Spectroscopic study of high-current vacuum arcs considering anode activity

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Outline

- Motivation
  - High-current anode modes
    - Video spectroscopy (high-speed spectroscopy)
  - Absorption spectroscopy
- Summary and outlook
Motivation

Vacuum arcs
- used as working medium in vacuum circuit breakers
- environmentally friendly operation
- better understanding of arc physics necessary for applications at higher loads (currents)

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 phenomena
Switching arc ignition

vacuum circuit breaker
Model switch

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
Optical diagnostics

- **Advantages**
  - non-invasive (or of negligible influence)
  - quantitative measurements of plasma properties – temperature, pressure, species densities
  - high spatial resolution – local plasma properties
  - high temporal resolution – plasma dynamics
  - applicable in a wide parameter range due to variability of methods
  - precise and reliable instrument for model validation

- **Disadvantages**
  - optical access to the object necessary
  - radiation intensity must be high enough (emission methods)
  - distortions in the optical pathway through hot particle fluxes
  - costs of the devices, complex apparatus and evaluation methods
Optical diagnostics

Radiation can be emitted, absorbed or deflected, giving the opportunity for various diagnostic methods

- Emission
  - Optical emission spectroscopy (OES)
    - imaging, time resolved
  - High speed camera based
    - cinematography, velocimetry, video spectroscopy, imaging with filters, tomography
  - Ultra fast imaging (framing camera)
  - Fluorescence based (LIF, TALIF…)
  - Thermography, pyrometry

- Absorption
  - broad band (flash lamp)
  - laser based atomic and molecular absorption

- Diffraction/Refraction/Interferometry
  - Hook method, speckle, Shack-Hartmann, schlieren …
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Method choice

- Requirements to the method
  - simultaneous acquisition of spatial and temporal information
  - independent on plasma state (equilibrium/ non-equilibrium)
  - work with and without the plasma emission
- **Video spectroscopy** as possible solution for highly dynamic objects with sufficient light emission
- **Absorption spectroscopy** as possible solution for objects without sufficient light emission

**Objectives** of the work
- Study of plasma dynamics using methods of emission spectroscopy
- Determination of qualitative distributions of plasma species for different high-current anode modes
- Determination of absolute metal vapor density close to current zero crossing
Discharge modes in vacuum arc

Anode activity depends on discharge mode

- diffuse
- footpoint
- intense
- anode spot 1 and 2
- anode plume
High-current anode modes

Different discharge modes
High-current anode modes: anode plume formation

![Diagram showing current-voltage relationship and anode plume formation images.]

- Anode plume formation during high-current modes.
- Graphs depicting current and voltage over time.
- Images illustrating anode and cathode positions with different anode spot types.

**Legend**:
- cathode
- anode
- anode plume
- diffuse footpoint
- anode spot (type 1)
- anode spot (type 2)
- CuCr7525

**Graph Details**:
- X-axis: Time (ms)
- Y-axis: Current (kA)
- X-axis: Voltage (V)

**Image Descriptions**:
- a) Anode
- b) Anode
- c) Anode
- d) Anode
- e) Anode
- f) Anode
- g) Cathode
- h) Cathode
- i) Cathode

**Additional Notes**:
- Observations of plume length over time:
  - Plume length (nm) vs. time (ms)
  - Peaks and troughs indicating anode plume dynamics.
High-current anode modes

**successful termination**

- Anode spot type 2 formation at $t=0.9$ ms
- Anode plume touches the cathode at $t=3.6$ ms

**fail**

- Anode spot type 2 formation at $t=0.3$ ms
- Anode plume touches the cathode at $t=3.6$ ms
- Earlier formation of the anode spot type 2 and anode plume → stronger electrode evaporation
Video spectroscopy

Conventional OES

- High speed video camera
- ICCD camera
- Lens
- Entrance mirrors
- Focusing mirror
- Cathode
- Anode

iCCD image

- Position
- Wavelength

Spectrum

- Line radiation
  - Intensity
  - Line width
- Continuum radiation
  - Intensity
Video spectroscopy

- High-speed camera instead of iCCD
- Series of spectra within one experiment

- !!! No intensifier – sufficient light intensity or acquisition time is necessary (100 µs cmp to 2 µs@OES)
- !!! Linearity of camera chip must be proven
Video spectroscopy: experimental setup

- LC pulse generator
- AC 50 Hz, 3.7 kA

- Cu75Cr25 diameter 10 mm
- Contact opening speed 1 m/s

- Optical diagnostics
  - High-speed camera
  - Video spectroscopy
    - imaging spectrograph
    - high speed camera
    - time resolution 100µs
Video spectroscopy: experimental setup

- Spectral interval 508–517 nm
- Selected spectra lines
  - Cu I 510.55 and 515.32 nm
  - Cu II 512.45 and 508.90 nm
  - Cu III 509.42 and 516.89 nm
Video spectroscopy: results for AC 50 Hz

High speed camera

Video spectroscopy
Video spectroscopy: results for AC 50 Hz

Transition from diffuse to footpoint mode

Cu I
- slight changes near cathode.
- lower intensity in case of footpoint comparing to diffuse mode

Cu II
- similar behavior as for Cu I
- almost no changes near the cathode, slight decrease near the anode and in the gap in case of footpoint mode

Cu III
- much broader spatial profile comparing to Cu I, II
- remarkable changes while changing anode mode
Video spectroscopy: results for AC 50 Hz

Transition from footpoint to anode spot type 1

**Cu I**
- Insignificant changes

**Cu II**
- low intensity near the anode
- broad profile near the cathode

**Cu III**
- abrupt change in distribution by transition from footpoint to anode spot
- local maxima near the electrodes in anode spot mode
- one maximum in the gap in the footpoint mode

Decreased intensity between electrodes in anode spot mode visible from the dark region in HSC images
Video spectroscopy: results for AC 50 Hz

Transition from anode spot type 1 to anode spot type 2

- Significant increase of all line intensities near the anode
- Moderate increase of line intensities near the cathode
- More pronounced changes with increasing charge number
- Intensity maxima near the anode considerably higher than those near the cathode in the anode spot type 2
Optical absorption spectroscopy (OAS)

• Light source and detector

\[ I_0 \quad \text{light source} \quad I \quad \text{plasma} \quad I_{AB} \quad \text{detector} \]

• Determination of optical depth

\[ \tau(\lambda_L) = -\ln\left(\frac{I(L_{AB}, \lambda_L)}{I_0(\lambda_L)}\right) \]

• Density of absorbing species

\[ \frac{1}{L_{AB}} \int_0^\infty \tau(\lambda_L) d\lambda = \frac{\pi e^2 \lambda_0^2}{\varepsilon_0 m_e c^2} N_l f_{lu} \]
OAS: experimental setup

Vacuum chamber:
- residual pressure <10^{-7} mbar
- optical access

Actuator: opening speed 2 m/s

Contacts: CuCr7525, diameter 10 mm

Optical diagnostics
- High-speed camera
- Absorption spectroscopy
  - pulsed Xe lamp
  - imaging spectrograph
  - optical system
  - Acquisition time 200 µs

LC pulse generator
- AC 100 Hz, 7 kA
OAS: experimental setup
OAS: measurements with and without plasma

After CZ, without significant plasma radiation

\[ T = \frac{I}{I_0} \]

\[ \int_0^\infty kDd\lambda = \int_0^\infty \ln\left(\frac{I_0}{I}\right)d\lambda = \frac{\pi e^2 \lambda_0^2 DN_l f_{lw}}{4\pi \varepsilon_0 m_e c^2} \]

Active phase, strong plasma radiation

\[ T = \frac{PL - P}{L} \]

\[ \int_0^\infty kDd\lambda = \int_0^\infty \ln\left(\frac{L_\lambda}{PL_\lambda - P_\lambda}\right)d\lambda = \frac{\pi e^2 \lambda_0^2 DN_l f_{lw}}{4\pi \varepsilon_0 m_e c^2} \]
OAS: measurements after current zero

[Diagram showing light source, plasma, spectroscopy setup, and graphs of measured data and Cr density as a function of time.]
OAS: measurements during the active phase

- Spectrograph
- Xenon lamp
- Plasma
- Background light
- Anode
- Cathode

Wavelength (nm):

- Cr I 425.43 nm
- Cr I 427.48 nm
- Cr I 428.97 nm

Intensity (a.u.):

- Plasma
- Plasma + Lamp

4.57 ms
OAS: Cr density during high-current modes

During formation of anode spot type 1
- Current
- Voltage
- Lamp

During formation of anode spot type 2
- Current
- Voltage
- Lamp

During anode plume formation
- Current
- Voltage
- Lamp

Cr density during high-current modes
- Anode spot type 2
- Anode spot type 1
- Before CZ with anode plume
- Before CZ without anode plume
- After CZ

During extinction of anode spot type 2
- Current zero

Time (ms)
Current (kA)
Voltage (V)
OAS: spatial distribution of Cr density

distribution inside the plume

instant of current zero
Summary and outlook

Summary

- Video spectroscopy is used to examine high current anode mode during transition between different anode modes.
- High abrupt change of Cu atom and ion radiation during transition to anode spot type 2 is observed.
- An abrupt change in the distribution of the Cu III line during transition from footpoint to anode spot near the anode, cathode and inter-electrode gap.
- Absorption spectroscopy identified as suitable diagnostic method for study of vapour dynamics close to the current zero.
- Higher vapour density with anode spot formation.

Outlook

- Focus on plasma dynamics in decay phase: temperature and density determination.
- Comparison of absolute Cr and Cu vapour densities for various electrode compositions.
- First results will be presented at ISDEIV2018 in Greifswald.
You are welcome!

Topics

A. BREAKDOWN AND FLASHOVER
   A1. Vacuum breakdown and pre-breakdown phenomena
   A2. Surface discharges and flashover phenomena

B. VACUUM ARCS
   B1. Switching in vacuum and related phenomena
   B2. Interaction of vacuum arcs with magnetic fields
   B3. Vacuum arc physics
   B4. Computer modeling and computer aided design
   B5. Pulsed power physics and technology

C. APPLICATIONS
   C1. Vacuum Interrupters and their applications
   C2. Surface modification and related technologies
   C3. Electron, ion, neutron, X-ray and other beam and light sources
   C4. Accelerators and fusion reactor related issues
   C5. Space related technologies

Important dates

Homepage online: June 2017
First call for papers: June 2017
Abstract Submission opens: November 2017
Symposium: September 2018

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www.isdeiv2018.org
Thank you very much for your attention!

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