Spectroscopic study of high-current vacuum arcs considering anode activity

S. Gortschakow, A. Khakpour, St. Franke, R. Methling, D. Uhrlandt

Leibniz Institute for Plasma Science and Technology
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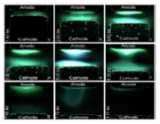
Leibniz Association

FROM IDEA TO PROTOTYPE

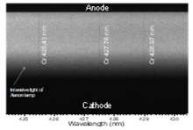
Outline

- Motivation

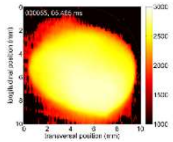


- High-current anode modes

- Video spectroscopy (high-speed spectroscopy)

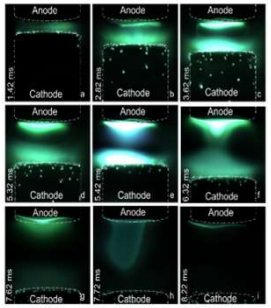


- Absorption spectroscopy



- Summary and outlook

Motivation



Vacuum arcs

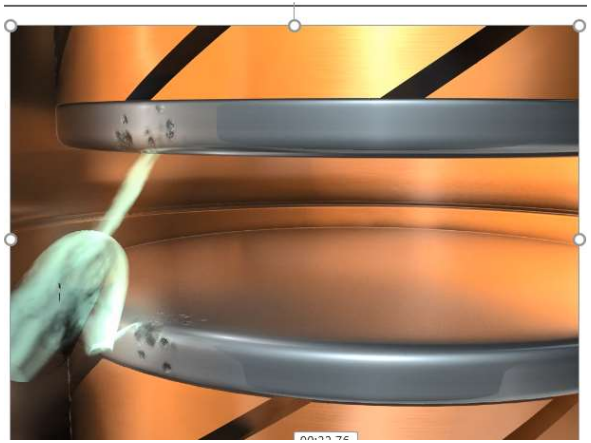
- used as working medium in vacuum circuit breakers
- environmentally friendly operation
- better understanding of arc physics necessary for applications at higher loads (currents)

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

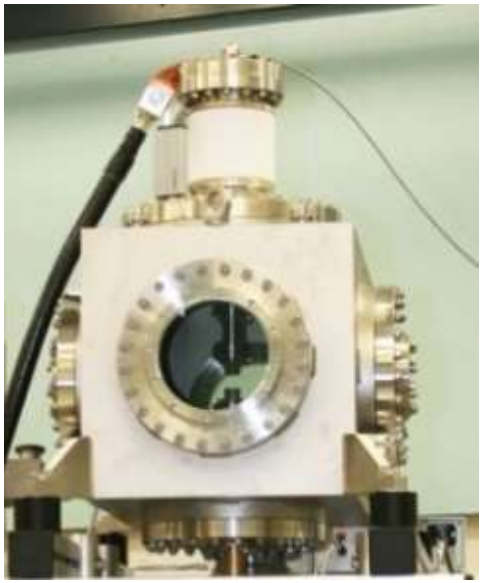


vacuum circuit breaker

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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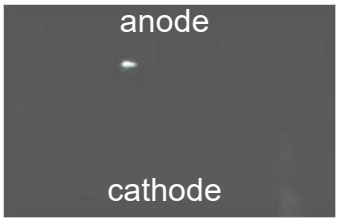
Method choice

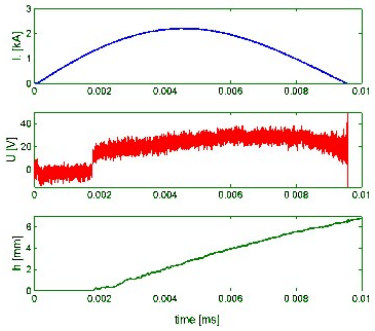
- Requirements to the method
  - simultaneous acquisition of spatial and temporal information
  - independent on plasma state (equilibrium/ non-equilibrium)
  - work with and without the plasma emission
- **Video spectroscopy** as possible solution for highly dynamic objects with sufficient light emission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

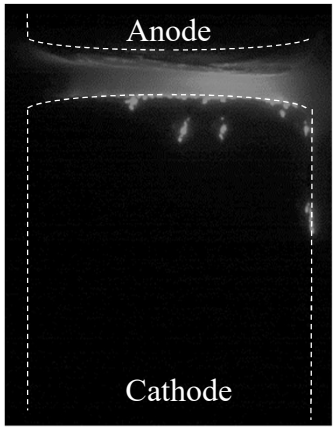
Discharge modes in vacuum arc



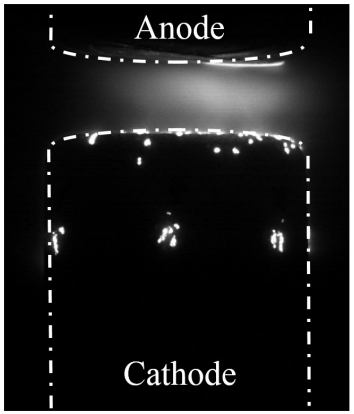


Anode activity depends on discharge mode

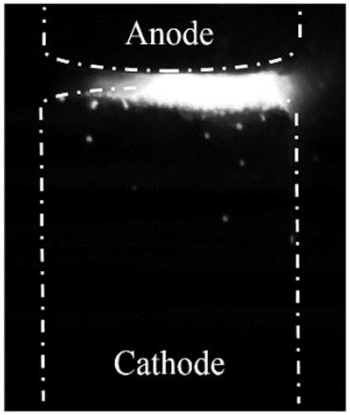
- diffuse
- footpoint
- intense
- anode spot 1 and 2
- anode plume



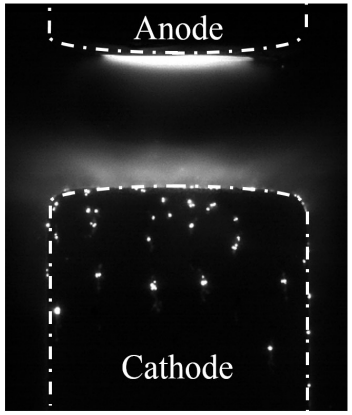
diffuse



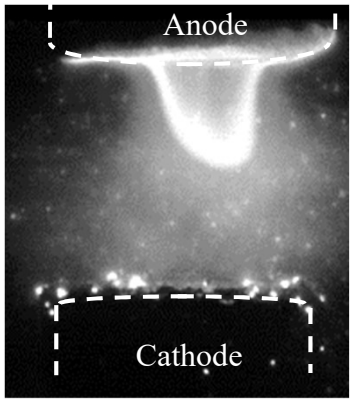
footpoint



intense mode

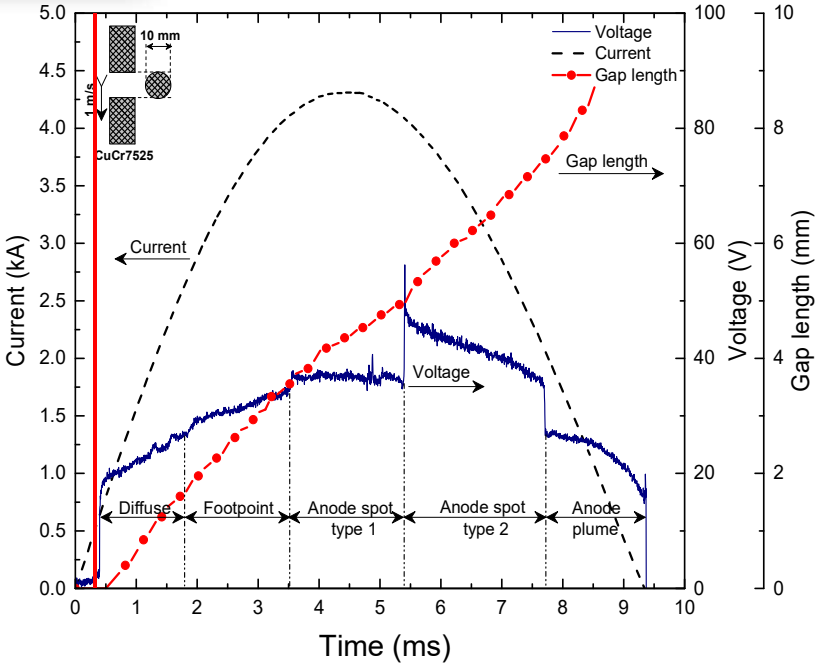


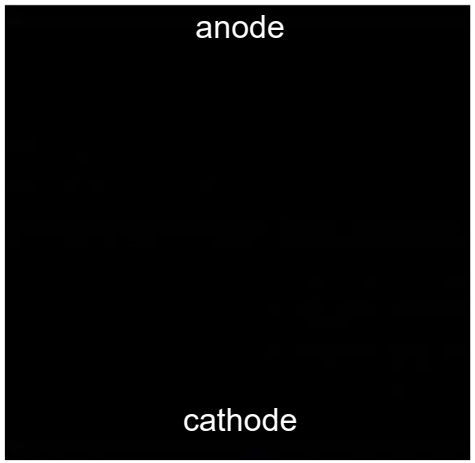
anode spot 1

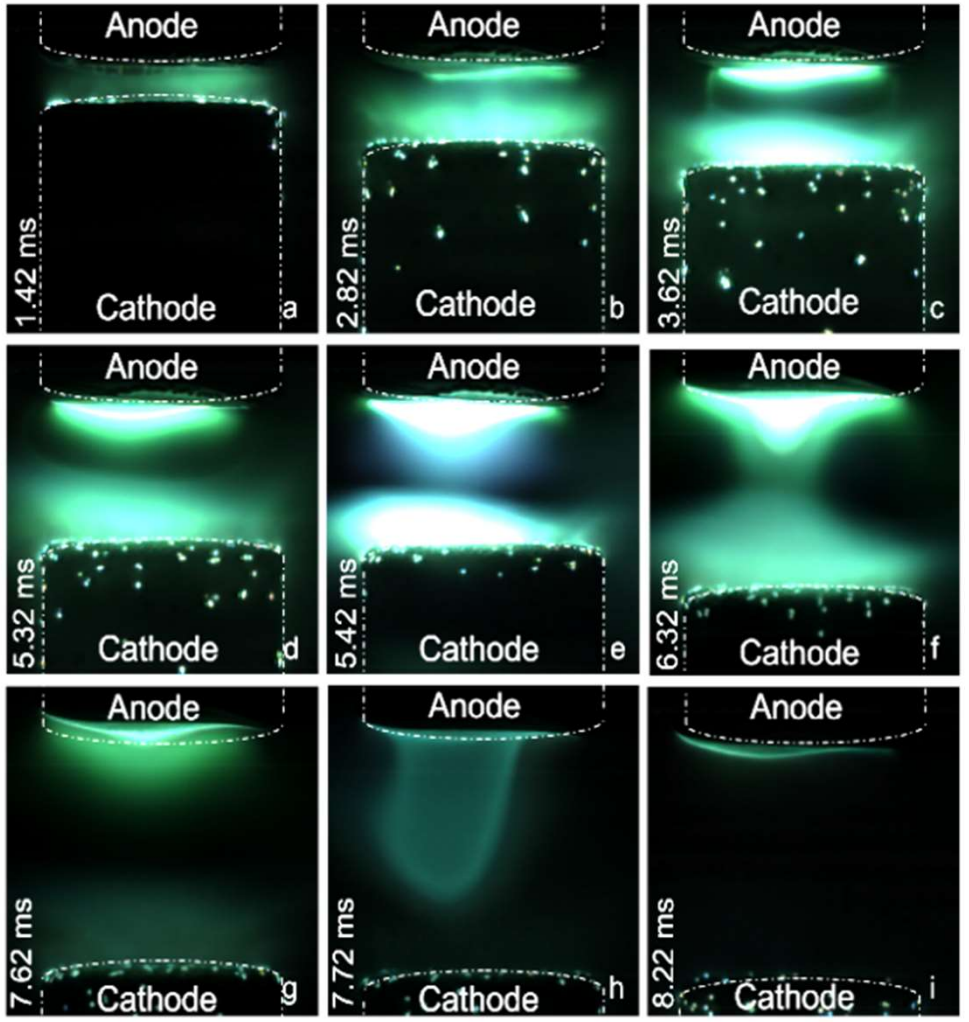


anode plume

High-current anode modes

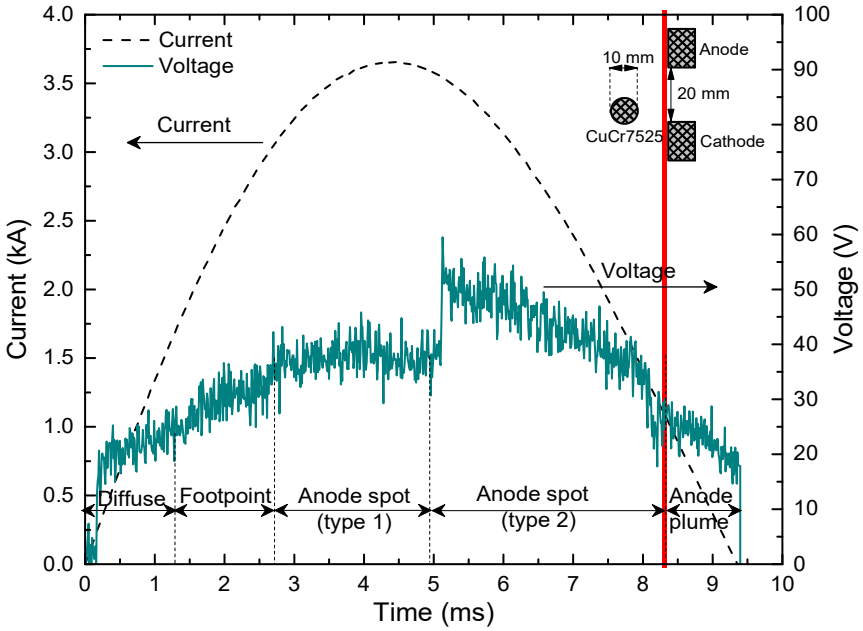


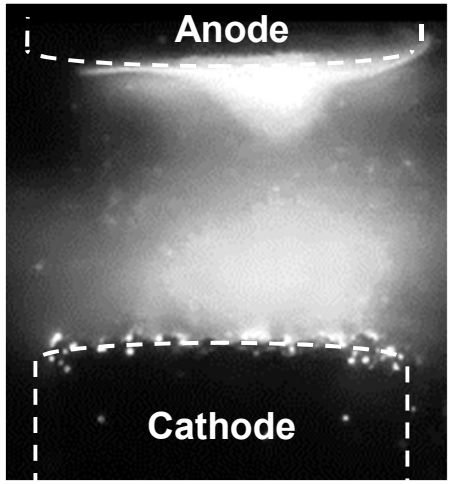


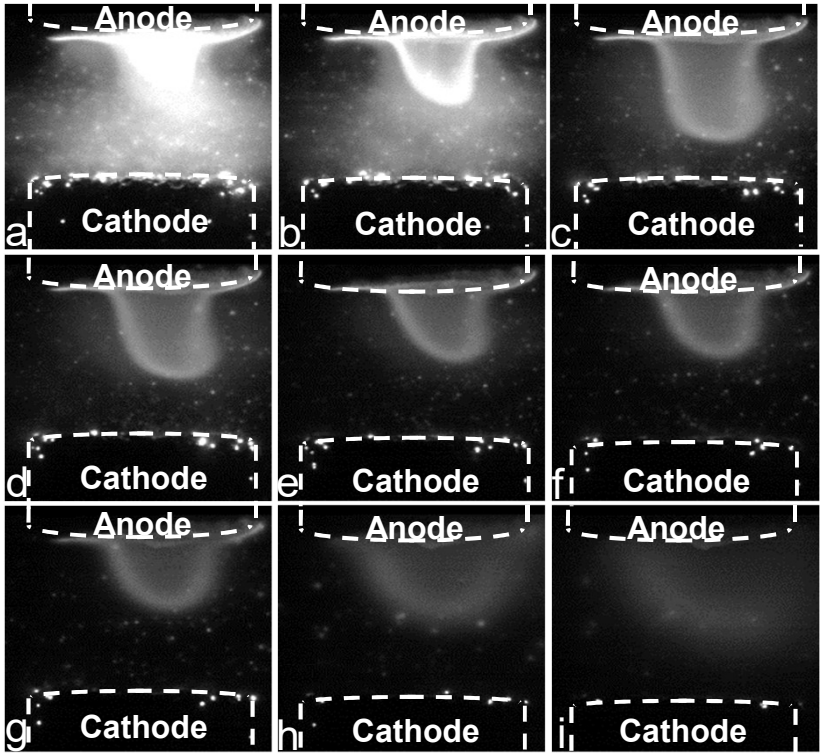


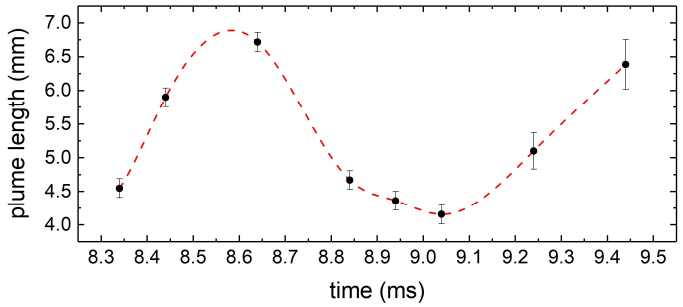
Different discharge modes

High-current anode modes: anode plume formation



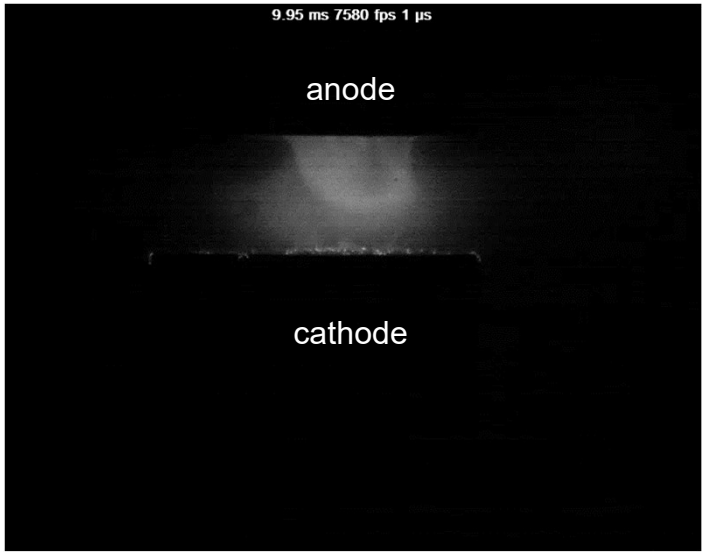






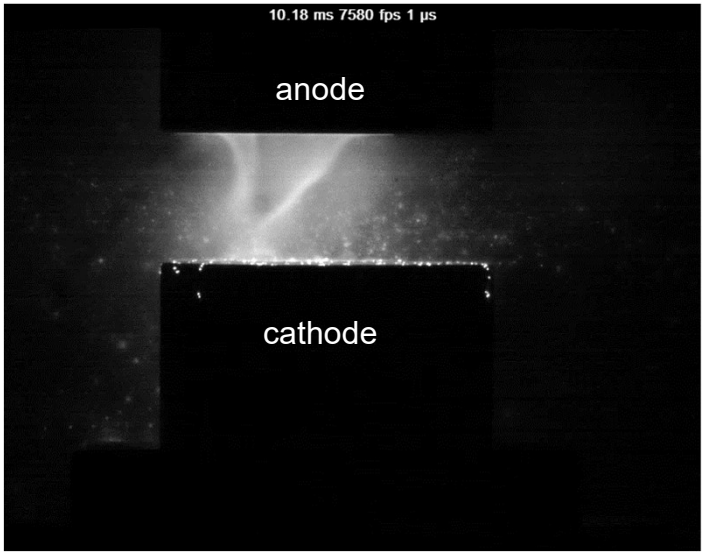
High-current anode modes

successful termination



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

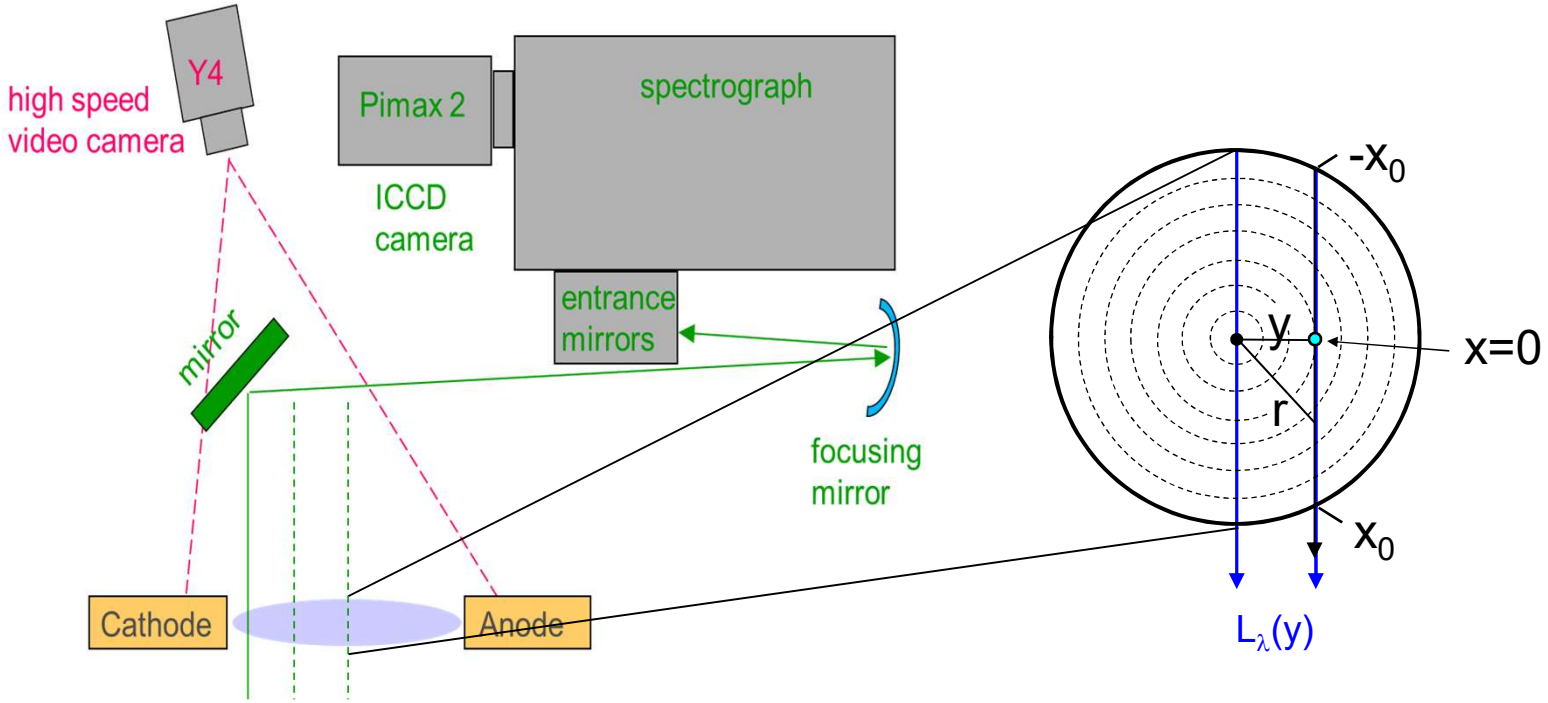
fail



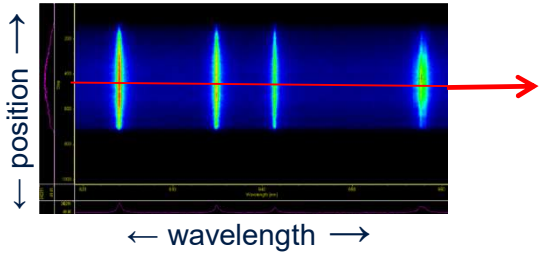
- Anode spot type 2 formation t=0.3 ms
- Anode plume touches the cathode at t= 3.6 ms
- Earlier formation of the anode spot type 2 and anode plume → stronger electrode evaporation

Video spectroscopy

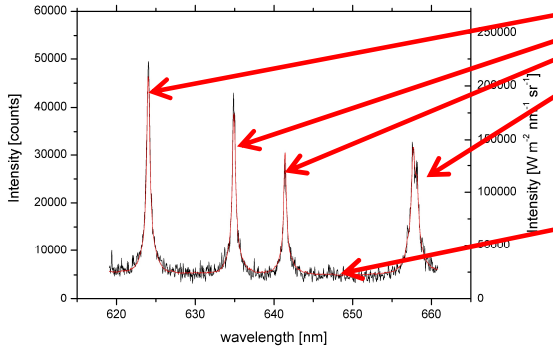
Conventional OES



iCCD image



spectrum



- Line radiation
  - intensity
  - line width
- Continuum radiation
  - intensity

Video spectroscopy

Conventional OES

Video OES

- 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

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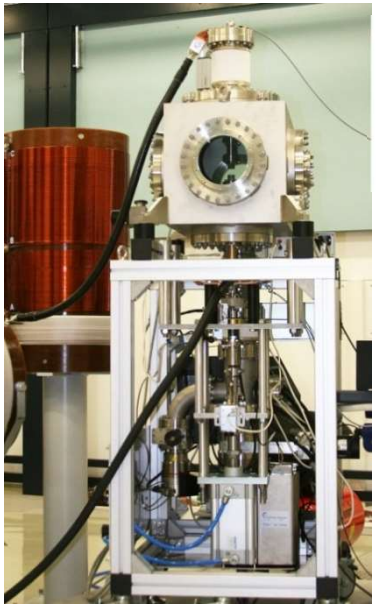

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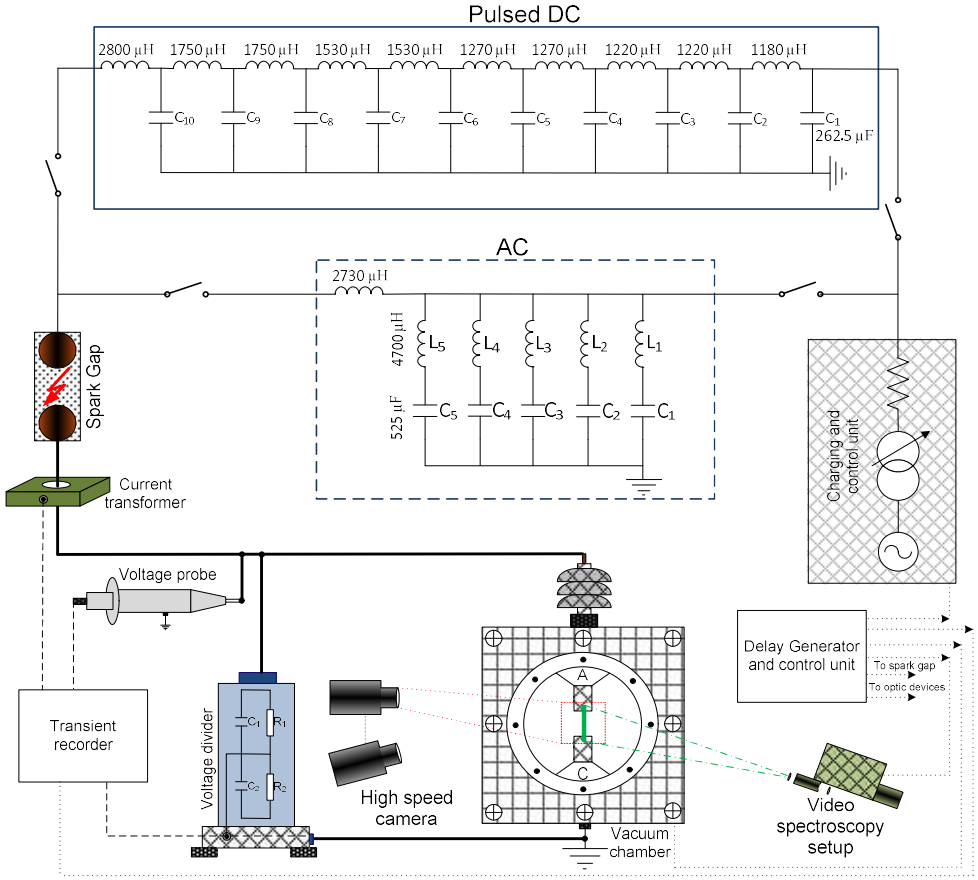
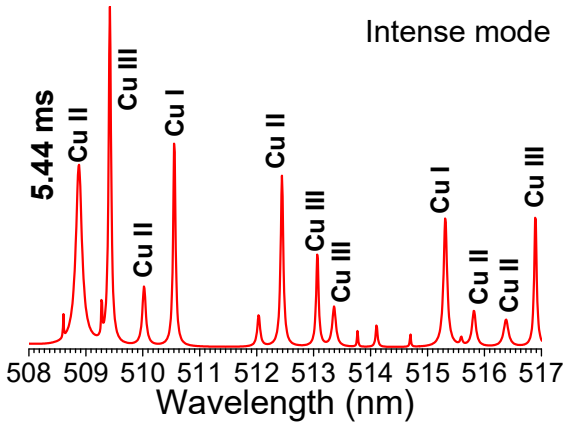
- LC pulse generator
- AC 50 Hz, 3.7 kA

- 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

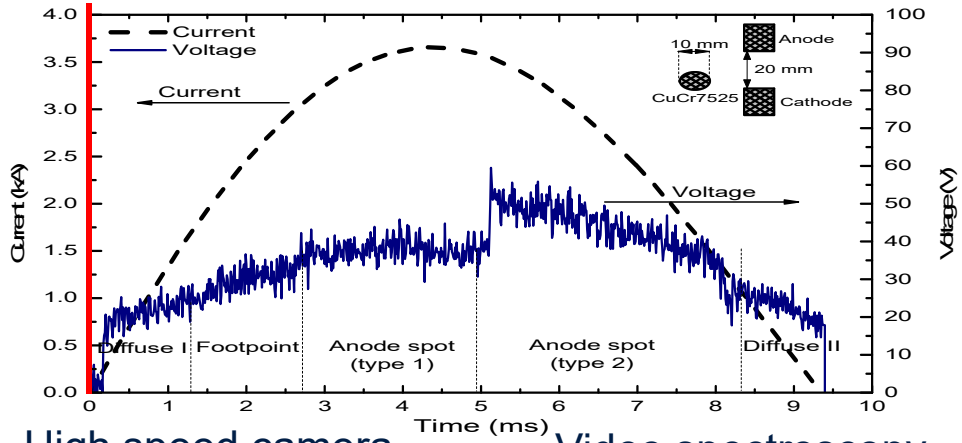
Video spectroscopy: experimental setup





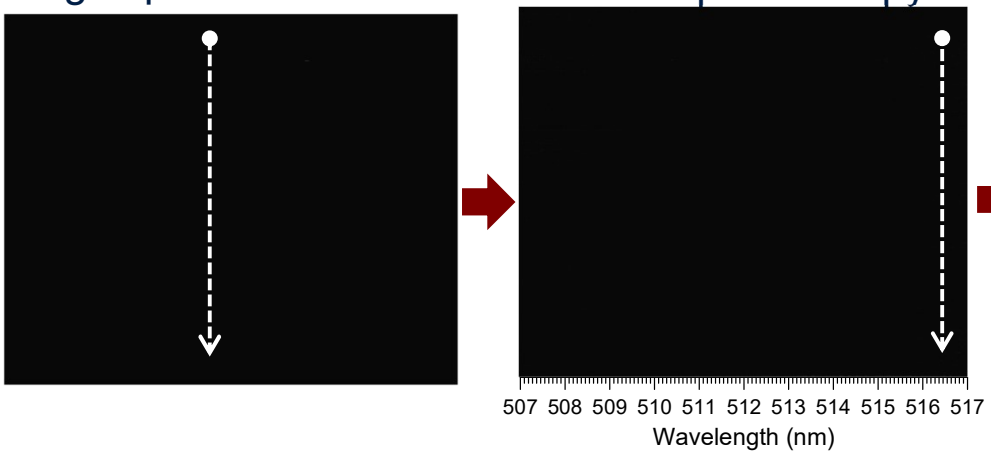
- Spectral interval 508–517 nm
- Selected spectra lines
  - Cu I 510.55 and 515.32 nm
  - Cu II 512.45 and 508.90 nm
  - Cu III 509.42 and 516.89 nm

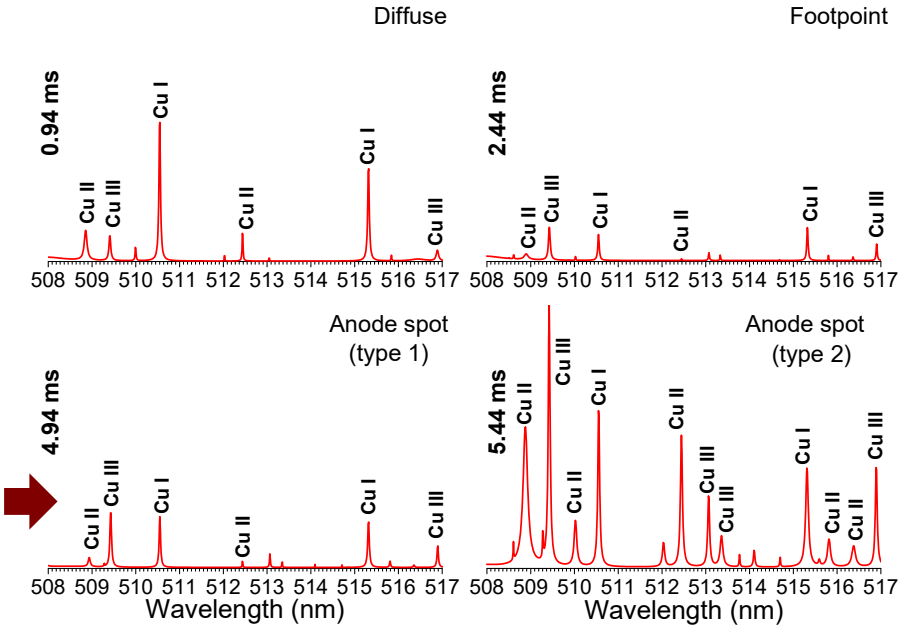
Video spectroscopy: results for AC 50 Hz



High speed camera

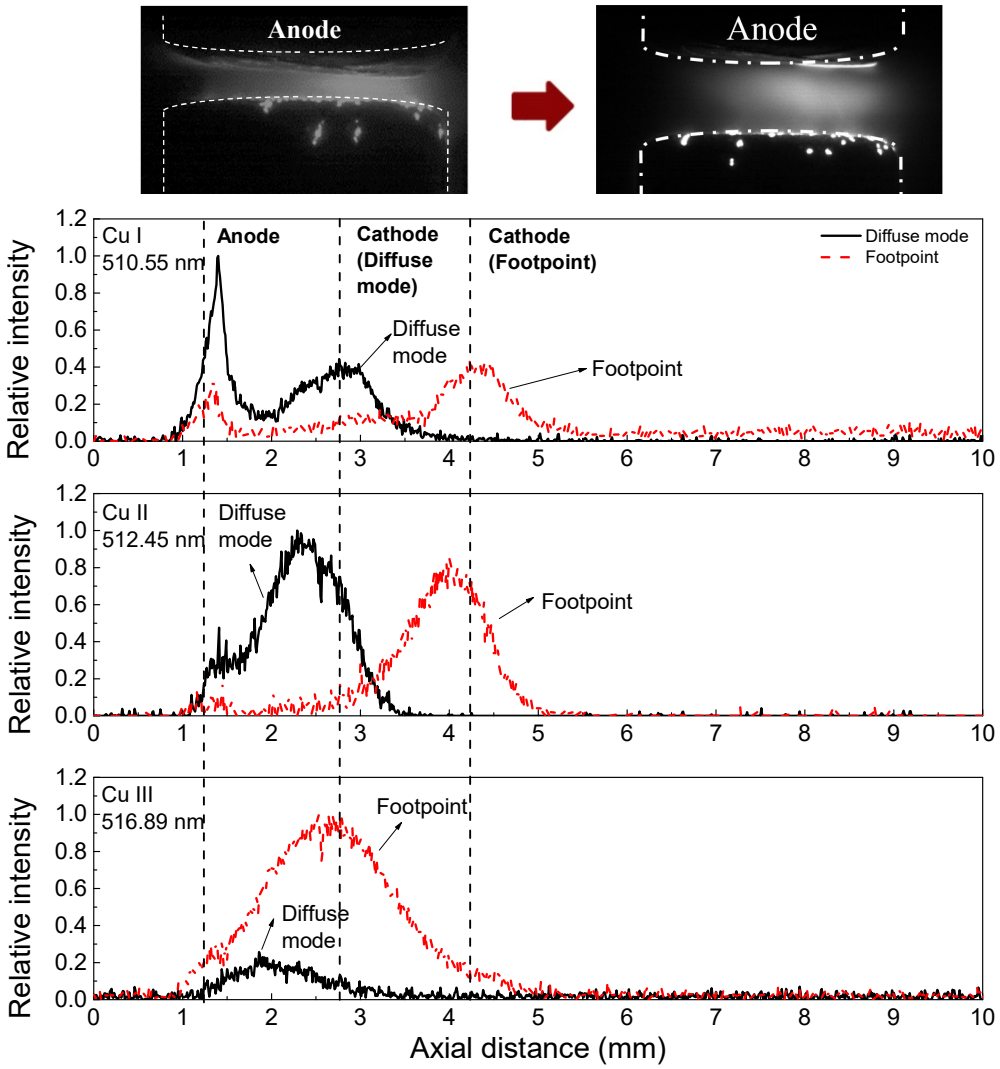
Video spectroscopy





Video spectroscopy: results for AC 50 Hz

Transition from diffuse to footpoint mode



Cu I

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

Cu II

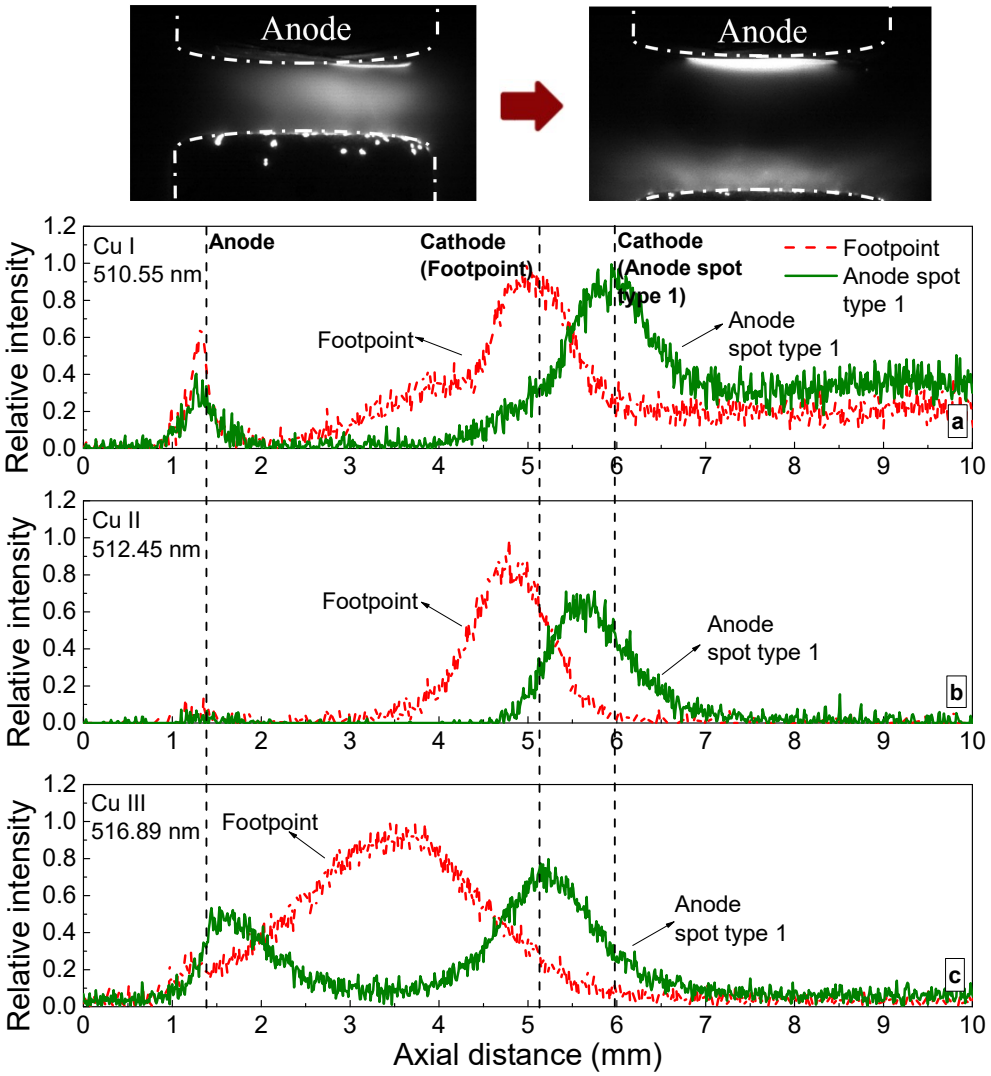
- similar behavior as for Cu I
- almost no changes near the cathode, slight decrease near the anode and in the gap in case of footpoint mode

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

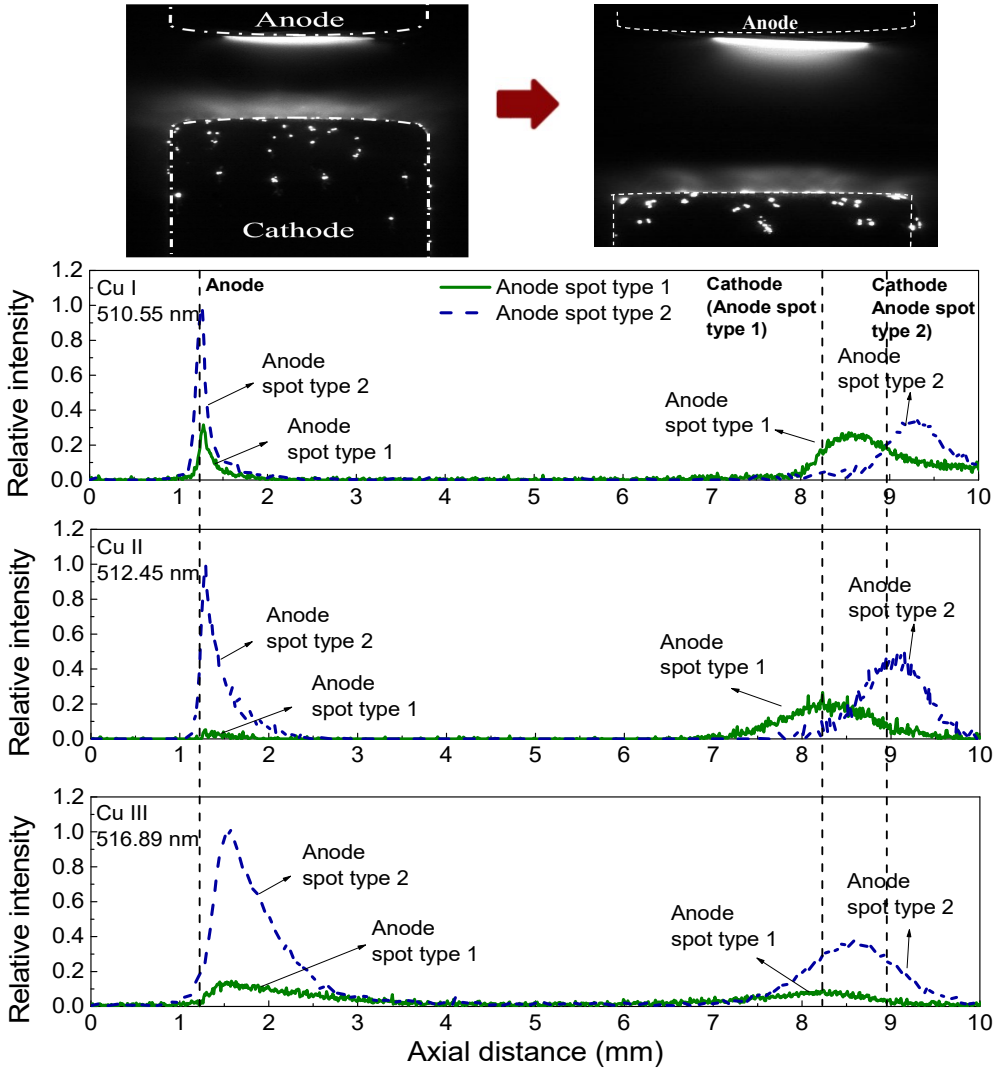
Cu III

- 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

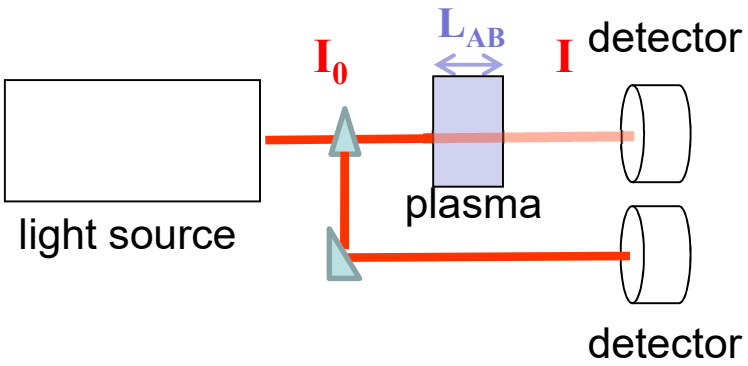
Transition from anode spot type 1 to anode spot type 2



- 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

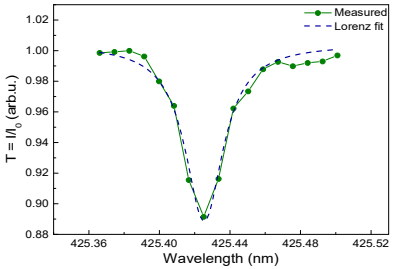
Optical absorption spectroscopy (OAS)

- Light source and detector



- 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

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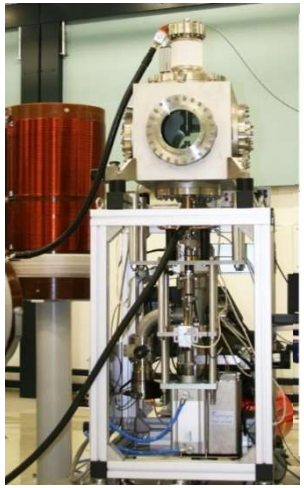

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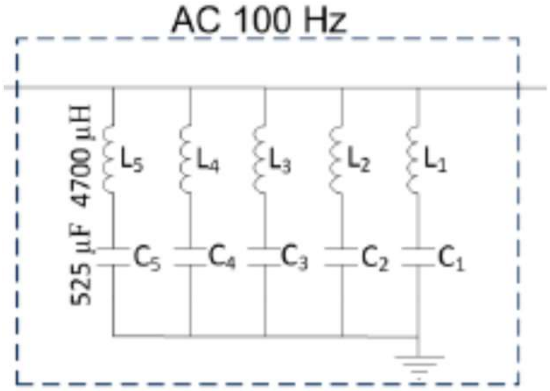


LC pulse generator

- AC 100 Hz, 7 kA

Vacuum chamber:

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

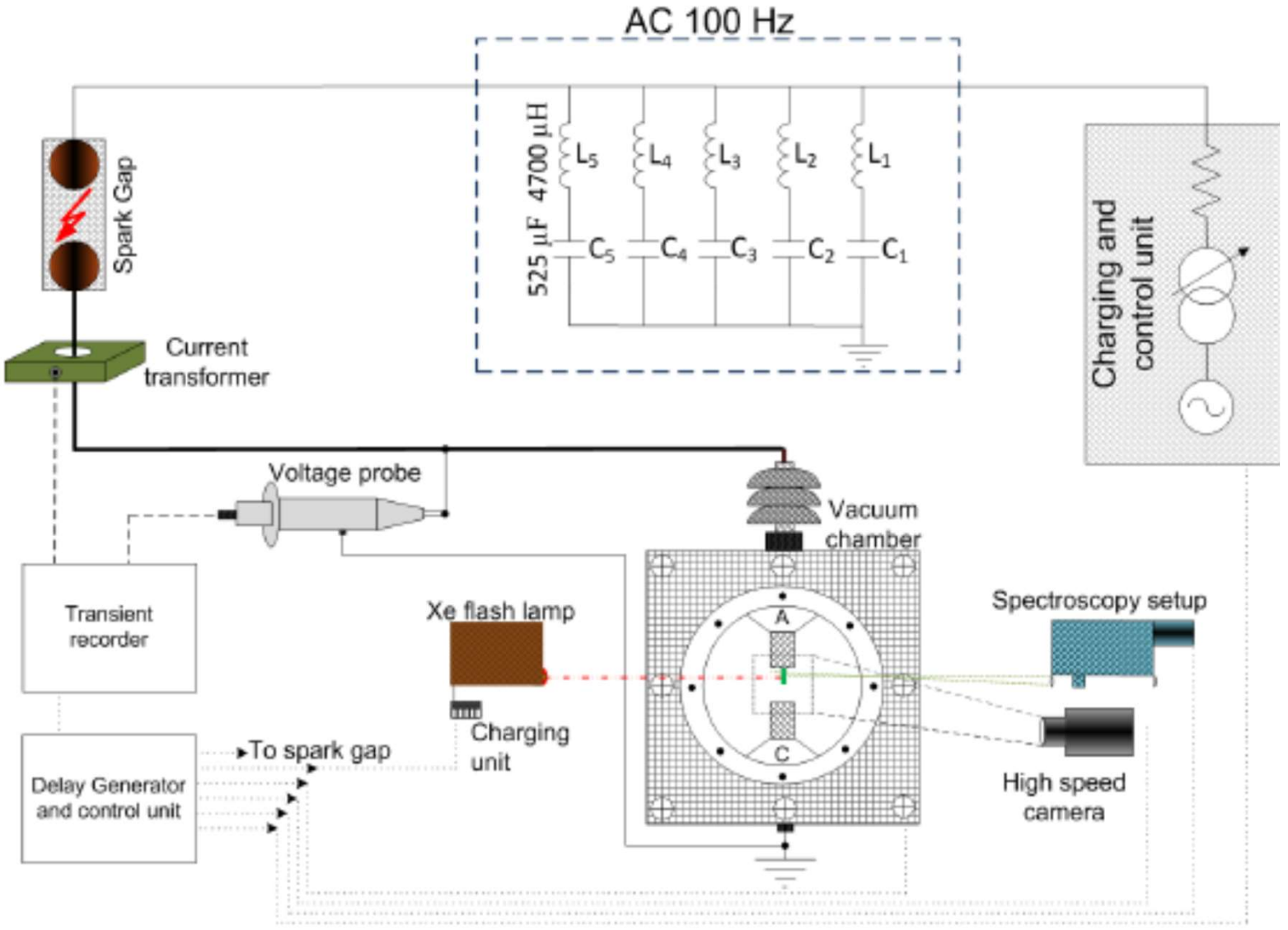
Actuator: opening speed 2 m/s

Contacts: CuCr7525, diameter 10 mm

Optical diagnostics

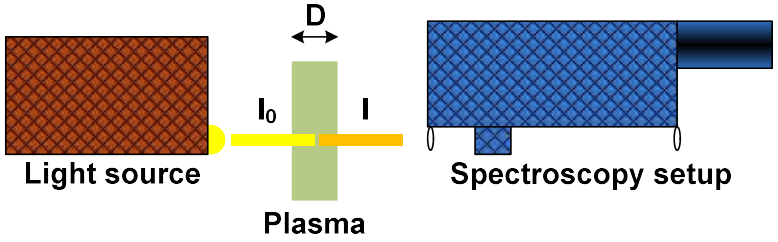
- High-speed camera
- Absorption spectroscopy
  - pulsed Xe lamp
  - imaging spectrograph
  - optical system
  - Acquisition time 200 µs

OAS: experimental setup



OAS: measurements with and without plasma

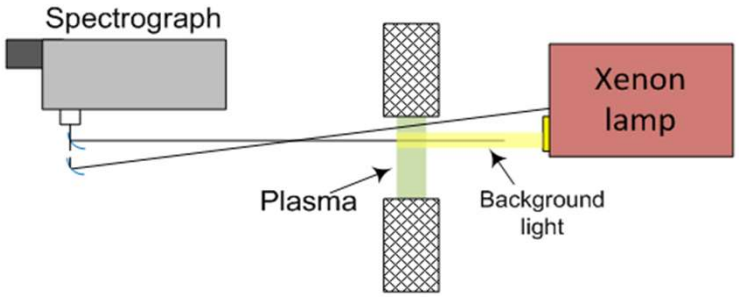
After CZ, without significant plasma radiation



$$T = \frac{I}{I_0}$$

$$\int_0^\infty kDd\lambda = \int_0^\infty \ln\left(\frac{I_0}{I}\right)d\lambda = \frac{\pi e^2 \lambda_0^2 D N_l f_{lu}}{4\pi\varepsilon_0 m_e c^2}$$

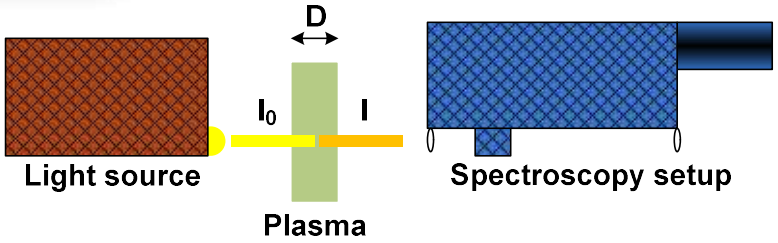
Active phase, strong plasma radiation

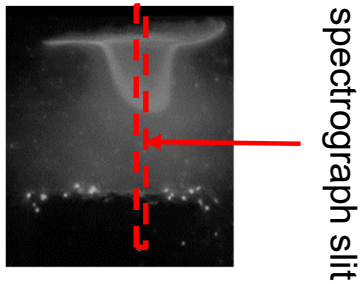


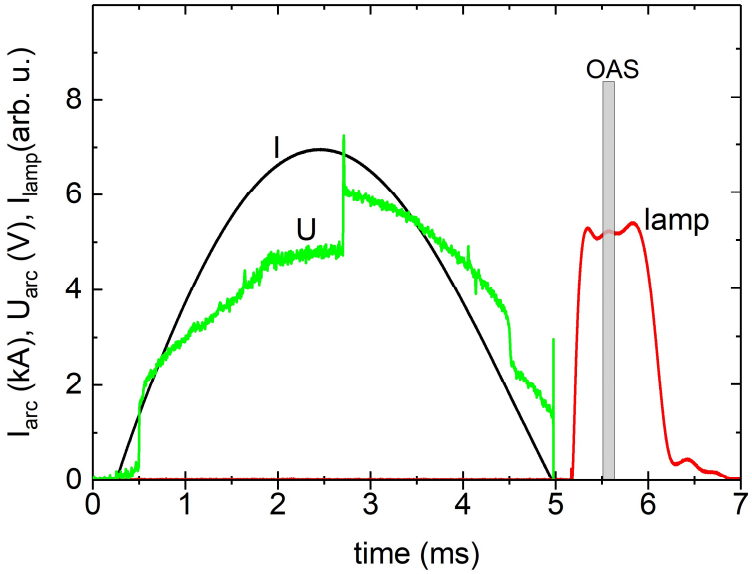
$$T = \frac{PL - P}{L}$$

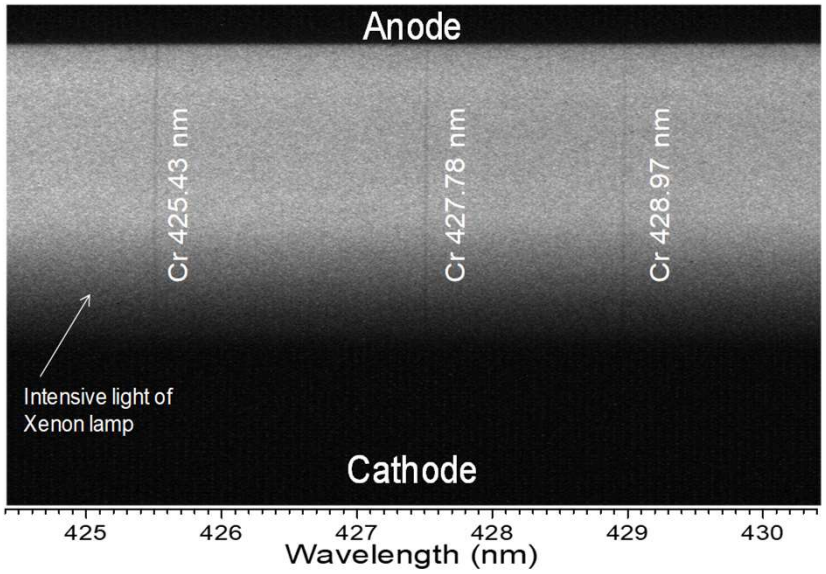
$$\int_0^\infty kDd\lambda = \int_0^\infty \ln\left(\frac{L_\lambda}{PL_\lambda - P_\lambda}\right)d\lambda = \frac{\pi e^2 \lambda_0^2 D N_l f_{lu}}{4\pi\varepsilon_0 m_e c^2}$$

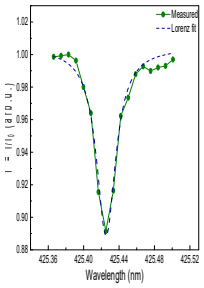
OAS: measurements after current zero

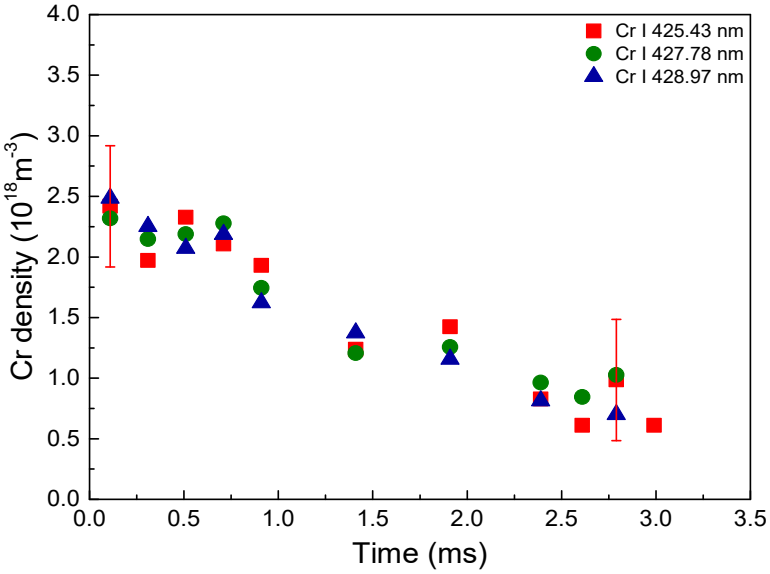




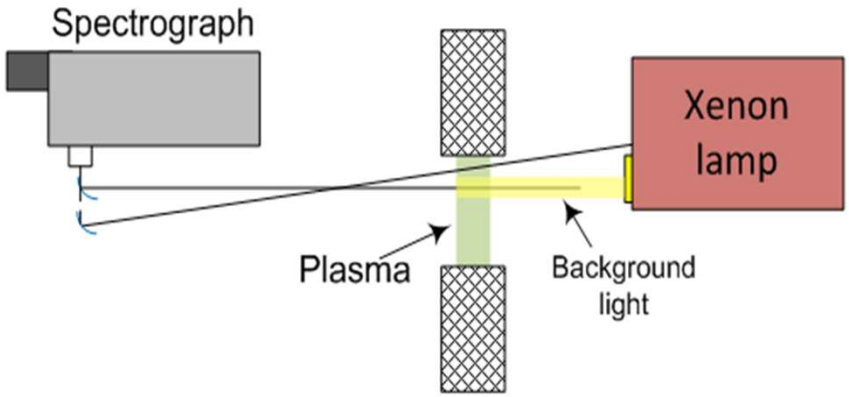


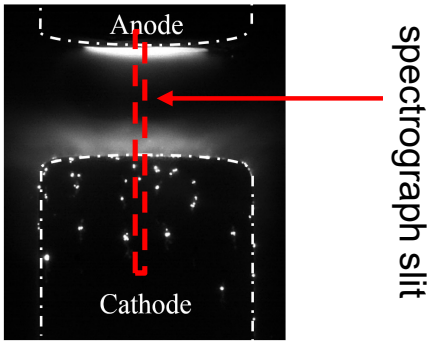


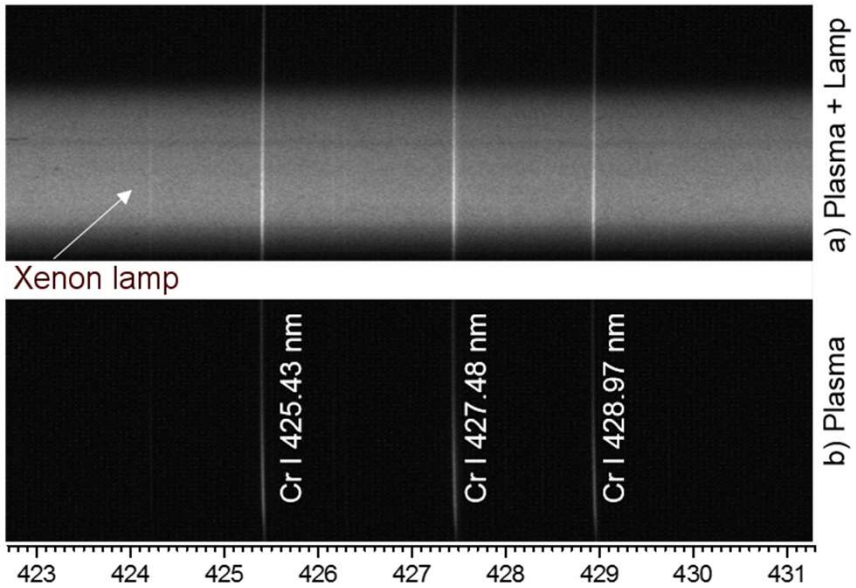


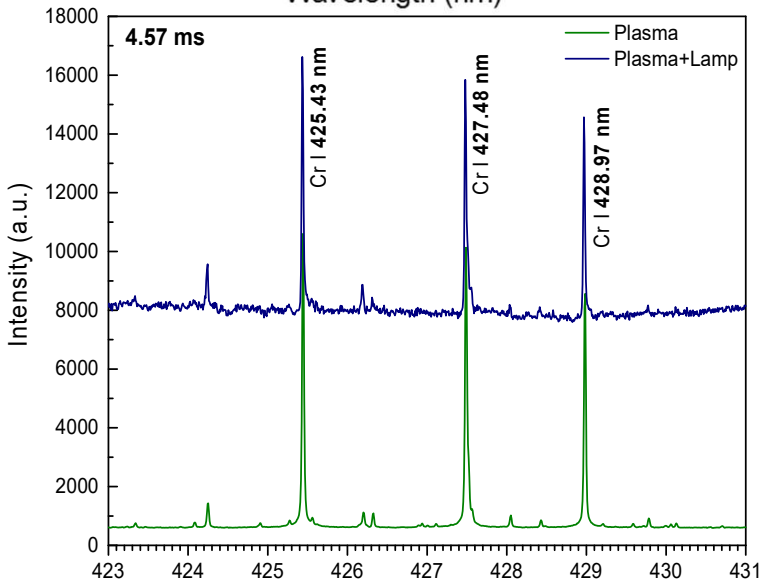


OAS: measurements during the active phase



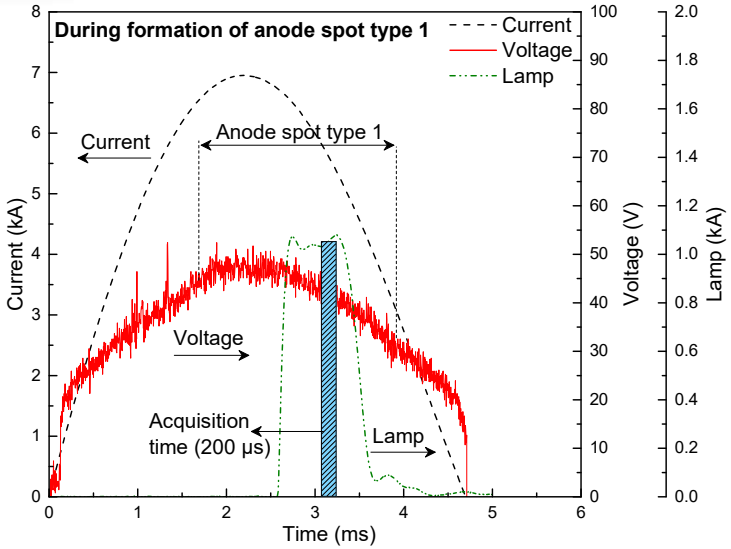




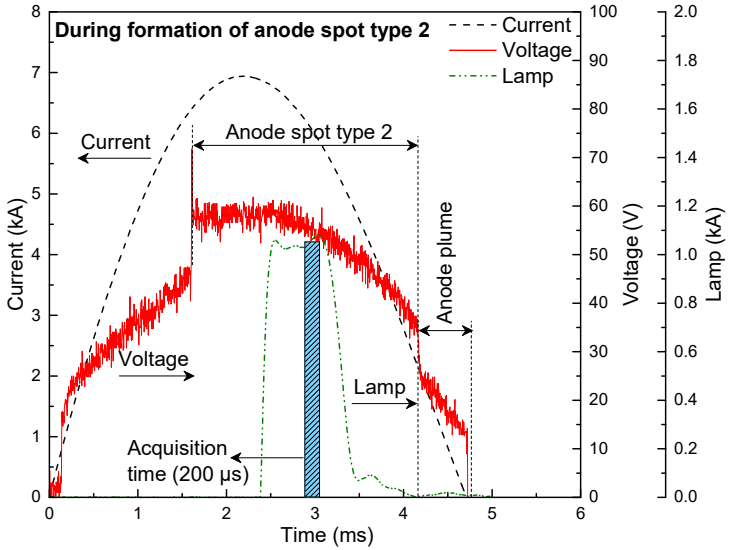


OAS: Cr density during high-current modes

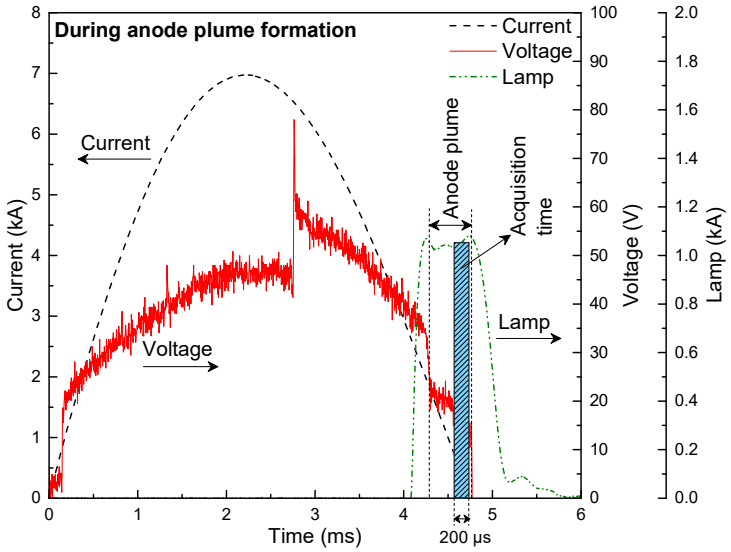
Anode spot type 1



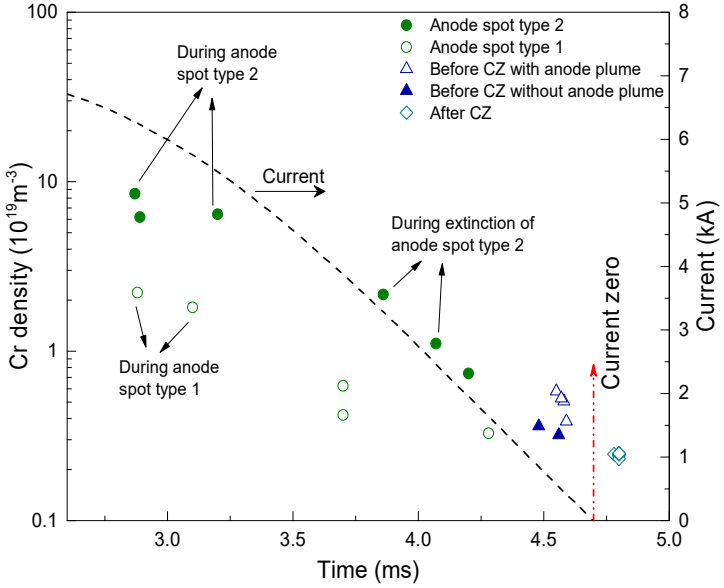
Anode spot type 2



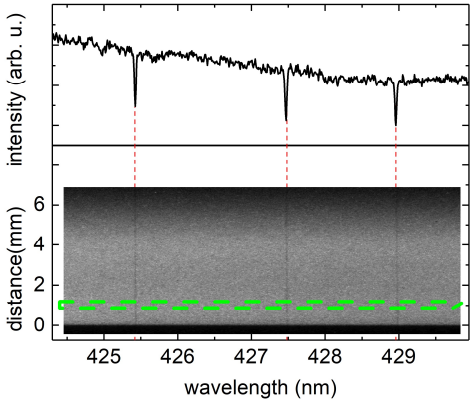
Anode plume

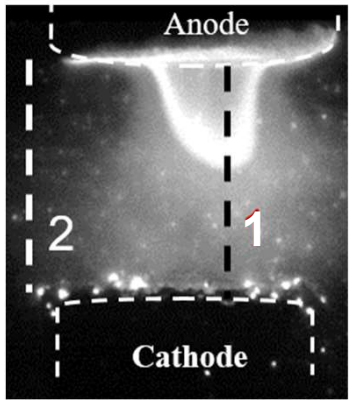


Cr density during high-current modes

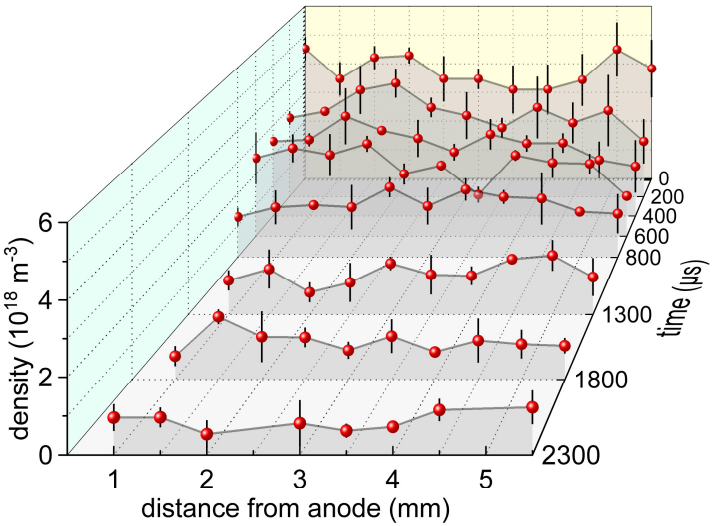


OAS: spatial distribution of Cr density

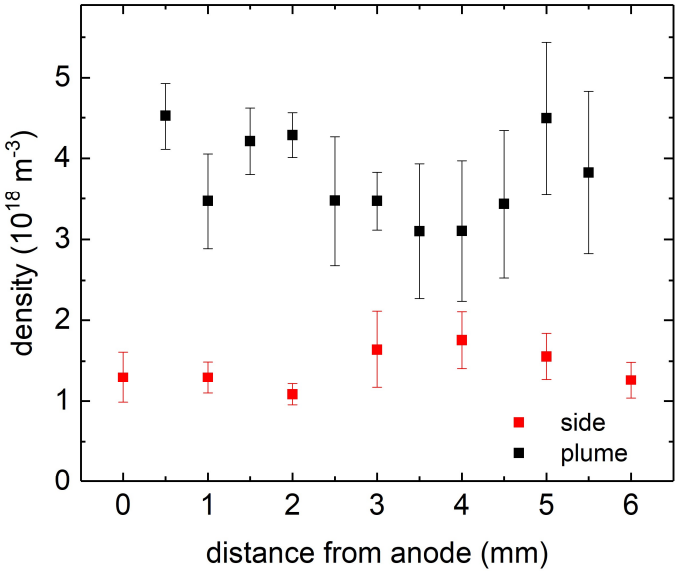




distribution inside the plume



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!

ISDEIV 2018

28th International Symposium on Discharges and Electrical Insulation in Vacuum

September 23-28, 2018
Greifswald, Germany

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*

Correspondence address

INP Greifswald
Felix-Hausdorff-Strasse 2
17489 Greifswald
Germany

Tel: +49 3834 554 300
Fax: +49 3834 554 301
Email: conferences@inp-greifswald.de

www.isdeiv2018.org

Thank you very much for your attention!

Leibniz Institute for Plasma Science and Technology
Address: Felix-Hausdorff-Str. 2, 17489 Greifswald
Phone: +49 - 3834 - 554 300, Fax: +49 - 3834 - 554 301
E-mail: werlcome@inp-greifswald.de
Web: www.leibniz-inp.de