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Georgian-German ScienceBRIDGE
CONNECTING PEOPLE AND KNOWLEDGE

JÜLICH FORSCHUNGSZENTRUM

1st QUALI-START-UP Science Letures

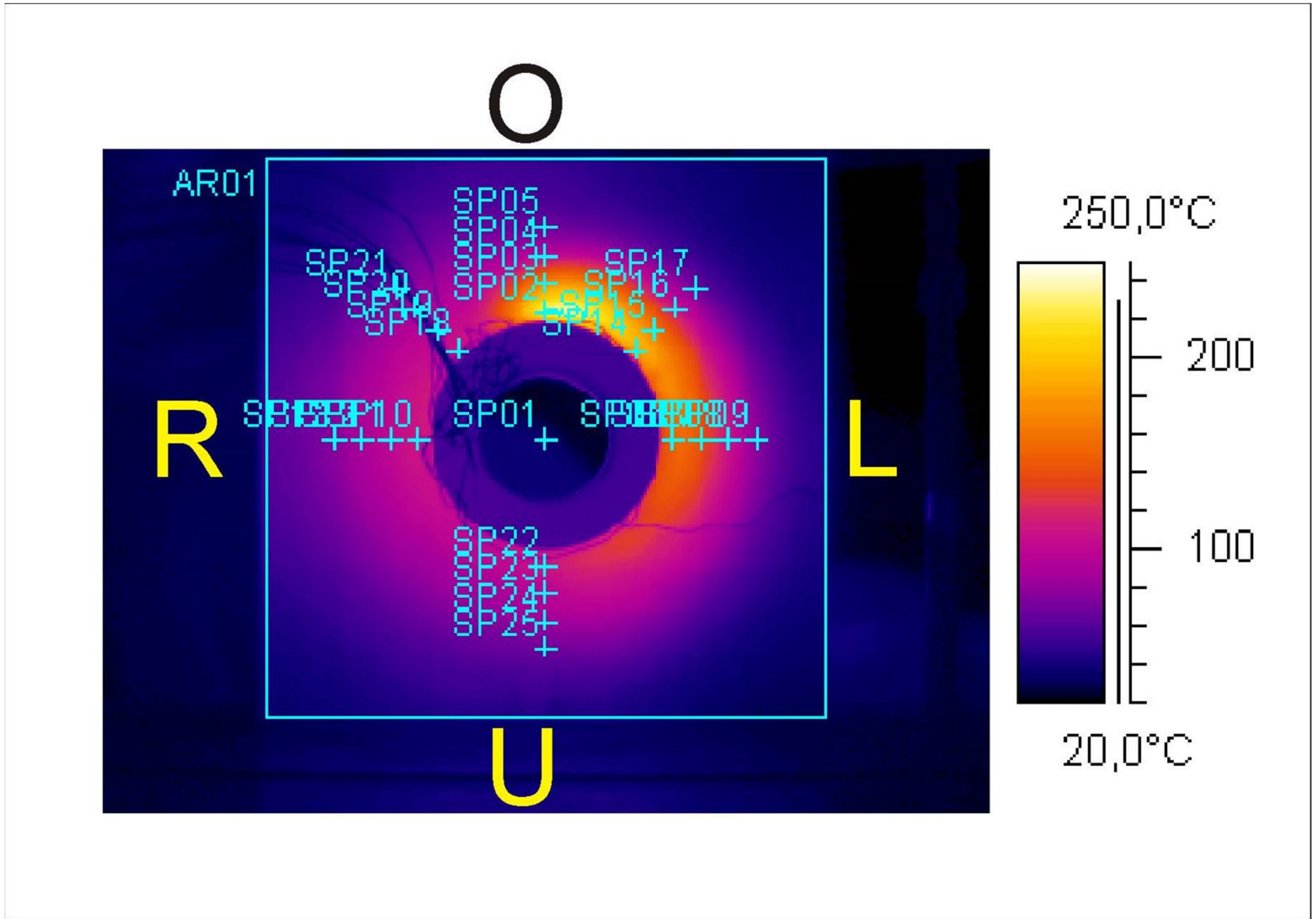
IR-Thermography

ZEA-1 | Technology for Cutting Edge Research

15.09.2017

Dr. H. Glückler

Motivation



Measurement of thermal radiation –> determination of temperature

Outline

1. Something about thermal radiation
2. Methods: passive and active thermography
3. Systems and laboratory at ZEA-1
4. Examples

Short history

Around 1800: Discovery of infrared-radiation (Herrschel)
1860: Kirchhoff‘s definition of the „black body“

$$\boldsymbol{\alpha = \epsilon = 1}, \quad (\, with\ \rho + \alpha + \tau = 1)$$

1879: Stefan–Boltzmann law – experimental (Stefan)
1884: Stefan–Boltzmann law – theoretical (Boltzmann)

$$\boldsymbol{P} = \sigma \cdot A \cdot \boldsymbol{T^4},\ \sigma = \frac{2\pi^5 k^4}{15h^3c^2} \approx 5{,}6704 \cdot 10^{-8}\,\frac{W}{m^2K^4}$$ (Stefan–Boltzmann constant)

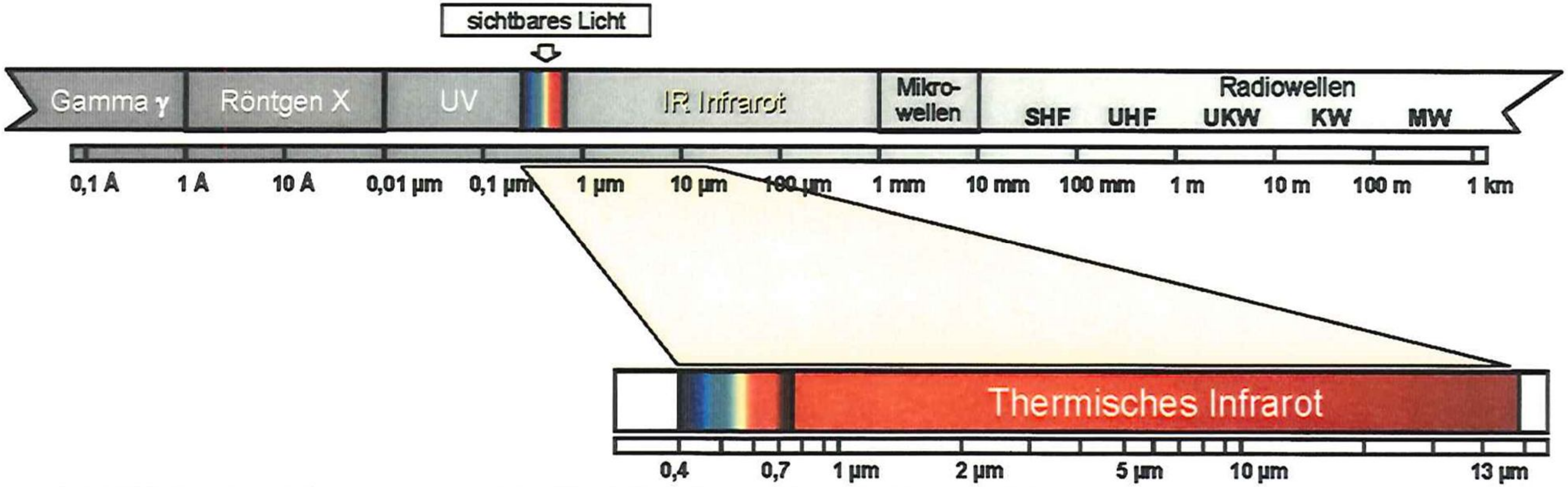
1887: Proof: infrared-radiation = electromagnetic radiation (Hertz)
1893: Wien‘s displacement law

$$\boldsymbol{\lambda_{max}} = \frac{b}{\boldsymbol{T}}\ ,\ b \approx 2897{,}8\ \mu m\ K$$ (*Wien's displacement constant)*

1900: Planck's law

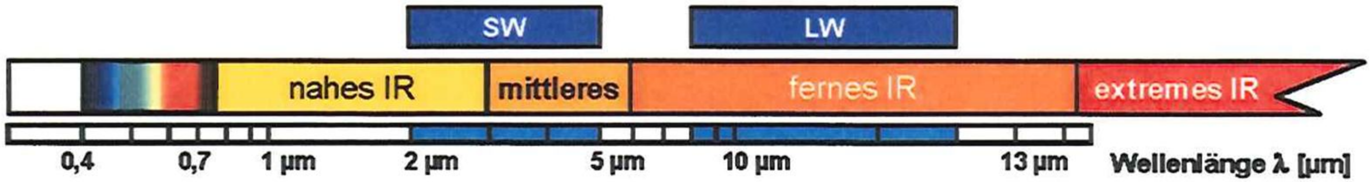
$$M(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{\left(\frac{hc}{\lambda kT}\right)} - 1}$$

Spectrum of electromagnetic radiation



sw: Short-wave band
2 µm – 5 µm

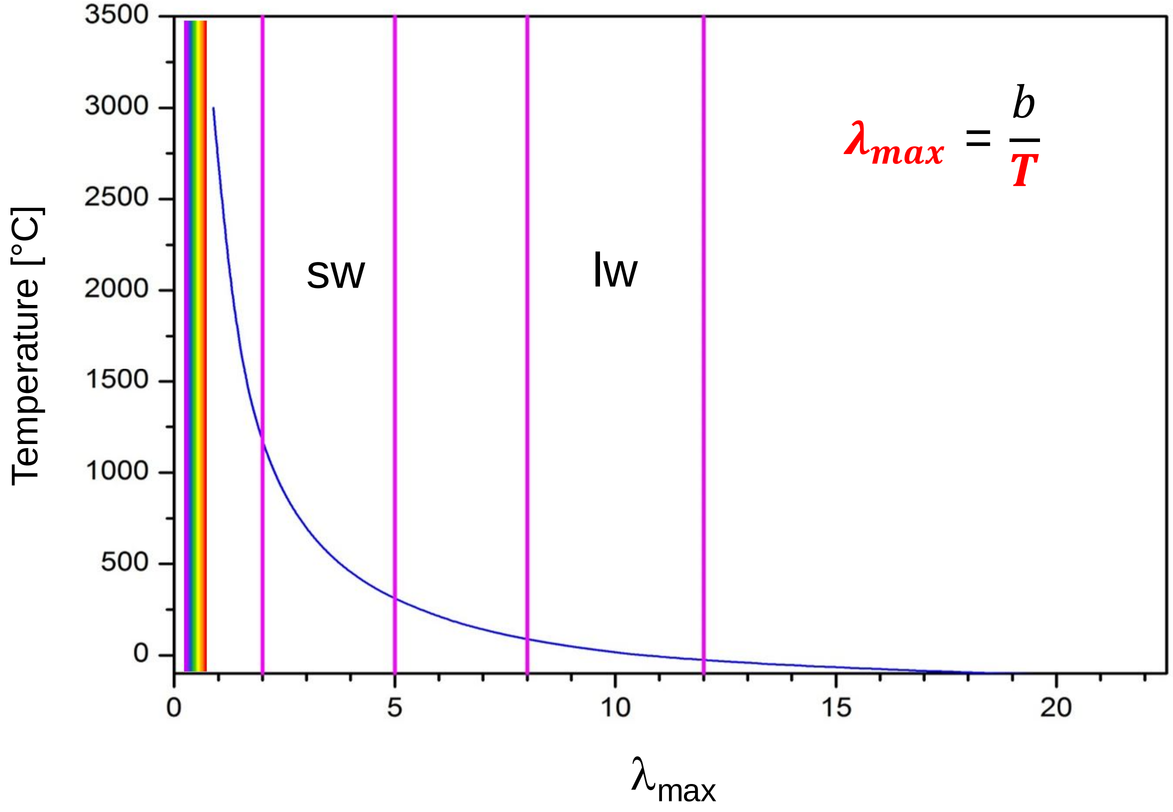
lw: Long-wave band
8 µm – 12 µm



The IR-systems used at ZEA-1 operates both in sw and lw band

Wien‘s displacement law

black body radiation for different temperatures peaks at a wavelength inversely proportional to the temperature.

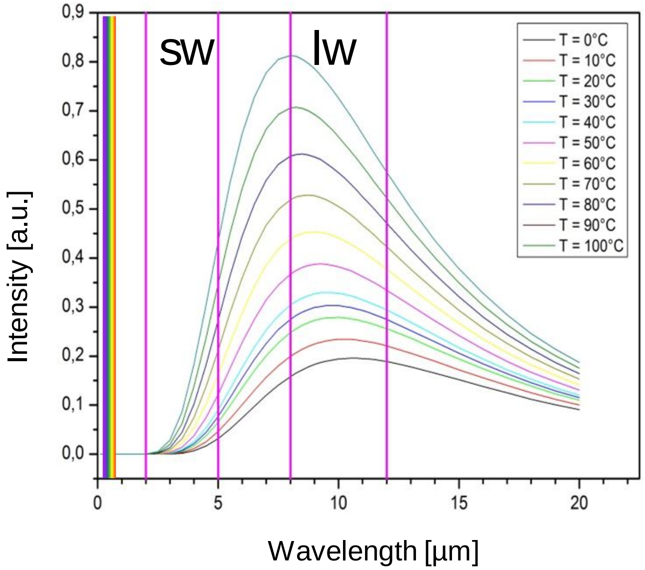


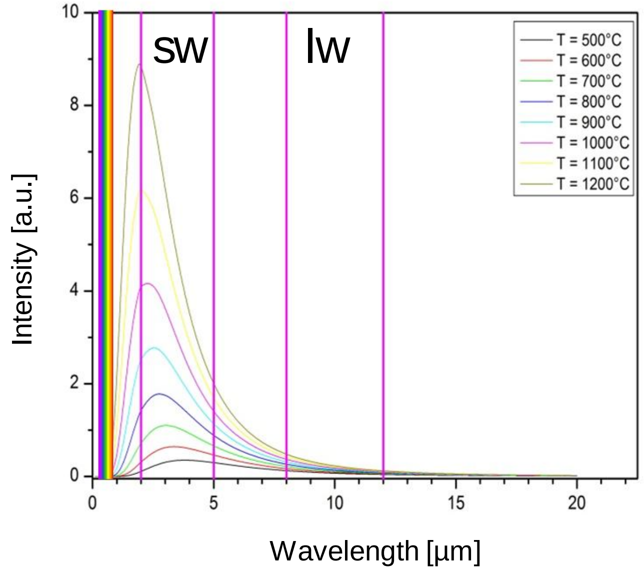
$$\lambda_{max} = \frac{b}{T}$$

Planck's law

describes the spectral density of electromagnetic radiation
emitted by a black body in thermal equilibrium at a given temperature T

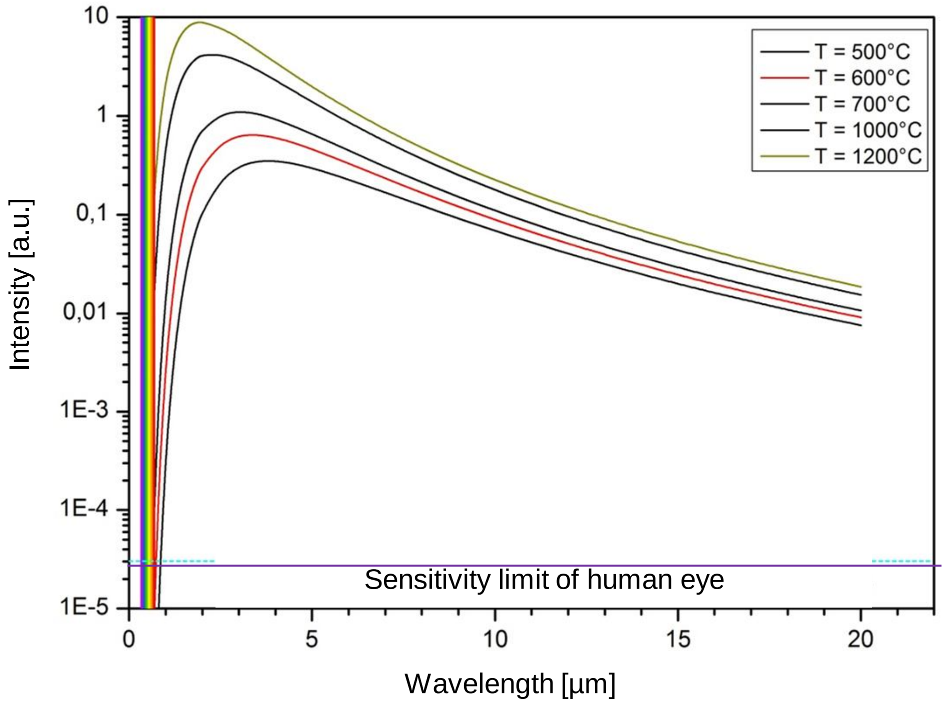
$$M(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{\left(\frac{hc}{\lambda kT}\right)} - 1}$$





Planck's law

Example: red and yellow heat

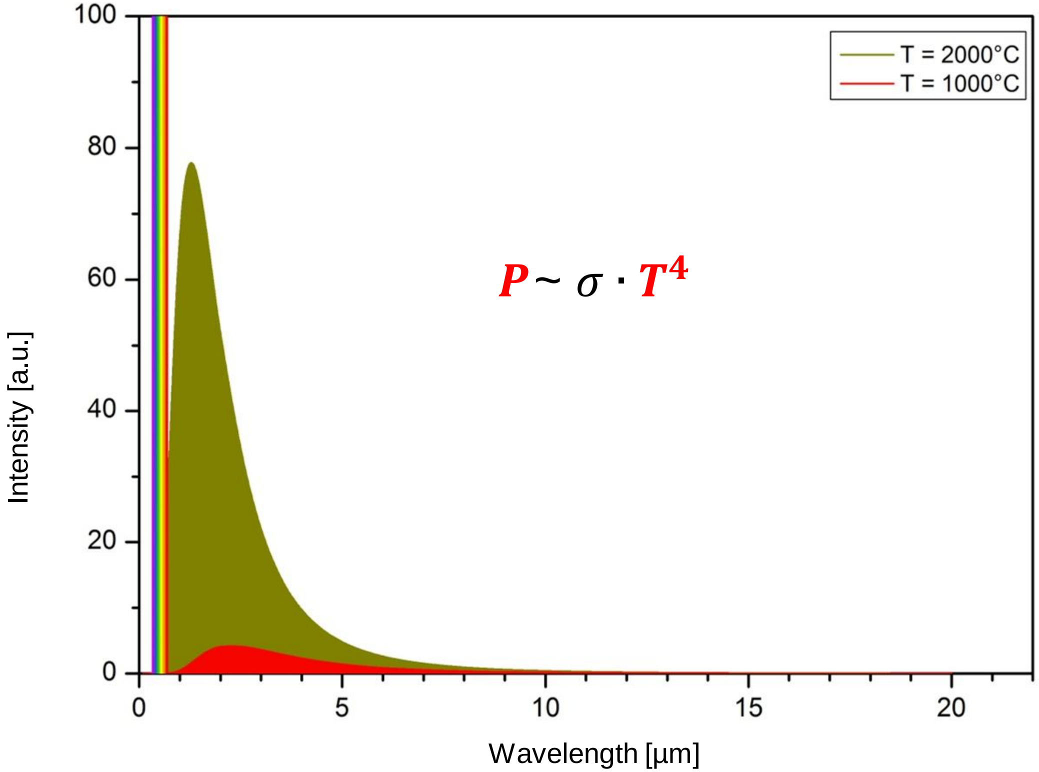


Annealing colors for different temperatures

Dunkelbraun	550
Braunrot	630
Dunkelrot	680
Dunkelkirschrot	740
Kirschrot	780
Hellkirschrot	810
Hellrot	850
Gut Hellrot	900
Gelbrot	950
Hellgelbrot	1000
Gelb	1100
Hellgelb	1200
Gelbweiß	>1300

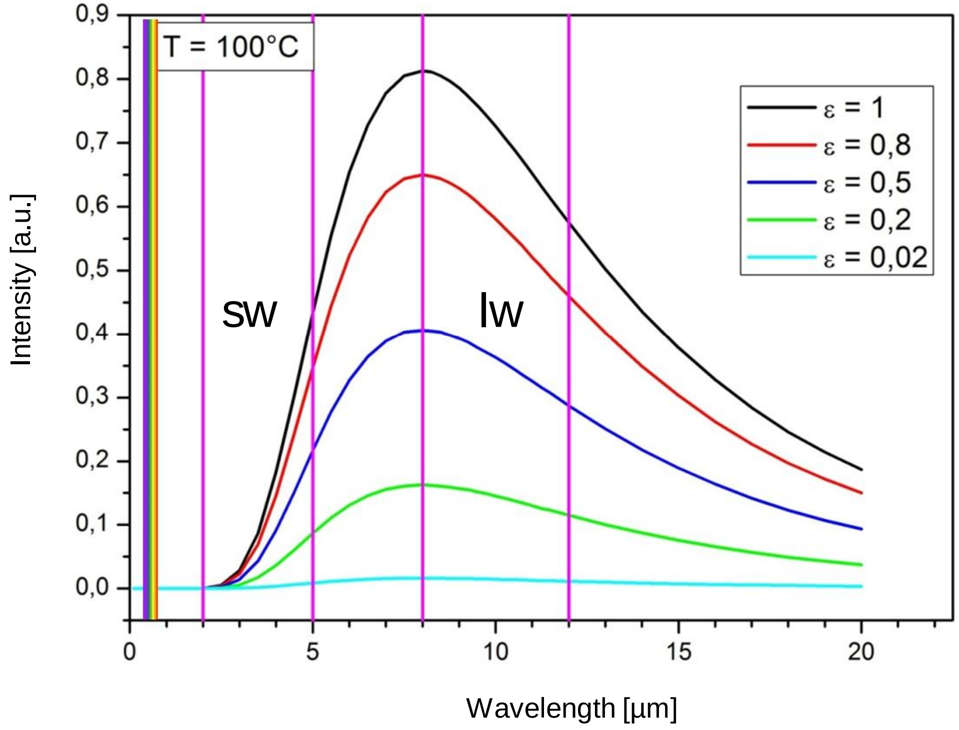
Stefan–Boltzmann law

Example: filament lamps



Some remarks about emissivity ε

Example: bodies with temperature of 100°C and different emissivities

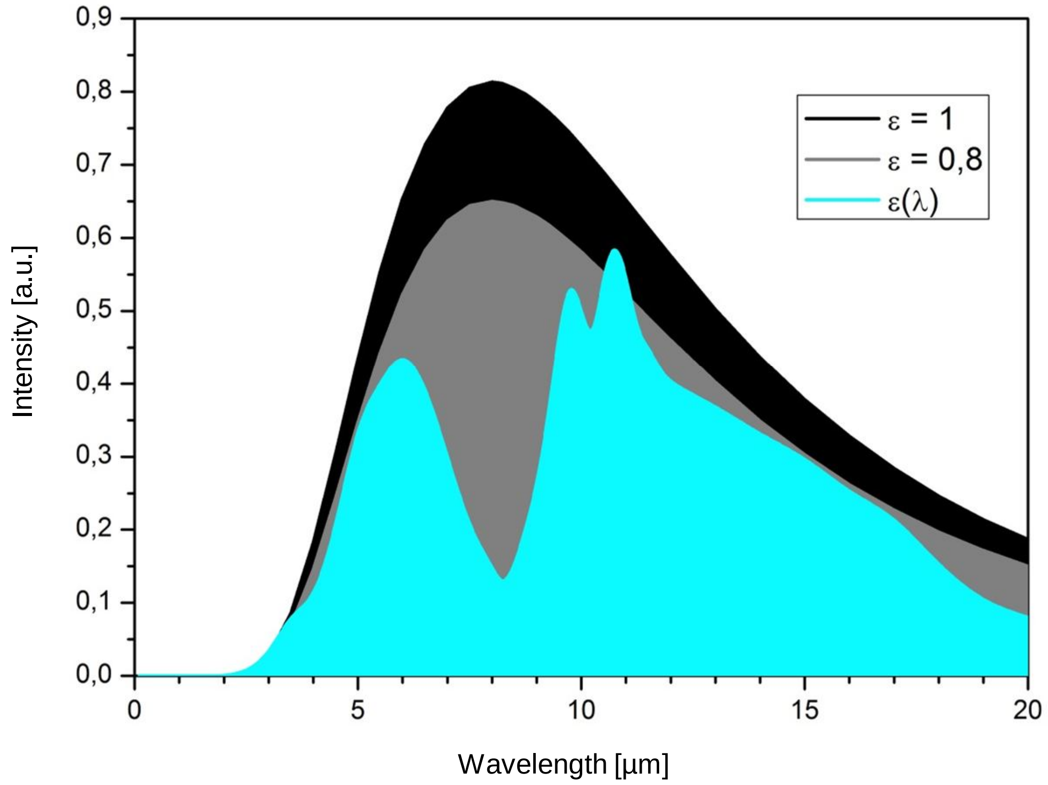


Black body $\alpha = \epsilon = 1$

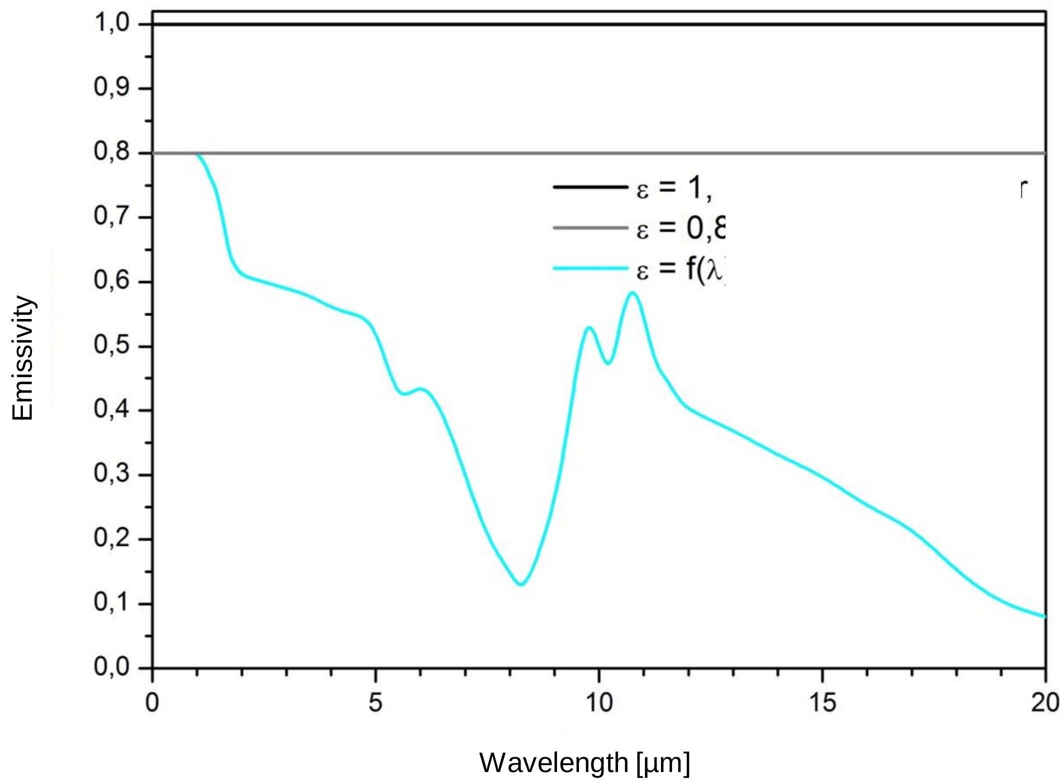
Every body in nature has an ε < 1 ! 0,999999 > ε > 0,000001

Emissivity ε and different emitters

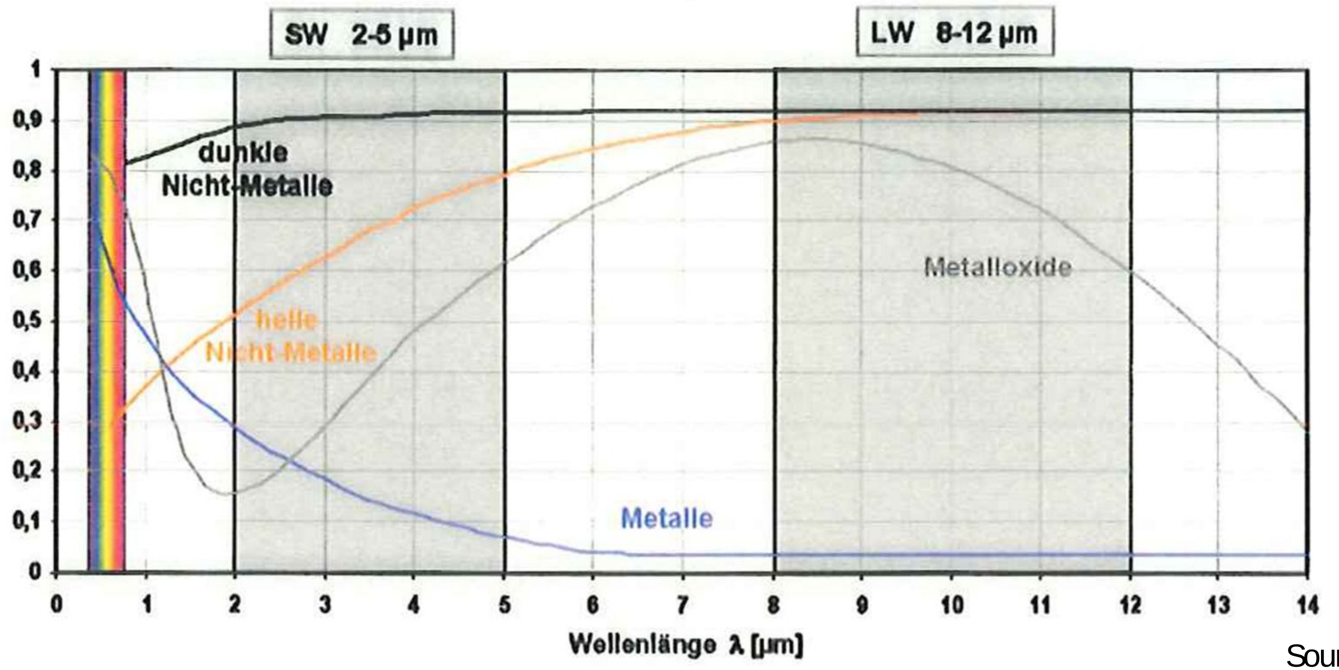
Black body, gray body, selective emitter



Emissivity ε for different emitters



ε(λ) for different materials



Source: itc-Germany

metals:

- in the lw-band only very small ε
- but we can increase ε by covering the surface (graphite spray, mylar foil,…)
- Rough surfaces or holes have larger ε
- in the sw-band ε significantly larger

nonmetals:

- Have in general larger ε
- e.g. human skin has $\varepsilon \approx 0{,}98$

Dependency of ε(λ) from other parameterns

Surface:

in general: the rougher the surface, the larger ε

in holes: ε increases
drilling a hole in a metal with depth 6 x larger then diameter
ε increases from 0,02 -> 0,9

Temperature:

ε can change due to phase transition
increases with increasing temperature

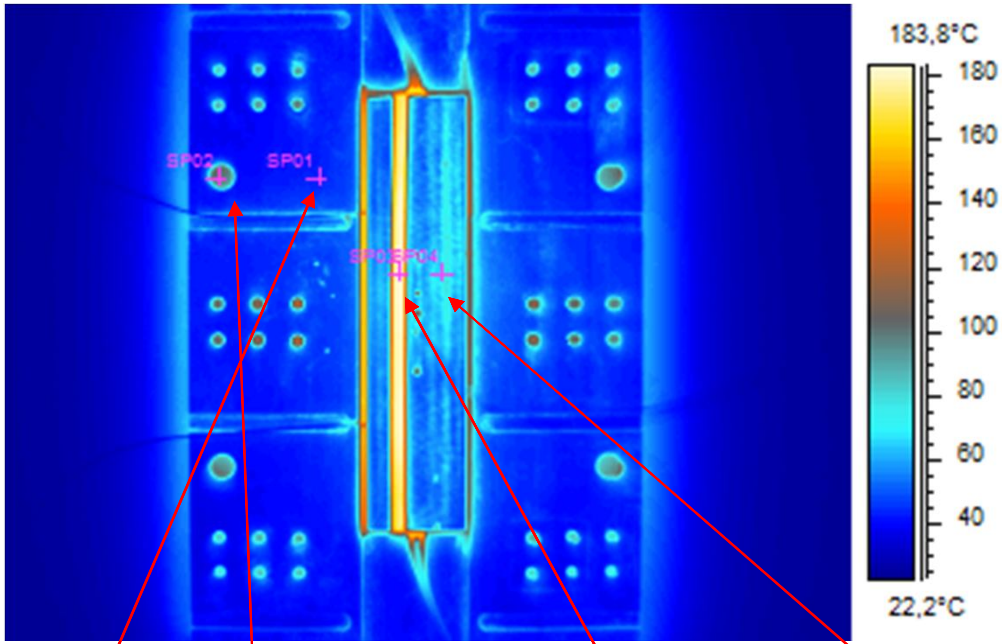
metal	T [°C]	ε
Al, uncoated	170	0,04
	500	0,05
Al, oxidized	200	0,11
	600	0,19
Stainless steel,	450	0,05
polished	500	0,065

Data from vdi-Wärmeatlas

All values of ε in literature depend on the experimental conditions!

Dependency of $\varepsilon(\lambda)$ from the surface

Example: preheating plate for Al-welding



SP01: 43°C stainless steel

SP02: 101,9° drilled hole

SP03: 184,3°C Cu covered with graphite spray

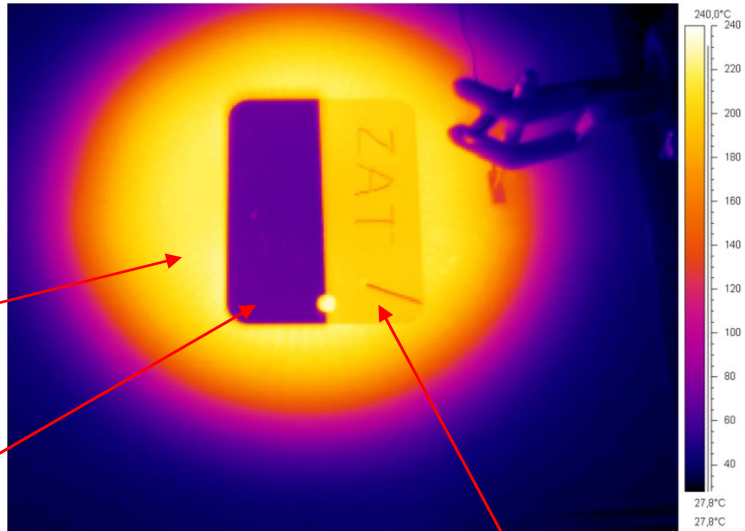
SP04: 71,2°C bare copper, part. oxidized

Dependency of ε(λ) from the surface

Metallic mirror on a heating plate, right side covered with graphite spray

≈ 200°C

≈ 55°C



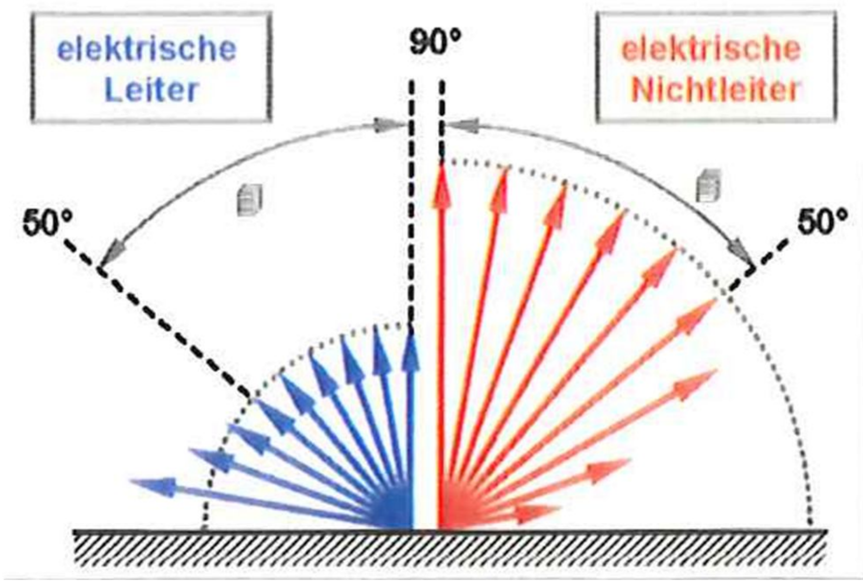
≈ 195°C

Dependency of ε(λ) from other parameters

Geometry or observation angle

metals: ε increases when the observation angle is increased

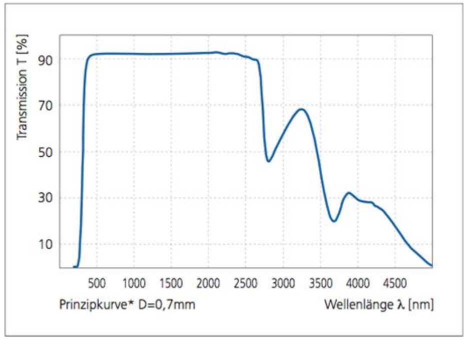
nonmetals: ε decreases when the observation angle is increased

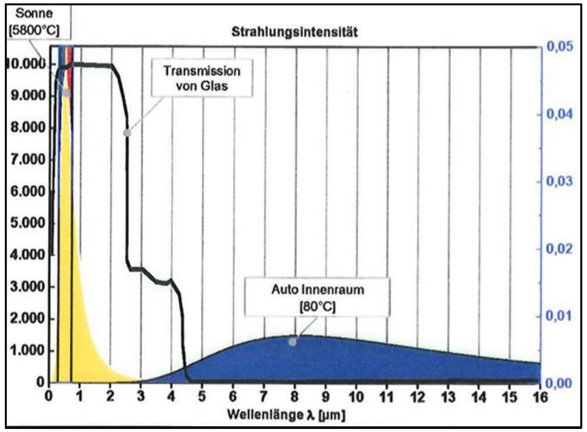


Source: itc-Germany

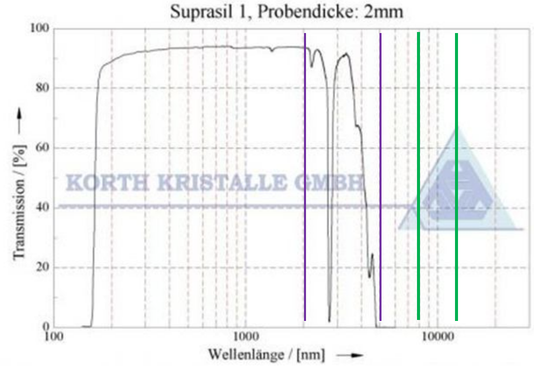
Transmission of glasses

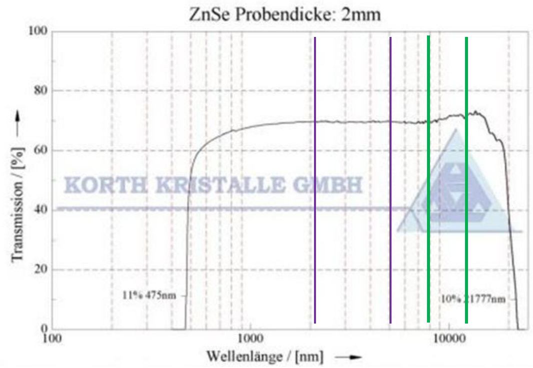
Glass 1737 - Alkaline Earth Boro-Aluminosilicate





sw lw





most glasses (and plastics) are nontransparent in the lw-band

Passive and active thermography

Thermography: measuring the radiation emitted from the surface of an object
Thermography is a contactless method
to determine the real temperature of an object, one needs to know:

ε, $T_{Ambient}$, τ, distance, relative humidity etc.

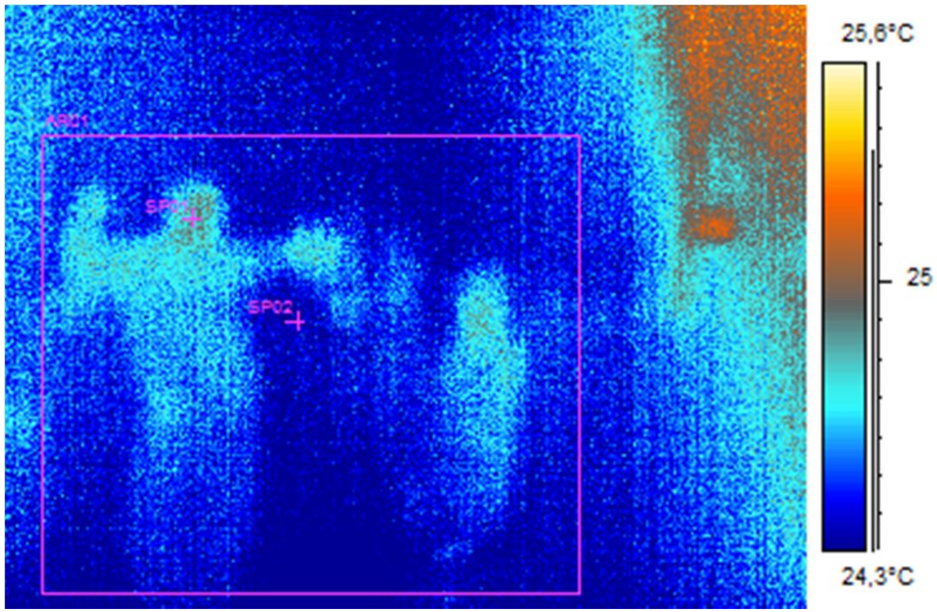
only useful in combination with conventionel measuring techniques like thermocouples or Pt_{100} -resistors
but if one needs only a relative measurement (i.e. temperature changing)

passive thermography: measuring the emitted radiation and nothing else
Applications:

- buidling- ,plant- and production supervision
- thermal processes
- medical applications
- safety precautions, defense

active thermography: thermal excitation of the object and measuring simultaneously the emitted radiation
Applications:

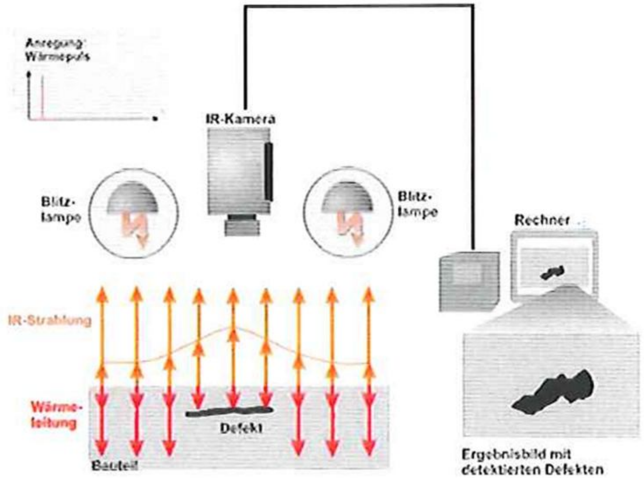
- Detection of defects like delamination, cracks, hidden structures,..
- Determination of material parametes like thermal diffusity, conductivity
- Nondestructive testing method



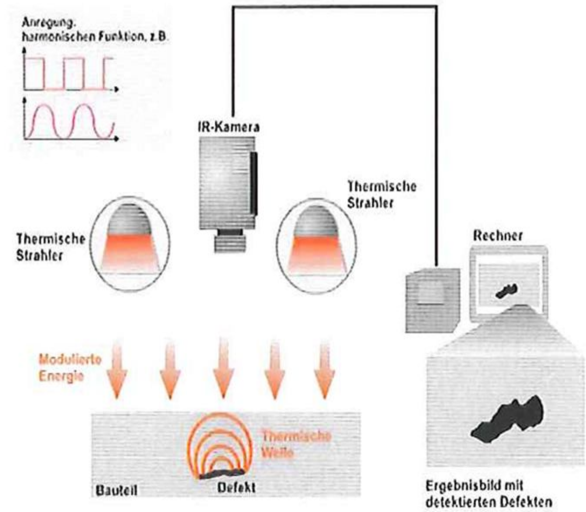
Infrared picture showing two persons.
Thermal relection at a fire door of two persons, which are behind the thermography camera
SP01: 24,9°C
SP02: 24,3°C

active thermography

Pulse thermography



Lock-In thermography



$$\mu = \sqrt{\frac{2\lambda}{\omega \rho c_{Wärme}}}$$

λ: heat conductivity
ω: modulation frequency
ρ: density
$c_{Wärme}$: heat capacity
μ: thermal penetration depth

Systems and laboratory at ZEA-1

sw-band: (two systems)

- Cooled (LN_2-Temperature) InSb-Detector with 640 x 512 IR-Pixel
- sensitive between 2,7 µm – 5,7 µm
- sensitive (calibrated) between -20°C und 2000°C
- thermal resolution at 30°C: better then 0,018 K
- full frame mode 125 fps , subframe mode > 1000 fps
- full frame mode 350 fps, subframe mode > 5 kfps
- Several different object lenses (wide angle, tele, makro)
- Several filters to suppress stray radiation

Systems are mainly used for active thermography

Systems and laboratory at ZEA-1

lw-band (7,5 µm – 14 µm)

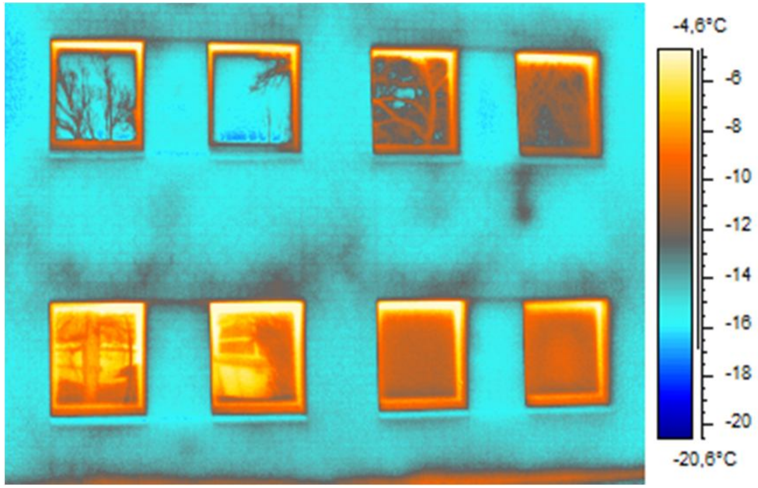
- Microbolometer, 1024 x 738 IR-Pixel, uncooled
- calibrated -40°C – 120°C, 0°C - 500°C, 500°C – 2000°C
- thermal resolution at 30°C: 0,03 K
- transportabel
- maximum full frame rate 60 (120) fps
- Several different object lenses (wide angle, tele, makro)

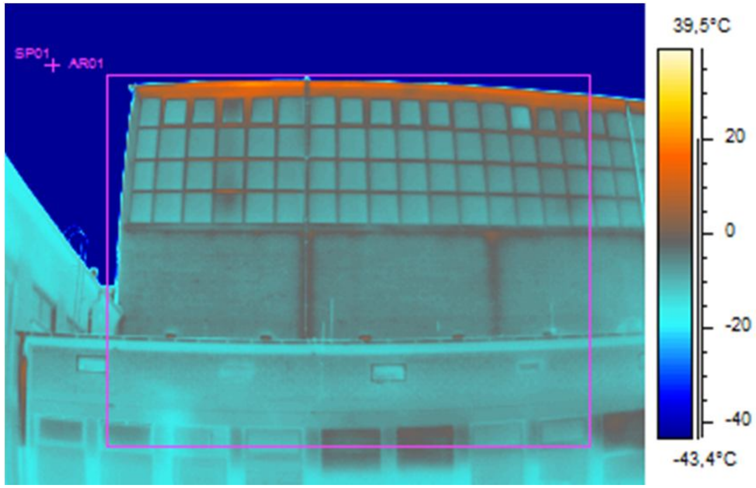
Mainly used for passive thermography

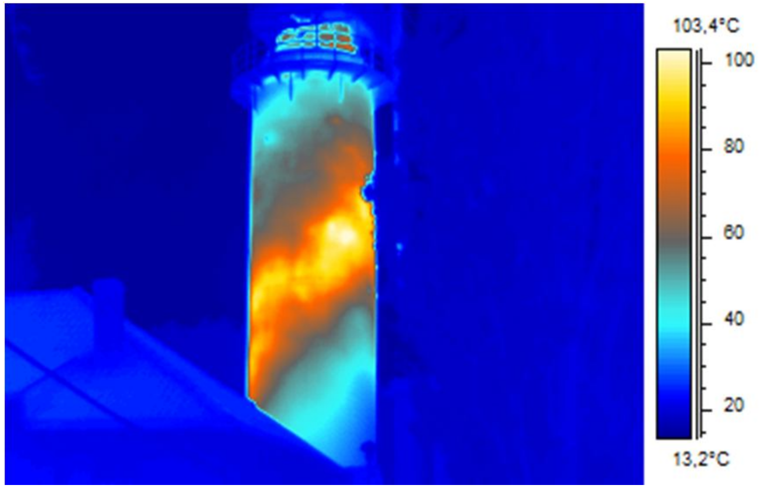
Systems and laboratory at ZEA-1

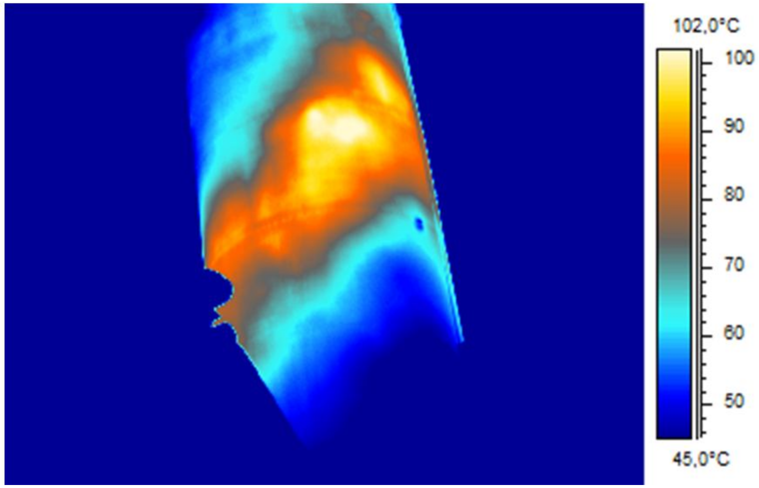
- Lock-In thermography, transient thermography, pulse thermography, flow thermography
- excitationssources like flash lamps, quartz radiator, eddy current generator, power supplies.
- TSA (Thermografic Stress Analysis
- Infrared calibrators
  - 25°C - 500°C, ε(lw) = 0,93 ; ε(sw) = 0,78
  - 500°C - 1500°C, ε(lw) = 0,98; ε(sw) = 0,98
  - Conventional thermal measurement equipment: thermo couples (Type K, S, B), Pt100,…
- Heat cabinets and furnaces

Examples for passive thermography: buildings

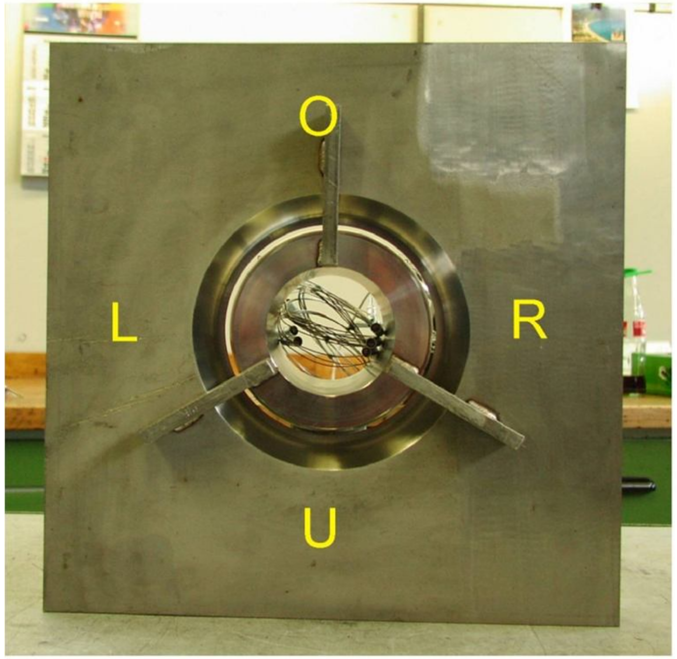


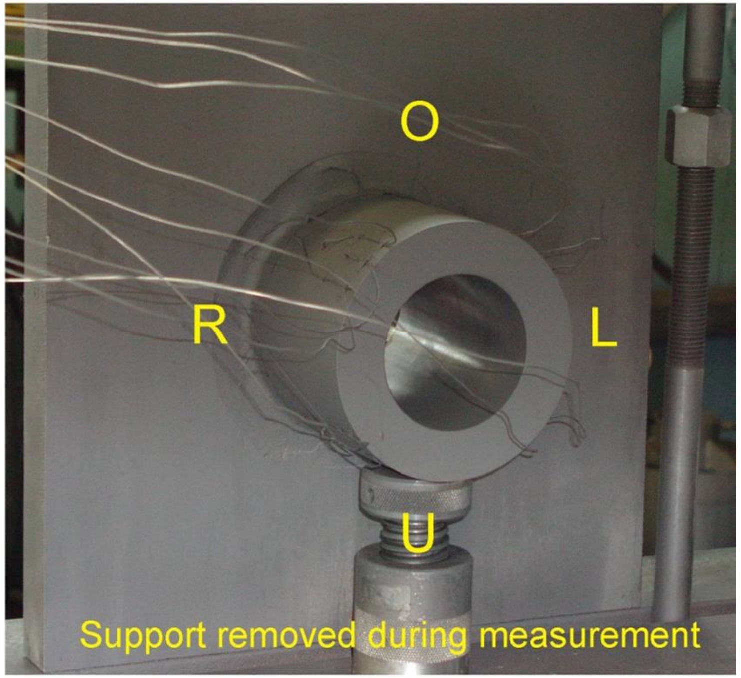






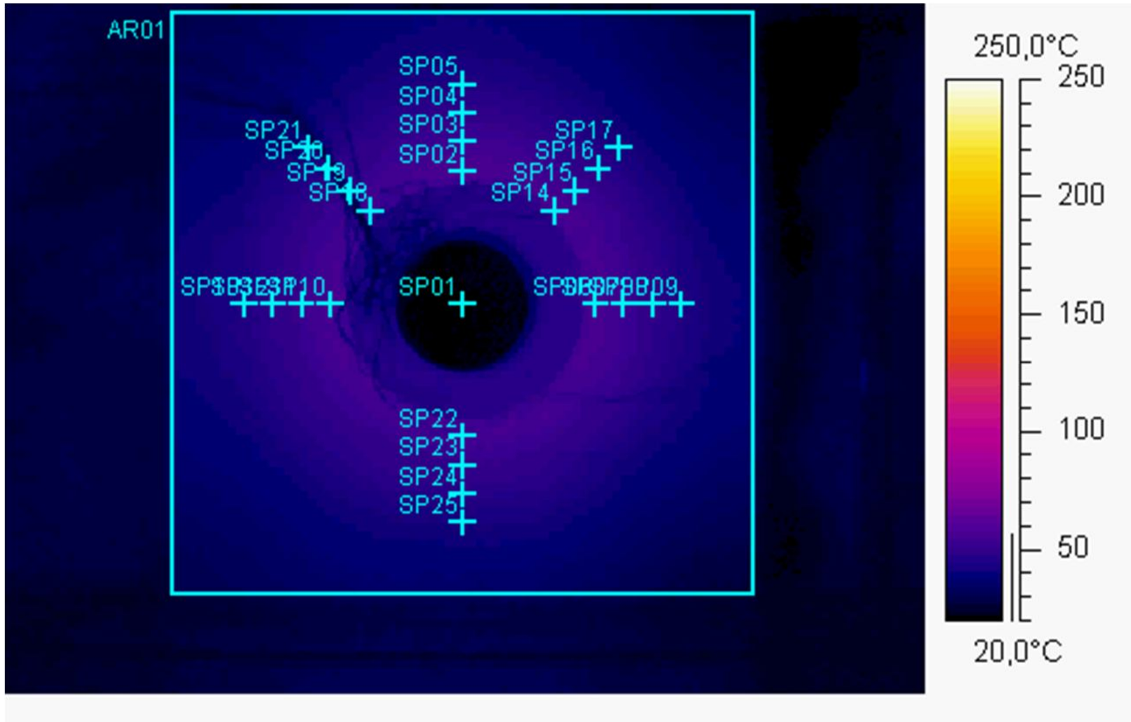
Examples for passive thermography: heat distribution after arc welding





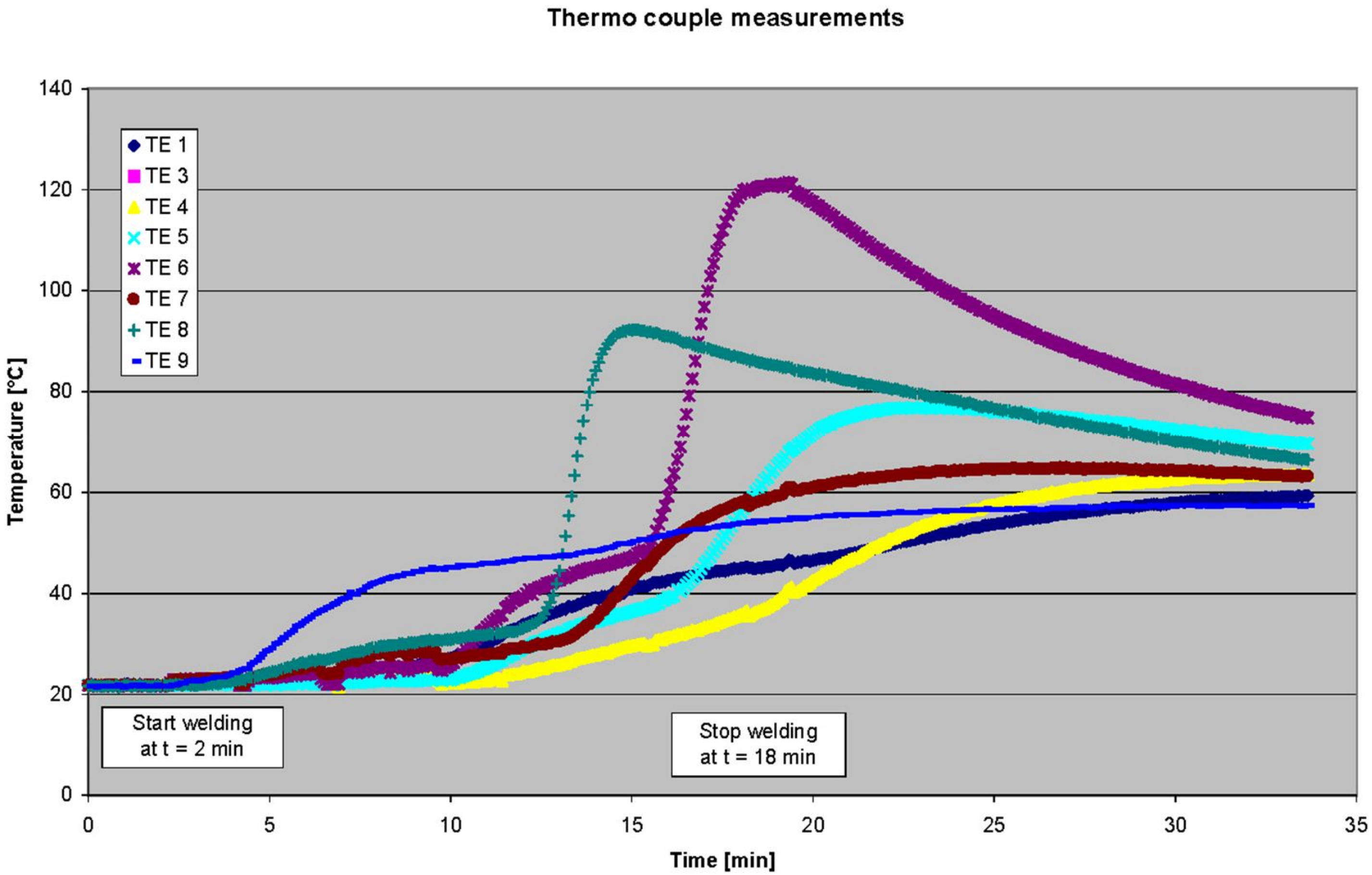
Part of coil separators of the fusion reactor W7-X

Examples for passive thermography: heat distribution after arc welding

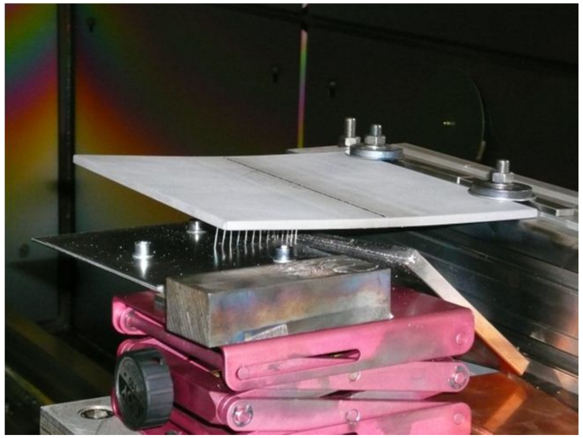


time lapse movie

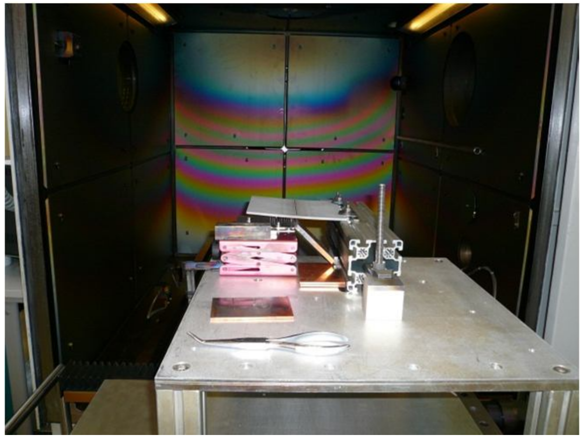
Examples for passive thermography: heat distribution after arc welding



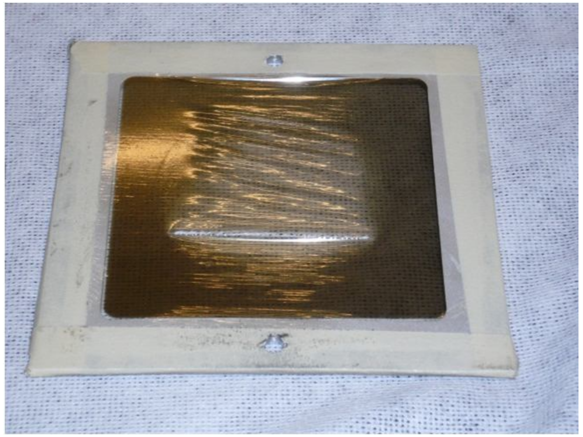
Examples for passive thermography: heat distribution during electron beam welding (under vacuum)



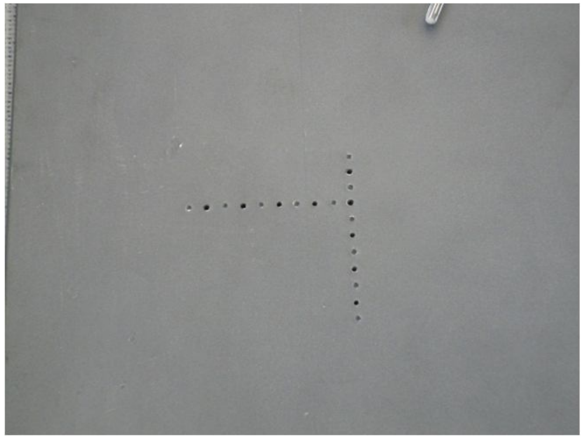
sample: stainless steel



sample mounted in the EB-vacuum chamber



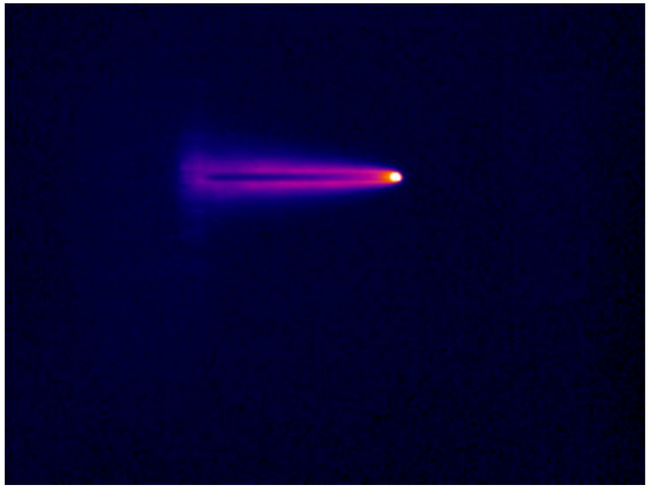
protective sheet for IR-window



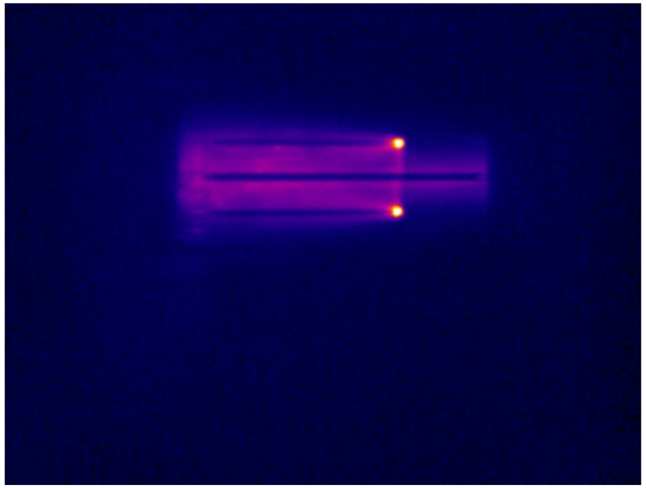
bottom side: holes for thermo couples

Examples for passive thermography: heat distribution during electron beam welding

After half of welding

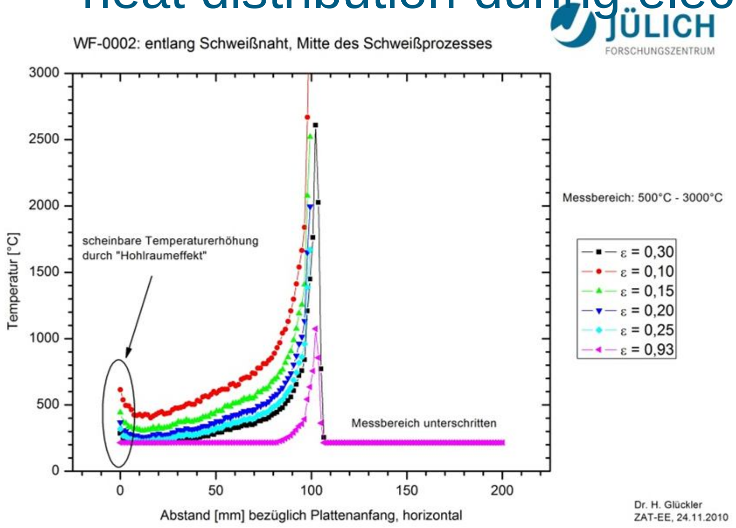


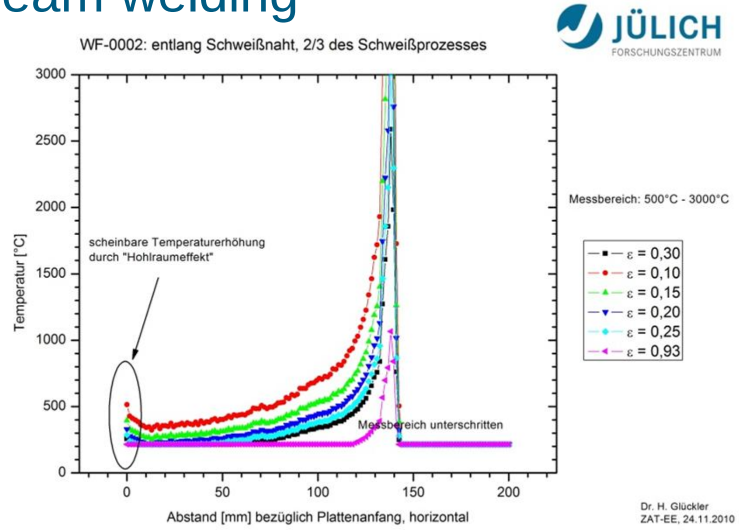
2/3 of welding

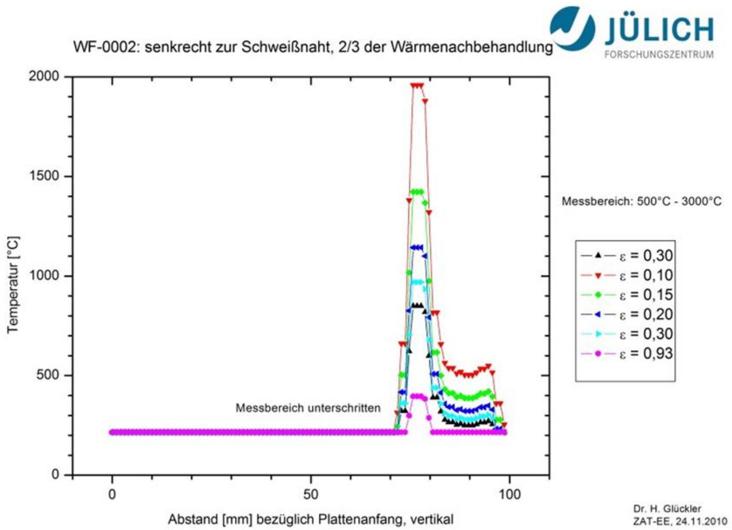


2/3 post heat weld treatment

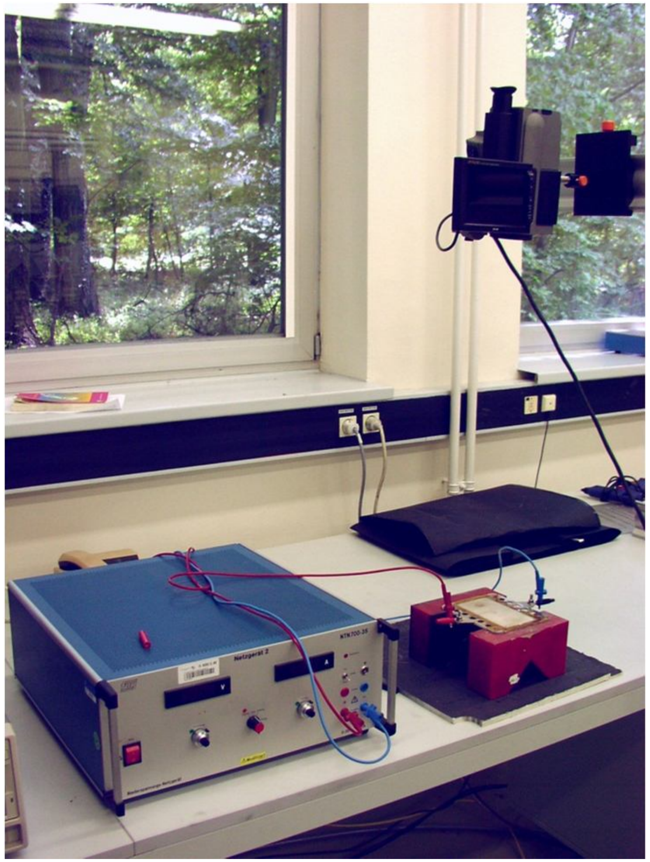
Examples for passive thermography:
heat distribution during electron beam welding

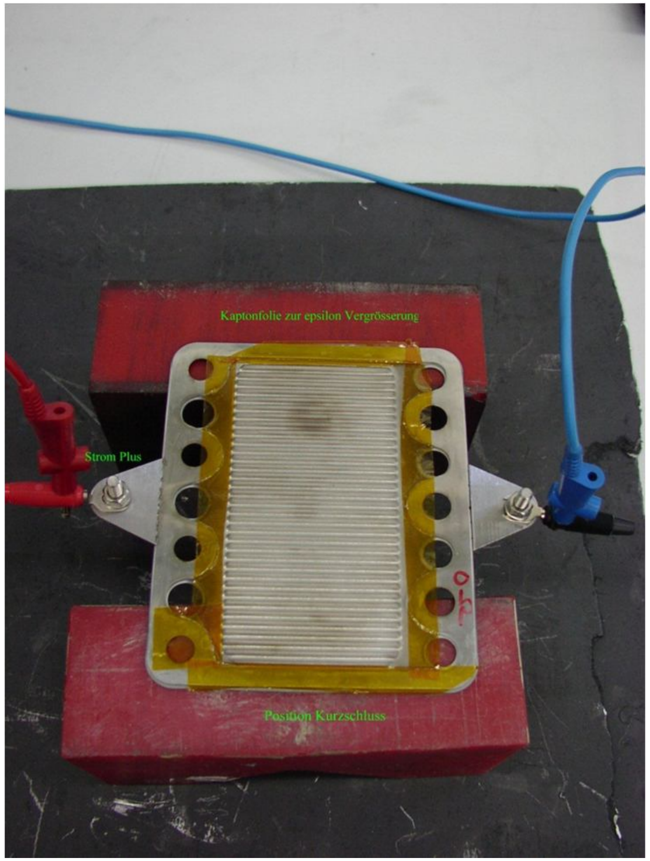




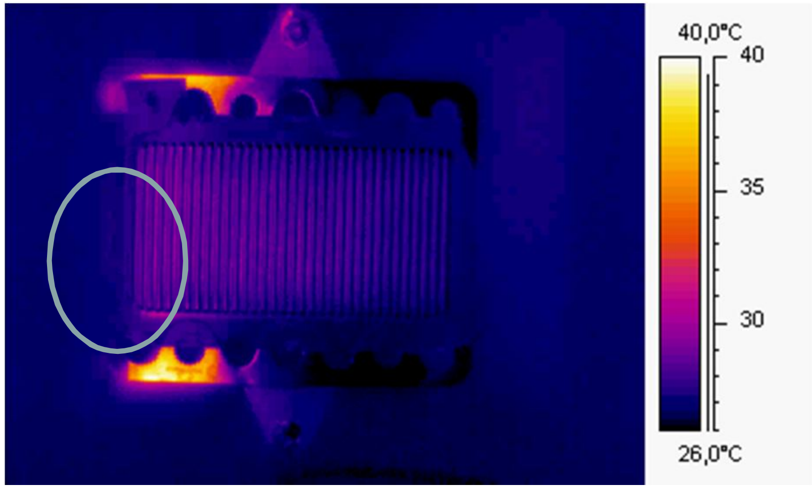


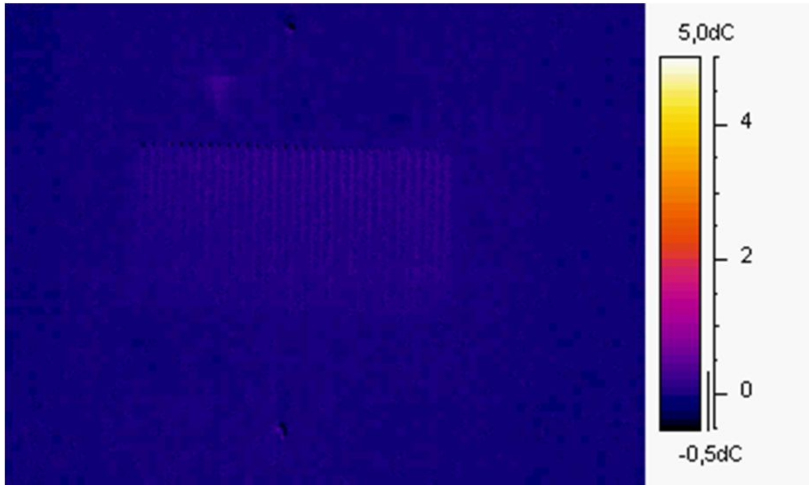
Examples for active thermography: short circuit in fuel cells





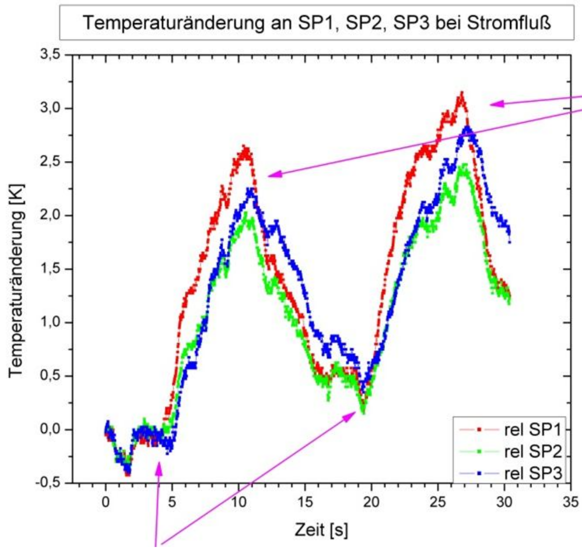
Examples for active thermography: short circuit in fuel cells





Examples for active thermography: short circuit in fuel cells

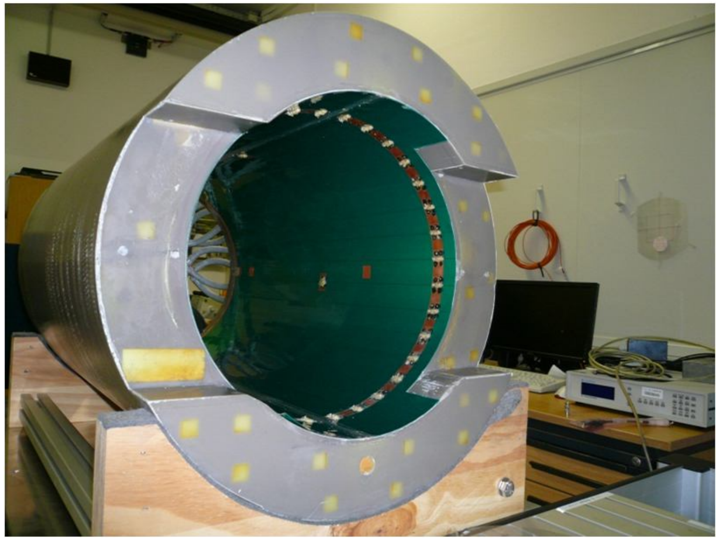
short circuit, visible by the thermal radiation



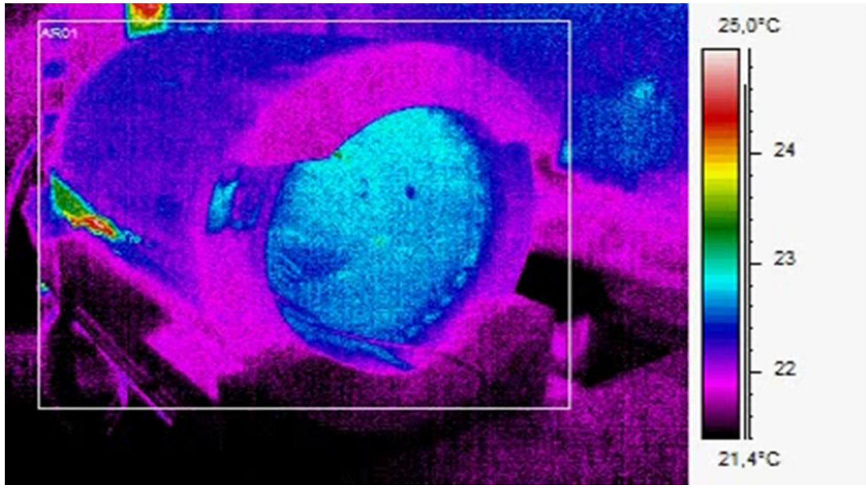
current off

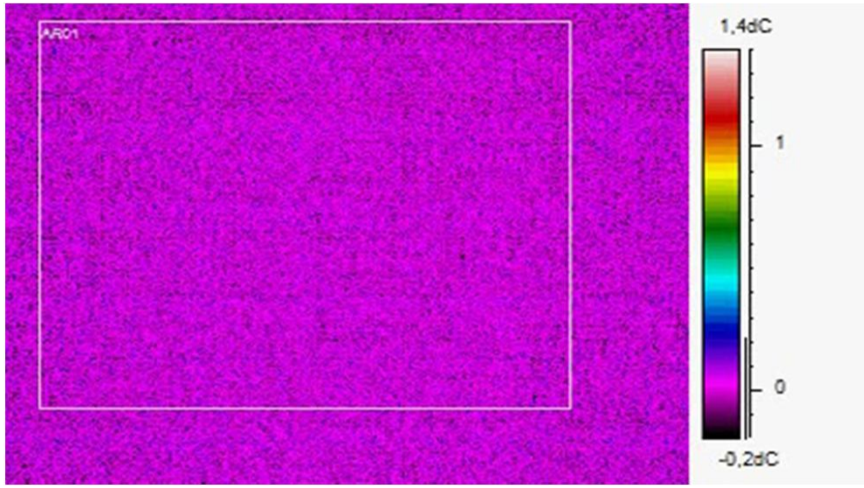
current switched on

Examples for active thermography: gradient coils for MRT-spectrometers



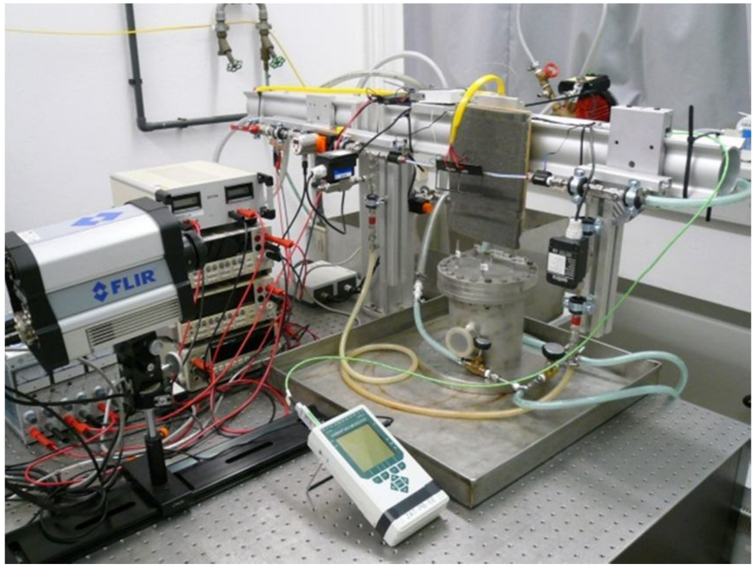
Examples for active thermography: gradient coils for MRT-spectrometers

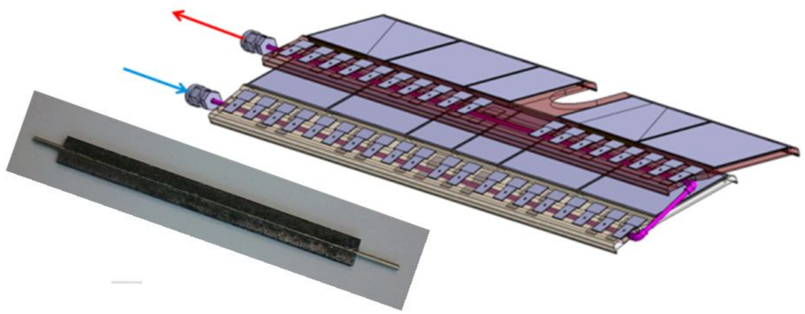


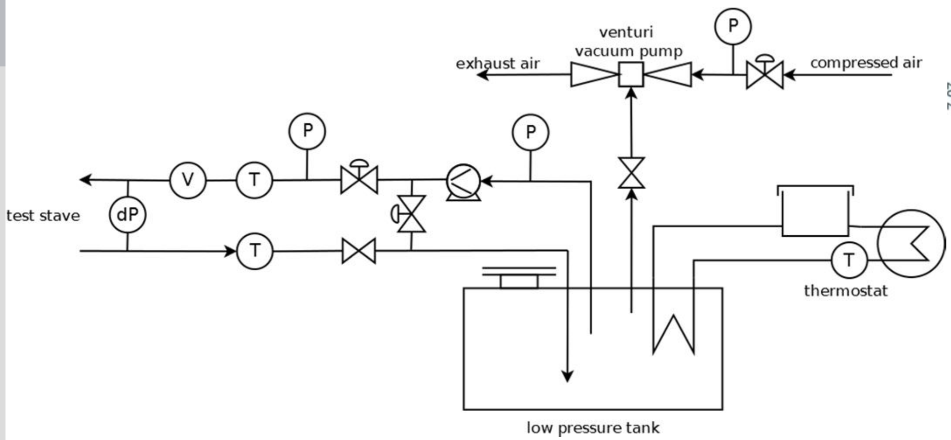


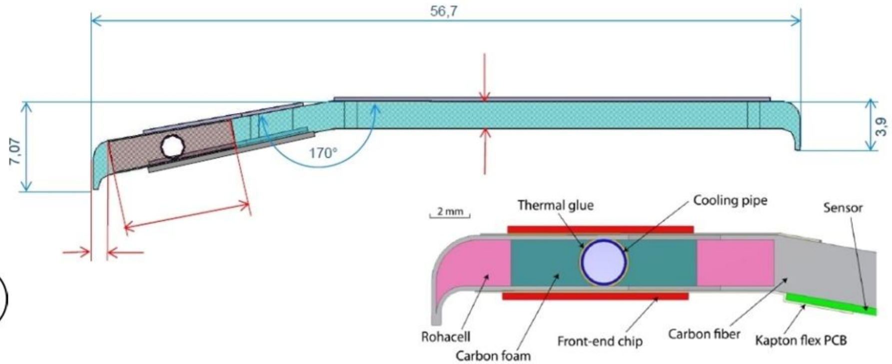
Three different coils G_x, G_y, G_z
used current: I = 60 A, U = 4 V
Movie is in time lapse mode

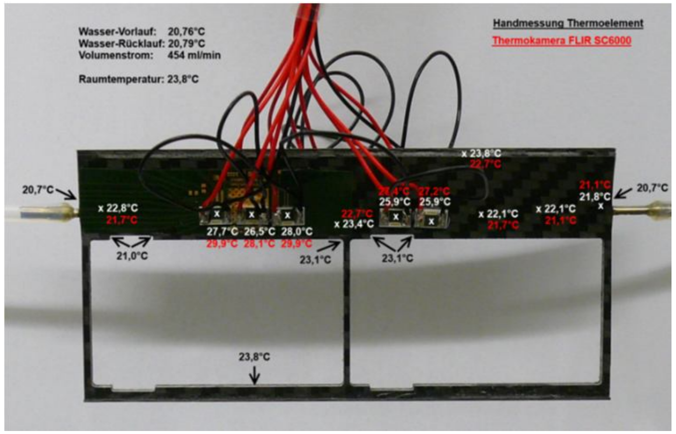
Examples for thermography:
cooling systems for new particle detectors (MVD for PANDA)

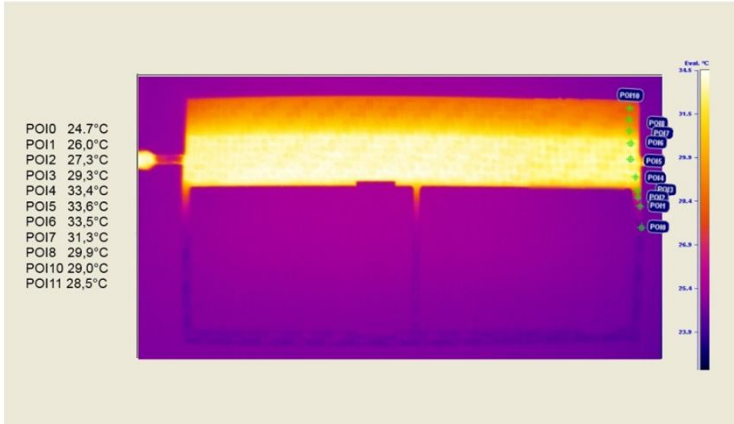


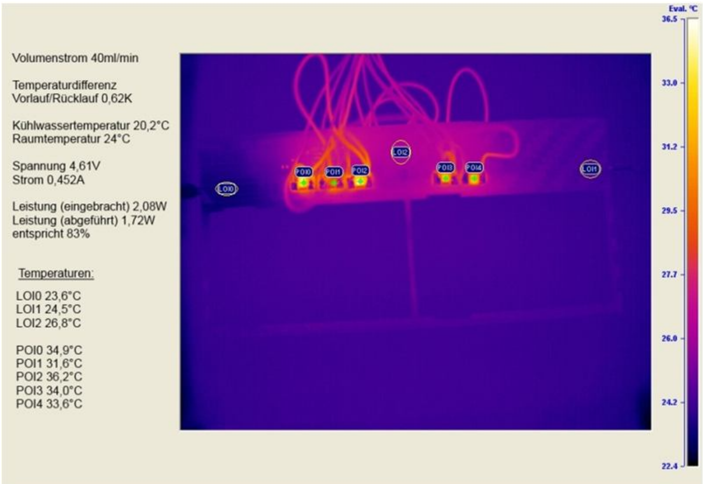






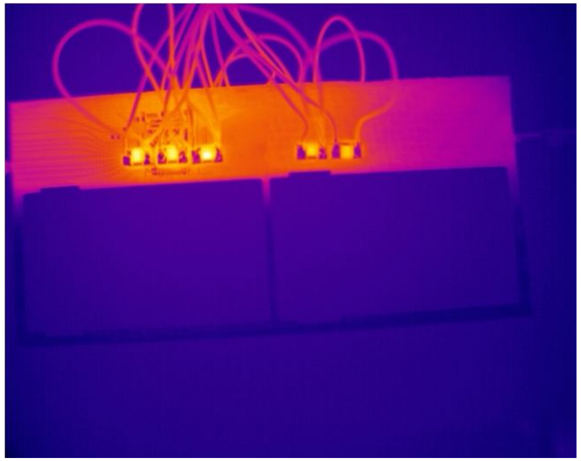

Wasser-Vorlauf: 20,76°C
Wasser-Rücklauf: 20,79°C
Volumenstrom: 454 ml/min
Raumtemperatur: 23,8°C
Handmessung Thermoelement
Thermokamera FLIR SC6000
20,7°C
x 22,8°C
21,7°C
27,7°C 26,5°C 28,0°C
29,9°C 28,1°C 29,9°C
21,0°C
22,7°C
x 23,4°C
23,1°C
25,9°C 25,9°C
27,2°C
23,1°C
x 23,8°C
22,7°C
x 22,1°C
21,7°C
x 22,1°C
21,1°C
21,1°C
21,8°C
20,7°C
23,8°C


POI0 24.7°C
POI1 26,0°C
POI2 27,3°C
POI3 29,3°C
POI4 33,4°C
POI5 33,6°C
POI6 33,5°C
POI7 31,3°C
POI8 29,9°C
POI10 29,0°C
POI11 28,5°C


Volumenstrom 40ml/min
Temperaturdifferenz
Vorlauf/Rücklauf 0,62K
Kühlwassertemperatur 20,2°C
Raumtemperatur 24°C
Spannung 4,61V
Strom 0,452A
Leistung (eingebracht) 2,08W
Leistung (abgeführt) 1,72W
entspricht 83%
Temperaturen:
LOI0 23,6°C
LOI1 24,5°C
LOI2 26,8°C
POI0 34,9°C
POI1 31,6°C
POI2 36,2°C
POI3 34,0°C
POI4 33,6°C
Eval. °C
36.5
33.0
31.2
29.5
27.7
26.0
24.2
22.4

Dynamic evaluation of the cooling process

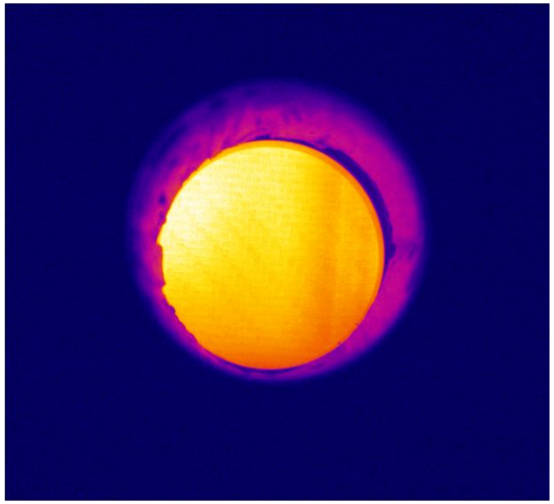
without cooling

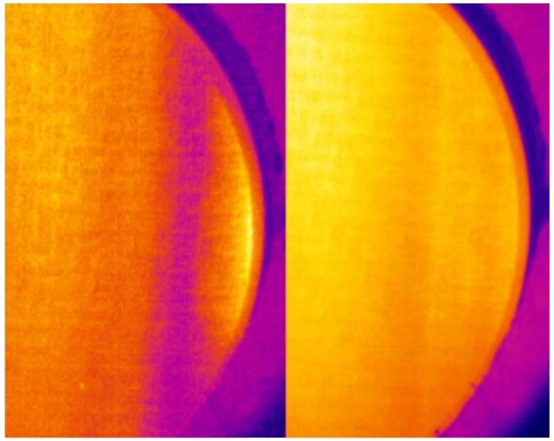


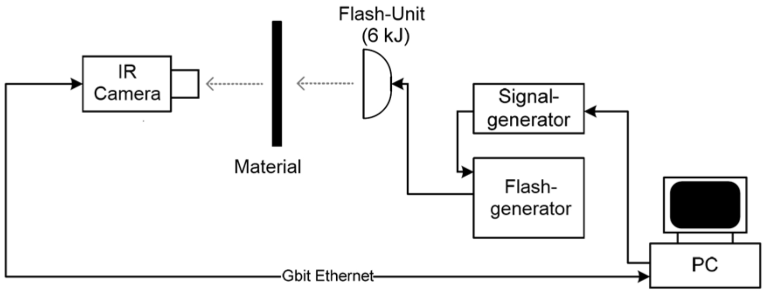
with cooling

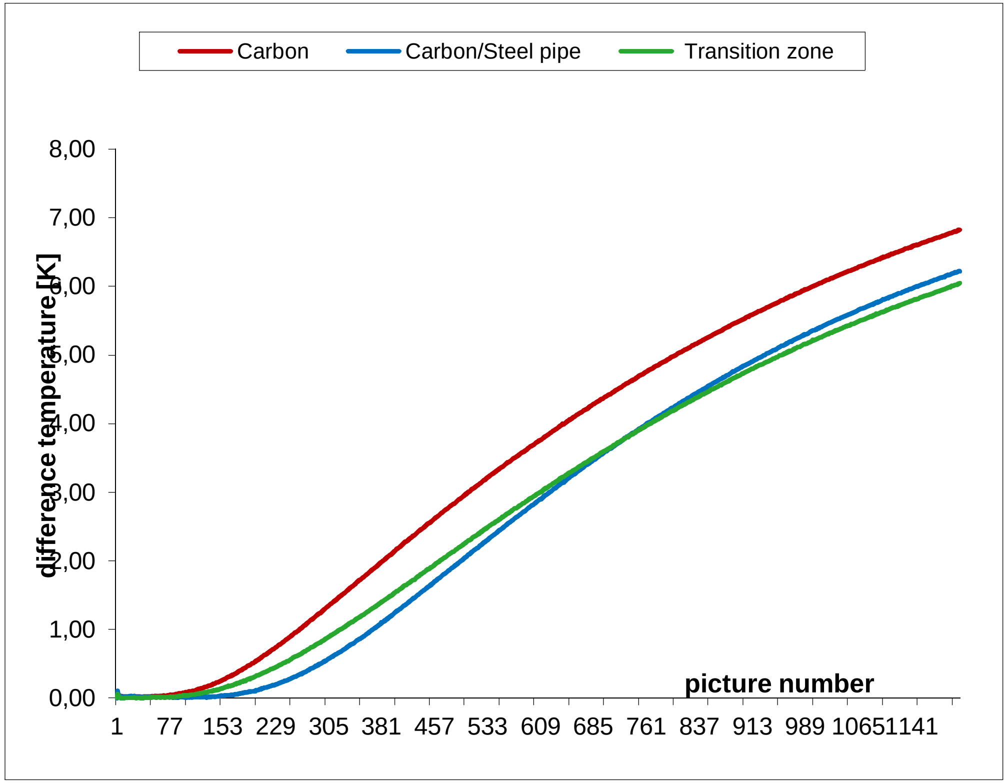
beginning of cooling

Analyzing the thermal behavior of a complex structure



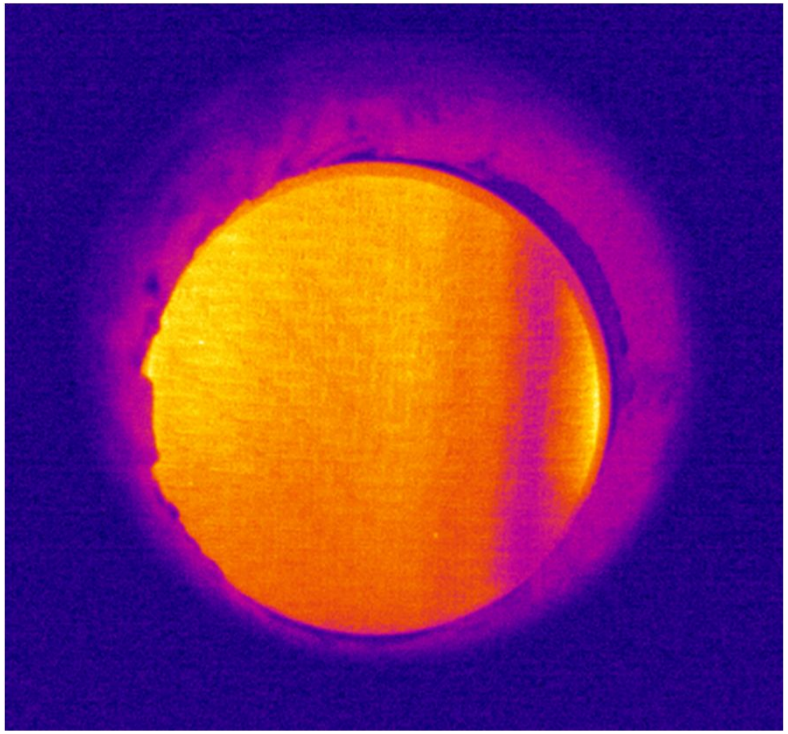






Analyzing the thermal behavior of a complex structure

Picture of a thermal wave going through a carbon carrier containing a cooling pipe



Calculated heat conductivity	
0,113 W/(m*K)	α = 1,115 E-07 m^2/K
0,117 W/(m*K)	α = 1,073 E-07 m^2/K
0,128 W/(m*K)	α = 1,216 E-07 m^2/K

estimated:
density:1500 kg/m^3
heat capacity: 700 J/(kg*K)

résumé

1. thermography is a useful modern measuring technique
2. ZEA-1 has state of the art thermography systems, labs and knowledge
3. To perform thermography investigations it is necessary to know all parameters, esp. the emissivity

Thank you very much for your attention