High-accuracy radiation thermometry at the Physikalisch-Technische Bundesanstalt (PTB)

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Physikalisch-Technische Bundesanstalt

Overview

- Introduction
- Low- / mid-temperature calibration facility
- High-temperature calibration facility
- High-temperature eutectic fixed-points
- Summary

Introduction

Temperature

- governs most production processes in industry
- crucial for optimized productivity and quality assurance

frequent measurement technique – radiation thermometry

- annual growth rate: more than 10%
- 600,000 radiation thermometers sold / year
- 15,000 thermography systems sold / year
- market volume: > 1 billion €

Introduction

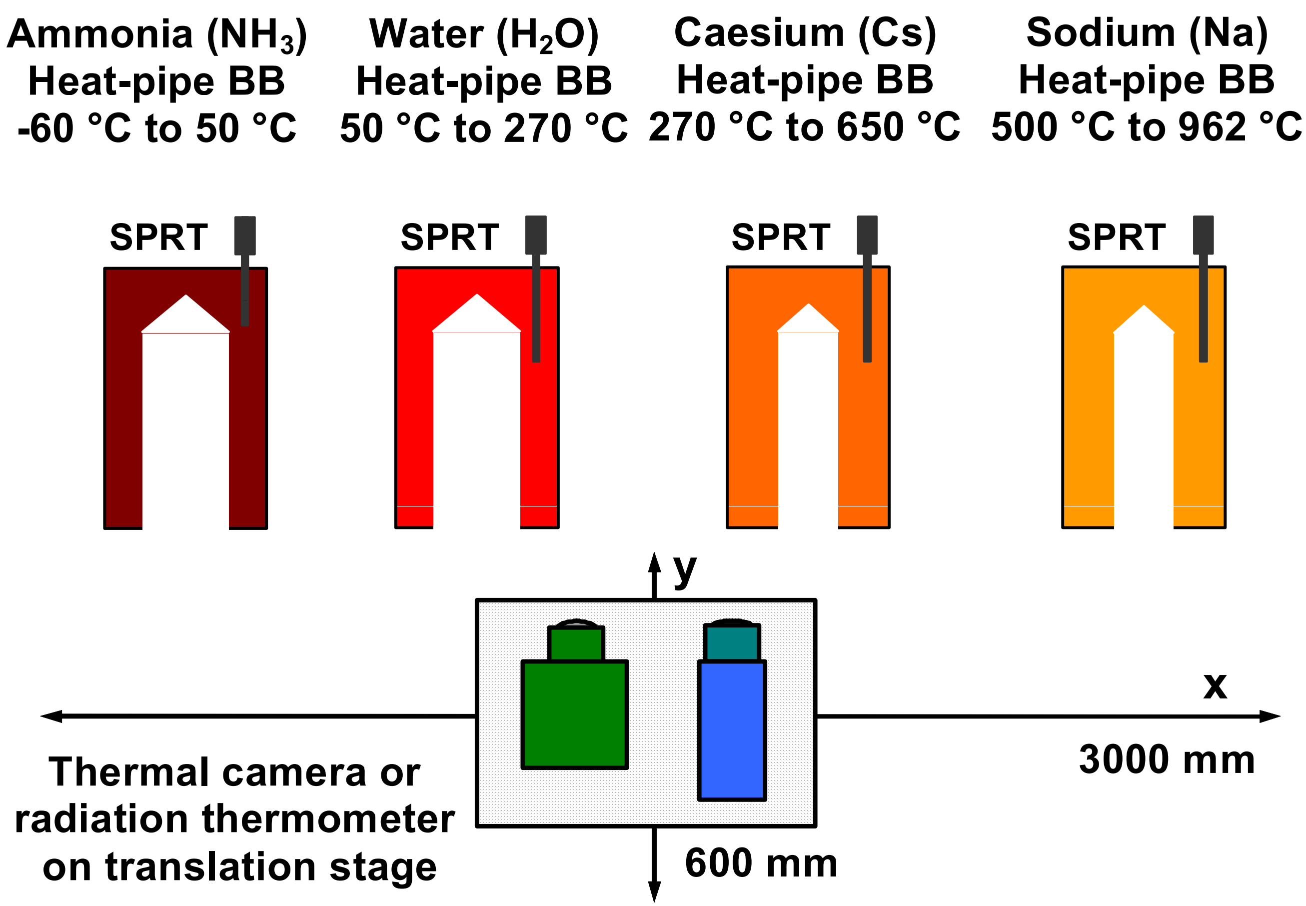
Increased demand of calibrations in the field of radiation thermometry

PTB operates two calibration facilities:

- **Low-/ mid-temperature calibration facility; temperature range: -60 °C to 962 °C**
- **High temperature calibration facility; temperature range: 900 °C to 3000 °C**
- **Realization and dissemination of radiation temperatures**

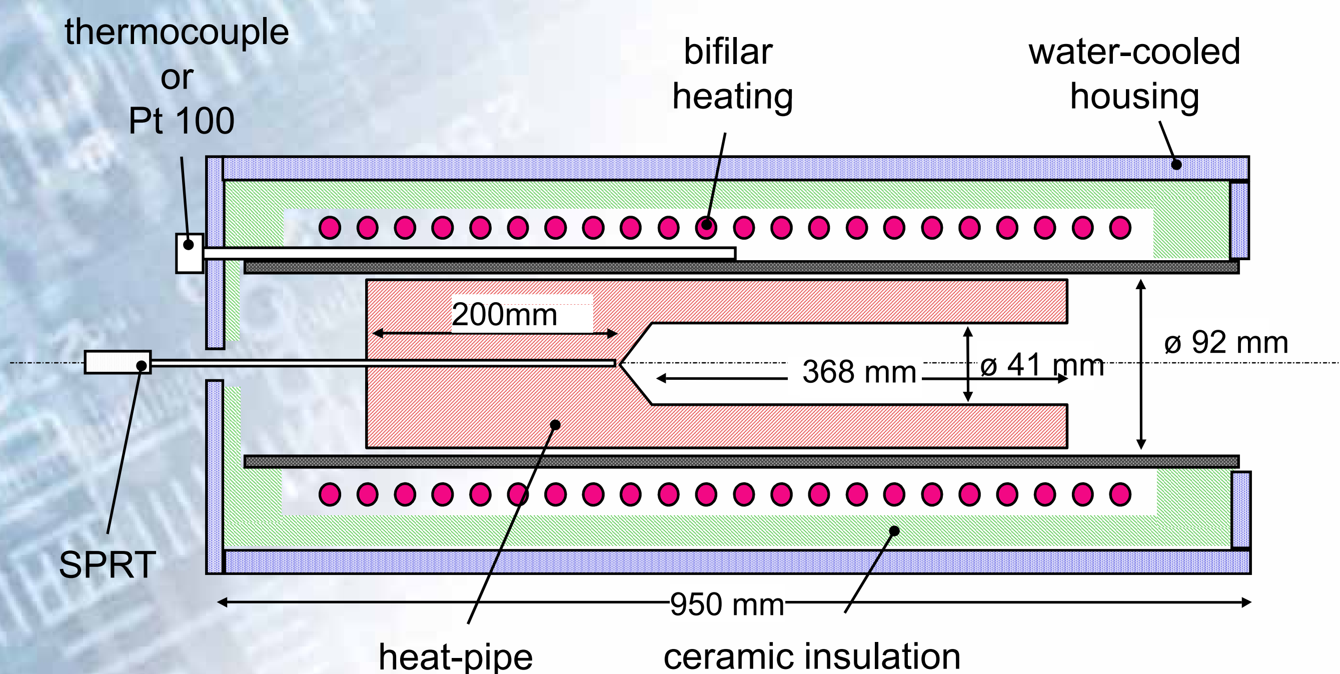
Low- / mid-temperature calibration facility

- schematic view



Low- / mid-temperature calibration facility

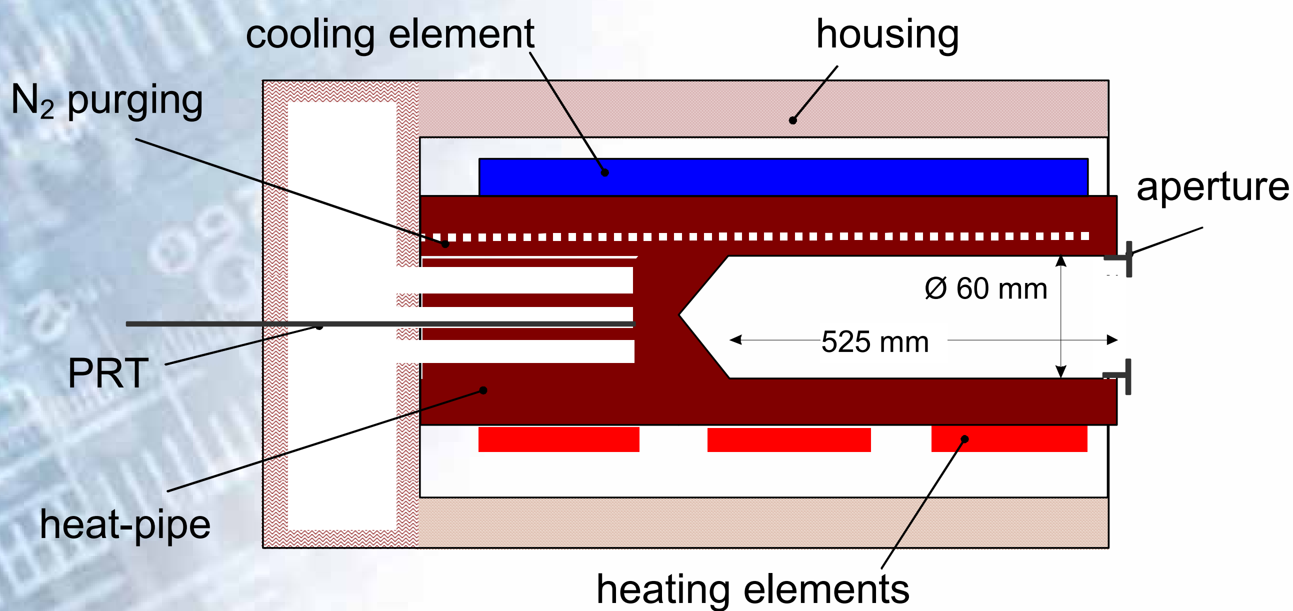
- **cross-section of sodium / cesium heat-pipe blackbody**



- heater temporal stability: 0.1 K
- heat-pipe temperature stability: **10 mK**

Low- / mid-temperature calibration facility

- **cross-section of H_2O / NH_3 heat-pipe blackbody**



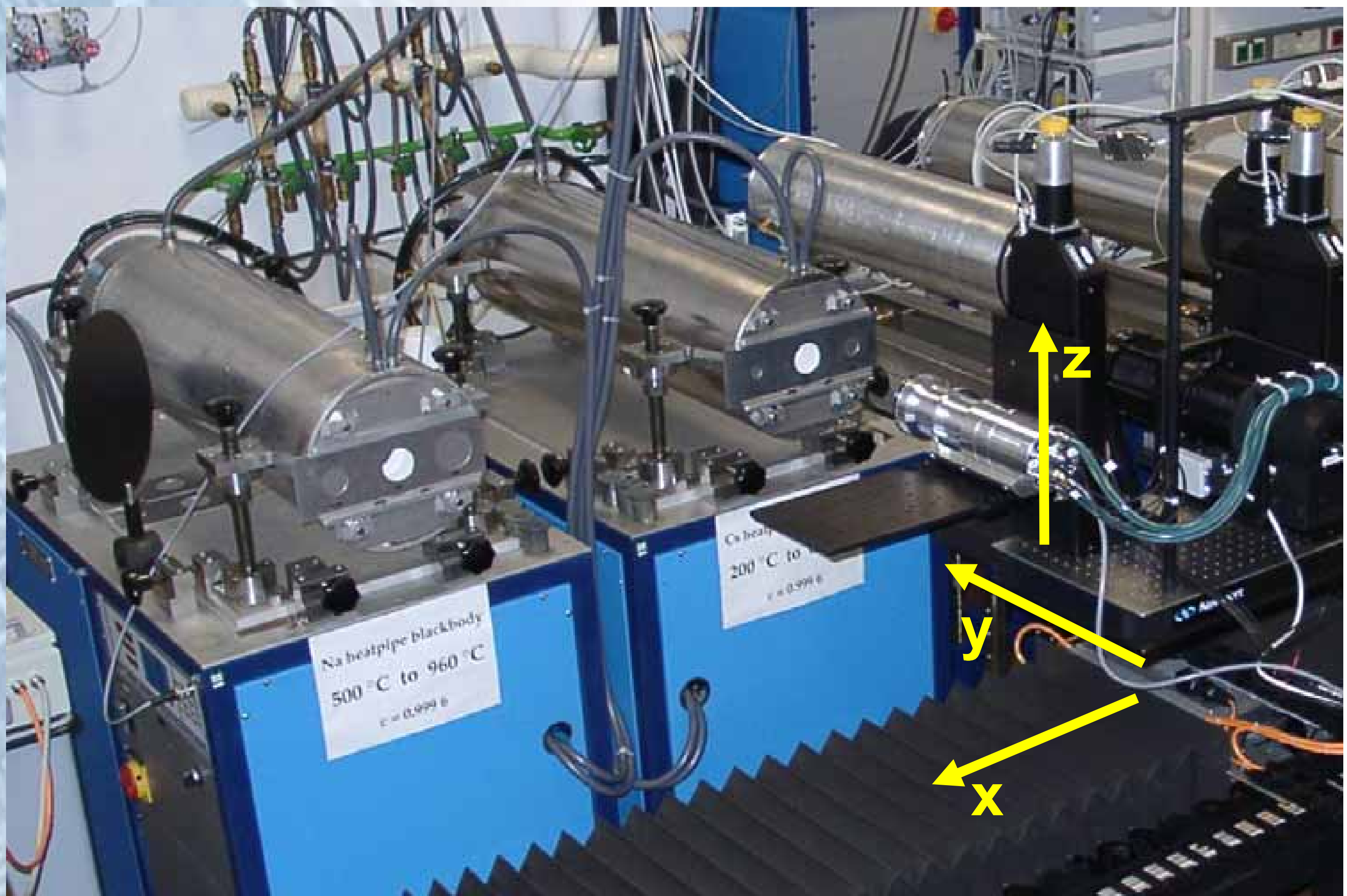
- heater temporal stability: 0.1 K
- heat-pipe temperature stability: **10 mK**

Low- / mid-temperature calibration facility

PTB heat-pipe blackbodies

Blackbody	Temperature range / °C	Cavity diameter / mm	Cavity Emissivity
NH_3-BB	-60 to 50	60	0.99990 ± 0.00006
H_20-BB	50 to 270	60	0.99980 ± 0.00015
Cs-BB	270 to 650	41	0.99960 ± 0.00017
Na-BB	500 to 962	41	0.99960 ± 0.00017

Low- / mid-temperature calibration facility



Low- / mid-temperature calibration facility

- **radiation temperature standard uncertainties (*k*=1)**

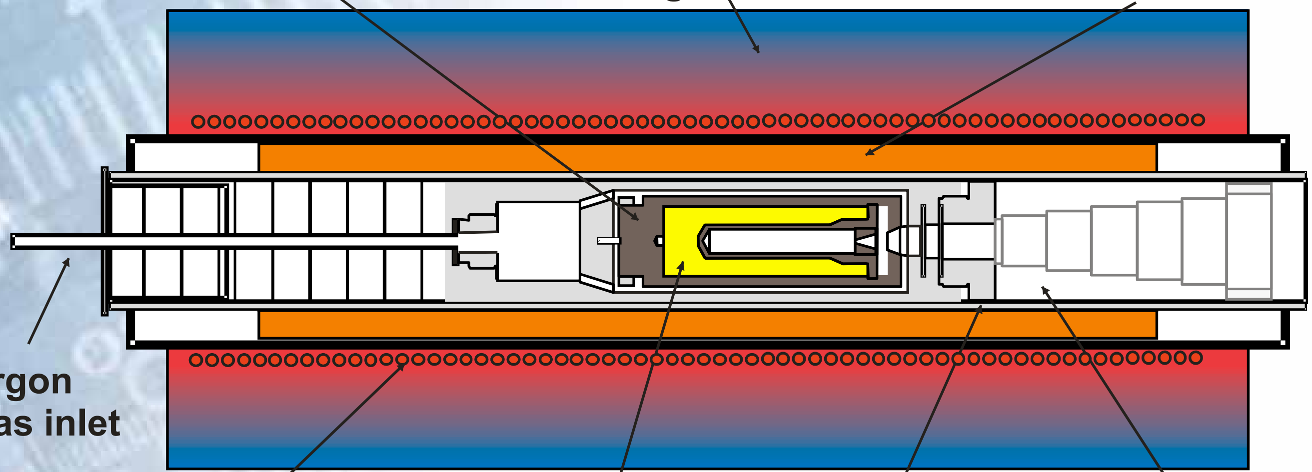
Radiation temperature / °C	Uncertainty of radiation temperature / °C		
	1.6 µm	3.9 µm	10 µm
-60		0.1	0.035
0	0.035	0.035	0.035
50	0.035	0.035	0.035
100	0.035	0.035	0.035
200	0.08	0.08	0.08
300	0.1	0.10	0.10
400	0.02	0.03	0.05
600	0.03	0.05	0.08
800	0.06	0.07	0.11
960	0.08	0.10	0.14

High temperature scale

Realization and dissemination of radiation temperature scale above the Ag-FP (961.78 °C):

- Gold fixed-point (Au-FP) blackbody radiator: 1064.18 °C
- High temperature blackbody (HTBB): variable temperature, 900 °C to 3000 °C
- High quality transfer standard radiation thermometers (LP3)
- Tungsten strip lamps operated as radiation temperature standards

Gold fixed-point blackbody

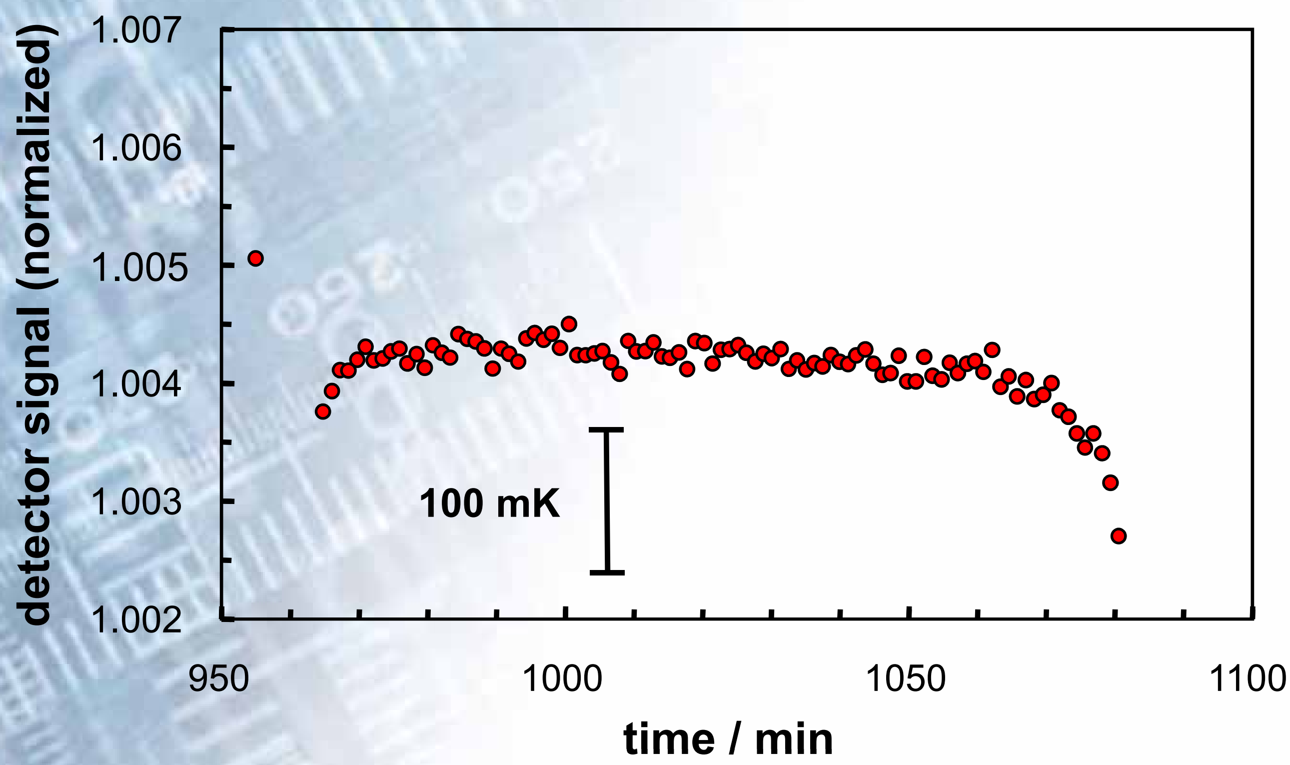


- heat-pipe based design
- cavity aperture diameter: 3 mm
- ε = 0.99999
- large fixed-point material amount (~ 3 kg Au)

→ excellent performance

Gold fixed-point blackbody

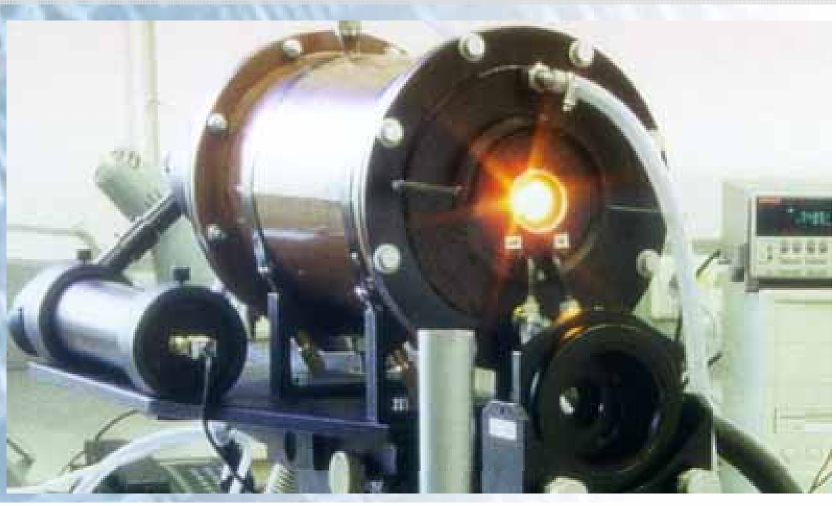
- freezing plateau

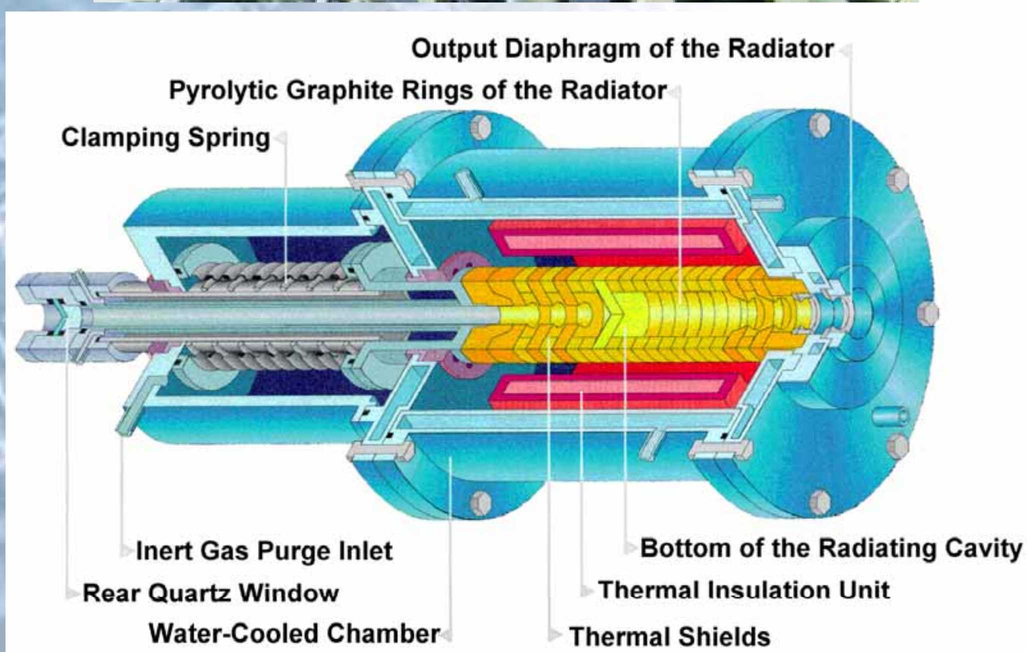


- freezing plateau duration: ~ 90 minutes
- temperature stability: ~ 10 mK

but: limitation to <u>one</u> temperature: 1337.33 K !

High Temperature Blackbody (HTBB 3200pg)





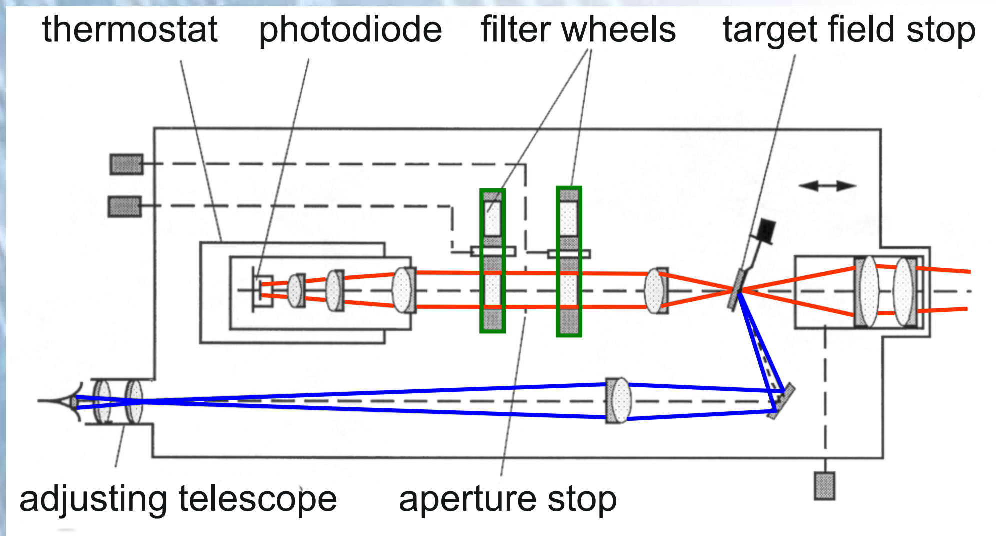
PTB primary standard

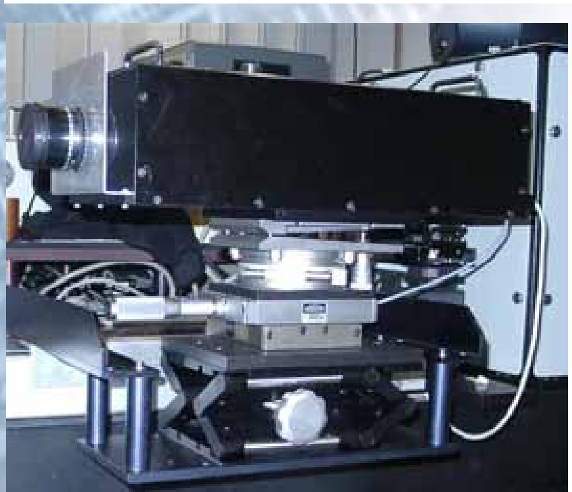
- **Radiation temperature above the Ag-FP**
- **Spectral radiance**

- **directly Joule-heated cavity (DC, 700 A max.)**
- **operating temperature range: 1000 K to 3200 K**
- **temporal stability: better than 250 mK**
- **large aperture diameter : 20 mm**
- ε **= 0.999 ± 0.001**

Linear pyrometer LP3

- **schematic view**





Transfer radiation thermometer for:

- **International scale comparisons**
- **Internal high-temperature scale dissemination**

Main characteristics:

- λ_{eff} = 650 nm (950 nm)
- Temperature range:
  800 °C to 2900 °C
- FOV: 0.8 mm Ø at 690 mm
- Good stability and linearity
- Small SSE

$$I_{photo}(T) = C \cdot \exp\left(-\frac{c_2}{A \cdot T + B}\right)$$

Standard uncertainty:
0.3 °C at 800 °C
to
1.0 °C at 2900 °C

High temperature scale – realization and dissemination

Radiation temperature
CALIBRATION ARTEFACT

COMPARISON / DISSEMINATION

Radi

adiance

DY

T_{90} (

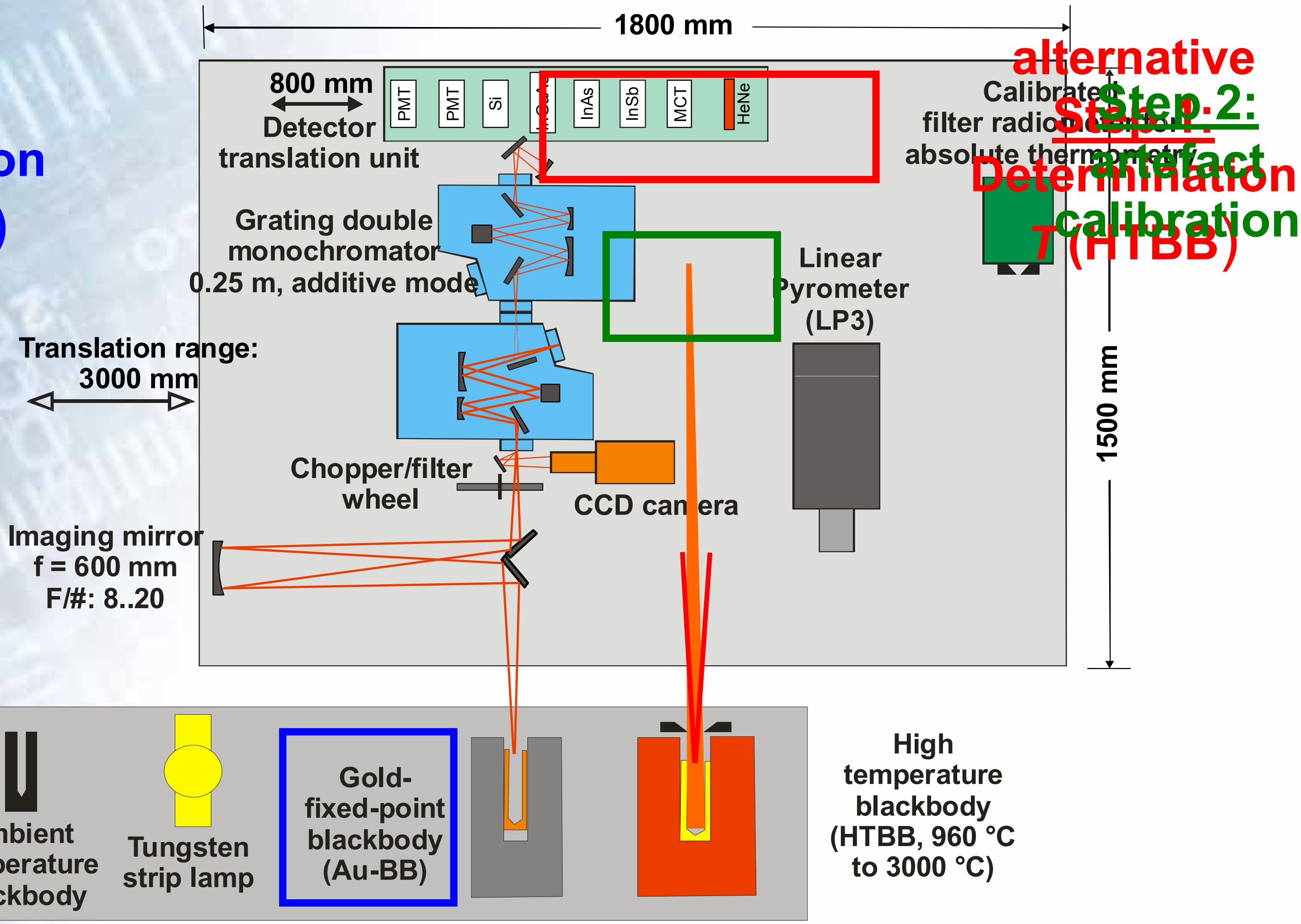
filter radiometry)

Temperature *T*
PRIMARY STANDARD
GOLD-FIXED-POINT BLACKBODY (Au BB)

Detector *Φ*
ARY STANDARD
CRYOGENIC RADIOMETER

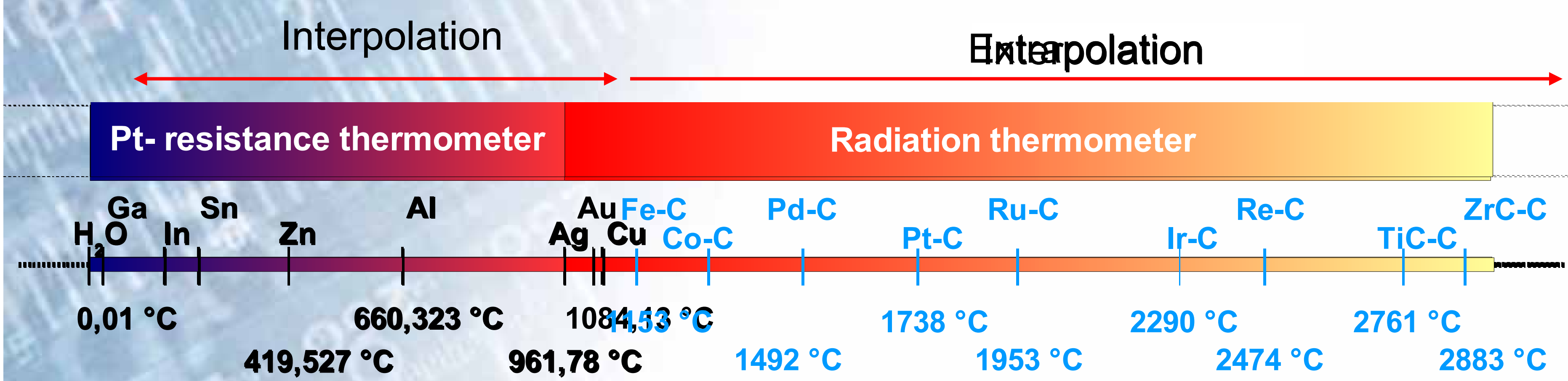
Spectral radiance comparator facility

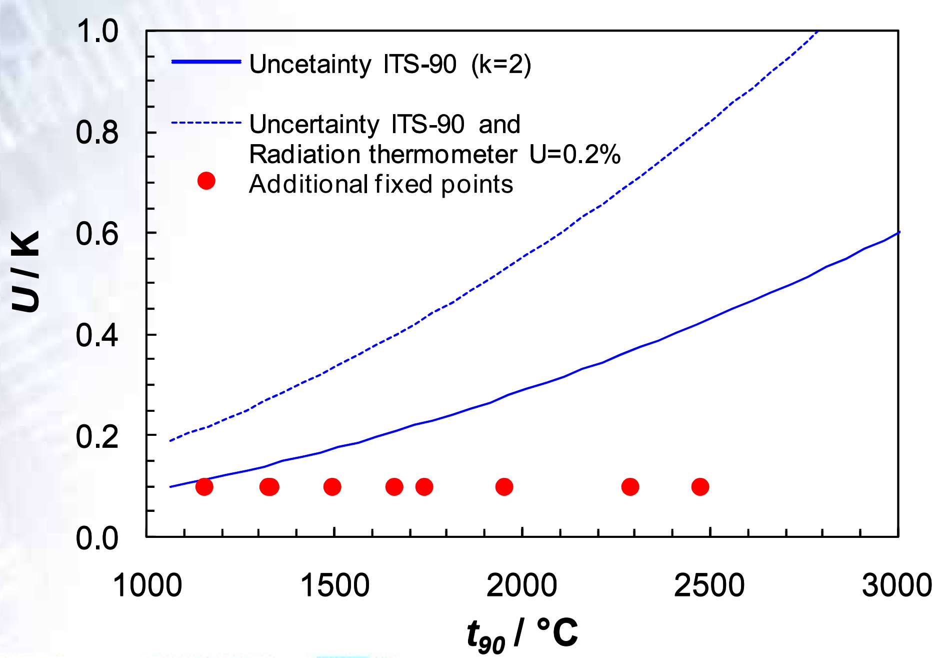
Step 1:
Determination
T_{90} (HTBB)



Spectral Radiance Comparator Facility

ITS-90 and high-temperature fixed points

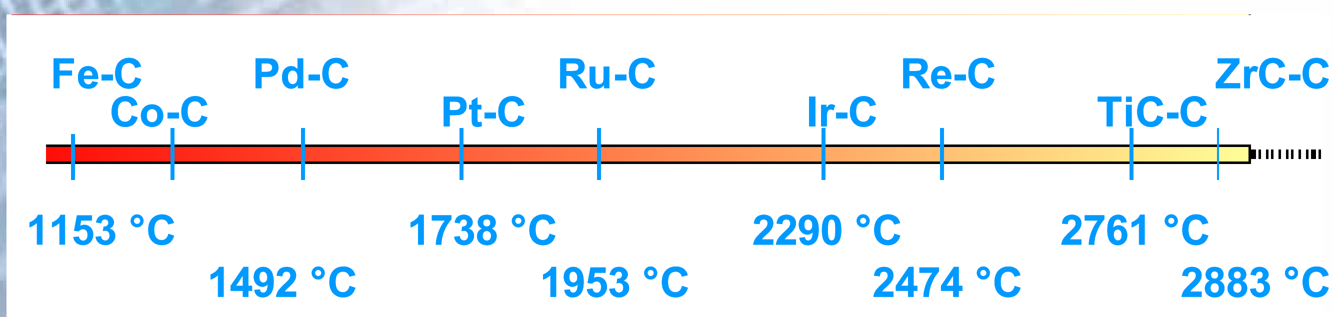


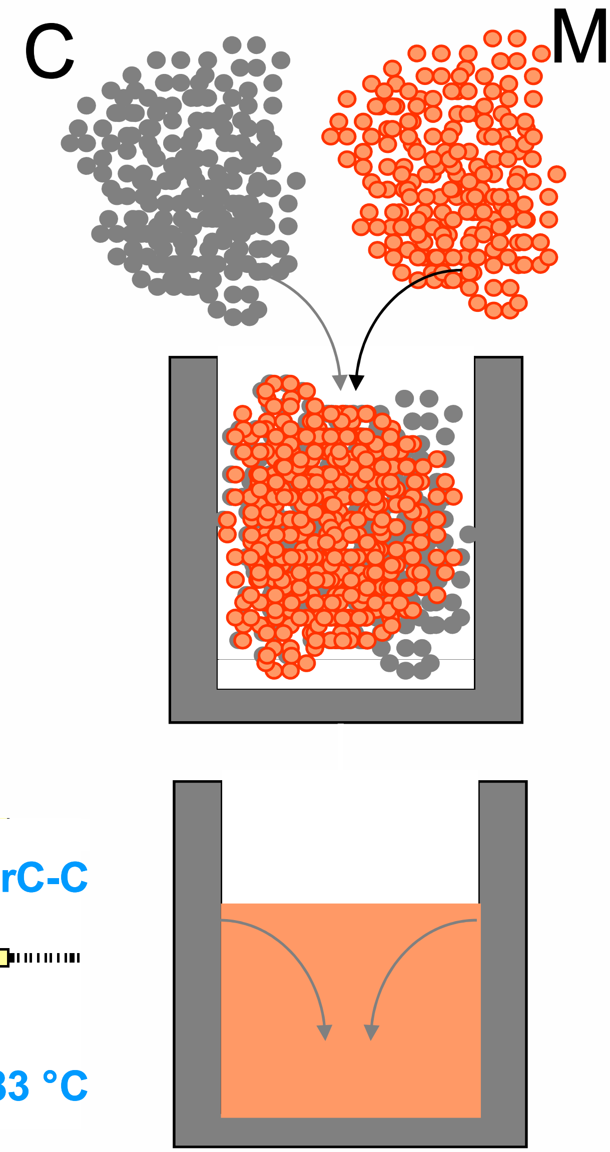


Eutectic fixed-point blackbodies

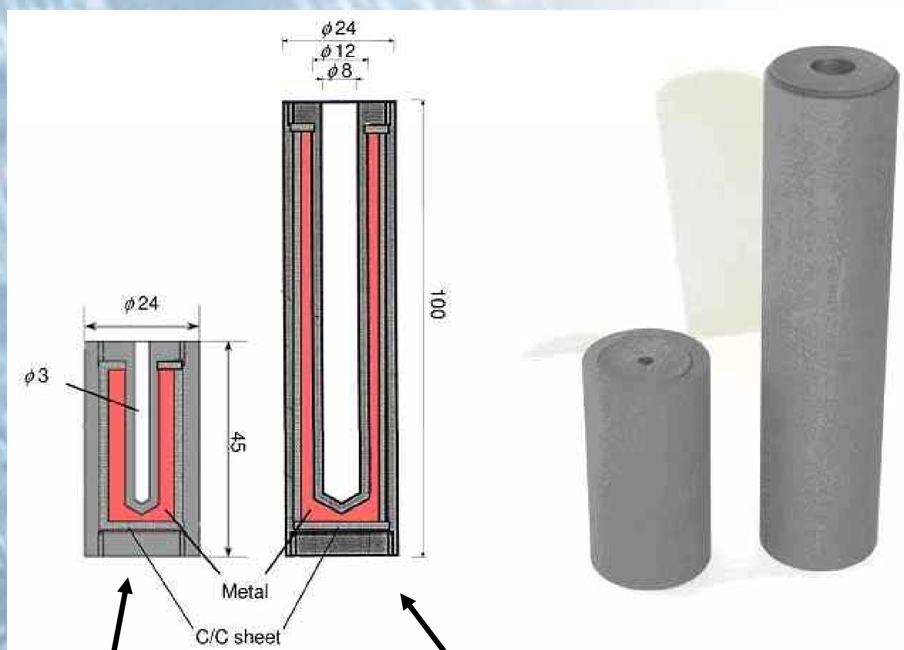
Metal-Carbon-Fixed points in graphite crucibles

- crucible material is part of the fixed point material
- no contamination through crucible material
- higher stability
- better reproducibility





Design / construction of eutectic fixed-point blackbodies



3 mm Ø cavity: radiation thermometry

8 mm Ø cavity: radiometry, photometry

Both fixed-point cells designs have:

- the same outer diameter
- the same length/diameter ratio of the cavity
- a calculated emissivity 0.9997
- several layers of C/C sheet insulation

Anhalt et al. (2008)
Large- and small- aperture fixed-point cells of Cu, Pt-C, and Re-C
International Journal of Thermophysics, 29(3), pp. 969 - 983.

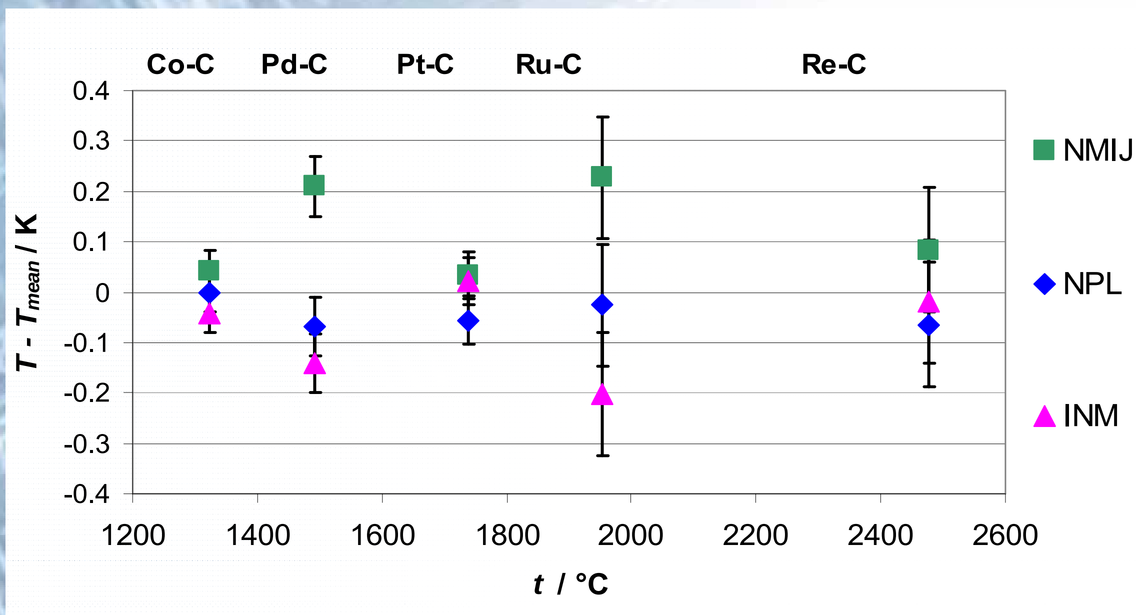
Eutectic fixed-point cell relative comparison

2 identical furnaces

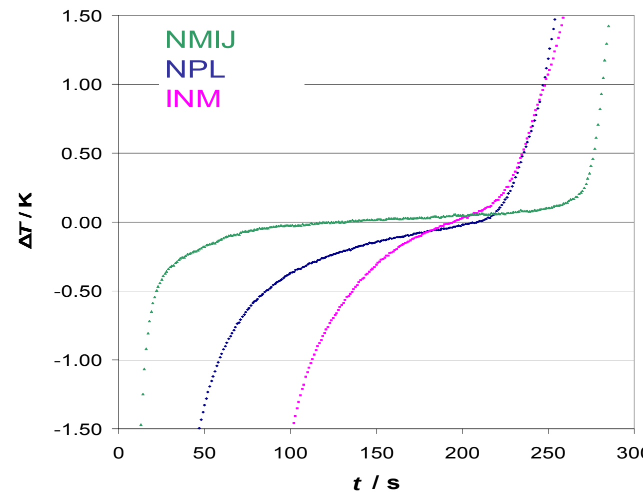
2 radiation thermometer LP3

15 fixed point cells

(NMIJ, BNM-INM, NPL)

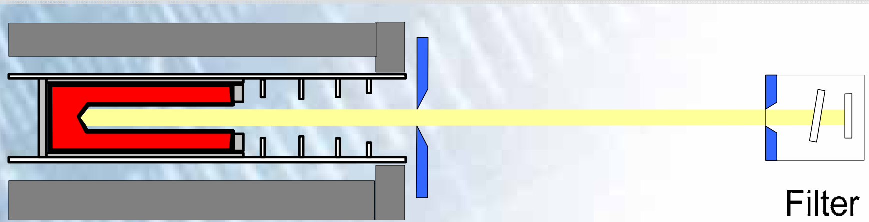


Pt-C



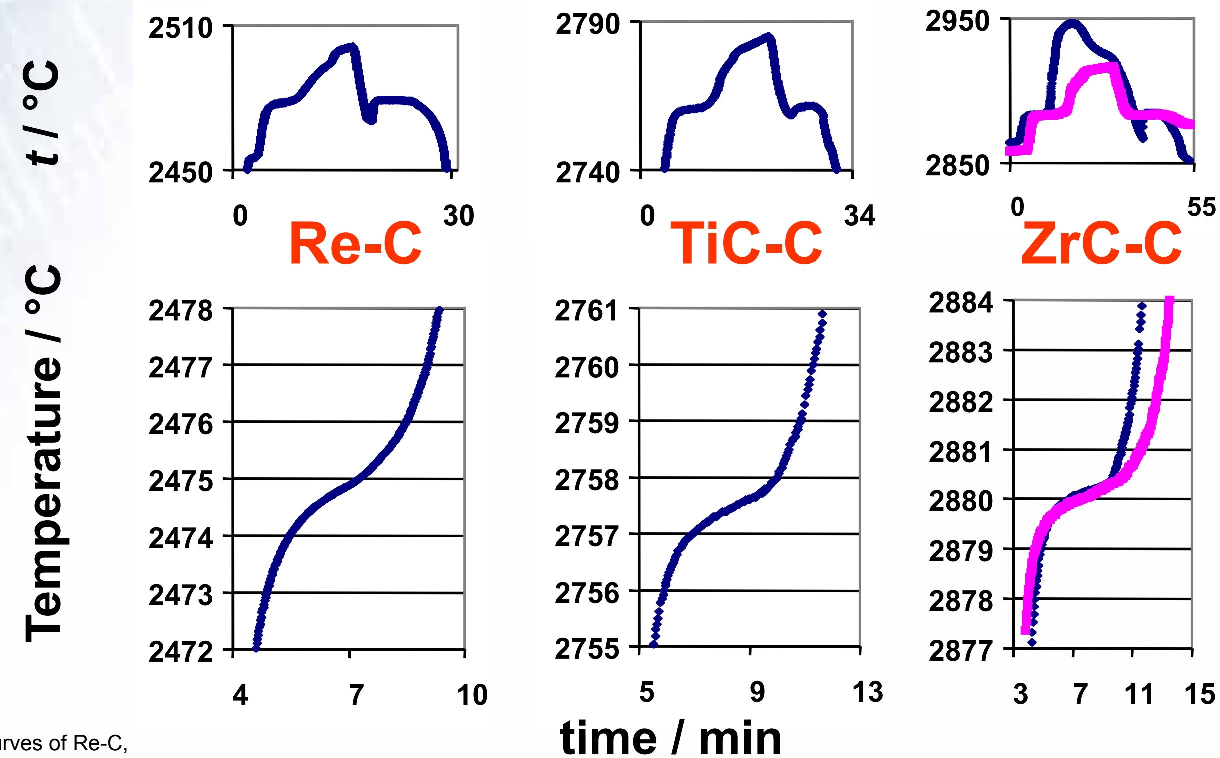
- **reproducibility single cell:** **< 50 mK**
- **difference T_{melt} Co-C, Pt-C, Re-C:** **~ 200 mK**
- **difference T_{melt} Pd-C, Ru-C:** **~ 400 mK**

Thermodynamic temperature determination



Reproducibility
0.2 K – 0.5 K

Measurement uncertainty
***k*=2, 0.6 K – 1.2 K**

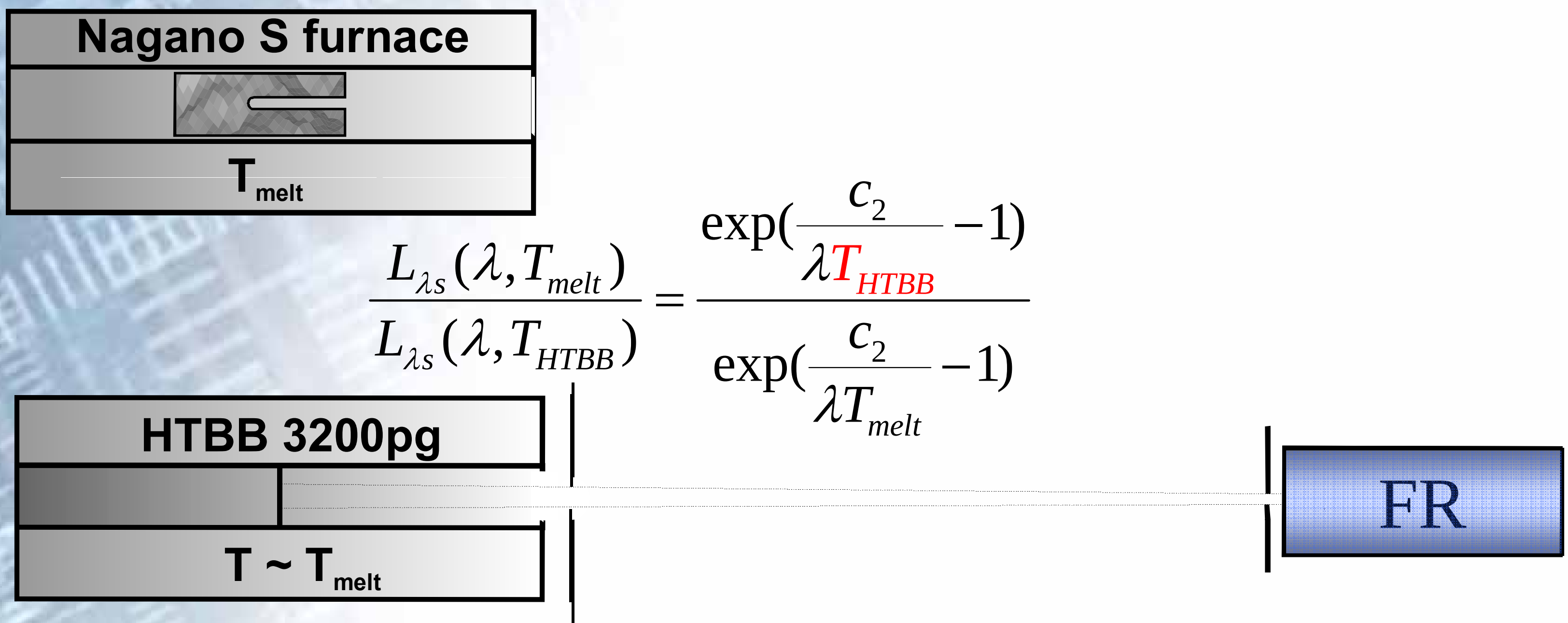


Hartmann, J., Anhalt, K., et al. (2005).
Thermodynamic temperature measurements of the melting curves of Re-C, TiC-C and ZrC-C eutectic irradiance mode fixed point cells.
In D. Zvizdic (ed.). 9th Int. Symp. on Temp. and Thermal Measurements (pp. 189 - 194).

Thermodynamic temperature determination

- **radiance comparison method**

1. HTBB temperature ~ T_{melt}
2. Measurement of thermodynamic temperature of HTBB with FR

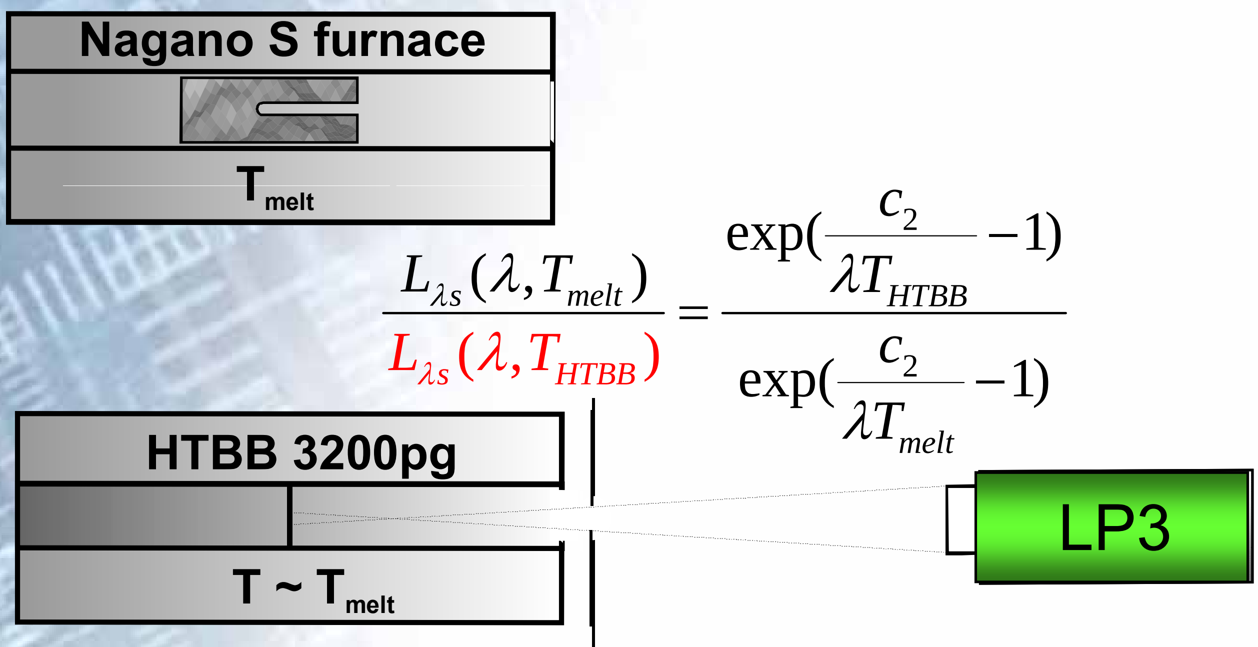


$$\frac{L_{\lambda s}(\lambda, T_{melt})}{L_{\lambda s}(\lambda, T_{HTBB})} = \frac{\exp(\dfrac{c_2}{\lambda T_{HTBB}} - 1)}{\exp(\dfrac{c_2}{\lambda T_{melt}} - 1)}$$

Thermodynamic temperature determination

- **radiance comparison method**

1. HTBB temperature ~ T_{melt}
2. Measurement of thermodynamic temperature of HTBB with FR
3. Spectral radiance measurement of the HTBB with the LP3



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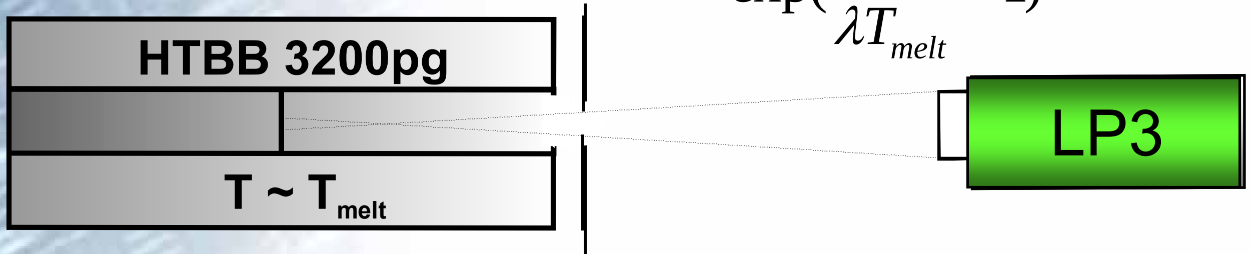
Thermodynamic temperature determination

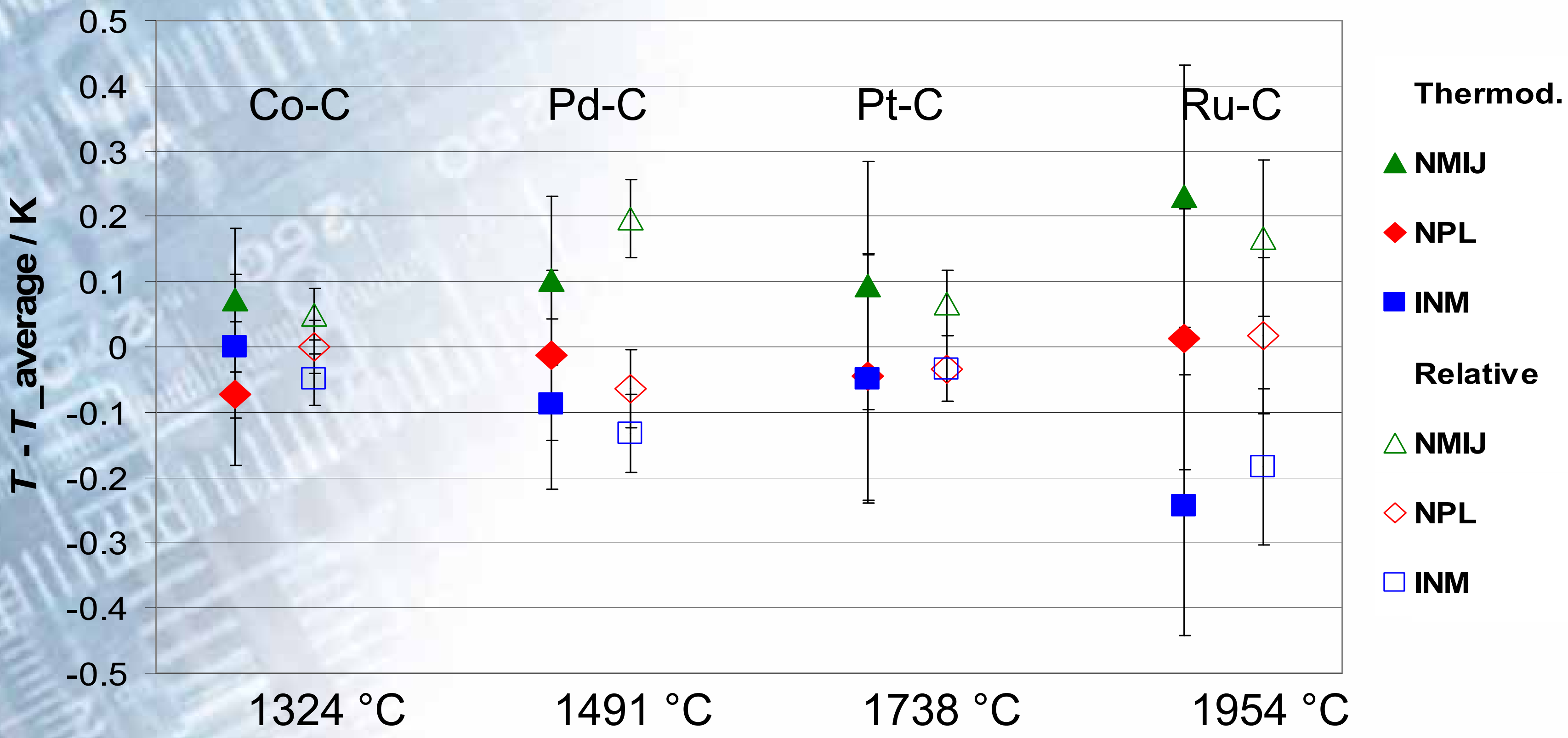
- **radiance comparison method**

1. HTBB temperature ~ T_{melt}
2. Measurement of thermodynamic temperature of HTBB with FR
3. Spectral radiance measurement of the HTBB with the LP3
4. Spectral radiance measurement of the eutectic cell in the Nagano furnace with the LP3

$$\frac{L_{\lambda s}(\lambda, T_{melt})}{L_{\lambda s}(\lambda, T_{HTBB})} = \frac{\exp(\frac{c_2}{\lambda T_{HTBB}} - 1)}{\exp(\frac{c_2}{\lambda T_{melt}} - 1)}$$

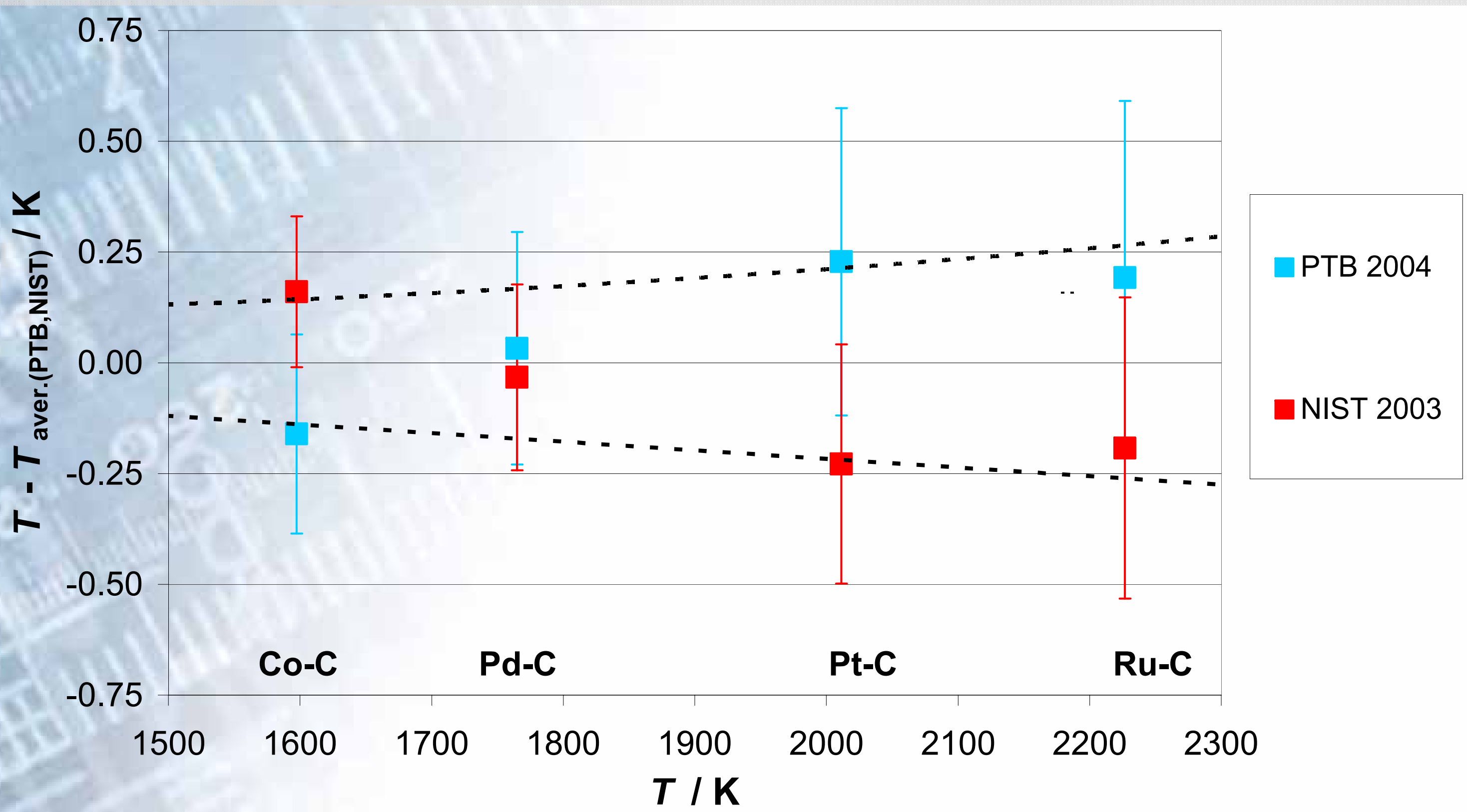


Thermodynamic temperature determination / relative comparison



Anhalt et al.
Thermodynamic temperature determinations of Co-C, Pd-C, Pt-C and Ru-C eutectic fixed-point cells
Metrologia, 43, 2006, pp. S78-S83

Absolute temperature comparison NIST – PTB using NPL cells



	PTB	*U*, *k*=2	NIST	*U*, *k*=2	PTB-NIST	*U*(PTB/NIST), *k*=2
Co-C	1597.16	0.22	1597.43	0.17	-0.27	0.28
Pd-C	1765.02	0.27	1764.95	0.21	0.12	0.34
Pt-C	2011.67	0.32	2011.21	0.27	0.53	0.42
Ru-C	2227.12	0.41	2226.74	0.34	0.48	0.52

Summary

- **PTB instrumentation and experimental techniques for the realization and dissemination of the temperature scale with optical methods**
- **Low-/ mid-temperature calibration facility: -60 °C to 962 °C**
  High temperature calibration facility: 962 °C to 3000 °C
- **Standard uncertainty of the disseminated radiation temperature:**
  - **40 mK at - 60 °C**
  - **10 mK at the Au-FP (1064.18 °C)**
  - **1000 mK at 3000 °C**
- **Achievable standard uncertainties for radiation thermometer calibrations:**
  - **60 mK at - 60 °C**
  - **30 mK at 400 °C**
  - **1000 mK at 3000 °C**
- **PTB meets <u>all</u> industrial requirements in the range from -60 °C to 3000 °C**

Emissivity determination at the PTB in the temperature range from 0 °C to 600 °C

C. Monte, M. Becker, B. Gutschwager, E. Kosubek and J. Hollandt

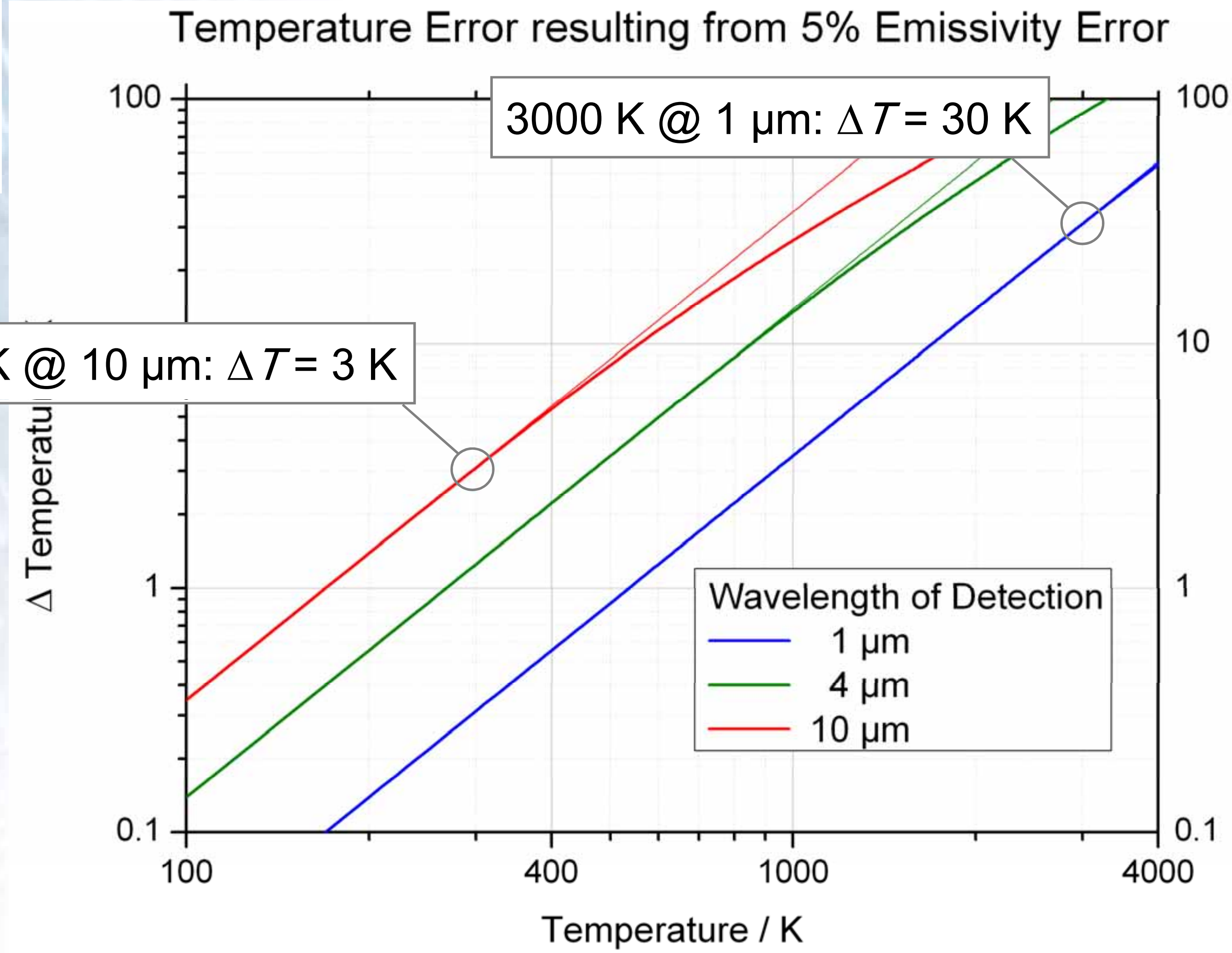
Physikalisch-Technische Bundesanstalt

Outline

- Motivation for an accurate emissivity determination
- Experimental setup for emissivity measurement in air
- Uncertainty
- New experimental setup for emissivity measurement under vacuum
- Summary

Motivation

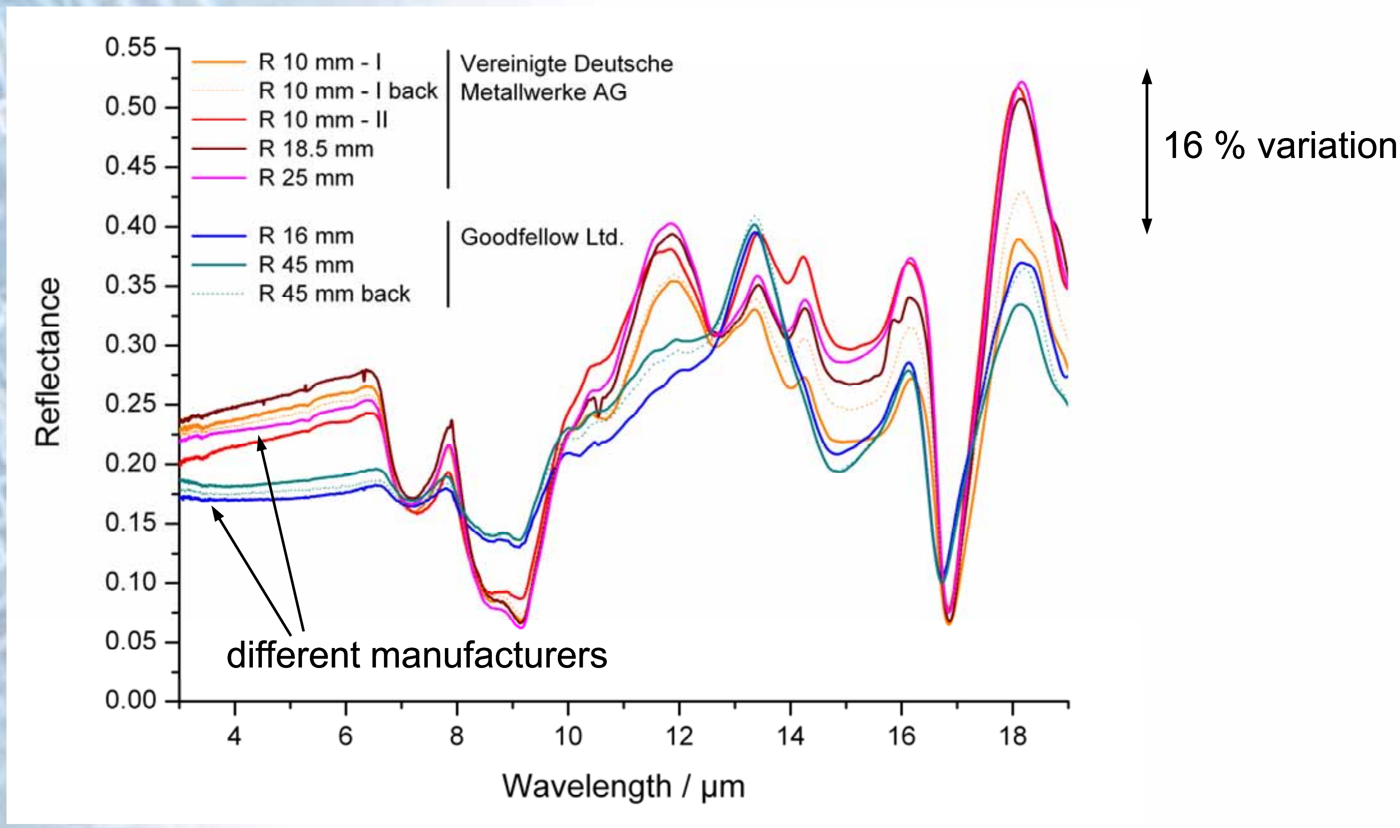
$$\Delta T \approx \frac{\lambda \cdot T^2}{c_2} \cdot \frac{\Delta\varepsilon}{\varepsilon}$$



Motivation

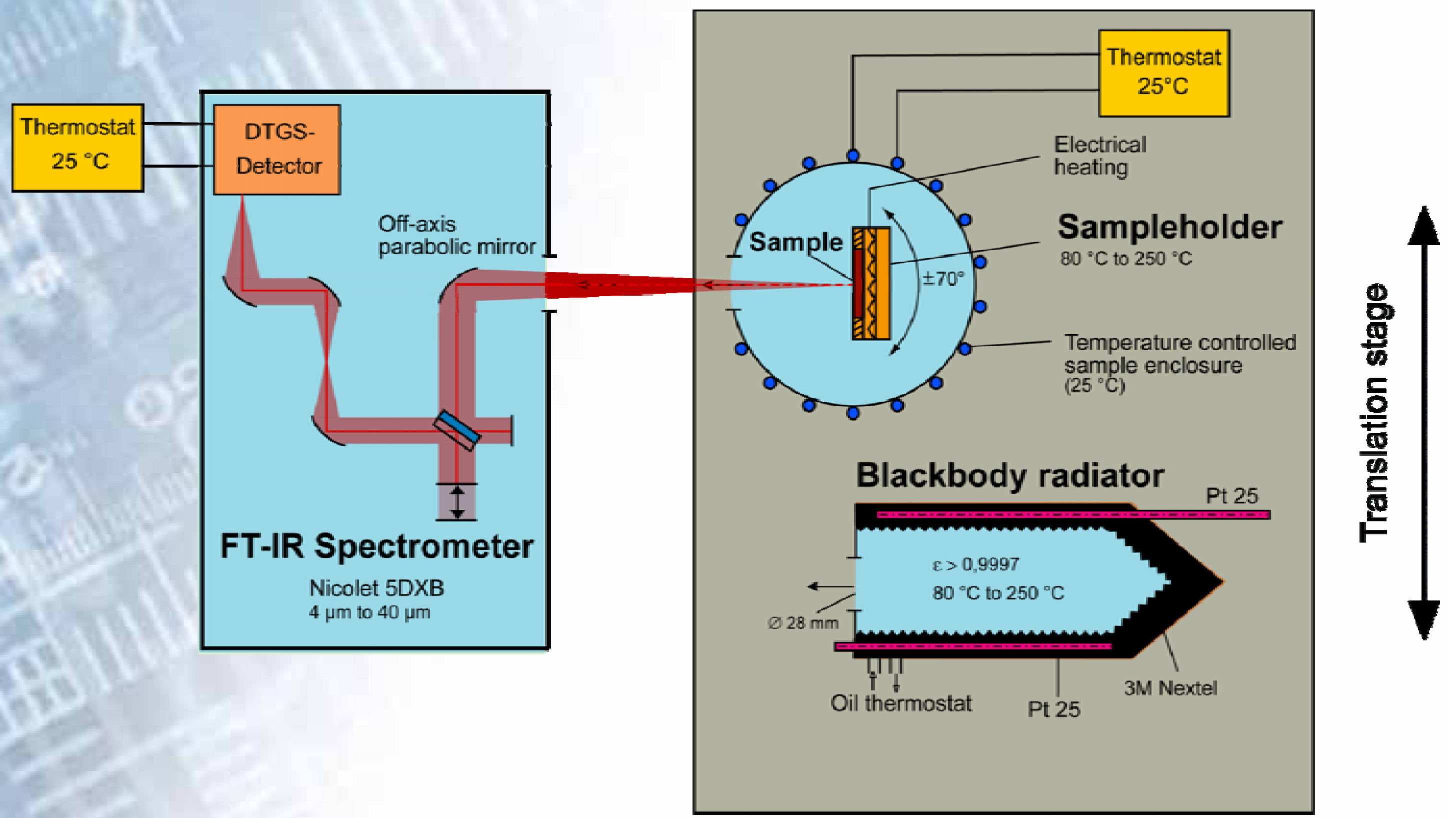
Variability of INCONEL 600 samples

- Preparatory work for the spectral emissivity pilot study of CCT-WG9
- Identical sample preparation, two different sample manufacturers



Only <u>individual</u> emissivity determination allows an accurate temperature measurement

Spectral emissivity measurement in air - setup



Measurement principle:

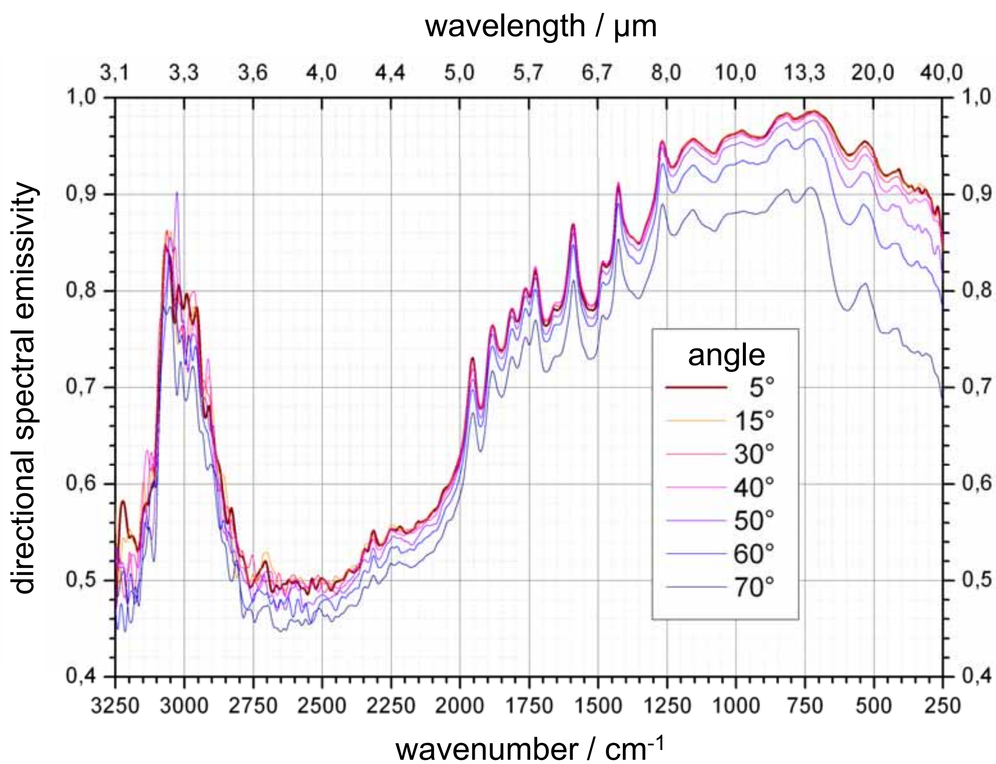
- Ratio of the spectral radiance of the sample / spectral radiance of the reference blackbody
- Radiance of the detector / surrounding
- Reflectivity of the sample

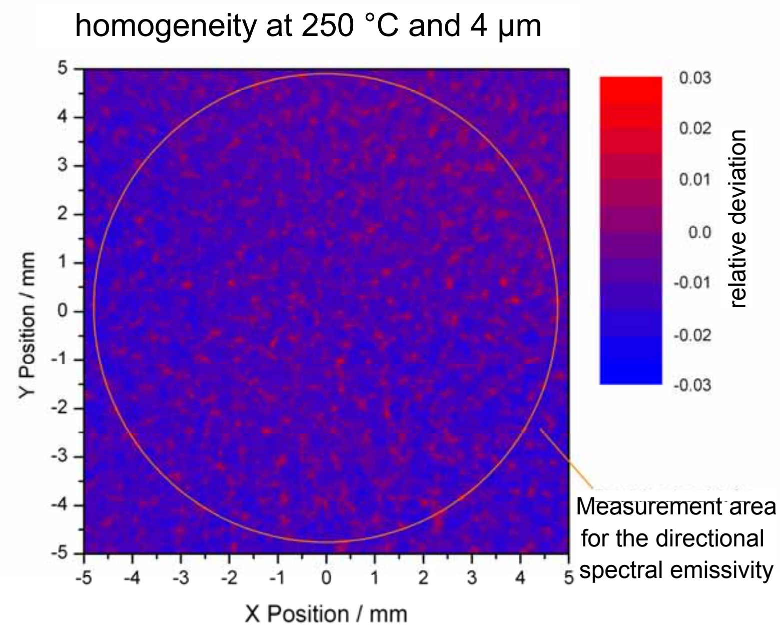
Spectral emissivity measurement ranges (air)

Temperature range:	80 °C to 430 °C
Wavelength range:	4 µm to 40 µm (2500 cm^{-1} to 250 cm^{-1})
Direction of observation:	0° to 70°
Size of measured area:	circular, 10 mm diameter
Acceptance angle of the optics:	+/- 3°, NA 0.05
Homogeneity (camera):	circular measurement area, 20 mm diameter

The **directional total emissivity** and the **hemispherical emissivity** are calculated from the **directional spectral emissivity**

Spectral emissivity measurement in air - example



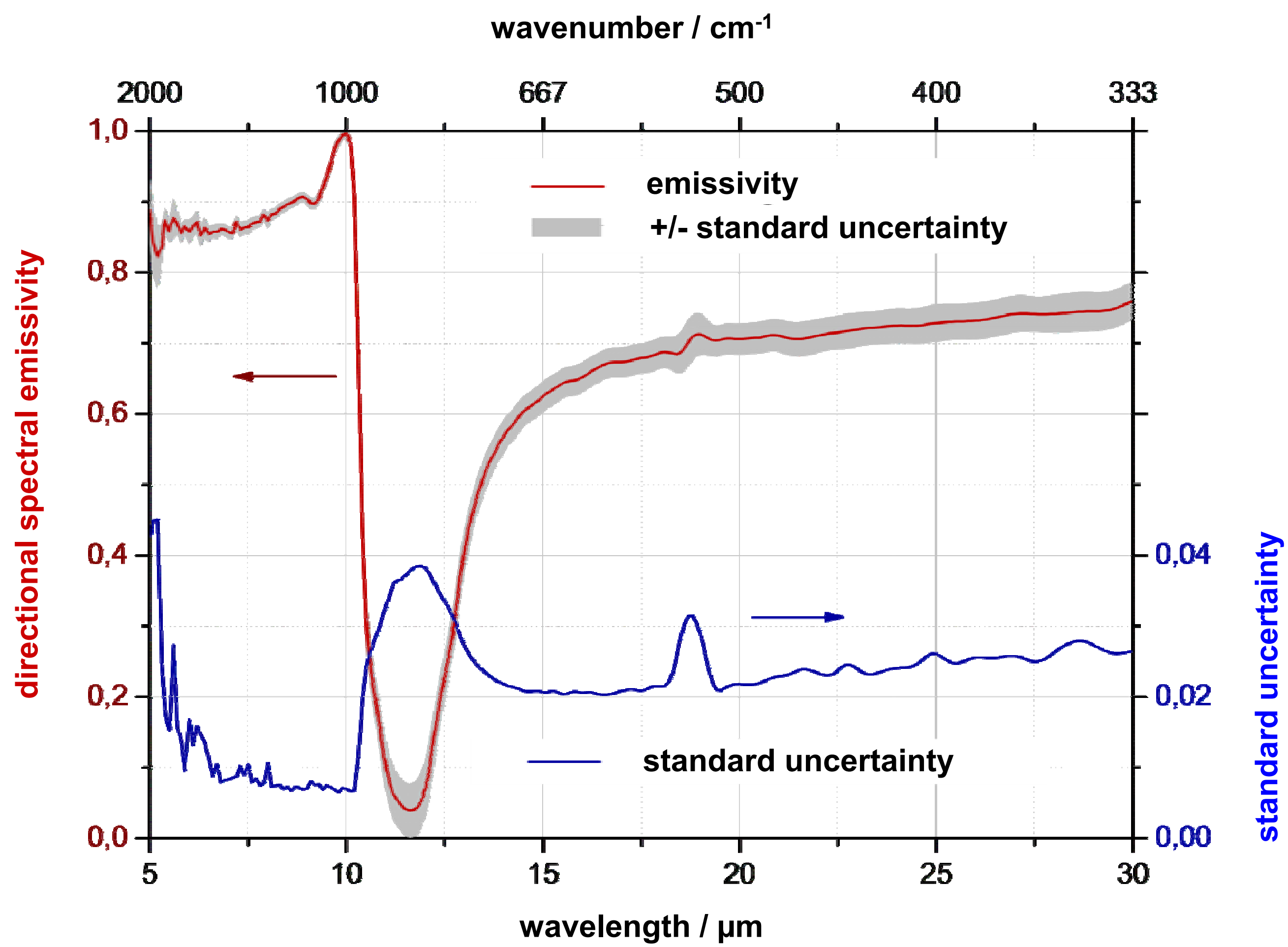


High-emissivity coating at 250 °C

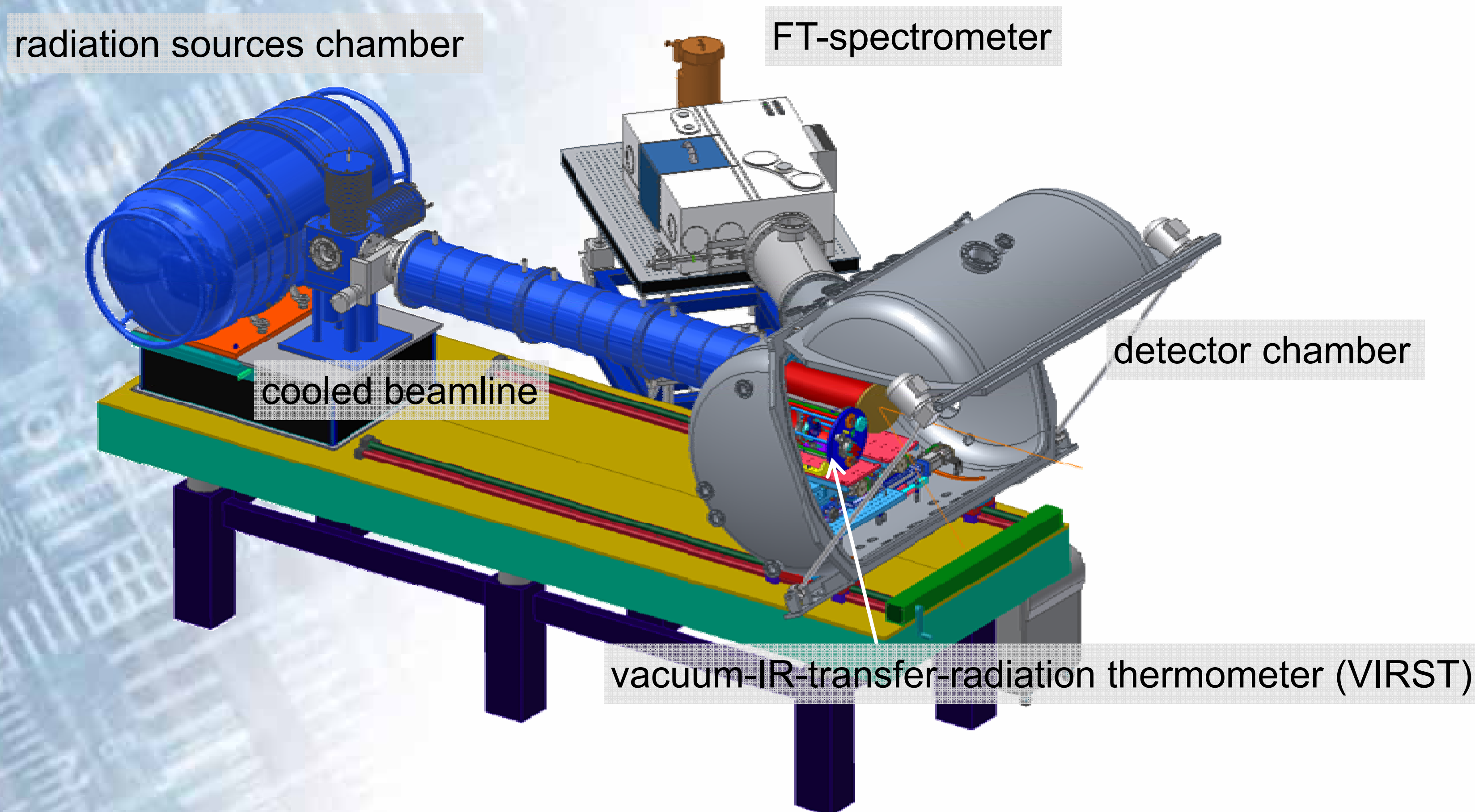
Application: reference coating for radiation thermometry up to 800 °C

Uncertainty

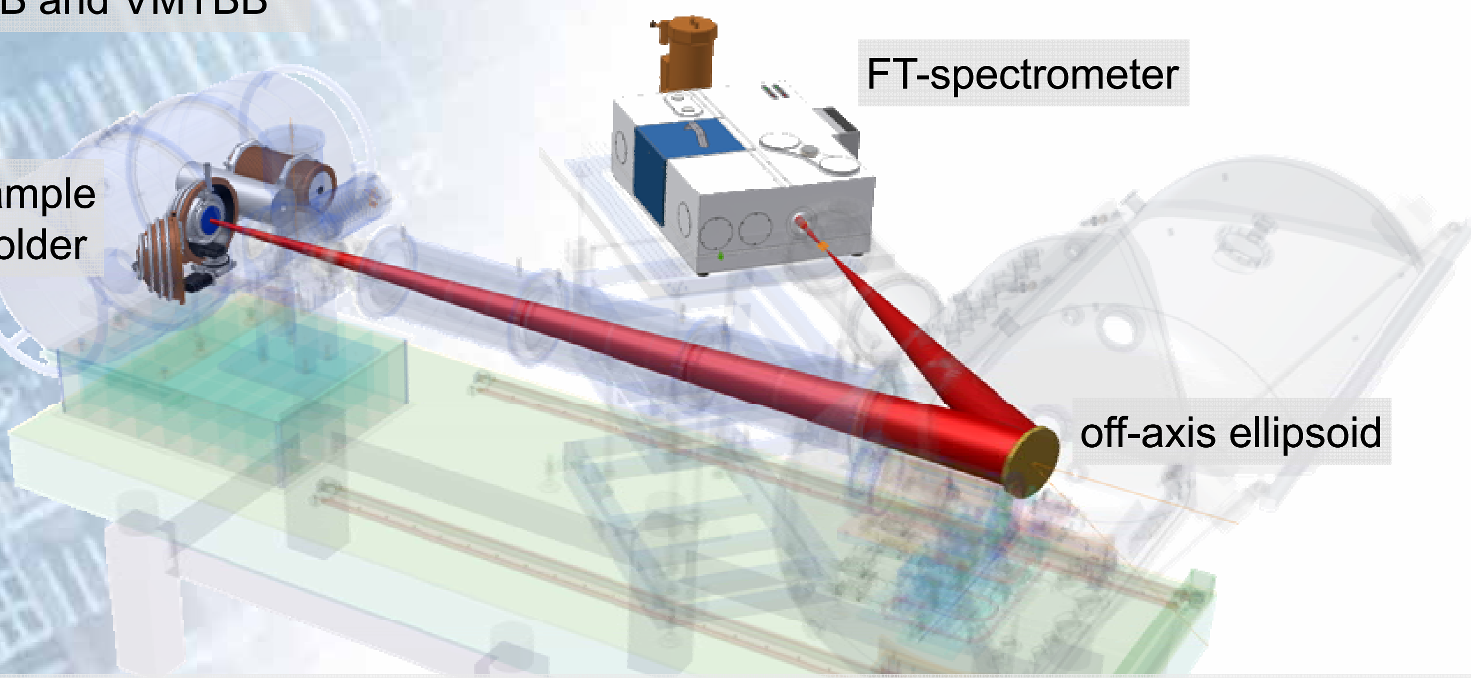
Emissivity of a SiC-sample at 150 °C



Emissivity measurement under vacuum - setup



Emissivity measurement under vacuum - setup

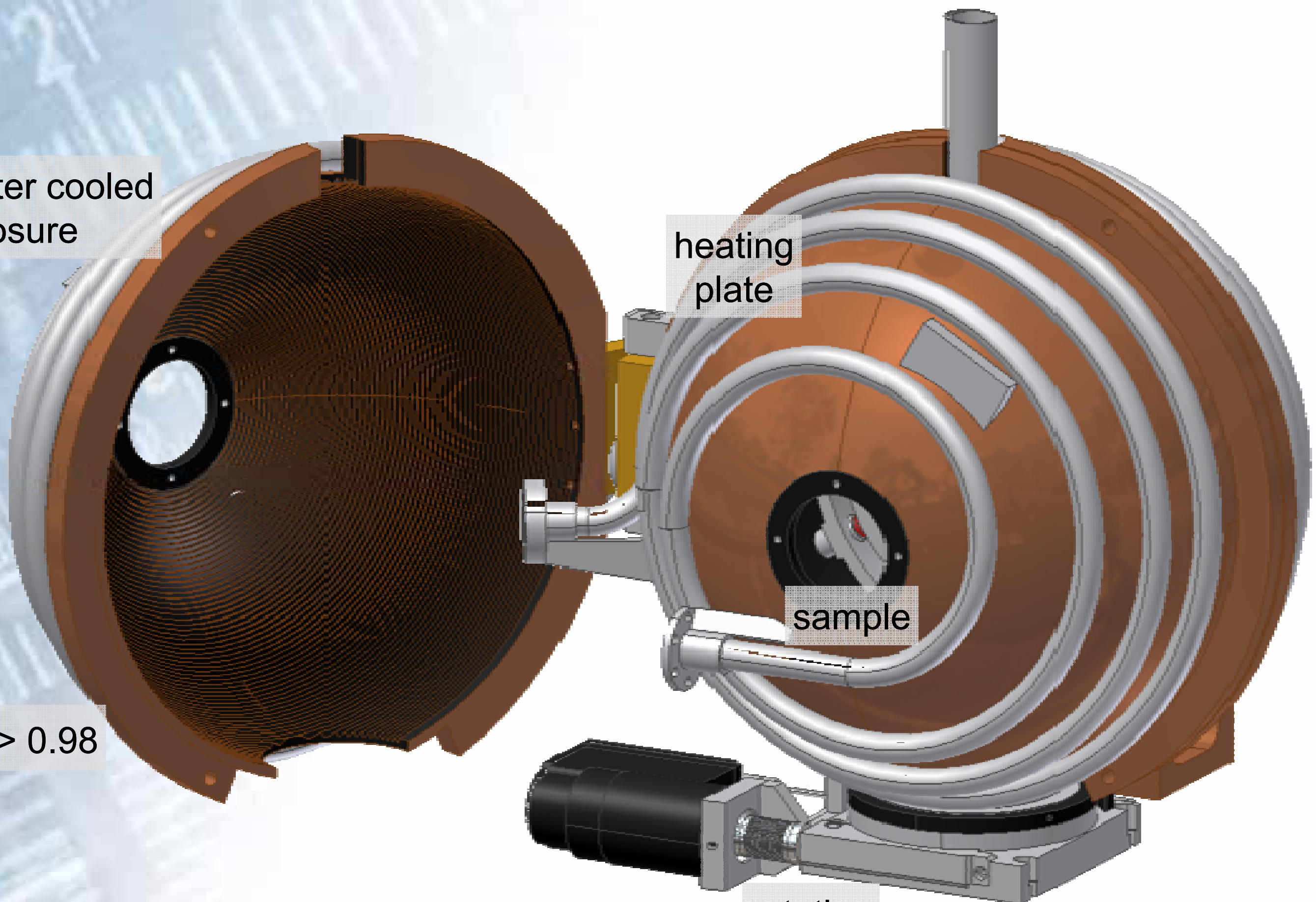


- No atmospheric interference
- No convection → accurate determination of the sample surface temperature

Temperature range: 0 °C to 600 °C

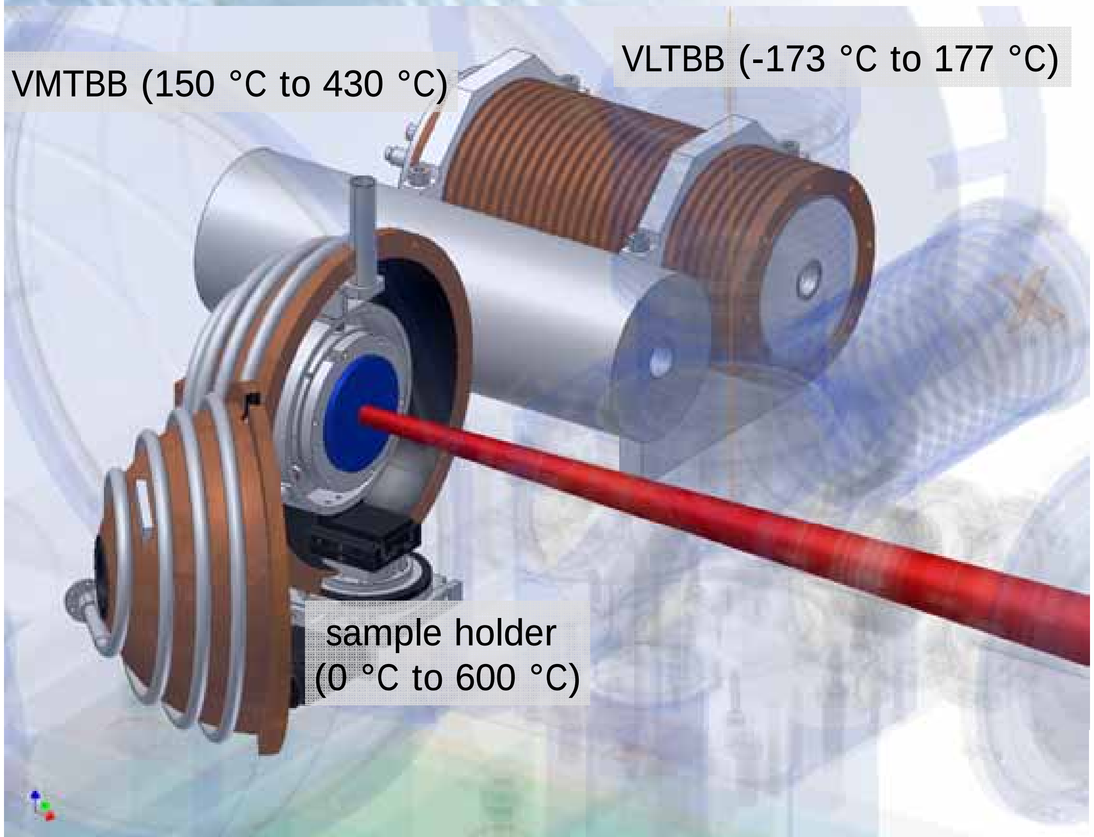
Wavelength range: 1 µm to 1600 µm (10000 cm^{-1} to 6 cm^{-1})

Emissivity measurement under vacuum - setup



vacuum sample holder 0 °C to 600 °C

Emissivity measurement under vacuum



Measurement principle:

measurement of the sample against two blackbodies at two different temperatures

Advantage of the method:

the background radiation, the warm components of the FT-spectrometer and the spectral responsivity of the detection system are cancelled

Summary

- Determination of the directional spectral emissivity in air in the temperature range from 80 °C to 430 °C (4 µm to 40 µm)
- Determination of the directional spectral emissivity under vacuum in the temperature range from 0 °C to 600 °C (1µm to 1600 µm)
- Determination of the total and hemispherical emissivity
- Standard uncertainty for the emissivity 1% for samples with an emissivity > 0.3 and a sample temperature starting from 150 °C

Muster