Setting the Standard for Automation™

Surface Temperature Measurements from a Stator Vane Doublet in a Turbine Engine Afterburner Flame Using an Ultra-Bright Cr-Doped $GdAlO_3$ Thermographic Phosphor

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Jeff Eldridge

- In a NASA career spanning over twenty years, Dr. Eldridge has worked towards developing spectroscopy-based health monitoring tools for both space and turbine engine applications. He has coauthored over 70 publications and has made over 50 conference presentations and invited tutorials/lectures. Dr. Eldridge is a senior scientist of the Optical Instrumentation and NDE Branch at NASA Glenn Research Center.

Background

- Recent laboratory 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).
- Orders of magnitude stronger luminescence emission above 1000 ºC than previous state-of-the-art rare-earth-doped thermographic phosphors.
- Demonstrated luminescence-decay-based temperature measurements to 1250 ºC.
- Cr:GAP performance promising for turbine engine environment measurements.
  - High-intensity luminescence emission from thin Cr:GAP surface coatings will stand out in presence of strong radiative (flame) environment.
  - Broadband excitation and emission allows flexible choice of excitation and detection wavelengths.

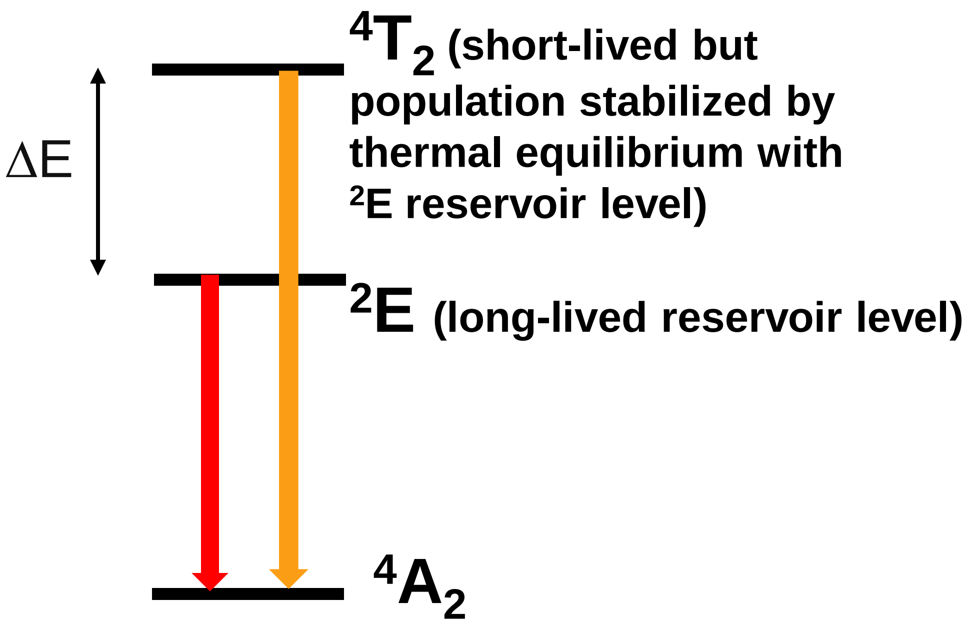
***J.I. Eldridge & M.D. Chambers**

Objectives

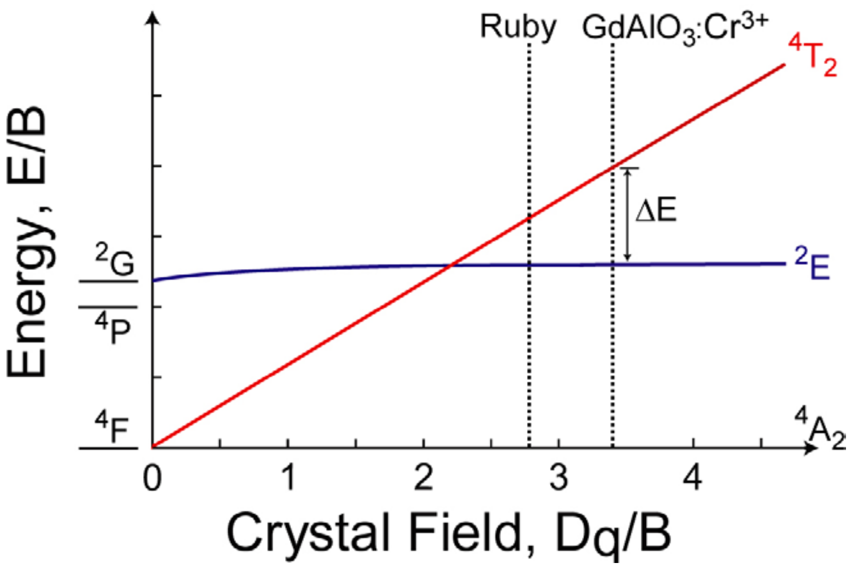
- Transition to engine environment implementation
  - Measurements of engine component surface in high-velocity, high-temperature radiative (flame) environment.
- Demonstrate temperature measurements from Cr:GAP coated Honeywell stator vane doublet in afterburner flame of UTSI J85-GE-5 turbojet test stand.
- Challenges:
  - Coating complex component shape.
  - Optical probe design integrating non-intrusive excitation & collection with thermal protection.
  - "See" through flame environment.
  - Remote measurement control from a safe distance.

Basis for High Temperature Ultra-Bright Cr:GAP Luminescence

Cr^{3+} $3d^3$ energy levels



Tanabe-Sugano Diagram



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

Spin-allowed broadband emission (short decay)
$^4T_2 \rightarrow {}^4A_2$

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

Strong crystal field increases ΔE.

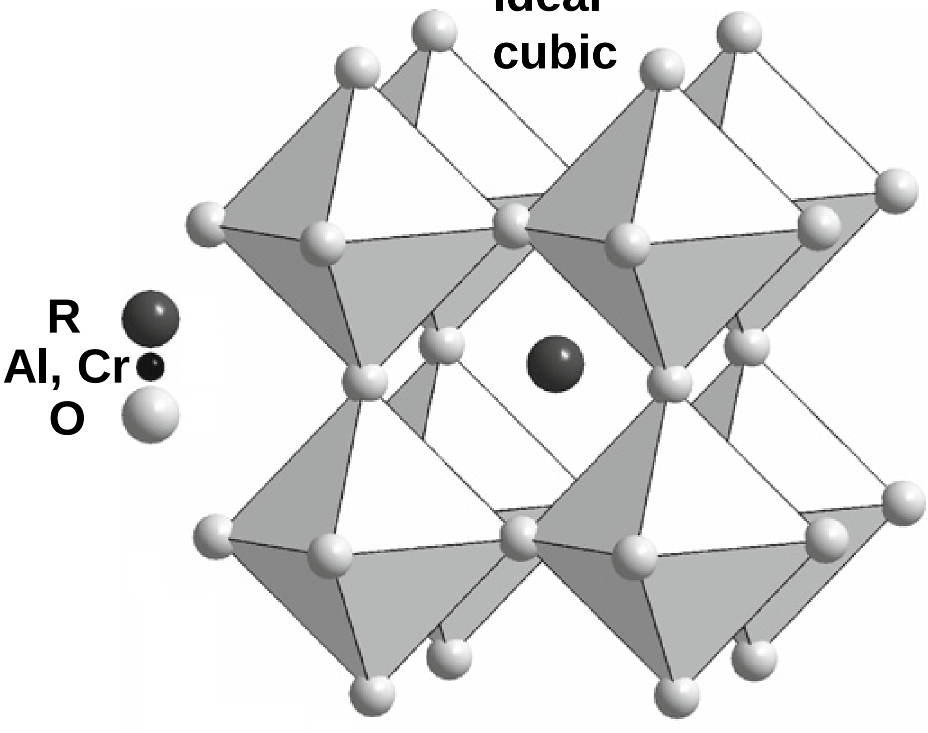
For long τ at high T → increase ΔE, ΔEq.

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

Orthorhombic Rare Earth Perovskites $RAlO_3$ Meet Criteria

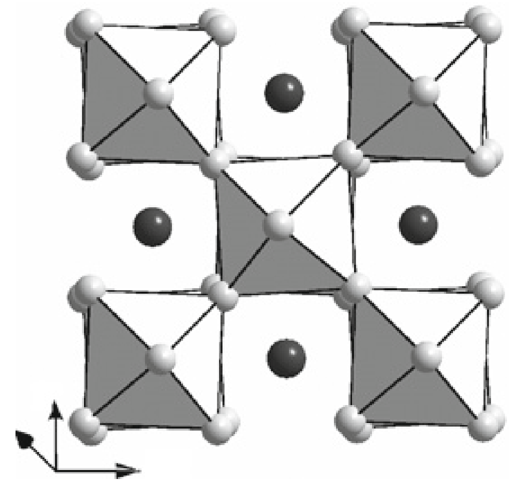
Tightly bonded AlO_6 Octahedra Exhibit Strong Crystal Field High ΔE

Ideal cubic

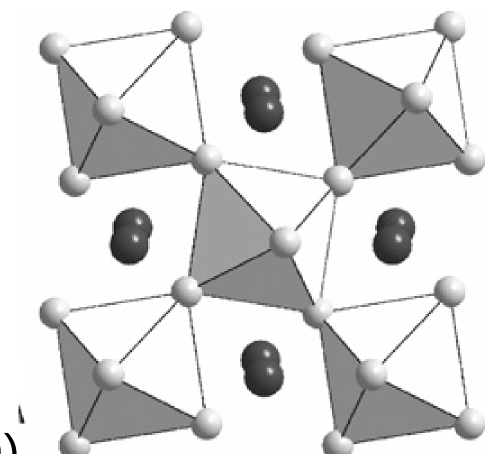


(No parity-forbidden ${}^4A_2 \rightarrow {}^2T_1$, ${}^2T_2$ absorption)

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

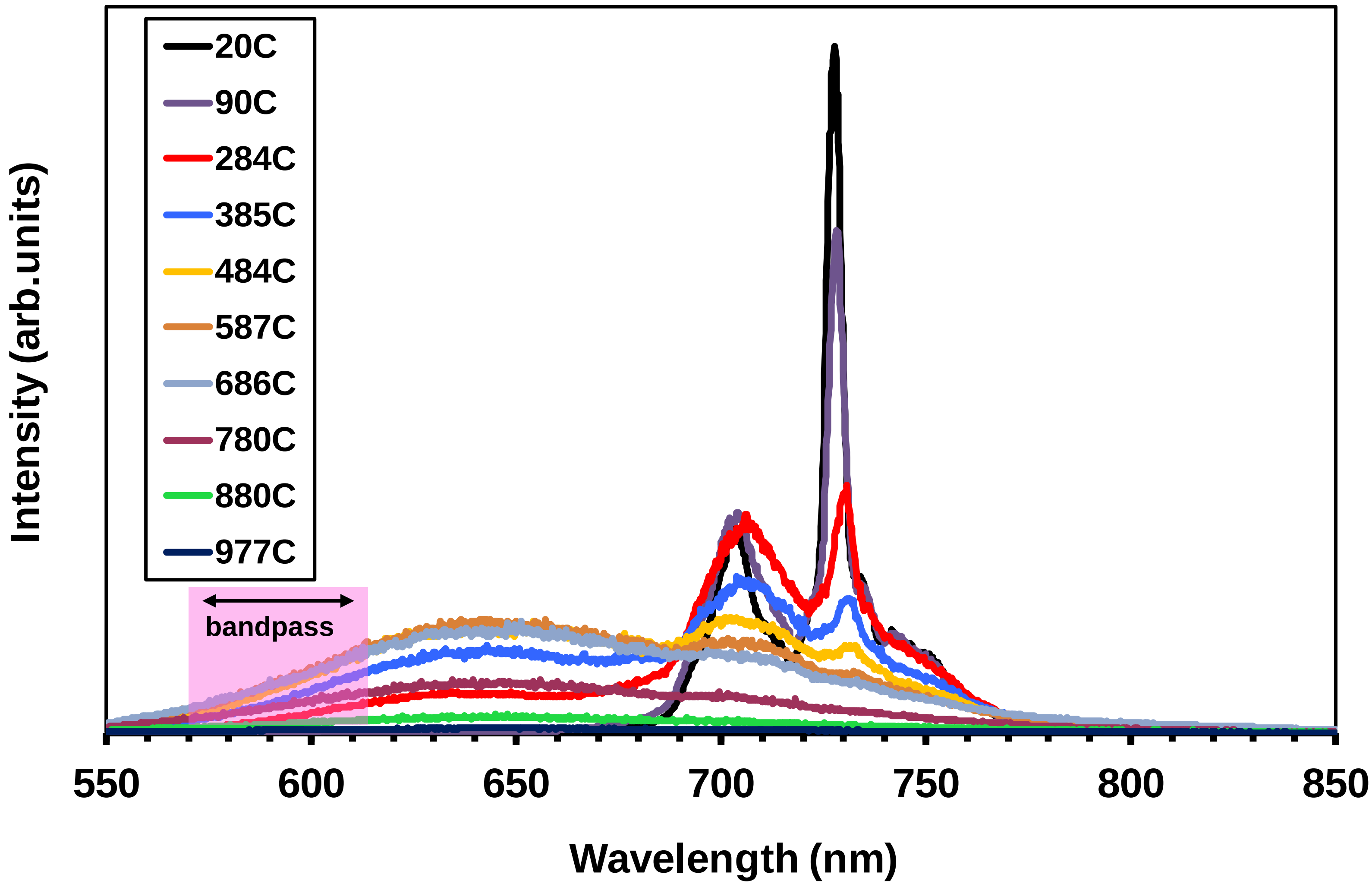


Rhombohedral
(near-cubic symmetry, weak absorption)



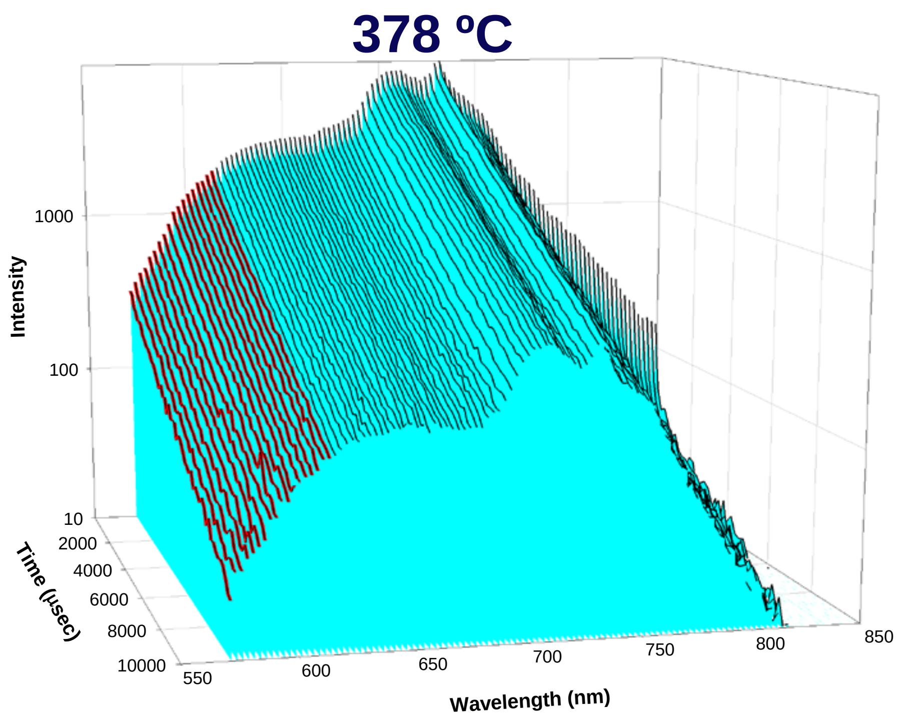
Orthorhombic
(distorted octahedra, strong absorption)

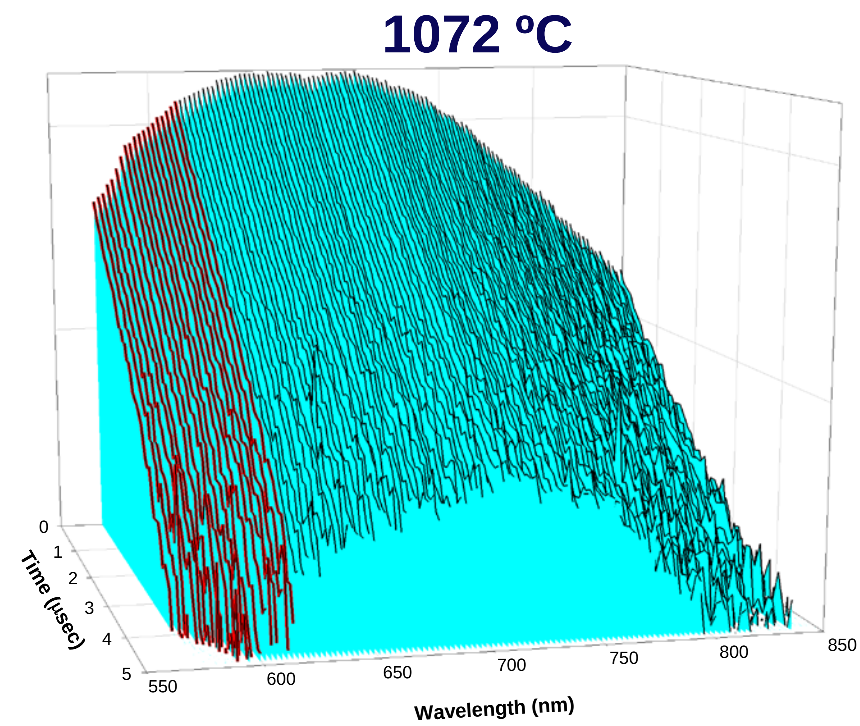
Temperature Dependence of Luminescence Emission from Cr(0.2%):GAP Puck



Time-Resolved Luminescence Emission from Cr:GAP

Logarithmic Intensity Scale

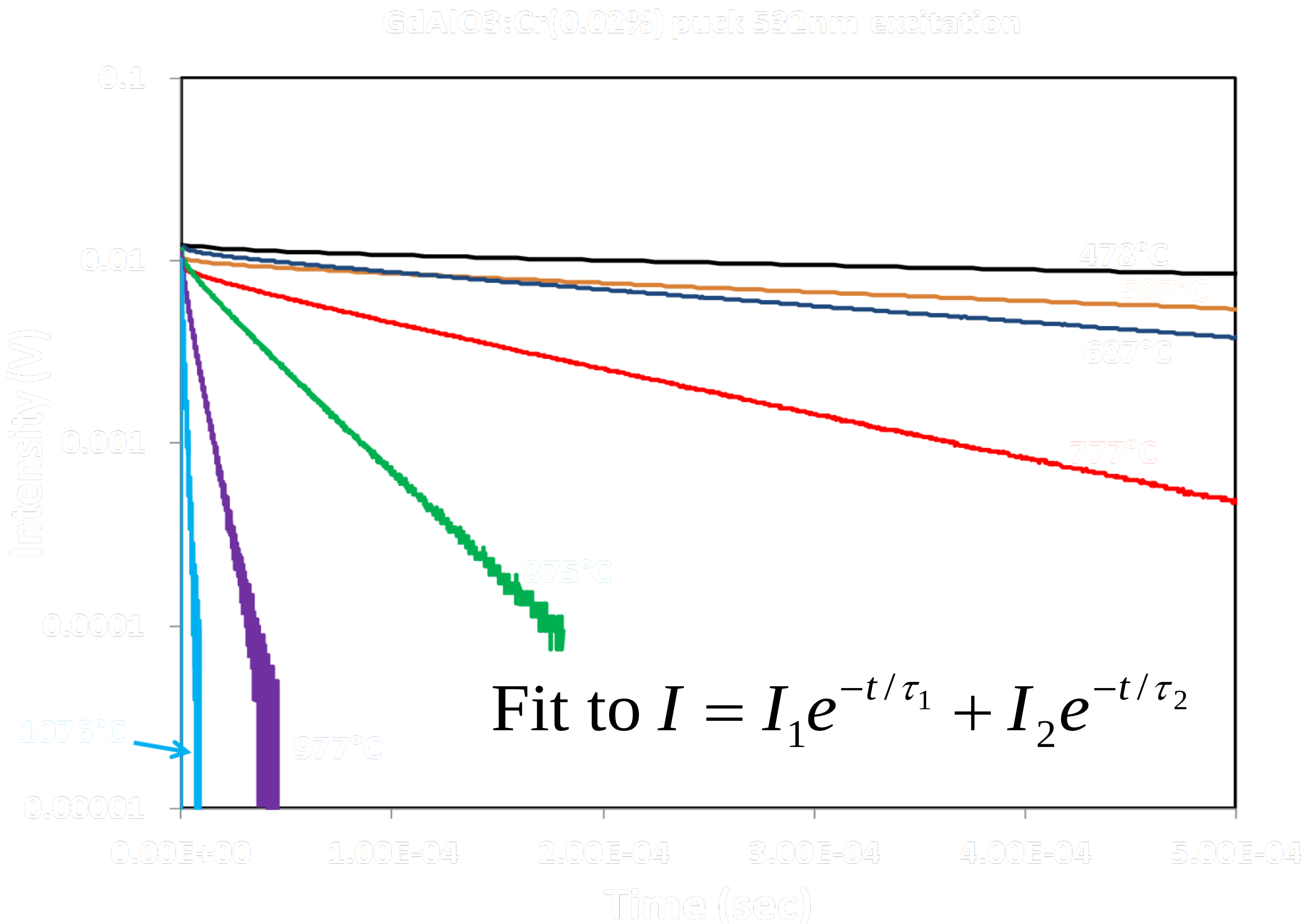




- Nearly single exponential.
- Uniform decay rate over wavelength range.
- Adequate signal for decay time determination at wavelengths as short as 570 nm.
- Collect luminescence decay measurements with bandpass filter @593 nm, FWHM = 40 nm to minimize interference from thermal radiation background.

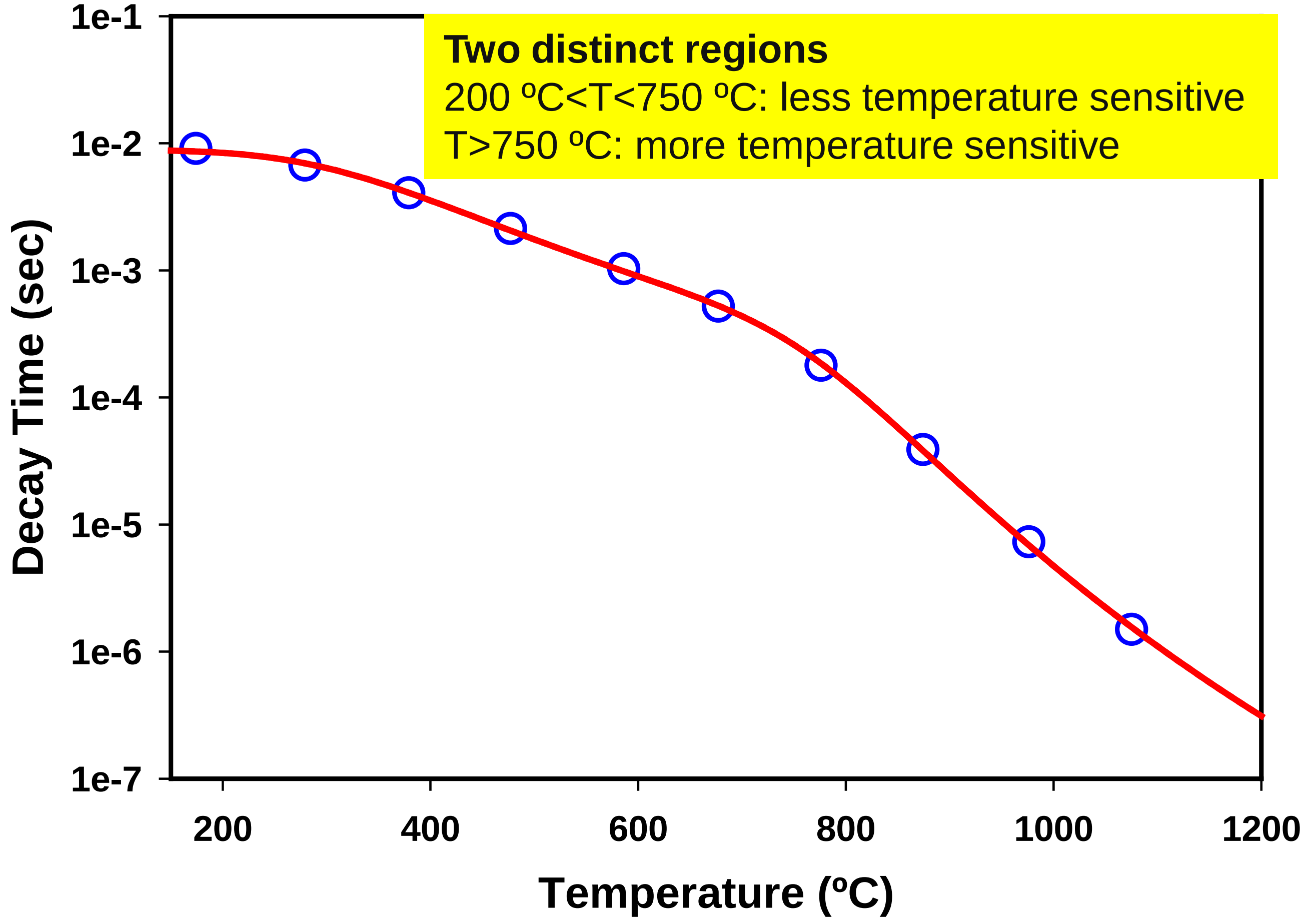
Demonstrating Temperature Sensitivity of Luminescence Decay Curves from Cr:GAP Puck

Bandpass filter: CL = 593 nm; FWHM = 40 nm



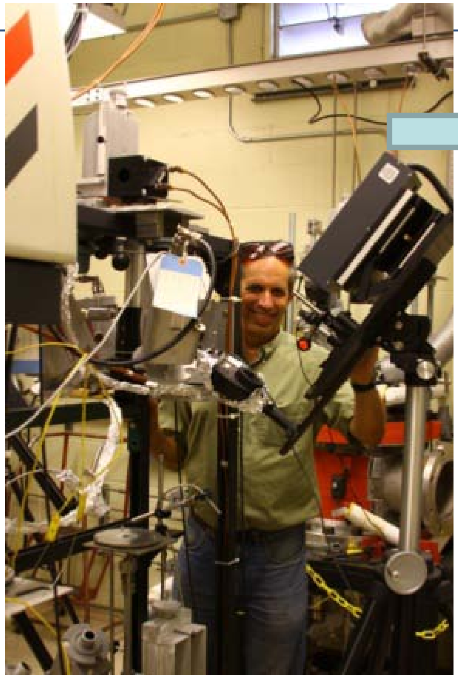
Demonstrating Temperature Measurement Capability

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



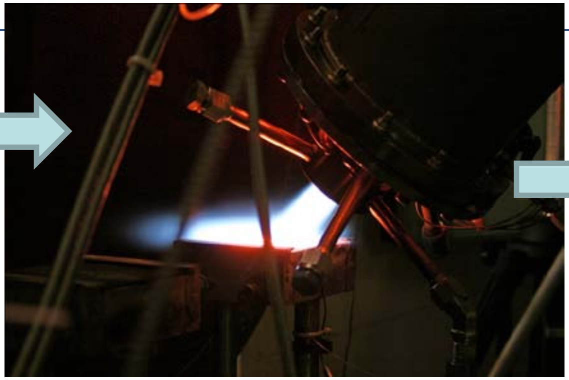
$$\text{Fit to } \tau = \tau_{2E}^{R} \frac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta Eq + \Delta E)/kT}}$$

AFRL VAATE Project
Gas Turbine Engine Sensor and Instrumentation Development
Stepping Stone Approach



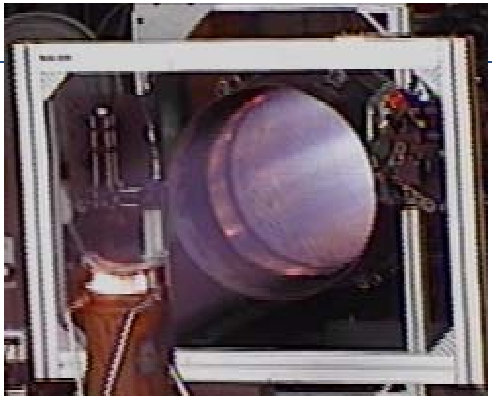
NASA GRC High-Heat-Flux Laser Facility
•Proof-of-concept with easy optical access, no radiative background, no probe heating issues.

Demonstrated to 1360 ºC. ✓



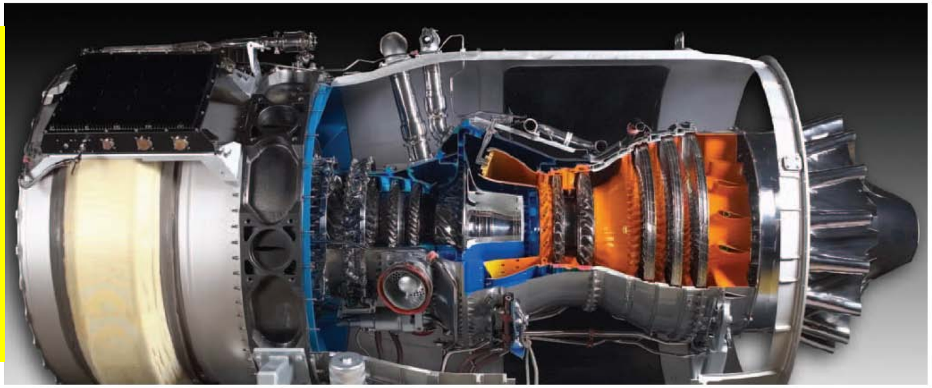
Williams International Combustor Burner Rig
•Address probe/TP survivability & ability to "see" through flame.

Demonstrated to >1400 ºC. ✓



AEDC J85-GE-5
•Probe/translate through afterburner flame.
•Test integrated excitation/collection probe.
•Opportunity to test new Cr:GAP thermographic phosphor.

Honeywell TECH7000

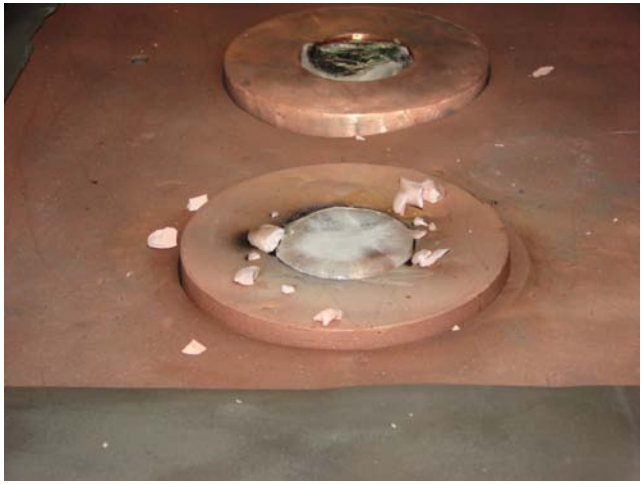


Goal: Demonstrate thermographic phosphor based temperature measurements to 1300 ºC on TBC-coated HPT stator on Honeywell TECH7000 demonstrator engine.

Cr:GAP Coatings for Surface Temperature Measurements

Electron Beam Physical Vapor Deposition Challenges

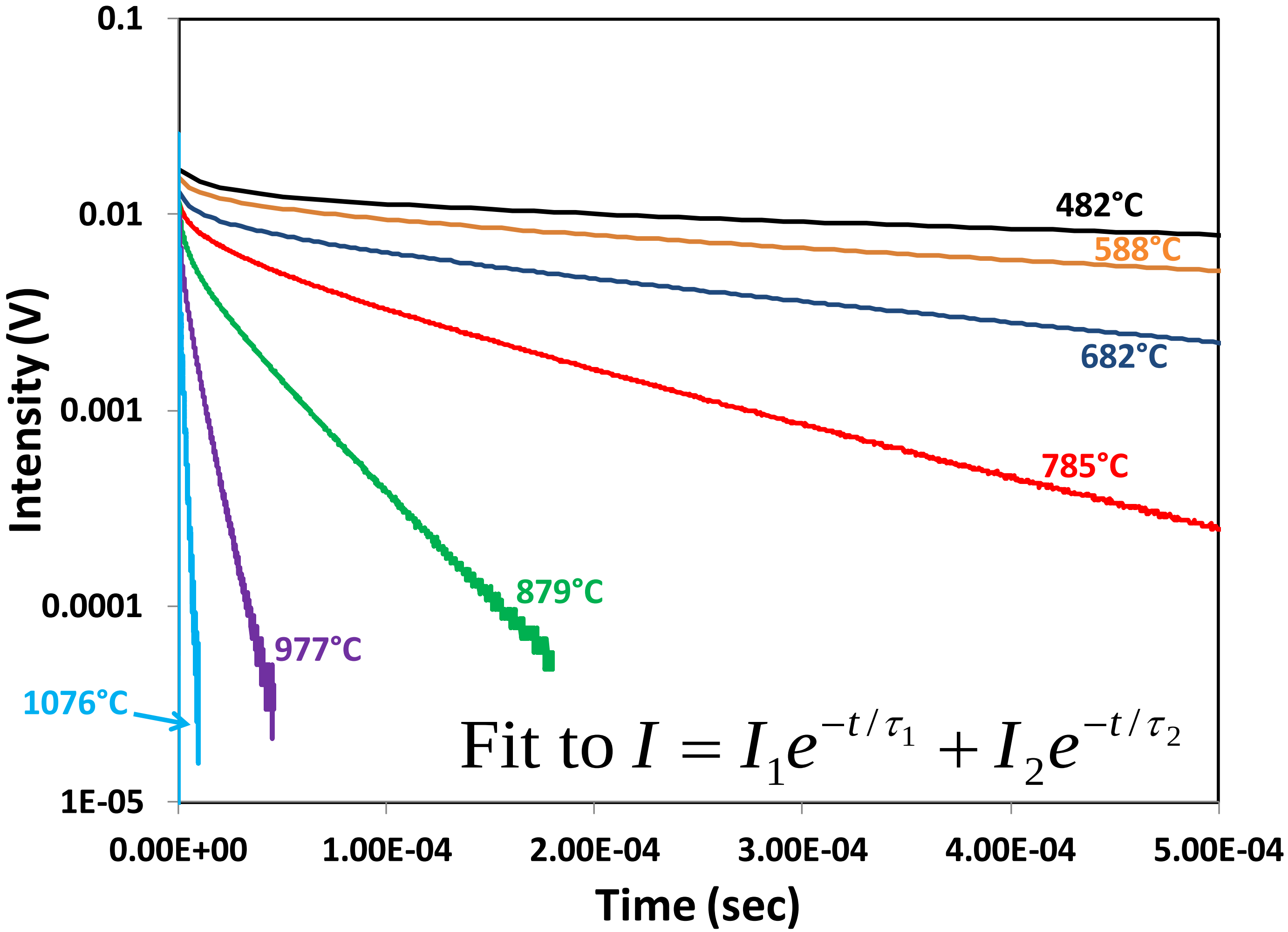
Ingot in EB-PVD chamber showing explosion debris from electron beam heating



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

- Deposition of Cr:GAP by EB-PVD at Penn State proved to be challenging.
  - 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.

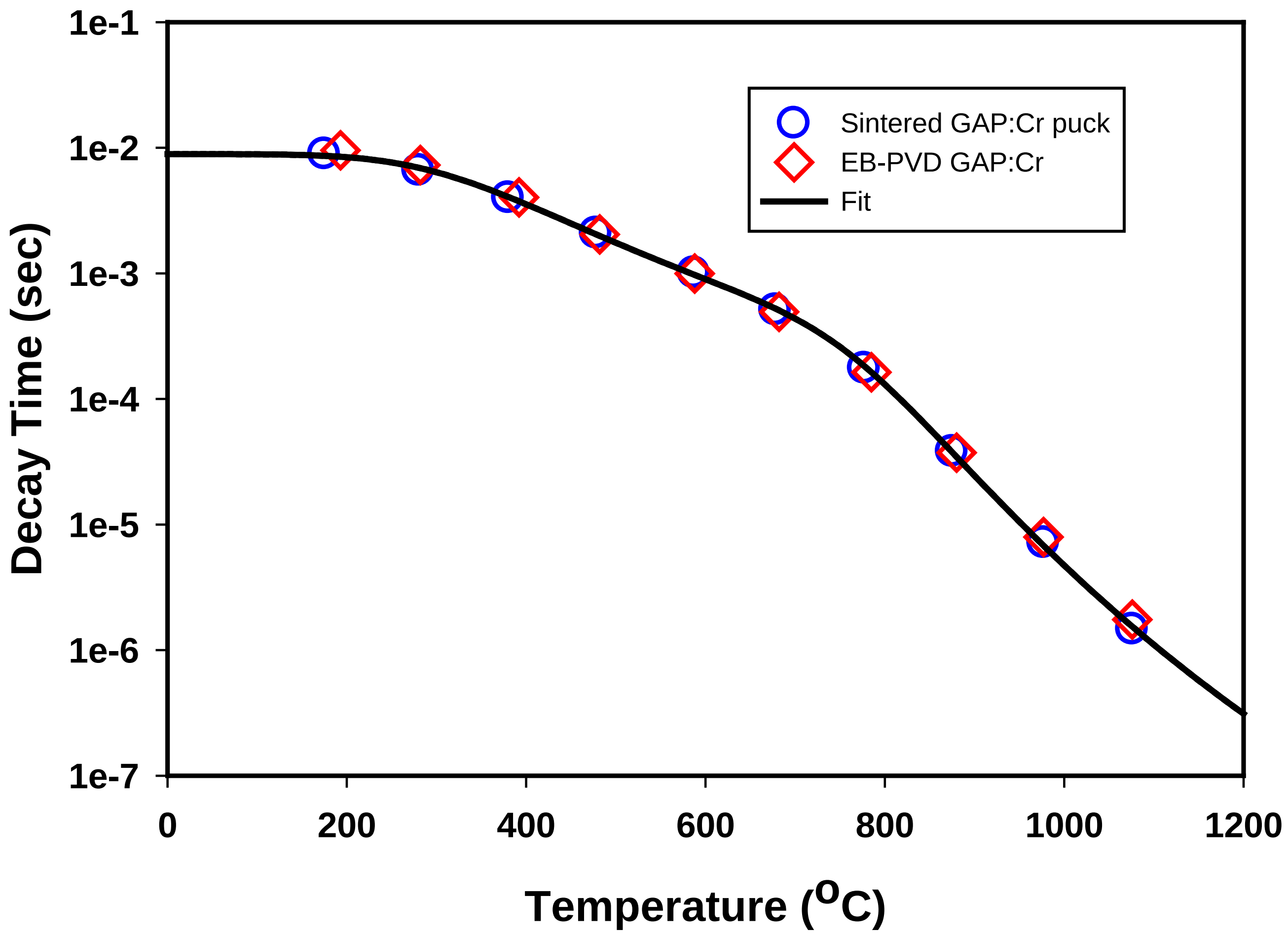
Luminescence Decay Curves from 25 µm Thick EB-PVD Cr:GAP Coating



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

Demonstrating EB-PVD Cr:GAP Temperature Measurement Capability

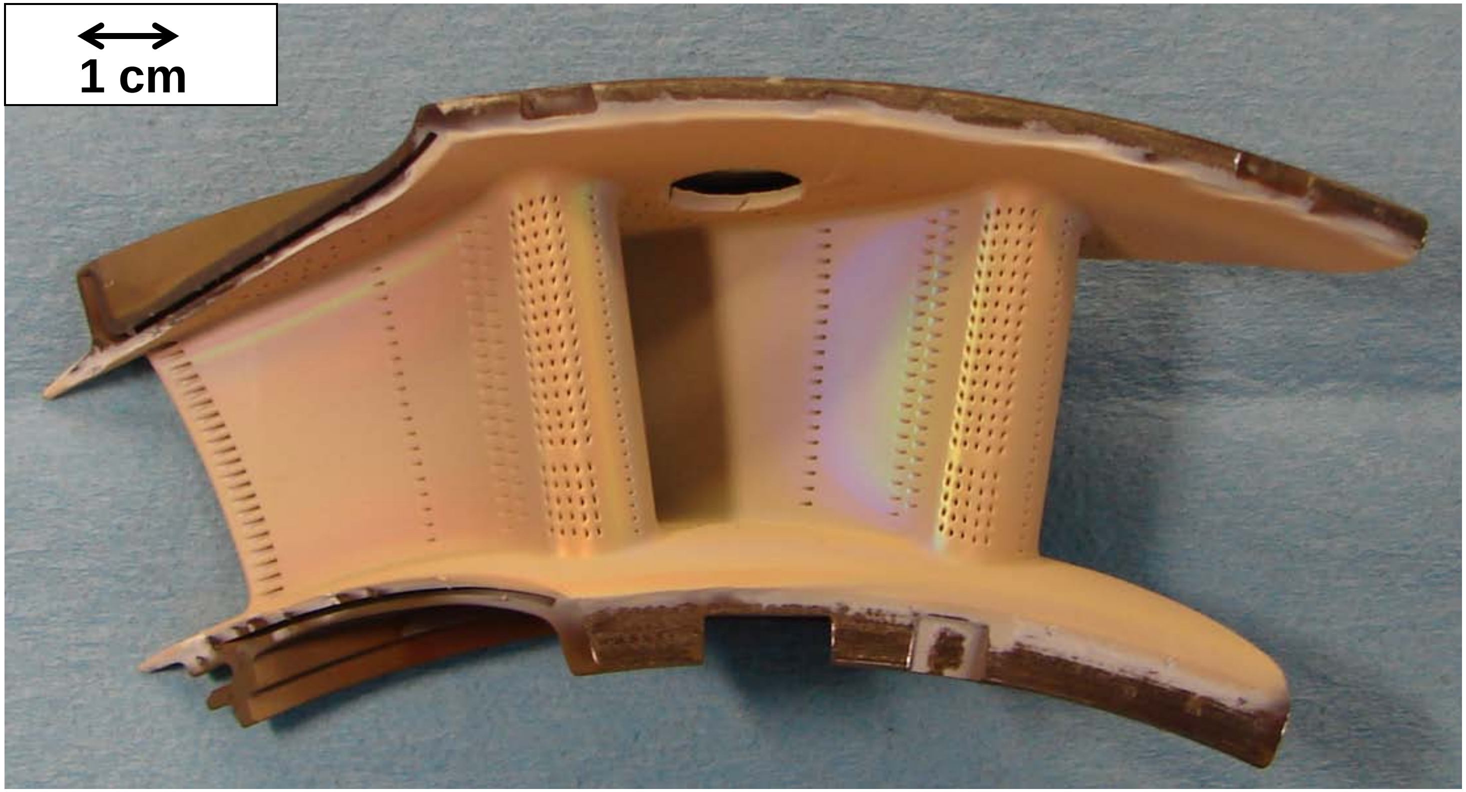
Decay Time vs. Temperature for 25 µm Thick EB-PVD Cr:GAP Coating

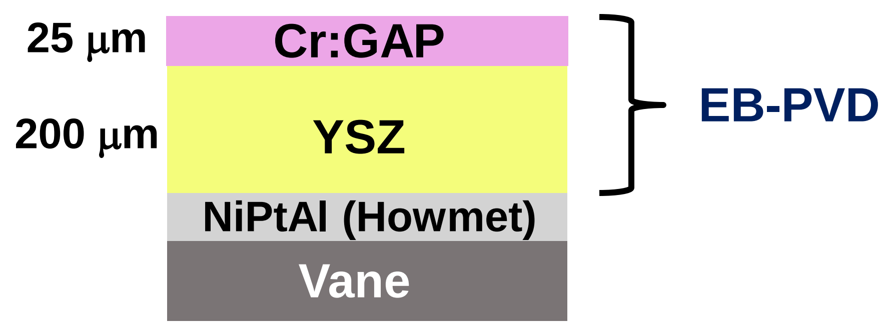


Decay time (τ_2) vs. temperature dependence for thin EB-PVD Cr:GAP coating follows same calibration curve as Cr:GAP puck.

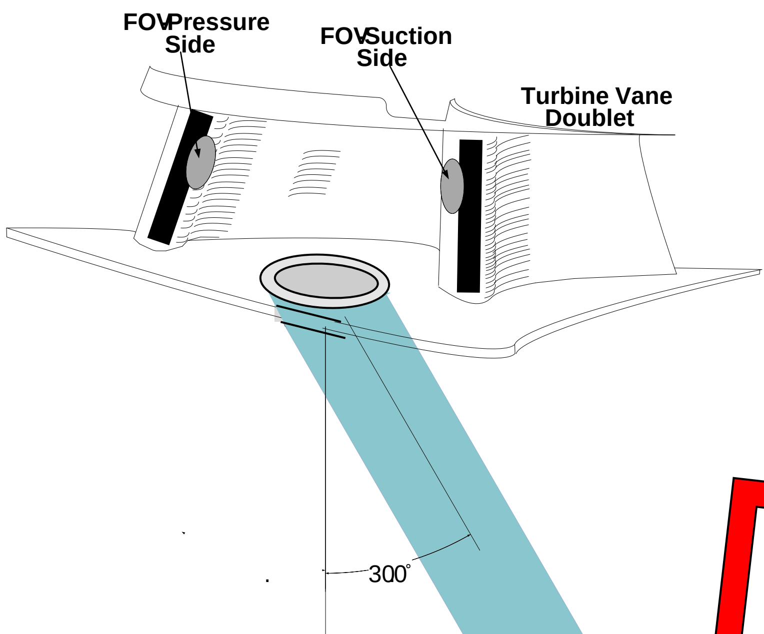
Cr:GAP-Coated Stator Vane Doublet

EB-PVD at Penn State





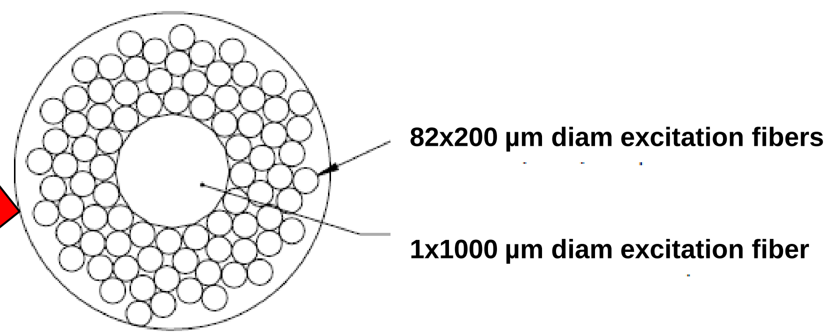
Probe Design for Vane Measurements

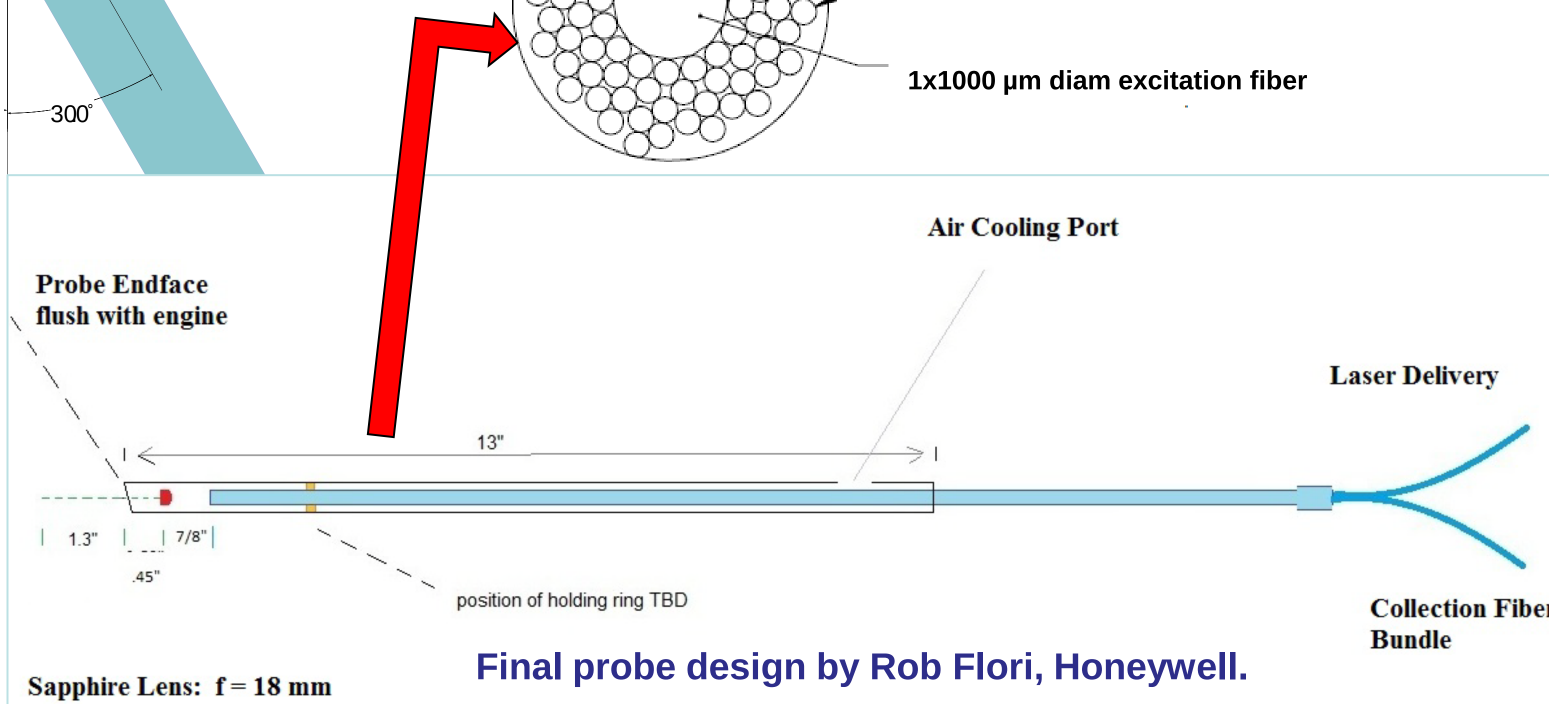


Constraints for probe design

- Do not protrude into gas flow.
- Limited space: integrated excitation & collection.
- End of probe exposed to gas flow temperatures.
- Temperature-sensitive optical components require cooling.

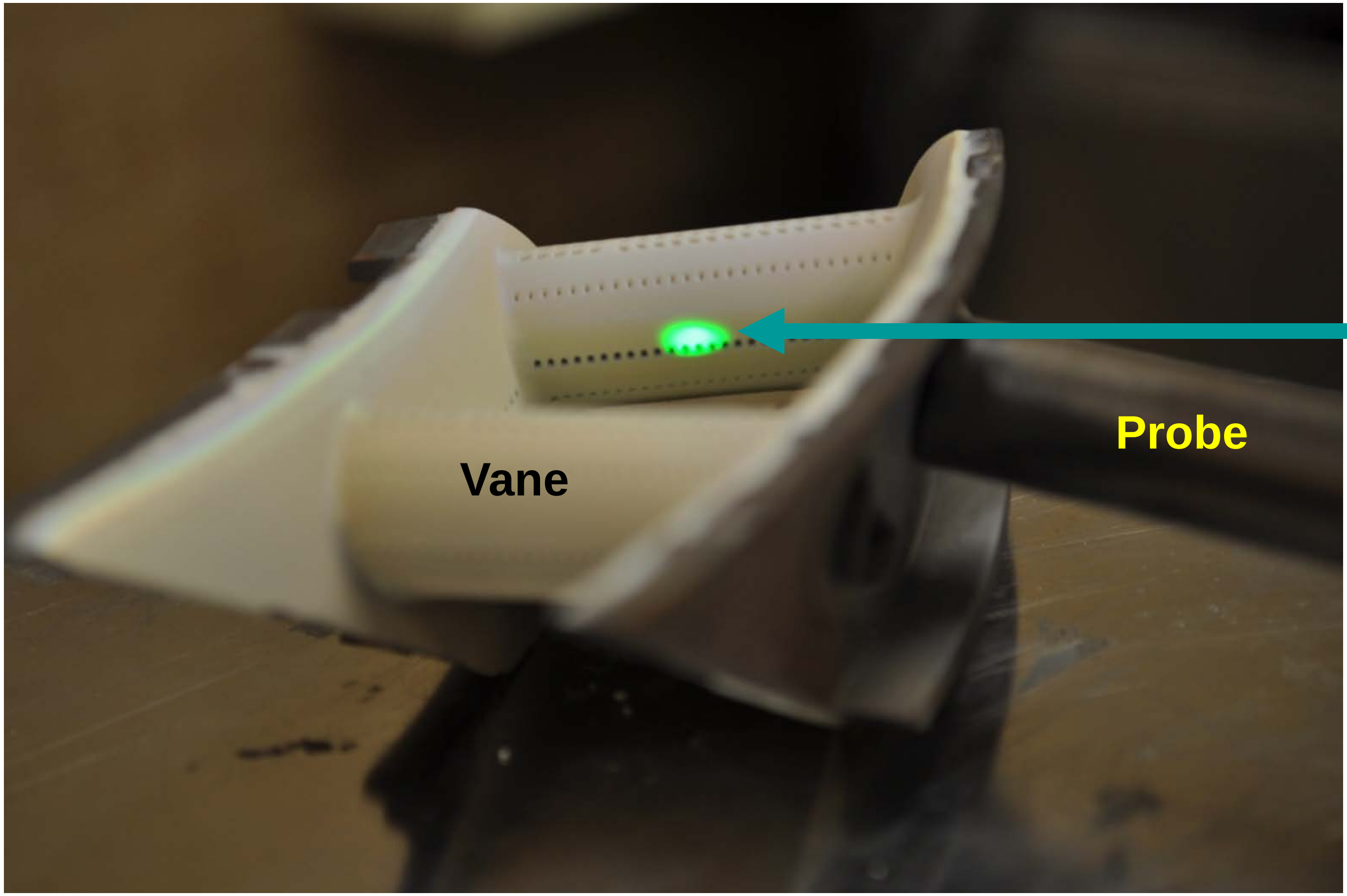
Fiber bundle cross-section





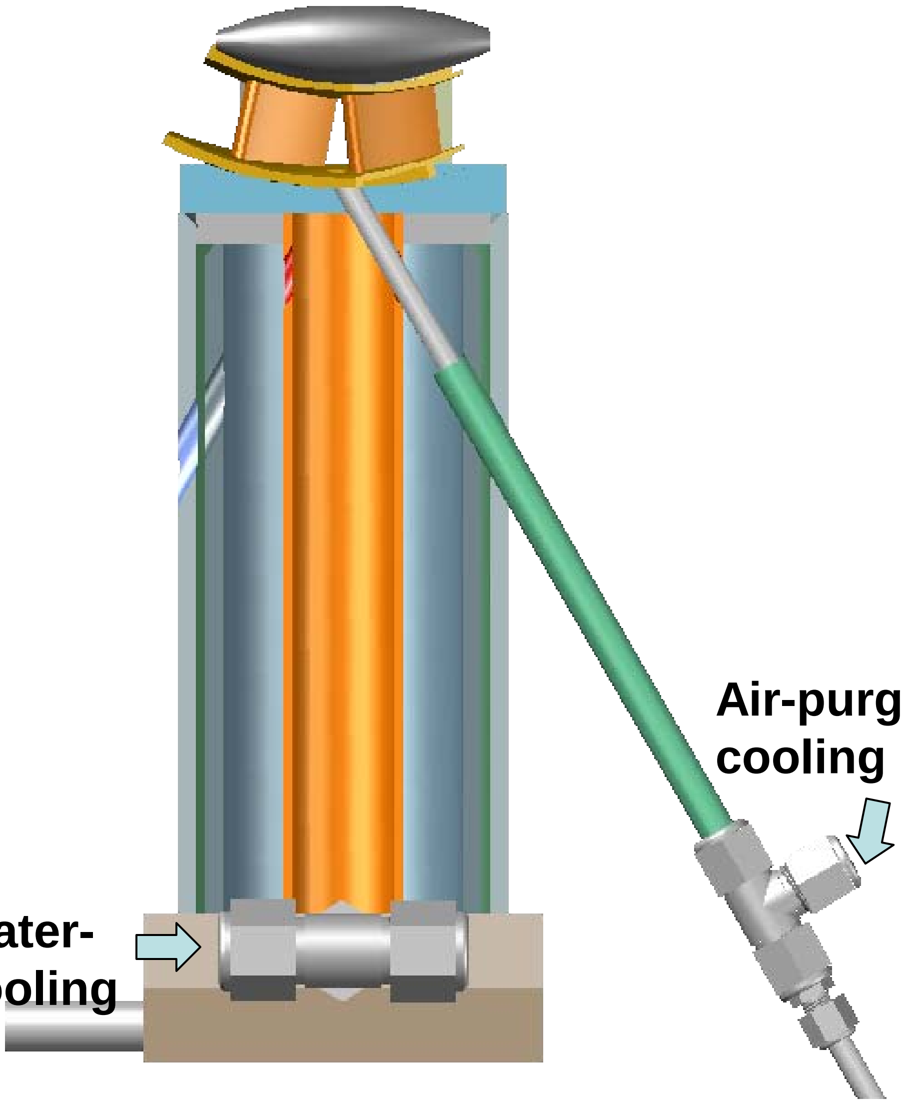
Final probe design by Rob Flori, Honeywell.

Optical Probe Setup

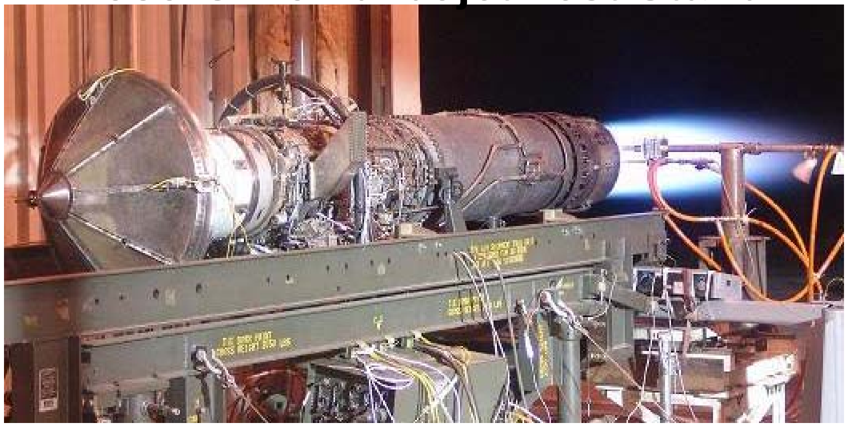


Cooling Fixture for Mounting in Afterburner Flame at UTSI J85 Test Stand

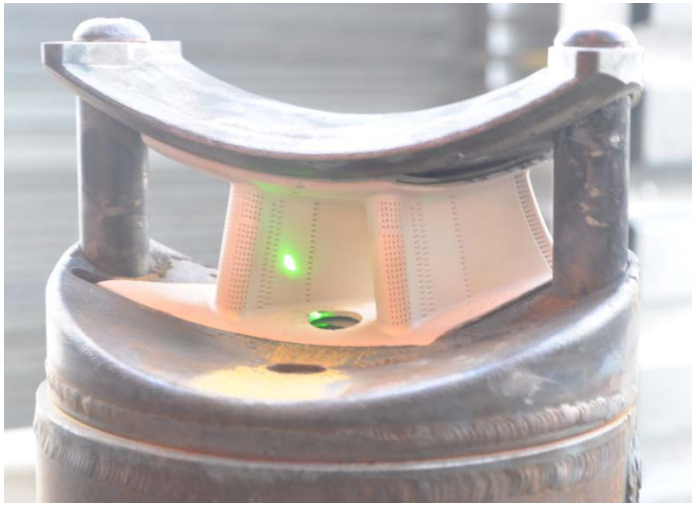
High-Velocity Exhaust Gas up to 1760 °C



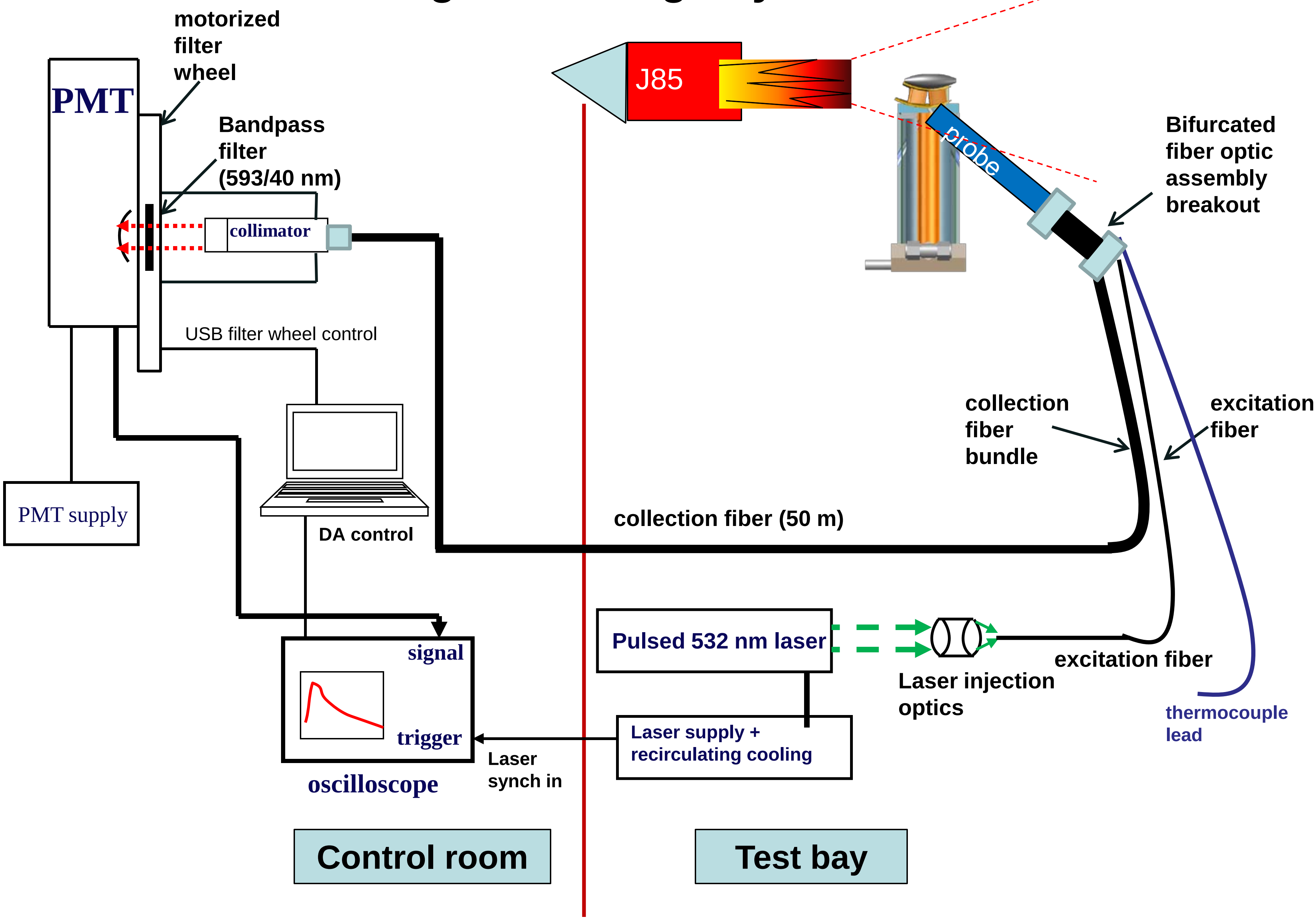
J85-GE-5 Turbojet Test Stand



Mounted vane doublet

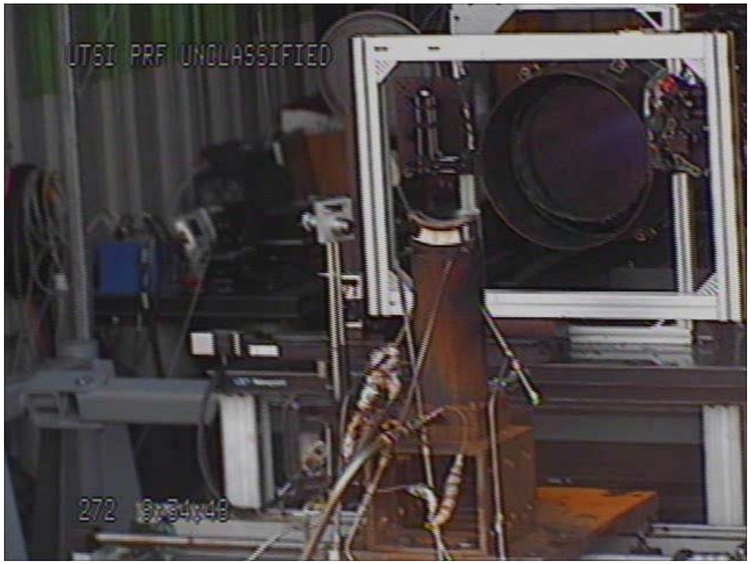


J85 Engine Testing Layout



J85-GE-5 Engine Test at UTSI

Engine Aft View



Overhead View of Vane in Afterburner Flame

Afterburner Flame at Night

Initial J85 Test Runs Reveal Unintended Probe Cooling Effect!*

PLA (power lever angle) # = throttle setting

Probe cooling air cools target area!
Highly perturbing temperature measurement!

*Directed probe cooling effect will be considerably smaller inside engine where combustion gas cross-flow will be much greater.

Reduce Probe Cooling Air Pressure to Minimize Unintended Probe Cooling Effect

PLA (power lever angle) # = throttle setting

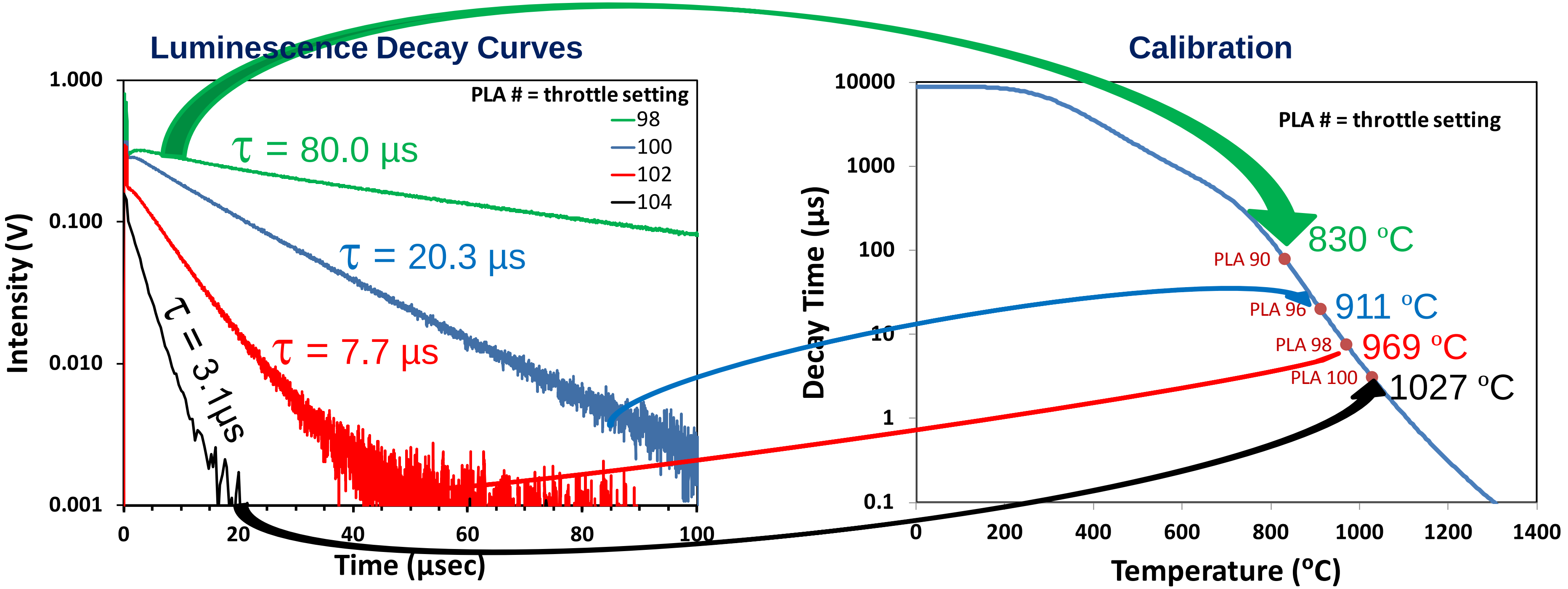
Probe cooling air at high pressure

Probe cooling air at low pressure

Reduced pressure greatly reduces but does not completely eliminate probe cooling effect. Less measurement time before probe overheats.

Temperature Determination from Luminescence Decay Curves

J85 Engine Tests at Different Afterburner Settings



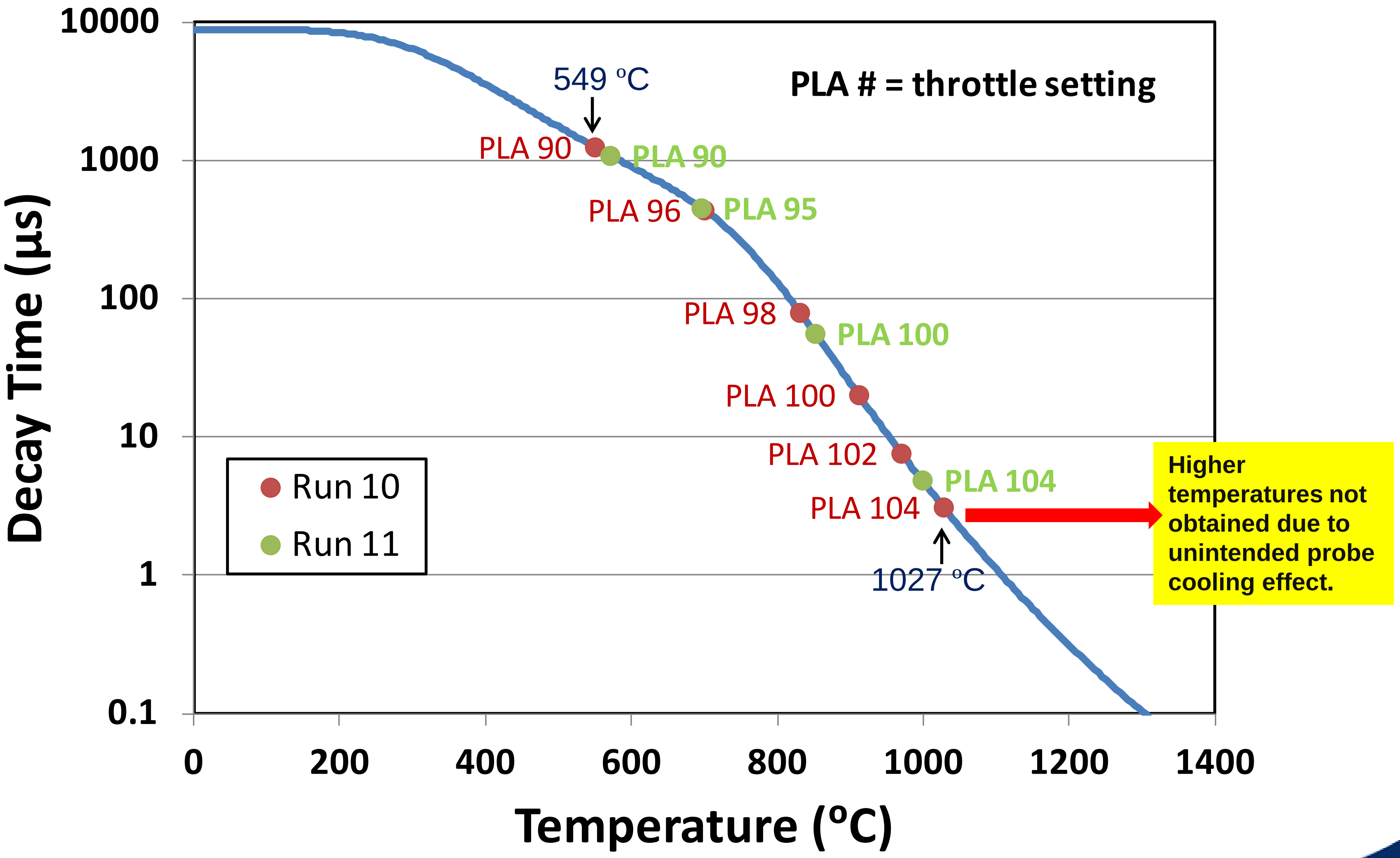
Fit to bi-exponential:

$$I = I_1 e^{-t/\tau_1} + I_2 e^{-t/\tau_2}; \tau_2 > \tau_1$$

Determine T from τ vs. T calibration

$$\tau_2 = \tau_{2E}^{R} \frac{1 + 3e^{-\Delta E/kT}}{1 + ae^{-\Delta E/kT} + \beta e^{-(\Delta E_q + \Delta E)/kT}}$$

Temperature Determination Summary for Cr:GAP-Coated Vane During J85 Engine Test Sequences



Summary

- Successfully demonstrated temperature measurements from Cr:GAP coated Honeywell stator vane doublet in afterburner flame of UTSI J85-GE-5 turbojet test stand.
  - Successful coating deposition onto complex stator doublet shape by EB-PVD.
  - Excellent emission intensity and temperature sensitivity from 25 µm thick surface coating.
  - Wide temperature range 549 ºC to 1027 ºC measured over range of afterburner conditions.
  - Engine-compatible probe design demonstrated
    - Integrated excitation and collection. ✓
    - Thermal protection of probe. ✓
    - Unintended cooling of measurement surface to be corrected in future. ✗
- Future Plans
  - Cr:GAP downselected as one of two thermographic phosphors for upcoming AFRL VAATE temperature measurements of high-pressure turbine stator in Honeywell TECH7000 demonstrator engine.
  - Cr:GAP downselected as one of three thermographic phosphors for upcoming NASA VIPR temperature measurements of rotating blade surfaces in Pratt & Whitney F117 engine.
  - 2D surface temperature mapping by gated imaging underway at NASA GRC.

Acknowledgments

- NASA ARMD Seedling Project for funding Cr:GAP development.
- AFRL VAATE Project for funding the J85 test & probe design.
- Honeywell for providing stator vane doublet.
- AEDC/UTSI Propulsion Research Facility Team for providing the J85 test opportunity & mounting structure.
- Allen Koller, GE, for providing independent pyrometer measurements.

Test Team at UTSI