Study of electrode erosion in switching vacuum arcs by optical methods

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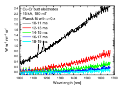
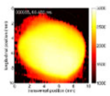
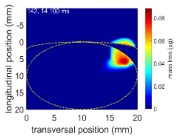
FROM IDEA TO PROTOTYPE

Outline







- Introduction: switching vacuum arc
- Optical methods for determination of electrode temperature
  - NIR spectroscopy
  - high-speed camera techniques enhanced by optical filters
- Experimental setup
- Results for CuCr contacts
  - NIR measurements
  - HSC measurements
  - simplified mass loss model
- Summary and outlook

Introduction: switching vacuum arc

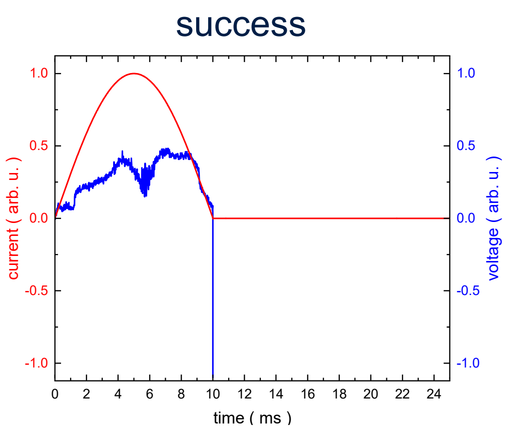
vacuum interrupter

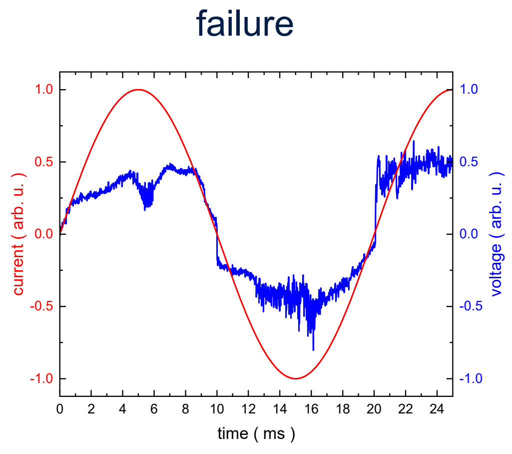
- Switching vacuum arc
  - working medium of vacuum interrupters, appears by contact separation under current flow
  - typical current level 100 A – 100 kA @ arc duration 1 – 30 ms
  - dual role of electrode erosion: source of plasma and source of “troubles”
  - mostly used electrode material: CuCr alloy electrode diameter 20 - 160 mm, electrode distance 5 - 20 mm
- Most challenging working regime - high-current operation:
  especially strong electrode melting and evaporation
- Methods for characterization of electrode erosion for qualification of electrode materials necessary

Subject

- Study of applicability of optical methods for surface temperature determination and characterization of surface erosion

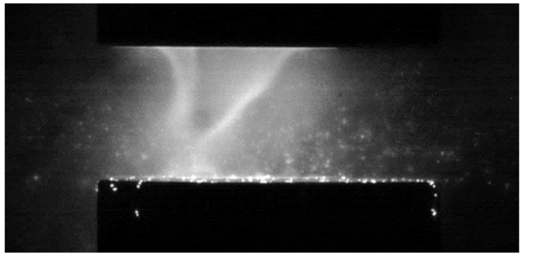
Introduction: interruption failure



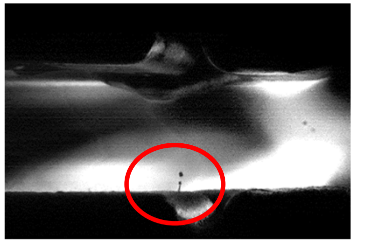


Major reasons for interruption failure:

- high metal vapour density
  - overheated electrodes, esp. anode
- droplets
  - overheated electrodes
- Focus on anode-related phenomena
  - surface temperature
  - erosion rate



anode plume



droplets

cathode

anode

Optical diagnostics of electrode surface

- “Conventional” 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 and temporal resolution – local properties and dynamics
  - applicable in a wide parameter range due to variability of methods
- Method choice and requirements
  - sensitivity → surface should emit radiation (T high enough)
  - plasma radiation is either absent or can be excluded from consideration
- **Challenge**: unknown surface emissivity
  - *ín-situ* measurements simultaneously with temperature measurements
  - use of method combinations

Method I: NIR spectroscopy

NIR 900-1600 nm
exposure 50 -100 µs
temporal resolution 1.25 ms

+

NIR optics

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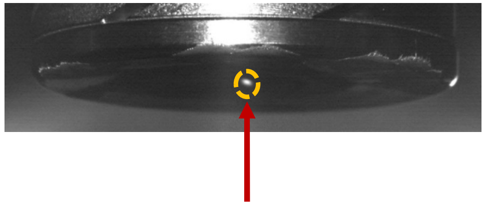
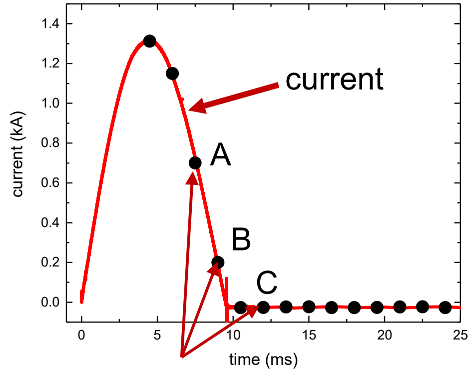
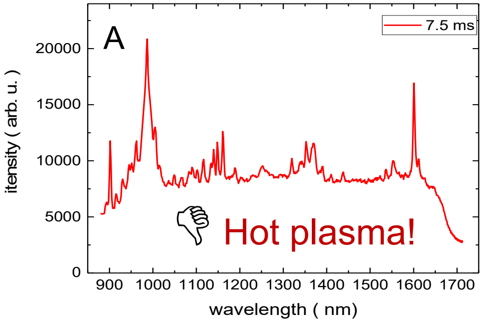
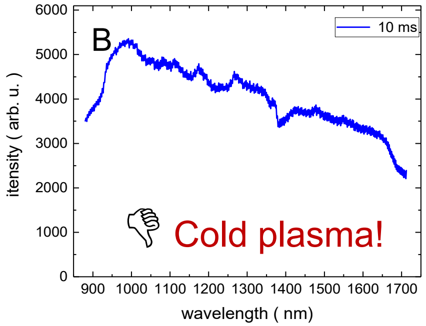


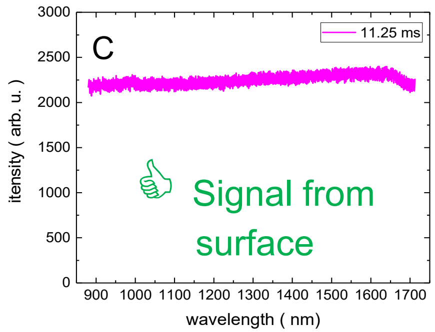
measuring point



acquisition times







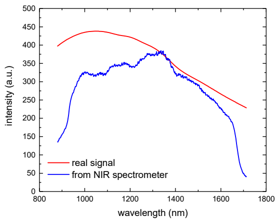
- Method gives **quantitative time-dependent** temperature in a small **spot**
- **Challenges:** spot position, disturbance by plasma radiation (→ measurements mainly after CZ)

Method I: NIR spectroscopy

Steps necessary after spectra acquisition

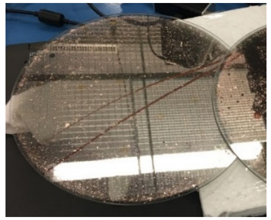
- Calibration

W strip lamp

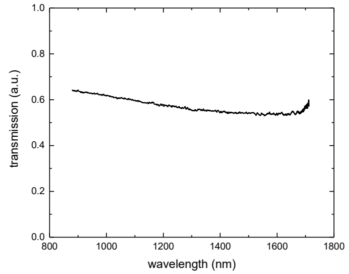


spectrum vs calibration curve

- Correction by window transmission

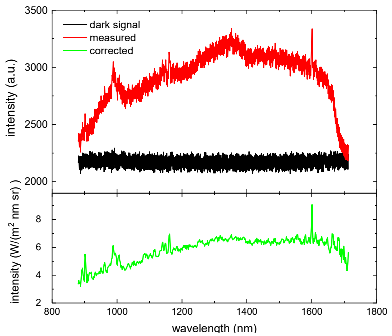


coated window



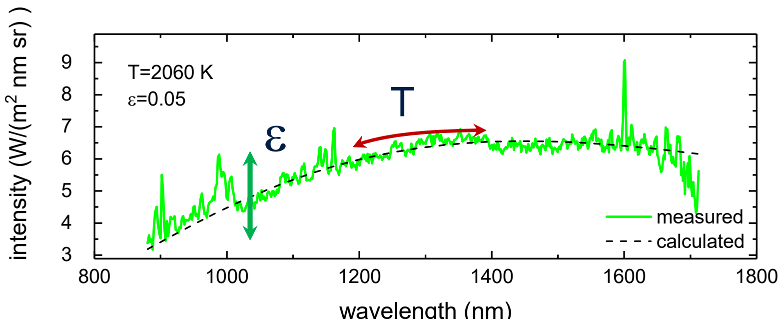
transmission curve

- Background subtraction



spectrum before and after correction

- Temperature evaluation

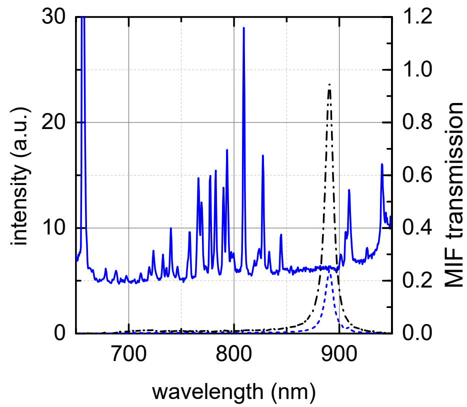


$$B_\lambda(T) = \varepsilon(\lambda, T)\frac{2hc^2}{\lambda^5}\cdot\frac{1}{e^{\frac{hc}{\lambda kT}}-1}$$

Method II: High-Speed Camera (HSC) with filter

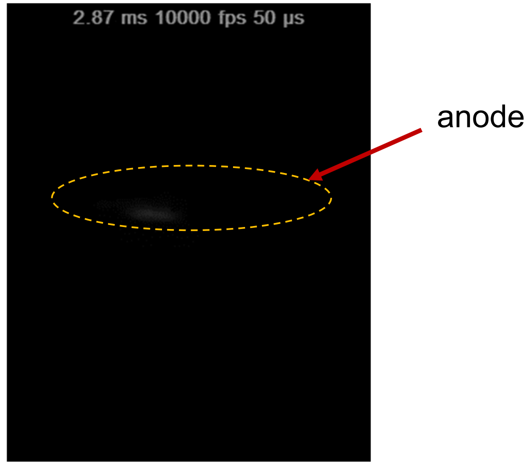
high-speed camera
Photron FASTCAM Nova S6
5000-25000 fps

+



filter, which “blocks”
plasma radiation

=



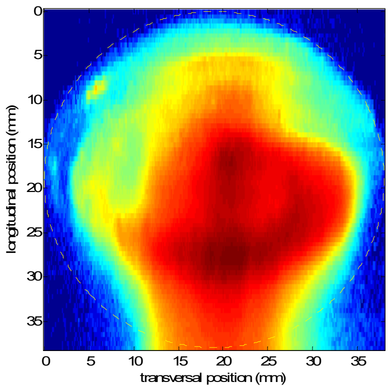
radiation image dominated
by surface contribution

- The method gives **qualitative** 2D temperature distribution with high temporal resolution
- **Quantitative** temperature can be obtained after comparison with results of NIR measurements at certain spatial position and time instant
- **Challenge**: continuum radiation of plasma must be taken into account (“removed”)

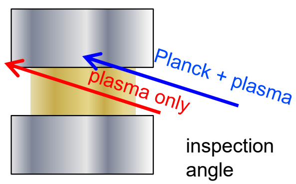
Method II: High-Speed Camera (HSC) with filter

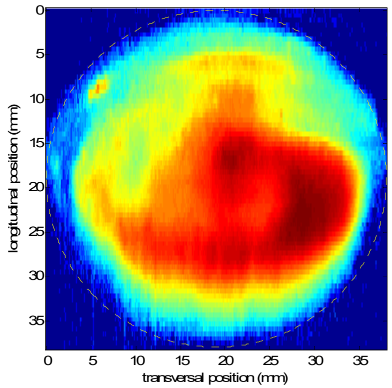
Steps necessary after image acquisition

- Correction for plasma radiation



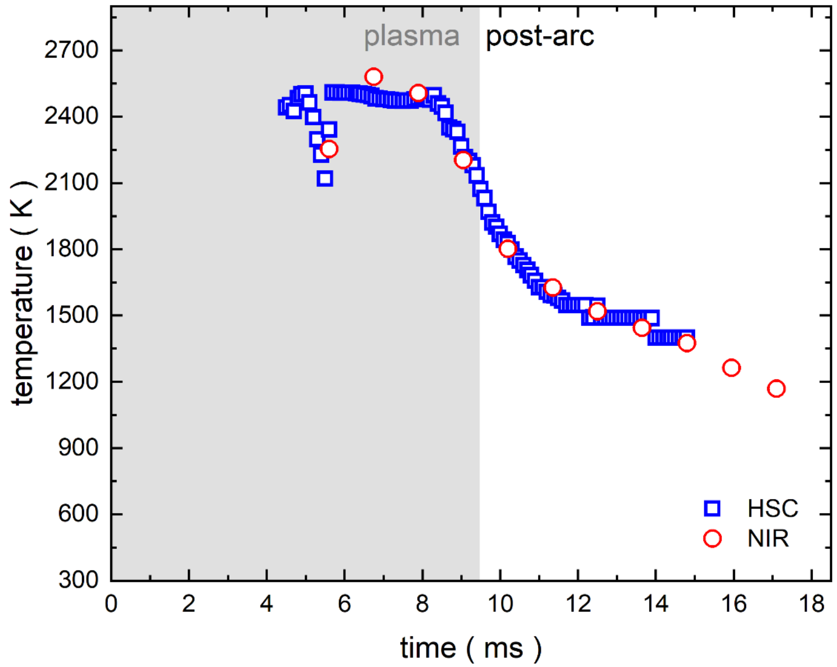
without correction for plasma radiation



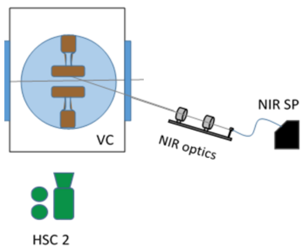


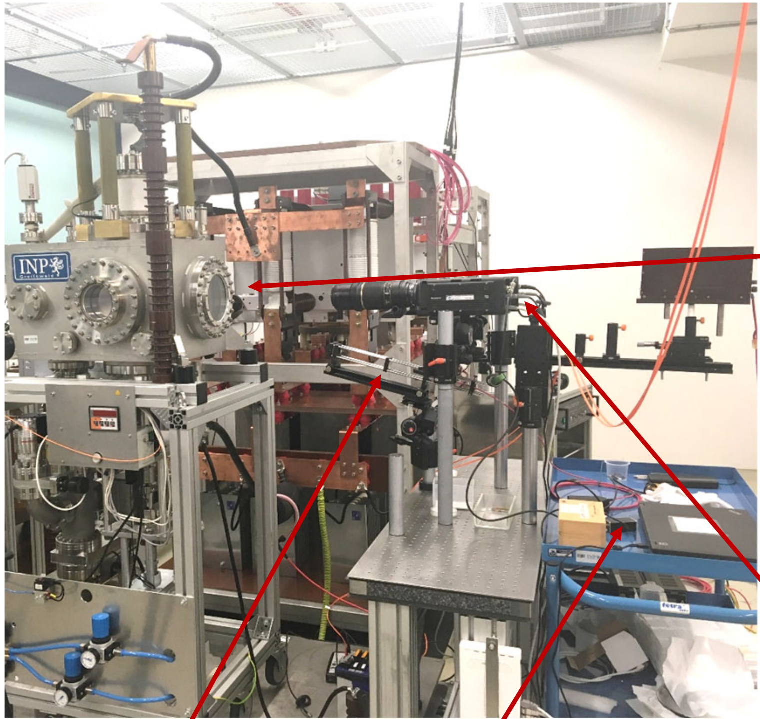
with correction for plasma radiation

- Calibration



Experimental setup

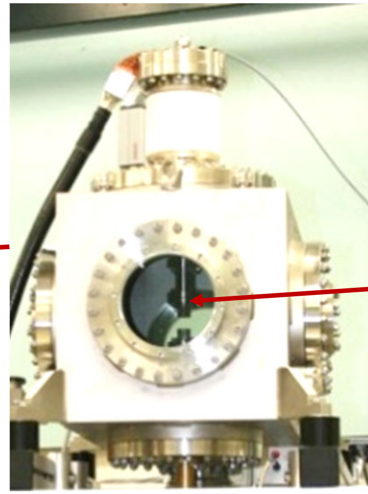




NIR optics

NIR spectrometer

high-speed cameras with filter

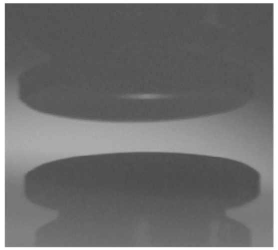


vacuum chamber with moveable electrodes

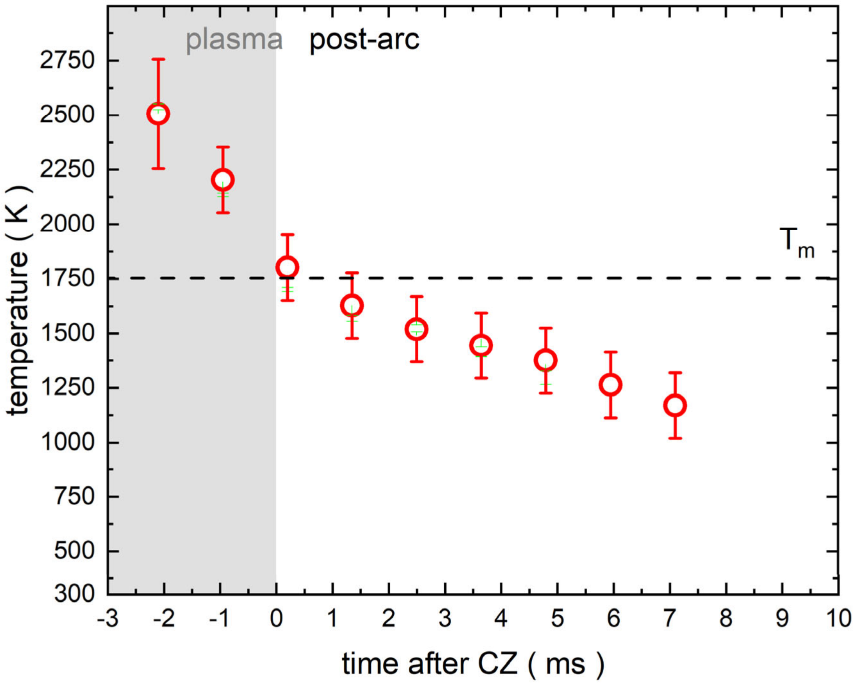
model electrodes
CuCr alloy, ∅20 mm

- Use of optical diagnostics: non-invasive methods, quantitative characterization of electrode surface

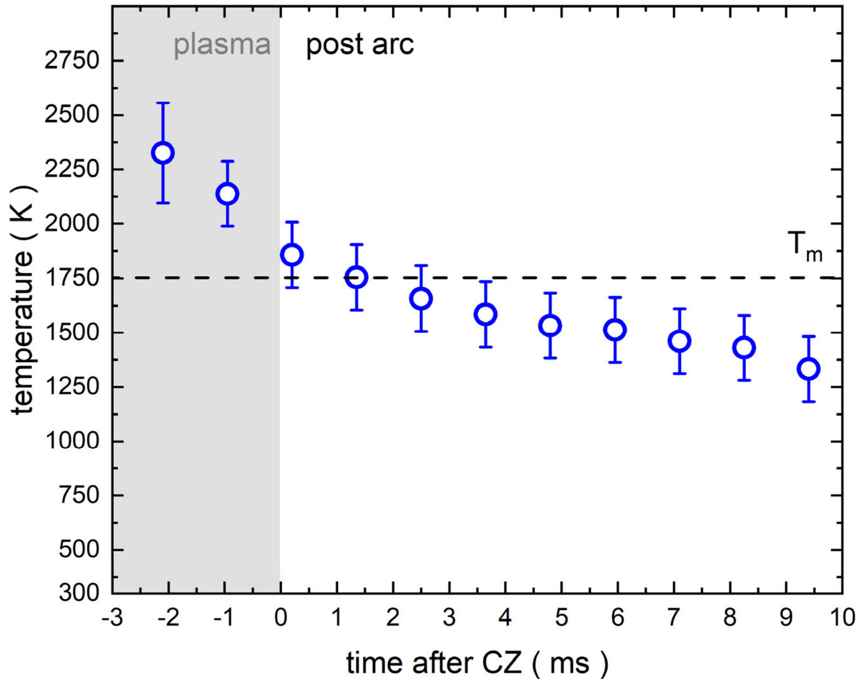
NIR results: surface temperature



CuCr40 anode

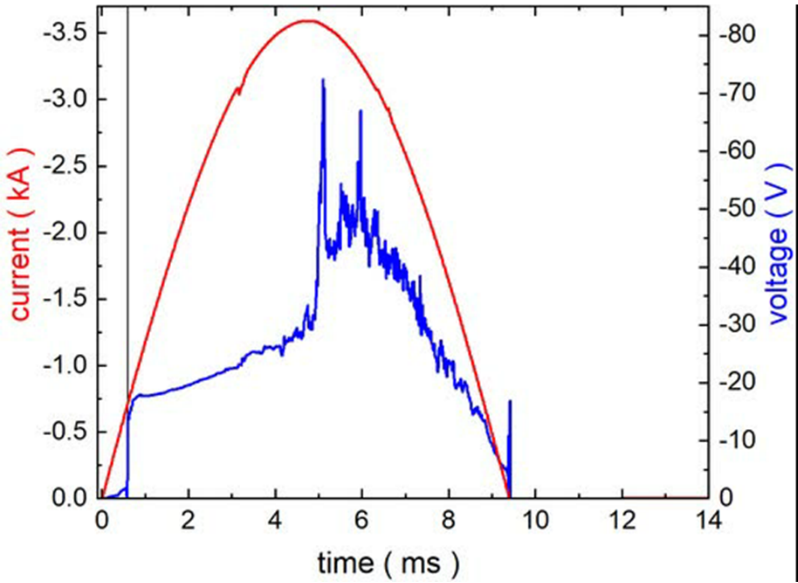


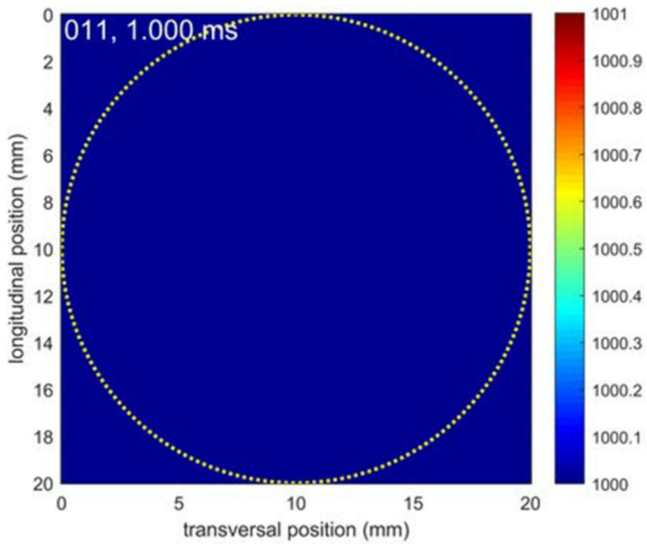
CuCr50 anode



- Initial temperature at current zero about 1800 K
- Slightly higher temperature and longer decay for contacts with higher Cr content

HSC results: anode surface temperature



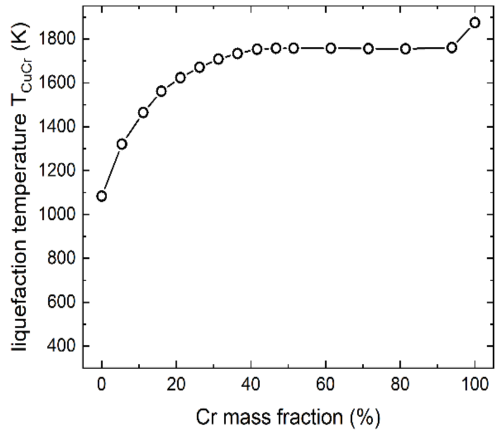


- Evaluation in a wide temporal range possible
- Melting point reached at anode spot location point

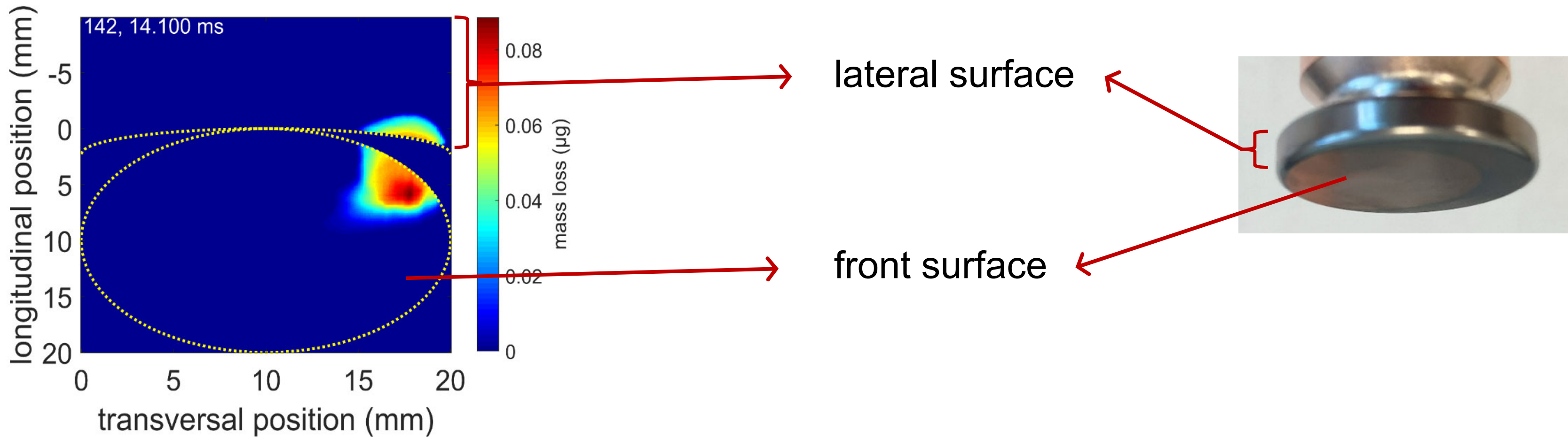
Estimation of mass loss

Simplified mass loss model

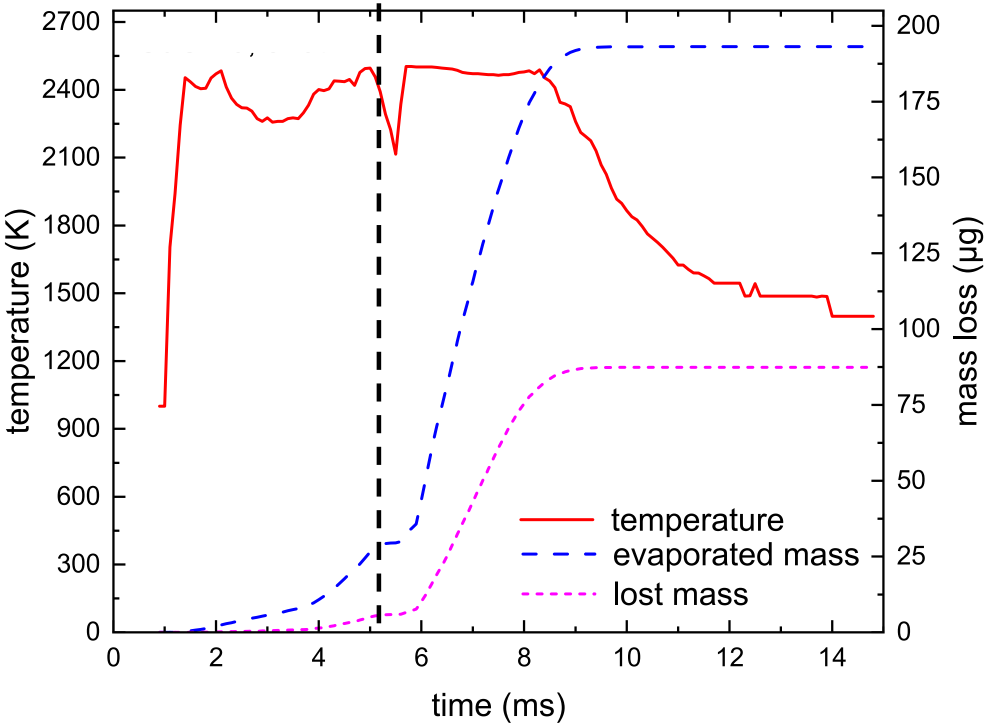
- Sputtering and droplet formation ignored
- Material loss due to evaporation only
- Correction of melting point taking into account the data for CuCr alloys
- Mass loss correction through introduction of solid angle which is blocked by opposite electrode



derived from R. Müler
Siemens F&E Ber.1988

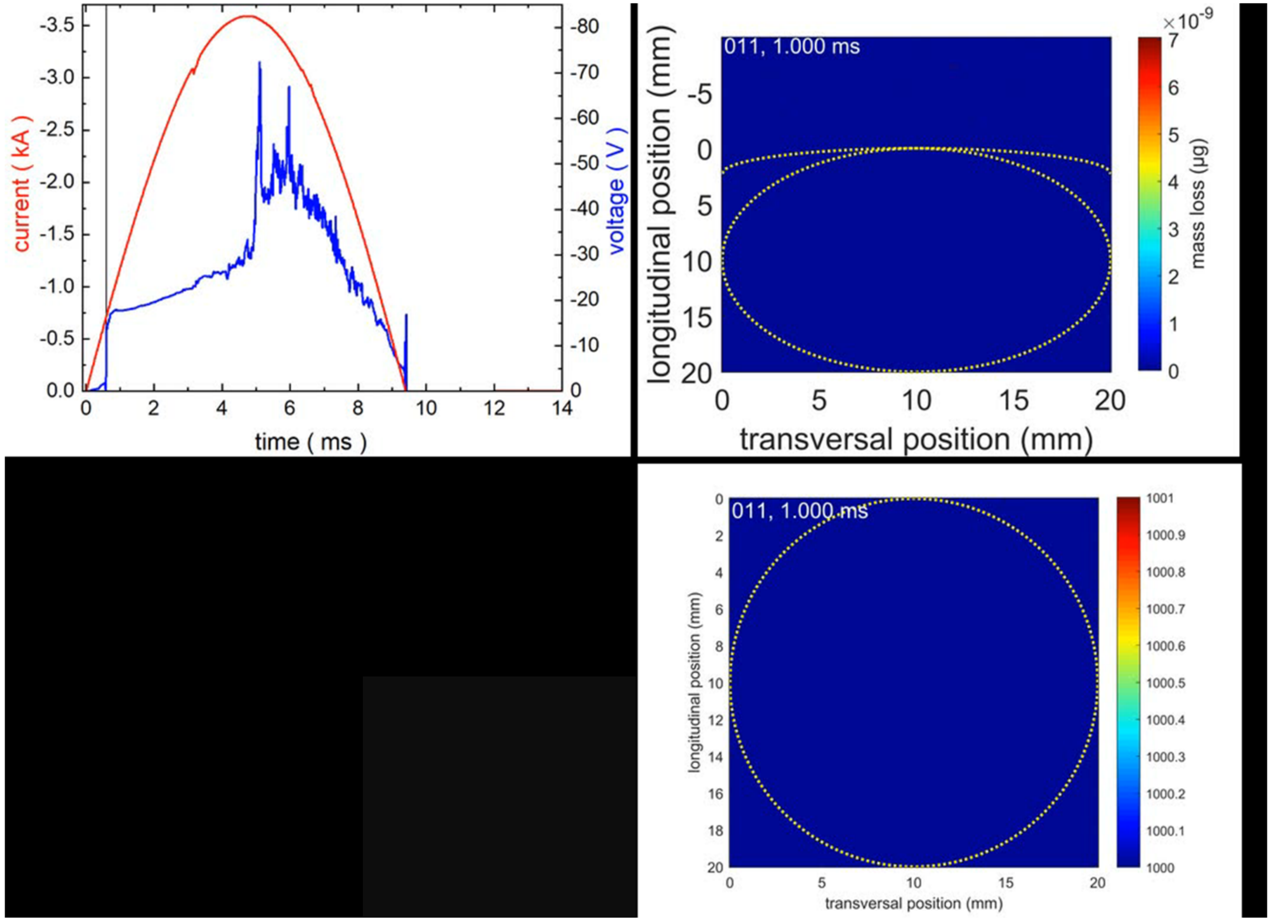


Estimation of mass loss



- Evaporated mass ca 193 µg, lost mass ca 87 µg, the rest is absorbed by opposite electrode

Estimation of mass loss



- Evaporated mass ca 193 µg

Summary

- Two optical methods for determination of surface temperature have been tested for switching vacuum contact systems.
- NIR spectroscopy works well after current interruption, when plasma radiation is negligible.
- The method based on the high–speed camera techniques has restricted applicability. It works well for diffuse arcs and at certain electrode distance, which is typically reached after current maximum.
- Simplified model for mass loss was developed and applied for study of erosion of CuCr anode.

Outlook

- Current methods and model works well for anode. Further development/adoption of experimental methods for cathode required.
- Model improvements
  - evaluation of mass loss from moving contact
  - approach for evaporation/ droplet formation
- Future experimental research – different materials used in switching applications

Thank you very much for your attention!

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