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# Surface Temperature Measurements from a Stator Vane Doublet in a Turbine Engine Afterburner Flame Using a YAG:Tm Thermographic Phosphor

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# Jeff Eldridge

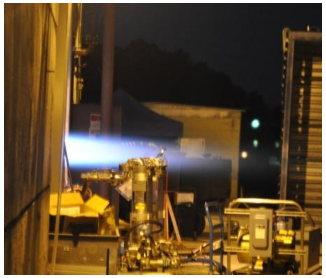
- In a NASA career spanning over twenty-five years, Dr. Eldridge has most recently worked towards developing spectroscopy-based health monitoring tools for both space and turbine engine applications. He has coauthored over 70 publications and has made over 50 conference presentations and invited tutorials/lectures.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

# Background

- Thermographic phosphors for temperature measurements exhibit unique advantages over thermocouples and pyrometers for turbine engine environments.
  - Non-contact
  - No interference from reflected radiation
  - Insensitive to surface emissivity
  - Intrinsically surface sensitive
- AFRL VAATE project successfully demonstrated temperature measurements from thermographic phosphor coated Honeywell stator vane doublet in afterburner flame of AEDC J85-GE-5 turbojet test engine.

**Component Testing in Engine Afterburner Flame**

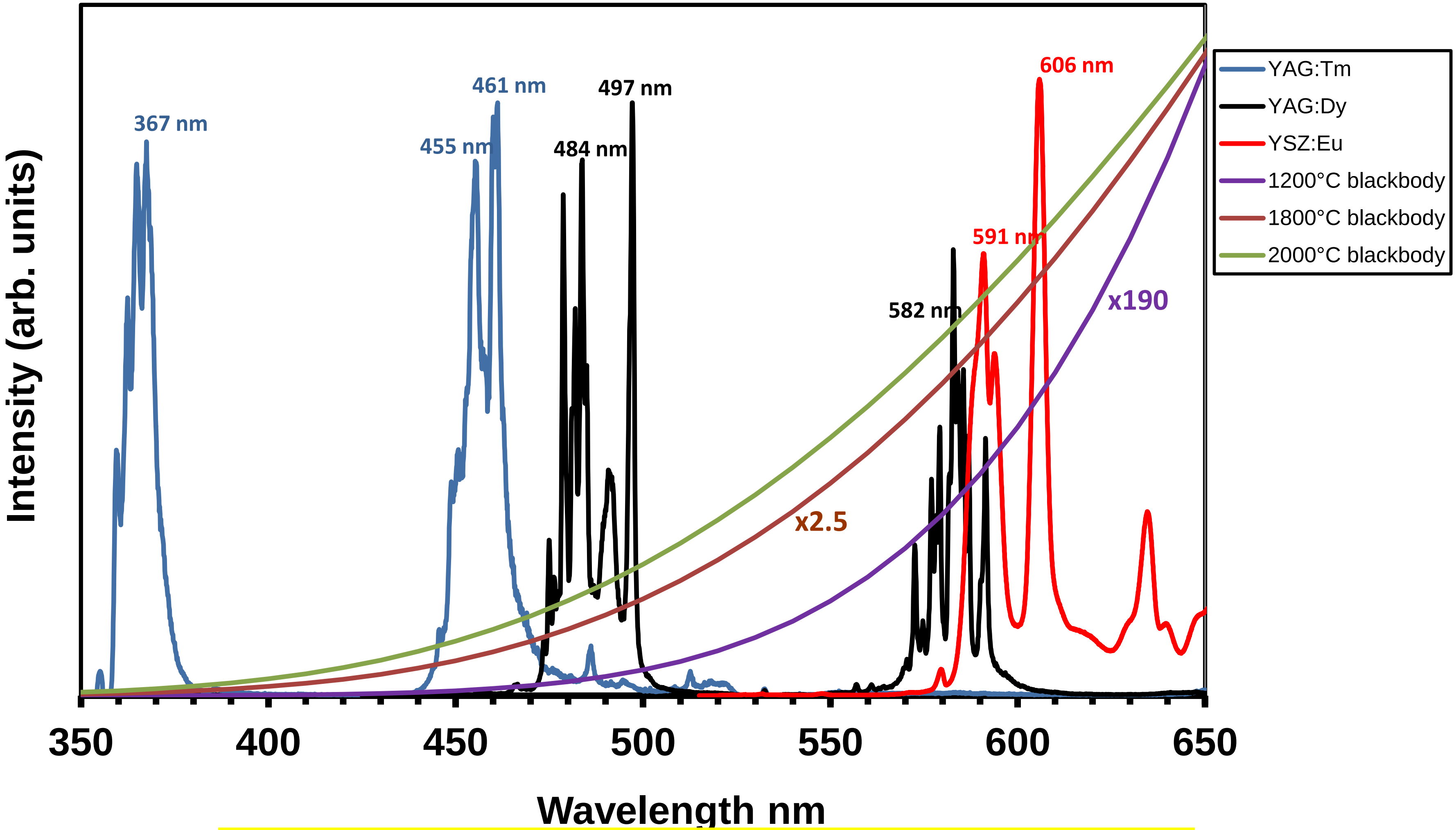
Vane doublet with temperature sensing coating in test fixture.



Afterburner flame from J85 test engine.

- However, overwhelmed by reflected combustion radiation during Honeywell HTF7000 engine test.
- **Challenge: Develop thermographic phosphor that emits at wavelength coinciding with greatly reduced reflected radiation intensity.**

# Thermographic Phosphor Emission vs. Blackbody Background Intensity



- Blue emission effective for low thermal background produced by hot surface.
- UV emission will be necessary for low thermal background from reflected combustor radiation.

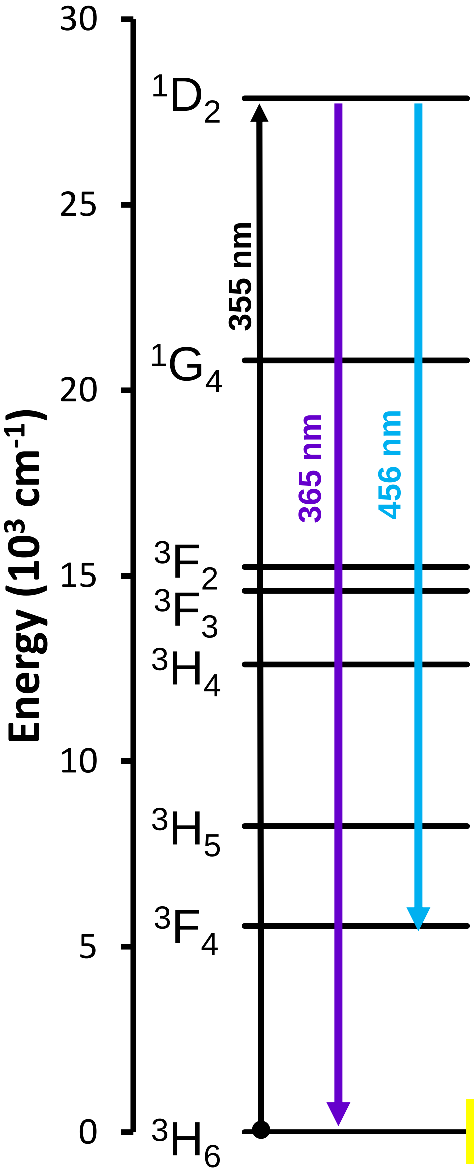
# Objectives

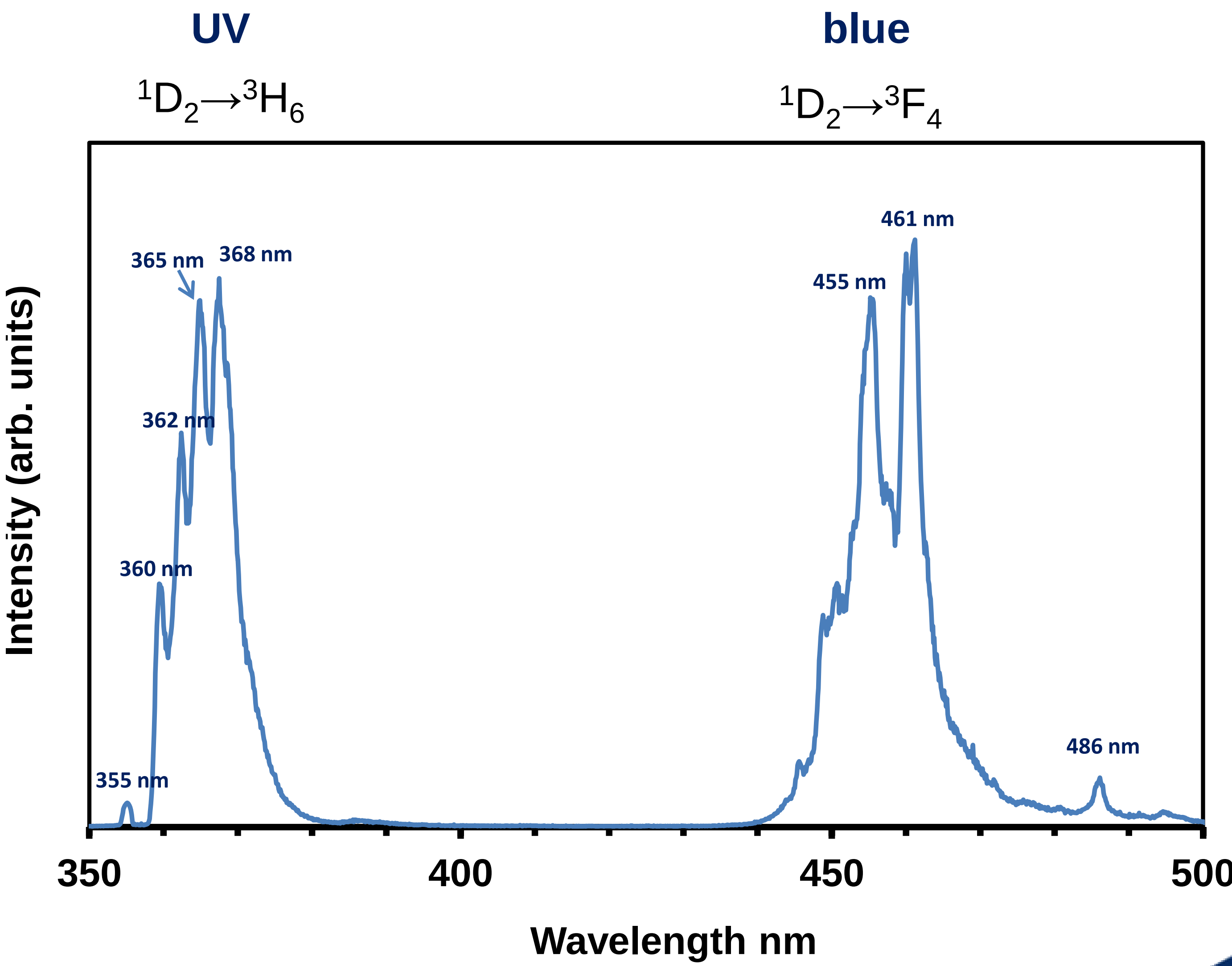
- Implement blue and UV emission bands from YAG:Tm for engine probe measurements.
- Demonstrate temperature measurements from YAG:Tm-coated Honeywell stator vane doublet in afterburner flame of UTSI J85-GE-5 turbojet test stand.
  - Monitor vane surface temperature
    - Steady-state conditions
    - Engine acceleration

# Characterize and Calibrate YAG:Tm Luminescence Decay Temperature Dependence (blue and UV Emission)

# Emission Spectrum from YAG:Tm-Coating

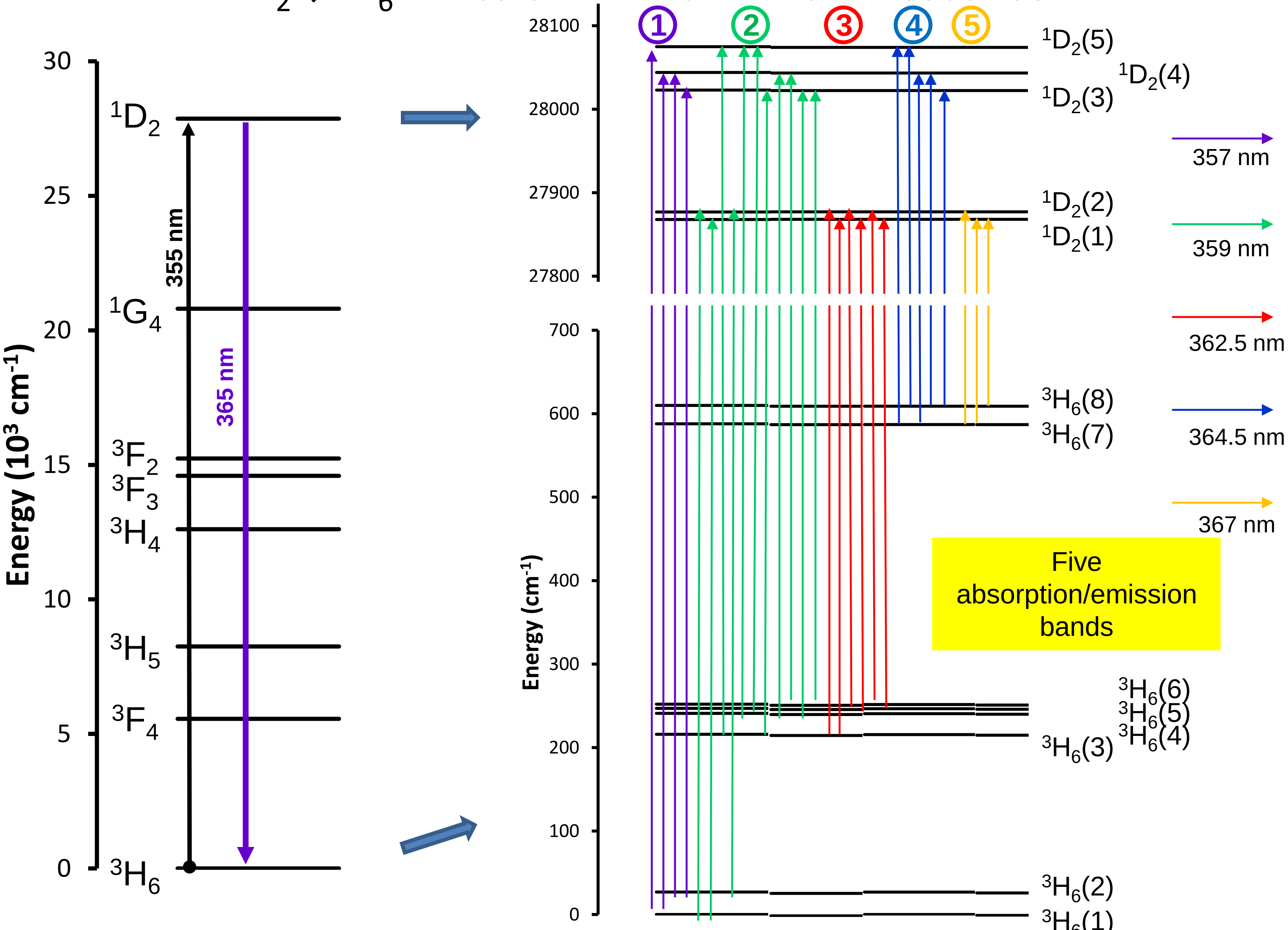
## 355 nm excitation





UV emission will be needed in presence of reflected combustor radiation.

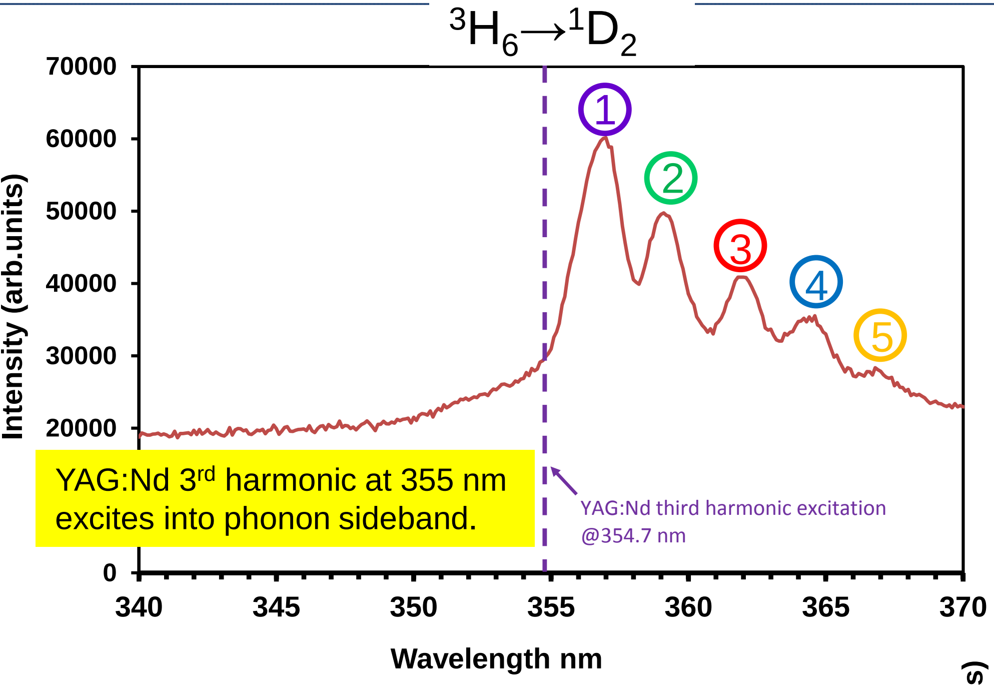
# Stark Energy Levels Associated with $^3H_6 \rightarrow {}^1D_2$ Absorption and $^1D_2 \rightarrow {}^3H_6$ Emission in YAG:Tm Luminescence



Five absorption/emission bands

Skipped forbidden transitions between like symmetry Stark levels & transitions involving $^3H_6$(9-13)

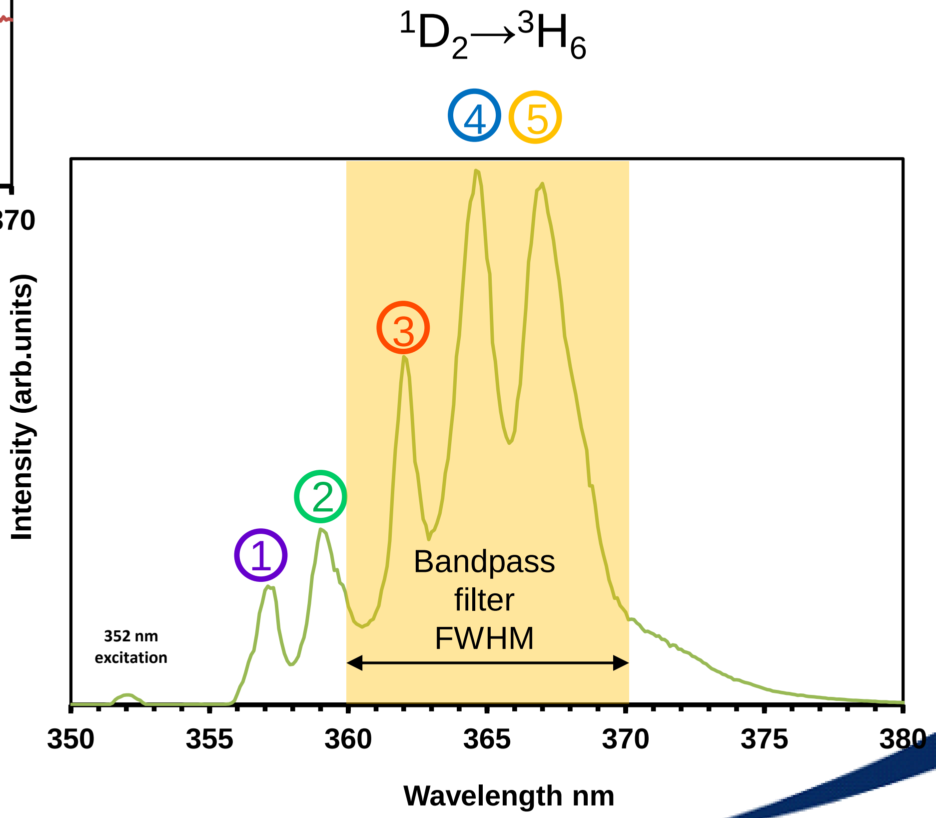
# YAG:Tm(0.8%) Powder Excitation & Emission Spectra



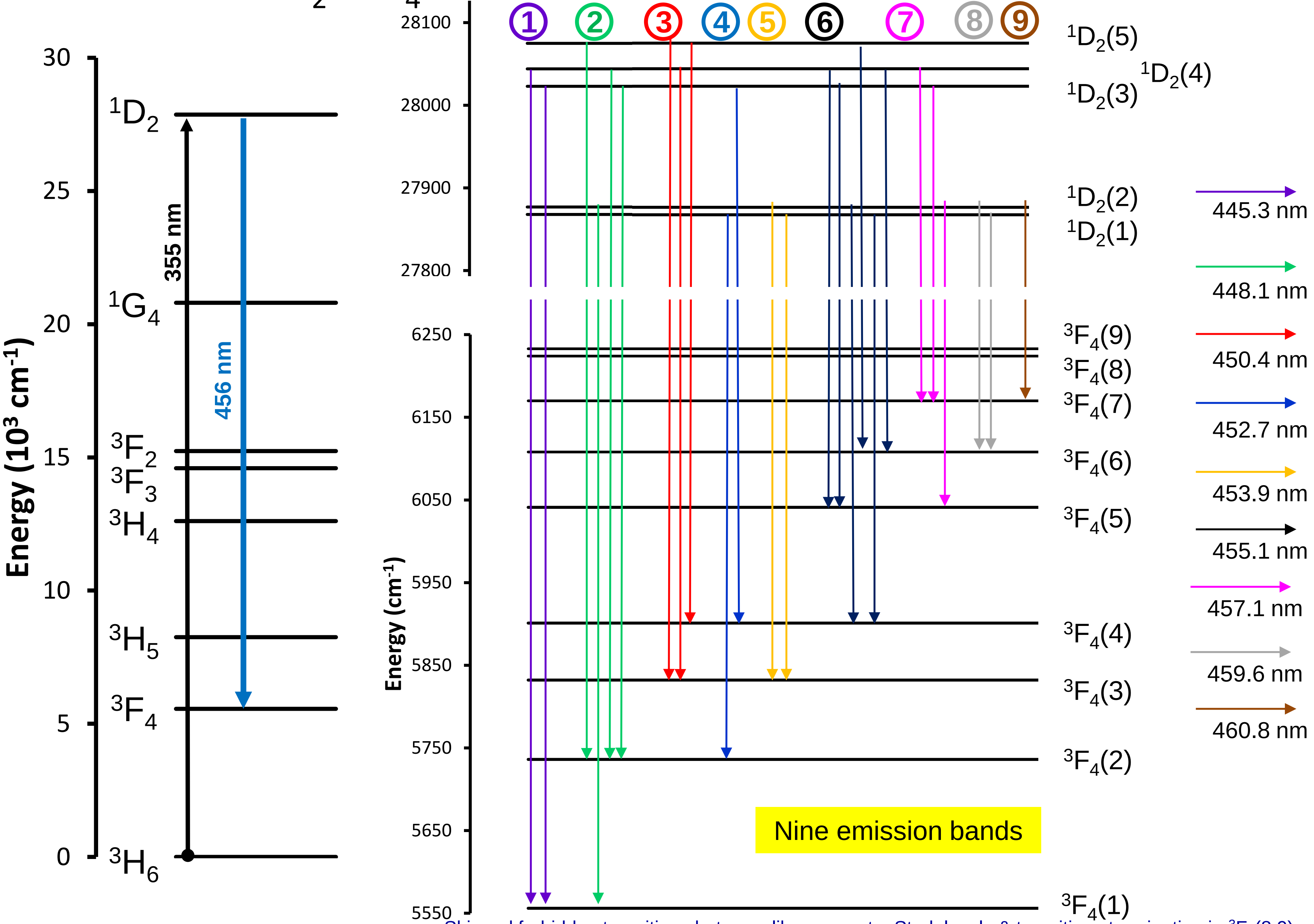
YAG:Nd 3rd harmonic at 355 nm excites into phonon sideband.

## Excitation Spectrum @460 nm Emission

## Emission Spectrum @352 nm Excitation

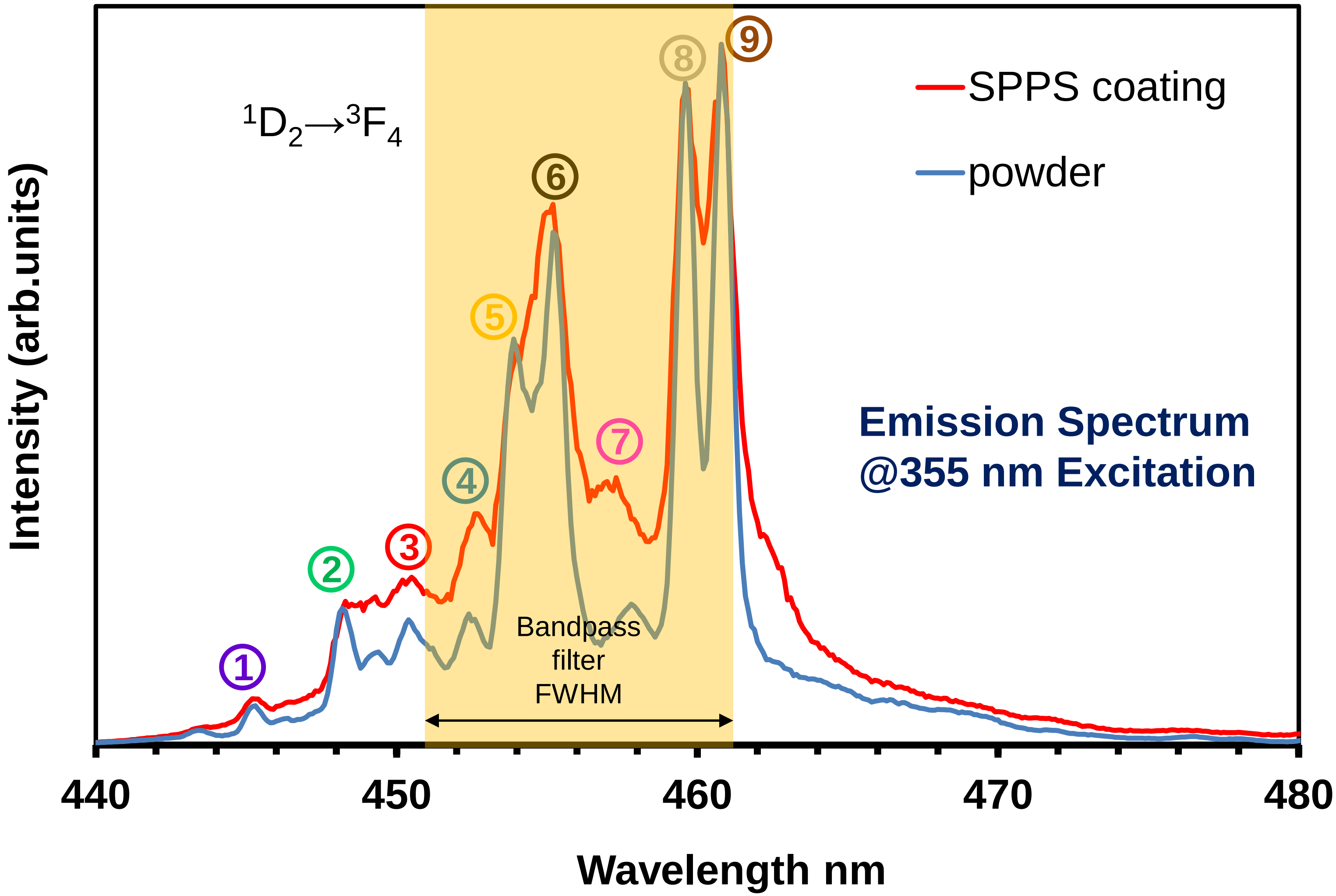


# Stark Energy Levels Associated with $^3H_6 \rightarrow {}^1D_2$ Absorption and $^1D_2 \rightarrow {}^3F_4$ Emission in YAG:Tm Luminescence



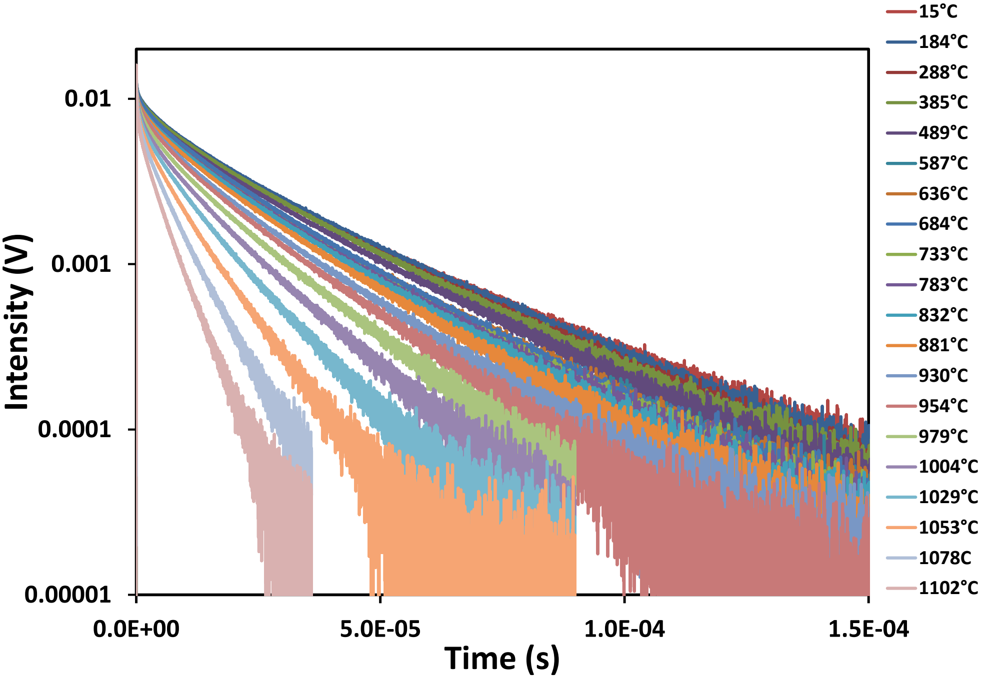
Skipped forbidden transitions between like symmetry Stark levels & transitions terminating in $^3F_4(8,9)$

# YAG:Tm $^1D_2 \rightarrow {}^3F_4$ Emission Spectra



- The $^1D_2 \rightarrow {}^3F_4$ emission is more complex than the $^1D_2 \rightarrow {}^3H_6$ emission.
- Broad background in SPPS coating suggests somewhat more disordered structure.

# SPPS YAG:Tm(1.0%) Coating Emission Decay Curves



365 nm Decay

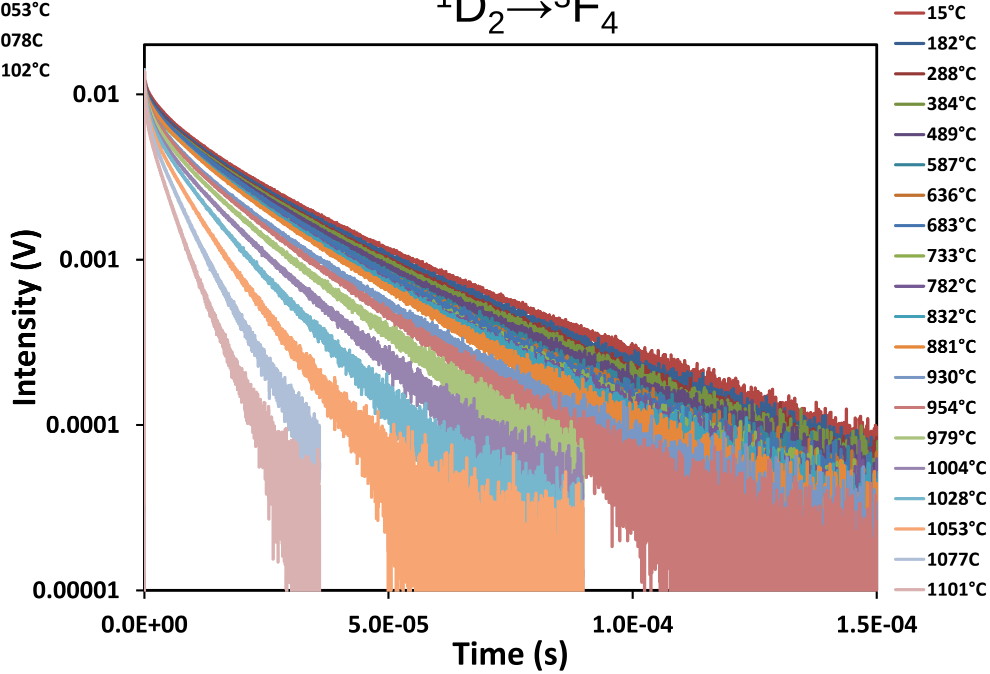
$^3H_6 \rightarrow {}^1D_2$

Decay behavior os 365nm emission matches behavior observed at 456nm emission.

Decay rate (slope) sensitive to temperature for T > 800°C.

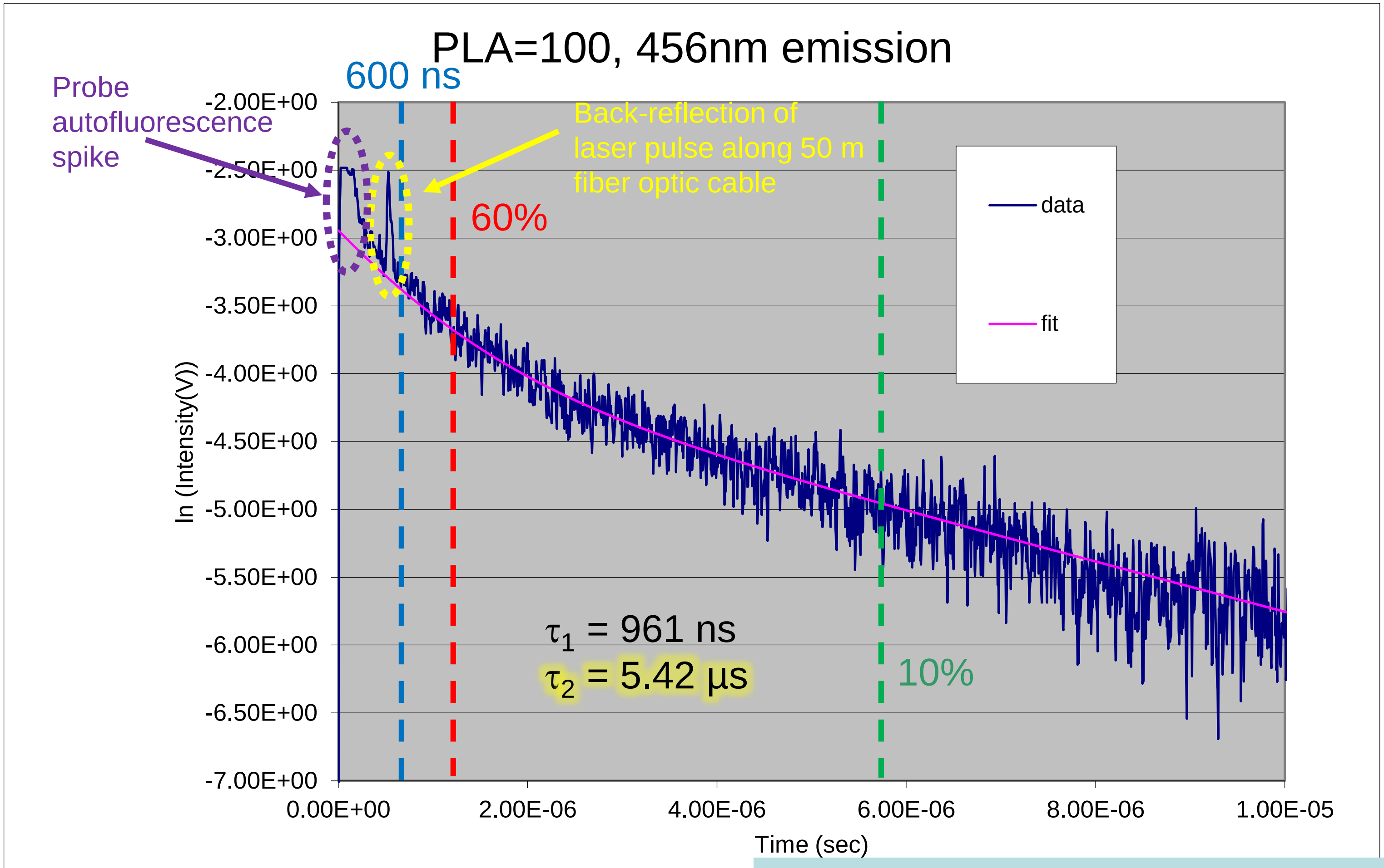
456 nm Decay

$^1D_2 \rightarrow {}^3F_4$



# Fitting Procedure for Emission Decay

- **Fitting Window Selection Based on Probe Data**
- **Model for Emission Decay**



Probe autofluorescence spike

Back-reflection of laser pulse along 50 m fiber optic cable

$\tau_1$ = 961 ns

$\tau_2$ = 5.42 µs

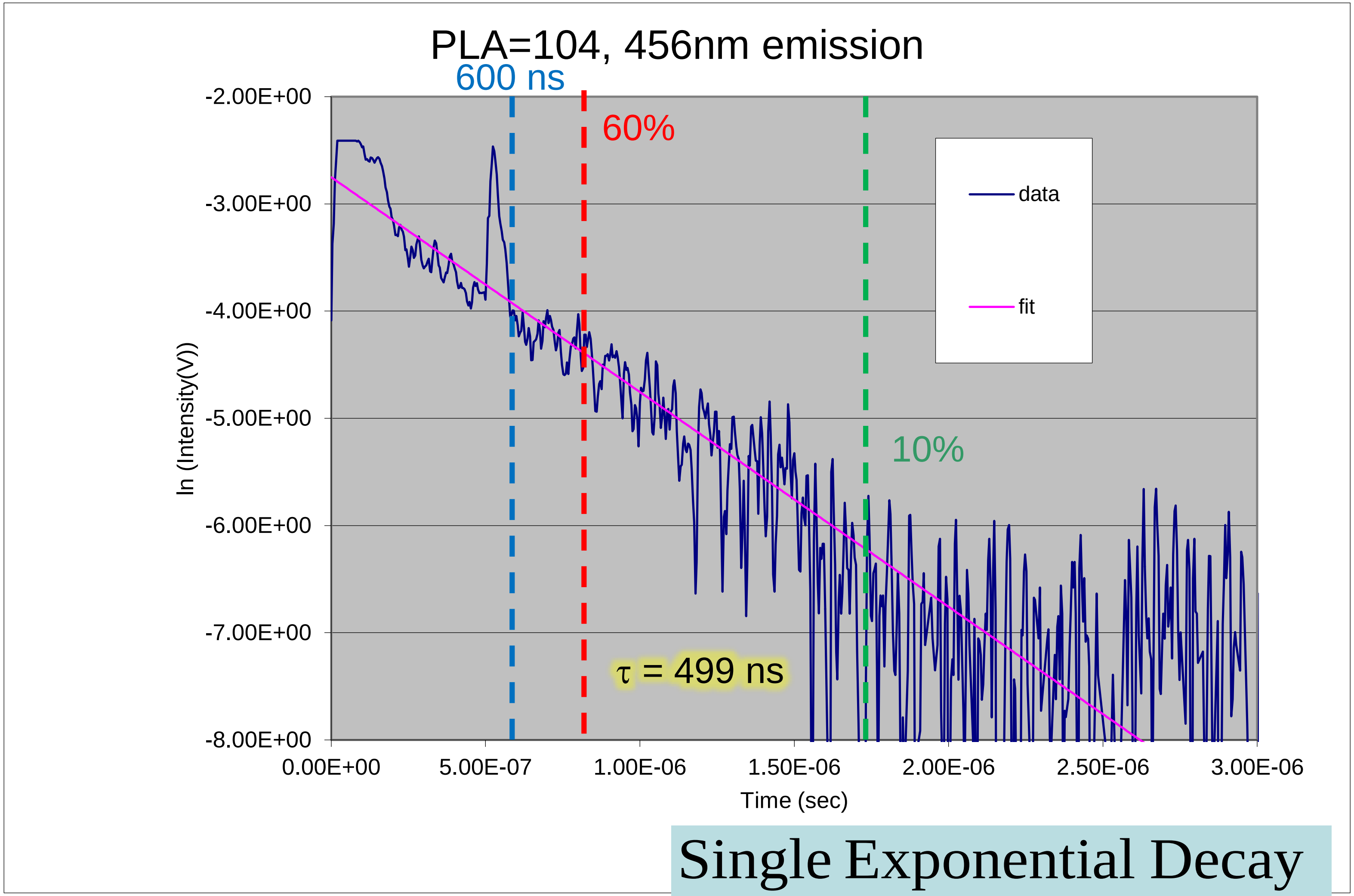
1. Select 600 ns as $I_0$. (avoids backreflection peak)
2. Intensity-based fitting window from 60% to 10% $I_0$.
3. Fit with double exponential.
4. Discard $\tau_1$.
5. Use $\tau_2$ for temperature indication.

### Biexponential Decay

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

# Fitting Procedure for Emission Decay

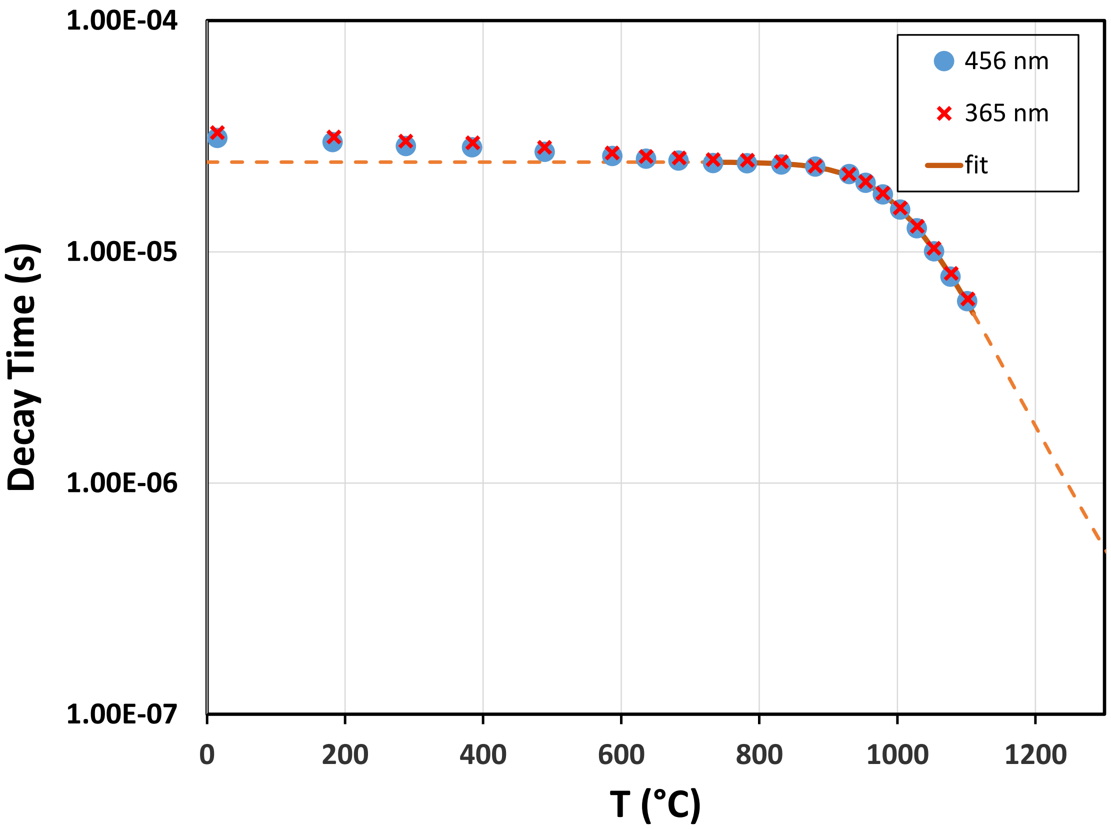
- When fit to double exponential is unstable at high temperatures
- Fit with single exponential instead



Single Exponential Decay

$$I = I_0 e^{-t/\tau}$$

# Modeling Decay Time Temperature Dependence
# SPPS YAG:Tm 365 & 456nm emission bands

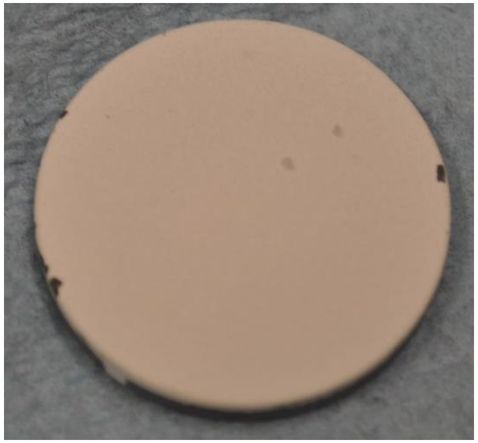


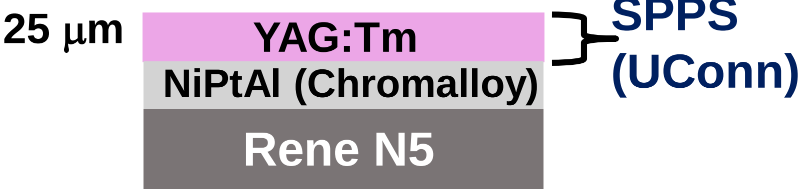
$$\frac{1}{\tau}=\frac{1}{\tau_R}+\frac{1}{\tau_{NR}}e^{-\Delta E/kT}$$

Simple model with quenching due to thermally activated nonradiative decay (by cross-over to charge transfer state).

# Transitioning from Coupon Specimens to Engine Component Testing

2.54 cm diam





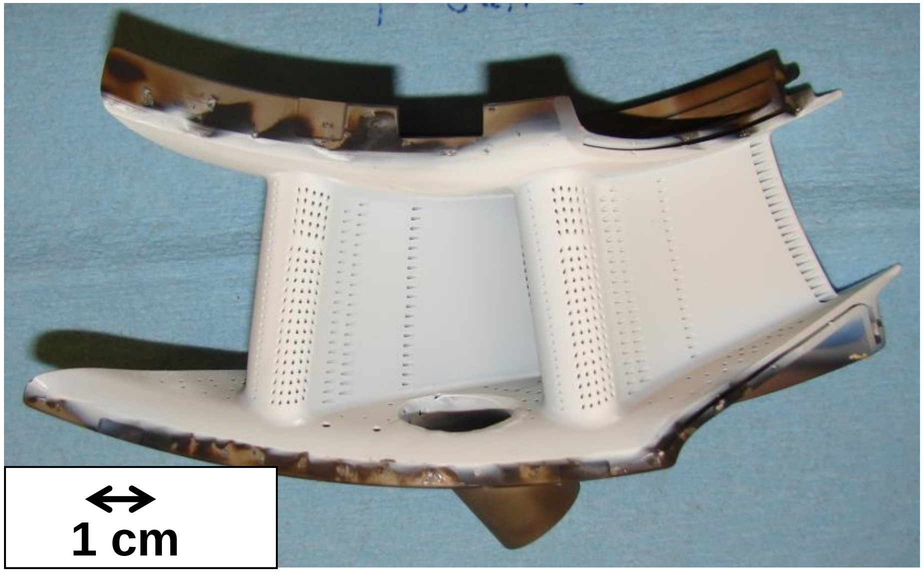
25 μm

YAG:Tm

NiPtAl (Chromalloy)

Rene N5

SPPS (UConn)

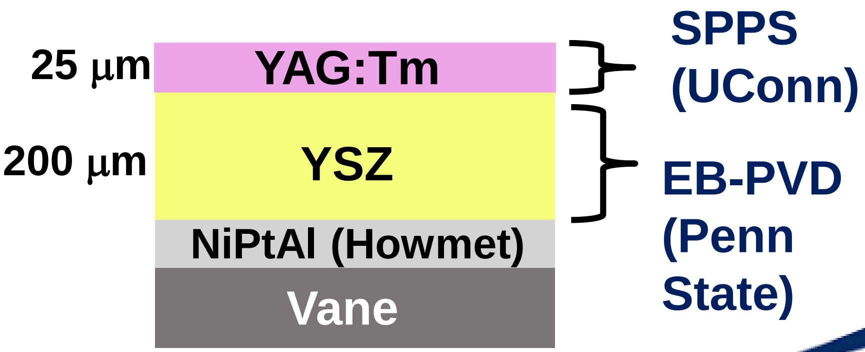


YAG:Tm coated superalloy coupon

YAG:Tm coated Honeywell stator vane doublet

**SPPS = solution precursor plasma spray**

**EB-PVD = electron-beam physical vapor deposition**



25 μm

YAG:Tm

200 μm

YSZ

NiPtAl (Howmet)

Vane

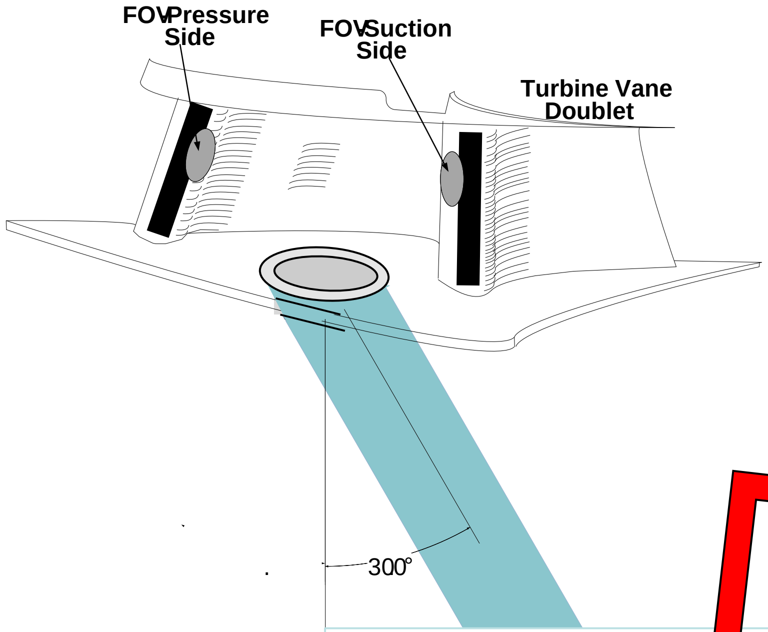
SPPS (UConn)

EB-PVD (Penn State)

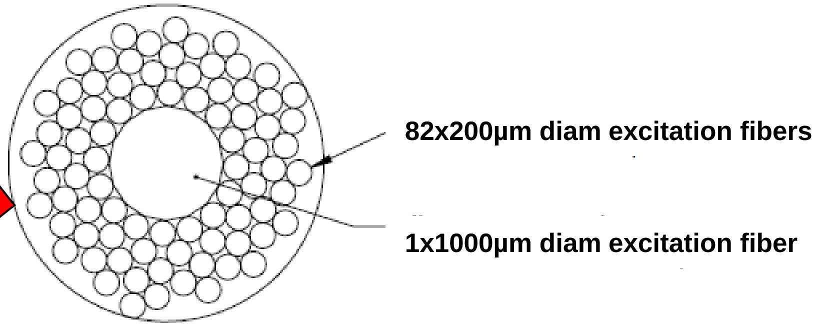
# Probe Design for Vane Measurements

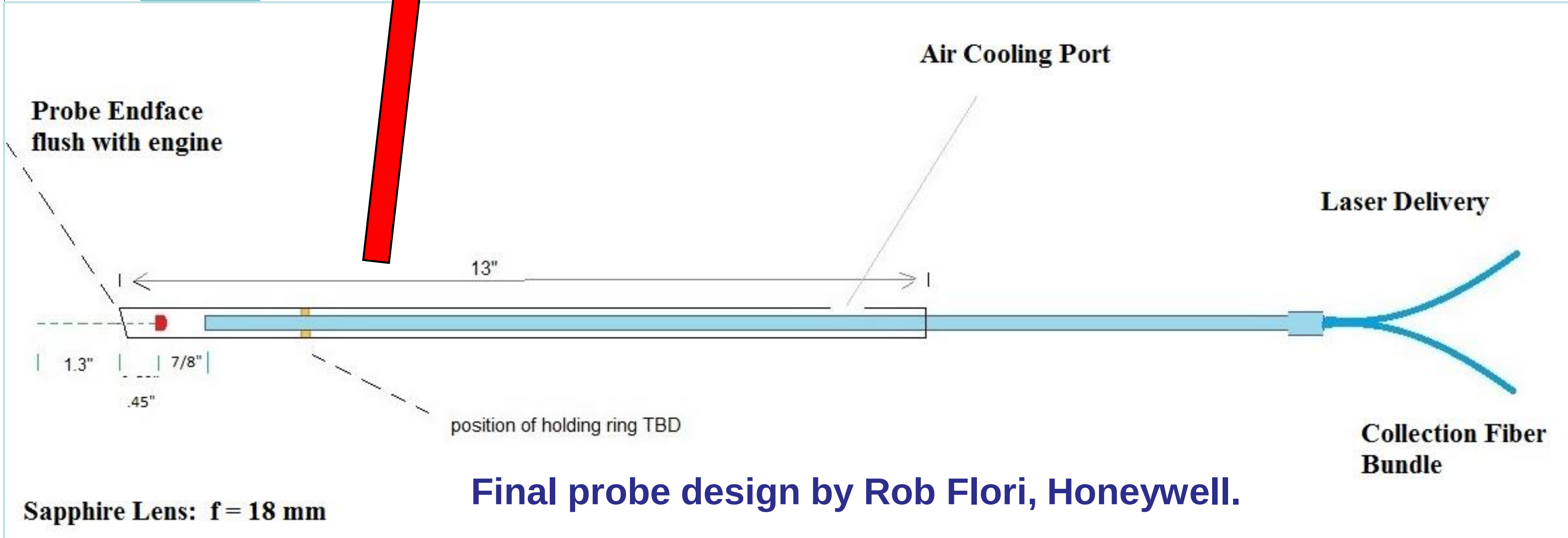
## Constraints for probe design

- •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

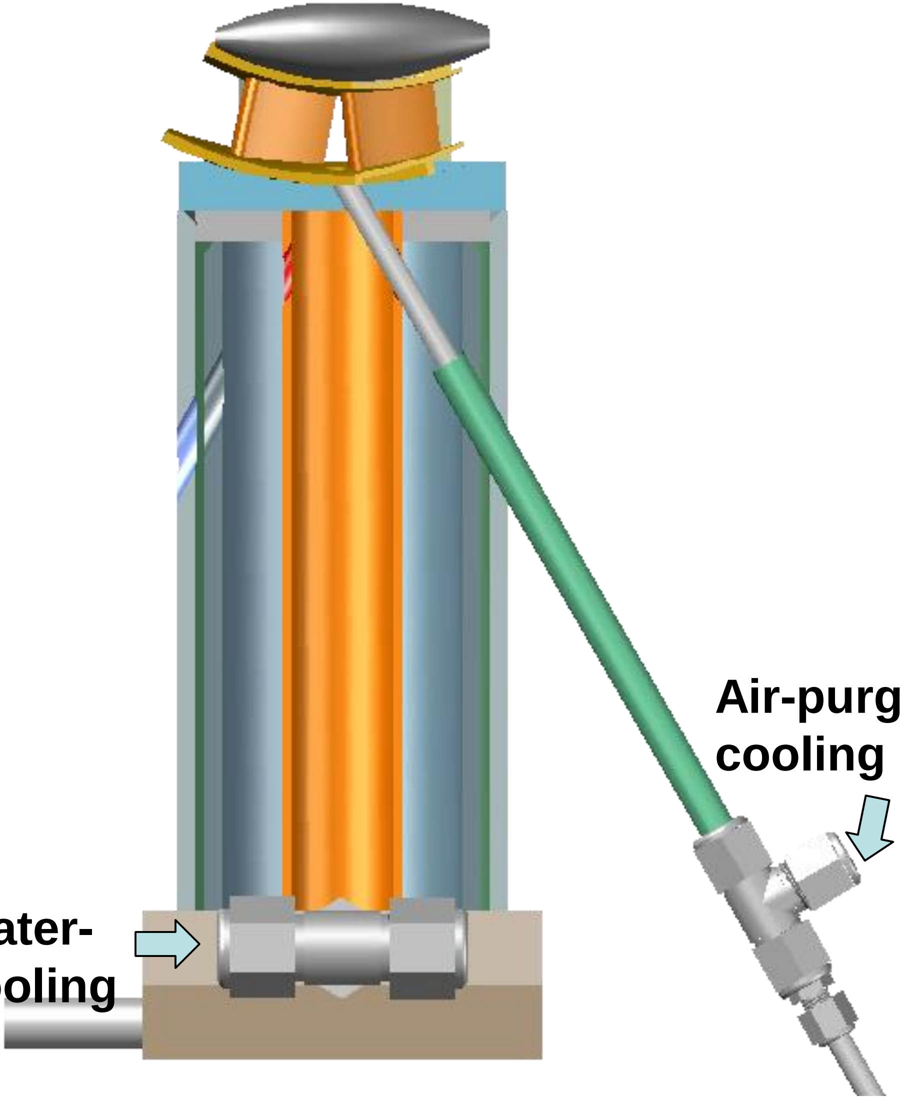




Final probe design by Rob Flori, Honeywell.

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

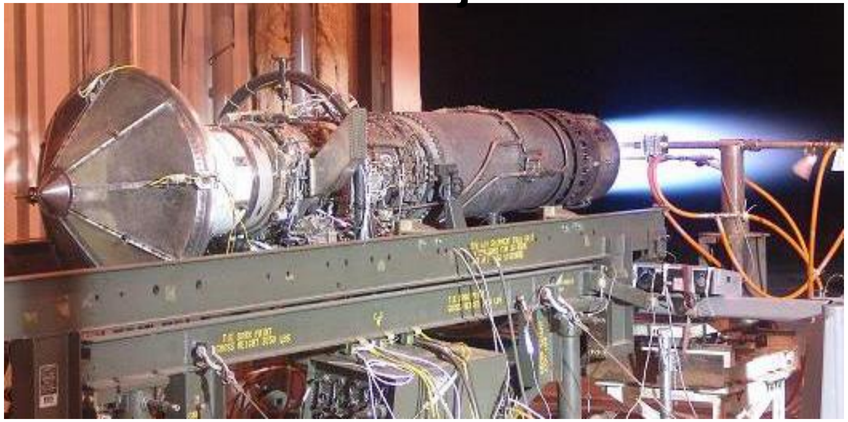
## High-Velocity Exhaust Gas up to 1760ºC



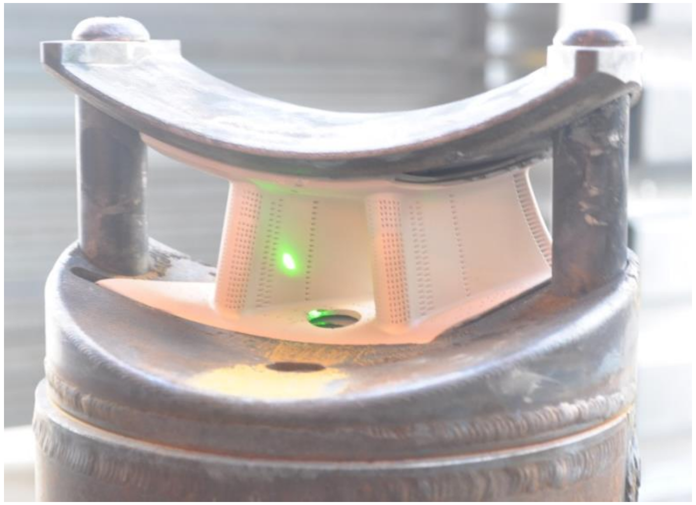
Air-purge cooling

Water-cooling

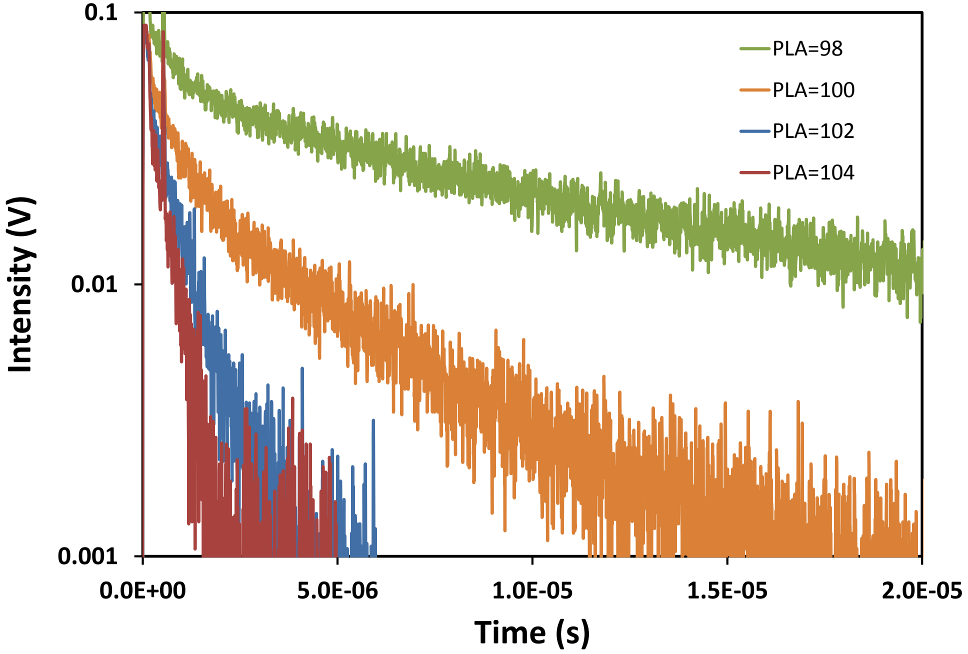
J85-GE-5 Turbojet Test Stand



Mounted vane doublet



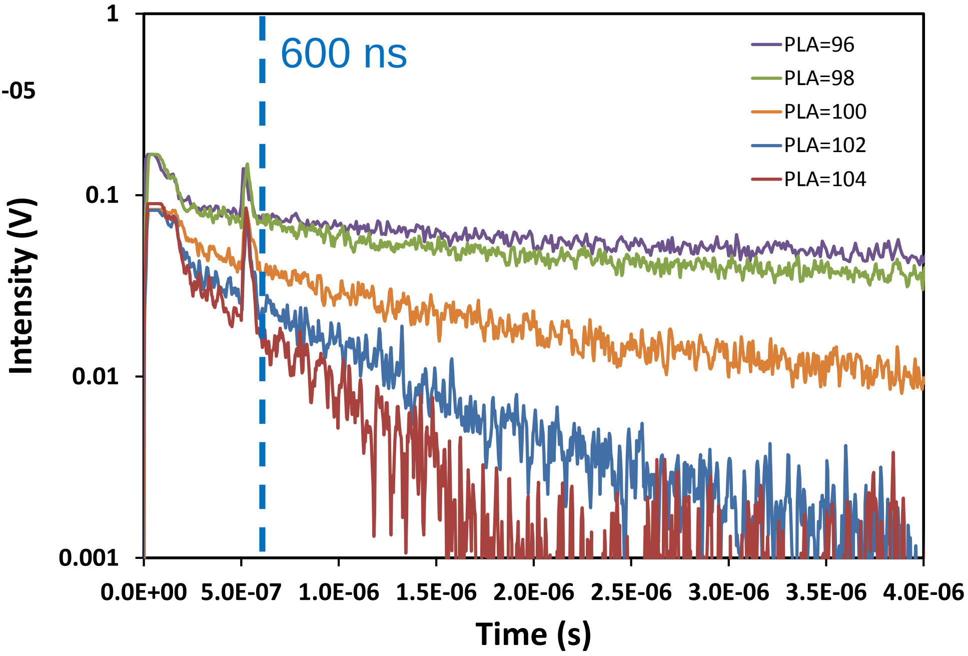
# YAG:Tm Emission Decay at Steady-State Afterburner Conditions
# 456 nm decay



Measurements acquired at:

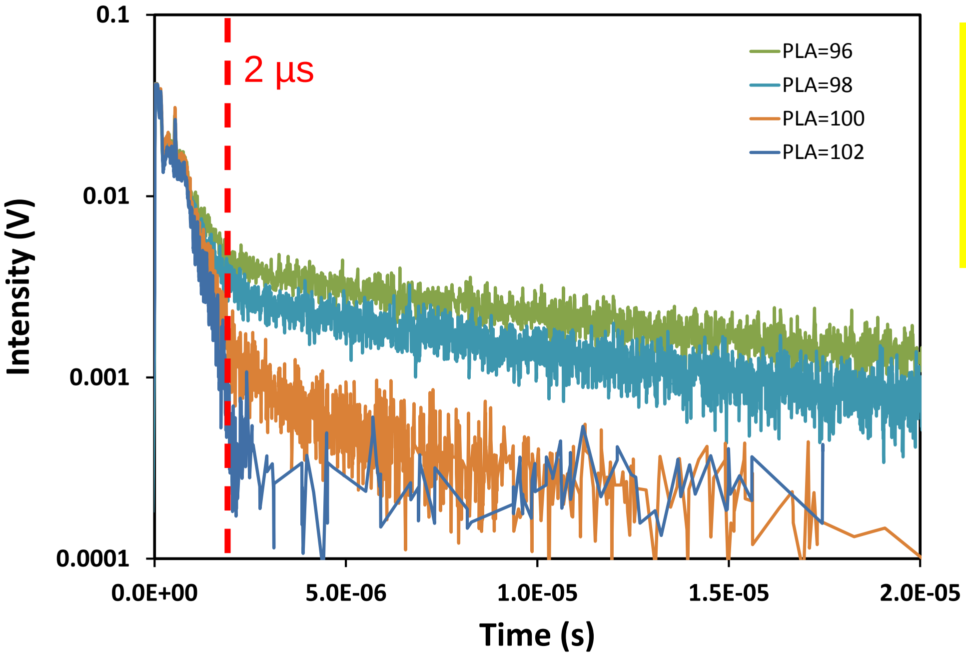
- PLA = 15 (idle)
- PLA = 90 (full military)
- PLA = 94 (with afterburner)
- PLA = 96
- PLA = 98
- PLA = 100
- PLA = 102
- PLA = 104

Each decay was averaged over 16 laser pulses (20 pulses/s)



PLA = 98 is onset of obvious temperature sensitivity.

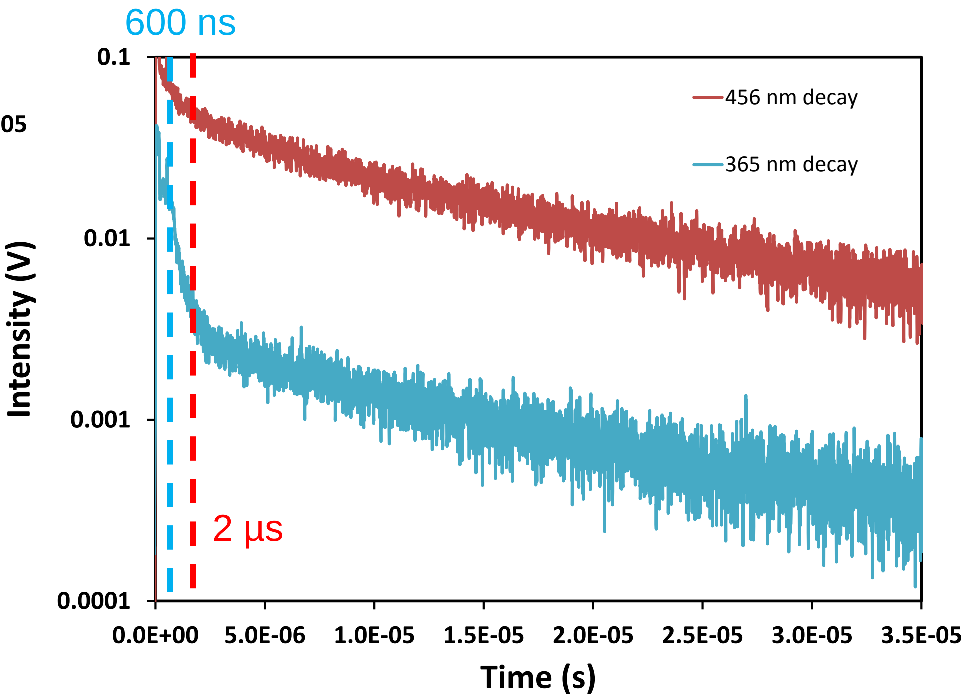
# YAG:Tm Emission Decay at Steady-State Afterburner Conditions
# Comparison of 456 nm & 365 nm Decay



365 nm Decay
PLA = 96 to 104

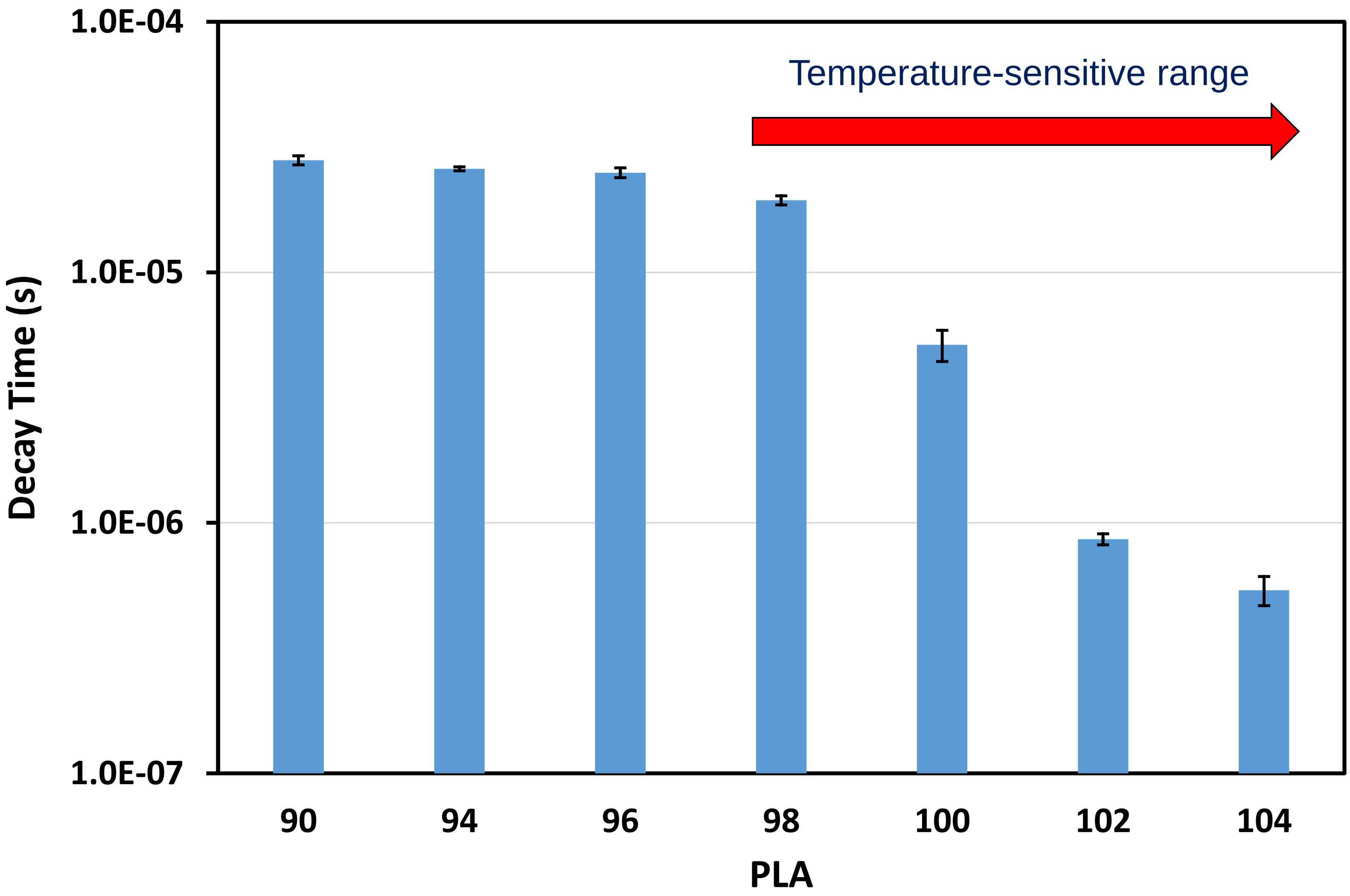
- Much longer, more intense probe autofluorescence distortion out to 2 µs.
- Can only use decay past 2 µs.
- Data not useable beyond onset of temperature sensitivity at PLA = 98.

## 456 vs 365 nm Decay
## PLA = 98



Only 456 nm emission decay could be used to make temperature measurements for afterburner tests with probe.

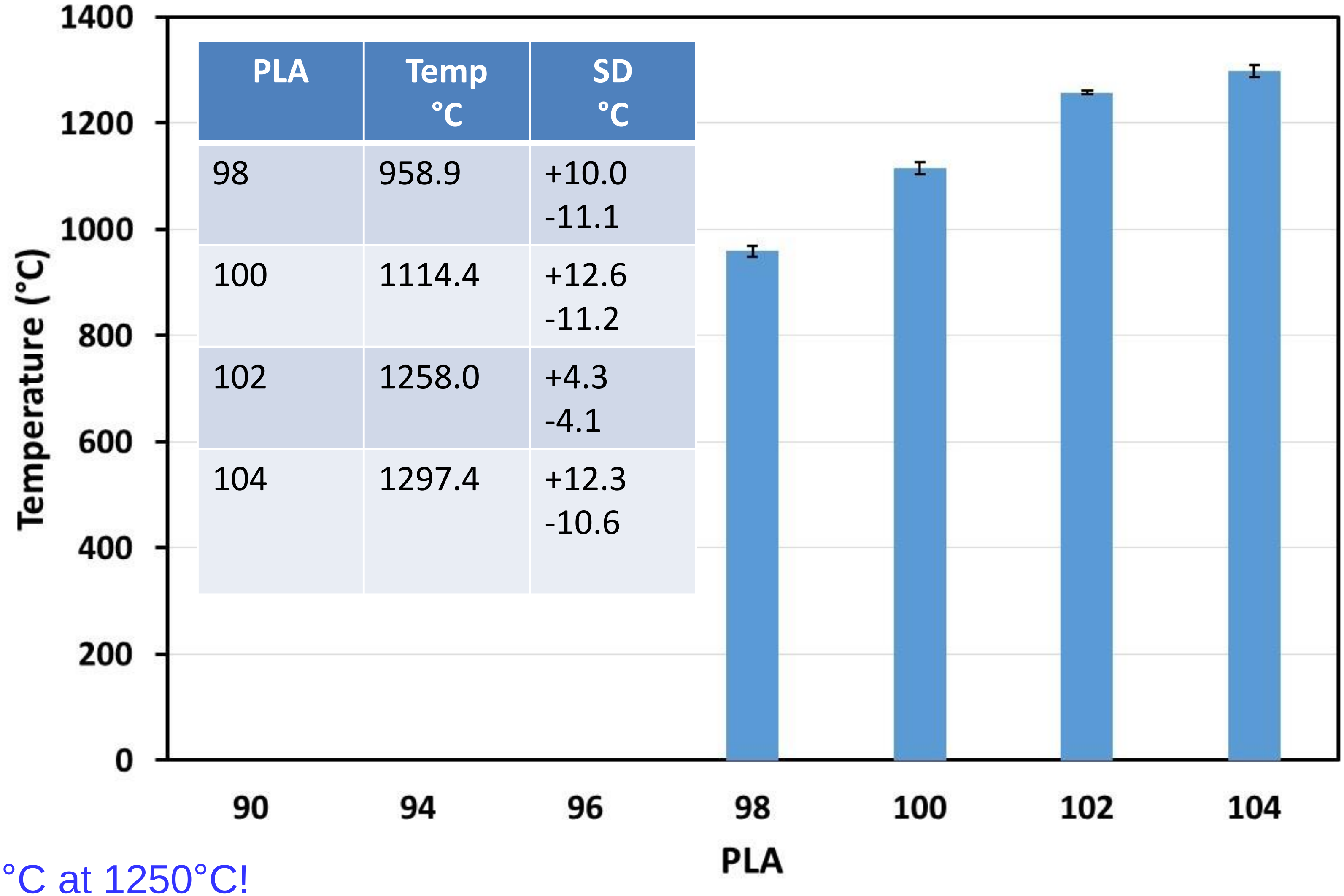
# YAG:Tm Emission Decay Time vs. PLA Throttle Setting



PLA = 98 is onset of obvious sensitivity of decay time to temperature.

# Temperature vs. PLA Throttle Setting

## (temperature determined from YAG:Tm decay time)



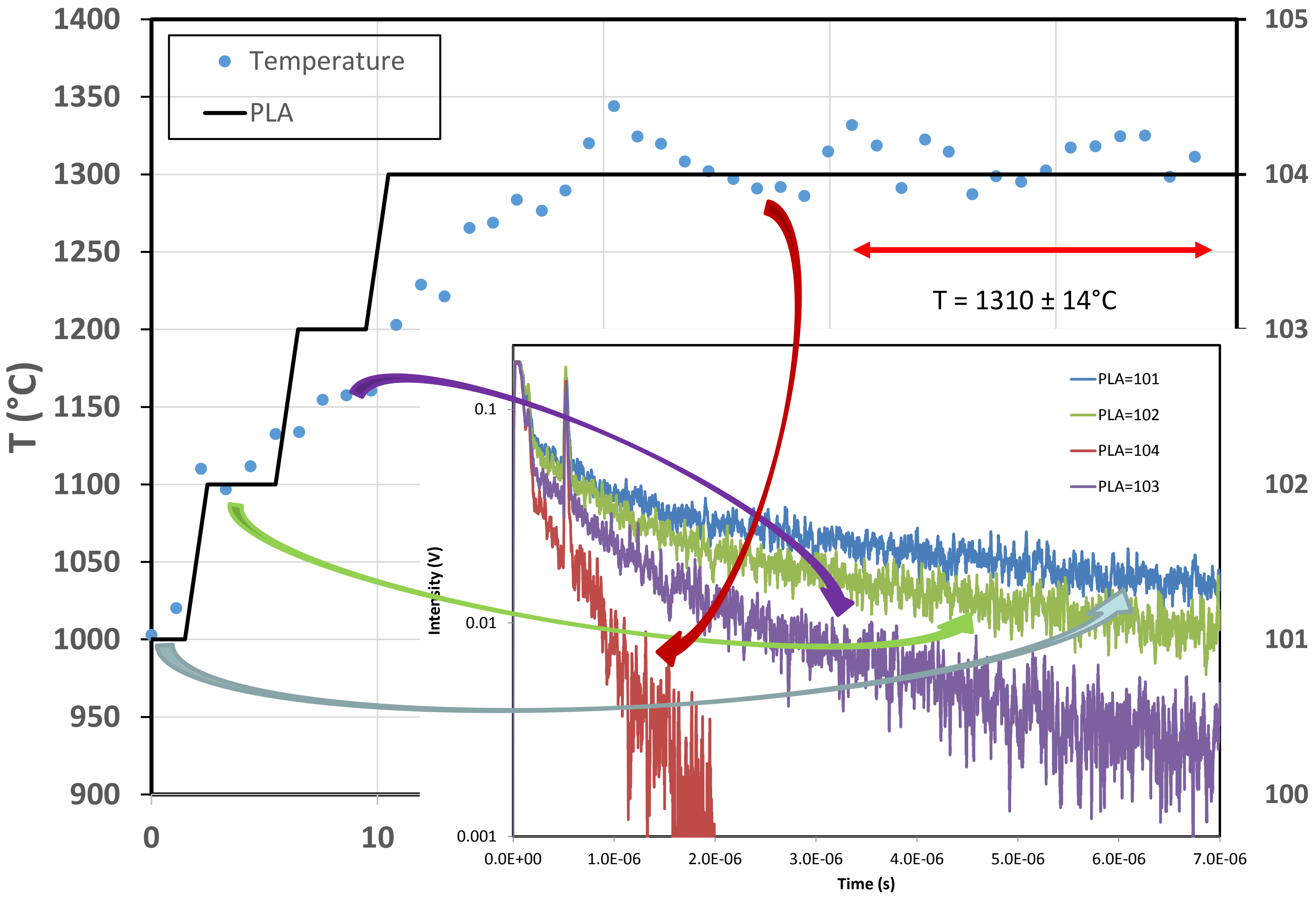
| PLA | Temp °C | SD °C |
|---|---|---|
| 98 | 958.9 | +10.0<br>-11.1 |
| 100 | 1114.4 | +12.6<br>-11.2 |
| 102 | 1258.0 | +4.3<br>-4.1 |
| 104 | 1297.4 | +12.3<br>-10.6 |

- ±5°C at 1250°C!
- 1297°C highest temperature for thermographic phosphor field measurement!

# Temperature Measurements During Throttle Acceleration

## from PLA = 94 to 104

## ~1 Hz temperature reading acquisition rate



# Probe Artifacts and Recommended Remedies

- Laser back reflection spike at 530 ns using 50 m collection fiber optic.
  - *Remedy: Locate PMT near engine & use short collection fiber.*
- Probe introduces distortion of initial decay that is much more severe for 365 vs. 456 nm emission.
  - Greater distortion prevented useful 365 nm emission decay data from afterburner tests.
  - Distortion associated with Raman scattering inside fiber optics that is worse for 365 nm emission because it is near 355 nm excitation wavelength.
  - *Remedy: appropriate short-pass filter at output of laser delivery fiber and long-pass filter before collection fibers.*

# Conclusions

- Successfully demonstrated temperature measurements in lab environment for both blue and UV emission band decays from YAG:Tm.
- Successfully demonstrated temperature measurements (static & dynamic) up to 1300°C from YAG:Tm-coated Honeywell stator vane doublet in afterburner flame of UTSI J85-GE-5 turbojet test stand using blue YAG:Tm emission band decay.
- Redesign of engine probe optics will allow implementation of UV YAG:Tm emission band decay for superior rejection of background reflected combustion radiation.

# Acknowledgments

- Funding from NASA Aeronautics Research Mission Directorate.
- AFRL VAATE Project for foundational research and leveraging of VAATE probe design & cooling mount for afterburner testing.
- Honeywell for providing stator vane doublet & critical aspects of probe design.
- AEDC/UTSI Propulsion Research Facility Team for conducting J85 afterburner tests.
- Penn State (Doug Wolfe) for EB-PVD coatings.
- UConn (Eric Jordan & Jeff Roth) for SPPS coatings.
- Dave Beshears (EMCO) for testing assistance.