

# Investigation of High-Current Vacuum Arcs during the Formation of Anode Modes by Time and Space Resolved Spectroscopy

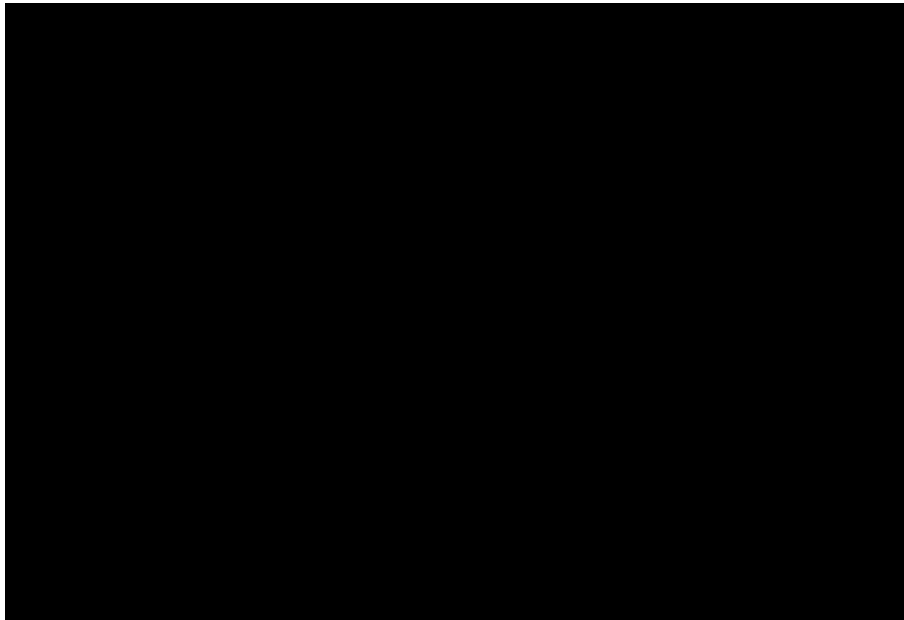
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# Vacuum circuit breaker

- Mechanical contact-separation - ignition of high-current arcs
- Electrode evaporation is only source of the conducting metal plasma
- Impact on electrode material can be reduced by axial or radial magnetic fields to diffuse or rotate the arc
- Fast plasma dilution around current zero – voltage recovery (vacuum)
- Widely applied in medium voltage range up to ~100 kV



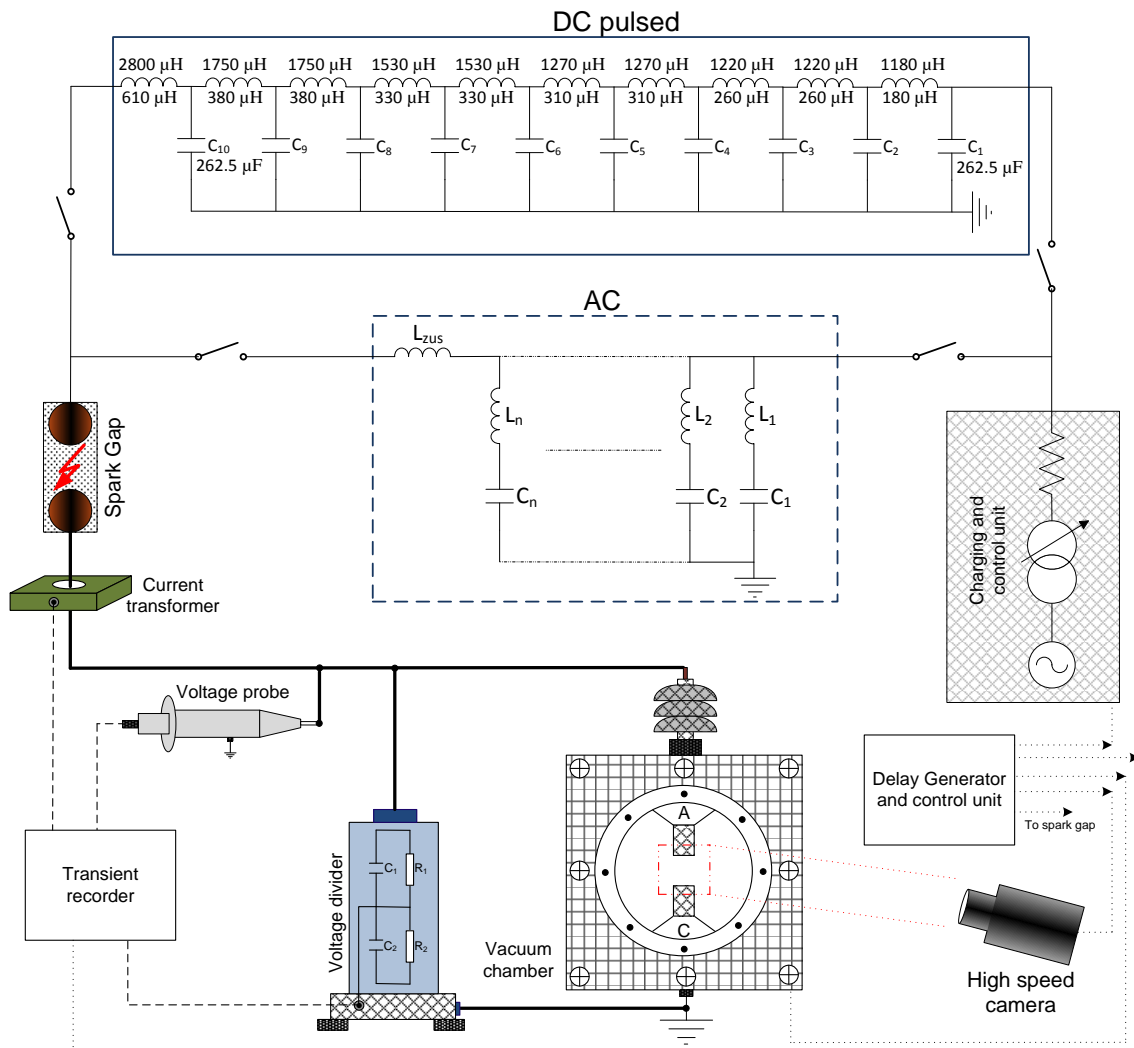
## Motivation

- Increasing breaking current capability
- Increasing nominal operating voltage
- Increasing life time
- Increasing reliability

# Experimental setup

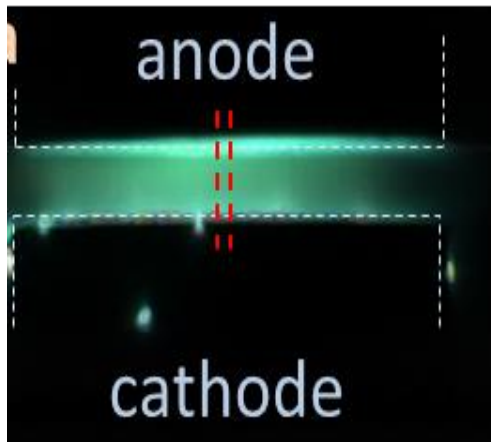
## Typical available waveforms with current ranges

Waveform	A or B	A + B
Lightning pulse (10/250 $\mu$ s)	1 – 50 kA	---
DAC 16.7 Hz	0.8 – 4 kA	4 – 6 kA
DAC 25 Hz	1.3 – 6.5 kA	6.5 – 10 kA
DAC 50/60 Hz	0. – 15 kA	15 – 24 kA
DAC 100 Hz	1 – 25 kA	25 – 40 kA
DAC 200 Hz	2 – 50 kA	50 – 80 kA
DC 5 ms	2.5 – 10 kA	---
DC 10 ms	1.25 – 5 kA	---
DC 20 ms	0.5 – 2 kA	---



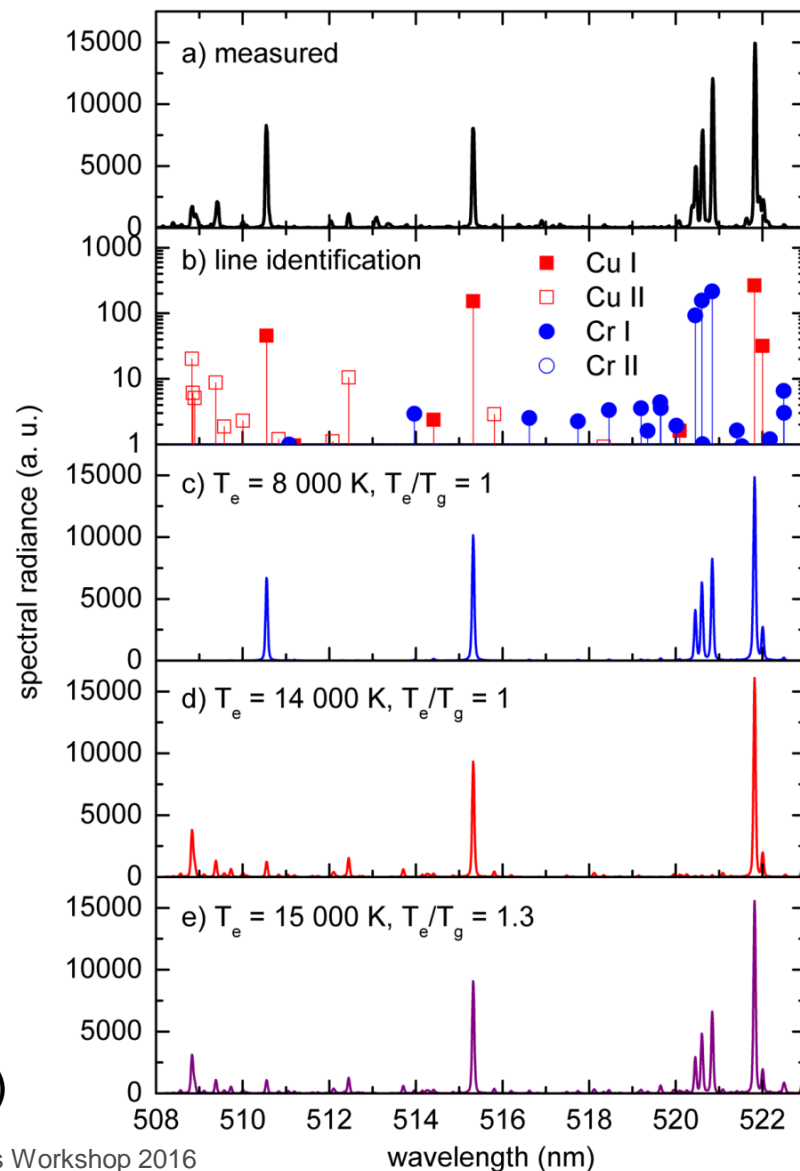
# Temperature & density close to anode (diffuse mode)

Comparison between acquired and two-temperature spectrum simulation



50 Hz, 2.2 kA, Cu-Cr Ø20 mm

Result: total pressure 0.03 bar  
(Stark broadening)  
electron temperature 15 000 K,  
gas temperature 11 500  
(Methling et al., TPS 43, 2015, p. 2303)



# High-current anode phenomena

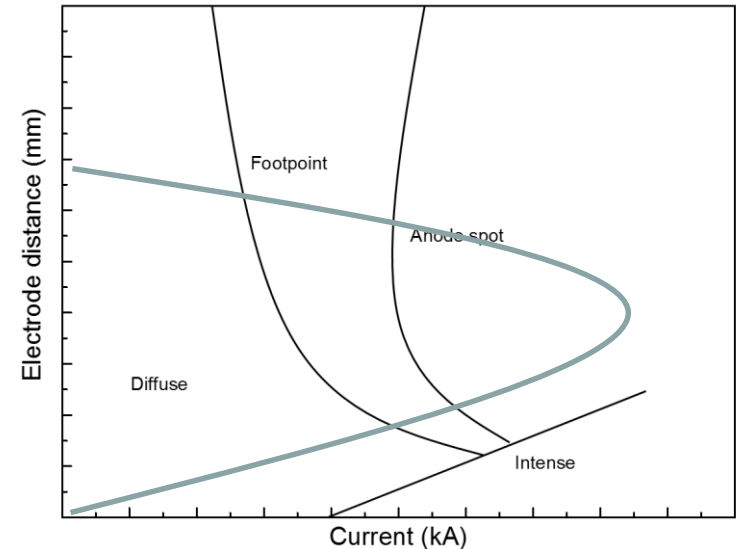
## High-current anode phenomena can lead to

- Higher contact erosion
- Increase of restrike probability
- Decrease of life time
- Interruption failure

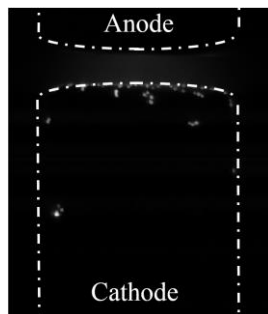
## Different discharge modes

- Diffuse
- Footpoint
- Anode spot (type 1 and type 2)
- Intense mode

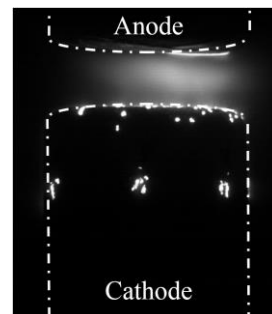
Schematic existence diagram



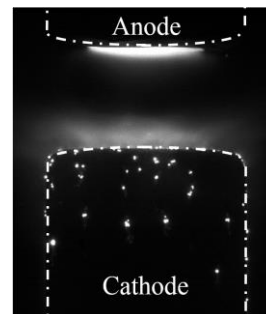
AC  
50 Hz  
> 3 kA



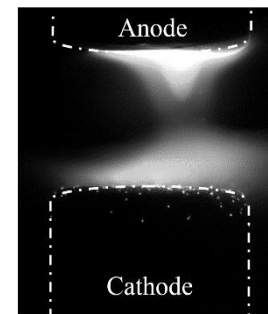
Diffuse



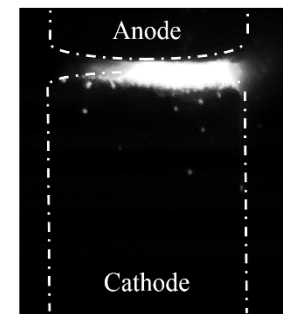
Footpoint



Anode spot  
(Type 1)



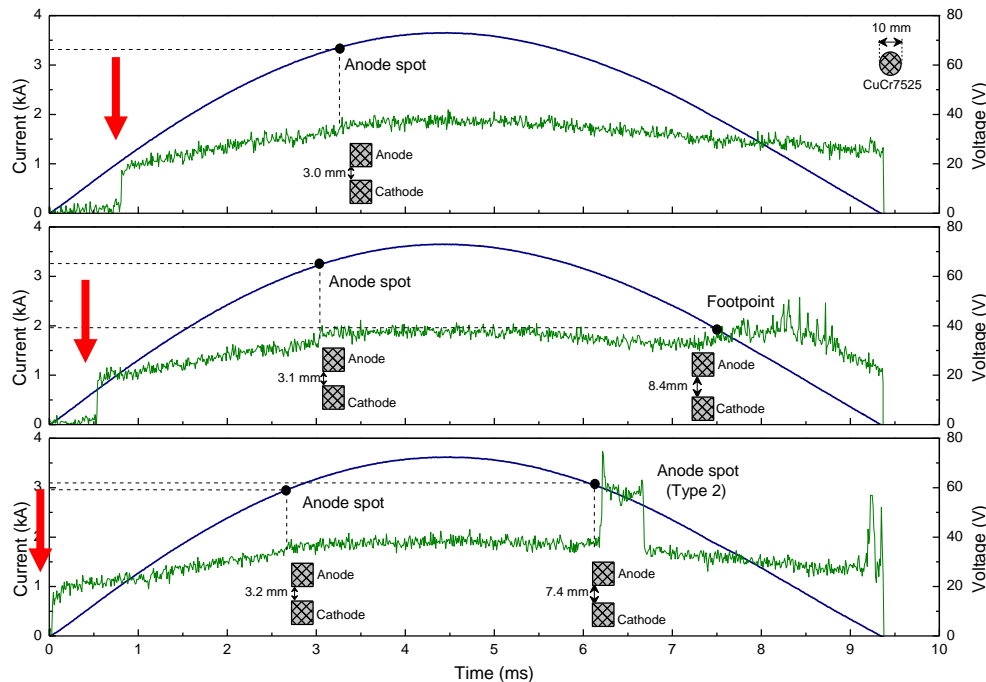
Anode spot  
(Type 2)



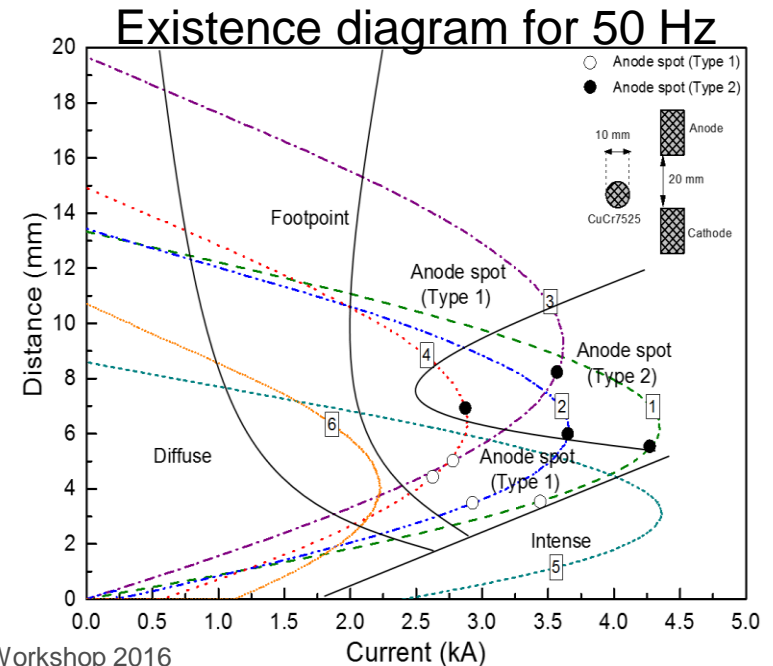
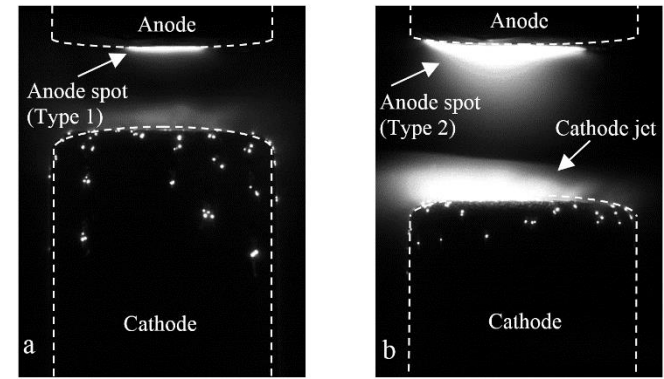
Intense  
mode

# Impact of contact opening time

- Increase of arcing time (early contact opening) can lead to anode spot type 2:
  - both anode and cathode are active
  - appears at higher electrode distance
  - can appear even at lower current

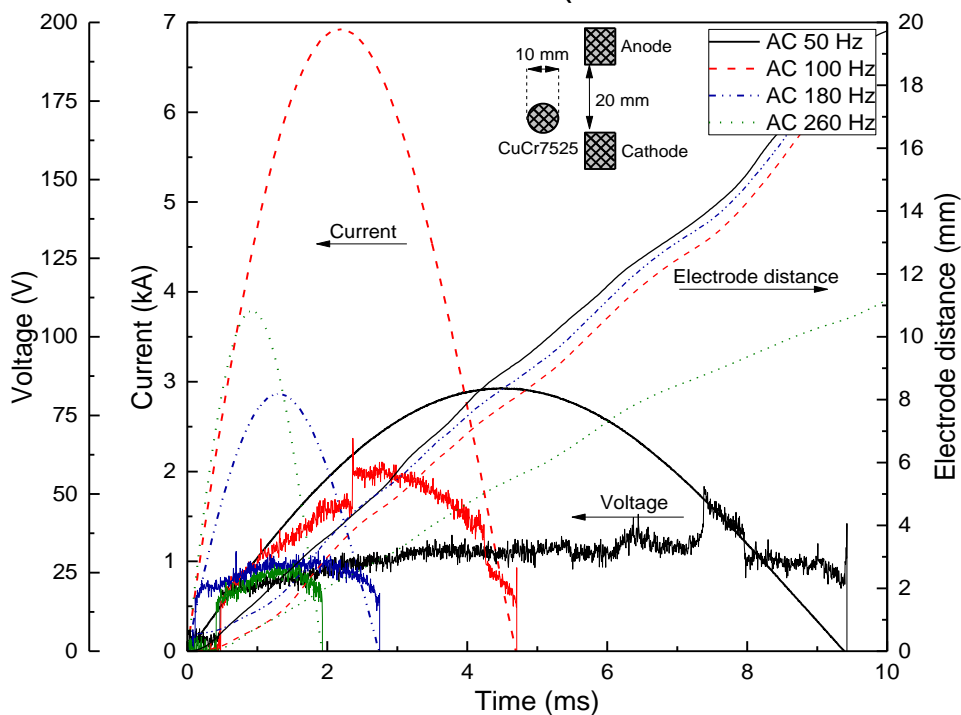


Early opening: Successive formation of anode spot types 1 and 2

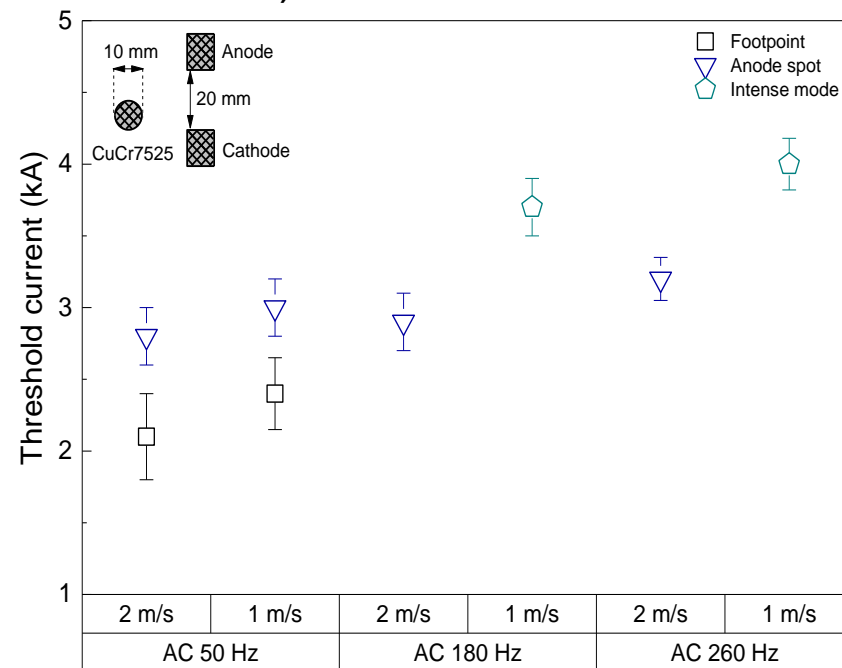


# Variation of AC pulse frequency and contact speed

- Increasing the pulse frequency - increase of threshold current
- 50 Hz: First observed high-current mode is footpoint at both contact speeds
- Higher frequency pulses (180 Hz, 260 Hz): First mode is anode spot (2 m/s) or intense mode (1 m/s, smaller electrode distance)



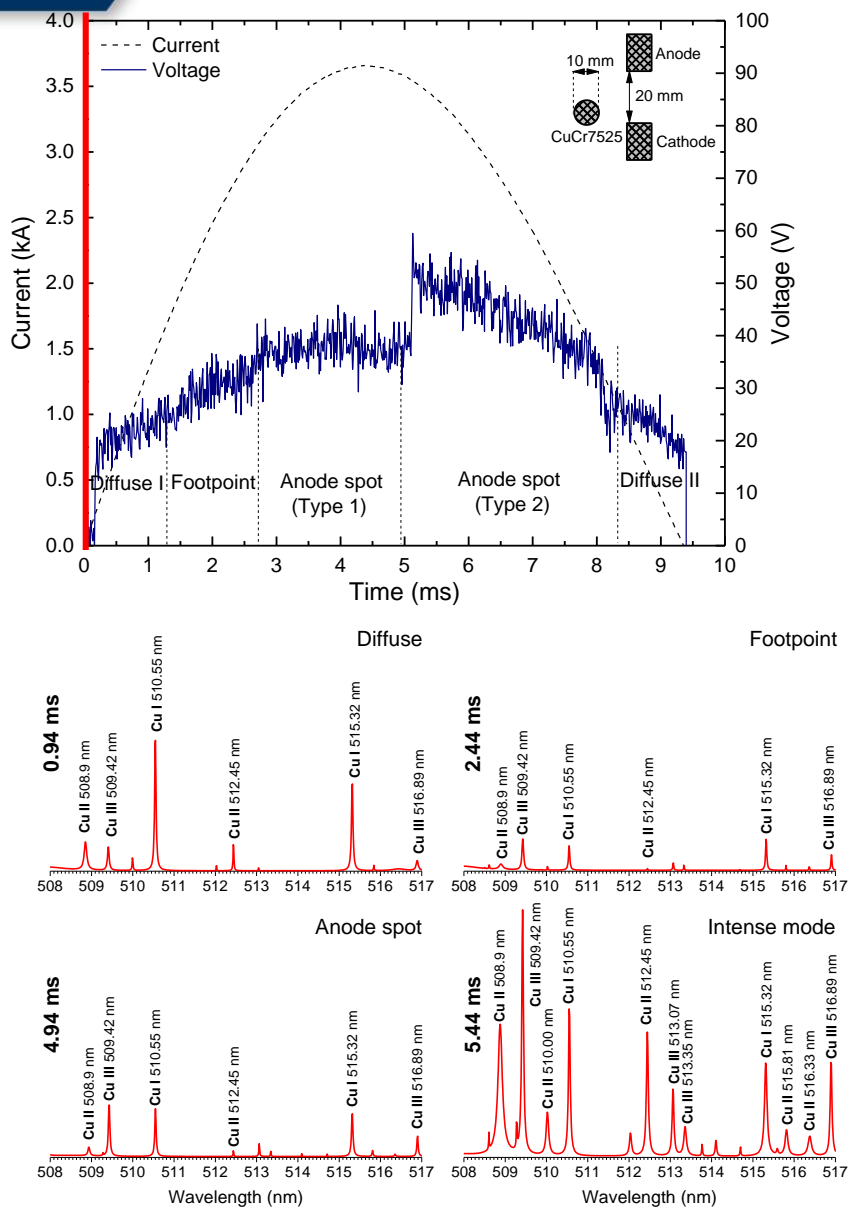
Current, voltage, and electrode distance



Waveform and contact speed

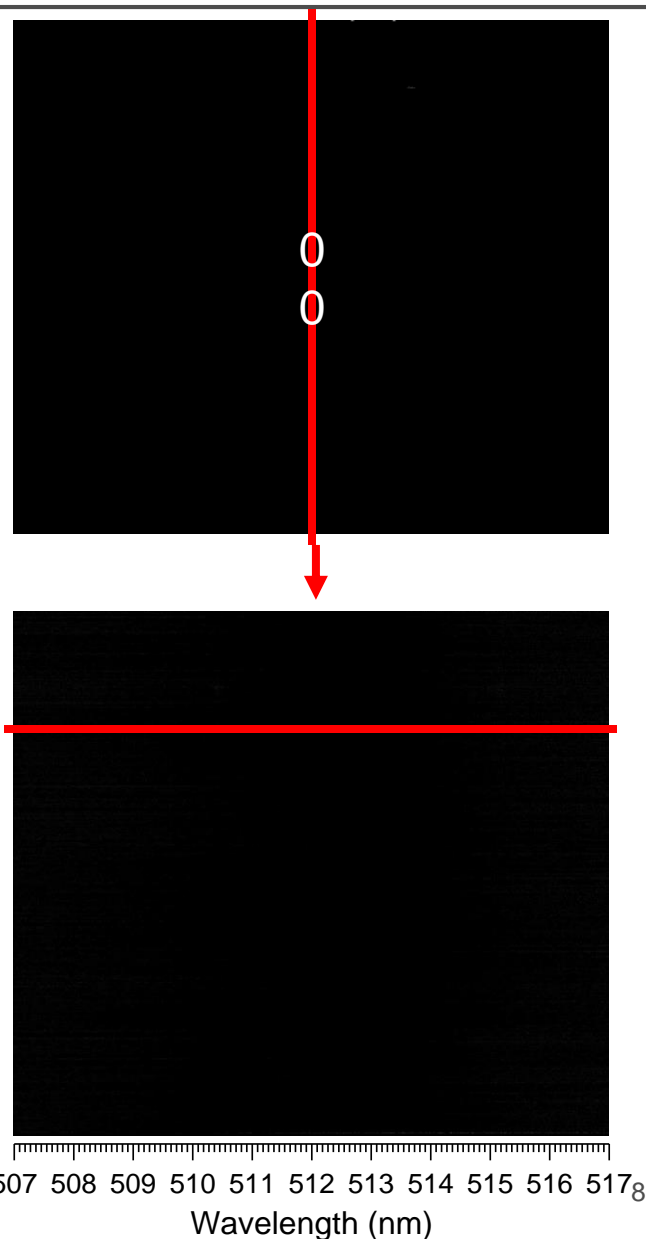
Threshold currents

## Video spectroscopy of high-current anode modes



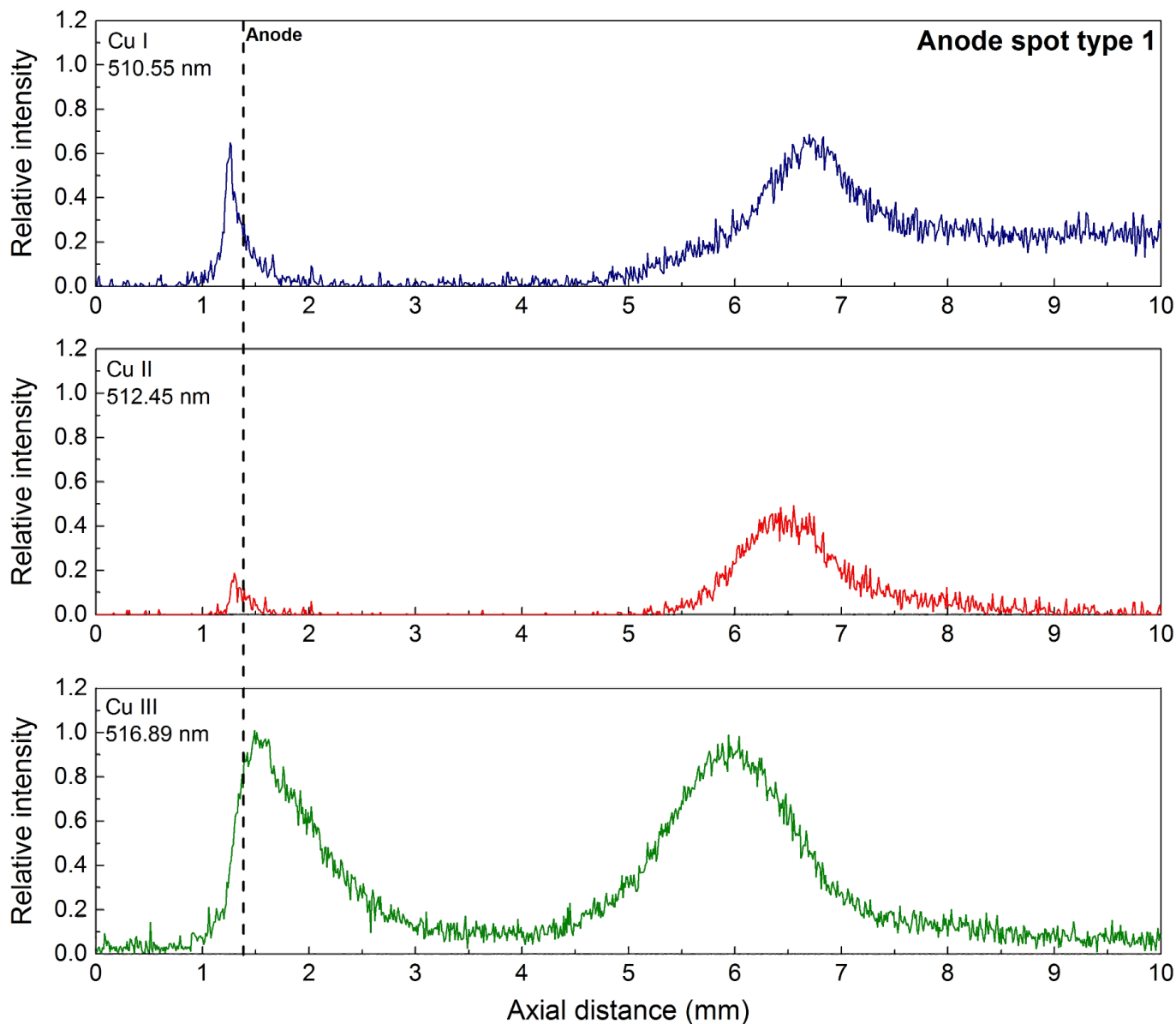
## High speed camera

## Video spectroscopy



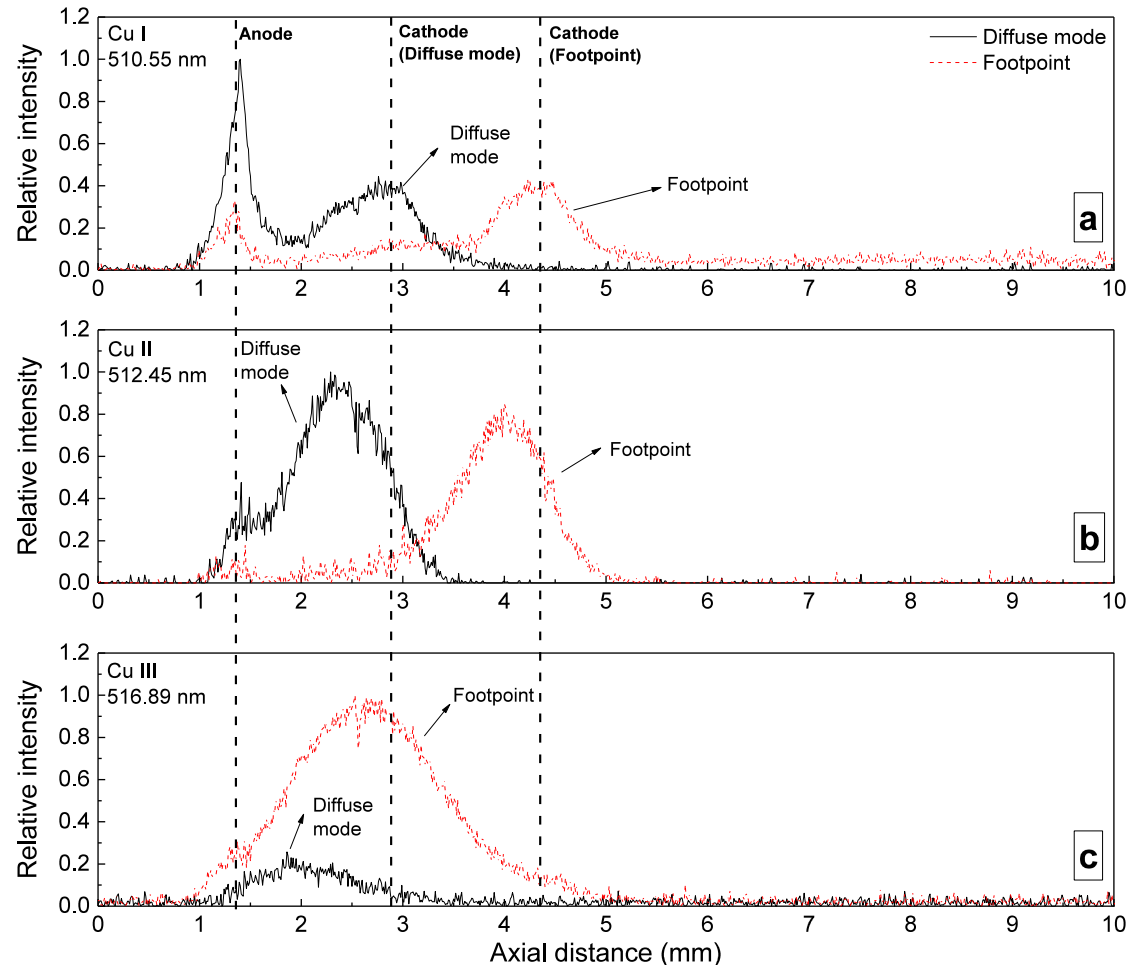


# Transition of anode modes – selected spectral lines



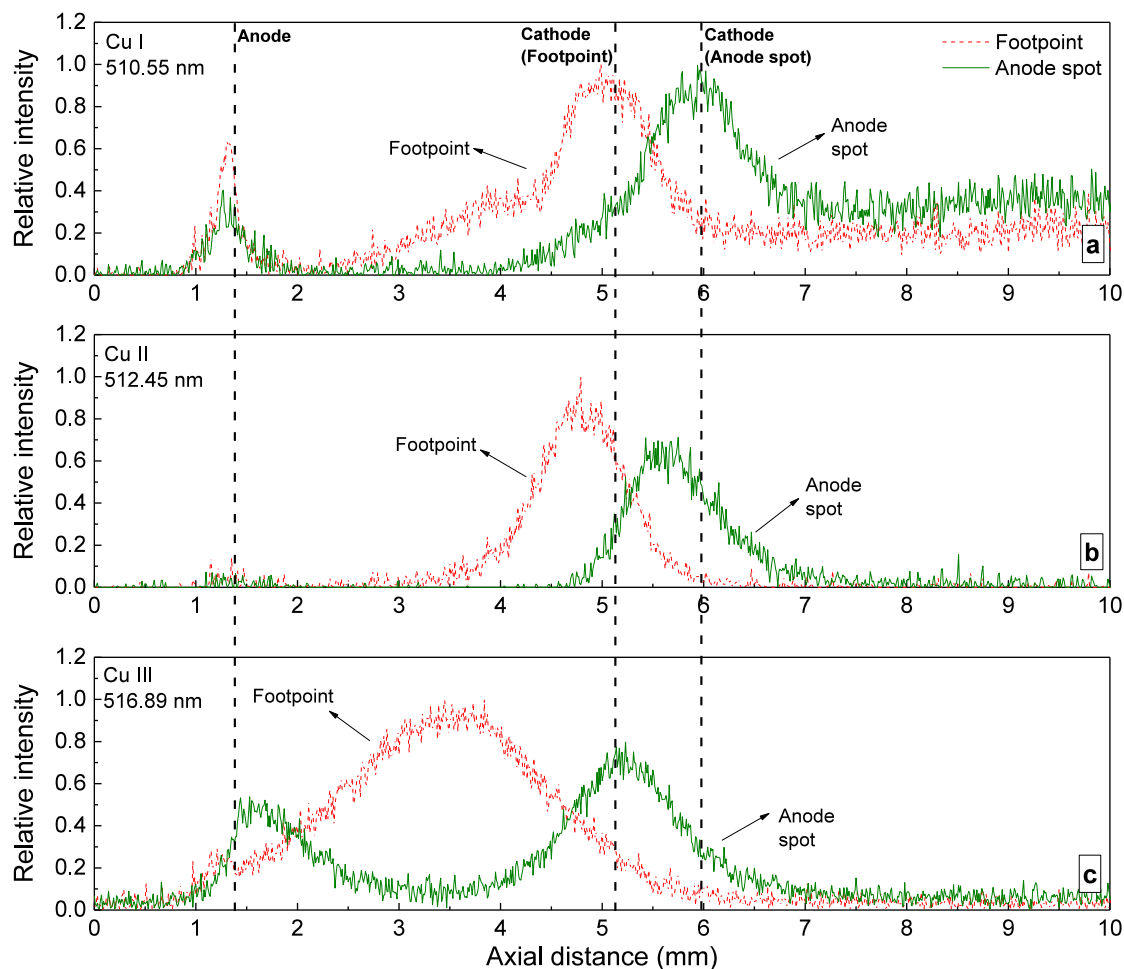
# Transition from **diffuse** to **footpoint** mode

- Cu I & Cu II: almost no changes near the cathode, decrease near to the anode and in the inter-electrode gap.
- Cu III: much broader spatial profile along the discharge axis that changes remarkably.



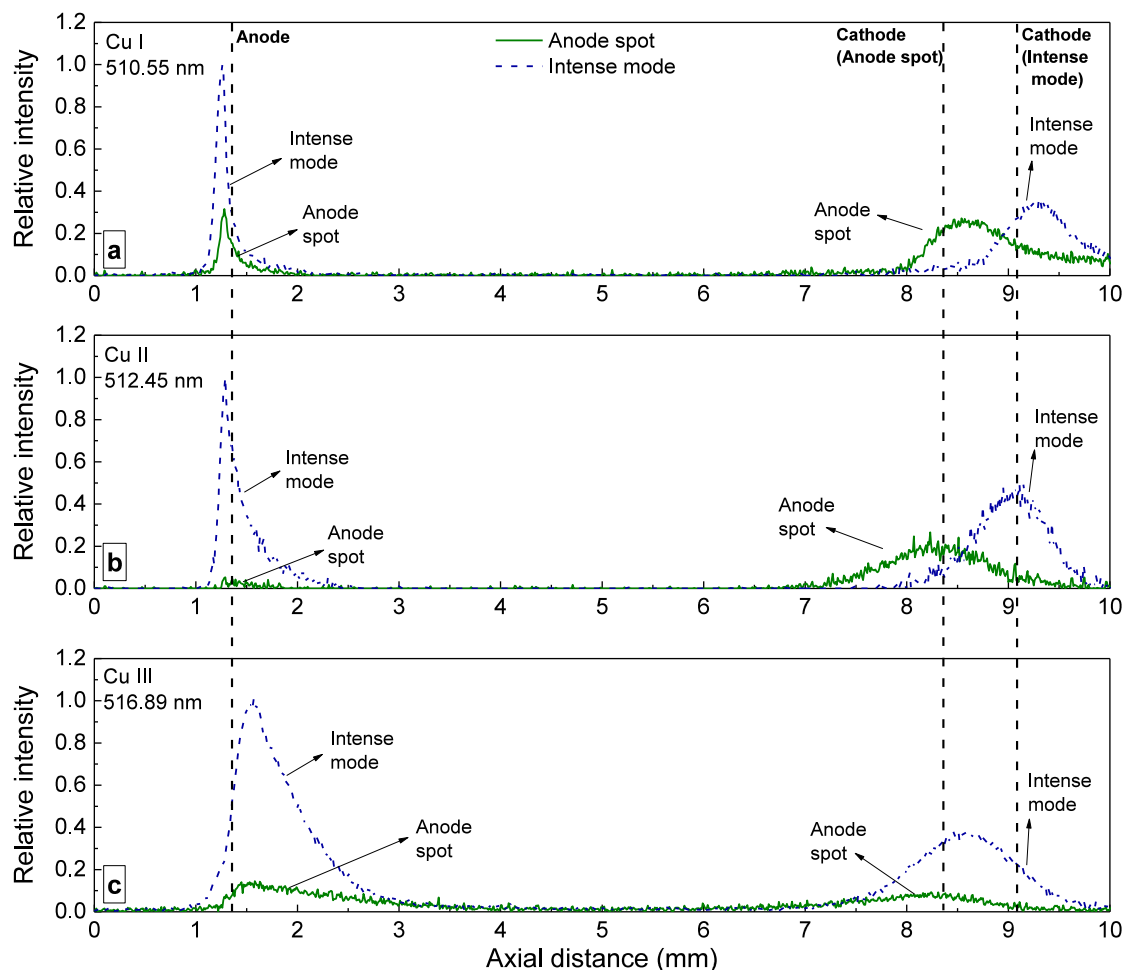
# Transition from **footpoint** to **anode spot** mode

- Cu I line in both modes are similar with a pronounced increase towards the cathode.
- Cu II: very low near anode; broad profile near the cathode in high-current modes
- Cu III distribution - abrupt change: local maxima near anode and cathode during anode spot but one maximum in inter-electrode gap in footpoint mode.
- Decreased intensity of atoms and ions between the electrodes in the anode spot mode can be also realized from the dark region in high speed camera images.

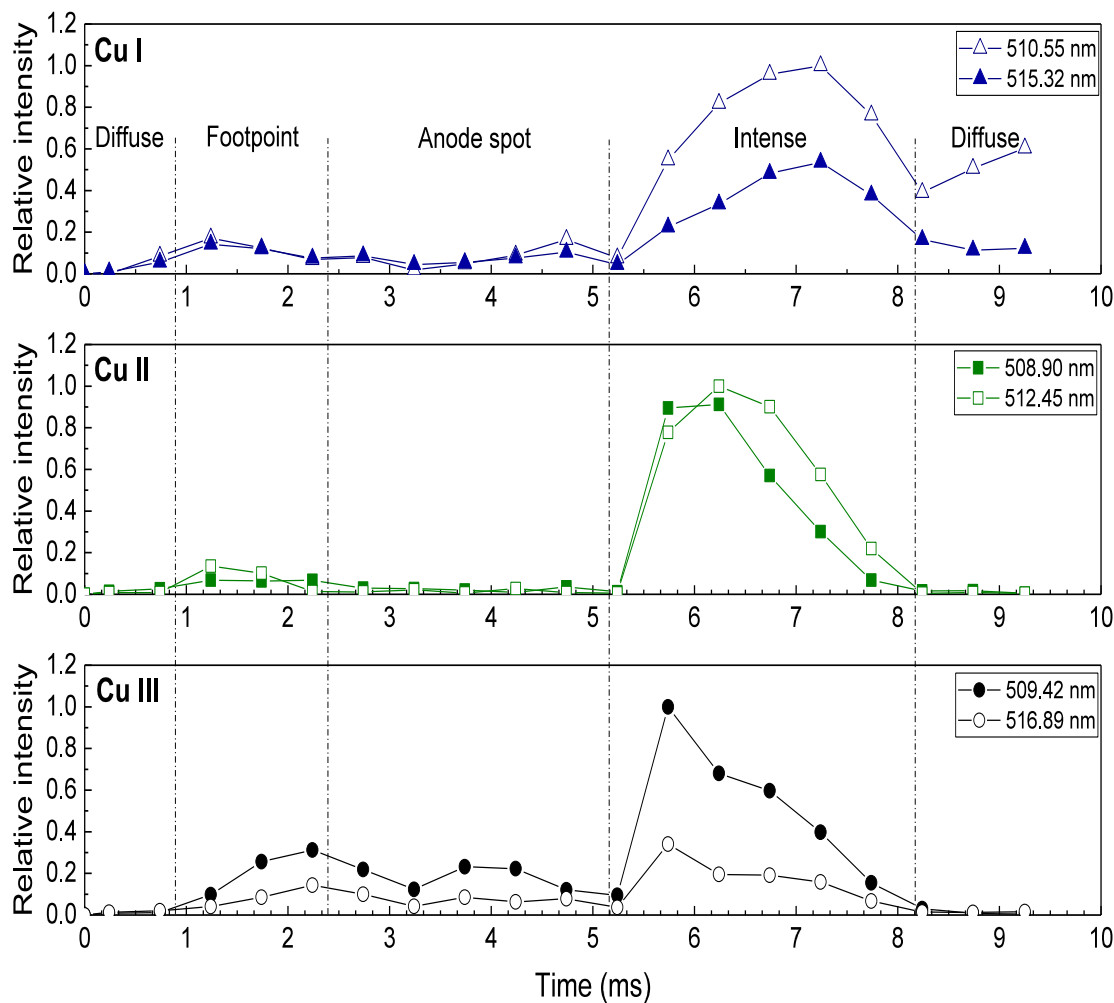


# Transition from **anode spot** to **intense** mode

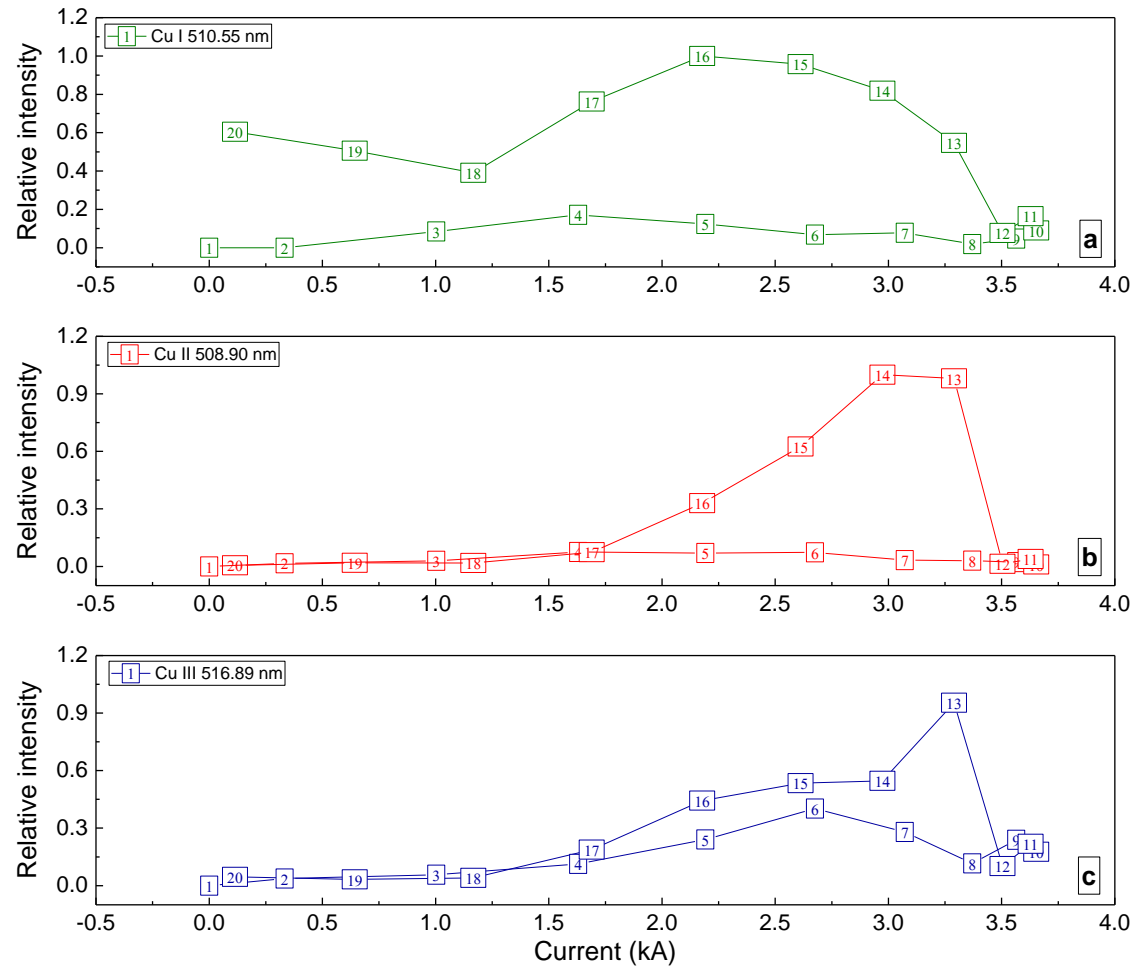
- All line intensities increase considerably near anode and more moderate near cathode.
- The change is larger the higher the charge number is.
- Intense mode: The intensity maxima near the anode are considerably higher than the intensities near the cathode.



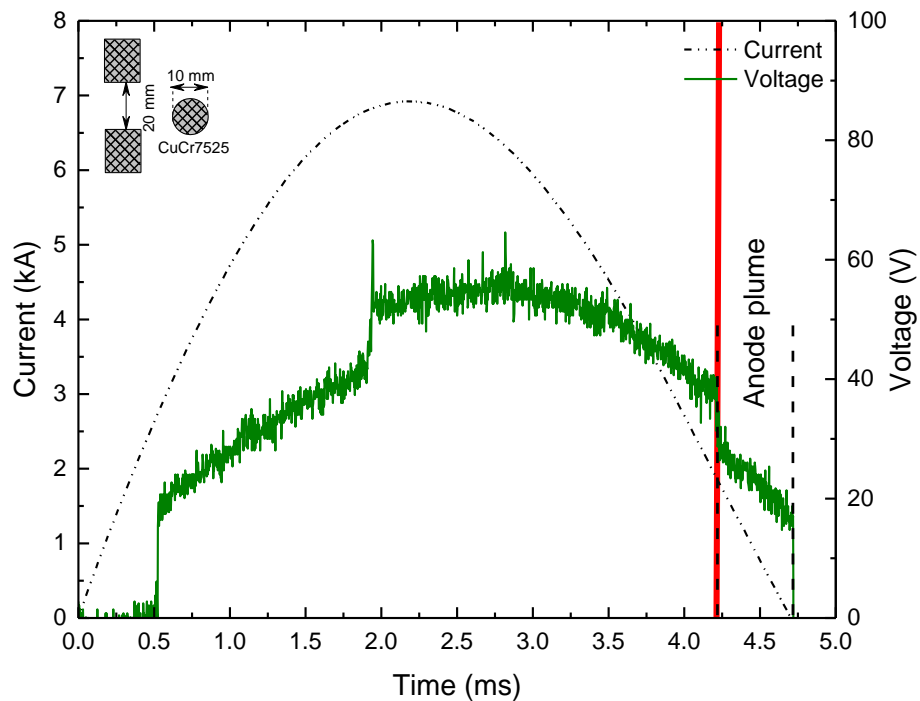
# Temporal evolution of lines as a function of time



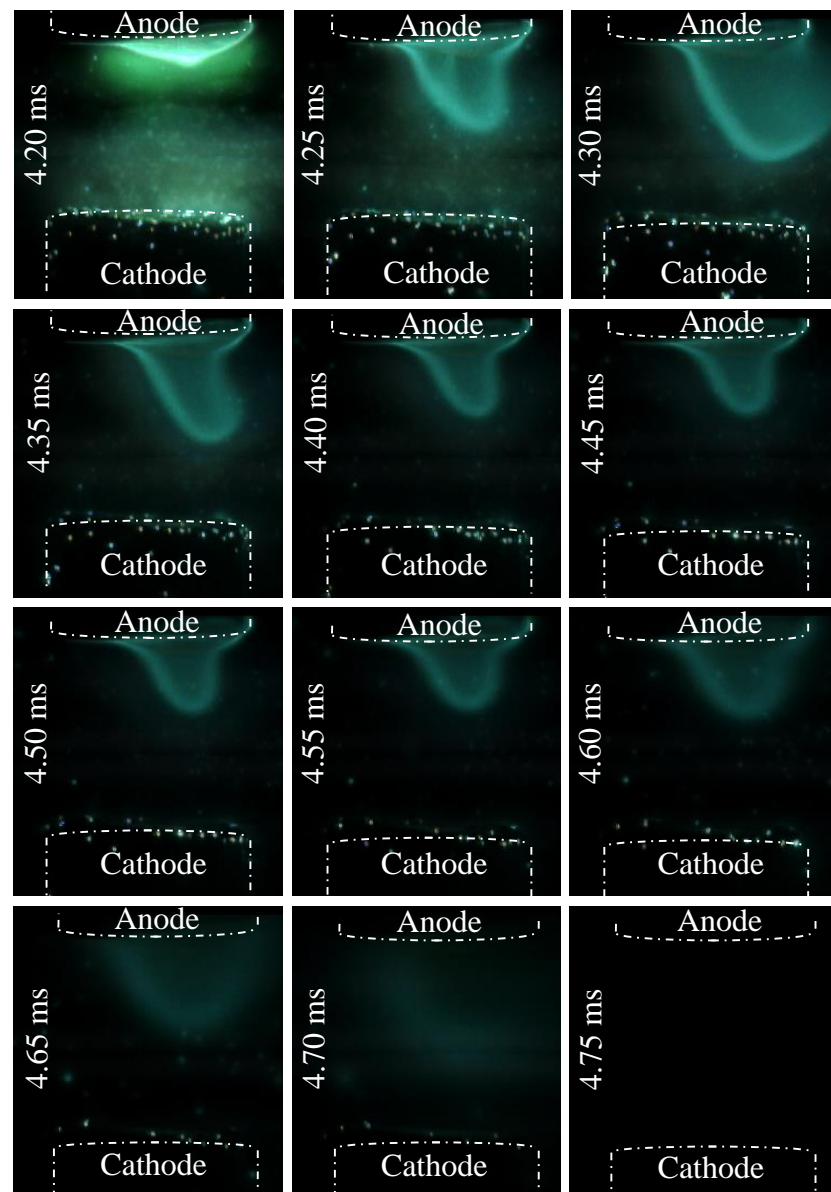
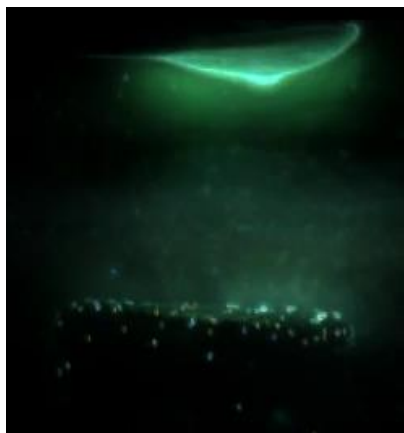
## Temporal evolution of lines as a function of **current**



# New phenomenon: Anode plume



Formation after  
anode spot type 2  
~ 500  $\mu$ s before CZ  
instead of diffuse mode

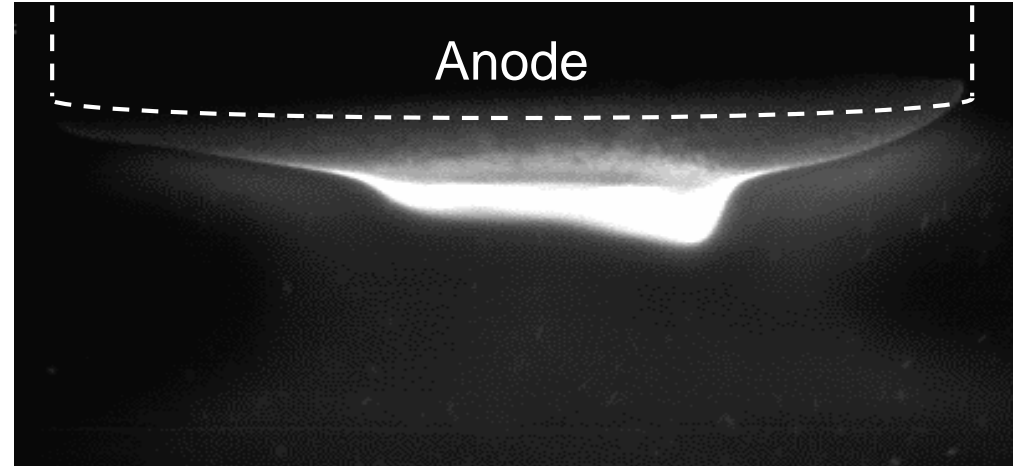


# Video spectroscopy during anode plume formation

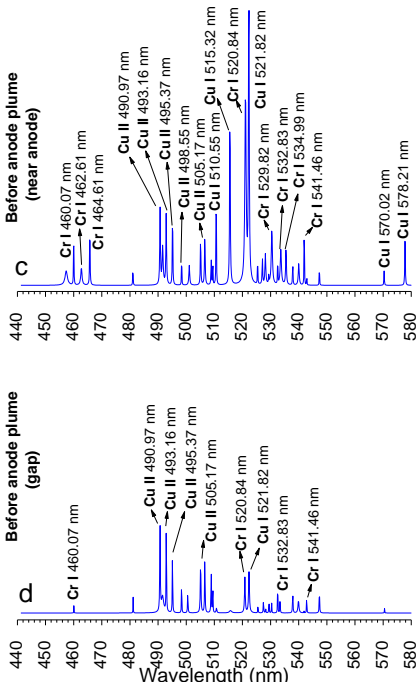
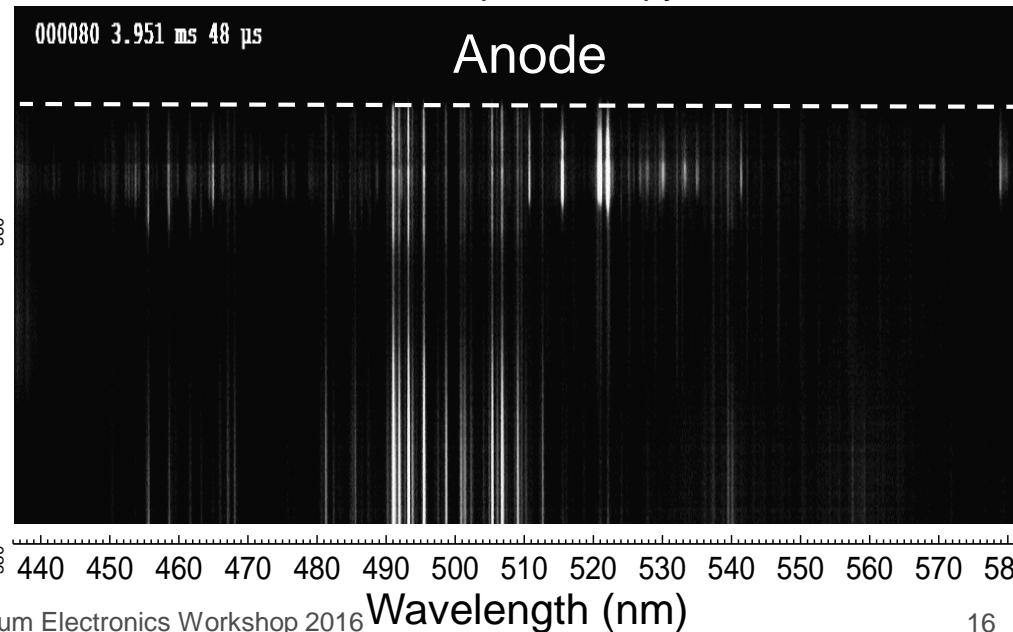
Vertically and horizontally oriented slit

Spectra before and after anode plume formation near the anode and inter-electrode gap

High speed camera

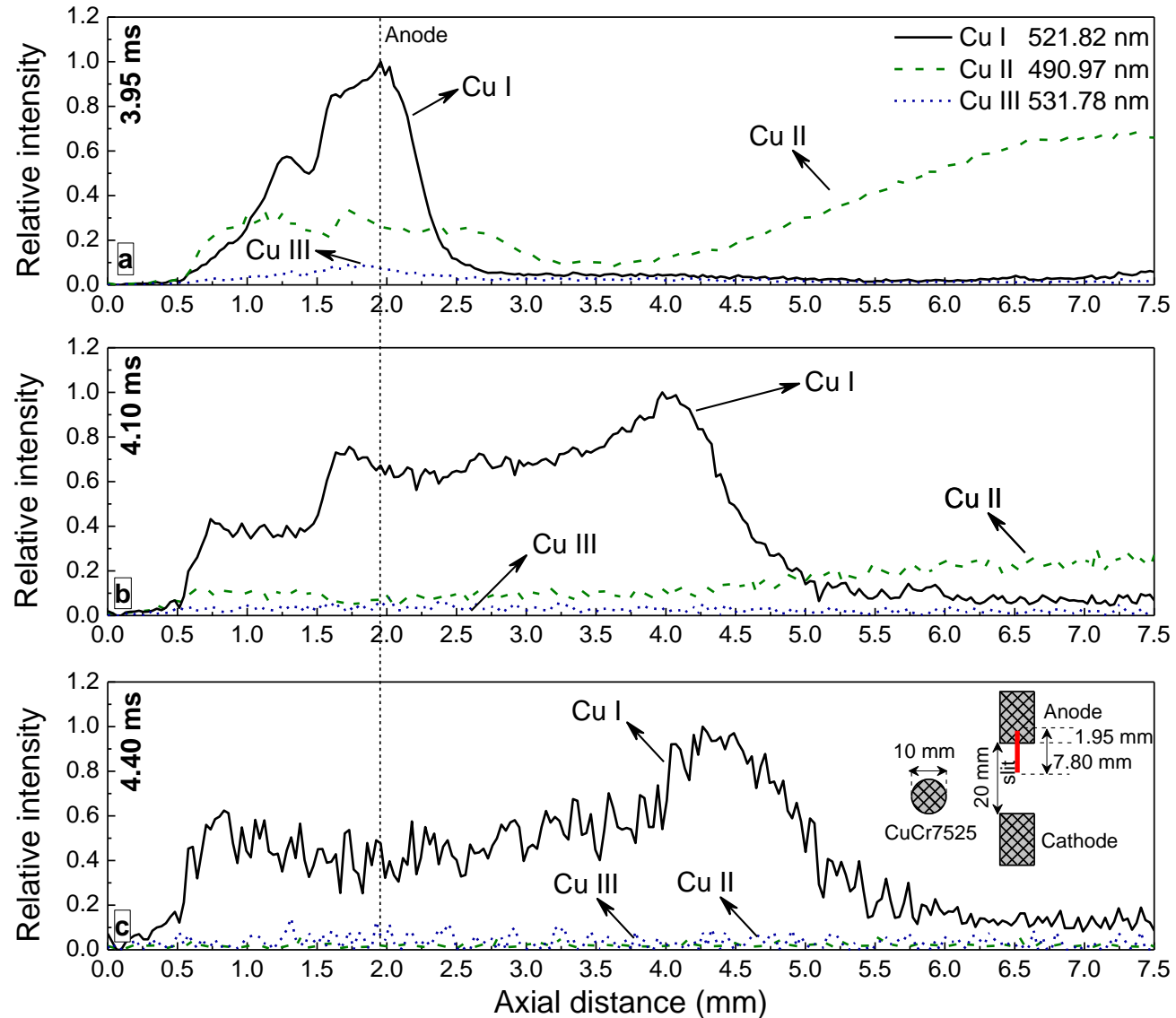
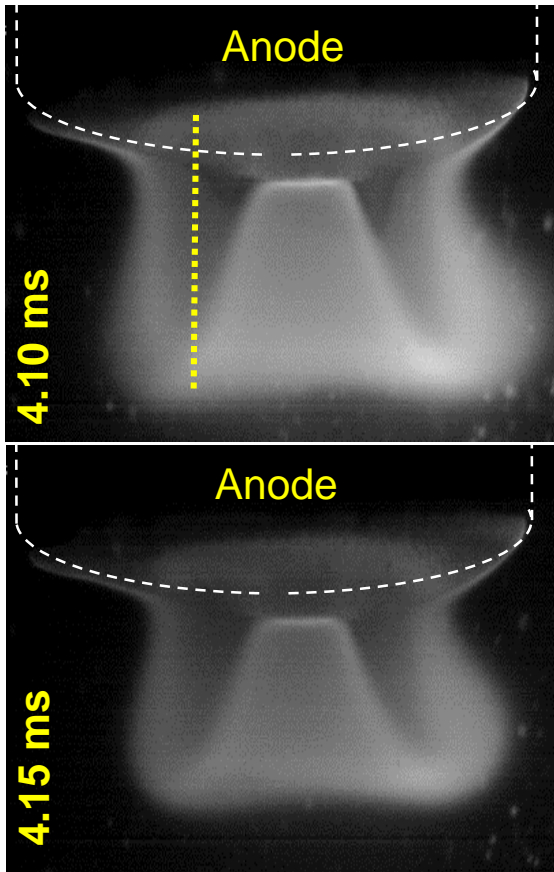


Video spectroscopy

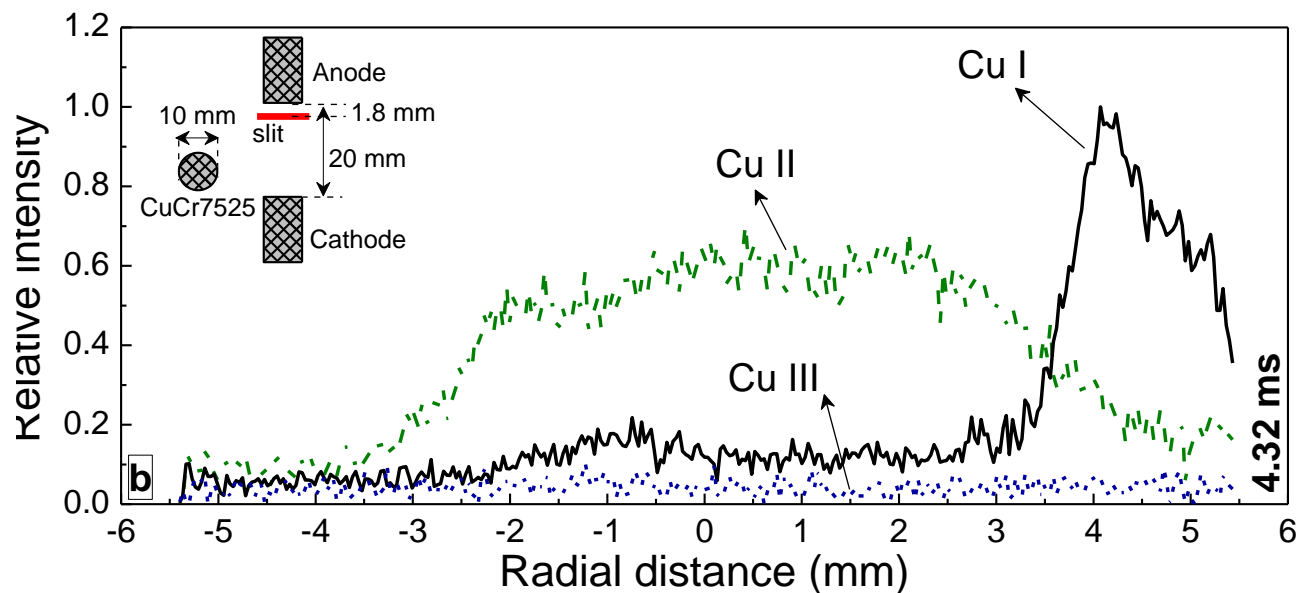
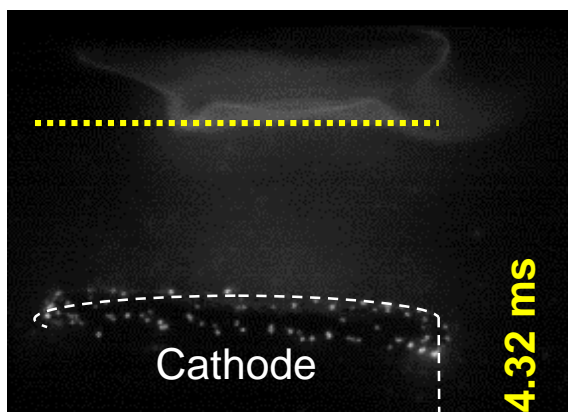
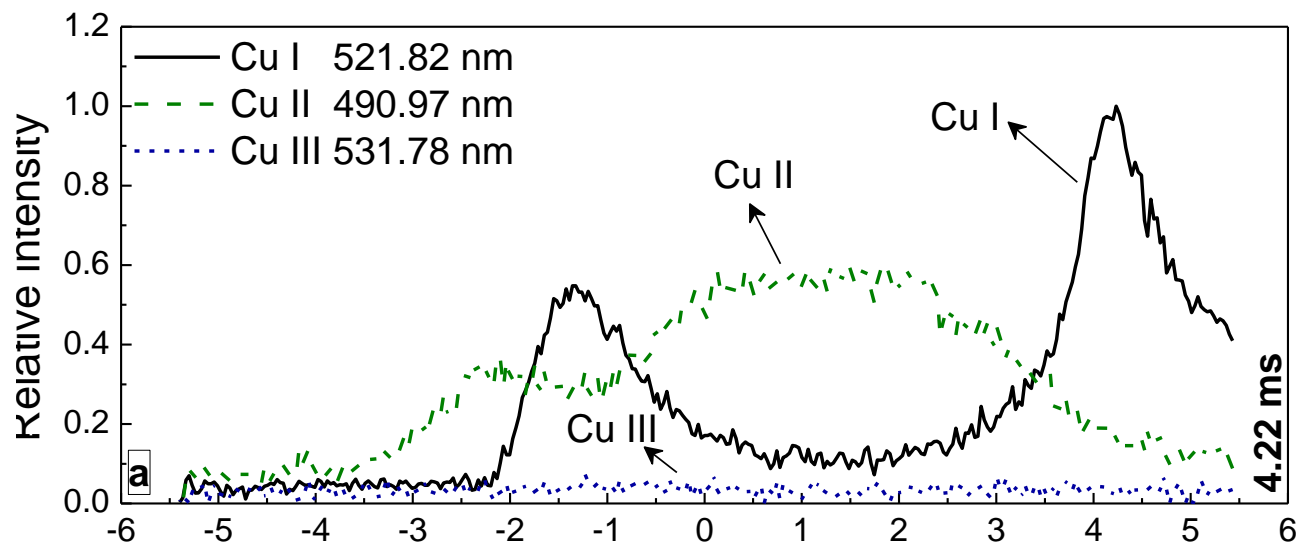
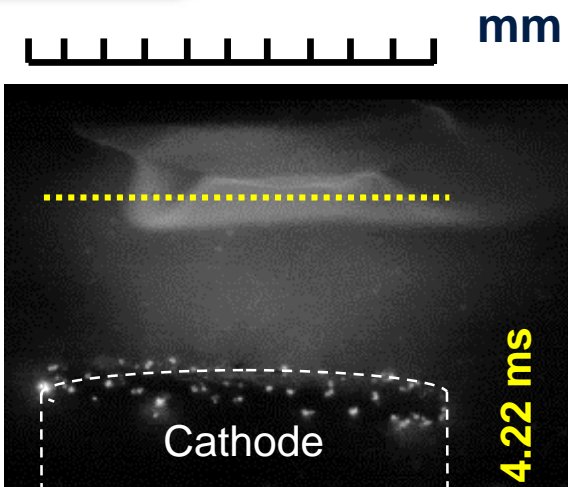




# Axially time and space resolved analysis



# Radially time and space resolved analysis



# Summary and outlook

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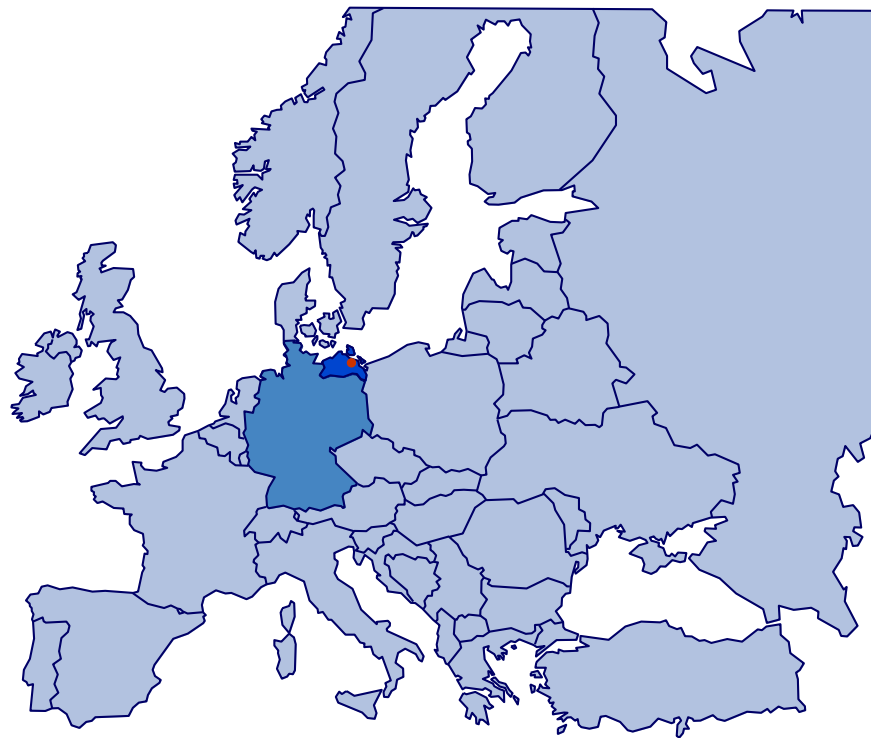
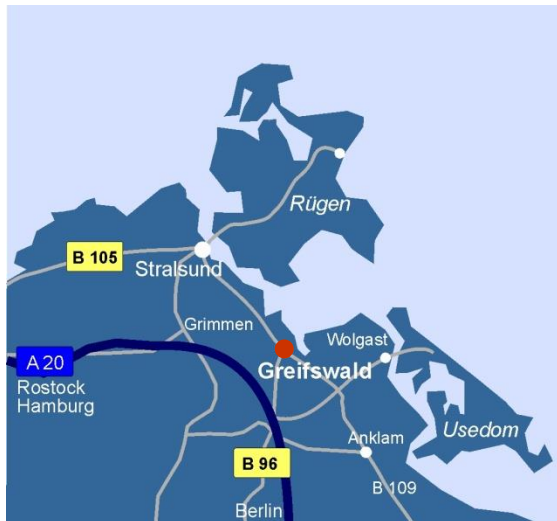
## Summary

- Video spectroscopy is used to examine high current anode modes during transition between different modes.
- Significant changes are observed in both the intensities and the spatial distribution of atomic and ionic Cu lines.
- High abrupt change of Cu atom and ion radiation during transition to anode spot type 2 is observed.
- Anode plume is identified as source of copper atom radiation just before current-zero crossing.

## Outlook

- Focus on plasma dynamics: temperature and density determination
- Impact of electrode materials on post-arc plasma properties
- „Arc memory“ effect

# Contact



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