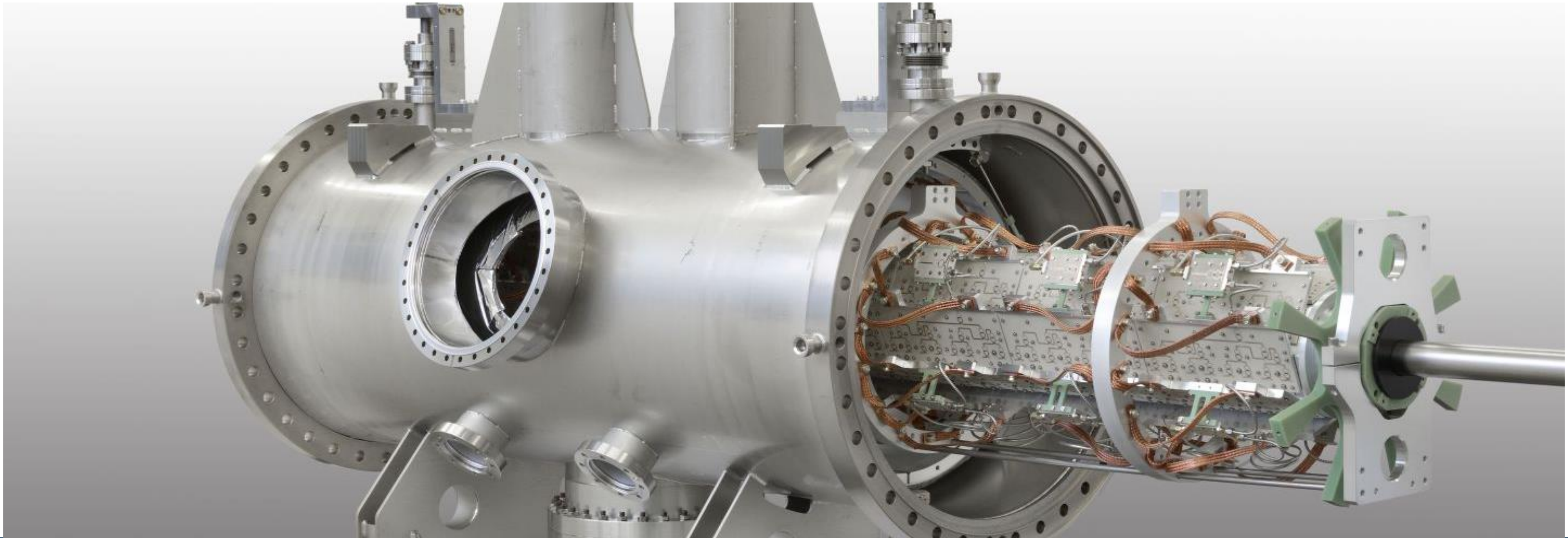
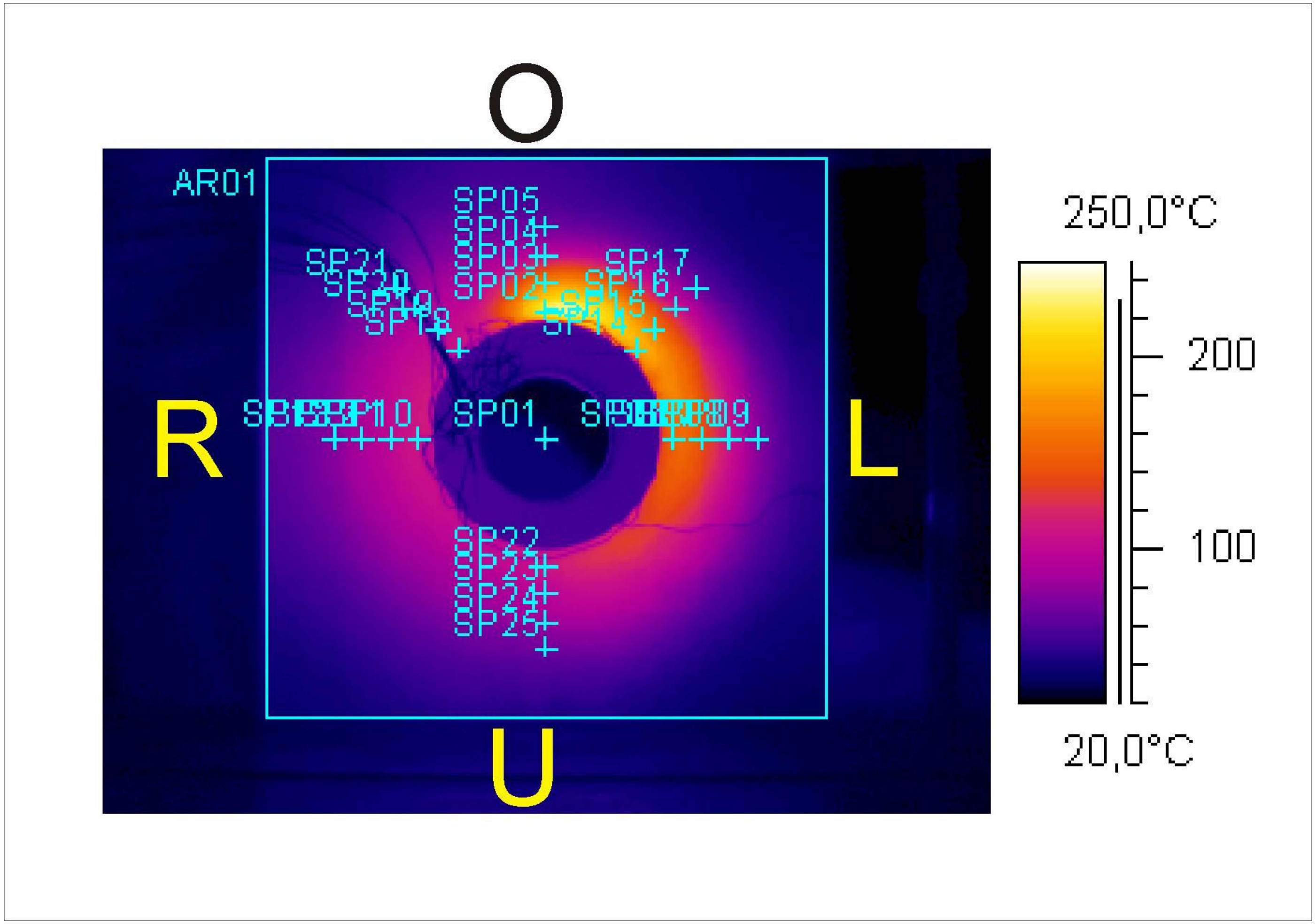


QUALI-START-UP SCIENCE LECTURE about IR-THERMOGRAPHY

09.09.2019, DR. HARALD GLÜCKLER

ZEA-1 | TECHNOLOGY FOR CUTTING EDGE RESEARCH

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 about IR-radiation

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)

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

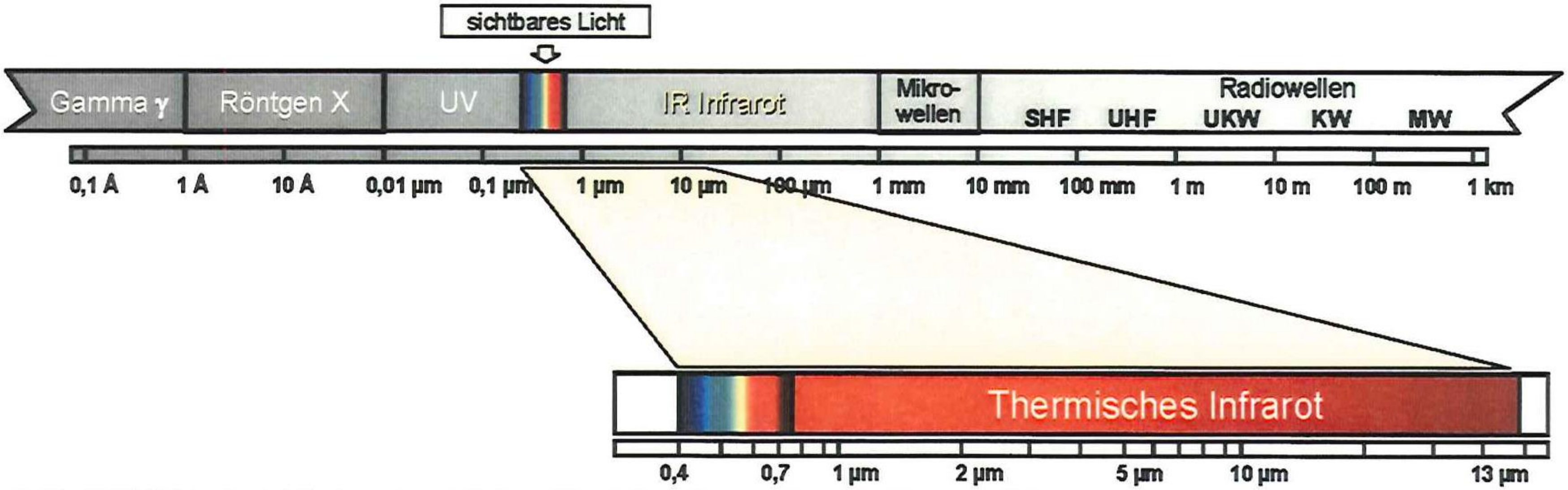
1887: Proof: infrared-radiation = electromagnetic radiation (Hertz)
1893: Wien's displacement law

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

1900: Planck's law

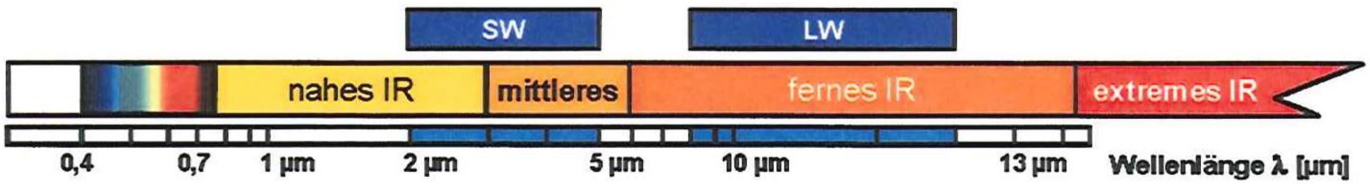
$$M(\lambda, T) = \frac{2\pi h c^2}{\lambda^5} \cdot \frac{1}{e^{\left(\frac{hc}{\lambda k T}\right)} - 1}$$

Spectrum of electromagnetic radiation



sw: Short-wave band 2 µm – 5 µm

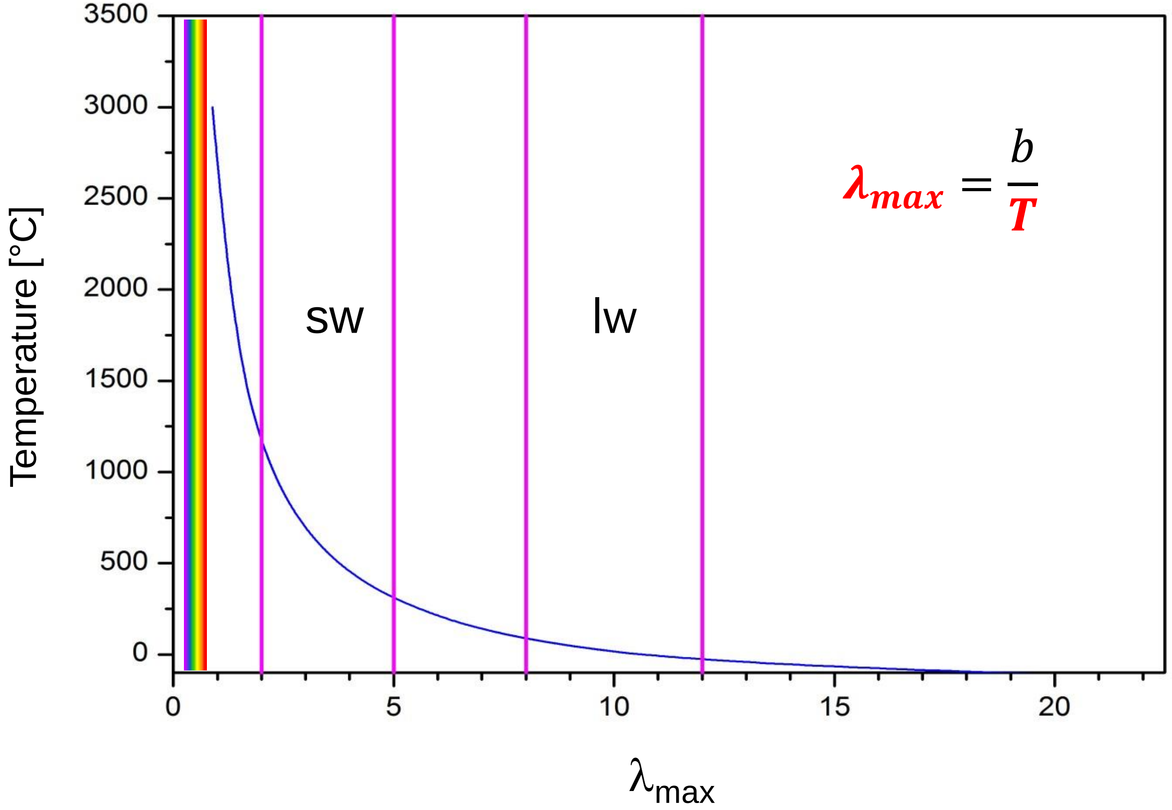
lw: Long-wave band 8 µm – 12 µm



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

Wien‘s displacement law

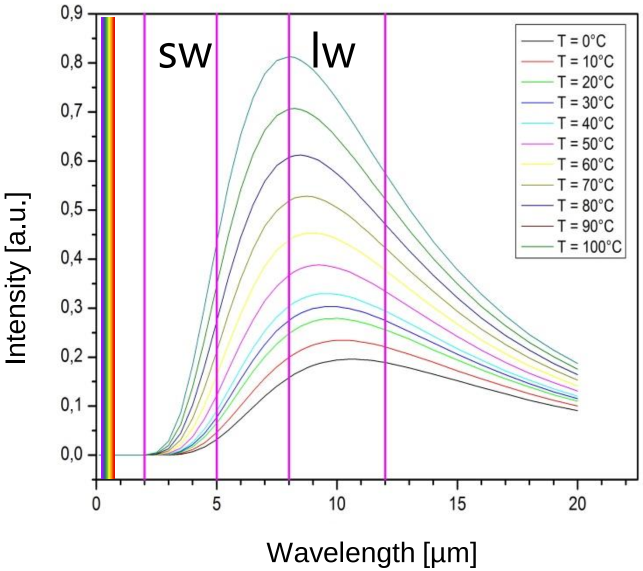
black body radiation for different temperatures peaks at a wavelength inversely proportional to the temperature.

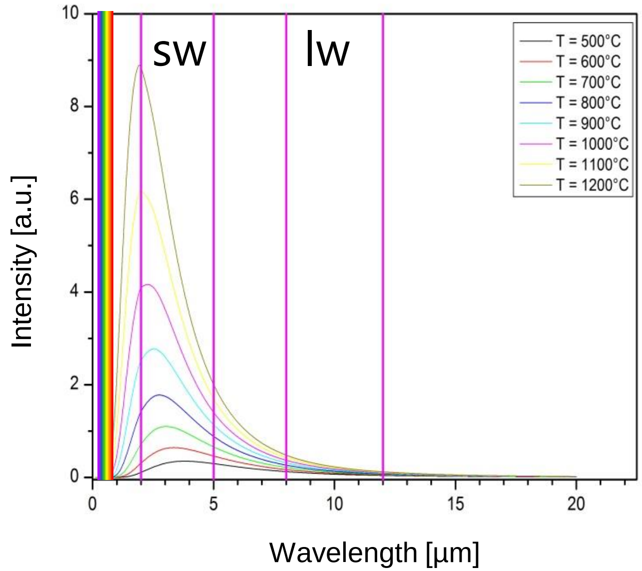


Planck's law

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

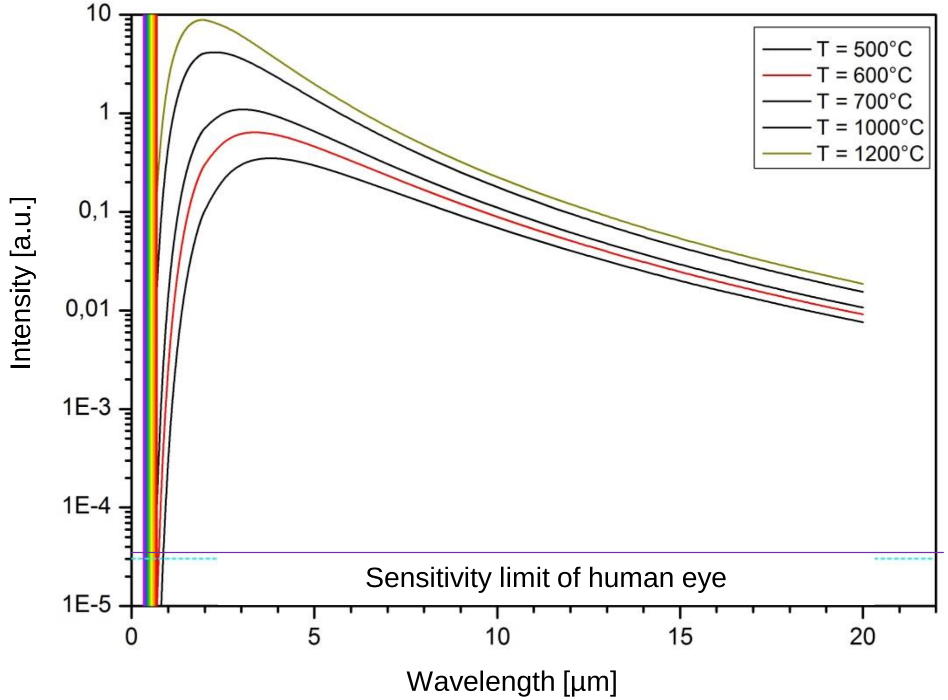
$$M(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{\left(\frac{hc}{\lambda kT}\right)} - 1}$$



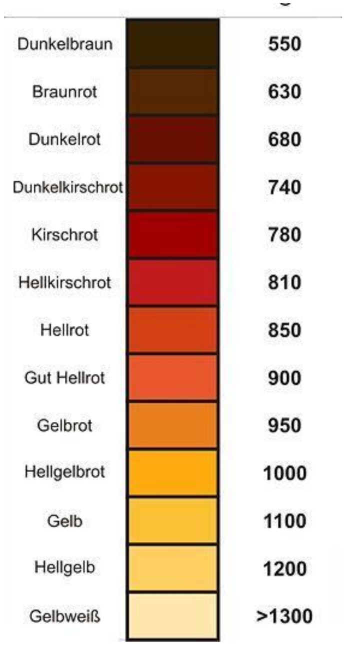


Planck's law

Example: red and yellow heat

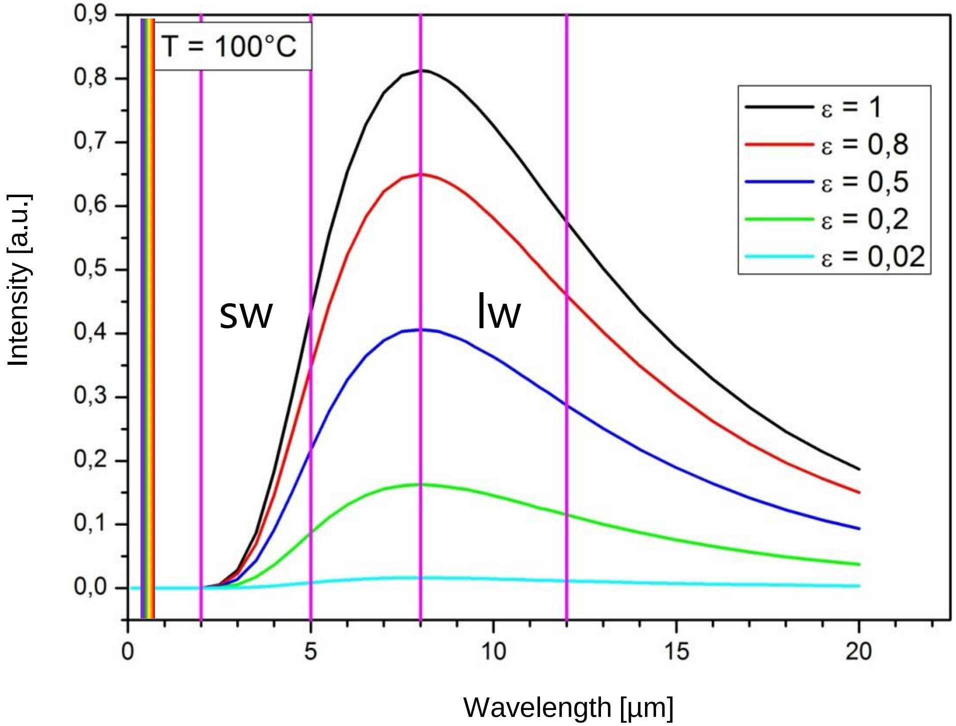


Annealing colors for different temperatures [T in °C]



Some remarks about emissivity ε

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

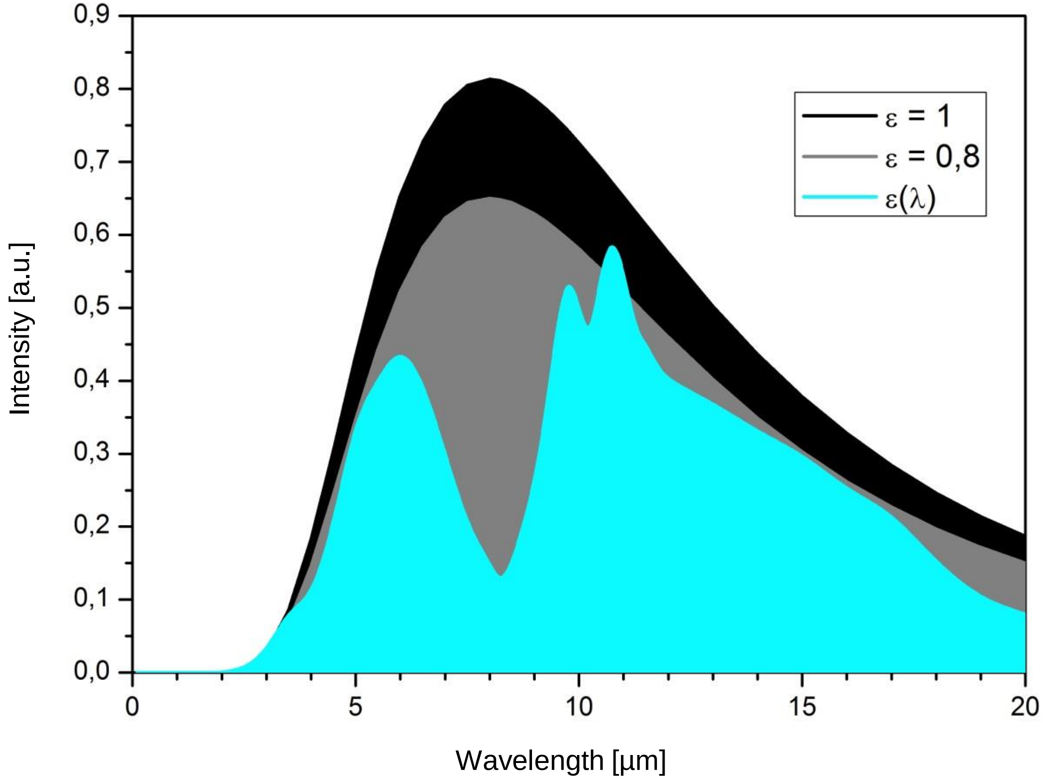


Black body $\alpha = \epsilon = 1$

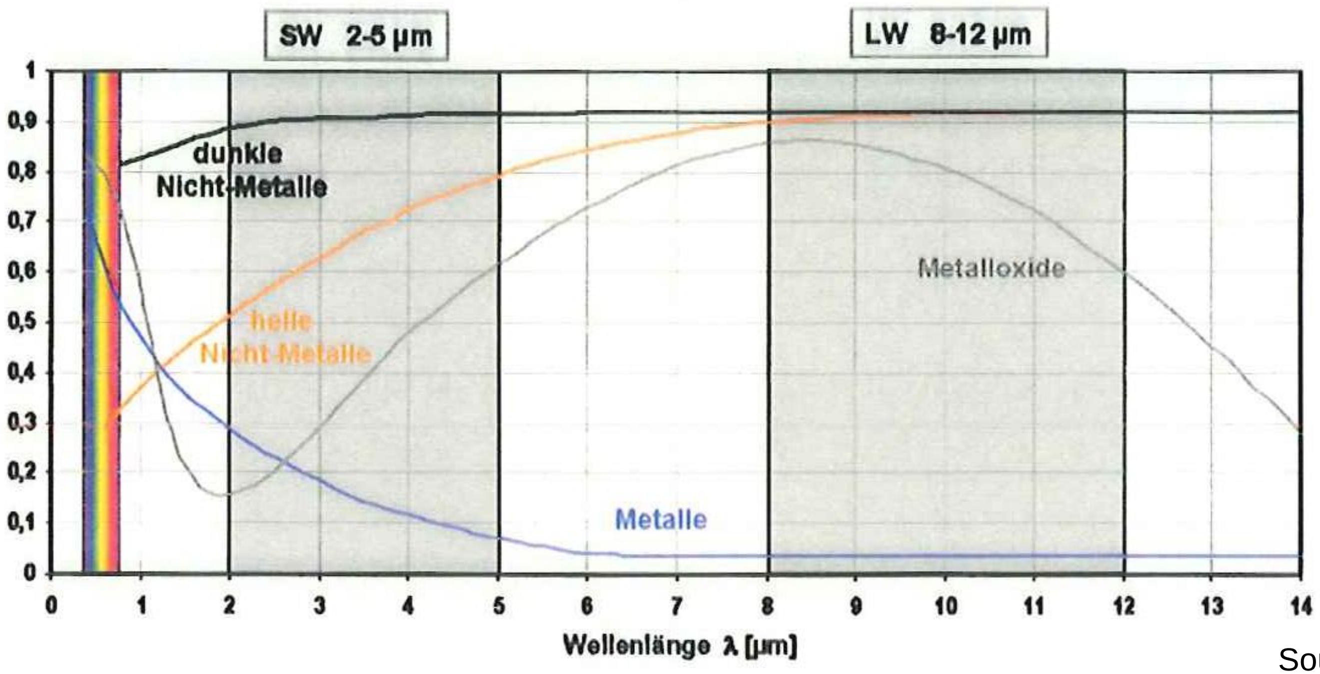
Every body in nature has an ε < 1 ! 0,999999 > ε > 0,000001

Some remarks about emissivity ε

Different emitters: Black body, gray body, selective emitter



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, rusty surfaces or holes
have a larger ε
in the sw-band ε is significantly larger

nonmetals:

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

Dependency of $\varepsilon(\lambda)$ 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

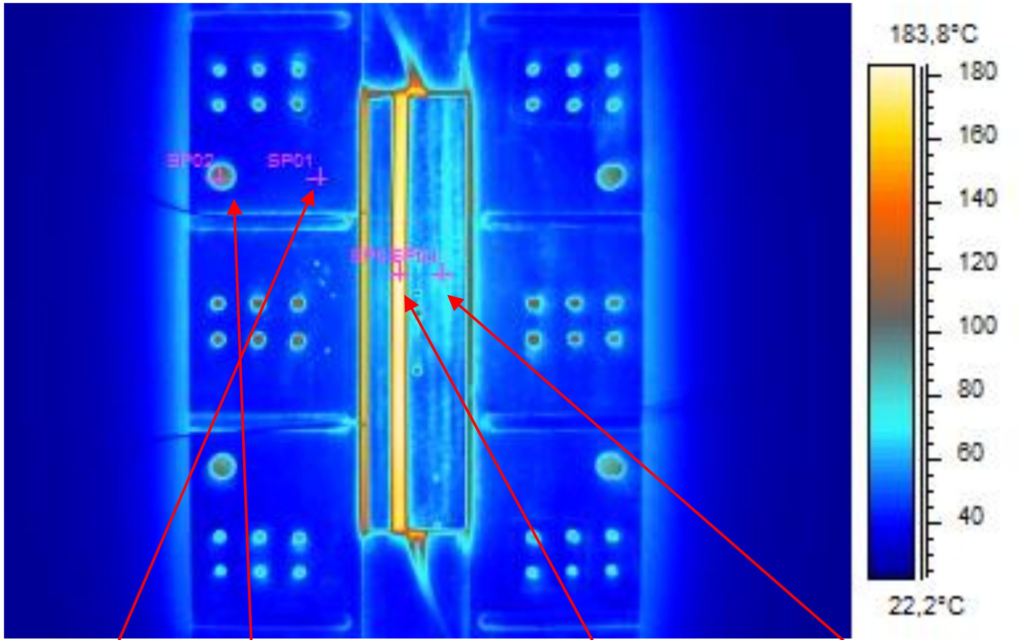
metal	T [°C]	ε
Al, uncoated	170	0,04
	500	0,05
Al, oxidized	200	0,11
	600	0,19
Stainless steel,	450	0,05
polished	500	0,065

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 welding



SP01: 43°C
stainless steel

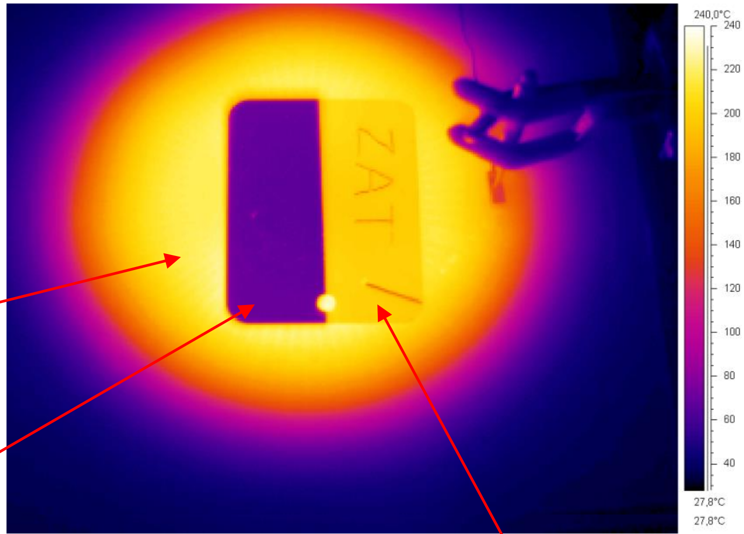
SP02: 101,9°
drilled hole

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

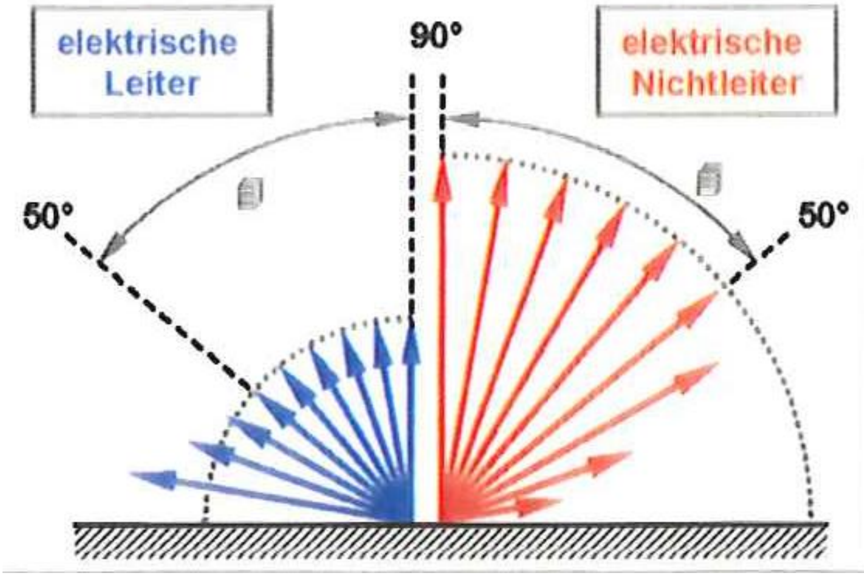
≈ 195°C

Dependency of $\varepsilon(\lambda)$ from other parameters

Geometry or observation angle

metals: ε increases when the observation angle is increased

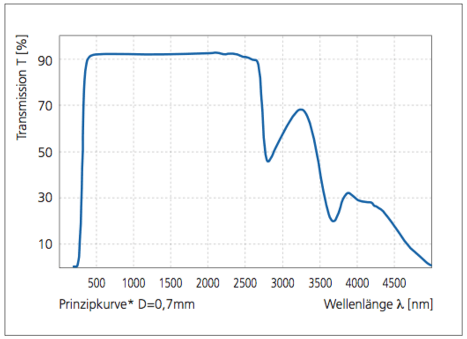
nonmetals: ε decreases when the observation angle is increased

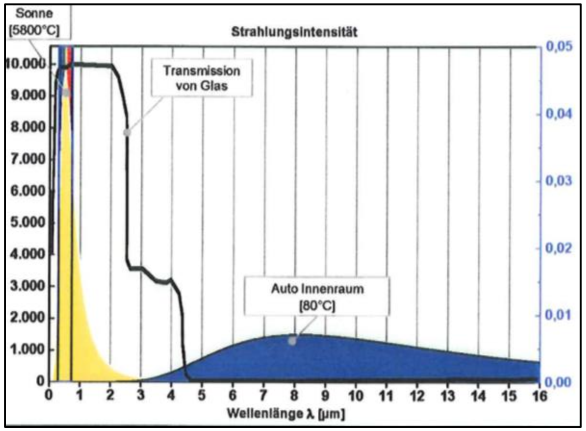


Source: itc-Germany

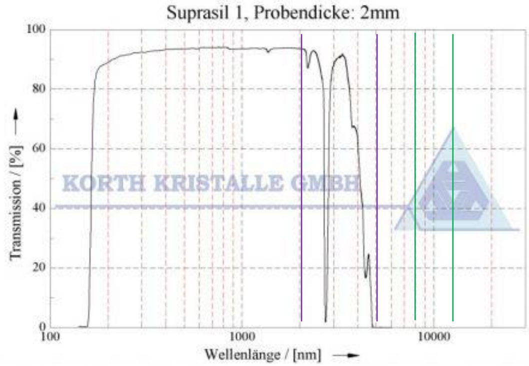
IR-Transmission of glasses

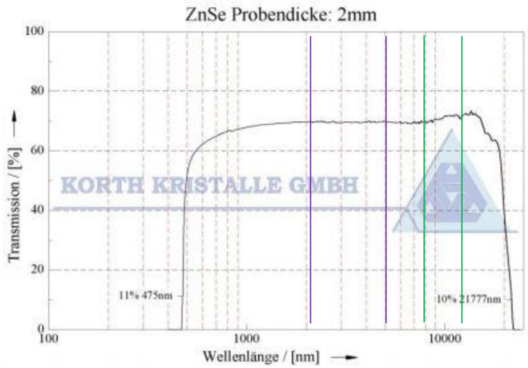
Glass 1737 - Alkaline Earth Boro-Aluminosilicate





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:

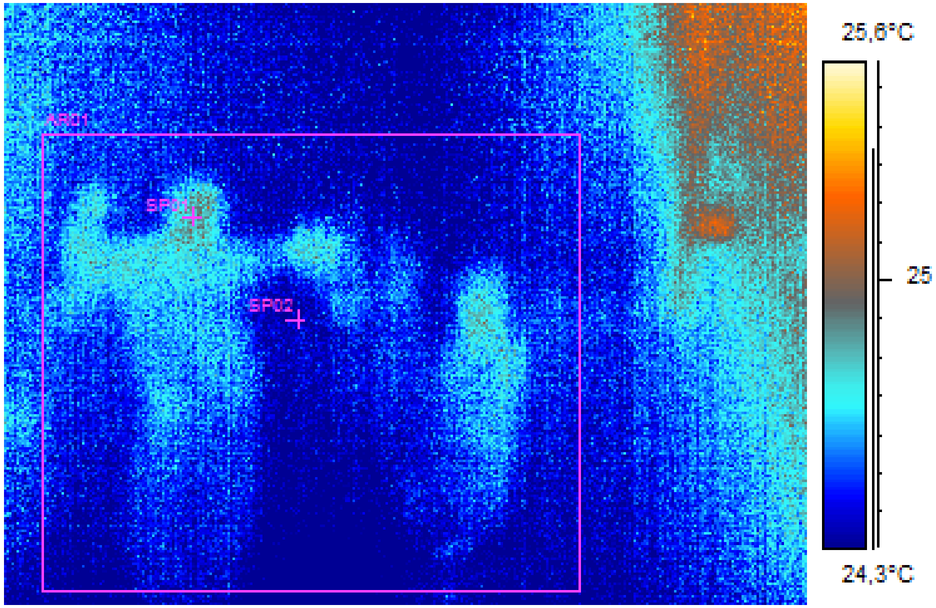
- buidling- ,plant- and production supervision
- thermal processes
- medical applications
- safety precautions, defense

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

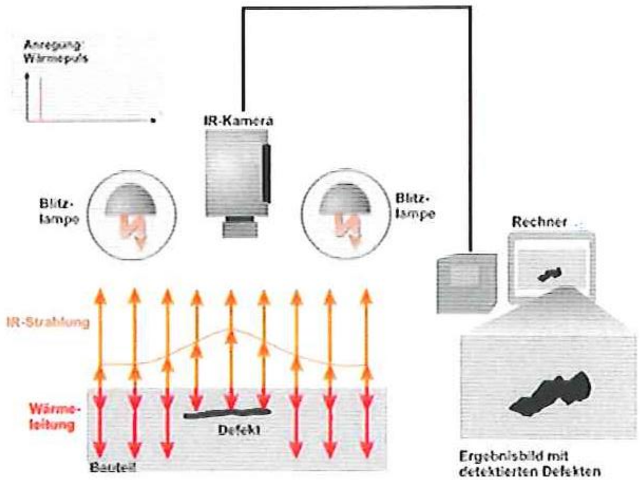
Passive thermography



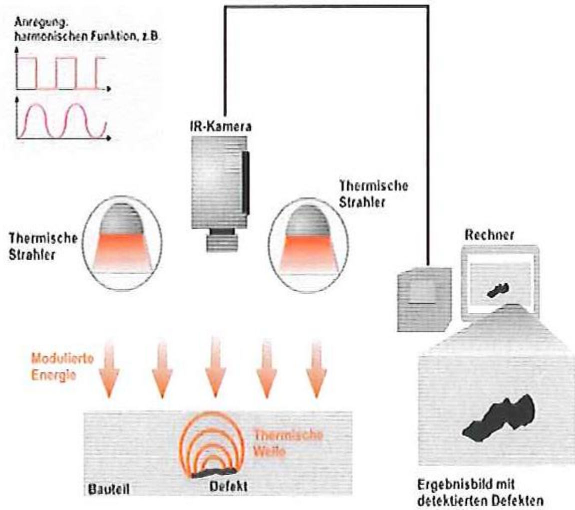
Thermal relection at a fire door of two persons, which are standing the thermography camera
SP01: 24,9°C
SP02: 24,3°C

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
Not „transportable“

Systems and laboratory at ZEA-1

lw-band (7,5 µm – 14 µm)

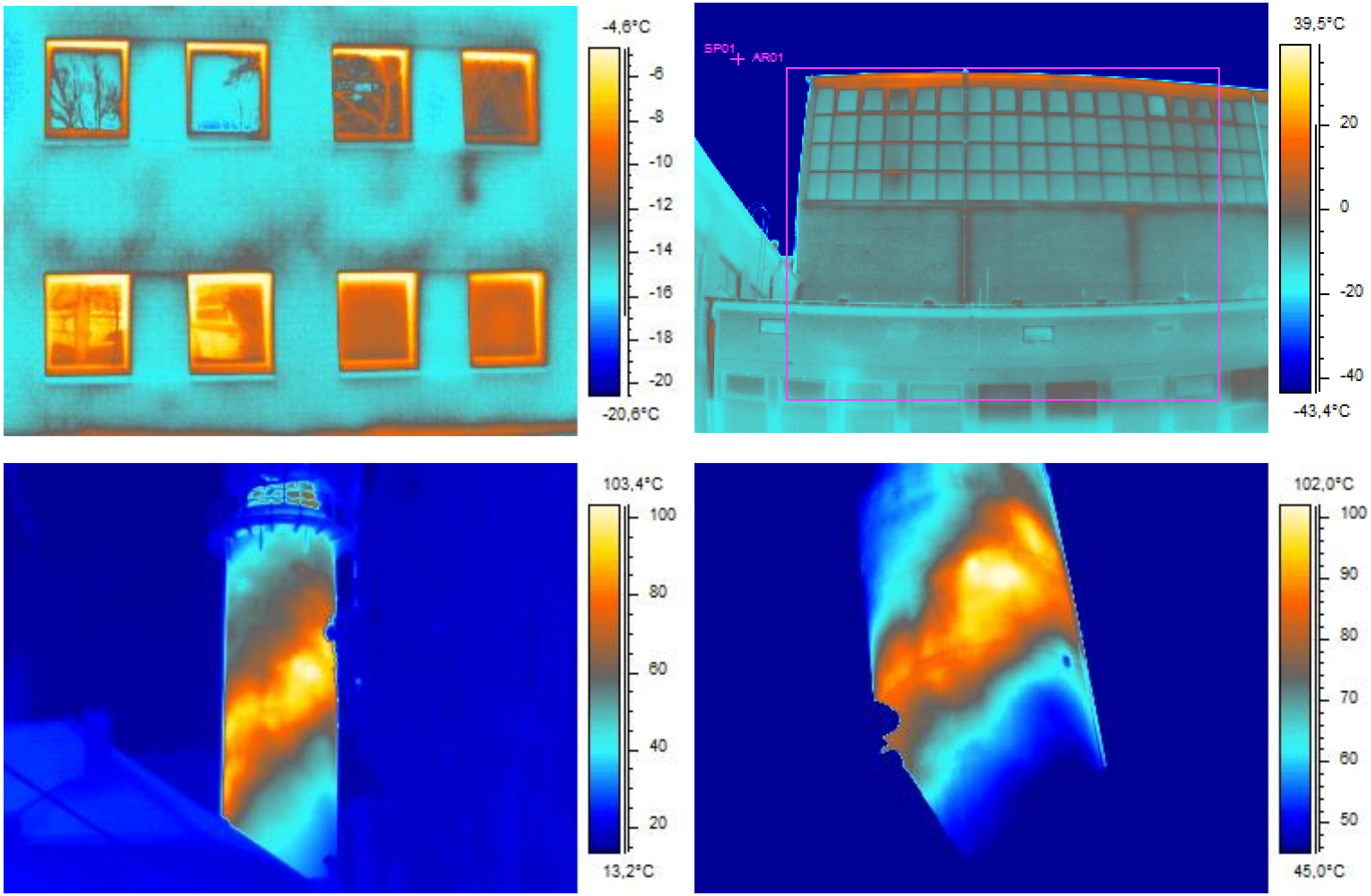
- Microbolometer, 1024 x 738 IR-Pixel, uncooled
- calibrated -40°C – 120°C, 0°C - 500°C, 500°C – 2000°C
- thermal resolution at 30°C: 0,03 K
- transportabel
- maximum full frame rate 60 (120) fps
- Several different object lenses (wide angle, tele, makro)

Mainly used for passive thermography
Transportable

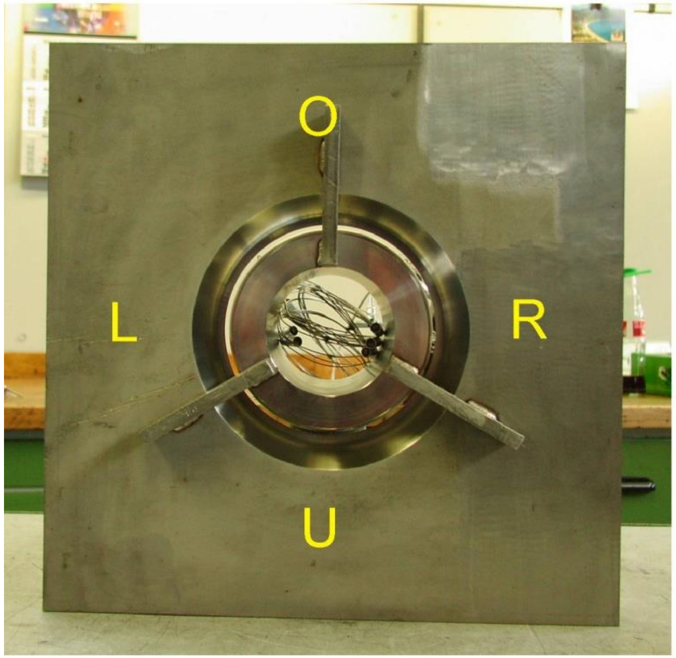
Systems and laboratory at ZEA-1

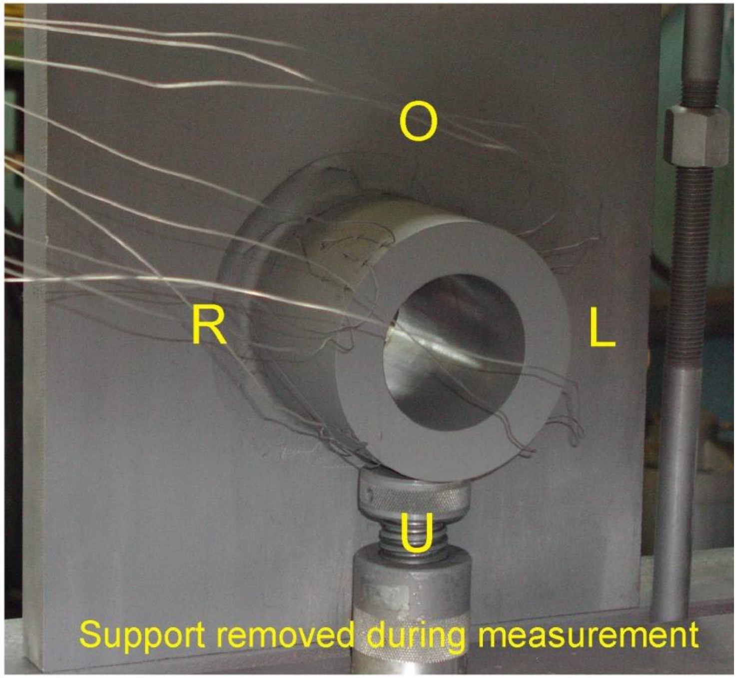
- Lock-In thermography, transient thermography, pulse thermography, flow thermography
- excitationssources like flash lamps, quartz radiator, eddy current generator, power supplies.
- TSA (Thermografic Stress Analysis
- Infrared calibrators
  - 25°C - 500°C, ε(lw) = 0,93 ; ε(sw) = 0,78
  - 500°C - 1500°C, 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



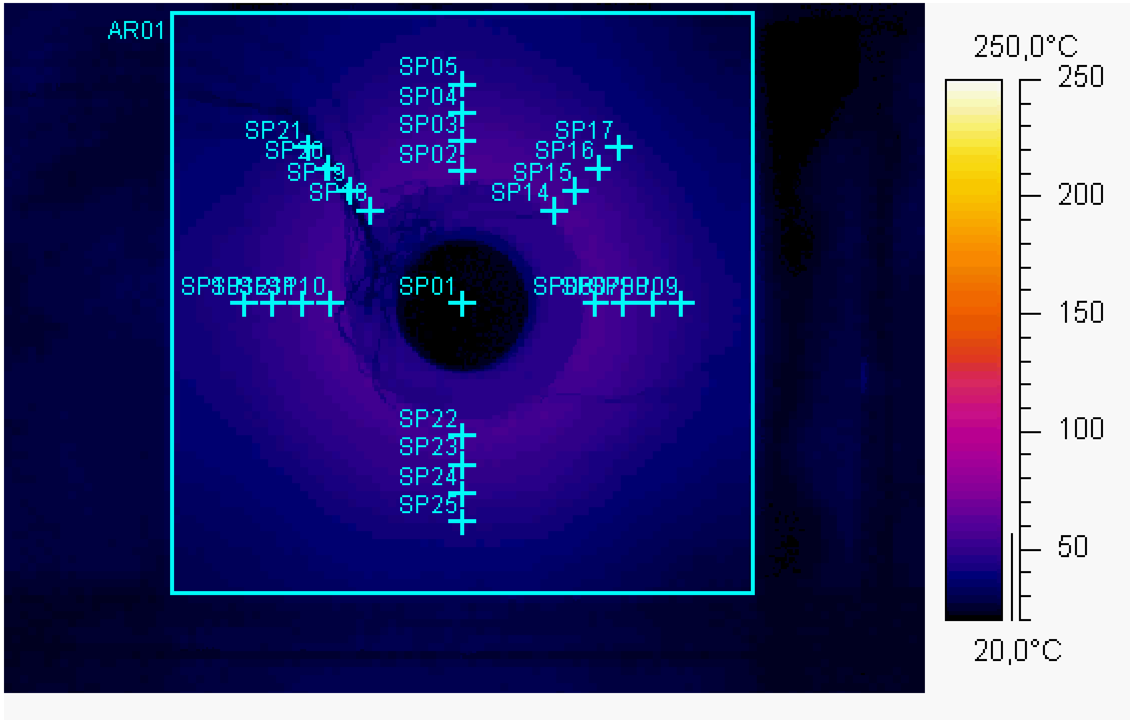
Examples for passive thermography: heat distribution during and after arc welding





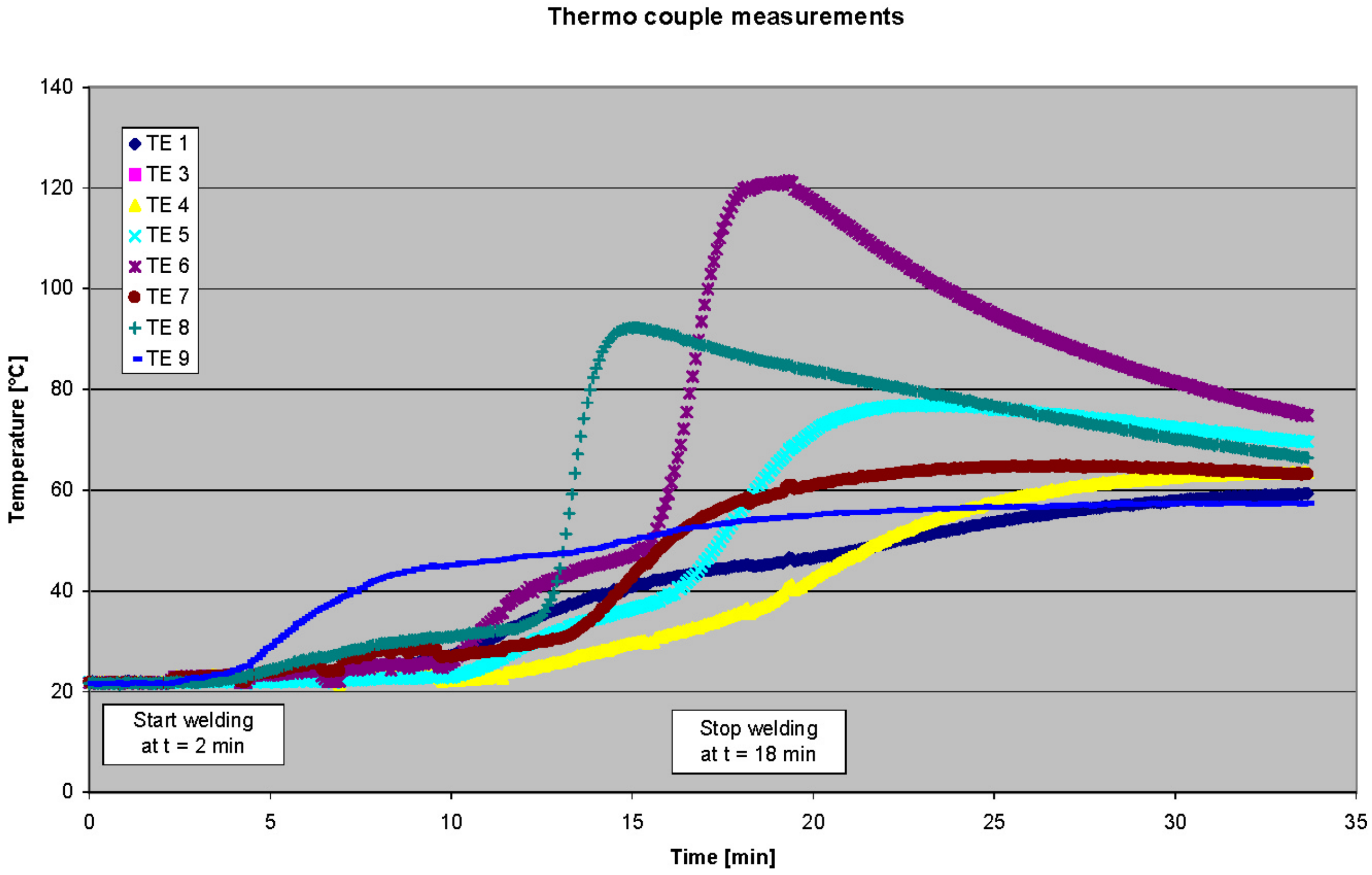
Part of coil separators of the fusion reactor W7-X

Examples for passive thermography: heat distribution during and after arc welding

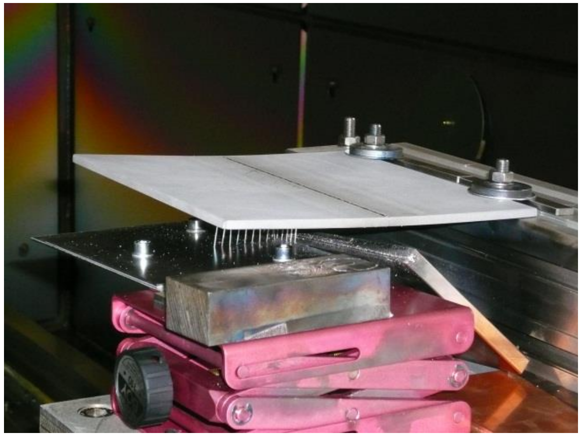


time lapse movie

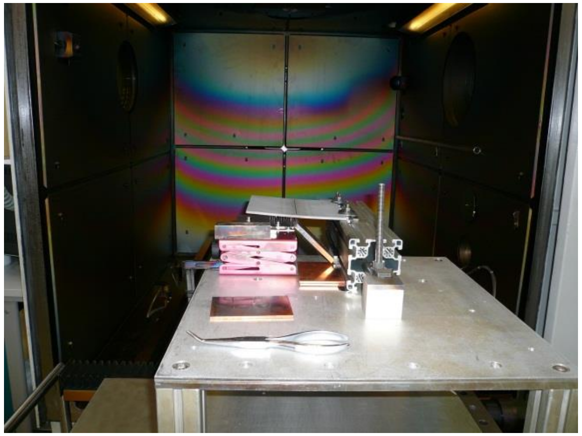
Examples for passive thermography: heat distribution during and after arc welding



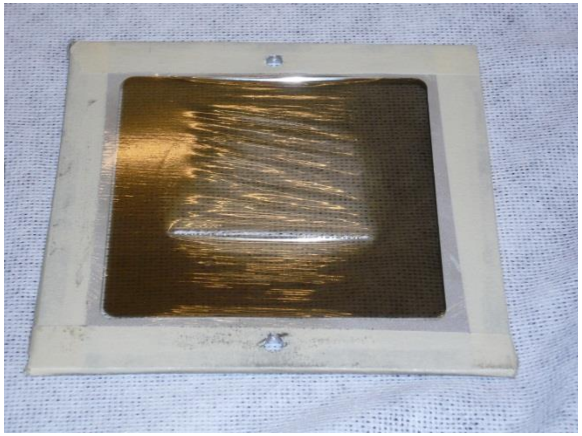
Examples for passive thermography: heat distribution during electron beam welding



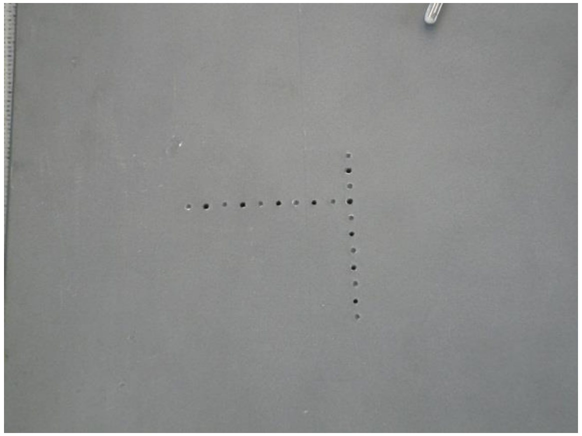
sample: stainless steel



sample mounted in the EB-vacuum chamber

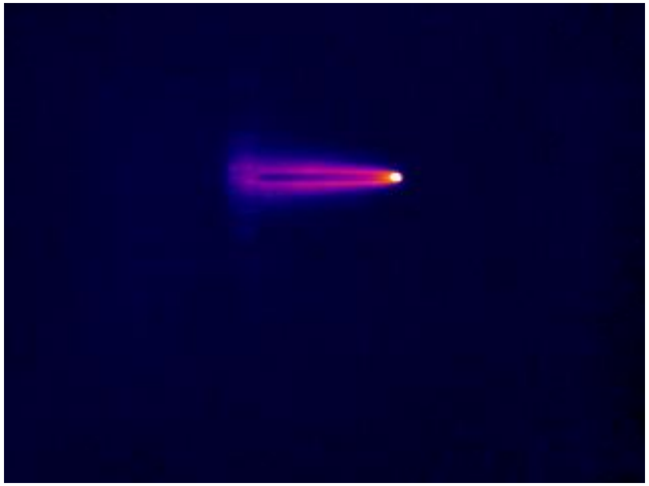


protective sheet for IR-window

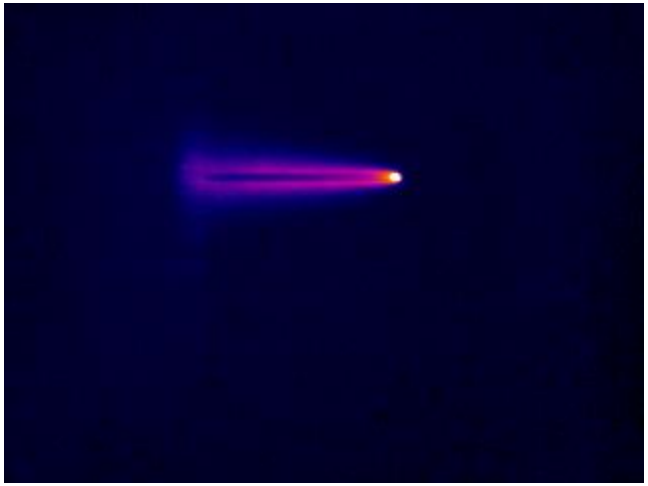


bottom side: holes for thermo couples

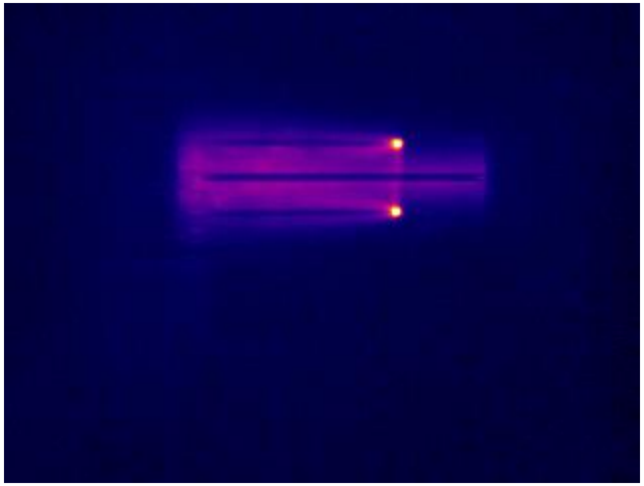
Examples for passive thermography: heat distribution during electron beam welding



After half of welding



2/3 of welding



2/3 post heat weld treatment

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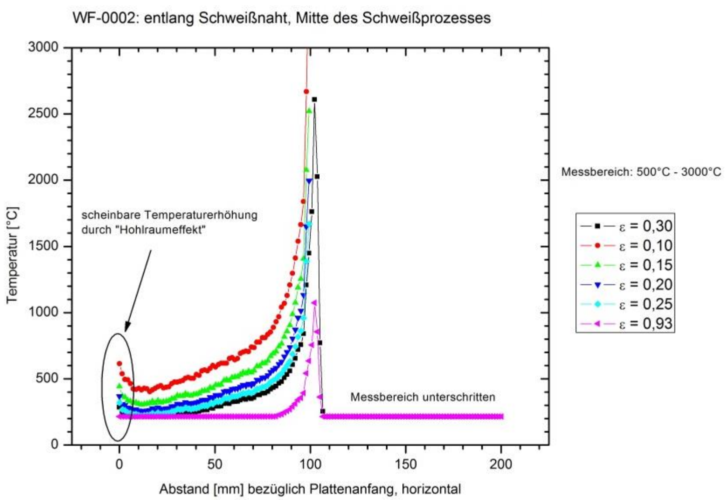
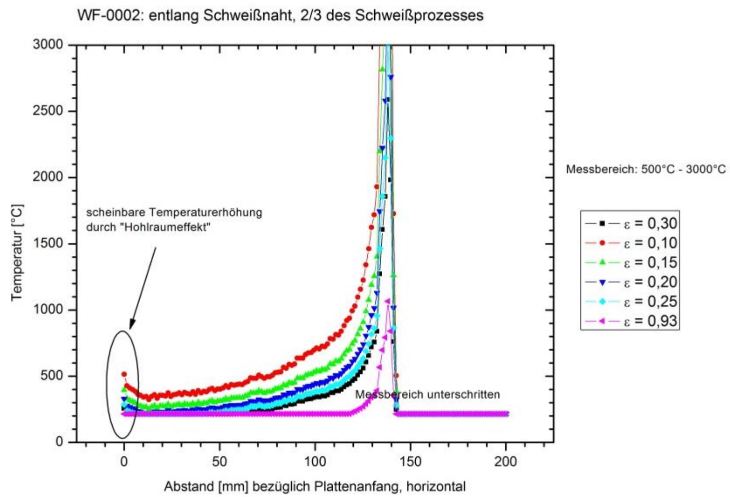
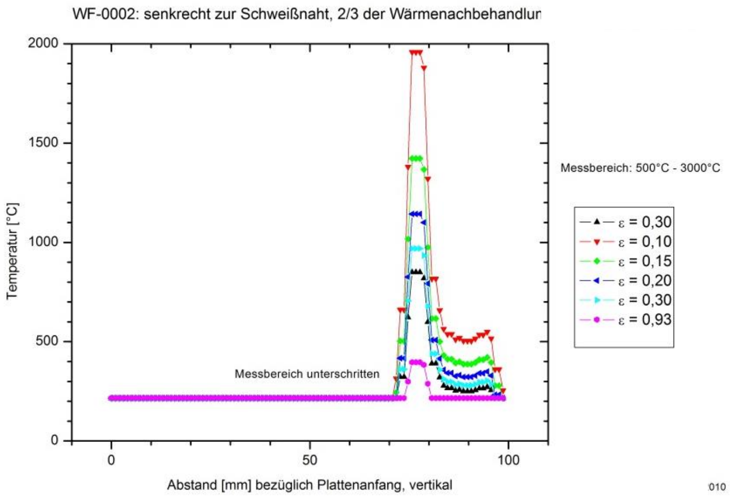
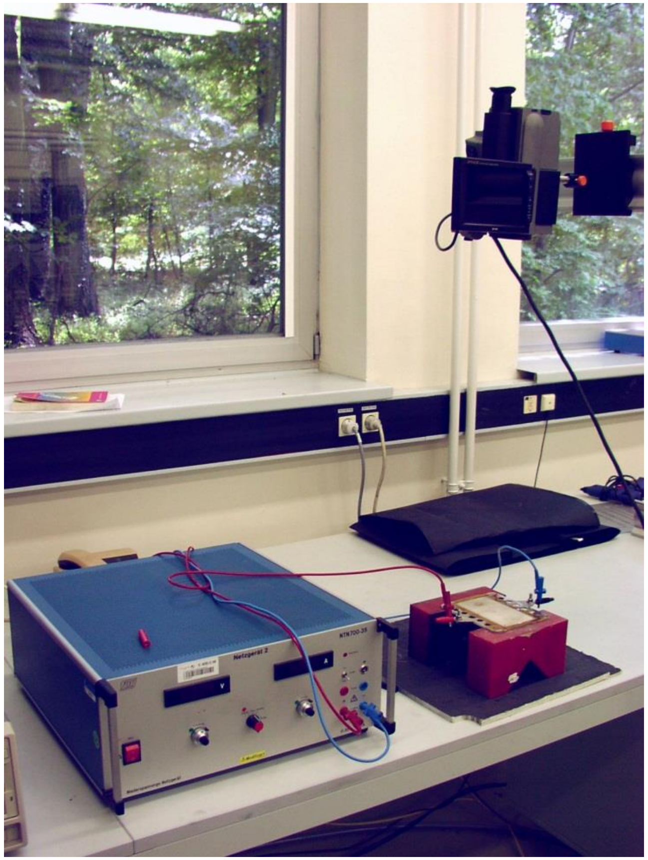
Examples for passive thermography: heat distribution during electron beam welding

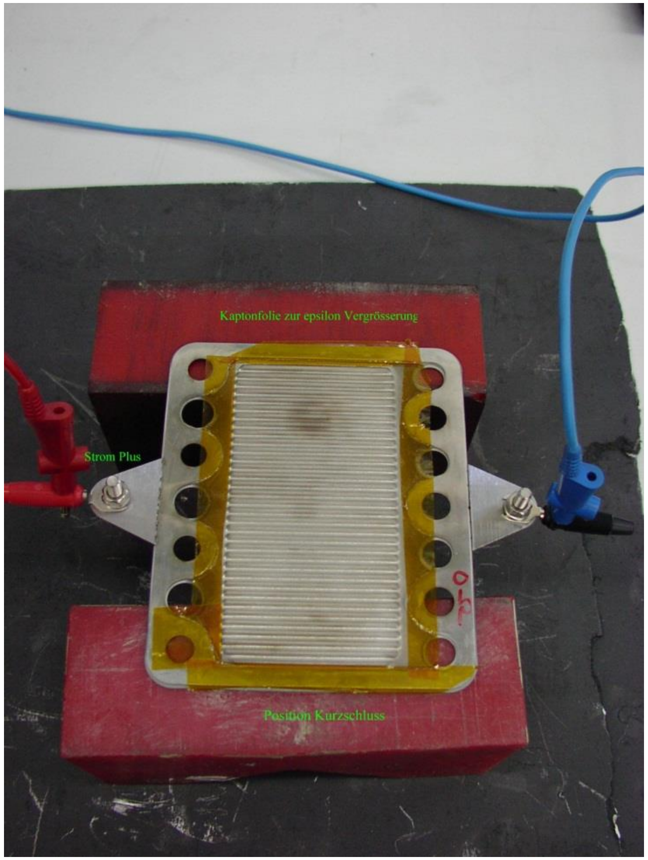




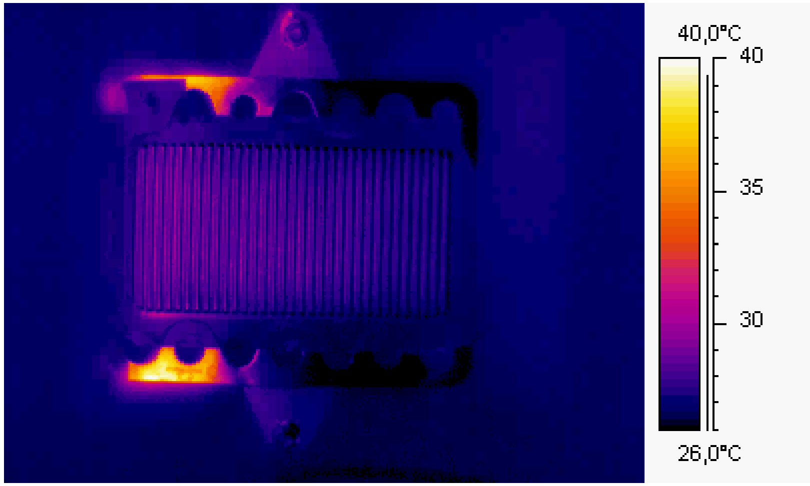


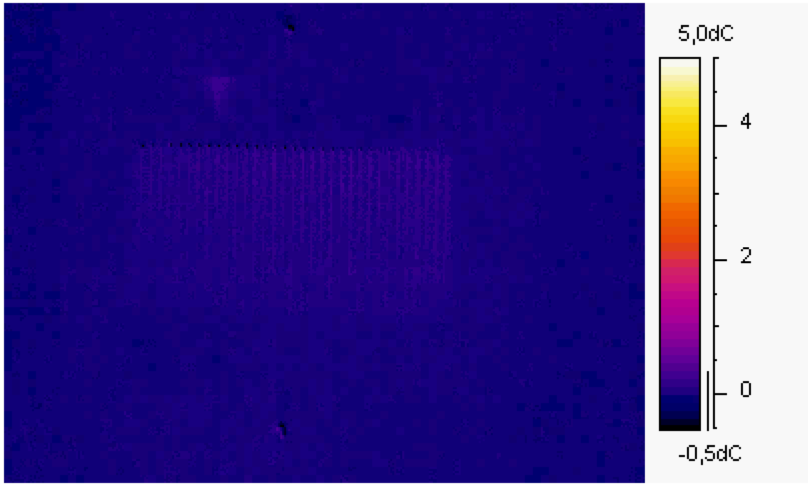
Examples for active thermography: short circuit in fuel cells



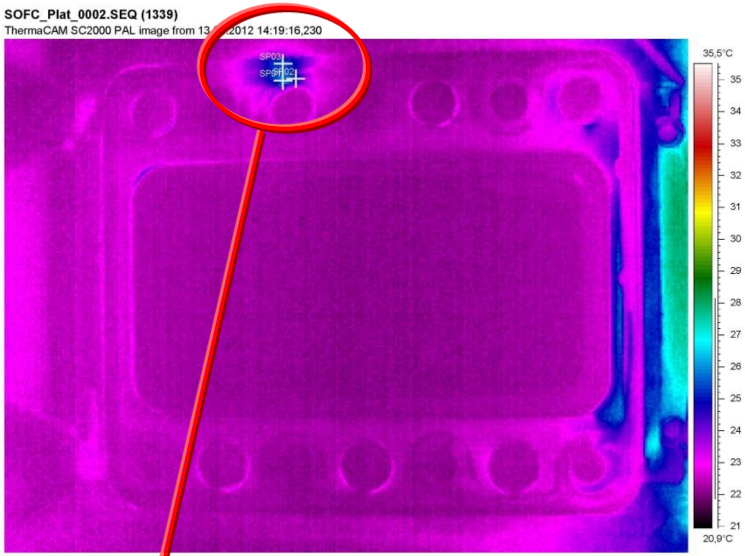


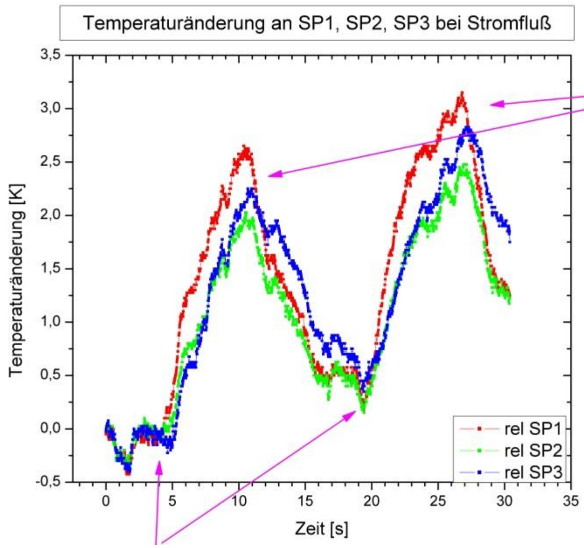
Examples for active thermography: short circuit in fuel cells





Examples for active thermography: short circuit in fuel cells



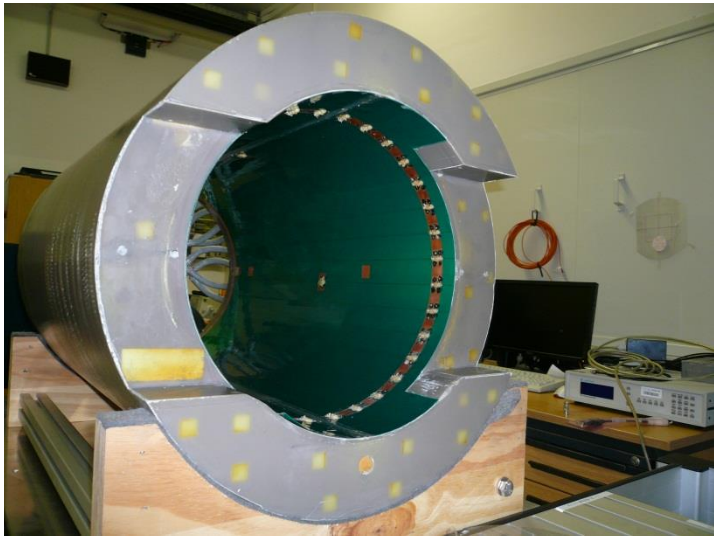


current off

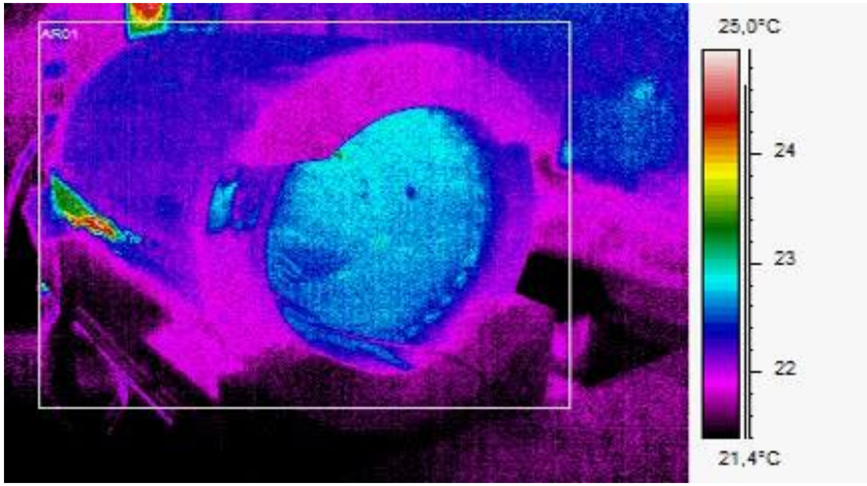
current switched on

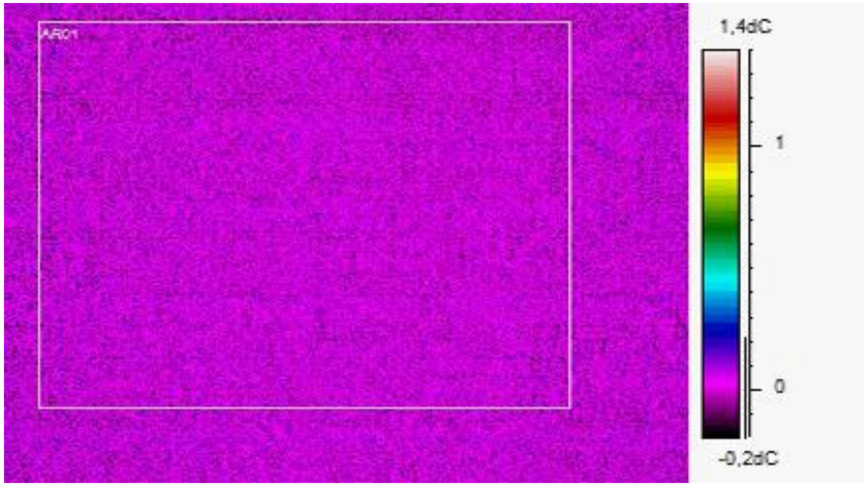
short circuit, visible by the thermal radiation

Examples for active thermography: gradient coils for MRT-spectrometers



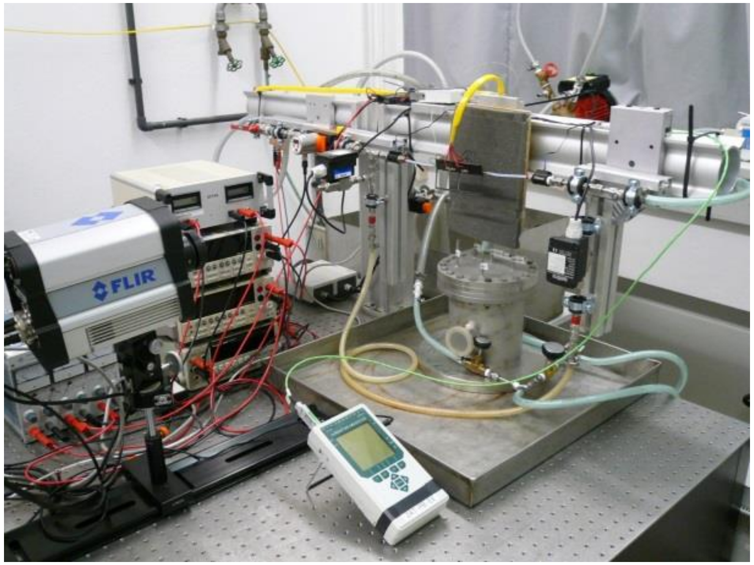
Examples for active thermography: gradient coils for MRT-spectrometers

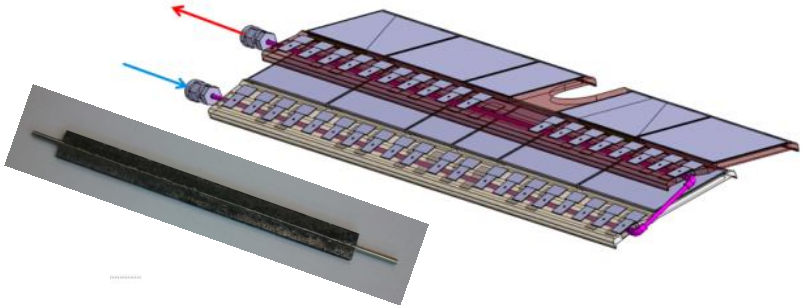


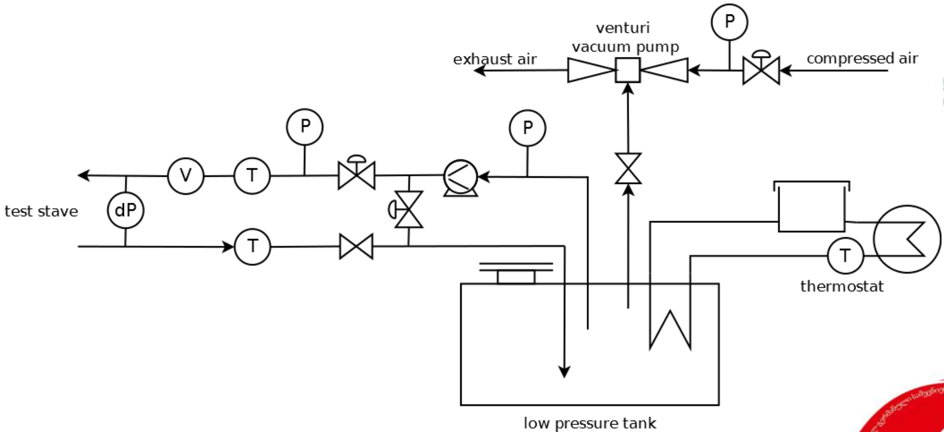


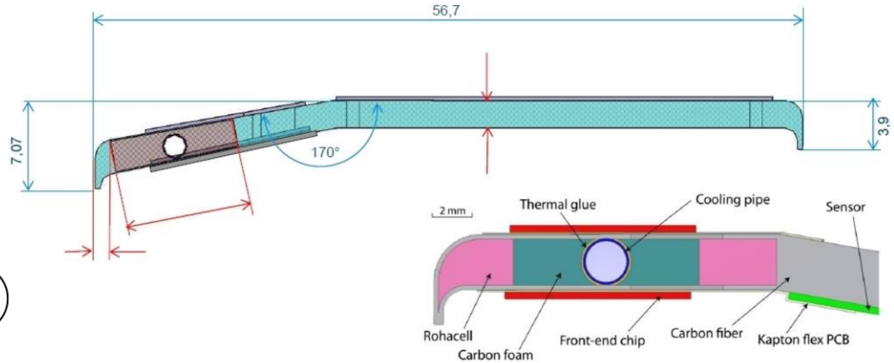
Three different coils G_x, G_y, G_z
used current: I = 60 A, U = 4 V
Movie is in time lapse mode

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









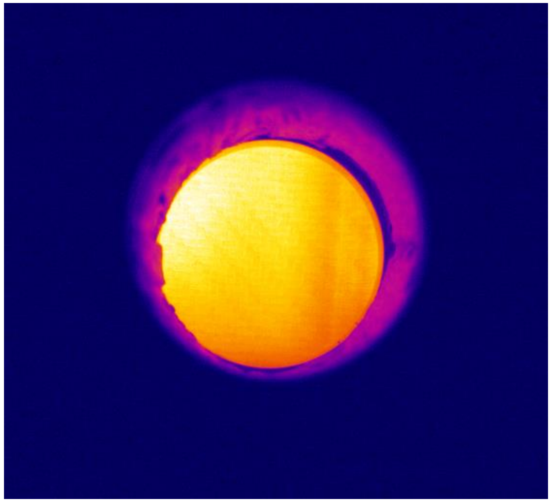
Examples for passive thermography:
Dynamic evaluation of the cooling process

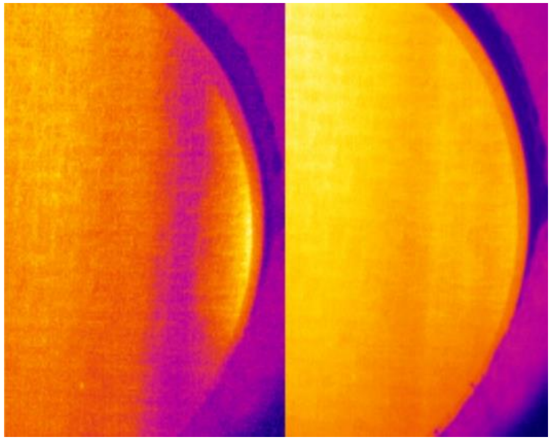
without cooling

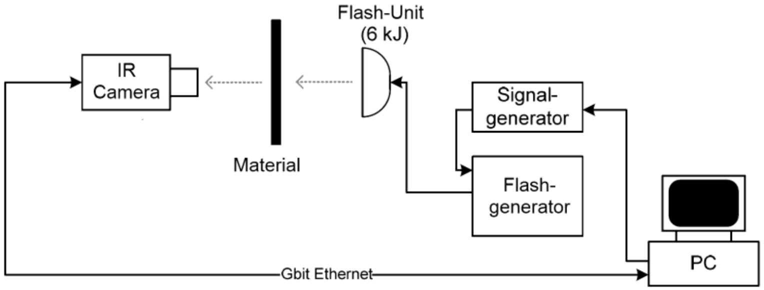
beginning of cooling

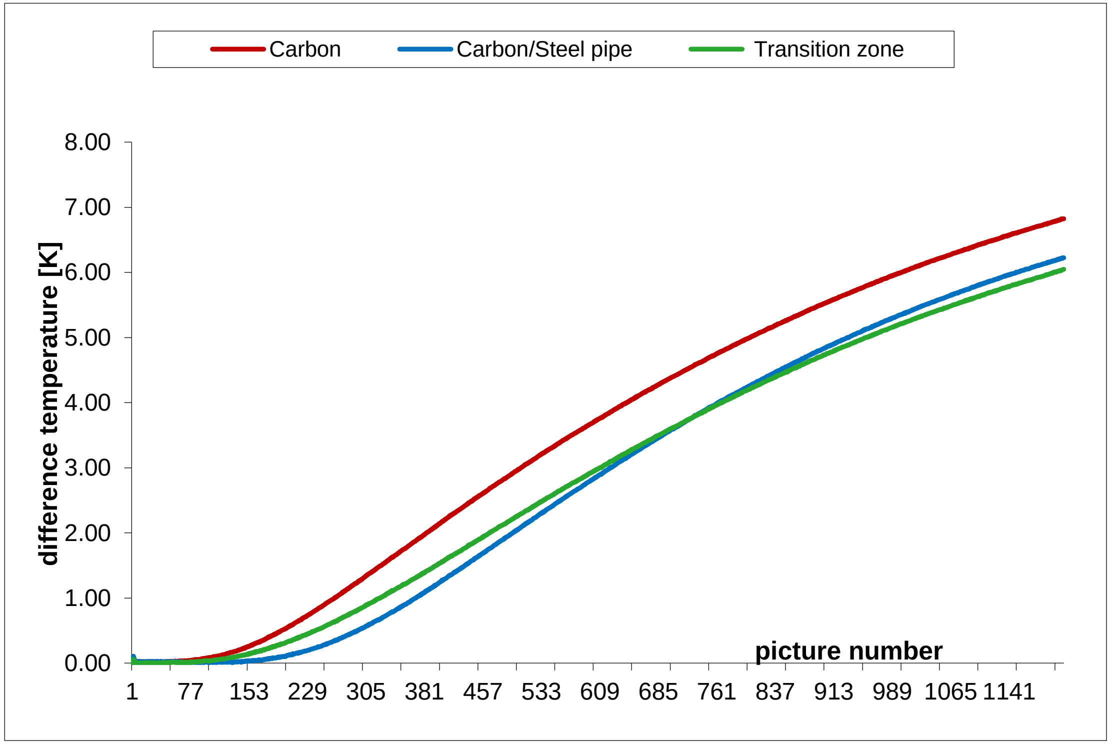
with cooling

Analyzing the thermal behavior of a complex structure



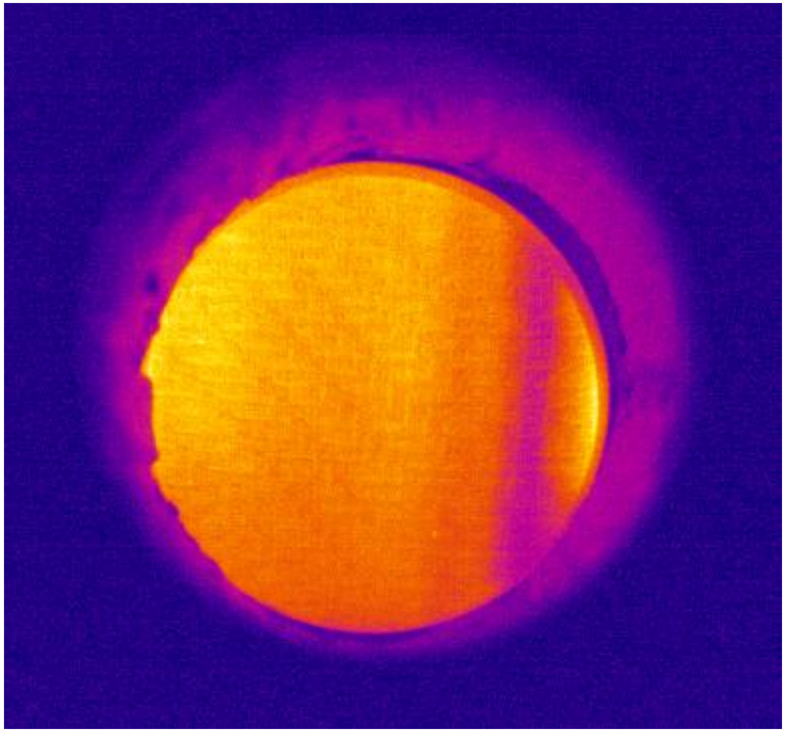






Analyzing the thermal behavior of a complex structure

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