Implementation of an Ultra-Bright Thermographic Phosphor for Gas Turbine Engine Temperature Measurements

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Objectives

Implement the ultra-bright luminescence temperature sensing capability of Cr-doped $GdAlO_3$ (Cr:GAP) thermographic phosphors demonstrated in Phase I to:

- Overcome the usually intensity-starved nature of the severely restricted solid angle of light detection associated with engine probes.
- Demonstrate on-wing-compatible temperature measurements to 1000°C using low-powered LED or laser diode excitation integrated into engine probe.
- Transition from spot temperature measurements to 2D temperature mapping by simply broadening the excitation laser beam to cover the region of interest.
  - Not previously practical because expansion of laser beam reduced S/N to unacceptable levels.
  - Demonstrate 2D temperature mapping of thermal gradients surrounding cooling holes under conditions approaching turbine engine environment.

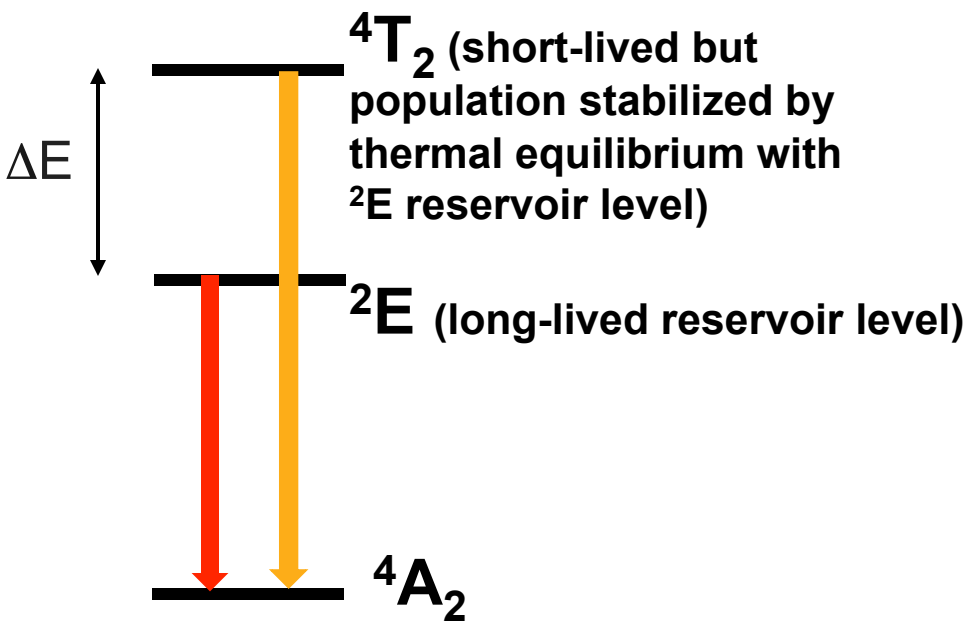
Innovation

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°C.
- Huge advance over state-of-the-art ultra-bright luminescence upper limit of 600°C.
- Innovative implementations to enable 2D temperature mapping of engine component surfaces as well as demonstrating low-power laser-diode excitation suitable for on-wing diagnostics.

Basis for High Temperature Ultra-Bright Cr:GAP Luminescence

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

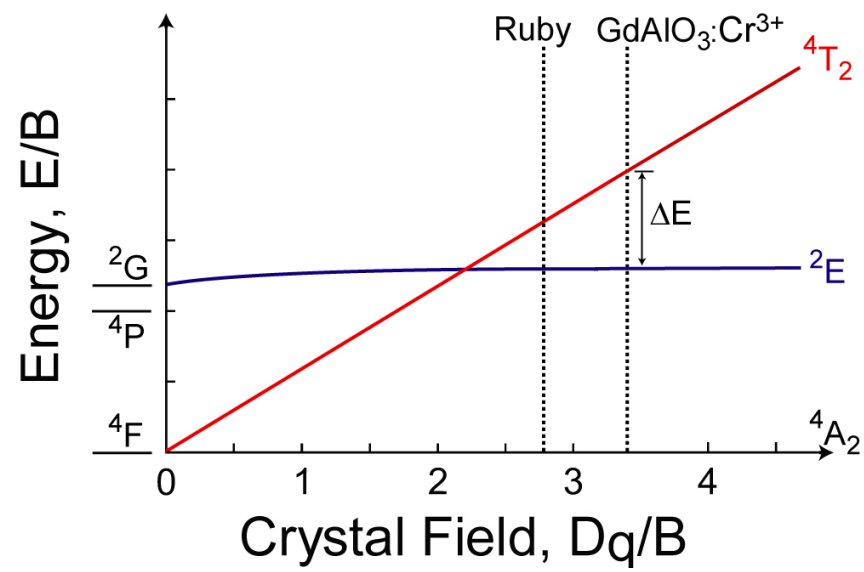


Spin-forbidden R-line emission (long decay)
$^2E \rightarrow {}^4A_2$

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

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

Tanabe-Sugano Diagram



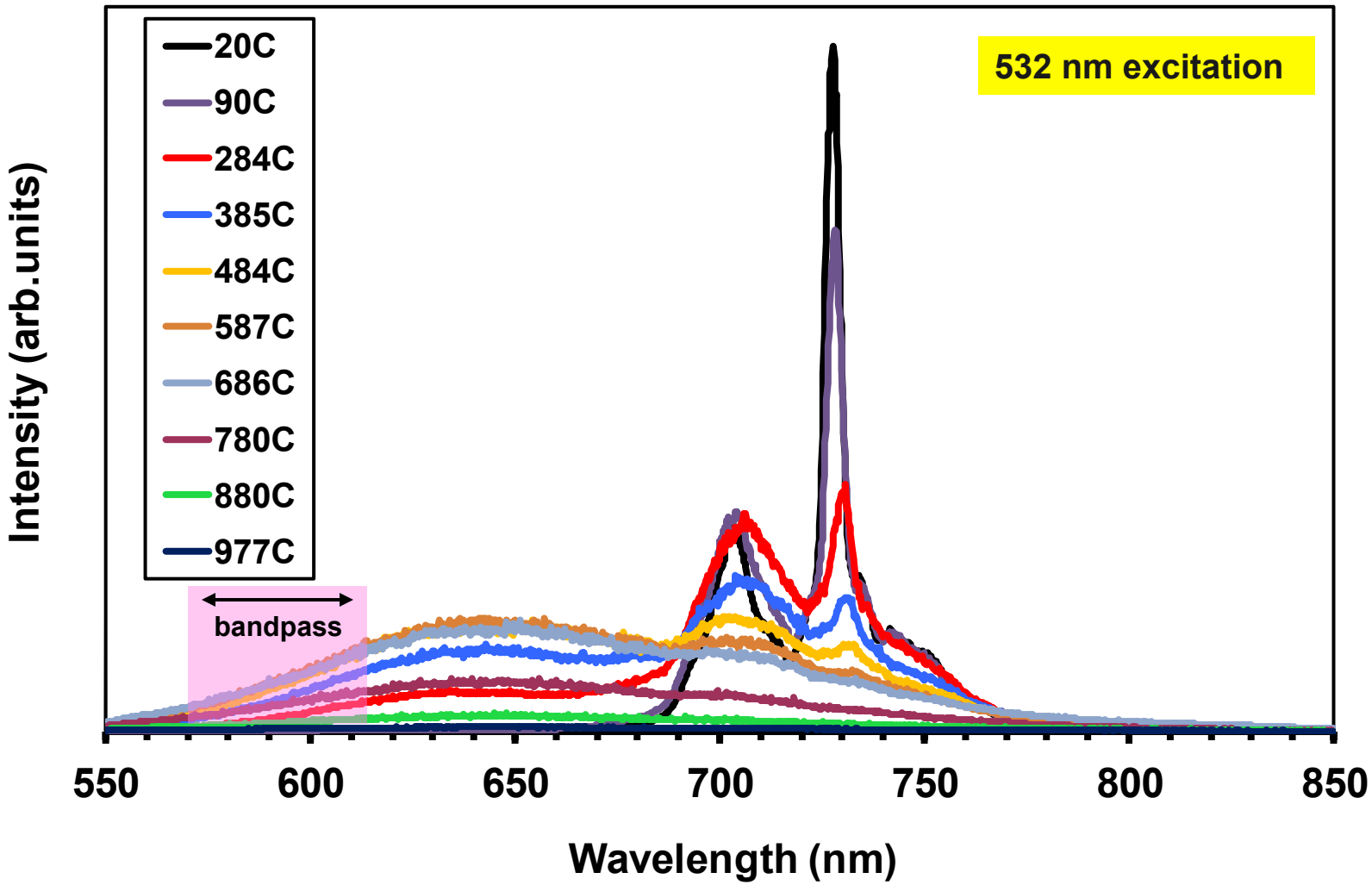
Strong crystal field increases ΔE.

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).

Demonstrating Temperature Measurement Capability

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



Time-Resolved Luminescence Emission from Cr:GAP

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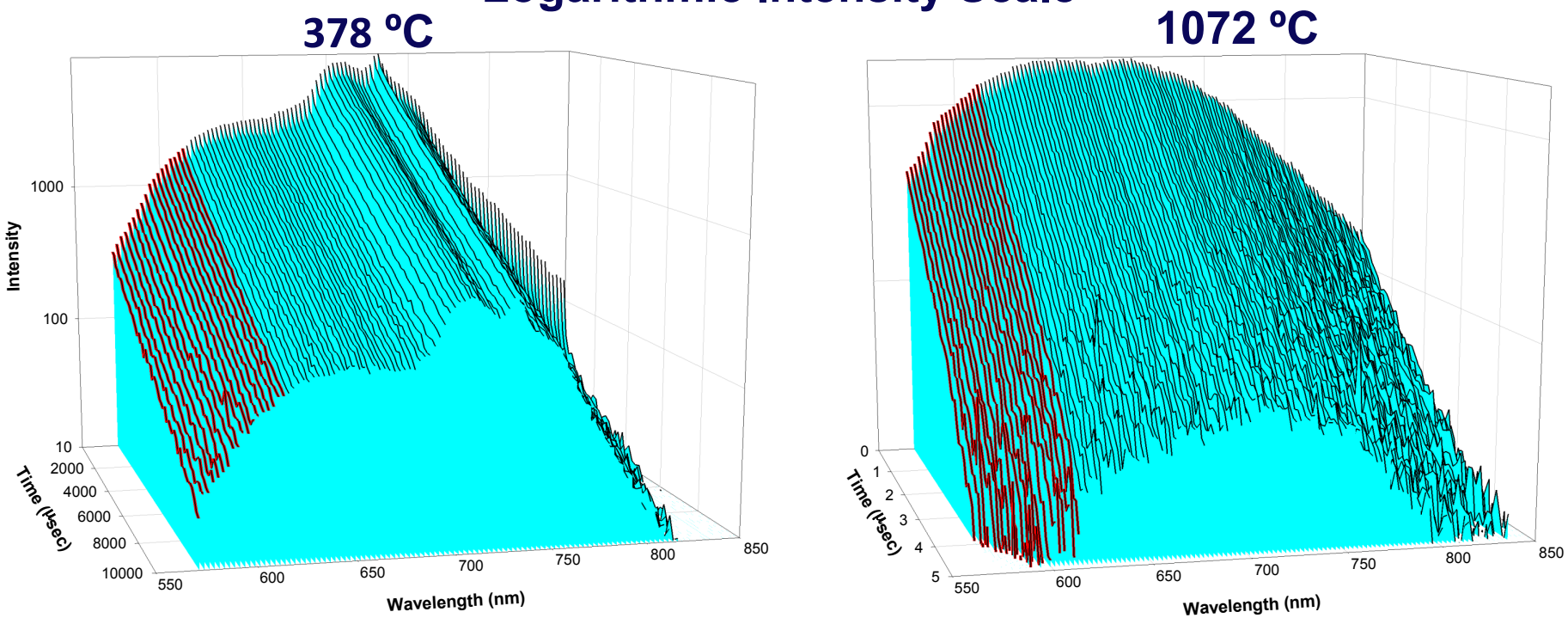
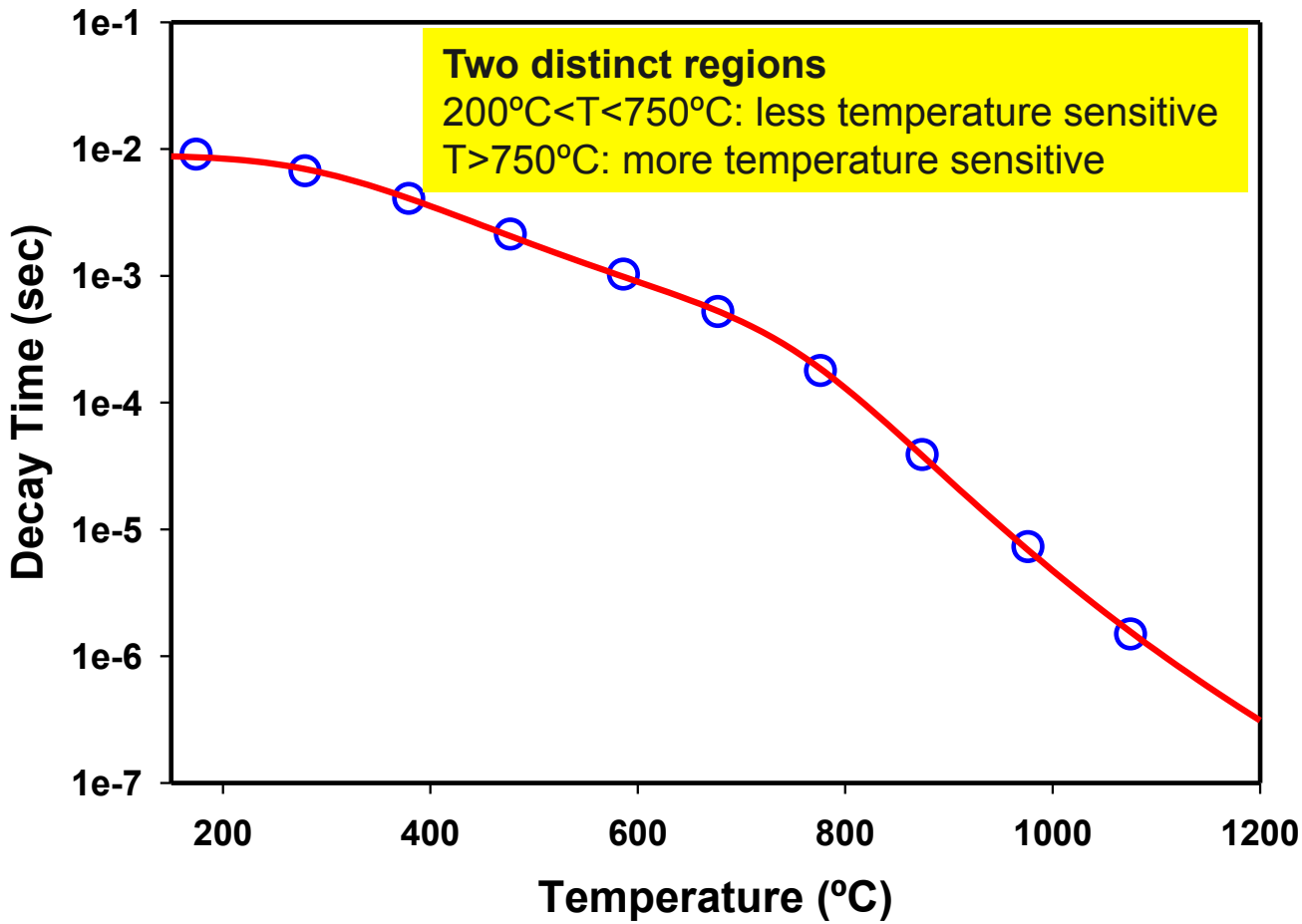
Logarithmic Intensity Scale



- 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 Measurement Capability

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



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

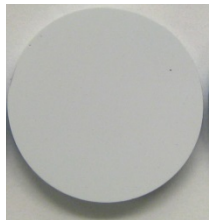
Phase II Progress

- Cr:GAP phosphor excels in engine probe spot measurements in afterburner environment.
- On-wing-compatible laser diode excitation successful to 900°C.
  - Decay is too fast for extended excitation to be effective at higher temperatures.
- Surface temperature mapping very successful.
  - Thermal test patterns demonstrate excellent combination of spatial resolution & temperature sensitivity.
    - 2-gate option explored for fast acquisition
  - Engine-relevant temperature mapping
    - Cooling air jet impingement on button specimens
    - Cr:GAP-coated stator vane doublet with air film cooling
      - »NASA burner rig tests
      - »AEDC J85 afterburner tests

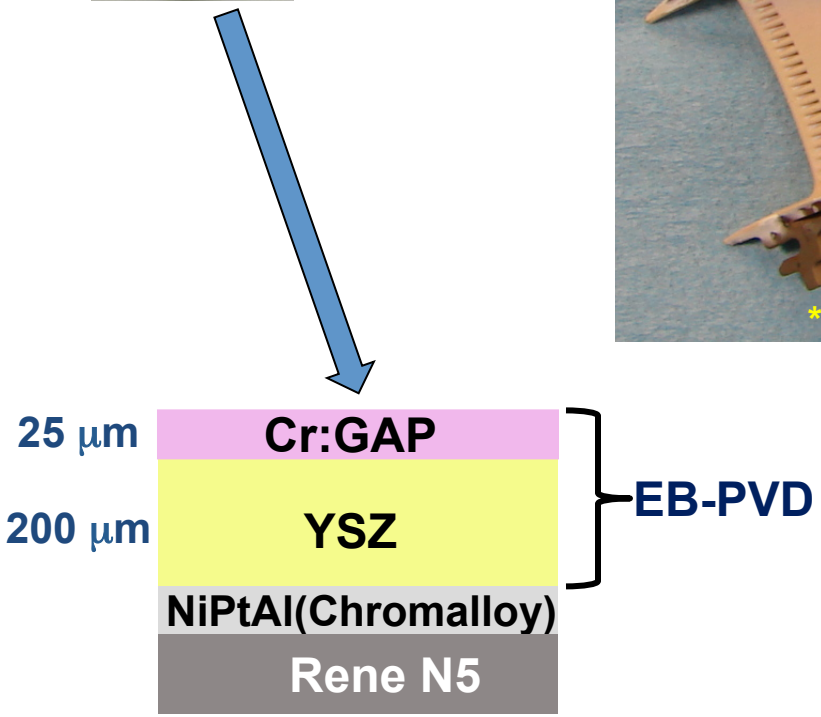
Cr:GAP-Coated Specimens

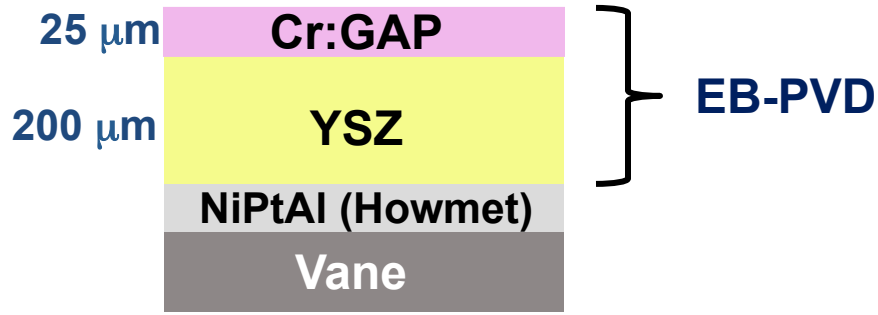
EB-PVD at Penn State

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



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





Coatings for 2D Temperature Mapping

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

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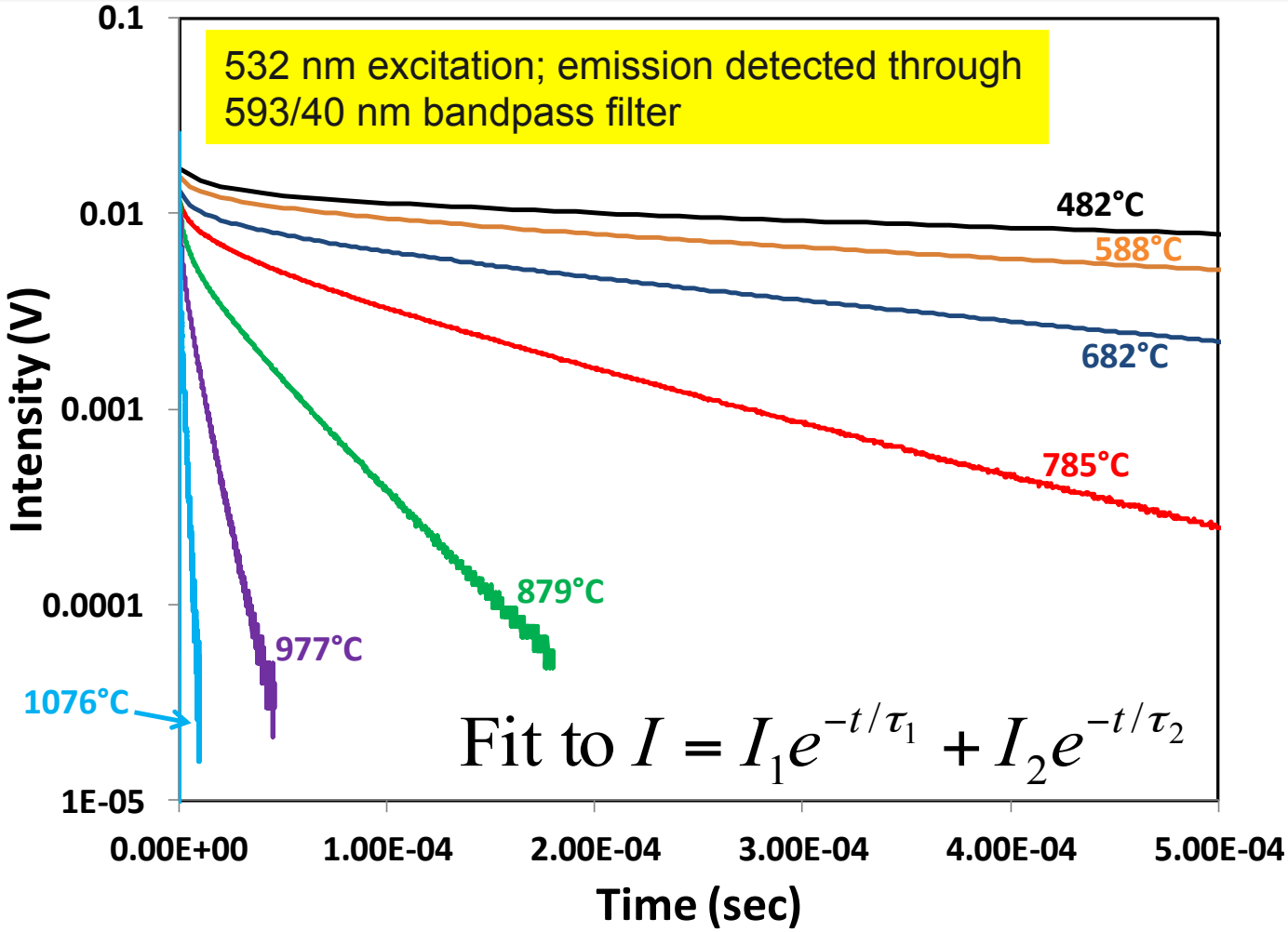
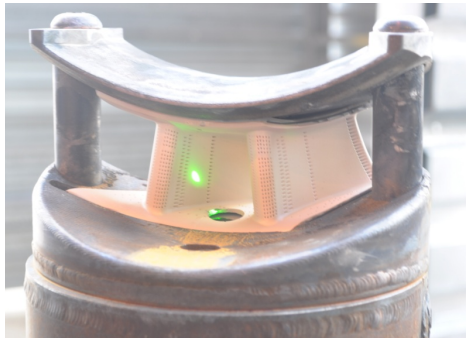


Superb signal-to-noise from thin 25 µm thick coating confirms retention of ultra-bright luminescence at high temperatures.

J85-GE-5 Engine Test at UTSI

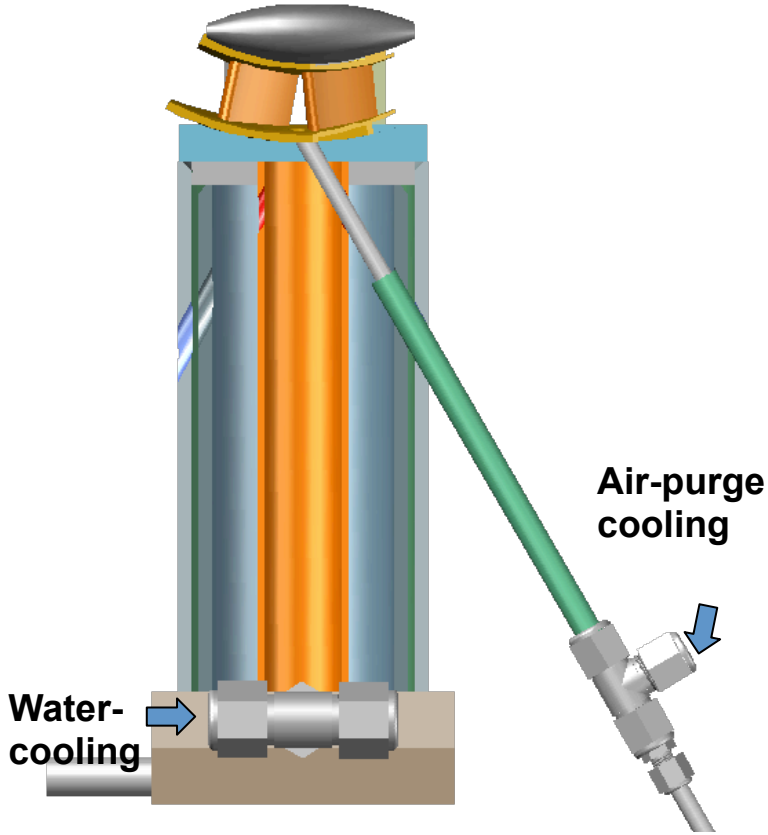
Vane Mounted in Afterburner Flame

- Spot temperature measurements successfully obtained from coated vane in aggressive afterburner flame environment of AEDC J85 test engine.

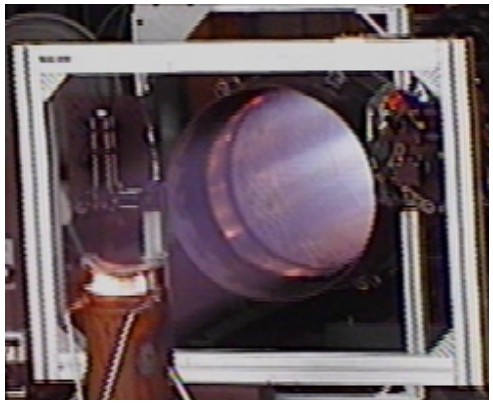


Mounted vane doublet

AEDC cooling mount design



Front view of vane in afterburner flame



Aft view of vane doublet in afterburner flame

Temperature Determination from Luminescence Decay Curves

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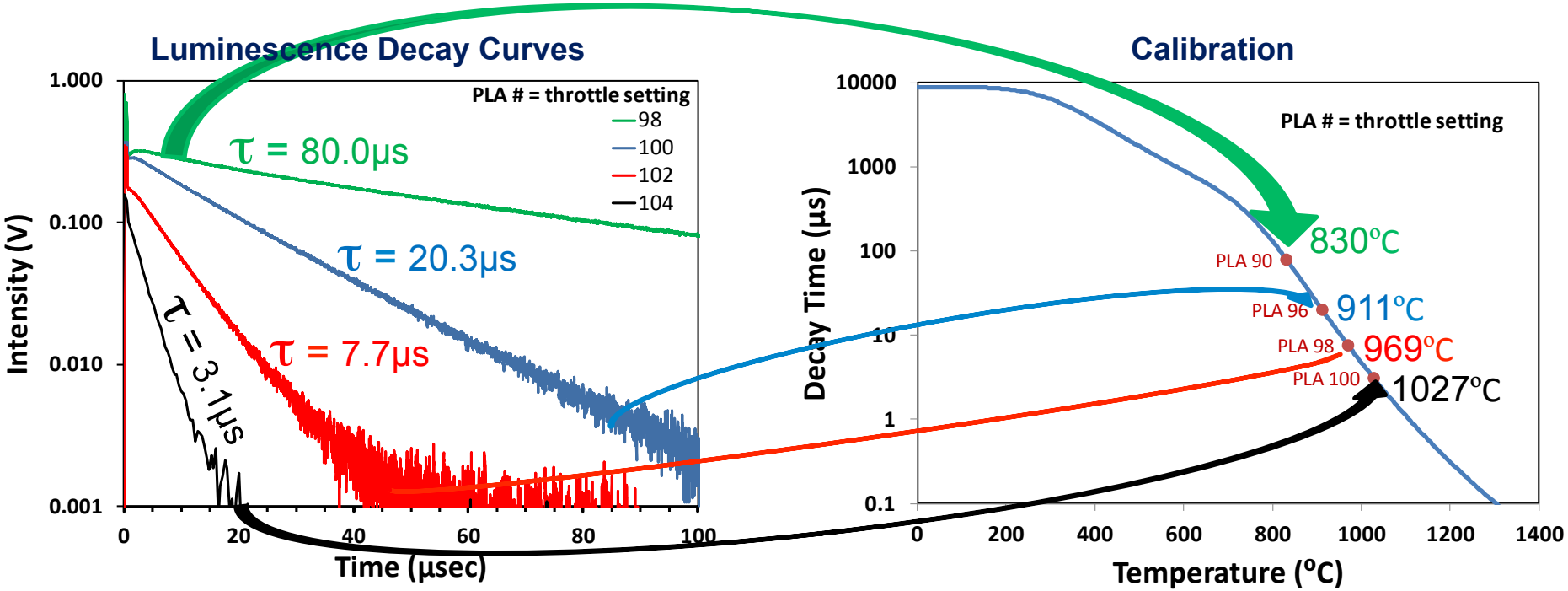
J85 Engine Tests at Different Afterburner Settings



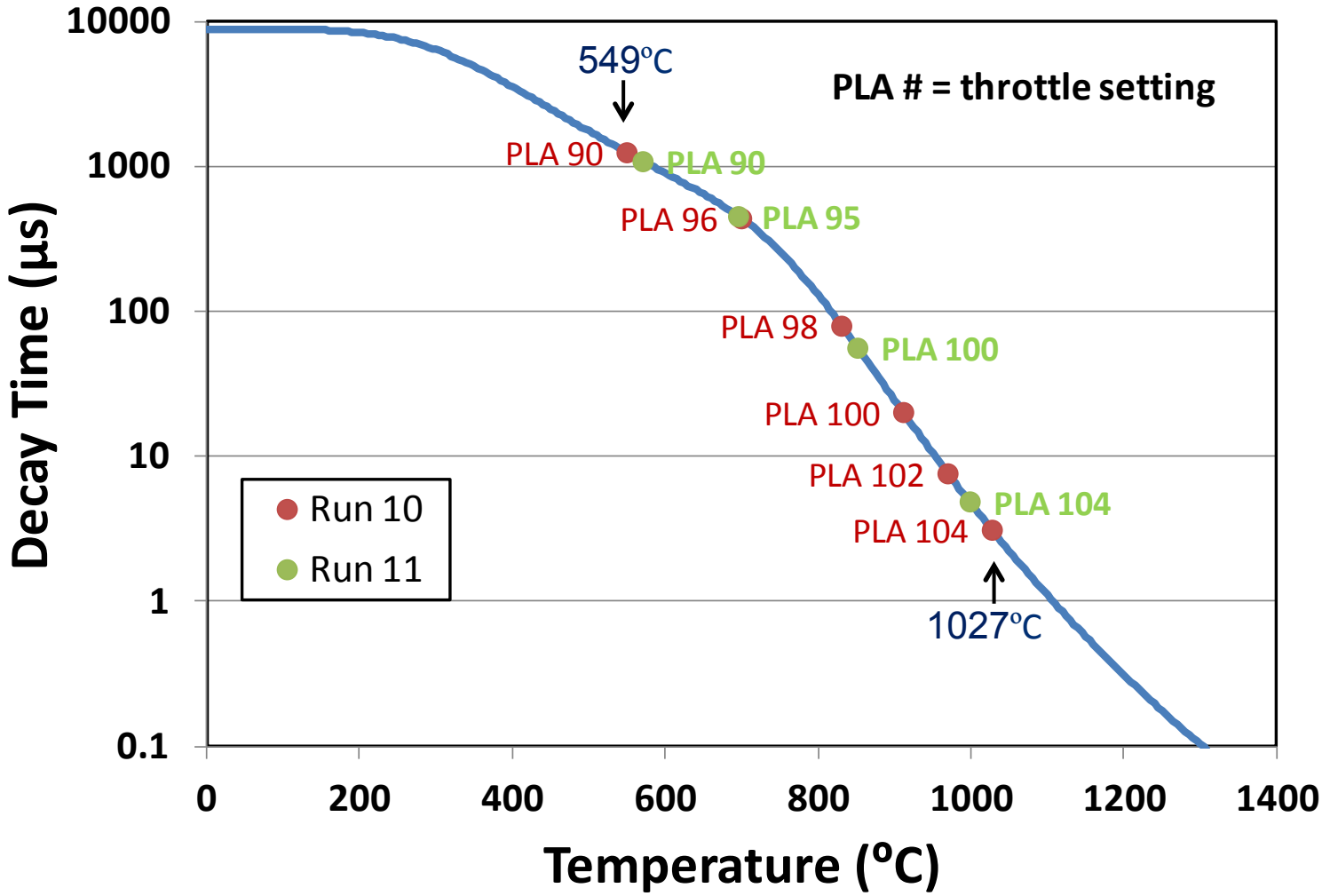
Fit to bi-exponential:

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

Determine T from τ vs. T calibration

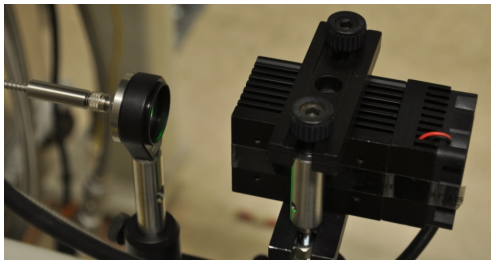
$$\tau_2 = \tau_{2E}^{R} \frac{1 + 3e^{-\Delta E/kT}}{1 + ae^{-\Delta E/kT} + \beta e^{-(\Delta E_q + \Delta E)/kT}}$$

Temperatures Determined for Different Engine Throttle Settings

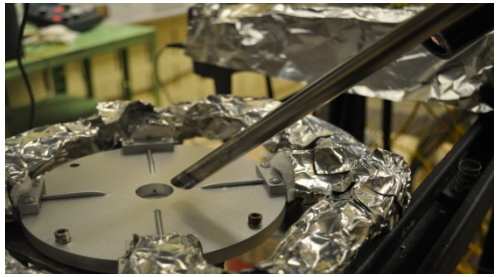


On-Wing-Compatible Laser Diode Excitation Integrated Into Engine Probe

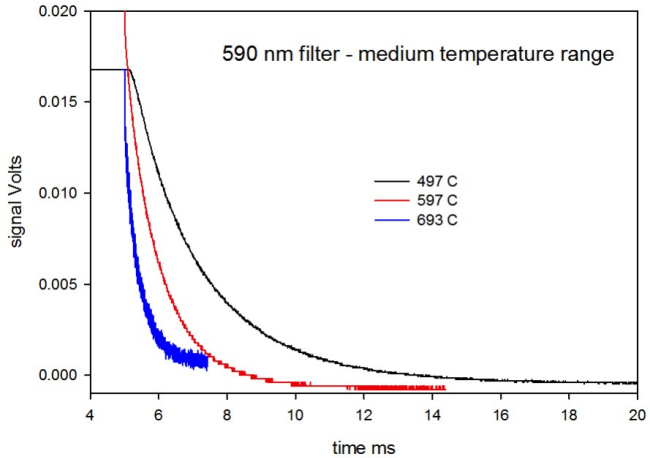
Laser diode coupling into excitation leg of probe



Engine probe above specimen

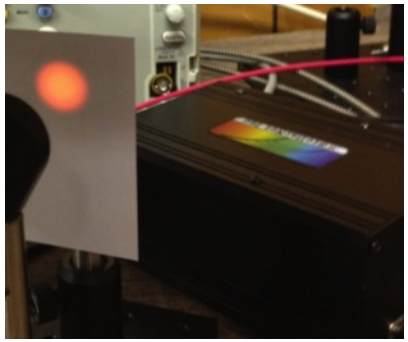


- Good temperature sensitivity up to 900°C demonstrated.

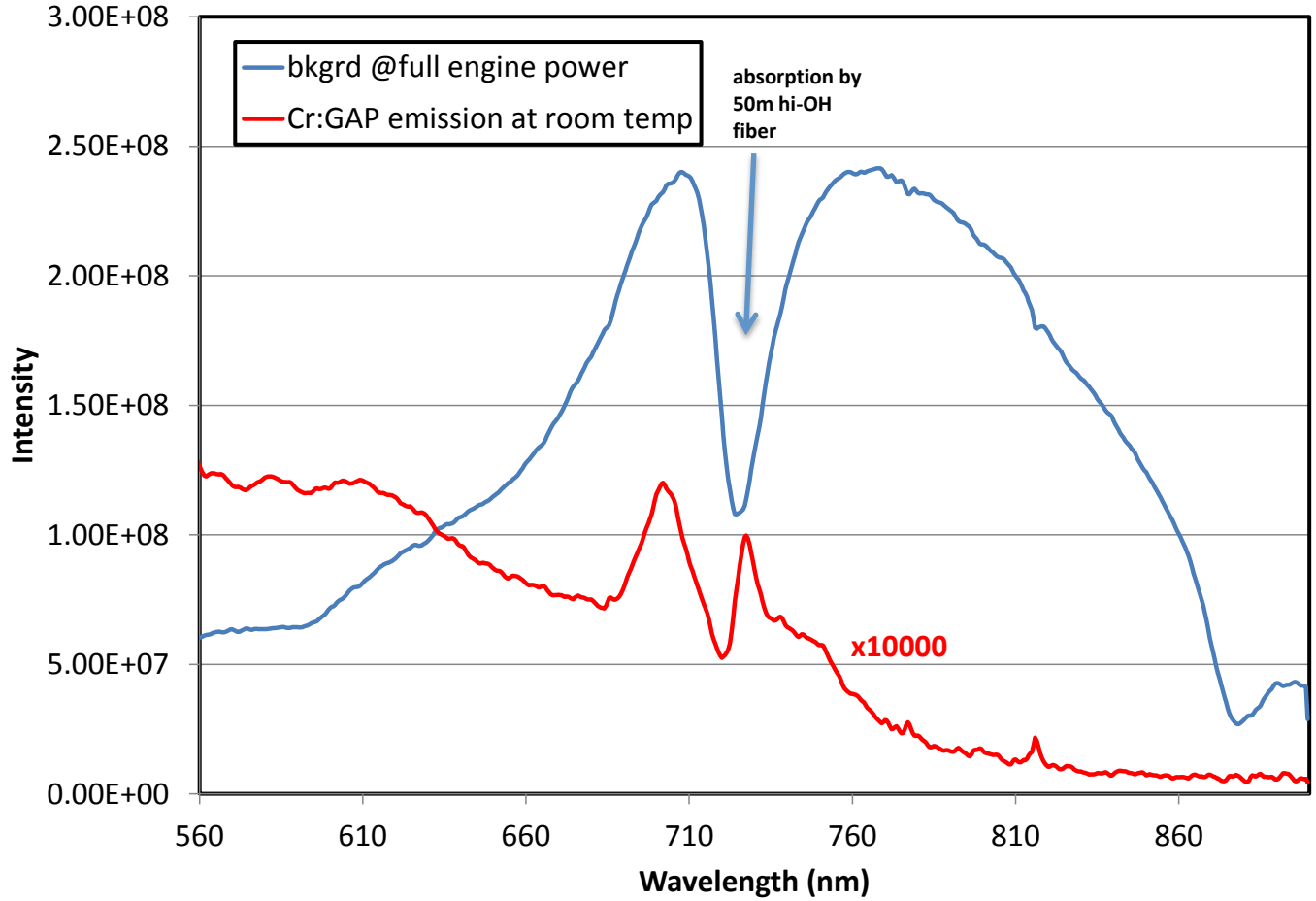


- Fundamental obstacle to higher temperature measurements where decay is too fast to build adequate excitation.

Background Thermal Radiation at Engine Full Power
Honeywell Engine Test



Background radiation exiting collection fiber



Full engine power background radiation overwhelms luminescence emission.

Mapping Thermal Gradients Produced by High-Heat-Flux Laser

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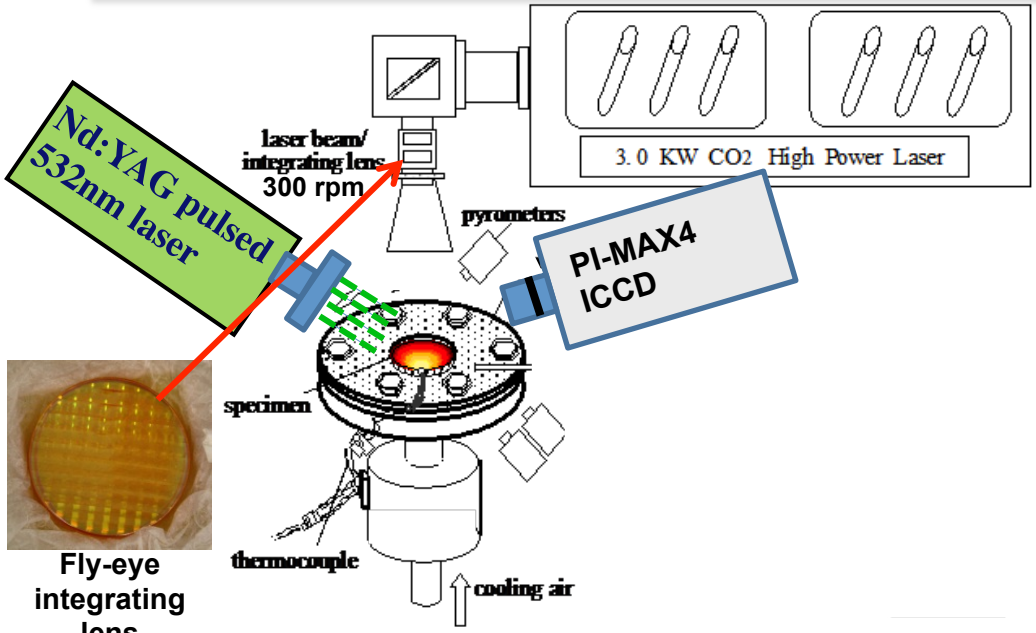
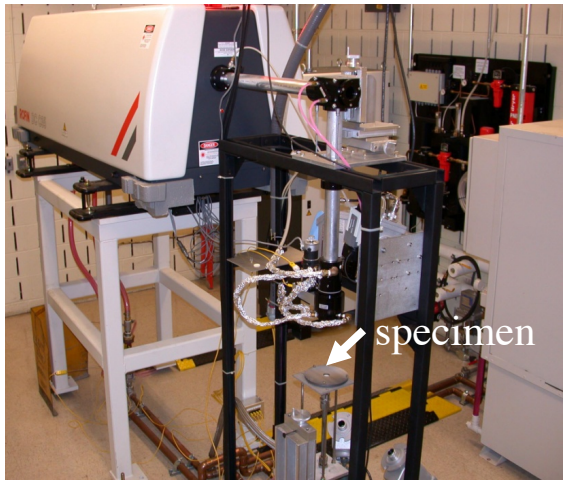
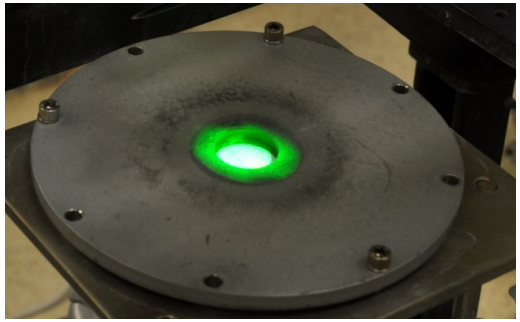


Fly-eye integrating lens

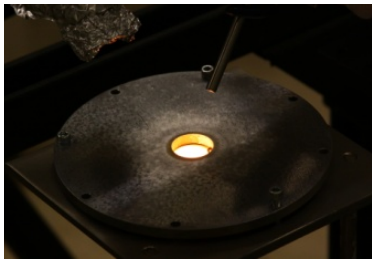
High power CO_2 laser high-heat-flux rig

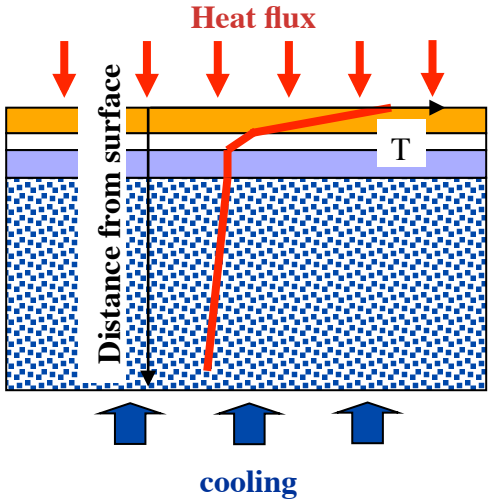


Illumination of Specimen by Expanded Laser Beam



CO_2 laser heating





2D Temperature Maps of Thermal Test Pattern

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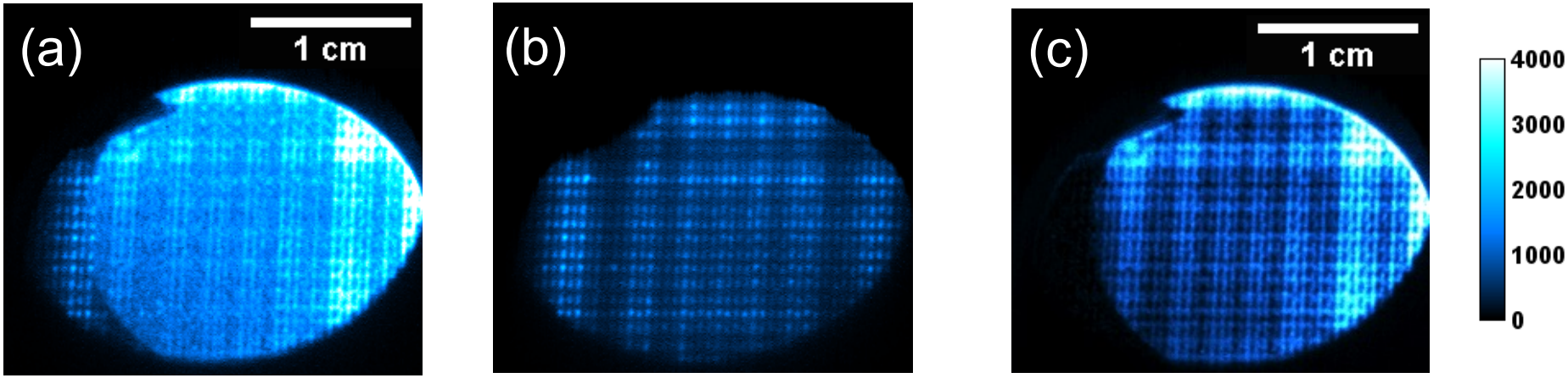
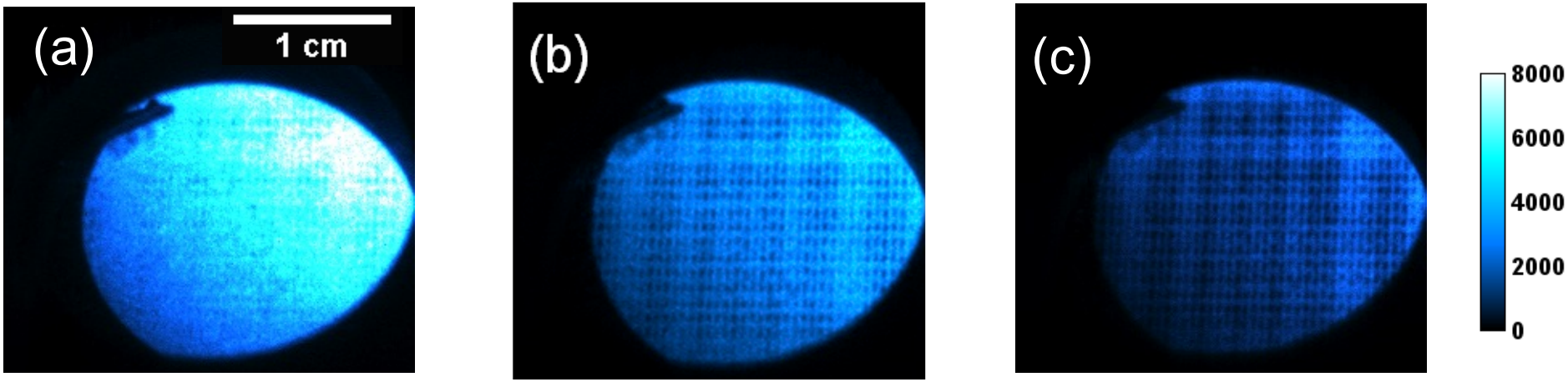
- Multi-step procedure:
  - Step 1: Remove thermal radiation background from each image collected.

Luminescence before background subtraction Background (no laser) Luminescence after background subtraction



  - Step 2: Collect sequence of background-corrected time-gated images over sequence of delay times.

0.5 μs after laser pulse 2.5 μs after laser pulse 5.0 μs after laser pulse



2D Temperature Maps of Thermal Test Pattern

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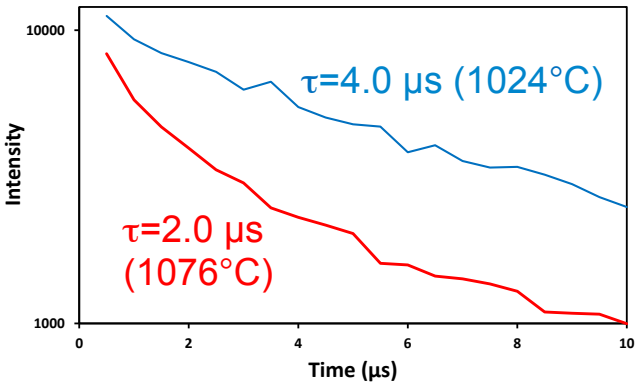
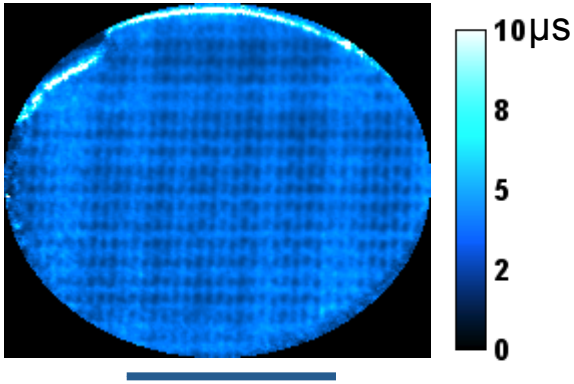
– Step 3: Fit luminescence decay curve at each pixel to produce decay time map.

Individual Pixel Decays

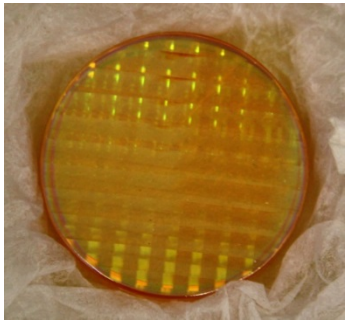


Decay Time Map



1 cm

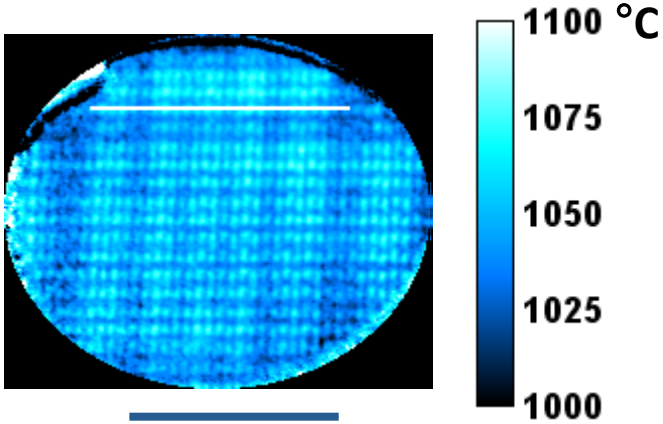
Fly-eye integrating lens



3.8 cm diam

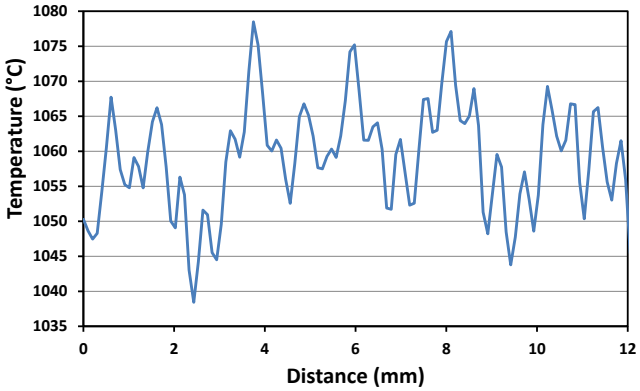
– Step 4: Use calibration data to convert decay time map to temperature map.

Temperature Map



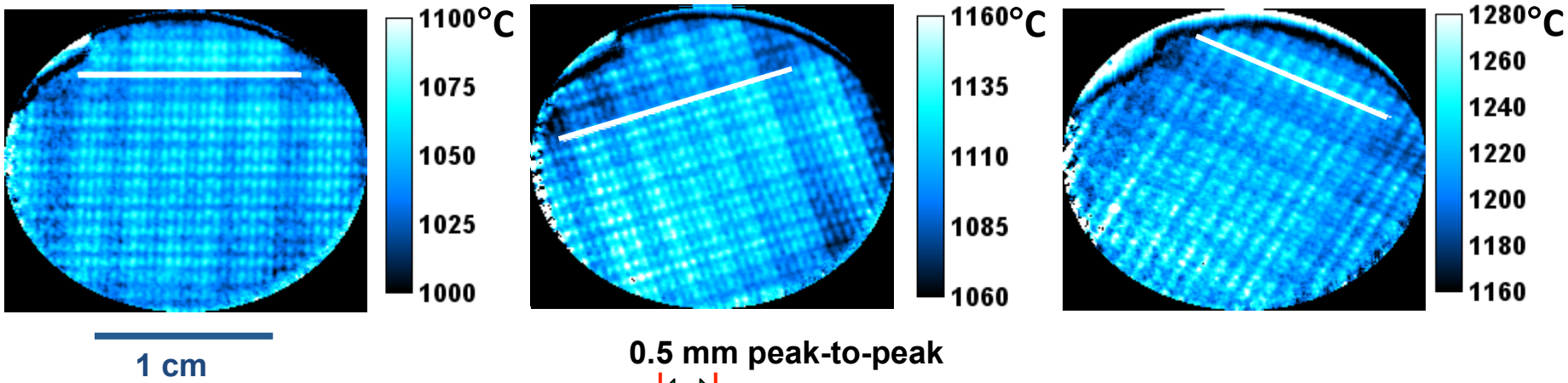
1 cm

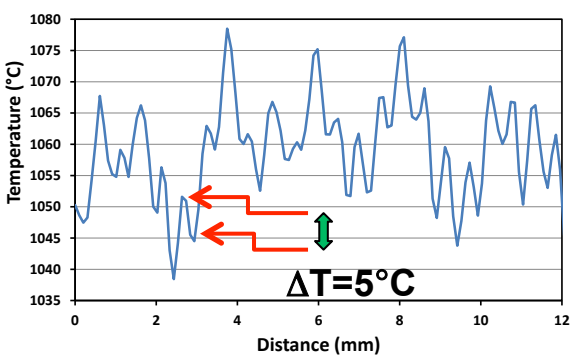
Temperature Line Scan

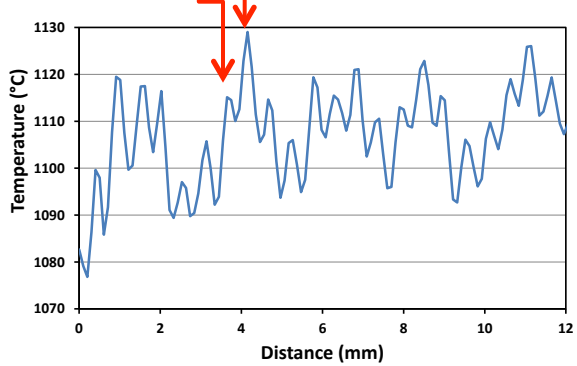


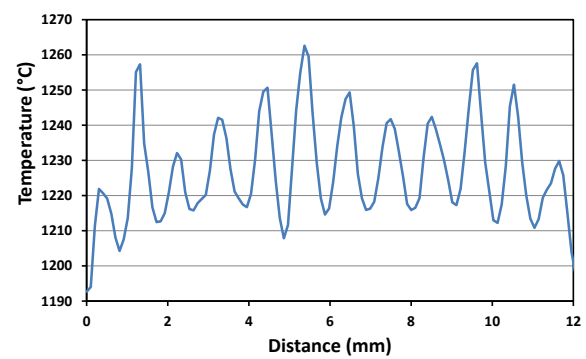
Thermal Test Pattern Temperature Maps at Increasing Heat Flux

Temperature Maps





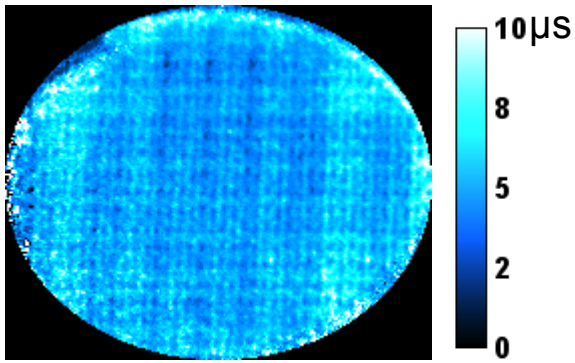




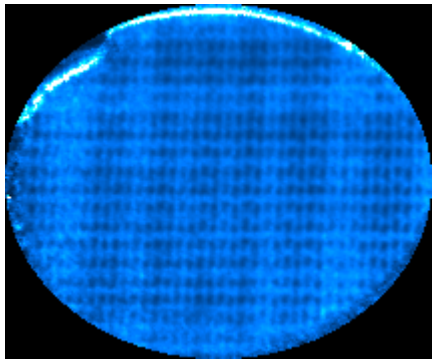
Thermal test pattern demonstrates excellent temperature sensitivity/spatial resolution.

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

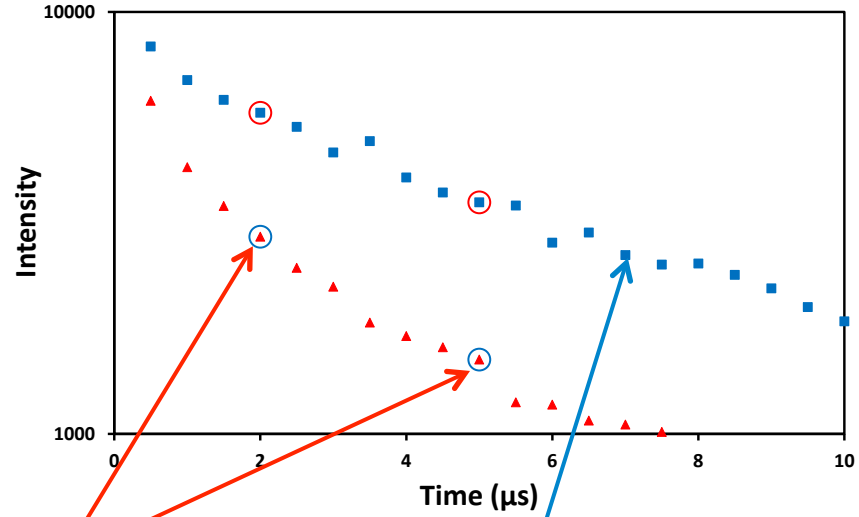
Fast Dual-Gate vs. Slow Multi-gate Approach



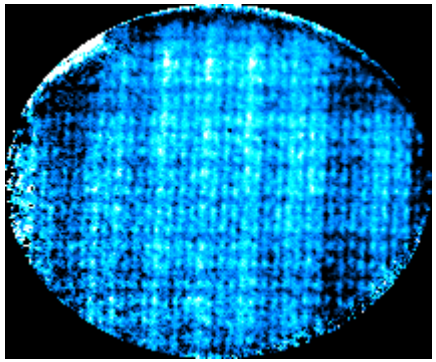
Decay time map
Dual gate



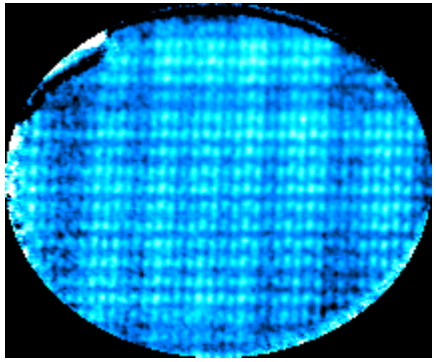
Decay time map
20-gate fit

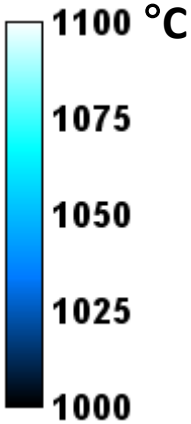


Temperature map
Dual gate (2 & 5μs,
0.5μs wide)



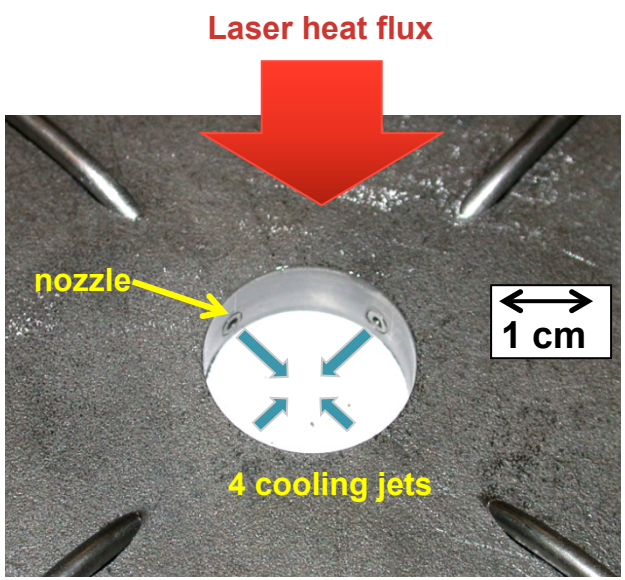
Temperature map
20-gate fit



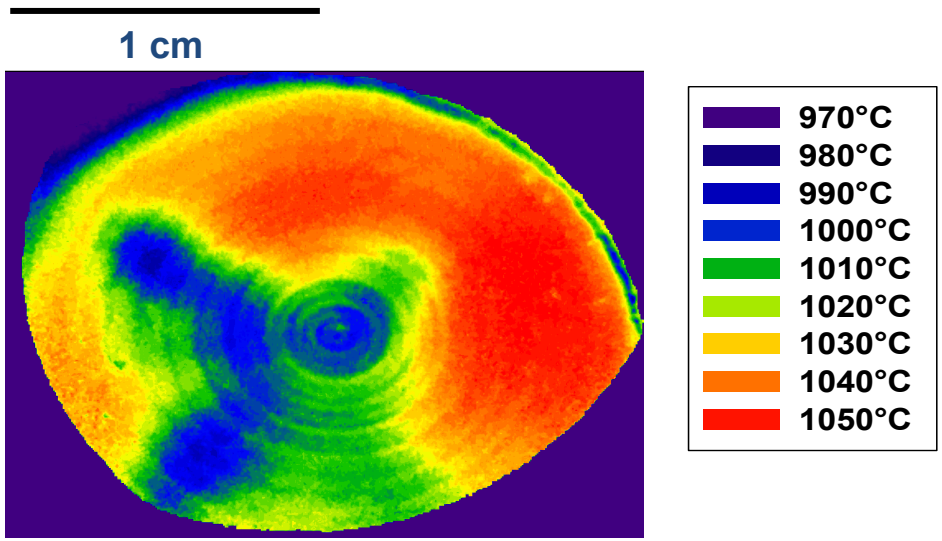


Dual-gate temperature maps offers faster acquisition at expense of signal to noise.

2D Temperature Mapping of Effect of Air Cooling Jet Impingement



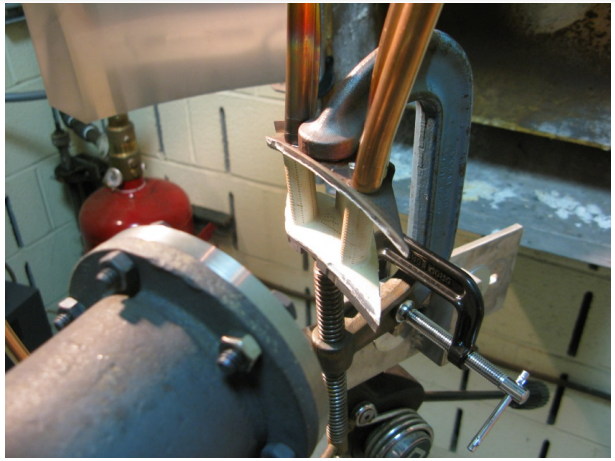
Cooling air jet fixture in high heat flux laser facility



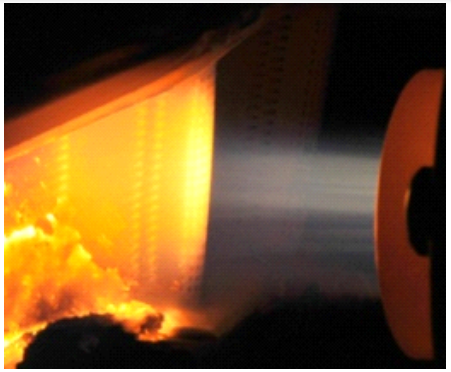
2D temperature map of cooling produced by air jet impingement

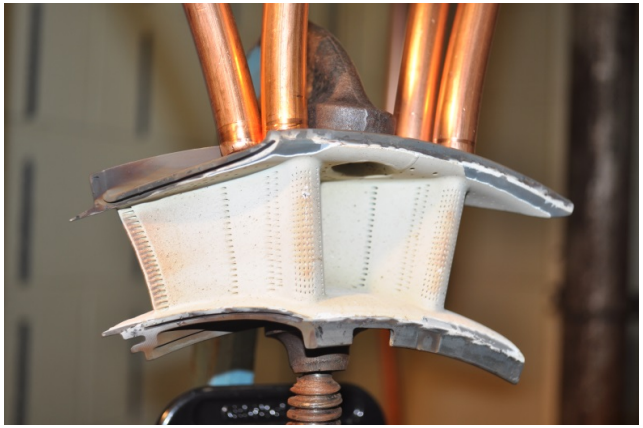
Insensitive to surface emissivity & reflected radiation!

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

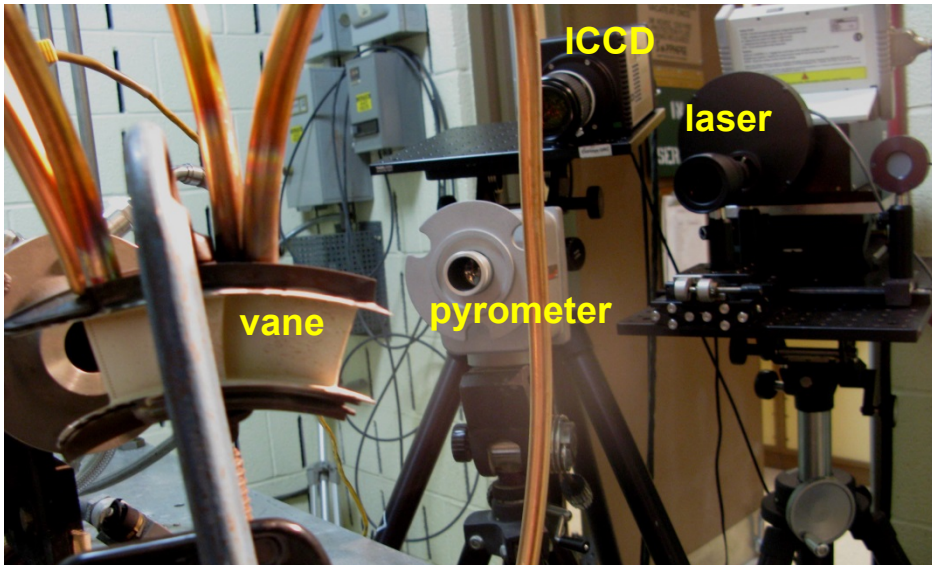


Burner/vane orientation





Cr:GAP coated vane with cooling air supply tubing

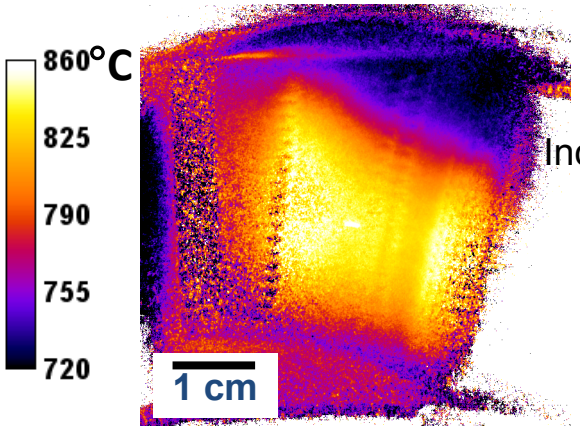


ICCD, laser, & pyrometer pointed at vane

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

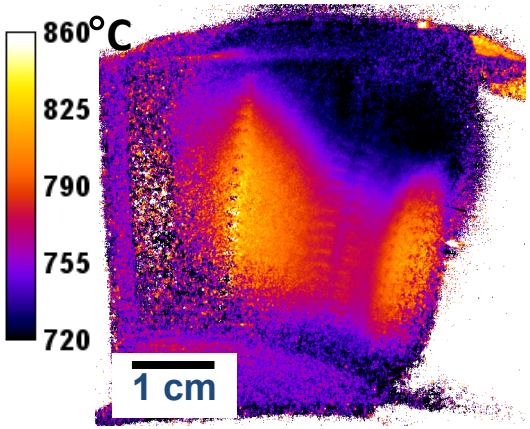
NASA Aeronautics Research Institute

Surface temperature maps



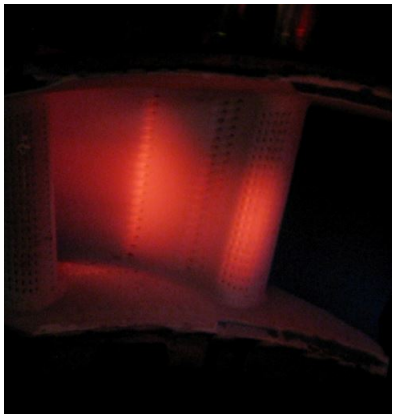
Min flow

Increase air flow through cooling holes



High flow

Visible



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

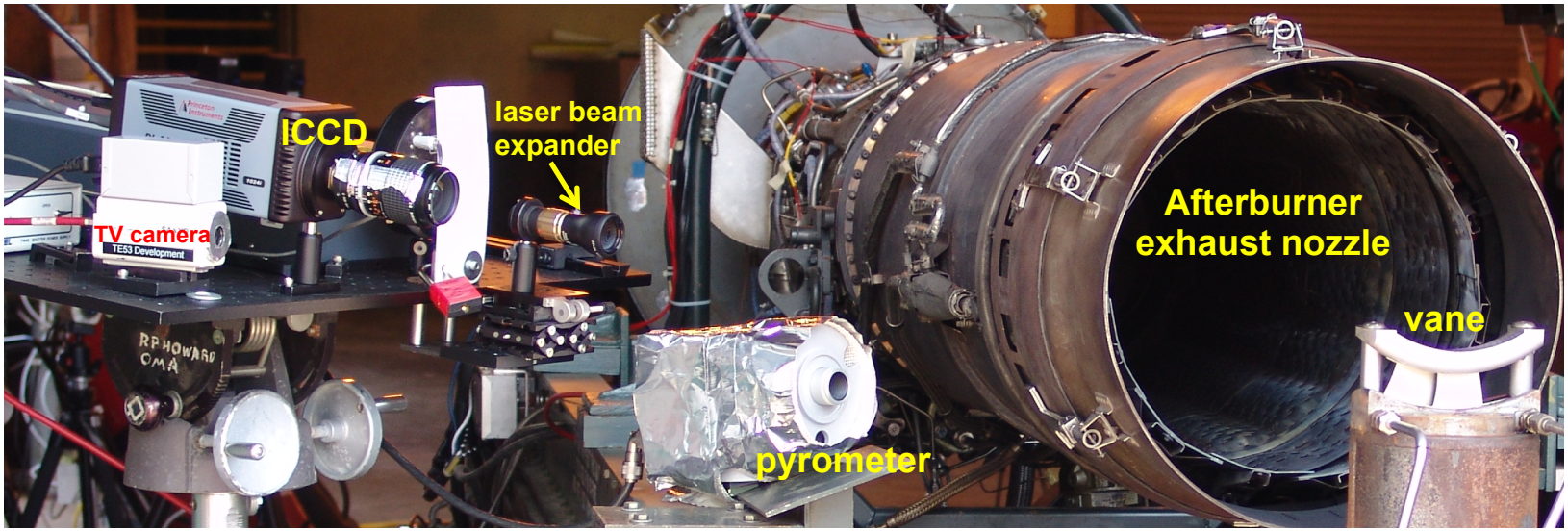
Before burner rig test

After burner rig test

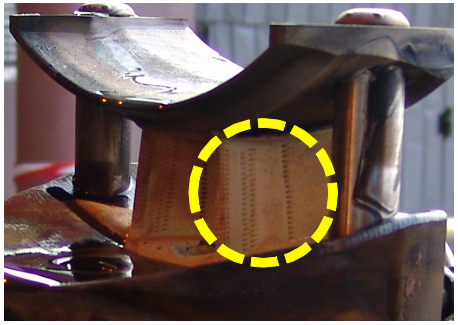
J85-GE-5 Engine Test at UTSI

Broad, Uniform Heat Flux at Center of Flame

Surface Temperature Mapping Configuration



Afterburner Flame at Night

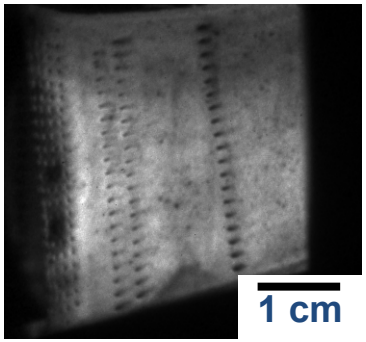


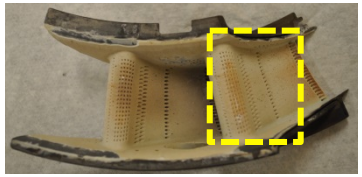
Expanded Laser Target

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

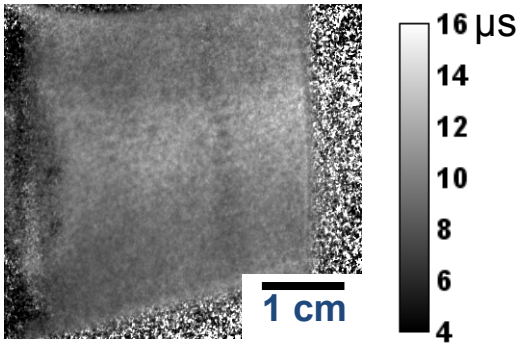
PLA (throttle) = 99°

First gate image

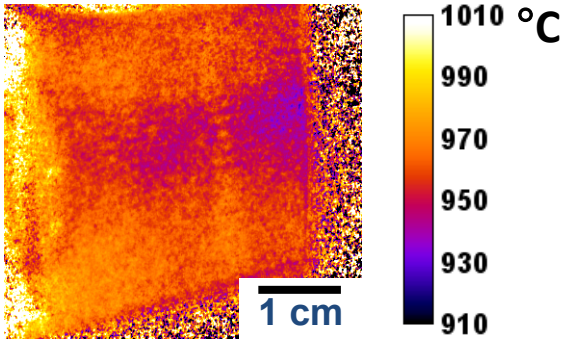




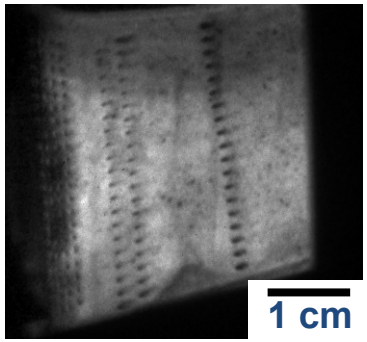
Decay Time Map

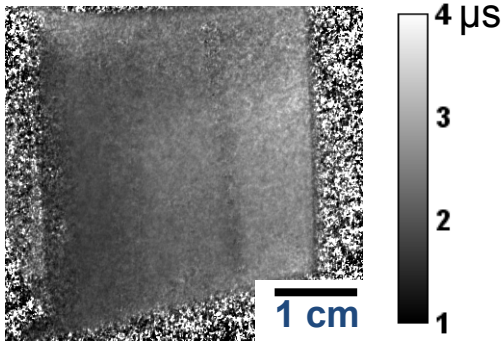


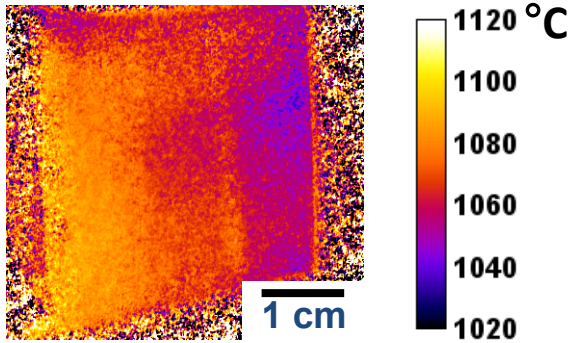
Surface Temperature Map



PLA (throttle) = 101°







Evidence of air film cooling

Distribution/Dissemination

- Patent
  - Patent application filed in November 2012: "Temperature and Pressure Sensors Based on Spin-Allowed Broadband Luminescence of Doped Orthorhombic Perovskite Structures."
- Presentations
  - J.I. Eldridge, T.P. Jenkins, S.W. Allison, D.E. Wolfe, and R.P. Howard, "Surface Temperature Measurements from a Stator Vane Doublet in a Turbine Engine Afterburner Flame Using an Ultra-Bright Cr-Doped $GdAlO_3$ Thermographic Phosphor," 59th International Instrumentation Symposium, Cleveland, May 2013.
  - J.I. Eldridge, "Luminescence-Based Diagnostics of Thermal Barrier Coating Health and Performance," invited lecture to the Division of Combustion Physics, Lund University, Sweden. (included but not exclusively Seedling research)
  - J.I. Eldridge, T.J. Bencic, D.Zhu, M.D. Cuy, D.E. Wolfe, T.P. Jenkins, S.W. Allison, D.L. Beshears, and B. Heeg, "Temperature Measurements of Thermal Barrier Coating Surfaces Using a Cr-Doped $GdAlO_3$ Thermographic Phosphor," 38th International Conference on Advanced Ceramics and Composites, Daytona Beach, January 2014.

Distribution/Dissemination

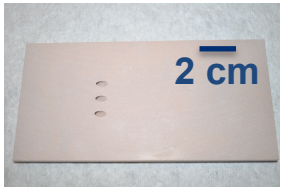
- Papers
  - J.I. Eldridge and M.D. Chambers, "Temperature Sensing Above 1000°C Using Cr-Doped $GdAlO_3$ Spin-Allowed Broadband Luminescence," in *Temperature: Its Measurement and Control in Science and Industry*, Vol 8, AIP Conf. Proc. 1552, 873-878 (2013).
  - 3 papers planned for future
    - Optical thermometer measurements
    - 2D temperature measurements of laser-induced thermal gradient patterns
    - Surface temperature measurements of engine component
- Highlights
  - NASA Glenn Research & Technology Weekly Highlight (twice)
  - AEDC High Mach News press release
- Technology Transfer
  - Cr:GAP downselected for stator vane temperature measurements in Honeywell engine test (AFRL VAATE project). Engine test 5/13.
  - Cr:GAP downselected for turbine blade temperature measurements in Pratt & Whitney F117 engine (NASA VIPR project). Preliminary engine test 12/13; final engine test 2015.
  - Incorporated into Phase I seedling award titled "Real-Time Closed-Loop Modulated Turbine Cooling."

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 be used to calibrate pyrometers when effects of reflected radiation and unknown emissivity create temperature uncertainty.
- Will become important validation tool for thermal profiling of turbine engines designed for reduced fuel consumption and cleaner fuel burn.
- Will be ideal testing technology to validate engine cooling designs.
- Near-term: Attractiveness as thermographic phosphor for turbine engine environments may lead to adoption as phosphor of choice in many non-NASA applications.

Next Steps

- 2D temperature mapping of thermal gradients produced by better designed air-film cooling (in collaboration with Vik Shyam).



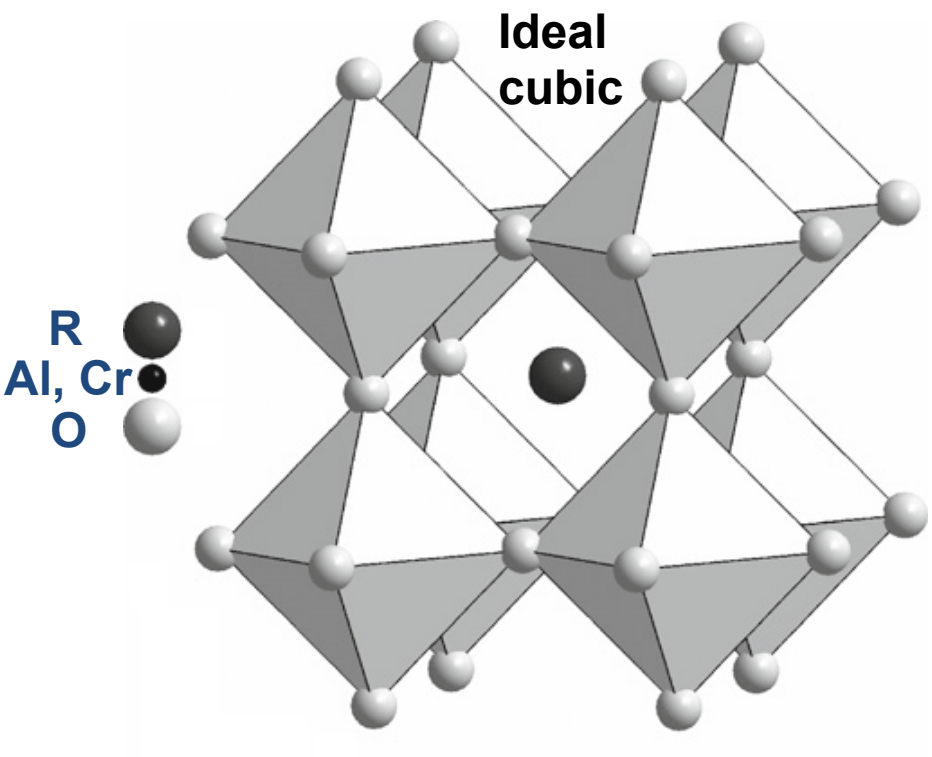
- Improve and automate image analysis for temperature mapping.
  - Include temperature uncertainty estimates.
- Write papers on technological advance & implementations.
- Advocate for adoption as combustion test cell diagnostic.
- Search for shorter wavelength emission phosphor for internal engine measurements.
- Transfer technology to Aeronautical Sciences & Vehicle Systems Safety Technologies (VSST).

Thank you to ARMD Seedling Fund for opportunity to devote time & resources to bring an innovation to maturation.

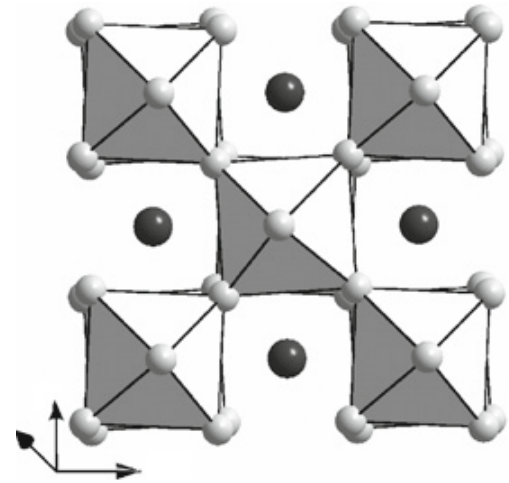
Orthorhombic Rare Earth Perovskites $RAlO_3$ Meet Criteria

Tightly bonded AlO_6 Octahedra Exhibit Strong Crystal Field

High ΔE



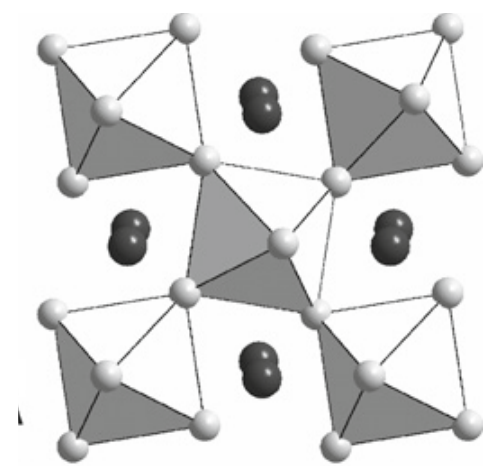
(No parity-forbidden $^4A_2 \rightarrow {}^2T_1$, $^2T_2$ absorption)



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)

Background

- 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.