

12th International Workshop on Mechanism
of Vacuum Arcs

MeVArc 2025

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A high-resolution optical study of repetitive but random vacuum arc spot ignition

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A piece of history: Thermionic to cathodic arc transition

voltage

arc with graphite electrodes

silent arc

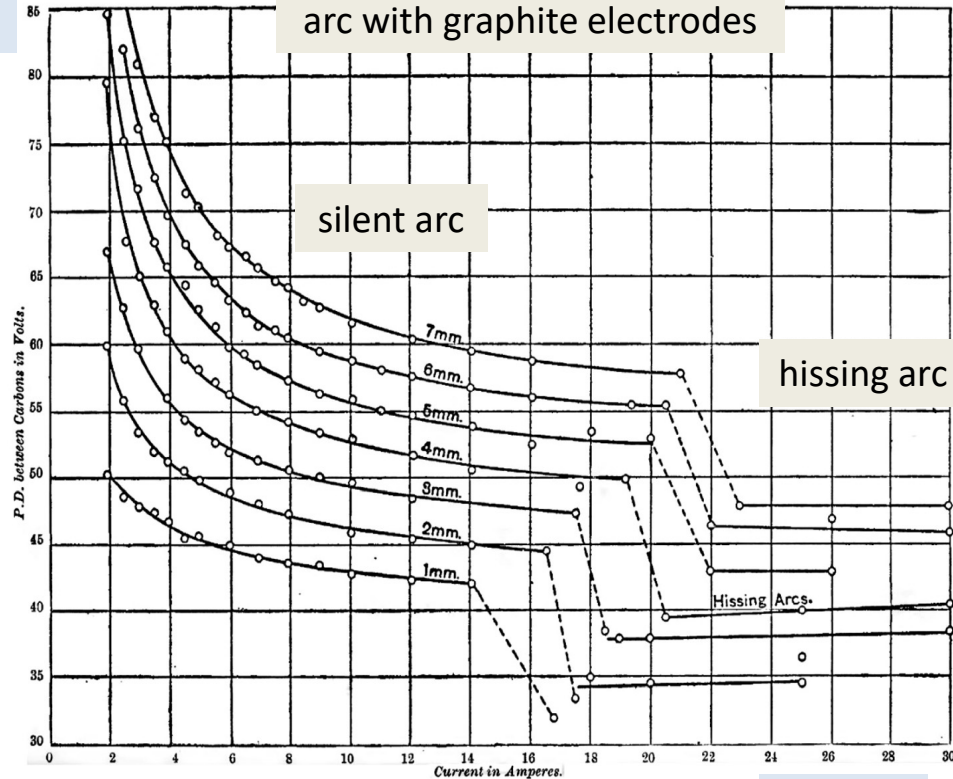
hissing arc

current

- Hertha Ayrton (1854–1923)**
- the first woman member of the Institute of Electrical Engineers of the UK (1899)
 - the first woman nominated to be a Fellow of the Royal Society of London (1902); however, she was held to be ineligible "**because she is a married woman**".



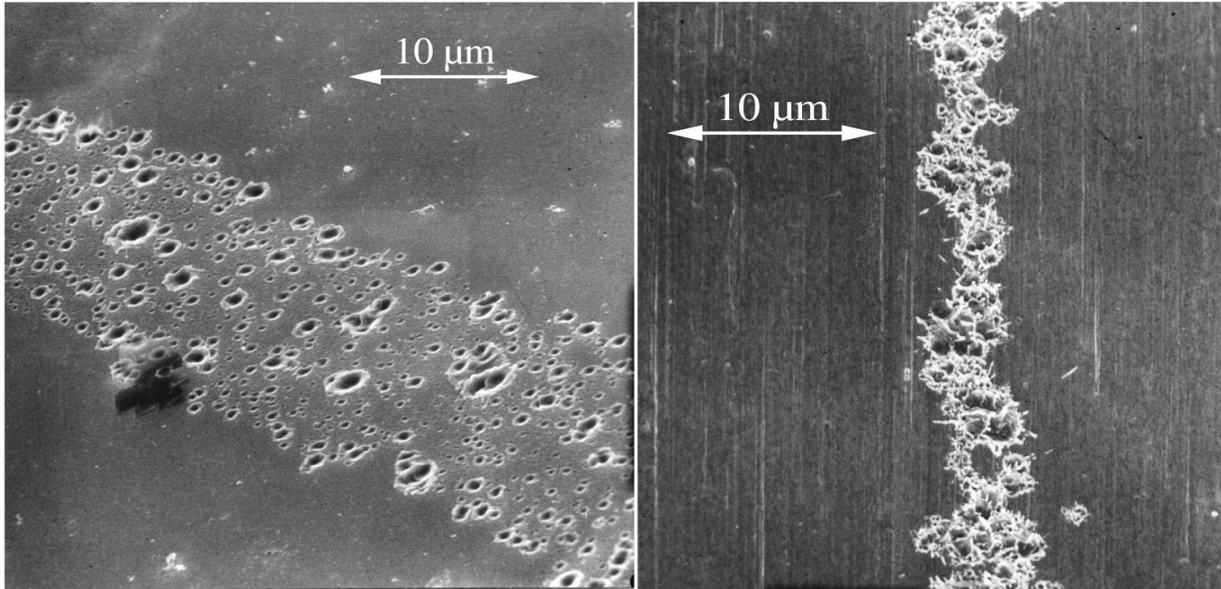
Hertha Ayrton, Portrait at Girton College, University of Cambridge [Wikipedia]



Arc spots in the absence and presence of plasma

Absence of plasma → “breakdown” at high voltage. The main subject of this Workshop. *Key is the high electric field at cathode surface.*

Presence of plasma → continued spontaneously pulsed plasma generation. *Key is again the high electric field, even at low voltage, this time facilitated by the sheath.*



arc traces on oxidized and clean metal cathode surfaces

Potential distribution in the presence of a plasma → High field possible even at low voltage

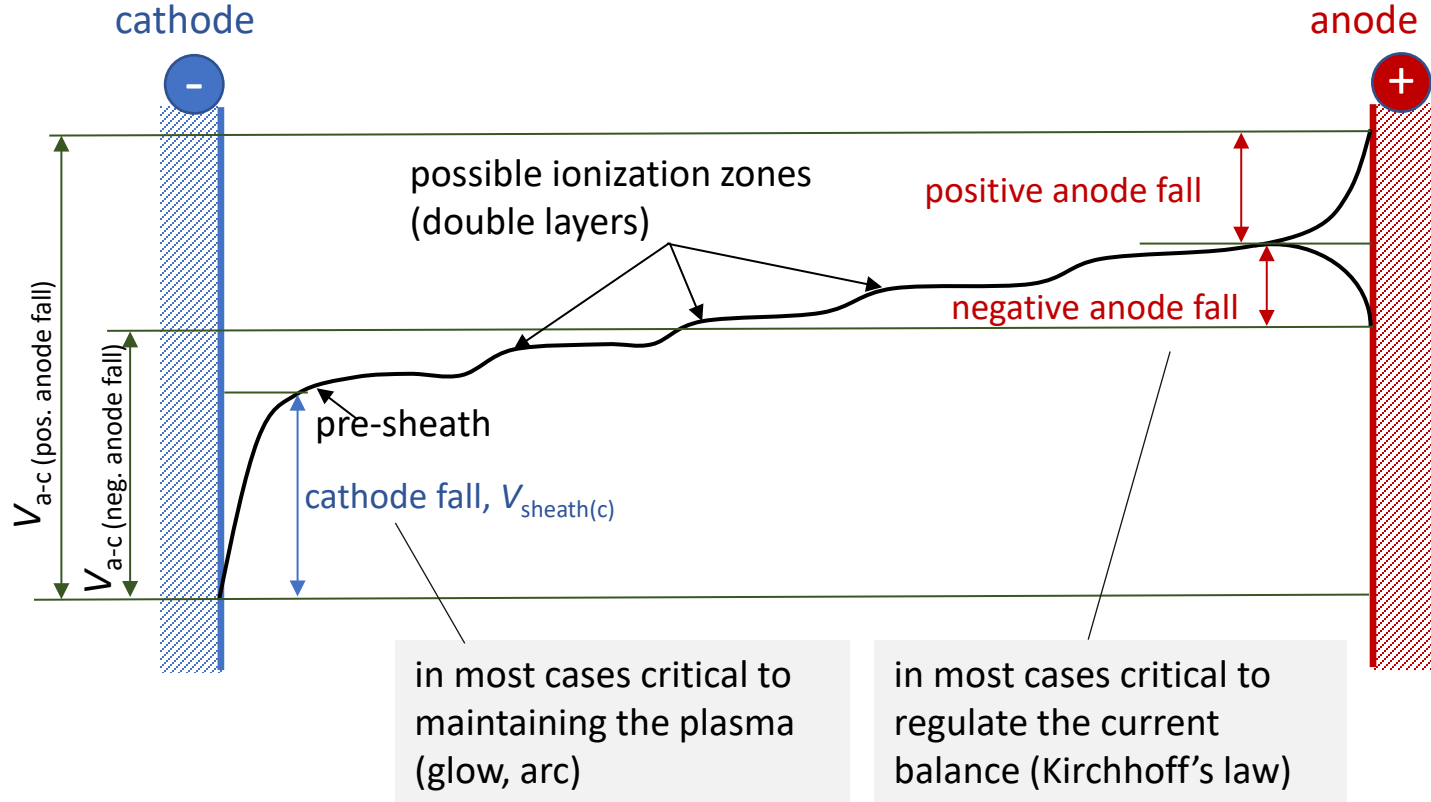
Poisson equation



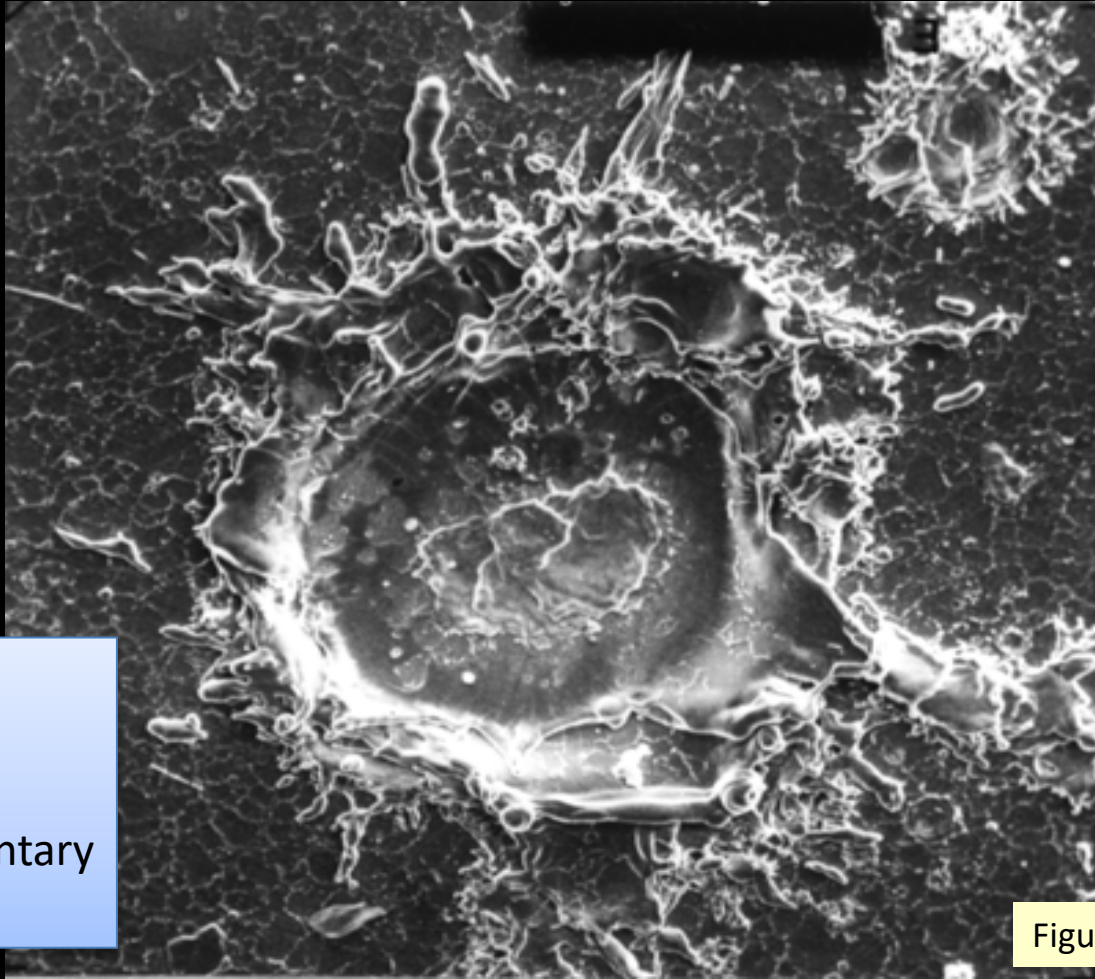
sheath thickness approximated by Child-Langmuir equ.



surface field approximated by Mackeown equ.



Plasma Formation of Cathodic Arcs



This is

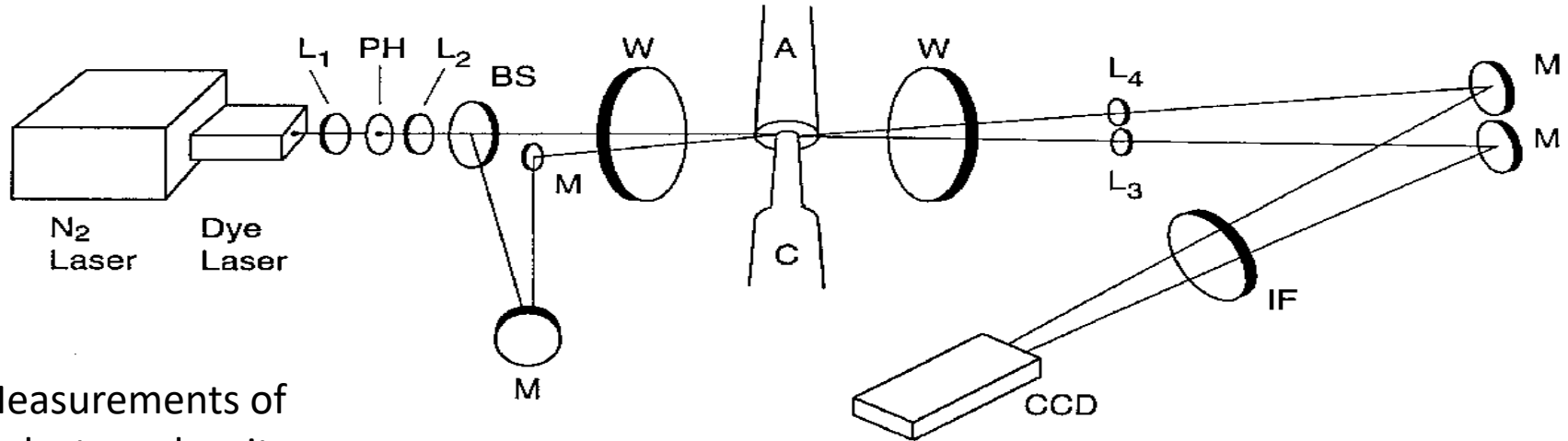
- not sputtering
- not evaporation

but result of momentary
high power density

Figure: Courtesy of B. Jüttner

Laser Plasma Diagnostics of Cathodic Arc Plasma

Differential Laser Absorption Photography and Spectrometry



Measurements of

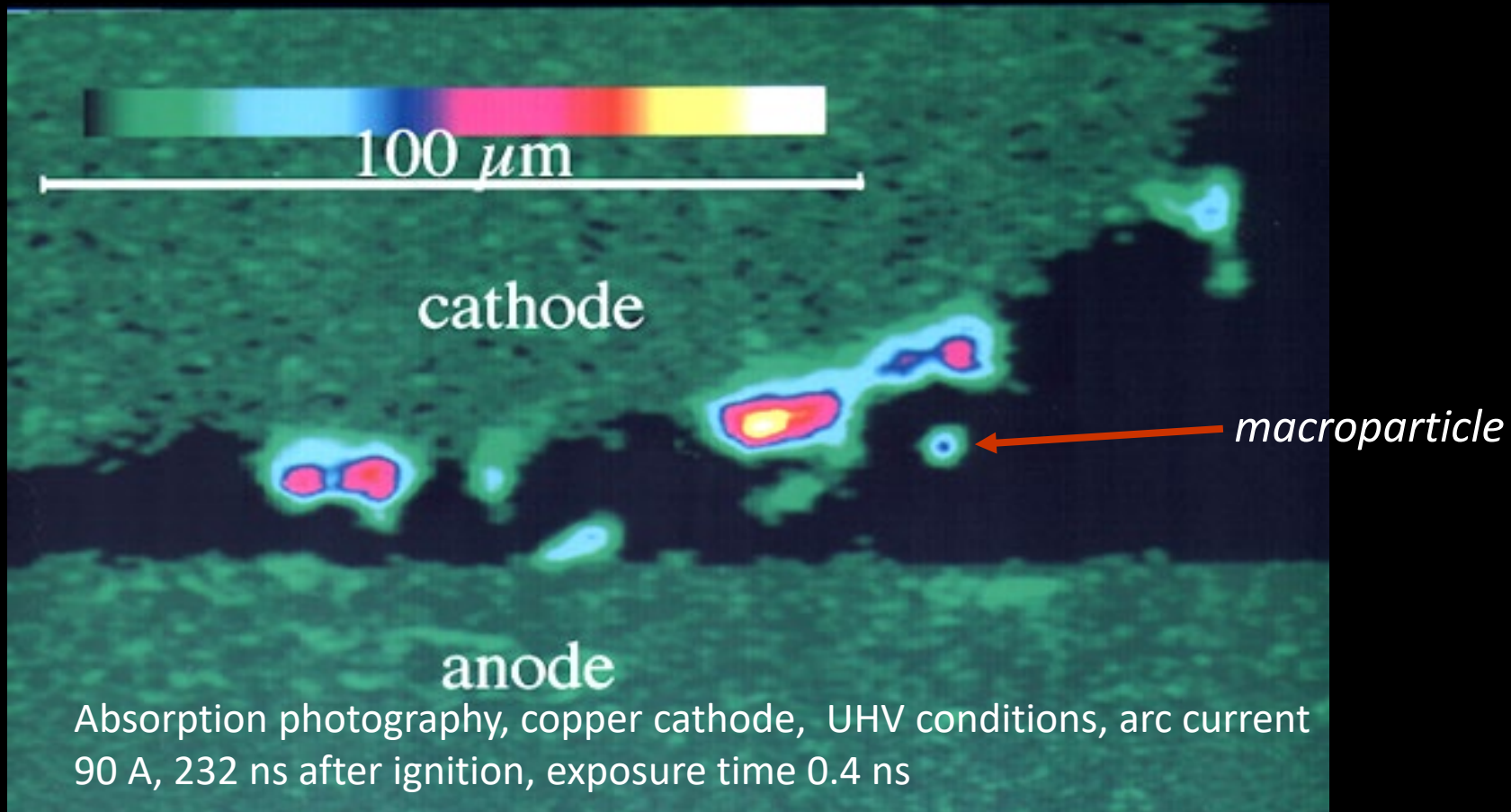
- electron density
- temporal development (400 ps laser pulses)

To determine

- Current density
- Understanding plasma formation

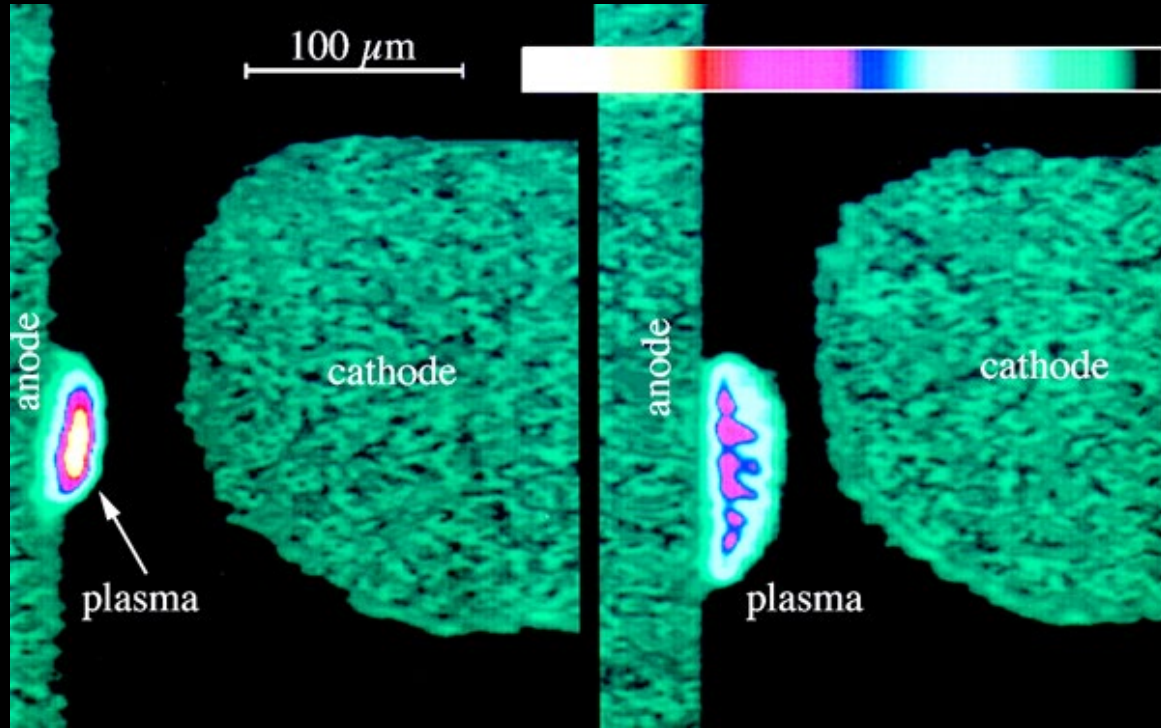
A. Anders *et al*, IEEE Trans.
Plasma Sci. 20 (1992) 466-472

Cathodic Arc Spot Diagnostic by Laser Absorption Imaging



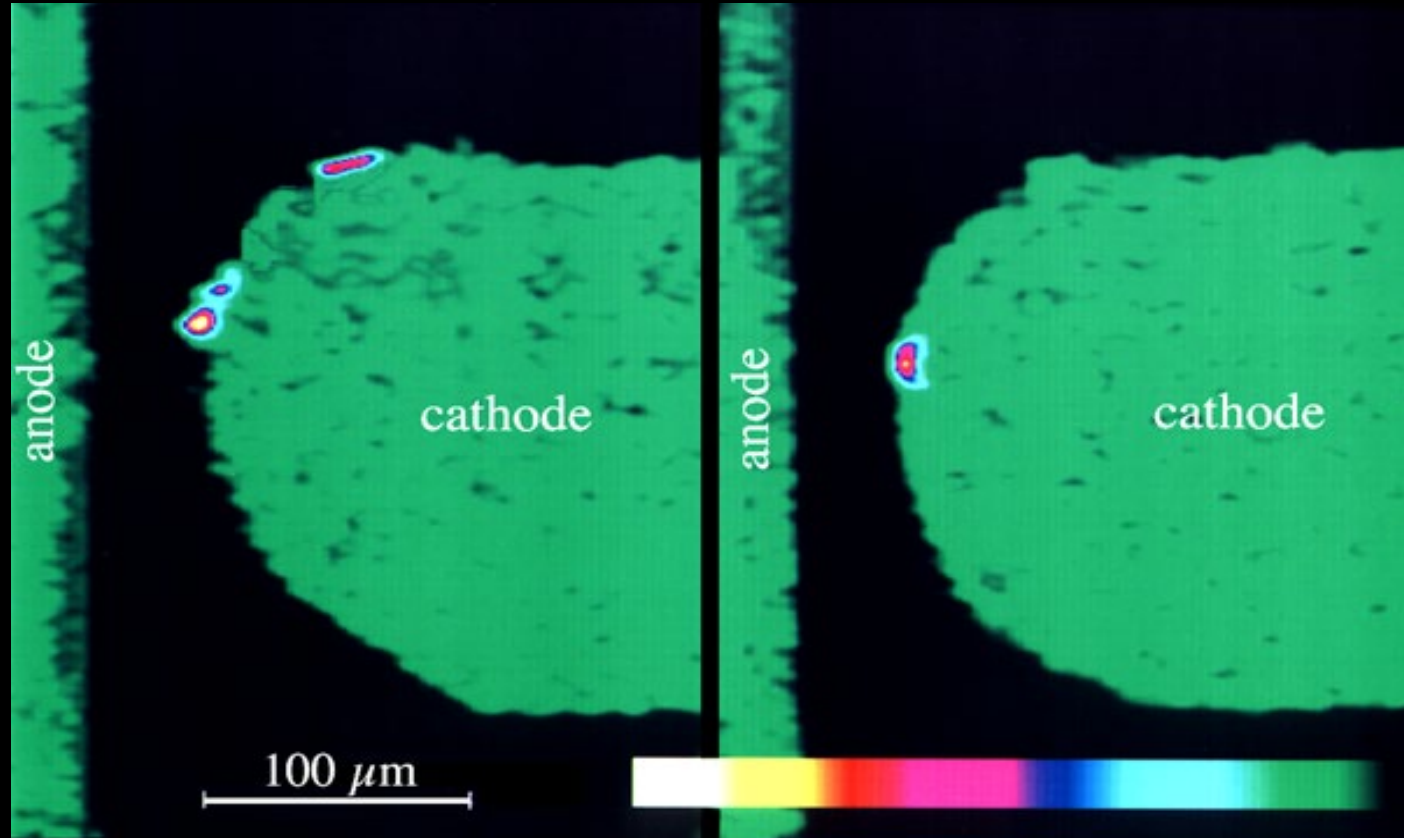
High Voltage Gap Breakdown in UHV

- ❑ Laser absorption photography of vacuum breakdown event, Cu, 100 A, time between pictures 3 ns
- ❑ Spark phase of the arc: voltage is still high
- ❑ Interpretation here: field-emitted electrons cause anode plasma that bridges the gap



Cathode spot dynamics after breakdown

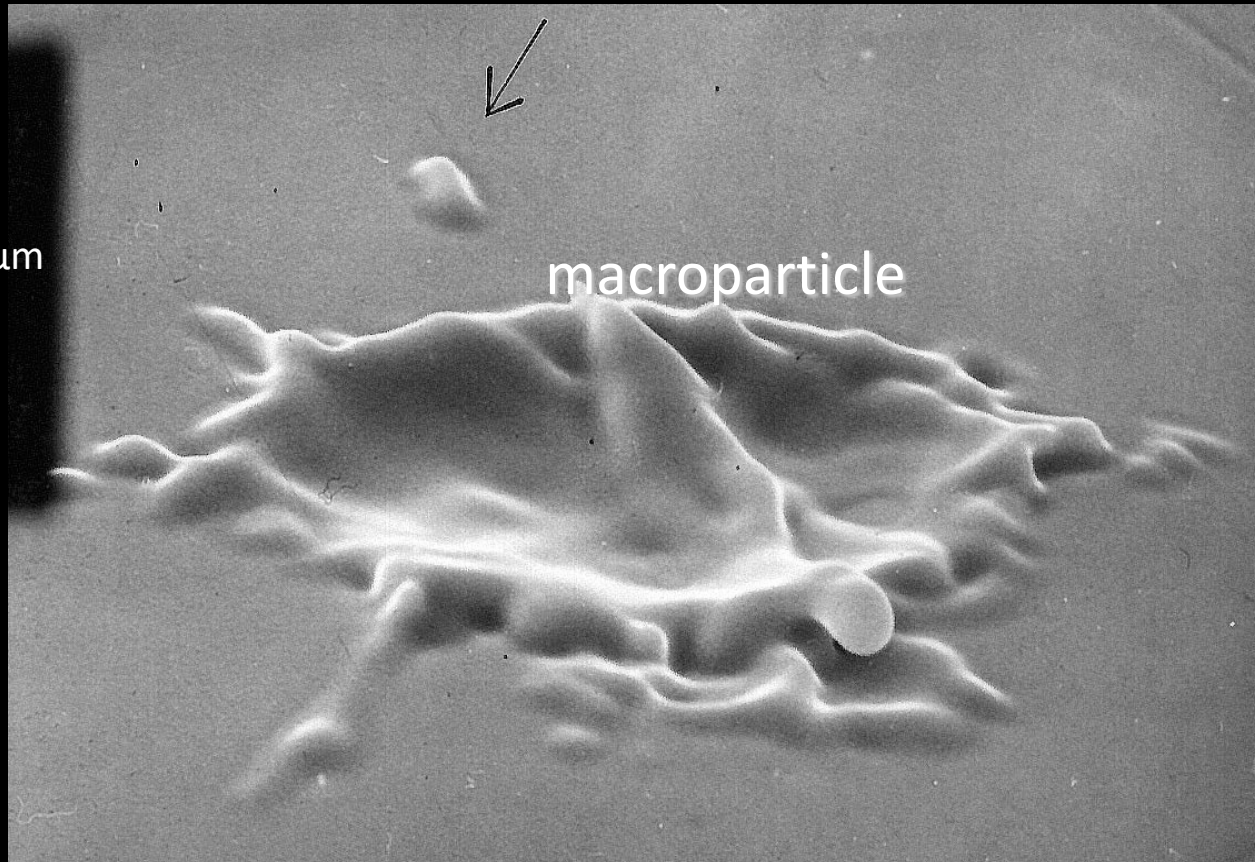
development of
cathode spots,
observed by
absorption
photography, Cu,
100 A, Δt between
pictures 3ns



Self-Generation of Arc Ignition Conditions

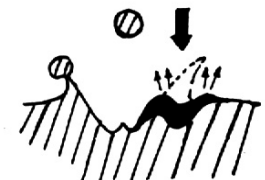
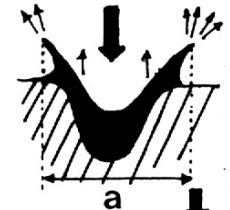
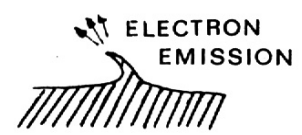
10 μm

macroparticle



10 ns discharge on Mo in UHV.

Photo by B. Jüttner (about 1980).



High-speed Photography of Cathodic Arc Plasmas

Dynamics of cathode spots:
carbon arc as seen with a high-
speed framing camera
arc current up to 5 kA, 200 ns
exposure time per frame

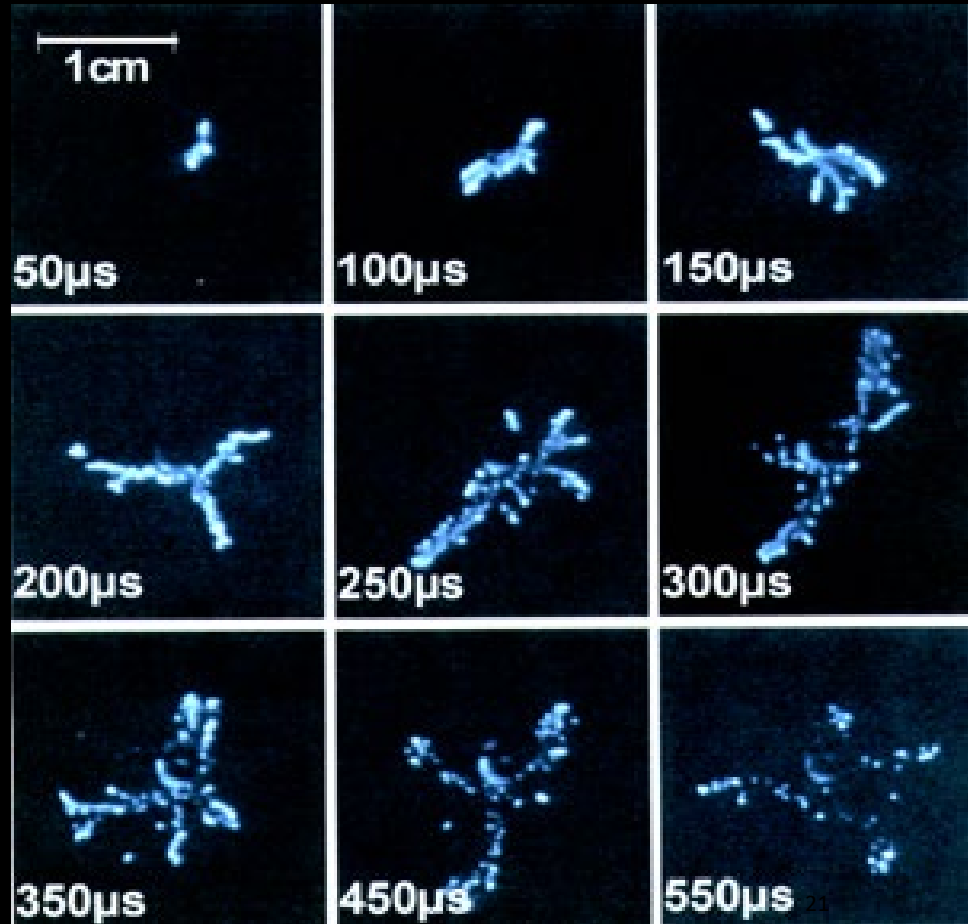
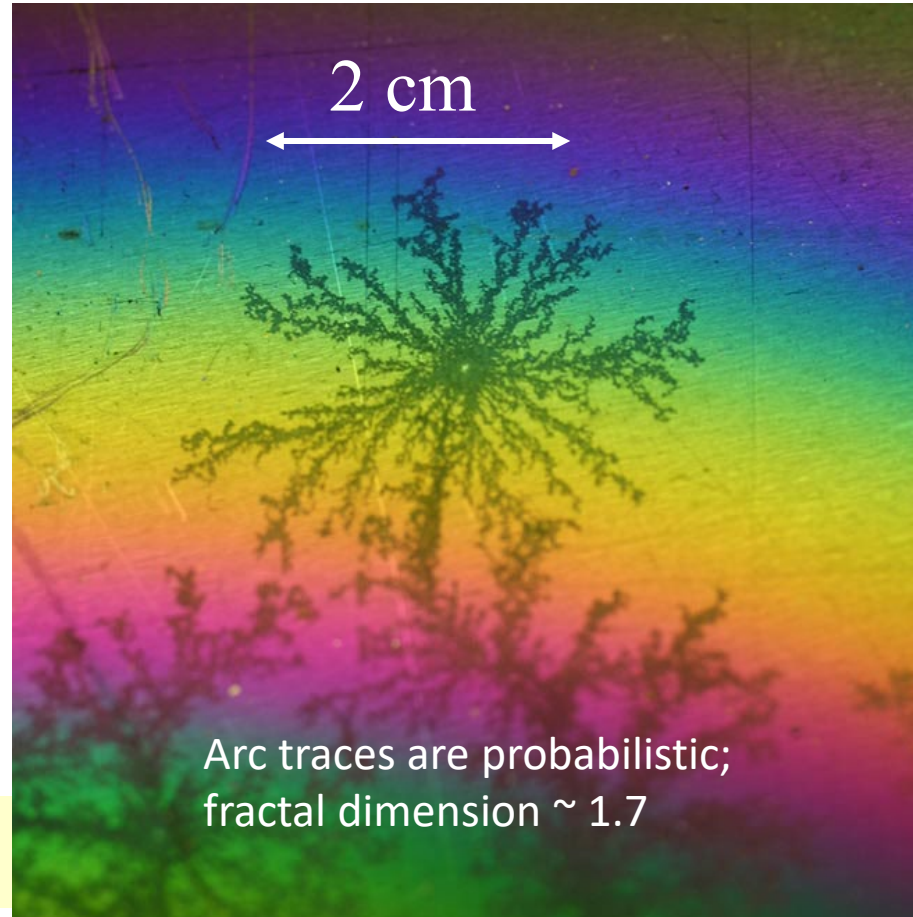


Figure: Courtesy of P. Siemroth and T. Schülke (about 2000)

The Fractal Nature of Cathode Spots

- An object (“fractal”) is self-similar (invariant with scaling) if it is reproduced when magnifying some portion of it.
- Self-similarity may be discrete or continuous, deterministic or probabilistic.
- Self-similarity can be mathematically exact or only approximate and asymptotical.

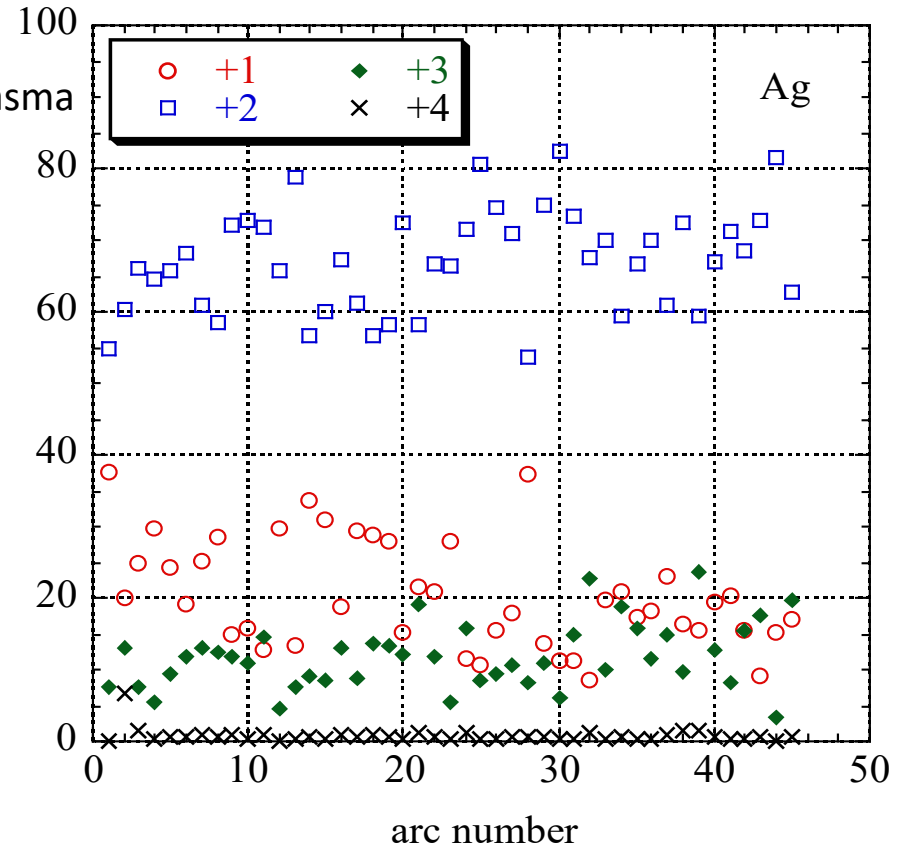


Arc traces are probabilistic;
fractal dimension ~ 1.7

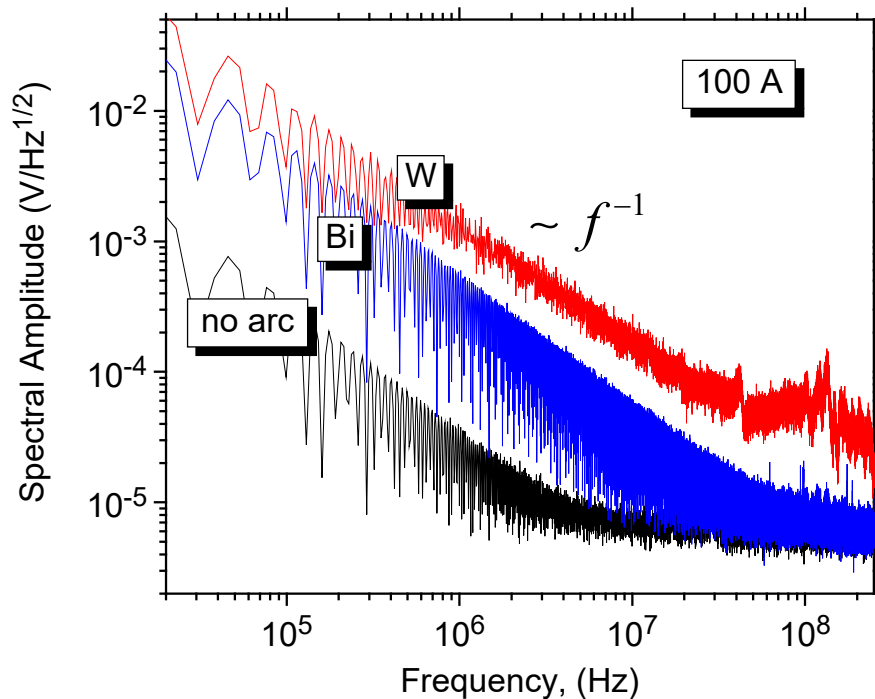
“Noise” or Fluctuations due to Explosive Electron Emission and Plasma Formation of Vacuum Arcs

Percentage of ion charge state in plasma

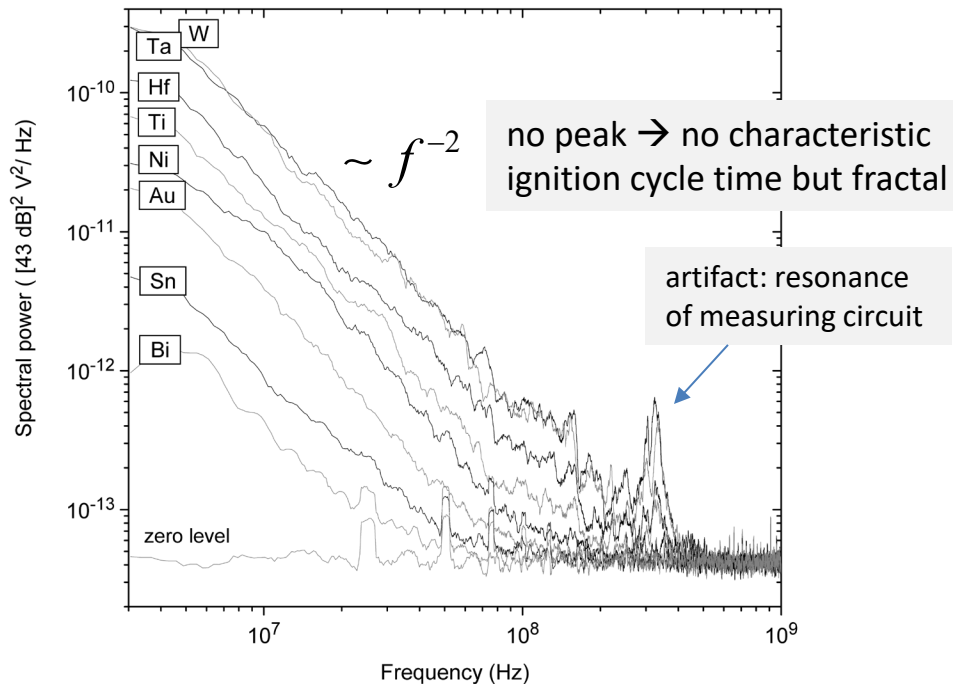
- ❑ Fluctuations are present in practically all parameters (voltage, density, ion charge state, plasma temperature,...)
- ❑ Example: Sampling of ion charge states of silver arcs in vacuum



Alternative high-resolution measurements: Analyze the spectrum of fluctuations of the vacuum arc voltage

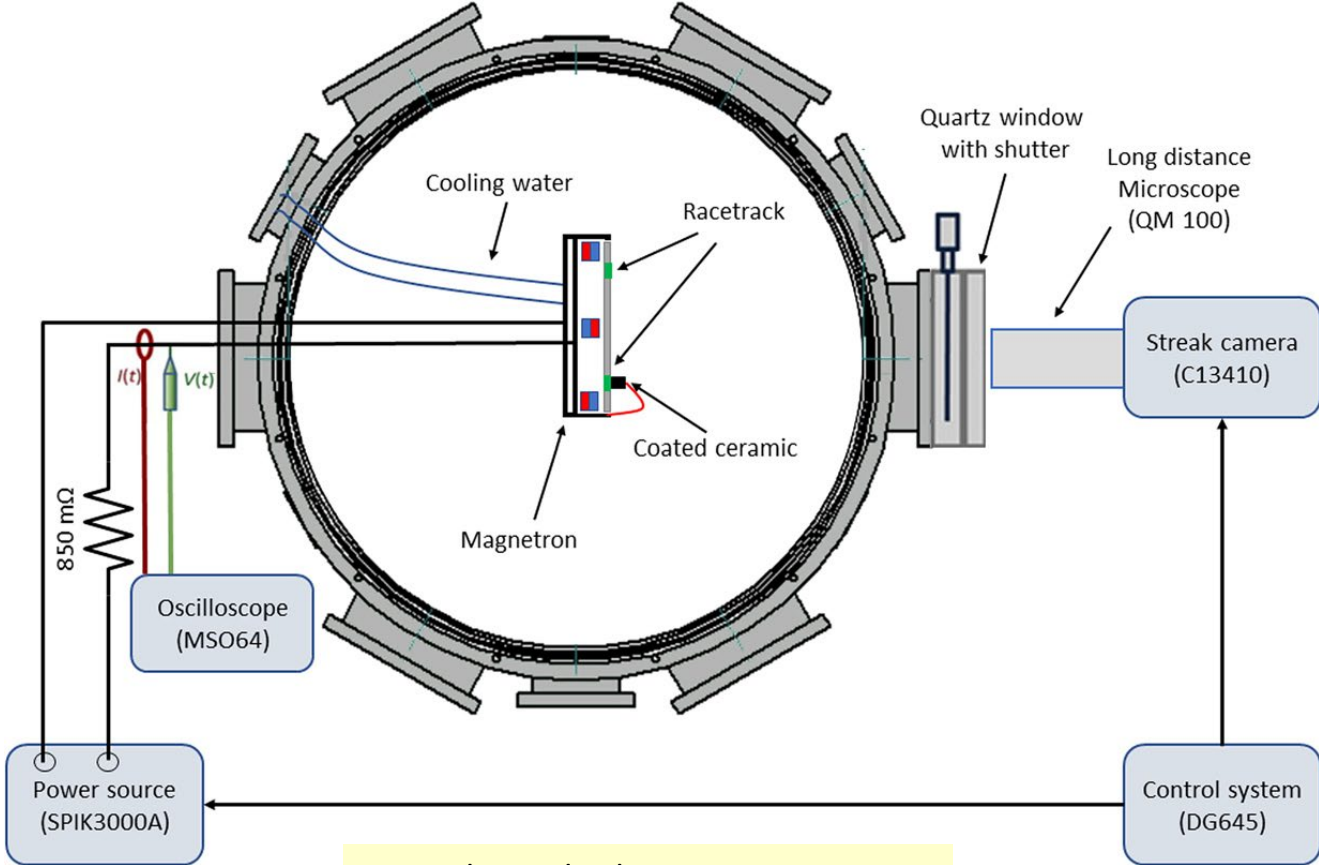


A. Anders, et al., Appl. Phys. Lett., 86 (2005) 211503.



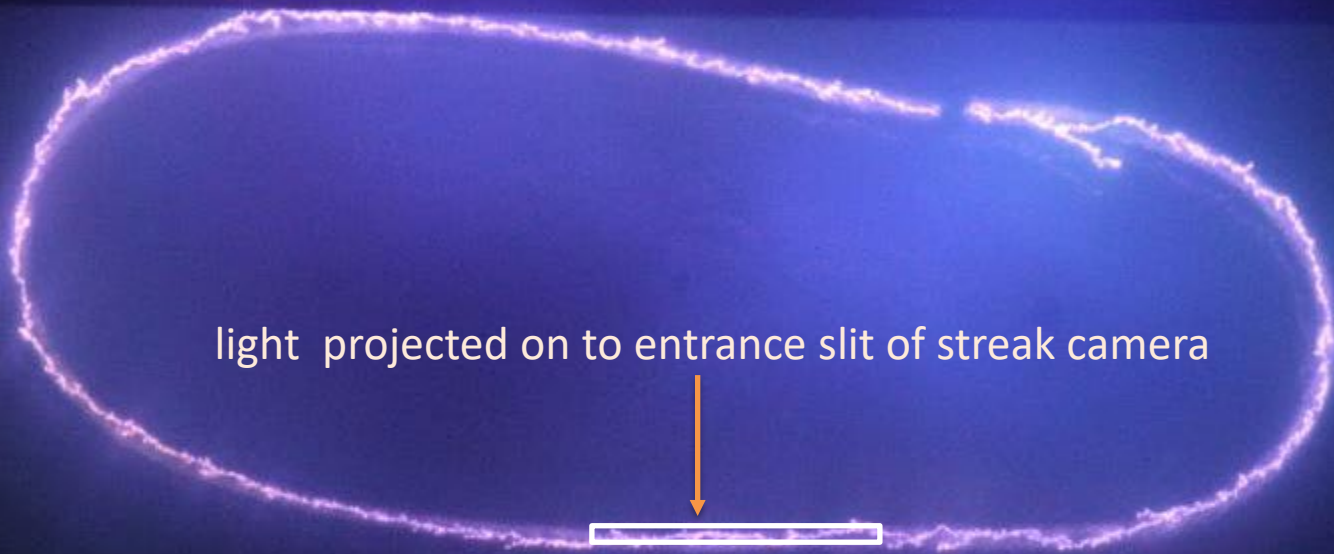
J. Rosén, A. Anders, J. Phys. D: Appl. Phys., 38 (2005) 4184.

Experimental setup for vacuum arc imaging using a fast streak camera



K. Oh, *et al.*, Plasma Sources Sci. Technol., 30 (2021) 095005.

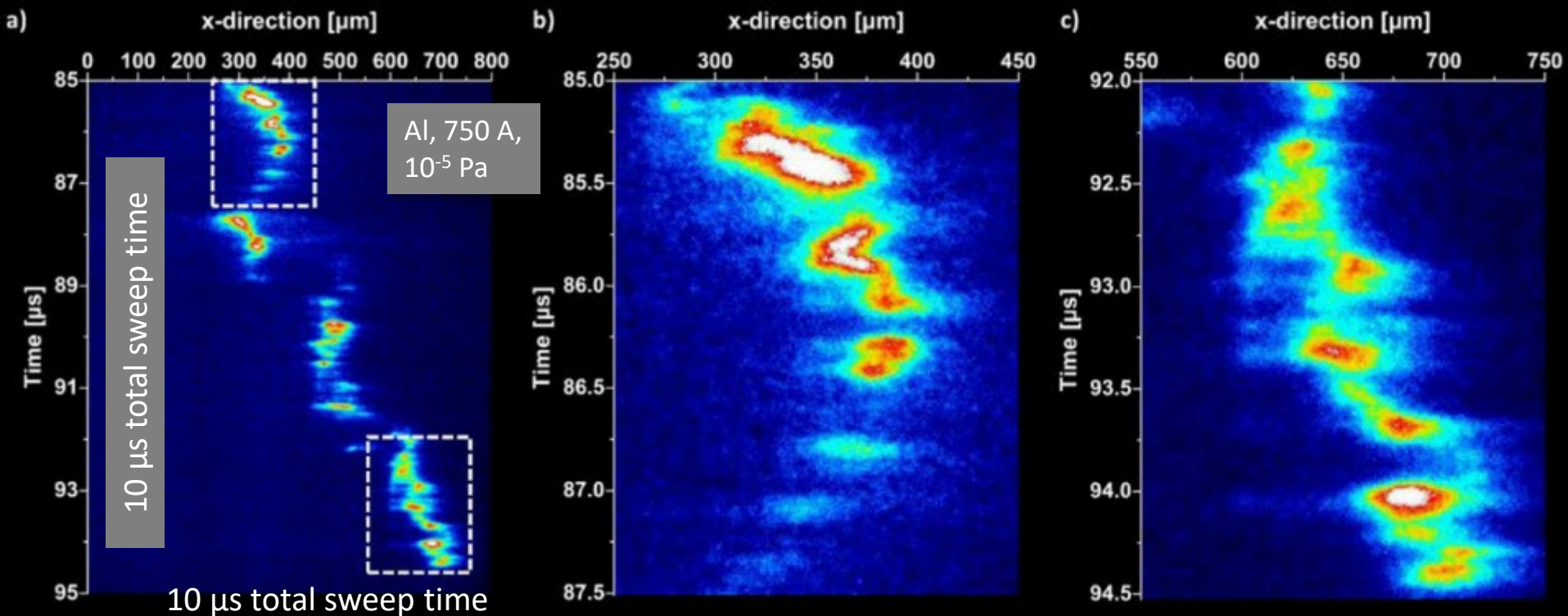
“Magnetically Steered” Arc



light projected on to entrance slit of streak camera

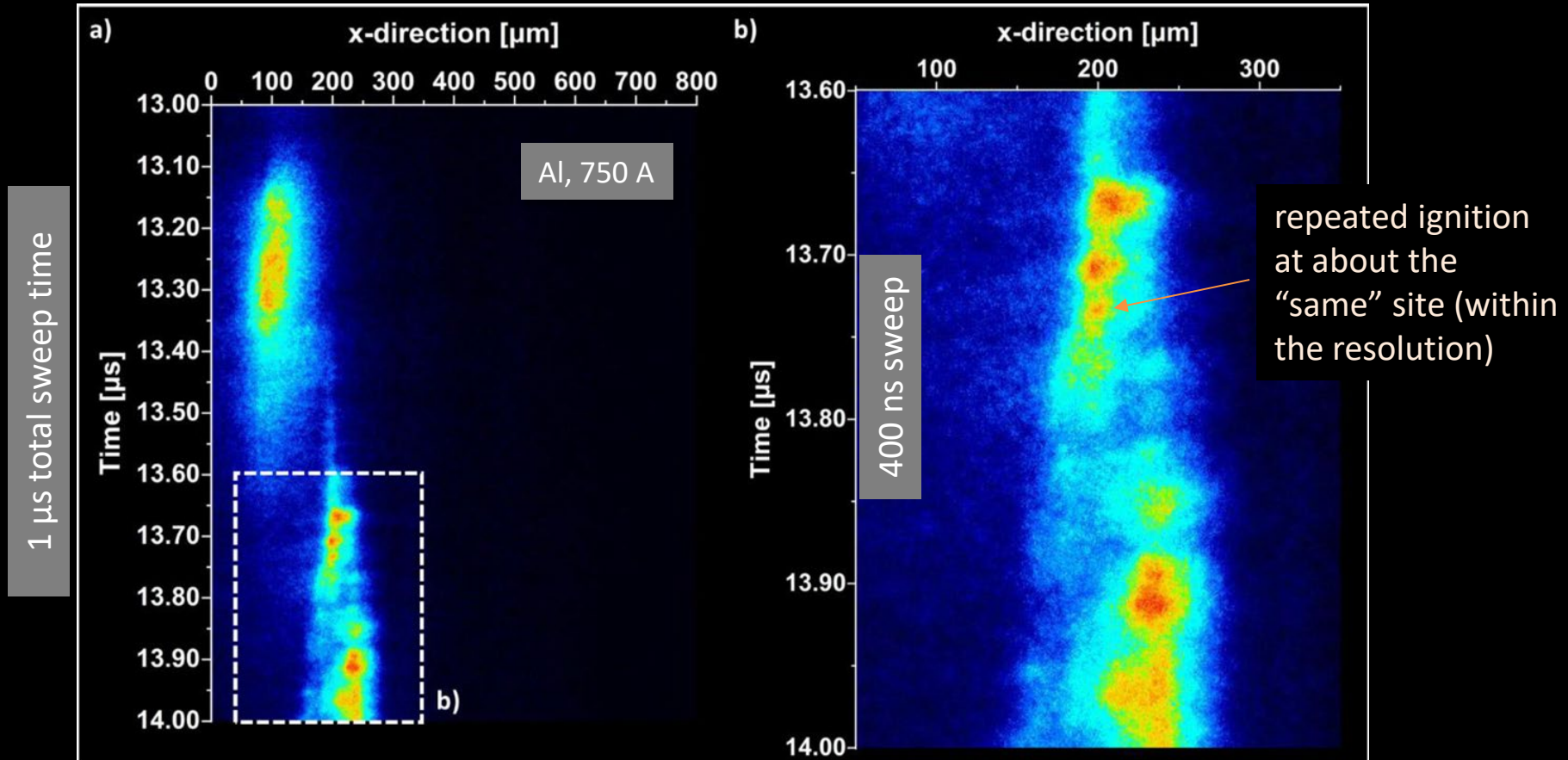
(slit not to scale)

Streak camera study of fluctuations: Cathode spots are fractals



FFT of emitted light analysis \rightarrow spots do not show periodic but self-similar (fractal) features

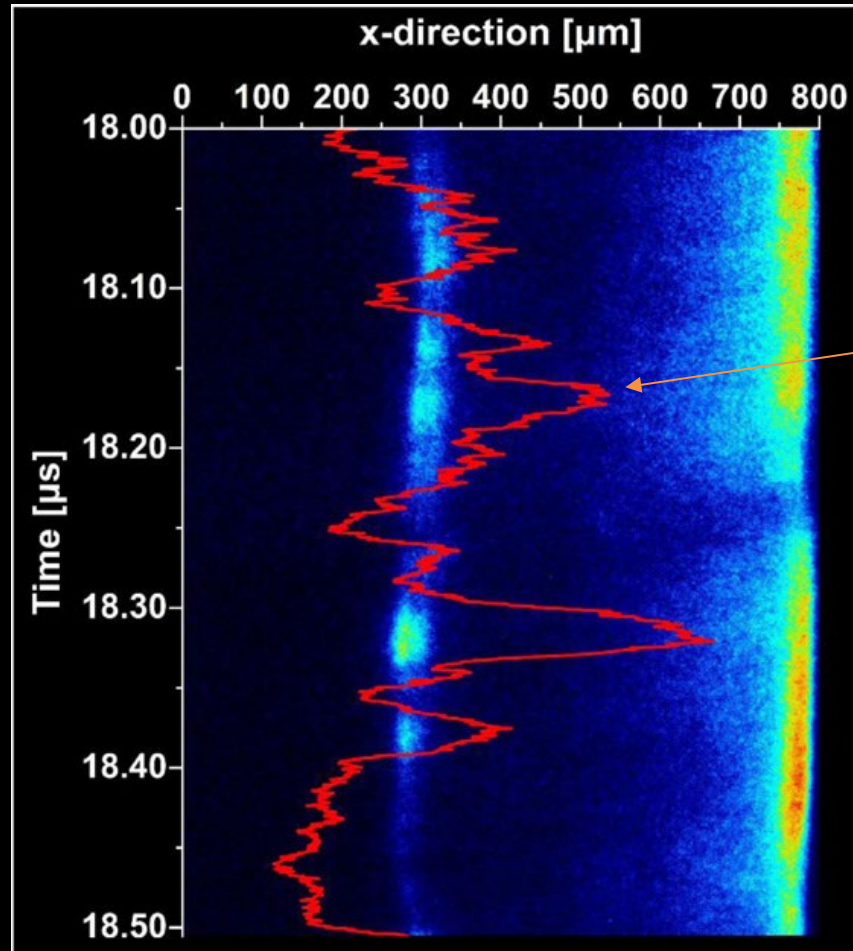
Streak camera study of fluctuations: Cathode spots are fractals



Streak camera study of fluctuations: Cathode spots are fractals

Al, 750 A

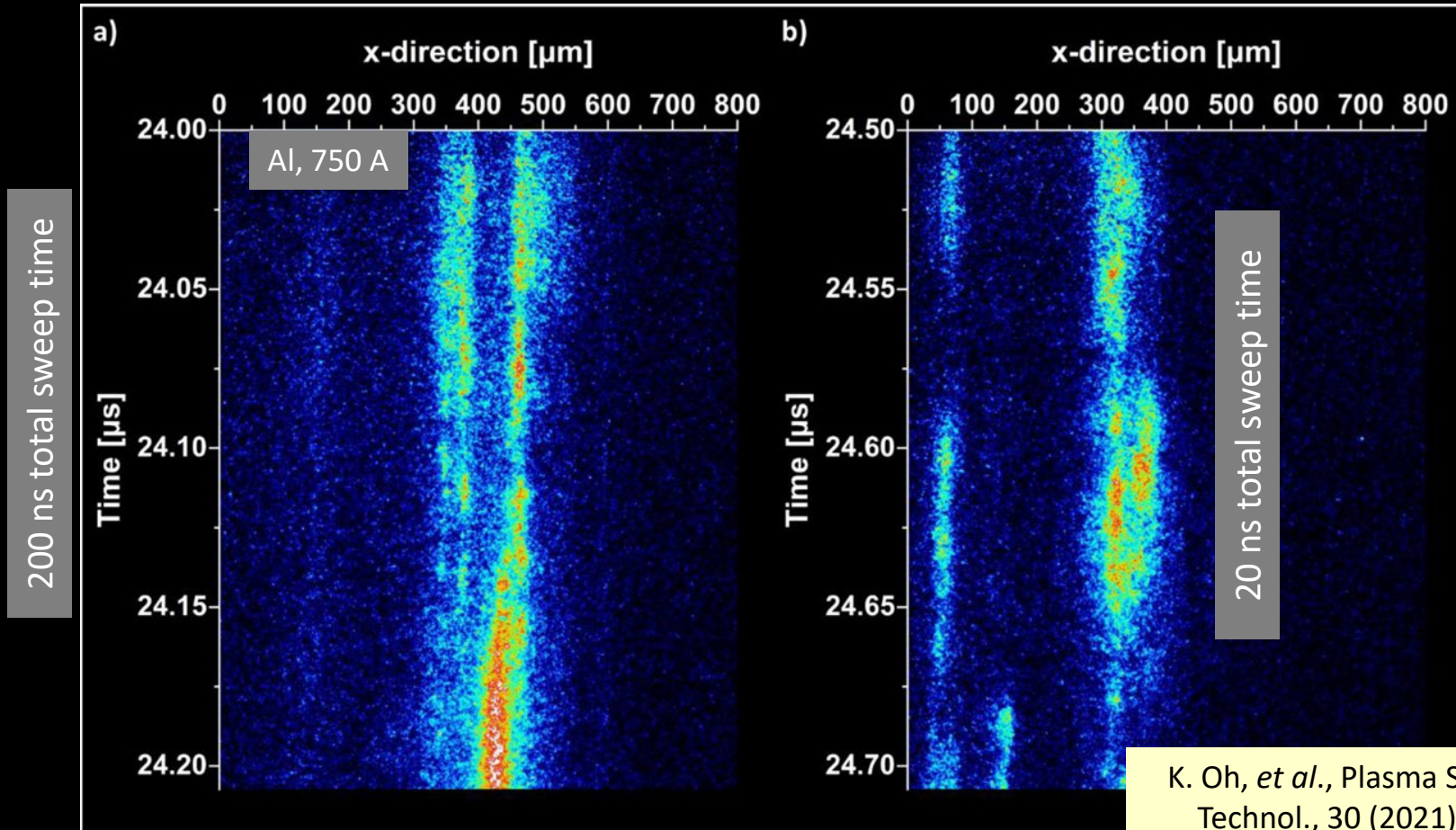
500 ns total sweep time



scan of light emission,
used for fluctuation
analysis

K. Oh, et al., Plasma Sources Sci.
Technol., 30 (2021) 095005.

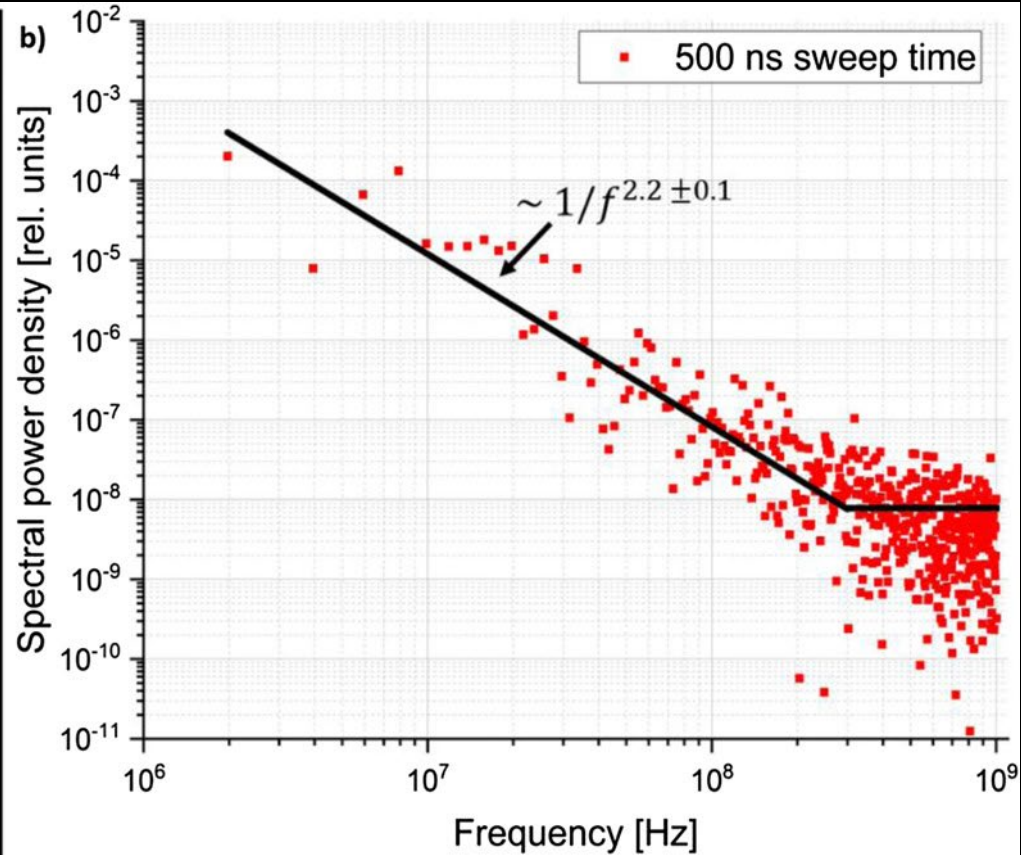
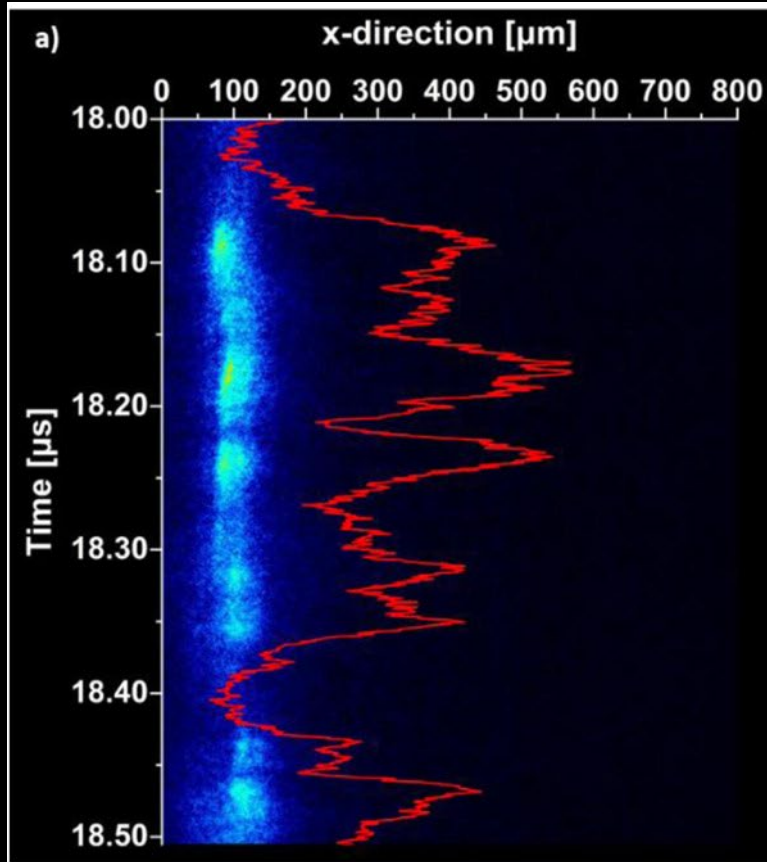
Streak camera study of fluctuations: Cathode spots are fractals



K. Oh, *et al.*, Plasma Sources Sci. Technol., 30 (2021) 095005.

Streak camera study of fluctuations: Cathode spots are fractals

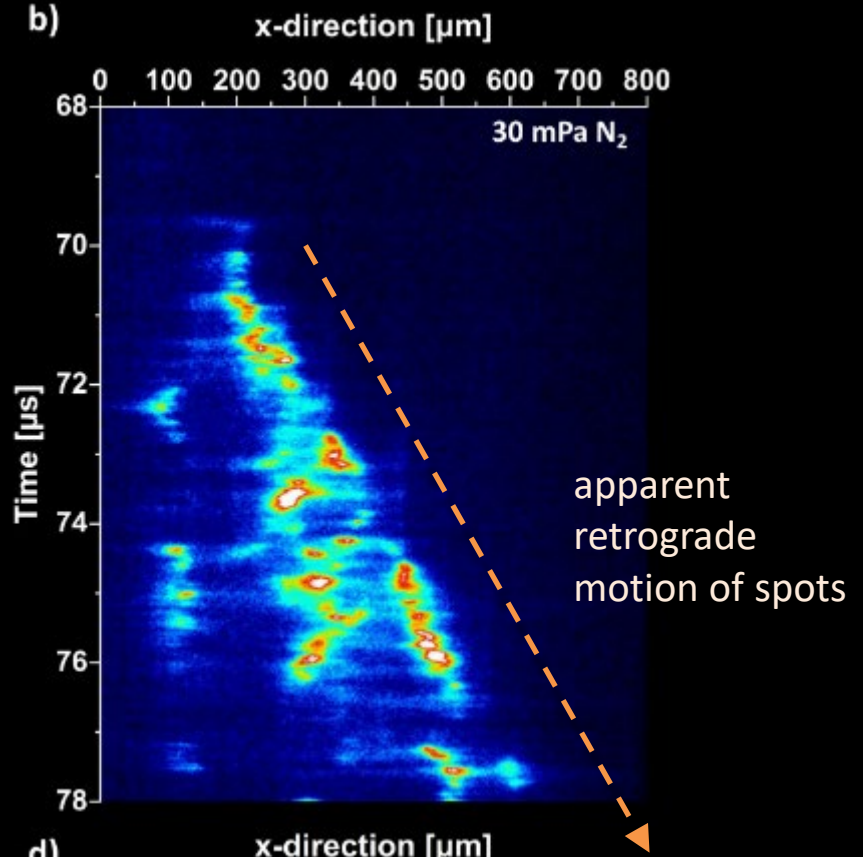
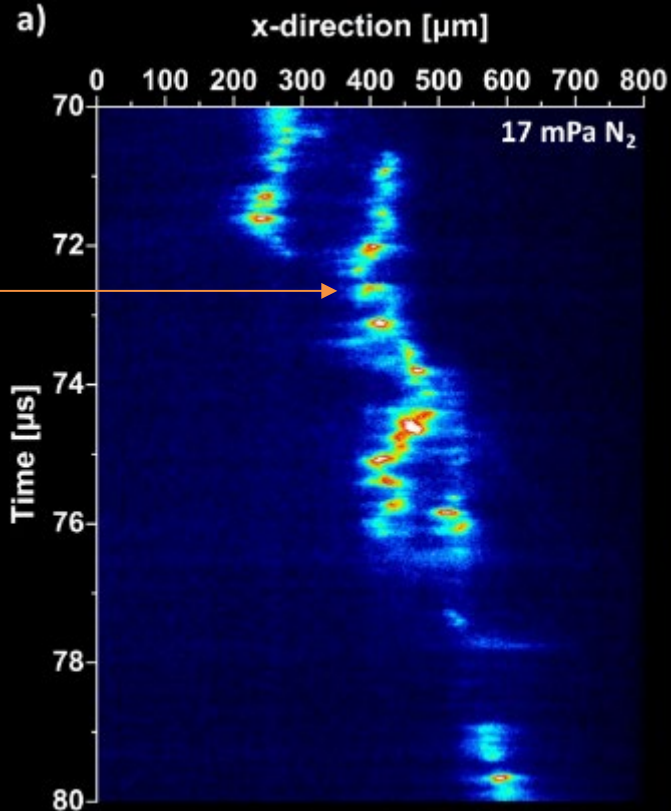
500 ns total sweep time



Study of cathode spot fluctuations; nitrogen background

Al, 750 A

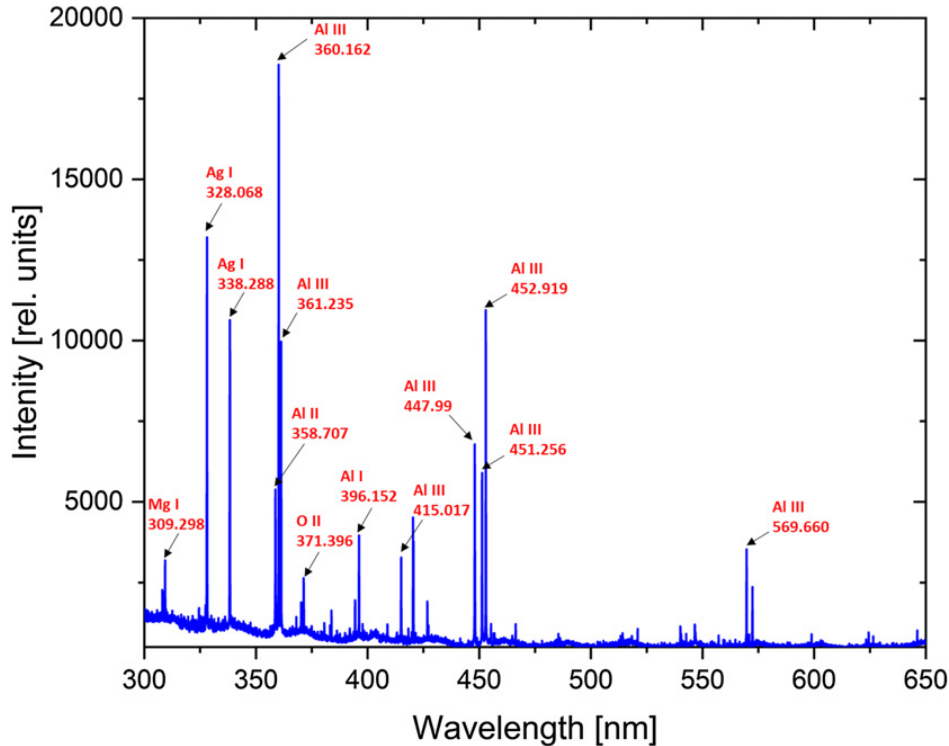
ignition near
the previous
site



c) x-direction [μm]

d) x-direction [μm]

Physical resolution limits when using light emission



Einstein coefficient of the Al III transitions

$$(\Delta t)^{-1} = A_{ij} = 1.3 - 2.5 \times 10^8 \text{ s}^{-1}$$

and

transverse ion velocity $v_{\perp i} \approx 10^3 \text{ m/s}$



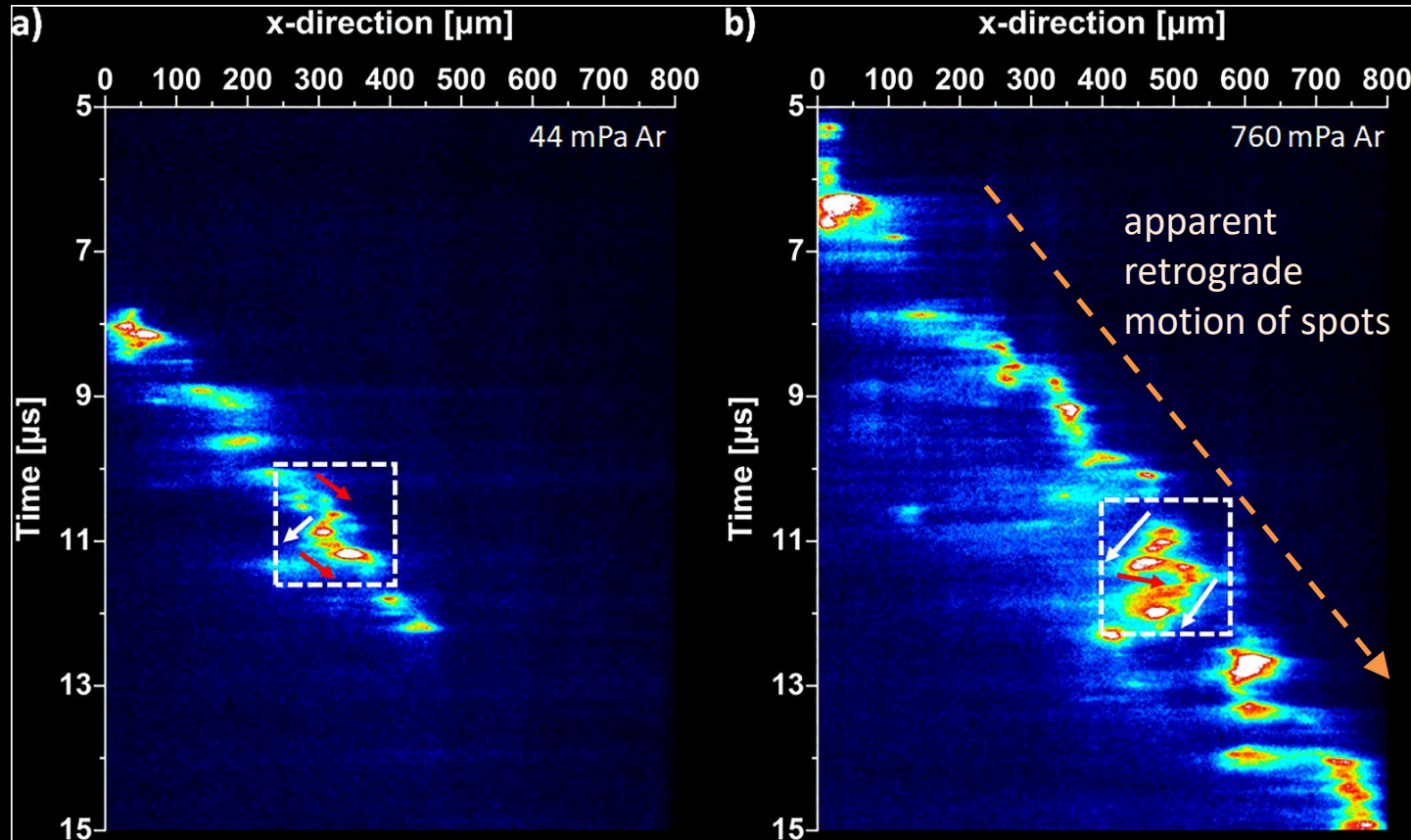
smearing out of emission profile

$$\Delta s = \Delta t \times v_{\perp i} \approx 5 \times 10^{-5} \text{ m} = 5 \mu\text{m}$$

→ in optical emission,
ultimate resolution limits are
5 ns and 5 μm

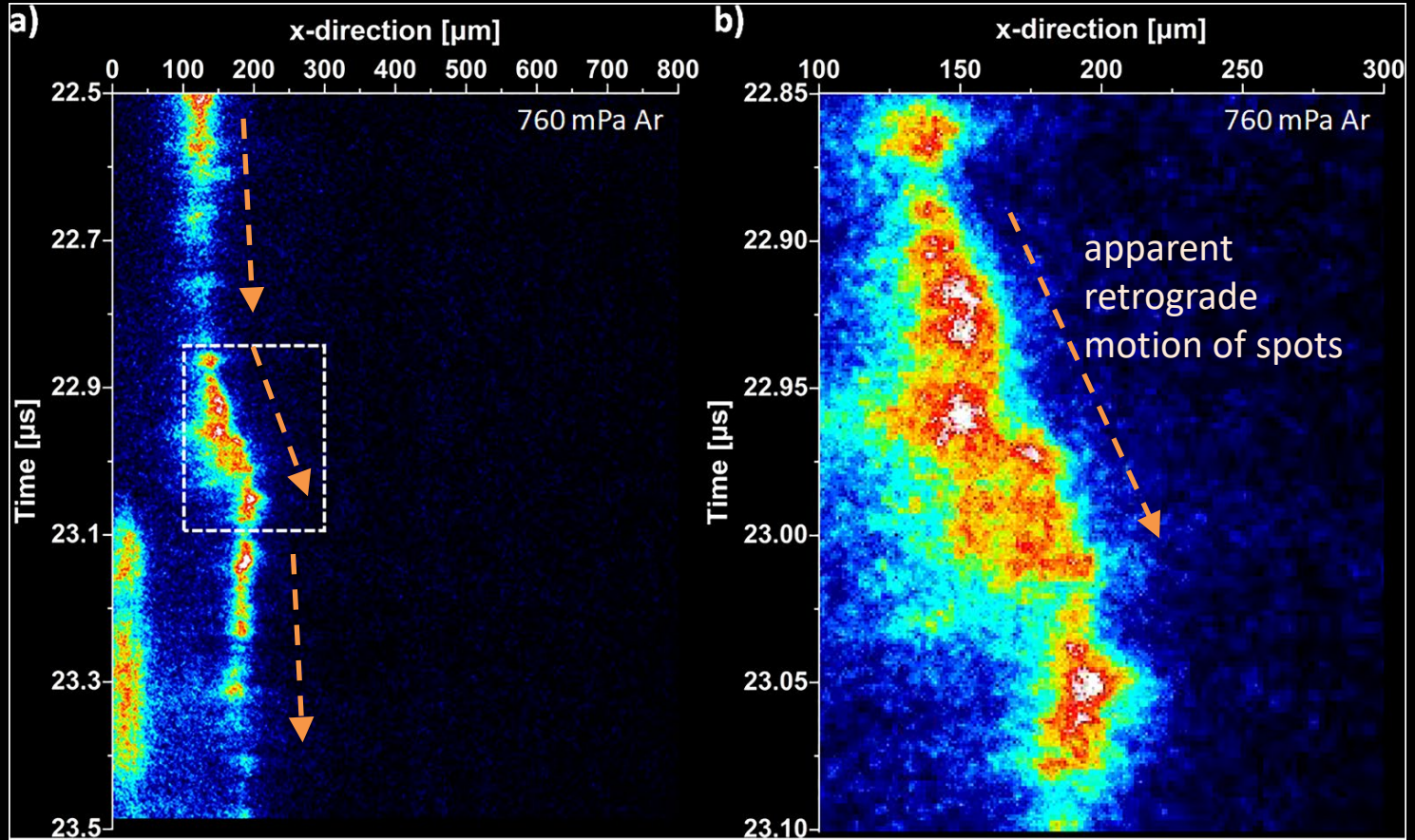
Study of cathode spot fluctuations, argon background

Al, 750 A

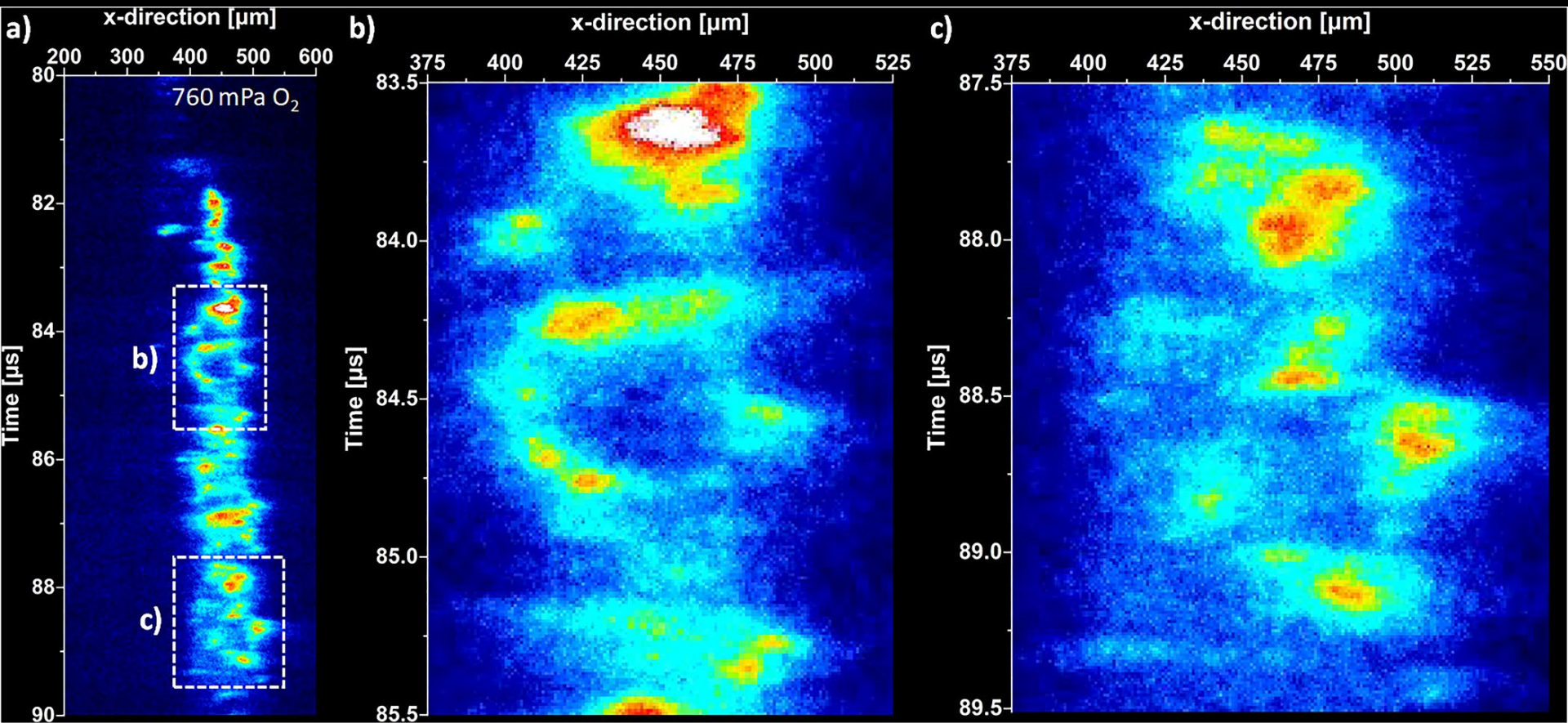


Study of cathode spot fluctuations, argon background

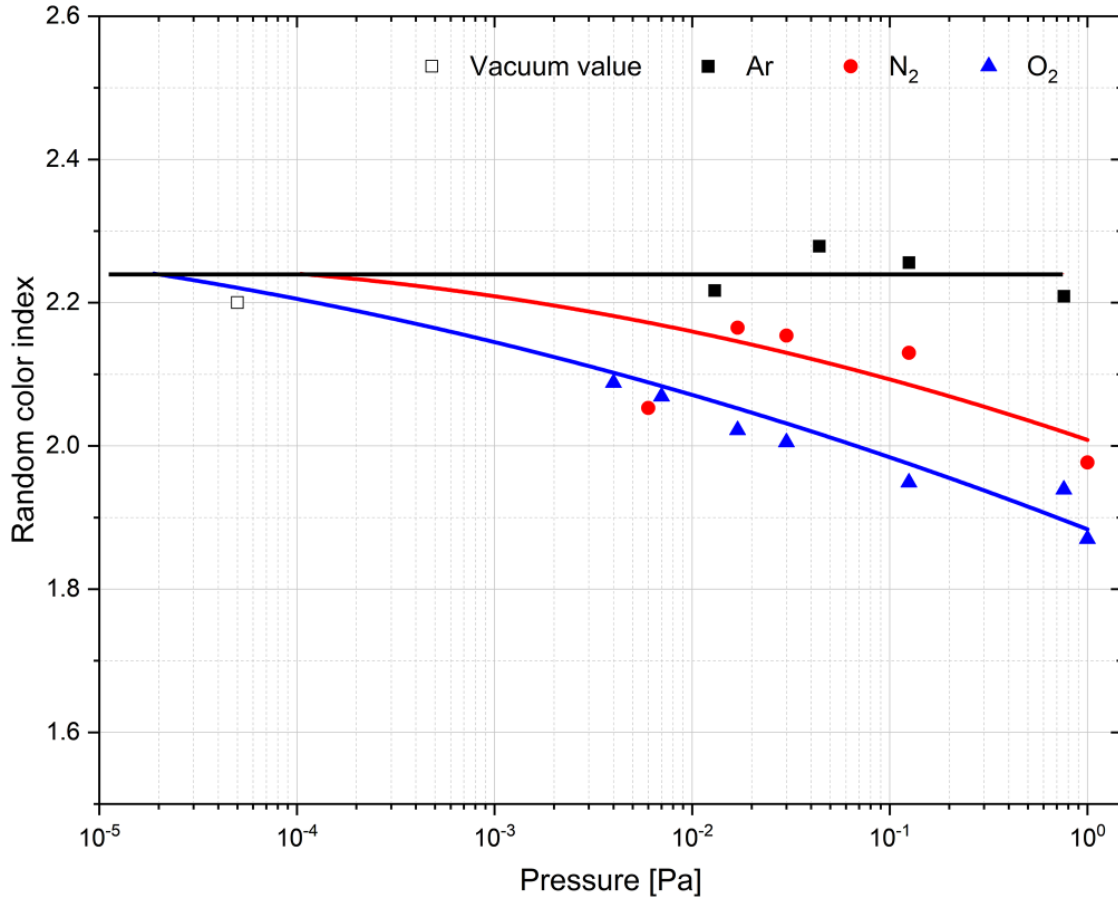
Al, 750 A



Study of cathode spot fluctuations, oxygen background



Fractal Analysis of Streak Images

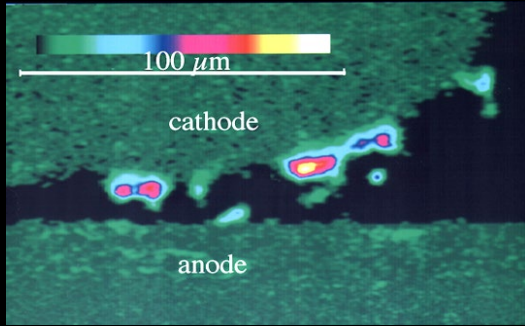


Analyzing the spectral power density of streak images to determine the Random Color Noise index α

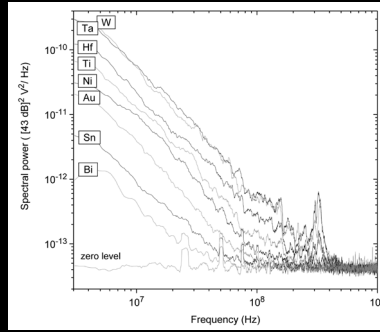
$$F(f) \sim f^{-\alpha}$$

The greater α , the greater the correlation: feedback, dependence on prior events, here plasma density, surface condition.

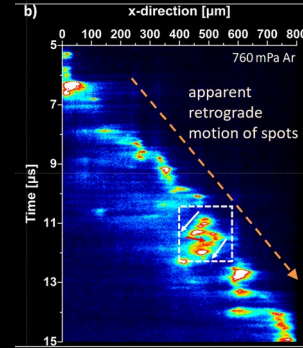
Summary and Conclusions



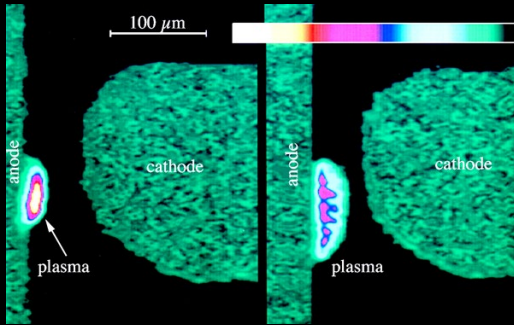
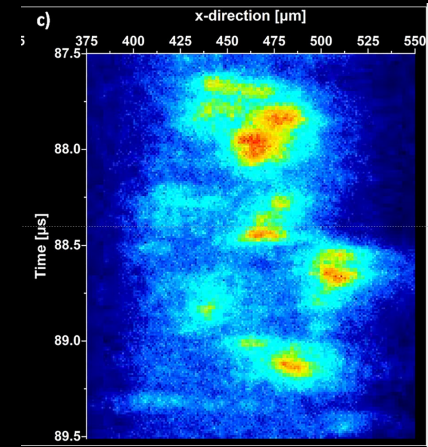
cathode spot diagnostic by laser absorption: unifying the crater and optical features of spots



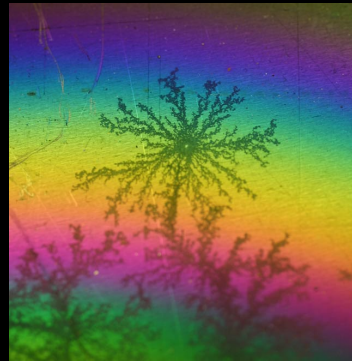
power law for arc voltage spectrum (→fractal)



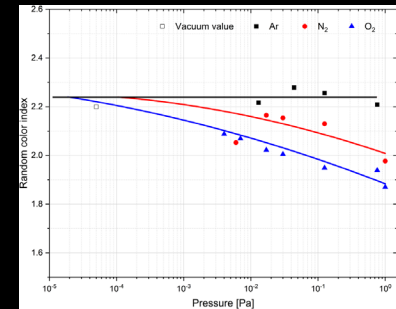
high resolution streak analysis: ignition often near prior emission center, ignition in jxB and $-jxB$ directions possible



breakdown can have anode plasma first



fractal nature of cathodic arcs



Random Color Noise Index depends on surface state