Monitoring Delamination of Thermal Barrier Coatings by Near-Infrared and Upconversion Luminescence Imaging

J.I. Eldridge, NASA Glenn Research Center, R.E. Martin, Cleveland State University,
J. Singh, D.E. Wolfe, Penn State University.

Previous work has demonstrated that TBC delamination can be monitored by incorporating a thin luminescent sublayer that produces greatly increased luminescence intensity from delaminated regions of the TBC. Initial efforts utilized visible-wavelength luminescence from either europium or erbium doped sublayers. This approach exhibited good sensitivity to delamination of electron-beam physical-vapor-deposited (EB-PVD) TBCs, but limited sensitivity to delamination of the more highly scattering plasma-sprayed TBCs due to stronger optical scattering and to interference by luminescence from rare-earth impurities. These difficulties have now been overcome by new strategies employing near-infrared (NIR) and upconversion luminescence imaging. NIR luminescence at 1550 nm was produced in an erbium plus ytterbium co-doped yttria-stabilized zirconia (YSZ) luminescent sublayer using 980-nm excitation. Compared to visible-wavelength luminescence, these NIR emission and excitation wavelengths are much more weakly scattered by the TBC and therefore show much improved depth-probing capabilities. In addition, two-photon upconversion luminescence excitation at 980 nm wavelength produces luminescence emission at 562 nm with near-zero fluorescence background and exceptional contrast for delamination indication. The ability to detect TBC delamination produced by Rockwell indentation and by furnace cycling is demonstrated for both EB-PVD and plasma-sprayed TBCs. The relative strengths of the NIR and upconversion luminescence methods for monitoring TBC delamination are discussed.

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J.I. Eldridge
NASA Glenn Research Center

R.E. Martin
Cleveland State University

J. Singh and D.E. Wolfe
Penn State University

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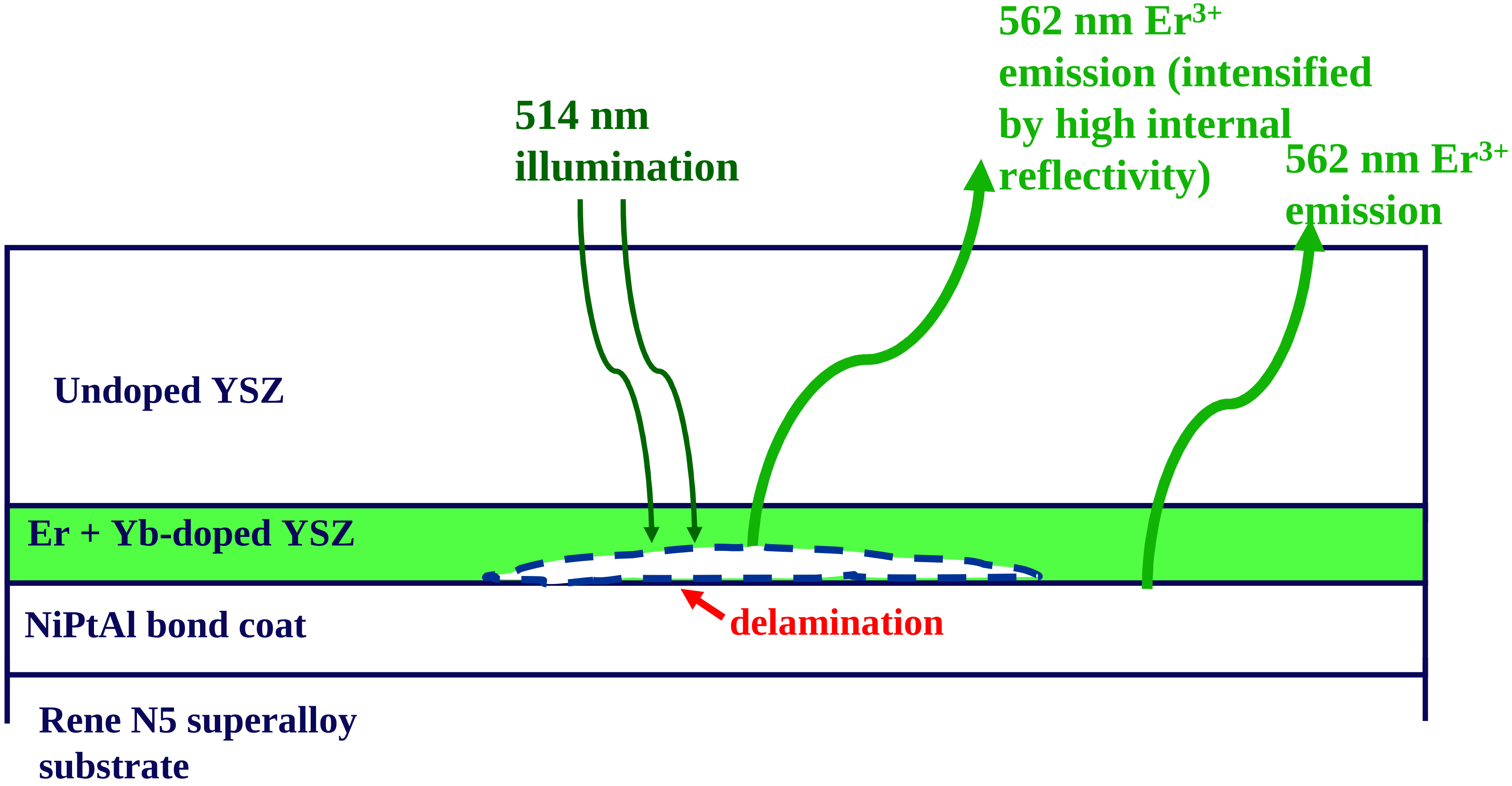
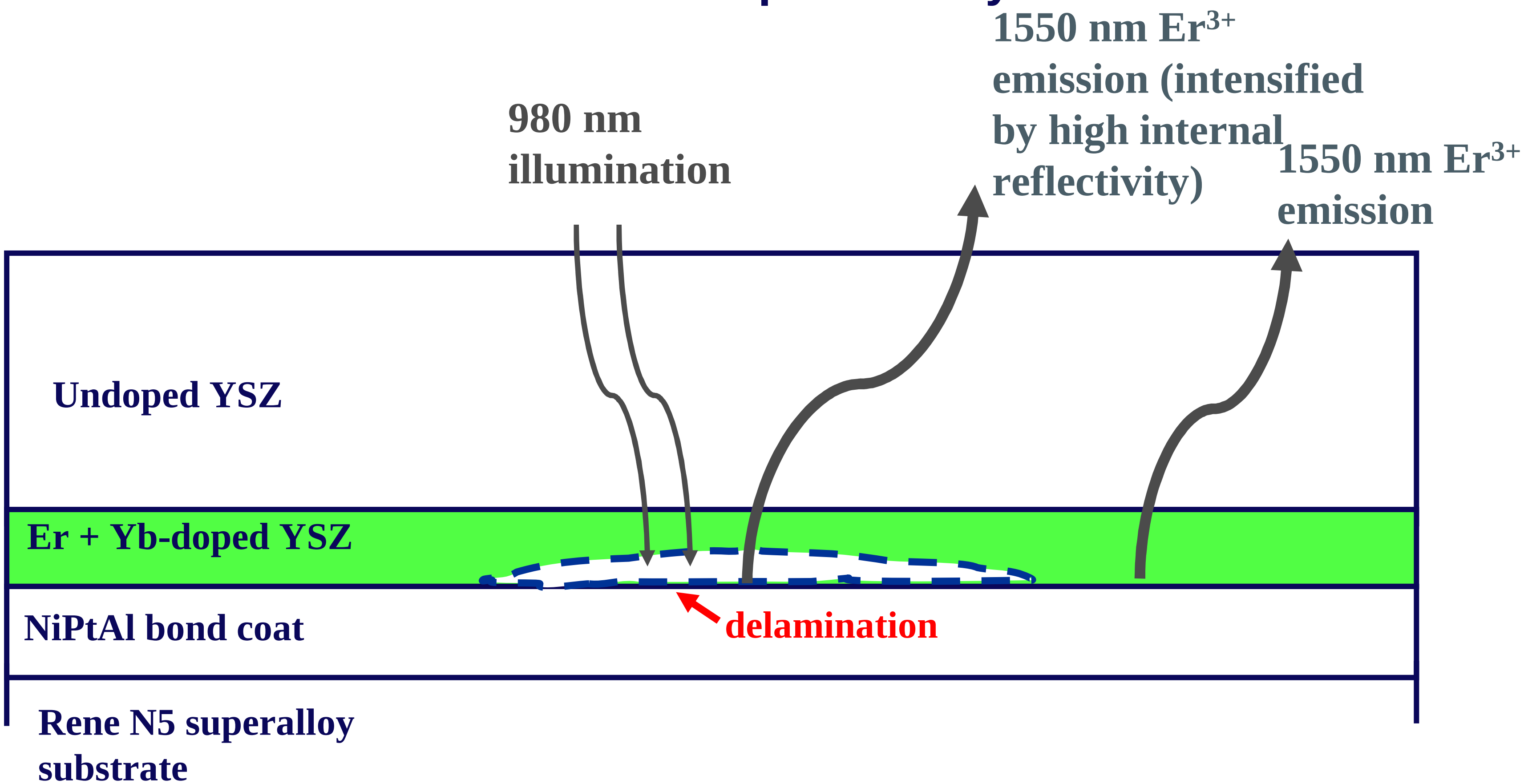
Objectives

- Improved TBC delamination monitoring using near-infrared (NIR) & upconversion luminescence imaging.
  - Greater transmittance using longer wavelengths
  - Co-doping strategy reduces interference from impurity luminescence
  - Luminescent sublayer fully integrated into TBC
- Monitor delamination progression produced by furnace cycling.
- Evaluate delamination progression for both EB-PVD & plasma-sprayed TBCs.
- Show that added dopants do not reduce TBC life.

Detecting TBC Delamination by Reflectance-Enhanced Luminescence
Er + Yb Co-Doped Sublayer



Detecting TBC Delamination by Reflectance-Enhanced Luminescence Er + Yb Co-Doped Sublayer



Motivation for erbium + ytterbium co-doping

- Er^{3+} produces strong NIR luminescence at 1550 nm where TBC is much more transparent.
- Yb^{3+} is a good absorber of 980 nm excitation and produces luminescence in Er^{3+} by energy transfer. Luminescence from Er^{3+} impurities in undoped overlayer are not effectively excited without Yb^{3+} co-dopant.

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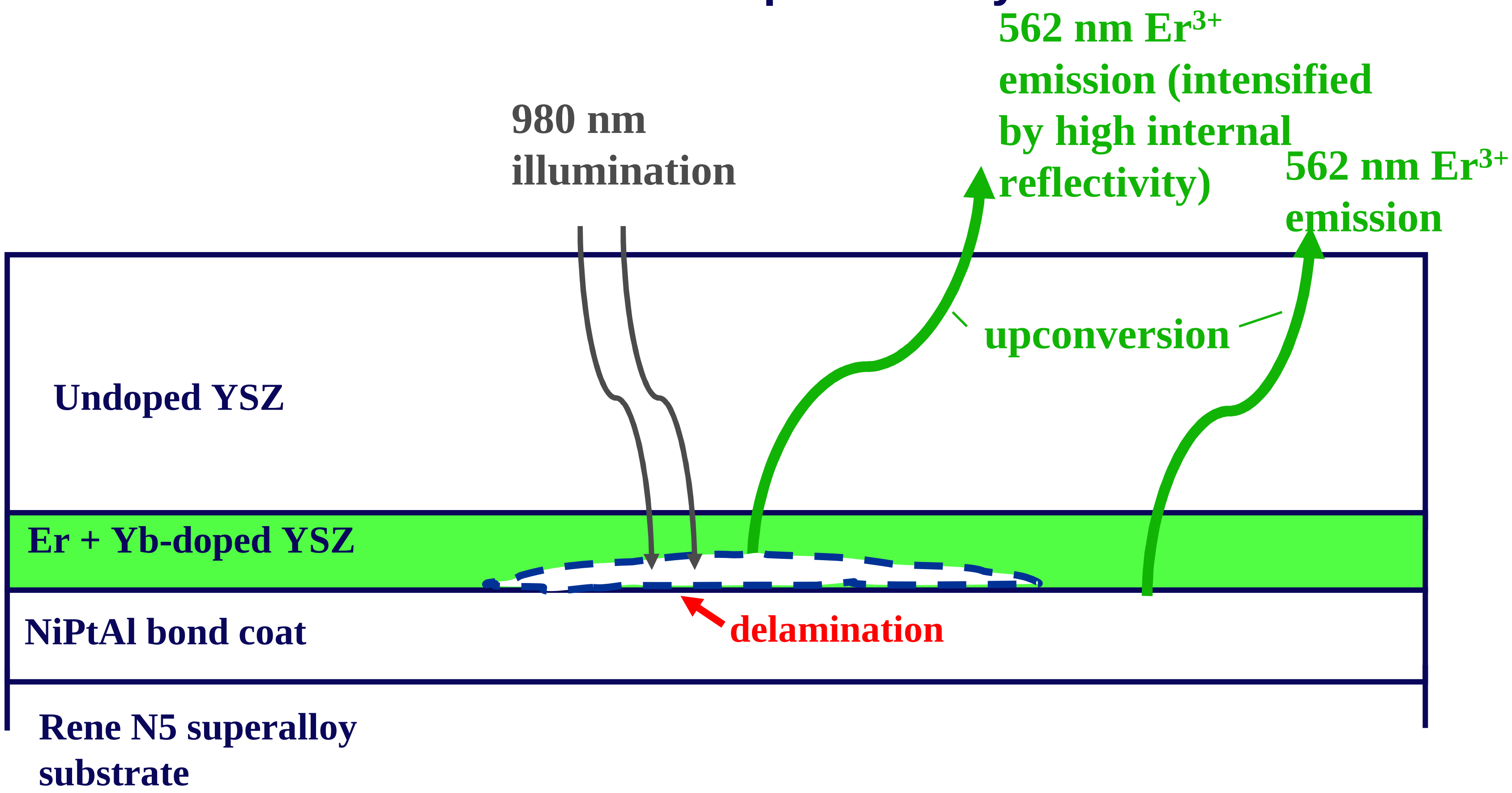

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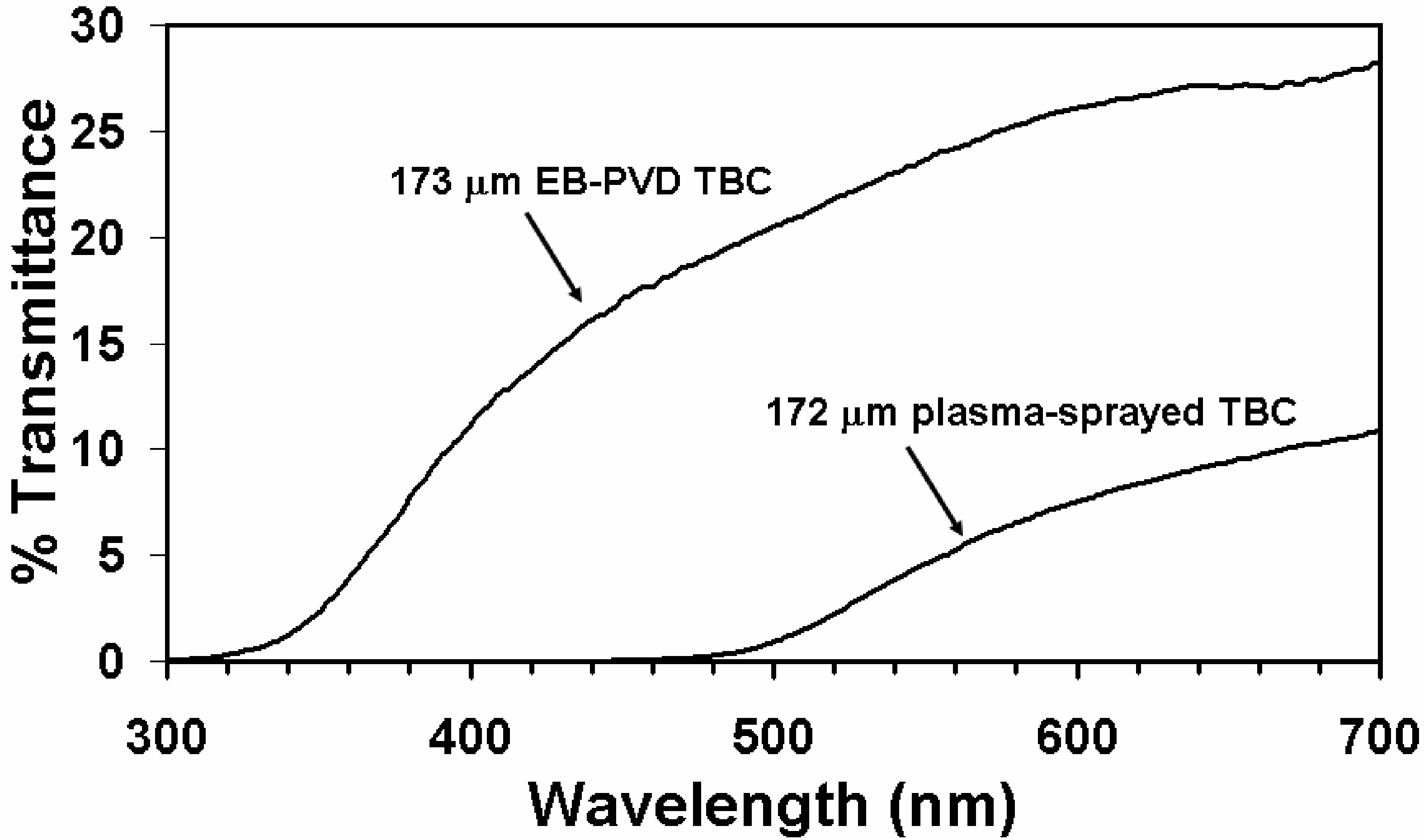
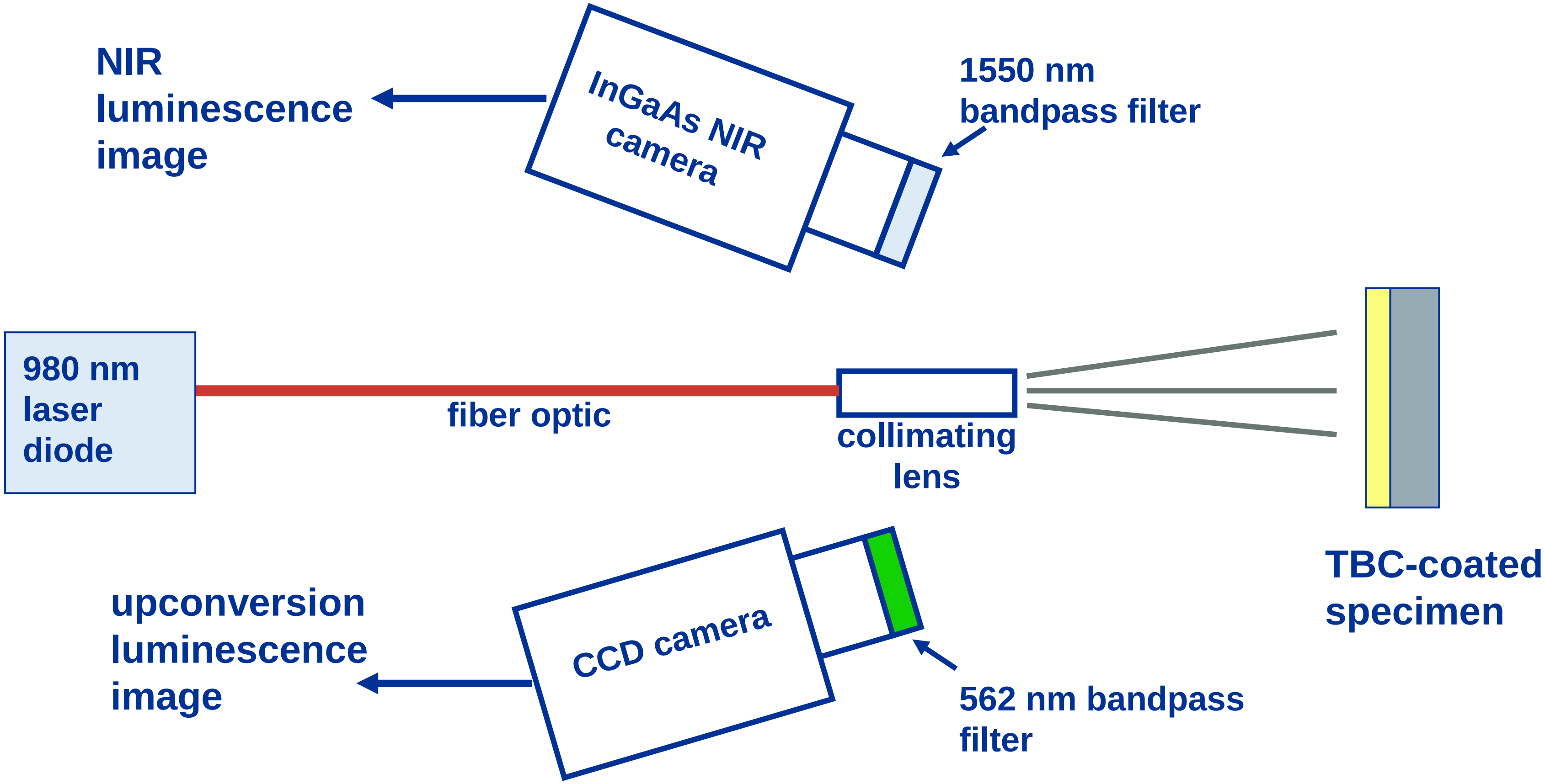
- Er^{3+} produces upconversion luminescence at 562 nm with near-zero background for strong delamination contrast.

TBC Transmittance
Plasma-Sprayed vs. EB-PVD



Type of Luminescence	$\lambda_{excitation}$ (nm)	$\lambda_{emission}$ (nm)	$T_{excitation}$ PS	$T_{excitation}$ EB-PVD	$T_{emission}$ PS	$T_{emission}$ EB-PVD	$T_{excitation}*T_{emission}$ PS	$T_{excitation}*T_{emission}$ EB-PVD
Visible	514	562	1.8%	21.4%	5.4%	24.3%	0.10%	5.20%
NIR	980	1550	18.8%	37.4%	23.5%	42.6%	4.42%	15.9%
Upconversion	980	562	18.8%	37.4%	5.4%	24.3%	1.02%	9.09%

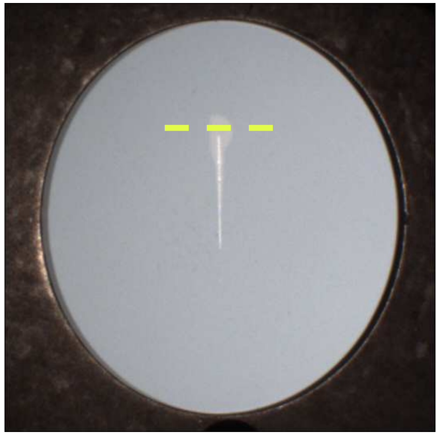
NIR and Upconversion Luminescence Imaging



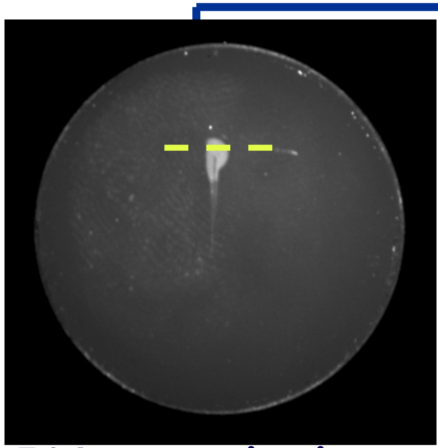
EB-PVD TBCs

Er^{3+} Luminescence Imaging of Scratch-Induced Delamination for EB-PVD TBC with YSZ:Er(1%),Yb(3%) Base Layer

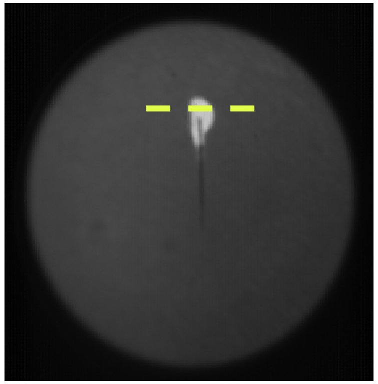
White light image



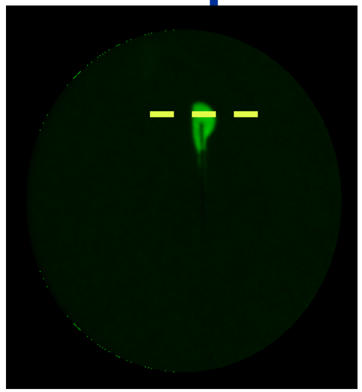
Luminescence images



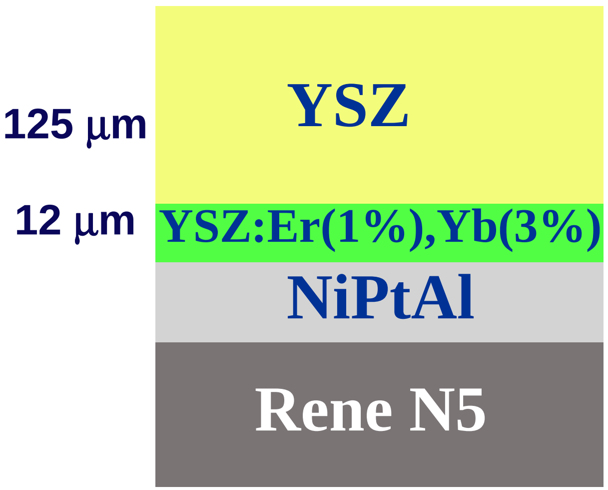
514 nm excitation
562 nm emission
1 sec

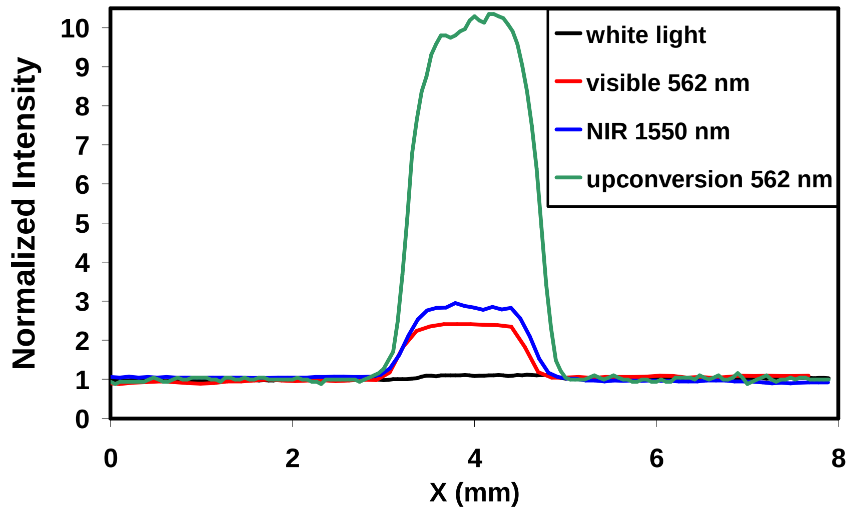


980 nm excitation
1550 nm emission
16 msec



980 nm excitation
562 nm emission
6 sec



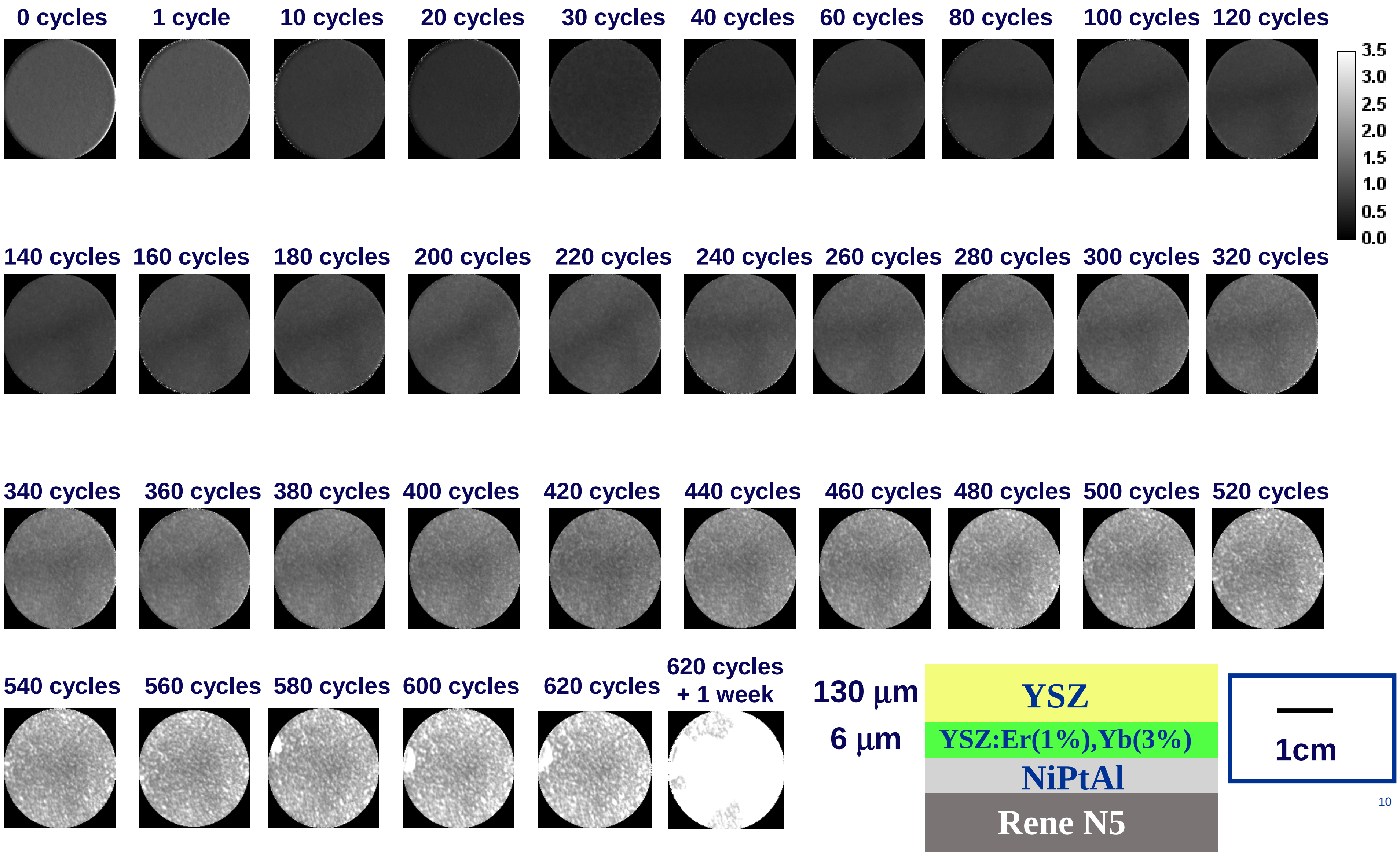


Line Scans across Delaminated EB-PVD TBC Region

Upconversion Luminescence Images During Interrupted Furnace Cycling for EB-PVD TBC with YSZ:Er(1%),Yb(3%) Base Layer

1 furnace cycle = 45min @1163°C + 15 min cooling

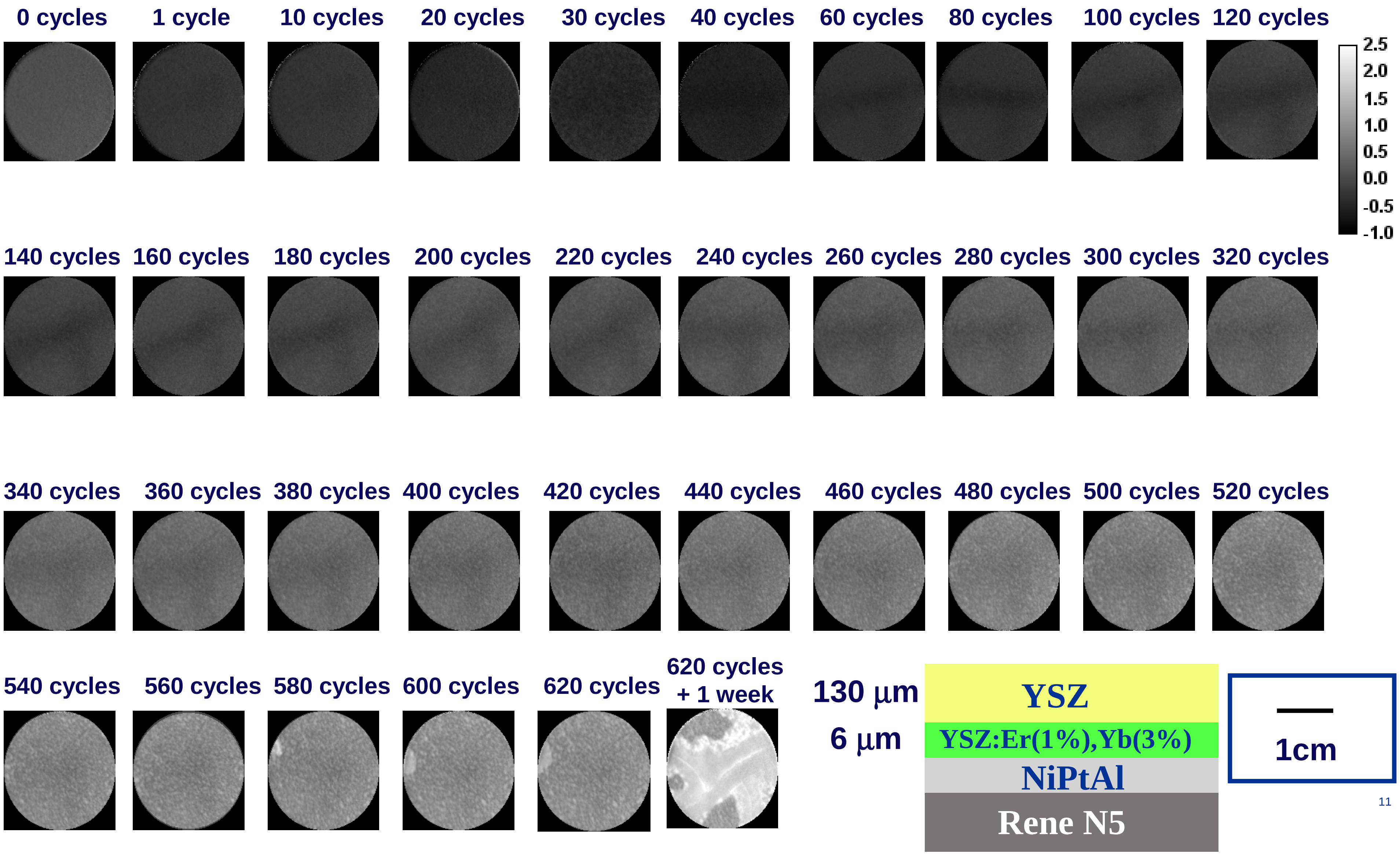
2 sec acquisition



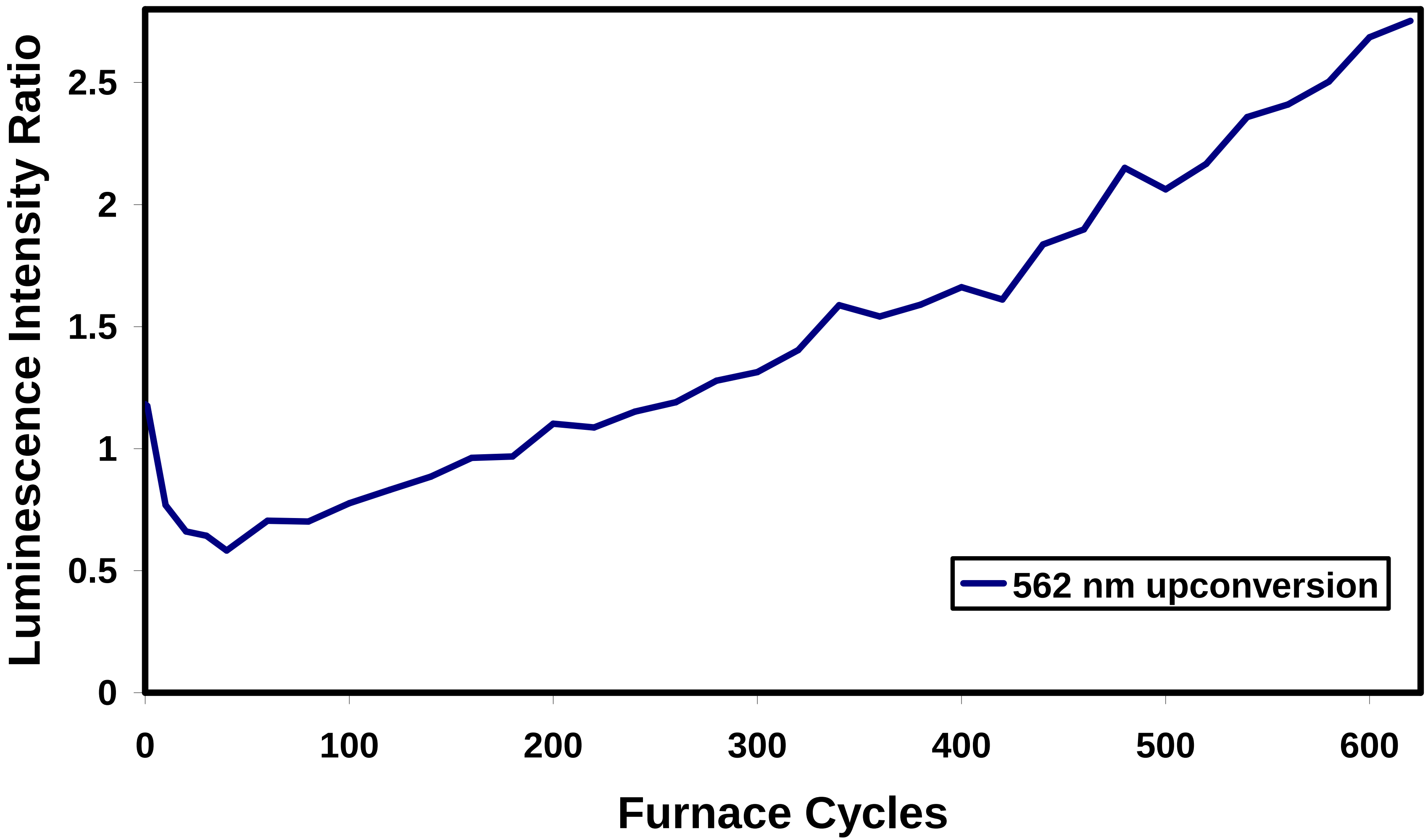
Log Upconversion Luminescence Images During Interrupted Furnace Cycling for EB-PVD TBC with YSZ:Er(1%),Yb(3%) Base Layer

1 furnace cycle = 45min @1163°C + 15 min cooling

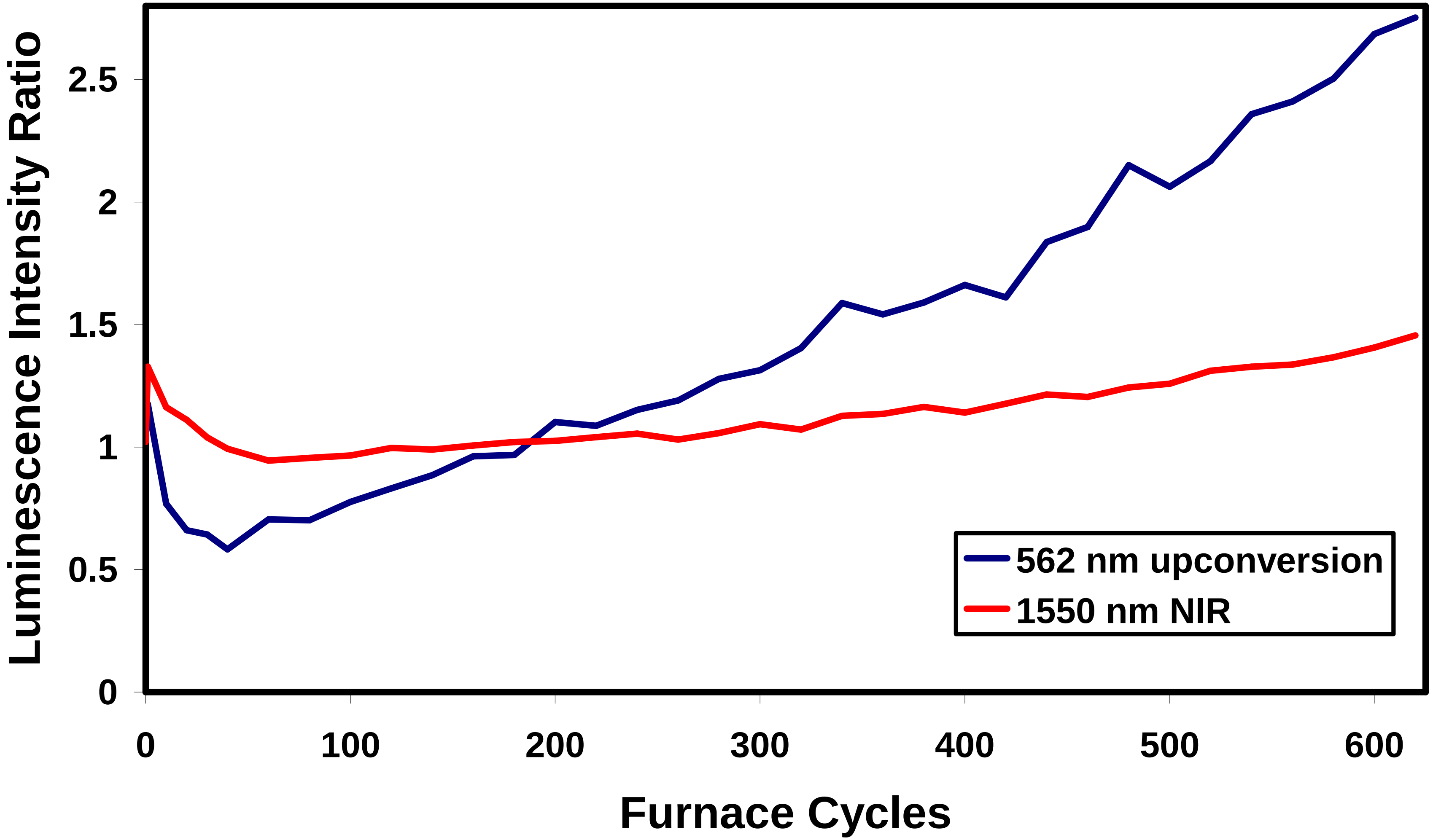
2 sec acquisition



Change in Luminescence Intensity with Furnace Cycling

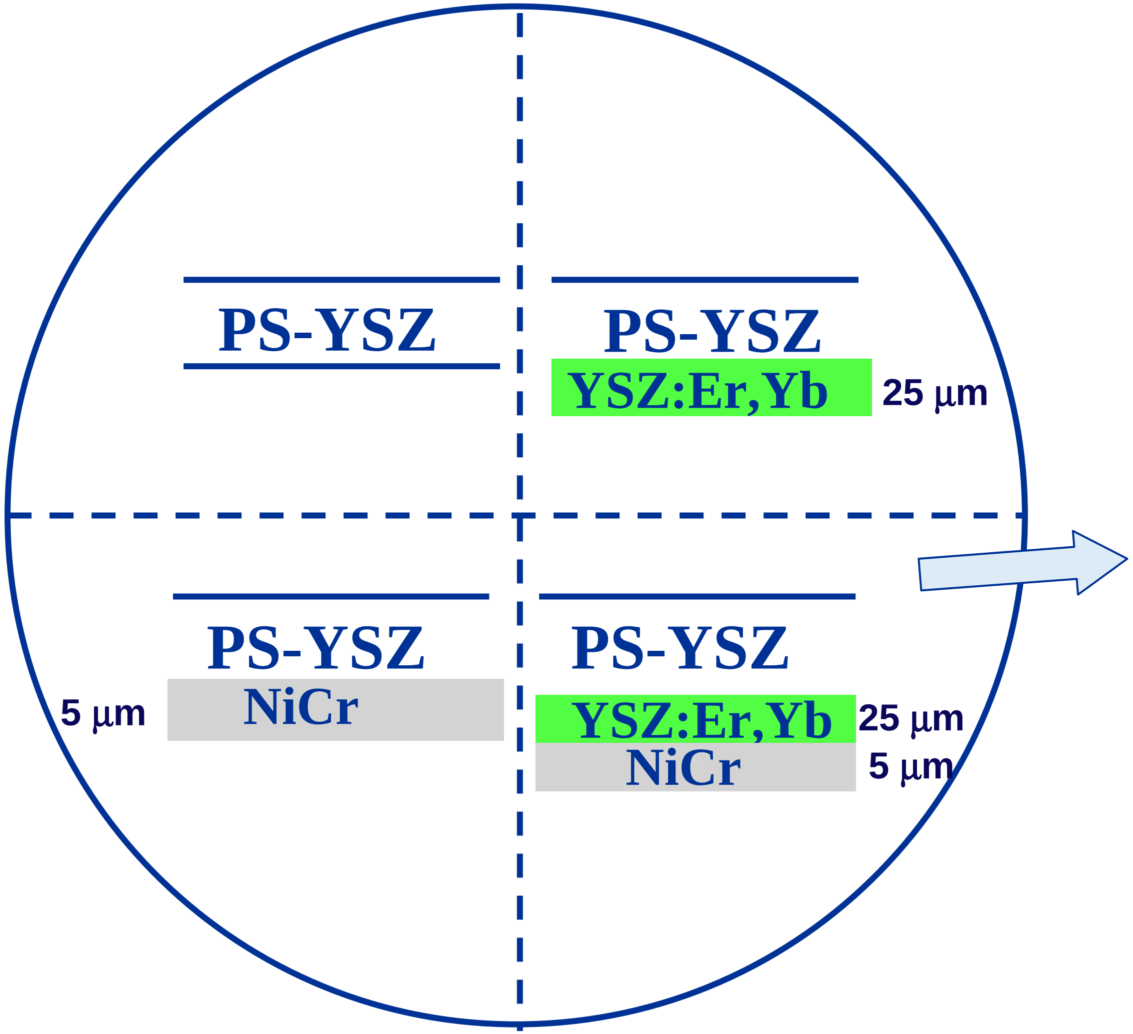


Change in Luminescence Intensity with Furnace Cycling



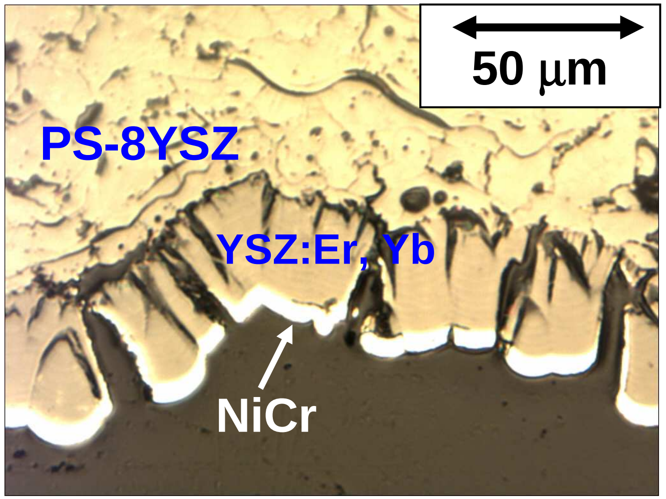
Plasma-Sprayed TBCs

Partitioned Multilayer Coating Design



Top View

White light image



NIR & Upconversion Luminescence Imaging of YSZ:Eu,Yb *below* Metco PS-8YSZ Shows Tremendous Sensitivity to Attached Substrate

top coat thickness ⇨ **145 μm** **190 μm** **230 μm** **430 μm**

White light

1cm

NIR

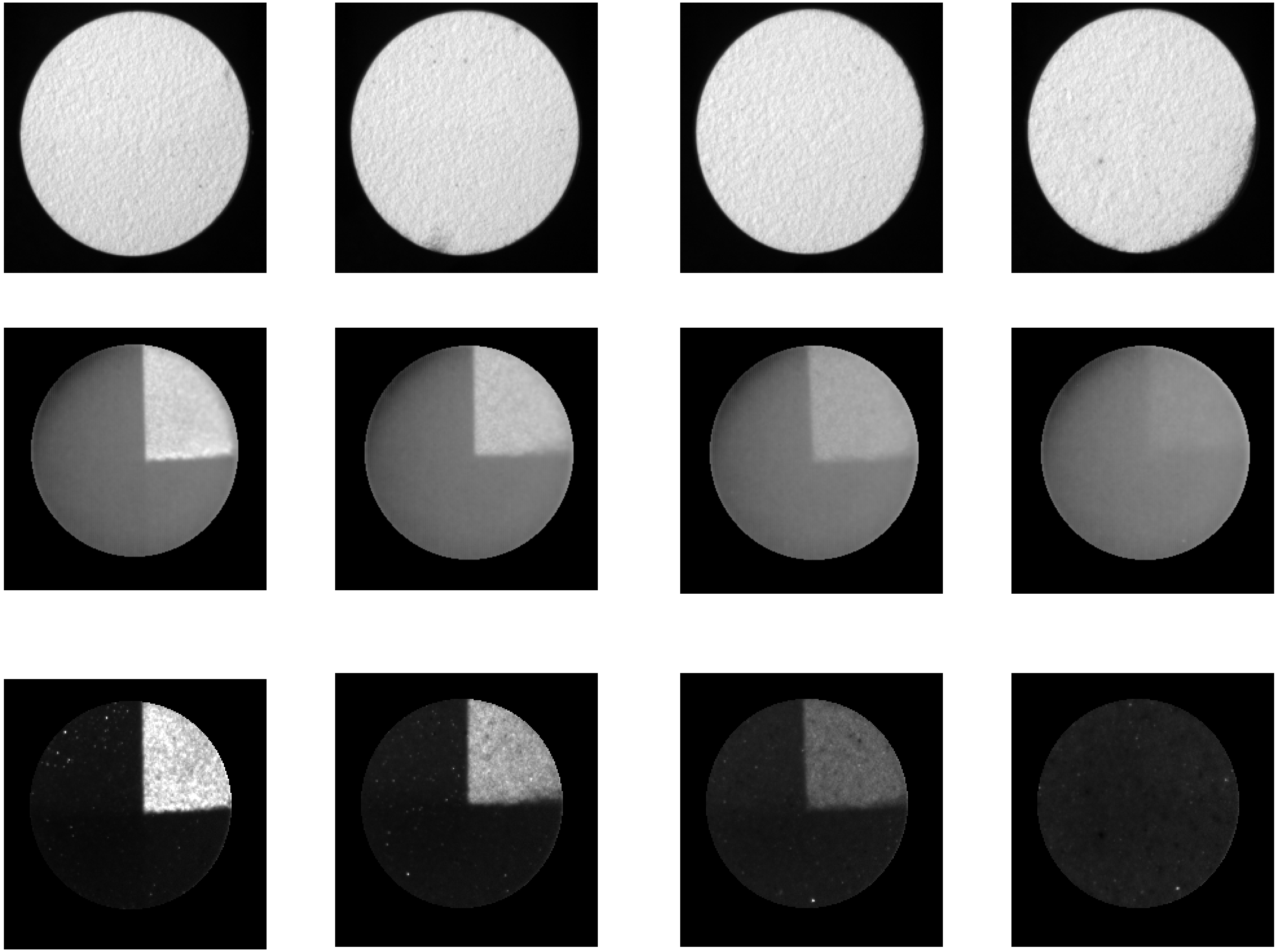
980 nm excitation
1550 nm emission

12 msec acquisition

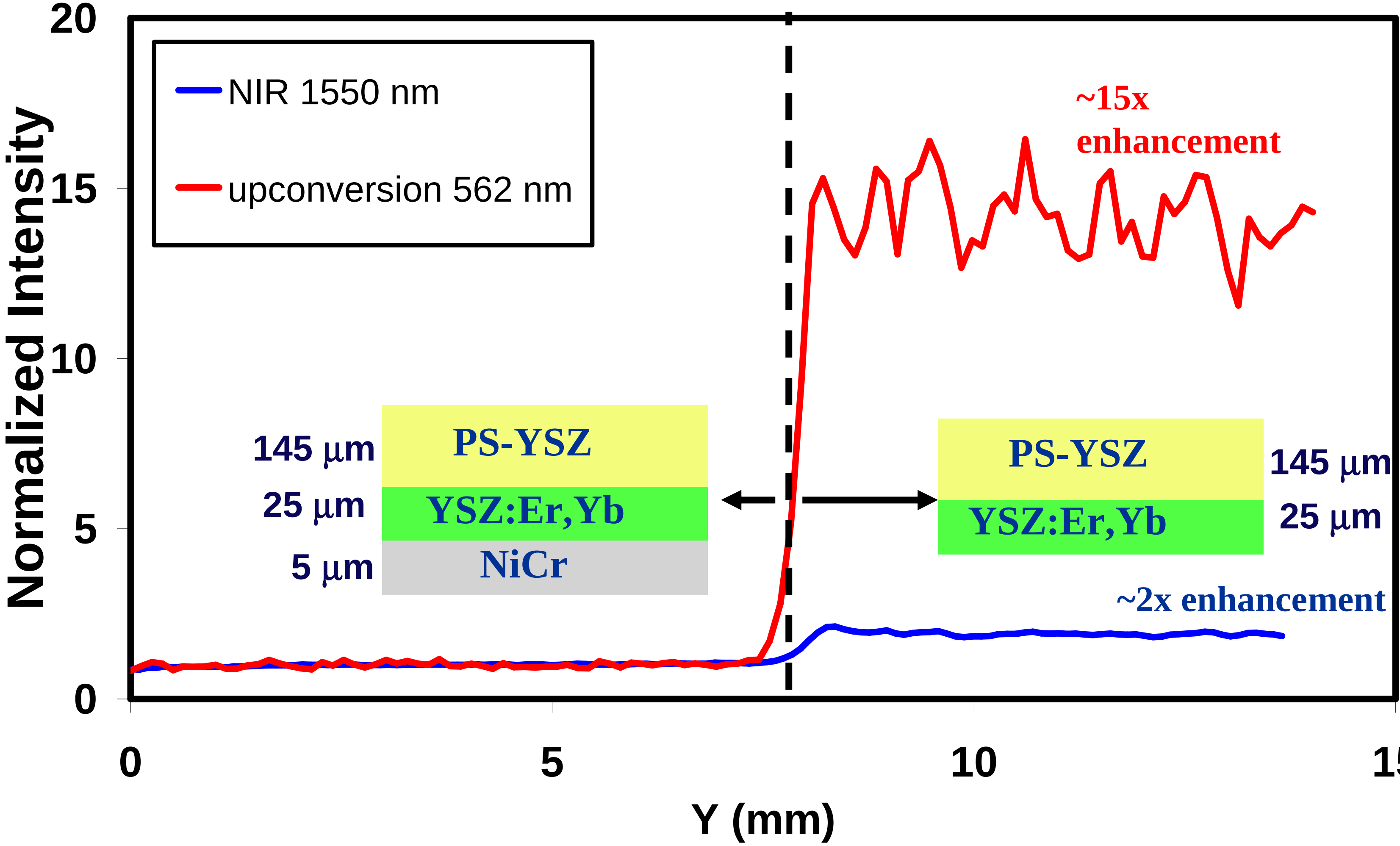
Upconversion

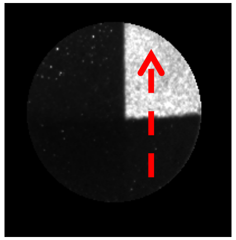
980 nm excitation
562 nm emission

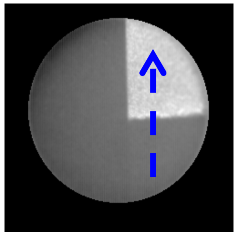
25 sec acquisition



Line Scans Showing NIR & Upconversion Delamination Enhancement

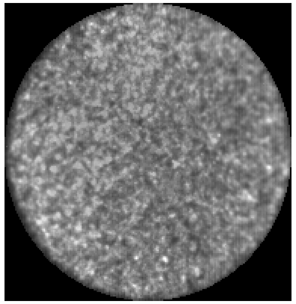




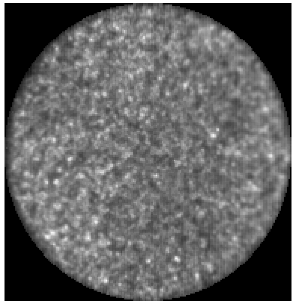


NIR Luminescence Imaging Monitors Advancing Delamination Front During Interrupted Furnace Cycling of Plasma-Sprayed TBC with YSZ:Er(1%),Yb(3%) Base Layer

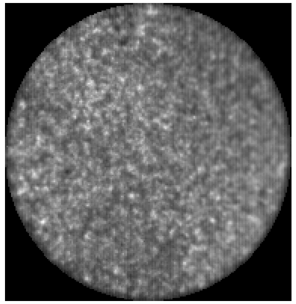
1cm



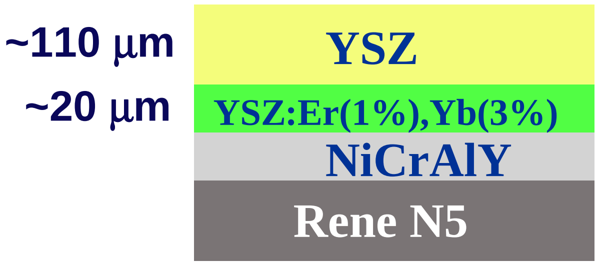
0 cycles

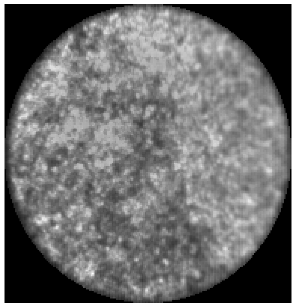


10 cycles



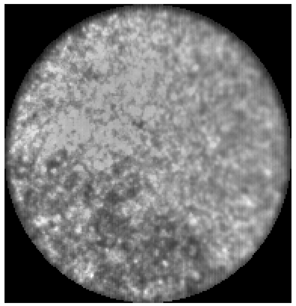
20 cycles





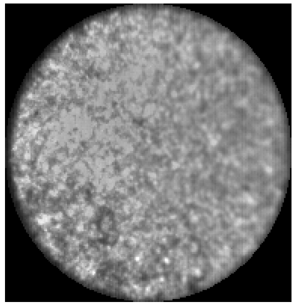
30 cycles

1



30 cycles

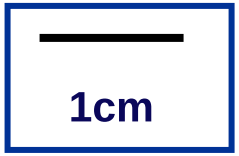
2

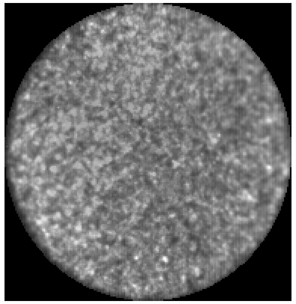


30 cycles

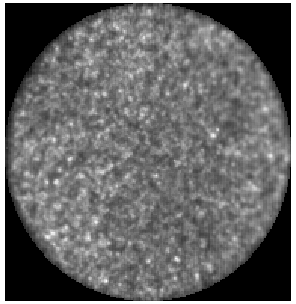
3

NIR Luminescence Imaging Monitors Advancing Delamination Front During Interrupted Furnace Cycling of Plasma-Sprayed TBC with YSZ:Er(1%),Yb(3%) Base Layer

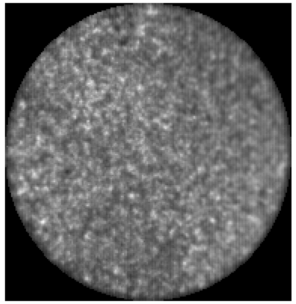




0 cycles



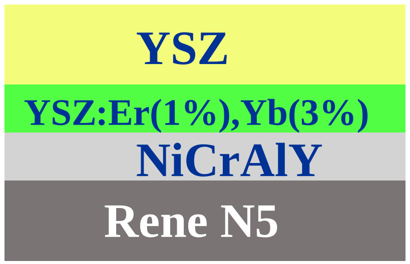
10 cycles

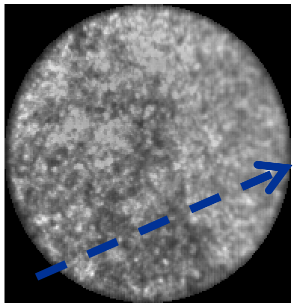


20 cycles

~110 μm

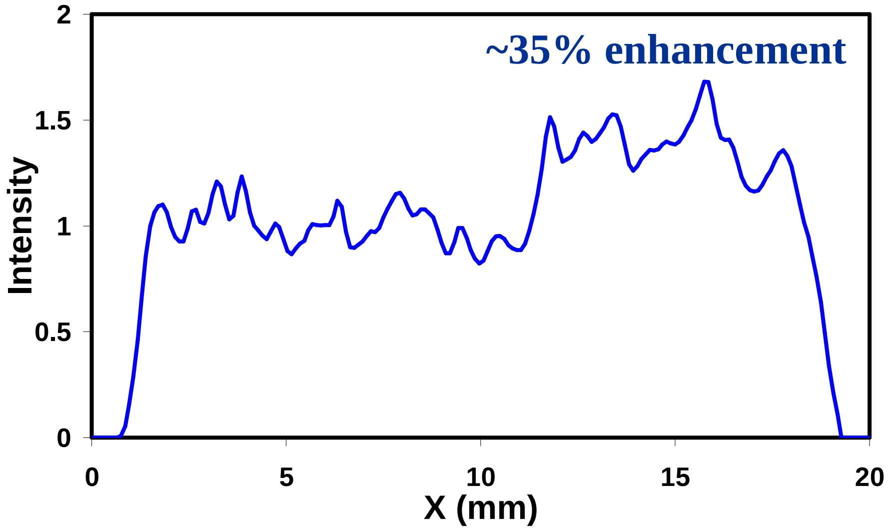
~20 μm





30 cycles

1

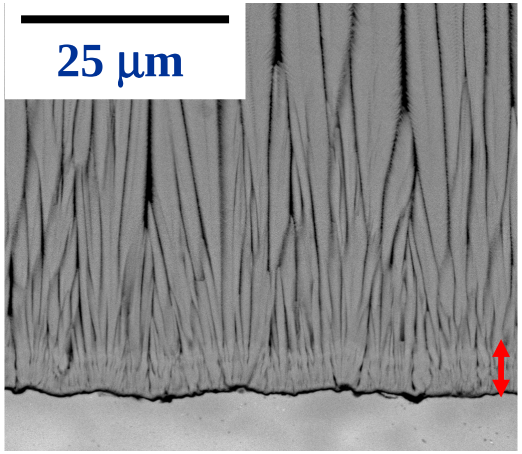
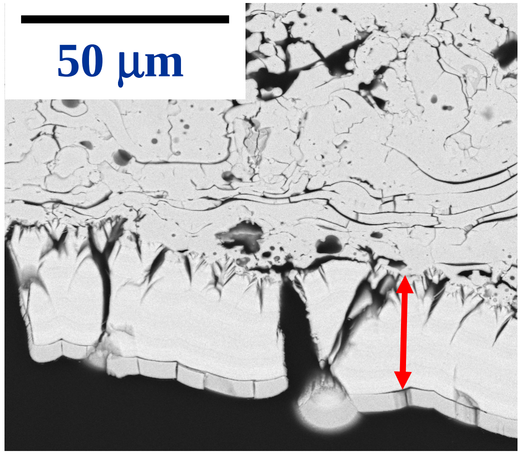
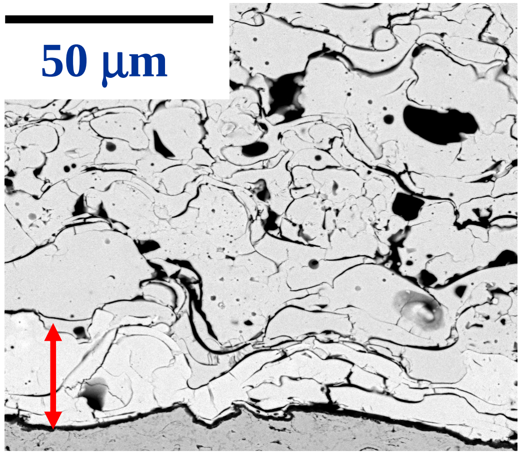


Line Scan across Delamination Front

Effect of YSZ:Er,Yb Base Layer Microstructure on Delamination Contrast

YSZ:Er, Yb base layer thickness

Partitioned Multilayer

EB-PVD	Plasma-Spray/EB-PVD Hybrid	Plasma-Sprayed
		
Vertical boundaries of columnar microstructure does not impede downward light propagation (wave guide).	**No scattering of downward propagating light in base layer. Many boundaries in overlayer to reflect light back into base layer.**	**Splat microstructure of base layer is highly scattering.**
Substantial reduction of luminescence by attached substrate absorption.	**Near-complete absorption of luminescence by attached NiCr layer.**	**Less absorption of luminescence by attached substrate absorption since there is significant scattering within base layer.**
Excellent delamination contrast	Superb delamination contrast	Modest delamination contrast

Summary

- NIR & upconversion luminescence imaging offer improved detection of TBC delamination progression.
  - Upconversion luminescence imaging
    - Enhanced contrast for discriminating between finer gradations of TBC delamination progression in EB-PVD TBCs.
  - NIR luminescence imaging
    - Superior penetration for detecting delamination in highly scattering plasma-sprayed TBCs.
  - Er^{3+} + Yb^{3+} co-doping strategy minimizes interference from Er^{3+} impurities above the luminescent sublayer.
- Integration of luminescent sublayer achieved (EB-PVD) without reducing TBC life. (in progress)