Chapter 6: Surface Thermometry – Thermographic Phosphors

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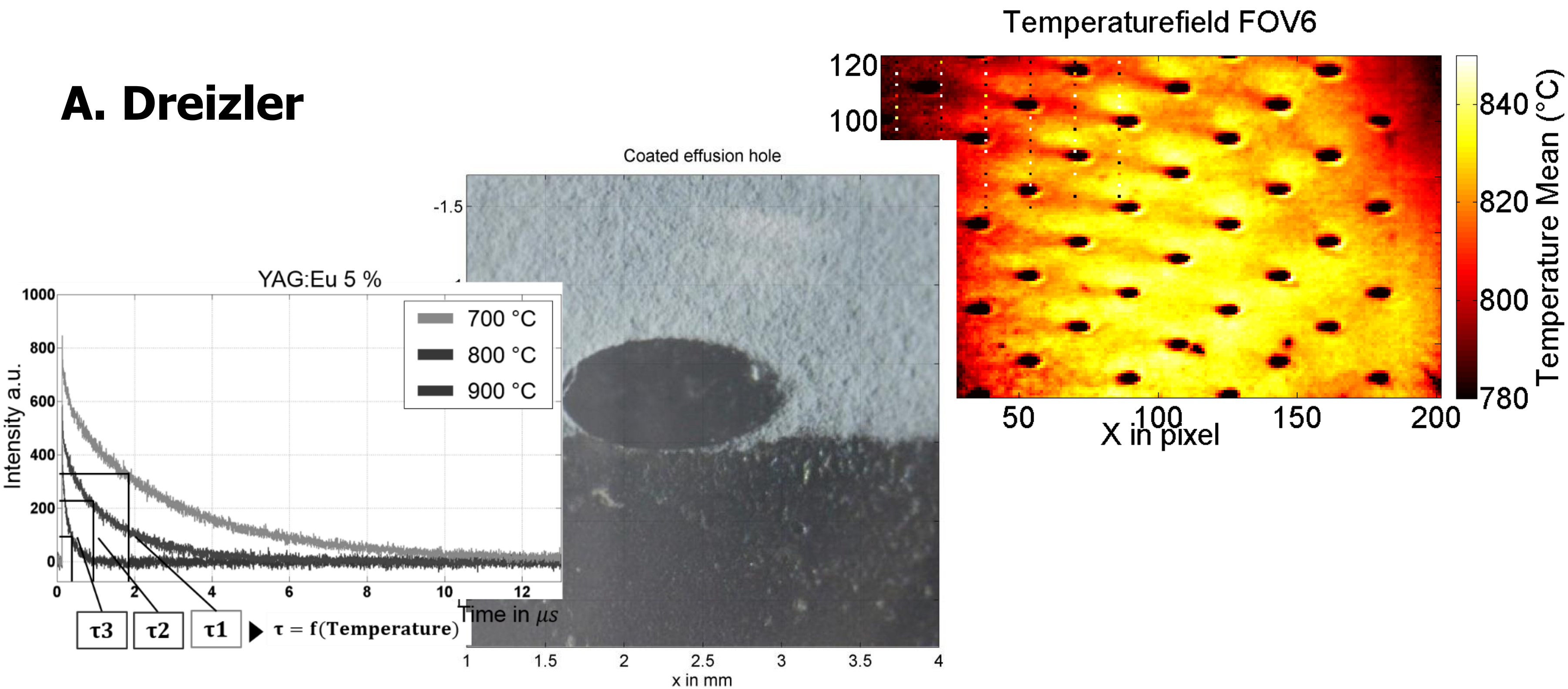
TECHNISCHE UNIVERSITÄT DARMSTADT

RSM Reaktive Strömungen + Messtechnik

A. Dreizler



Outline phosphor thermometry

- Introduction & Motivation
- “Decay-Time Method” versus “Ratio Method”: comparing precision and accuracy
- Error treatment for decay-time method
- Application examples

Surface temperature: diagnostics

Thermocouples

- Invasive, limited spatial and temporal resolution, only point measurements

Pyrometry (Infrared thermometry)

- Emission coefficient generally unknown
- Sensitive against chemiluminescence and stray light

Temperature sensitive paints (TSP - coated), thermoliquid crystals (TLC)

- Temperature range < 380 K

Heat sensitive paints (HSP - coated)

- No temporal resolution

Thermographic phosphors (TGP – coated)

+ Broad temperature sensitive range (7 K -1870 K)

+ Insensitive against blackbody radiation, stray light and chemiluminescence

+ High spatial and temporal resolution, 2D diagnostics

Thermographic Phosphors

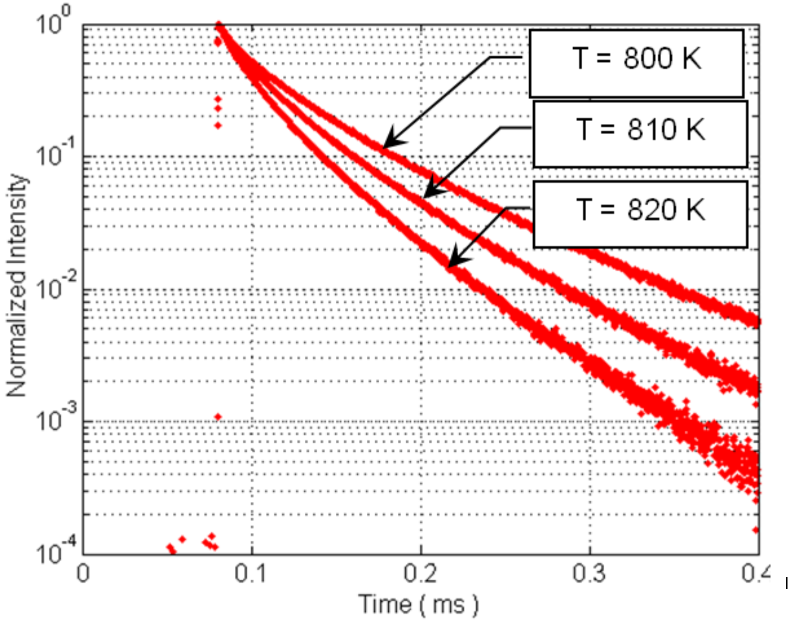
Thermographic phosphors:

- Rare-earth or transition metal doped ceramic materials
- Exploit temperature dependent spectroscopic properties following electronic excitation

Introduction & Motivation I

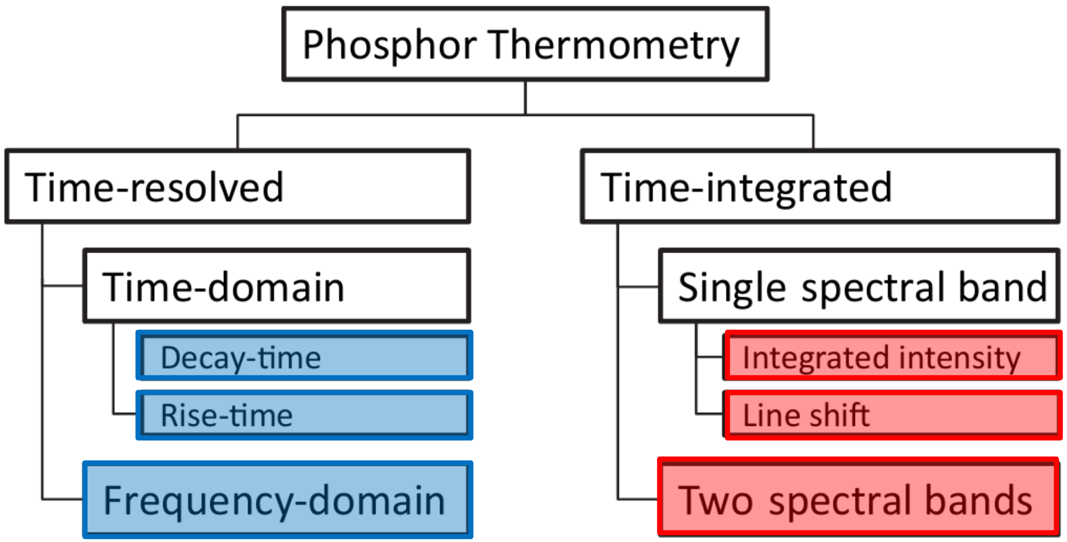
Principle of Phosphor Thermometry:

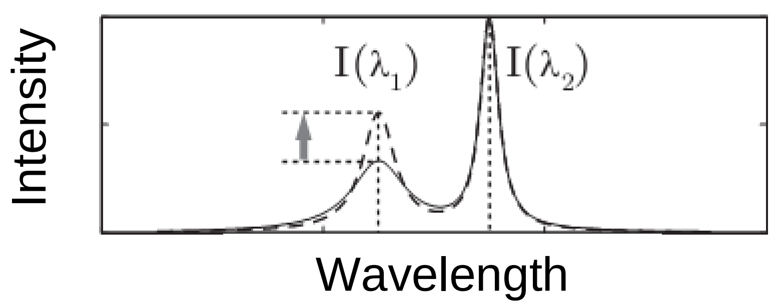
- Coat surface with thermographic phosphor
- Excite coating with UV-light source
- Detect emission with appropriate device either
    - time-resolved (fixed spectral range) or
    - Time-integrated and spectrally resolved (fixed temporal range)



Introduction & Motivation II

Approaches of Phosphor Thermometry



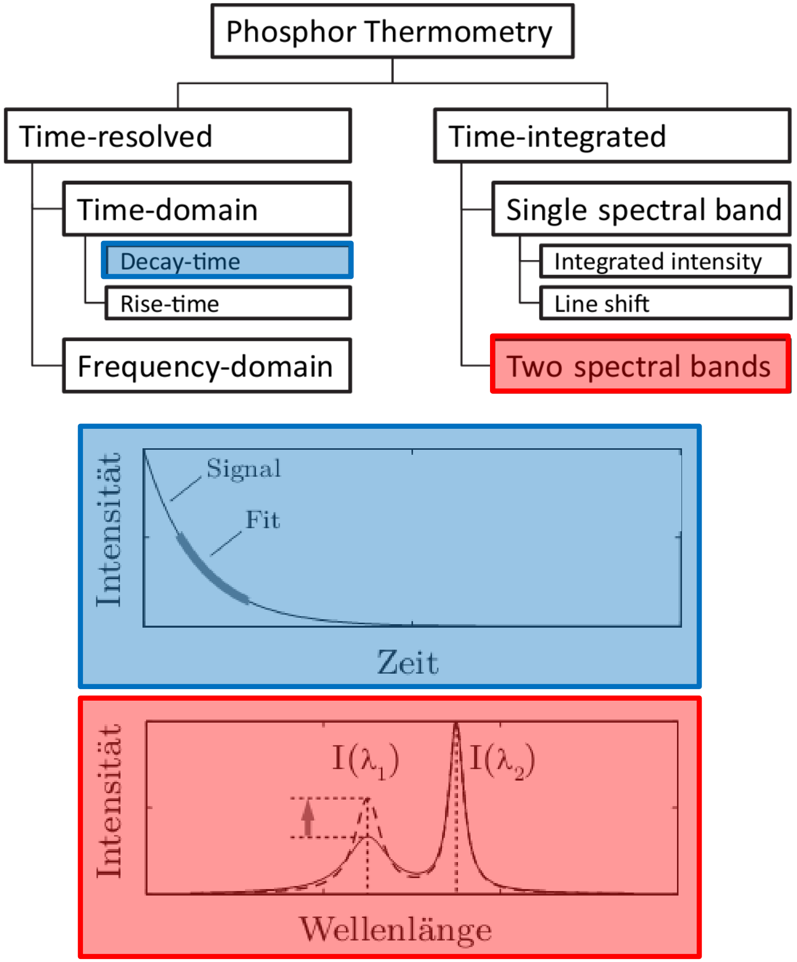


$$R = \frac{I(\lambda_1)}{I(\lambda_2)}$$

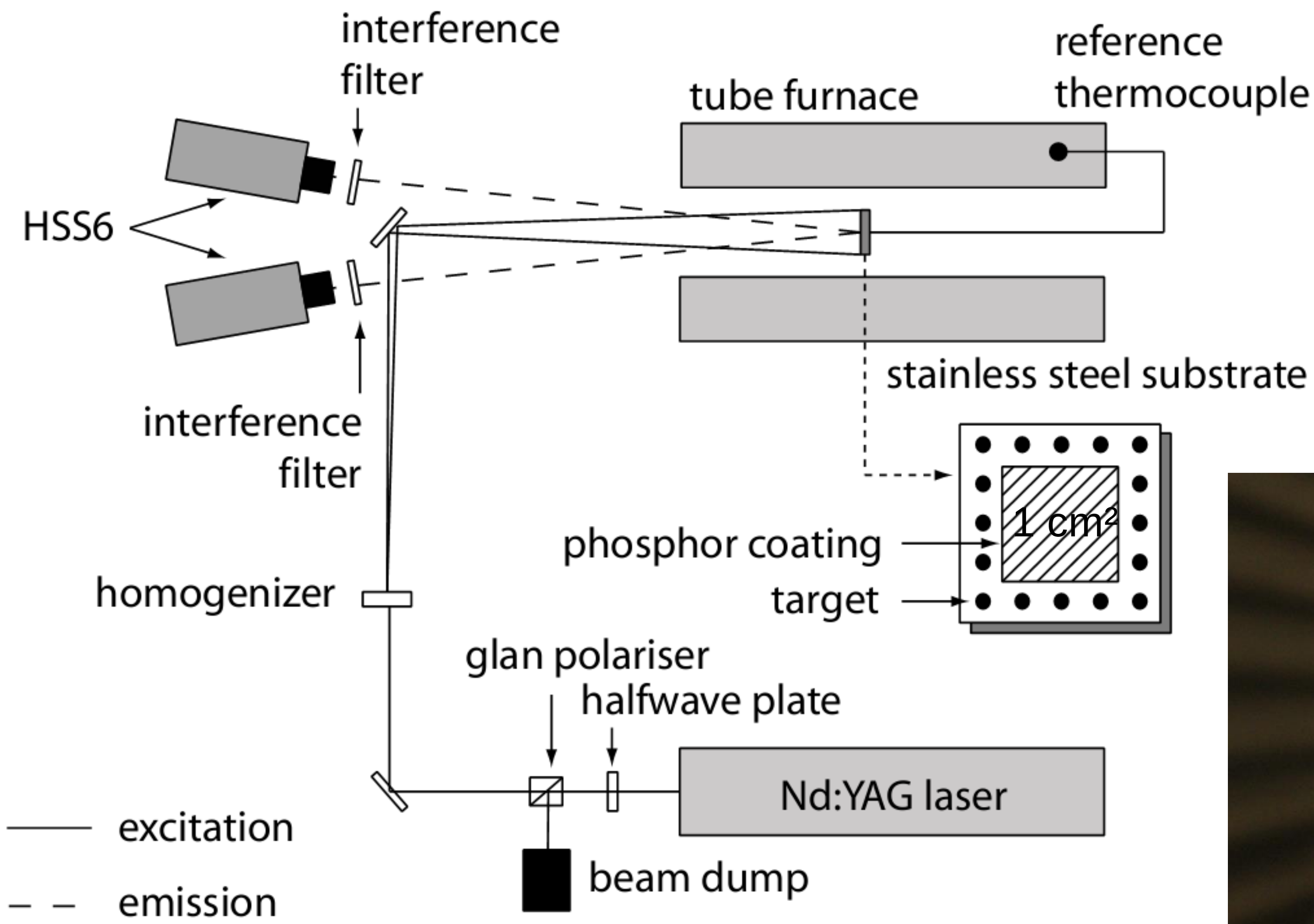
Fuhrmann et int. Dreizler. Proc. Combust. Inst. (2013) 34:3611 – 3618

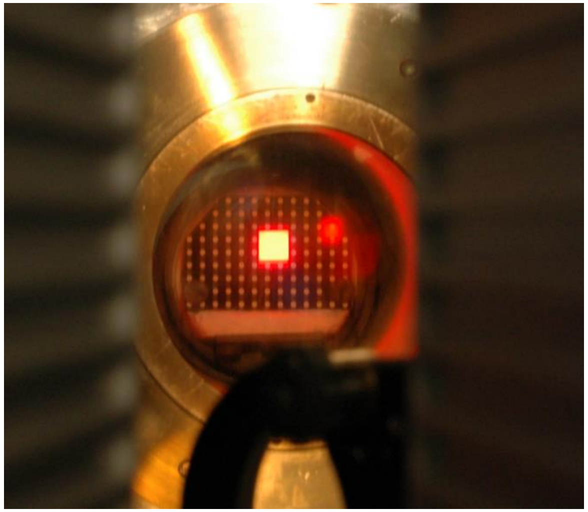
Introduction & Motivation III

- Comparison of the two most popular approaches:
  - Luminescence Lifetime (Decay-time)
  - Intensity Ratio (Two-line)
- Motivation:
  - Decision support required for users
  - Comparison to highlight pros vs cons
  - Investigation of sensitivities, precision, accuracy and application
- Procedure
  - Use two CMOS high-speed cameras (same data-set)
  - Exemplified for phosphor which exhibits sensitivities in both approaches: Mg_4FGeO_6: Mn



Experimental Setup



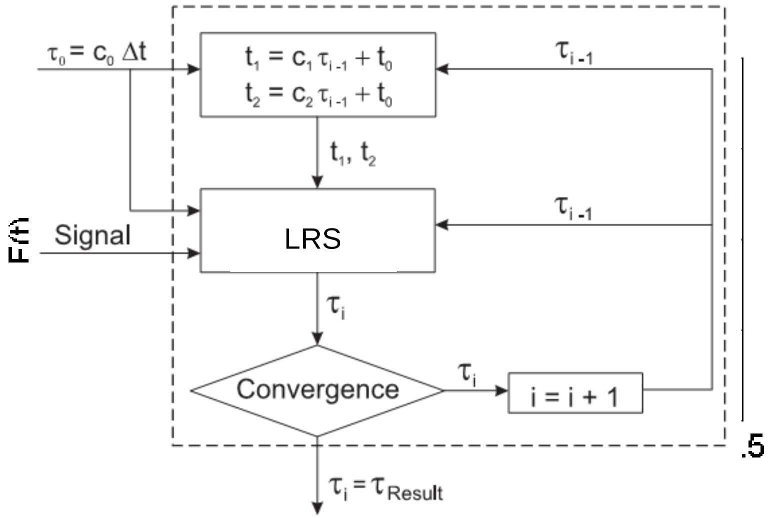


Data evaluation

- Nonlinearity intensity-correction of the CMOS Chip
- Image matching by pinhole model (Software: Davis 7)

<u>Lifetime</u>

- Pixelwise fitting of waveforms
- Brübach Algorithm + Linear Regression of the Sum (LRS)



Brübach, J. et al., Opt. Laser Eng., 47 (1), 2009
Everest, M. A. et al., Rev. Sci. Instrum., 79, 2008

<u>Intensity ratio</u>

- Pixelwise temporal integration:

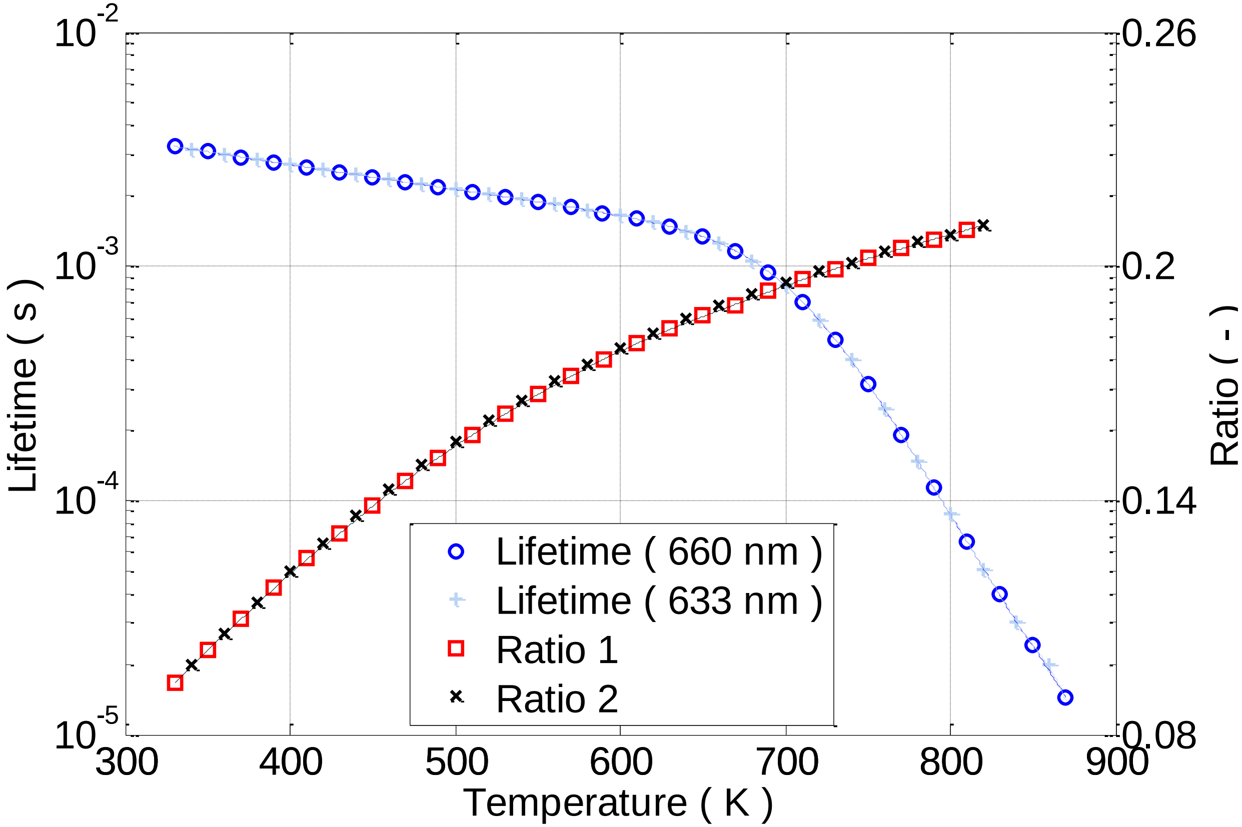
$$R = \frac{\int_{t_1}^{t_2} I_{633\,\mathrm{nm}}(t)\,dt}{\int_{t_1}^{t_2} I_{660\,\mathrm{nm}}(t)\,dt}$$

- Two ratios R1 and R2 used:
  - R1: $t_1 = t_0 + 100\,\mu s$
    $t_2 = t_0 + 120\,\mu s$
    (corresponds to 1 image @50kHz)
  - R2: $t_1 = t_0 + 100\,\mu s$
    $t_2 = t_0 + 1100\,\mu s$
    (corresponds to 50 images @50kHz)

Fuhrmann et int. Dreizler. Appl. Phys. B (2014) 116:359 – 369

Results: Temperature dependent characteristics

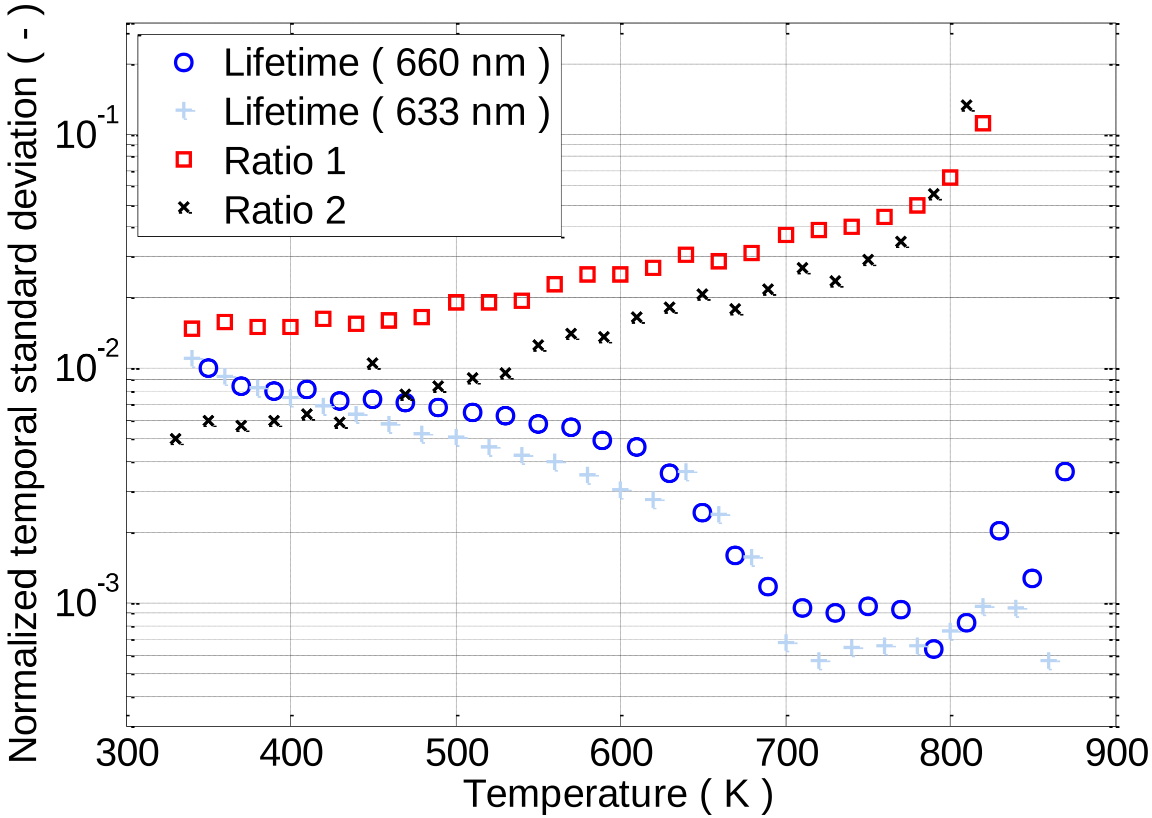
- Temperature-Lifetime / Temperature-Ratio characteristics



- Temperature-Lifetime characteristics of both spectral bands similar
- Temperature-Ratio characteristics for both ratios similar as well
- Very different sensitivities for lifetime approach and only slightly differing sensitivities for ratio approach

Results: Precision I

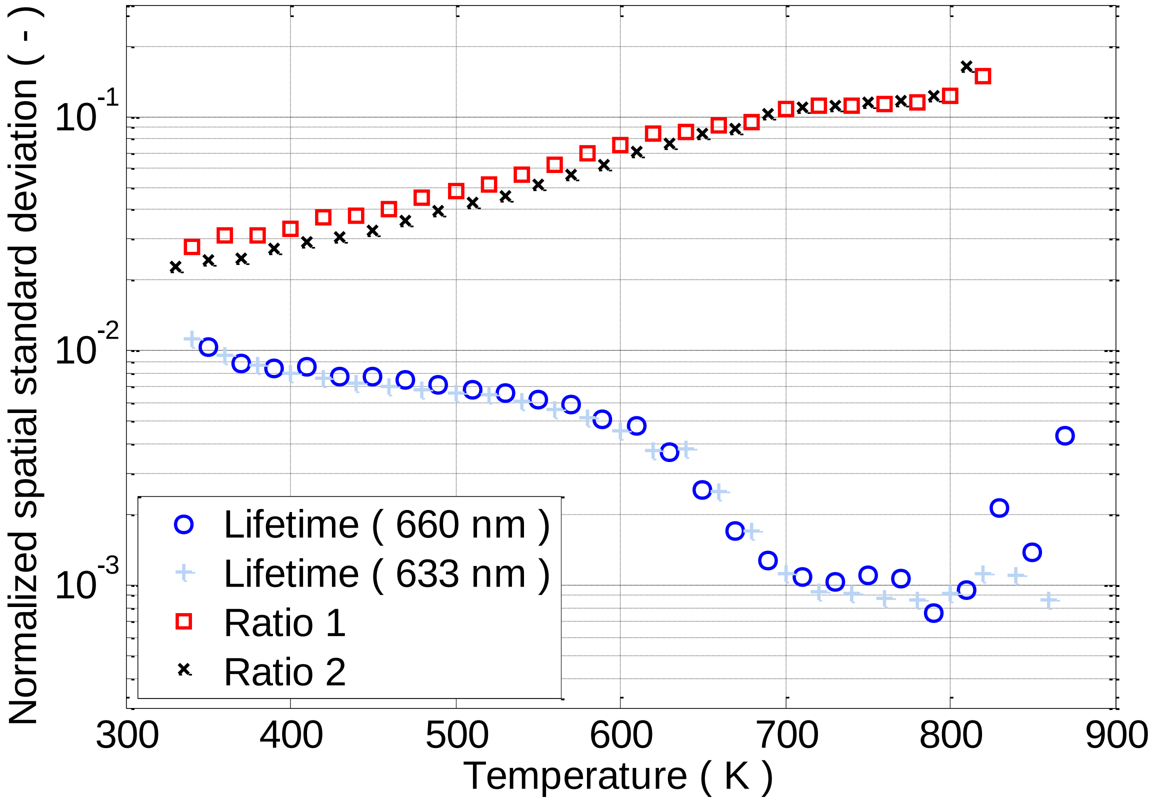
- Shot-to-Shot (**temporal**) standard deviations



- Comparable precision of both techniques at lower temperatures
- Lifetime method ~2 orders of magnitude better at higher temperatures

Results: Precision II

- Pixel-to-pixel (**spatial**) standard deviations

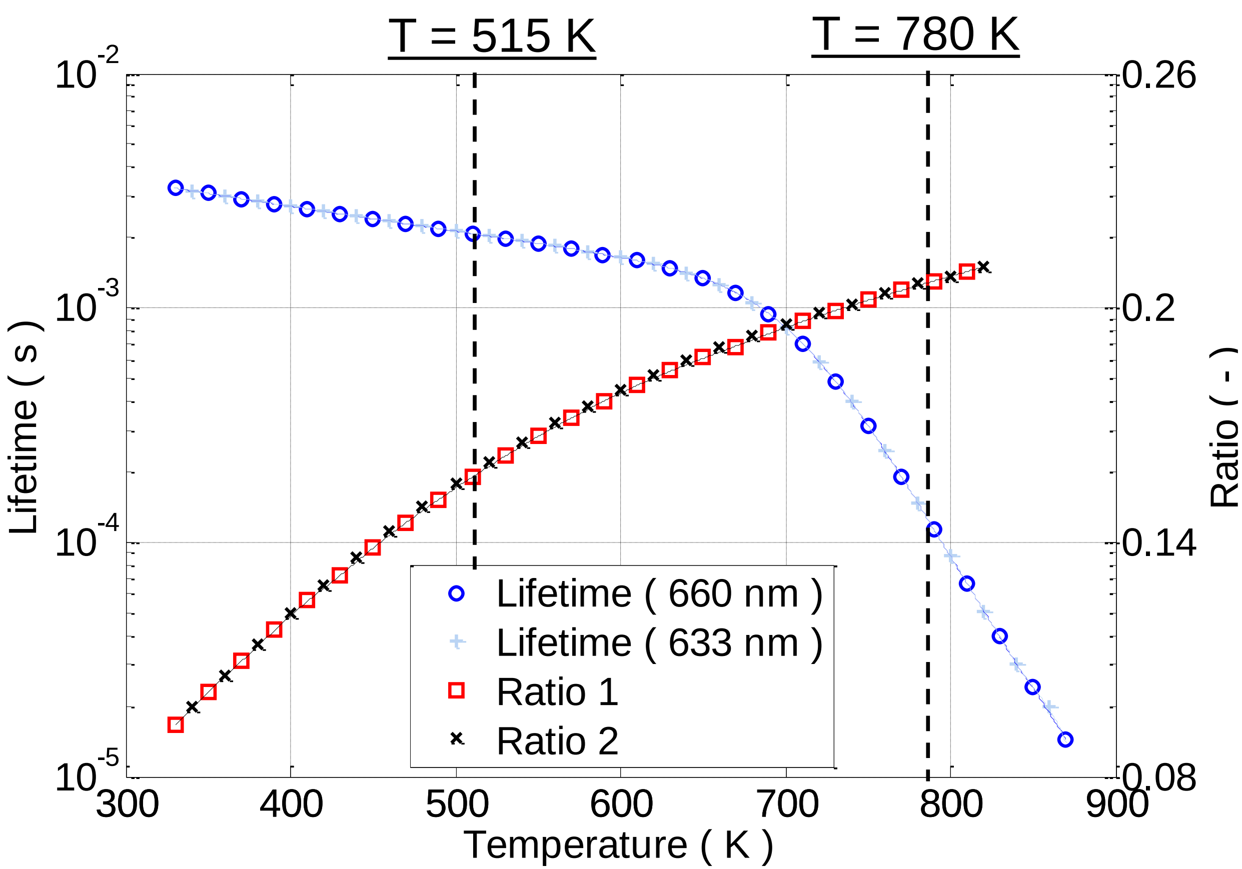


- Huge difference in spatial precision between the two techniques

- Spatial precision of lifetime method superior over the entire temperature range

Results: Accuracy I

- Evaluation of systematic errors

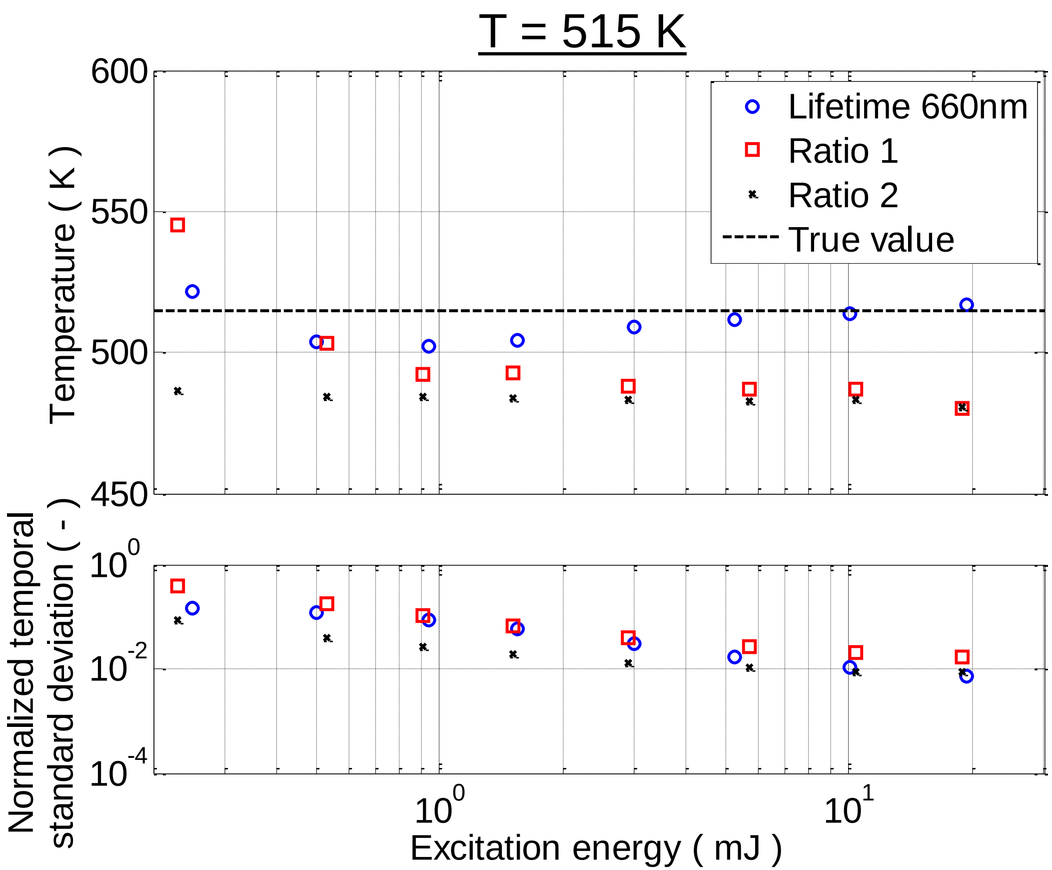


- Evaluated at two different temperatures corresponding to two different sensitivities in the temperature lifetime characteristic

- Calibration at fixed conditions and then parametric variation:
  - Energy variation
  - Changing settings in optical setup

Results: Accuracy II

- Dependency on excitation energy at T = 515K

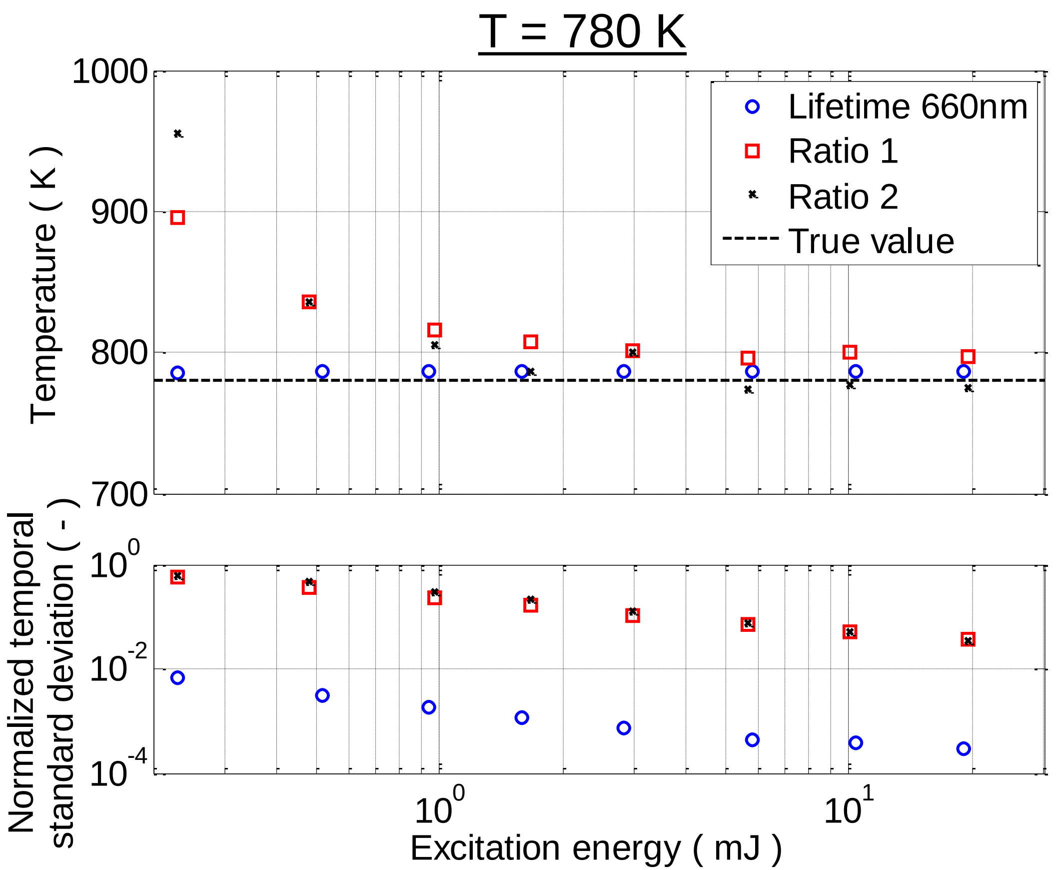


- Inaccuracy for too low excitations energies of lifetime approach well known (i.e. Brübach et al. 2008)

- Ratio 2 rather robust against energy variations, but inaccuracy over whole energy range

Results: Accuracy III

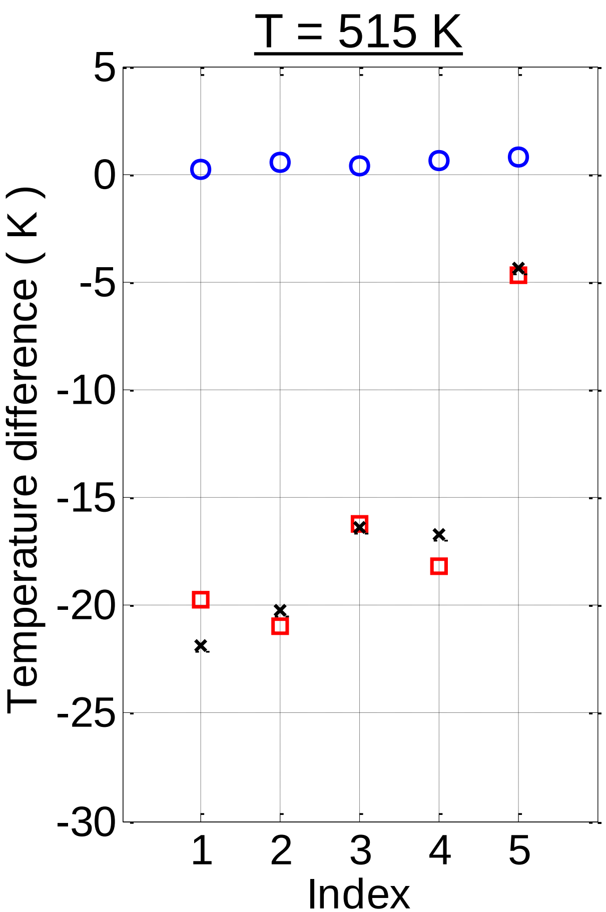
- Dependency on excitation energy at T = 780K



- Lifetime approach very accurate due to high sensitivity
- Ratio 1 & 2 show overestimation of more than 100 K at lower energies

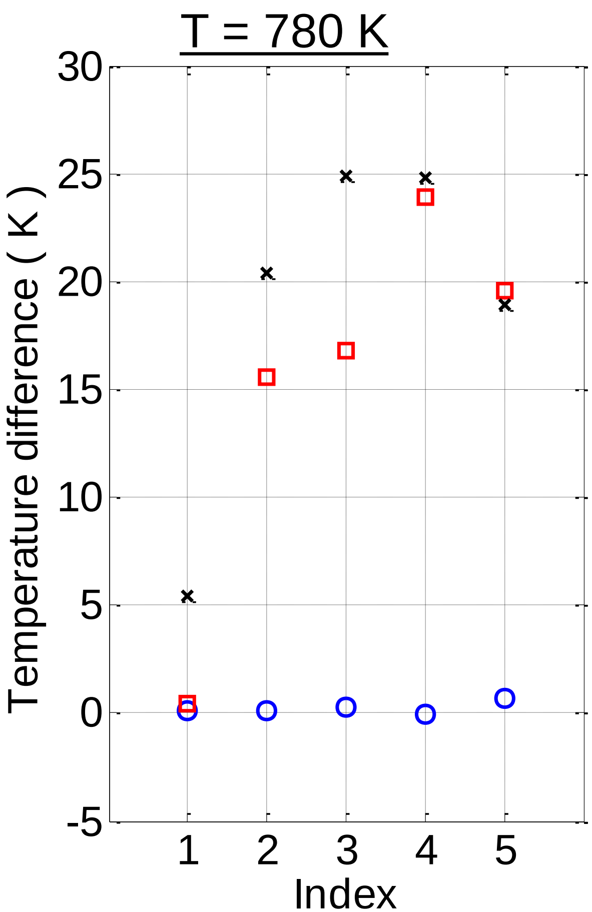
Results: Accuracy IV

- Accuracy due to changes of settings in the optical setup



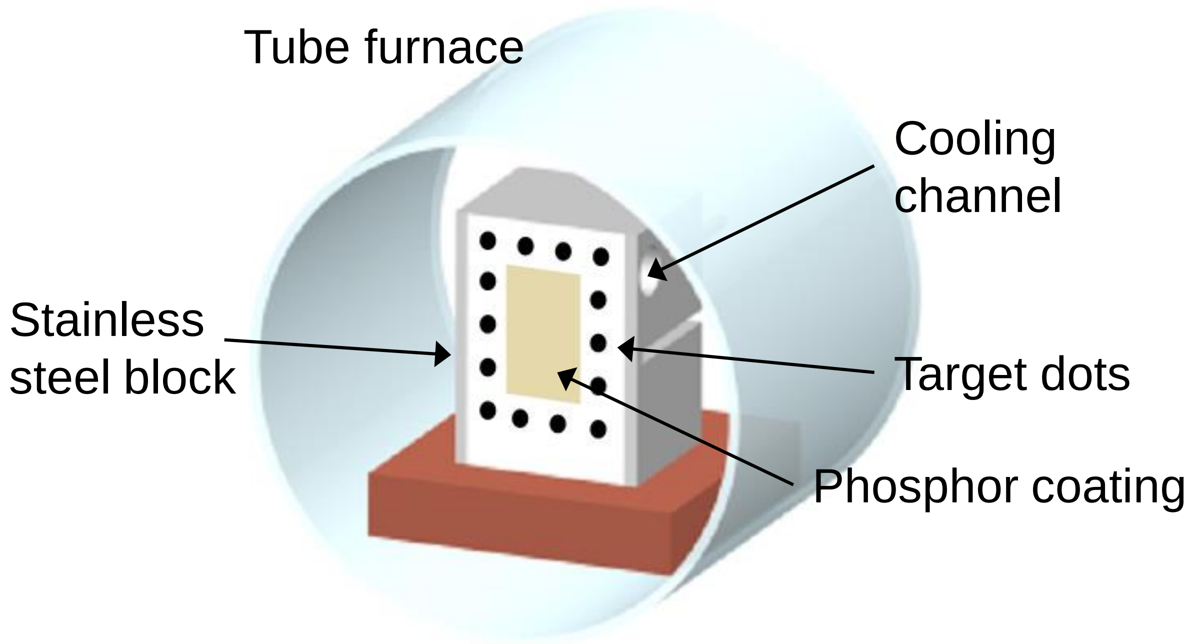
Lifetime (660 nm)
Ratio 1
Ratio 2

Index
1 – Filter rotation
2 – Increase distance (1cm)
3 – Increase distance (2cm)
4 – Increase distance (4cm)
5 – Change camera angle



Results: Cooling device I

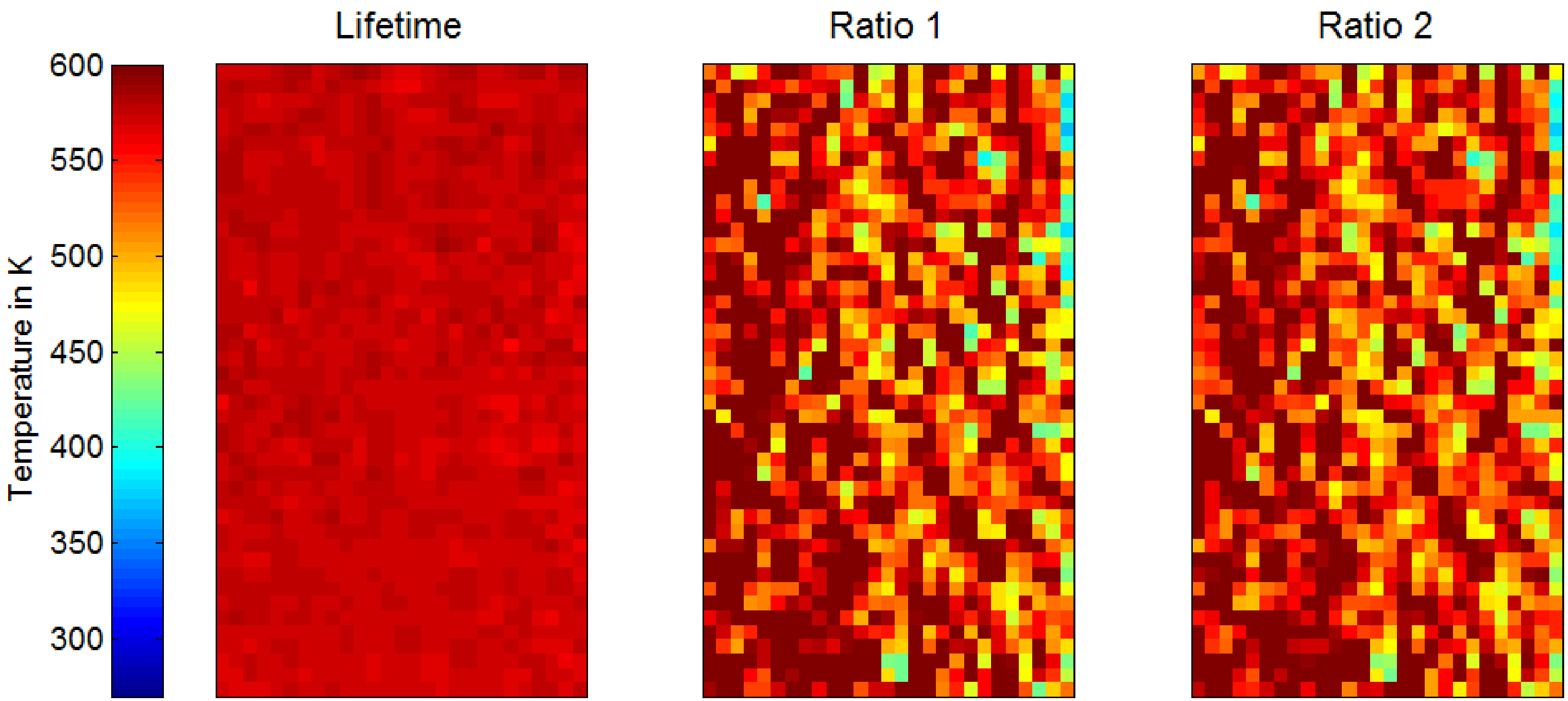
- Stainless steel block with cooling channel placed inside oven
- When block is at designated temperature, cold water is pumped through cooling channel
- For image mapping purposes target dots have been transferred to device



Kissel, T., PhD Thesis, TU Darmstadt, 2011

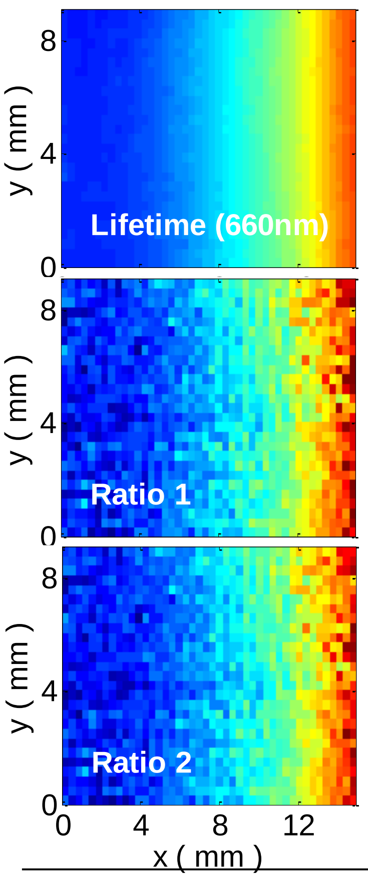
Results: Cooling device II

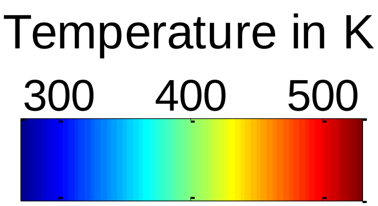
- Transient Experiment
- Same set of data for all three methods

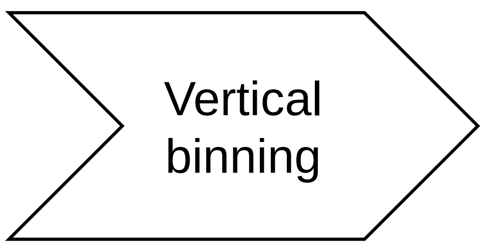


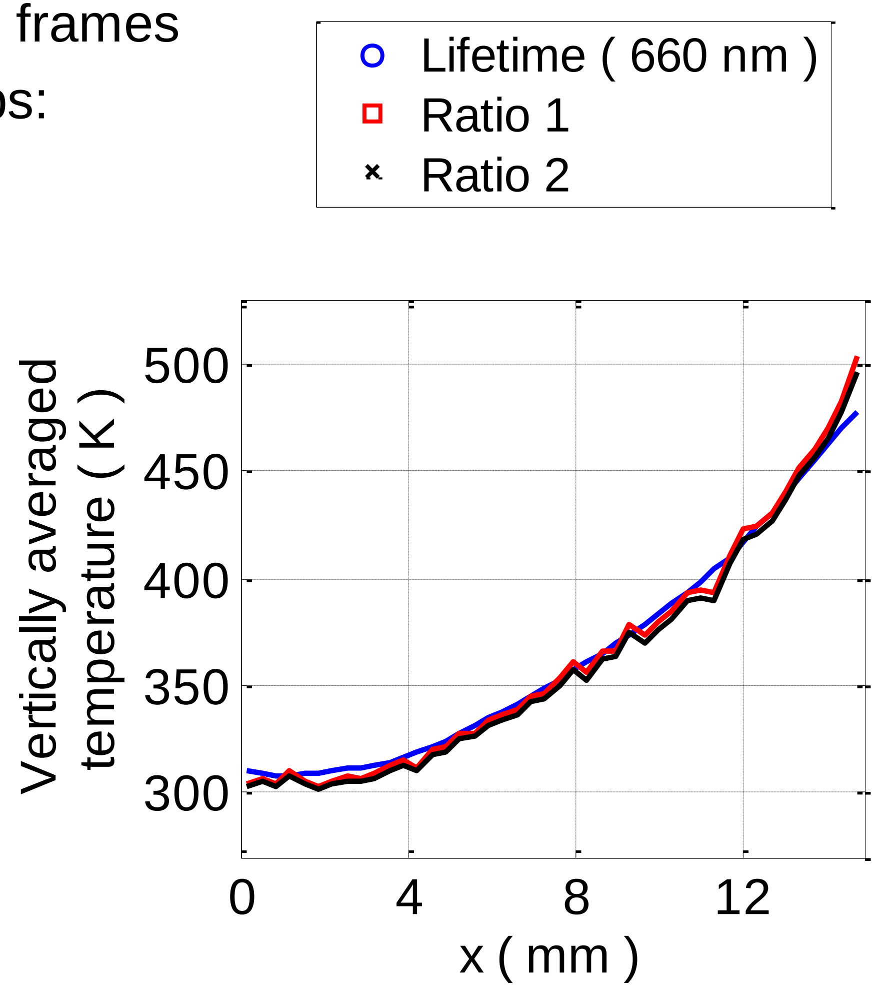
Results: Cooling device III

- Stationary T-distribution over last 16 frames
- Statistics for these temperature maps:









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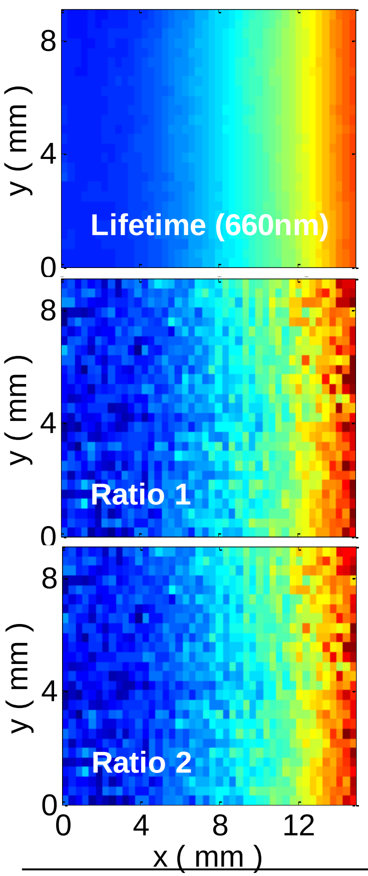

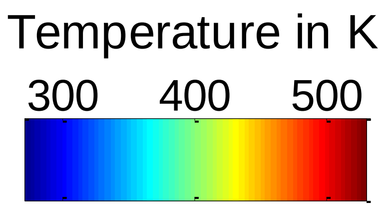

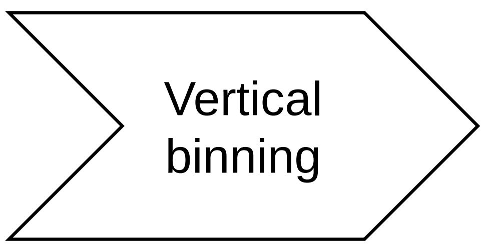

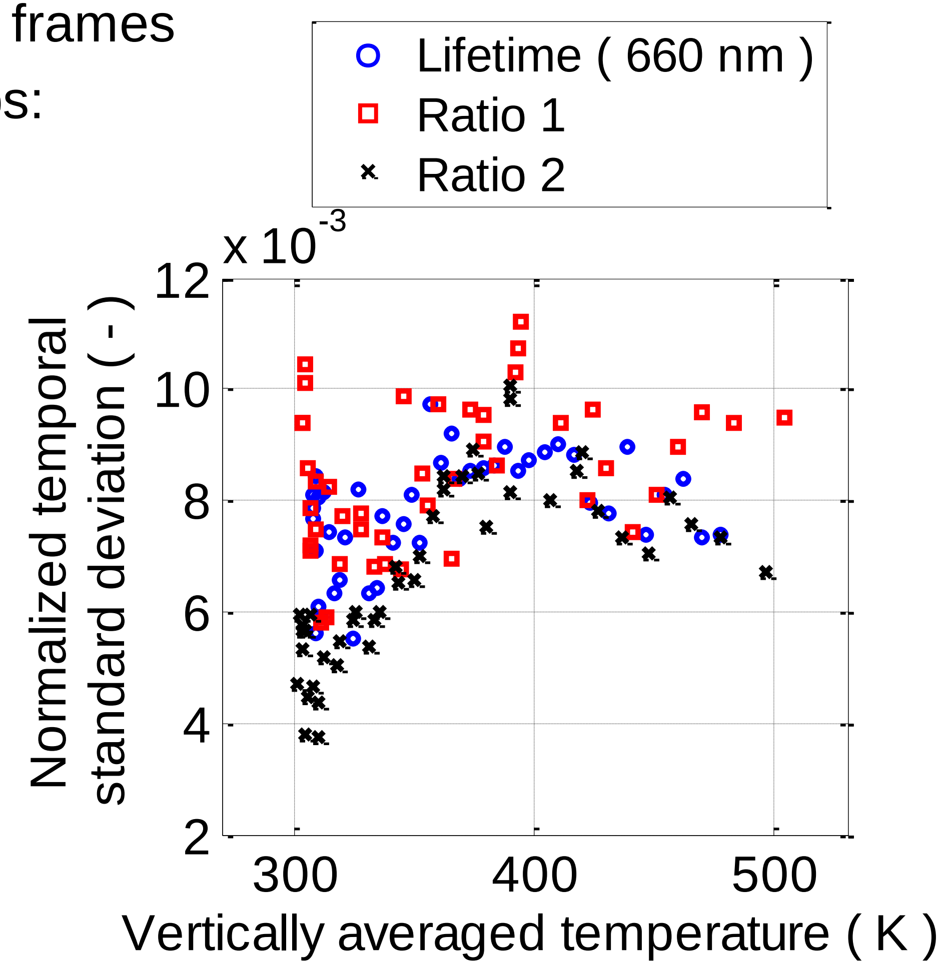

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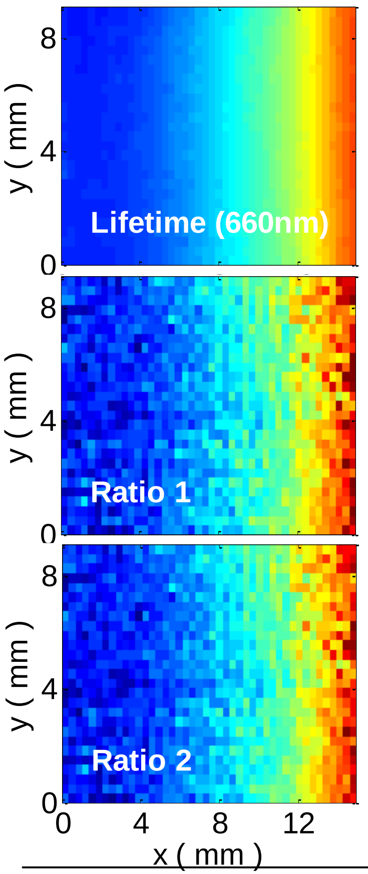
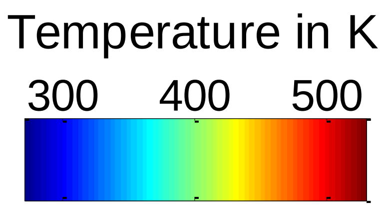
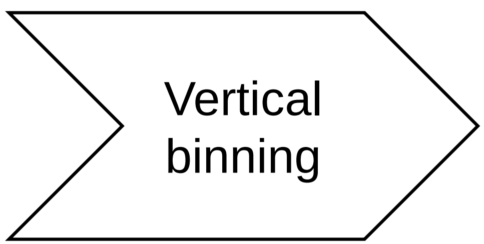
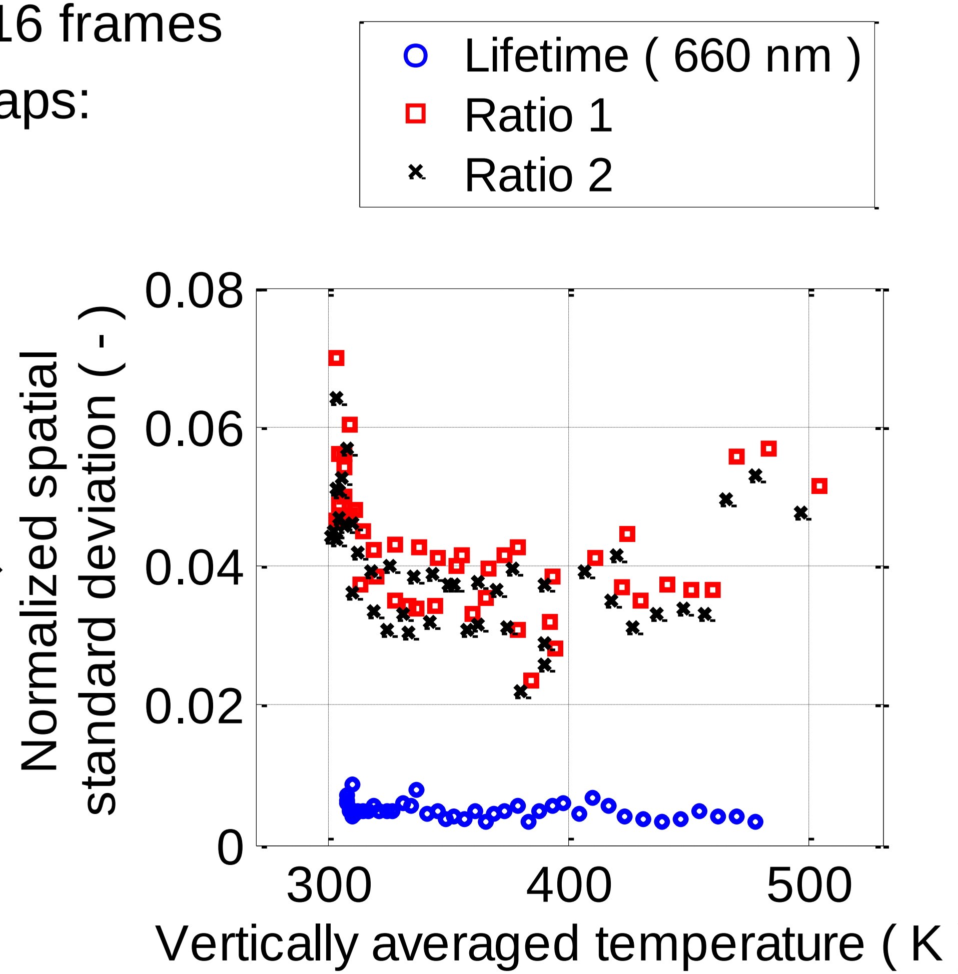








Summary & Conclusions

Comparison of Mg_4FGeO_6: Mn for the lifetime and the intensity ratio method in terms of

- Precision
- Accuracy
- Application (cooling device)

Main results

- High temperature range (>650K): Lifetime method is superior in all aspects
- Low temperature range: Lifetime method superior for spatial standard deviation and for accuracy, similar temporal standard deviations
- Only valid for the phosphor under consideration
- For other phosphors similar investigations required

Fuhrmann et al. PCI 34, 2013

Error treatment for the decay-time method

1. Introduction
2. Measurement chain / Error sources
3. Applications
4. Summary

For **details** see: Brübach, Pflitsch, Dreizler, Atakan. Prog. Energy Combust. Sci. 39, 37 – 60 (2013)

1. Introduction

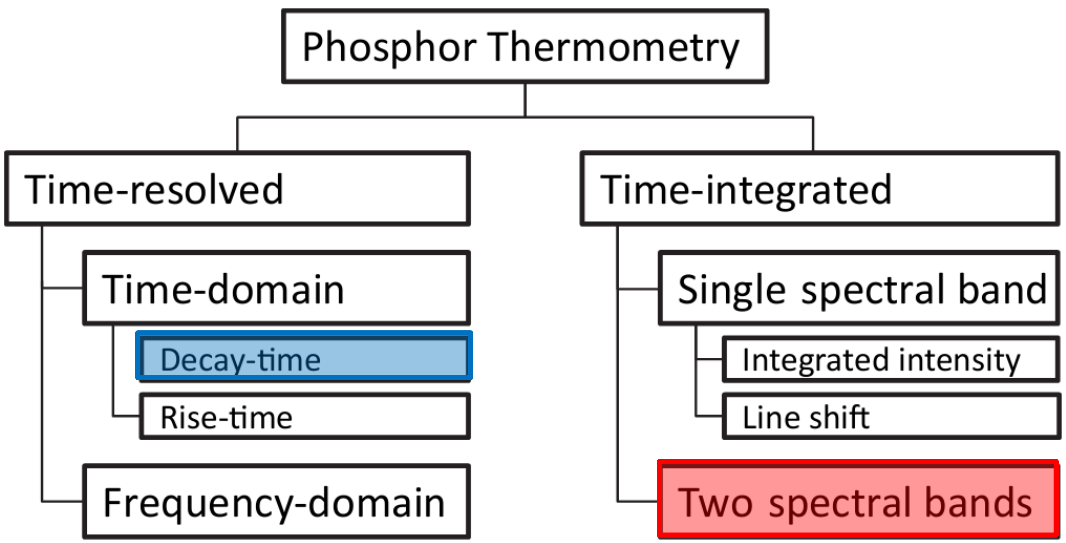
2. Measurement chain / Error sources

3. Applications

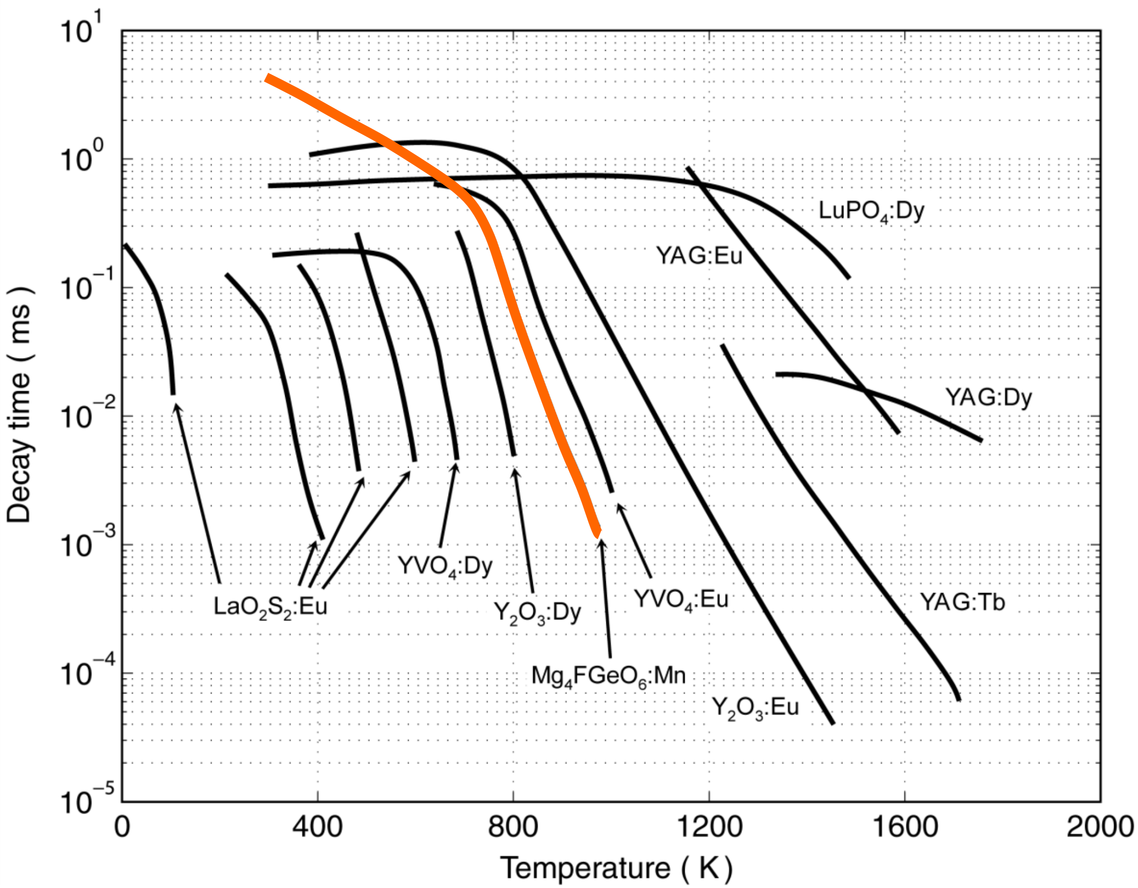
4. Summary

Combustion applications: mostly used approaches

- Most often used approaches are decay-time and two-spectral-band-method
- As discussed: Decay-time method does have the potential for superior precision and accuracy (especially in 2D application); see Fuhrmann, Brübach and Dreizler, PCI 33, 2013
- Decay-time varies with temperature due to varying energy transfer processes



Thermographic Phosphors: materials showing temperature dependent decay times



Approx. 100 different phosphors documented in literature
See Brübach et al. PECS 2013

Magnesium-Fluorogermanate doped with manganese:

Mg_4FGeO_6:Mn

Allison and Gillies, Rev. Sci. Instr., 68:2615-2650, 1997.

Spectra

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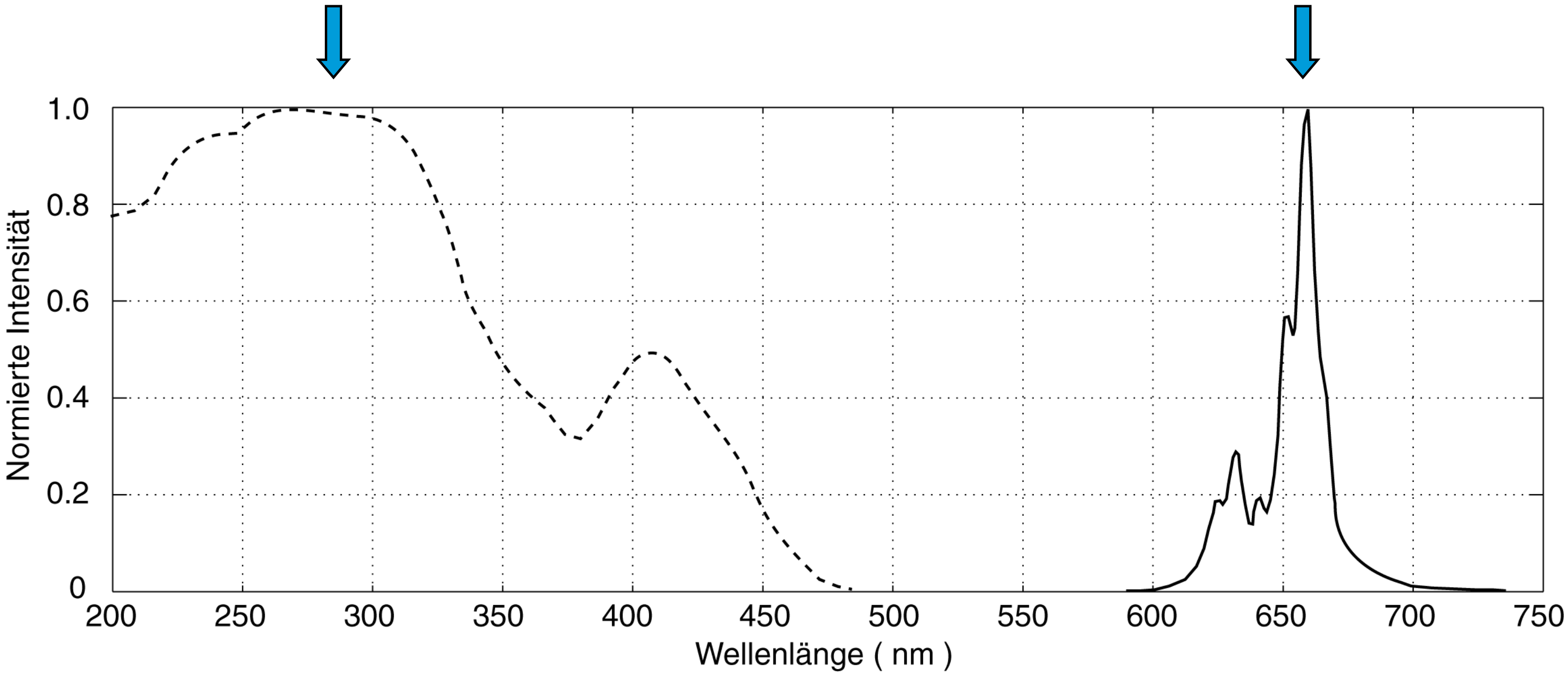
Mg_4FGeO_6:Mn

Excitation

Possible by standard laser wavelength

Emission

may interfere with luminous combustion



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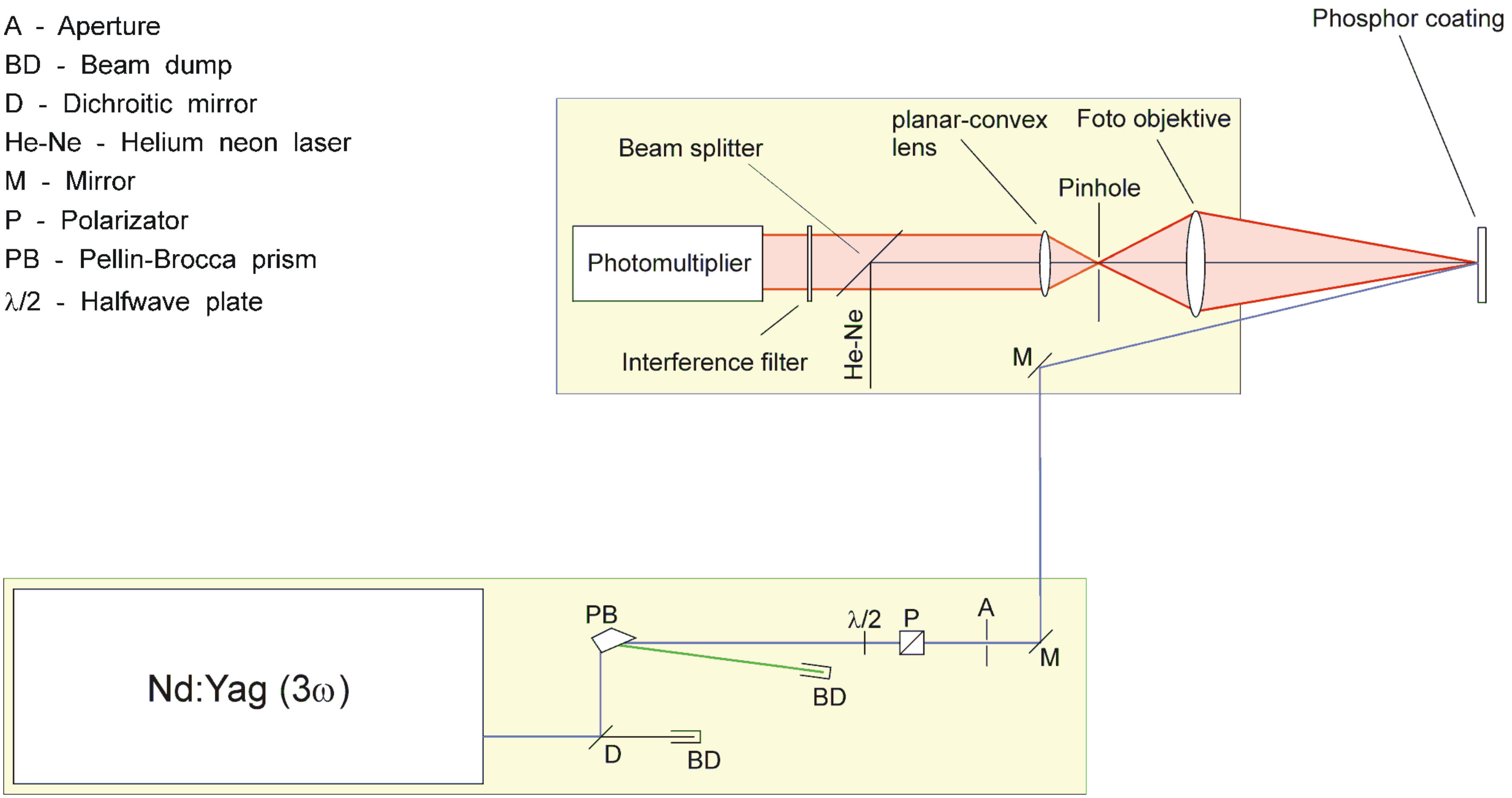
Experimental Setup – 0D

- A - Aperture
- BD - Beam dump
- D - Dichroitic mirror
- He-Ne - Helium neon laser
- M - Mirror
- P - Polarizator
- PB - Pellin-Brocca prism
- λ/2 - Halfwave plate

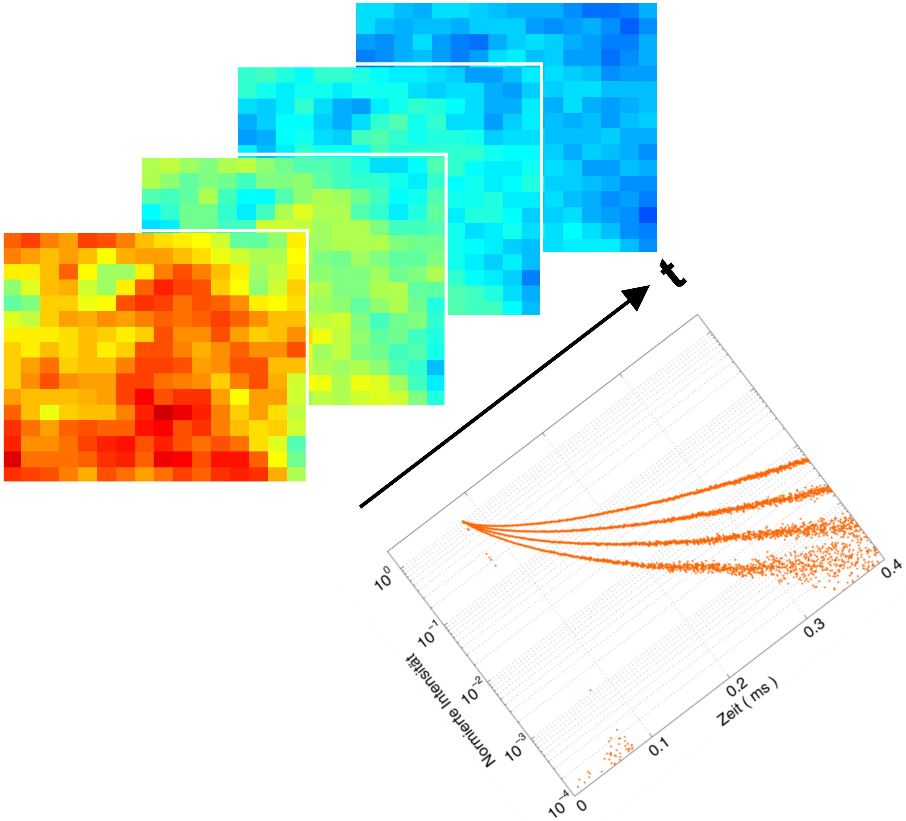


Experimental Setup – 2D

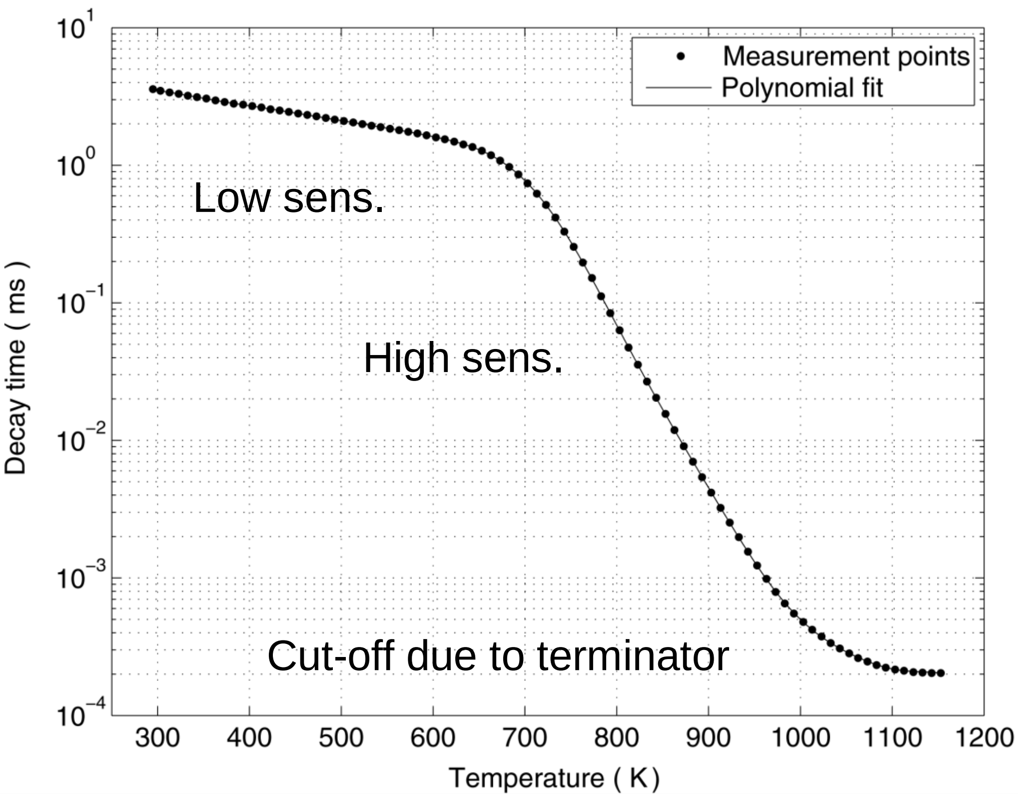
CMOS Kamera LaVision HSS6:

• Dynamic Range: 12 bit

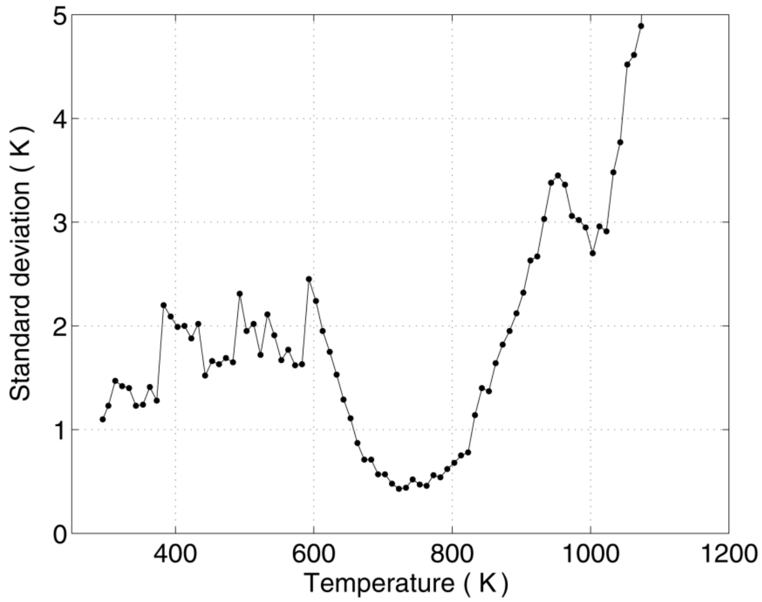
• max. frame rate of 675 kHz at a resolution of 64 x 16 Pixels



Calibration in well-controlled environments (oven)



- Phosphor: Mg_4FGeO_6:Mn
- Substrate: Stainless Steel (1.4301)
- Gas phase pressure: 1 bar (air)
- Detection: PMT at 500 Ω



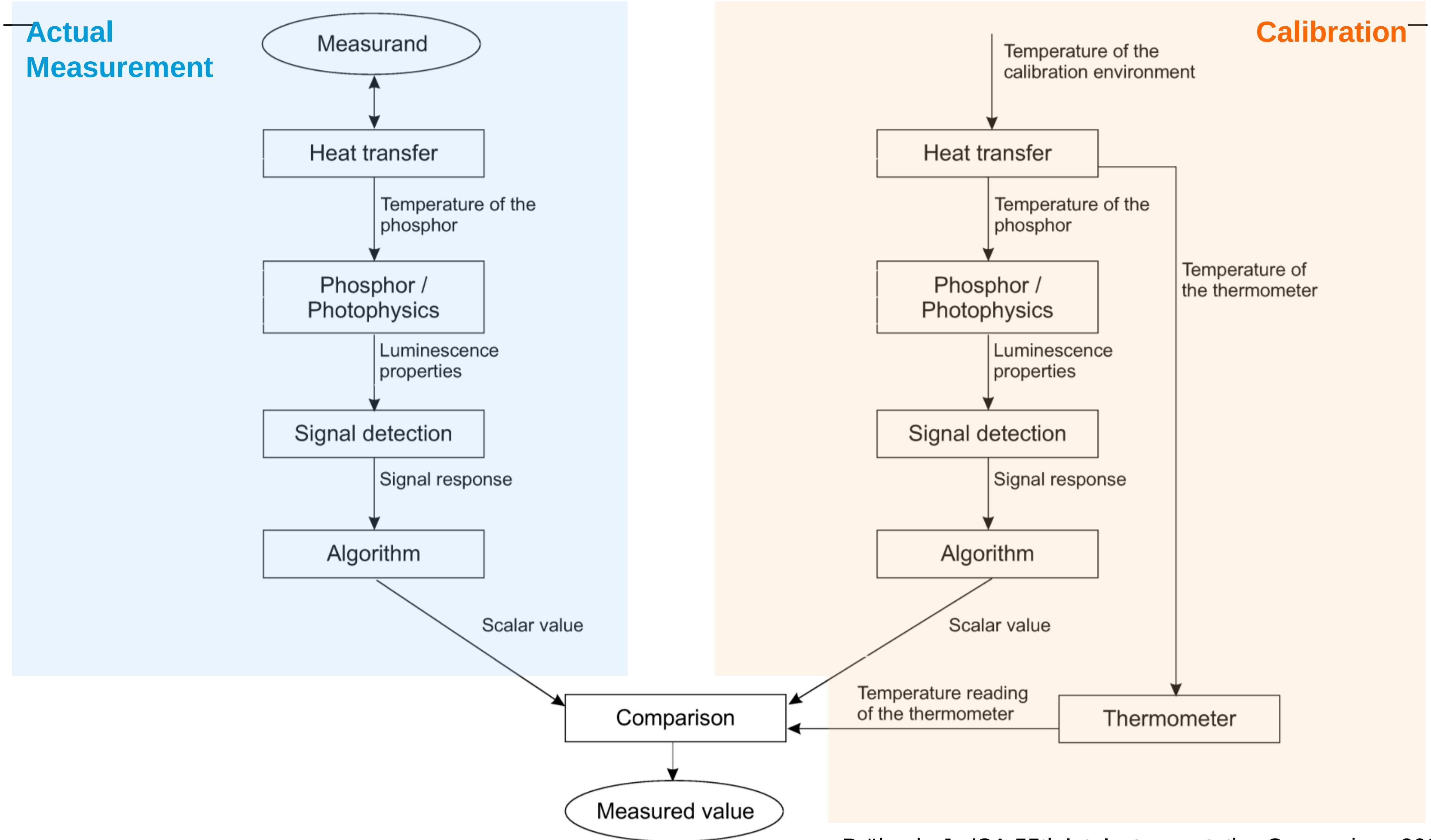
1. Introduction

2. Measurement chain / Error sources

3. Applications

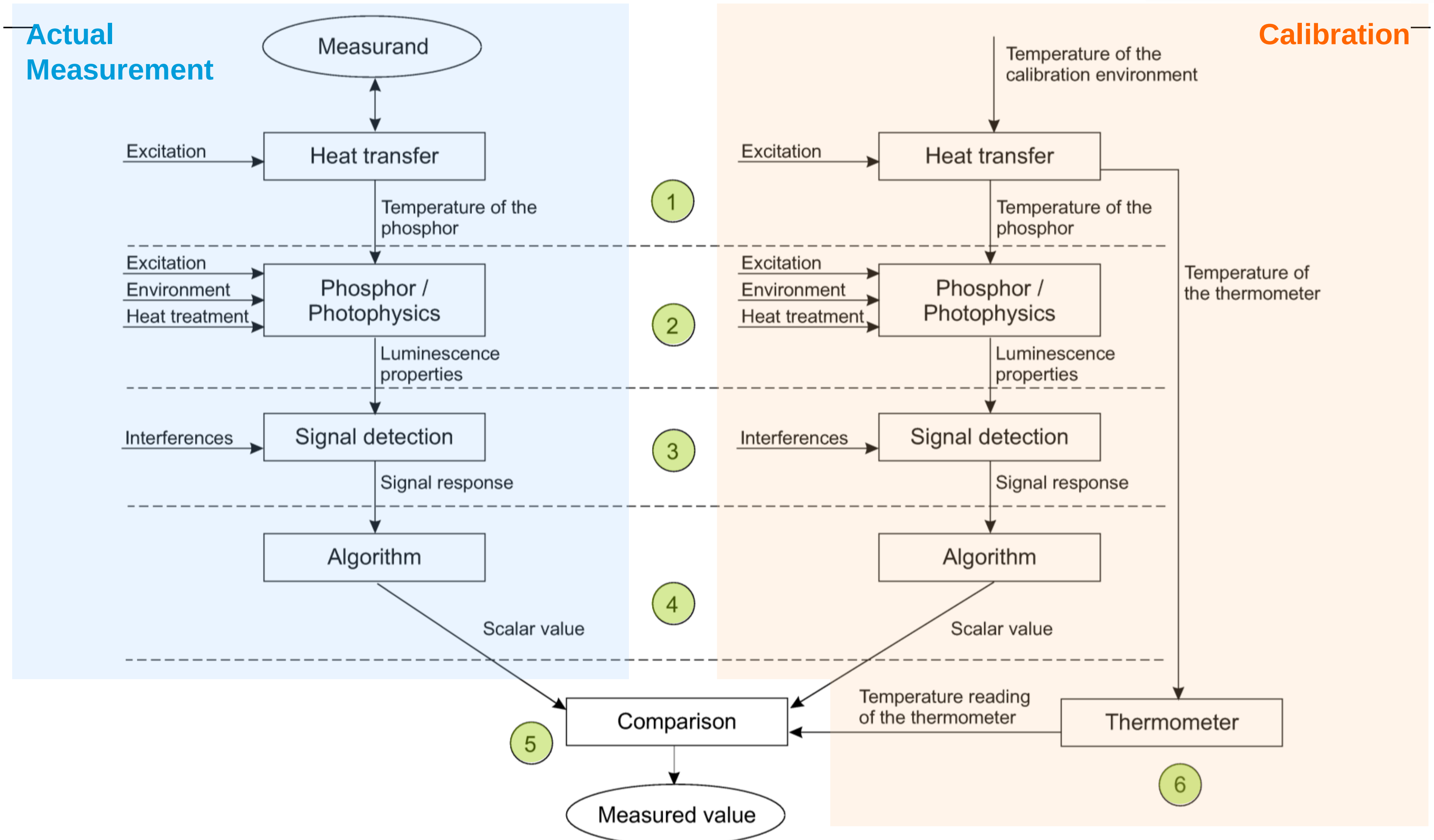
4. Summary

Measurement chain



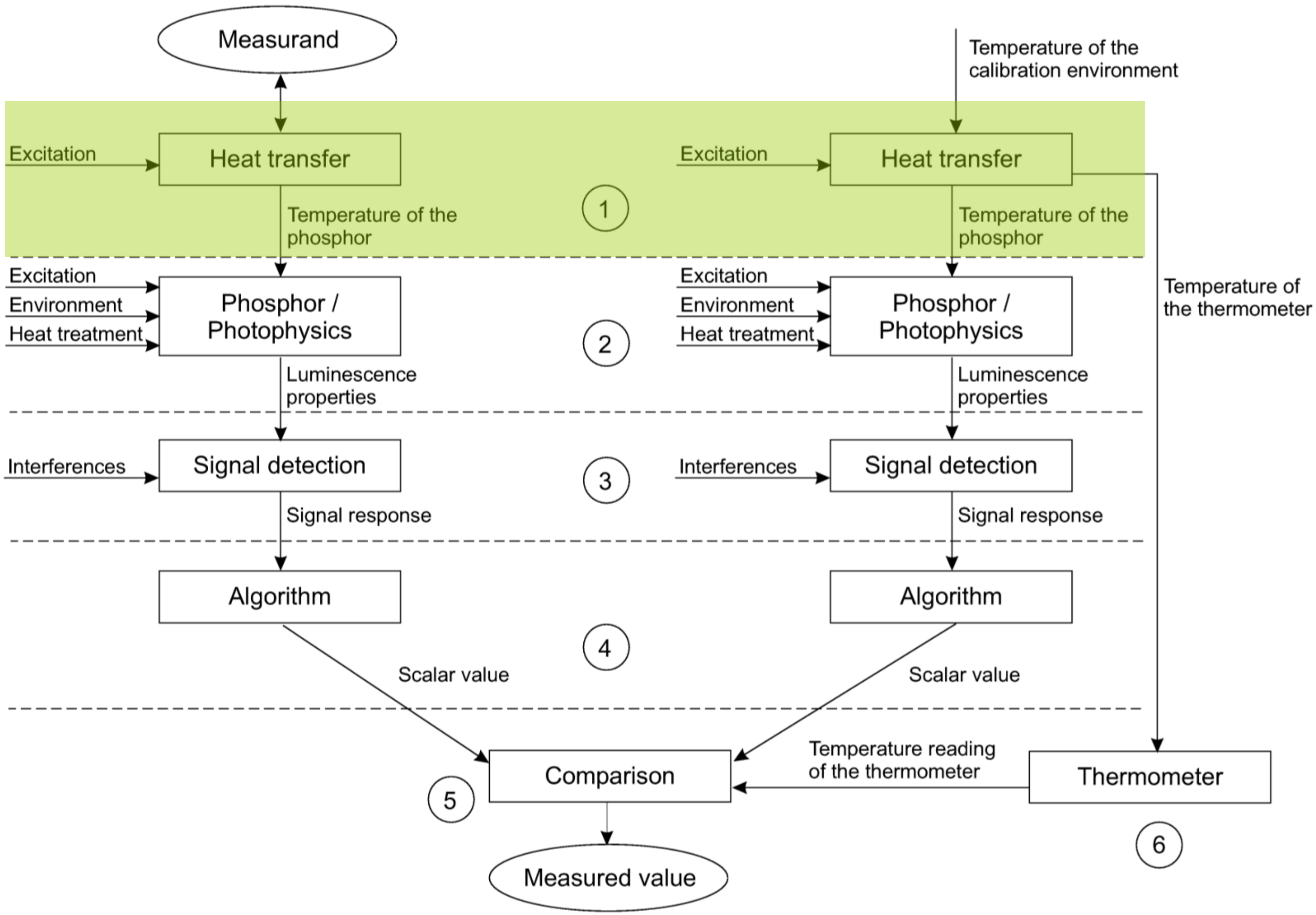
Brübach, J.; ISA 55th Int. Instrumentation Symposium, 2009

Measurement chain



Brübach, J.; ISA 55th Int. Instrumentation Symposium, 2009

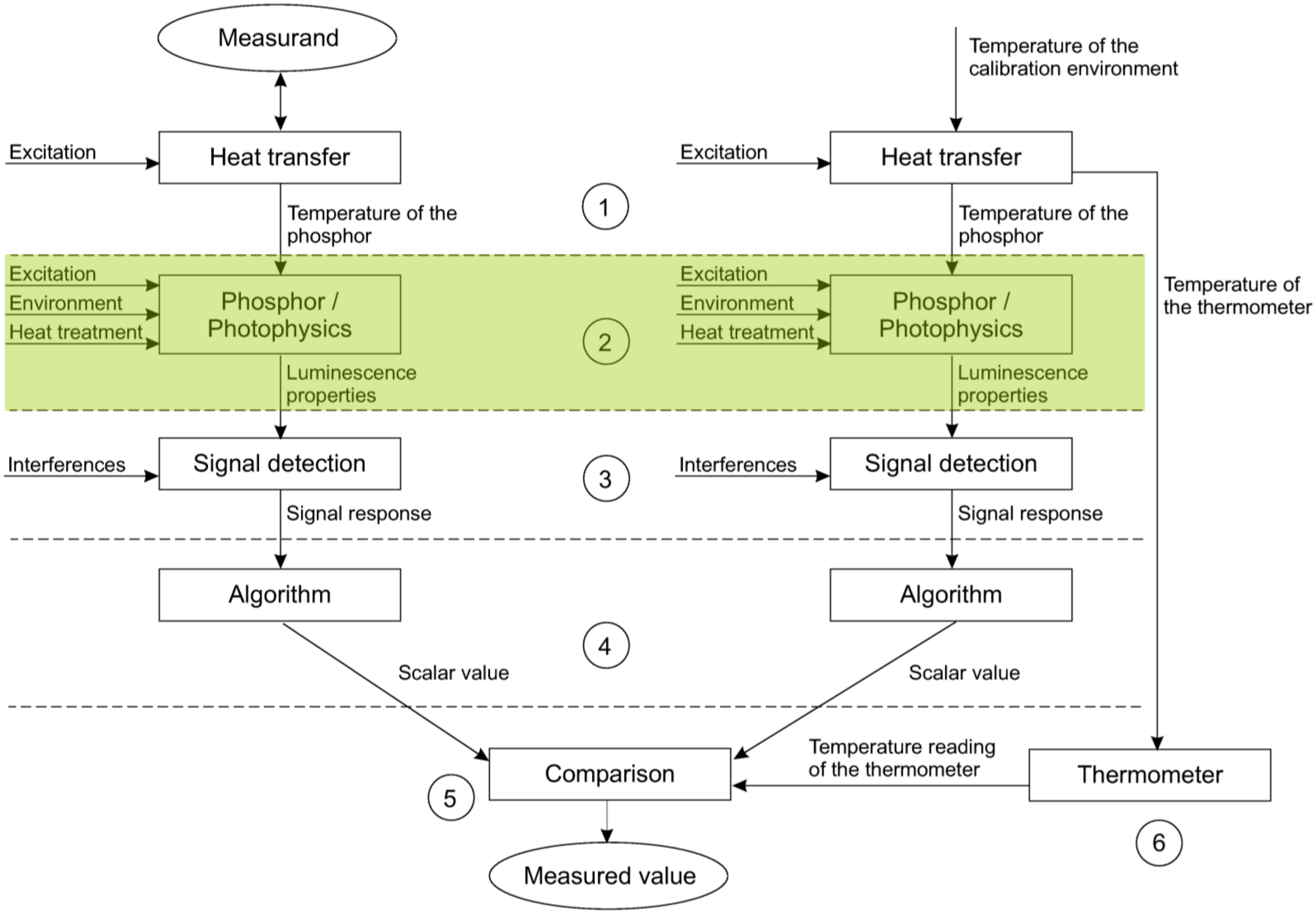
Error class 1:
Thermal interactions



Error class 1: Thermal interactions

- Device under test (DUT) and phosphor or phosphor and calibration thermometer are not in thermal equilibrium
- Impact of the presence of the phosphor on the thermal state of the DUT (e.g. heat insulation) → “semi-invasive” method
- Excitation induced heating of the phosphor → check by power scan

Error class 2:
Photophysical properties of the phosphor

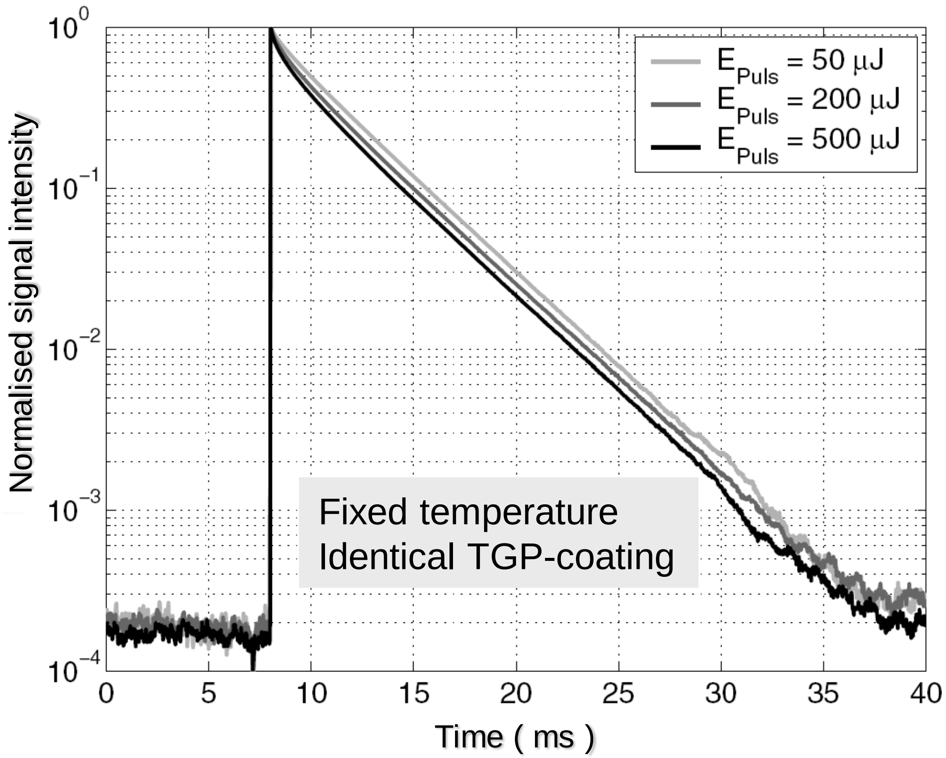


Error class 2:
Photophysical properties of the phosphor

- Impact of the transfer function of the phosphor
  - ➔ Temperature sensitivity, varies with temperature
  - ➔ Temporal low pass character due to finite decay time (thermal inertia versus decy time)

- Parameters that manipulate the transfer function of the phosphor
  - ➔ Diffusion processes between the phosphor material and the substrate due to heat treatments
  - ➔ Chemical and physical environment (oxygen quenching)
  - ➔ Laser excitation (variations with intensity)

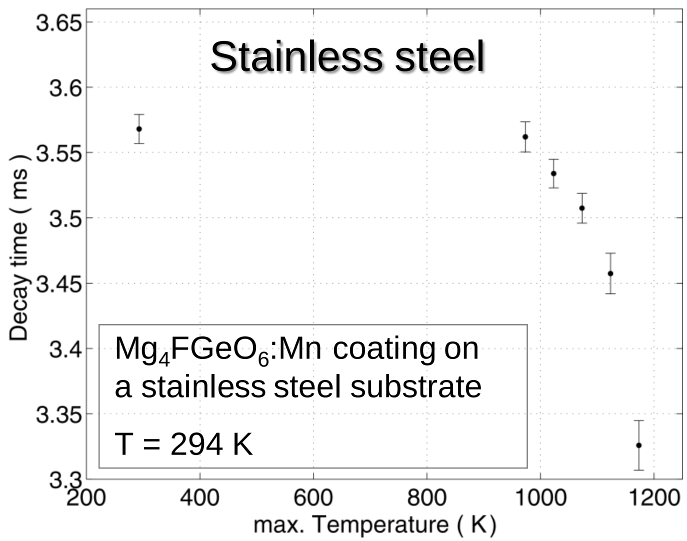
Error class 2:
Excitation irradiance

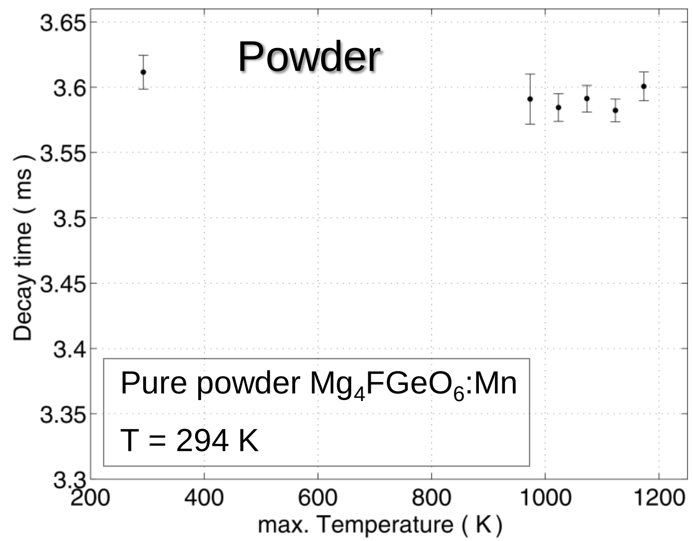


- Decay behaviour “more multi-exponential” at higher laser intensities
- Significant influence of the position of the fitting window

Brübach, J.; Feist, J. P.; Dreizler, A.: Meas. Sci. Technol., 19(2):025602, 2008.

Error class 2:
Decay time @ 294 K after heat treatment



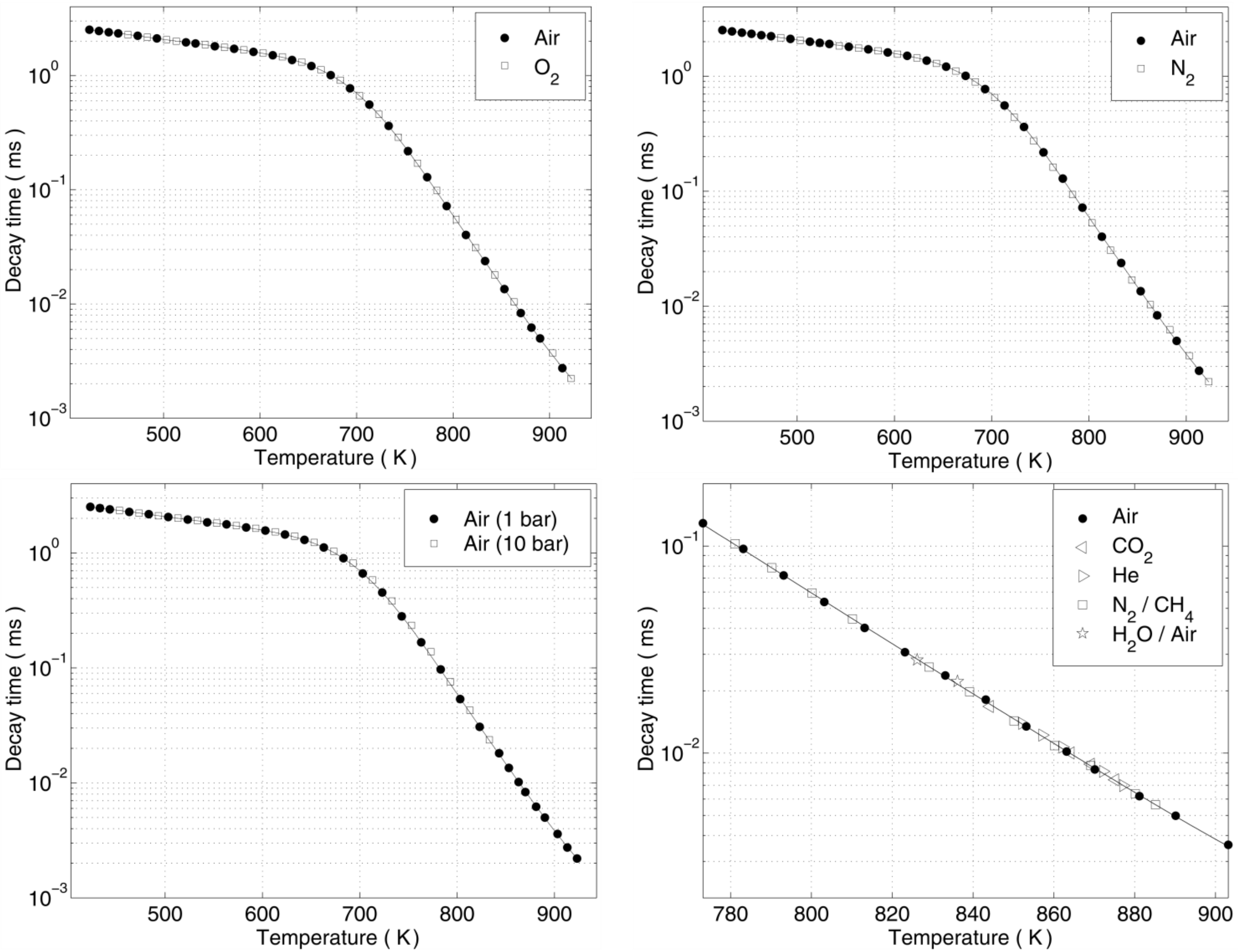


Dependency on:
- Substrate material
- Duration of the heat treatment
- Heat treatment temperature

Diffusion process between phosphor und substrate

Brübach, J.; Feist, J. P.; Dreizler, A.: Meas. Sci. Technol., 19(2):025602, 2008.

Error class 2:
Surrounding gas phase



Mg_4FGeO_6:Mn

No significant dependency on the composition and pressure of the gas phase

Brübach, J.; Dreizler, A.; Janicka, J.: Meas. Sci. Technol., 18(3):764–770, 2007.

Error class 2:
Surrounding gas phase

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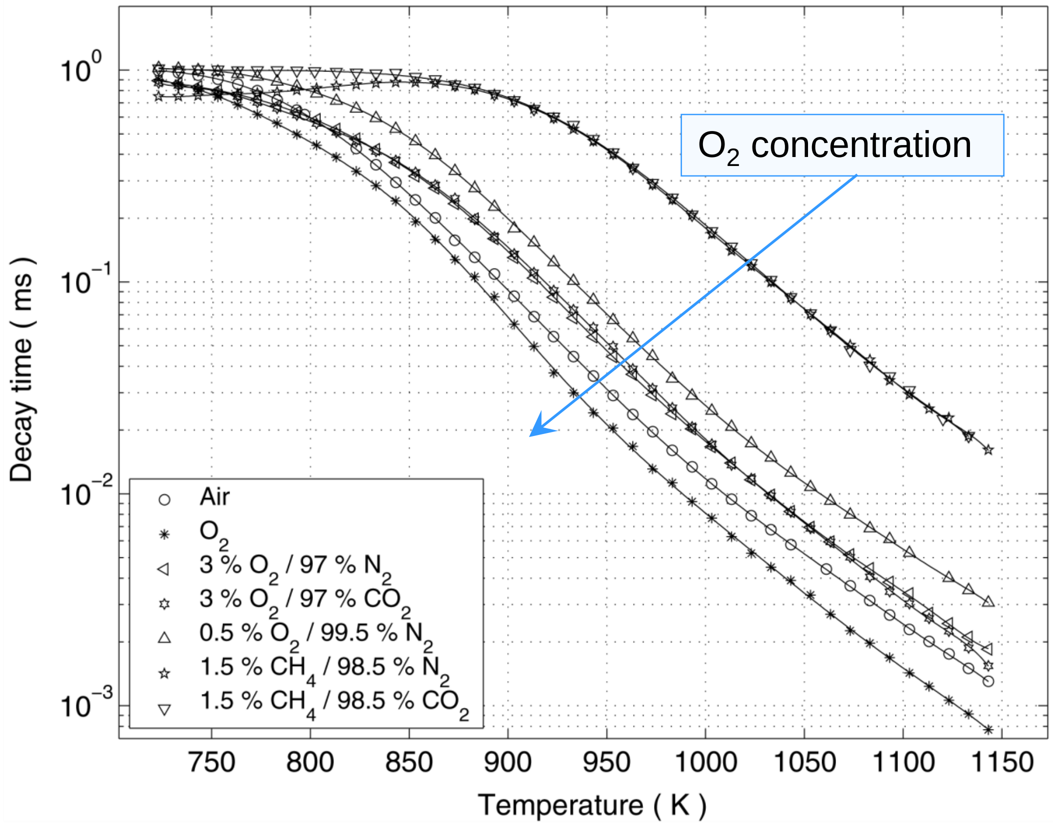

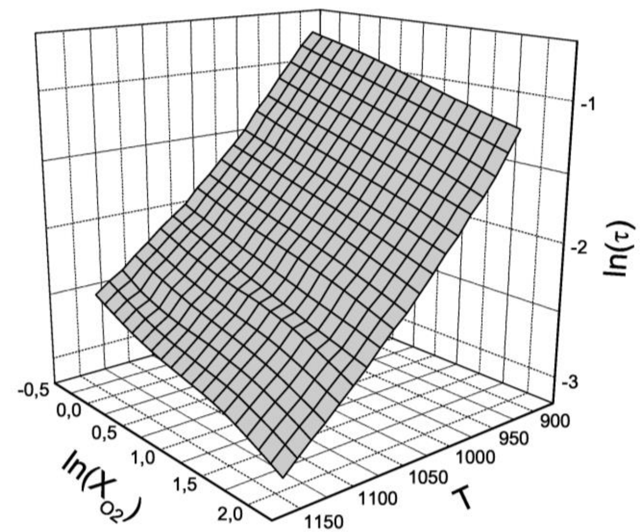

Y_2O_3:Eu

Dependency on the oxygen concentration

Brübach, J.; Dreizler, A.; Janicka, J.: Meas. Sci. Technol., 18(3):764–770, 2007.

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Error class 3:
Signal detection

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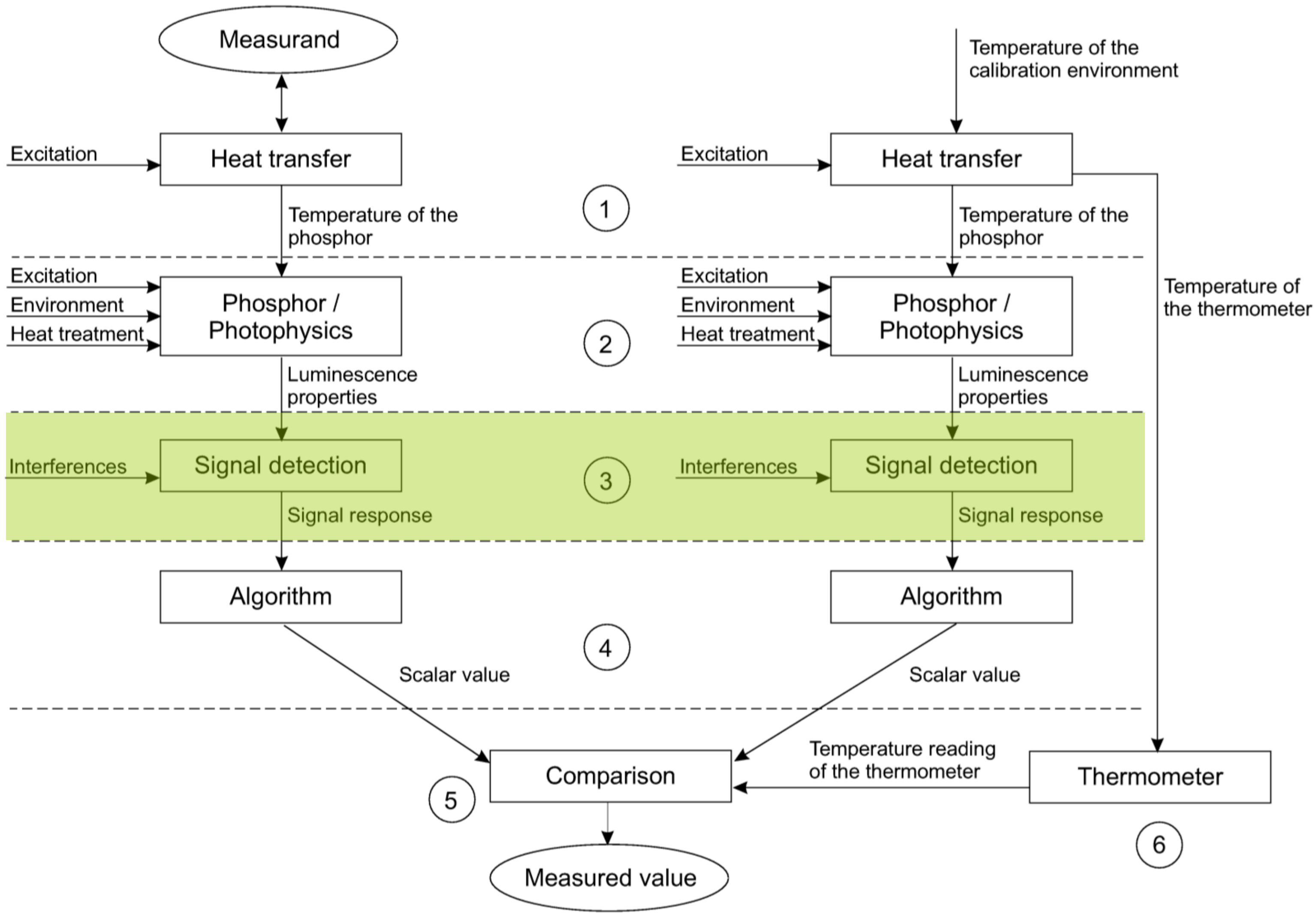


Error class 3:
Signal detection – overview

- Impact of the transfer function of the detection system
  - ➔ limited spatial, temporal and spectral resolution
  - ➔ nonlinear behaviour of the detector (CMOS camera)

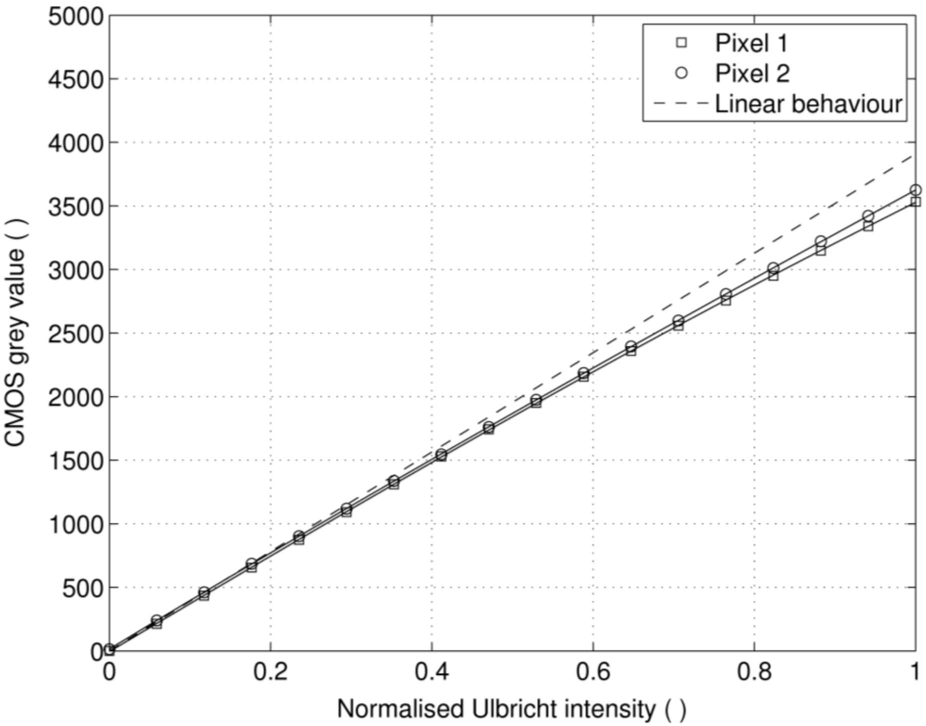
- Parameters that manipulate the transfer function of the detection system
  - ➔ small changes in the alignment (intensity ratio, see PCI 33-paper 2013)
  - ➔ terminating resistor, BNC length, amplifier (PMT, decay time)

- Optical and electrical interferences
  - ➔ optical interf. (e.g. background radiation, CL, fluorescence of substrate,…) most often temporally not correlated (worse precision)
  - ➔ electrical interf. (e.g. high voltage Q-switch electronics) might be temporally correlated (worse accuracy)

- Dynamic DUTs (e.g. moving surfaces)
  - ➔ signal decay might be superimposed by spatial variations of the absolute luminescence intensity; depending on the homogeneity of the excitation irradiance and the phosphor coating as well as on spatial temperature variation

Error class 3:
Signal detection – PMT versus CMOS

- Photomultiplier unproblematic
- CMOS camera shows problems regarding
  - ➔ Linearity
  - ➔ Pixel-to-pixel homogeneity
  - ➔ Offset stability



Kissel, T.; Baum, E.; Dreizler, A.; Brübach, J.: Appl. Phys. B, 96:731–734, 2009.

Error class 3:
Non-linear detector behaviour

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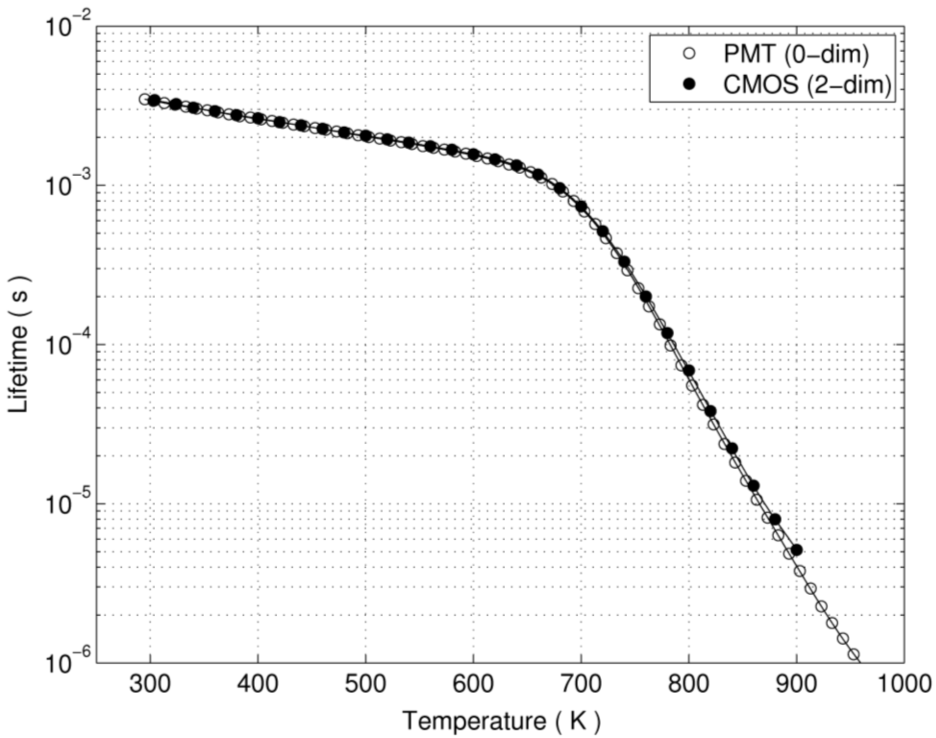
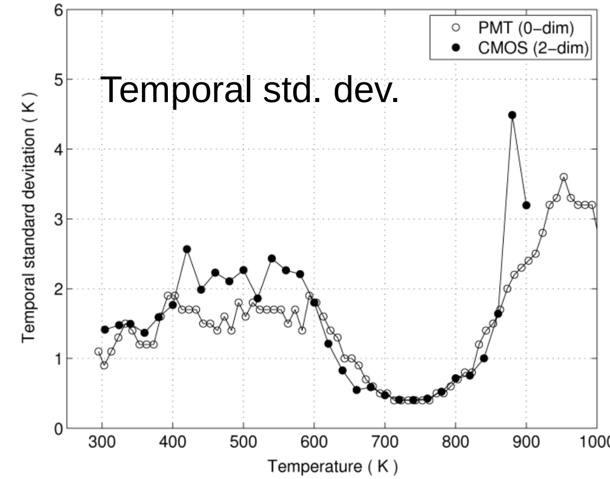
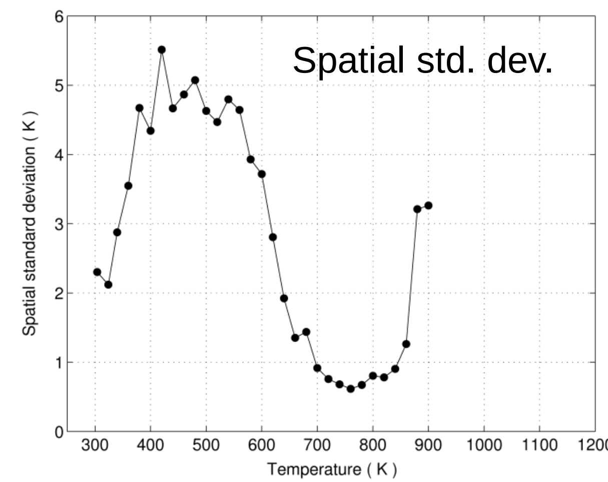
Correction function for each pixel fixes the problem







Kissel, T.; Baum, E.; Dreizler, A.; Brübach, J.: Appl. Phys. B, 96:731–734, 2009.

Error class 3:
Coating thickness and CMOS frame rate

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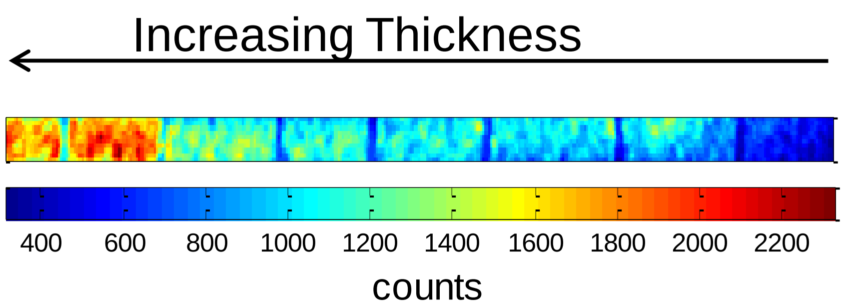
Variation of coating thickness and luminescence intensity

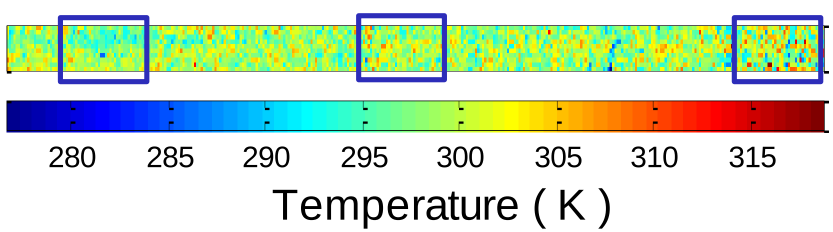


Resulting Temperature:

299,4 K ±3,0 K

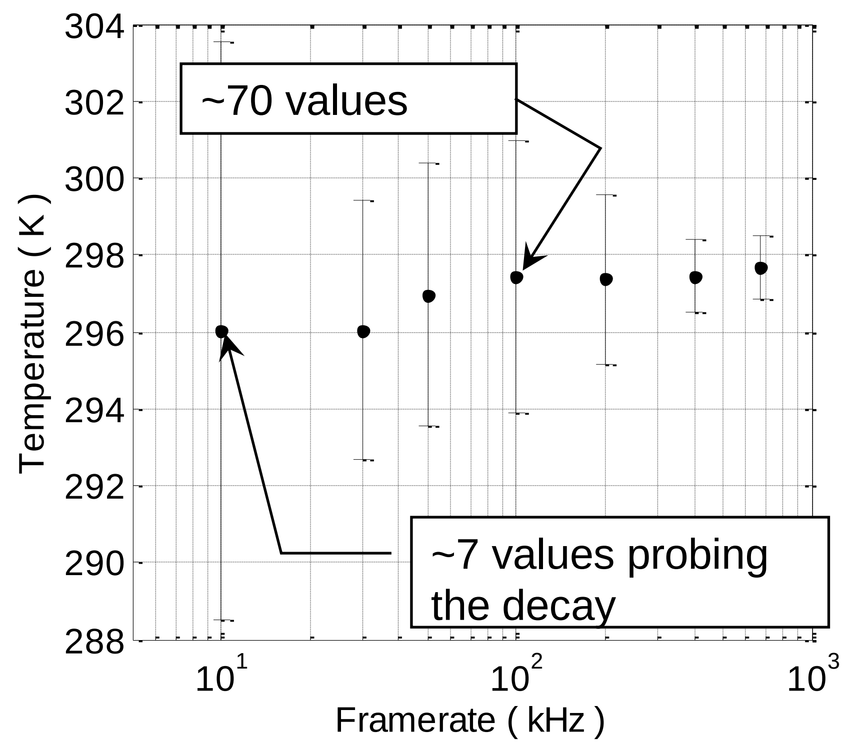
298,0 K ±3,3 K

297,4 K ±5,7 K



No significant influence!

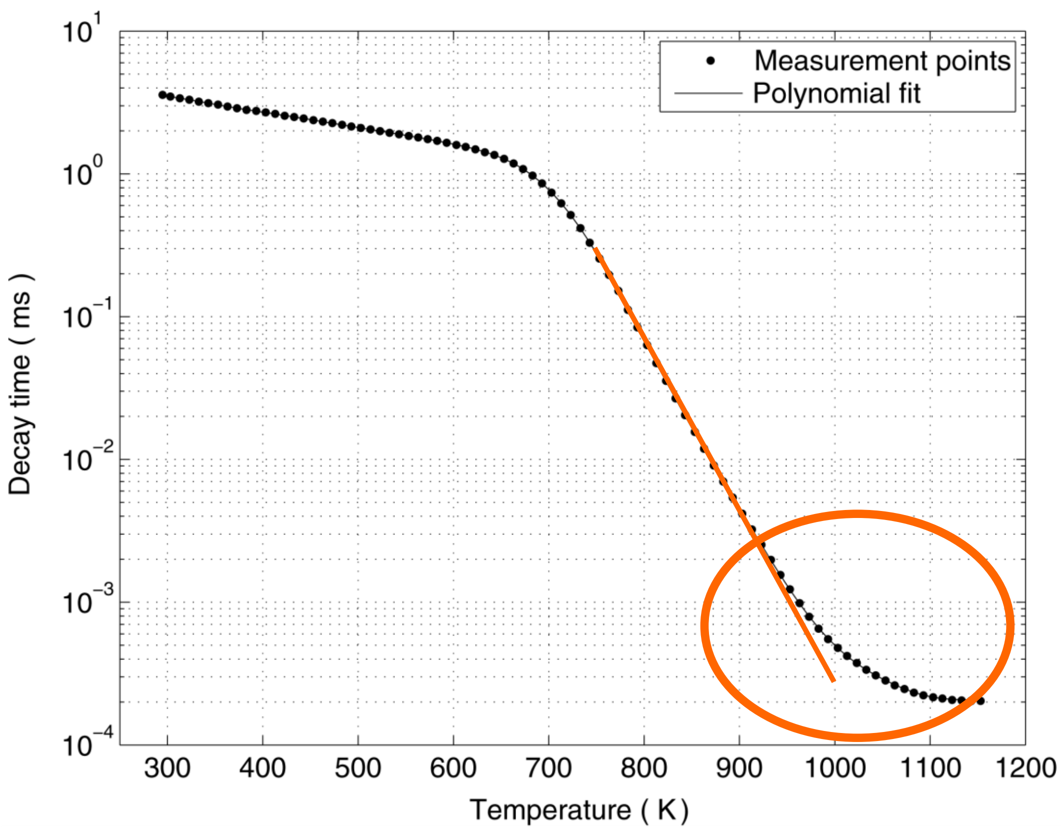
Variation of frame rate:



Minimum of standard deviation at high temporal discretisation.

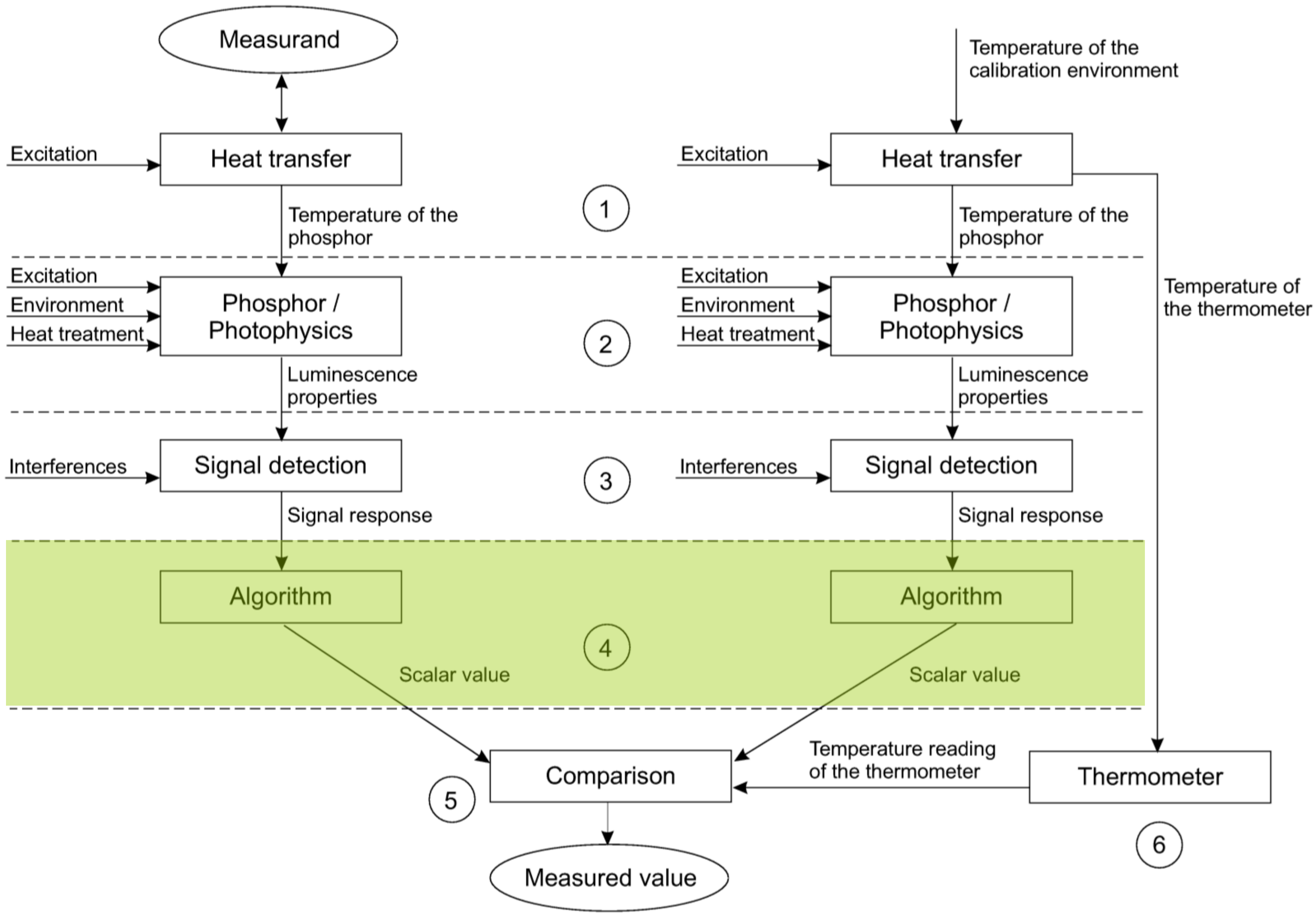
RSM

Error Class 3:
Parameters impacting the transfer function



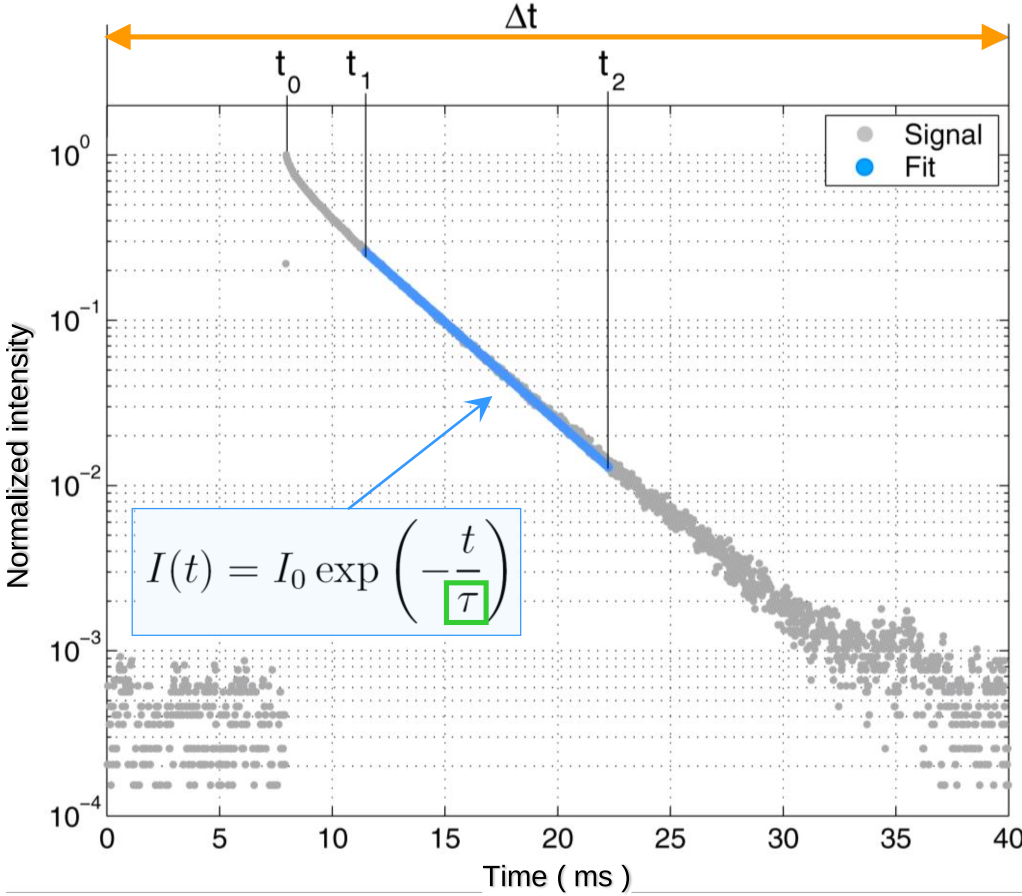
- ➔ Modified low pass character of the detection system (PMT) due to terminating resisitor
- ➔ might strongly change the calibration curve, especially at low decay times

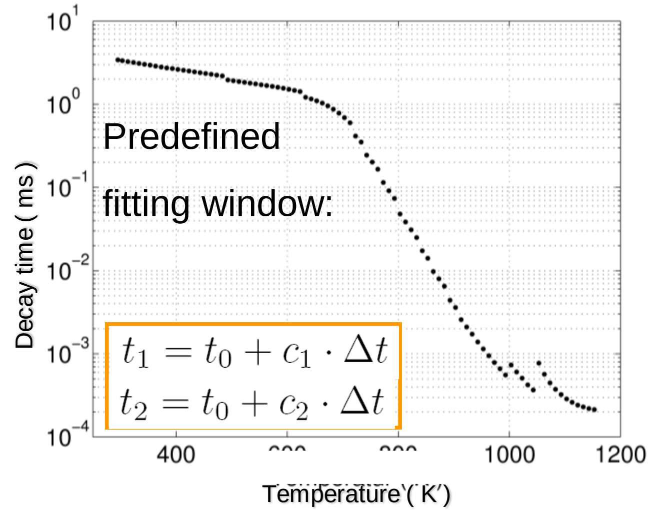
Error class 4:
Algorithm for the data reduction

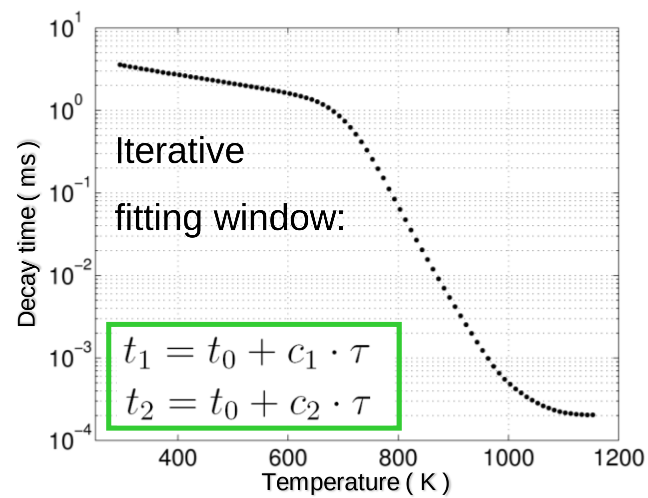


Error class 4:
Algorithm for the data reduction

Problem:
Decay characteristics are not single-exp.

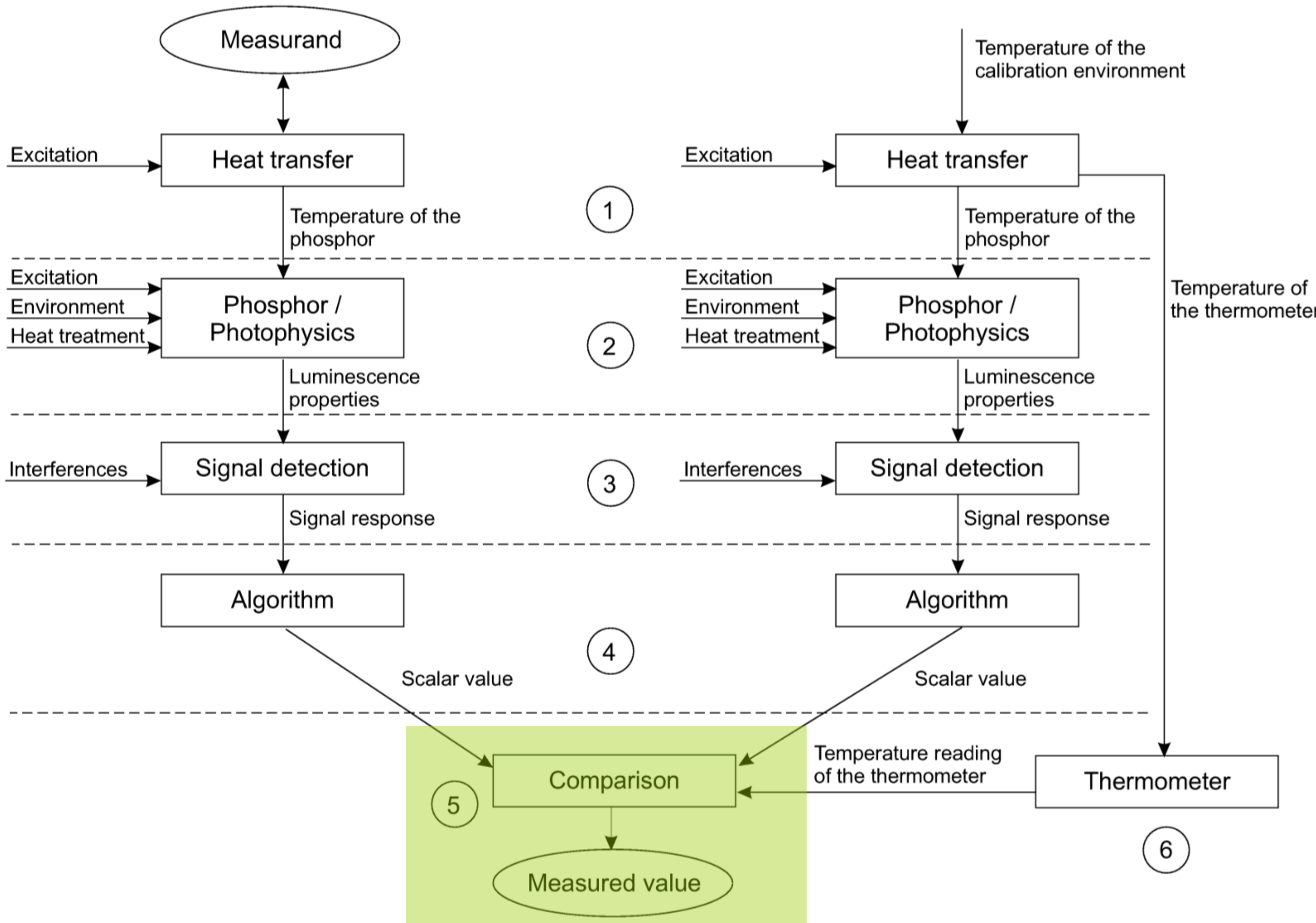






Brübach, J.; Janicka, J.; Dreizler, A.: Opt. Laser Eng., 47(1):75–79, 2009.

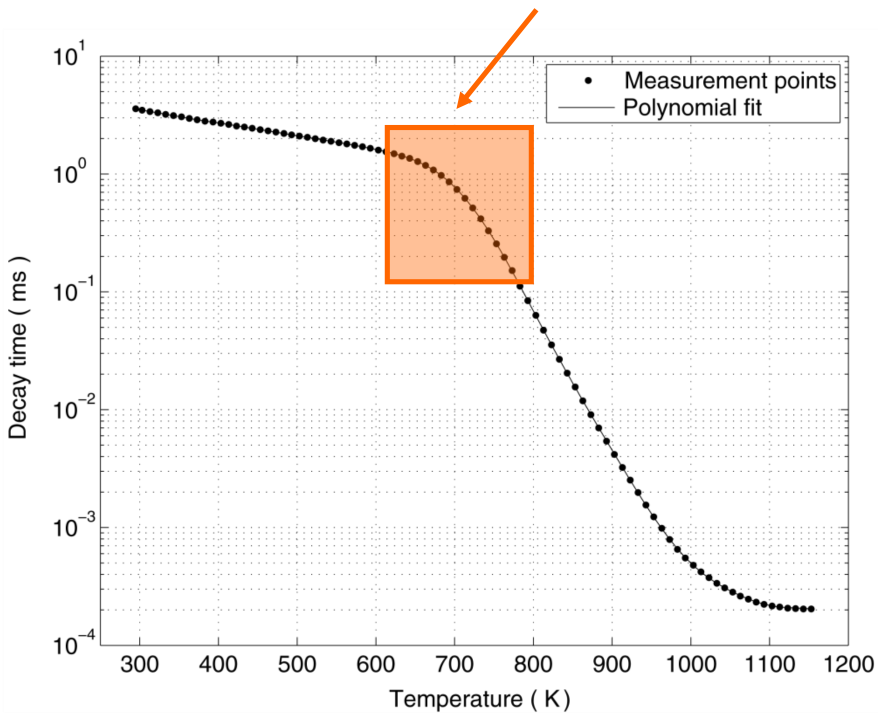
Error class 5:
Comparison of the scalar values



Error class 5:
Comparison of the scalar values

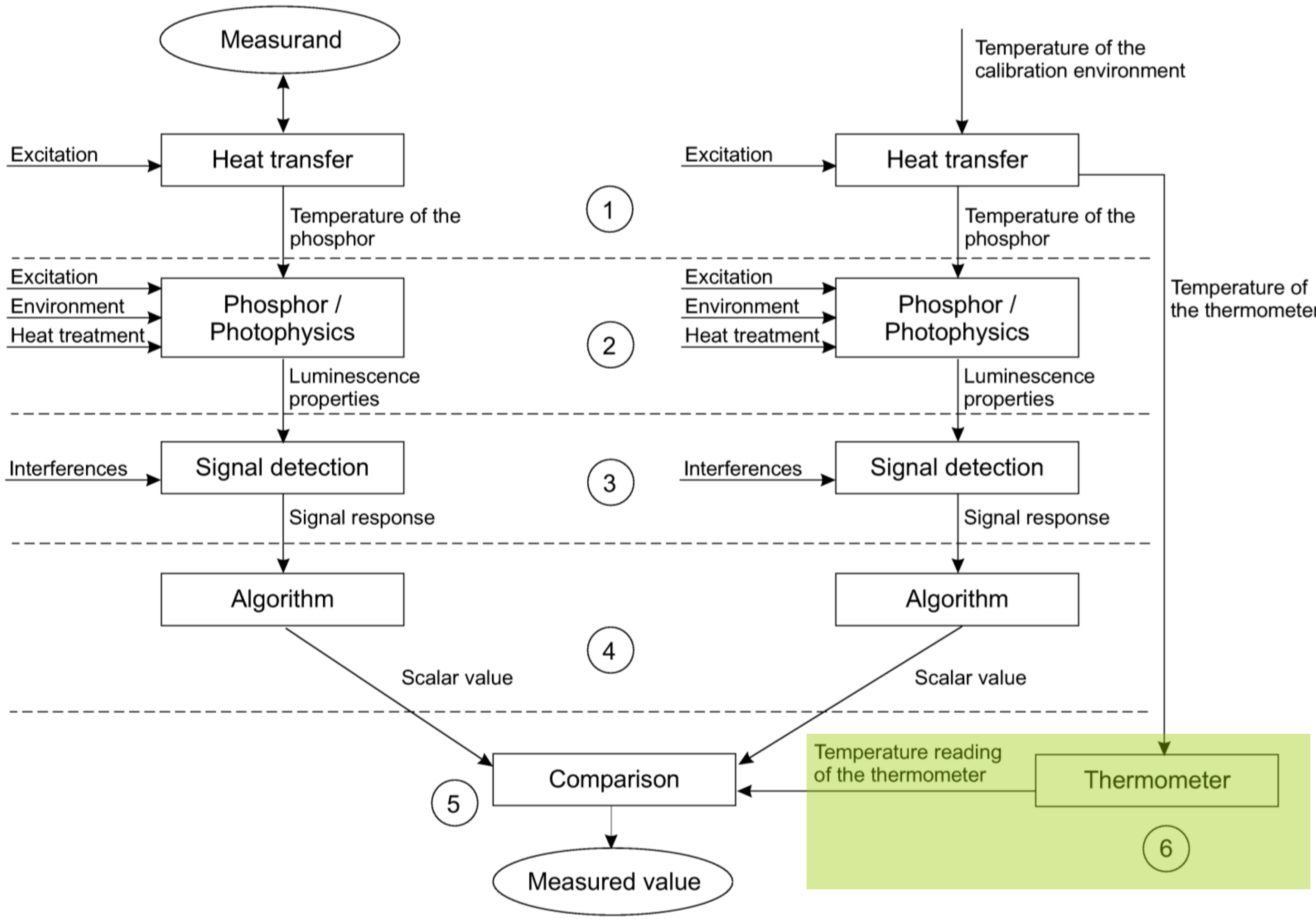
- Error depending on the calibration temperature intervals and the quality of the interpolation in between the calibration points.

- High error potential in strongly curved regimes of the calibration curve



- Calibration intervals of at least ΔT = 20K or even ΔT = 10K are recommended.

Error class 6:
Uncertainty of the calibration thermometer



Error class 6:
Uncertainty of the calibration thermometer

- Most often, thermocouples are employed

- High quality thermocouples offer an accuracy of better than 0.4 % of the absolute temperature.

Error Review

Provided a careful practice:
→ Systematic Error < 1 %

Systematic Error:

Error class		max. error
1. Heat transfer		?
2. Photophysics	Excitation	$O\ (10^1\ K)$
	Dopant concentration	$O\ (10^2\ K)$
	Heat treatments	$O\ (10^1\ K)$
	Surrounding gas phase	$O\ (10^2\ K)$
3. Detection system		$O\ (10^2\ K)$
4. Algorithm for data reduction		$O\ (10^1\ K)$
5. Comparison of calibration and measurement		$O\ (10^1\ K)$
6. Accuracy of the calibration thermocouple		$O\ (10^0\ K)$

Statistical Error:

Shot-to-shot standard devitation: approx. 2 K

Brübach, J.; ISA 55th Int. Instrumentation Symposium, 2009

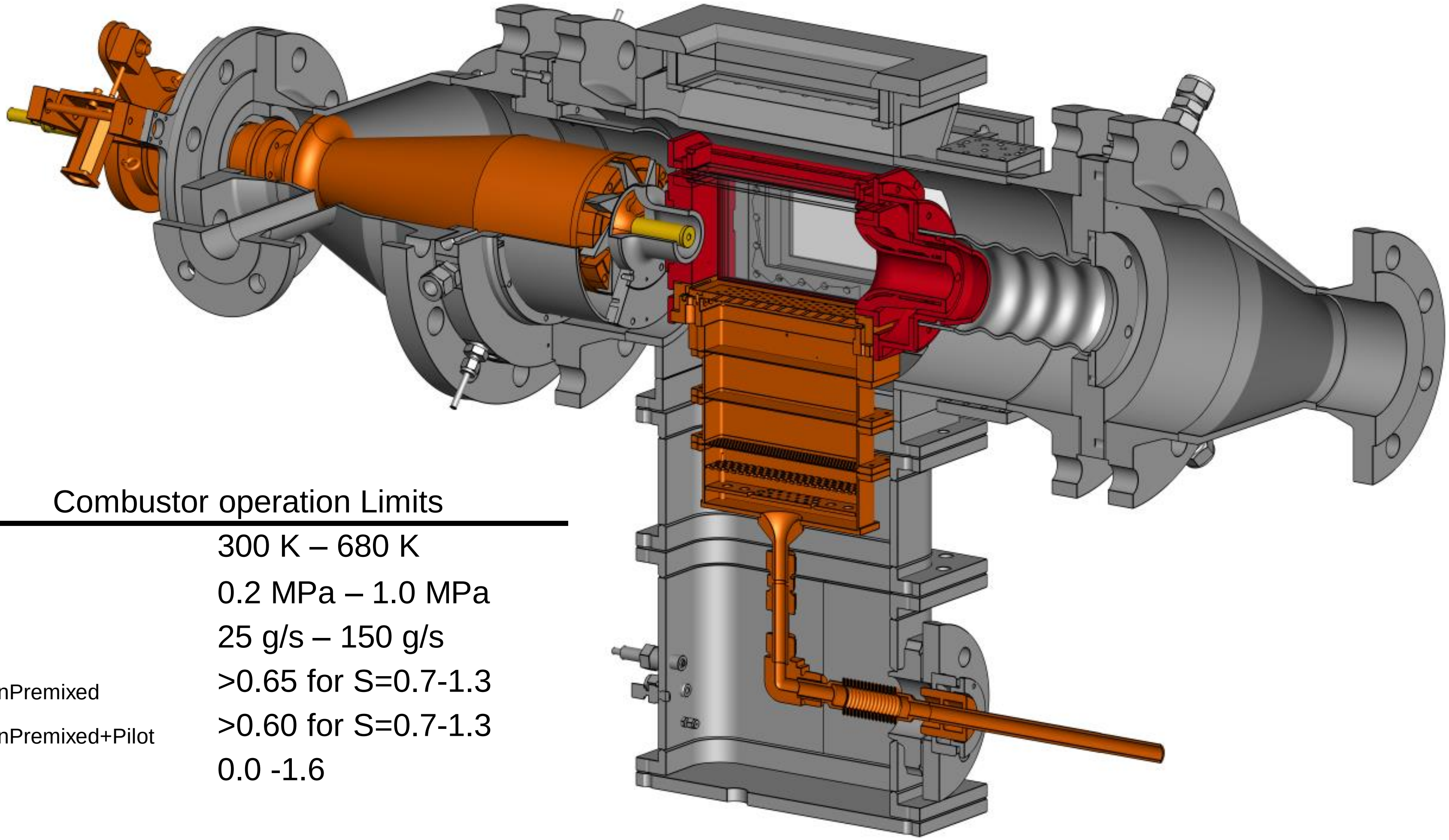
1. Introduction

2. Measurement chain / Error sources

3. Applications

4. Summary

RSM Combustor



Combustor operation Limits

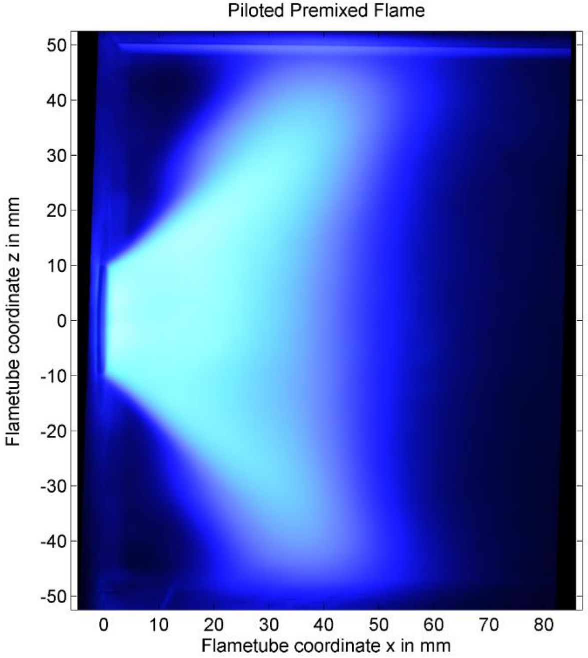
T_3	300 K – 680 K
P_3	0.2 MPa – 1.0 MPa
m_3	25 g/s – 150 g/s
$\varphi_{LeanPremixed}$	>0.65 for S=0.7-1.3
$\varphi_{LeanPremixed+Pilot}$	>0.60 for S=0.7-1.3
S	0.0 -1.6

Herrmann et int. Dreizler. Flow Turb. Combust. (2019) https://doi.org/10.1007/s10494-018-9999-y

RSM Combustor

- Standard operation point

Operation conditions	
T_3	623K
P_3	0.25 MPa
$\dot{m}_3$	0.030kg/s
$\Phi_{LeanPremixed}$	0.65/0% Pilot
$\Phi_{LeanPremixed+Pilot}$	0.65/10% Pilot
S	0.7
$\dot{m}_5$	0.0125 kg/s
T_5	623 K

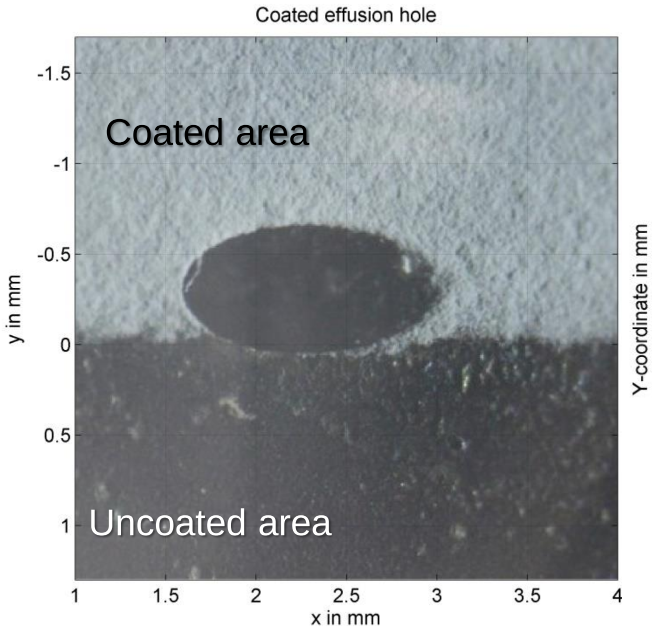


Low-pass (490nm) filtered
Chemiluminescence images from piloted and premixed flames

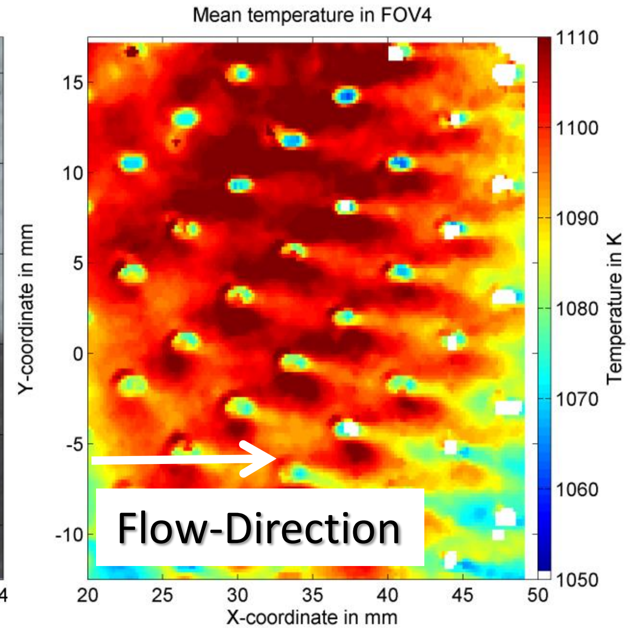
Selected results: wall thermometry

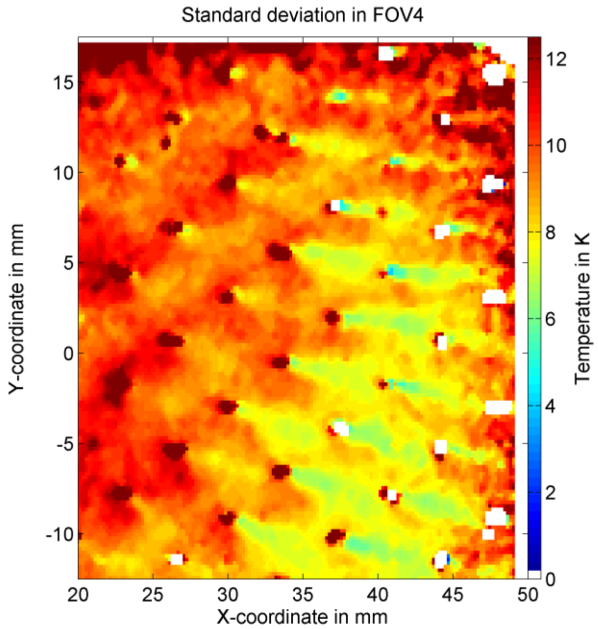
- 2d wall temperature fields

Magnified view of the coated liner.
Coating thickness t 10um <t <50um



Mean and standard deviation from 500 single shots at the liner surface

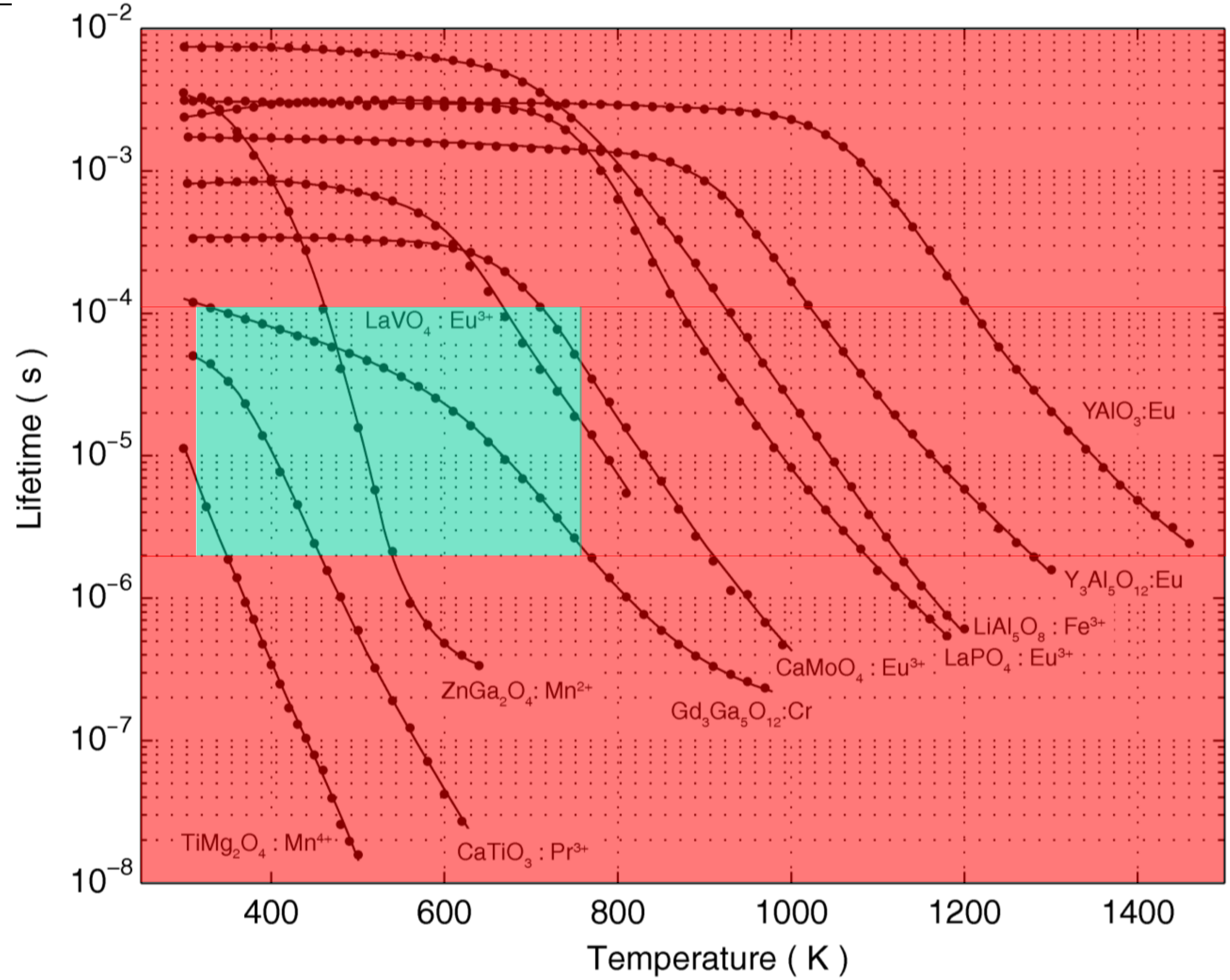




Greifenstein et int. Dreizler. Experiments in Fluids (2019) 60 (1):10

Optically accessible combustion engine

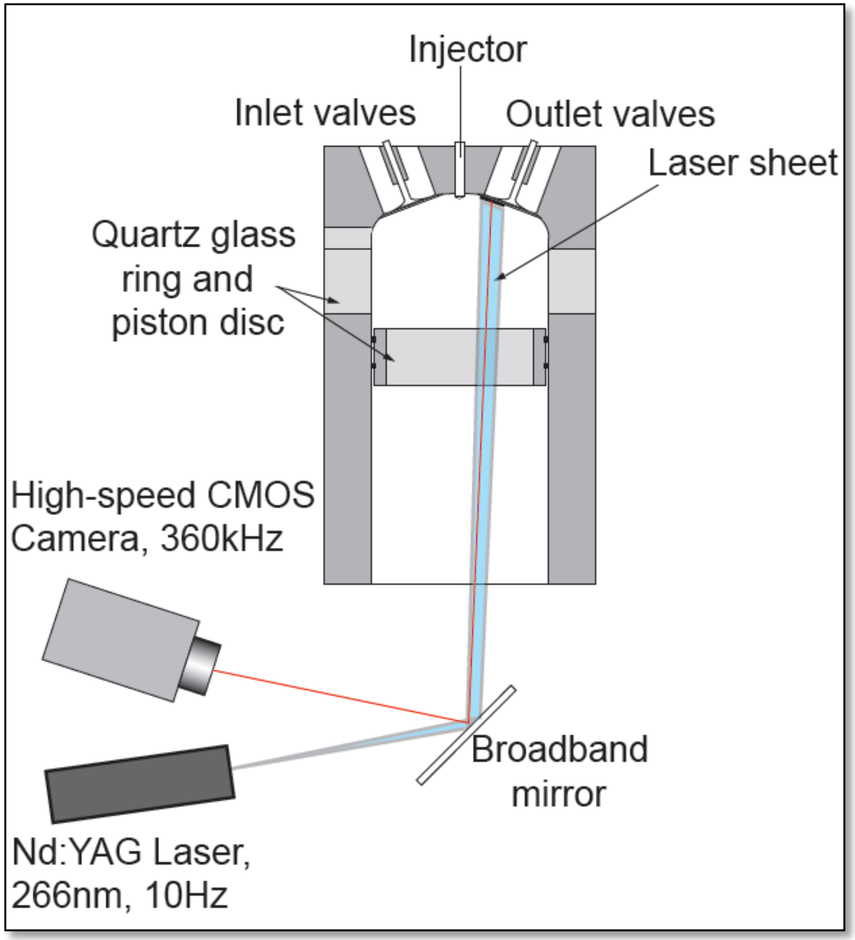
CMOS



Fuhrmann, N. ; Kissel, T. ; Dreizler, A. ; Brübach, J. : Meas. Sci. Technol., Meas. Sci. Technol.22 045301 (2011)
Brübach, J. ; Kissel, T. ; Frotscher, M. ; Euler, M. ; Albert, M. ; Dreizler, A. : J. Lumin., 131, 559 – 564 (2011)

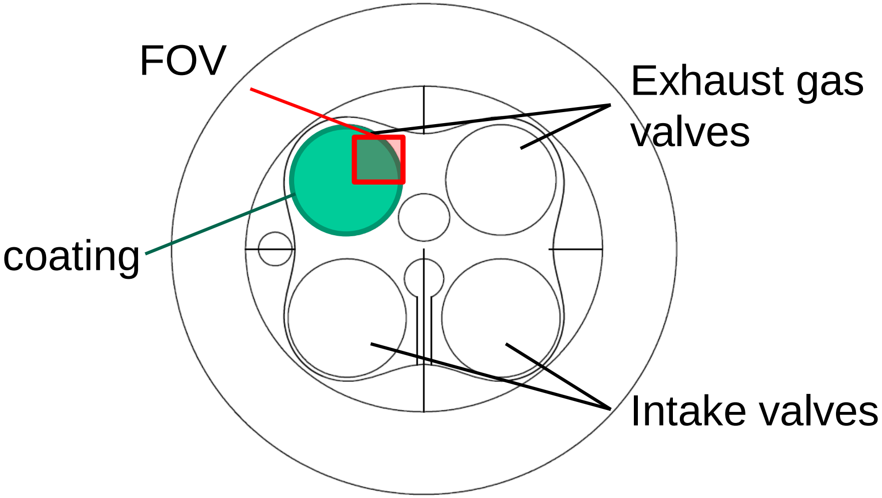
Optically accessible combustion engine

See Appl. Phys. B 2011, Fuhramnn et al.



Temperatur at exhaust valve:

- DI-ICE @ 2000 min^{-1}
- Coating: $Gd_3Ga_5O_{12}$:Cr + Ulfalux Ofenlack
- Spatial resolution: 188 µm/Pixel @ 64x64 Pixel (360 kHz framerate)



Optically accessible combustion engine

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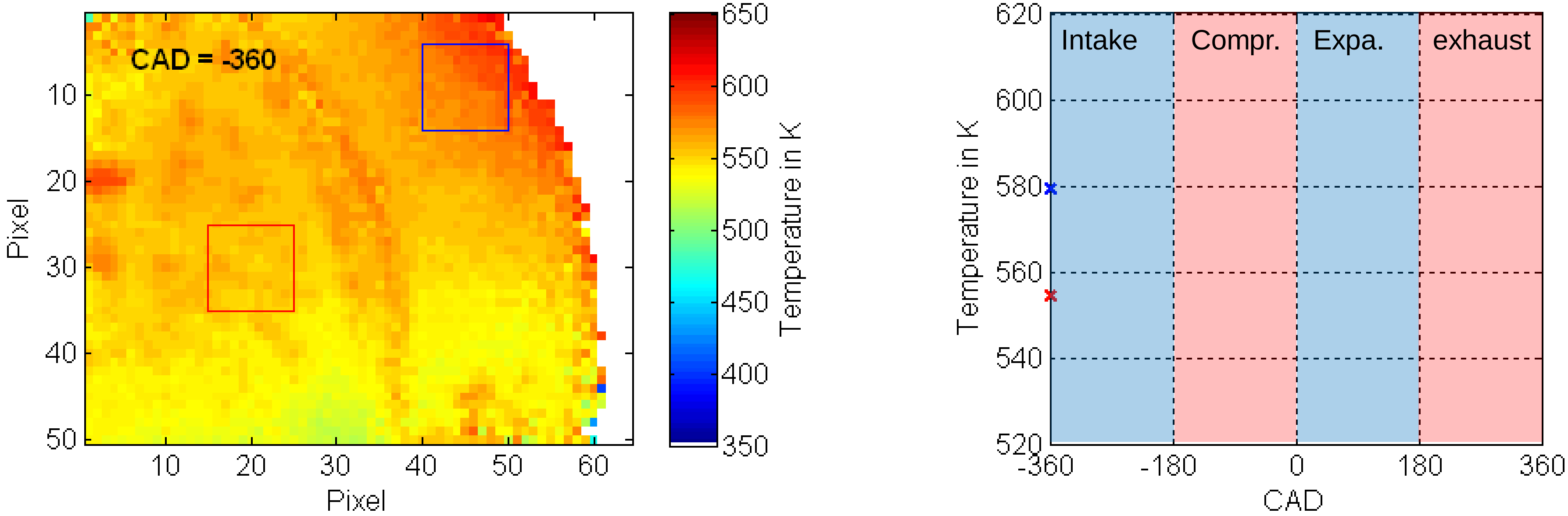
Fired engine operation:

- Temperature measurement at selected CAD

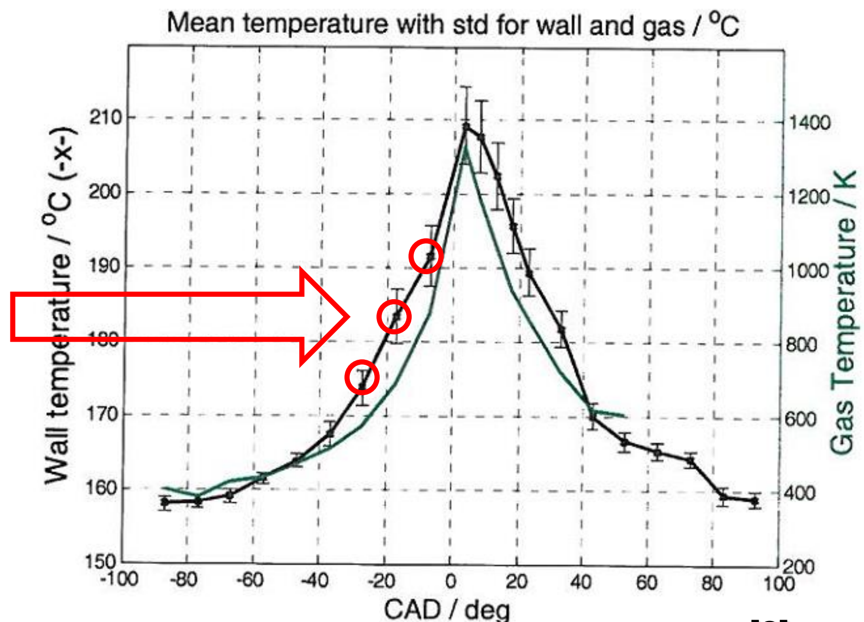


N. Fuhrmann, M. Schild, D. Bensing, S.A. Kaiser, C. Schulz, J. Brübach, A. Dreizler: *Two-dimensional cycle-resolved exhaust valve temperature measurements in an optically accessible internal combustion engine using thermographic phosphors;* Applied Physics B, DOI 10.1007/s00340-011-4819-2.

RSM

Extension to high speed phosphor thermometry in ICE

- Former measurements use 10Hz laser-systems for phosphor thermometry
- Temperatures originate from different cycles → averaging of uncorrelated single shots



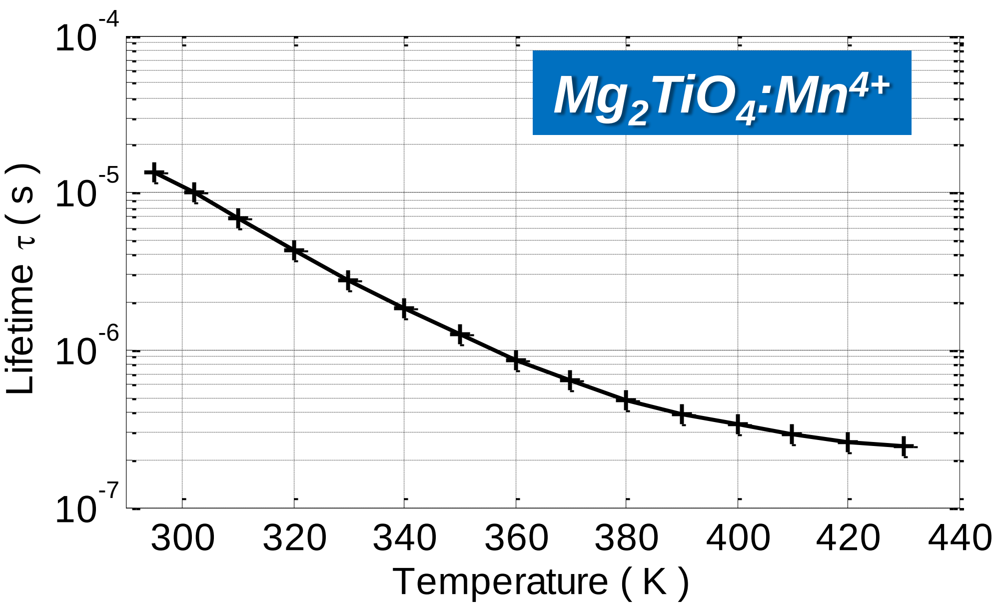
[2]

High speed phosphor thermometry

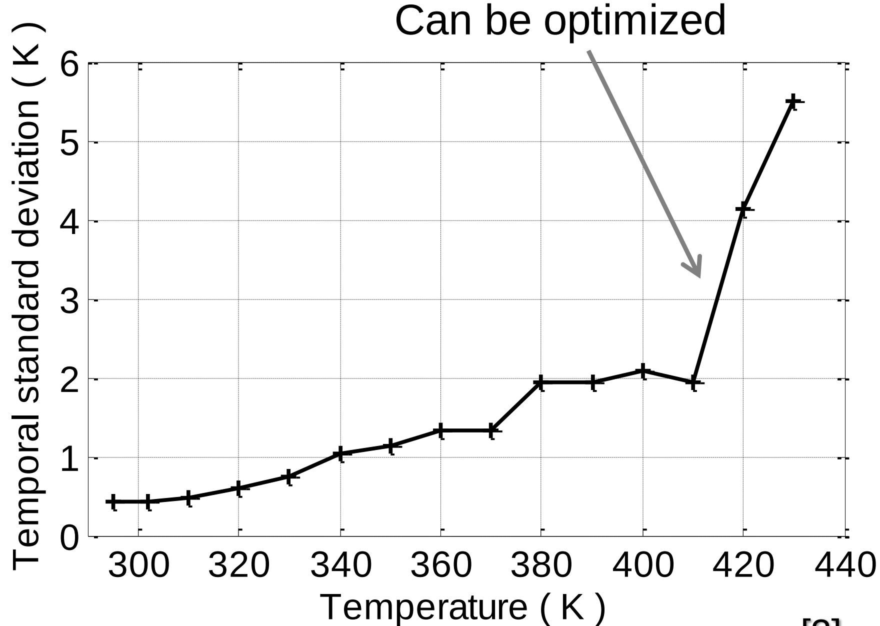
Use laser at high repetition rate to resolve temperatures within cycles

Resolving singly cycles by high speed TGP

- High speed phosphor thermometry
- Very fast decaying phosphors
- Well below 167µs (1°CA at 1000 rpm)



Steep increase due to detection system
Can be optimized

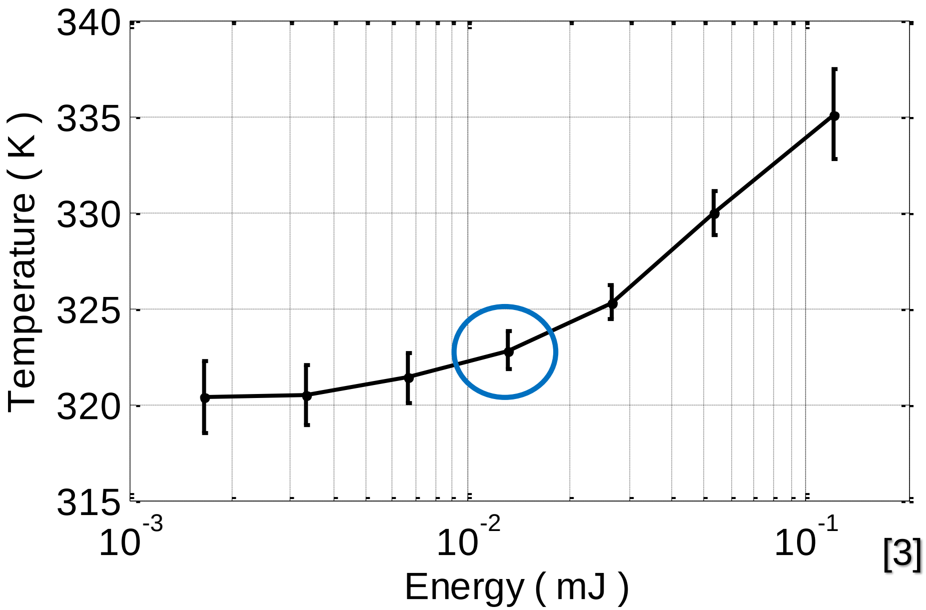


[3]

Influence of laser-induced heating

- Challenges when using High Speed Phosphor Thermometry:
- → Laser-induced heating effects

- Due to high power delivered by laser
- Quantify by energy-scan
- Trade-off between precision and accuracy



[3]

Optimum at E = 13µJ :

Standard deviation below 1K

Systematic error of 2.5K

Set-up and realization

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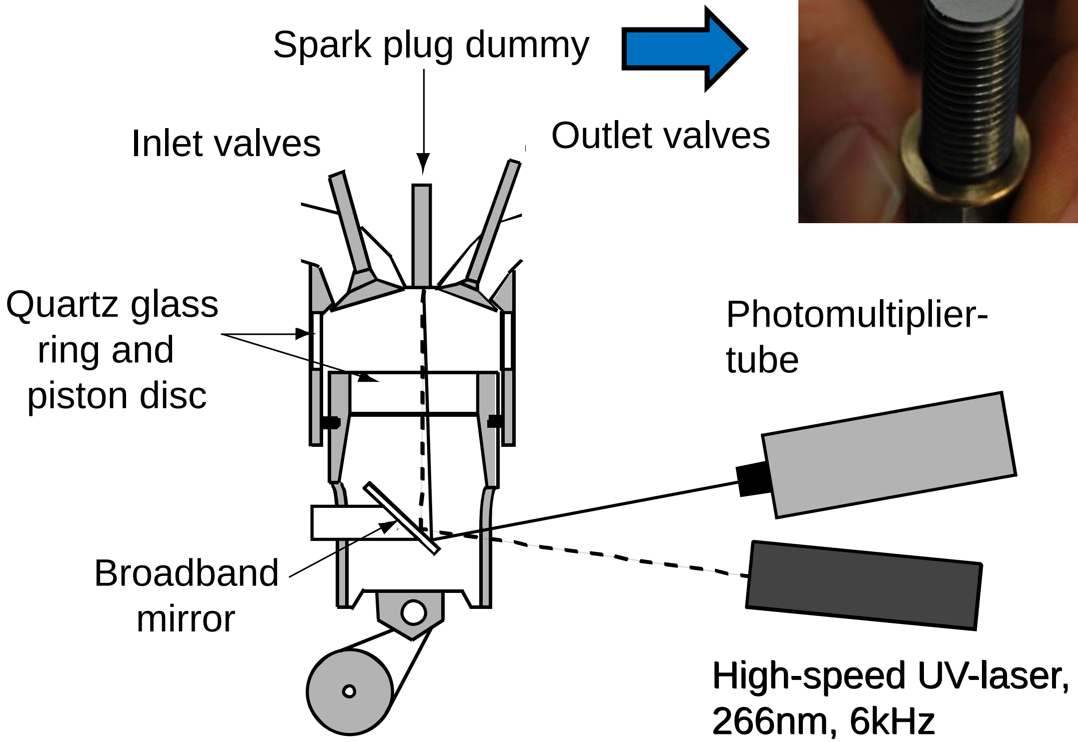
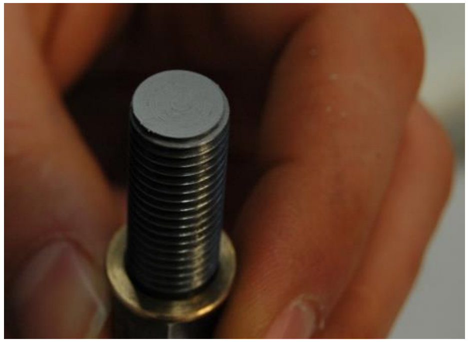
- Experimental Setup





Coating

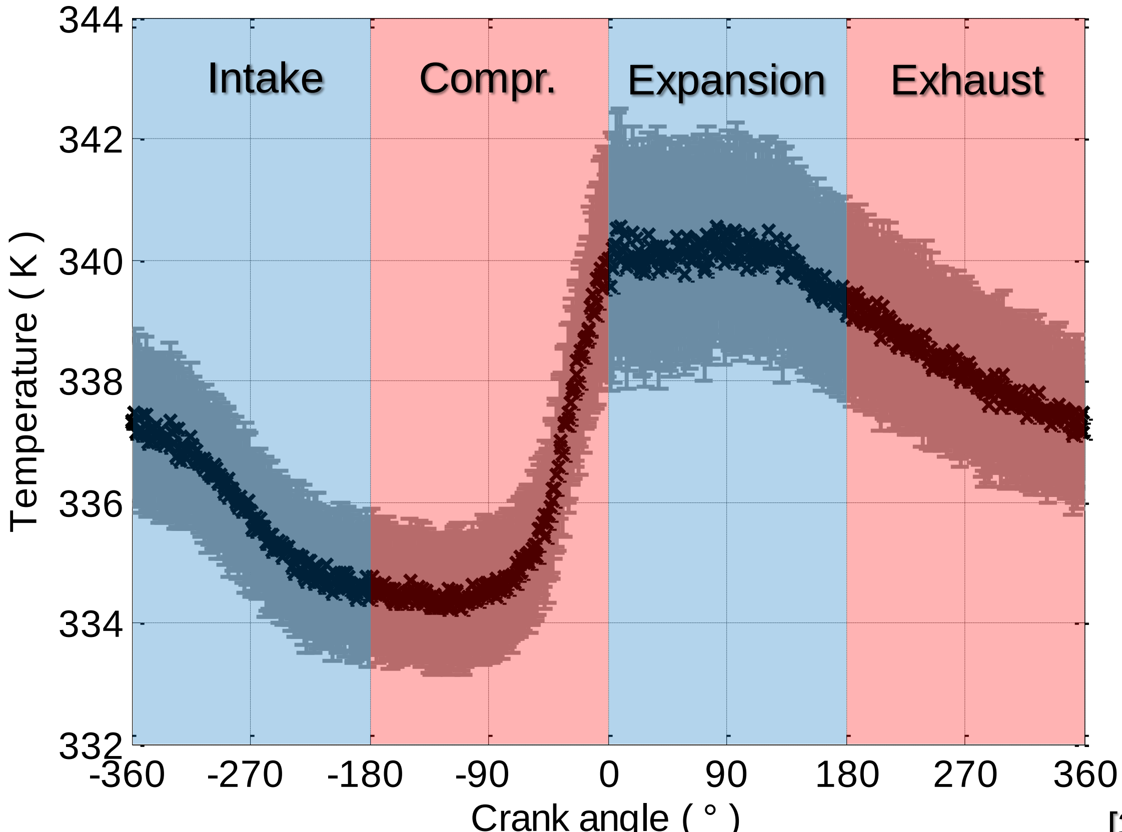
- Coated via airbrush
- Dispersion of binder and phosphor

Engine

- Motored at 1000rpm
- No injection and ignition
- Compression ratio 8.5:1

Results for motored engine (no combustion)

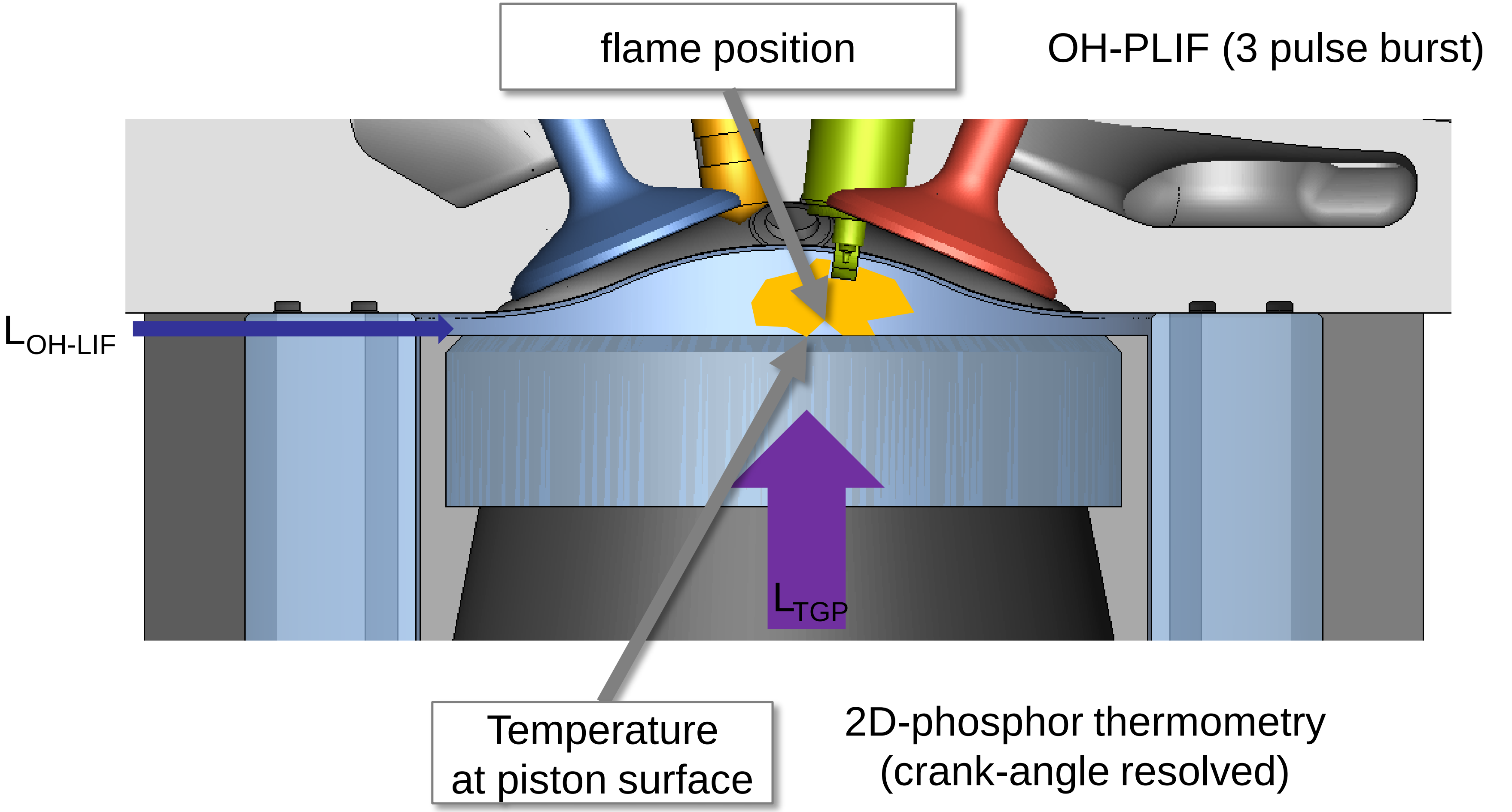
- Temperature progression of the spark plug dummy



[3]

- Mean values and temporal standard deviations of 100 cylces
- Resolution of 1 ° CA
- Precision of about 1-2 K

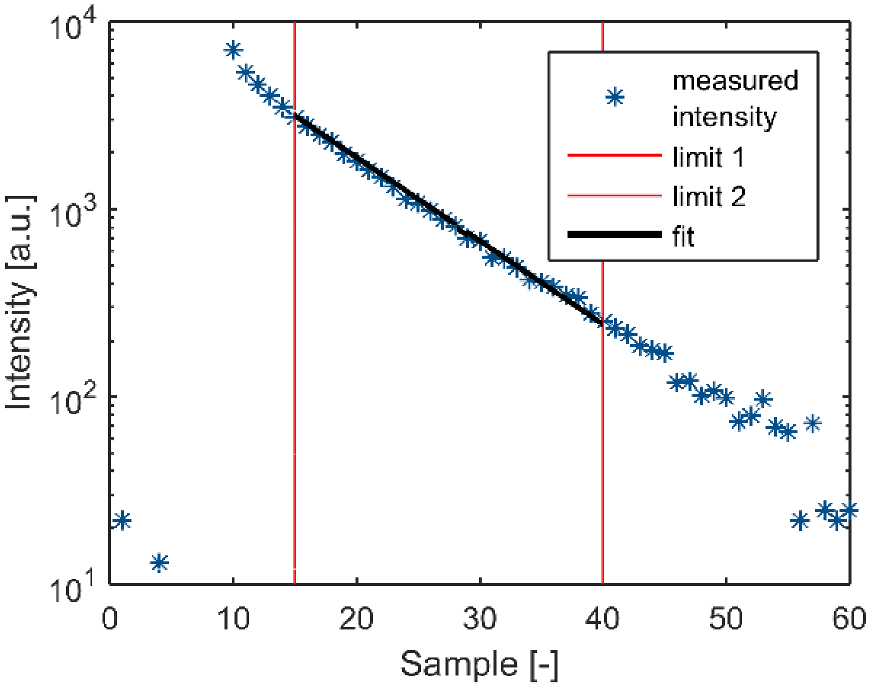
Wall temperature measurements during flame wall interactions in IC engine



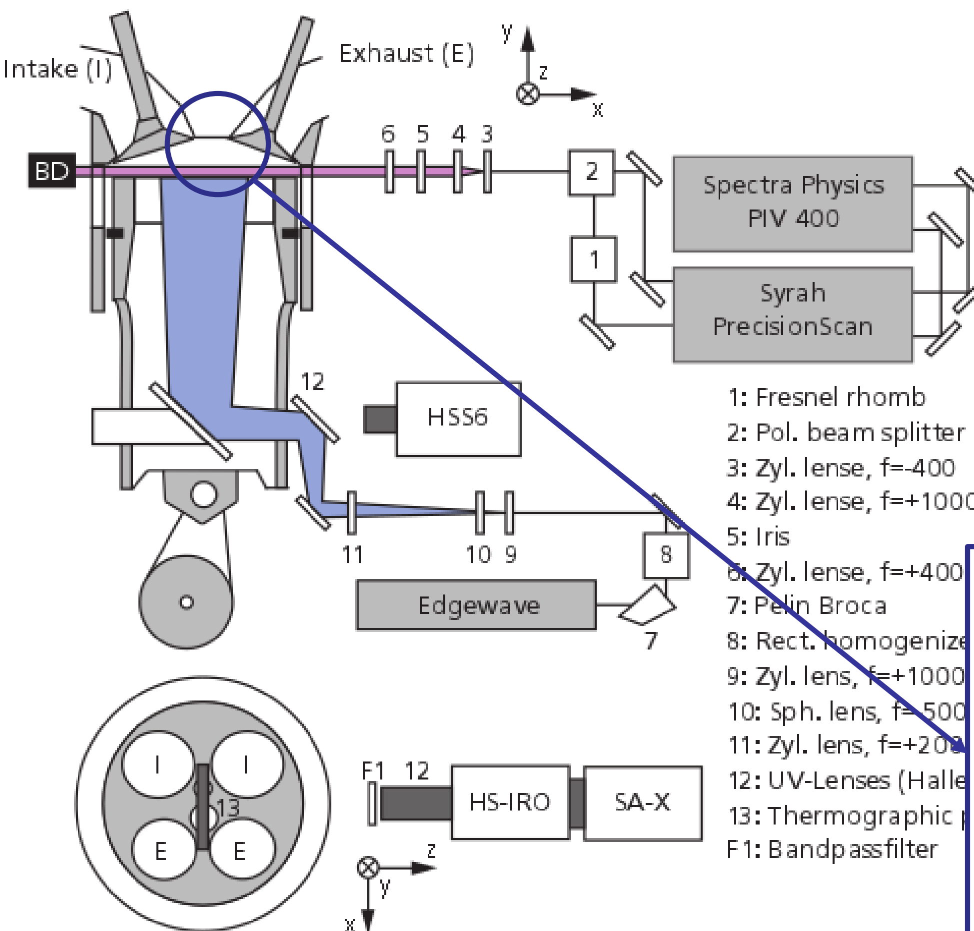
Ding et int. Dreizler, Böhm. Appl. Phys. B (2017) 123:110

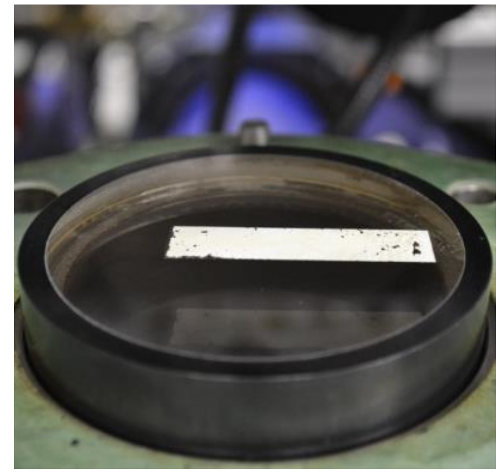
Phosphor thermometry

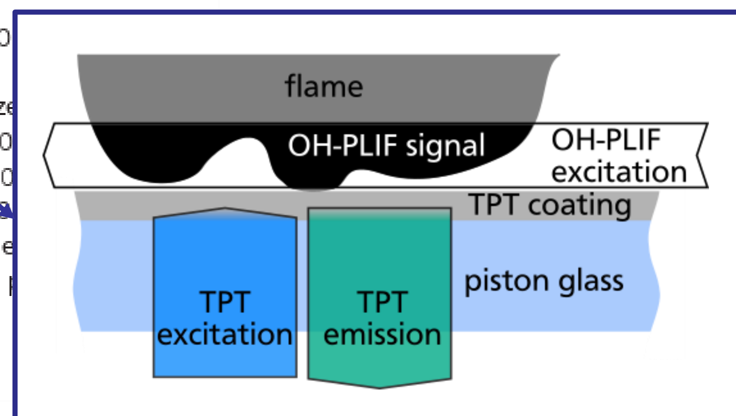
- Decay-time method
  - Ex-situ calibration
- Engine requirements
  - Fast temperature measurements (~ 10µs)
  - High sensitivity, high SNR (~ 5K)
- Suitable thermographic phosphor: $Gd_3Ga_5O_{12}$:Cr,Cer



Experimental setup for studying flame-induced heating







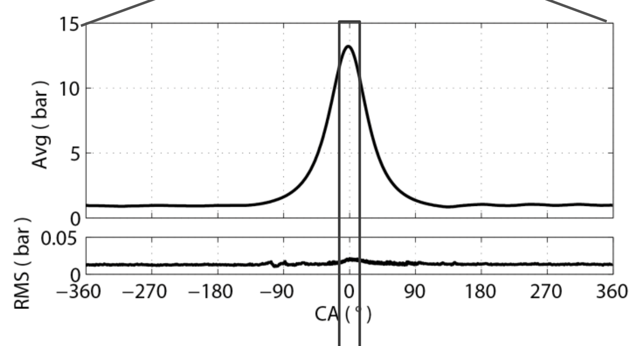
RSM Reaktive Strömungen + Messtechnik

Engine operational conditions

Heating up the engine for several runs → multiple runs recorded

300 cycles motored | 100 fired

100 cycles, every second is recorded

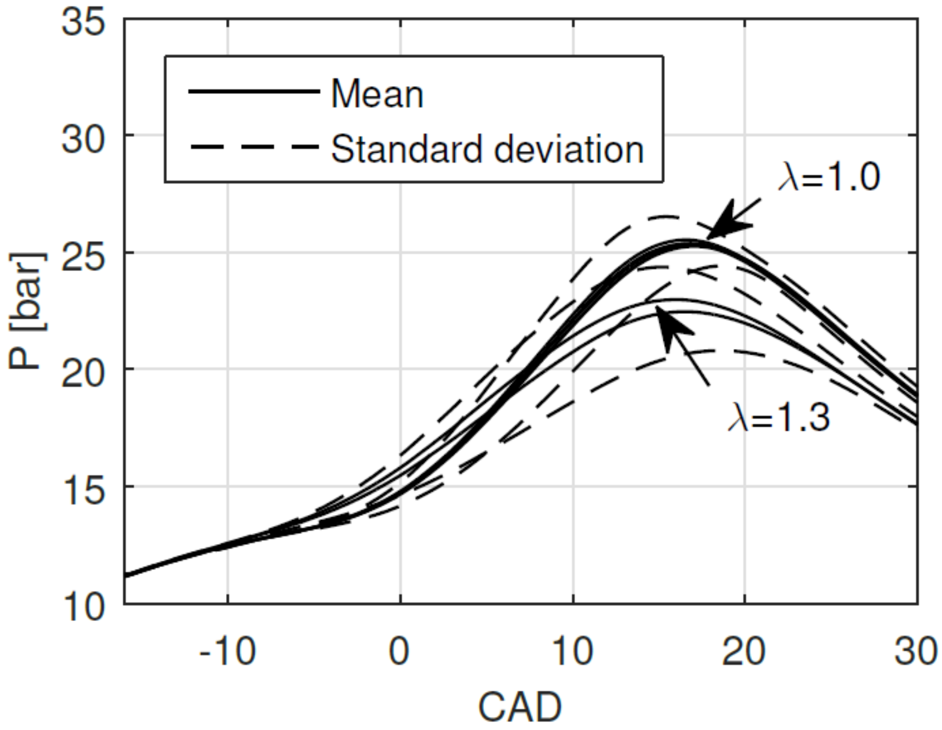


HS-TPT: 15 Images from -6.5 to 14.5 CAD aTDC

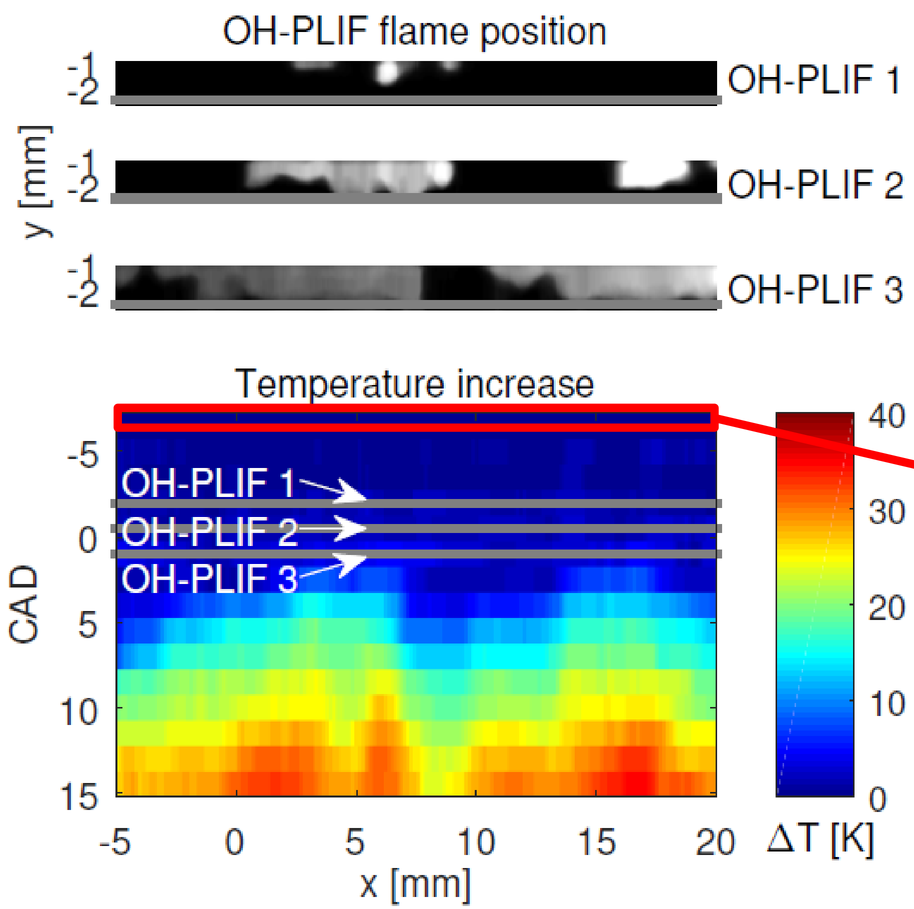
OH-PLIF: 3 Images at -2, -0.5 and 1.0 CAD aTDC

Engine operational conditions

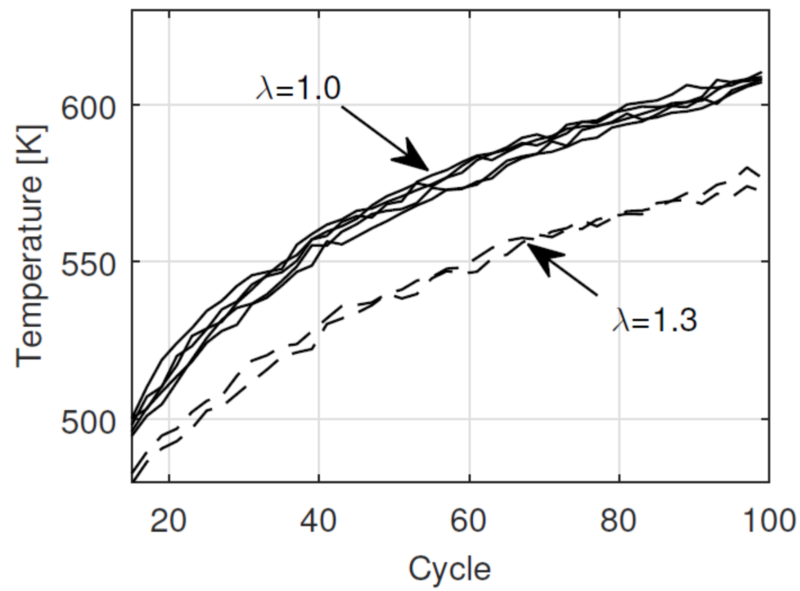
Operating Point	
fuel	CH_4
p_{in}	950 mbar
T_{in}	32°C
Speed	800 rpm
Imep	5.3 bar
lambda	1.0 and 1.3
$t_{ignition}$	-11 and -16 CAD aTDC



Flame position and wall temperature

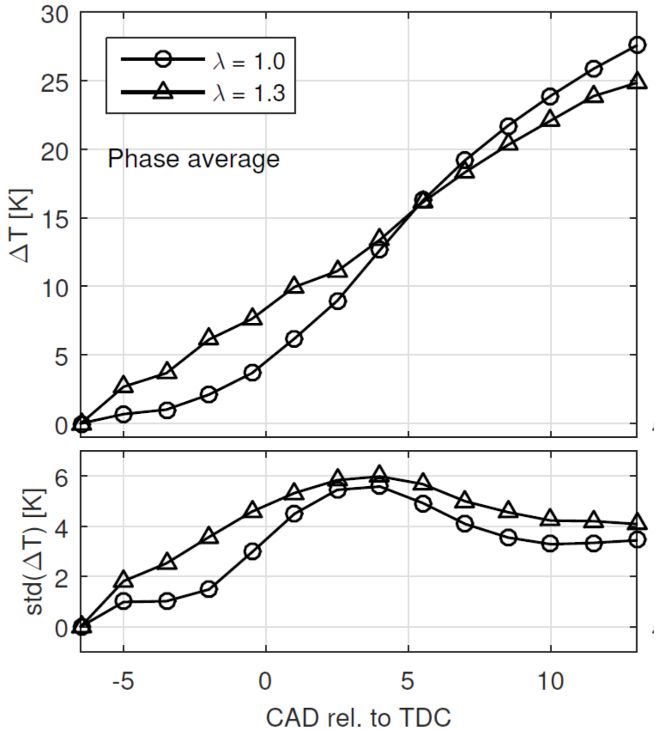


- coherence of flame impingement and wall temperature increase
- reproducible temperature evolution

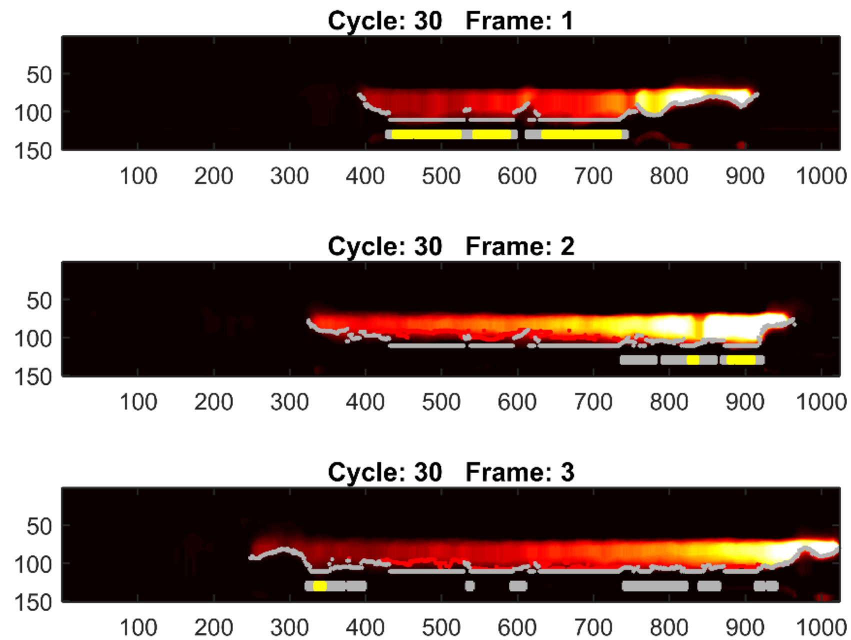


Temperature rise during flame-wall interaction

Phase averaged



Conditional averaged



- Maximum heating rates of up to 20,000 K/s

1. Introduction

2. Measurement chain / Error sources

3. Applications

4. Summary

Summary

- Systems for 0D und 2D phosphor thermometry
- Decay-time method superior compared to ratio method with respect to precision and accuracy
- Quantification of systematic and statistic error
- Application (relatively) straight forward, even to complex systems
- High potential for further applications