High-speed video spectroscopy in a vacuum arc during high-current anode modes

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FROM IDEA TO PROTOTYPE

Outline

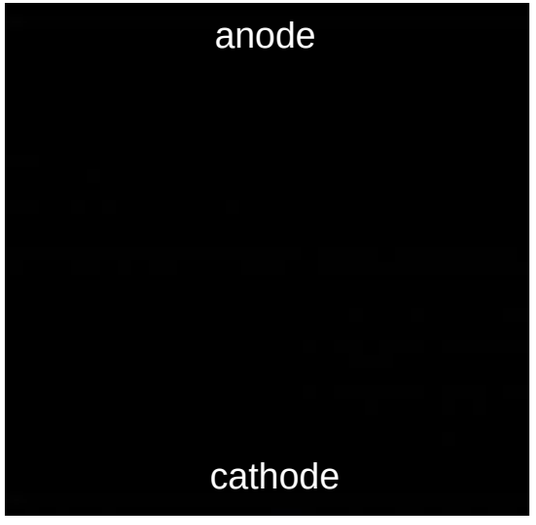
- Motivation
- Research focus
- Methodology
- Experimental setup
- High-speed video spectroscopy
- Results and Discussion
- Summary

Motivation

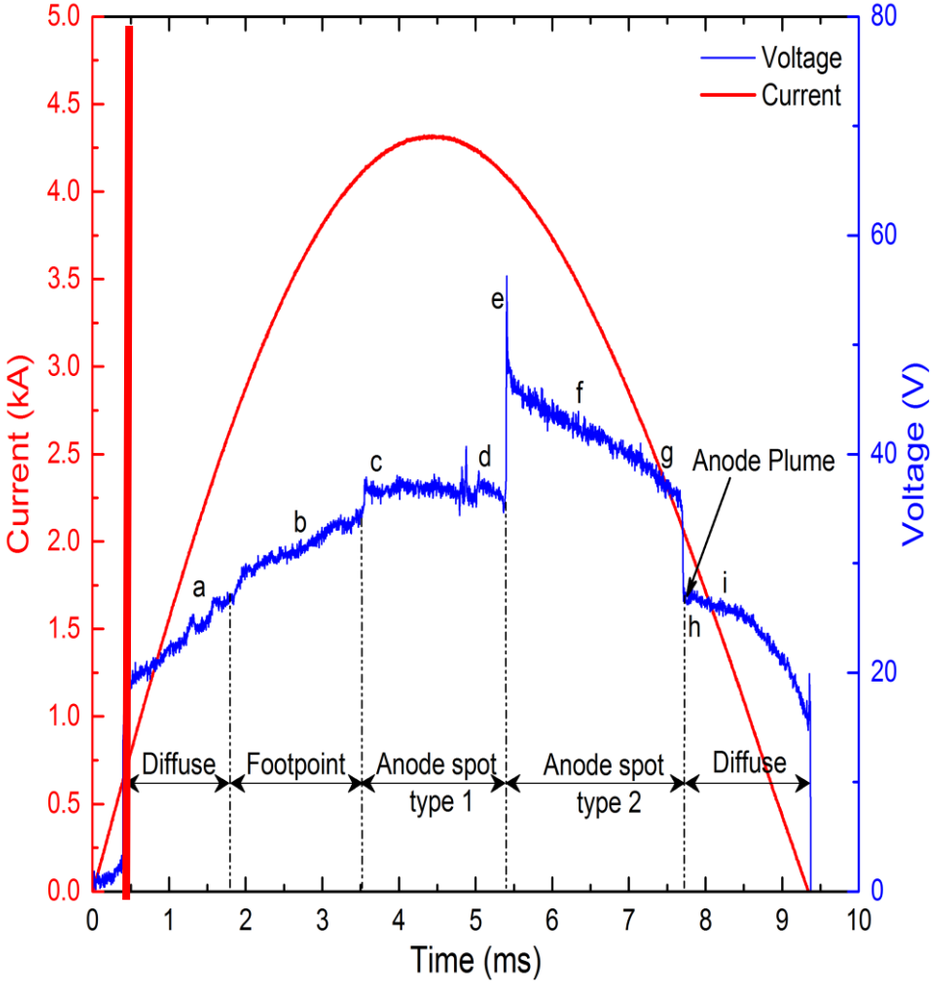
- Vacuum interrupters are important components on electrical systems up to 80 kV
- extension of their application field up to 125 kV
- better understanding of arc physics is necessary for applications at higher currents:
  - active role of the anode during high-current switching arcs,
  - impact of high-current anode phenomena on contact erosion,
  - high metal vapor emission → reduction of dielectric strength around current zero

Focus: Vacuum arc anode phenomena

high-speed video of a vacuum arc



recorded current and arc voltage



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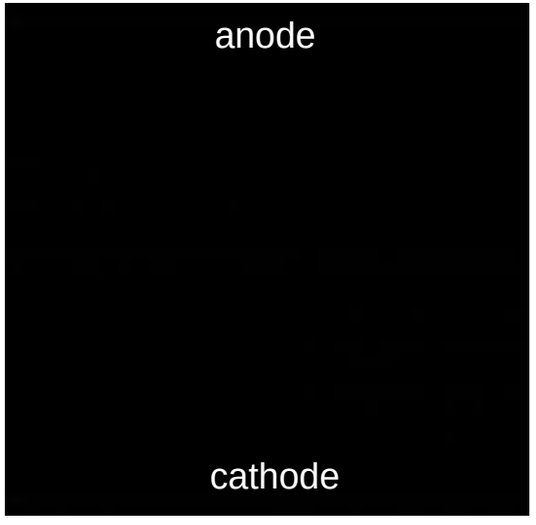

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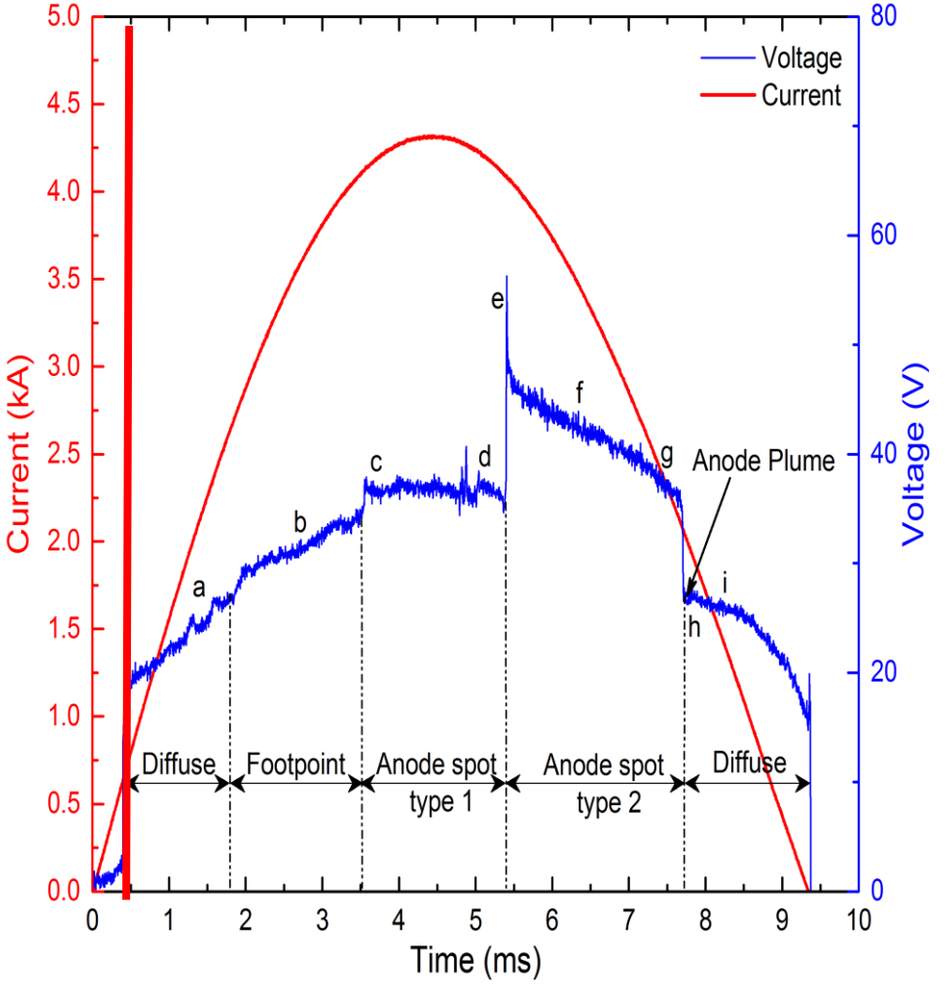
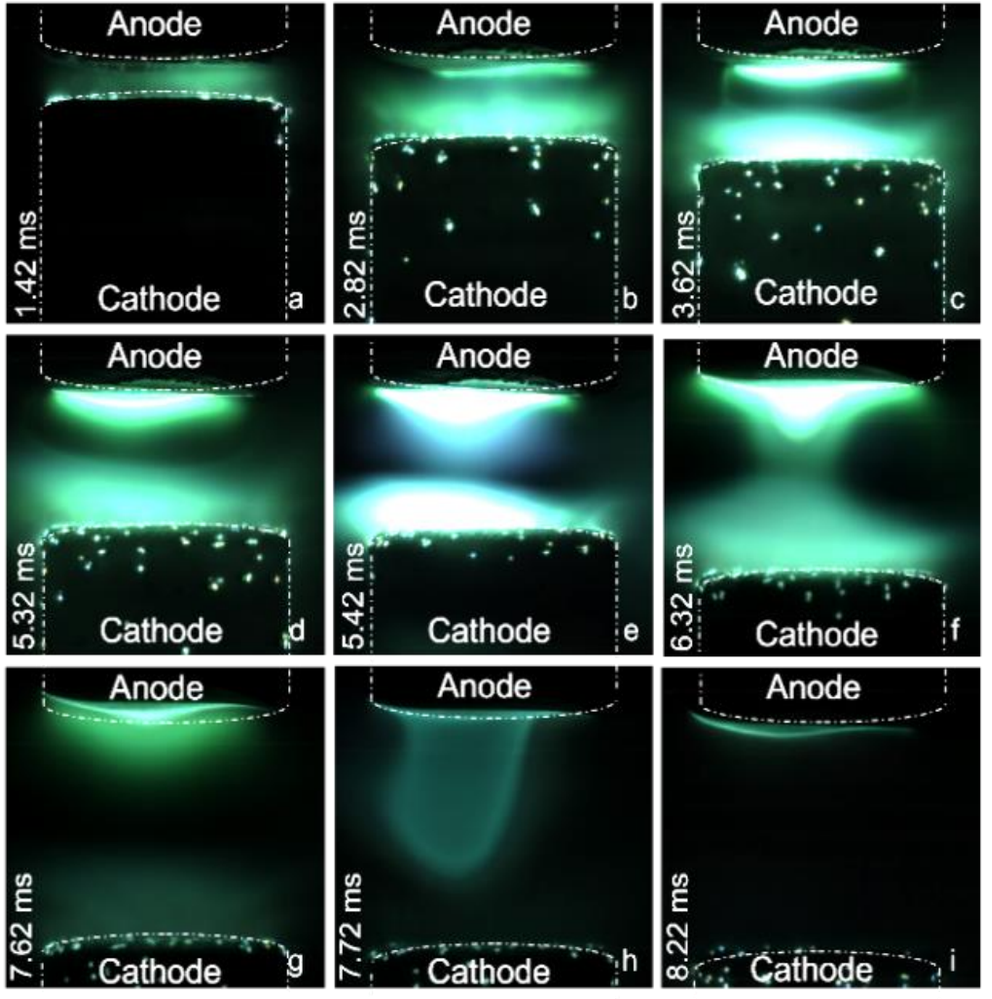


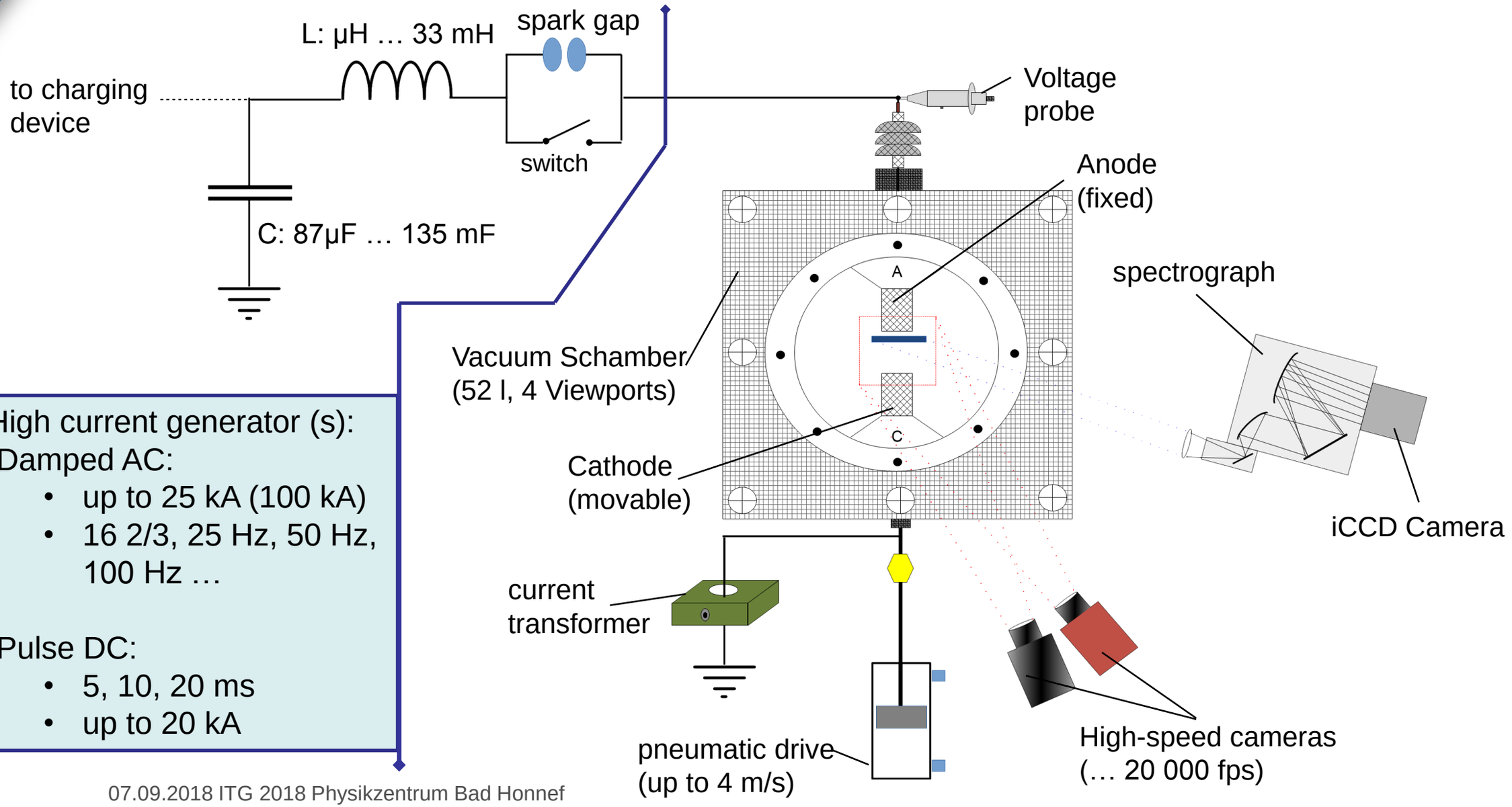
different anode attachment modes



Methodology

- Advantages of high-speed video spectroscopy for examination of temporal characteristics in experiments with limited reproducibility
- Specific focus is set on the high-current anode modes:
  - Anode spots type 1 and type 2 and
  - Anode plume after extinction of anode spot type 2.

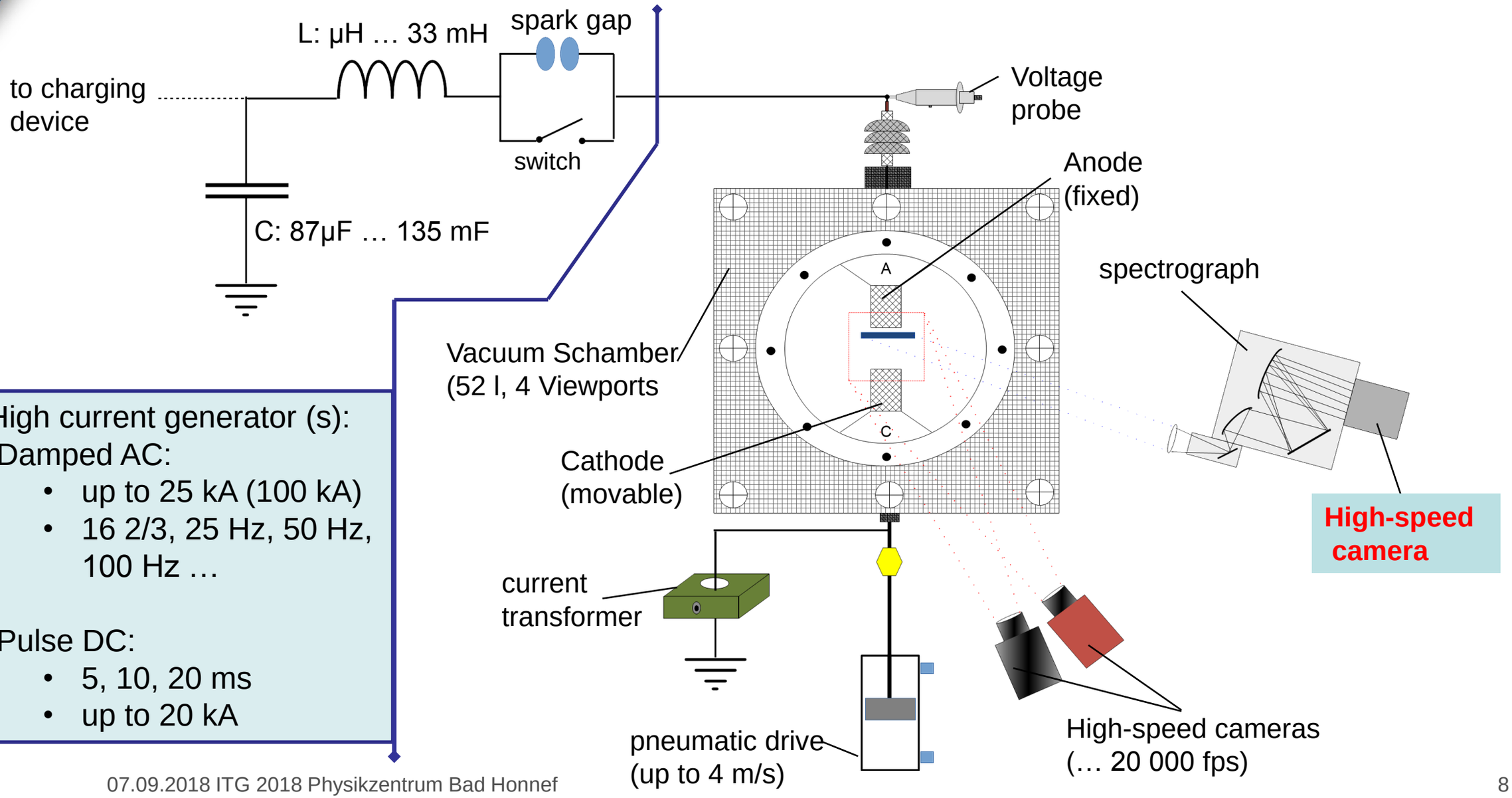
Experimental setup



High current generator (s):

- Damped AC:
  - up to 25 kA (100 kA)
  - 16 2/3, 25 Hz, 50 Hz, 100 Hz …
- Pulse DC:
  - 5, 10, 20 ms
  - up to 20 kA

Experimental setup and high-speed video spectroscopy



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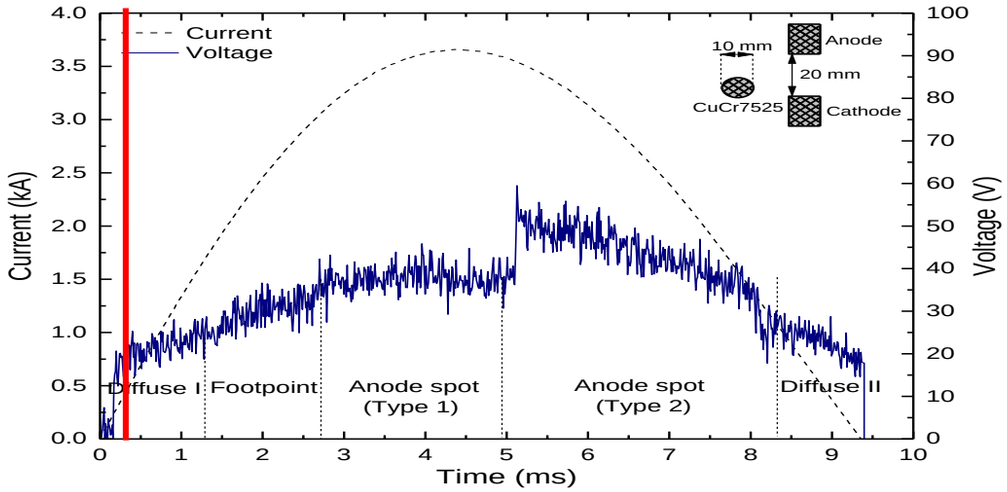
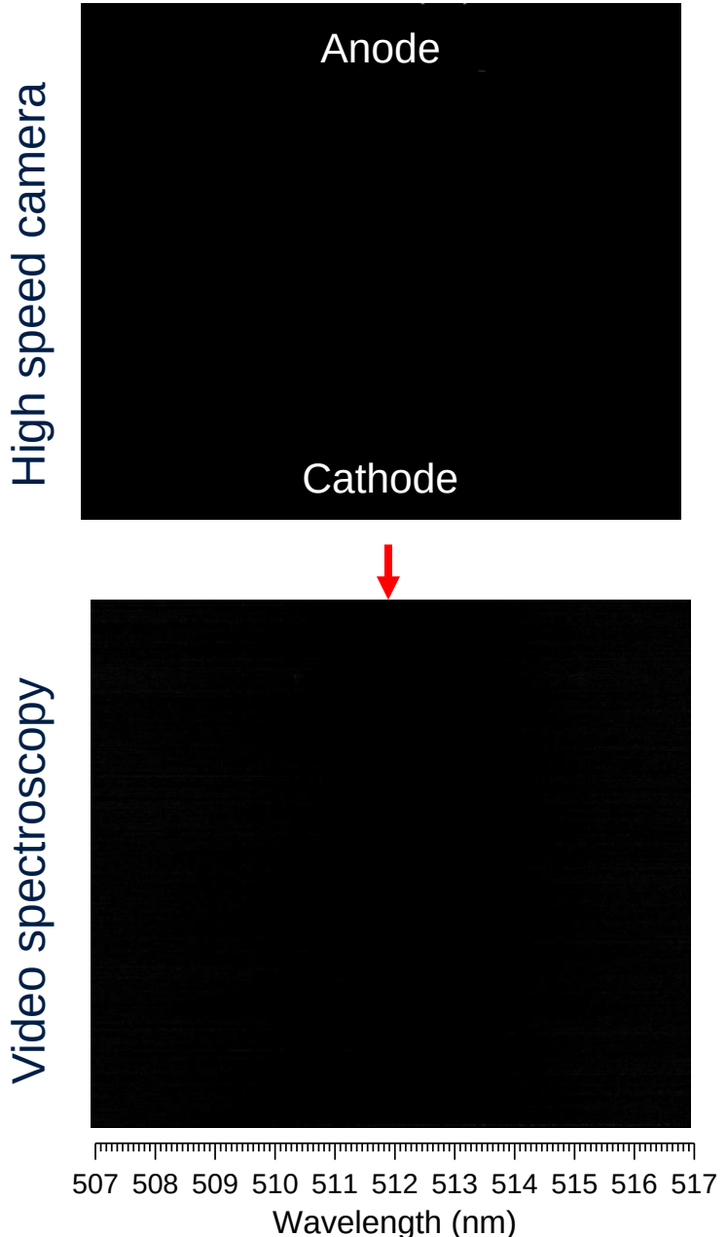
High-speed video spectroscopy

- High-speed spectroscopy:
  - High-speed camera instead of iCCD detector
  - high spatial and temporal resolution
  - series of spectra within one experiment (up to 20000 fps)
  - requires sufficient light intensity
  - requires proof of linearity of detector-chip
  - **study of the temporal evolution of line radiation of different atoms and ions**

- Conventional spectroscopy:
  - iCCD detectors for weak intensity radiation
  - high spatial resolution
  - temporal resolution of ns but low repetition rate (1 … 10 fps)

Results and discussion (overview)





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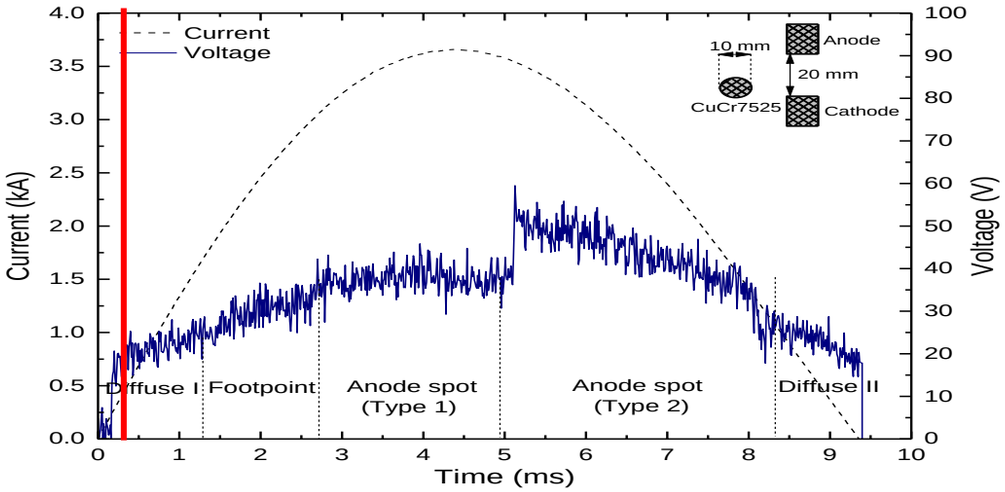
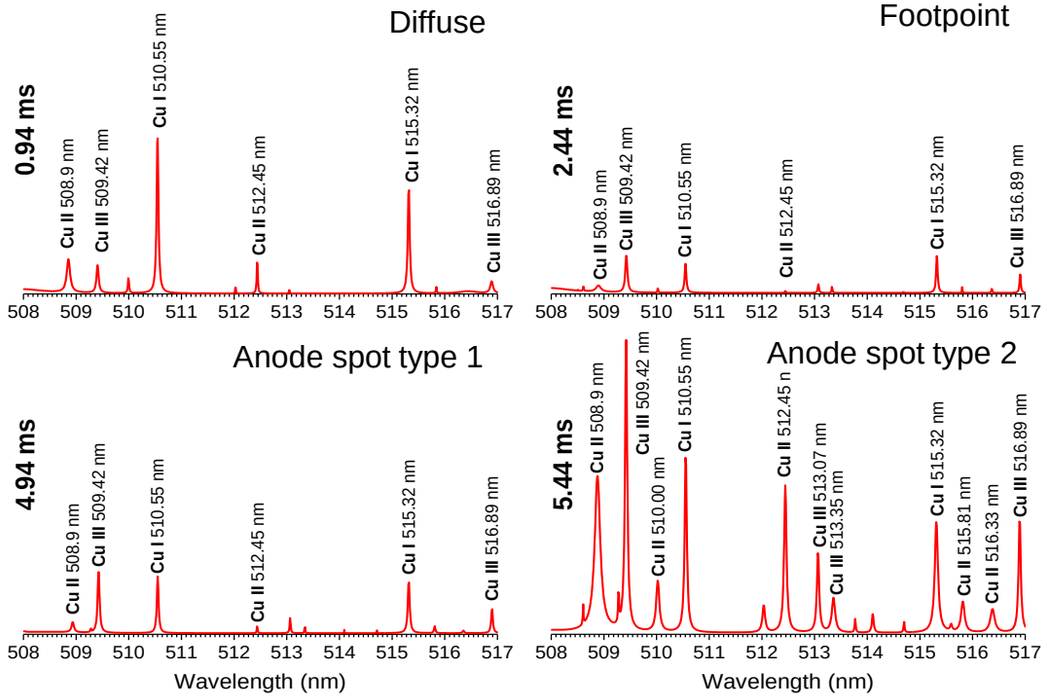
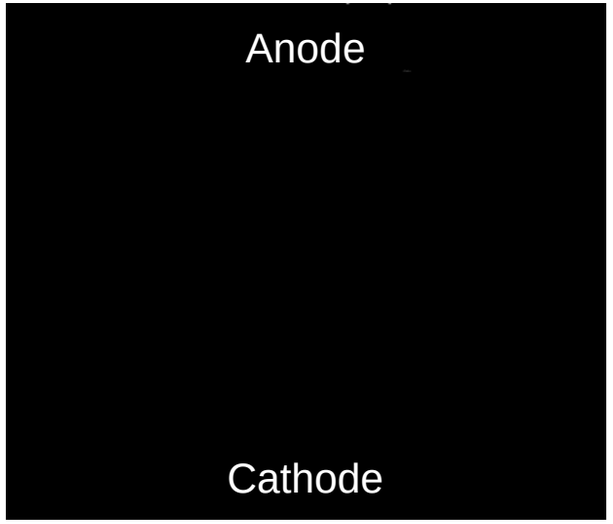
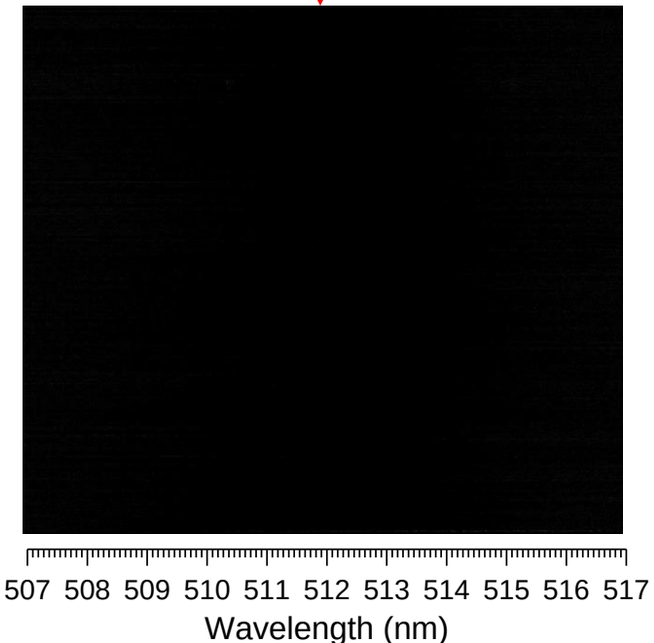




High speed camera

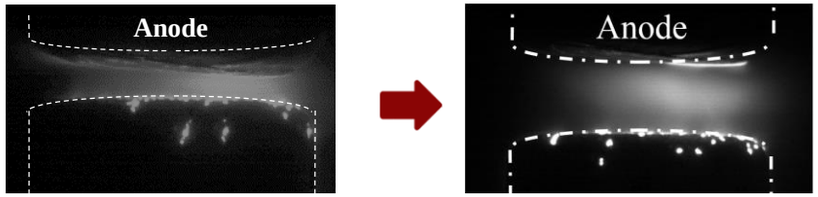


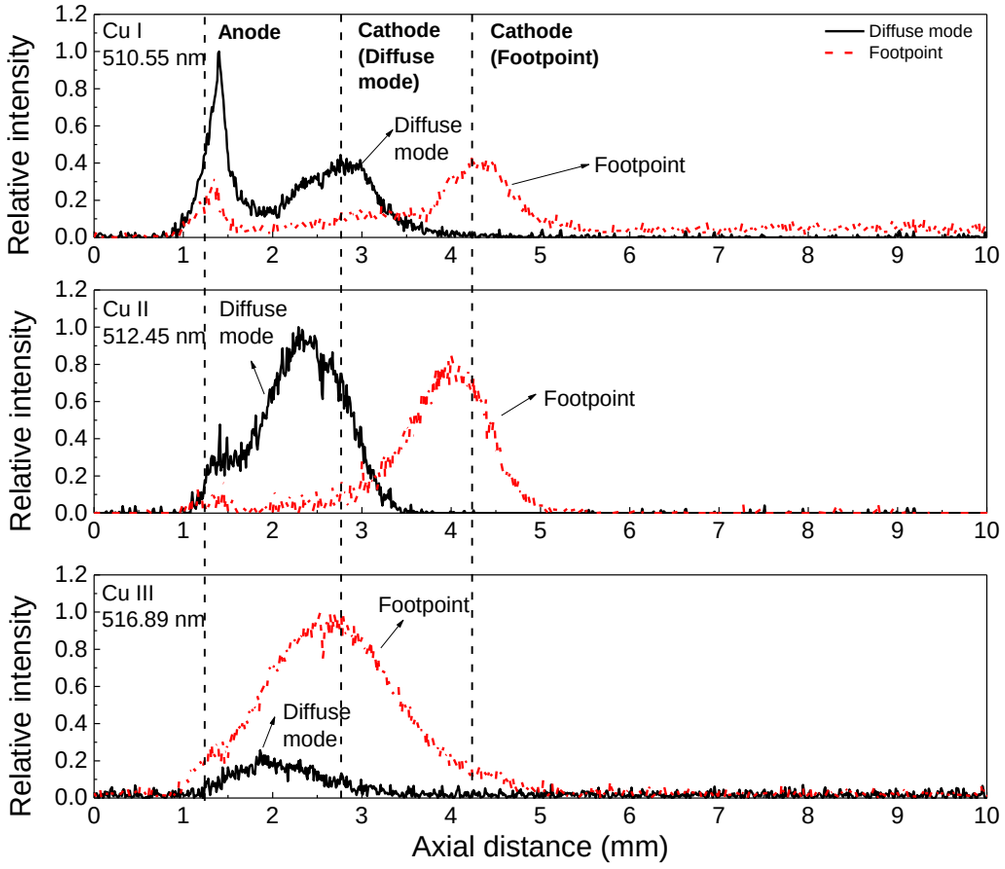
Video spectroscopy



Results and discussion (overview)

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

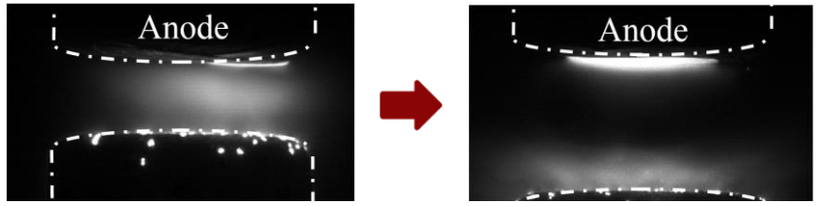
- similar behavior as for Cu I
- almost no changes near the cathode, slight decrease near the anode and in the gap in case of footpoint mode

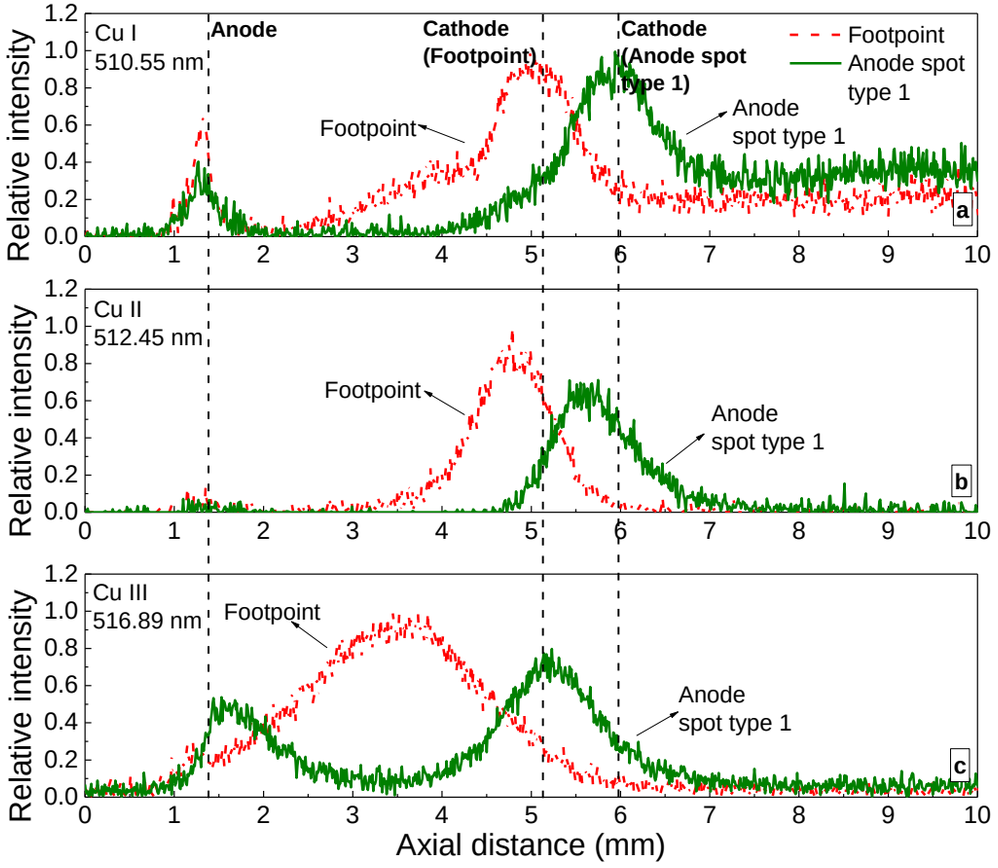
Cu III

- much broader spatial profile comparing to Cu I, II
- remarkable changes while changing anode mode

Results and discussion (overview)

Transition from footpoint to anode spot type 1





Cu I

- Insignificant changes

Cu II

- low intensity near the anode
- broad profile near the cathode

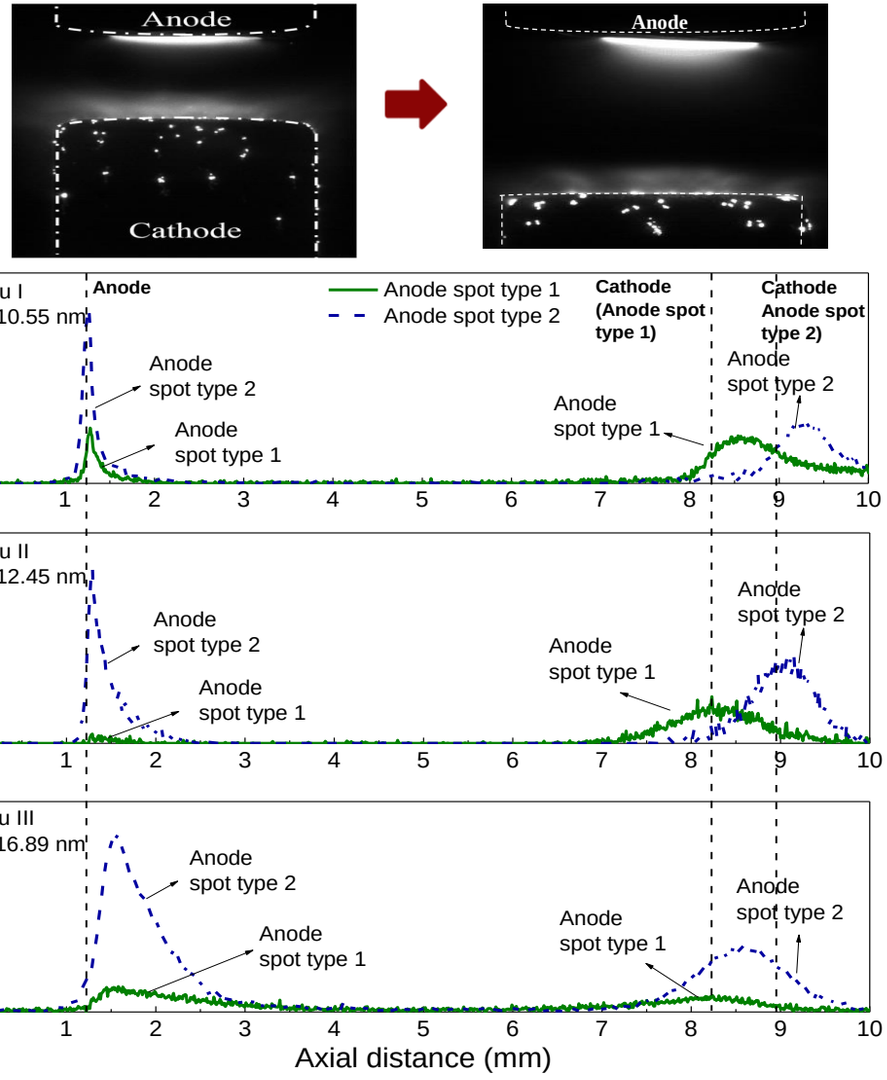
Cu III

- 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

Results and discussion (overview)

Transition from anode spot type 1 to anode spot type 2



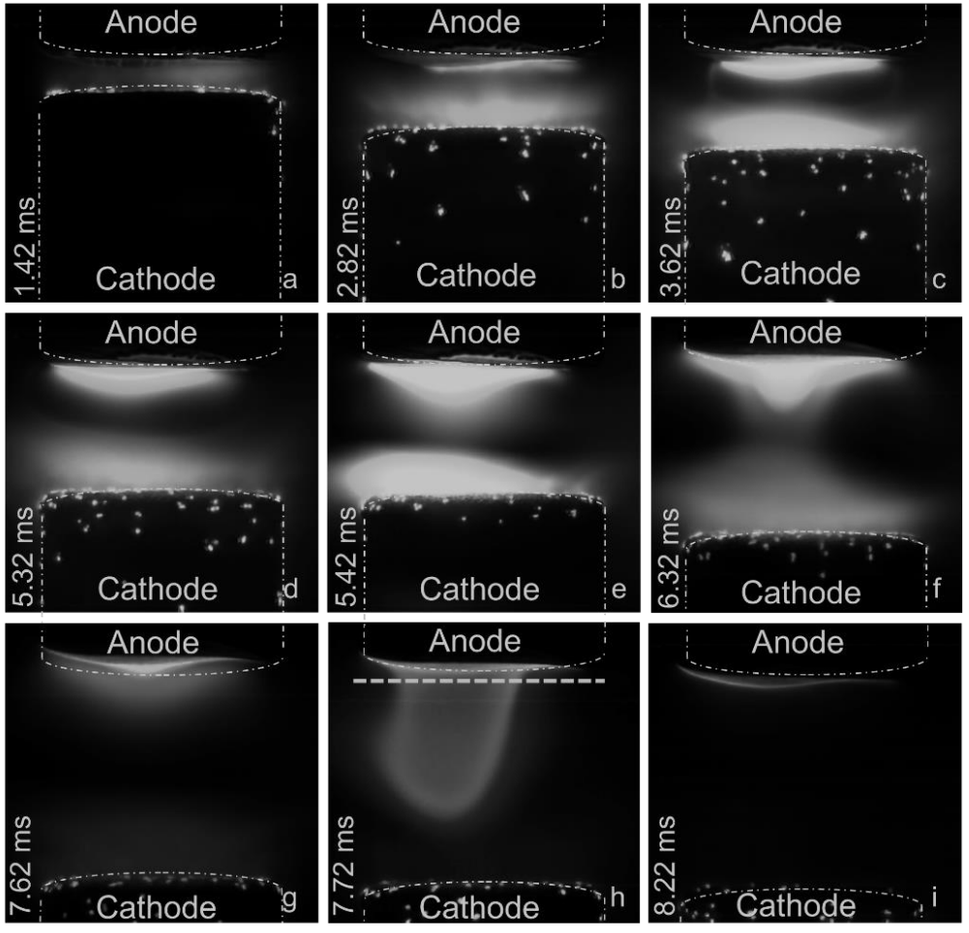
- Significant increase of all line intensities near the anode
- Moderate increase of line intensities near the cathode
- Intensity maxima near the anode considerably higher than those near the cathode in the anode spot type 2

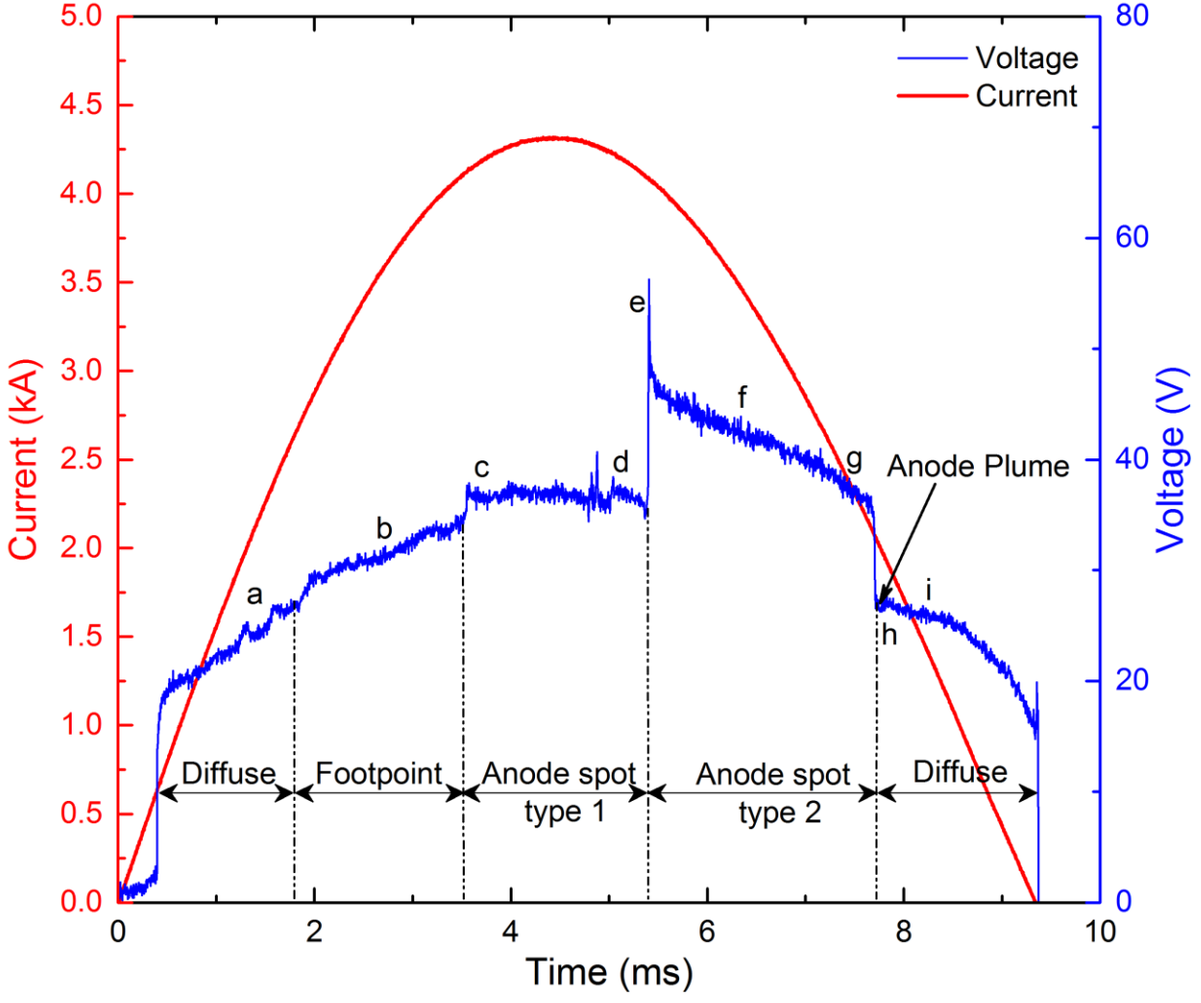
Results and discussion

- using high-speed spectroscopy is possible….
  - to obtain a very complete qualitative information about the arc discharge and,
  - to calculate quantitative information like:
    - ✓ Radiator densities,
    - ✓ Electron densities,
    - ✓ Temperature and
    - ✓ Pressure

Results and discussion

- Characteristics of arc current and voltage and corresponding high speed images





Results and discussion: Radiator density

- Evaluation procedure:
  - measurement of spectral radiance $L\lambda(y)$ over the wave length
  - Radiance $L(\lambda)$ integrated over spectral line (line fit)
  - Abel inversion
  - Emission coefficient $\varepsilon(r) = 1/(4\pi) \cdot h \cdot \nu \cdot n_u \cdot A_{ul}$
  - Radiator density $n_u(r)$
  - No LTE-assumption, absolute calibration required, optically thin plasma

Results and discussion: Temperature

- Evaluation procedure:
  - measurement of spectral radiance Lλ(y) over the wave length
  - Radiance L(λ) integrated over spectral line (line fit)
  - Abel inversion
  - Emission coefficient $\varepsilon(r) = 1/(4\pi) \cdot h \cdot \nu \cdot n_u \cdot A_{ul}$
  - Boltzmann-plot
  - Plasma temperature from slope
  - **No absolute calibration required**, relative values sufficient
  - LTE-assumption

$$\ln\left(\frac{\varepsilon_i \lambda_i}{g_{u,i} A_{ul,i}}\right) = \ln\left(\frac{hc}{4\pi}\frac{n_g}{Q(T)}\right) - \frac{1}{kT} E_{u,i}$$

Results and discussion: Neutral gas density

- Evaluation procedure:
  - measurement of spectral radiance Lλ(y) over the wave length
  - Radiance L(λ) integrated over spectral line (line fit)
  - Abel inversion
  - Emission coefficient $\varepsilon(r) = 1/(4\pi)\cdot h\cdot\nu\cdot n_u\cdot A_{ul}$
  - Boltzmann-plot
  - Neutral gas density from interception y_o at $E_u = 0$
  - **Absolute calibration required** to retrieve neutral gas density,
  - LTE assumption

$$\ln\left(\frac{\varepsilon_i \lambda_i}{g_{u,i} A_{ul,i}}\right) = \ln\left(\frac{hc}{4\pi}\frac{n_g}{Q(T)}\right) - \frac{1}{kT}E_{u,i}$$

Results and discussion: Electron density

- Evaluation procedure:
  - Spectral radiance $L_\lambda(y)$ (wavelength dependence)

    $\Rightarrow$ Abel inversion (before spectral line integration!)

    $\Rightarrow$ Emissions coefficient $\varepsilon(r=0,\lambda)$ on axis (wavelength dependent)

    $\Rightarrow$ Voigt profile line fit to spectrally dependent emission coefficient on arc axis

    $\Rightarrow$ Lorentz line width => Stark broadening

    $\Rightarrow$ Electron density n_e

  - Electron density and its temporal distribution (high resolution grating needed)

Summary

- High-speed video spectroscopy is a valuable tool for the examination of transient phenomena,
- qualitative and quantitative information of the plasma characteristics during arcing
- temporal characteristics of attachment modes of high-current vacuum arcs
- radiator density during anode type 2 is 10 times higher than during anode type 1
- arc voltage over the time follows one-to-one the radiator and neutral gas density
- the increase of vapor density during anode type 2 leads to a noticeable increase on arc voltage
- the electron density during anode spot type 2 is about 10 … 20 times greater than during type 1
- **Further results are to be published in a forthcoming publication**
- Outlook:
  - Anode plume and critical current of anode spot type 2,
  - modelling and further experimental verification

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