Breakdown Physics Workshop

May 6-7, 2010 at CERN (40-S2-D01 - Salle Dirac)

chaired by Walter Wuensch, Sergio Calatroni (CERN),
and Kai Nordlund, Flyura Djurabekova (U Helsinki)

Physics of Arc Plasma Devices

André Anders

Lawrence Berkeley National Laboratory,
Berkeley, California

aanders@lbl.gov

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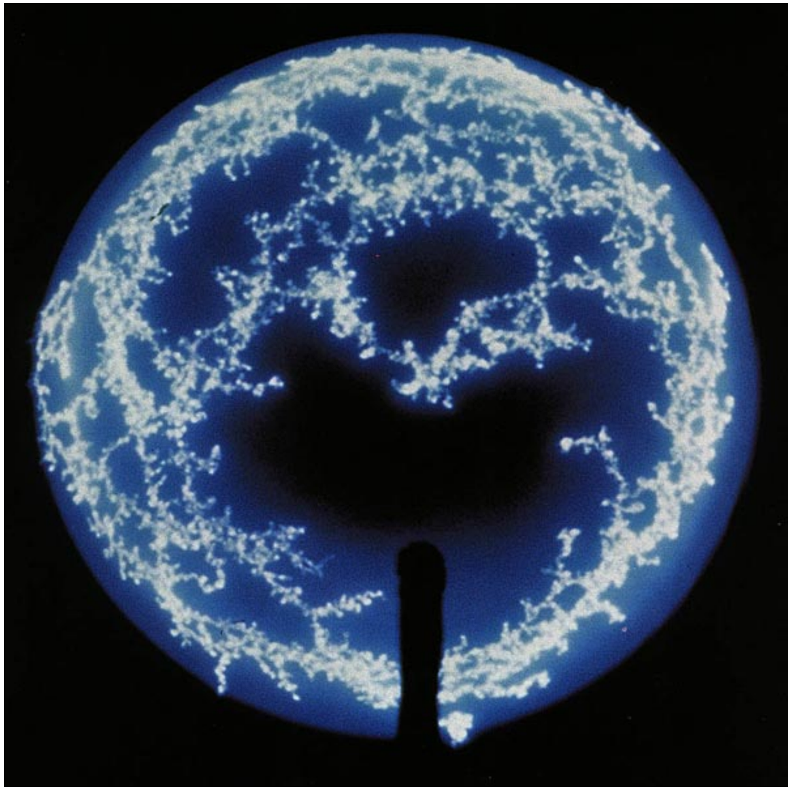
Cathodic Arcs

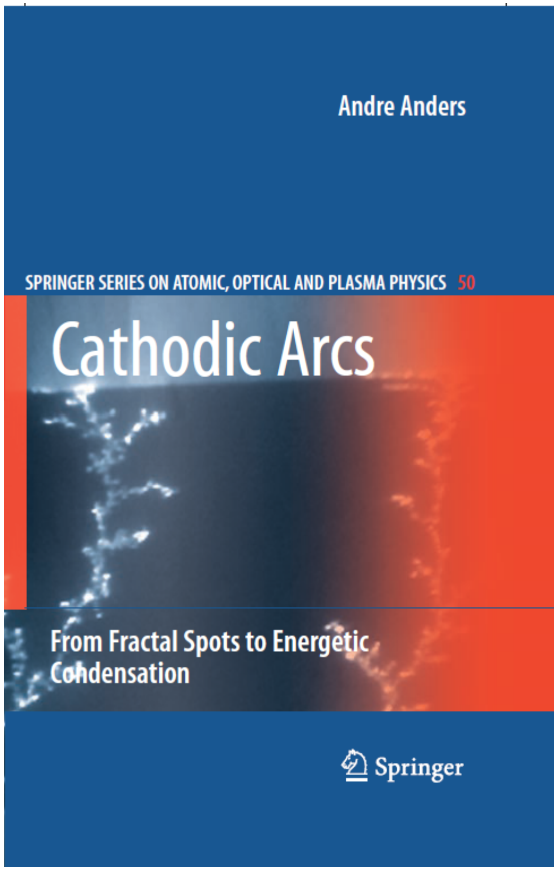
- Discharge:
  - low voltage (~ 20 V) after plasma bridges anode-cathode
  - current > chopping current
  - strongly depends on cathode surface conditions
  - plasma originates from "cathode spots" – material erodes from cathode surface
- Metal plasma:
  - formed explosively at cathode spots
  - fully ionized, multiple charge states
  - supersonic ions
- Devices:
  - vacuum arc interrupters
  - cathodic arc deposition of thin films and thick coatings (filtered and unfiltered): decorative, corrosion and wear resistant, hard
  - ultrathin ta-C films for storage industry
- Unwanted:
  - HV insulation,
  - SFR cavities
  - sputtering magnetrons
  - discharge lamps
  - Walls of Fusion Reactors



Macroscopic, time-integrated view on cathode spots
Photo courtesy of MultiArc, Inc.

Properties of Cathodic Arc Plasmas

- Plasma expands from near solid state density (10^{27} m^{-3}) in the cathode spot to very rarified plasma far from spot (e.g. down to 10^{14} m^{-3});
- at "large" distances from spot: plasma is in non-equilibrium
- *Jüttner's formula*: in absence of magnetic field and for r > 100 μm $$n \approx \gamma\, I_{arc} / r^2$$
- For copper cathode: $\gamma \approx 10^{13}\ \mathrm{A^{-1} m^{-1}}$
- electron temperature near spot 2-4 eV
- plasma expansion velocity $v_i \approx 0.8 - 2.2 \times 10^4\ \mathrm{m/s}$
- average ion charge state for most metals ~ 2
- ion charge state near spots is even higher
- Electron current > arc current (this is not a typo!)
- for details see book "Cathodic Arcs" (Springer, NY 2008)



Electron Emission Mechanisms

- Physics problem: Current transfer between solid electrodes *in vacuum*
- Nature's solution: Electron emission + plasma generation
- "*collective*" electron emissions:
  - Thermionic emission
  - Field emission
  - Thermo-field emission
  - Explosive emission

arc discharge

thermionic arc

cathodic arc

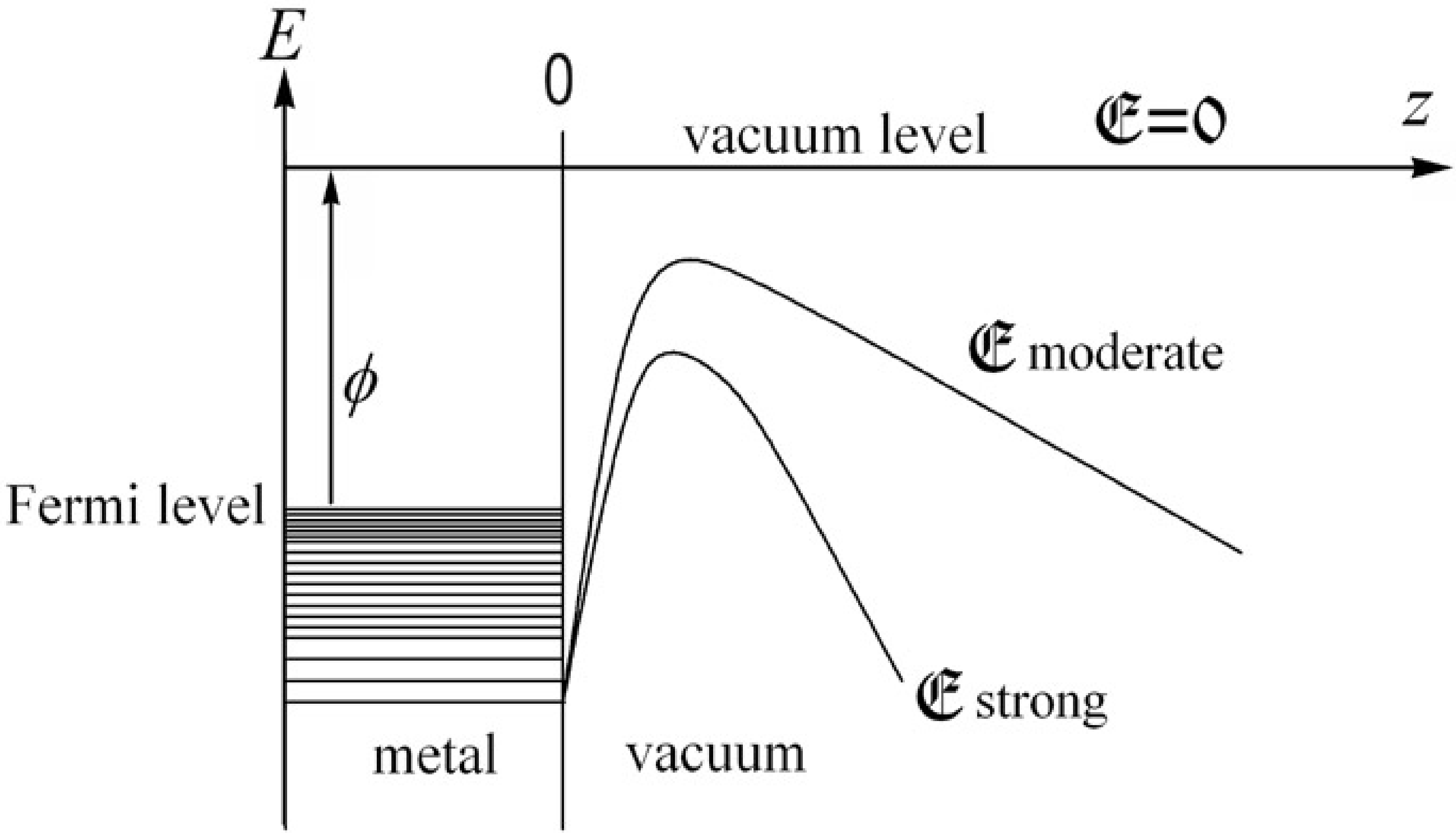
As opposed to "*individual*" e-emission mechanisms:

- Secondary electron emission by primary ion, electron, or excited atom impact
- Photo-emission

glow discharge

Arc Discharge

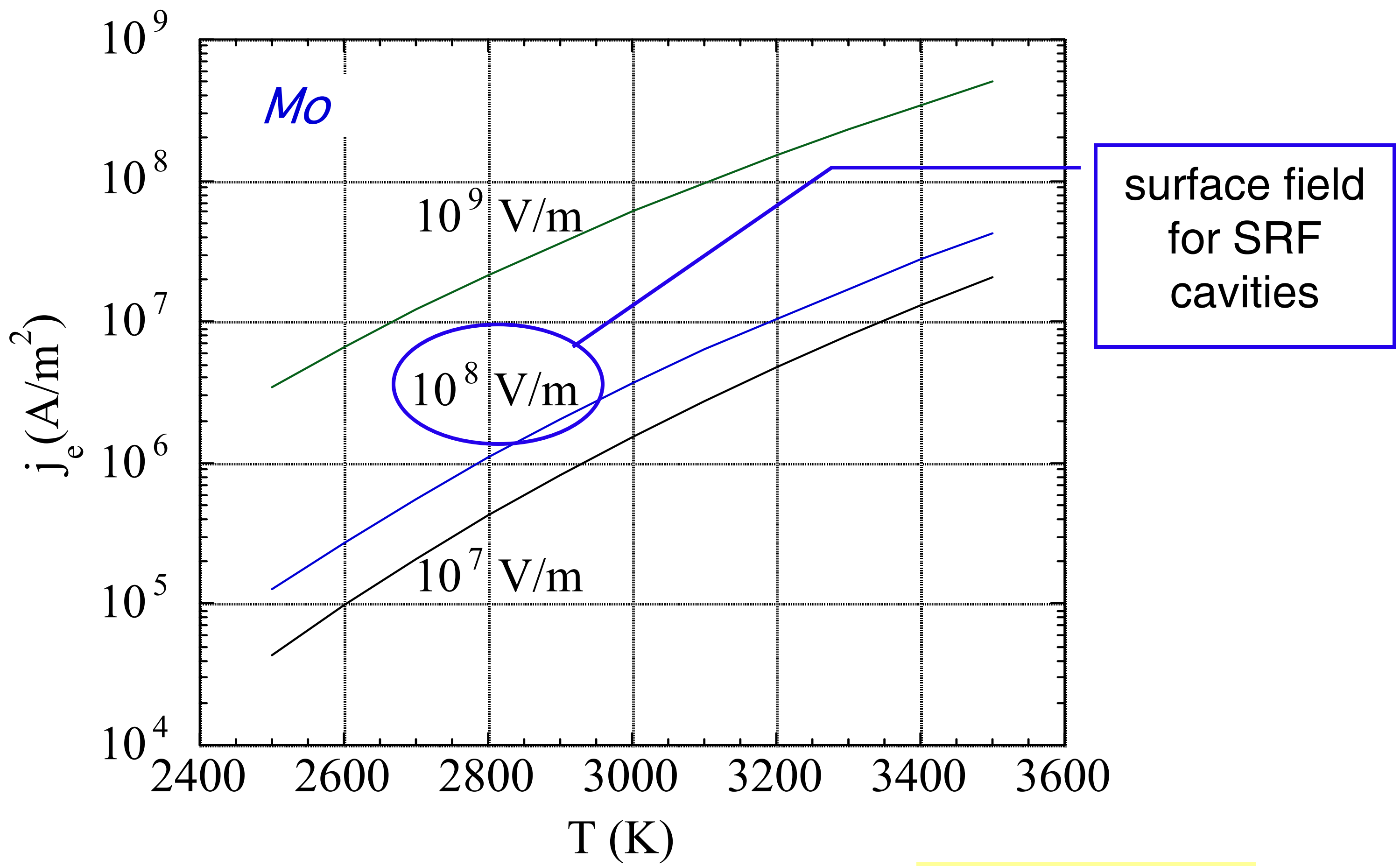
Work Function, Schottky Effect, Tunneling



Thermofield Electron Emission

- Current density of thermofield emission is necessarily associated with great power density → plasma formation can become explosive on ns time scale

log scale



linear scale

Arc Spot Ignition: The current paradigm

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

High electric field, enhanced by

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

↓

1. higher field leads to locally greater e-emission
2. Joule heat enhances temperature of emission site
3. higher temperature amplifies local e-emission non-linearly

positive feedback!

- Thermal Runaway creates highly localized, dense plasma
- consequences:
  - ion bombardment of surrounding cathode area
  - non-uniform cathode sheath with non-uniform surface field

Highly Localized Plasma Formation: Cathode Spots

- high resolution SEM shows clearly the violent, non-stationary nature of spot processes
- plasma is NOT produced by sputtering or evaporation but by phase transition from solid to dense plasma

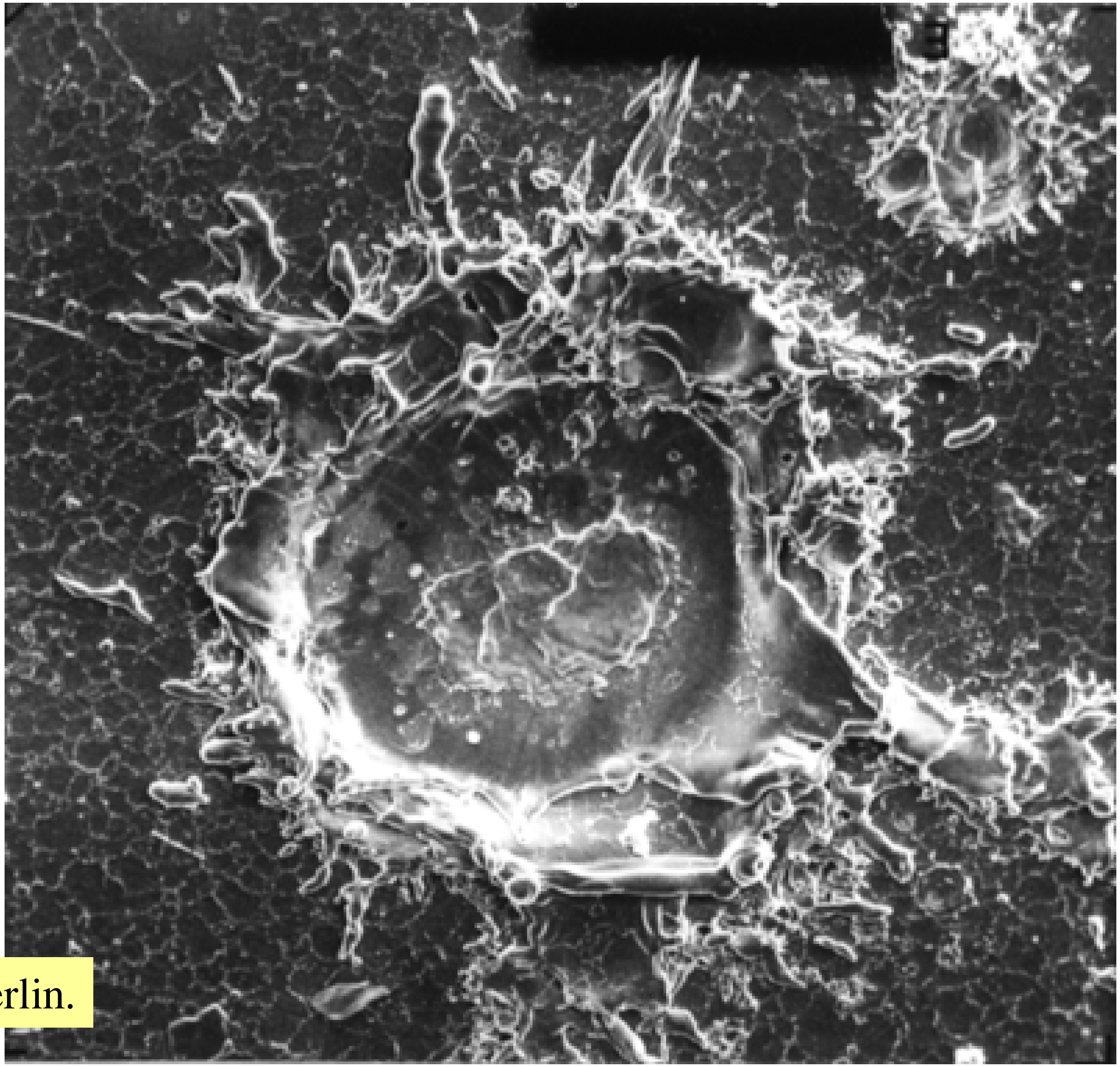
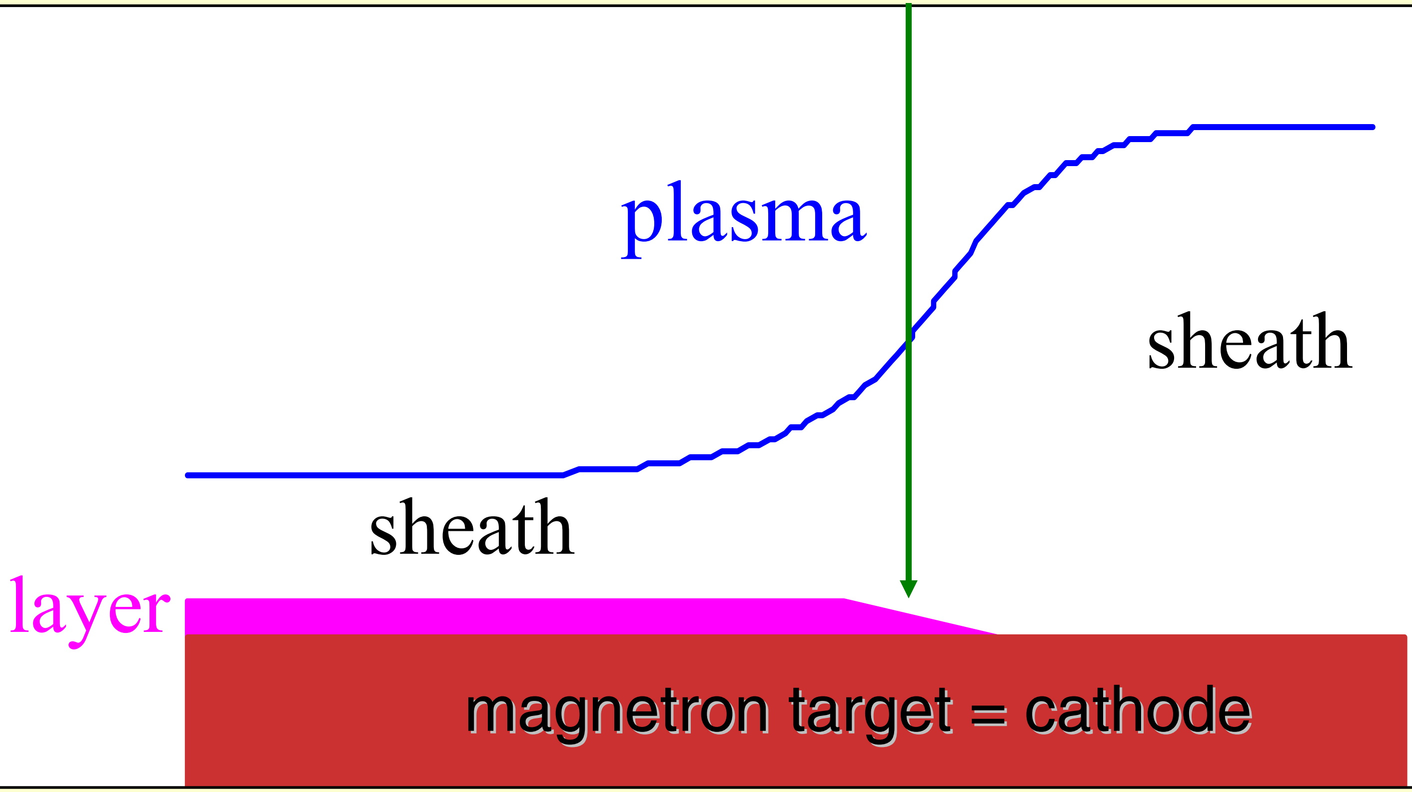


Figure: Courtesy of B. Jüttner, Berlin.

A related problem: Arcing in Sputtering Magnetron

here is the highest field strength, breakdown for $E > 0.5$ V/nm



→ Model needs at least 2 spatial dimensions

A. Anders, "Physics of arcing, and implications to sputter deposition," Thin Solid Films 502 (2006) 22-28.

Preferred Spot Ignition Area

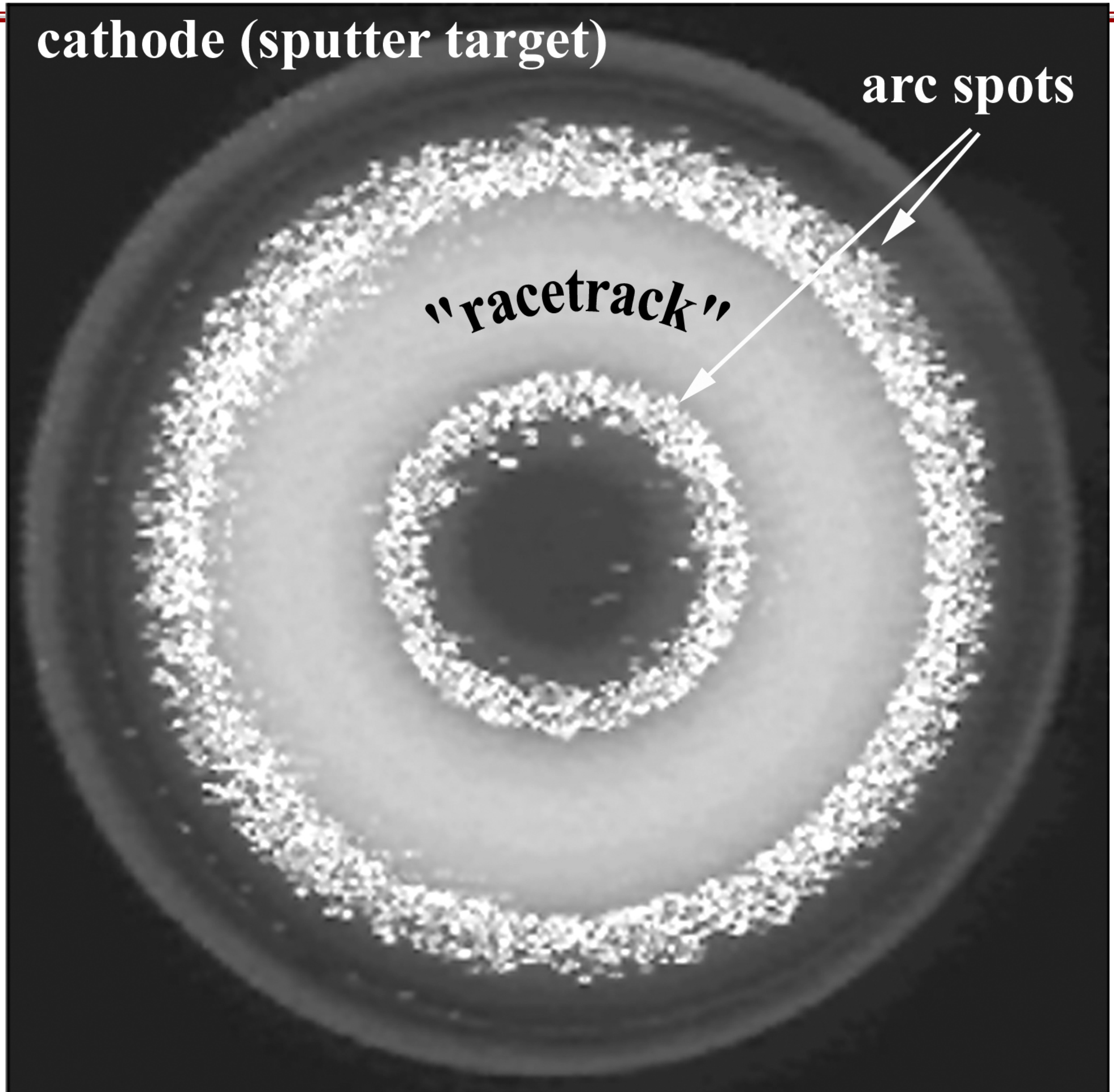
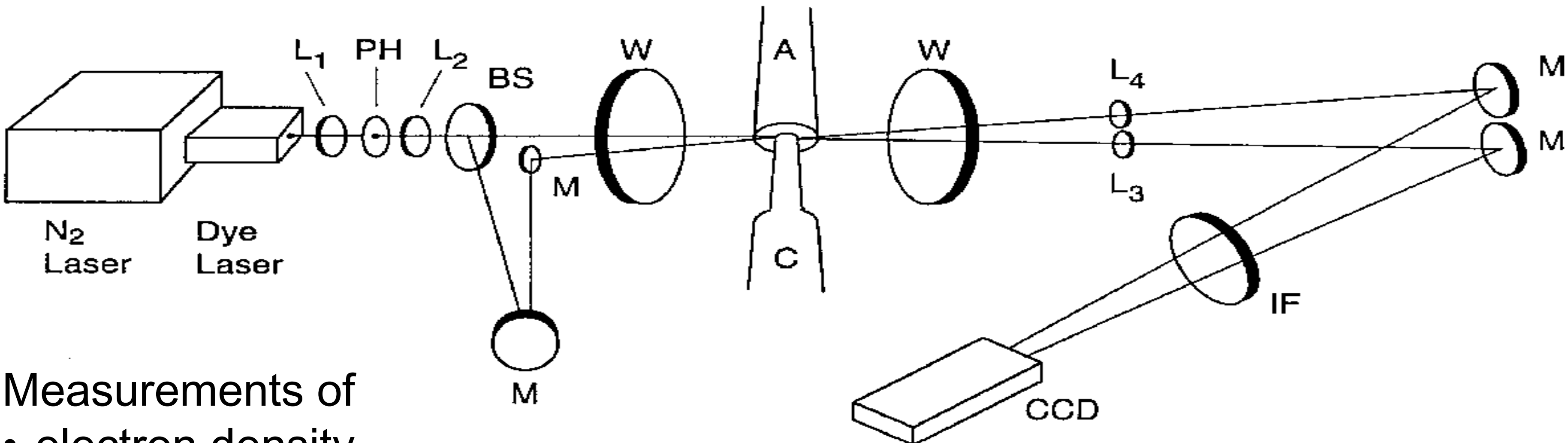


Photo courtesy of Prof. R. De Gryse, Ghent

Laser Plasma Diagnostics of Cathode Spots

Differential Laser Absorption Photography and Spectrometry



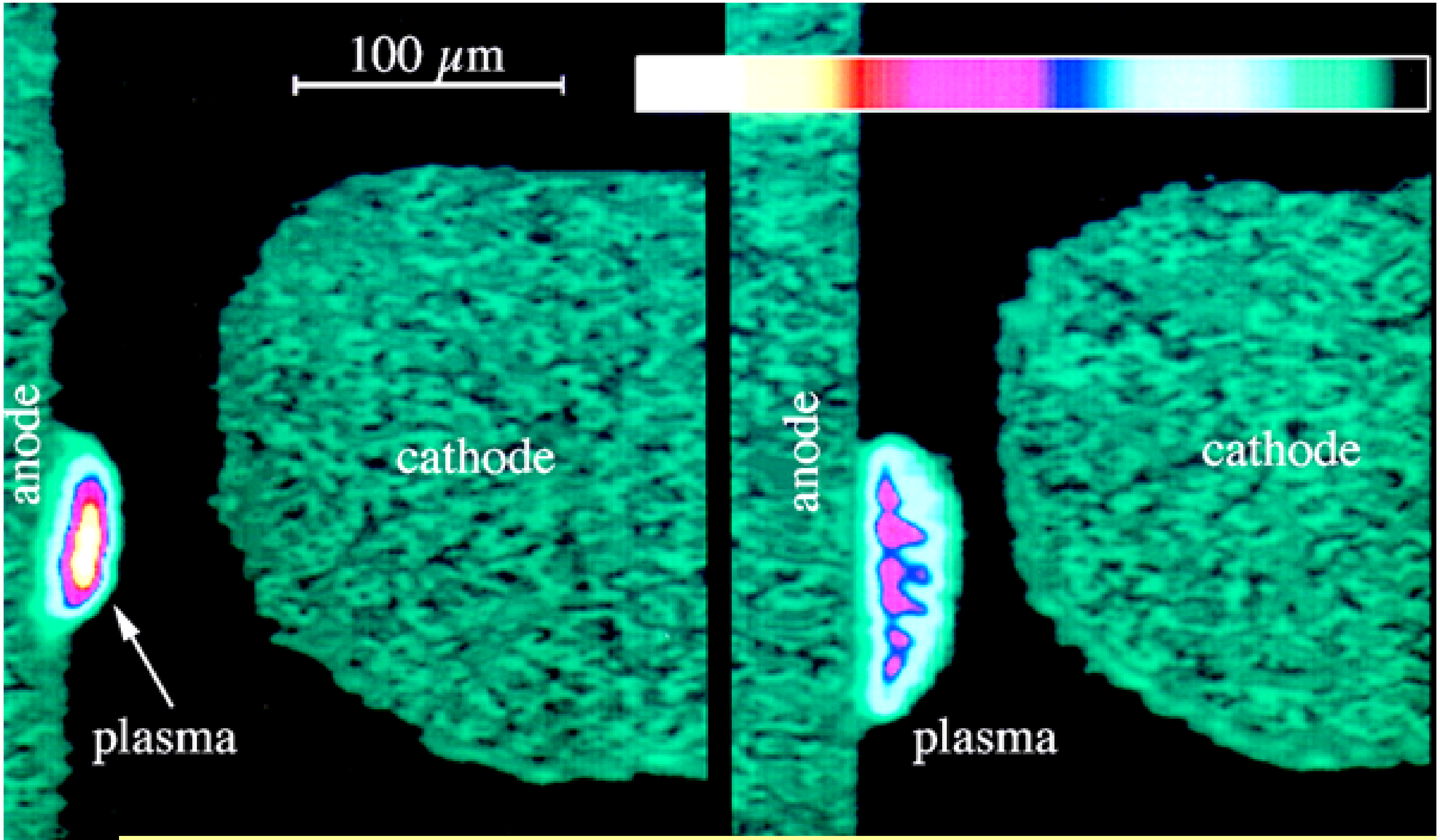
Measurements of
- electron density
- temporal development

With consequences for
- Current density
- Understanding of plasma formation

A. Anders, *et al.*, IEEE Trans. Plasma Sci. **20** (1992) 466.
A. Batrakov, *et al.*, IEEE Trans. Plasma Sci. 31 (2003) 817.

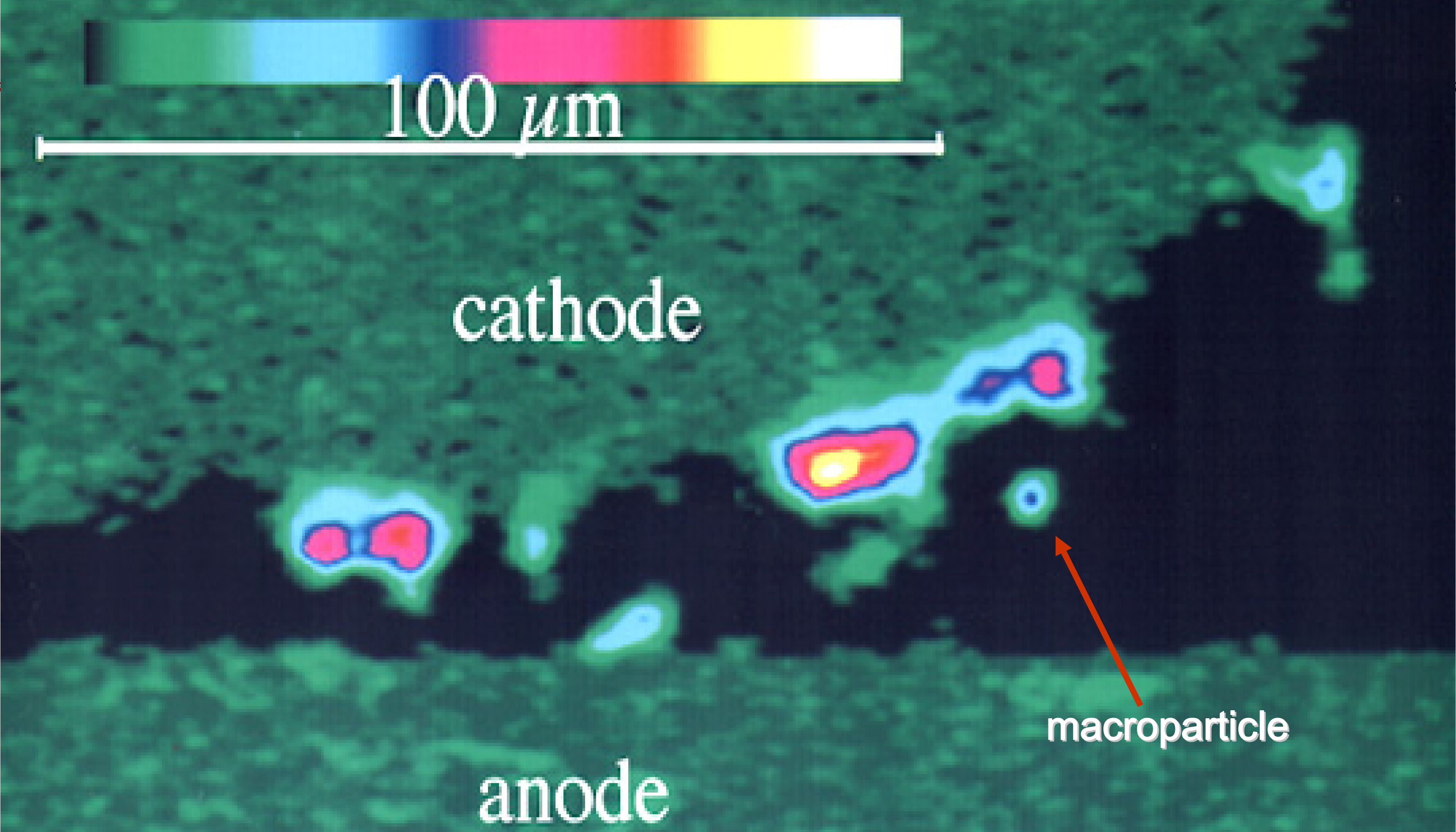
Observation of Small Gap Vacuum Breakdown

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



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

Spot & Spot Fragment Formation

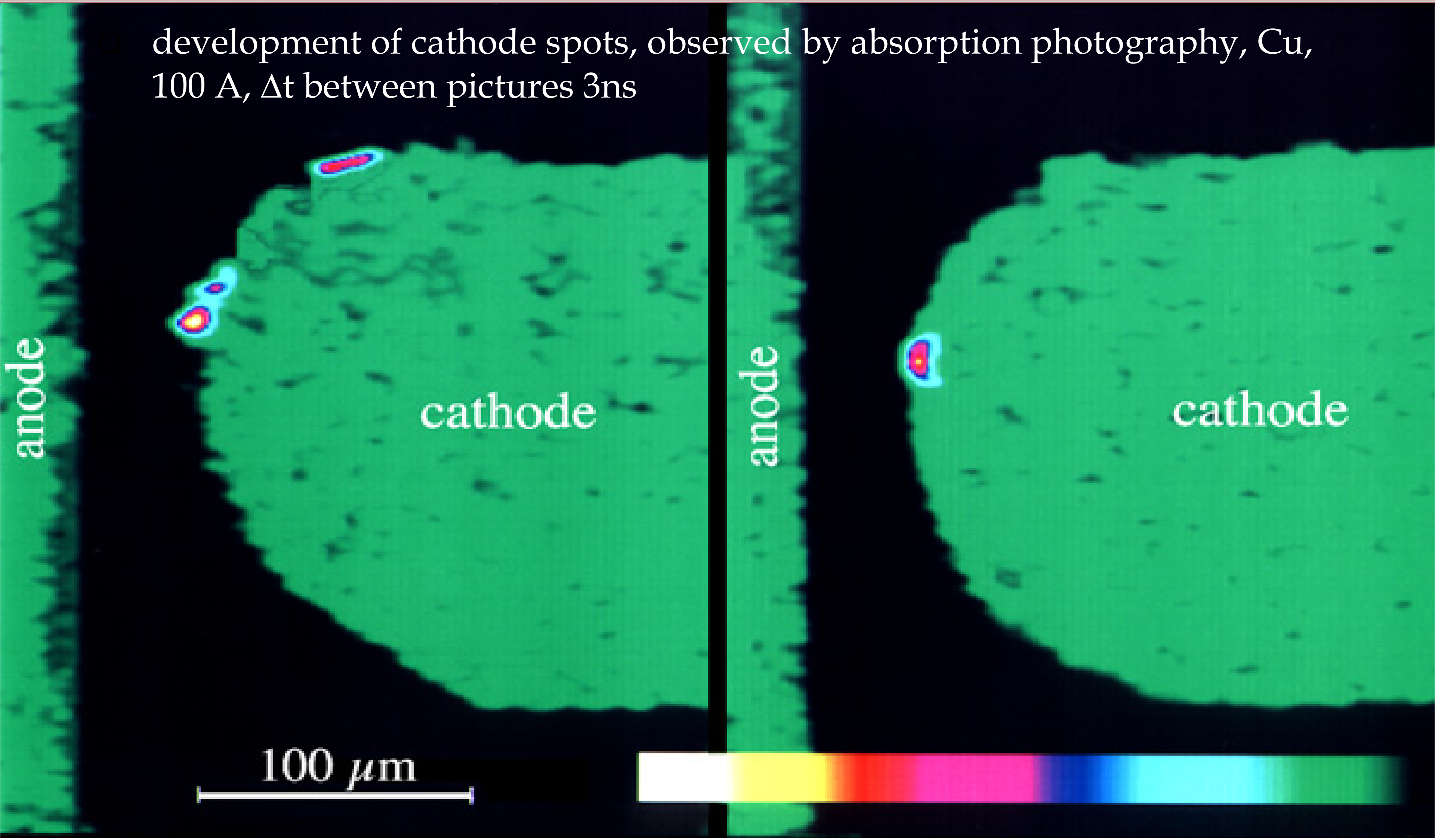


Absorption photography, copper cathode, UHV conditions, arc current 90 A, 232 ns after ignition, exposure time 0.4 ns

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

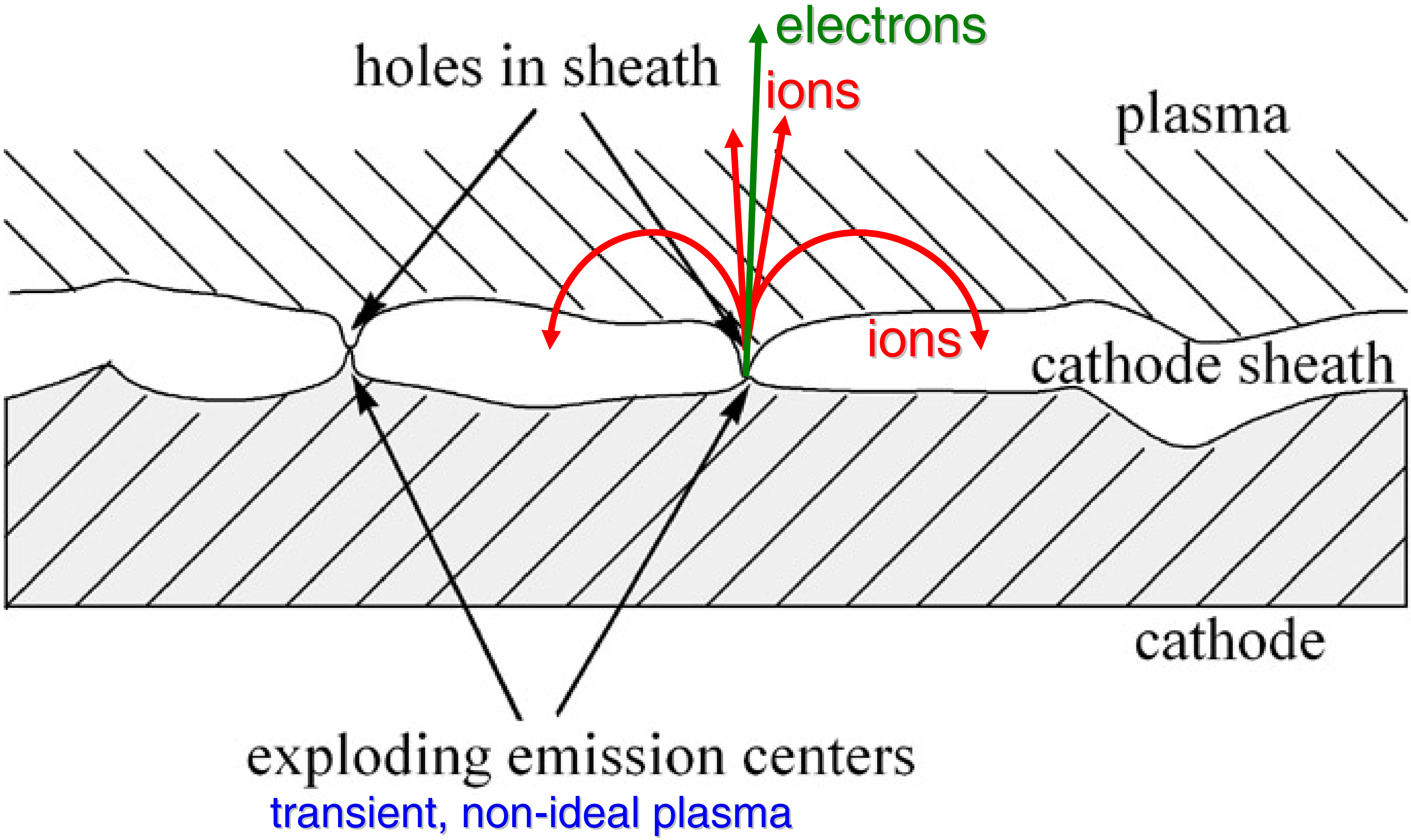
Cathode Spot Dynamics

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



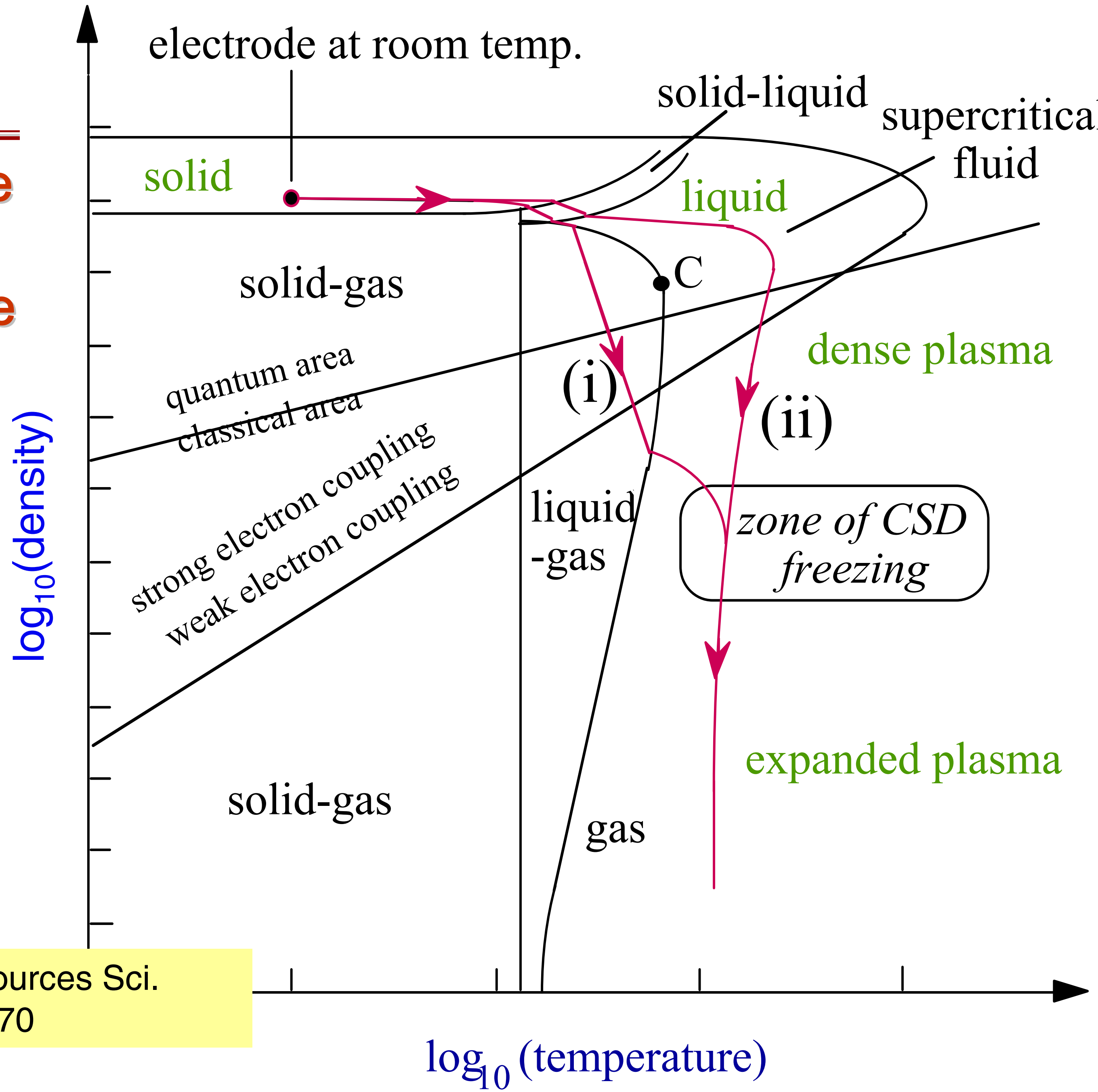
A. Anders, *et al.*, IEEE Trans. Plasma Sci. **20** (1992) 466-472

Highly non-uniform, non-stationary emission



→ electron and ion emission currents at emission centers > measured net currents

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



Anders *et al.*, Plasma Sources Sci. Technol. **1** (1992) 263-270

Cohesive Energy Rule

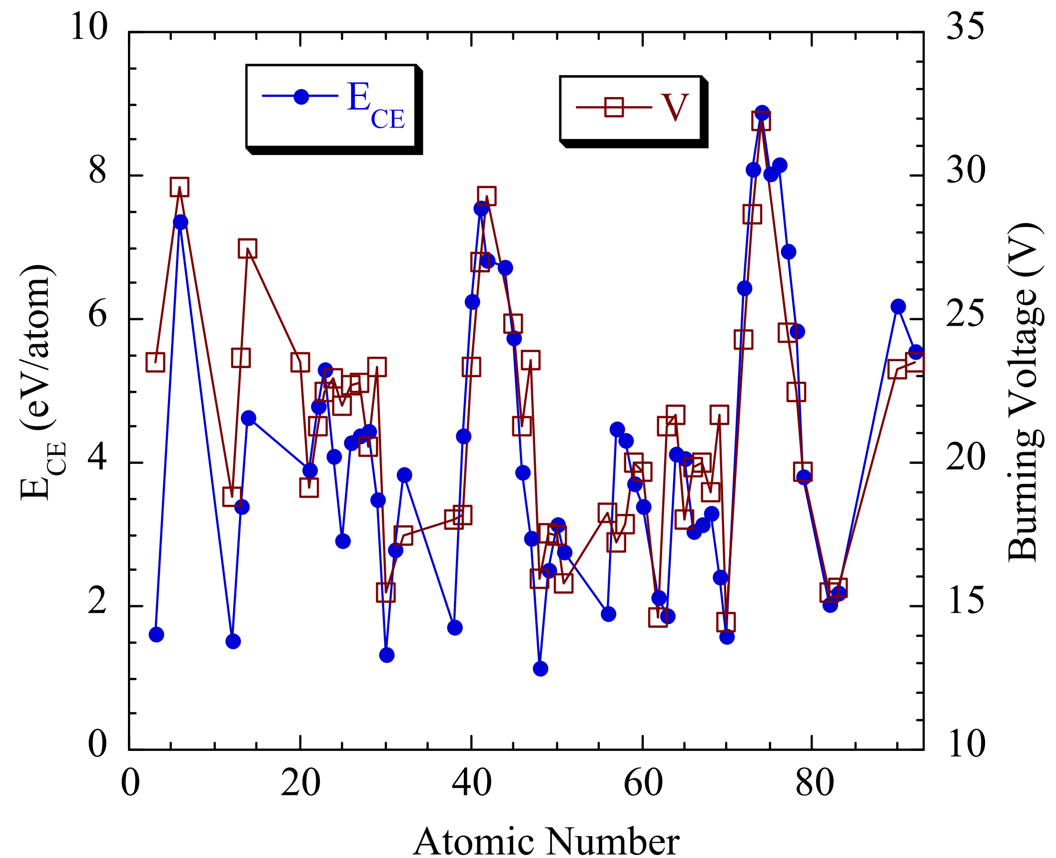
cohesive energy = energy needed to free an atom from the solid

From energy balance considerations:

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

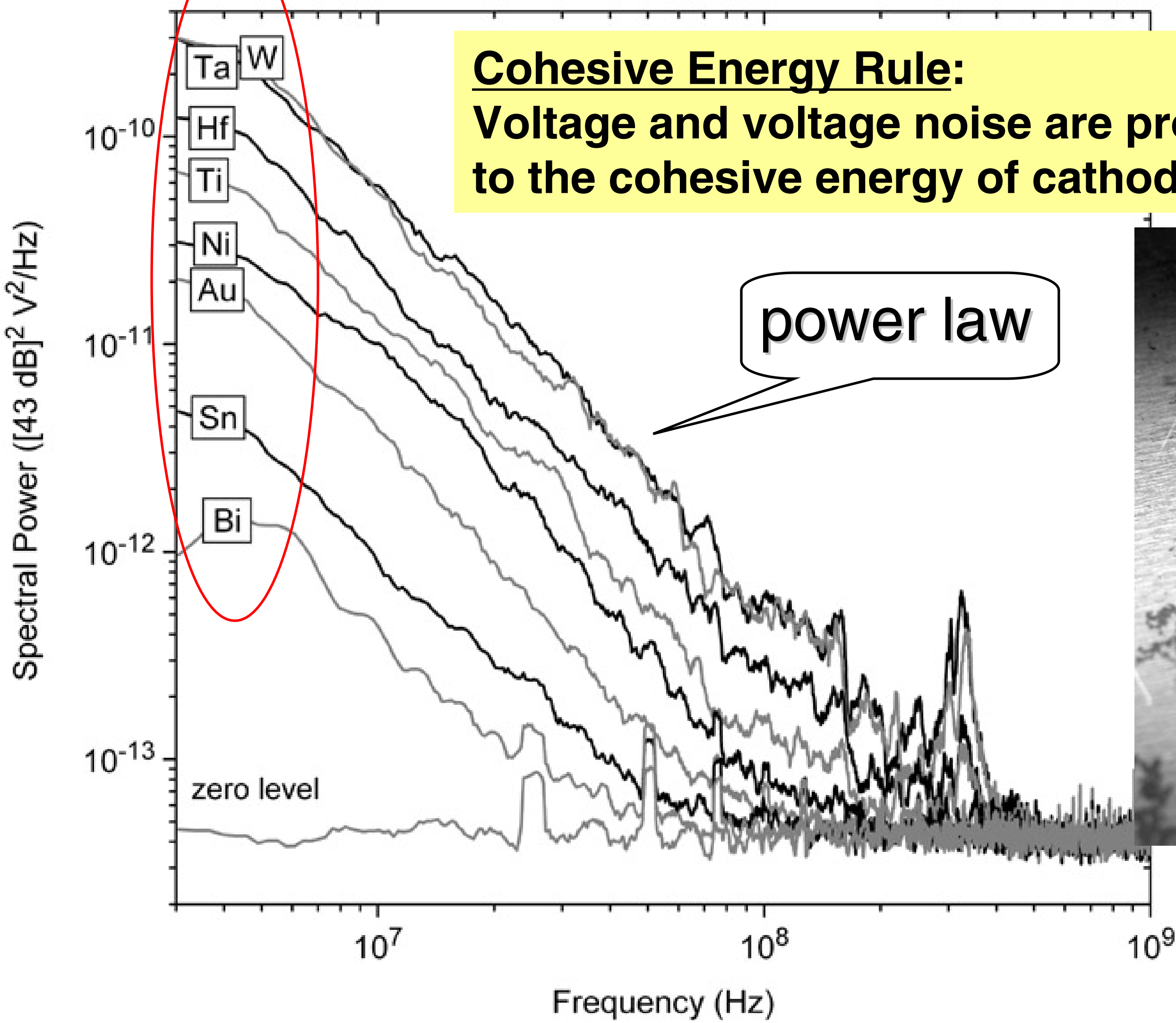
$$V = 14.3\text{ V} + 1.69\frac{\text{eV}}{\text{V}} E_{CE}\,[\text{eV}]$$

for 300 A vacuum arcs

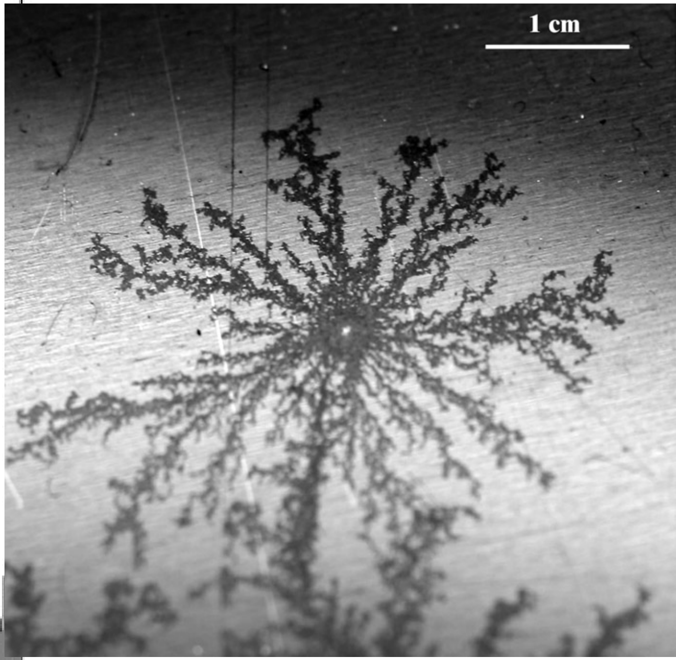


A. Anders, *et al*, J. Appl. Phys. 89 (2001) 7764; A. Anders "Cathodic Arcs" Springer, NY 2008

Fractal Nature of Cathode Spots

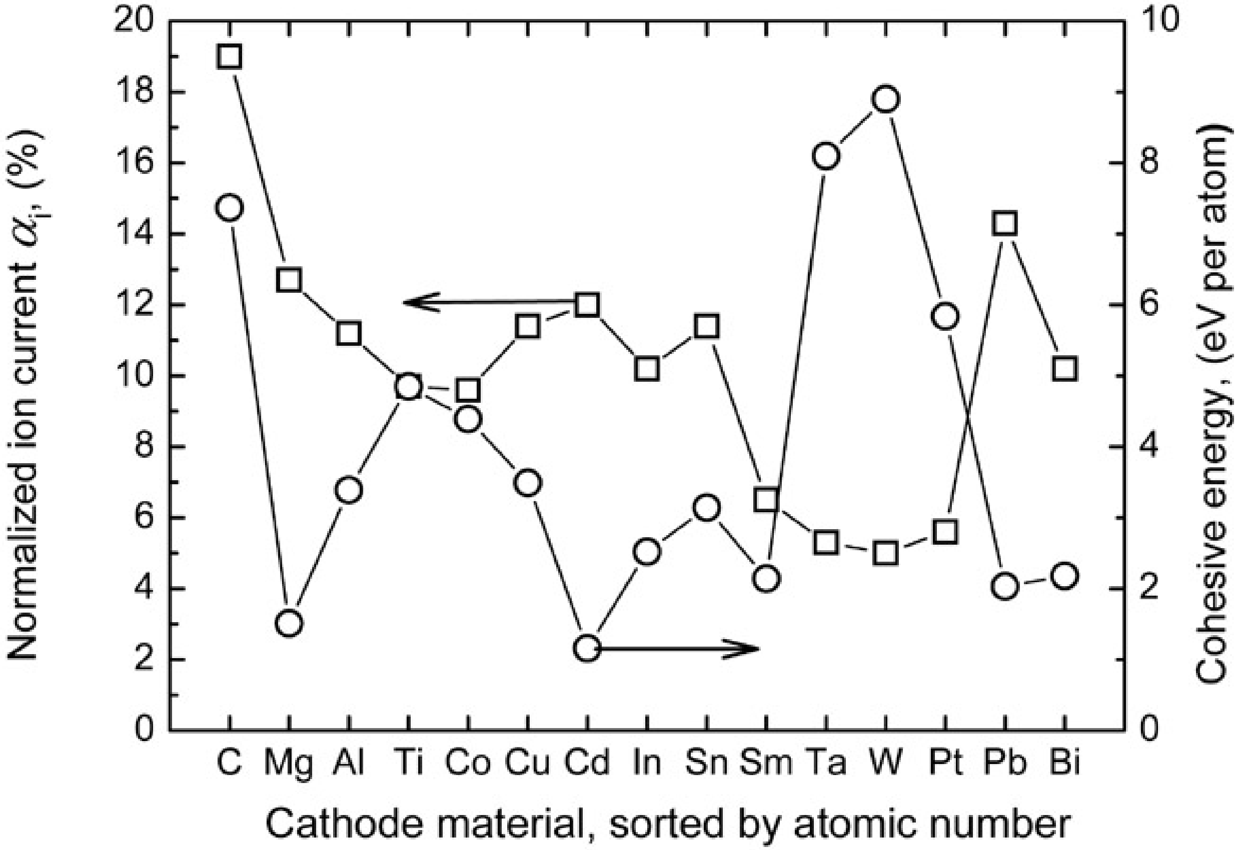


Cohesive Energy Rule:
Voltage and voltage noise are proportional to the cohesive energy of cathode material



A. Anders, et al., APL 86 (2005) 211503; J. Rosén, A. Anders, J. Phys. D 38 (2005) 4184.

Cohesive Energy Rule and Ion Erosion Rate

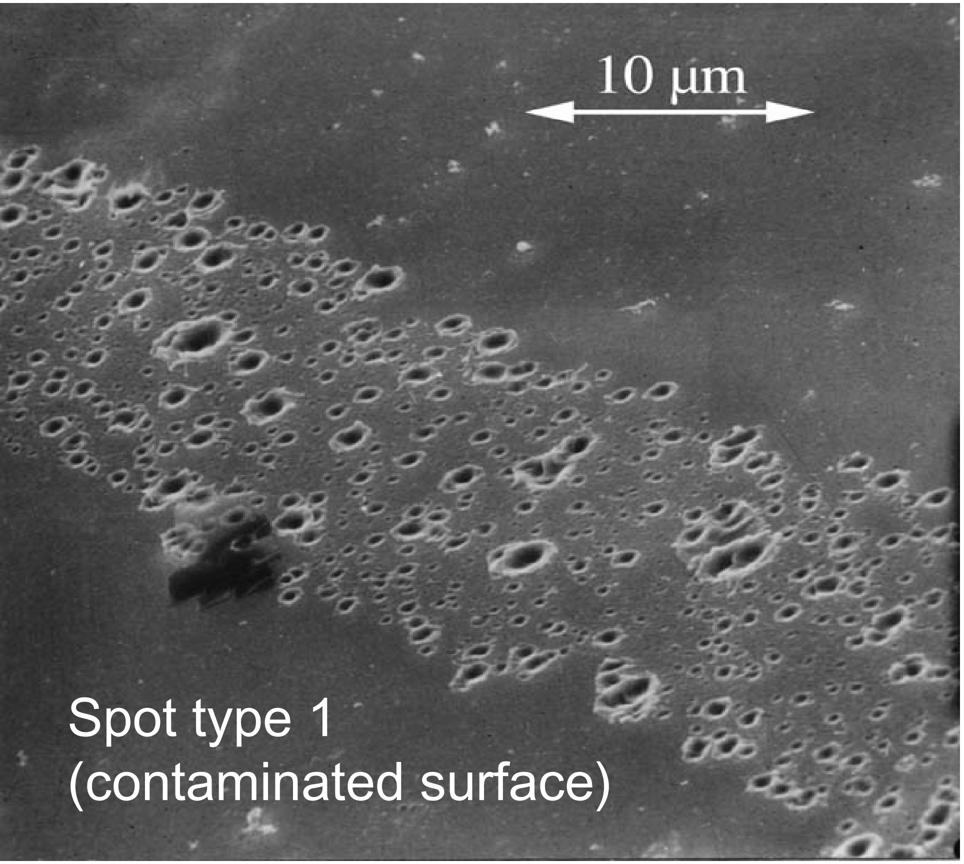


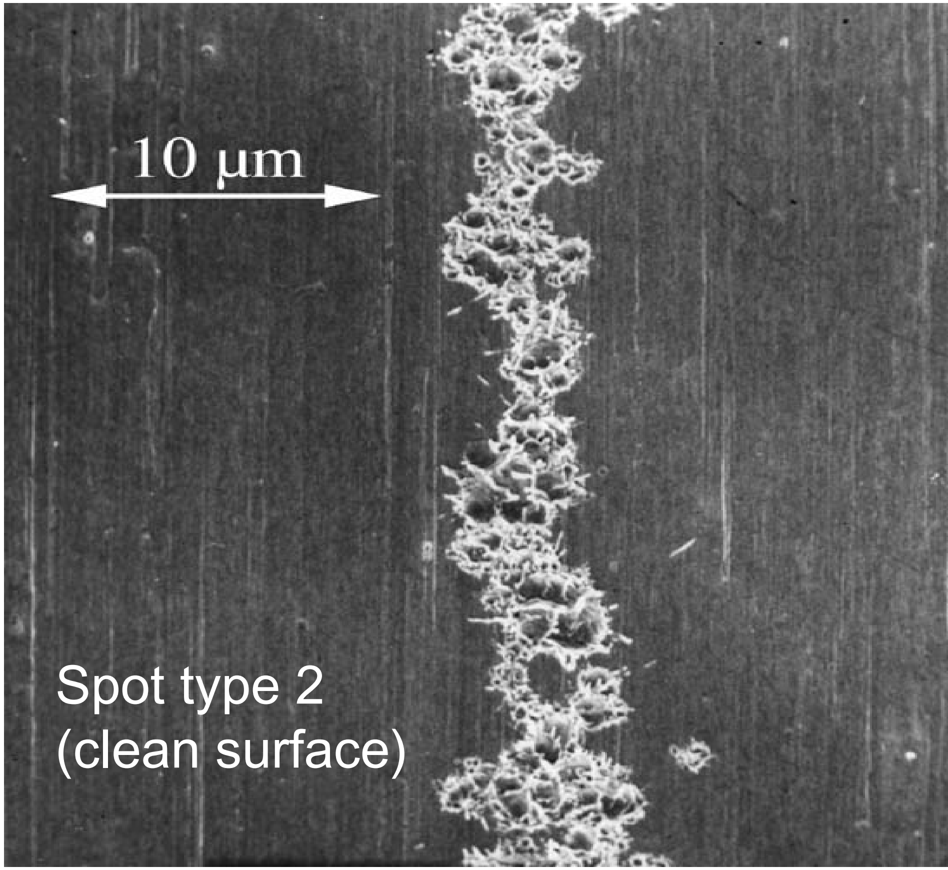
… and other consequences like mean ion charge state ~ E_{CE}

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

Surface Dependence of Ignition of Emission Centers

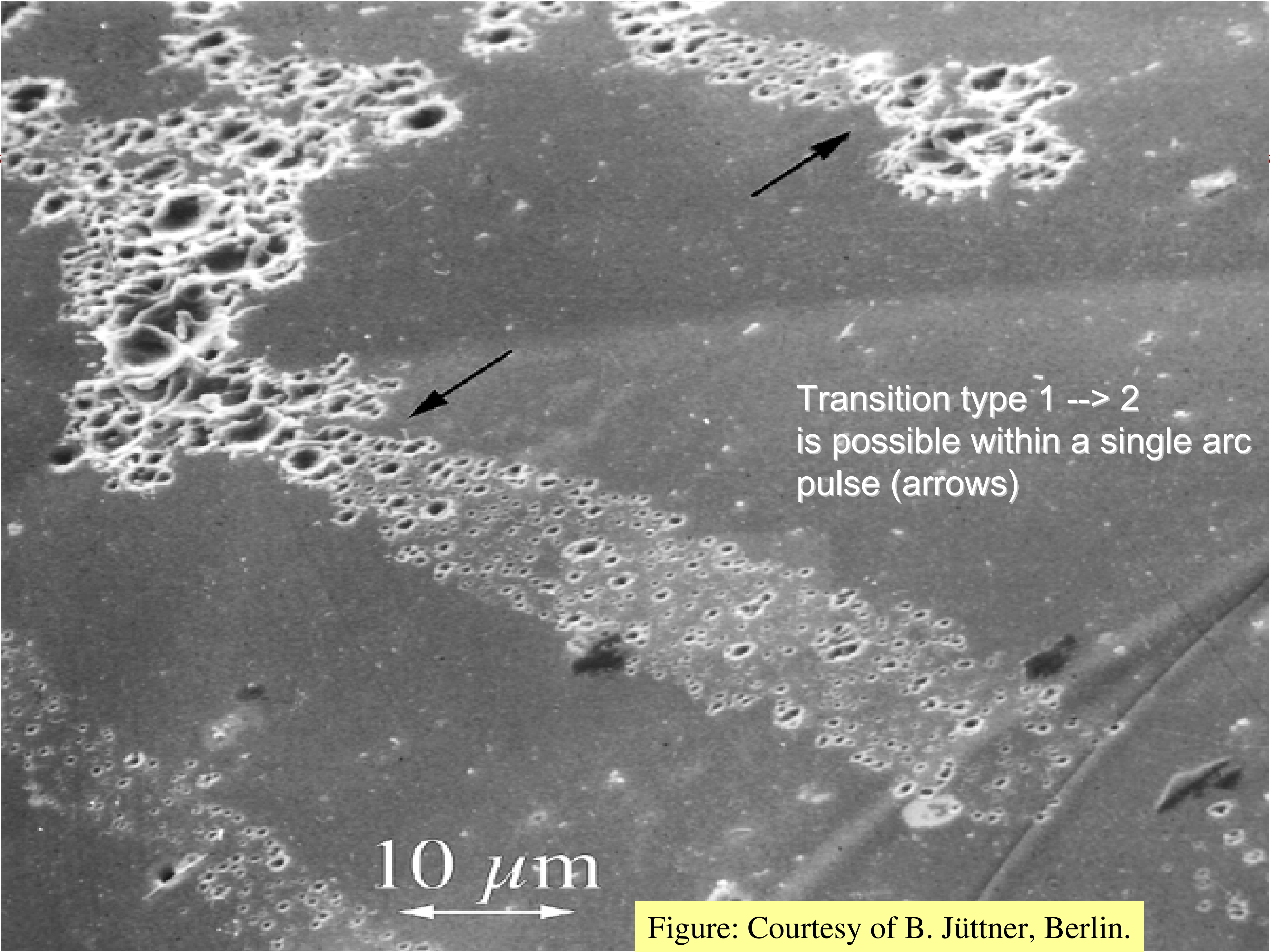
Examples of spot motion (crater traces) in magnetic field:





proves the importance of non-metallic surface layer for emission center ignition & arc operation

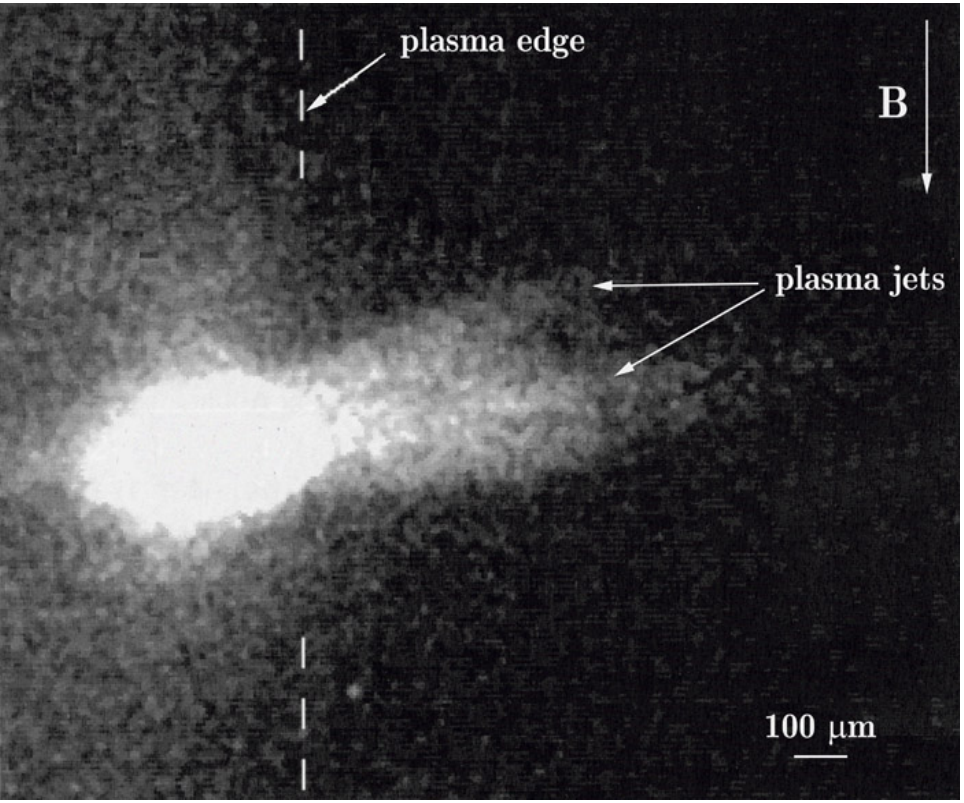
Figures courtesy of B. Jüttner, Berlin.

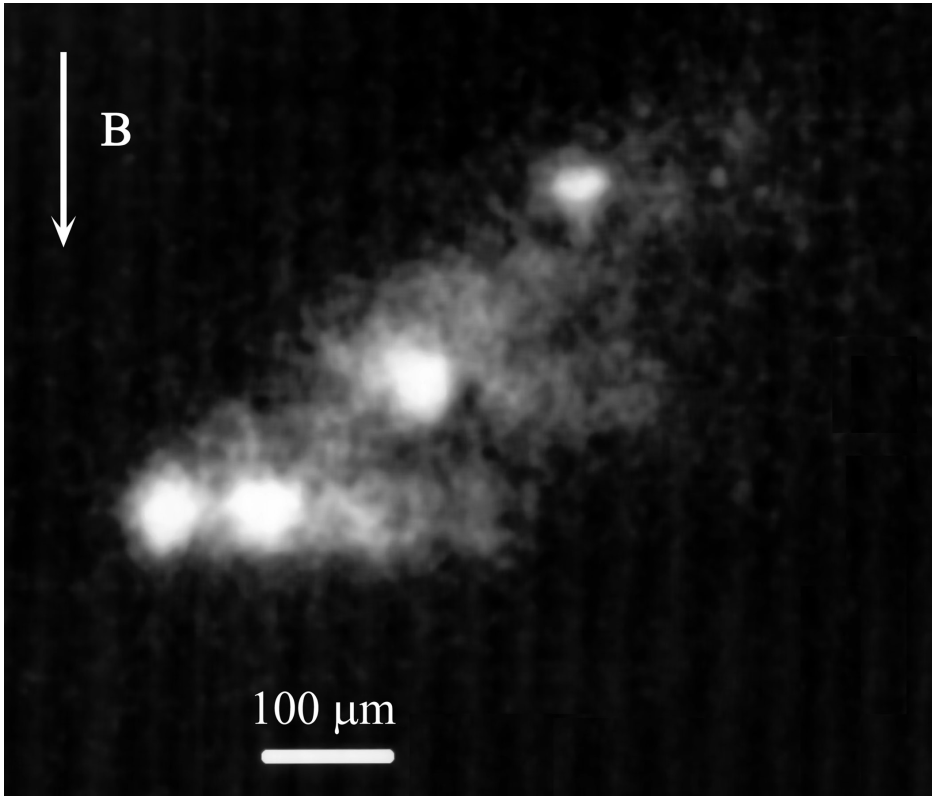


Transition type 1 --> 2
is possible within a single arc
pulse (arrows)

Figure: Courtesy of B. Jüttner, Berlin.

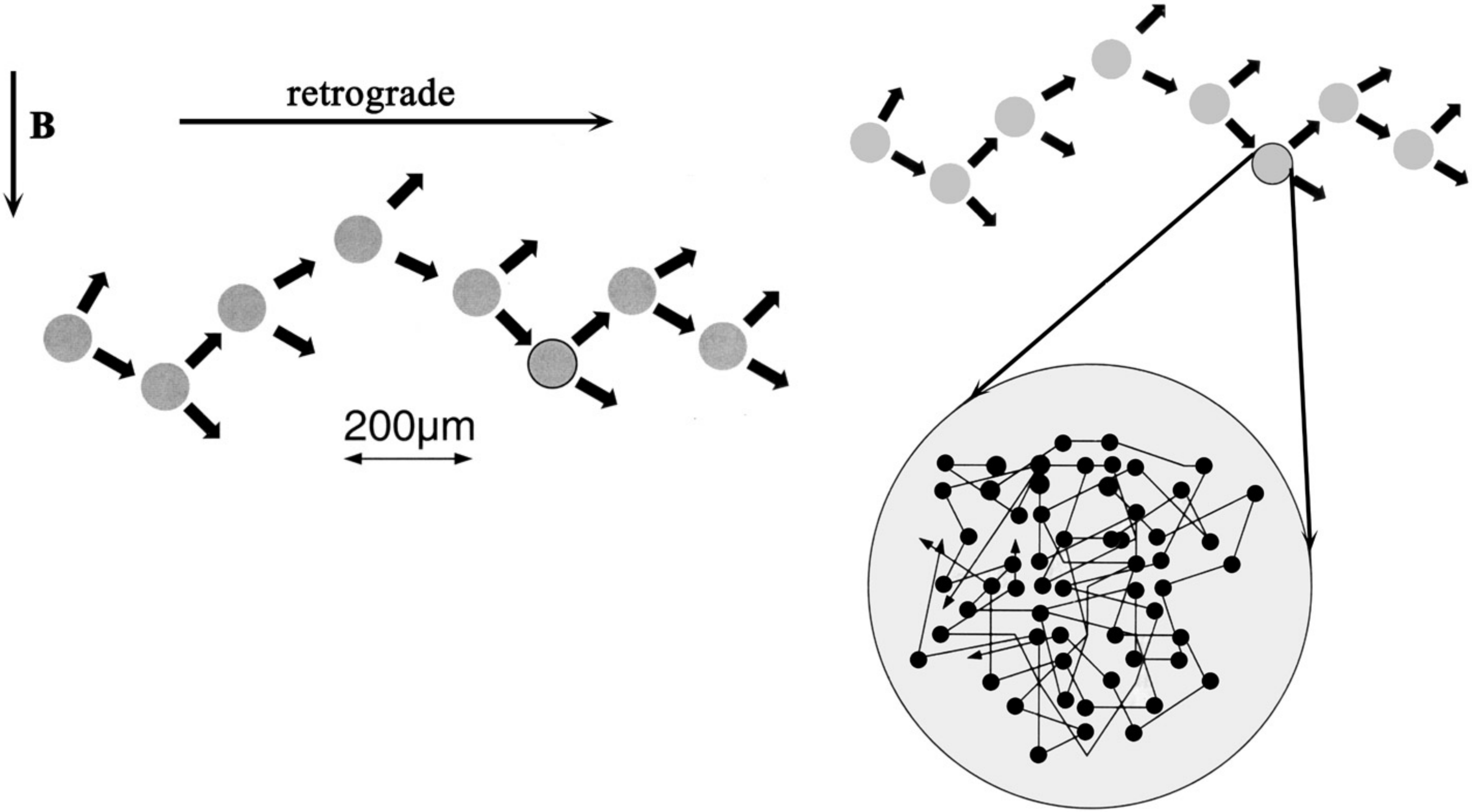
Apparent Motion of Emission Centers





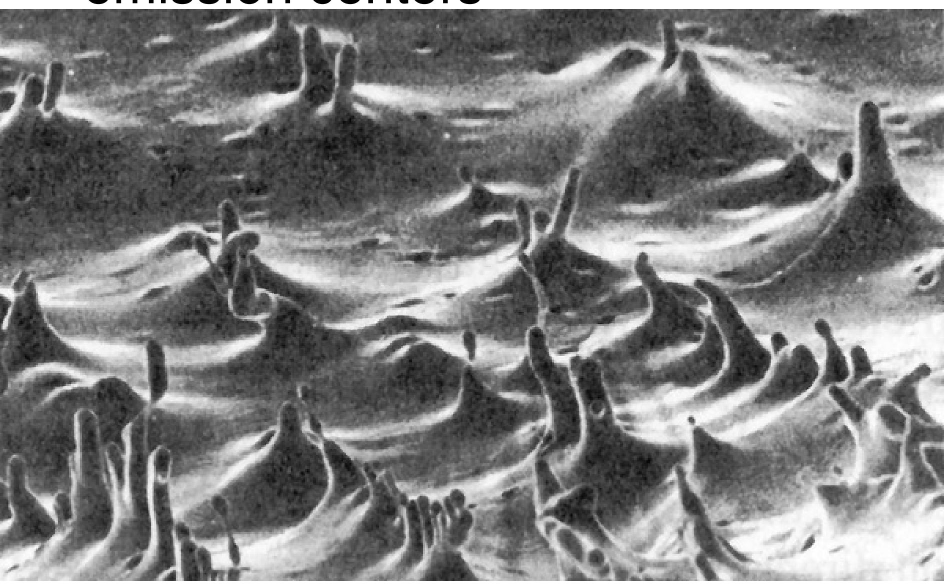
B. Jüttner, I. Kleberg, J Phys. D: Appl. Phys. 33 (2000) 2025.

Jüttner-Kleberg Model



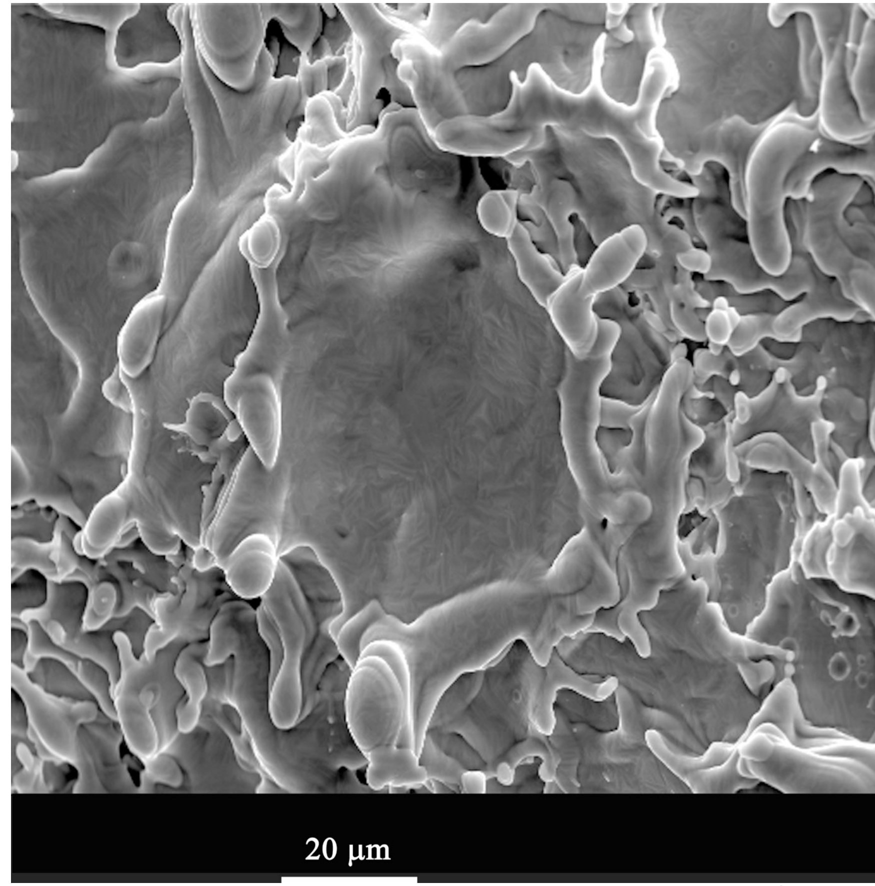
Erosion reduces and creates roughness

- erosion is used to condition electrodes, thereby increasing breakdown voltage, however:
- emission centers also produce roughness, potentially new emission centers



Field-stimulated non-linear waves

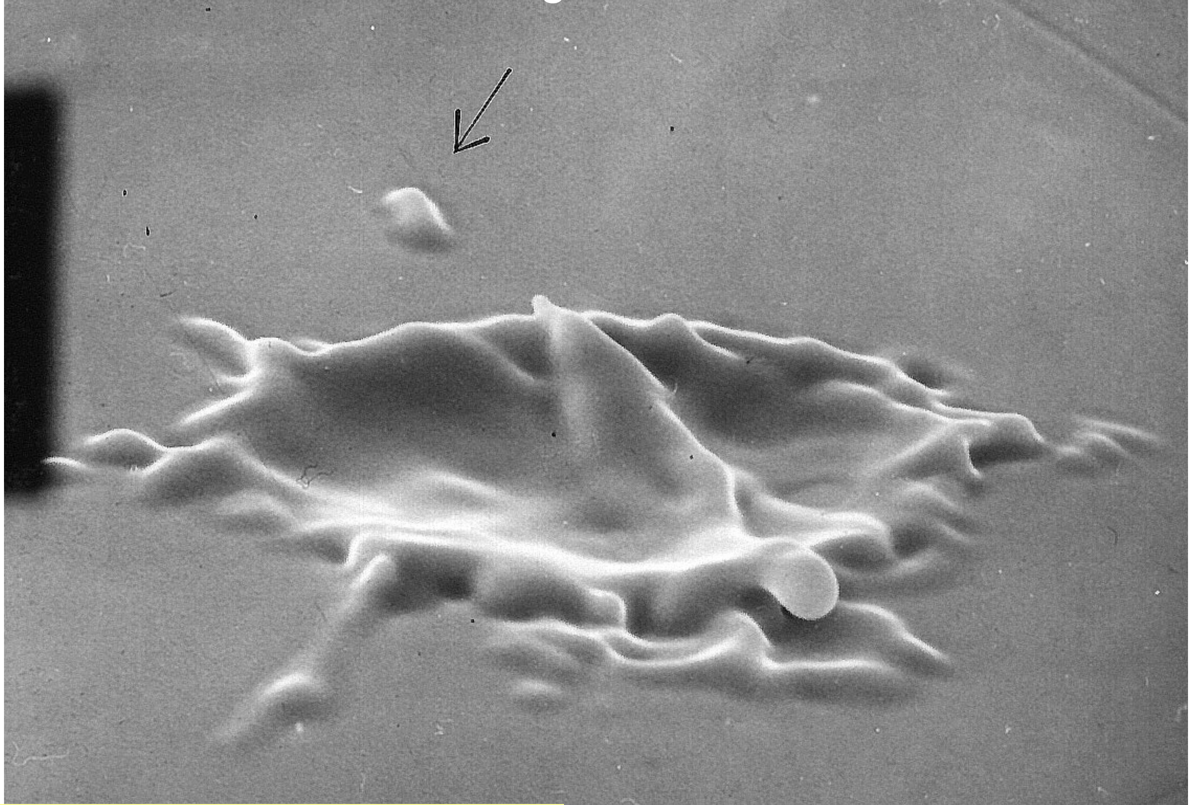
M.D. Gabovich, V.Y. Poritskii, JETP Lett. 33 (1981) 304.

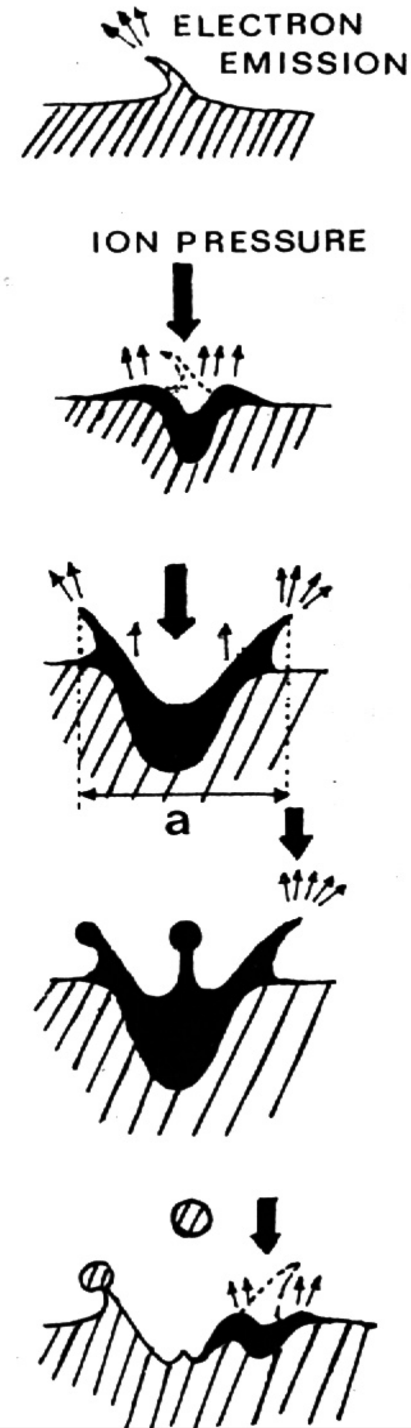


arc traces indicate a response of liquid cathode matter to high pressure

Macroparticle Generation

- Macroparticles are formed as part of the explosive plasma formation
- Materials is ejected from the liquid pool between plasma and solid
- Picture: 10 ns discharge on Mo





Figures courtesy of B. Jüttner, Berlin.

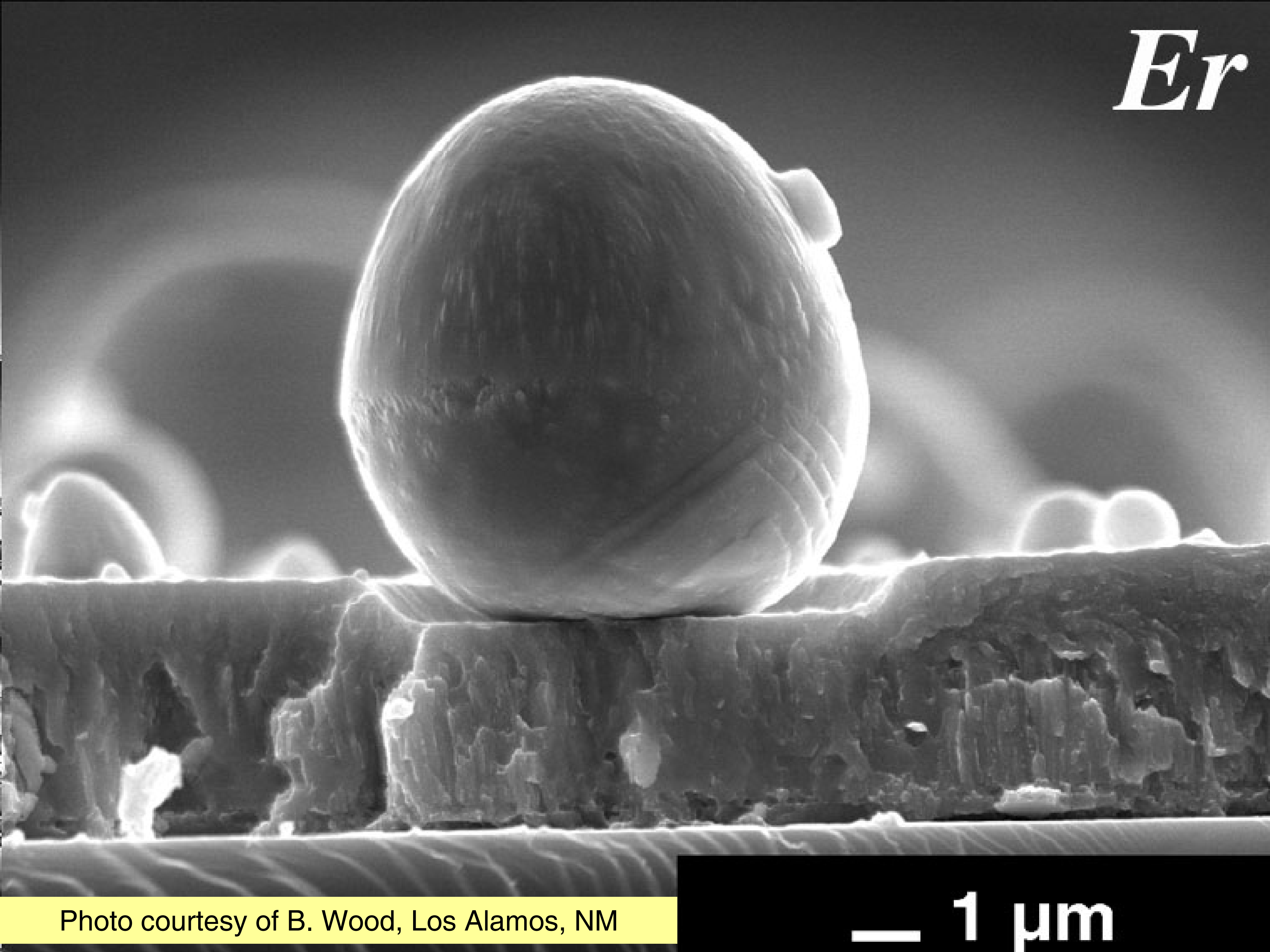


Photo courtesy of B. Wood, Los Alamos, NM

Summary and Conclusions

- Cathodic Arcs are initiated and perpetually maintained by local field enhancement and runaway process
- ignition probability and plasma properties greatly depend on cathode surface conditions
- plasma formed is highly nonstationary, goes through a transient non-ideal phase
- high pressure gradients are main drivers for ion acceleration
- charge states at cathode spots higher than measured far away
- local currents greater than net currents measured
- hypothesis: cathodic arcs and unipolar arcs are essentially the same, though the latter has no net current and needs high sheath voltage