Diagnostics of hot anode surface by optical methods

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Leibniz Institute for Plasma Science and Technology
Greifswald, Germany

MeVArc 2019
Padova

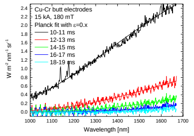
INP FROM IDEA TO PROTOTYPE

Outline

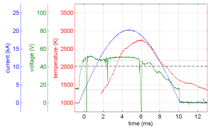
- Introduction

- Motivation

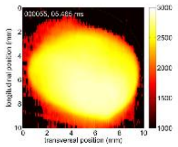
- Optical methods for temperature determination
- Application examples:



  - Measurements in the post-arc phase



  - Measurements during the active phase
  - Surface with impurities



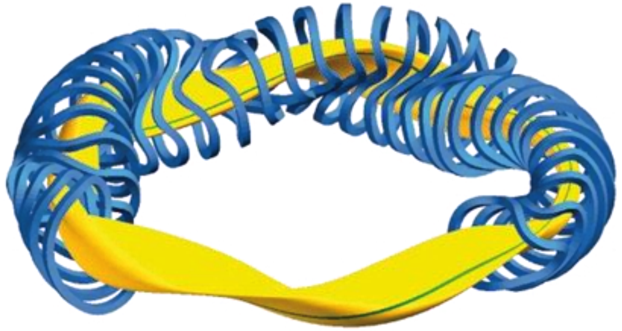
- Summary and outlook

Introduction

- 972 km from Padua
- 235 km from Berlin, 265 km from Hamburg

Introduction

Greifswald - Center of Plasma Science



Leibniz Institute for Plasma Science and Technology (INP)

Max Planck Institute for Plasma Physics (IPP)
Nuclear fusion reactor Wendelstein 7-X

Institute of Physics (IfP) of Greifswald University

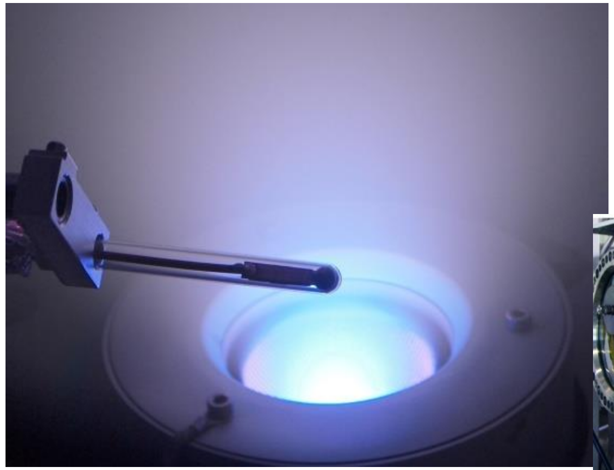
Introduction

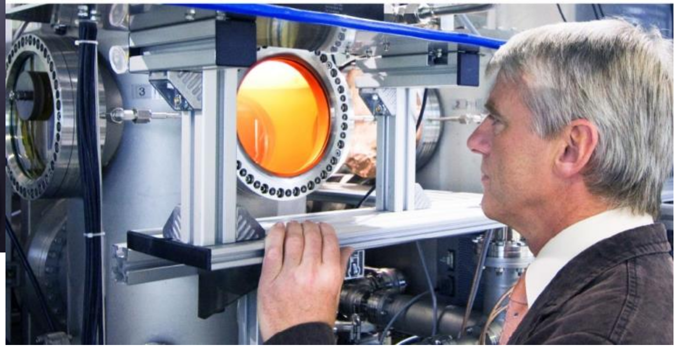
Leibniz Institute for Plasma Science and Technology (INP)

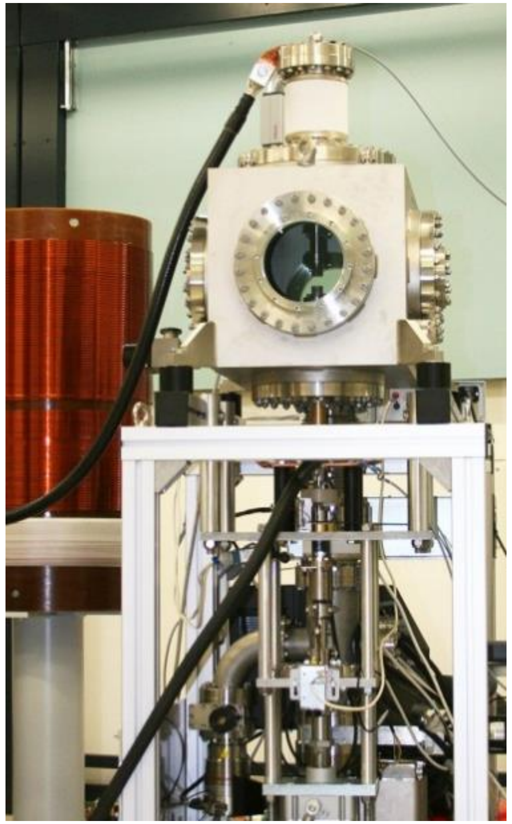
- 49 laboratories
- 200 employers
- annual budget 20 M€

Application-driven research

- surface modification and chemistry
- process diagnostics and monitoring
- biomaterials and surfaces
- plasma medicine, plasma decontamination
- high-voltage techniques
- switching and welding arcs

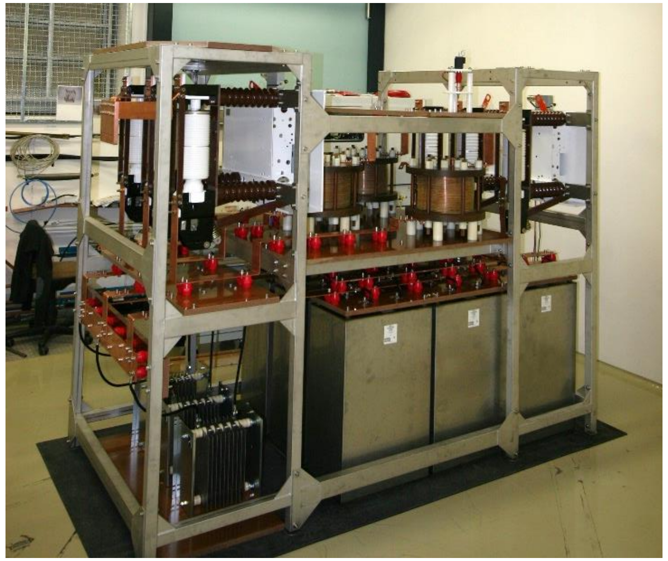






Introduction: switching arc research

since 06.2015	since 07.2019



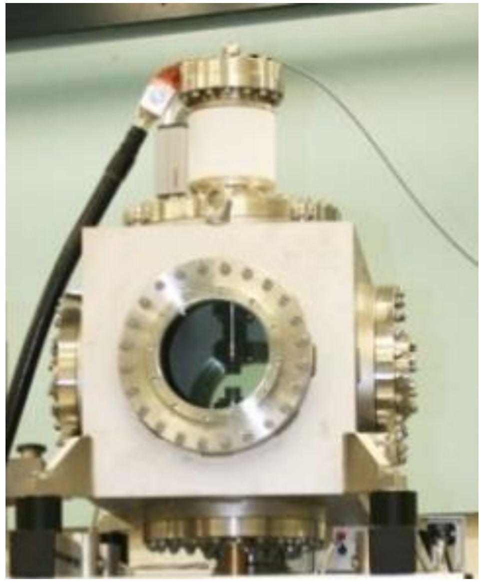
Charging voltage	500 V – 18000 V
Min current	100 A@ 50 Hz
Max current	10 kA @ 50 Hz
Other features	No TRV Flexible frequency 16 Hz – 1000 Hz, pulsed DC operation

Charging voltage	50 V – 3500 V
Min current	1.3 kA@ 50 Hz
Max current	100 kA @ 50 Hz
TRV level	41.5 kV @ 1000 Hz DAC

Introduction: switching arc research

vacuum circuit breaker

- Volume 0.003 – 10 l
- Stroke 0.5 – 25 mm
- Operation velocity 0.1 - 5 m/s



model circuit breaker

- Volume 52 l
- Mountings for various electrodes
- Stroke 0.5 - 25 mm
- Operation velocity 0.5 - 4 m/s

Motivation

- Electrodes in high-power applications
  - current transfer
  - interaction with substrate
  - material source (vacuum arcs, welding, coating)
  - source of problems – damage through erosion → contamination of plasma, gas, walls with electrode material, strong surface deformation → operation failure

- Processes to be understand, behavior to be characterized
  - heating and cooling dynamics
  - behavior of melted surface
  - erosion behavior → vapor and droplets
  - interaction with plasma

- Monitoring of electrode temperature is crucial for phenomena understanding and device optimization

Motivation

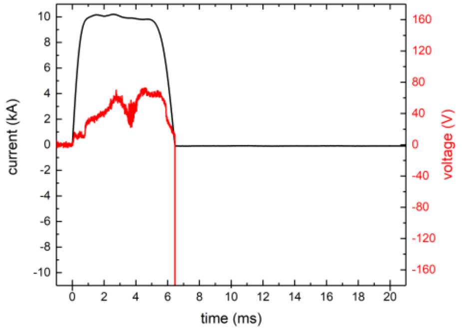
Vacuum circuit breakers

- environmentally friendly operation

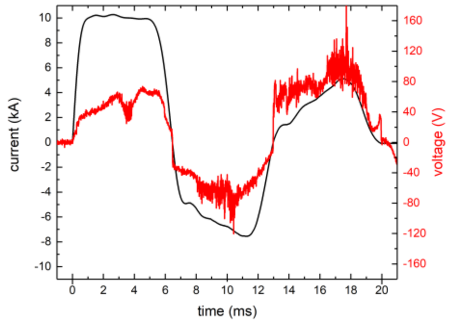
High-current operation

- (strong) electrode melting and evaporation
- atomic vapour as possible source for restrikes
- hot anode – major source of atomic vapour

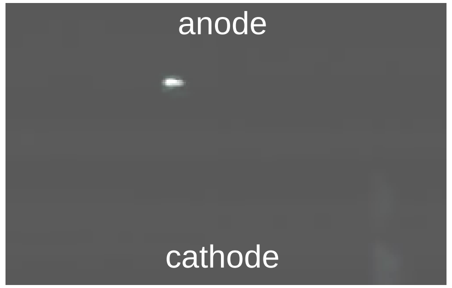
Focus on the anode surface temperature measurements



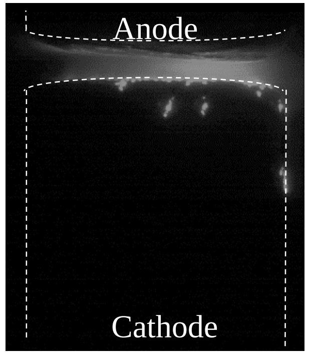
success



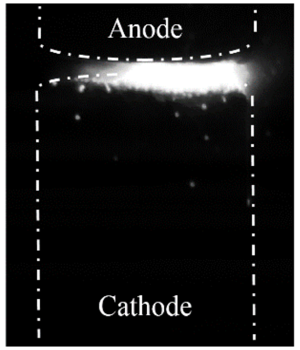
failure



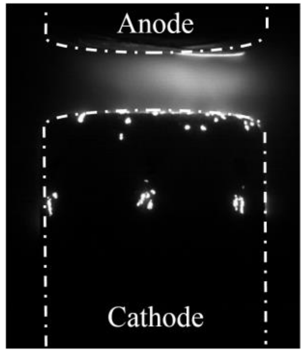
diffuse



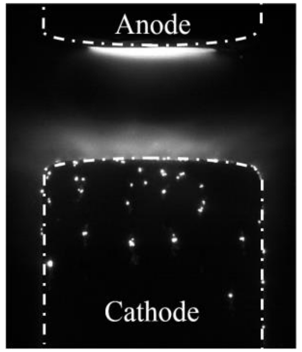
intense mode



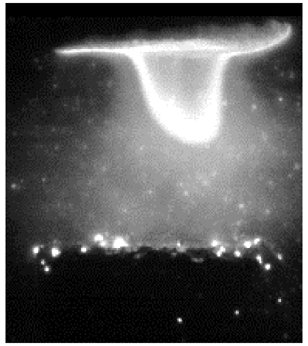
footpoint



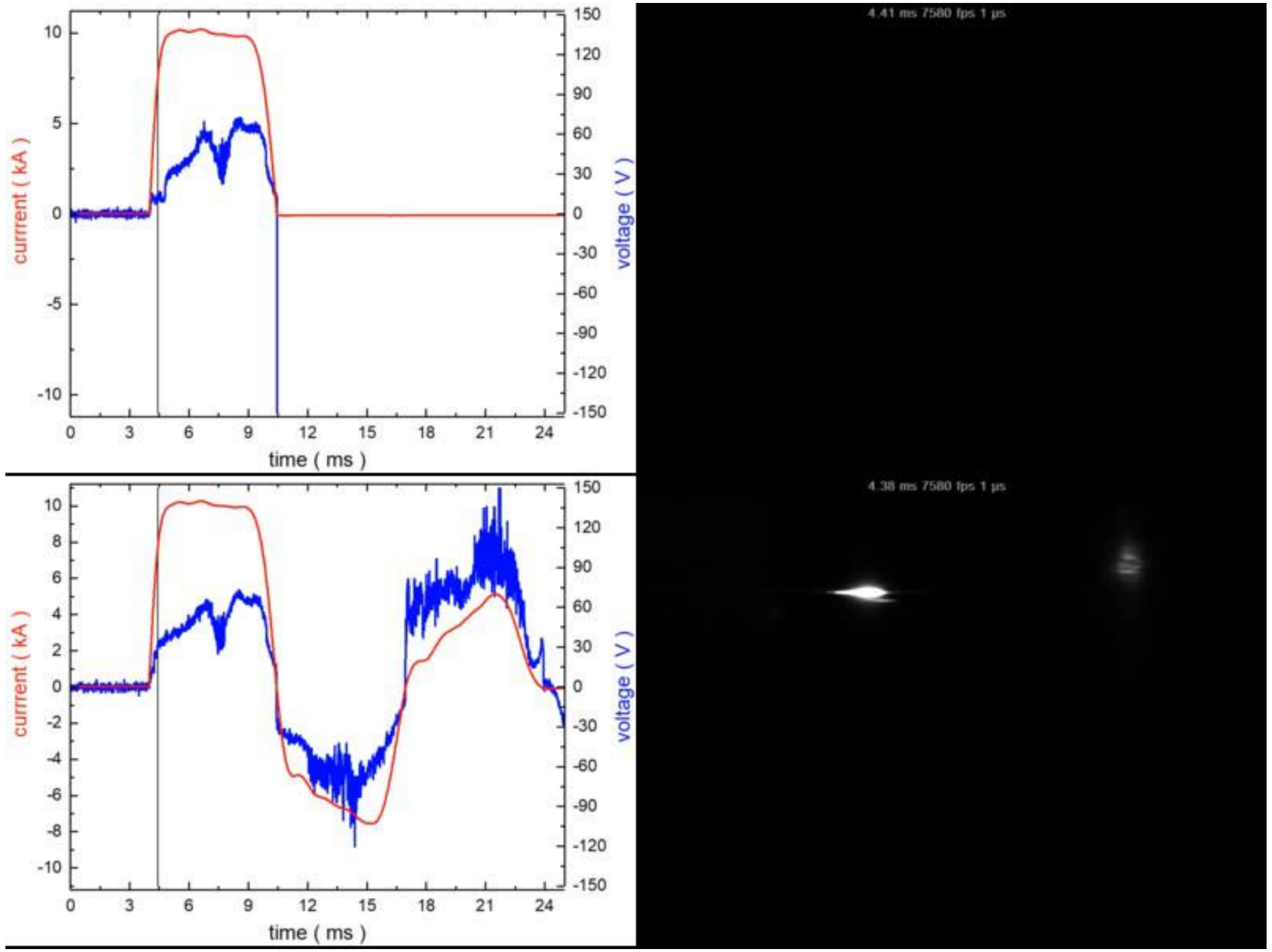
anode spot

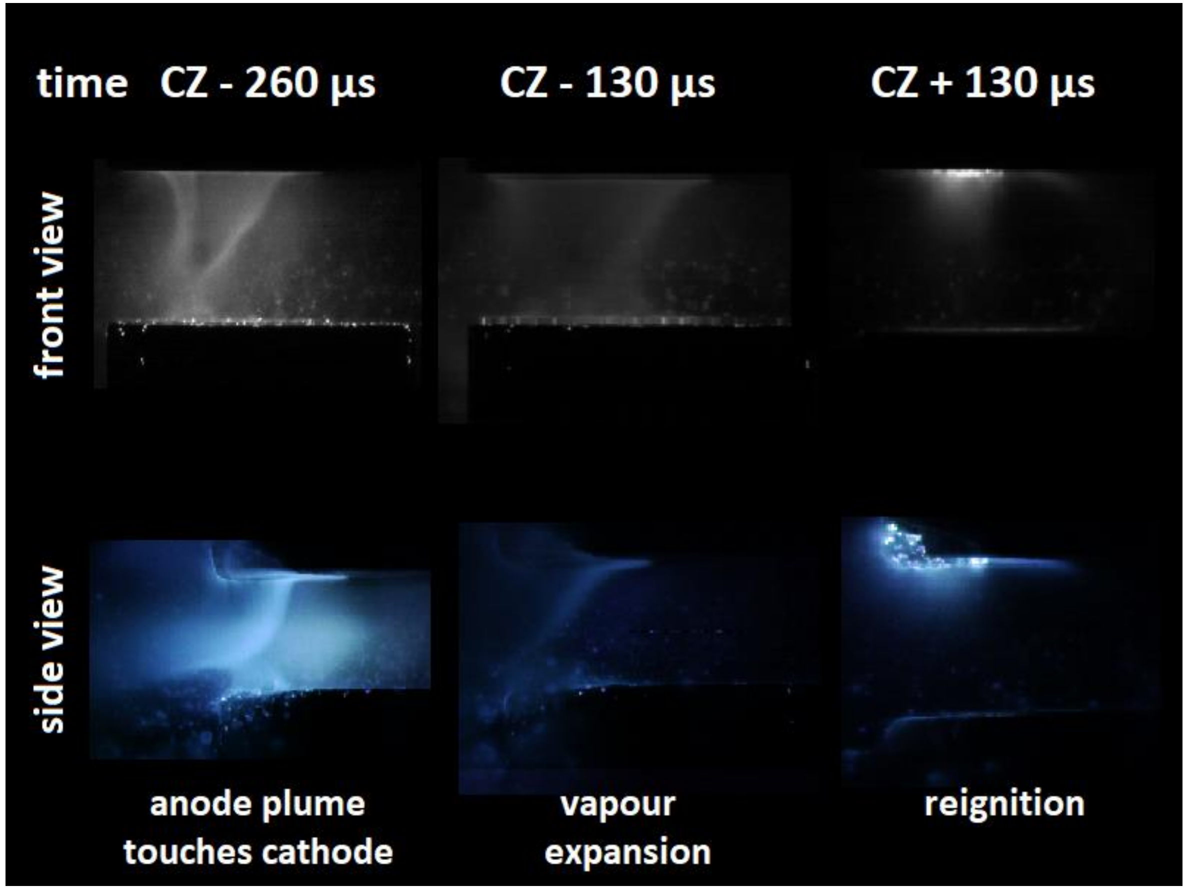


anode plume



Motivation


4.41 ms 7580 fps 1 µs
4.38 ms 7580 fps 1 µs
current (kA)
voltage (V)
time (ms)


time
CZ - 260 µs
CZ - 130 µs
CZ + 130 µs
front view
side view
anode plume touches cathode
vapour expansion
reignition

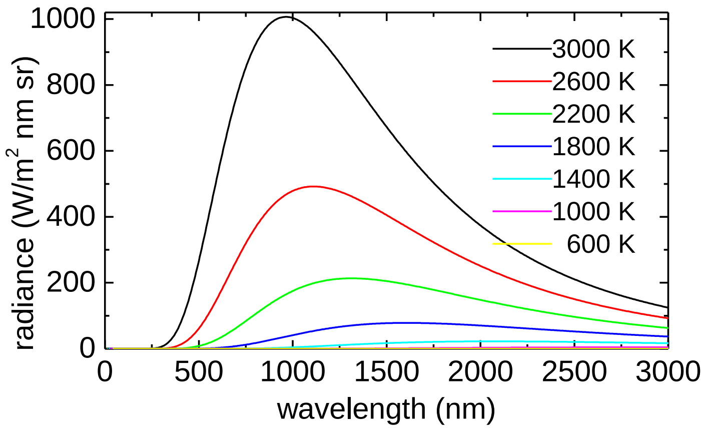
Optical diagnostics: advantages and disadvantages

- “Classical” method (thermocouple) fails
  - probes will be damaged when placed within the region of interest
  - signal distortion due to EM fields
  - high spatial (and temporal) resolution required
- Clear advantages of optical methods
  - non-invasive
  - qualitative and quantitative measurements possible
  - high spatial resolution – local properties
  - high temporal resolution – dynamics
  - applicable in a wide parameter range due to variability of methods
- Some disadvantages of optical measurements
  - optical access to the object necessary
  - radiation intensity must be sufficient
  - distortions in the optical pathway through hot fluxes and plasma itself
  - costs of the devices, complex apparatus and evaluation methods

Optical diagnostics: basics of temperature determination

- Black-body radiation acc. to Planck's law

$$B_\lambda(T) = \varepsilon(\lambda, T)\frac{2hc^2}{\lambda^5}\cdot\frac{1}{e^{\frac{hc}{\lambda\cdot kT}}-1}$$

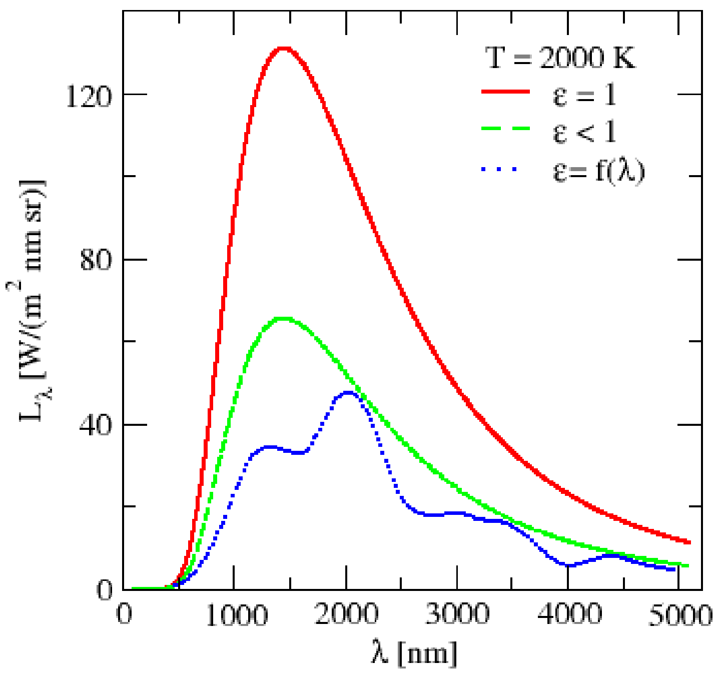


- One measured value, but two unknowns – standard solution ways
    - known emissivity from other measurements or theory
    - measurements at two different wavelengths

Optical diagnostics: basics of temperature determination

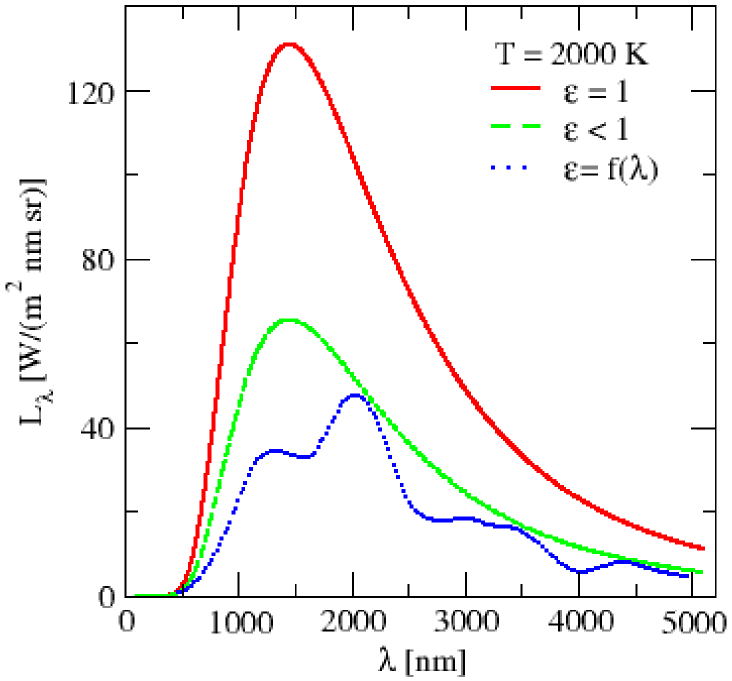
$$B_\lambda(T) = \varepsilon(\lambda, T)\,\frac{2hc^2}{\lambda^5}\cdot\frac{1}{e^{\frac{hc}{\lambda\cdot kT}} - 1}$$

- Data for emissivity
  - Mostly known for “clean” surfaces
  - measured at idealized conditions
  - however emissivity depends on
    - chemical composition
    - surface roughness
    - surface “state” – solid, liquid, boiling, phase transition…
    - view angle
- Best solution – *ín-situ* measurements simultaneously with temperature measurements



Optical diagnostics: basics of temperature determination

$$B_\lambda(T) = \varepsilon(\lambda, T)\,\frac{2hc^2}{\lambda^5}\cdot\frac{1}{e^{\frac{hc}{\lambda\cdot kT}}-1}$$



- Two-colour pyrometry
  - Assumption $\varepsilon(\lambda, T) = \varepsilon(T)$ and Wien approximation

$$\frac{1}{T} = \frac{k}{hc}\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right) ln\left(\frac{B_1\lambda_1^5}{B_2\lambda_2^5}\right)$$

  - Assumption could be too rough due to
    - complex chemical composition
    - surface roughness
    - surface “state” – solid, liquid, boiling, phase transition…
  - Best solution – small difference between the wavelengths, but (!) significant errors
    $\rightarrow$ careful choice of wavelength range necessary

Optical diagnostics: methods

- Selected methods
  - Pyrometry (commercial)
  - Thermography (commercial)
  - Optical Emission Spectroscopy (OES) (scientific)
  - High-speed camera (HSC) techniques enhanced by filter (scientific)
- Method choice and requirements
  - sensitivity $\rightarrow$ surface should emit radiation (T high enough)
  - possible distortions
    $\rightarrow$ plasma radiation is either absent or can be excluded from consideration
    $\rightarrow$ oxides and surface impurities influences the results
    $\rightarrow$ smooth surfaces/low roughness preferable

Optical diagnostics: pyrometry

Advantages

- Commercially available devices (pyrometer)
- Acquisition time between 10µs and 1s
- Temperature range 200-4000 K
- Simple setup and arrangement
- Determination of the cooling dynamics possible

Disadvantages/ restrictions

- Emissivity of the surface must be known (exception two-colour pyrometer)
- Special optics (windows) depending on the temperature and spectral range necessary
- Time resolved measurements with rough spatial resolution (min spot size 0.5 - 1mm)

Kleiber Pyroskop

Optical diagnostics: thermography

Advantages

- Commercially available devices
- 2D temperature distribution at one shot
- Temperature range 200-5000 K
- Simple setup and arrangement
- Determination of the cooling dynamics possible

Disadvantages/ restrictions

- Emissivity of the surface must be known (exception – two color cameras)
- Special optics (windows) depending on the temperature and spectral range necessary
- Time resolved measurements with full size typically with 60 -125 Hz, but (!) temporal resolution with reduced number of pixels possible (up to 10 kHz)

IR camera VarioCAM with 60 Hz techniques

IR camera FLIR with 125 Hz techniques

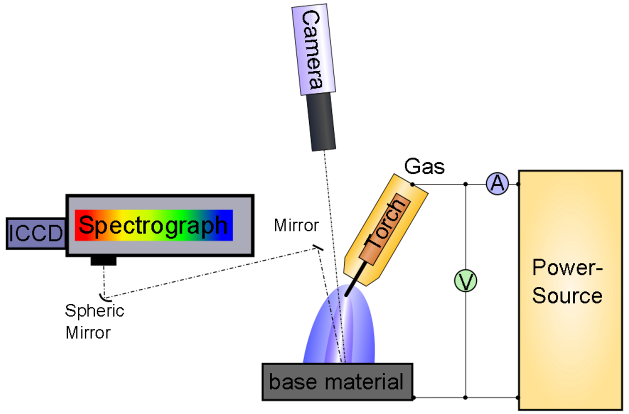
Optical diagnostics: emission spectroscopy

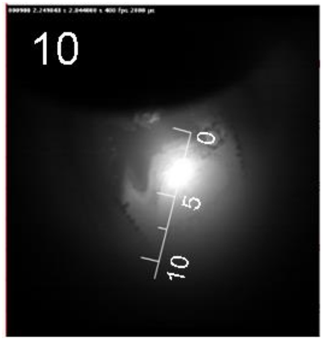
Advantages

- Time resolve measurements possible
- Simultaneous determination of surface emissivity possible
- Flexibility by choice of spectral range
- Characterization of surface impurities possible

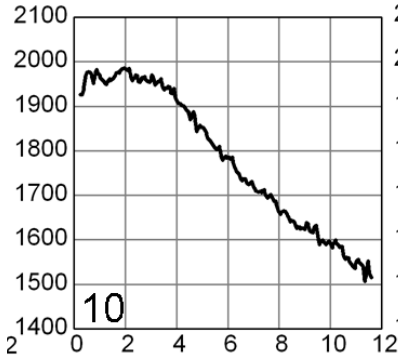
Disadvantages/Restrictions

- Light intensity calibration necessary (tungsten strip lamp)
- Space resolved measurements along the slit
- Additional optical setup necessary





Projection of the entrance slit



Temperature distribution

Optical diagnostics: high-speed camera techniques

Advantages

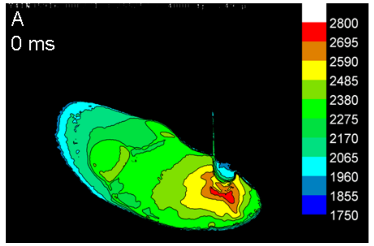
- Time resolved measurements
- 2D picture of the surface
- Manageable effort for setup

Disadvantages/Restrictions

- Special optical filters (MIF, narrow band)/ optical modules necessary
- Light intensity calibration necessary
- Possible impurities of the surface should be taken into account

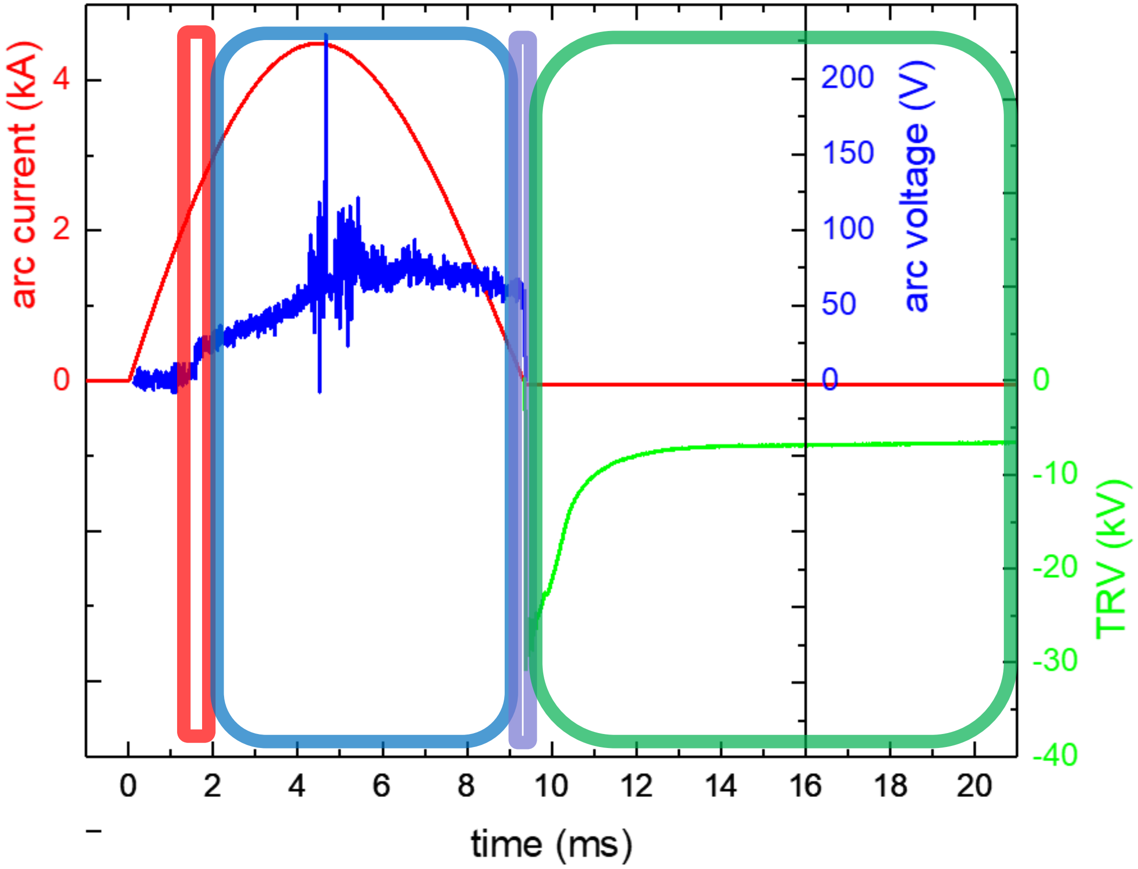
HSC MotionPro Y4

HSC image



Temperature distribution

Optical diagnostics: method applicability

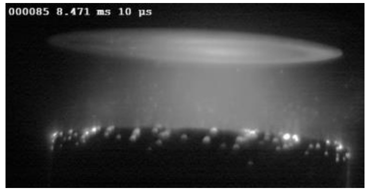


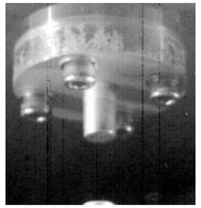
- Ignition phase
- High-current phase (active phase)
- Current zero crossing
- Post-arc phase

T measurement possible

	ignition	High-current	CZ	post-arc
pyrometry	-	(+)	+	-
thermography	-	(+)	+	-
OES	-	(+)	+	+
HSC	-	(+)	+	-

Practical examples





Clean surface with known chemical composition – CuCr contacts for vacuum arcs

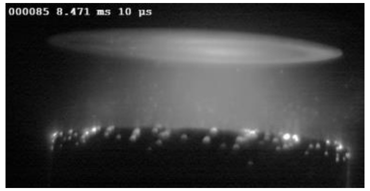
- Measurements in post-arc phase by
  1. NIR spectrometer
- Measurement in the active phase
  2. pyroscopic measurements
  3. 2D temperature profiles by enhanced high-speed camera techniques
  4. use of current cut-off techniques

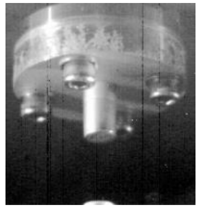
- Surface with impurities
  5. characterization of cold metal transfer welding by OES and HSC

Practical examples

Operation conditions:

- Pulsed current, sinusoidal, 10 ms, 1- 20 kA
- Electrodes diameter 10-60 mm; maximum distance 10 mm
- Rough unpolished surface
- Electrodes are moving from closed position (1 m/s)
- Arc initialization (“breakdown”) from bridge explosion
- Arc plasma separates the electrode from diagnostic setup

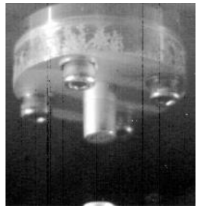




Simplification:

- Anode is fixed, cathode is moving

Measurements in post-arc phase by NIR



NIR 900-1600 nm

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NIR optics

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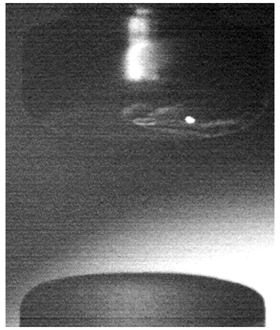
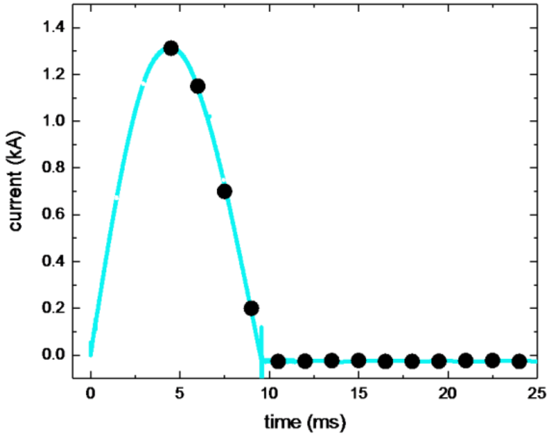
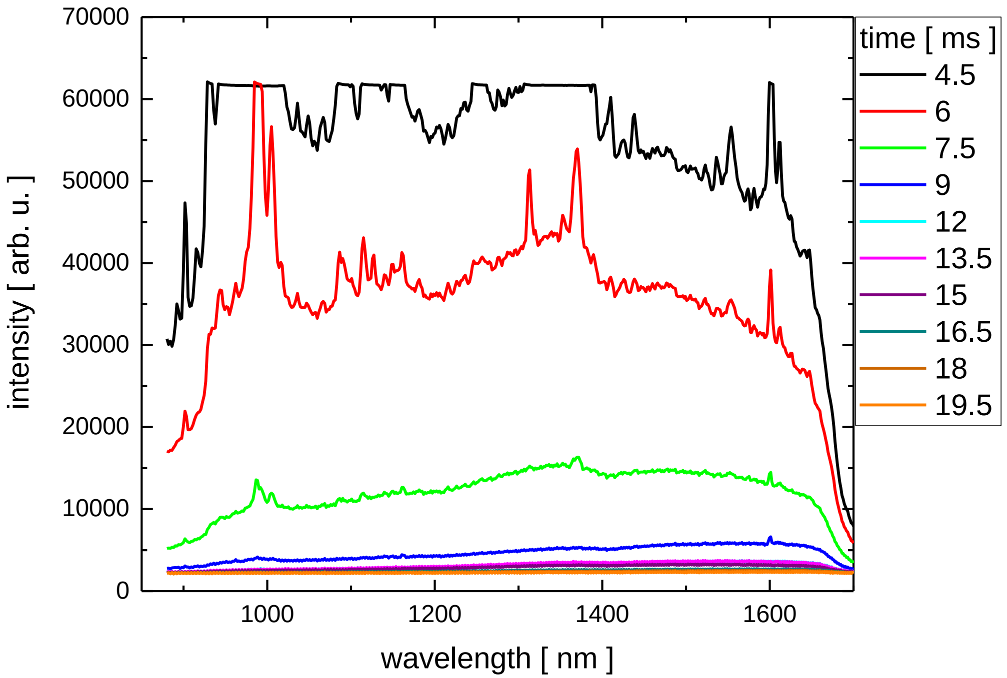
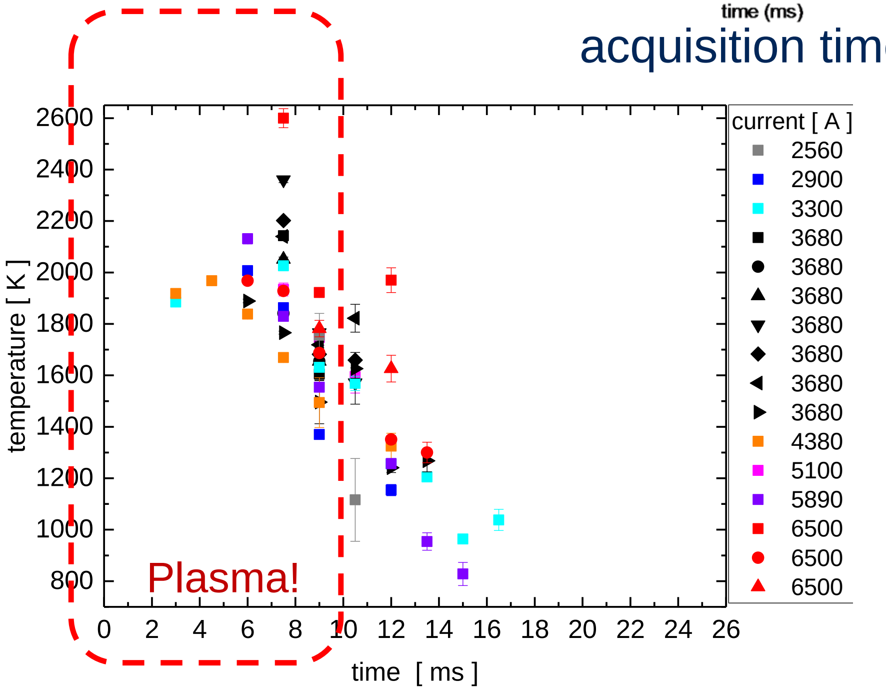




acquisition times

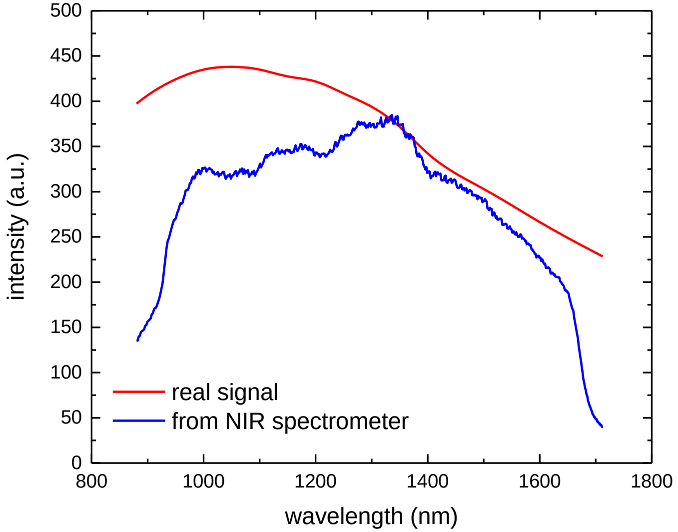




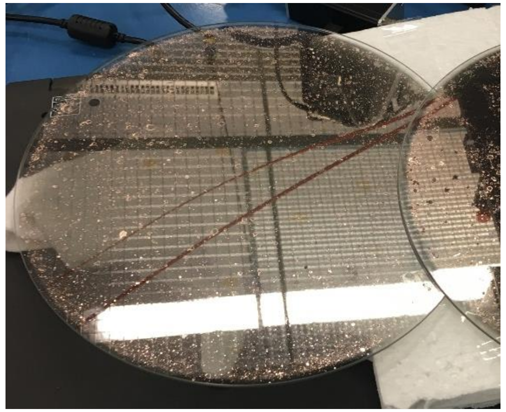
Measurements in post-arc phase by NIR

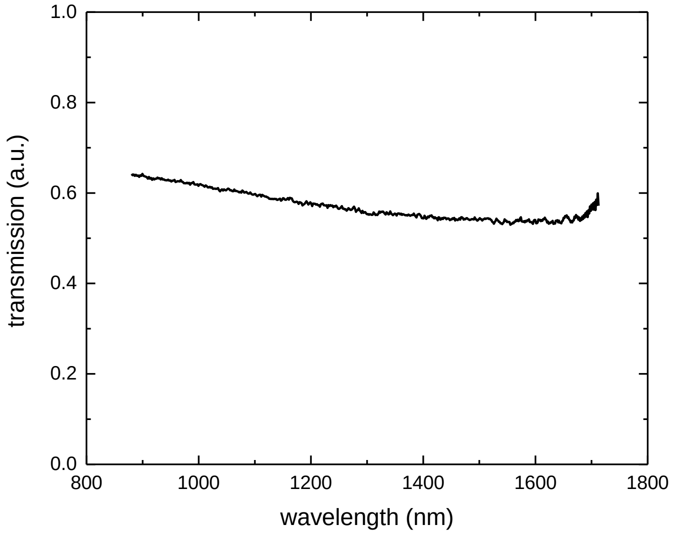
W strip lamp

calibration

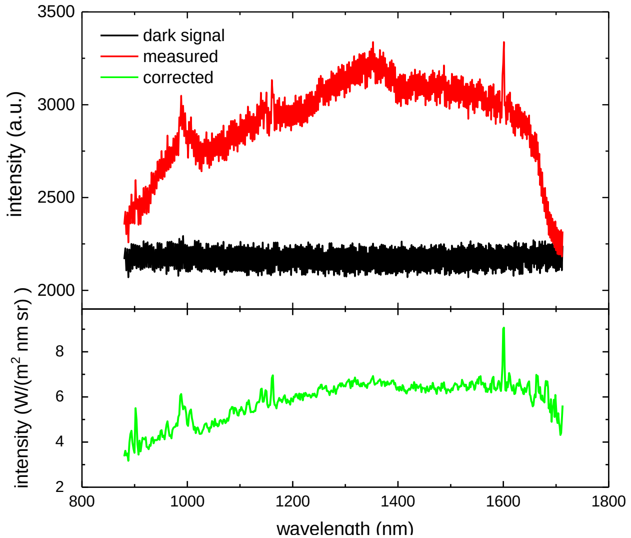


window transmission

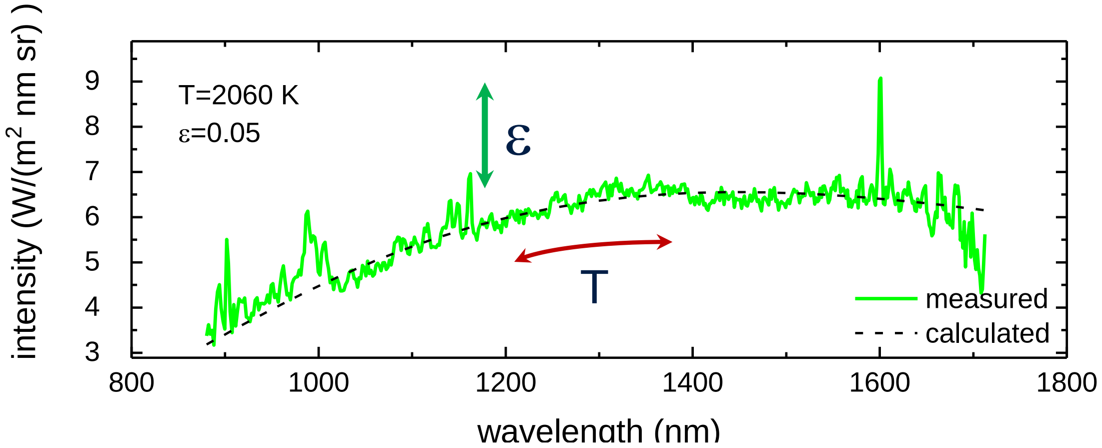




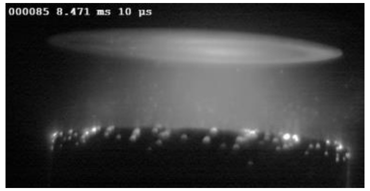
background correction

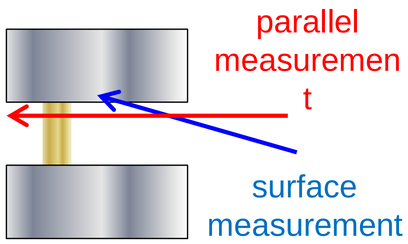


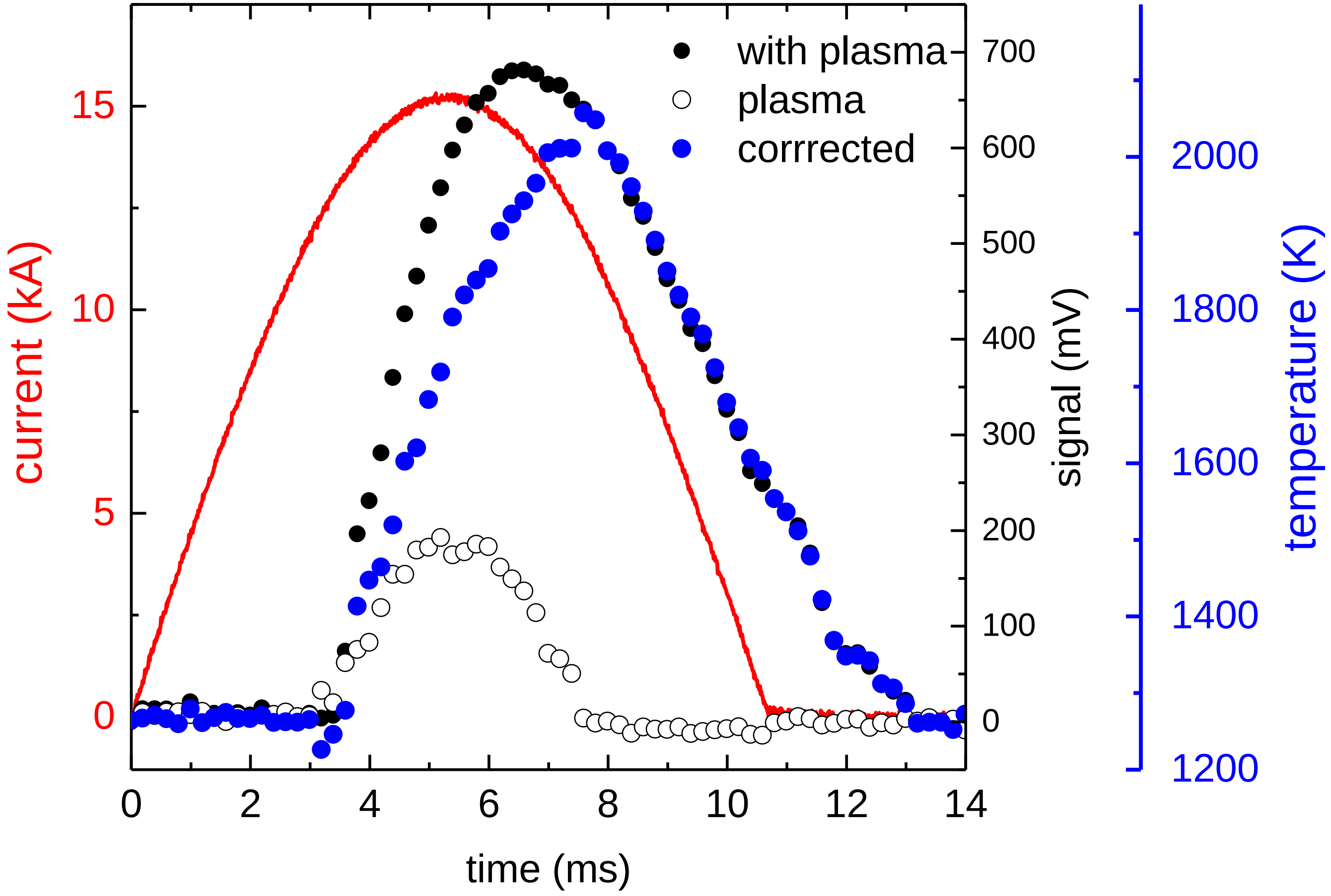
determination of T and ε



Measurements in active phase by pyroscope

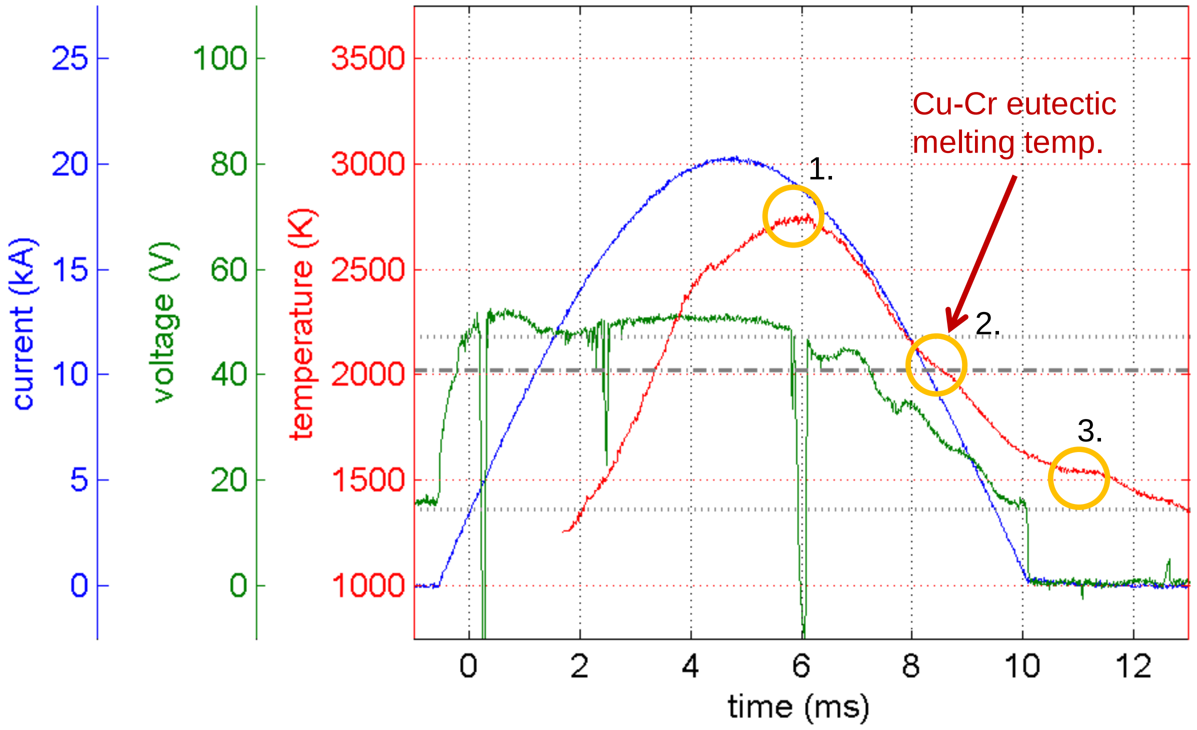






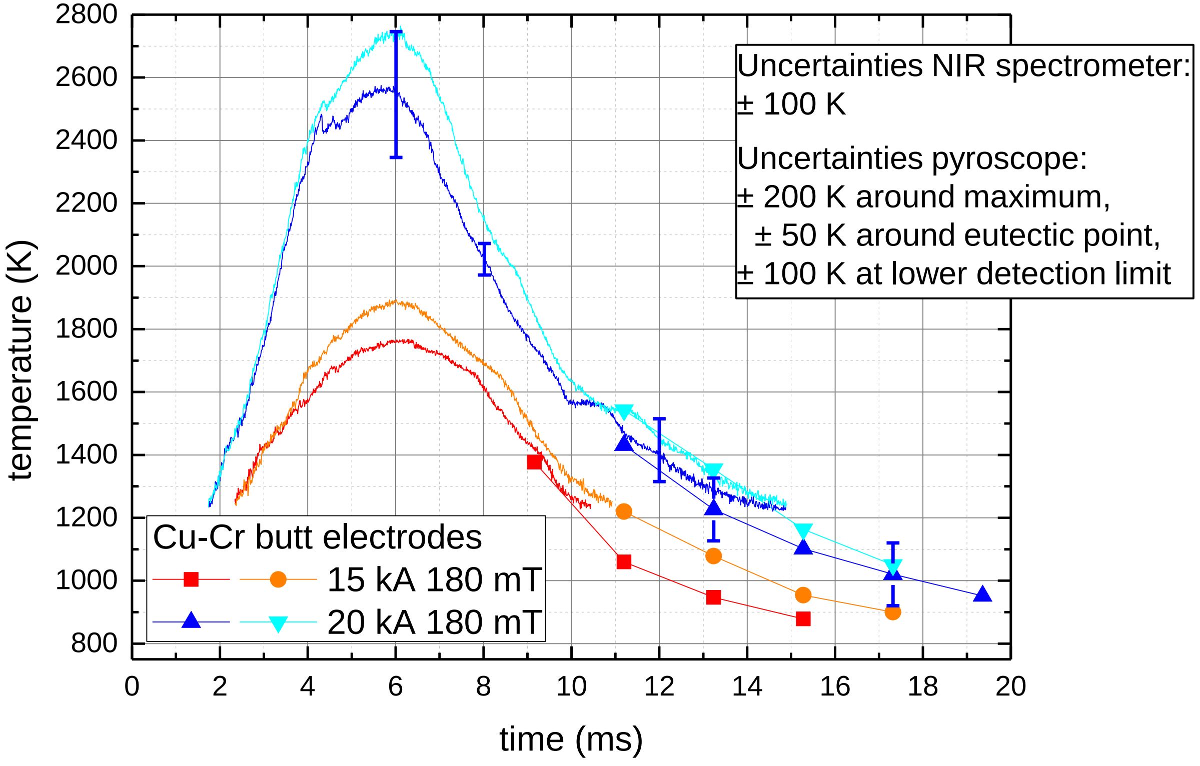
- Measurements parallel to surface for approximation of plasma contribution
- Plasma contribution sufficiently low
- Corrected signal gives reasonable temperature

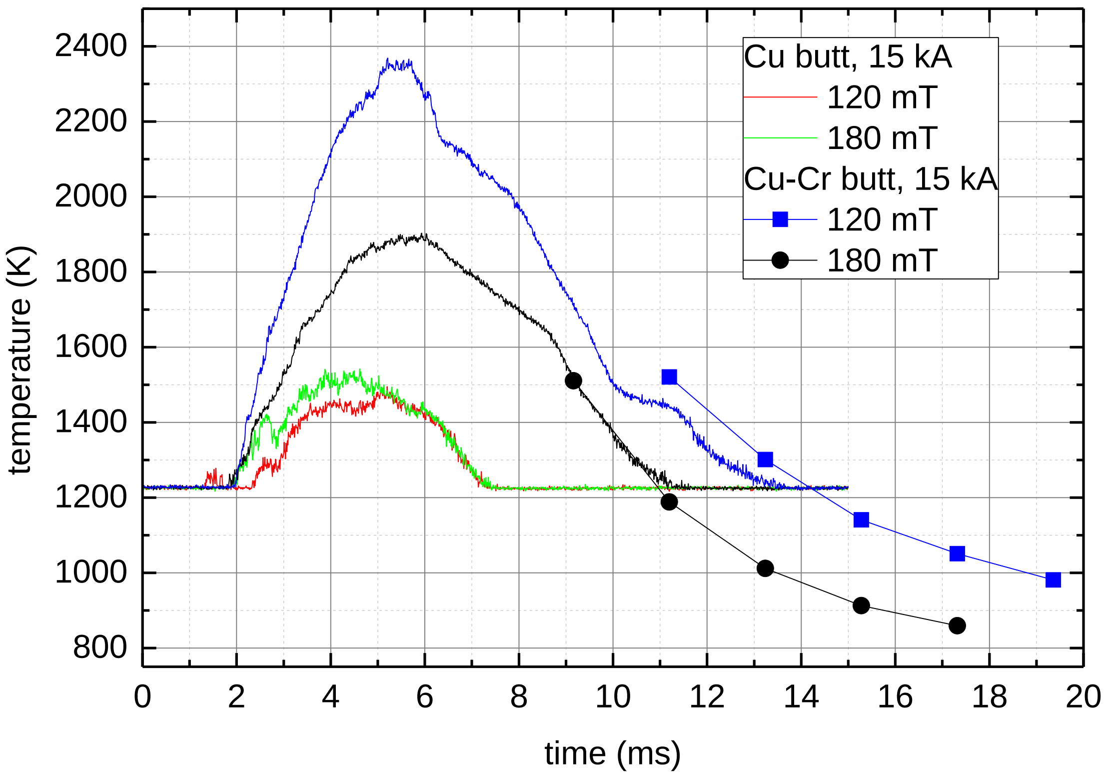
Measurements in active phase by pyroscope



- Temperature maximum around 6 ms, i.e. after current maximum
- Accelerated temperature decay after 6 ms up to Cu-Cr eutectic melting point (at 2020 K).
- Plateau closely after current zero (occurs at different temperatures)

Measurements in active phase by pyroscope

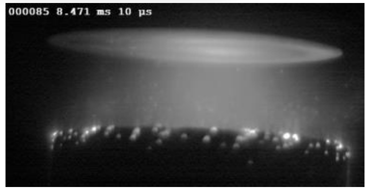




- Good agreement between temperatures from pyroscope and from NIR spectra
- Higher currents lead to higher anode surface temperatures

- Lower thermal radiation for Cu
- No continuum emission observed after CZ with NIR
- Due to comparable emissivity the anode surface temperatures for Cu should be considerably lower than for Cu-Cr

Measurements in active phase by HSC



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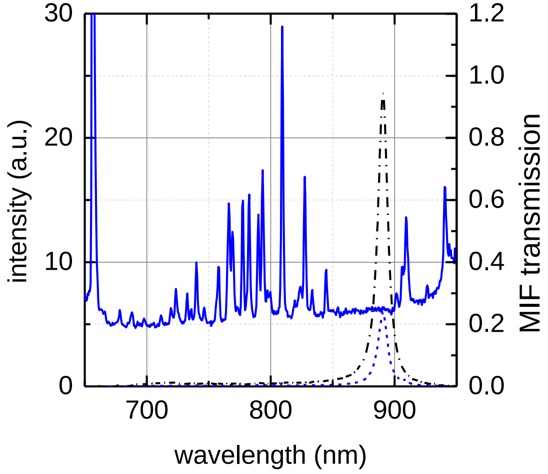

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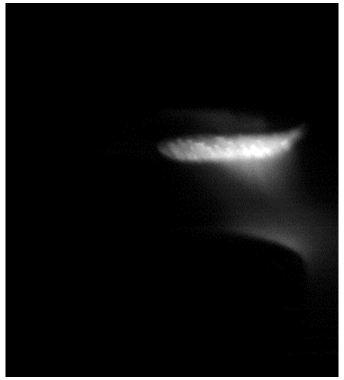
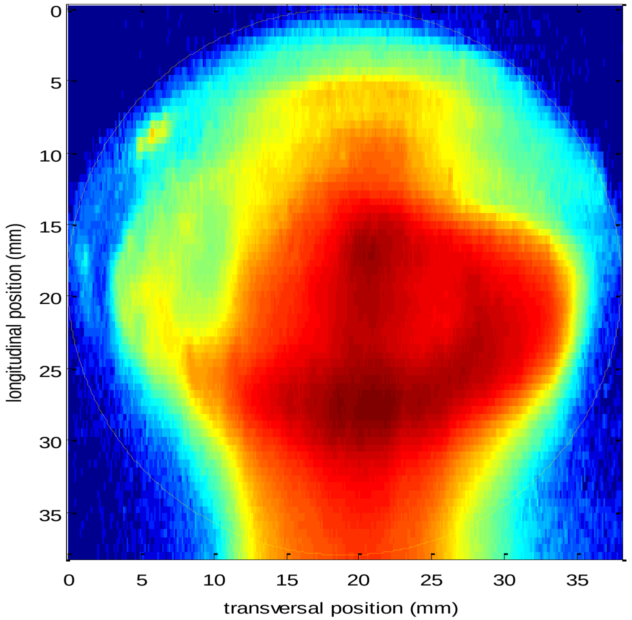
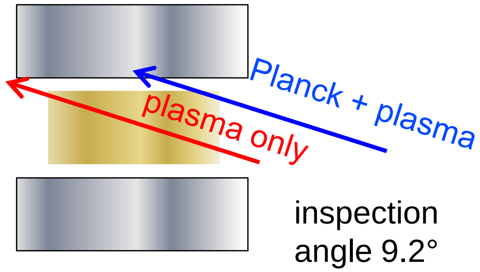
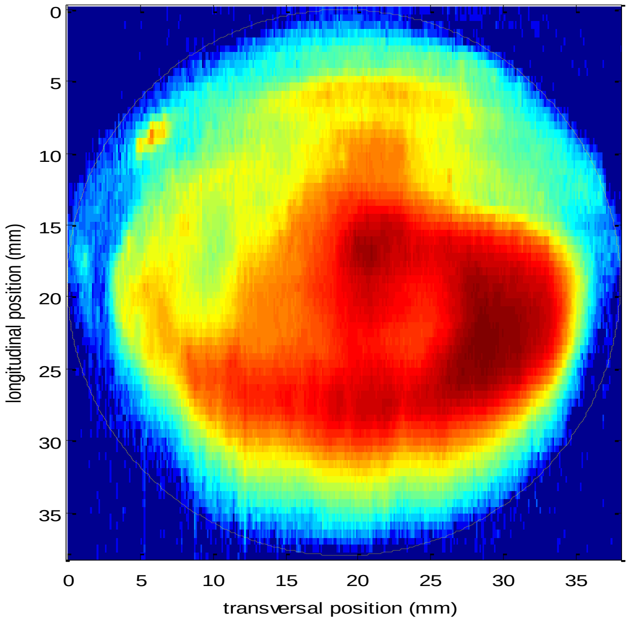




Without correction for plasma background radiation.

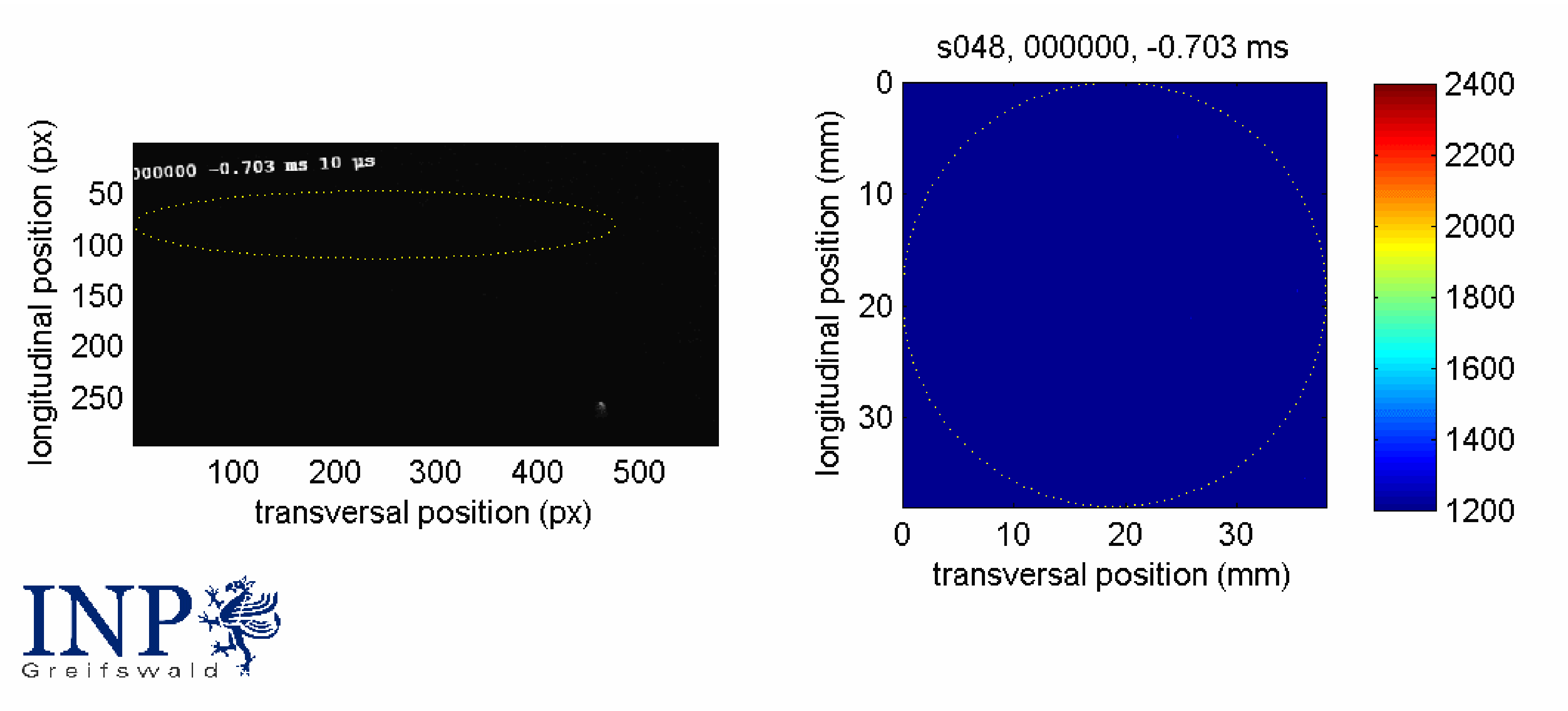




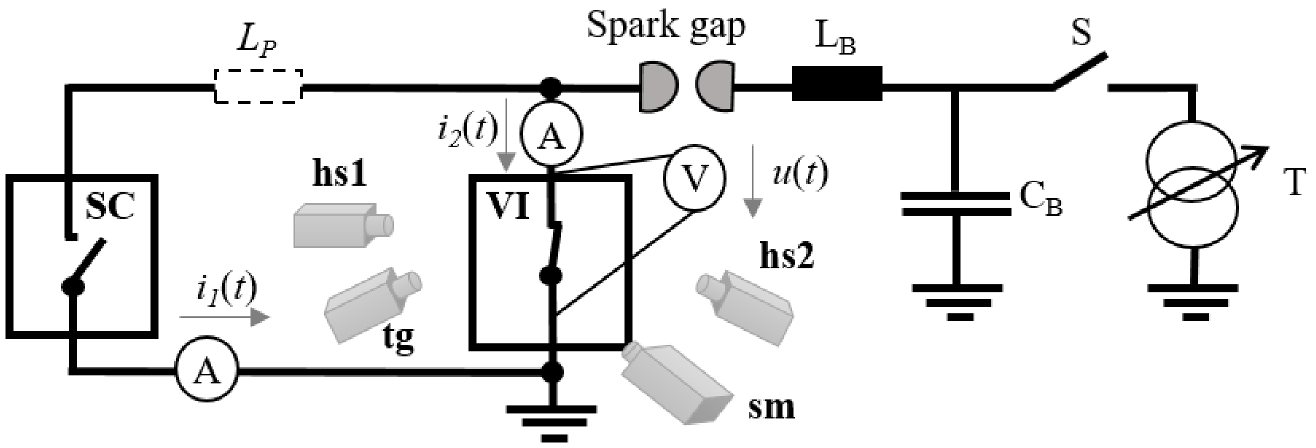
With correction for plasma background radiation

Measurements in active phase by HSC

Quantitative temperature from calibration with addition measurements, like e.g. NIR spectroscopy



Measurements in the active phase: current cut-off



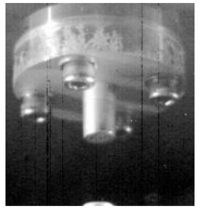
Current flow through test object VI was switched artificially to zero by means of bypath SC

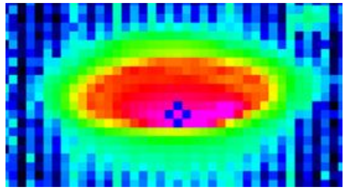
Diagnostics by

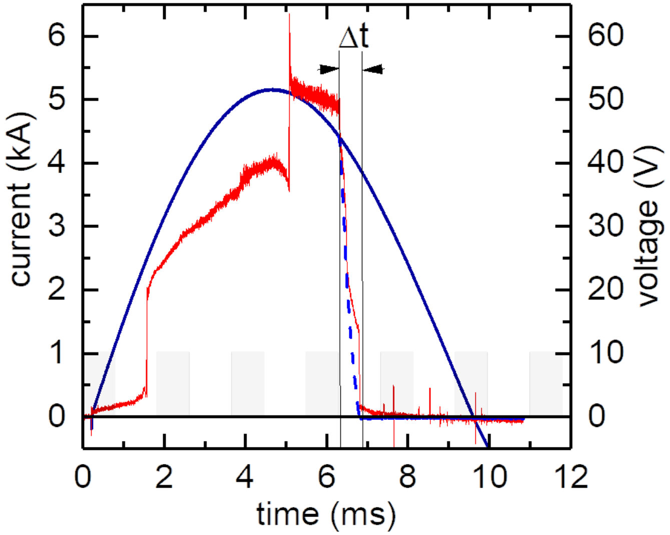
- 3 channel rackmount spectrometer
  VIS 200-1000 nm / NIR 880-1700 nm / NIR 1.6-2.4 µm

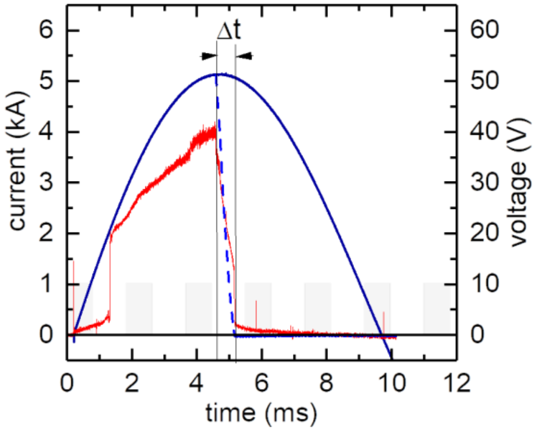
- High-speed NIR camera
  1.5 – 1.7 µm, 6100 fps with 128 x 24 pix resolution

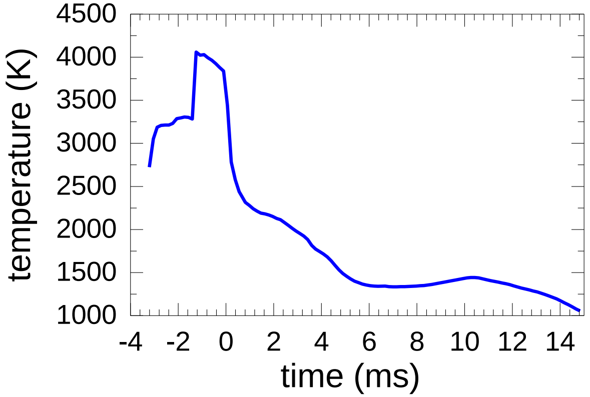
Measurements in the active phase: current cut-off

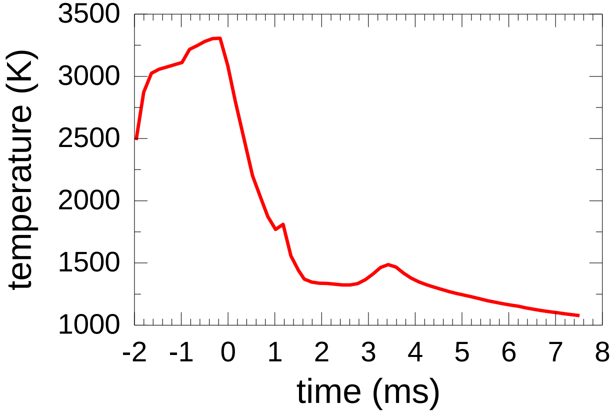






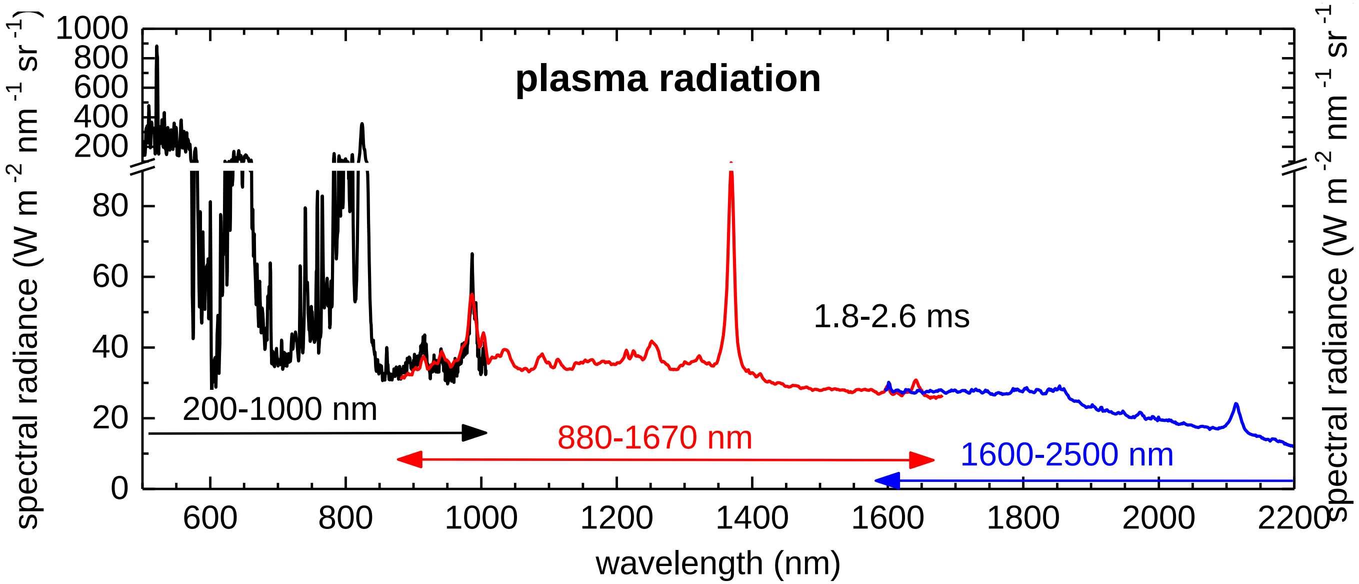


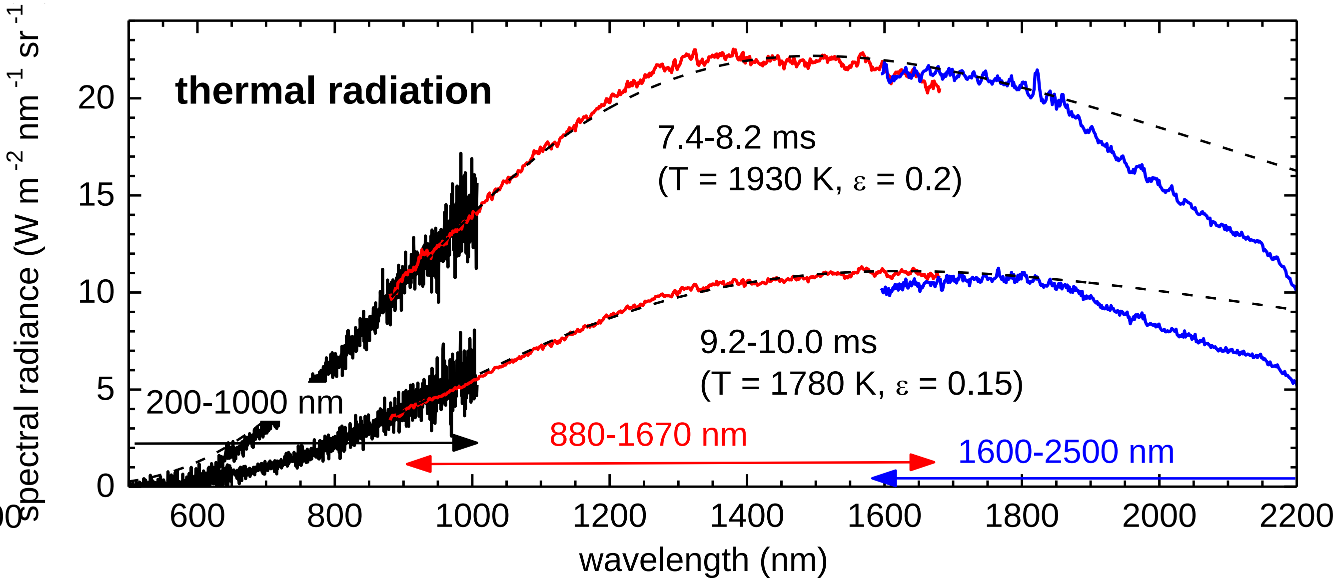




- Current cut-off within Δt ~ 0.56 ms
- Temperature about 3300 K before and about 4000 K after anode spot type 2

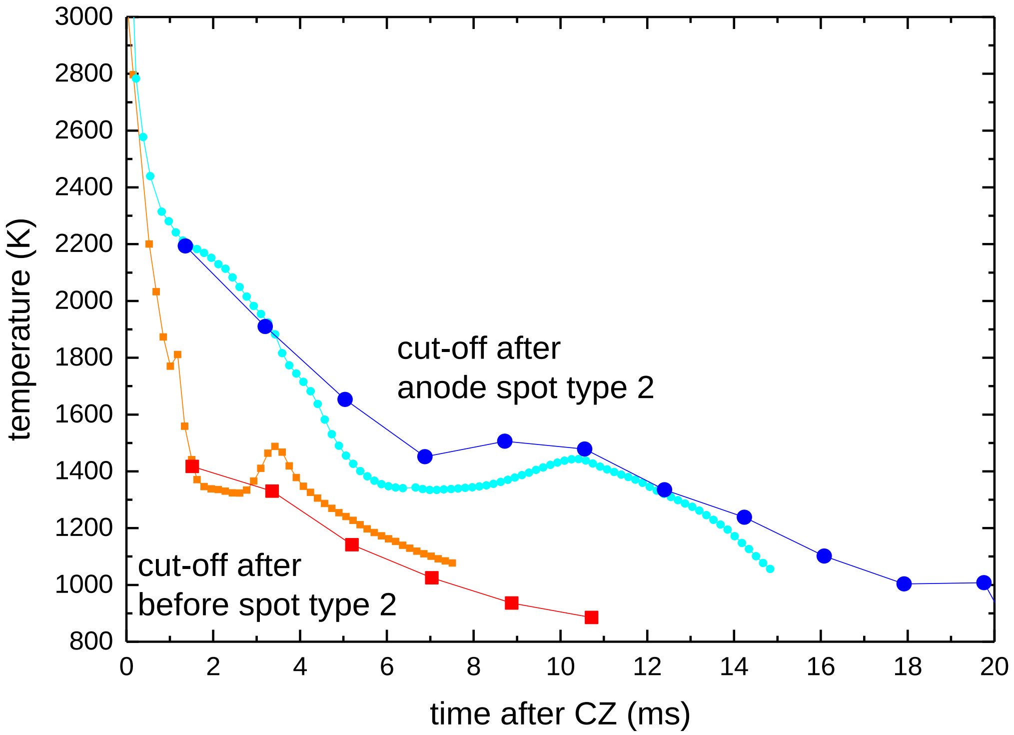
Measurements in the active phase: current cut-off





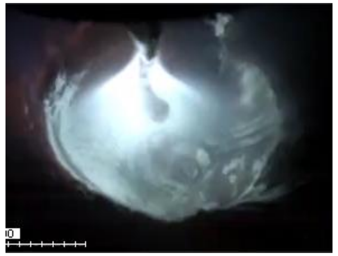
- Before CZ: plasma radiation dominates emission → no information on anode temperature
- After CZ: fit to Planck curve → anode surface temperature determinable

Measurements in the active phase: current cut-off

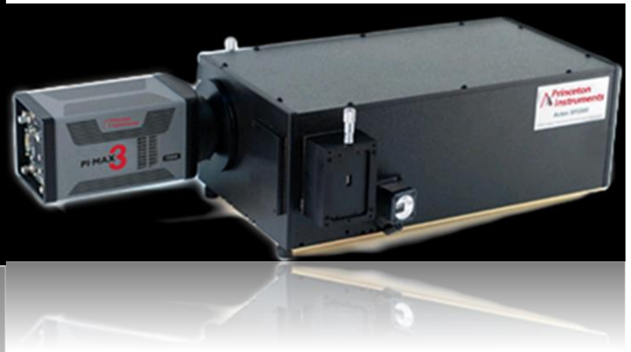


- Higher anode surface temperatures and longer cooling in case of anode spot type 2
- Peaks in temperature curve from thermography (lines) due to changing emissivity during solidification process – in spectroscopic method (dots) the emissivity was adapted during Planck curve fitting

Example 5: Surface with impurities



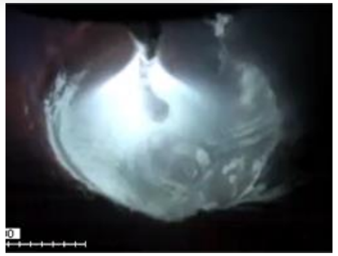
CMT welding – pulsed arc operation

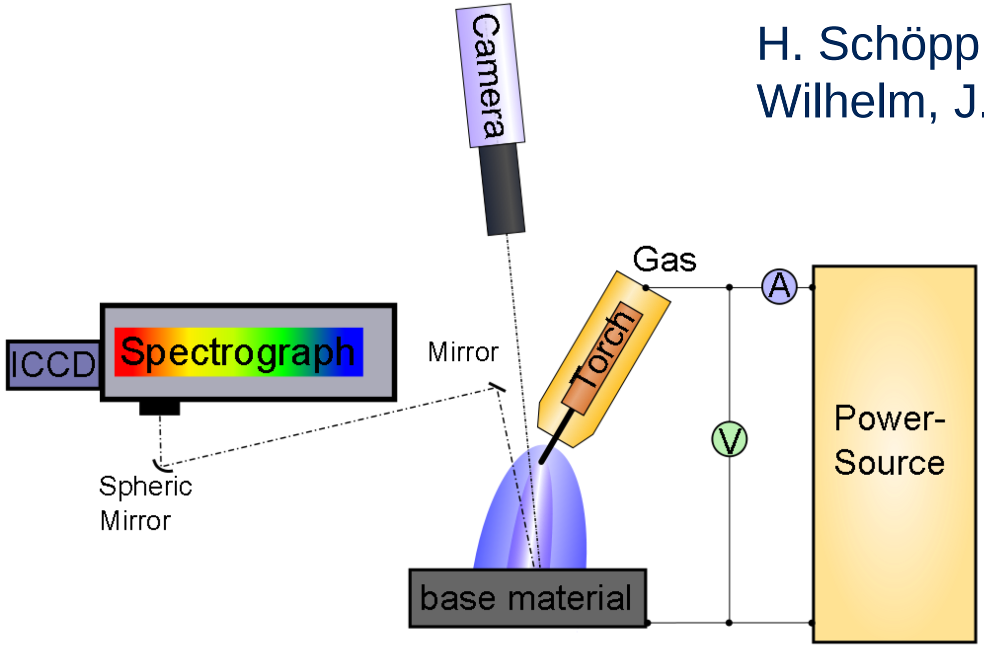


High-speed camera

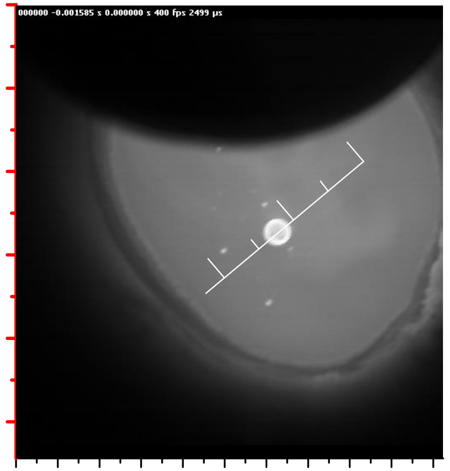
Spectrograph

Example 5: Surface with impurities





H. Schöpp, A. Sperl, R. Kozakov, G. Gött, D. Uhrlandt, G. Wilhelm, J. Phys. D: Appl. Phys. 45(2012) 235203

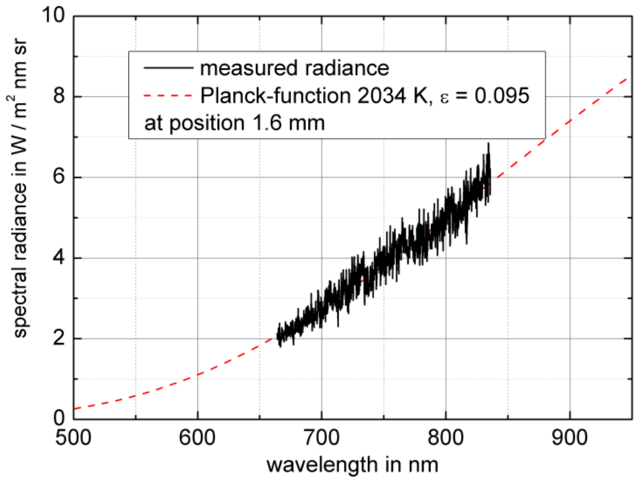


HSC image

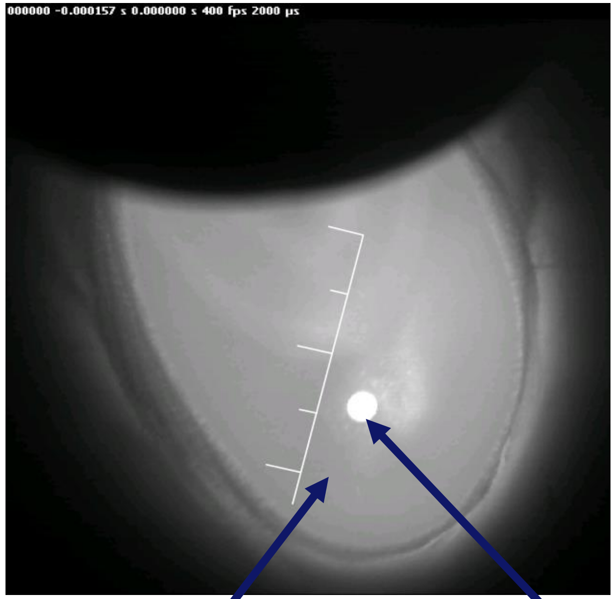
Material steel S235
Slit length 12 mm
Results after current cut-off

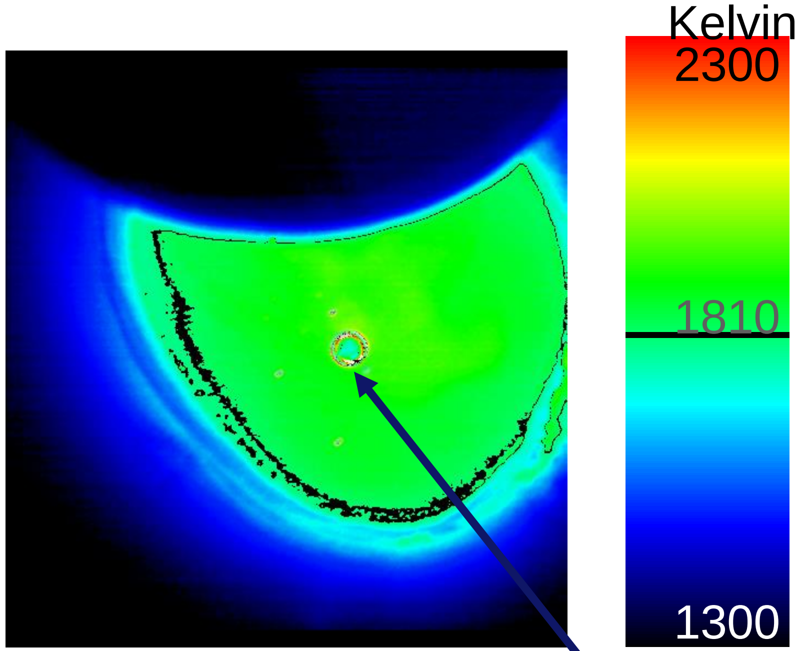
INP FROM IDEA TO PROTOTYPE

Example 5: Surface with impurities

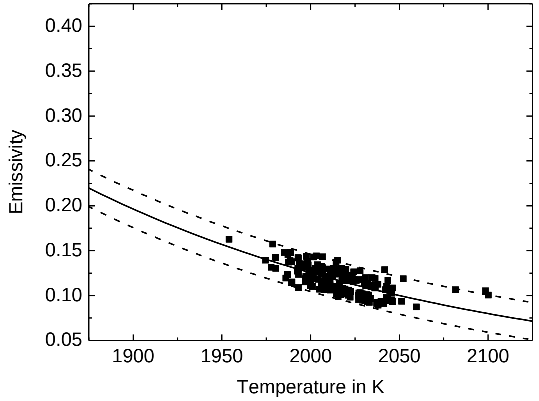


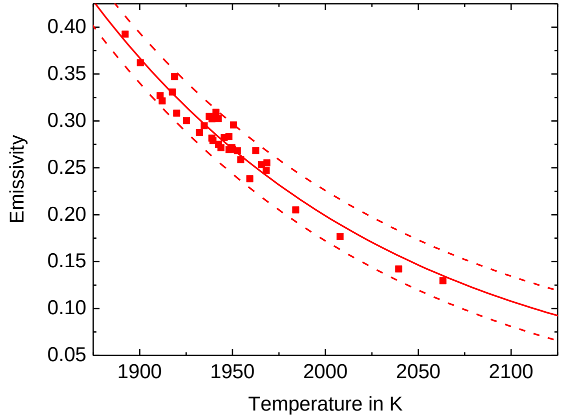
Planck-fit for each spatial position





Colder slag due to higher emissivity





Summary and outlook

Summary

- Various of optical methods for temperature determination is available
- In case of an arc discharge:
  "easy case" – measurements in the post-arc phase;
  "complex case" – measurements during the active phase
- Combinations of various methods increase applicability range

Outlook

- Further development is necessary for temperature measurements within the active phase
- Increase of temporal resolution

- Further results will be presented at ISDEIV2020/Padova (IT), ICEC2020/ St. Gallen (CH) and **GD2020/Greifswald**

You are kindly invited to participate in

Thank you very much for your attention!

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Literature

H. Schöpp, A. Sperl, R. Kozakov, G. Gött, D. Uhrlandt, G. Wilhelm, J. Phys. D: Appl. Phys. 45(2012) 235203

R. Methling, M. Kurrat, T. Pieniak, St. Franke, D. Uhrlandt, B. Weber, S. Gortschakow, Proc. of 28th ISDEIV, V 2, 2018

R. Methling, St. Franke, S. Gortschakow, M. Abplanalp, R.-P. Sütterlin, Th. Delachaux, K. O. Menzel, IEEE TPS 45 (2017)