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MeVArc 2012

Perspective on the state-of-the-art for vacuum arcs and cathode processes

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BERKELEY LAB

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Some topics to consider….

☐ why do arc cathode spots form?
☐ spot appearance and spot types
☐ mechanisms of spot ignition, role of roughness and chemistry
☐ high resolution diagnostics
☐ ecton and fractal models of arc processes
☐ charge states of ions produced in spots
☐ cohesive energy rule
☐ vacuum arc versus “unipolar arc”

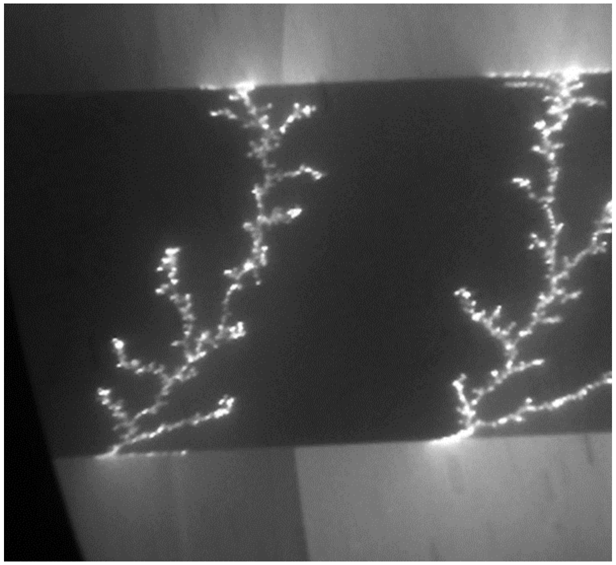
Why do arc spots form?

Why do arc spots form?

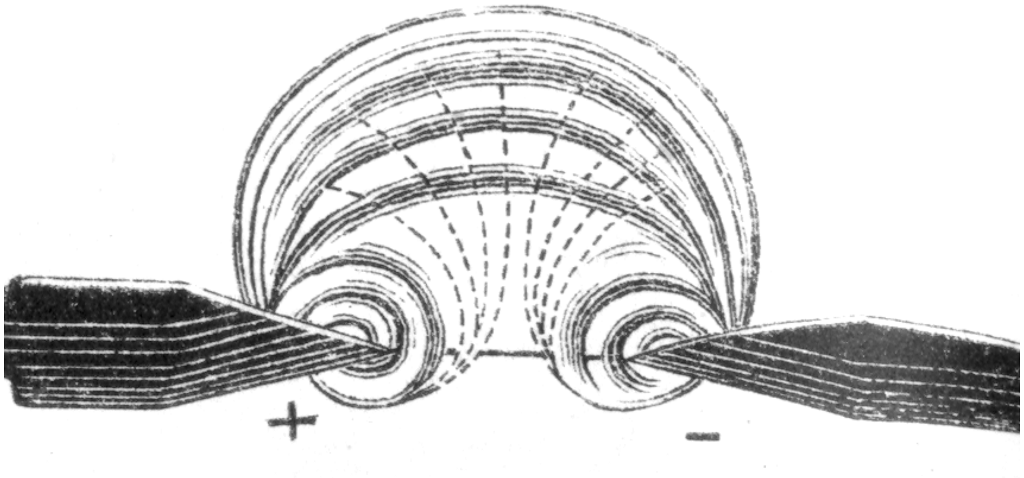
arcs

cathodic (vacuum) arcs

thermionic arcs



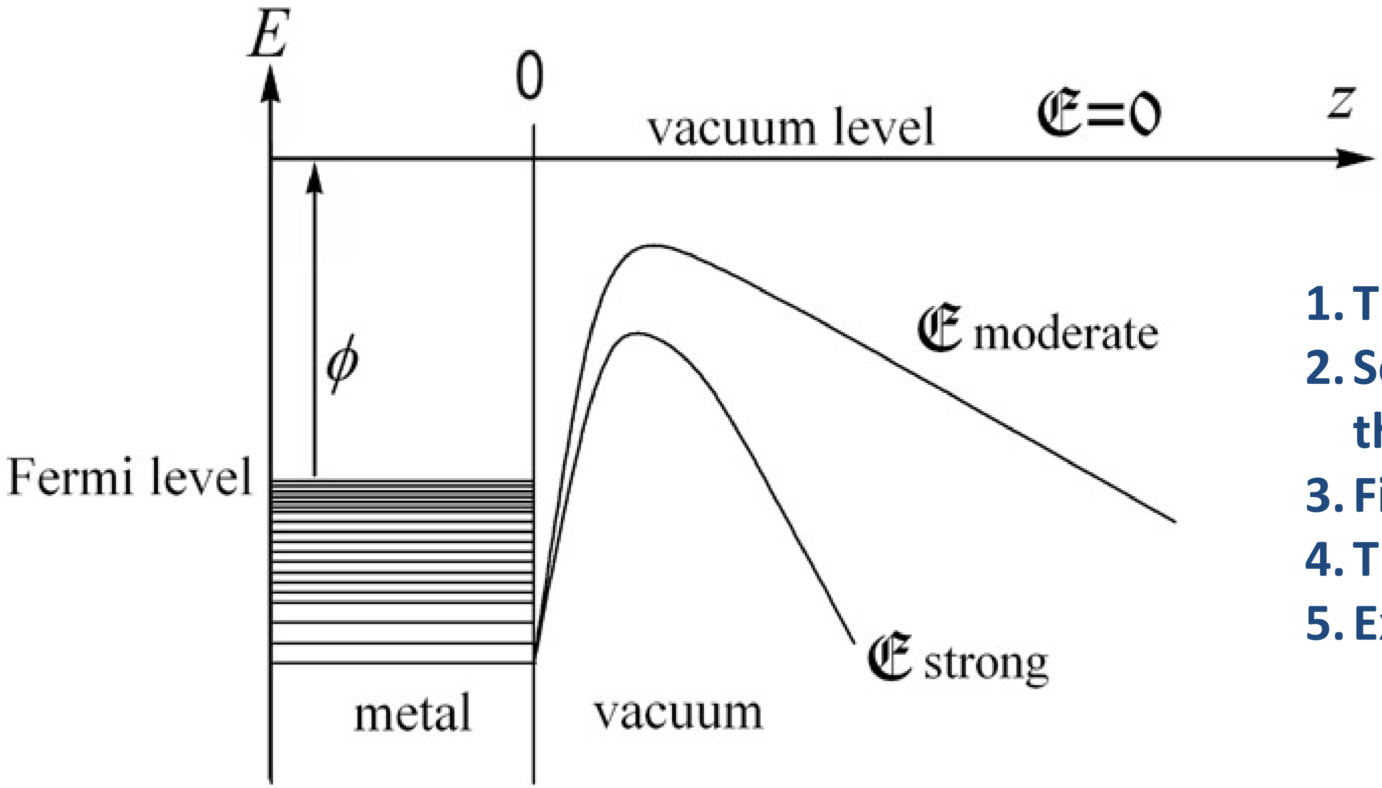
A. Anders, Cathodic Arcs, Springer, New York 2008



G. Wiedemann, Die Lehre von der Elektricität, Vieweg, Braunschweig, 1885

The fundamental problem:
How do electrons escape from the cathode?

Potential Barrier, Work Function and Schottky Effect



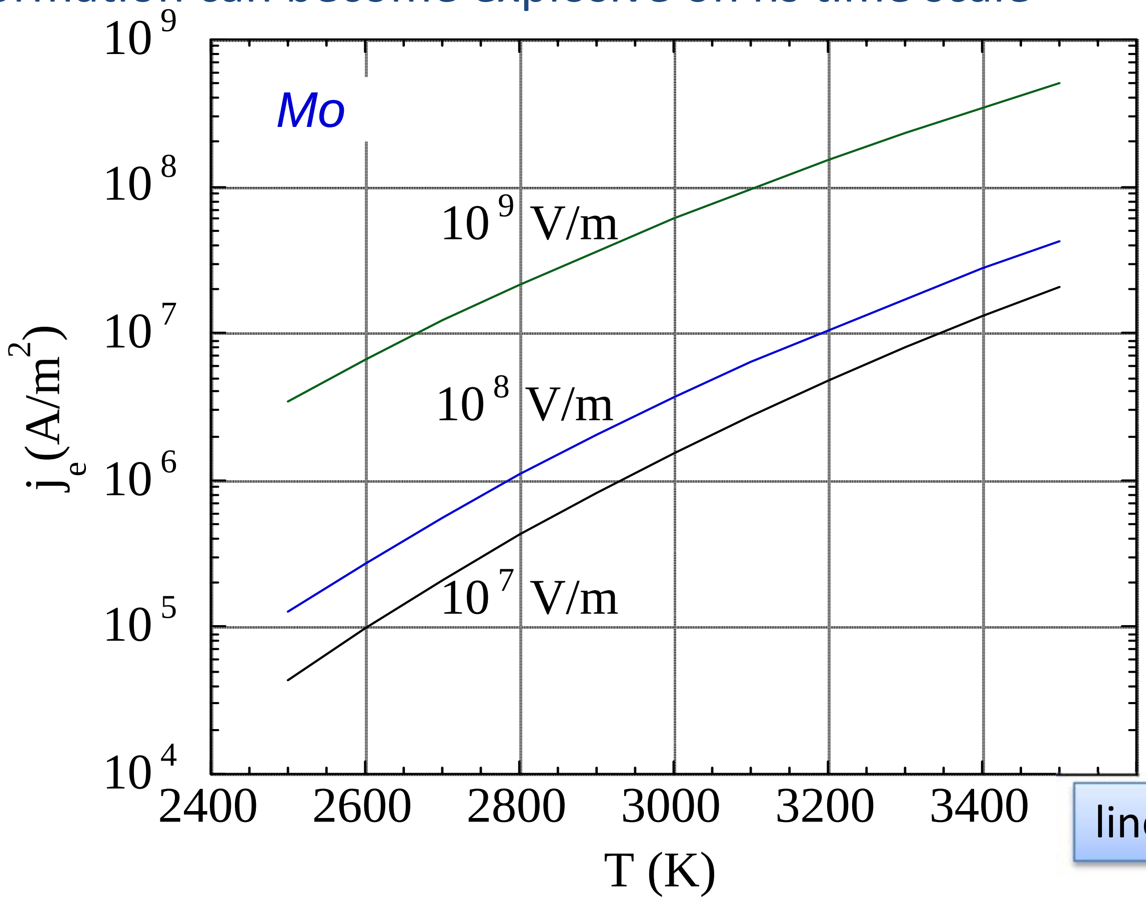
1. **Thermionic emission**
2. **Schottky-enhanced thermionic emission**
3. **Field emission**
4. **Thermo-field emission**
5. **Explosive emission**

Thermofield Electron Emission

Current density of thermofield emission is

- highly nonlinear in temperature and electric field
- necessarily associated with great power density

→ plasma formation can become explosive on ns time scale



log scale

linear scale

Why do arc spots form?

The current scales linear with area but highly non-linear with *T*, $\mathfrak{E}$

$$j_{TF}\left(T,\mathfrak{E}\right)\approx k\left(AT^{2}+B\mathfrak{E}^{9/8}\right)\exp\left[-\left(\frac{T^{2}}{C}+\frac{\mathfrak{E}^{2}}{D}\right)^{-1/2}\right]$$

Therefore,

- strongest electron emission occurs by concentrating the energy in small location, the emission center or spot.

- In other words: producing the highest temperature and field strength on a small area gives higher emission than from a lower temperature and lower field on a larger area.
- Consistent with experience: one observes a glow → cathodic arc transition but no cathodic arc → glow transition

Spot Appearance, Types, Ignition, Apparent Motion, Life-Cycle

Appearance of Cathodic Arcs

- Metal plasma is formed explosively at cathode spots
- Cathode spots ignite and go through a “life cycle” → craters are left on cathode.

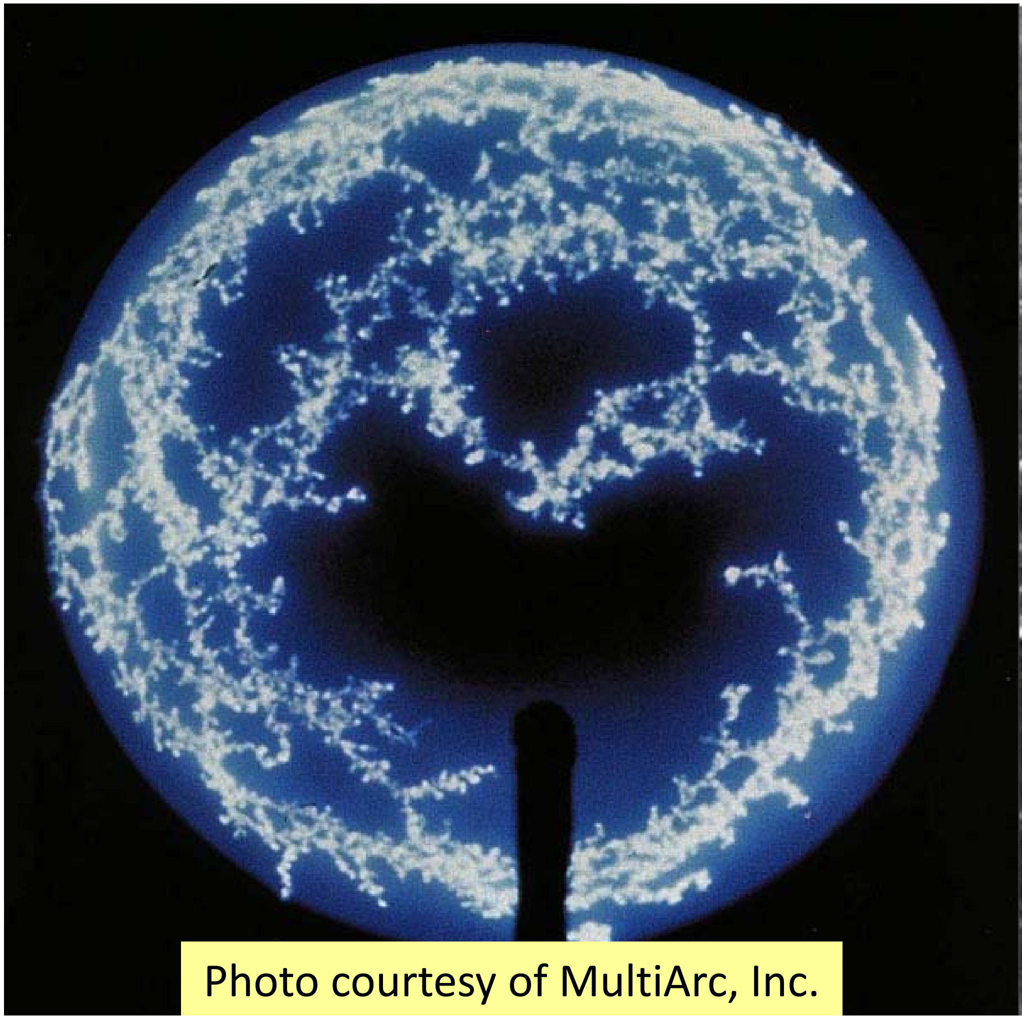


Photo courtesy of MultiArc, Inc.

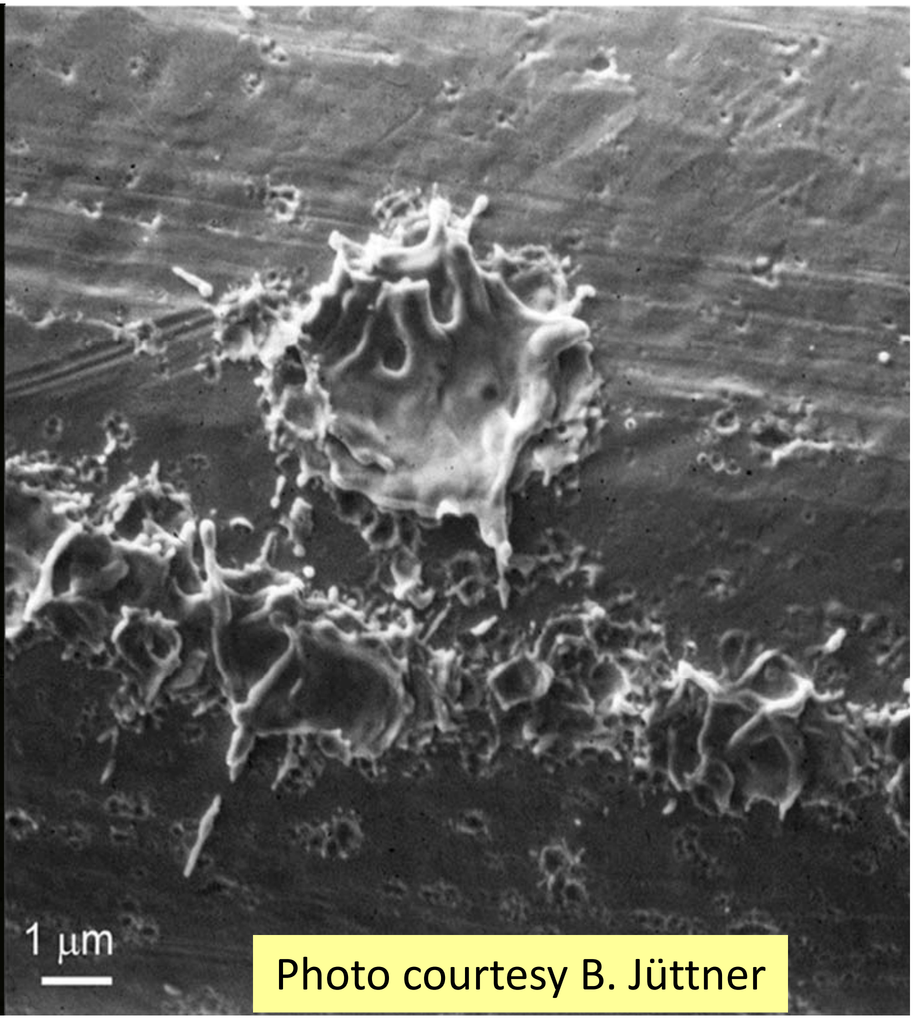


Photo courtesy B. Jüttner

Arc Spot Ignition

Local thermal run-away process leads to micro-explosion and formation of extremely dense plasma:

High electric surface field, enhanced by

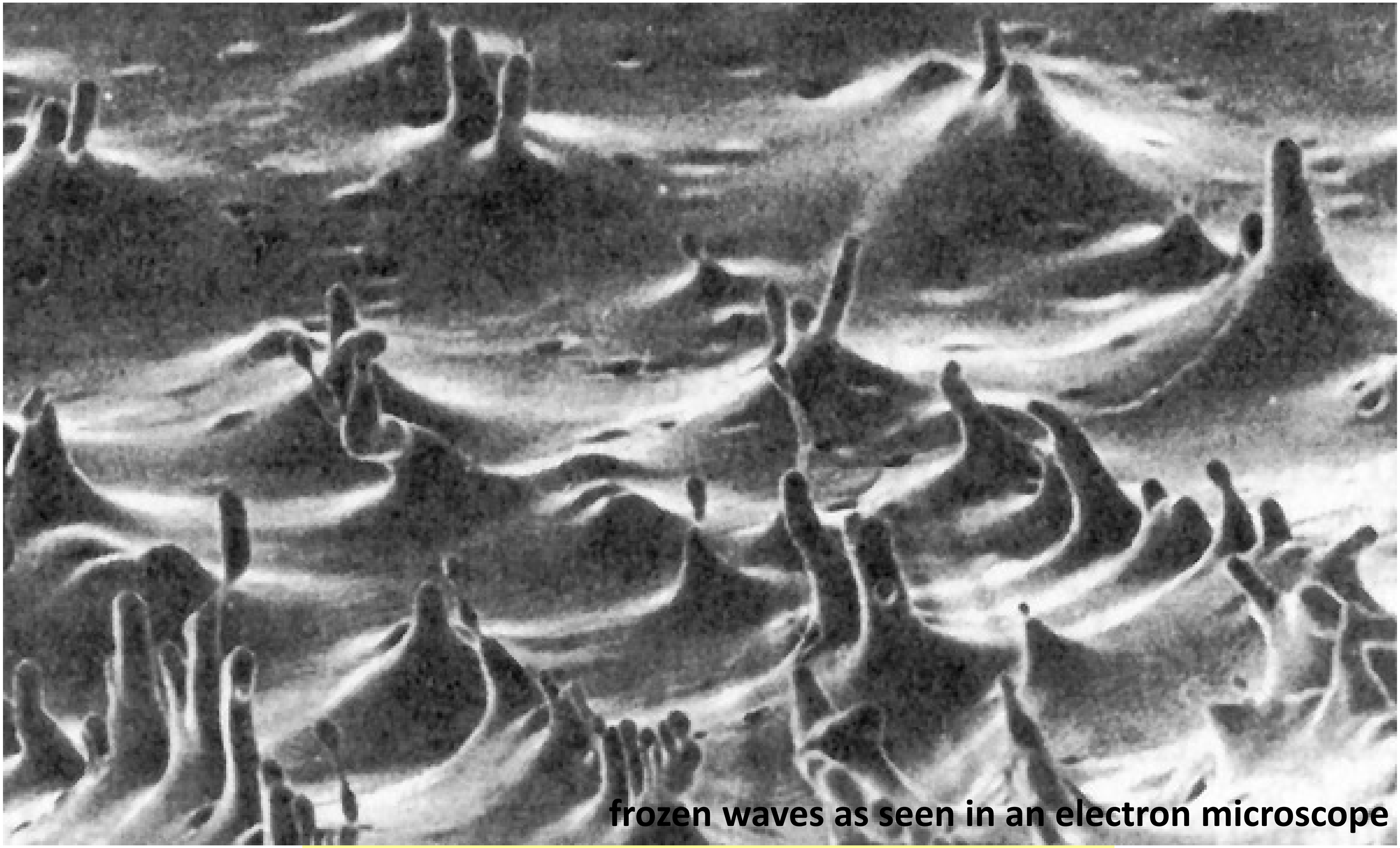
1. protrusion (e.g. roughness, previous arcing)
2. charged dielectrics (e.g. dust particles, flakes)

- higher electric field leads to locally greater e-emission
- Joule heat enhances temperature of emission site
- higher temperature amplifies e-emission non-linearly

feedback

Feedback can lead to local thermal runaway, → plasma formation, breakdown of sheath, and spot goes through life cycle.

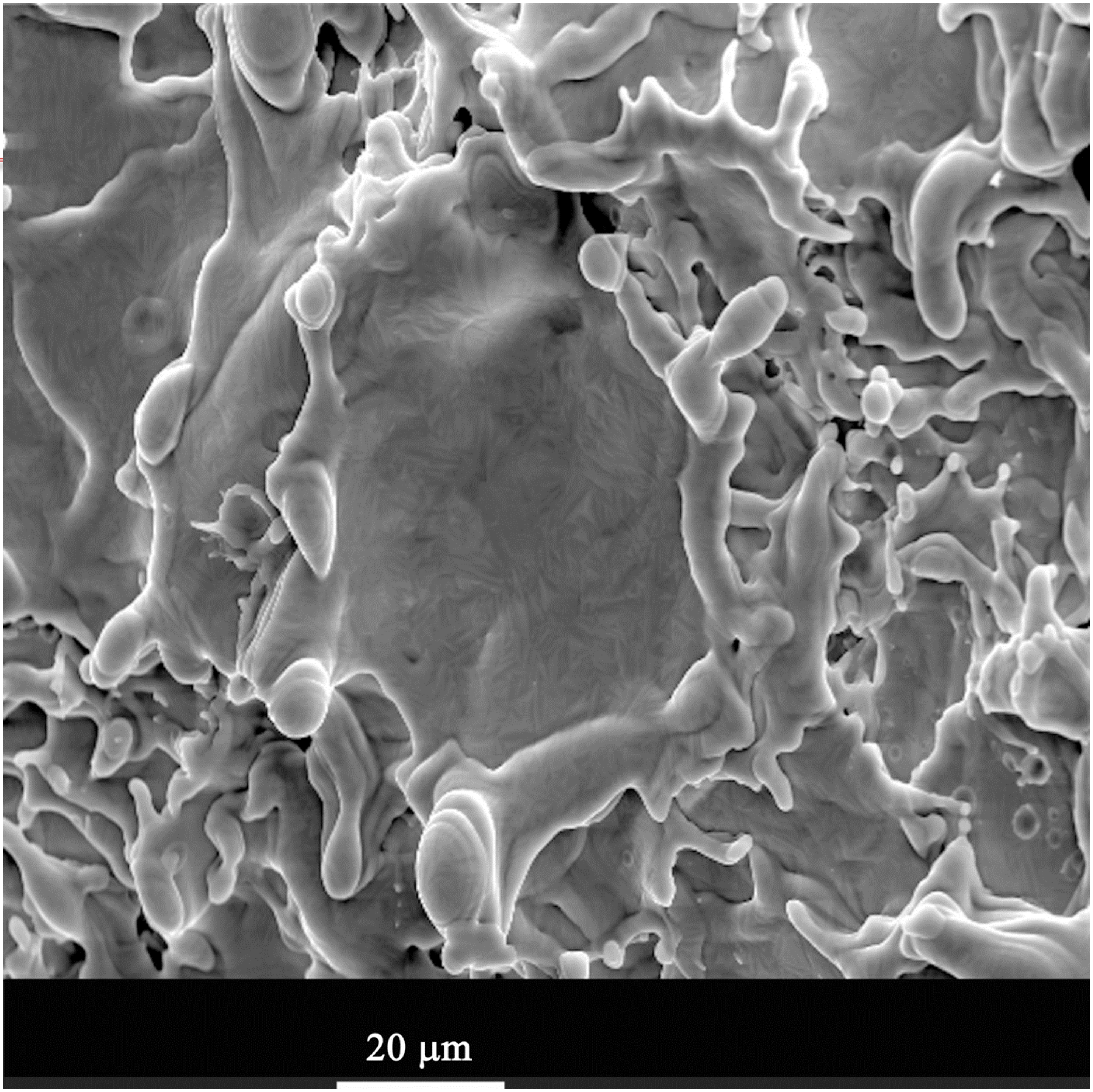
Field-stimulated non-linear waves of liquid metal



frozen waves as seen in an electron microscope

M.D. Gabovich, V.Y. Poritskii, JETP Lett. 33 (1981) 304.

arc erosion may condition the surfaces but produces its own cathode surface roughness



Preferred Spot Ignition Area

Open-shutter photograph of sputtering target: clues on arc spot ignition conditions

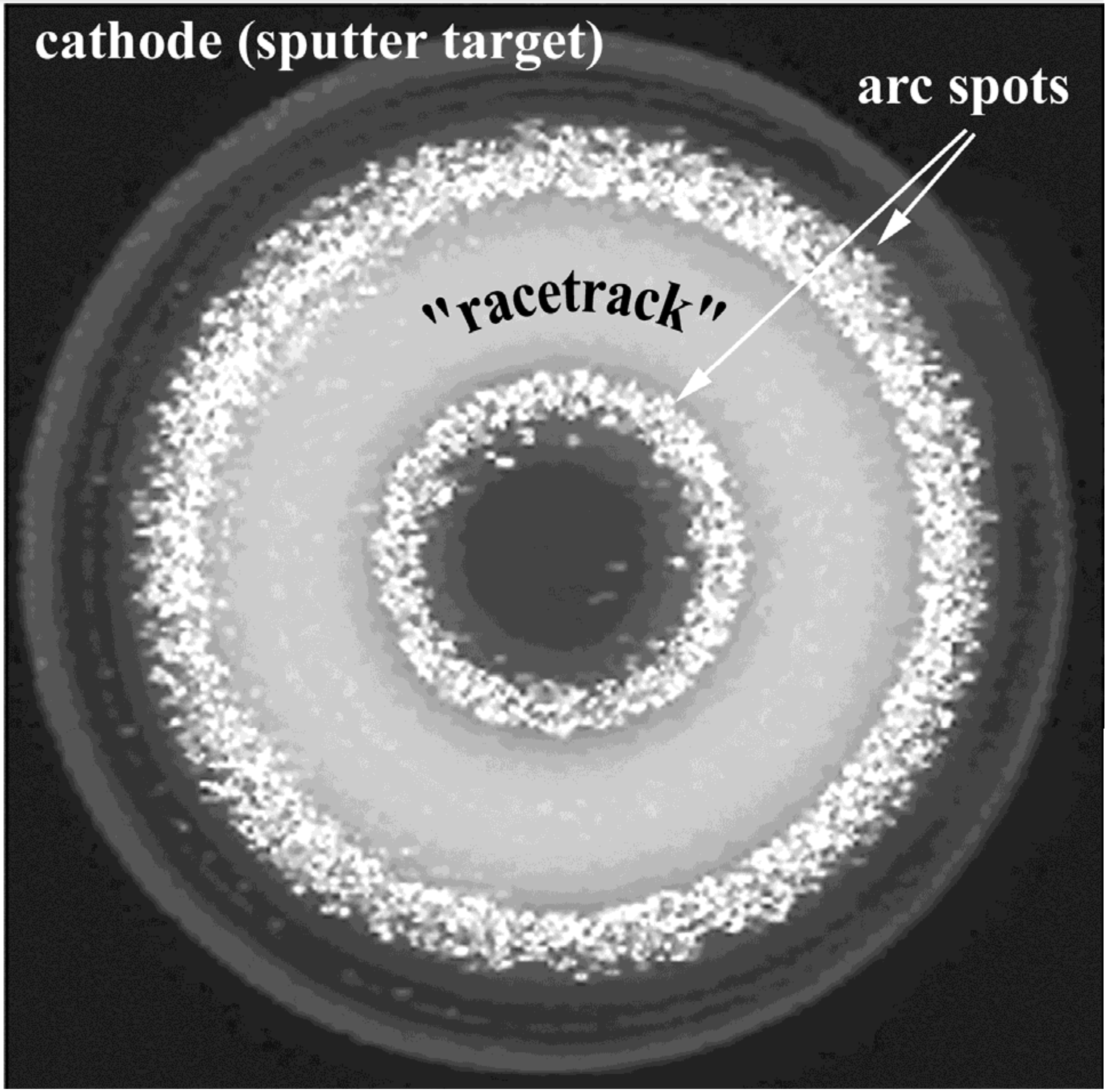
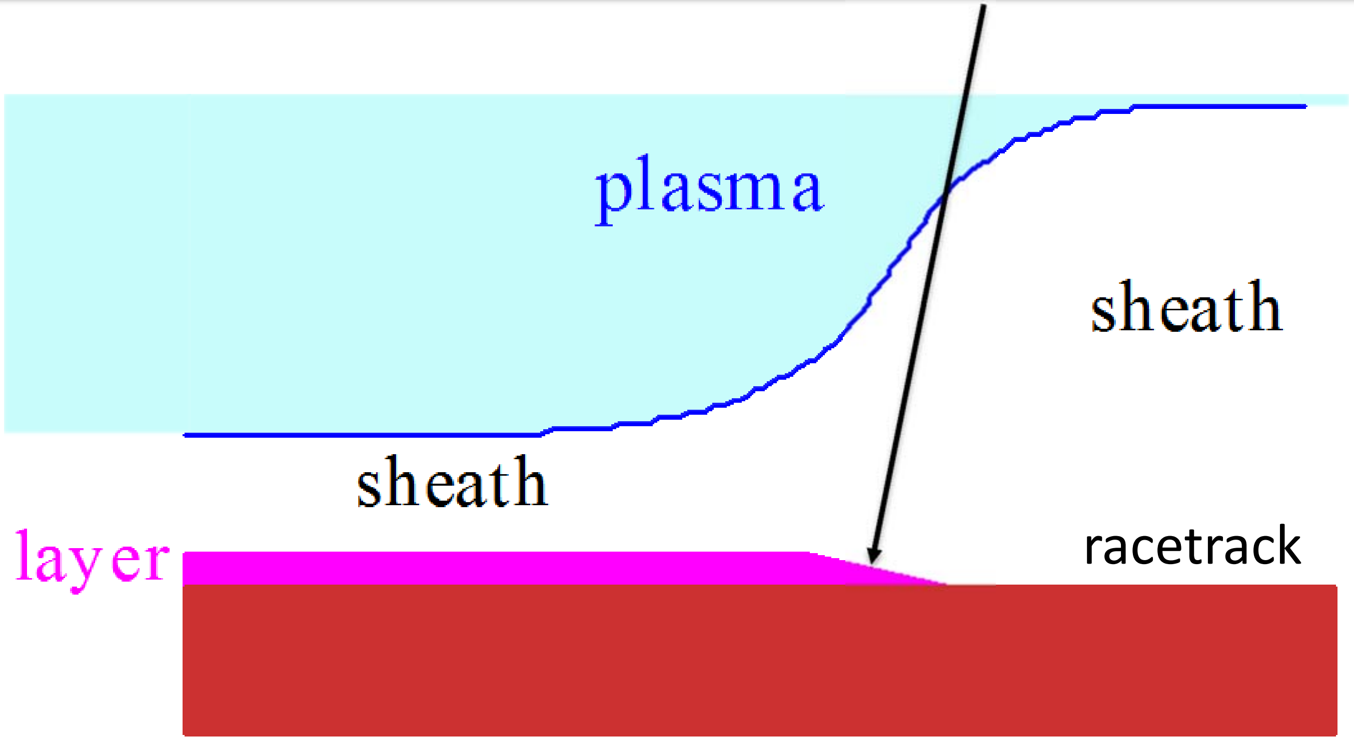


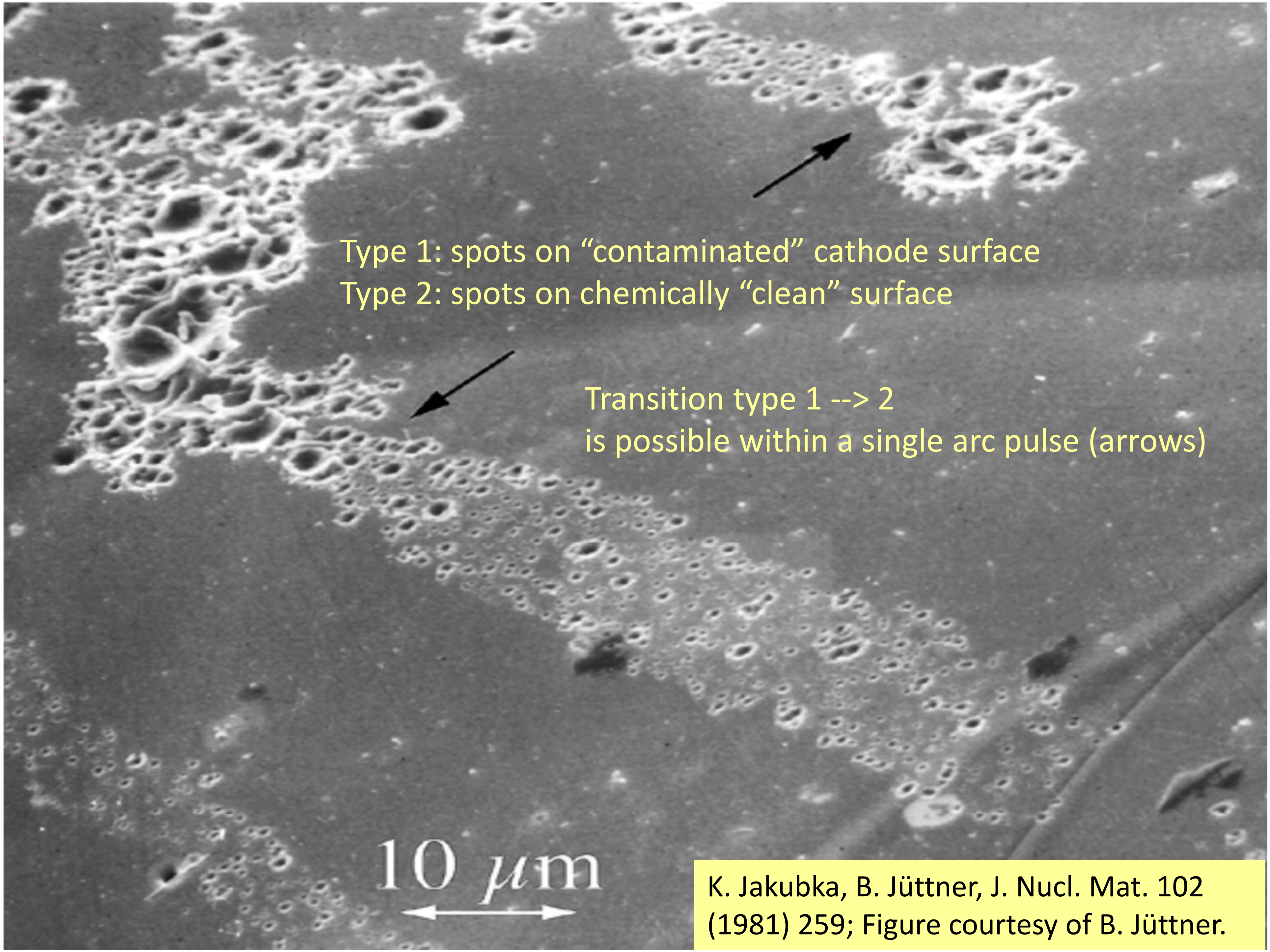
Photo courtesy of Prof. R. De Gryse, Ghent

Sputtering Magnetron: Variable Sheath Thickness and Field Strength

here is the highest field strength: breakdown and transition to arcing occurs for about *E* > 0.5 V/nm



A. Anders, Thin Solid Films 502 (2006) 22.



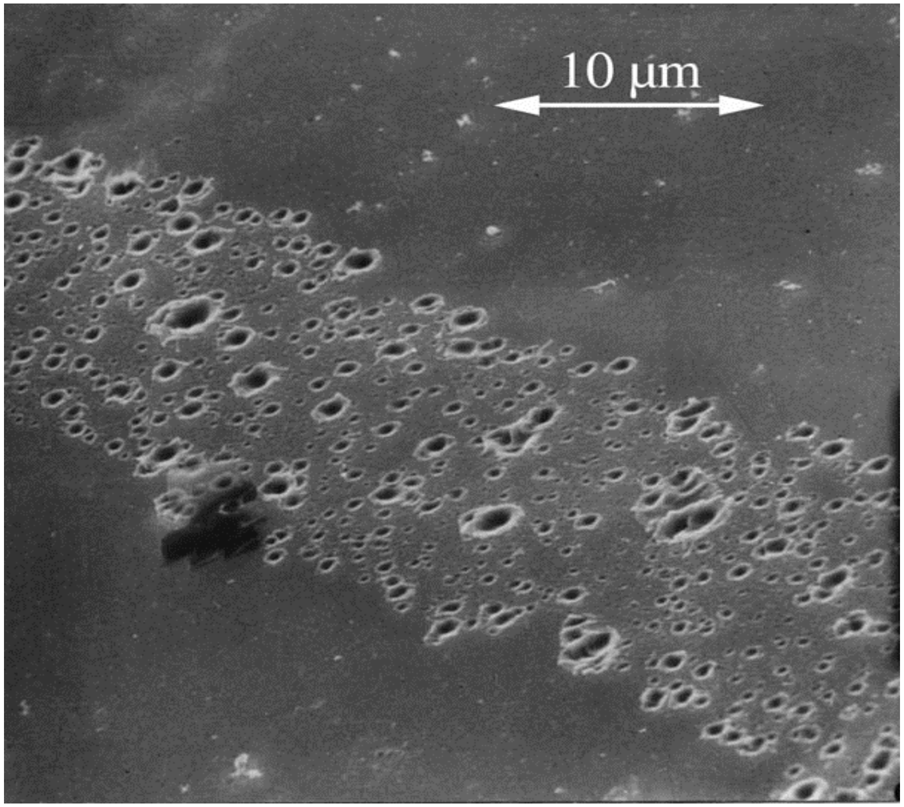
Type 1: spots on “contaminated” cathode surface
Type 2: spots on chemically “clean” surface

Transition type 1 --> 2
is possible within a single arc pulse (arrows)

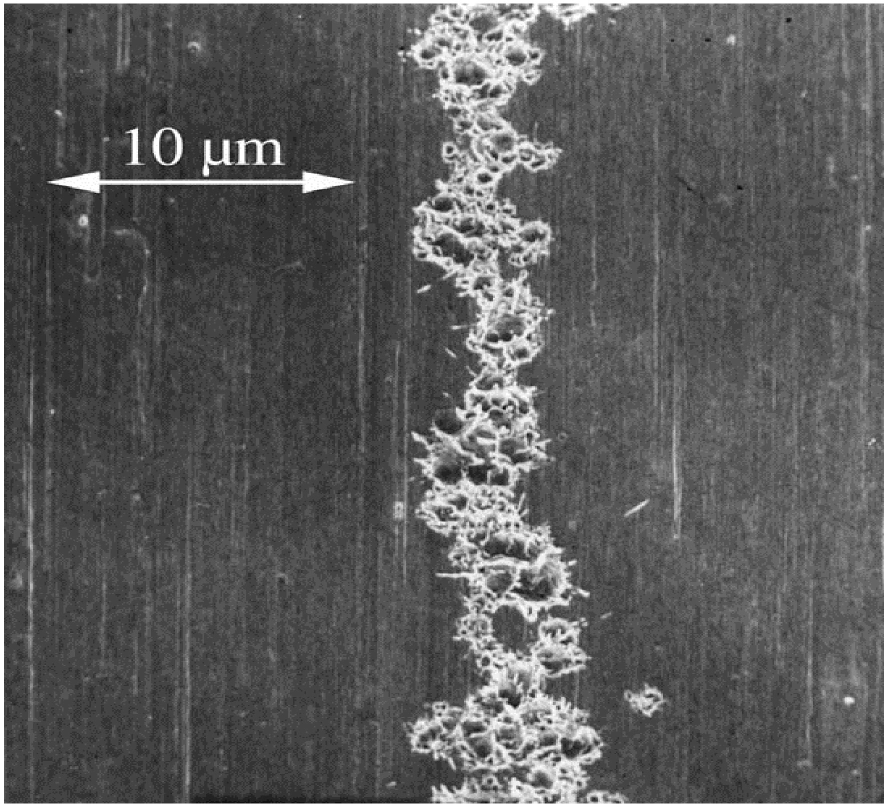
K. Jakubka, B. Jüttner, J. Nucl. Mat. 102 (1981) 259; Figure courtesy of B. Jüttner.

Cathodic Arcs: Spot Motion

Examples of (virtual!) spot motion in steering magnetic field; looking at crater traces:



Spot type 1
(contaminated surface)

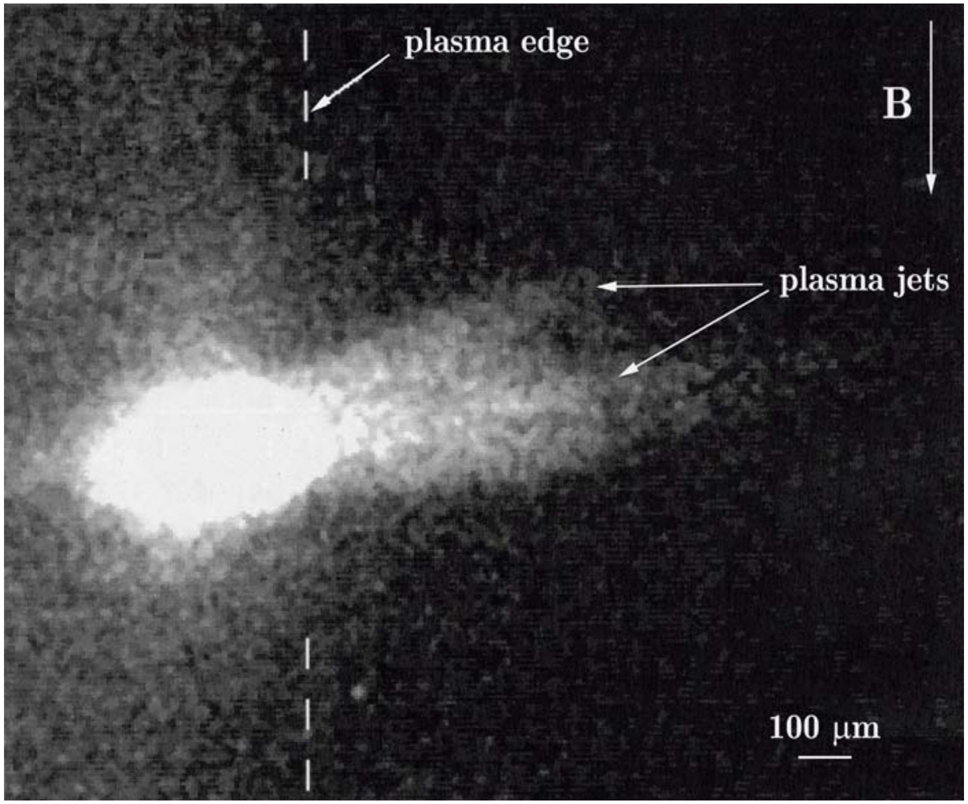


Spot type 2
(clean surface)

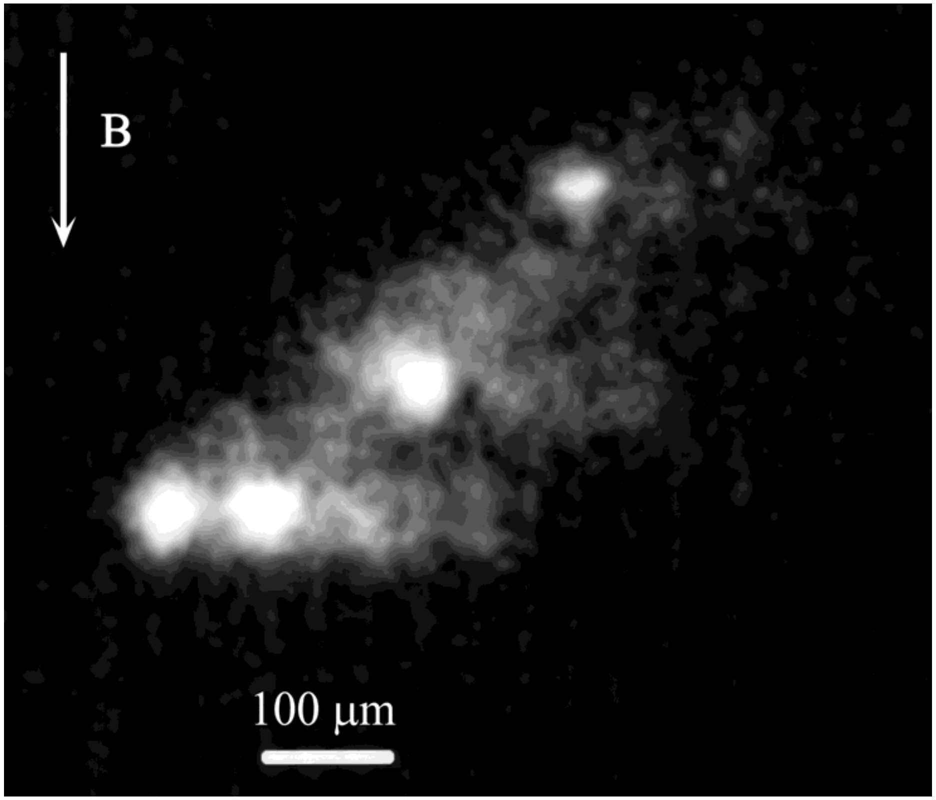
K. Jakubka, B. Jüttner, J. Nucl. Mat. 102 (1981) 259; Figures courtesy of B. Jüttner.

Apparent Motion of Emission Centers

relatively high exposure to show plasma jets in retrograde direction

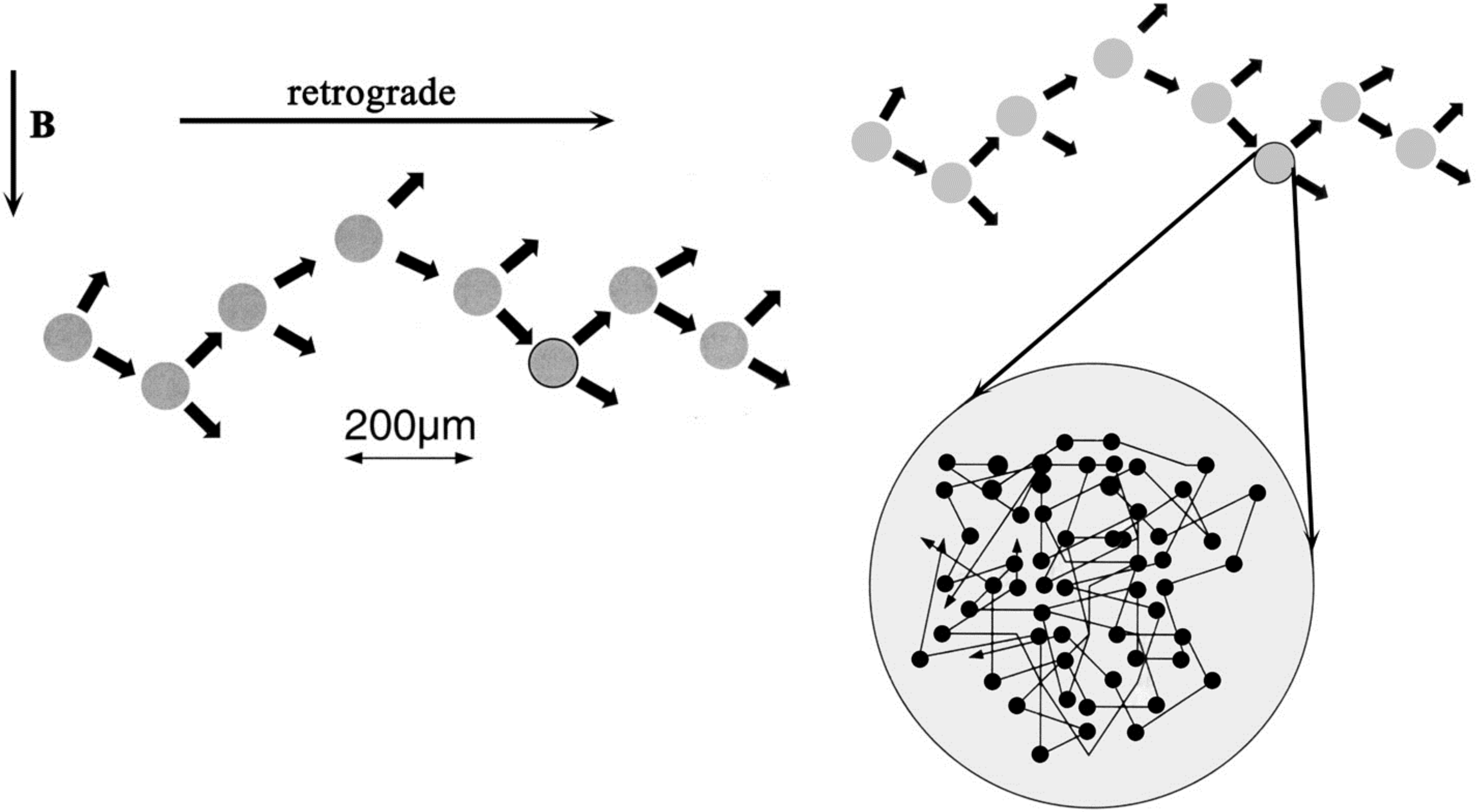


4-fold exposure, 200 ns each, separated by 10 μs



B. Jüttner, I. Kleberg, J Phys. D: Appl. Phys. 33 (2000) 2025.

Jüttner-Kleberg Model



B. Jüttner, I. Kleberg, J Phys. D: Appl. Phys. 33 (2000) 2025.

High Resolution Diagnostics

Probe Diagnostics

Probes have clear limits in terms of spatial resolution and being disturbing the discharge system.

B. Jüttner, Beitr. Plasmaphys. 19 (1979) 25.

Probe Diagnostics

- spots are point sources, at least for > 10 μm distance
- n ~ r^{-2} verified that plasma is expanding without significant recombination or ionization (“frozen” ionization state)

V.A. Ivanov, B. Jüttner, H. Pursch, IEEE Trans. Plasma Sci. 13 (1985) 334.

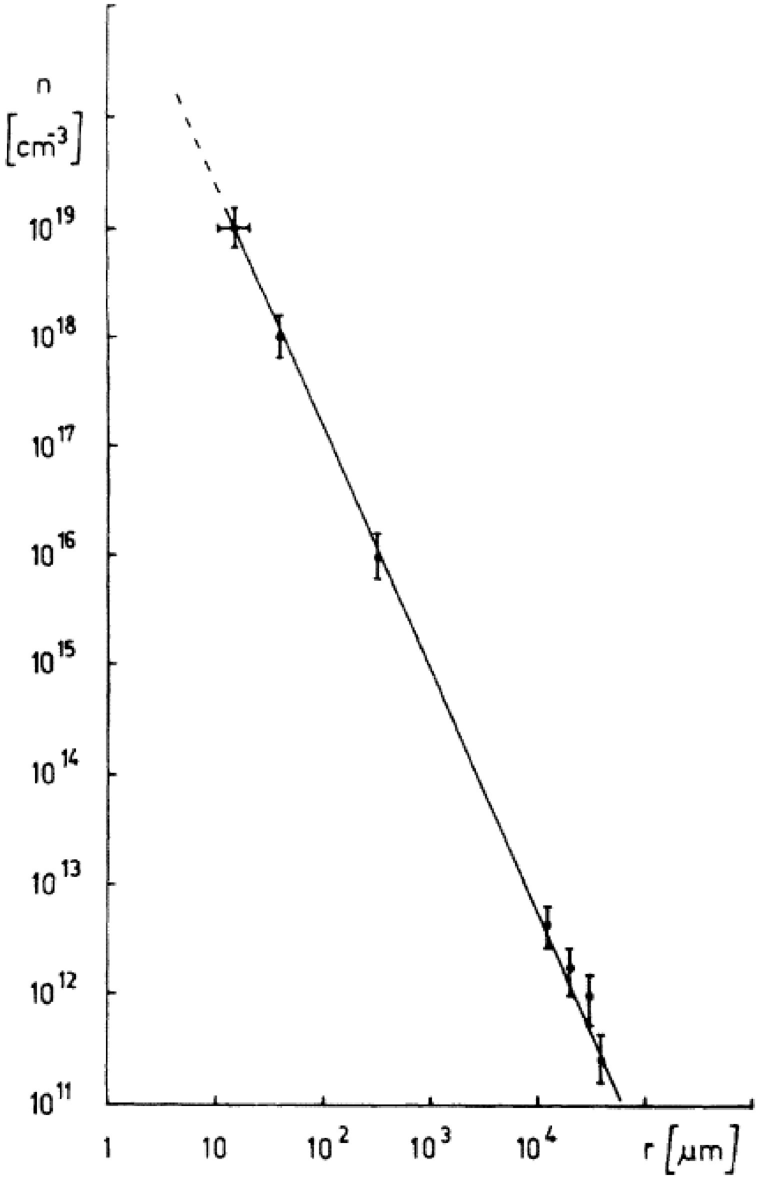


Fig. 4. Electron density n as a function of distance r to the cathode spot 10 μs after arc ignition. Arc current I = 30–100 A; t = 10 μs.

Imaging is powerful!

(and non-disturbing)

2012-09-21

Imaging is powerful!

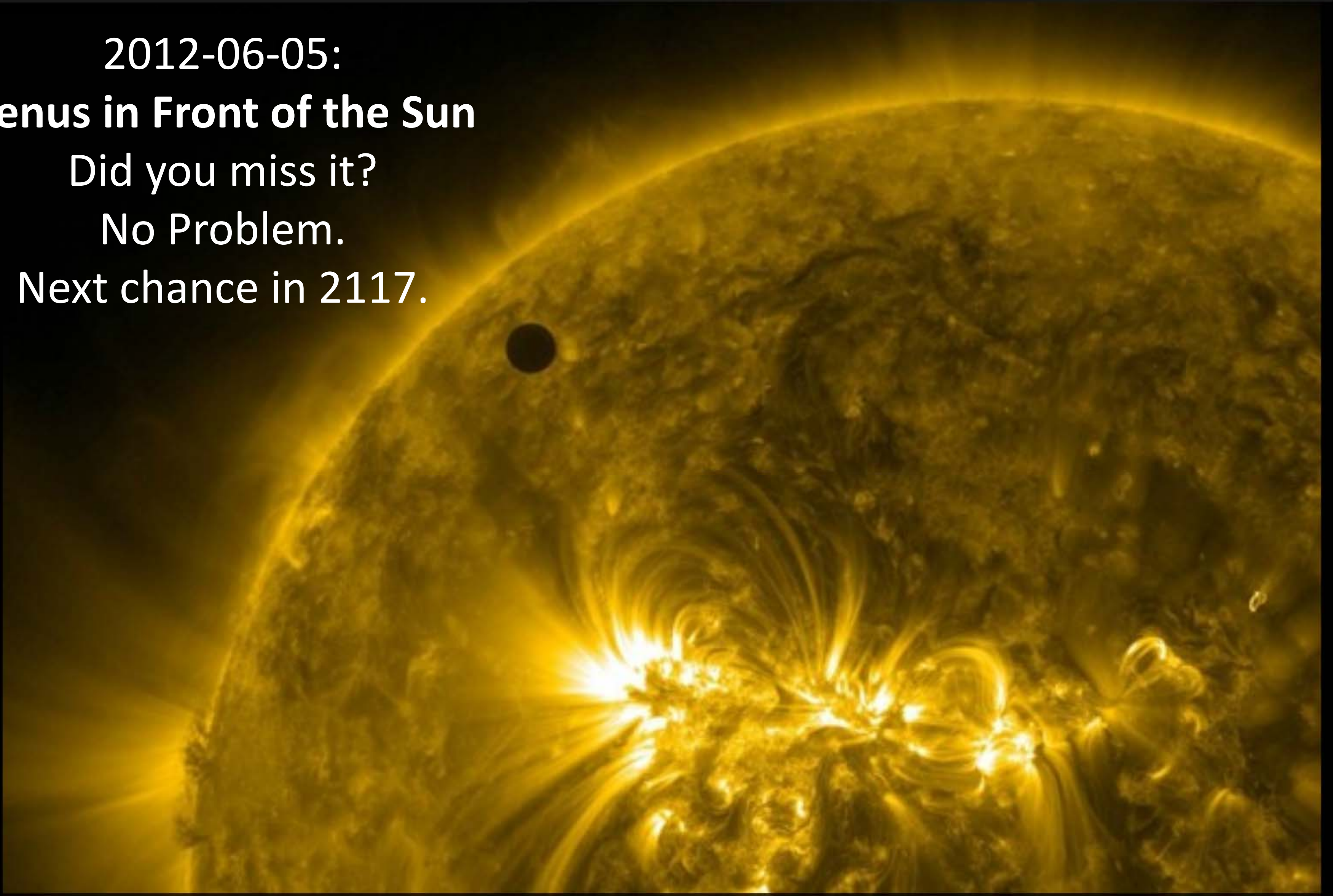
2012-06-05:

Venus in Front of the Sun

Did you miss it?

No Problem.

Next chance in 2117.



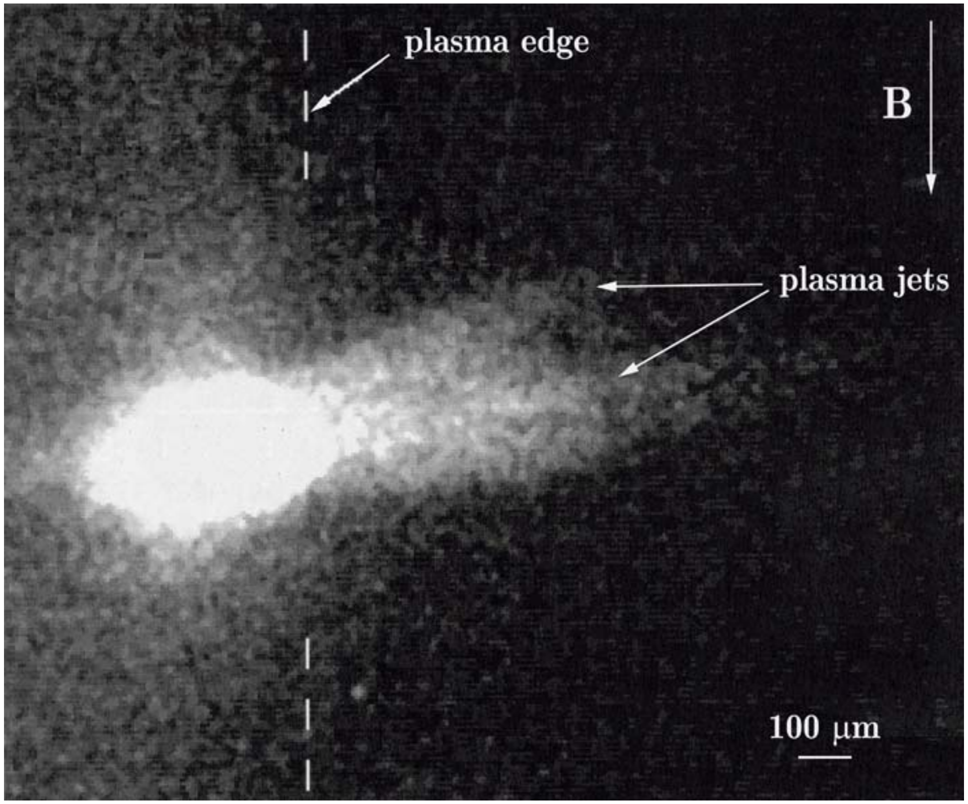
June 5, 2012

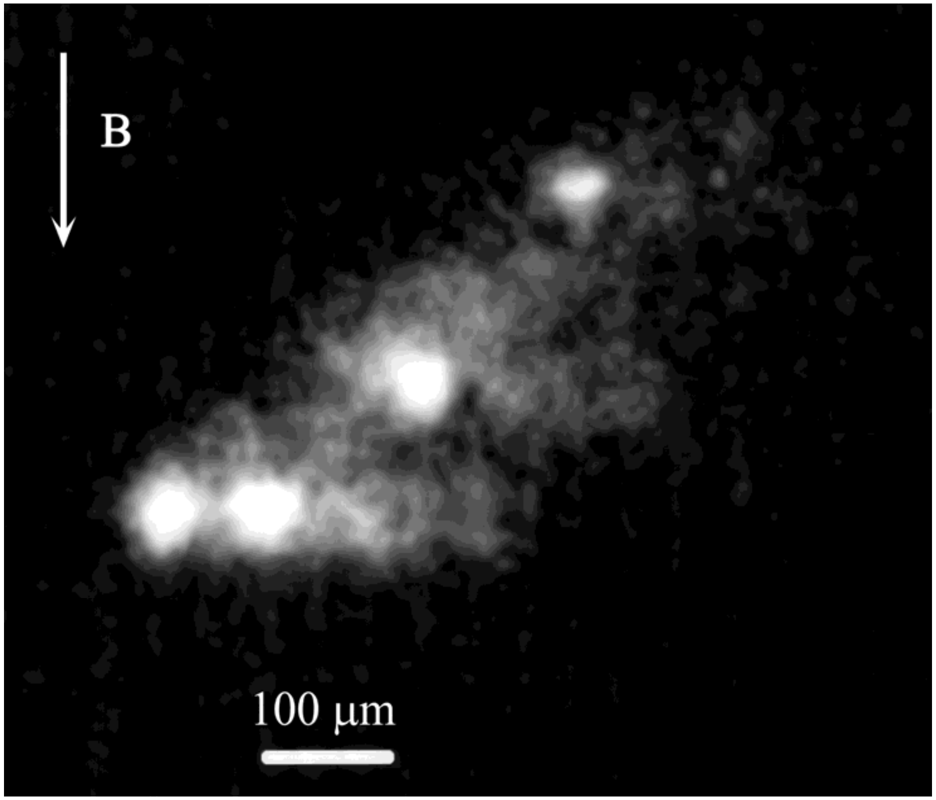
The planet Venus at the start of its transit of the sun. One of the rarest astronomical events occurs on Tuesday and Wednesday when Venus passes directly between the sun and Earth, a transit that won't occur again until 2117.

NASA / Reuters

Again: Apparent Motion of Emission Centers

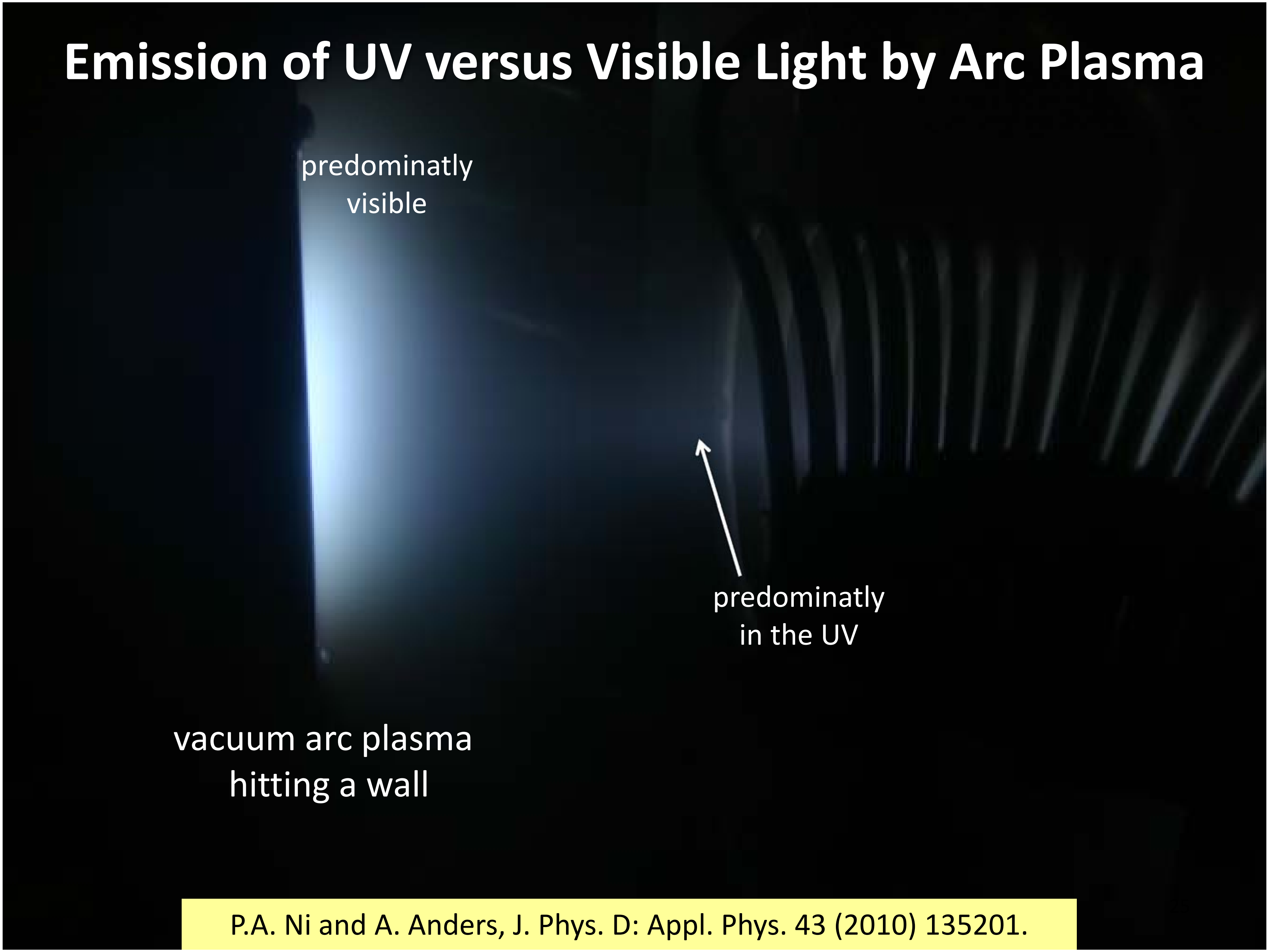
Fast framing camera is one kind of high-resolution diagnostics, **making use of plasma-emitted light…**





B. Jüttner, I. Kleberg, J Phys. D: Appl. Phys. 33 (2000) 2025.

Emission of UV versus Visible Light by Arc Plasma



predominatly
visible

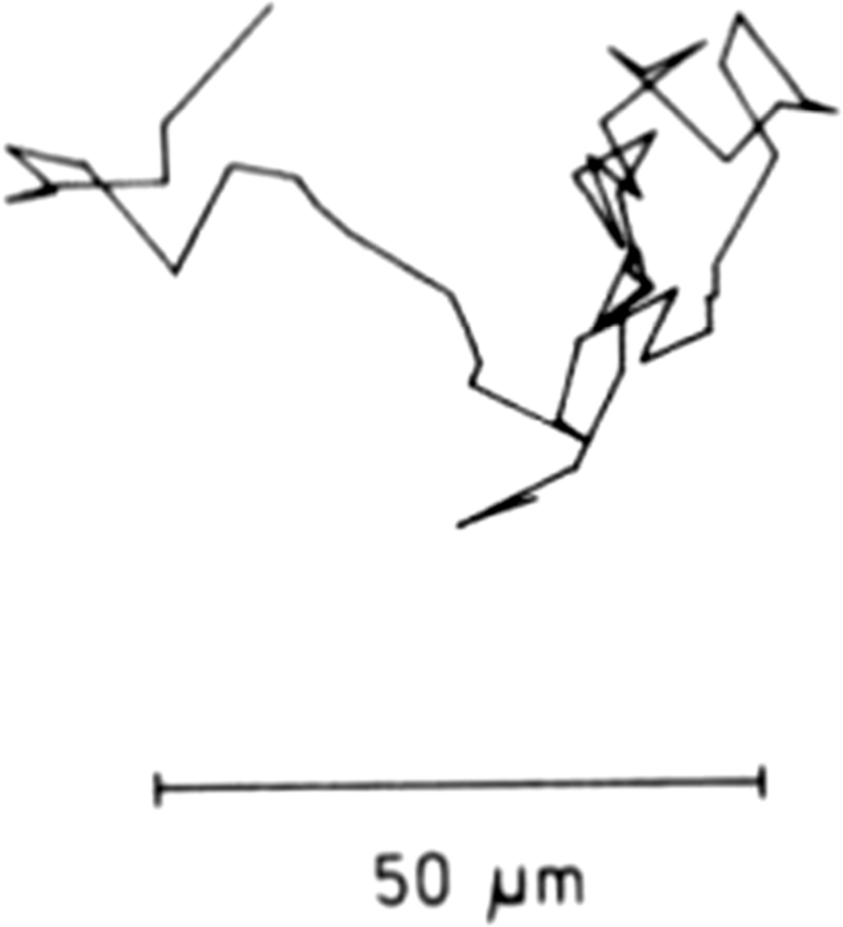
predominatly
in the UV

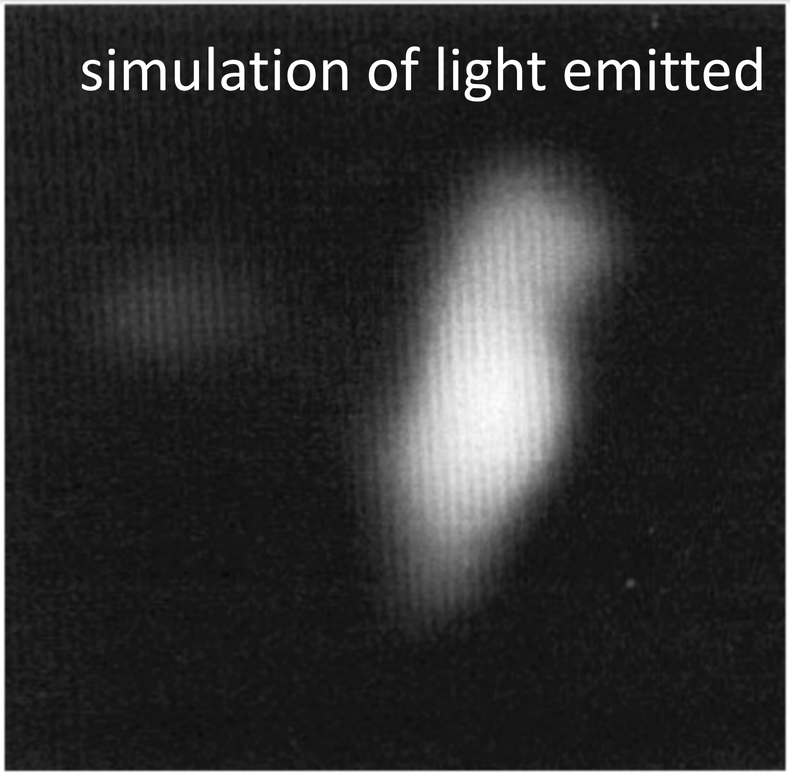
vacuum arc plasma
hitting a wall

P.A. Ni and A. Anders, J. Phys. D: Appl. Phys. 43 (2010) 135201.

Fundamental Limits to Emission Measurements

simulation of random walk





Due to finite lifetime of excited states, features smaller than about 10 μm cannot be resolved by emission measurements.

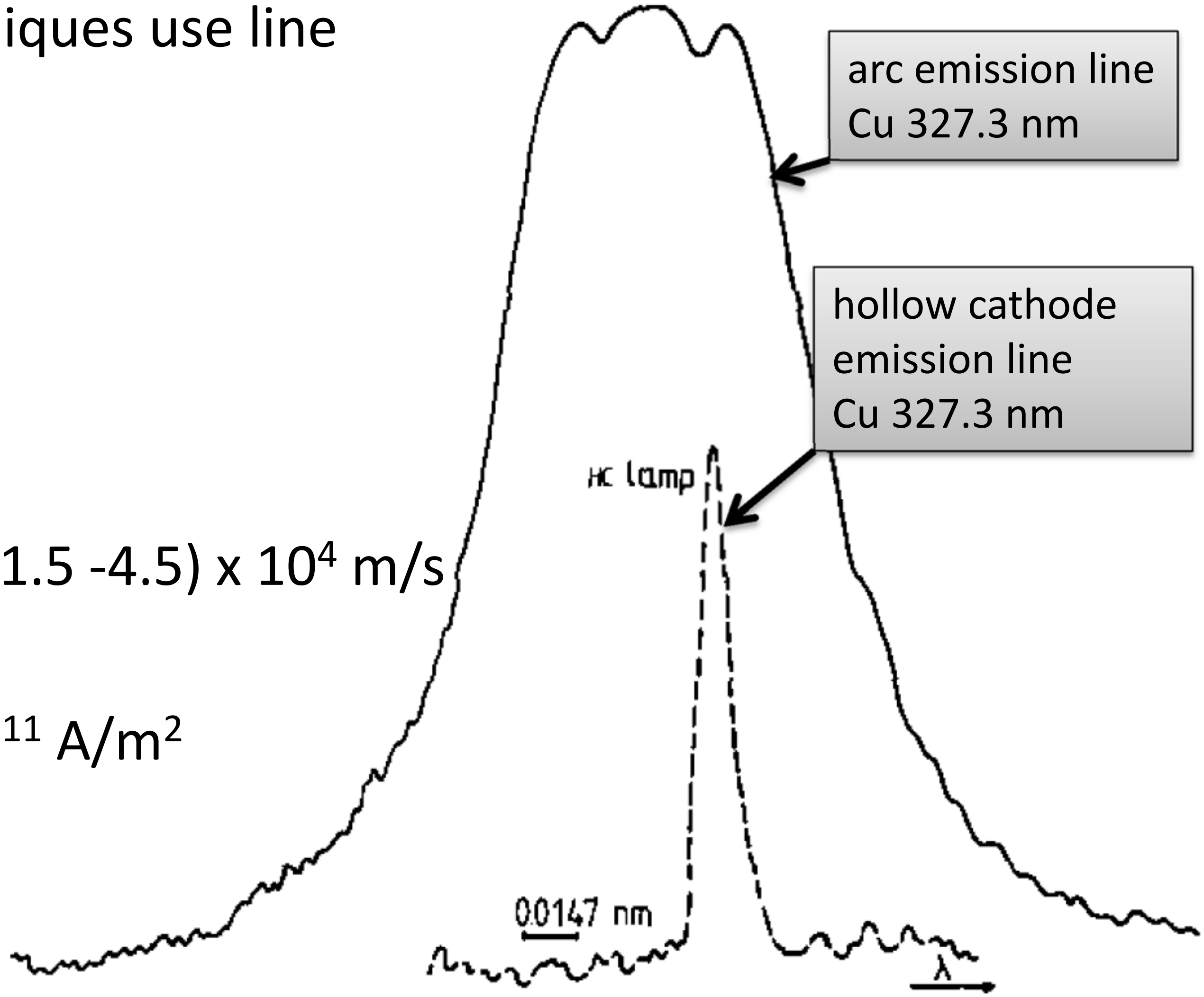
S. Anders, et al., J. Phys. D: Appl. Phys. 25 (1992) 1591.

Emission Spectroscopy

- sophisticated techniques use line profiles, consider
  - Stark broadening
  - Doppler effect
  - self-absorption
  - Zeeman splitting
- Doppler shift →

  directed velocity of (1.5 -4.5) x 10^4 m/s
- Zeman splitting →

  current density > 10^{11} A/m^2

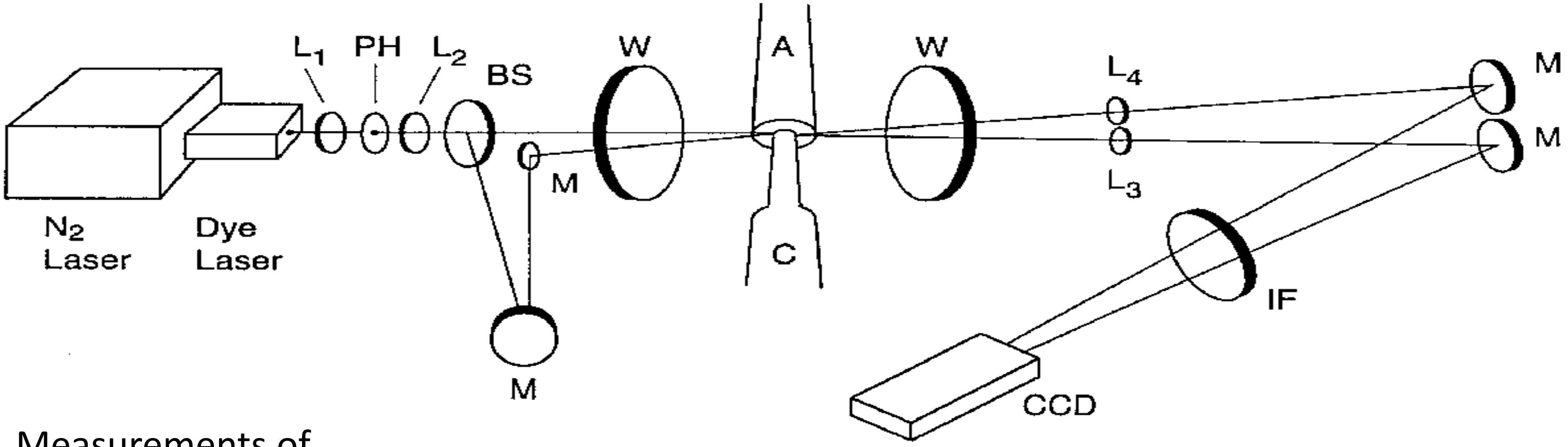

arc emission line Cu 327.3 nm

hollow cathode emission line Cu 327.3 nm

N. Vogel and B. Jüttner, J. Phys. D: Appl. Phys. 24 (1991) 922.

Laser Plasma Diagnostics: Using Absorption

Differential Laser Absorption Photography and Spectrometry



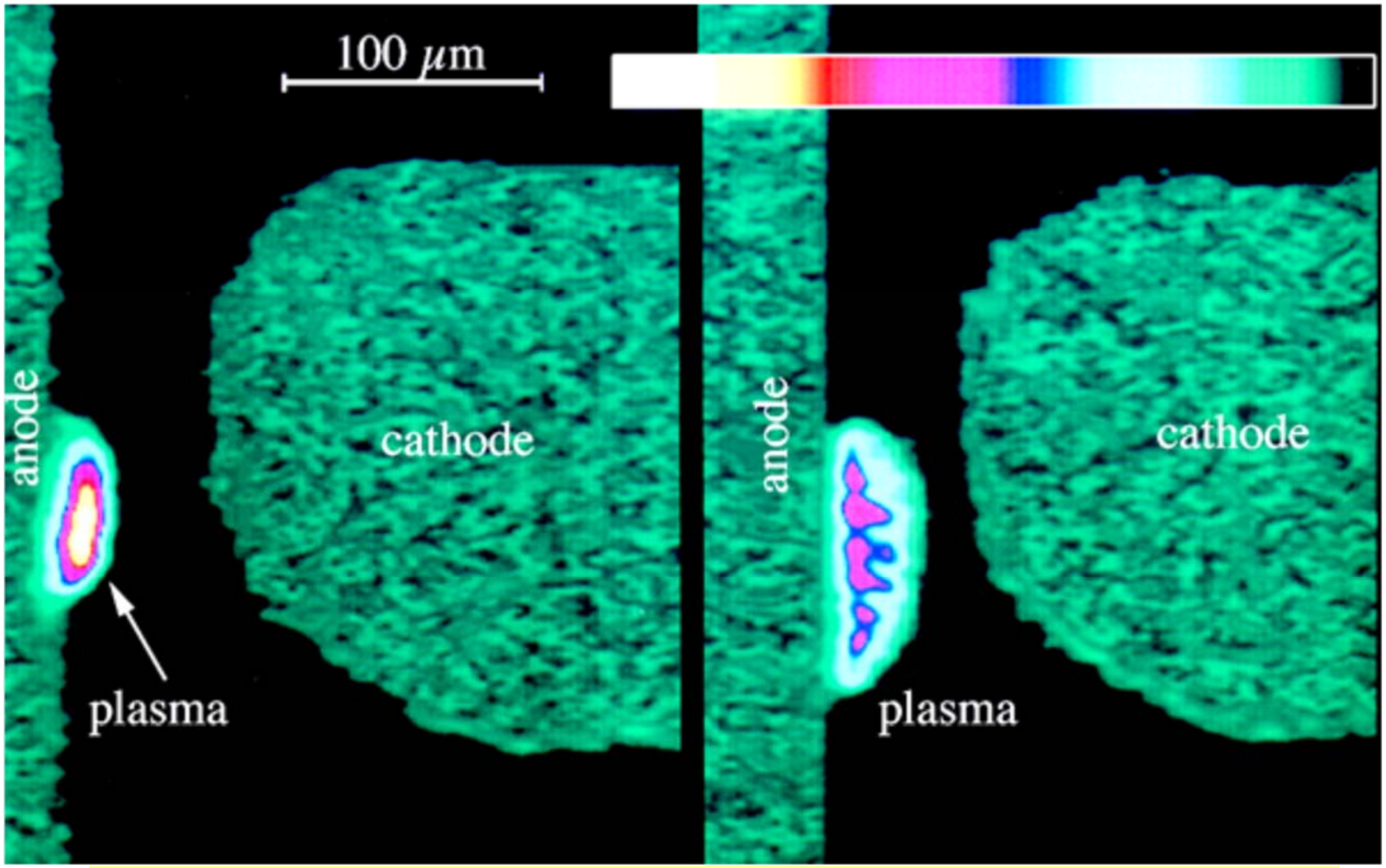
Measurements of
- electron density
- temporal development

With consequences for
- Current density
- Understanding of plasma formation

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

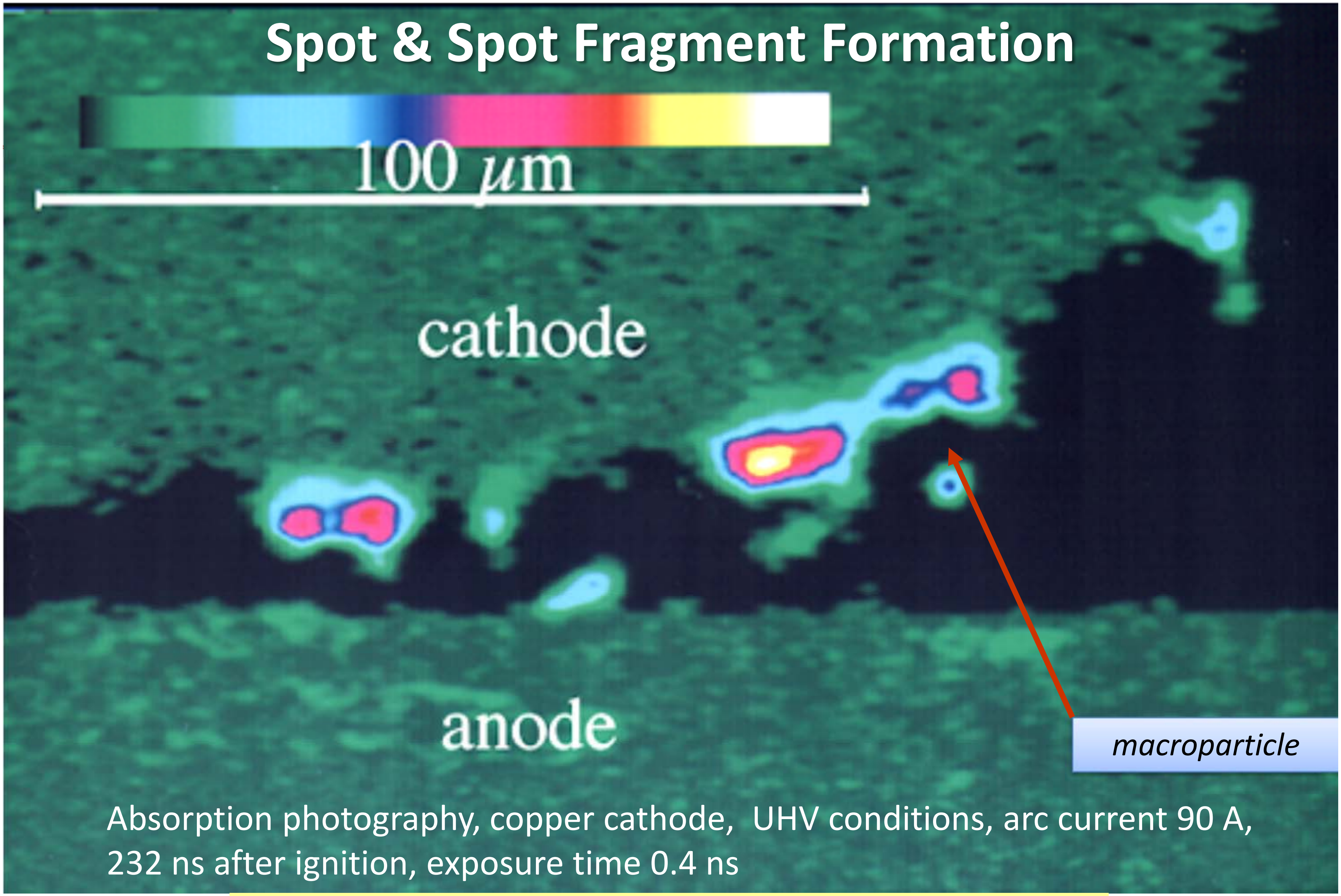
Observation of Gap Breakdown in Vacuum

- ❑ Laser absorption photography of a vacuum breakdown event, Cu, 100 A, Δt between pictures 3 ns
- ❑ Spark phase of the arc: voltage is still high (kV)



A. Anders *et al.*, IEEE Trans. Plasma Sci. 20 (1992) 466;
and IEEE Trans. Plasma Phys. 24 (1996) 69.

Spot & Spot Fragment Formation

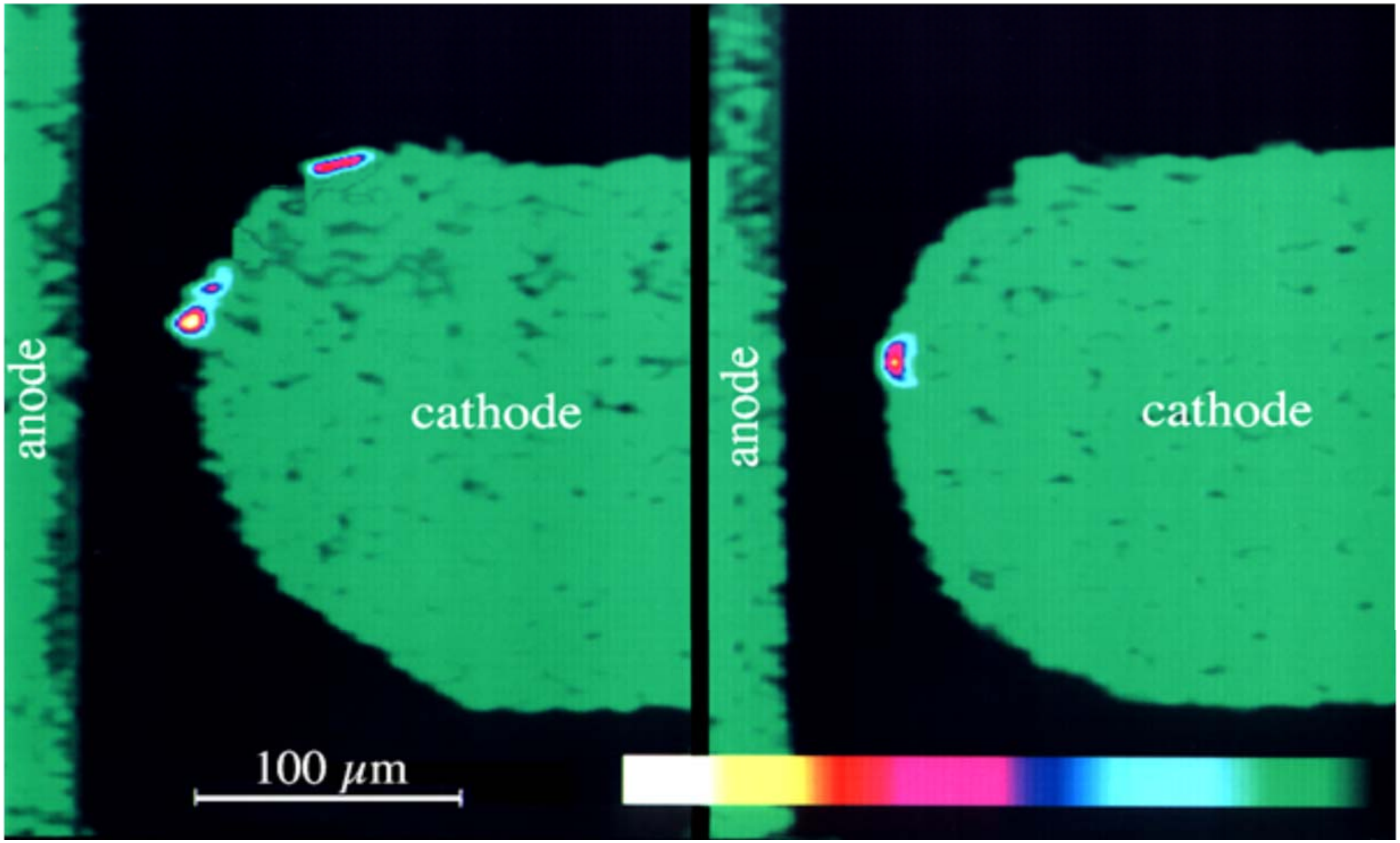


Absorption photography, copper cathode, UHV conditions, arc current 90 A, 232 ns after ignition, exposure time 0.4 ns

A. Anders *et al.*, IEEE Trans. Plasma Sci. 20 (1992) 466;
and IEEE Trans. Plasma Phys. 24 (1996) 69.

Spot Dynamics

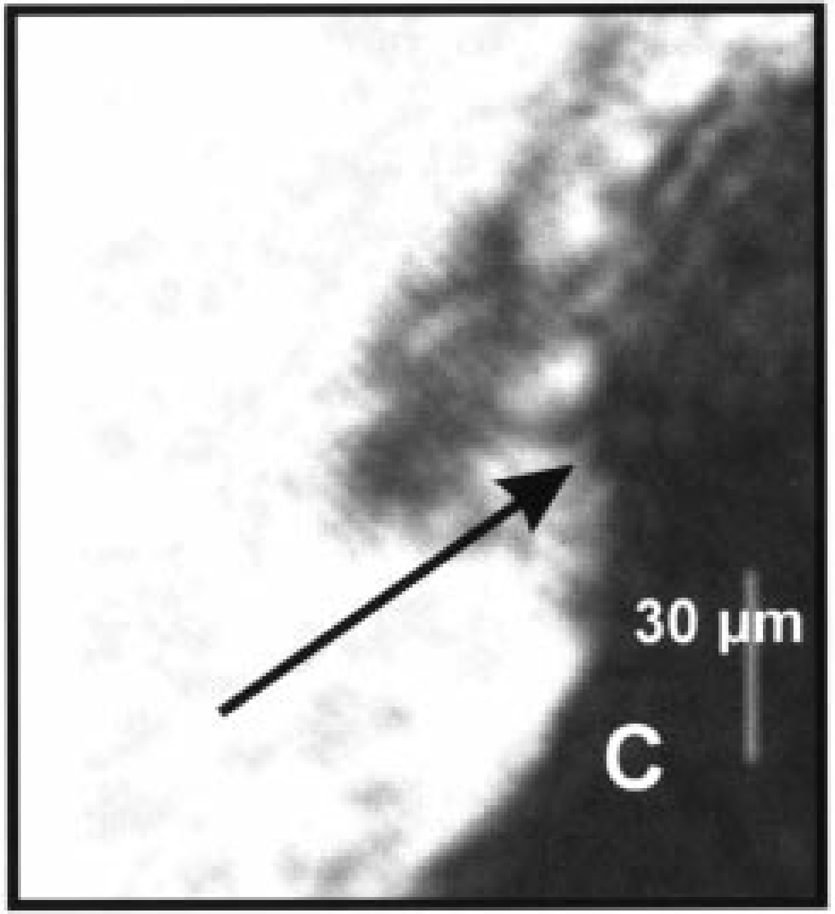
development of cathode spots, observed by absorption photography, Cu, 100 A, Δt between pictures 3ns



More Absorption Measurements at Cathode Spots

Absorption photograph for a pulsed vacuum discharge between Cu electrodes;

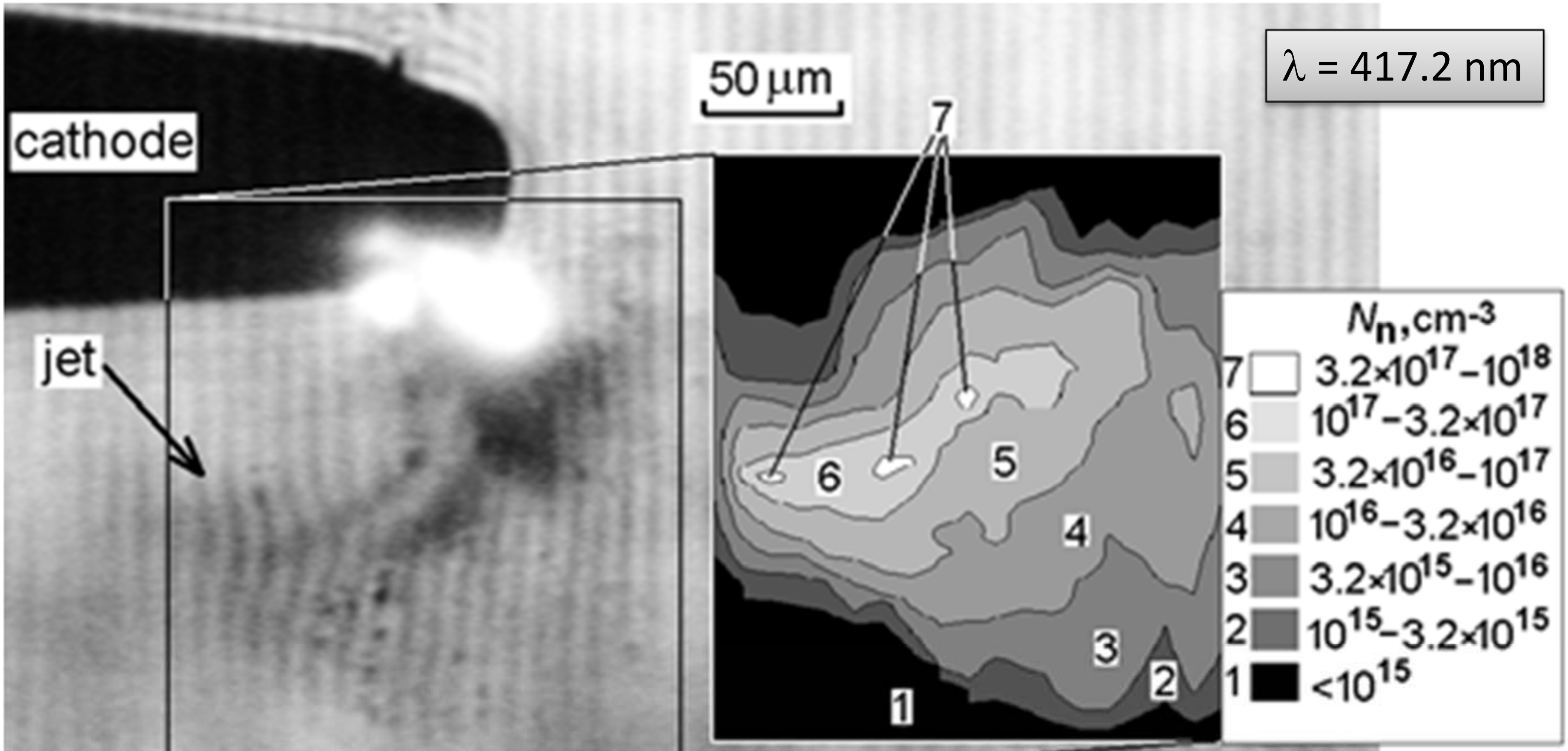
- current 8.75 A, IR laser triggered
- discharge time 750 ns,
- delay time after ignition t = 18 ns,
- laser illumination for absoprtion picture, 532 nm, exposure time = 100 ps
- **→ electron density ~ 10^{26} m^{-3}.**



N. Vogel, V.A. Skvortsov, IEEE Trans. Plasma Sci. 25 (1997) 553.

Resonant Laser Interferometry and Shadowgraphy

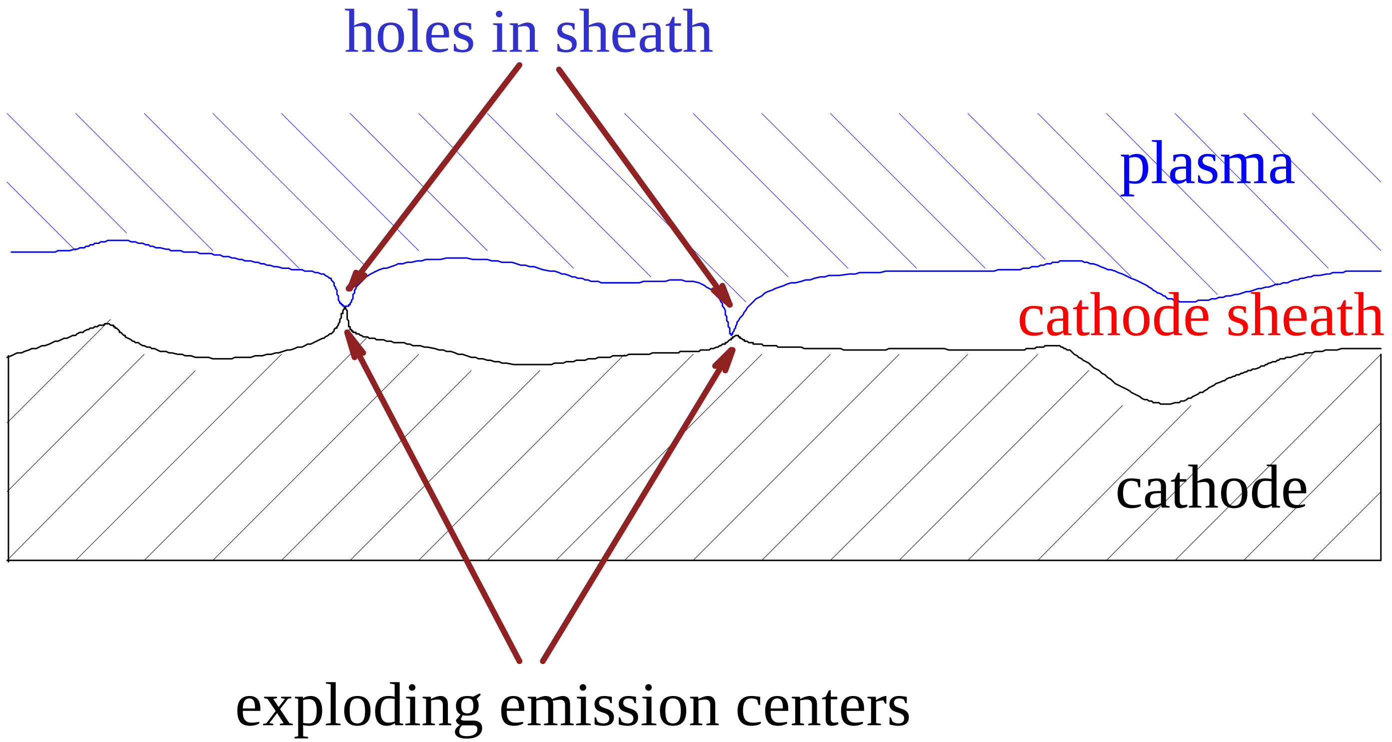
- Ga cathode in UHV, subnanosecond laser for resonant backlight
- vapor emission is superposition of isotropic and jet-like structures



A. Batrakov, *et al*., IEEE Trans. Plasma Sci. **31** (2003) 864.

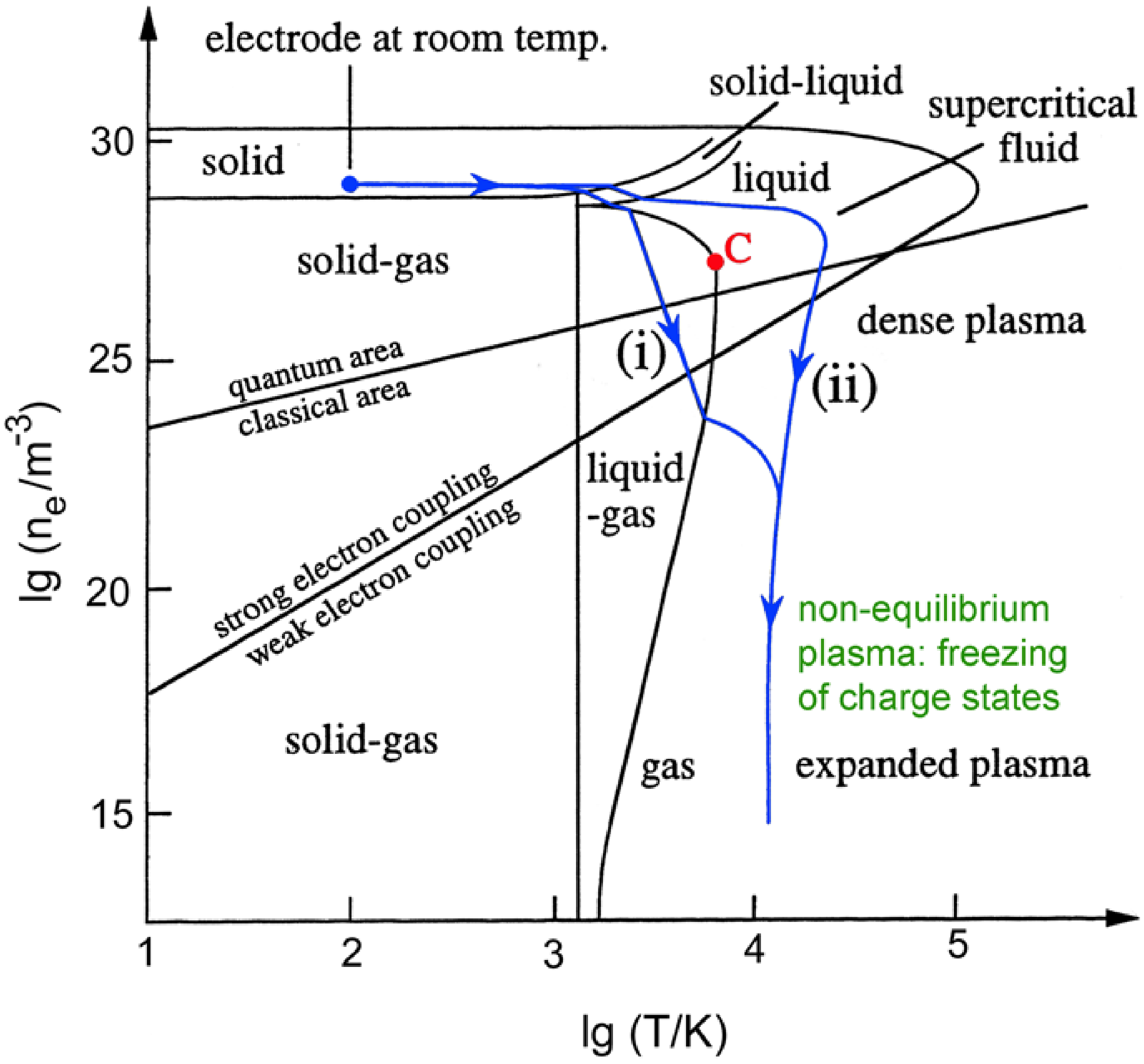
(Fractal) Sheath with “Holes”

- sheath thickness scales scales with$1/\sqrt{n}$
- no sheath but voltage drop in nonideal plasma of (exploding) emission centers: “holes” in sheath – no flux to cathode



A. Anders, Cathodic Arcs, Springer, New York, 2008.

Path of the Cathode Material in the *n-T* Phase Diagram



- path is time-dependent: depends on stage of spot development,
- interestingly, measurements of expanded plasma are not giving clues on path

A. Anders, *et al.,* Plasma Sources Sci. Technol. 1 (1992) 263-270
A. Anders, Phys. Rev. E 55 (1997) 969.

Ecton and Fractal Models

Ecton Model

- G.A. Mesyats: learning from wire explosions, there is a minimum action needed to obtain explosive phase transformation.
- crater diameter formed by local Joule heating:

$$d = \frac{\sqrt{2i}}{\pi}\left(\frac{t}{\bar{h}}\right)^{1/4}$$

↖

material-specific action

Ecton = "quantum" for explosive electron emission

(as we will see: this can be seen as lower-bound cutoff in a fractal model approach)

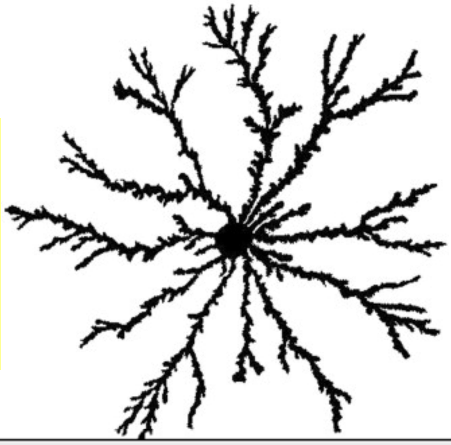
G.A. Mesyats, IEEE Trans. Plasma Sci. 23 (1995) 879.
G.A. Mesyats, S.A. Barengolts, IEEE Trans. Plasma Sci. 29 (2001) 704.

Fractal Model

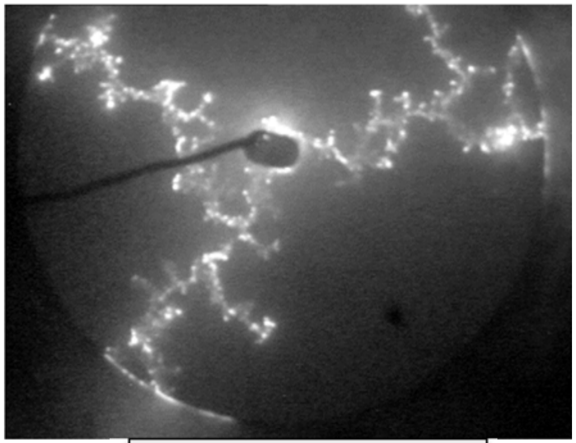
1. *An object (a "fractal") is self-similar (i.e., invariant with scaling) if it is reproduced by magnifying some portion of it.*
2. *Self-similarity may be discrete or continuous, deterministic or probabilistic.*
3. *Self-similarity can be mathematically exact or only approximate and asymptotical.*

M. Schroeder, *Fractals, Chaos, Power Laws*, Freeman, New York, 2000.

Y.H. Shaikh, et al., Chaos, Solitons & Fractals 42 (2009) 2796.



dendritic copper sulfate growth by electro-deposition



pulsed vacuum arc image

Example of a Mathematically Exact Self-Similarity

courtesy of Jim Tucek

Fractal Model of Cathode Spots

- ❑ Perhaps the first explicitly making the connection between spots and fractals:

P. Siemroth, T. Schülke and T. Witke, IEEE Trans. Plasma Sci. **25** (1997) 571

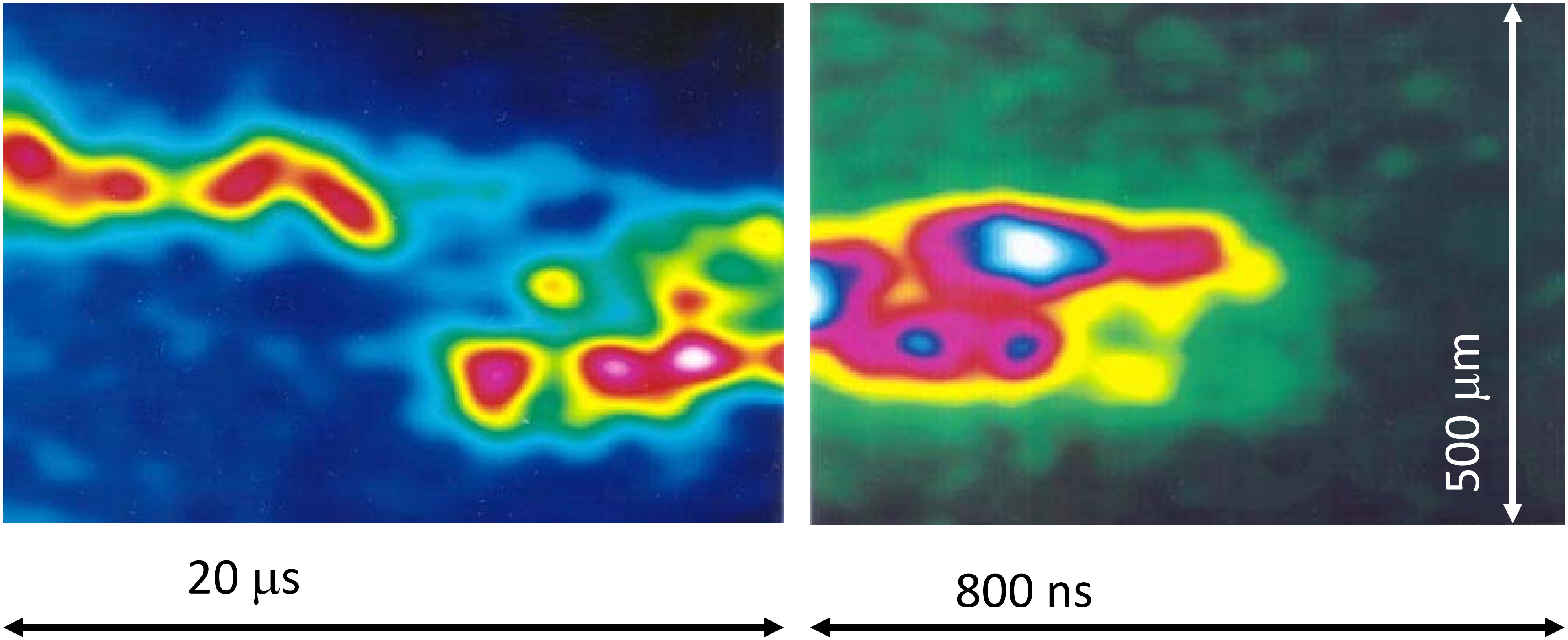
- ❑ **Self-similarity** at four levels:
  1. "group-spot": for I_{arc}> 1 kA, tens or hundreds of spots
  2. "macrospot level": photographically and visually one spot but containing microspots when observed with better resolution
  3. "microspot level": bright centers, each carrying some A of current, some mm in apparent diameter
  4. cell or crater level

Can we identify this as the final, limiting level?
Or can we expect deeper levels if we had better instrumentation?

Spatial and Temporal Self-Similarity

Streak camera pictures at different time resolution

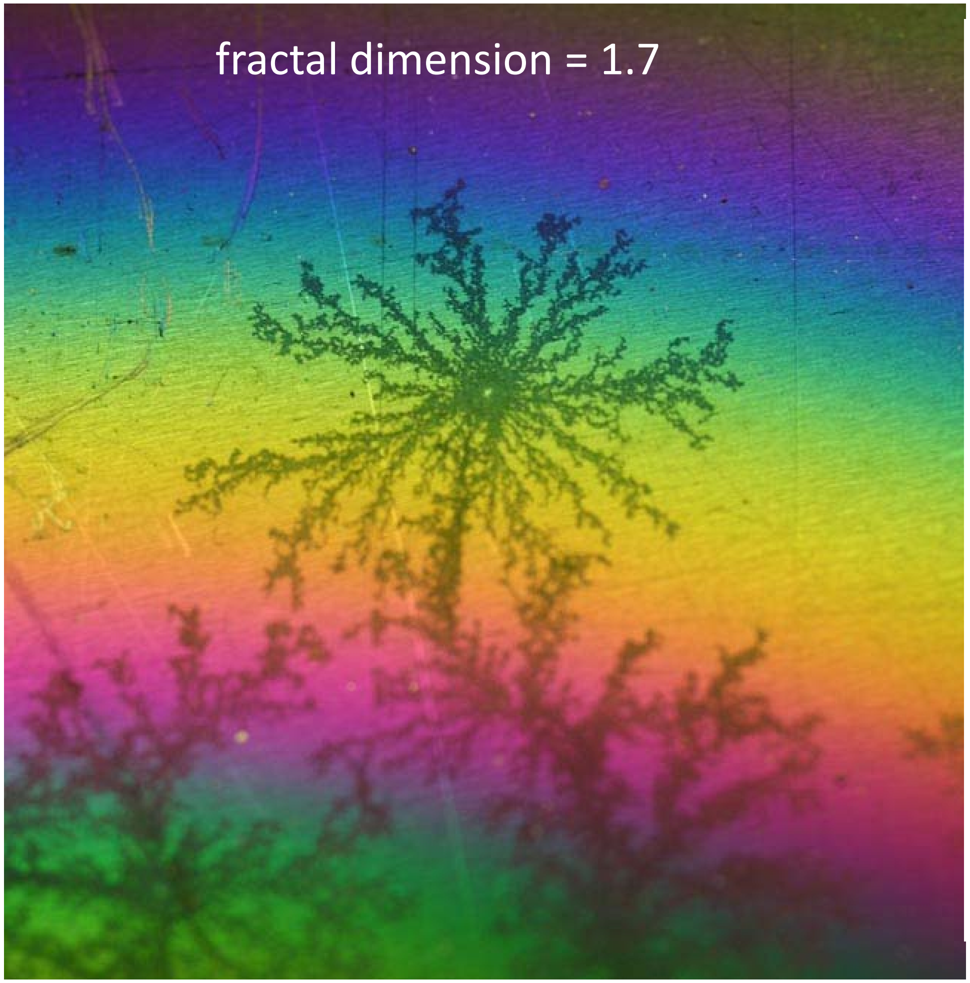
(courtesy of B. Jüttner)

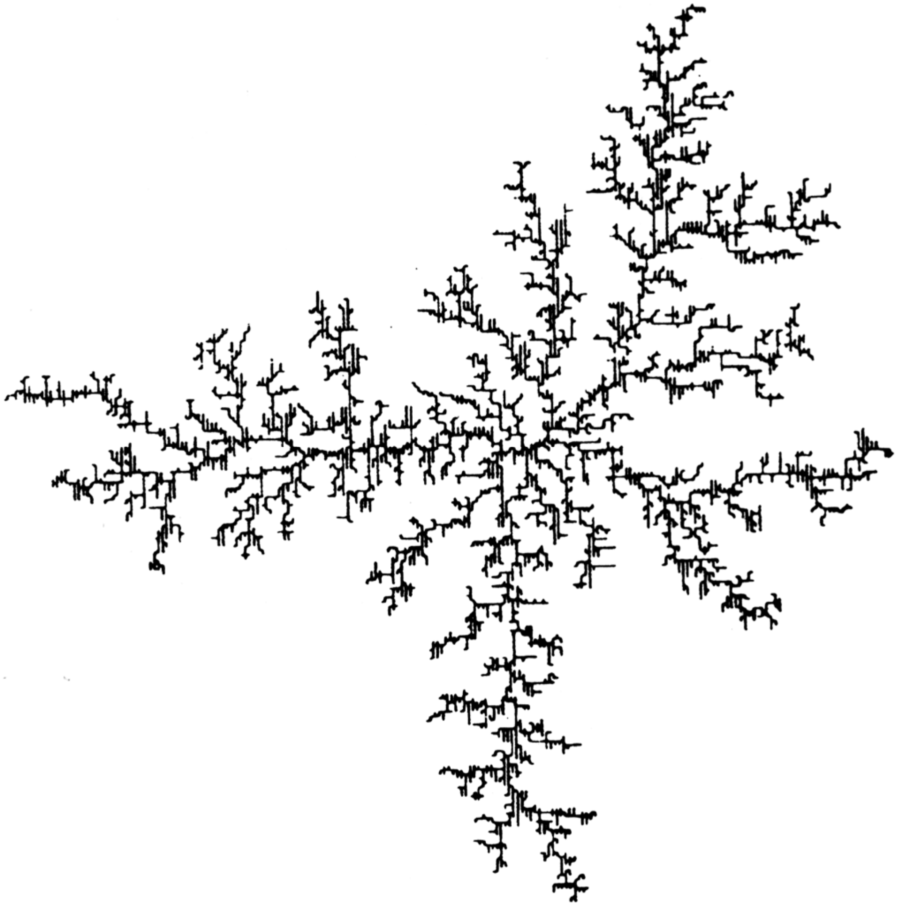


A. Anders, IEEE Trans. Plasma Sci. 33 (2005) 1456.

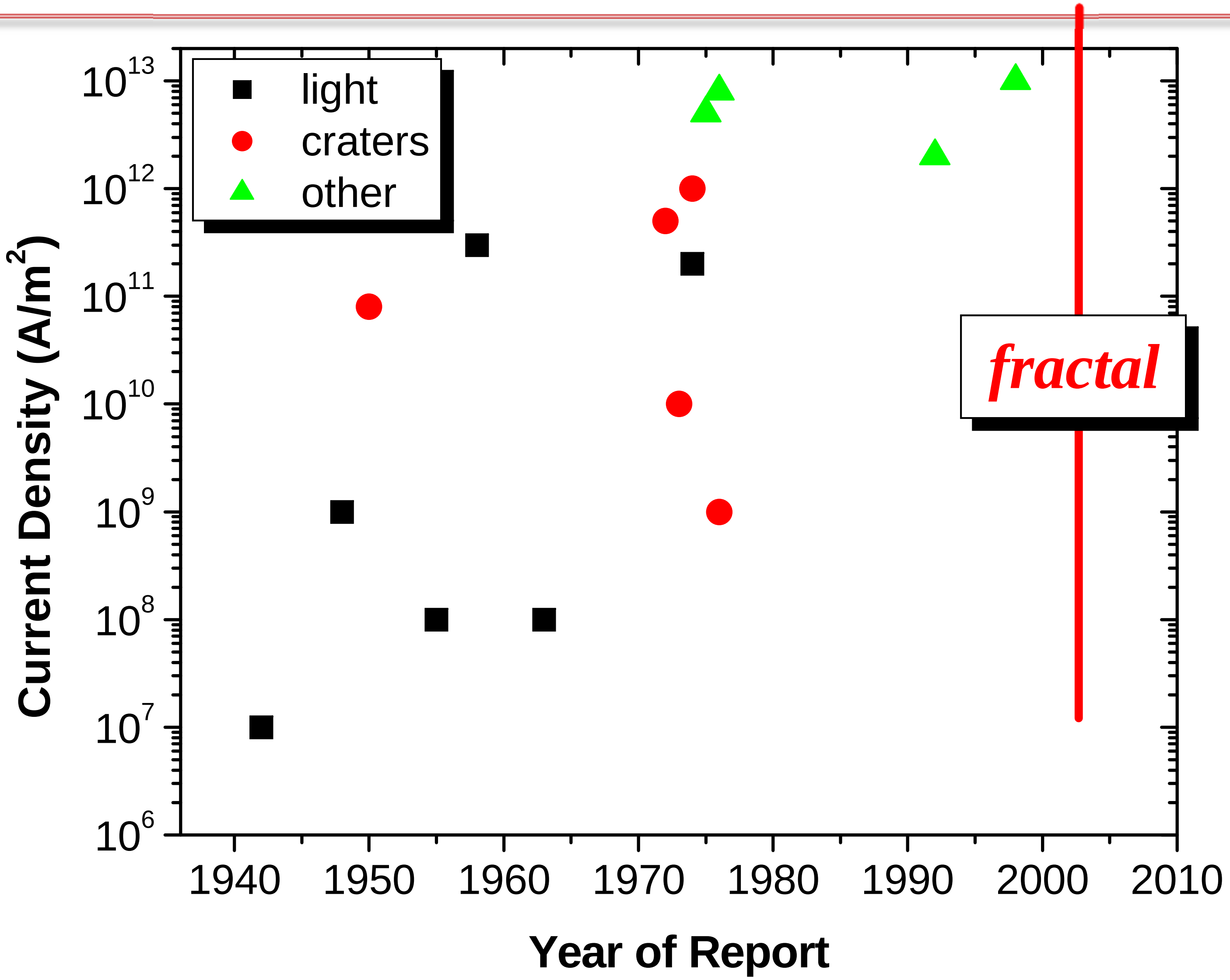
Fractal Model and Ignition

The fractal approach to “***Diffusion-limited Aggregation***” is applicable to random walk model of spot motion; ignition of a new spot corresponds to attachment of a molecule to nucleation site





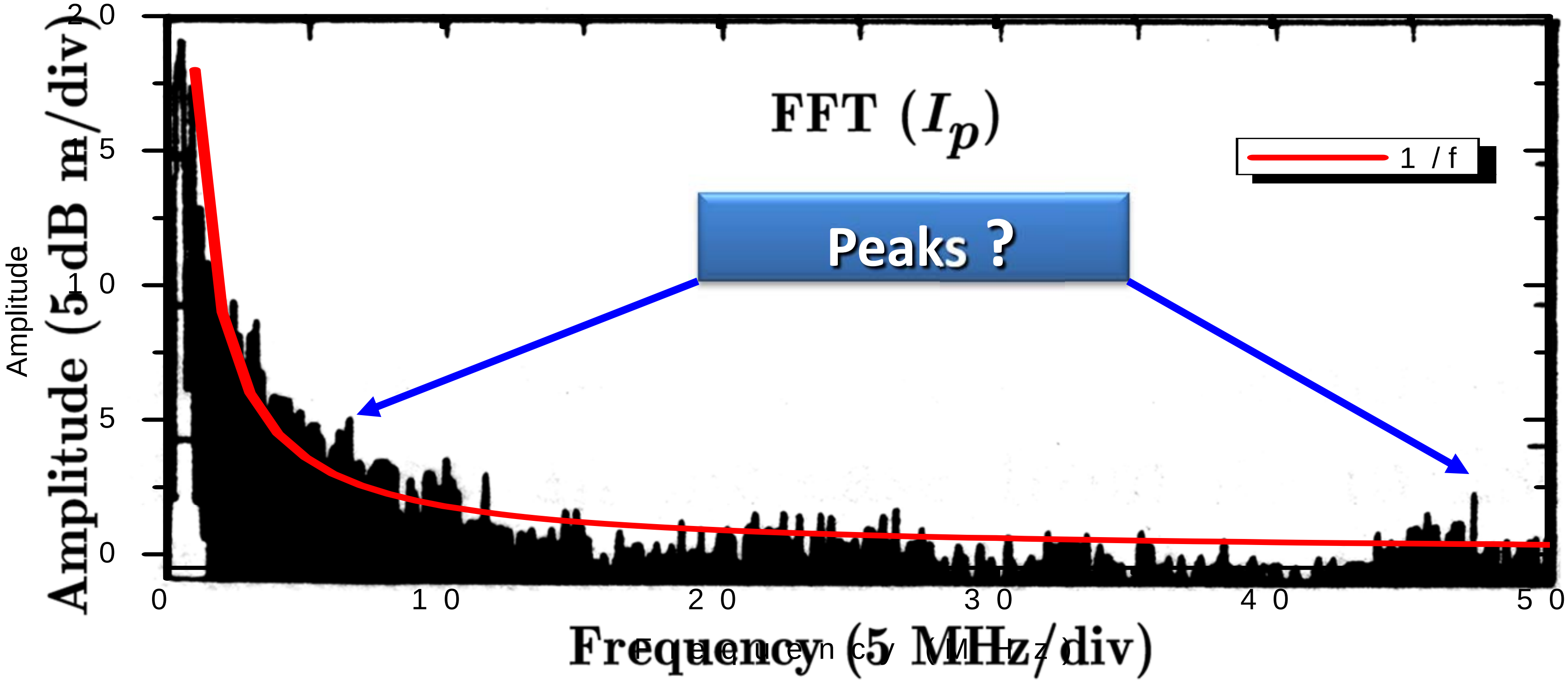
Current Density as a Fractal



A. Anders, IEEE Trans. Plasma Sci. 33 (2005) 1456.

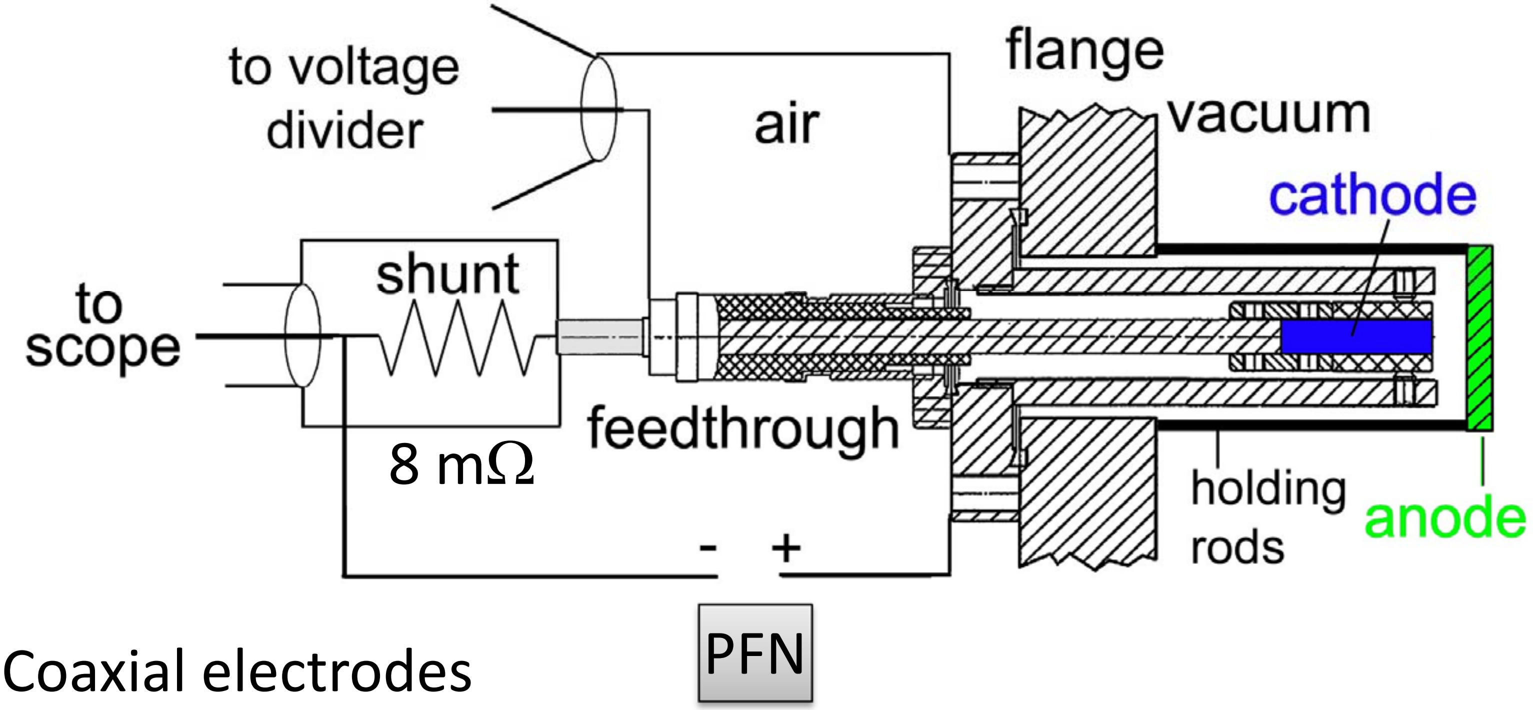
Arc Voltage as a Fractal

Early attempt to use Fourier Transform: Are there any “characteristic” Peaks?
Smeets and Schulpen 1988: FFT: 1/*f* noise for *f*< 10 MHz, white noise for *f* > 10 MHz. There are no clear peaks (which would have indicated cyclic events).



Smeets and Schulpen, J. Phys. D **21** (1988) 301

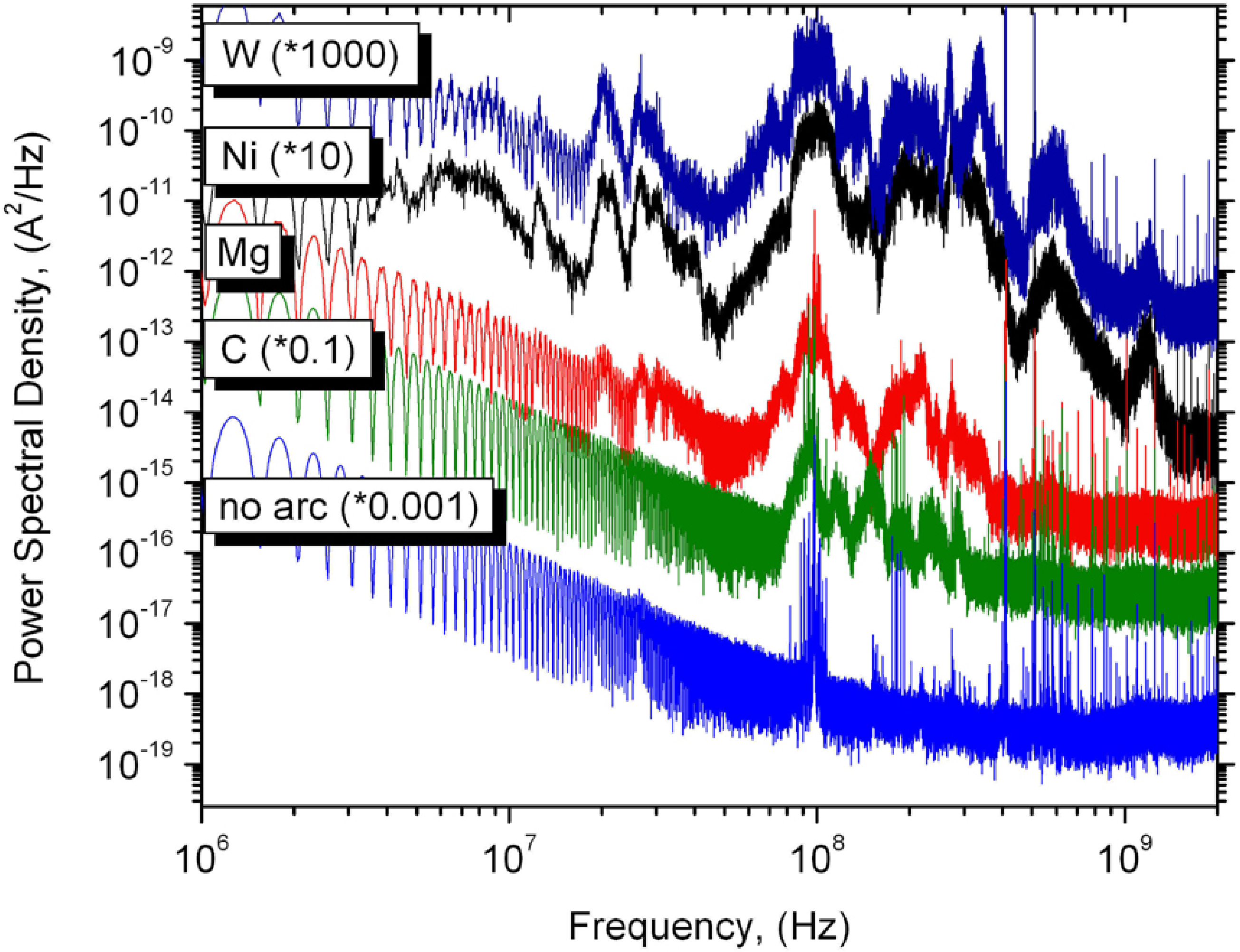
Experimental Setup For Arc Noise Measurements



- Coaxial electrodes
- fast digital oscilloscopes
- selecting only the "flat" potion of arc discharge pulse
- Fast Fourier Transform of each individual data set
- Repeat all steps 10 times and produce average

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

Power Spectrum of Arc Current for Different Materials

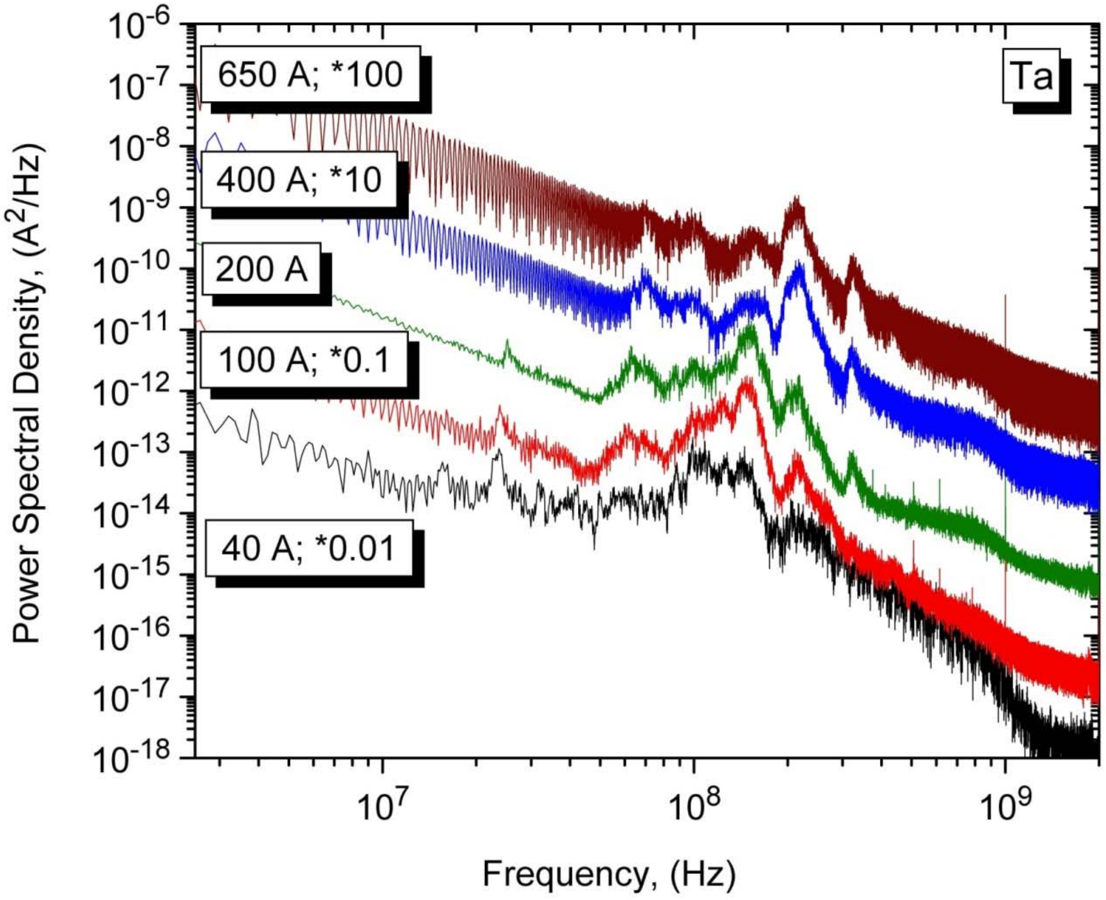


20 A

A. Anders, E. Oks, J. Appl. Phys. 99 (2006) 103301.

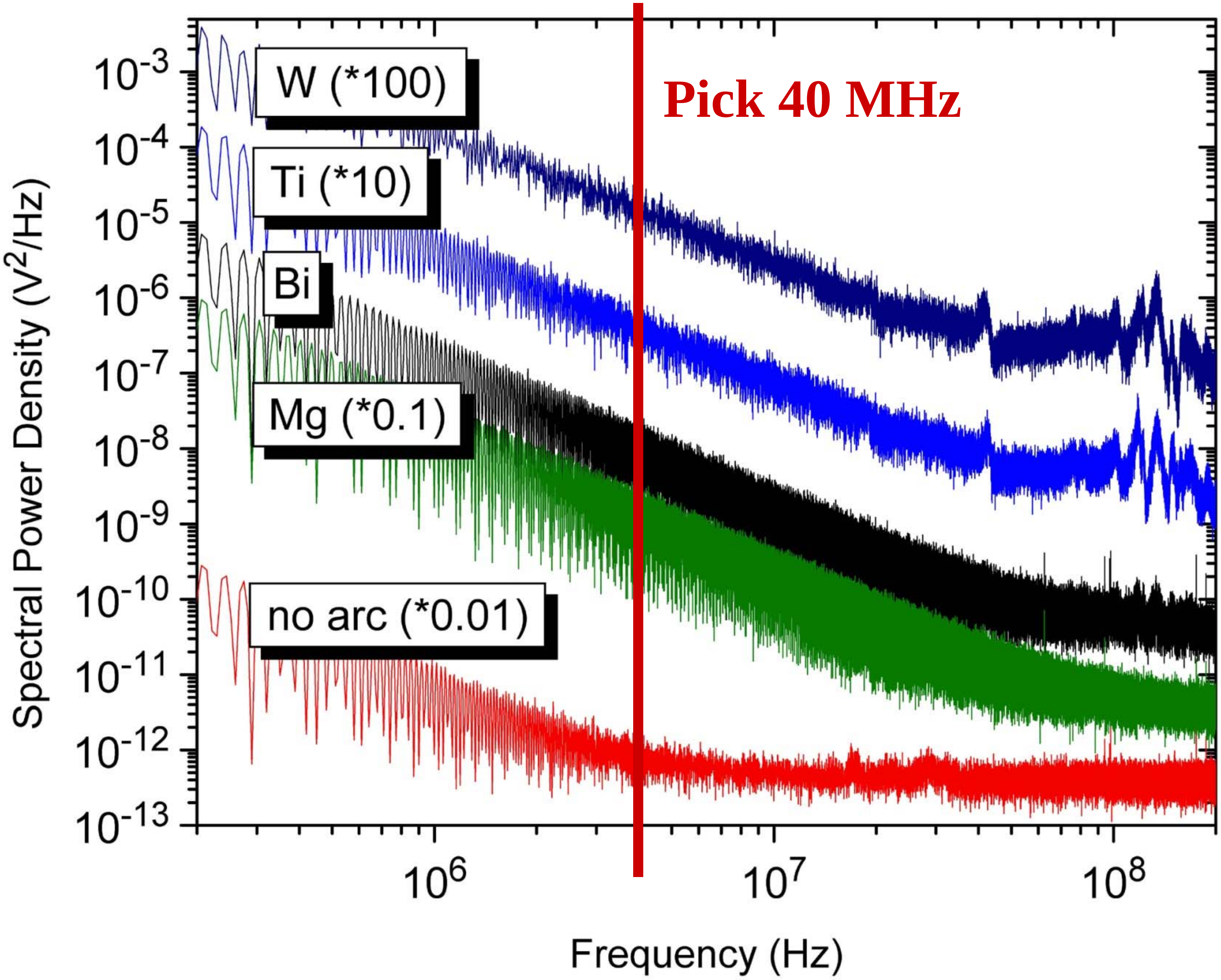
Current Noise as a Function of Arc Current Amplitude

- higher current smoothens-out the noise
- recall: more emission centers or spots are simultaneously active



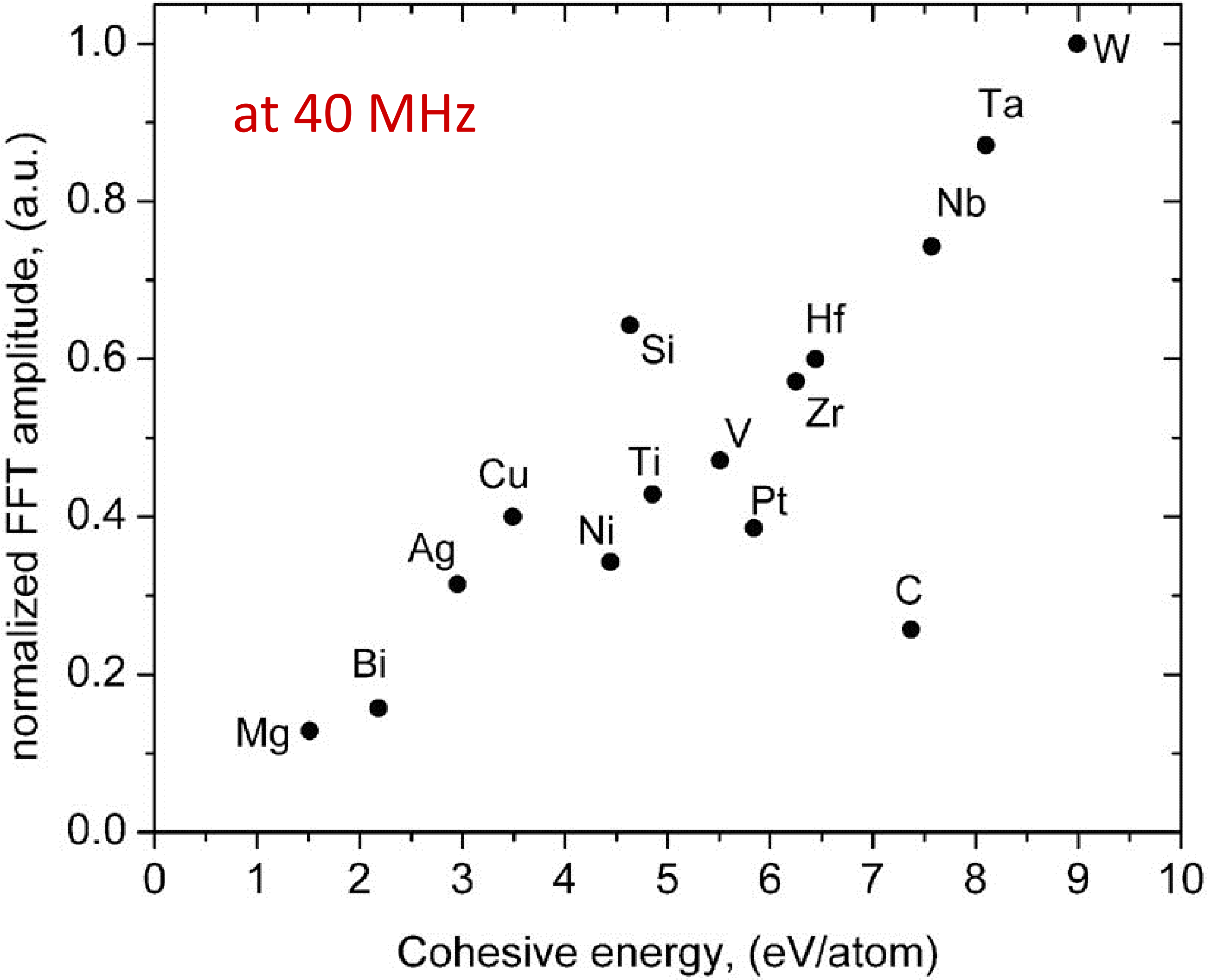
A. Anders, E. Oks, J. Appl. Phys. 99 (2006) 103301.

Power Spectrum of Arc Voltage



Pick 40 MHz

Material Dependence of Voltage Noise



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

Cohesive Energy Rule

Cohesive Energy Rule for Vacuum Arcs

cohesive energy = energy needed to free an atom from the solid

Energy balance consideration:

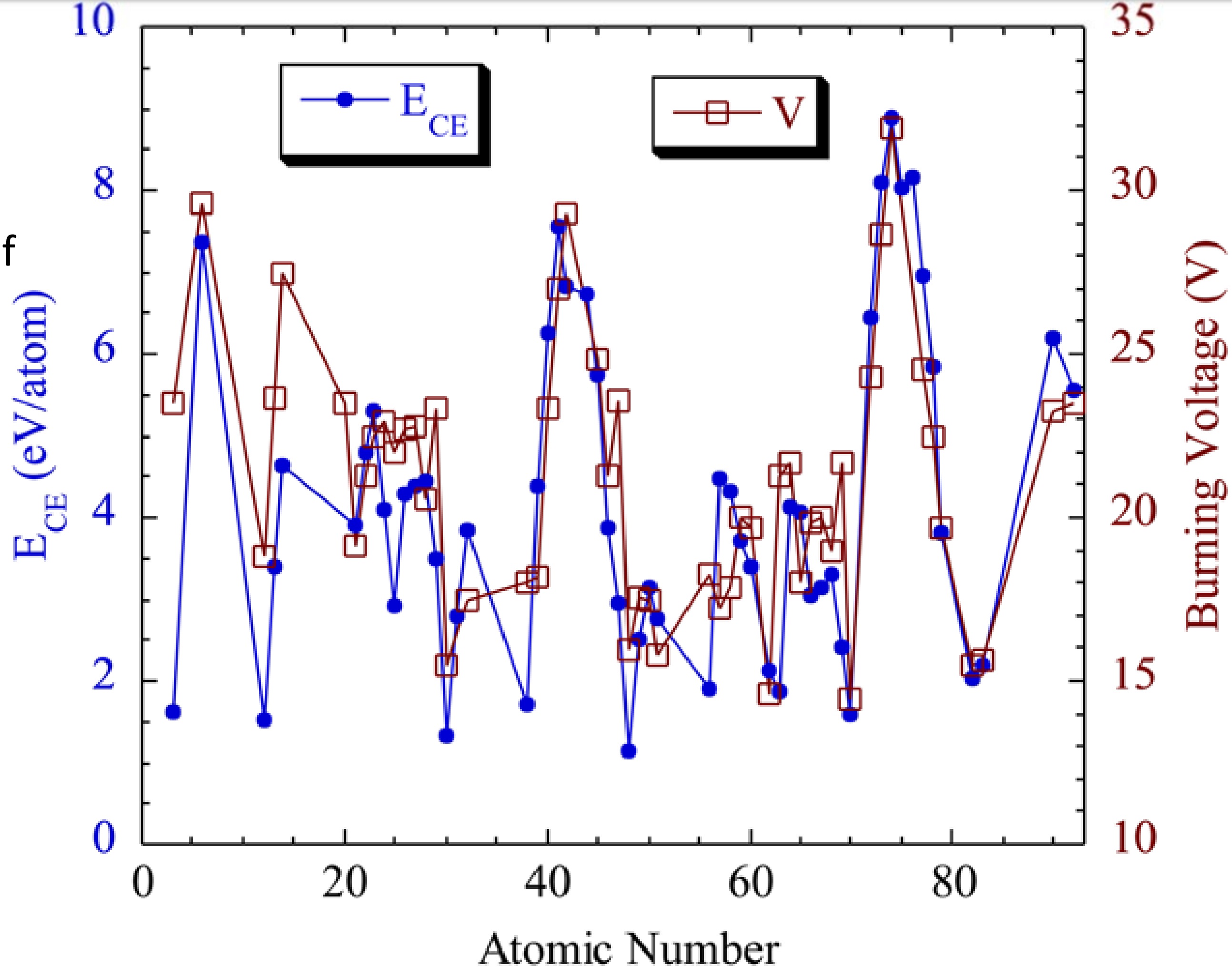
There is a direct correlation between cohesive energy of the cathode and burning voltage of vacuum arc

$$V = V_0 + A\,E_{CE}$$

with

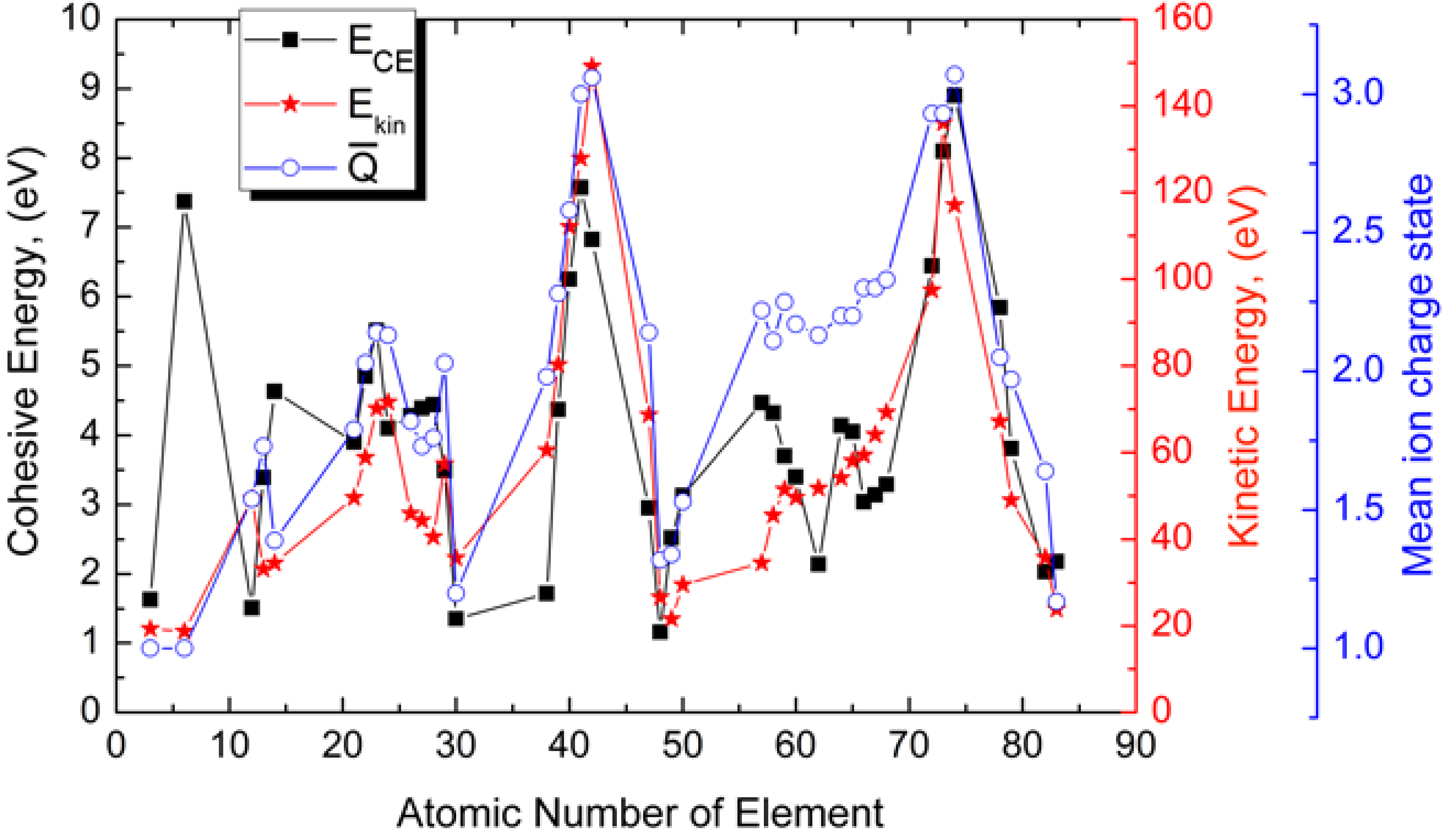
$$V_0 \approx 14.3\ \text{V and}$$

$$A = 1.69\ \text{V/(eV/atom)}$$



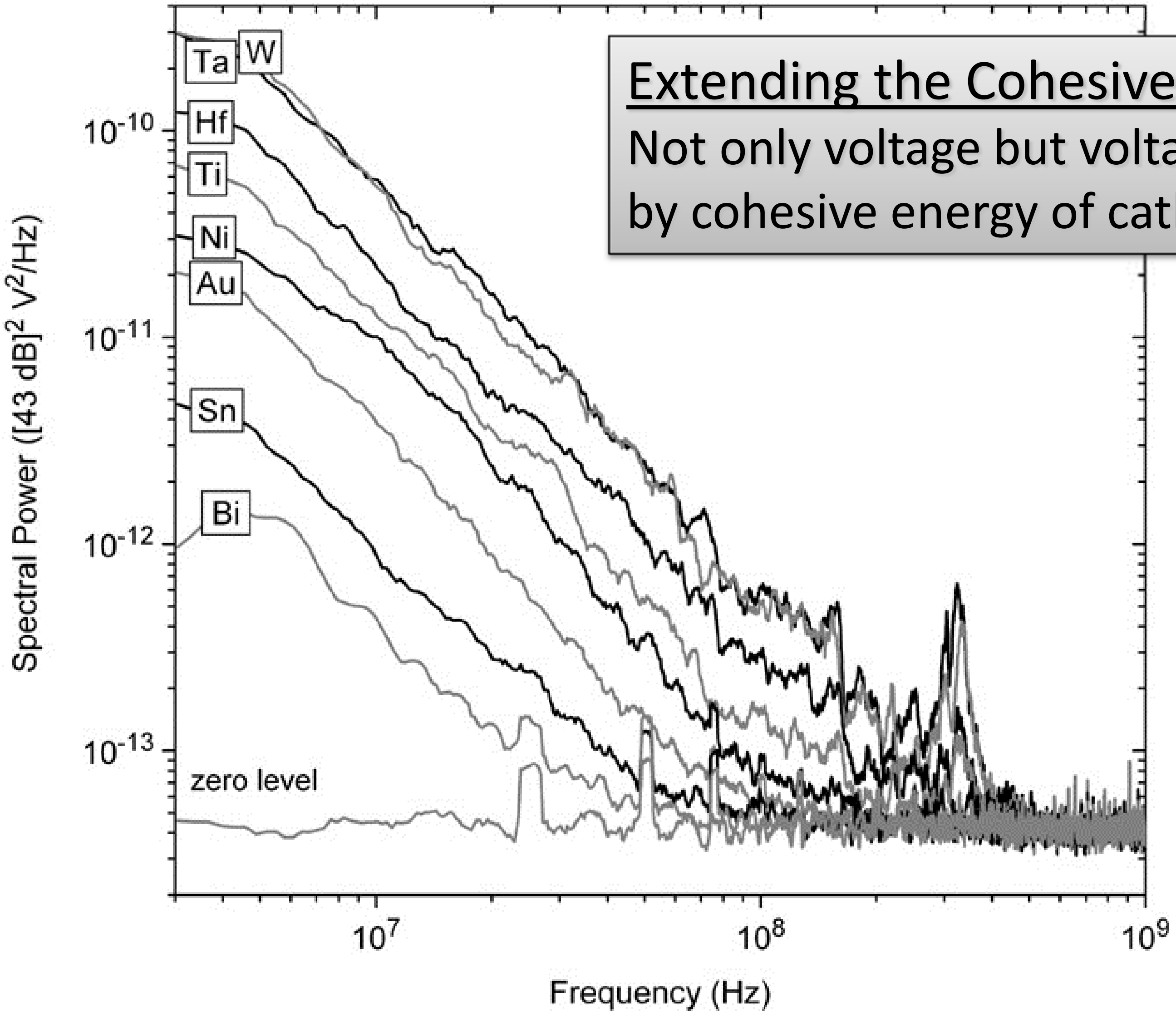
A. Anders *et al*, J. Appl. Phys. 89 (2001) 7764

Derived Rules or Relations for Vacuum Arc Plasmas



A. Anders, Cathodic Arcs, Springer, NY, 2008.

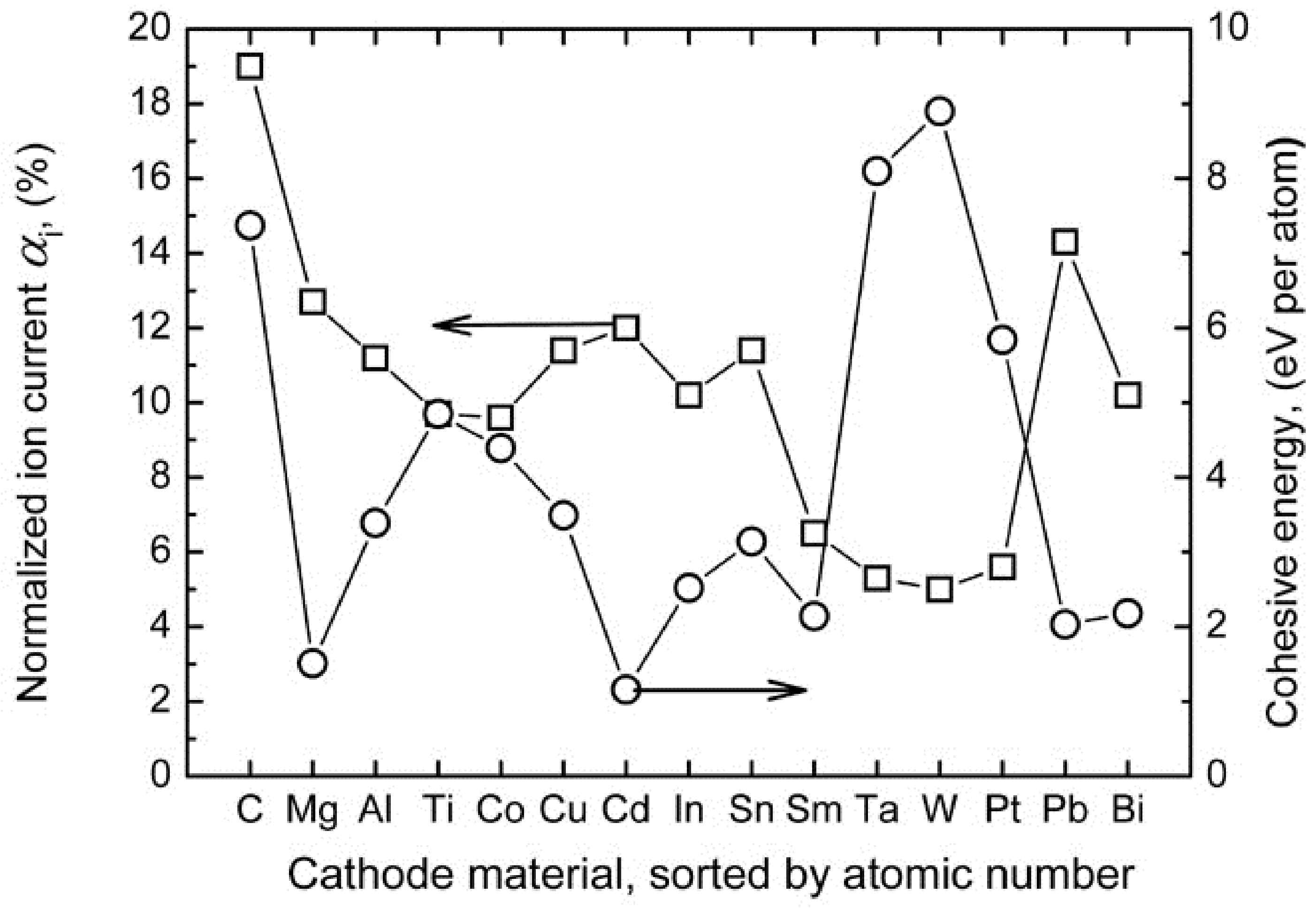
Connecting Fractal Model and Cohesive Energy Rule



Extending the Cohesive Energy Rule:
Not only voltage but voltage noise is governed by cohesive energy of cathode material

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

Cohesive Energy Rule and Ion Erosion Rate

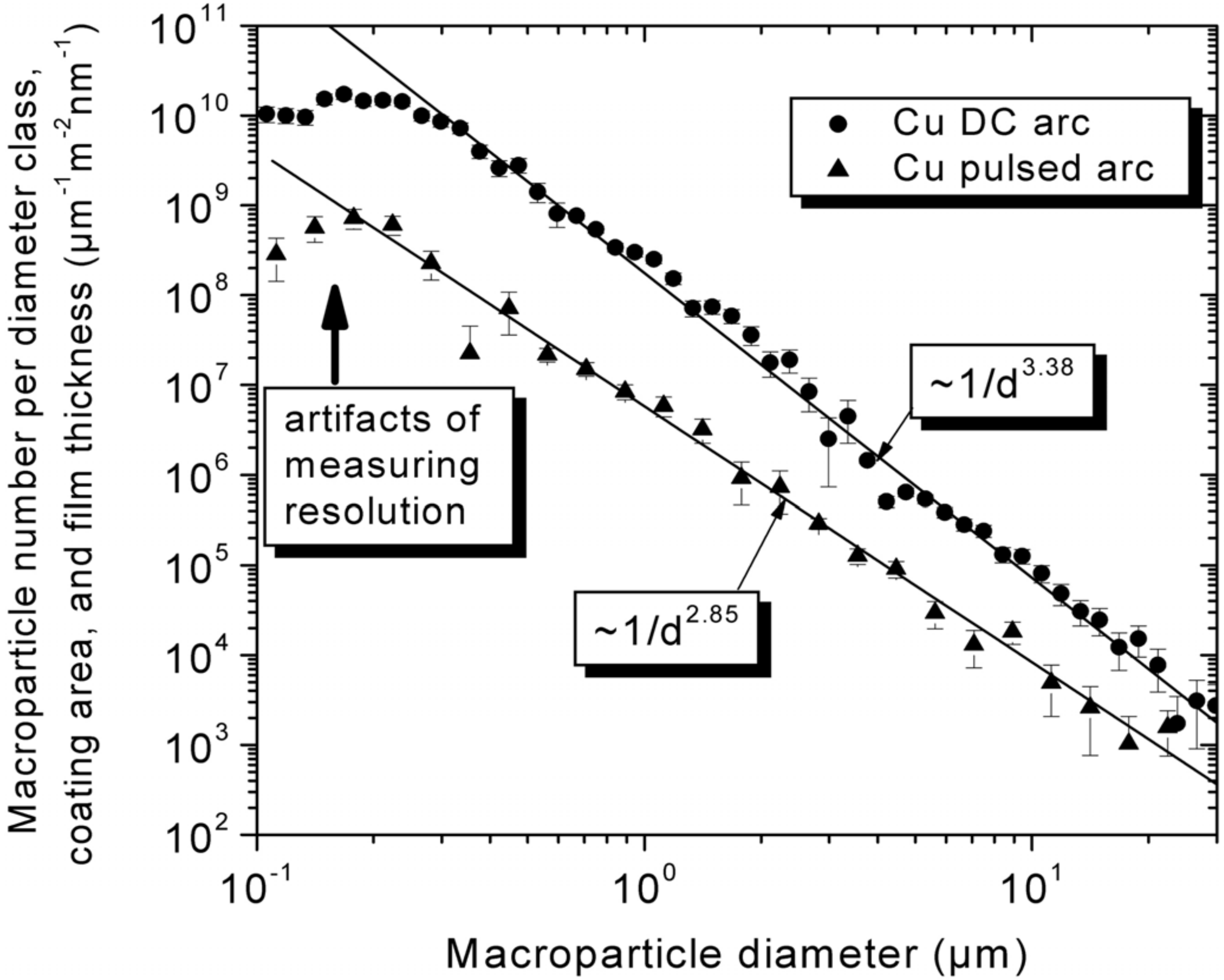


A. Anders, Cathodic Arcs, Springer, NY, 2008.

Macroparticles:

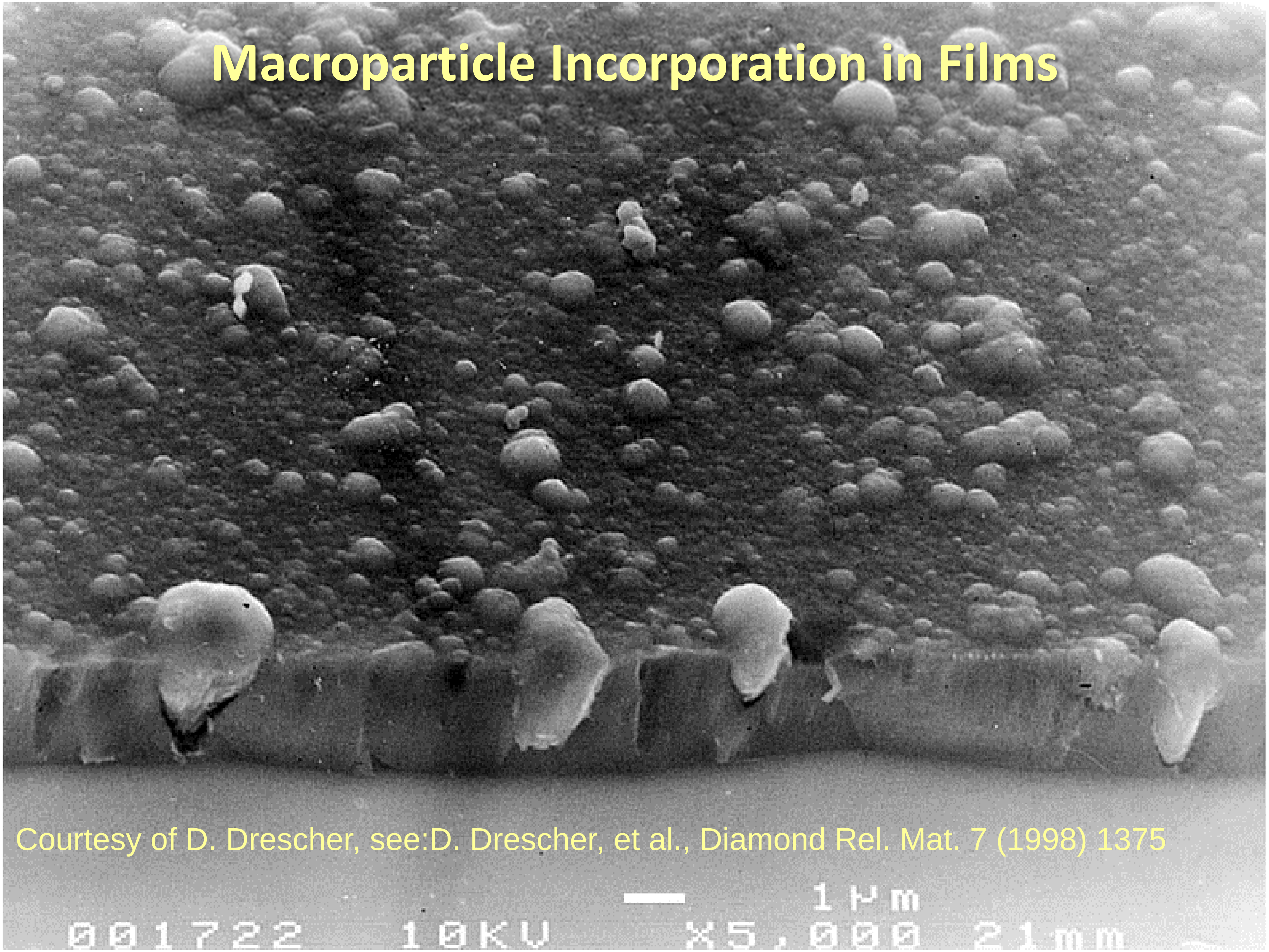
Fractal Distribution,
"Trouble Maker"

Fractal Macroparticle Distribution



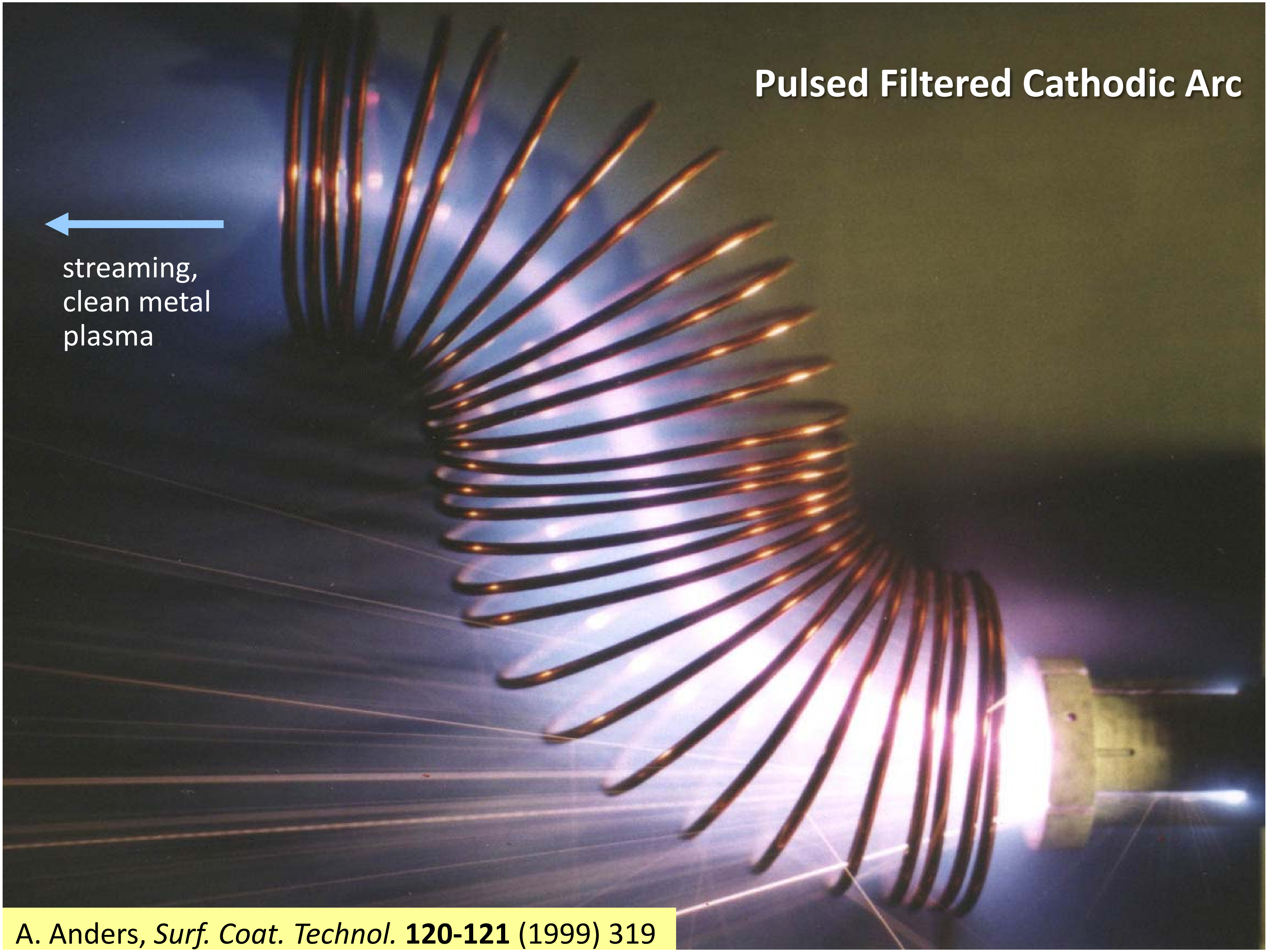
A. Anders, IEEE Trans. Plasma Sci. 33 (2005) 1456.

Macroparticle Incorporation in Films



Courtesy of D. Drescher, see:D. Drescher, et al., Diamond Rel. Mat. 7 (1998) 1375

Pulsed Filtered Cathodic Arc

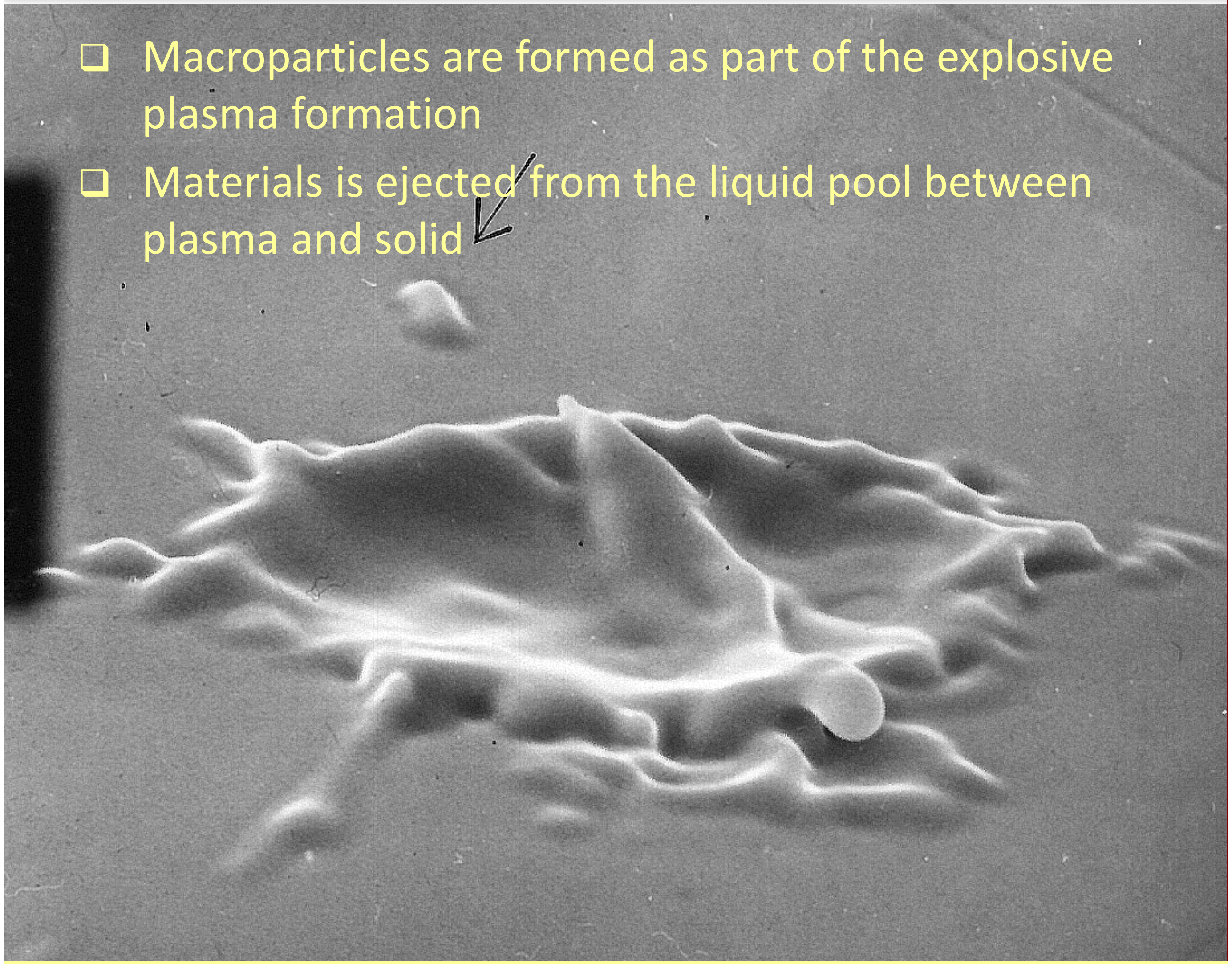


streaming,
clean metal
plasma

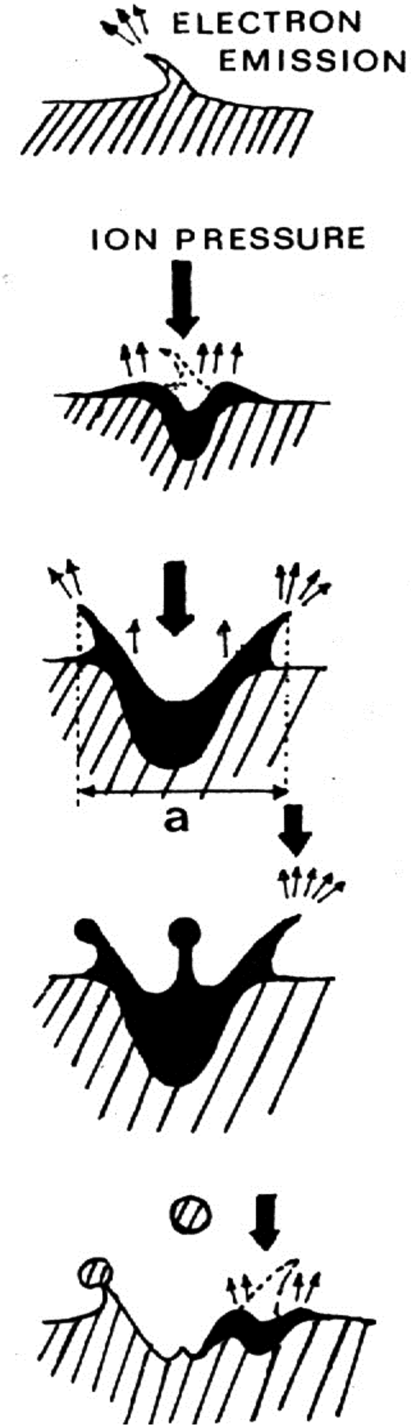
A. Anders, *Surf. Coat. Technol.* **120-121** (1999) 319

Macroparticle Generation

- Macroparticles are formed as part of the explosive plasma formation
- Materials is ejected from the liquid pool between plasma and solid

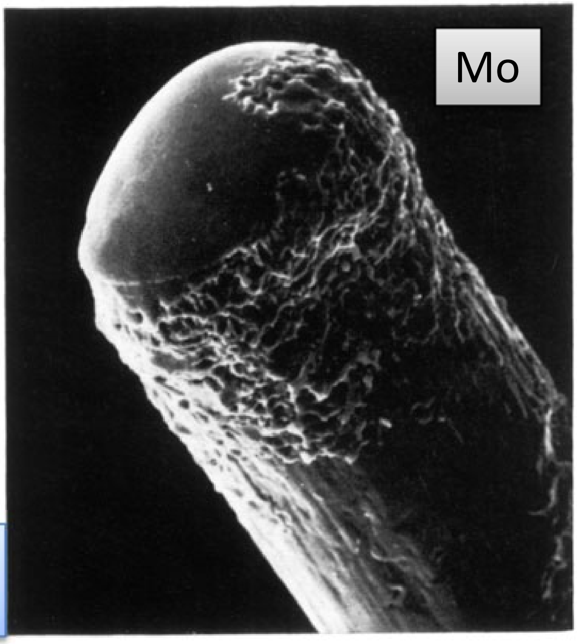


B. Jüttner, Beitr. Plasmaphys. **19** (1979) 25;
figures courtesy of B. Jüttner.

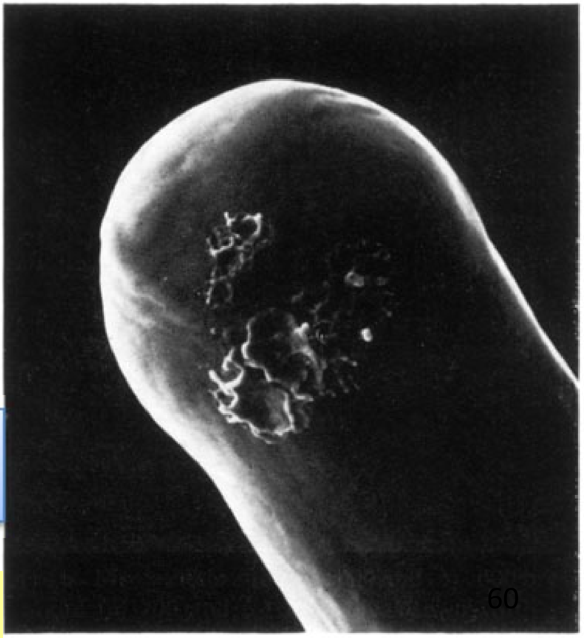


Polishing Effect

High voltage pulses lead to incomplete formation of spots → termination indicates 5 ns (Mo) crater formation time, and smoothening of surface.



5000 pulses with 10 ns

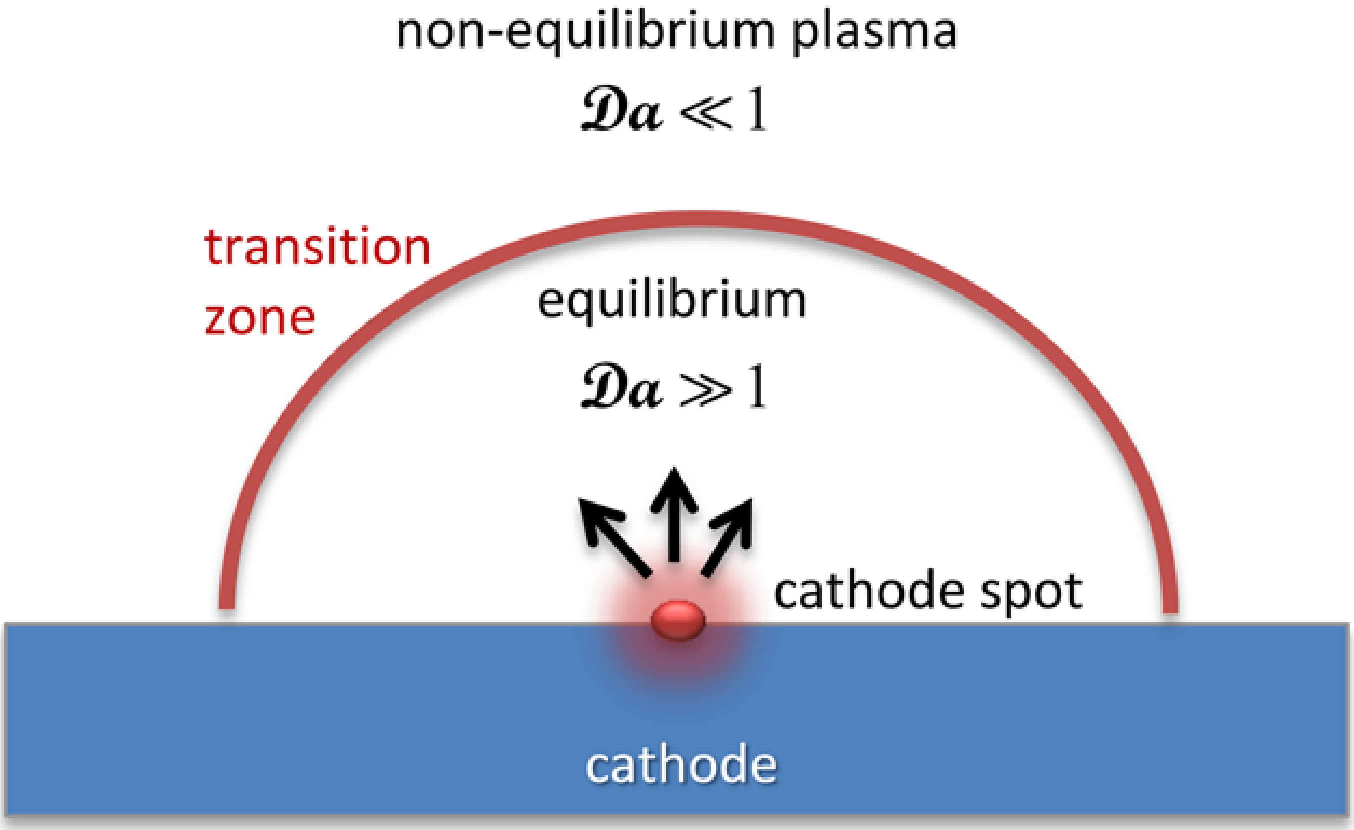


followed by 1000 pulses with 5 ns

E. Hantzsche, *et al.*, J. Phys. D: Appl. Phys. **9** (1976) 1771.

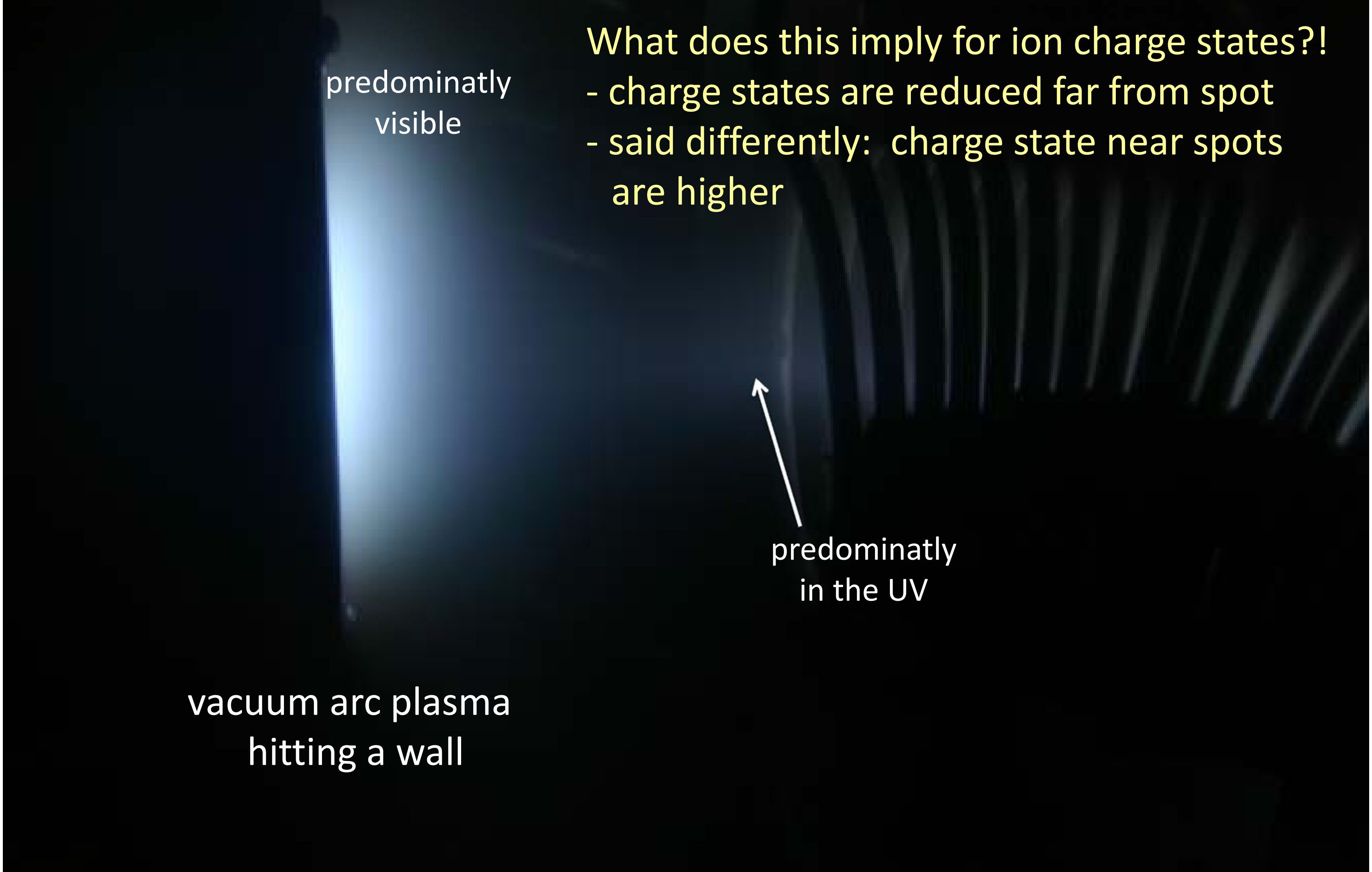
Ion Charge States:
Messengers from the Cathode Spot?

"Freezing" Approximation



A. Anders, Phys. Rev. E 55 (1997) 969.
A. Anders, Cathodic Arcs, Springer, NY, 2008.

Emission of UV versus Visible Light by Arc Plasma



What does this imply for ion charge states?!

- charge states are reduced far from spot
- said differently: charge state near spots are higher

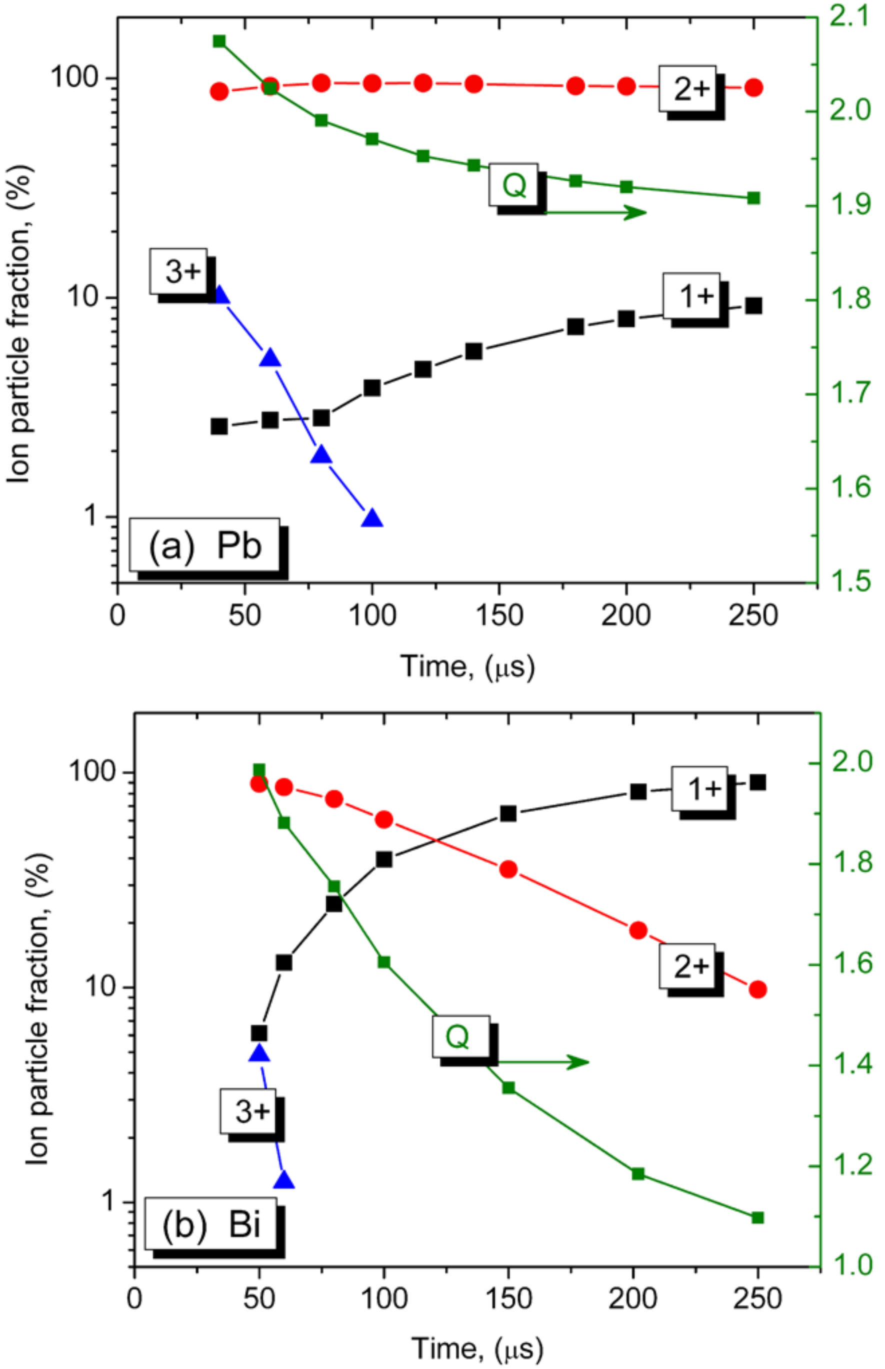
predominatly
visible

predominatly
in the UV

vacuum arc plasma
hitting a wall

P.A. Ni and A. Anders, J. Phys. D: Appl. Phys. 43 (2010) 135201.

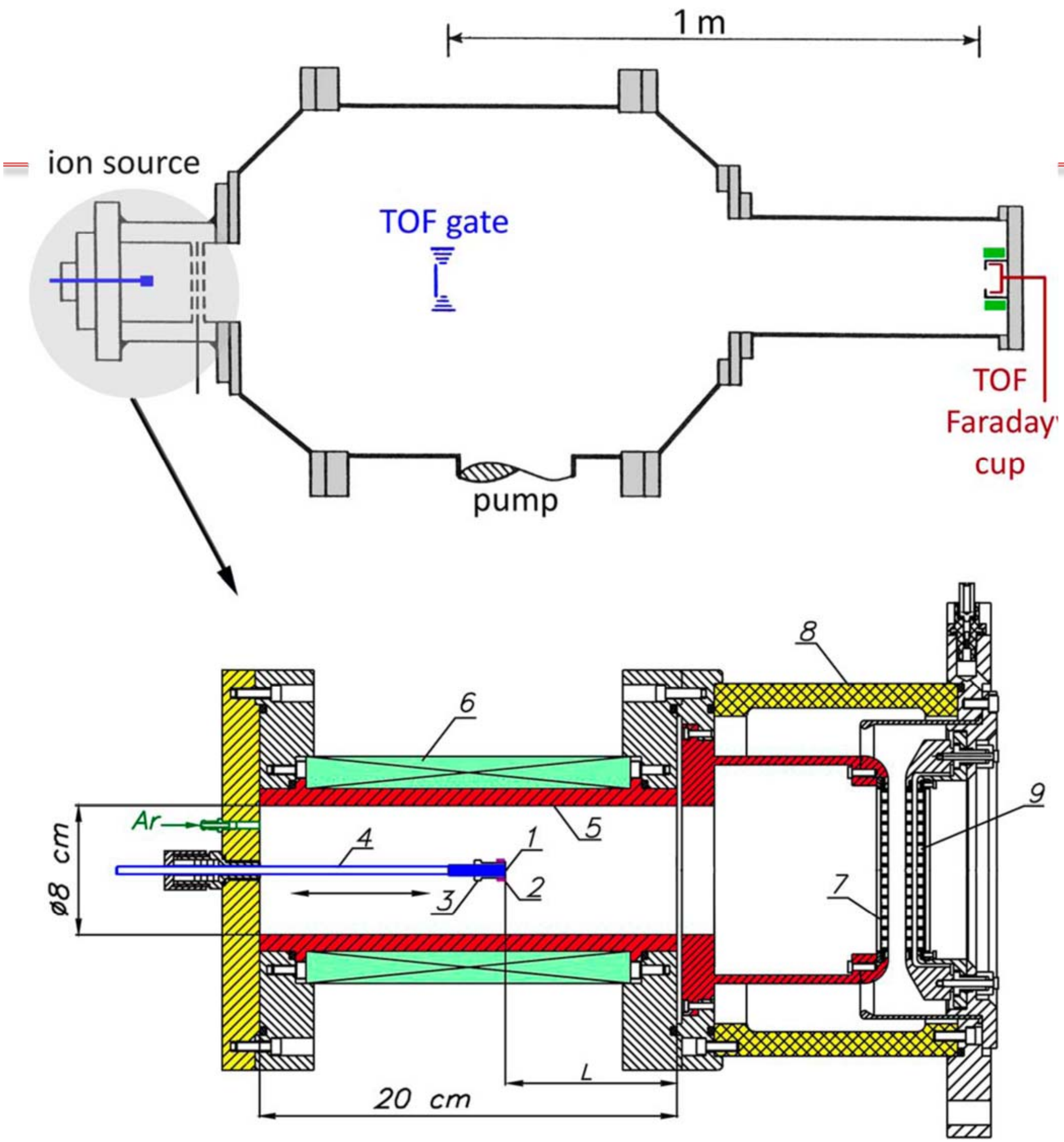
Role of Neutrals in Vacuum Arc Plasmas



Significant differences in Pb and Bi ion charge state distributions can be traced back to different amounts of neutrals in plasma

Bi has many more neutrals than Pb

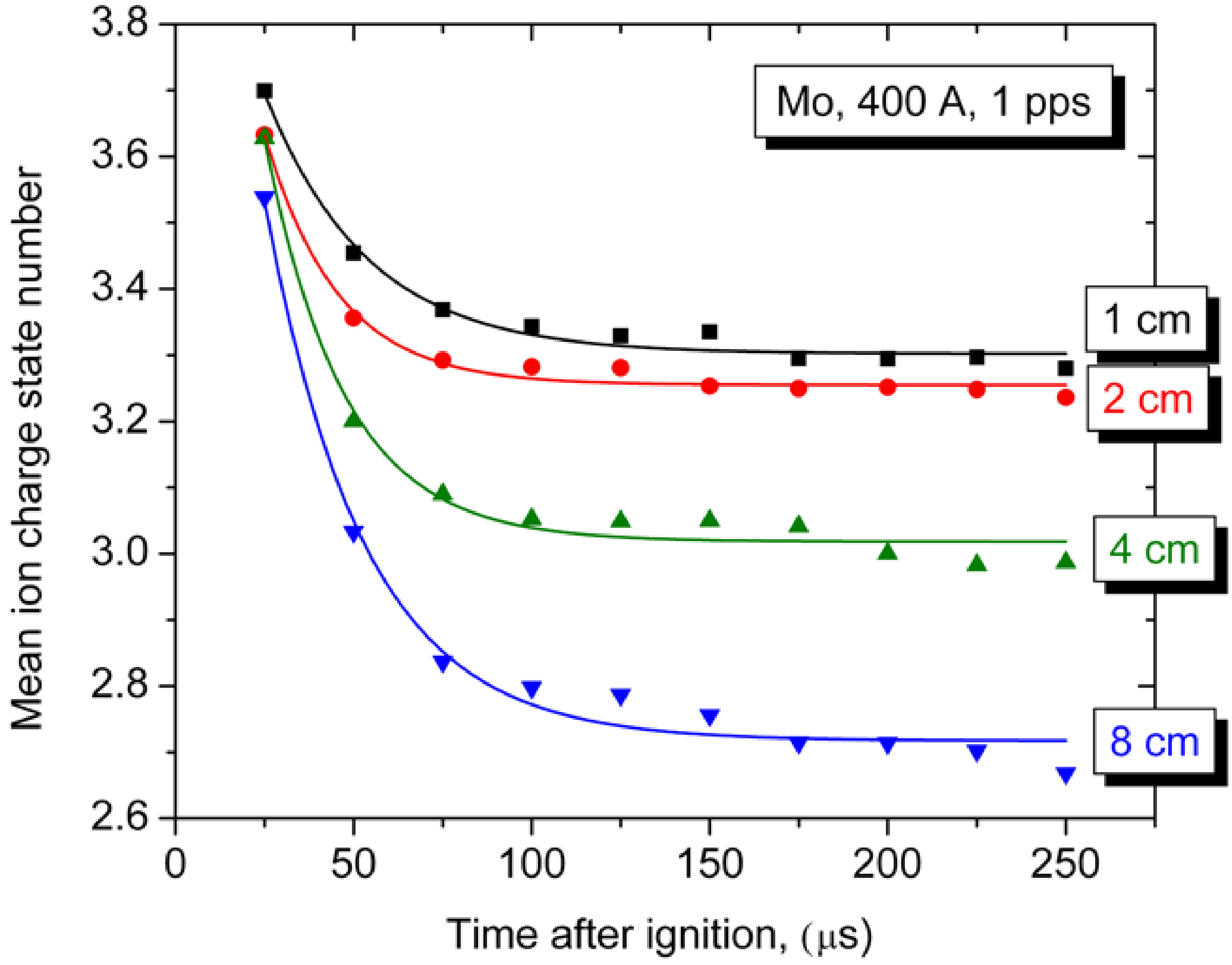
A. Anders, G.Y. Yushkov, Appl. Phys. Lett. 91 (2007) 091502.



Further Studies of the Role of Neutrals by TOF spectrometry

we can vary the distance of measurement from cathode spot

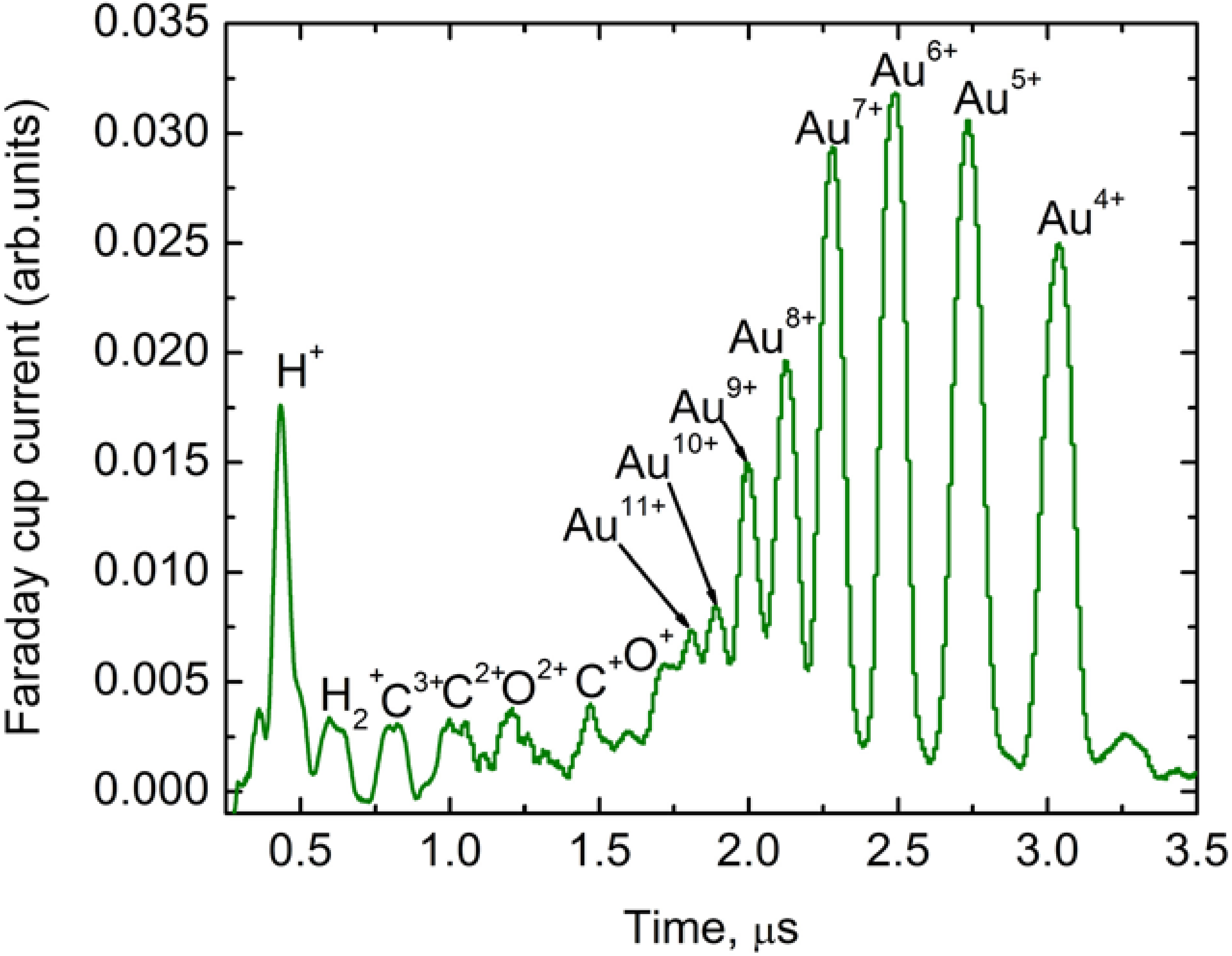
Extrapolation to spot location gives much higher ion charges states than usually considered!



A. Anders, E.M. Oks, G.Y. Yushkov, J. Appl. Phys. 102 (2007) 043303.

What Charge States Can Be Observed?

transition region between spark and arc

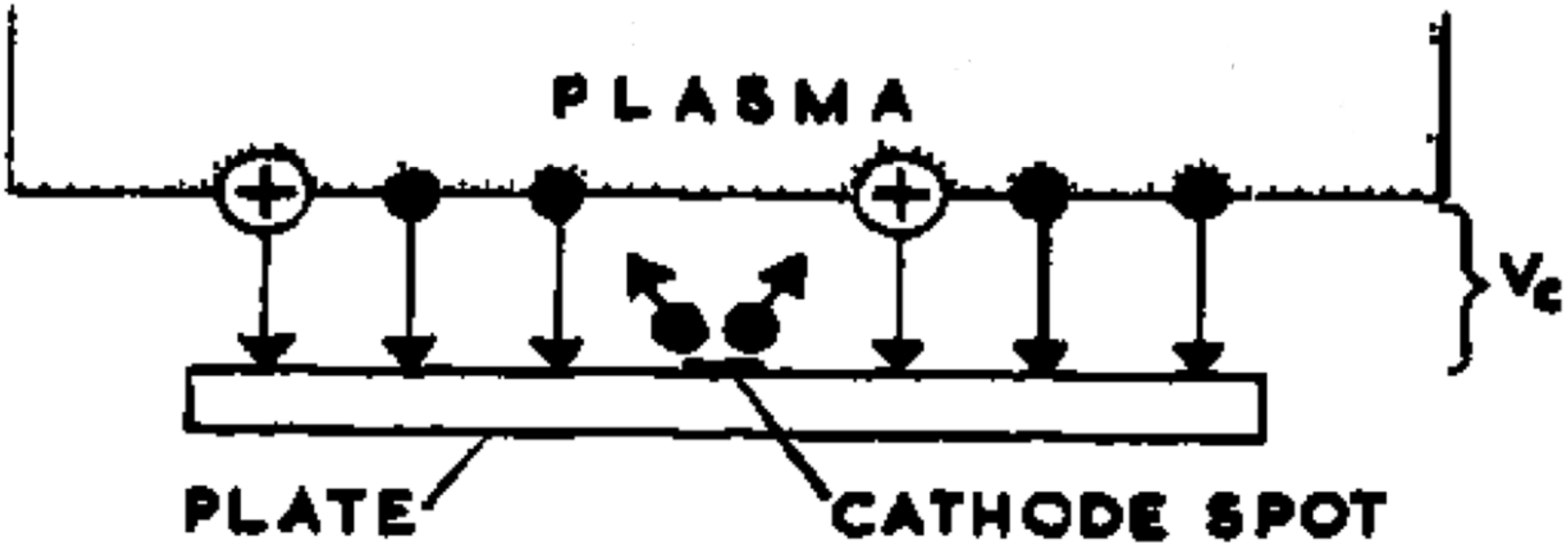


G.Y. Yushkov, A. Anders, J. Appl. Phys. 105 (2009) 043303.

Unipolar Arcs

Unipolar Arcs (Robson and Thonemann, 1959)

Mainly a theoretical paper, with 2 experiments, showing the existence of cathode spots on floating piece of metal immersed in a plasma



A.E. Robson and P.C. Thonemann, Proc. Phys. Soc. 73 (1959) 508.

Unipolar Arcs (Hantzsche, 1980)

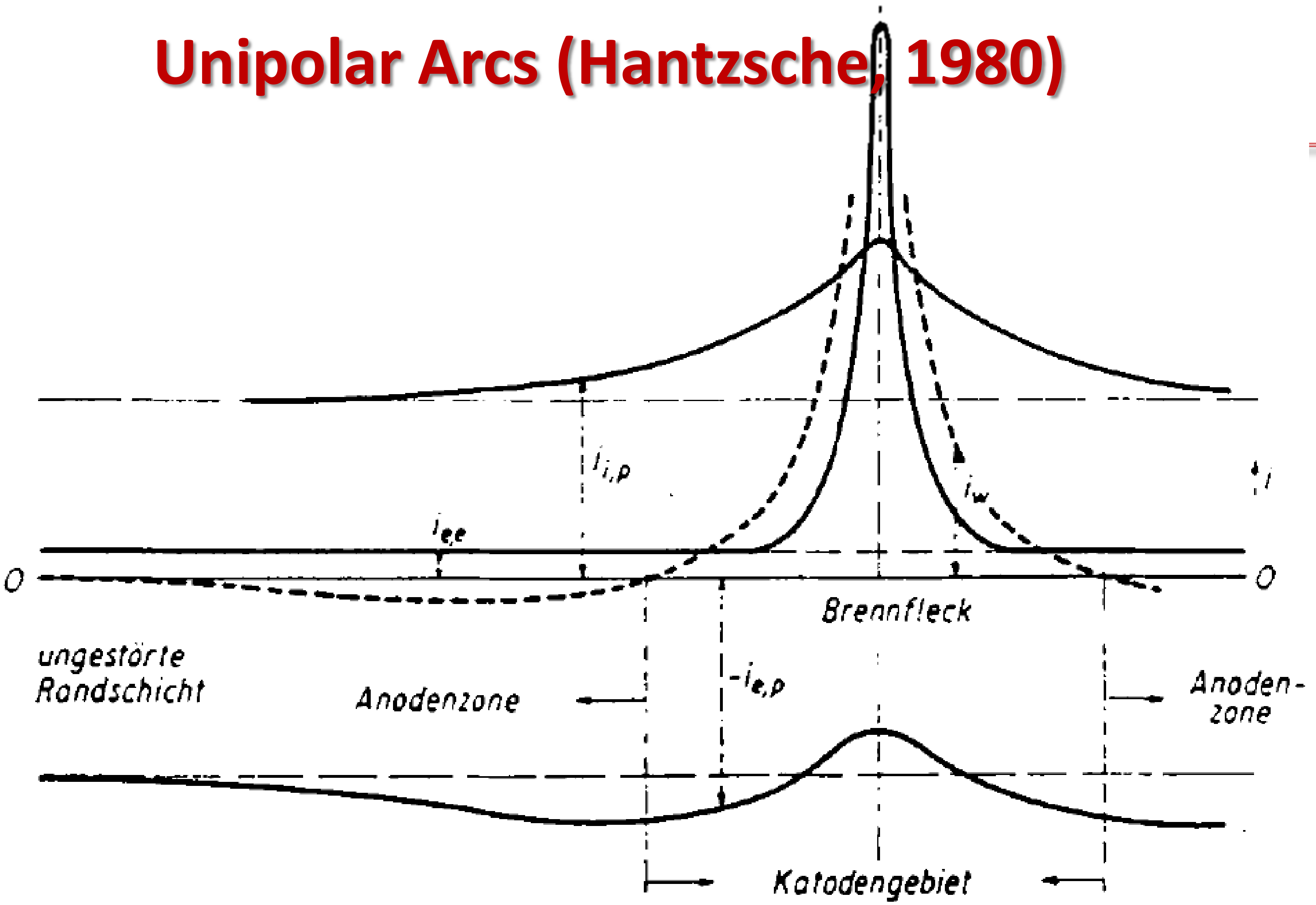


Abb. 2. Stromdichteverteilung der Plasmarandschicht, schematisch; i_w (punktiert) = Netto-Stromdichte

E. Hantzsche, Beitr. Plasmaphys. 20 (1980) 329.

Unipolar Arcs (Schwirzke, 1984)

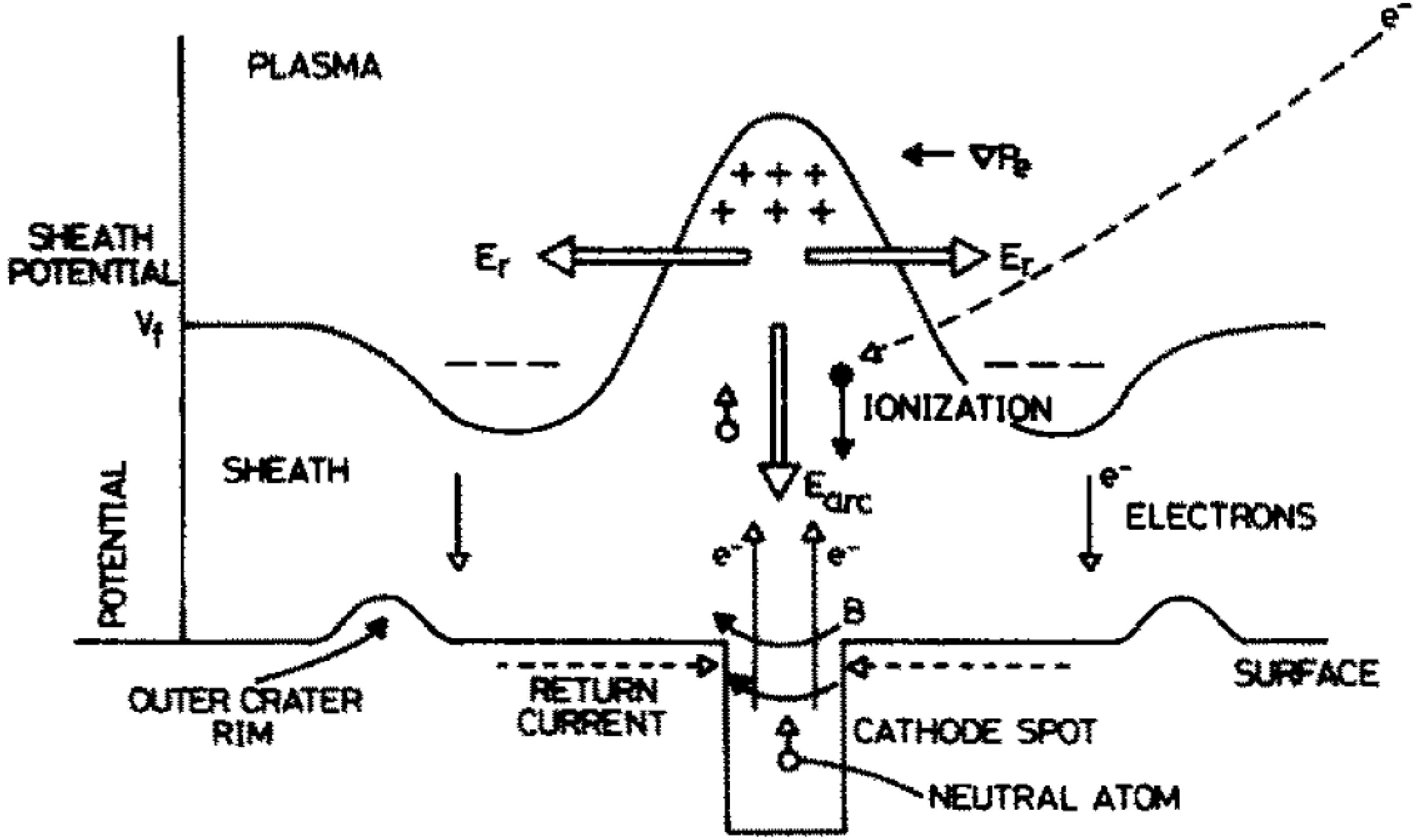
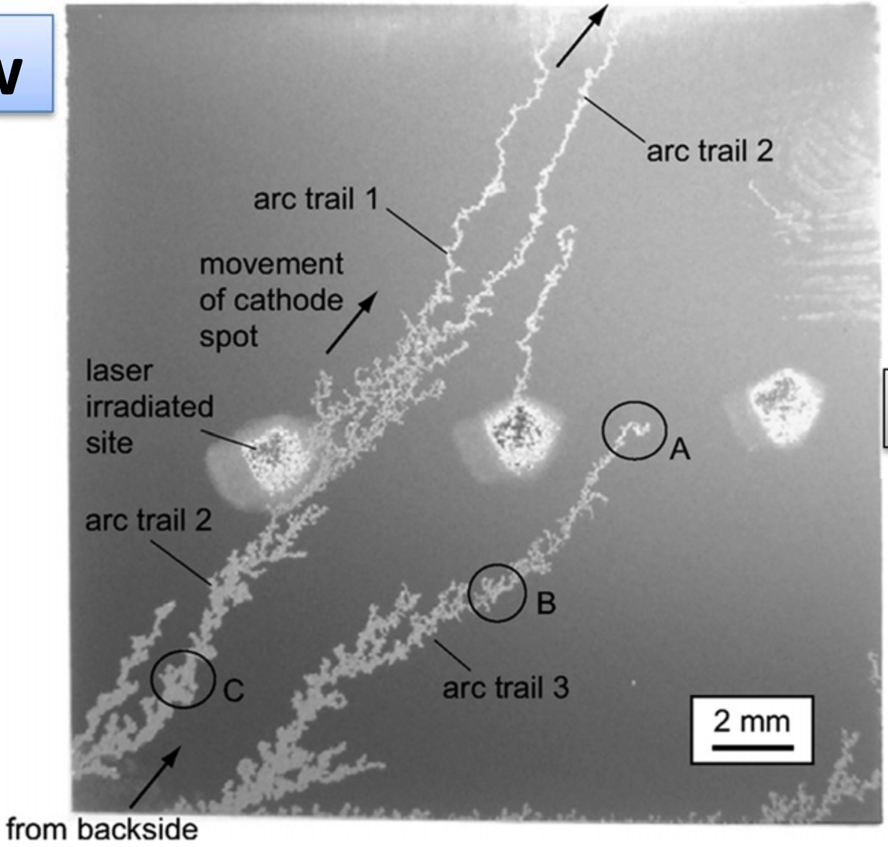


Fig. 2. Unipolar arc model.

F. Schwirzke, J. Nucl. Mater. 128-129 (1984) 609.

Unipolar Arcs on First Wall (W)

W

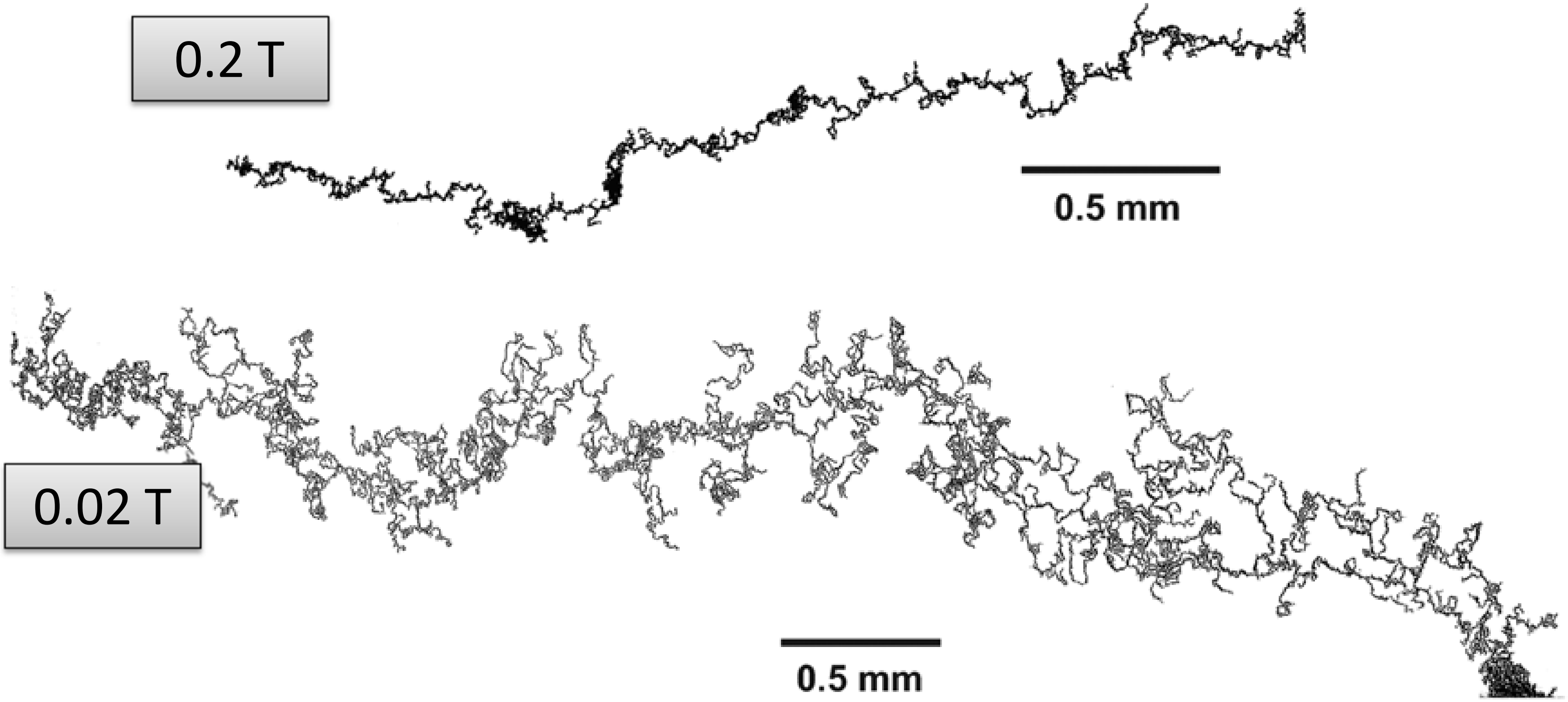


laser triggered

S. Kajita, S. Takamura, N. Ohno, Nuclear Fusion 49 (2009) 032002.

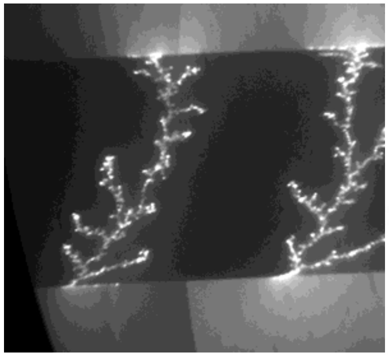
S.A. Barengolts, G.A. Mesyats, M.M. Tsventoukh, Nuclear Fusion 50 (2010) 125004.

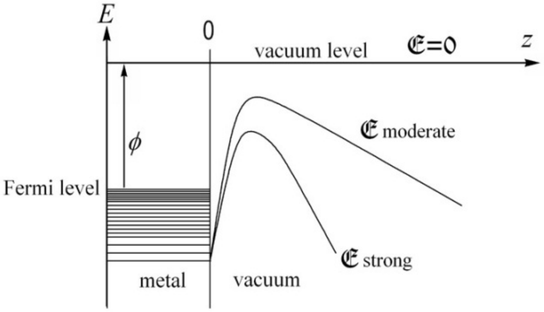
Fractal Spots: Random versus Steered, also applies to Unipolar Arcs

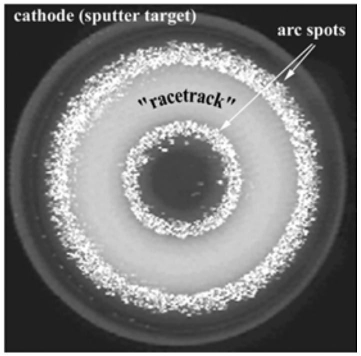


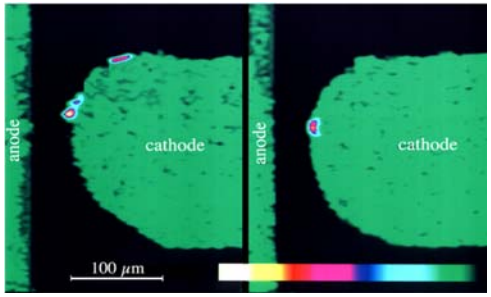
S. Kajita, et al., Plasma Phys. Controlled Fusion 53 (2011) 074002

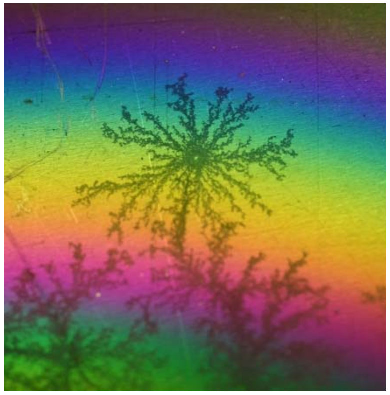
Summary

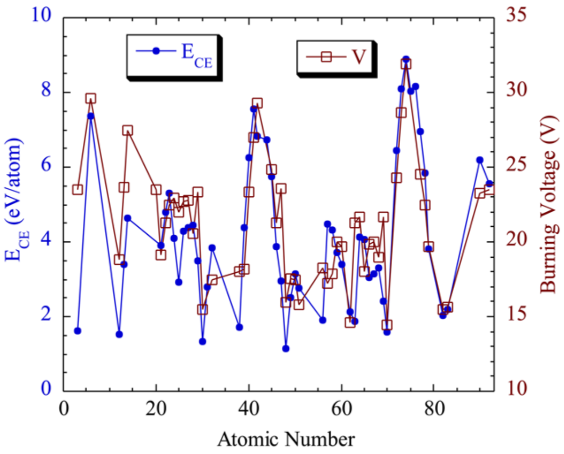


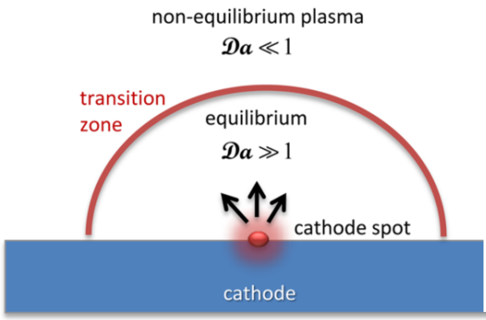












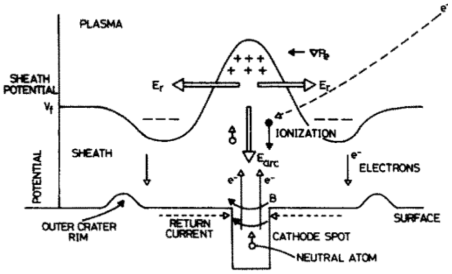


Fig. 2. Unipolar arc model.