Luminescence-Based Temperature Mapping at Turbine Engine Temperatures Using Breakthrough Cr-Doped $GdAlO_3$ Broadband Luminescence

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June 7, 2012

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Objectives

- Develop luminescence-based temperature measurement capability with major advantages over thermocouples and pyrometry for turbine engine environment.
  - Take advantage of breakthrough discovery of high temperature ultra-bright luminescence by Cr-doped $GdAlO_3$.
- Technical approach: take advantage of ultra-bright luminescence at high temperatures
  - Develop optical thermometer for probing engine environment.
  - Demonstrate 2D temperature gradient mapping using Cr-doped $GdAlO_3$ coatings.

Innovation

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Breakthrough 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).

- High crystal field in GAP suppresses thermal quenching of luminescence.
- Novel utilization of broadband spin-allowed emission extends luminescence to shorter wavelengths where thermal radiation background is reduced.

Enables luminescence-based temperature measurements in highly radiant environments to 1200^{o}C.

- Huge advance over state-of-the-art ultra-bright luminescence upper limit of 600^{o}C.

Turbine engine temperature measurements?
Now we're talking!

Background

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- Almost all thermographic phosphor temperature measurements use luminescence from transition metal or rare earth dopants.

Transition metal (e.g., Cr^{3+}) 3d transitions	**Rare earth (e.g., Dy^{3+}) 4f transitions**
Unshielded	Shielding by 5s & 5p electrons
Strongly phonon & bonding coupled	Weakly phonon & bonding coupled
Very strong oscillator strength ✓	Very weak oscillator strength by ~4 orders of magnitude
Strong thermal quenching $Cr:Al_2O_3$ performs up to 600°C	Weak thermal quenching ✓ Dy:YAG performs up to 1700°C
Short λ emission not available R lines @~700 nm	Short λ emission available ✓ Dy^{3+} @456 nm

- Turbine engine temperature measurements need best-of-both-worlds performance of high intensity emission that persists above 1000°C.

Physics Basis for Phosphor Matrix Selection

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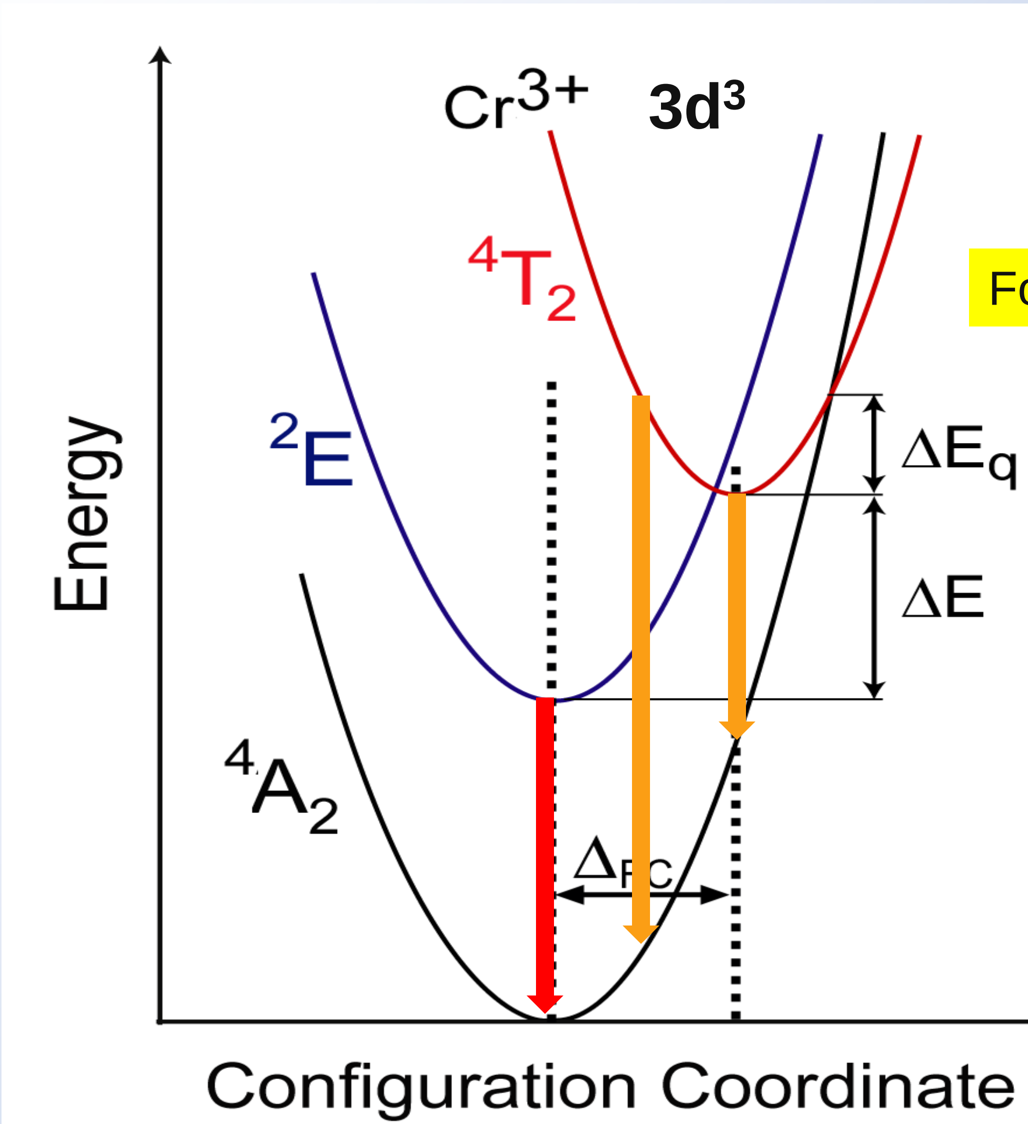

Spin-forbidden R-line emission $^2E \rightarrow {}^4A_2$

Spin-allowed broadband emission $^4T_2 \rightarrow {}^4A_2$

For long τ at high T $\rightarrow$ increase ΔE, ΔEq.

$^4T_2$ (short-lived but population stabilized by thermal equilibrium with ^2E reservoir level)

^2E (long-lived reservoir level)

$$\tau_{4T2} = \tau_{2E} = \tau_{2E}^{R} \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta Eq + \Delta E)/kT}}$$

From Zhang, Z., Grattan, K.T.V., and Palmer, A.W., *Phys. Rev. B* **48**, 7772 (1993).

$^4A_2$

Orthorhombic Rare Earth Perovskites $RAlO_3$ Meet Criteria

Tightly bonded AlO_6 Octahedra Exhibit Strong Crystal Field

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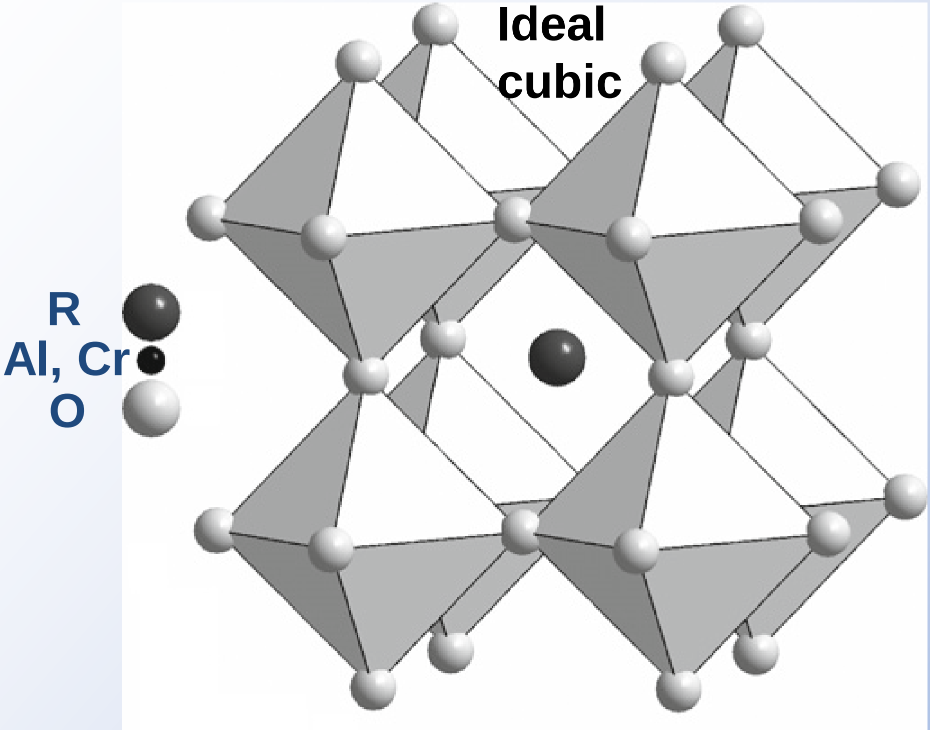
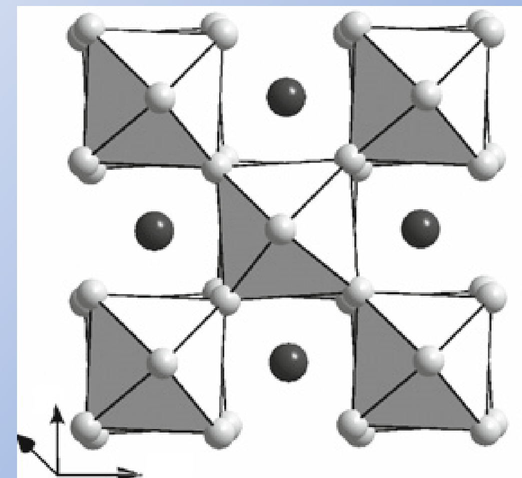
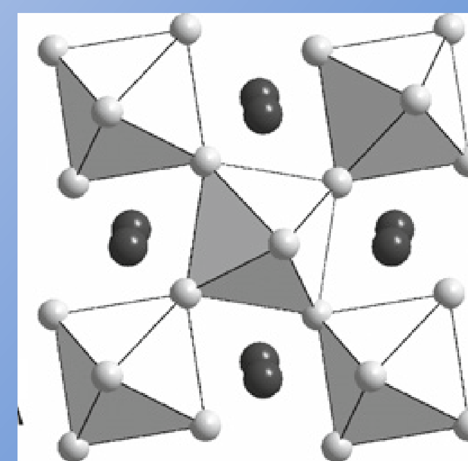


(No parity-forbidden $^4A_2 \rightarrow ^2T_1$, $^2T_2$ absorption)



Rhombohedral
(near-cubic symmetry, weak absorption)

Among all $RAlO_3$ perovskites, $GdAlO_3$ has highest ΔE among candidates with orthorhombic structure.



Orthorhombic
(distorted octahedra, strong absorption)

Progress to Date

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- Demonstrated temperature measurement capability of Cr:GAP luminescence.
- Successful development of optical thermometer using Cr:GAP-coated sapphire lightpipes.
- Coatings developed for 2D temperature mapping.
- Patent application, conference presentation, and article submitted for conference proceedings.

Demonstrating Temperature Measurement Capability

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

Temperature Dependence

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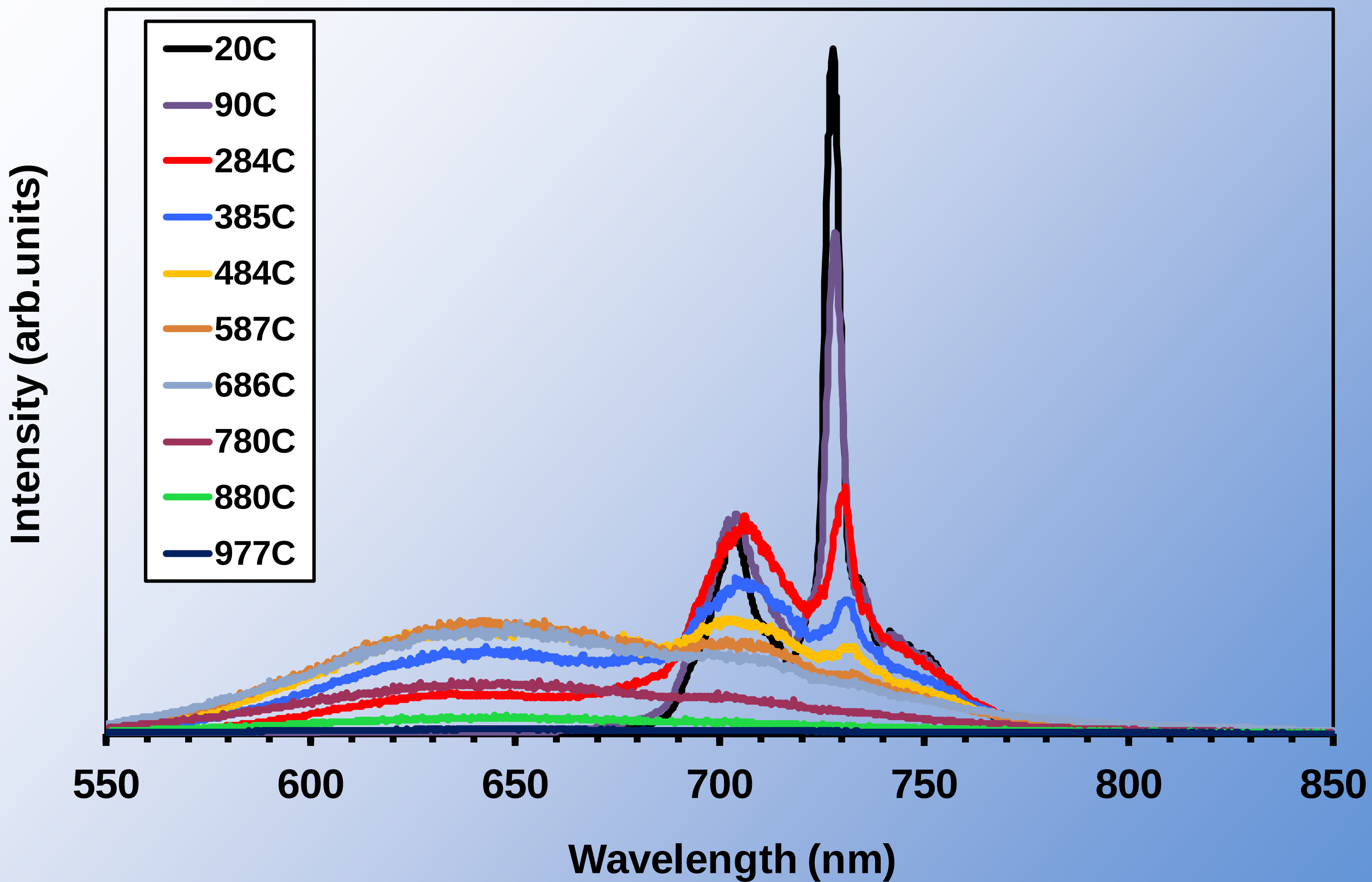

Demonstrating Temperature Measurement Capability

Time-Resolved Decay of Luminescence Emission from Cr(0.2%):GAP Puck

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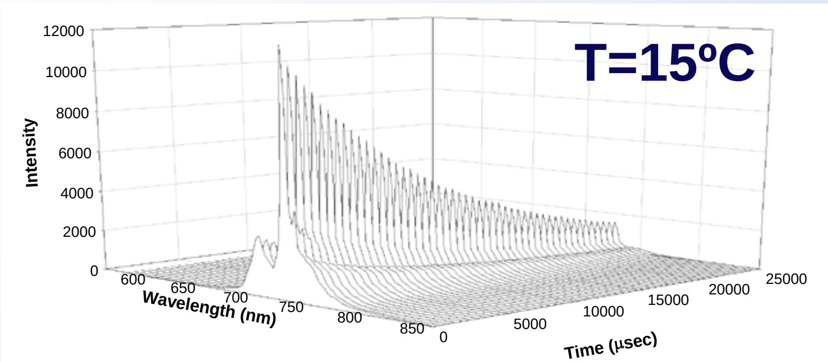

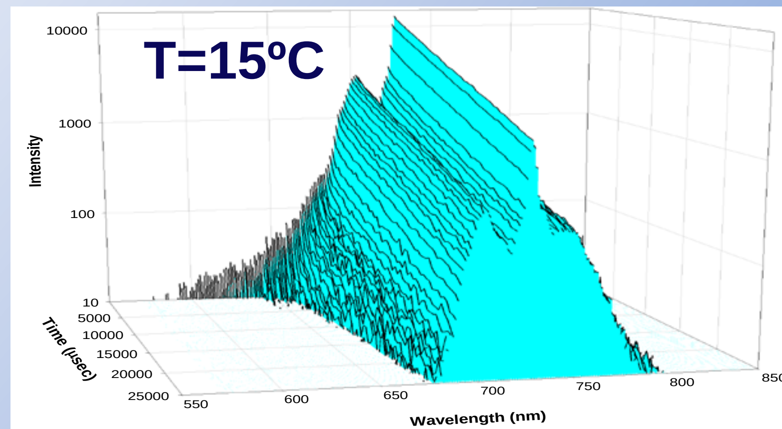

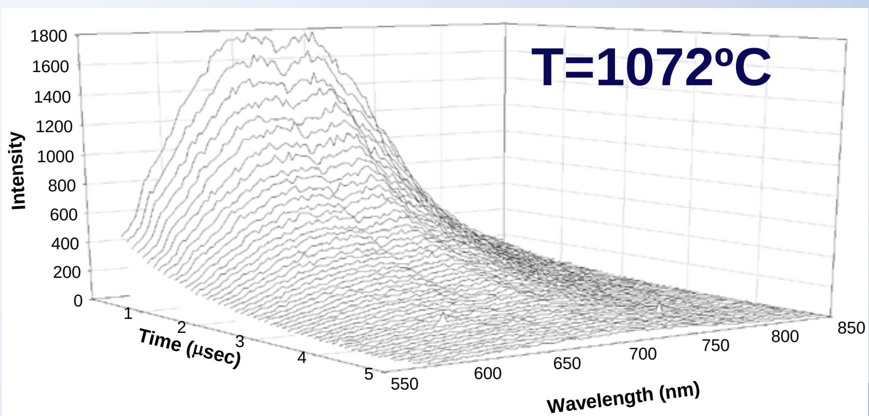

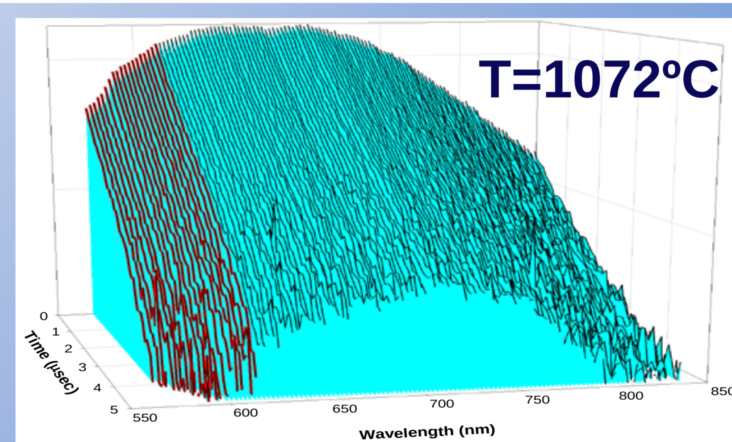

- Logarithmic intensity scale shows uniform decay rate over full wavelength range at each T.
- Adequate signal for decay time determination at wavelengths as short as 570 nm at 1072ºC.
- Subsequent luminescence decay measurements use bandpass filter @593 nm, FWHM = 40 nm.
- Best compromise between signal intensity & reducing thermal radiation background.

Demonstrating Temperature Measurement Capability

Luminescence Decay Measurement Setup

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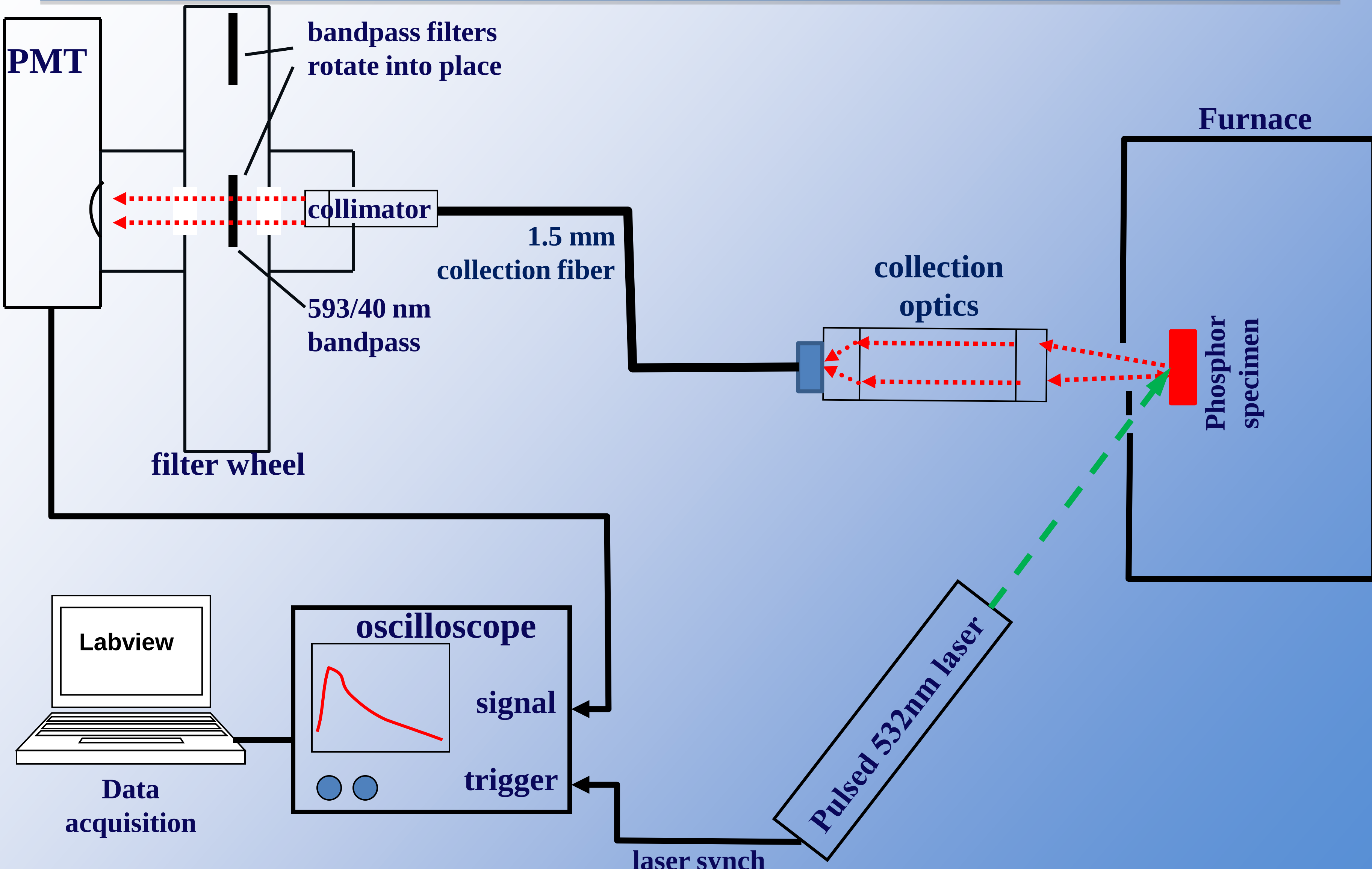

Demonstrating Temperature Measurement Capability

Luminescence Decay Curves from Cr:GAP Puck Using Bandpass Filter

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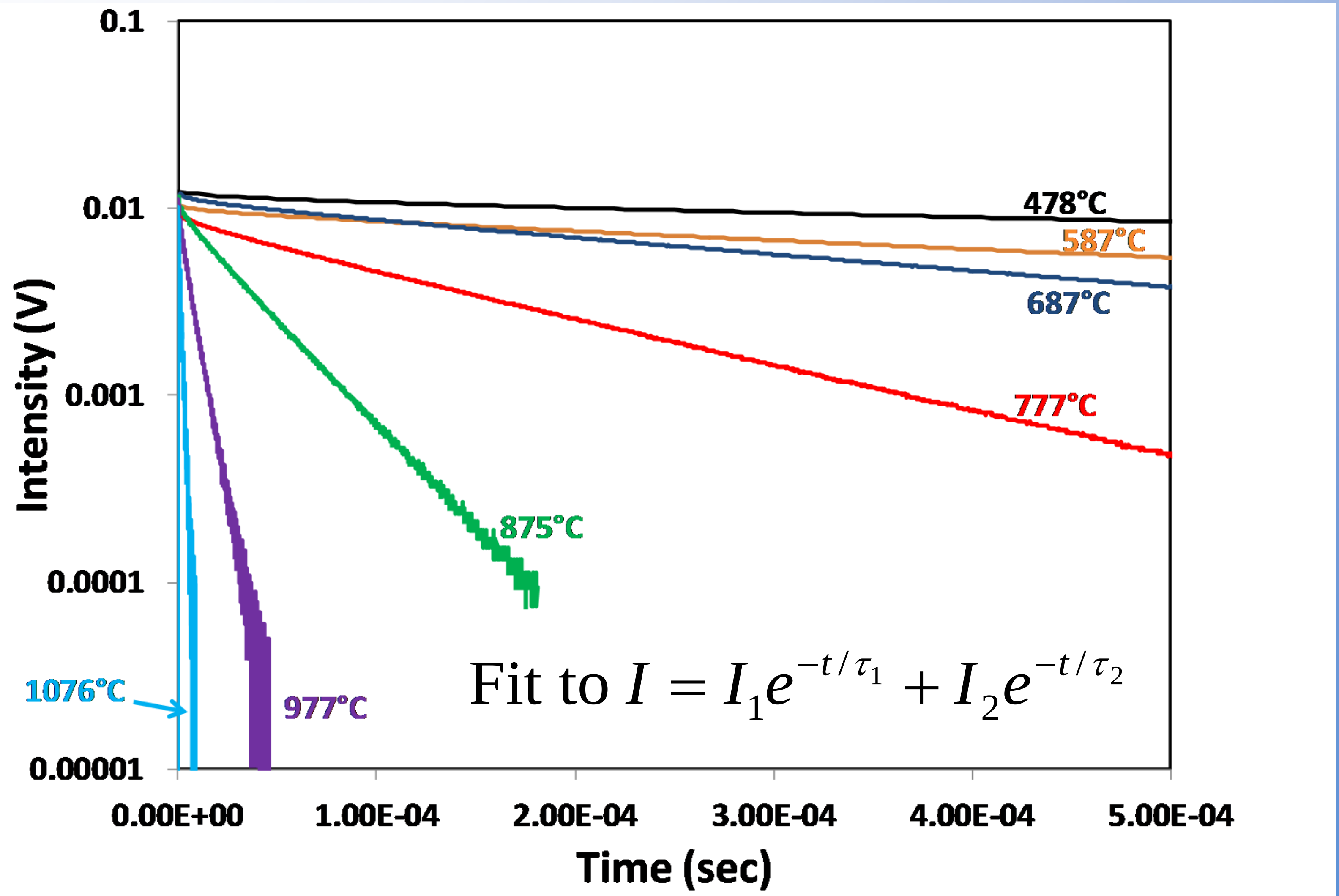

Demonstrating Temperature Measurement Capability

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

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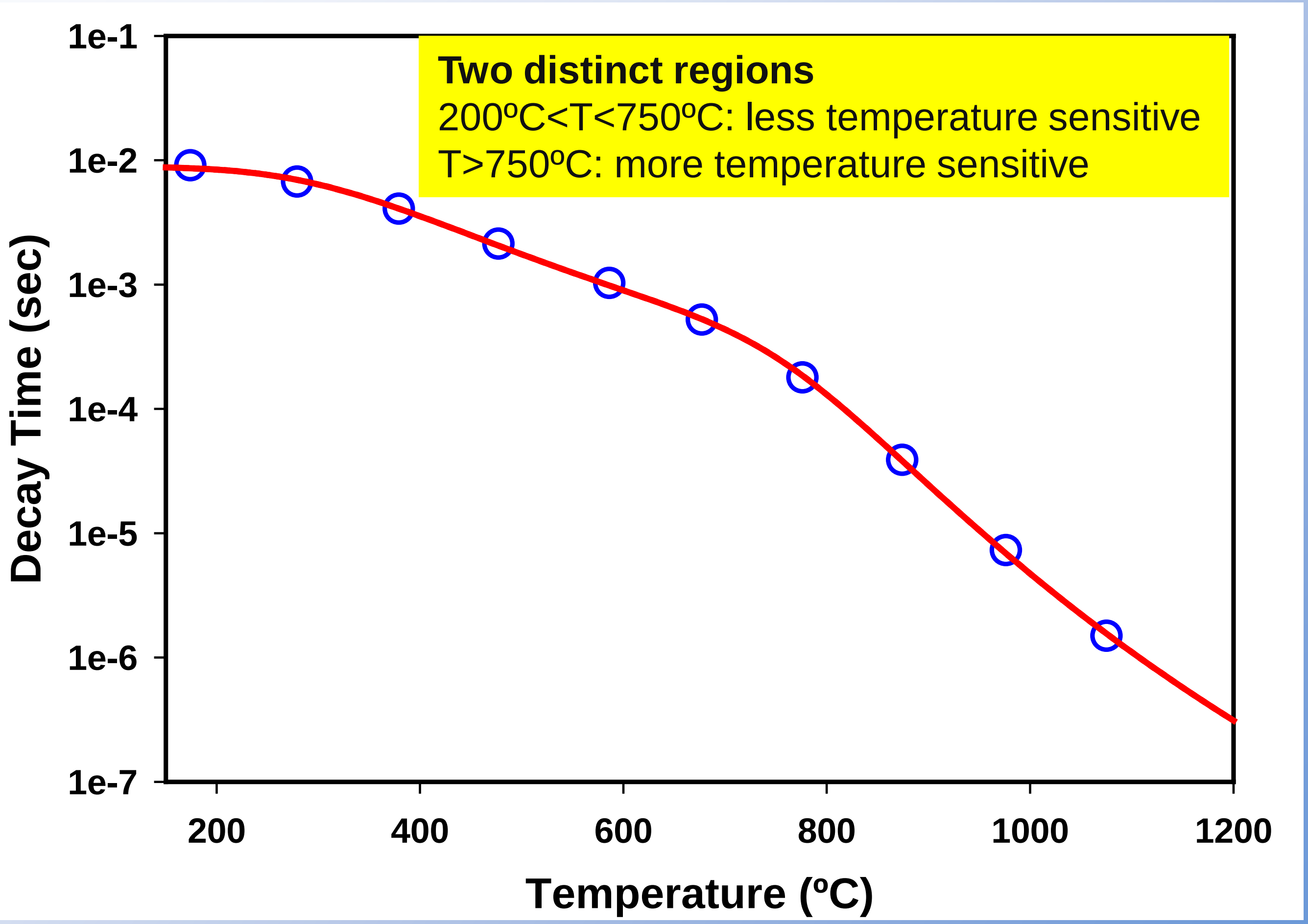

Fit to $\tau = \tau_{2E}^{R} \dfrac{1+3e^{-\Delta E/kT}}{1+\alpha e^{-\Delta E/kT} + \beta e^{-(\Delta Eq+\Delta E)/kT}}$

Optical Thermometer Demonstration

Setup

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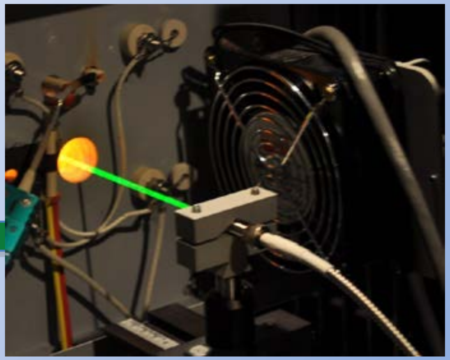

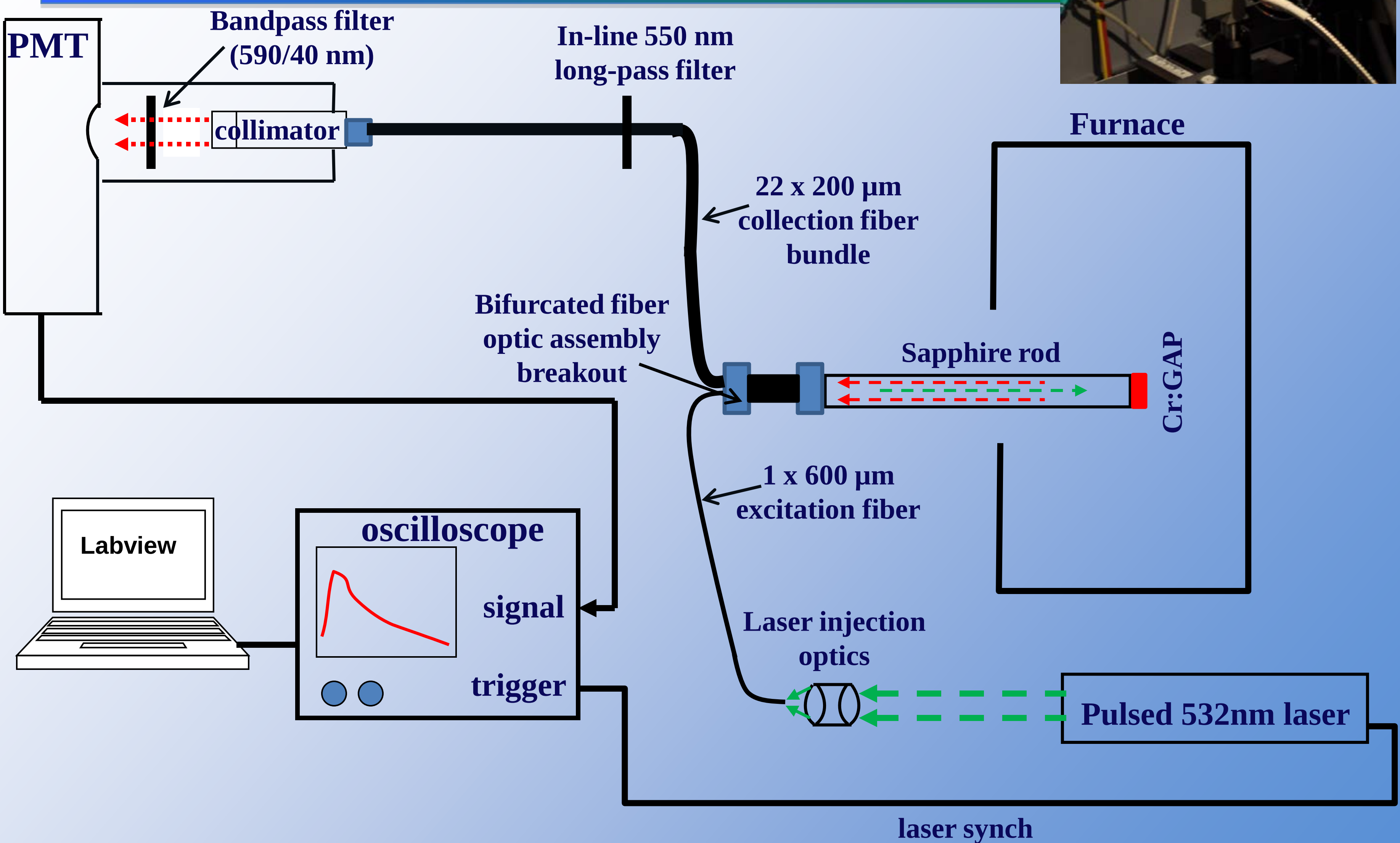

Optical Thermometer Demonstration

Luminescence Decay Curves from Cr:GAP on Tip of 2mm diam Sapphire Rod

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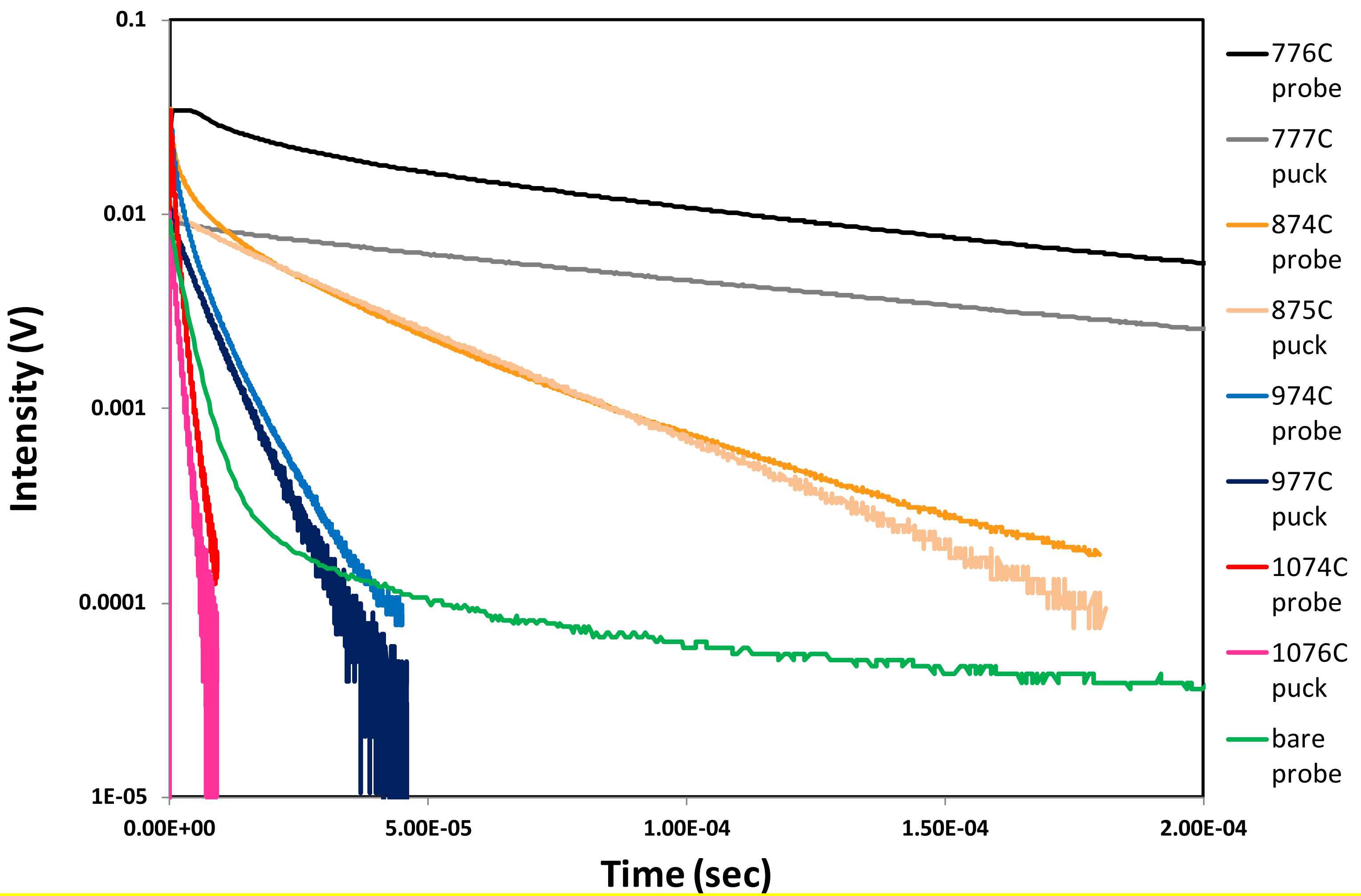

- Good agreement between decay curves from optical thermometer & Cr:GAP puck.
- Intrinsic luminescence from sapphire rod produces small upward deviation of thermometer decay curves.
- Easily corrected for temperature readings.

Optical Thermometer Demonstration

Limits to Sapphire Fiber Performance

400 µm diameter fiber at 975°C

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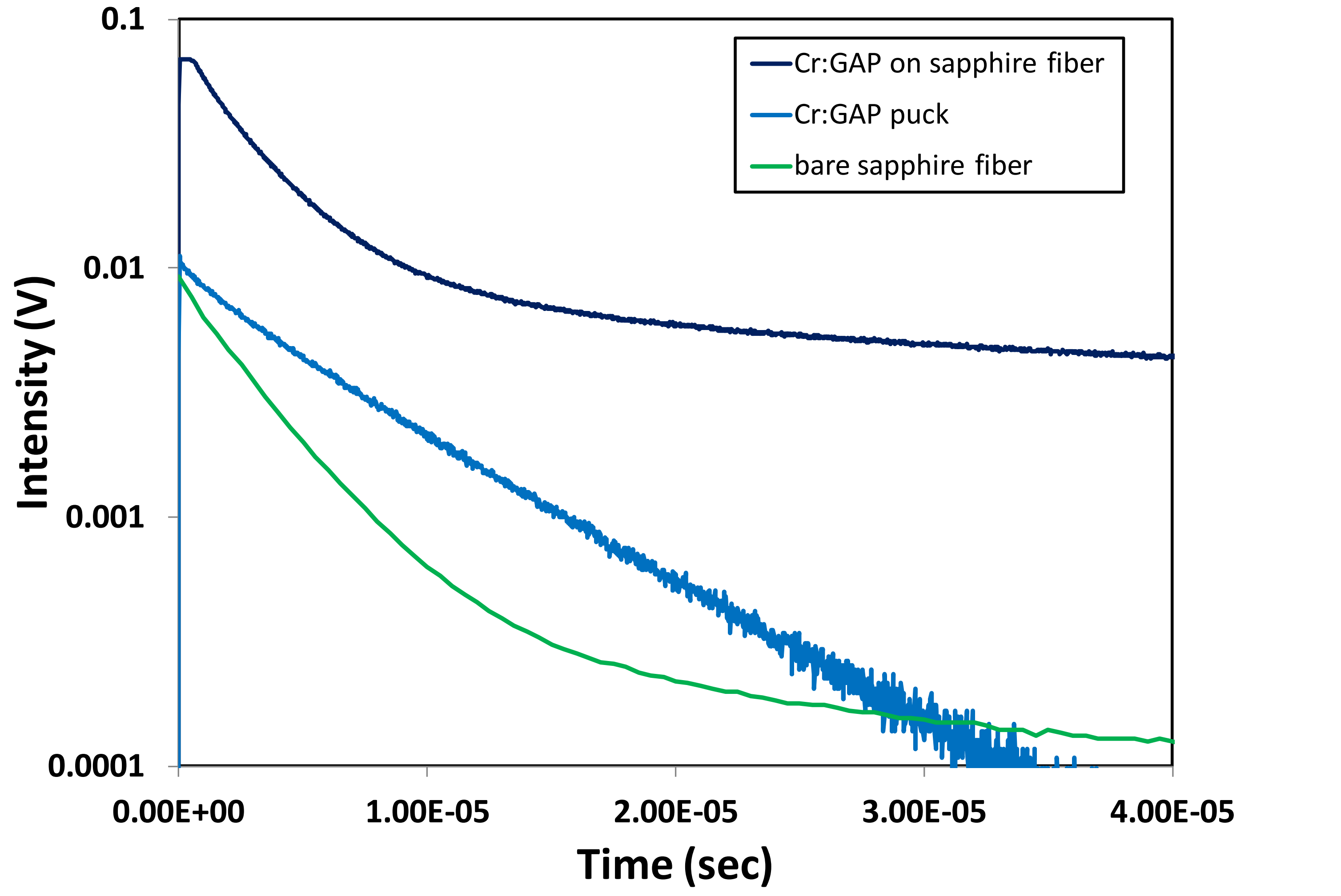

- Intrinsic luminescence from sapphire fiber overwhelms Cr:GAP luminescence.
- Interfering luminescence from Cr impurities in sapphire fiber.
- Solution: Lower Cr impurity sapphire fibers or YAG fibers (where Cr impurities produce less luminescence).

Coatings for 2D Temperature Mapping

Electron Beam Physical Vapor Deposition Issues

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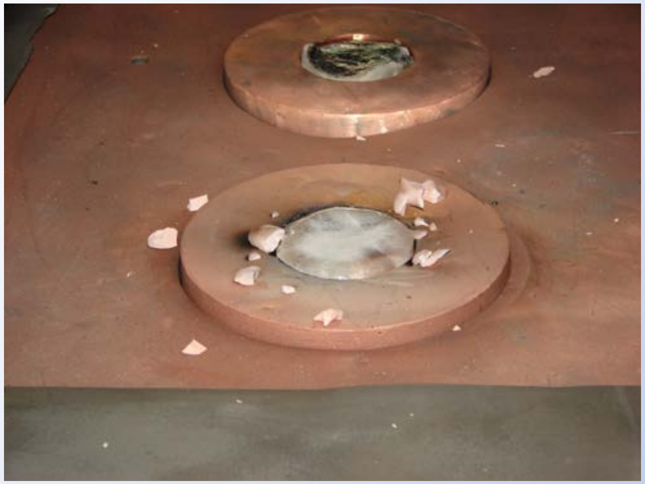
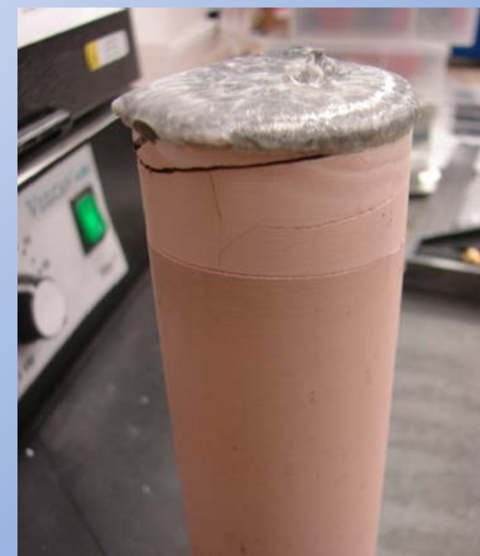
Ingot in EB-PVD chamber showing explosion debris from electron beam heating



Ingot removed from EB-PVD chamber showing thermal-shock fracture



- Deposition of Cr:GAP by EB-PVD at Penn State proved to be more challenging than anticipated.
  - Top of Cr:GAP ingot explodes under electron beam heating.
  - Ingot fractures due to thermal shock.
- Successful Resolution: Top section of ingot removed & then use extremely gentle electron beam heating.

Coatings for 2D Temperature Mapping

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

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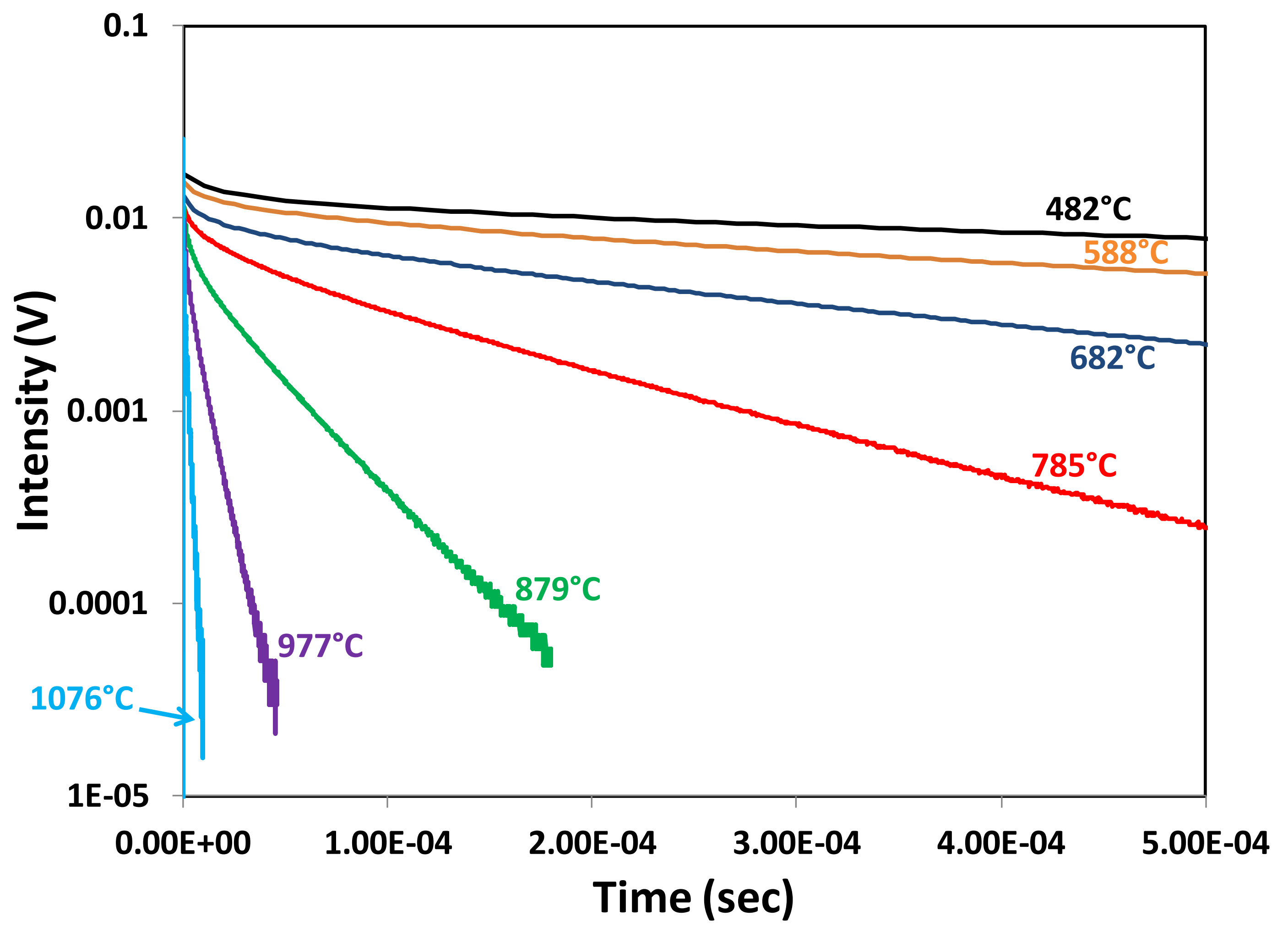

Superb signal-to-noise from thin 25 µm thick coating confirms retention of ultra-bright luminescence at high temperatures.

Coatings for 2D Temperature Mapping

Luminescence Decay Curves

25 µm Thick EB-PVD Cr:GAP Coating vs. Cr:GAP Puck

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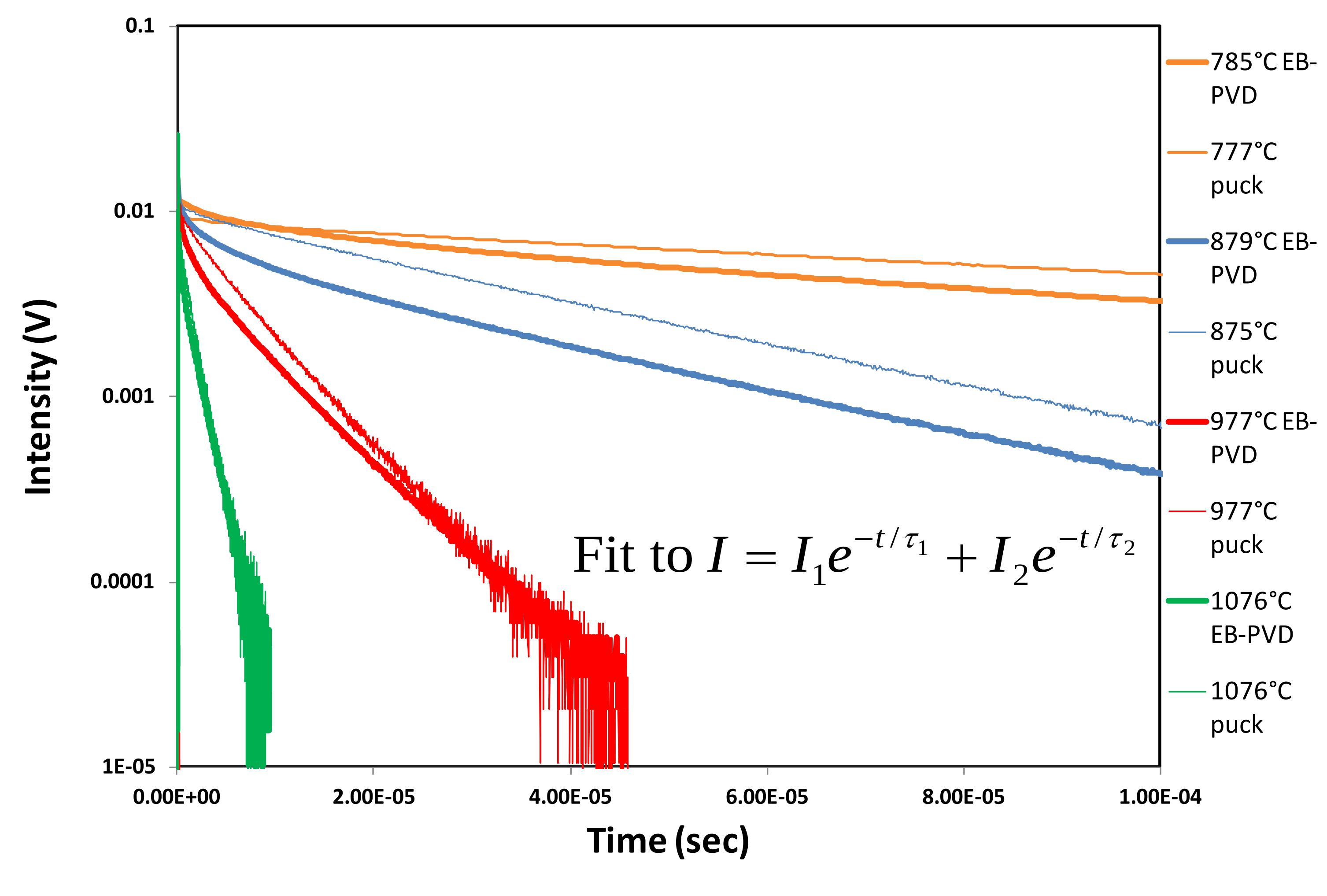

- More pronounced fast initial decay (τ_1) from EB-PVD coatings.
- Good agreement between long decay constants (τ_2).

Coatings for 2D Temperature Mapping

Decay Time vs. Temperature Calibration for 25 µm Thick EB-PVD Cr:GAP Coating

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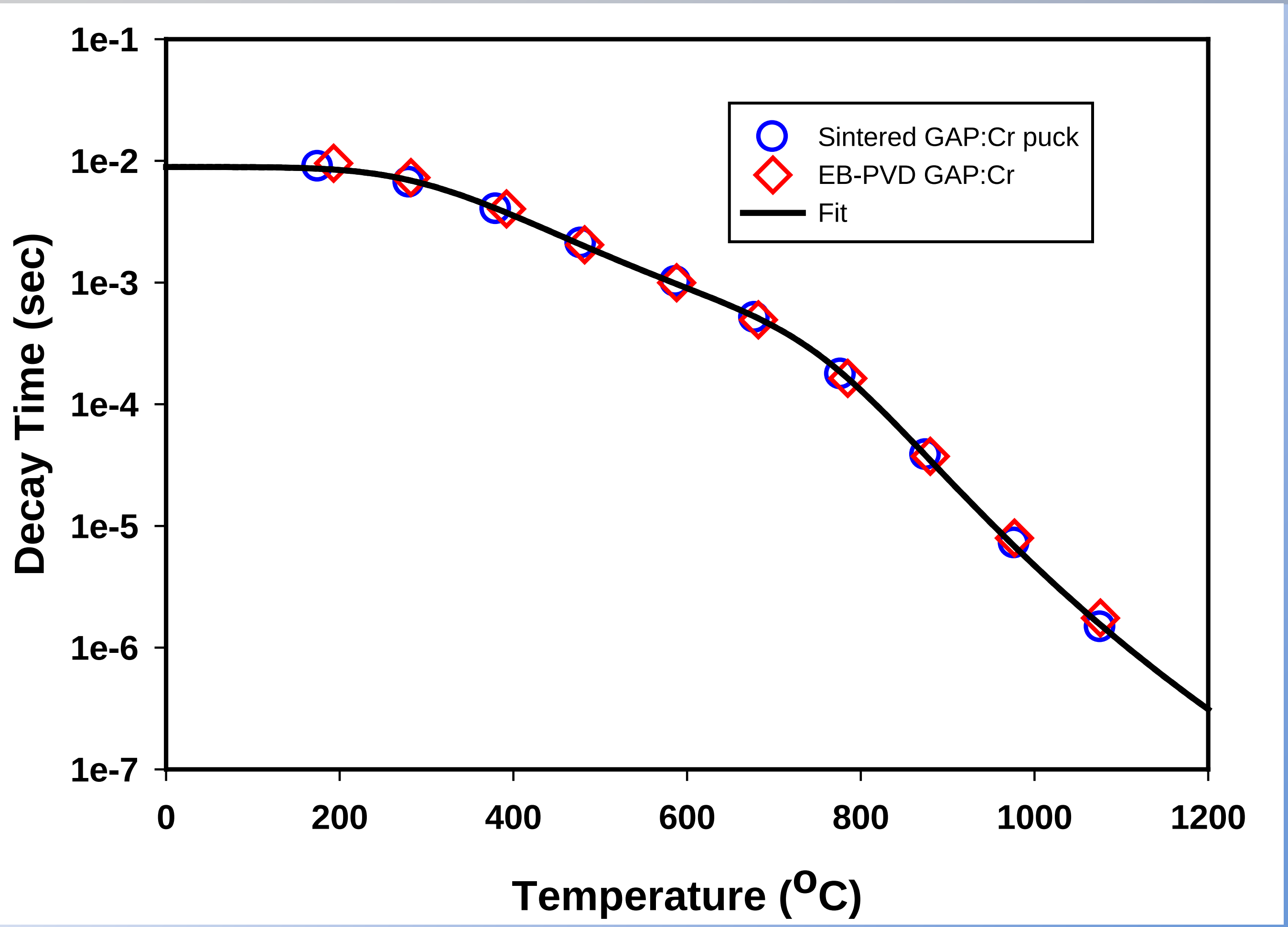

Decay time (τ_2) vs. temperature dependence for thin EB-PVD Cr:GAP coating follows same calibration curve as Cr:GAP puck.

Coatings for 2D Temperature Mapping

Cr:GAP-Coated Specimens with Cooling Holes Ready for 2D Temperature Mapping

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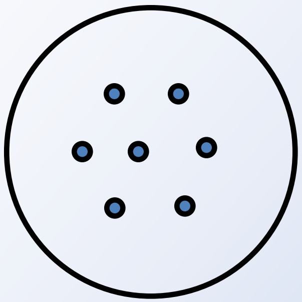
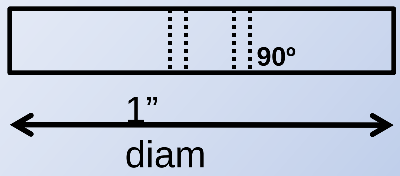
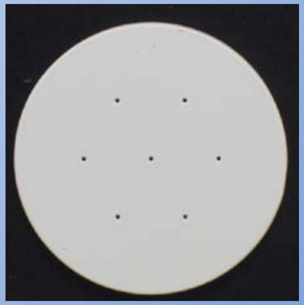
Top view | Side view | EB-PVD Cr:GAP coated specimens

EDM 90º holes

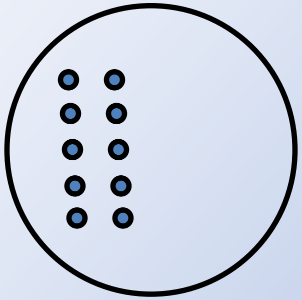


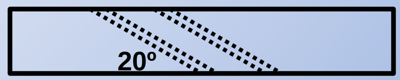


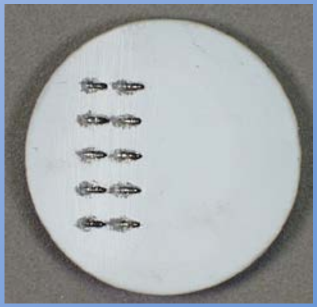
0.125” thick



Laser-drilled 20º holes







Procedure

- 90º or 20º cooling holes machined into TBC-coated specimen by EDM or laser drilling.
- 25 µm thick Cr:GAP deposited by EB-PVD.

Specimens ready for 2D mapping of thermal gradients around cooling holes during exposure to high heat flux laser. Scheduled for July 2012 for completion of Phase I milestones.

Distribution/Dissemination

•Patent application filed in November 2012: "Temperature and Pressure Sensors Based on Spin-Allowed Broadband Luminescence of Doped Orthorhombic Perovskite Structures."

•Presentation at 9th International Temperature Symposium, Anaheim, March 2012: "Temperature Sensing Above 1000^{o}C Using Cr-Doped $GdAlO_3$ Spin-Allowed Broadband Luminescence."

•Article submitted to 9th International Temperature Symposium Conference Proceedings (same title as presentation).

•Interest expressed from NASA Vehicle Integrated Propulsion Research (VIPR) and AFRL Versatile Affordable Advanced Turbine Engines (VAATE) projects.

Predicted Impact

- Will provide a ready-to-adopt technology for acquiring accurate noncontact surface temperature measurements in turbine engine environments (both air- & land-based engines).
- Will replace thermocouples and pyrometers whenever thermocouple attachment and pyrometer errors are issues.
- Will become important validation tool for thermal profiling of turbine engines designed for reduced fuel consumption and cleaner fuel burn.
- Near-term: Attractiveness as thermographic phosphor for turbine engine environments may lead to adoption as phosphor of choice in NASA VIPR and AFRL VAATE projects.

Next Steps

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- Extend optical thermometer capability from 1100^{o} to 1200^{o}C using either higher purity sapphire or alternative YAG fiber lightpipes.
- 2D mapping of thermal gradients around cooling holes in button specimens exposed to high heat flux laser.
    - Waiting for facility availability in July 2012 to complete Phase I milestones.

Phase II

- Move from coupon specimens in laboratory to actual components in combustion environment.
    - 2D temperature mapping around cooling holes in Honeywell vane during exposure to afterburner flame of J85 GE-5 engine at AEDC, made possible with in-kind support from AFRL & Honeywell.
- Integrate low-power LED excitation into on-wing-compatible temperature probe for engine insertion.

Summarized Accomplishments

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- Demonstrated temperature measurement capability of Cr:GAP luminescence to 1200^{o}C.
- Successful development of optical thermometer using Cr:GAP-coated sapphire lightpipes.
    - Sapphire-rod-based thermometer demonstrated to 1100^{o}C.
    - Higher purity sapphire fibers or YAG fibers expected to extend performance up to 1200^{o}C.
- EB-PVD deposition of Cr:GAP coatings successfully developed that exhibit desired ultra-bright luminescence above 1000^{o}C.
    - Specimens with cooling holes produced for 2D thermal gradient mapping.
- Phase II framework for transition to actual components in combustion environment.