Temperature Measurements of Thermal Barrier Coating Surfaces Using a Cr-Doped $GdAlO_3$ Thermographic Phosphor

Jeffrey I. Eldridge, Timothy J. Bencic, and Dongming Zhu
NASA Glenn Research Center, Cleveland, OH

Michael D. Cuy
Vantage Partners, Cleveland, OH

Douglas E. Wolfe
Penn State University, University Park, PA

Thomas P. Jenkins
MetroLaser, Inc., Laguna Hills, CA

Steven W. Allison and David L. Beshears
Emerging Measurements, Knoxville, TN

Bauke Heeg
Lumium, The Netherlands

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Background

- Discovery* of exceptional high temperature retention of ultra-bright luminescence by Cr-doped $GdAlO_3$ with orthorhombic perovskite crystal structure: Cr-doped gadolinium aluminum perovskite (Cr:GAP).
- Enables luminescence-based temperature measurements in highly radiant environments to 1250ºC.

Objectives

- Implement the ultra-bright luminescence temperature sensing capability of Cr:GAP to:
  - Overcome the usually intensity-starved nature of the severely restricted solid angle of light detection associated with engine probes.
  - Enable surface temperature mapping using luminescence lifetime imaging by simply broadening the excitation laser beam to cover the region of interest.
    - Not previously practical because expansion of laser beam reduces S/N to unacceptable levels.

***J.I. Eldridge & M.D. Chambers**

Approach

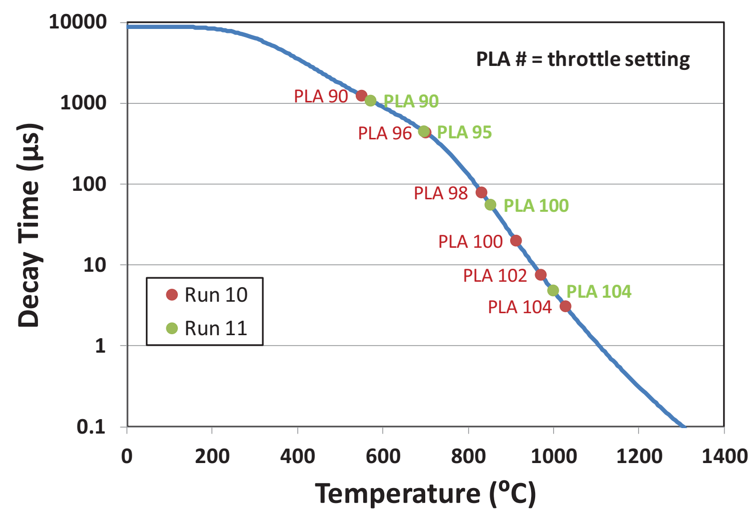
- Demonstrate successful spot temperature measurements using engine probe with restricted light collection.
  - Successfully demonstrated temperature measurements from Cr:GAP coated Honeywell stator vane doublet in afterburner flame of AEDC J85-GE-5 turbojet test engine.

Component Testing in Engine Afterburner Flame

Vane doublet with temperature sensing coating in test fixture.

Afterburner flame from J85 test engine.

Measured vane surface temperature vs. throttle setting

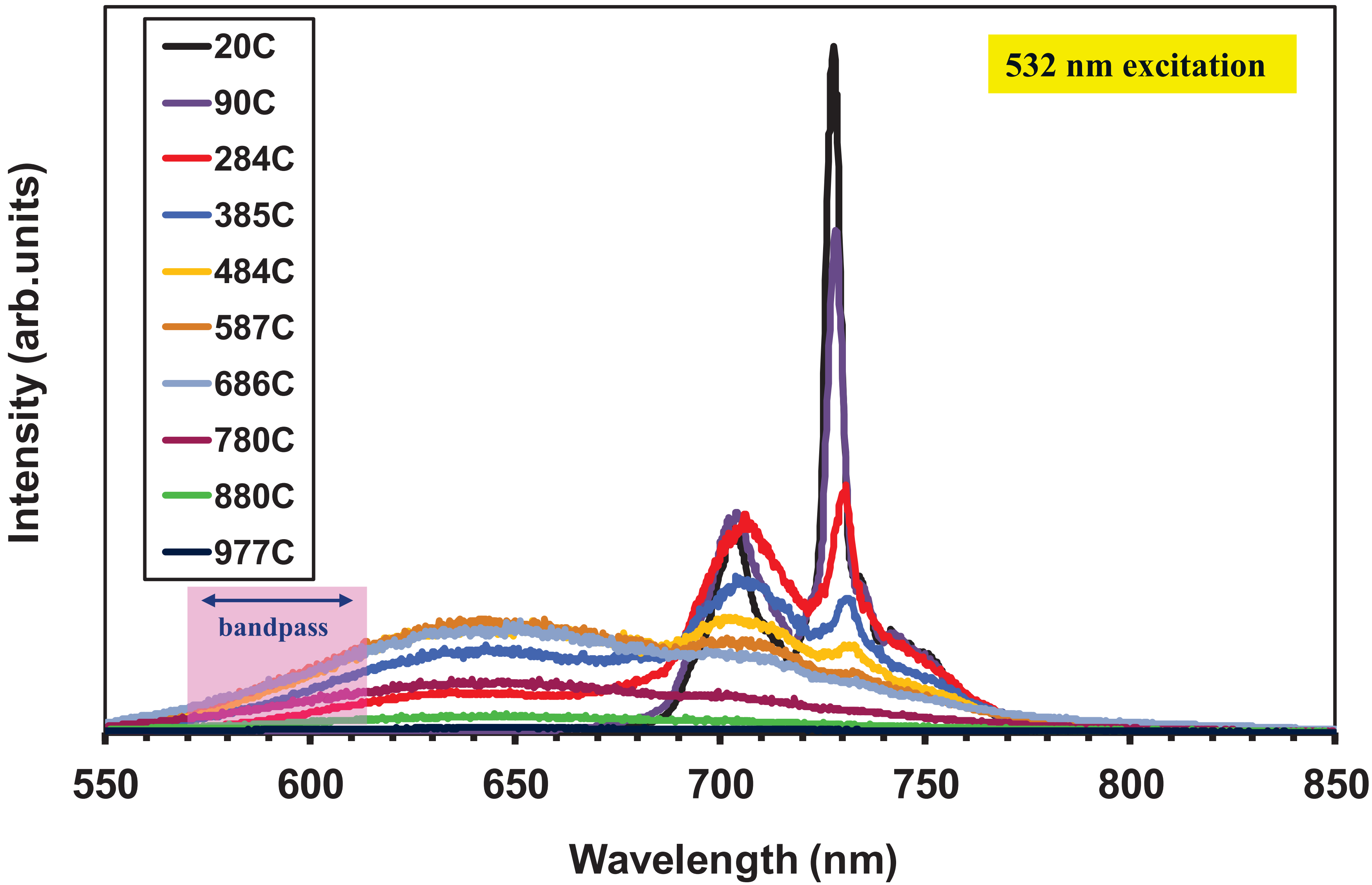


- Demonstrate 2D temperature mapping of thermal gradients on TBC-coated surfaces under conditions ranging from well-controlled laboratory conditions to approaching turbine engine environment.
  - Coated button specimens in NASA GRC high heat flux laser for well-controlled thermal gradients.
  - Coated stator vane doublet in NASA GRC Mach 0.3 Burner Rig.
  - Coated stator vane in AEDC J85 afterburner flame.

Demonstrating Temperature Measurement Capability

Time-Averaged Luminescence Emission from Cr(0.2%):GAP Puck

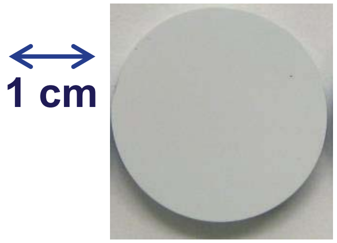
Temperature Dependence



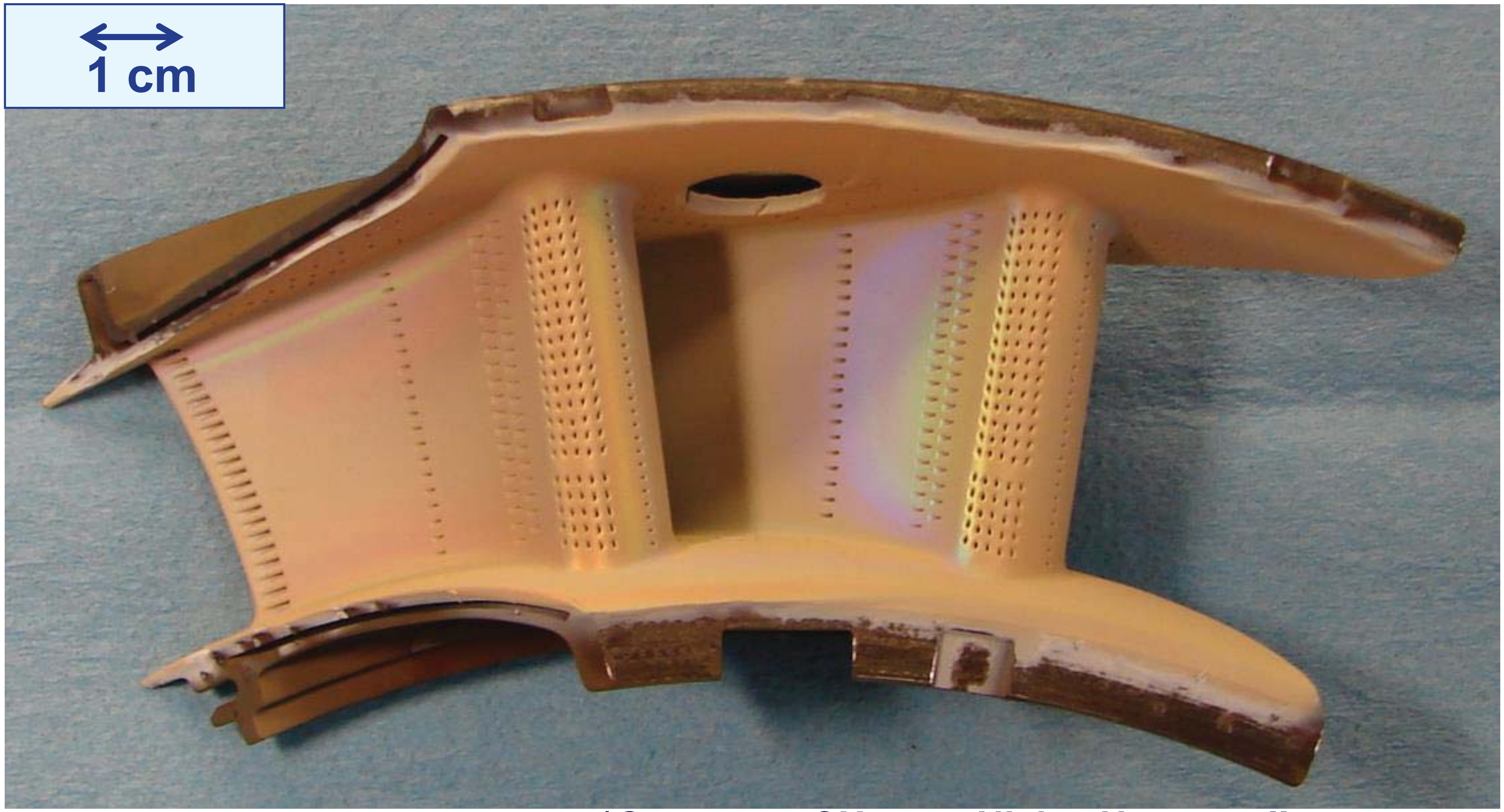
Cr:GAP-Coated Specimens

EB-PVD at Penn State

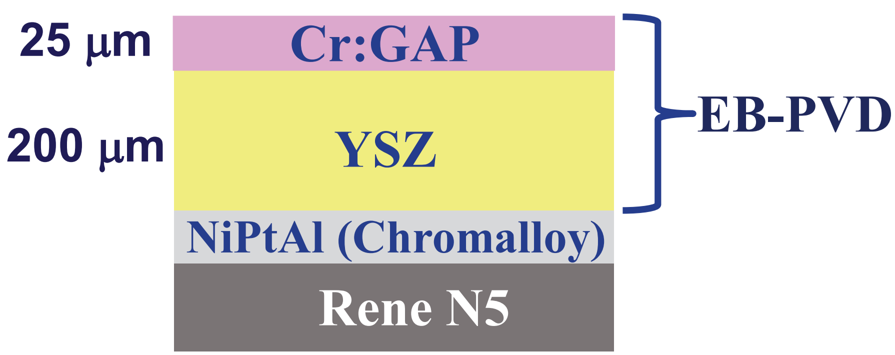
- **Buttons for furnace and laser heating tests**

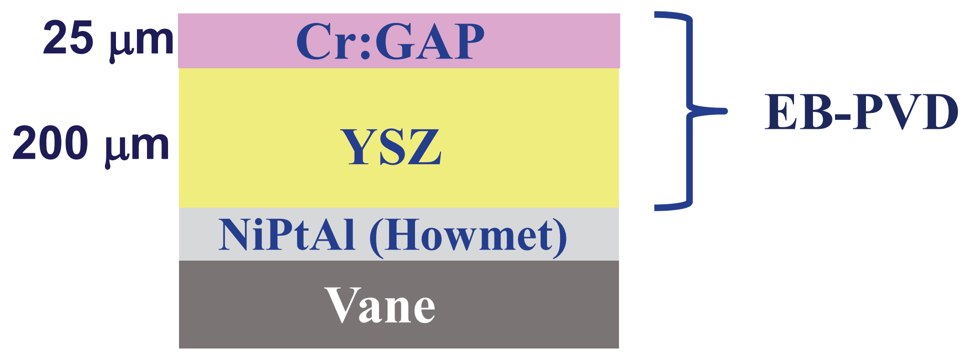


- **Honeywell Stator Vane Doublet for Burner Rig and Afterburner Tests***



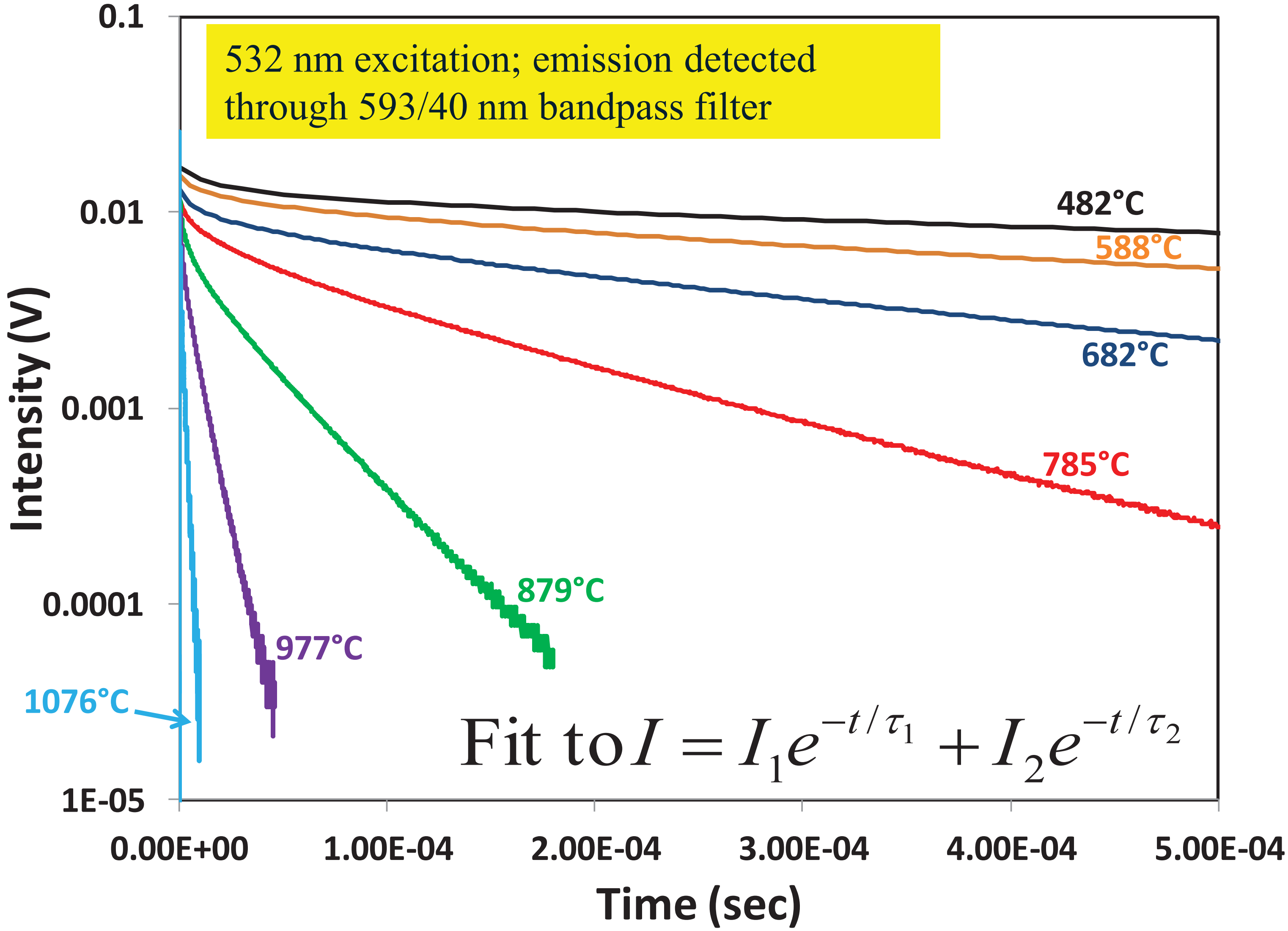
*Courtesy of Harvey Niska, Honeywell





Coatings for 2D Temperature Mapping

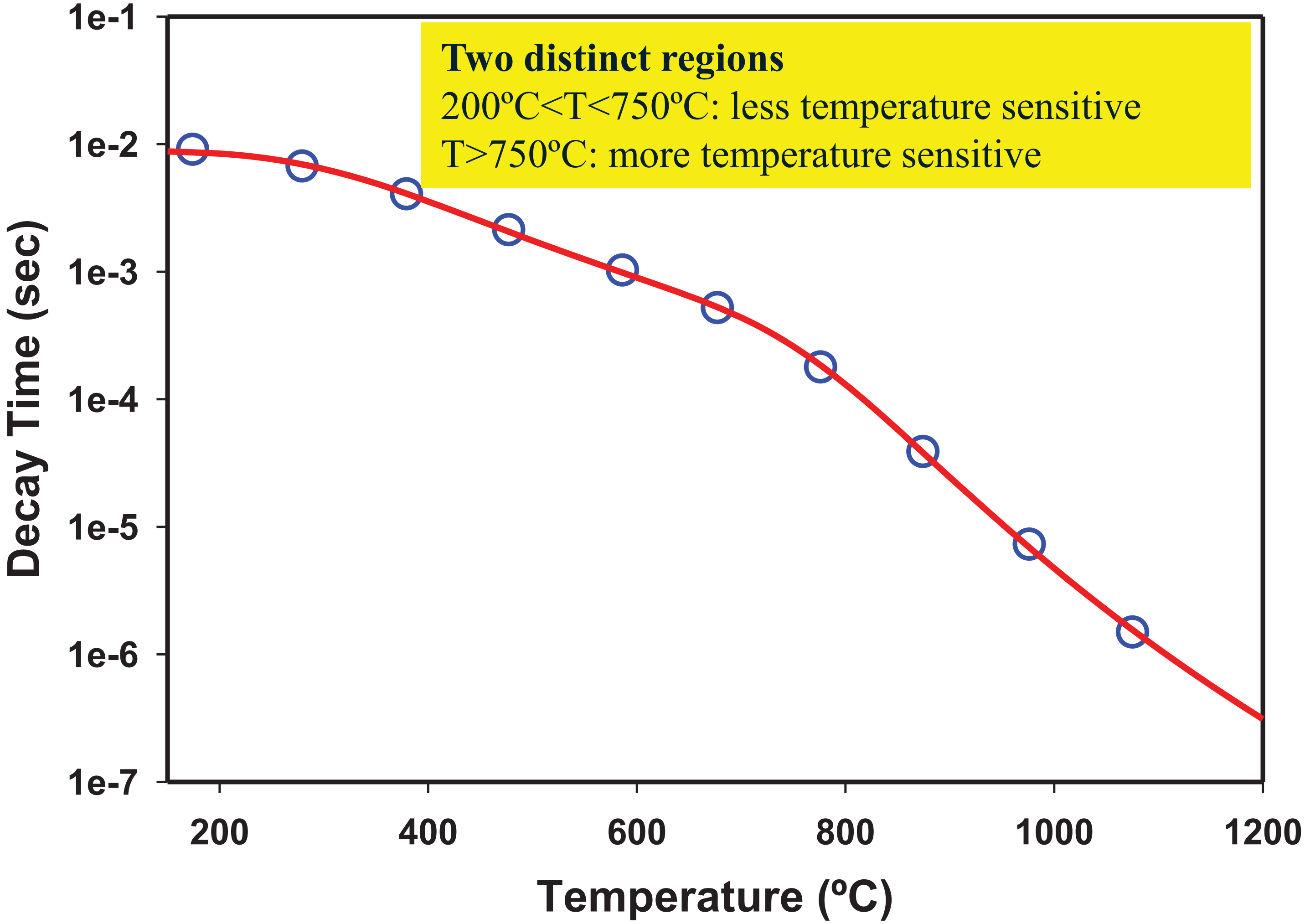
Luminescence Decay Curves from 25 µm Thick EB-PVD Cr:GAP Coating



Superb signal-to-noise from thin 25 µm thick coating confirms retention of ultra-bright luminescence at high temperatures.

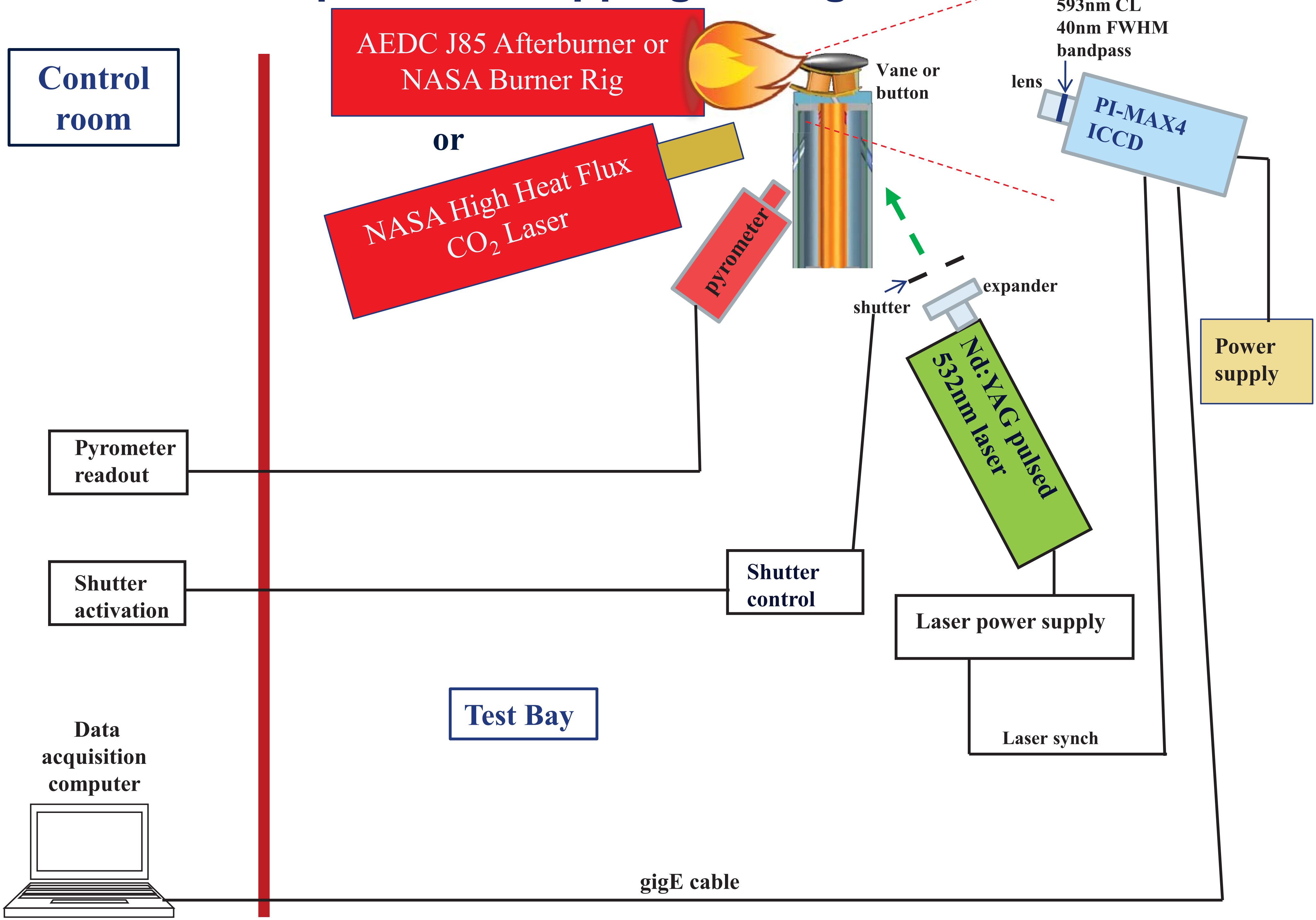
Demonstrating Temperature Measurement Capability

Calibration of Decay Time vs. Temperature for GAP:Cr Coating

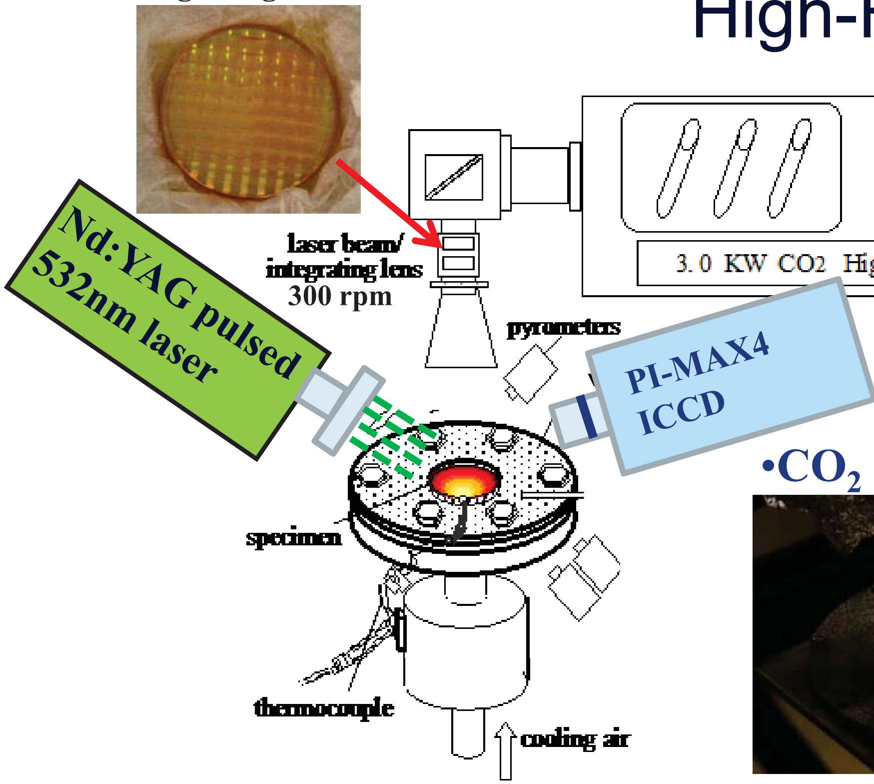


$$\text{Fit to } \tau = \tau_{2E}^{R} \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta Eq + \Delta E)/kT}}$$

Surface Temperature Mapping Configuration

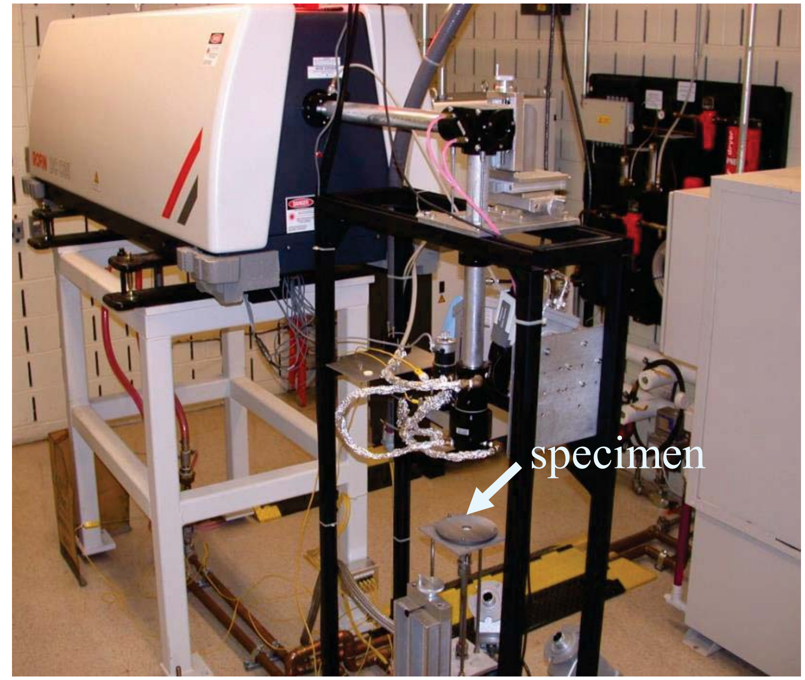


Mapping Thermal Gradients Produced by High-Heat-Flux Laser

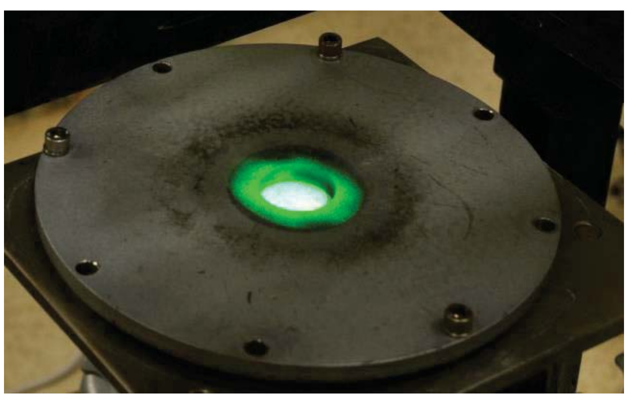


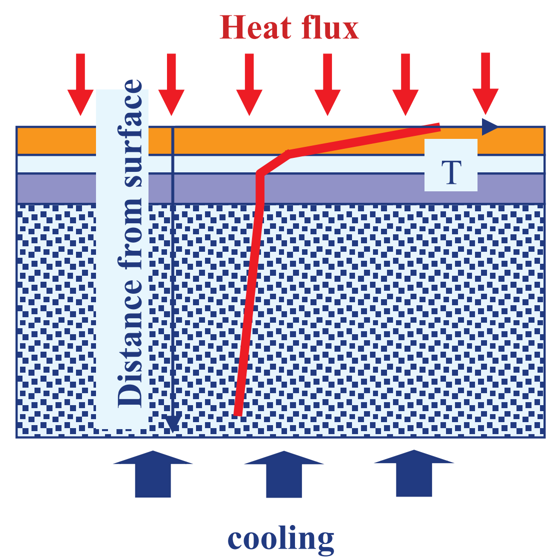
• CO_2 laser heating

• High power CO_2 laser high-heat-flux rig



• Illumination of Specimen by Expanded Laser Beam

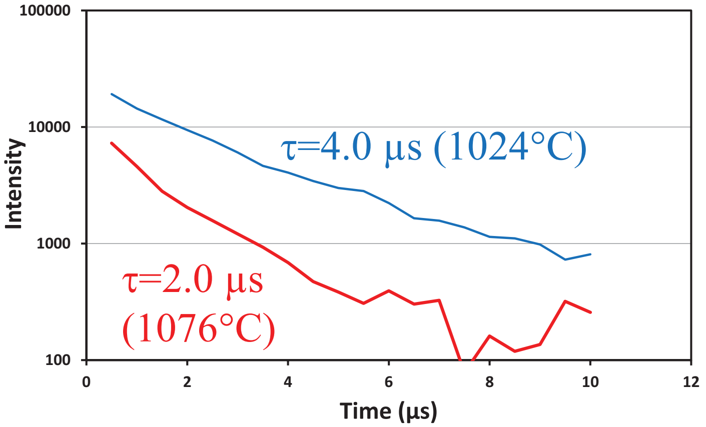




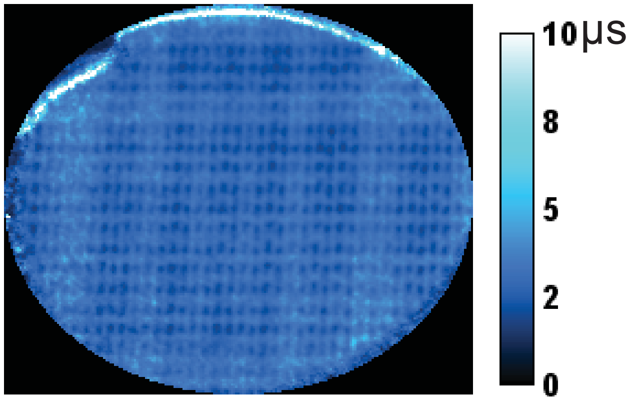
2D Temperature Maps of Thermal Test Pattern

- Step 1: Collect sequence of time-gated images at different delay times after laser pulse.
- Step 2: Remove thermal radiation background from each image in sequence.
- Step 3: Fit luminescence decay curve at each pixel to produce decay time map.

Individual Pixel Decays

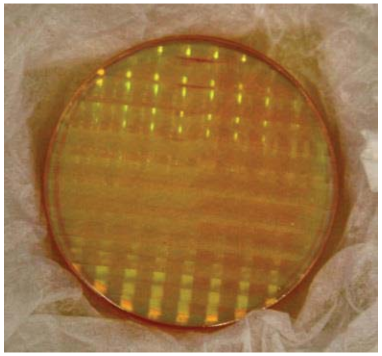


Decay Time Map



1 cm

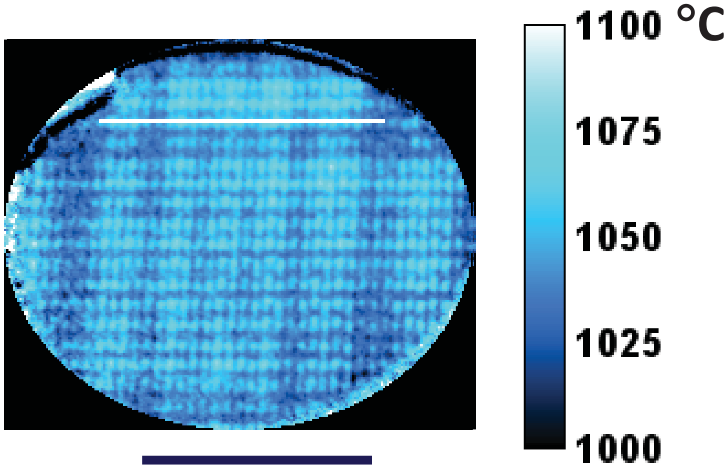
Fly-eye integrating lens



3.8 cm diam

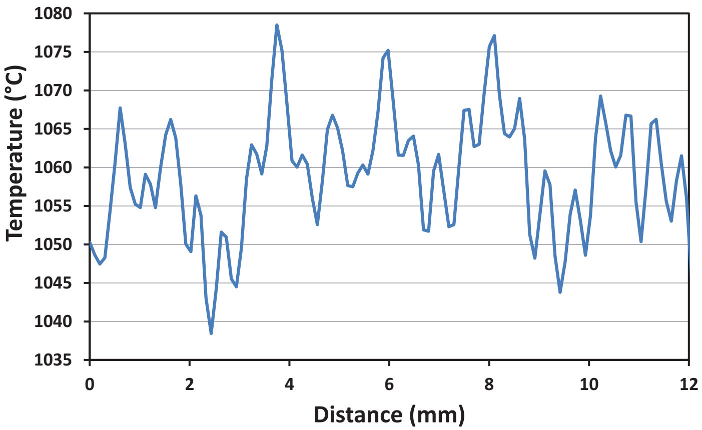
- Step 4: Use calibration data to convert decay time map to temperature map.

Temperature Map



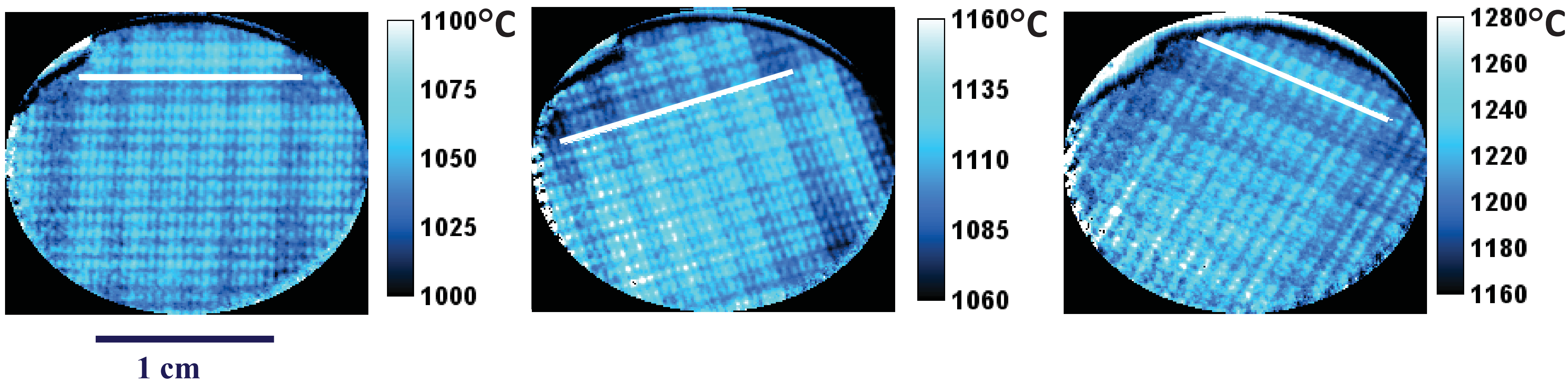
1 cm

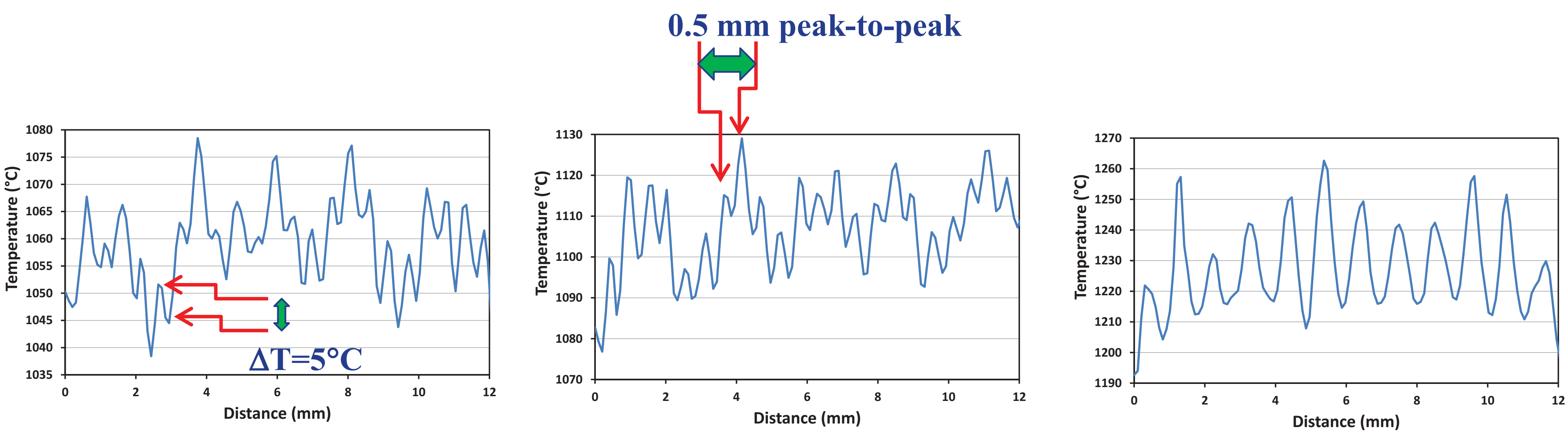
Temperature Line Scan



Thermal Test Pattern Temperature Maps at Increasing Heat Flux

Temperature Maps

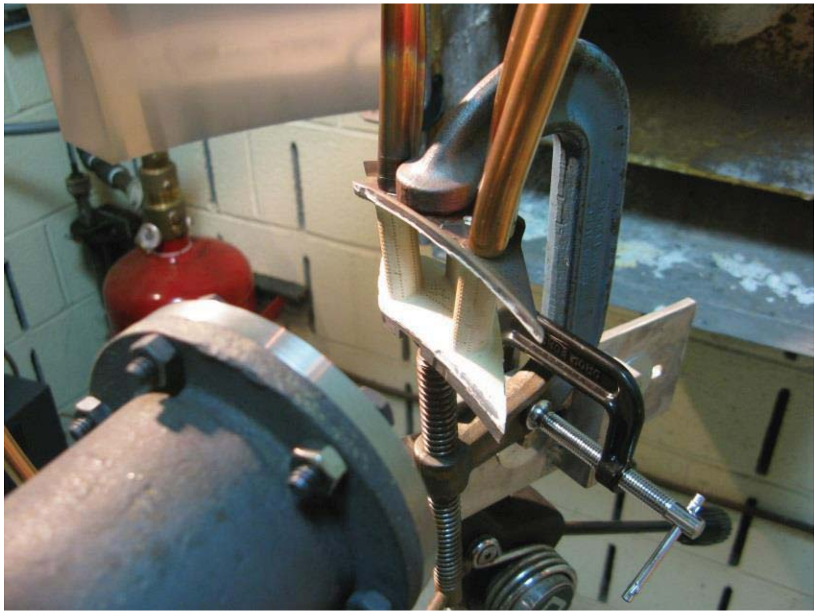




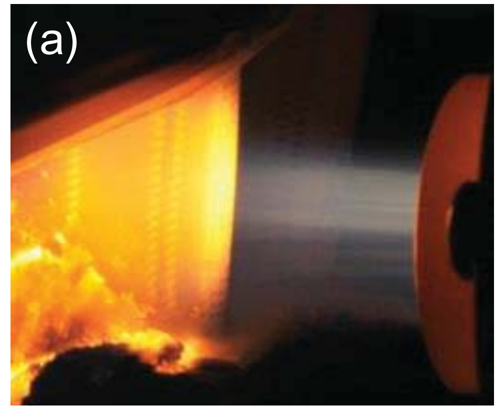
Thermal test pattern demonstrates excellent temperature sensitivity/spatial resolution

- Sensitive to ΔT of 5°C over distance of 0.5 mm
- Insensitive to surface emissivity & reflected radiation!

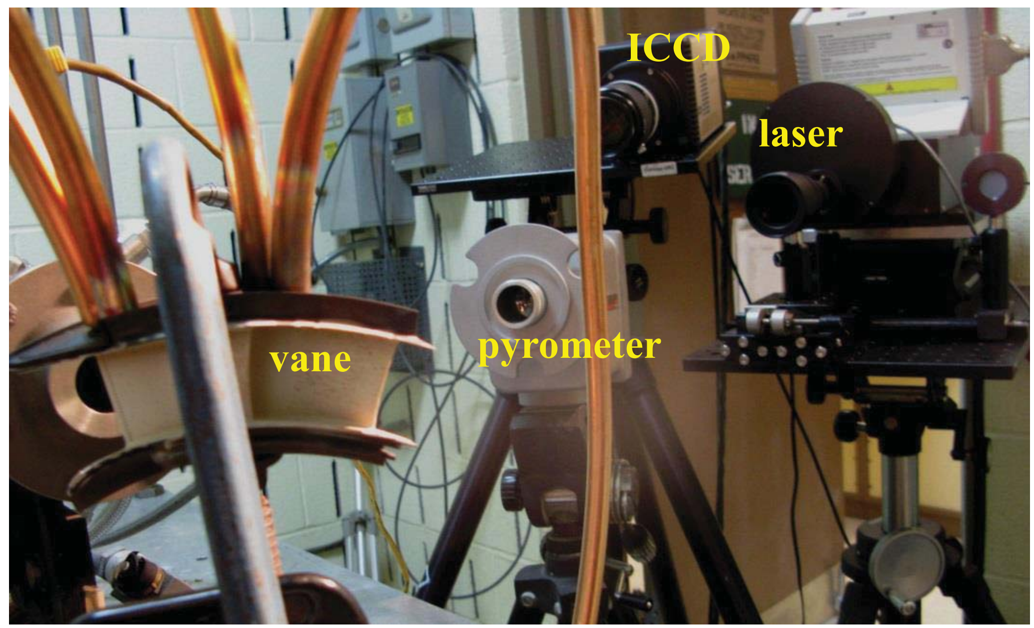
2D Temperature Mapping of Honeywell Stator Vane in NASA GRC Mach 0.3 Burner Rig Flame



Burner/vane orientation



Cr:GAP coated vane with cooling air supply tubing

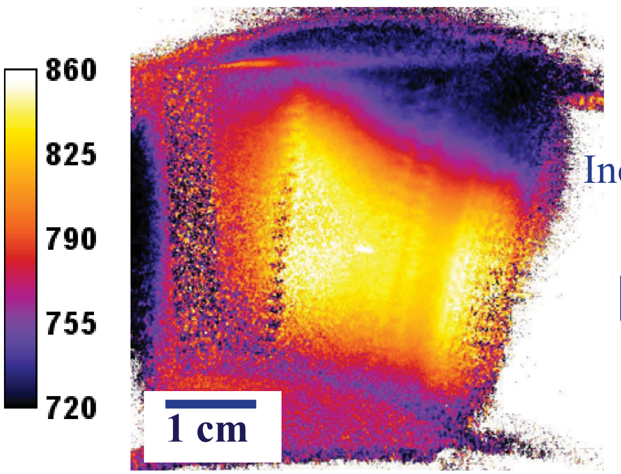


ICCD, laser, & pyrometer pointed at vane

Surface Temperature Mapping of Honeywell Stator Vane in NASA GRC Mach 0.3 Burner Rig Flame

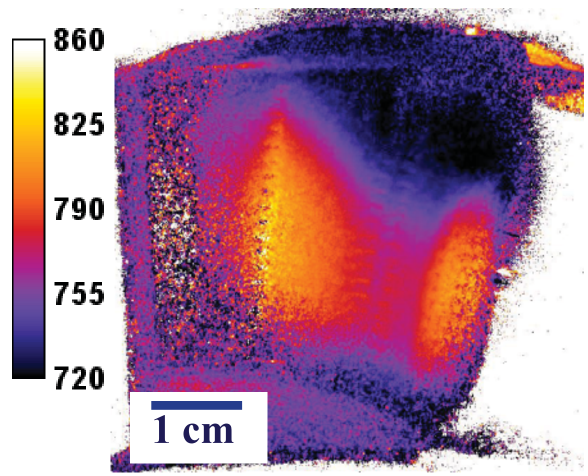
Surface temperature maps

Visible

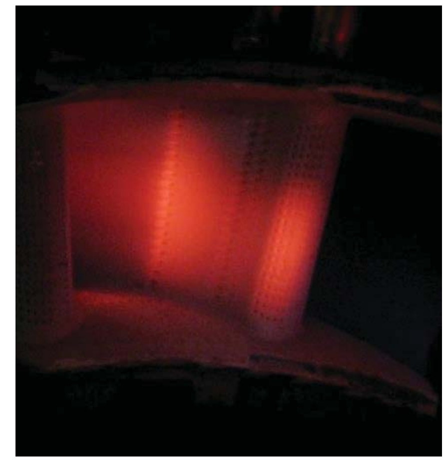


Min flow

Increase air flow through cooling holes



High flow



Good temperature measurements despite rust stain!
Would not be possible with pyrometer!

Before burner rig test

After burner rig test

J85-GE-5 Engine Test at UTSI

Engine Aft View

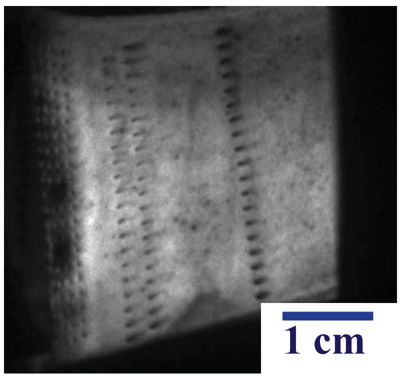
Overhead View of Vane in Afterburner Flame

Afterburner Flame at Night

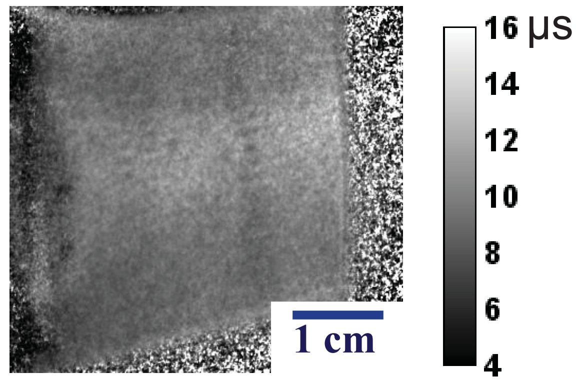
Surface Temperature Mapping of Honeywell Stator Vane in AEDC J85 Afterburner Flame

PLA (throttle) = 99°

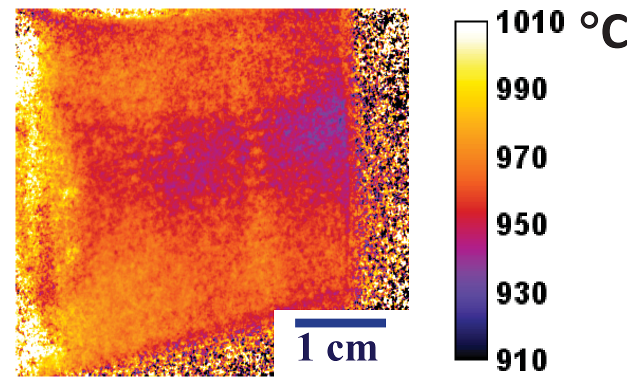
First gate image

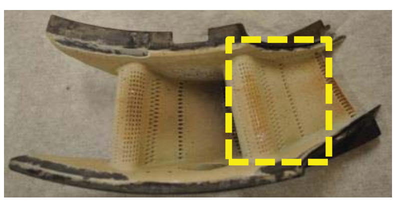


Decay Time Map

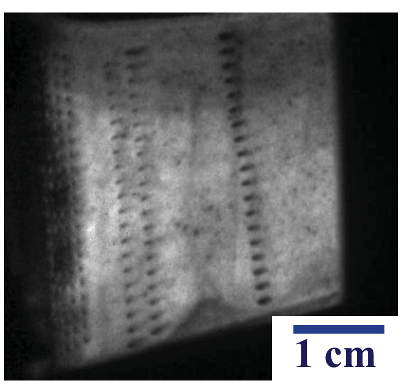


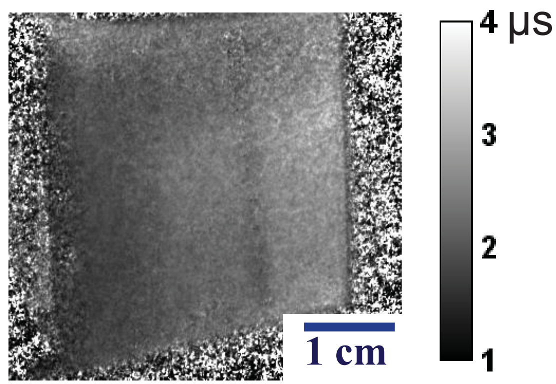
Surface Temperature Map

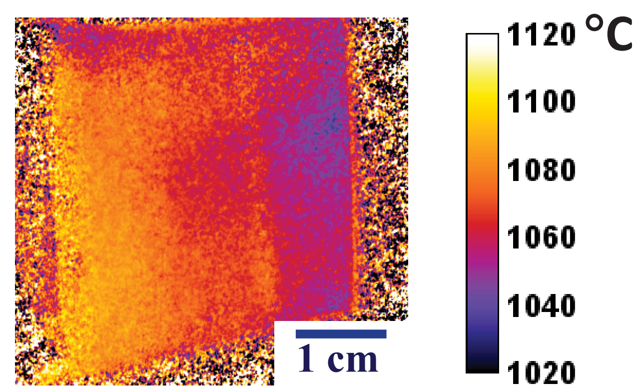




PLA (throttle) = 101°







Evidence of air film cooling

Summary

- Ultra-bright high-temperature luminescence of Cr:GAP enables practical temperature mapping of TBC-coated surfaces by luminescence lifetime imaging.
  - Advantages over pyrometry/thermal imaging
    - Emissivity-independent
    - Insensitive to reflected radiation
  - Disadvantages over pyrometry/thermal imaging
    - Requires Cr:GAP coating
    - Applicable to steady-state conditions only (at this time)
  - Impressive temperature sensitivity/spatial resolution.
    - ΔT of 5°C over sub-millimeter distances
  - Demonstrated over conditions ranging from well-controlled laboratory conditions to burner rig and engine afterburner environments.

Acknowledgments

- Funding from NASA ARMD Seedling Project.
- Honeywell for providing stator vane doublet.
- AEDC/UTSI Propulsion Research Facility Team for conducting J85 afterburner tests.