

Room Temperature rf
High Gradients: Physics, rf design and Technology
When Maxwell's equations just aren't enough

Part II: Deeper into the Physical Processes of Breakdown

Before we try to understand breakdown in an rf cavity, we will look in depth into the physics of breakdown – a spark if you will.

I will start by introducing the overall multi-step and **multi-scale** picture of breakdown, the big picture – *this will be shocking*.

Then we cover the individual steps in more detail all the while looking back at the big picture.

This chapter will primarily refer to dc sparks. This is partly because we can understand a simple system better and partly because most of the detailed work on breakdown is for dc. *Almost everything presented in this section applies to rf.*

The next section will then take those ideas and apply them in an rf cavity.

The big picture

Breakdown trigger

Charges collect at cathode non-uniformities under applied electric field [fs, nm]

Structure of surface modified under time/cycles [s, 10^7 pulses, nm]

Field (and thermionic) emission

Structure of surface modified under time/cycles [s, 10^7 pulses, nm]

Tensile electric stress [fs, nm]

Local joule heating [ns, μm]

Thermal stress

Avalanche starts

Field enhanced evaporation of neutrals

(from plasma feeding)

ionization electrons are accelerated away from cathode [mm]

Ionization

Plasma spot forms [few ns, 10-100's of μm]

Plasma dynamics

Plasma sheath forms [μm]

Plasma feeding process

Ions are accelerated towards cathode [μm]

Ions strike cathode and kick out neutrals, ions and electrons

enhanced electron emission due to sheath potential and temperature

surface melts due to ion bombardment [10-100's of μm]

Electron current accelerated in external field absorbs system energy [mm]

enhanced neutral emission, plasma feeding accelerates

(go to plasma dynamics)

Macroscopic energy transfer

Field emission

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Macroscopic energy transfer

Vacuum breakdowns, the kind relevant for rf cavities, start on the negatively charged electrode – the **cathode**.

The main physical effect on the cathode which drives the breakdown is **field emission**, electron currents which tunnel out of the surface due to the applied electric field, which we have already seen in dark current.

The field emission current flows through discrete locations on the surface called **emission sites**, the origin of which we will discuss later but they are very small.

The current heats the area around the emission site according to the same formulas we saw for pulsed surface heating – but current densities are much higher and we can easily go near the melting point of a metal surface.

Now we look in more detail at the physics of field emission.

Electron emission from a surface due to an applied electric field is described by the **Fowler-Nordheim** relation.

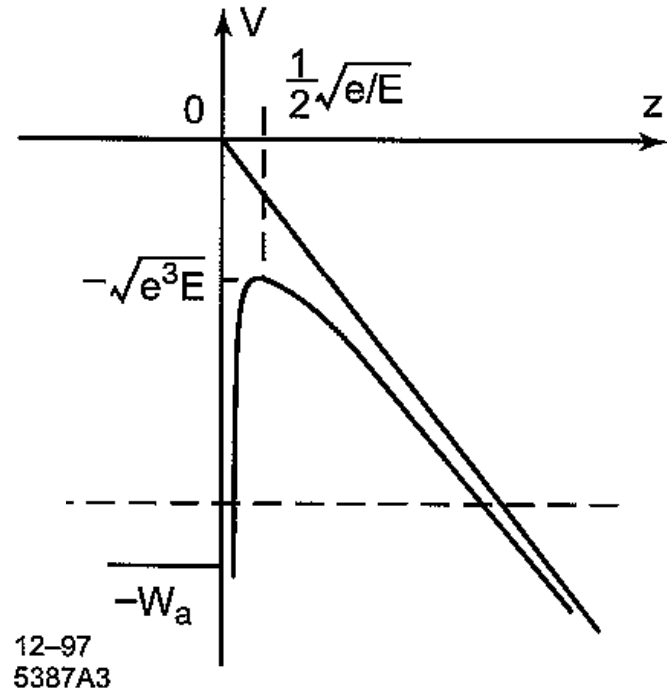
The basic physics contained in the equation describes the tunneling of electrons through the surface potential barrier.

The validity of the equation has been verified in nm-scale sharp tips such as those used in scanning tunneling microscopes for example

But correction factors must be applied to macroscopic metal surfaces because we see enhanced emission from surface non-uniformities. We'll return to this fact-of-life later.

The surface potential used for solving the Fowler-Nordheim equation

$$V(z) = \begin{cases} -W_a & \text{for } z < 0 \\ -eEz - e^2/4z & \text{for } z > 0 \end{cases}$$



The Fowler-Nordheim equation (approximate, practical form)

$$I = A_e \frac{1.54 \times 10^6 \beta^2 E^2}{\varphi} e^{10.41 \varphi^{-1/2}} \times e^{-6.53 \times 10^3 \times \varphi^{3/2} / \beta E}$$
$$= \xi E^2 e^{-6.53 \times 10^3 \varphi^{3/2} / \beta E}$$

Units: $[I]=\text{A}$, $[E]=\text{MV/m}$, $[A_e]=\text{m}^2$, $[\varphi]=\text{eV}$ and $[\beta]=\text{dimensionless}$

Values: $\varphi = 4.5 \text{ eV}$ for copper

Crazy little thing called β ...

If you measure emission from real, macroscopic metal surfaces – like you see in rf cavities and dc spark systems - you see that the Fowler Nordheim equation works perfectly except that you need to multiply the electric field by a factor typically of 30-100 to get the thing to fit.

This “minor” discrepancy is caused by the local surface non-uniformities I have referred to .

They are usually attributed to **dirt particles** or **microscopic tips** which give a **local electric field enhancement factor**.

But certain chemical contaminants and crystal dislocations can lower the **work function** and enhance field emission.

The Fowler-Nordheim equation

Analyzing real data

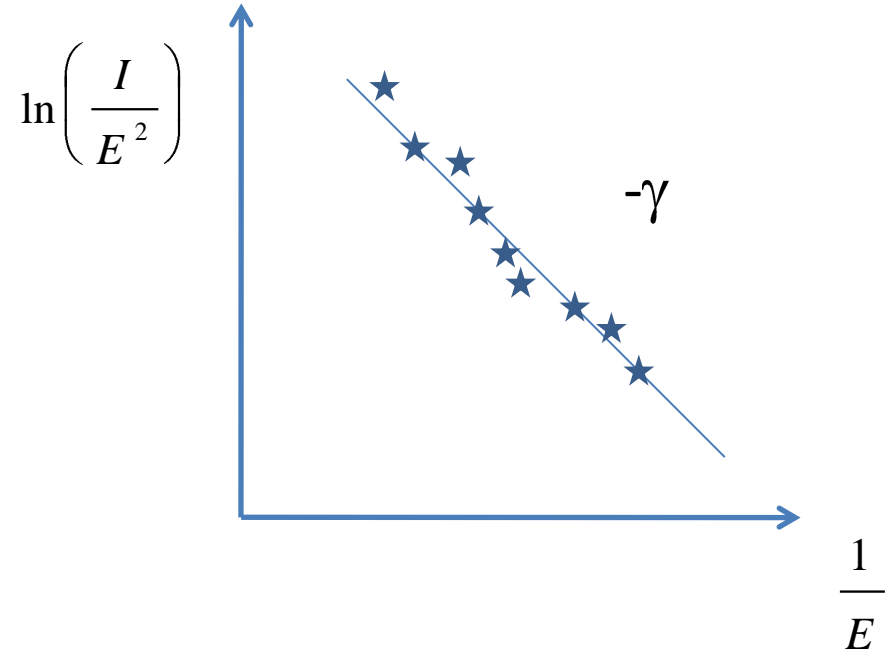
$$I = \xi E^2 e^{-\gamma/E}$$



$$\ln\left(\frac{I}{E^2}\right) = \ln \xi - \frac{\gamma}{E}$$

$$\beta = \frac{6.53 \times 10^3 \varphi^{3/2}}{\gamma}$$

$$\xi = A_e \frac{1.54 \cdot 10^6 \beta^2}{\varphi} \exp(10.41 \cdot \varphi^{-1/2})$$



You will have the opportunity to analyze a real set of data tonight for homework!

However high β features are rarely, if ever, observed independently of field emission.

Specifically the expected field enhancements samples are not predicted, from electron microscope images.

Part of the answer may be that the emission sites are small, nm size. In fact we get **nm scale** by fitting the FN equation in our dc spark tests assuming the origin are tips.

Why are we spending so much time on one box of the diagram?

The practical consequences of enhanced field emission are significant – we should be able to handle ≈ 10 GV/m surface fields but we can only manage ≈ 200 MV/m.

Also a large part of *conditioning* occurs with βE constant, with gains in E obtained through reduction in β .

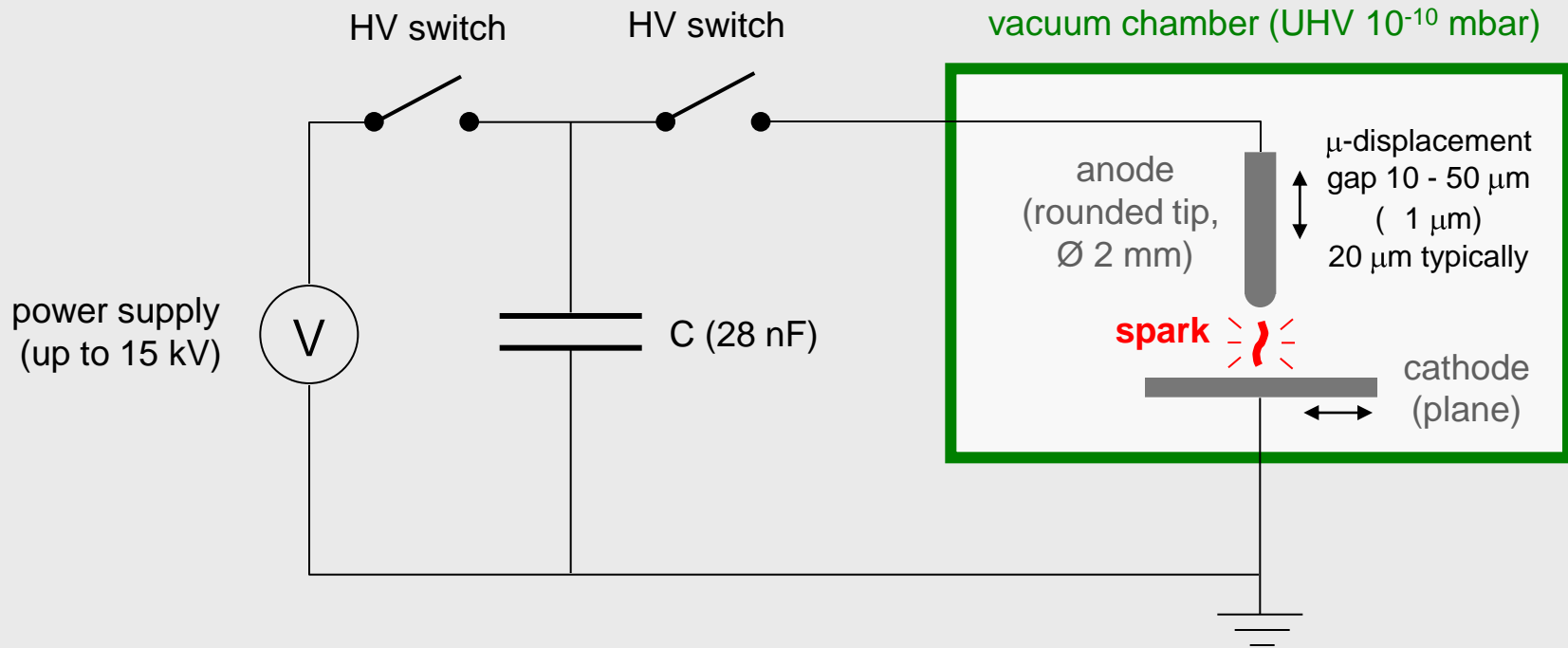
A typical measured value of βE near the breakdown limit for copper is 8 GV/m - alternatively this is 1 eV/Å.

To get an idea of the scale, the cohesive energy of a Cu atom in a crystal is 3.46 eV/atom and the inter-atomic spacing is 3.6 Å, hence...

So extracting β from the IV characteristics of a surface is important experimental exercise, and understanding where it comes from an important exercise for the field!

A short introduction to the dc spark system at CERN

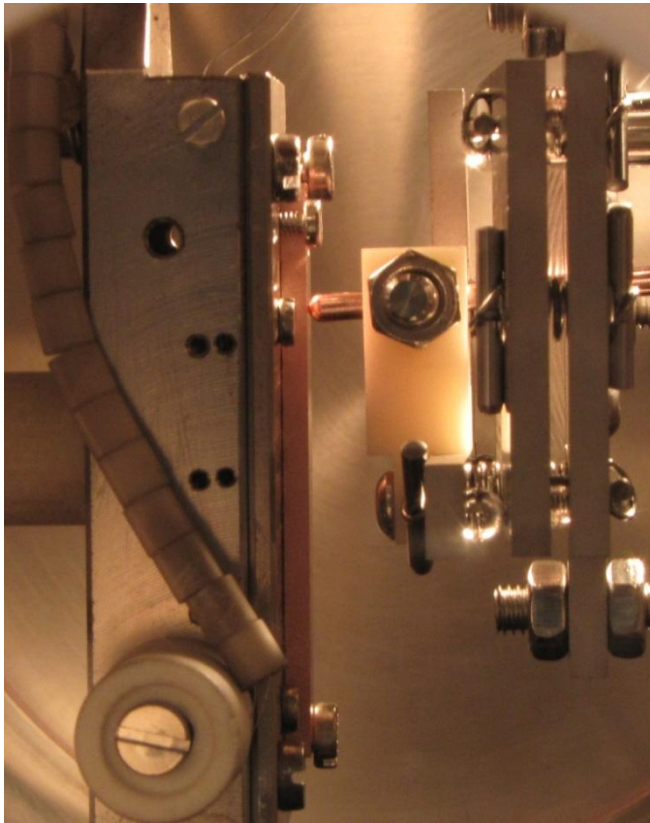
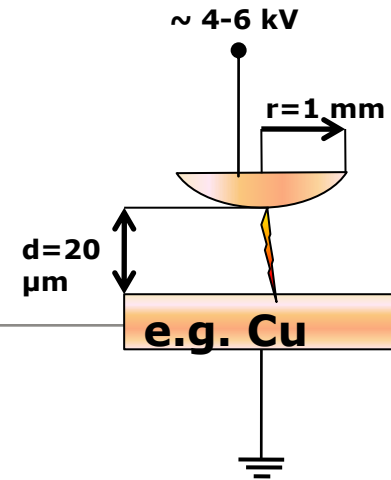
Experimental set-up : “ the spark system ”



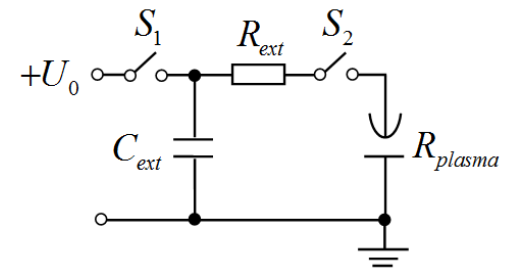
- Two similar systems are running in parallel
- Types of measurements :
 - 1) Field Emission ($\rightarrow \beta$)
 - 2) Conditioning (\rightarrow breakdown field E_b)
 - 3) Breakdown Rate (\rightarrow BDR vs E)



Modelling DC discharges



- First we have to understand **breakdowns in DC**, before we can generalise to RF
- Simple and cost-efficient testing of breakdown behaviour with two *DC setups at CERN*
 - We adjusted also out theoretical model to the DC experimental conditions
- However, results are completely **general!**

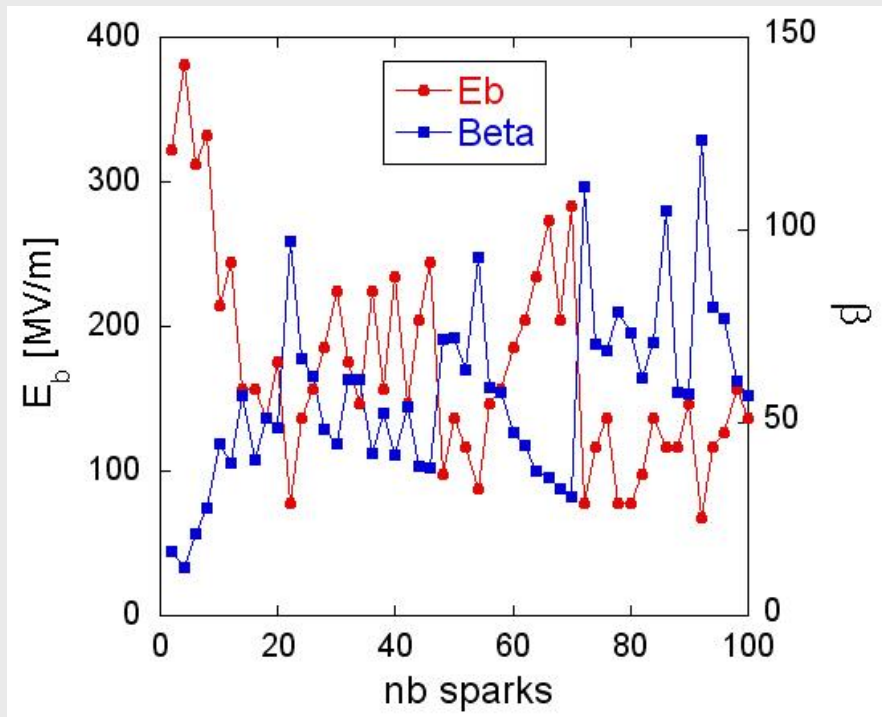


$$R_{ext} = 30 \Omega$$

$$C_{ext} = 0.1 - 27.5 \text{ nF}$$

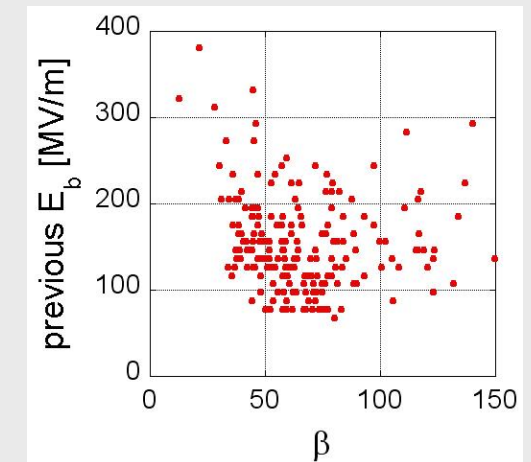
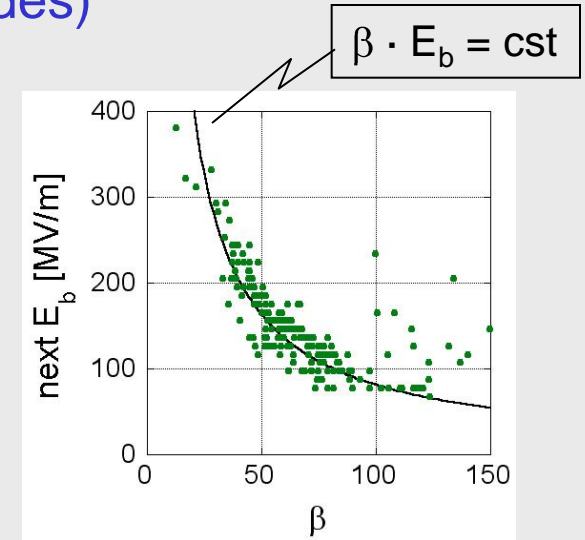
Evolution of β & E_b during conditioning experiments

- Measurements of β after each sparks (Cu electrodes)

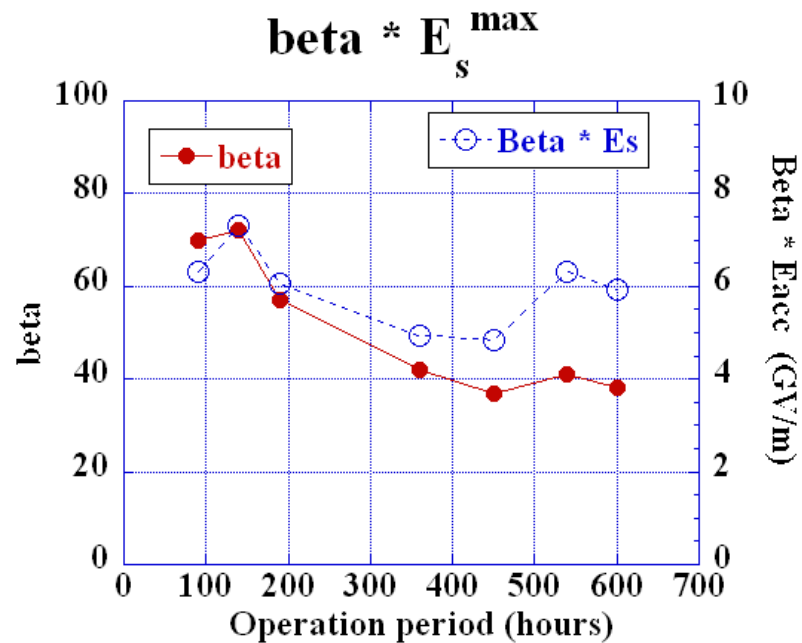


$\beta \leftrightarrow$ next E_b
correlation

$\beta \leftrightarrow$ previous E_b
no correlation



An example of the same thing in an rf cavity



T. Higo, KEK
Test of TD18

Identifying the origin of β , and finding a way of independently verifying it, is one of the big open issues in breakdown R&D. Reducing it is a goal for practical applications.

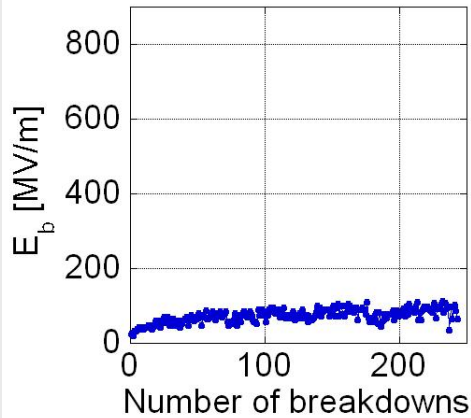
Dirt and dust clearly cause emission sites in early conditioning, and this is the dominant effect in the low, <100 MV/m surface fields in superconducting cavities.

But there seems to be a unique limiting gradient for each material – see next slide – which must have an explanation in the intrinsic properties of the material.

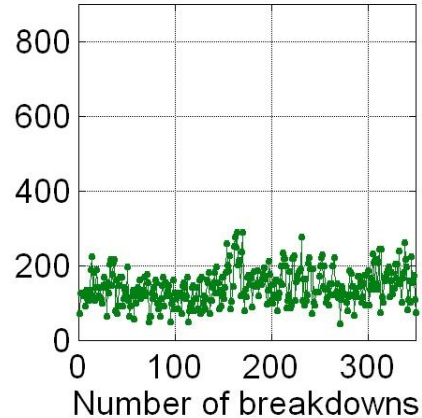
But to go further, we need to look at what else happens when we have field emission to understand how we go from **field emission to breakdown**.

Conditioning curves of pure metals

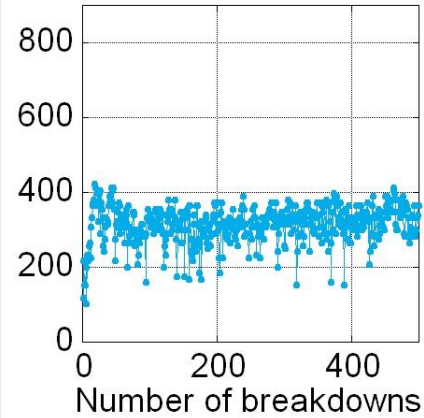
C



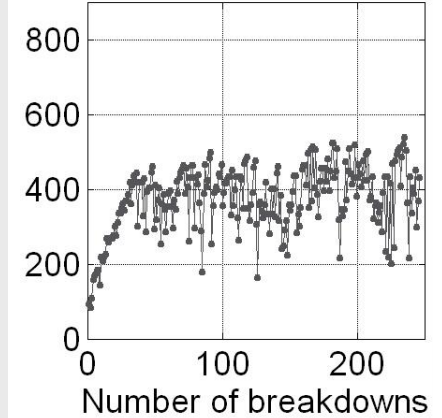
Cu



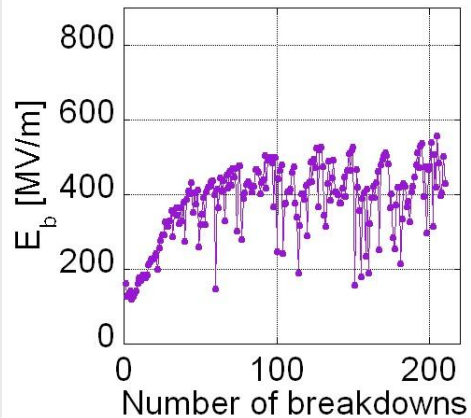
W



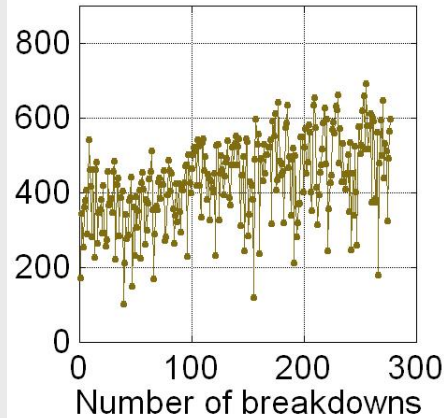
Nb



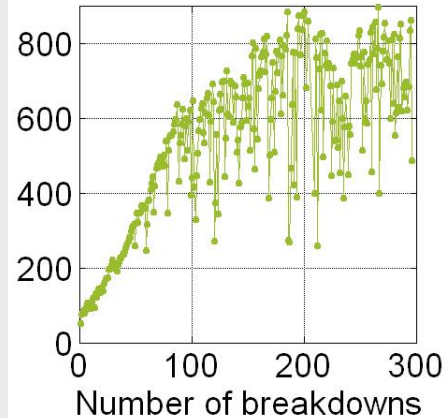
Mo



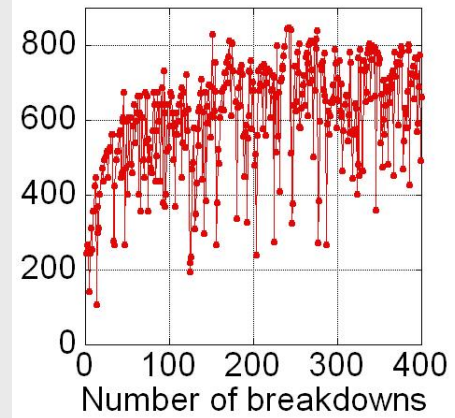
Cr



V



Ti



The breakdown trigger

Now we are going to discuss the next step – how and why field emission evolves into a breakdown.

The requirements for a low – 10^{-7} – breakdown rate in a linear collider gives us a unique perspective on breakdown.

(We have $O(10^5)$ structures rf units in CLIC so if we don't want to lose more than 1% luminosity to breakdown we have to have a breakdown rate of $O(10^{-7})$)

We need to answer not just the question “Why does a surface breakdown?” but also “Why does it breakdown sometimes?”

Trying to answer this question is leading us to new insights into the breakdown mechanism. Another look at the big picture...

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Macroscopic energy transfer

The breakdown rate issue

Let's look at the dependence of breakdown rate on gradient. This is a standard plot for **linear collider high-gradient tests** and we also measure it in dc.

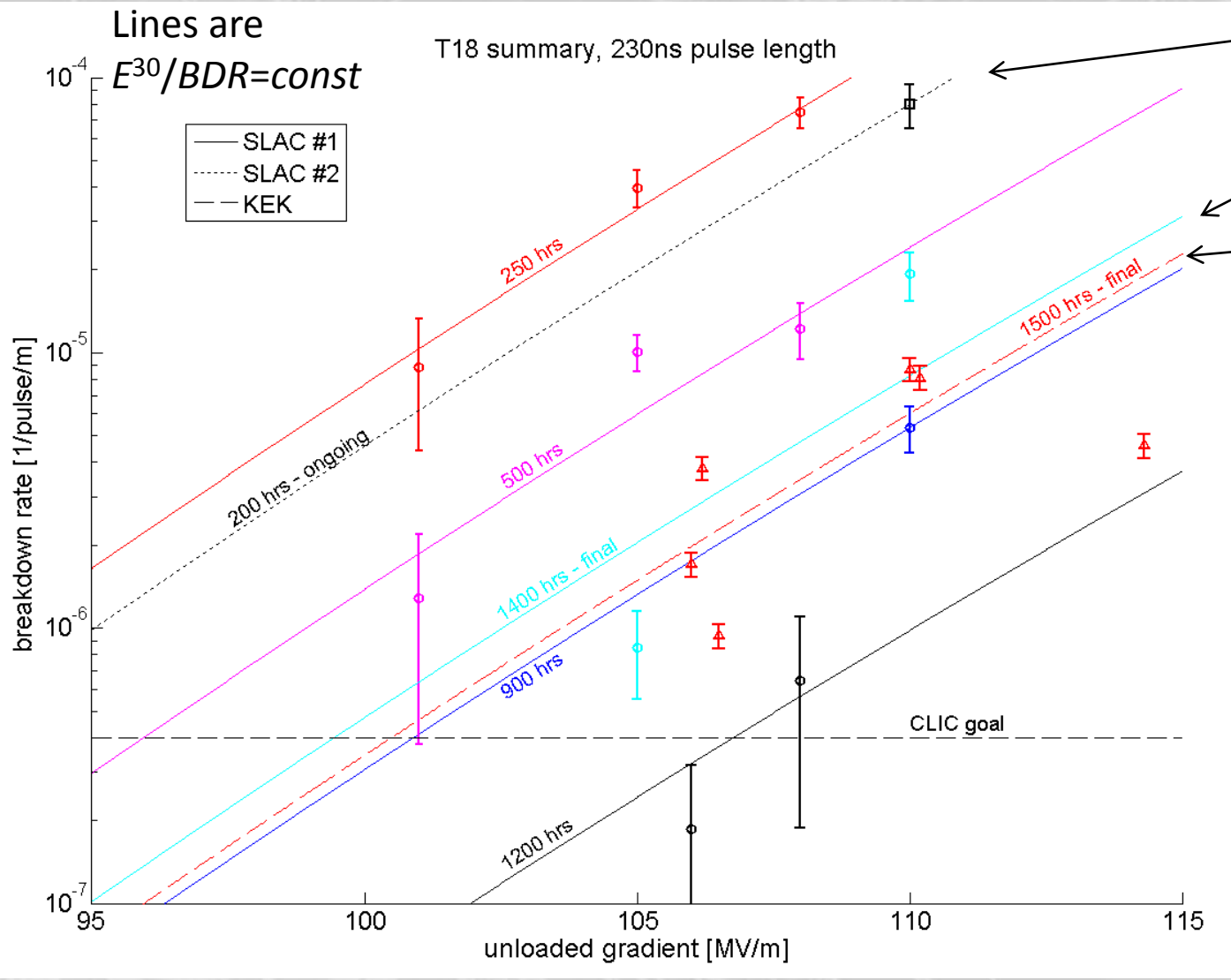
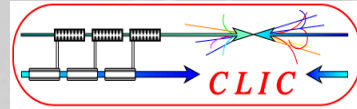
E^{29} ? Exponential? Very strong for sure.

Having a practical goal, we also ask “How can we influence it?”

To do this we need to understand the nature of the breakdown trigger but also the origin of its statistical nature.



CERN/KEK/SLAC T18 structure tests



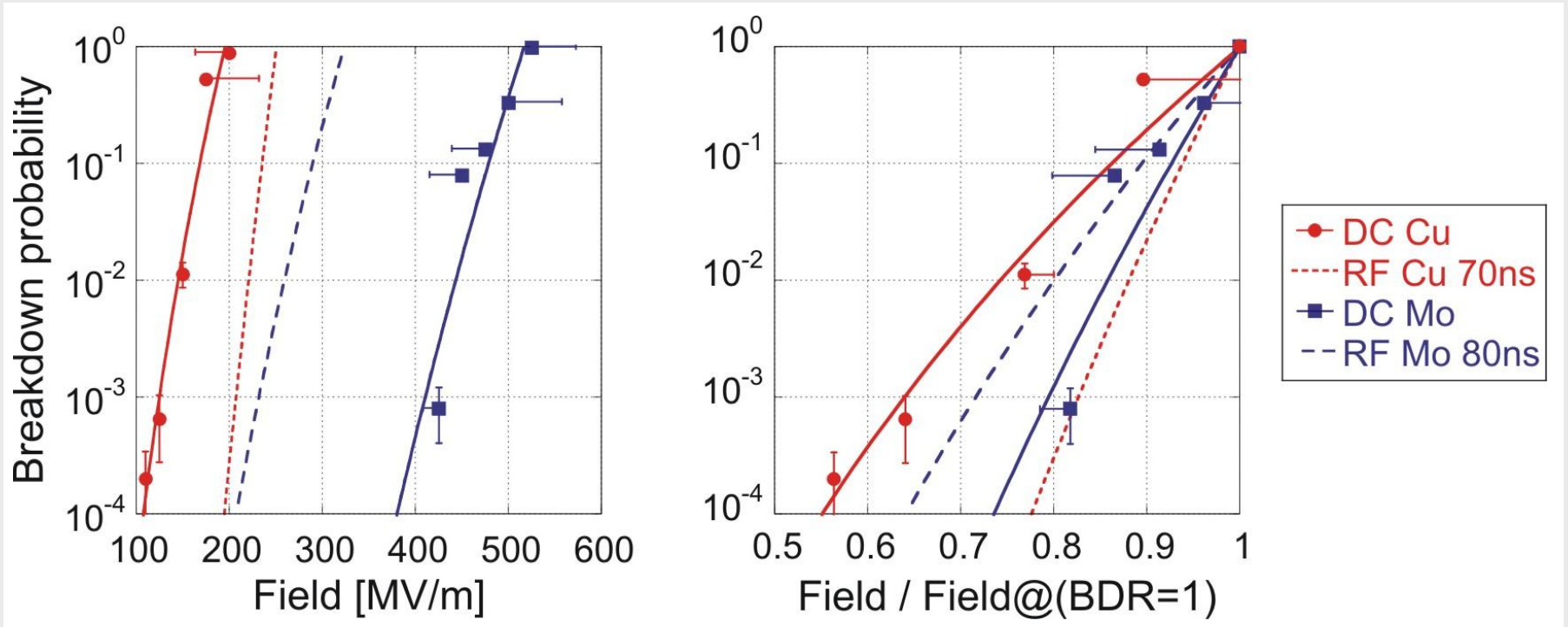
SLAC 2

SLAC 1

KEK

rf test results have been presented in detail at the X-band workshop, Monday morning, with a summary by S. Doebert on Wednesday morning.

Breakdown Rate : DC & RF (30 GHz)



γ = power in the fit

$$\text{BDR} \sim E^\gamma$$

	DC	RF
Cu	10 - 15	30
Mo	30 - 35	20

Same trend in DC and in RF,
but difficult to compare 'slopes'

n.b.

The breakdown rate over the long term is directly determined by the trigger mechanism but it can also be influenced indirectly by the damage caused by previous breakdowns. For example: more damage, higher β , higher local surface field, higher breakdown rate.

Lack of clarity in the distinction between what causes the breakdown and what the breakdown causes often results in confusion.

The two aspects of the breakdown trigger

1. How does the electric field pulse affect the surface when there is no breakdown? How does this surface modification lead to an increase the level of field emission to get to the critical value? Of course we would like to identify the origin of the enhanced emission in the first place.

These steps are highlighted in yellow in the big picture.

2. What happens when you reach the critical value, what other physical processes to kick in?

These steps are highlighted in blue.

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Macroscopic energy transfer

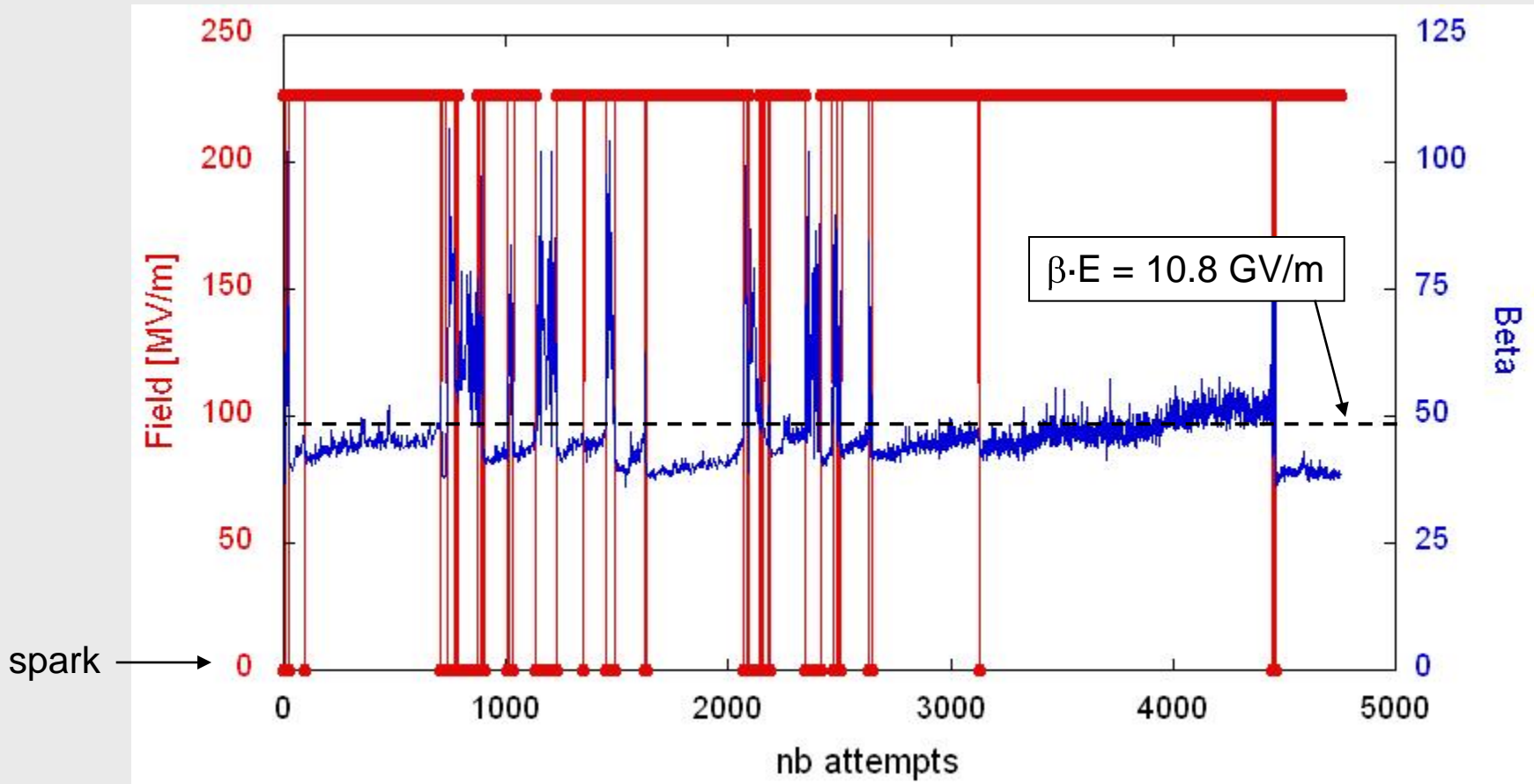
Evidence that β increases cumulatively from pulse to pulse, with breakdown occurring when a critical value is reached, can be seen in the next slide.

Breakdown rate comes from the growth rate of the surface features.

Not to be forgotten that there are potentially many emission sites on a surface, so the story of our rf structure is not that of a single site.

Please note that we are now entering an area of active research – I look to one of *you* to tell me the answer.

Evolution of β during BDR measurements (Cu)



- breakdown as soon as $\beta > 48$ ($\leftrightarrow \beta \cdot 225 \text{ MV/m} > 10.8 \text{ GV/m}$)
- consecutive breakdowns as long as $\beta > \beta_{\text{threshold}}$

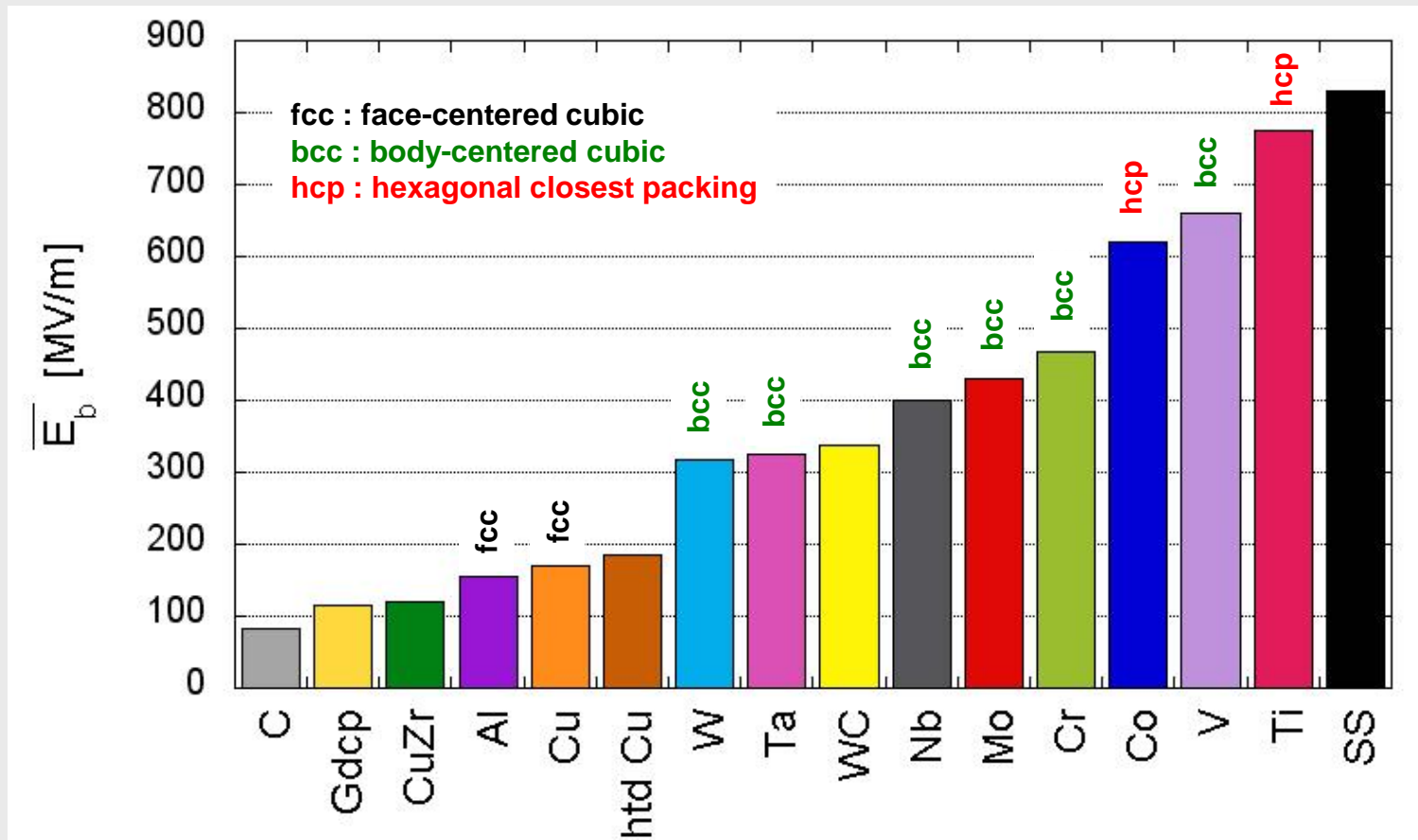
→ length and occurrence of breakdown clusters \leftrightarrow evolution of β

The two main classes of ideas on how the surface evolves in a way that field emission increases are,

1. Tip growth – geometrical field enhancement factor becomes larger.
2. Dislocation movement – local work function becomes lower and atomic level surface geometry can change. Experimental evidence from this is on the next slide.

It is quite possible that both processes occur.

Breakdown field of materials (after conditioning)



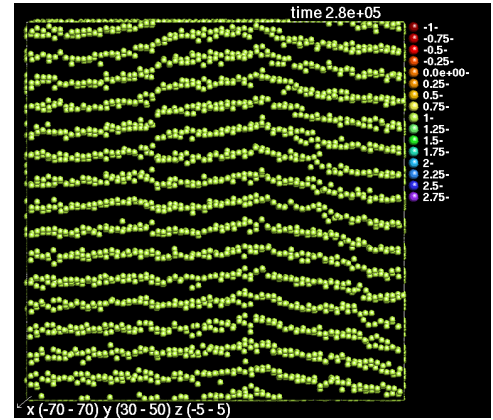
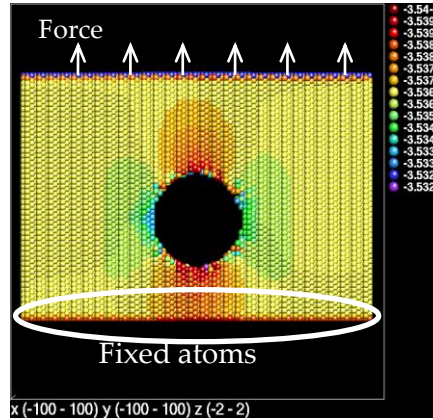
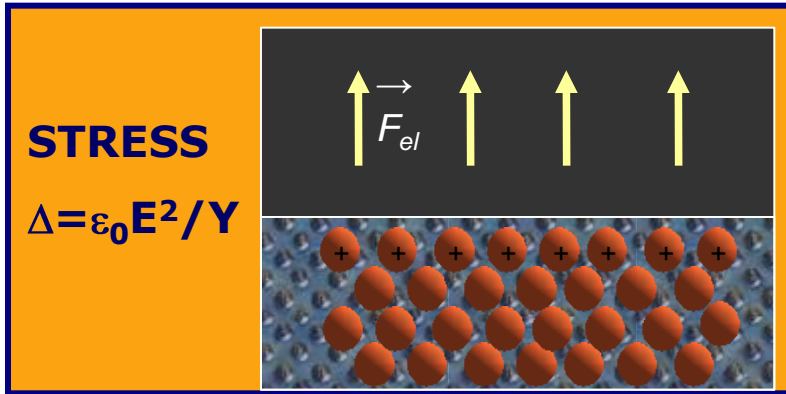
- In addition to other properties, also importance of crystal structure?
- reminder : Cu < W < Mo → same ranking as in RF tests (30 GHz)

More specifics on the ideas of breakdown rate

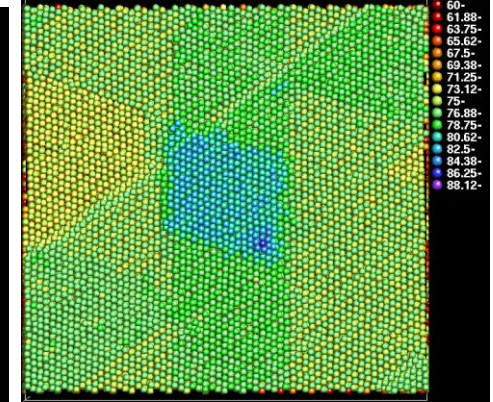
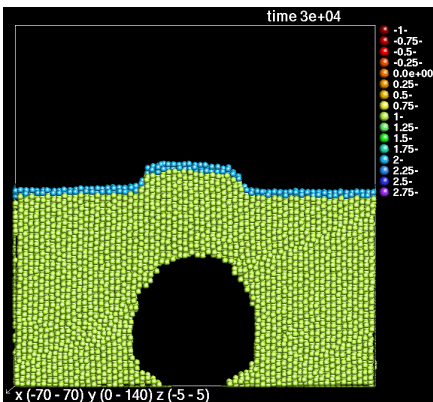
1. Geometric growth of the tips under induced stress, both electric field tension and thermal stress from emission current Joule heating. Crystal dislocations do act a nucleation points for whisker growth in certain conditions.
2. Accumulation of defects under stress, again both electric field tension and thermal stress - fatigue. Like in pulsed surface heating. Tips eventually form cracks and break off.
3. Defects are also areas of lower work function. This is very hard to calculate or measure (but I have the personal belief that this must be important).
4. **Alternative** - Migration of hydrogen atoms to the surface. Presence of hydrogen from the bulk could enhance evaporation and accelerate the trigger process. Clearer in next section.



Stage 3a: Onset of tip growth



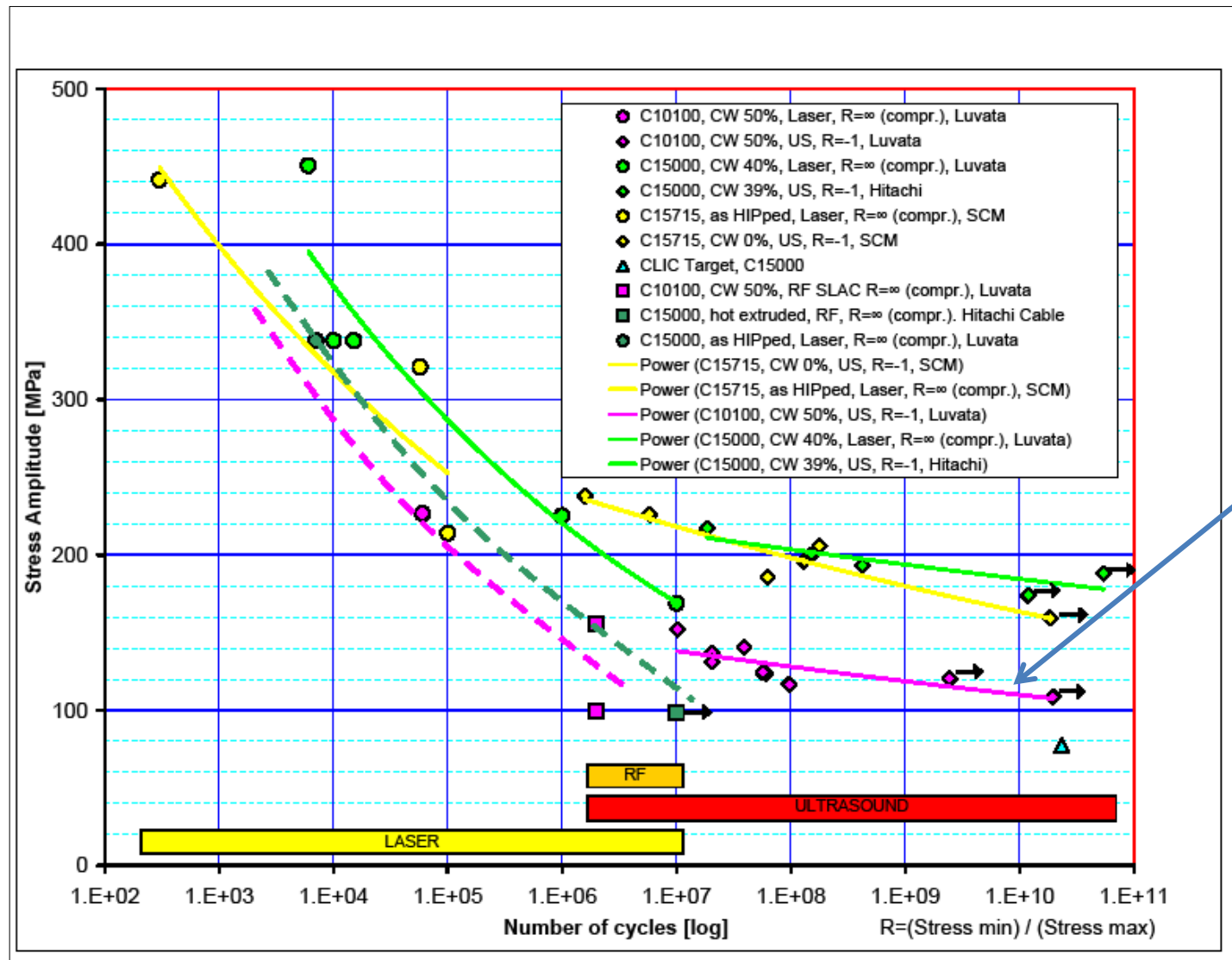
- Presence of an electric field exerts a **tensile stress** on the surface
- Presence of a near-to-surface void may **trigger the growth** of a protrusion



Submitted to **PRB: Rapid Commun.**,

A. S. Pohjonen, F. Djurabekova, A. Kuronen, and K. Nordlund, "Dislocation nucleation from near surface void under static tensile stress in Cu"

Wöhler curves for various types of copper relevant for rf cavities



Around 5% per decade!
Stress goes as E^2

From Samuli Heikkinen

Now what else starts to kick in as our emission sites evolve – back to the blue box in the big picture:

1. Field enhanced evaporation of neutrals – The field emission current densities give temperature rises near the melting point. Evaporation occurs. The applied field polarizes atoms in the crystal, pulls on them, and evaporation is enhanced.
2. **Alternative explanation** - Detachment of atomic clusters through a fatigue-like process – the electrostatic tensile force induced by 8 GV/m is of the order of the tensile strength of copper.

Electric field induced tensile force

$$P = \frac{1}{2} \epsilon_0 E^2$$

rewriting for our units

$$P = 4.43 \times 10^6 \left[\frac{E}{1 \text{ GV/m}} \right]^2 \text{ Pa}$$

The ultimate tensile strength of Cu is 220 Mpa and the measured βE is typically 8 GeV...

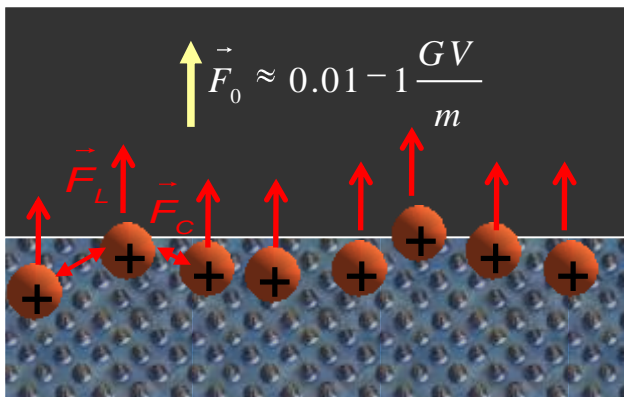


Stage 2: Hybrid ED&MD

- Atoms move according to the Molecular dynamics algorithm, solving Newton's equations of motion

$$\ddot{\vec{r}} = \frac{\vec{f}}{m_{at}}; \quad \vec{f} = -\nabla V(\vec{r}_i) \quad \vec{f} = -\nabla V(\vec{r}_i) + \vec{f}_L + \vec{f}_C$$

- In ED&MD hybrid code, due to the excess or depletion of electron density (atomic charge), we apply Gauss's law to calculate the charges for the surface atoms ; $\sigma = \epsilon_0 F_{loc}$
- F_{loc} is a solution of Laplace equation



Thus, the motion of surface atoms is corrected due to the pulling effect of the electric field



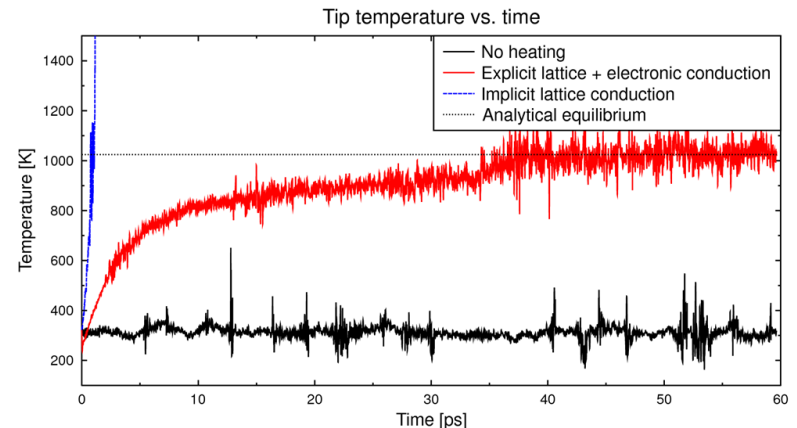
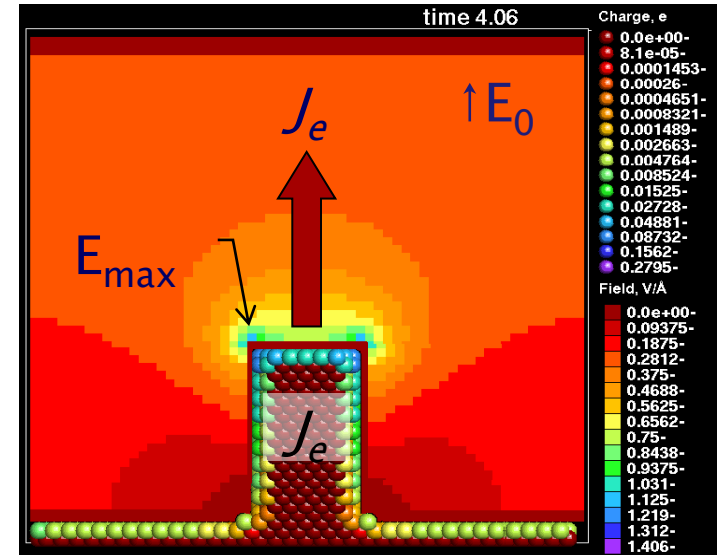
Stage 2: Dynamics of electrons for temperature account

- At such high electric fields, **field emission** is a non-negligible phenomenon
- Electrons escaping from the surface with significant current will heat the sharp features on the surface, causing eventually their melting.
- The change of temperature (kinetic energy) due to **Joule heating** and **heat conduction** is calculated by the 1D heat equation

$$\frac{\partial T(x,t)}{\partial t} = \frac{K}{C_V} \frac{\partial^2 T(x,t)}{\partial x^2} + \frac{\rho(T(x,t))J^2}{C_V}$$

Results are submitted to **Comput. Mater. Sci.**,
S. Parviainen, F. Djurabekova, H. Timko, and K. Nordlund,
“Implementation of electronic processes into MD simulations of
nanoscale metal tips under electric fields “

Helga Timkó



The situation gets out of hand

The crucial next step is that the liberated atoms are **ionized** by the field emission current that is accelerating away from the cathode.

These positively charged ions then turn around and accelerate towards the surface, strike it and sputter away more atoms.

We are now forming a **plasma** and the whole thing starts to run away.

Currents rise 12-15 orders of magnitude from p/nA to kA, we see light, X-rays, melt spots on the surface, capacitors discharge, rf power is absorbed etc.

We would need more time to cover these stages of the breakdown. I can refer you to an excellent book called “Cathodic arcs” by Andre Anders.

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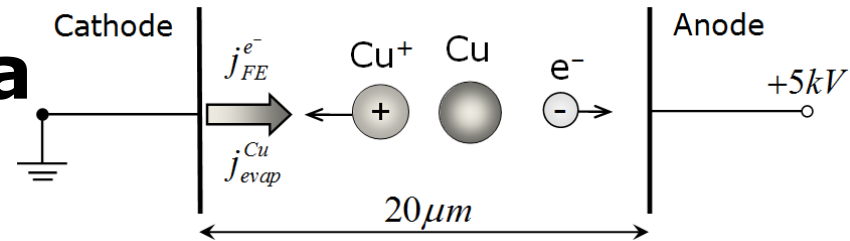
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(go to plasma dynamics)

Macroscopic energy transfer

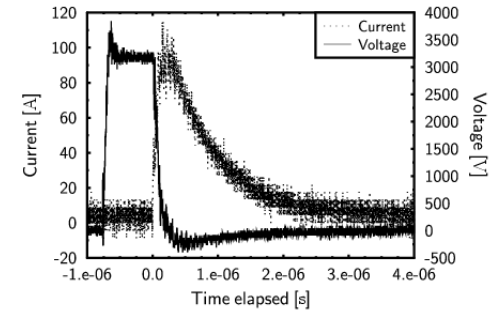


Stage 4: Plasma evolution



Corresponding to experiment...

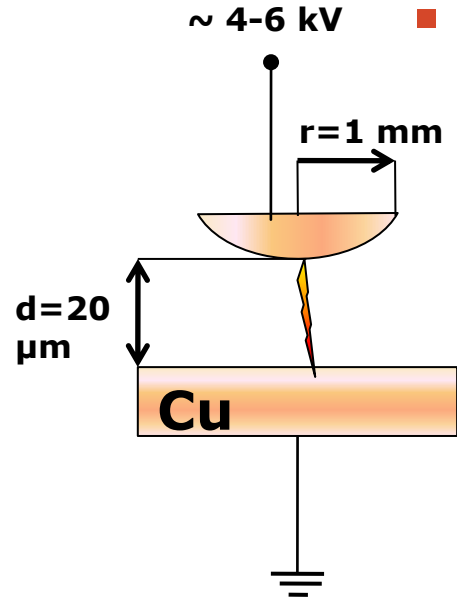
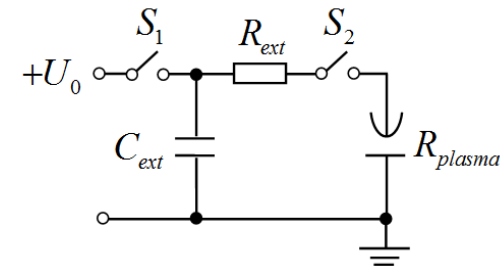
- 1d3v electrostatic PIC-MCC code
 - Resolving the main stream of plasma
 - Areal densities of physical quantities



- Exponential voltage drop mimicked
 - Limited energy from the circuit

$$R_{ext} = 30\Omega$$

$$C_{ext} = 0.1 - 27.5 nF$$



Accepted for publication in **Contrib. Plasma Phys.**,

H. Timko, K. Matyash, R. Schneider, F. Djurabekova, K. Nordlund, A. Hansen, A. Descoedres, J. Kovermann, A. Grudiev, W. Wuensch, S. Calatroni, and M. Taborelli ,

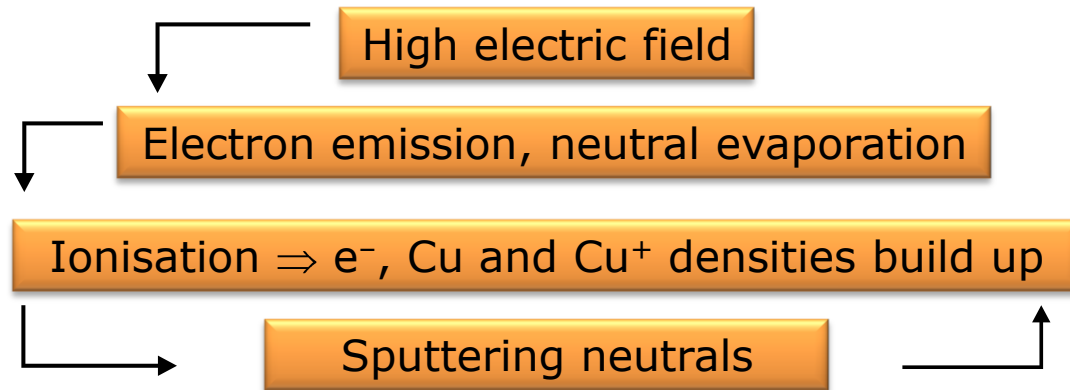
"A One-Dimensional Particle-in-Cell Model of Plasma Build-up in Vacuum Arcs"



Under what conditions will an arc form?

Two conditions need to be fulfilled: (→ scaling btw. DC and RF)

- High enough initial local field to have growing FE current
- Reaching a critical neutral density → ionisation avalanche
- The sequence of events leading to plasma formation:

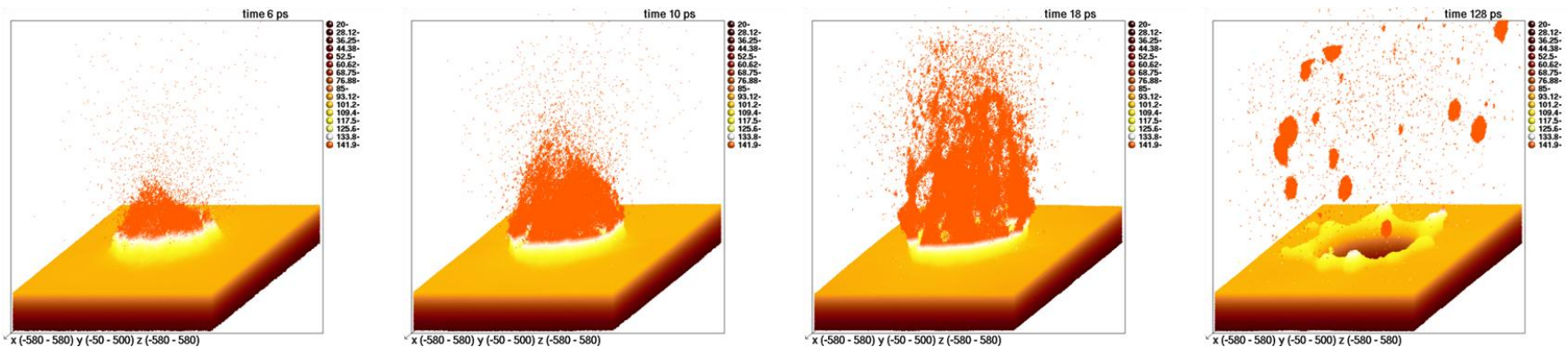


- "Point of no return": $I_{\text{mfp}} < I_{\text{sys}}$ – corresponding to a critical neutral density $\sim 10^{18} \text{ 1/cm}^3$ in our case ⇒ ionisation avalanche



Stage 5: Cathode damage due to ion bombardment

- Knowing flux & energy distribution of incident ions, erosion and sputtering was simulated with MD
- Flux of $\sim 10^{25} \text{ cm}^{-2}\text{s}^{-1}$ on e.g. $r=15 \text{ nm}$ circle $\Rightarrow 1 \text{ ion}/20 \text{ fs}$



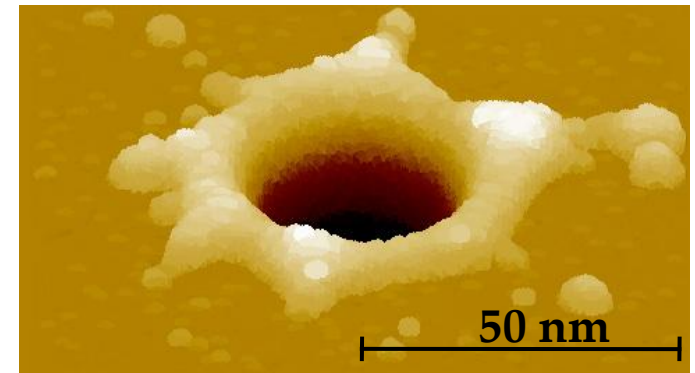
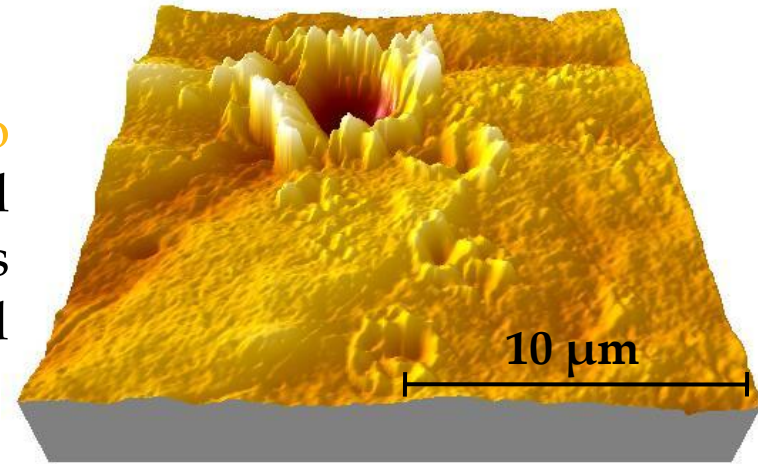
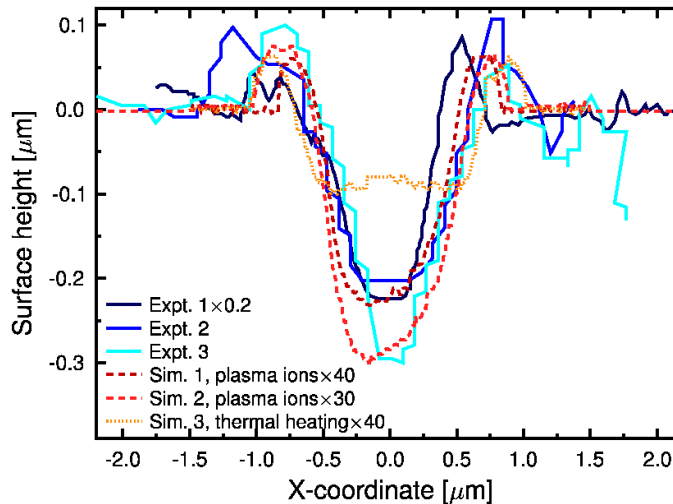
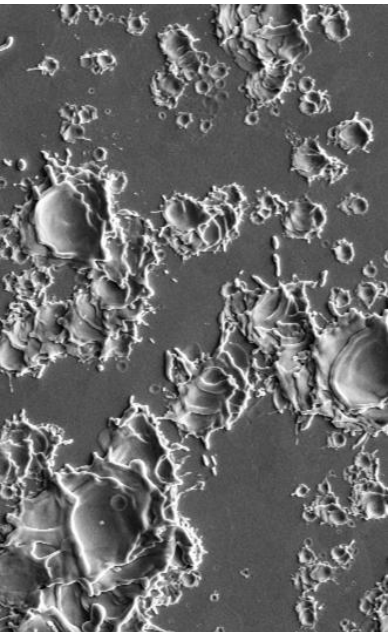
H. Timko, F. Djurabekova, K. Nordlund, L. Costelle, K. Matyash, R. Schneider, A. Toerklep, G. Arnau-Izquierdo, A. Descoeur, S. Calatroni, M. Taborelli, and W. Wuensch, "Mechanism of surface modification in the plasma-surface interaction in electrical arcs", **Phys. Rev. B** 81, 184109 (2010)

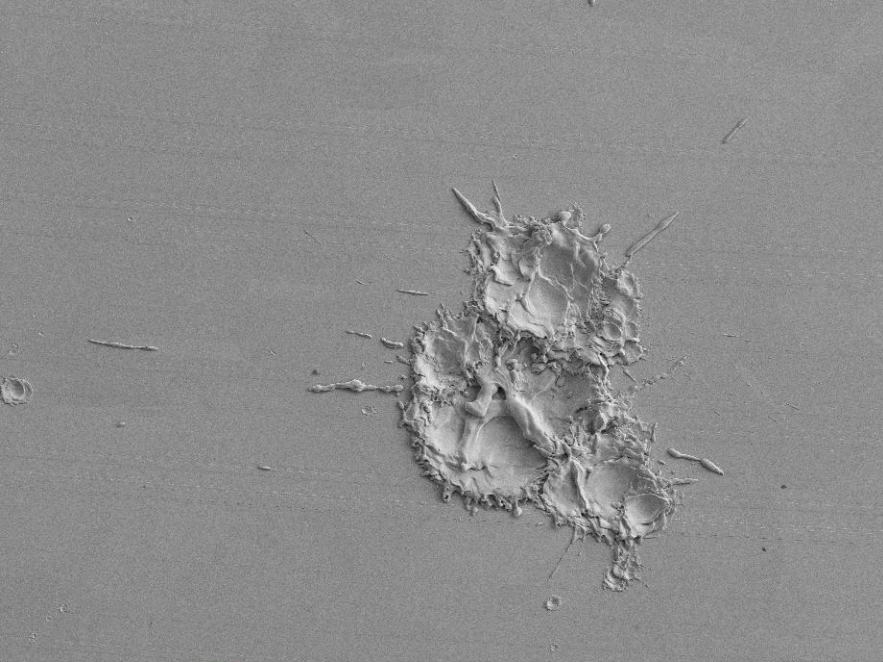



Comparison to experiment

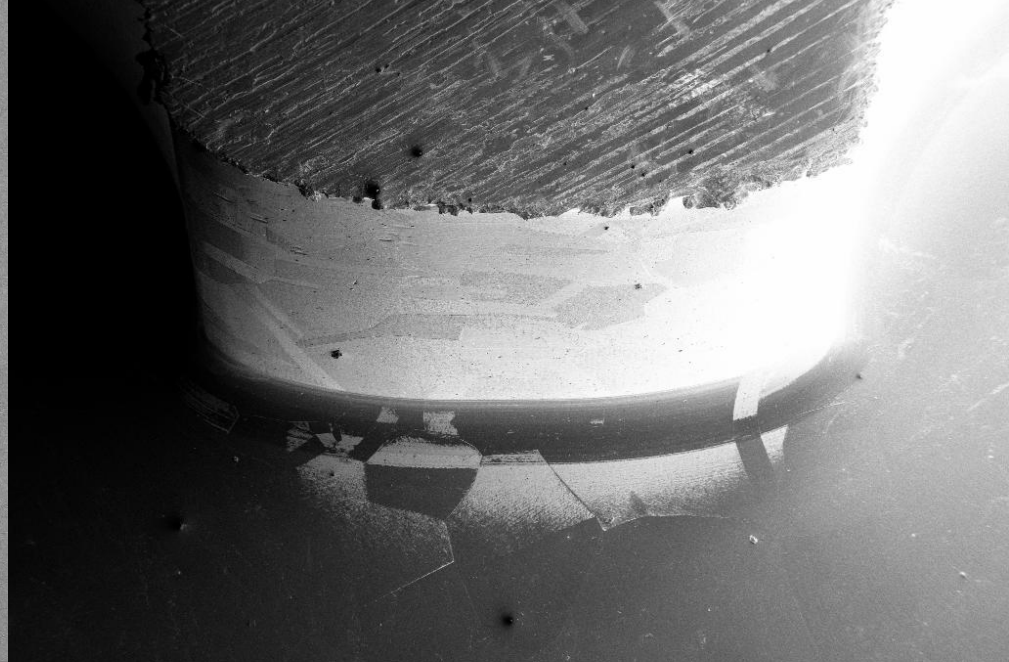
- Self-similarity:



Crater depth to width ratio remains constant over several orders of magnitude, and is the same for experiment and simulation

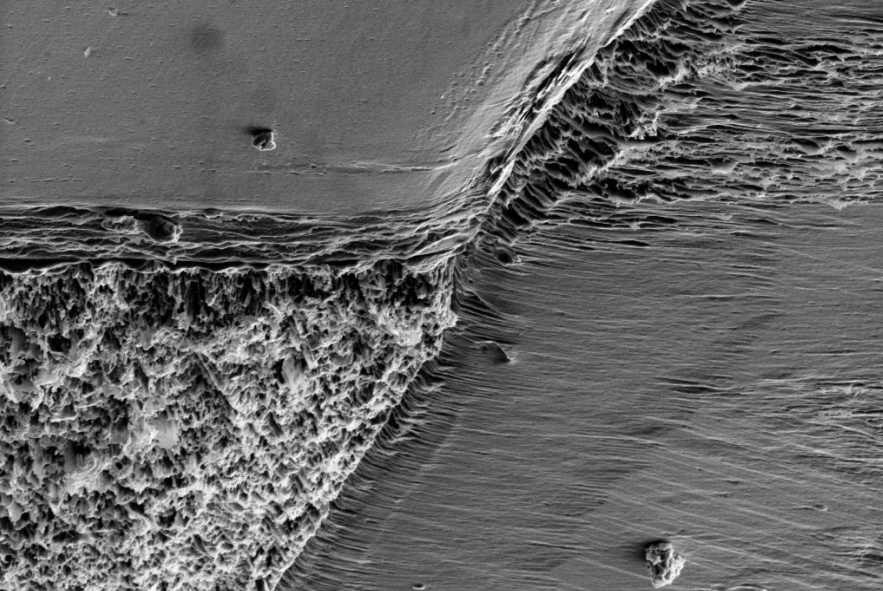




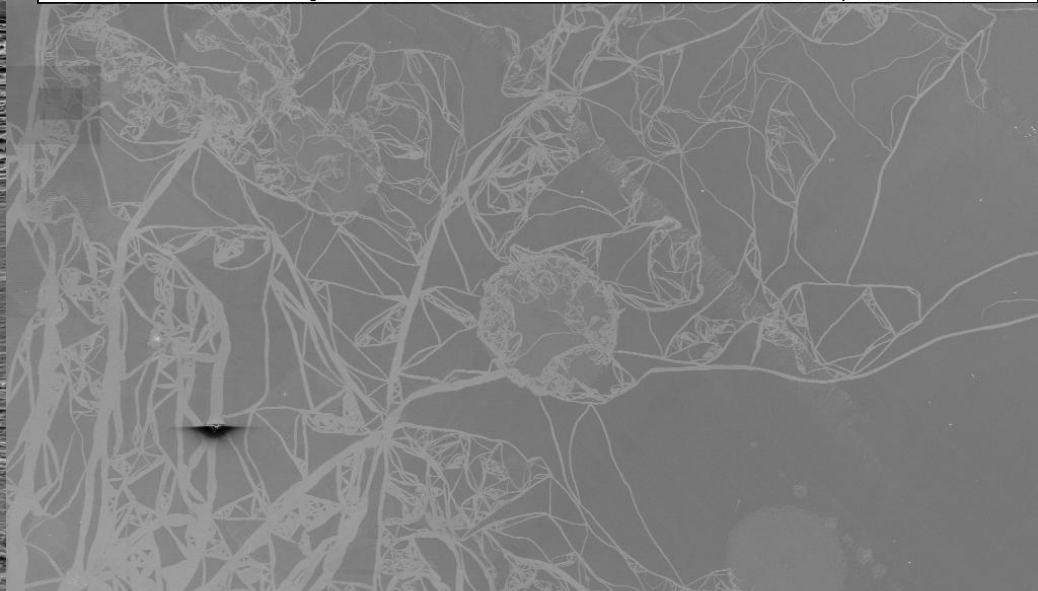
20 μ m  EHT = 3.00 kV
 WD = 5.1 mm DC-Spark sample Cu(47) Mag = 200 X
 Signal A = SE2 Spot 7 (4.65) Markus Aicheler
 Date :29 Jul 2010



1 mm  EHT = 5.00 kV
 WD = 25.9 mm TD18 KEK-SLAC Mag = 14 X
 Signal A = SE2 Part B Tilt 25° Markus Aicheler
 Up-Stream -- NW Date :2 Sep 2010 



1 μ m  EHT = 5.00 kV
 WD = 25.6 mm TD18 KEK-SLAC Mag = 5.00 K X
 Signal A = SE2 Part B Tilt 25° Markus Aicheler
 Up-Stream -- NW Date :2 Sep 2010 



20 μ m  EHT = 3.00 kV
 WD = 5.9 mm 7N-LG-Cu (45) P. Alknes EN/MME
 Signal A = InLens Spot #2 Date :24 Mar 2010
 Mag = 200 X Time :21:53:04 