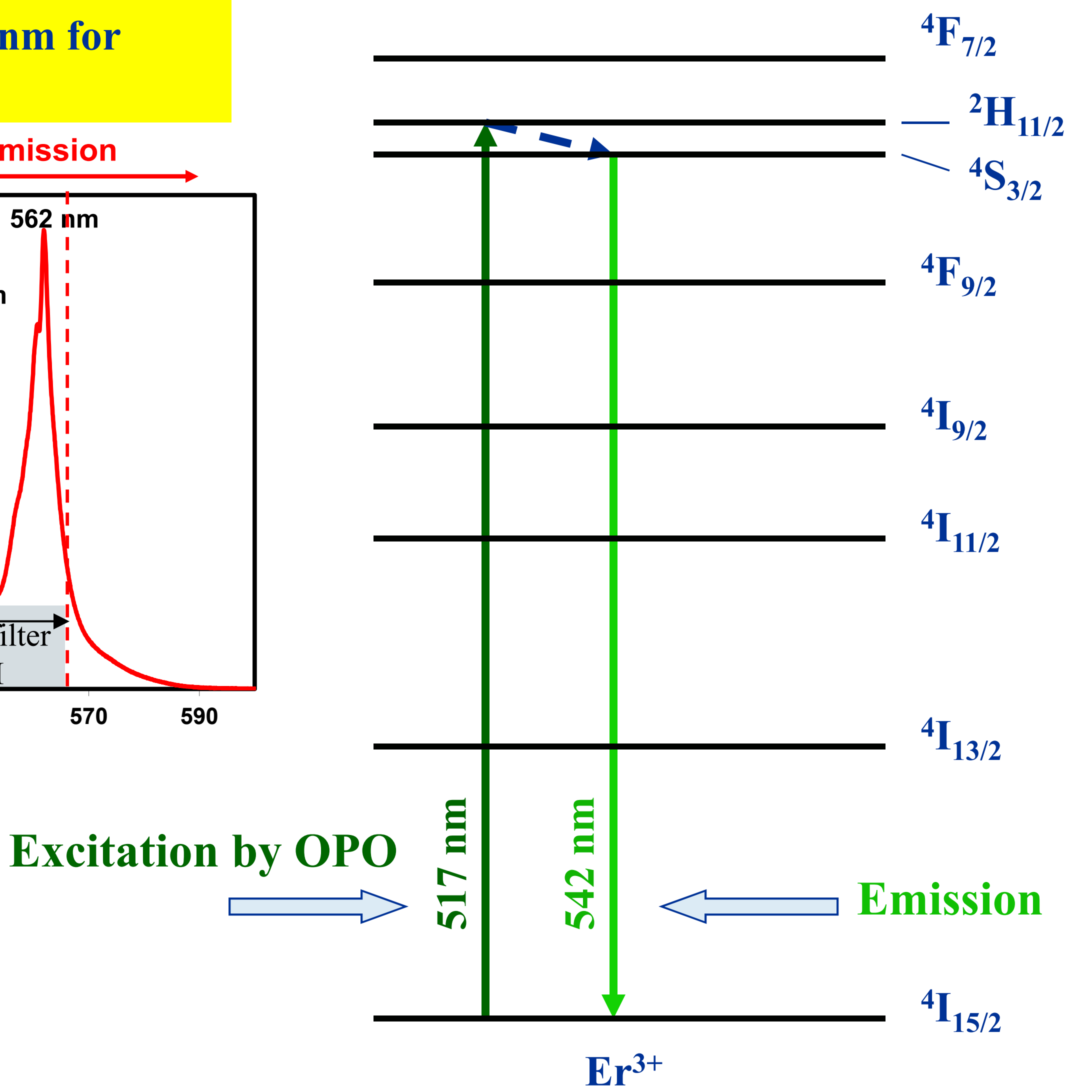
$^4I_{15/2} \rightarrow {}^2H_{11/2}$

Strong hypersensitive transition

$|\Delta J| = 2$ and

noncentrosymmetric

symmetry

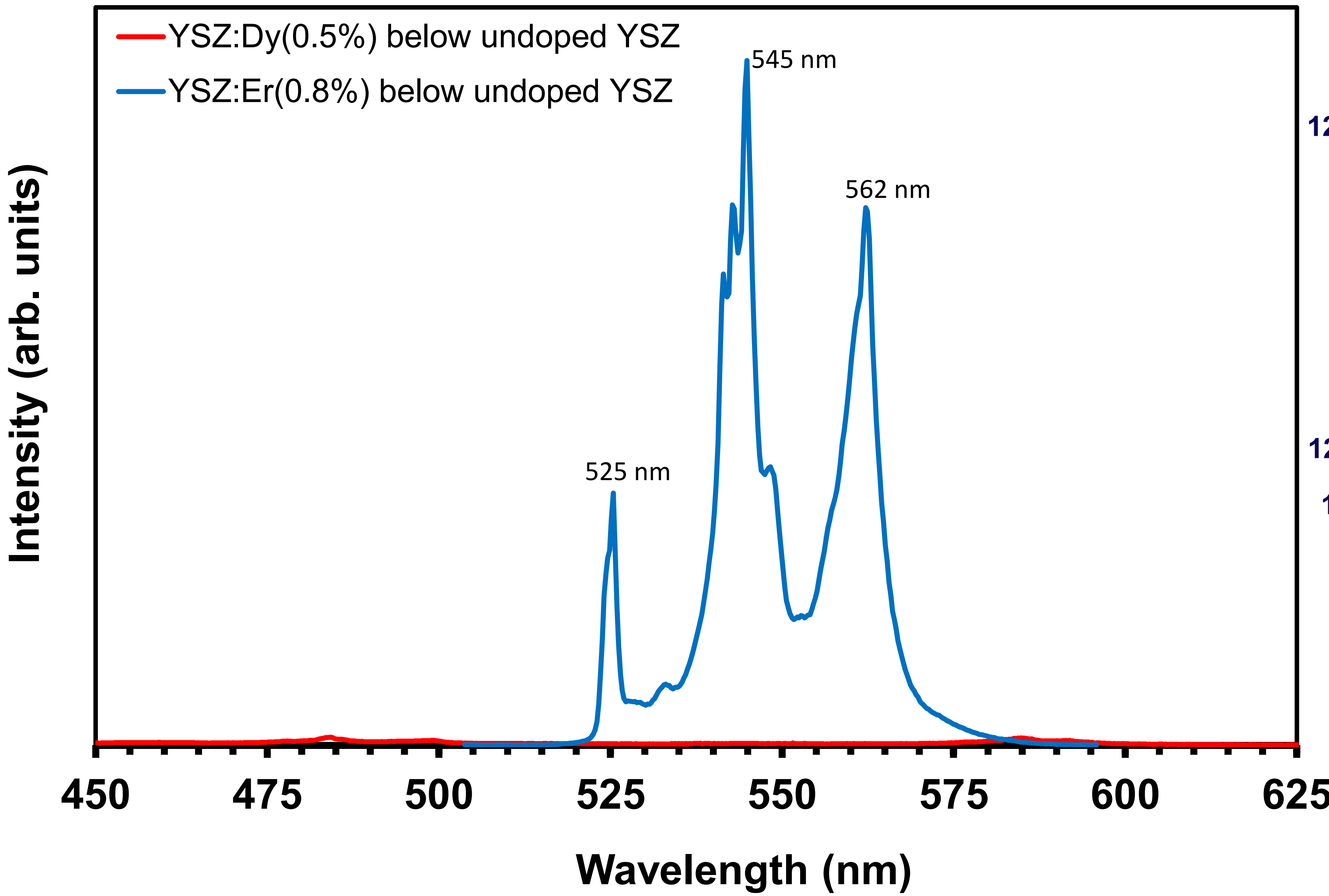


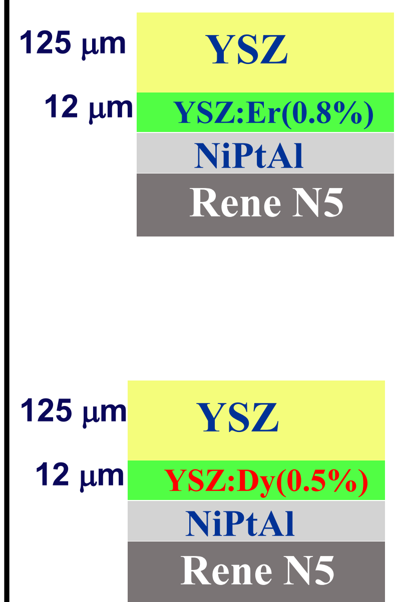
Emission Intensity Advantage of YSZ:Er vs YSZ:Dy*

Integrated First 10 μs Post-Excitation Pulse

*J.P. Feist and others.

1.1 mJ/pulse excitation (517 nm [YSZ:Er] or 355 nm [YSZ:Dy])





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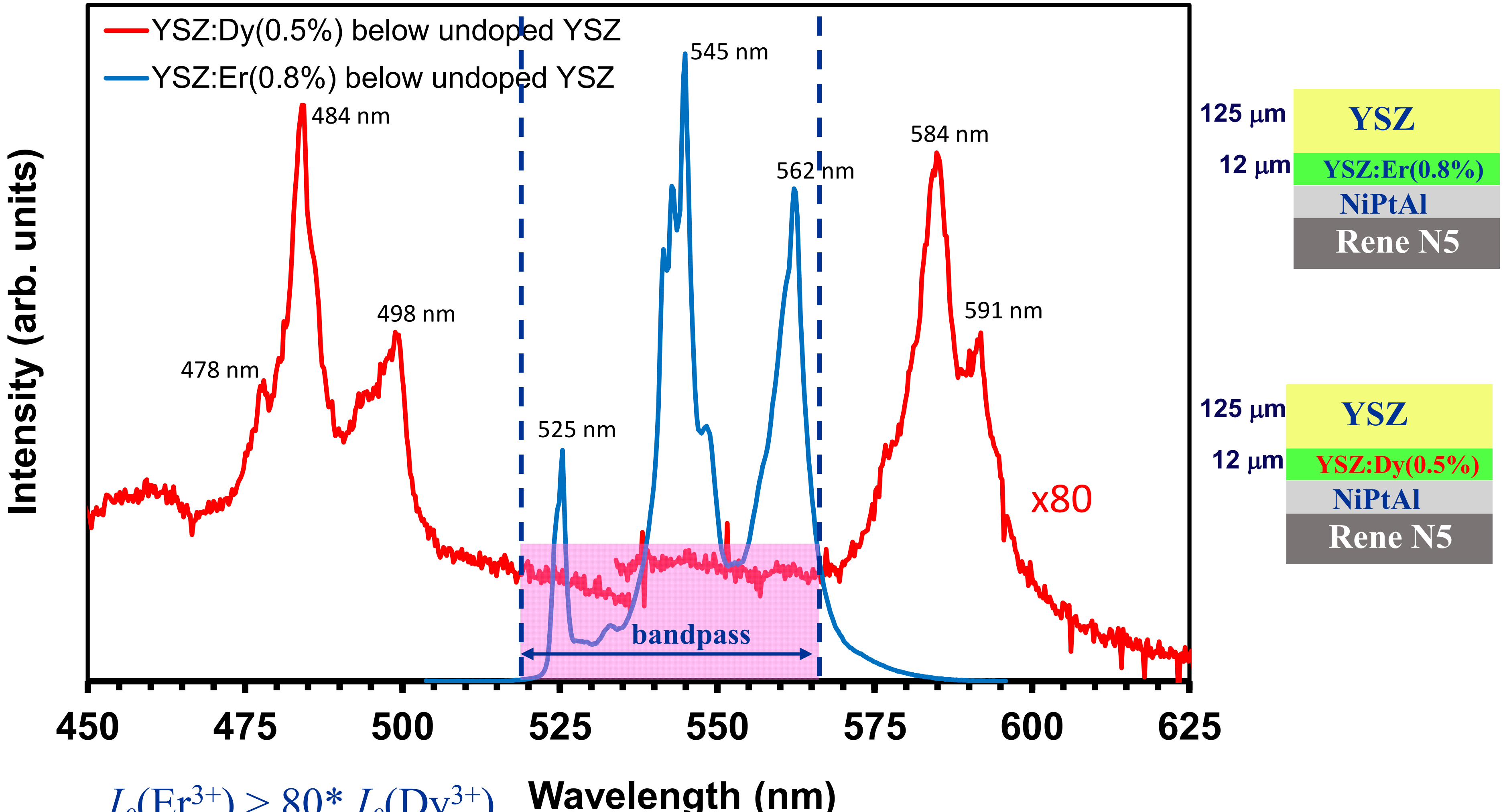
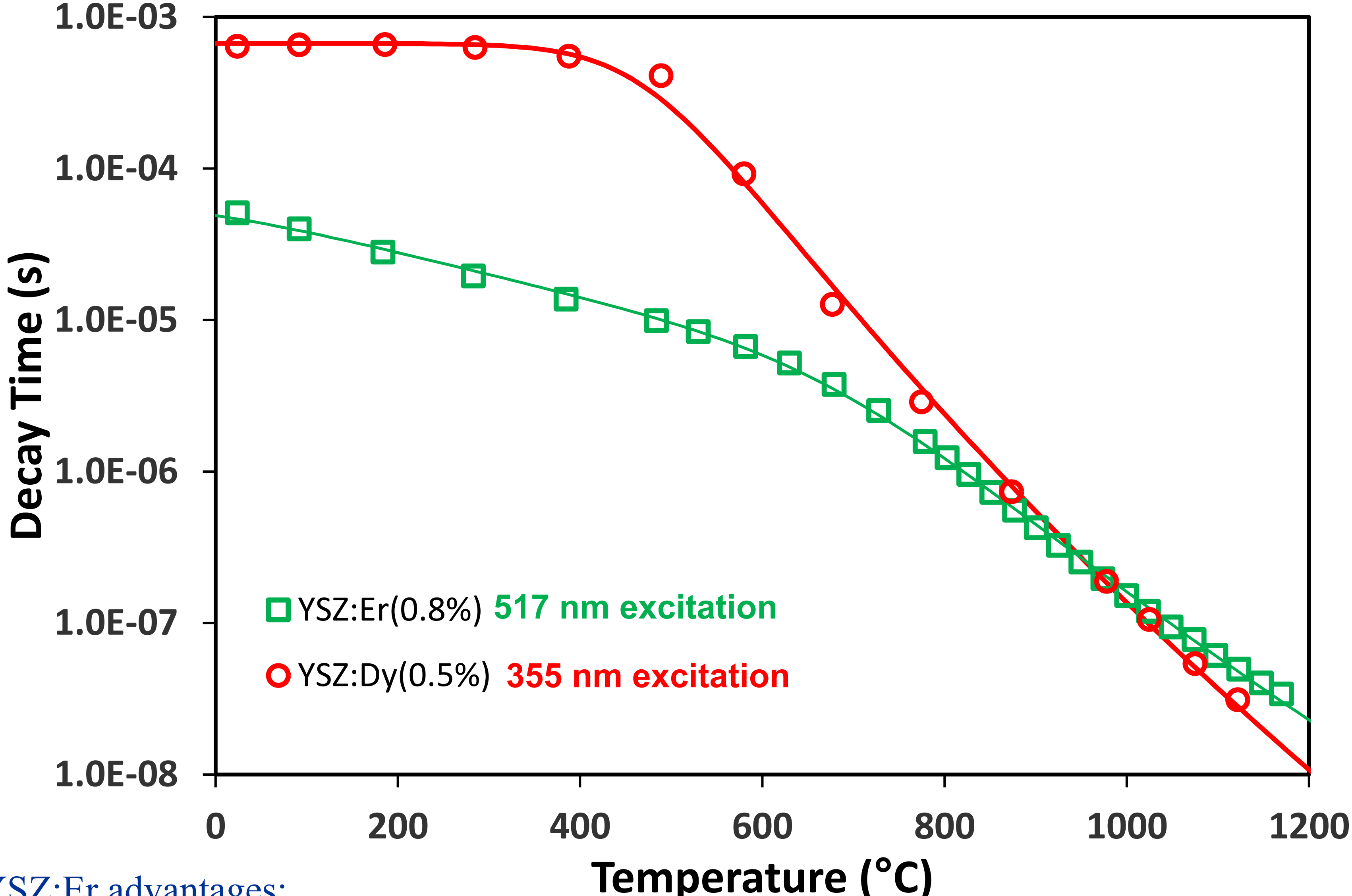


$I_0(Er^{3+}) > 80^* \, I_0(Dy^{3+})$

Hypersensitive excitation of Er^{3+} provides much higher S/N decay measurements, enabling below TBC temperature mapping with expanded laser beam.

Advantages of YSZ:Er vs YSZ:Dy

YSZ:Dy previously used for bottom of TBC spot temperature measurements*



YSZ:Er advantages:

- Extended temperature range (RT to 1200 °C vs. 500 to 1150 °C)
- Much higher (80x) emission intensity produces greater temperature measurement precision.

Luminescence Lifetime Image Stack

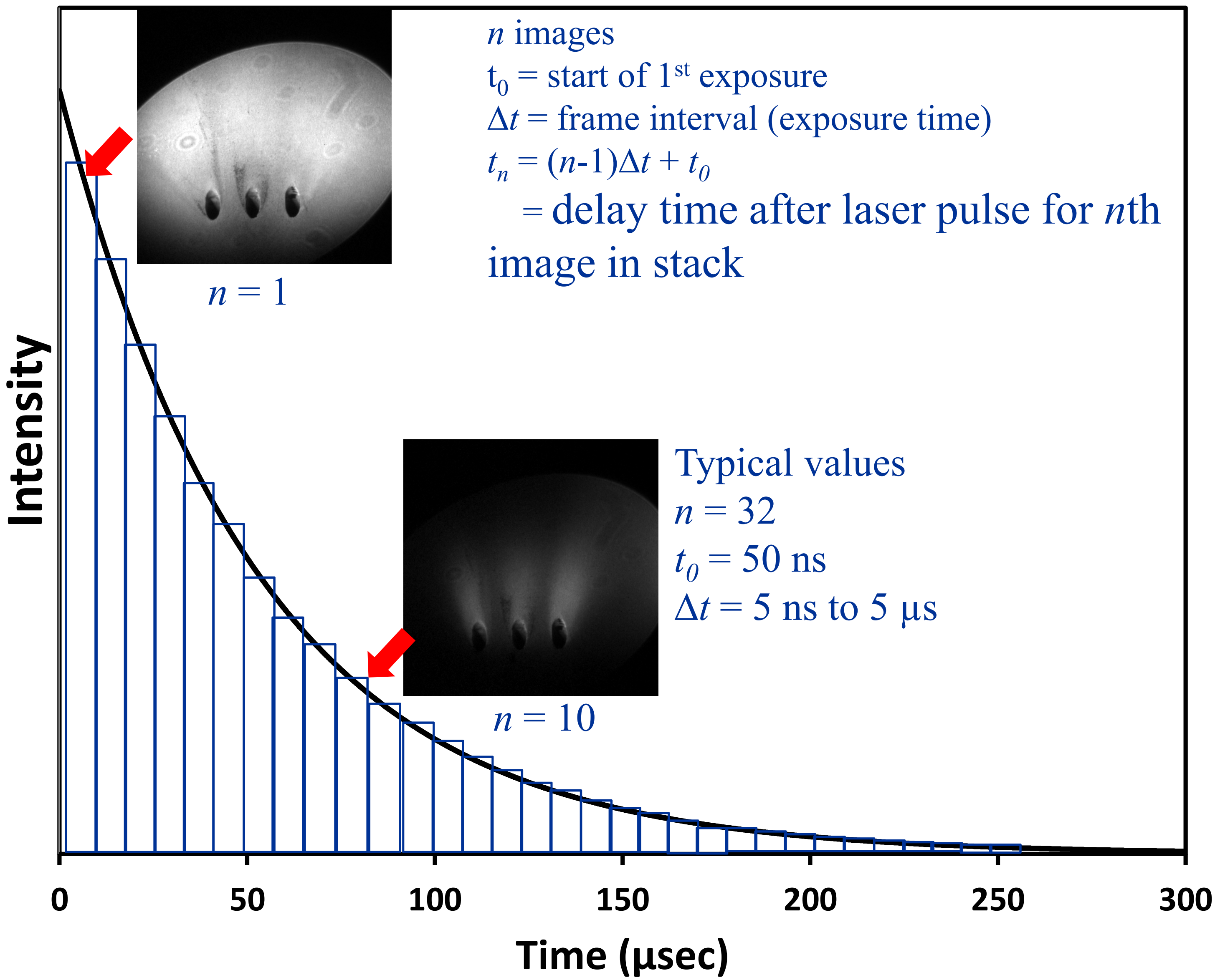
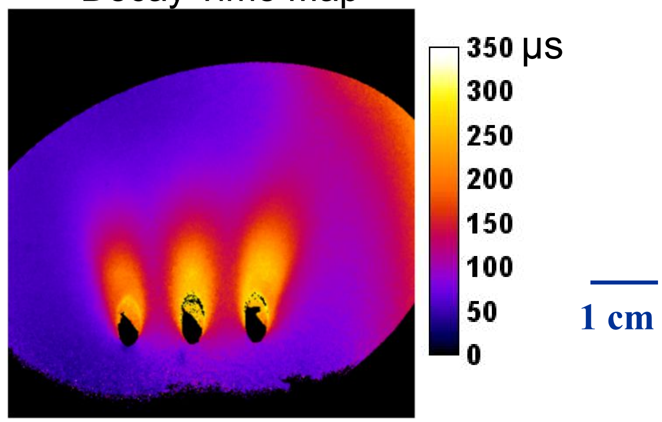


Image stack: Each image in stack obtained with an additional increment in delay after excitation pulse.

2D Temperature Maps from Luminescence Lifetime Imaging

- Step 1: Fit luminescence decay curve at each pixel to produce decay time map (Matlab routine).

Decay Time Map



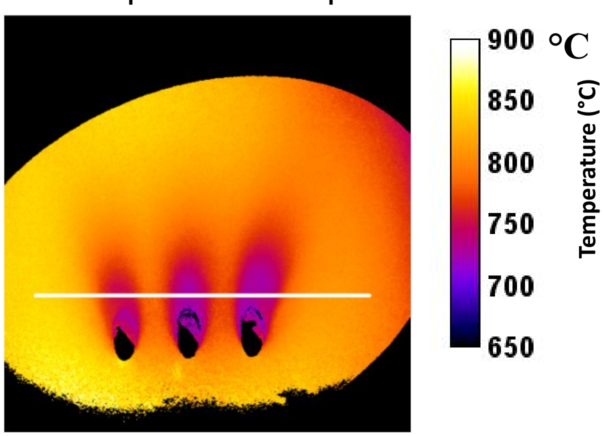
- Step 2: Use calibration data to convert decay time map to temperature map.

YSZ:Er

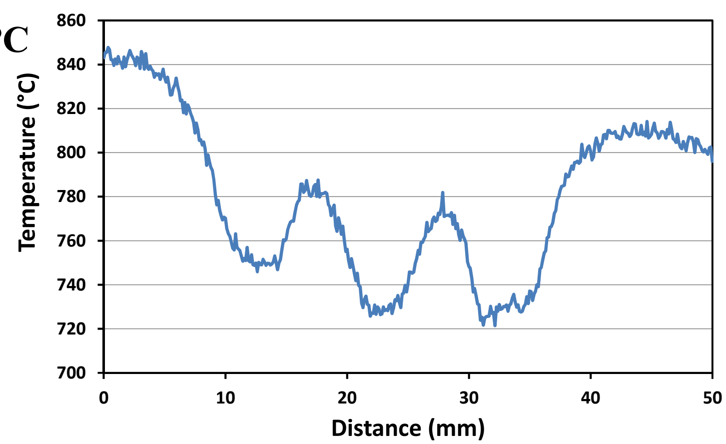
$$\tau = [W_{10}(1 - e^{-\frac{\Delta E}{p_1 kT}})^{-p_1} + W_{20}(1 - e^{-\frac{\Delta E}{p_2 kT}})^{-p_2}]^{-1}$$

Dual effective phonon energy model

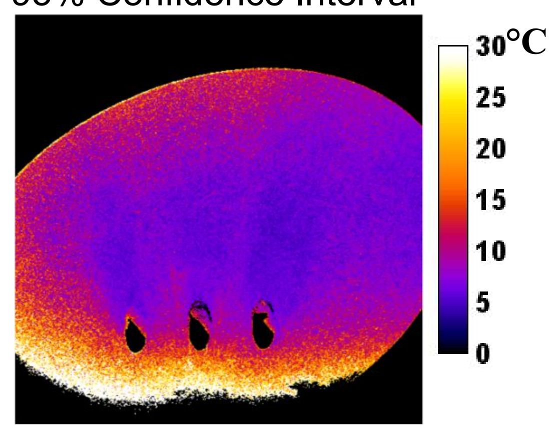
Temperature Map



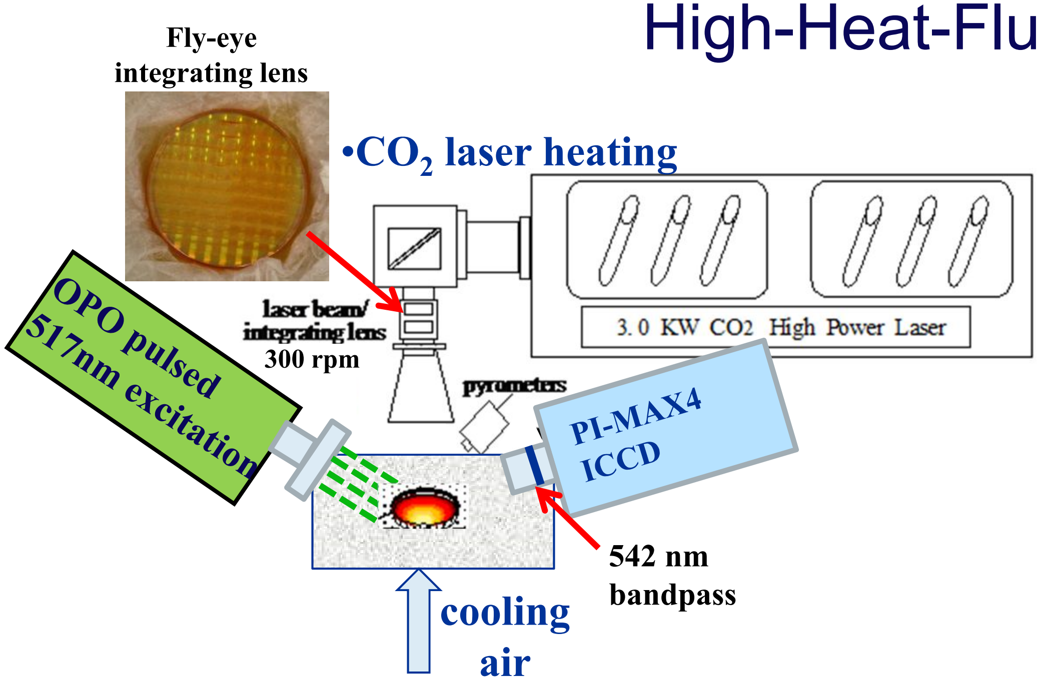
Temperature Line Scan



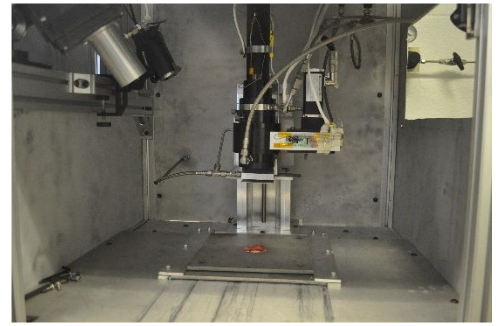
95% Confidence Interval



Mapping Thermal Gradients Produced by High-Heat-Flux Laser

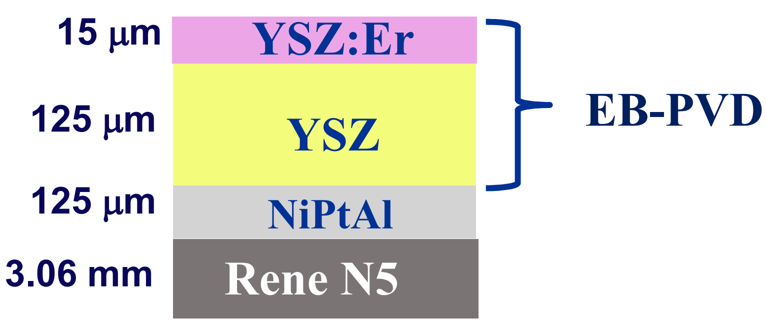


•High-heat-flux test chamber

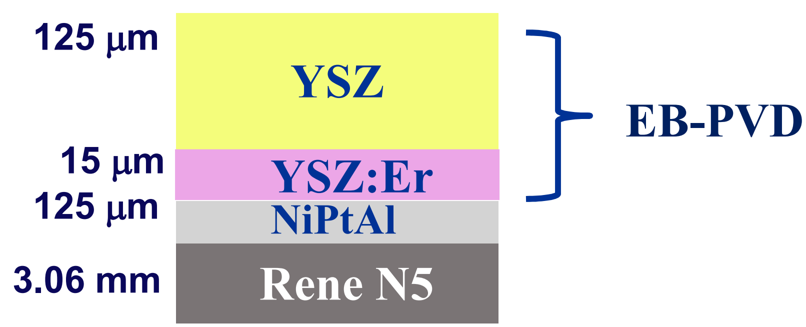


CO_2 laser on

TBC surface temperature sensing

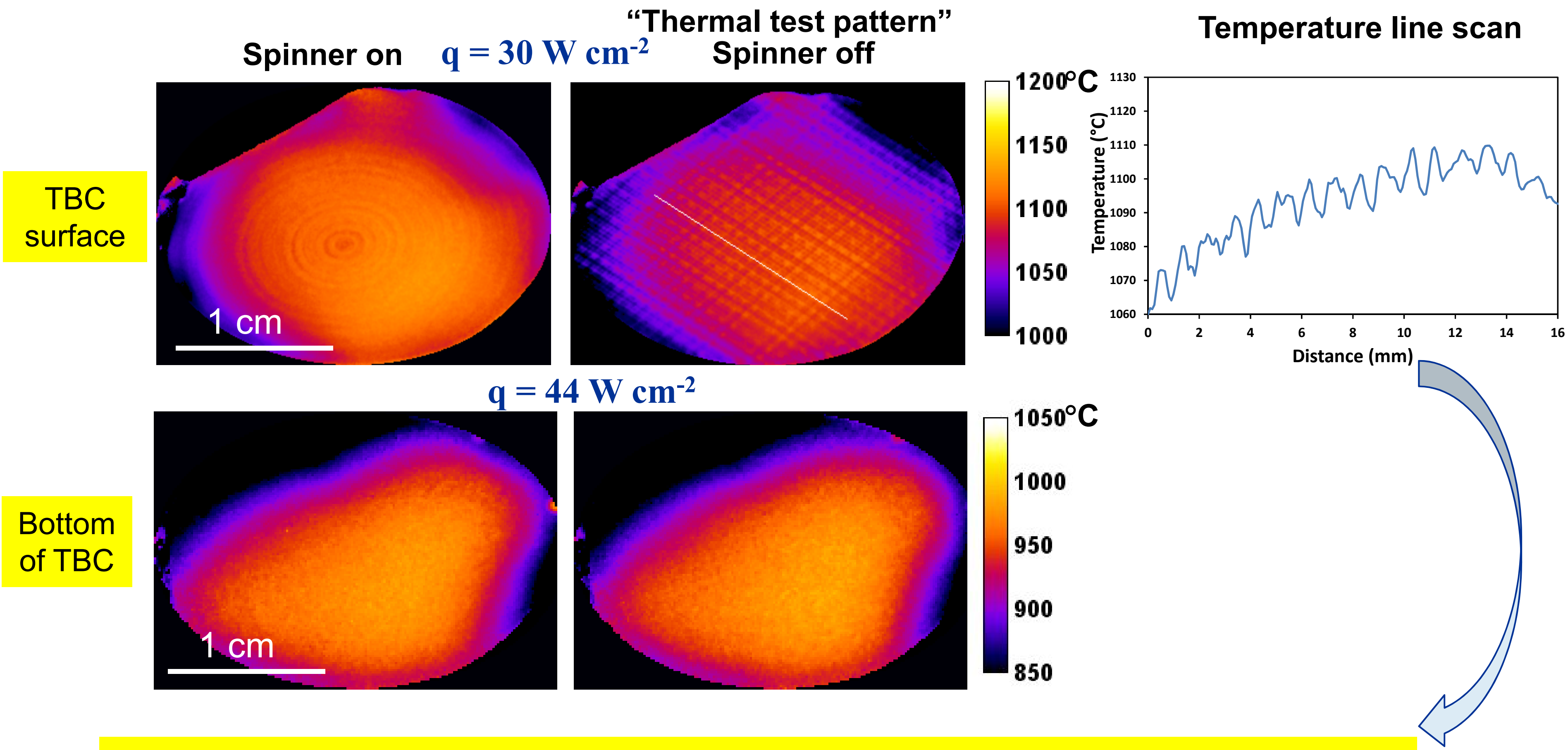


Bottom of TBC temperature sensing



2D Temperature Maps of Thermal Test Patterns

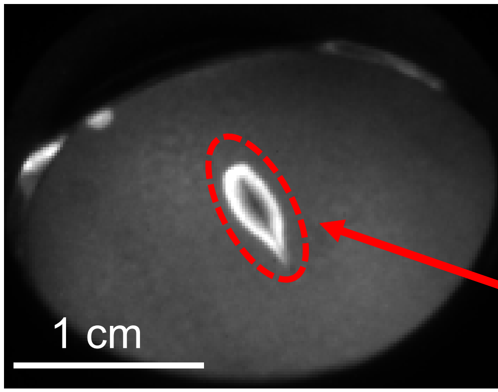
Obtained with integrating lens spinner “off”



- **Excellent spatial (submillimeter) and temperature (less than 5°C) resolution demonstrated in surface temperature maps.**
- **No observable “thermal test pattern” at bottom of TBC where TBC is in contact with thermally conductive bond coat.**

Simultaneous Delamination Monitoring and Subsurface Temperature Mapping above 1000 °C

High-temperature delamination detection



Scratch-induced delamination

Gated luminescence image obtained *at temperature*

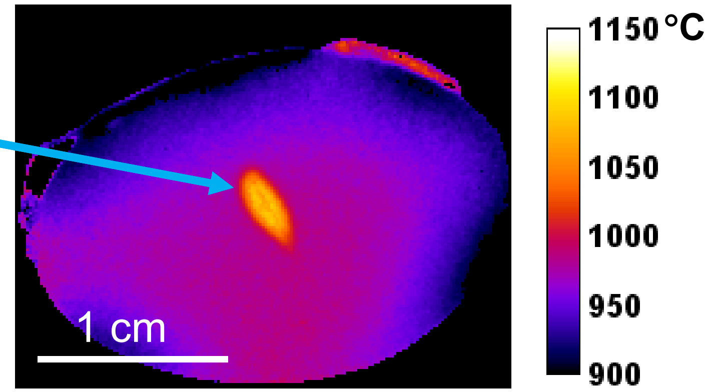
40 ns exposure – fast enough for rotating parts!

Gated detection suppresses thermal background.

q = 32 W cm^{-2}

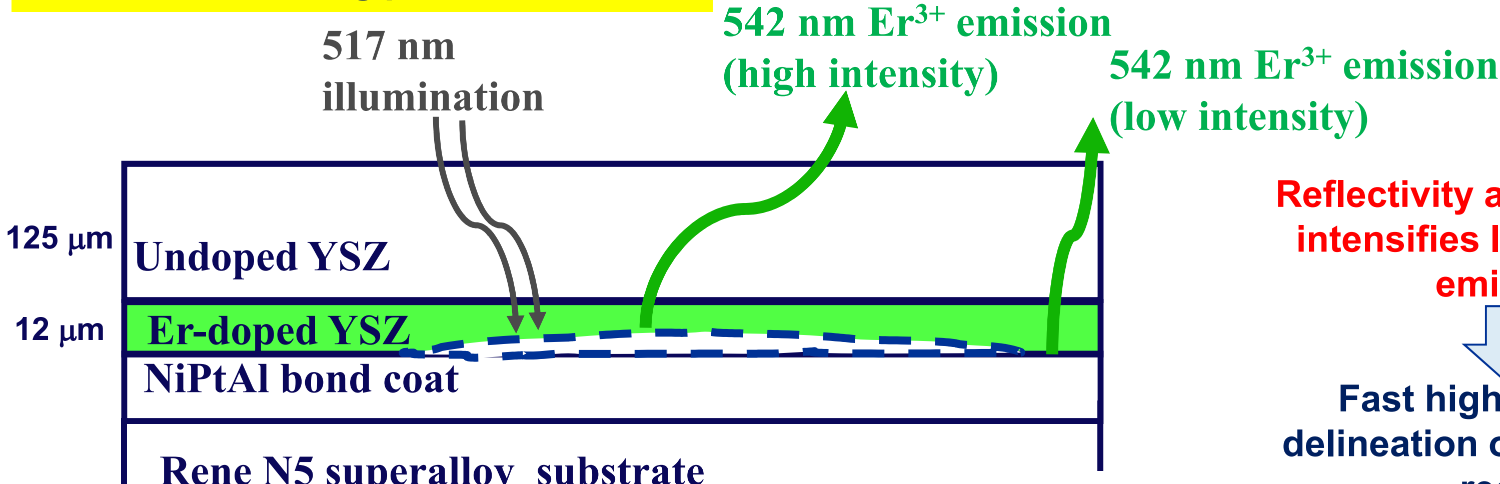
Delamination produces +100° C hotspot

Temperature Map *below* TBC



Temperature map from luminescence lifetime imaging

Thermal effect of delamination observed at bottom of TBC.

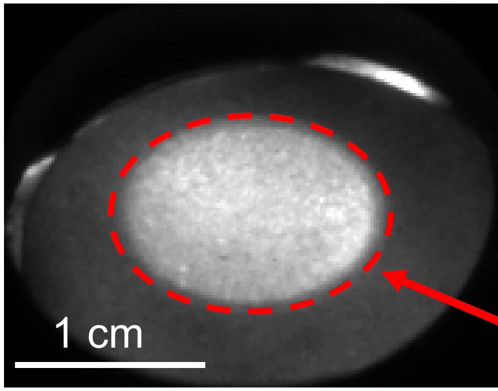


Reflectivity at delamination intensifies luminescence emission

Fast high-resolution delineation of delaminated region

Simultaneous Erosion Monitoring and Subsurface Temperature Mapping above 1000 °C

High-temperature erosion detection



Gated luminescence image obtained at temperature

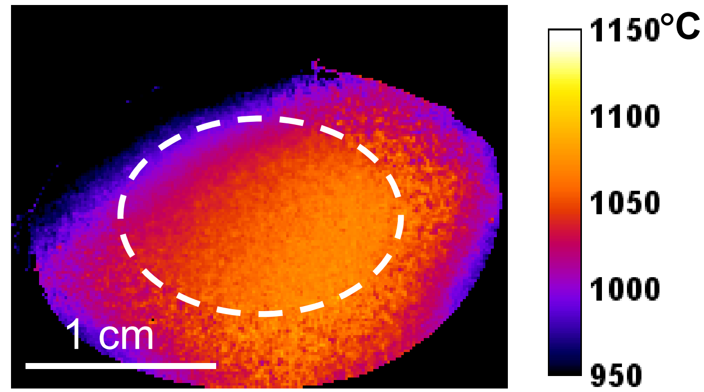
Eroded area produced by 50 μm alumina particles at 100 m/s.

40 ns exposure – fast enough for rotating parts!

Gated detection suppresses thermal background.

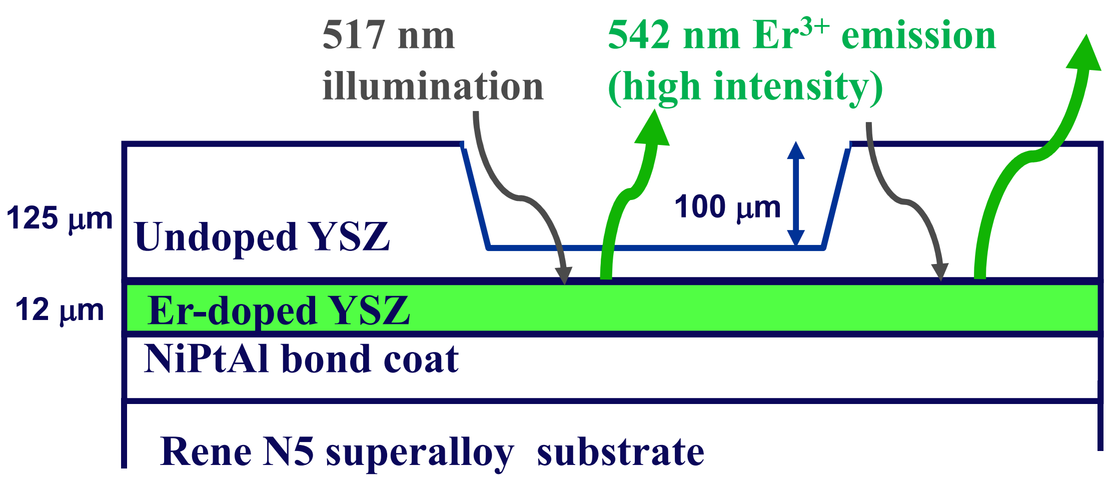
$q = 71\ W\ cm^{-2}$

Temperature Map *below* TBC



Temperature map from luminescence lifetime imaging

Thermal effect of erosion not clearly observed. Difficult to separate from nonuniform heating?

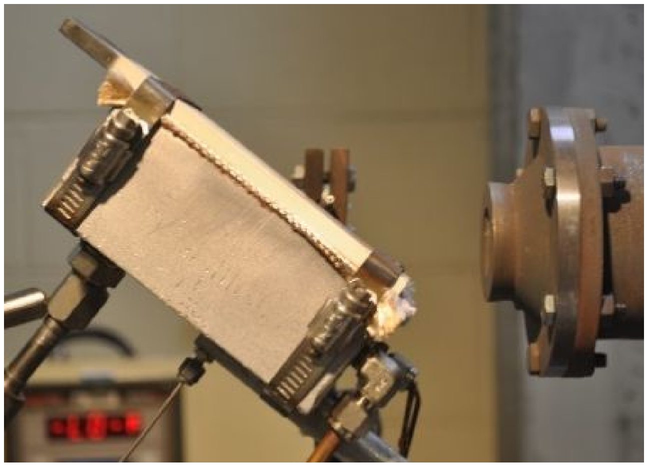


Less undoped YSZ above Er-doped layer in eroded area results in higher luminescence emission intensity

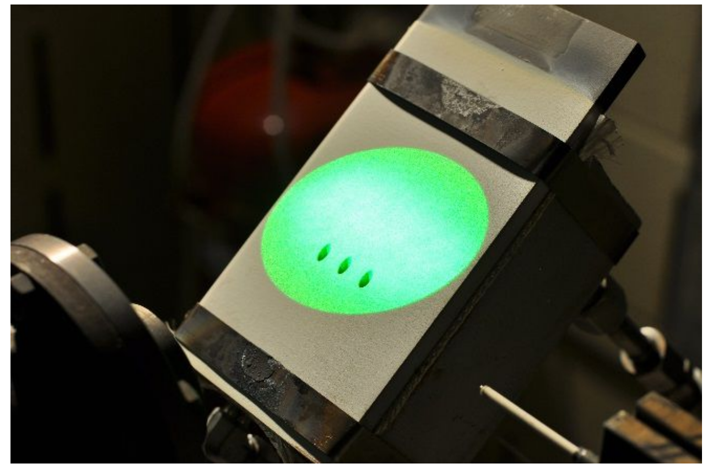
Fast high-resolution delineation of eroded region at engine temperature

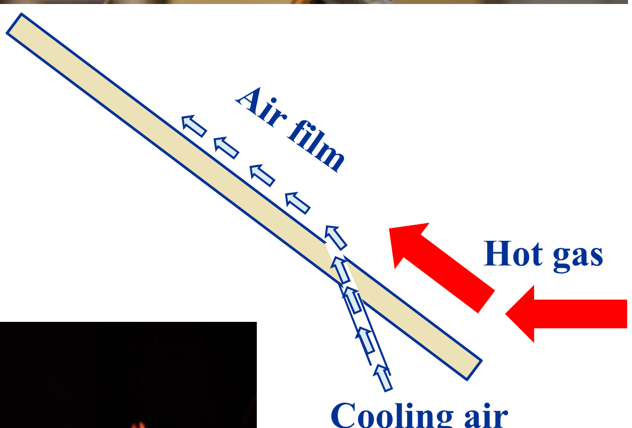
Examining Air Film Cooling Effectiveness *below* TBC in NASA GRC Mach 0.3 Burner Rig

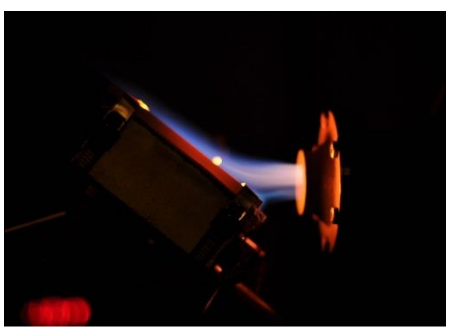
TBC-coated plate in front of burner



Temperature mapping from laser-illuminated area







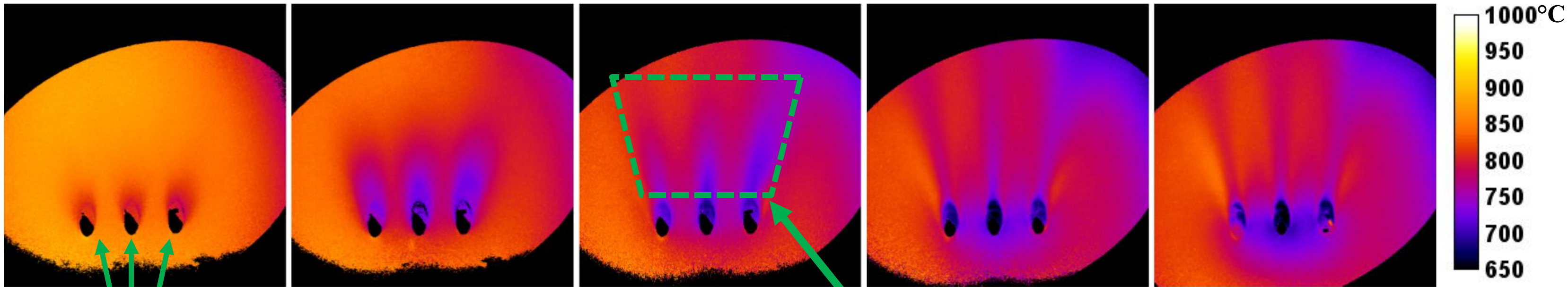
Coating layers

2D Temperature Maps in Vicinity of Cooling Holes

Increasing blowing ratio M′

Above TBC

M' = 0.238 | M' = 0.571 | M' = 0.951 | M' = 1.427 | M' = 1.665



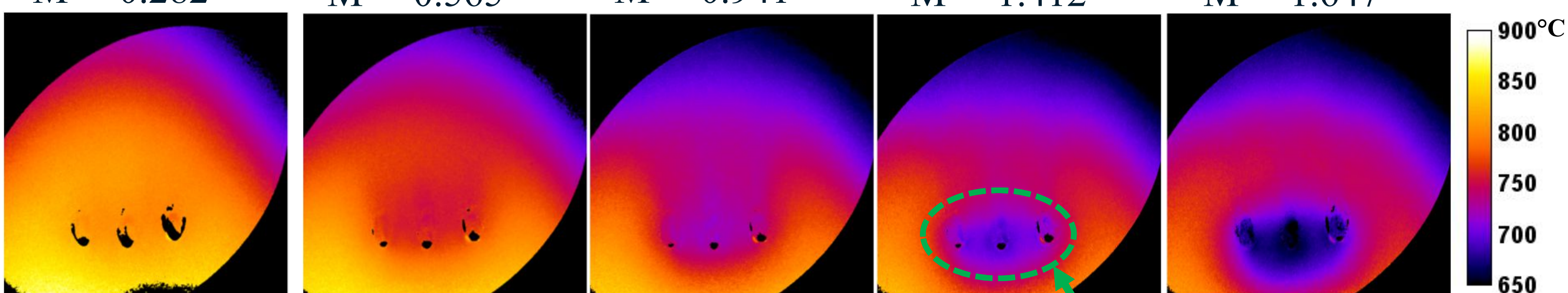
$T_{mainstream} = 1390°C$

15 µm	$GdAlO_3$:Cr(0.2%)
200 µm	YSZ
125 µm	MCrAlY
6.35 mm	Hastelloy X

- Air film cooling by air jets effective at surface.
- Air film cooling diminishes at high blowing ratios (air jet lift-off).
- In-hole convective cooling becomes prominent at high blowing ratios.

Below TBC

M' = 0.282 | M' = 0.565 | M' = 0.941 | M' = 1.412 | M' = 1.647



- In-hole convection cooling dominates at all blowing ratios.
- Weak, indistinct air jet cooling.

200 µm	YSZ
15 µm	YSZ:Er(0.8%)
125 µm	MCrAlY
6.35 mm	Hastelloy X

2D temperature maps show TBC degrades air jet film cooling but enhances in-hole convective cooling.

Conclusions

- Luminescence lifetime imaging of TBCs with thin Er-doped YSZ base layer produces temperature mapping of the TBC/bond coat interface, which is more relevant to thermal protection than surface temperature mapping.
- Combining at-temperature delamination/erosion monitoring with TBC/bond coat temperature mapping identifies TBC damage and quantifies associated thermal protection degradation.
- TBC/bond coat temperature mapping can be used as a new tool to examine the non-additive interplay between the TBC and air film cooling towards achieving thermal protection of the metal below the TBC.

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