DC breakdown measurements

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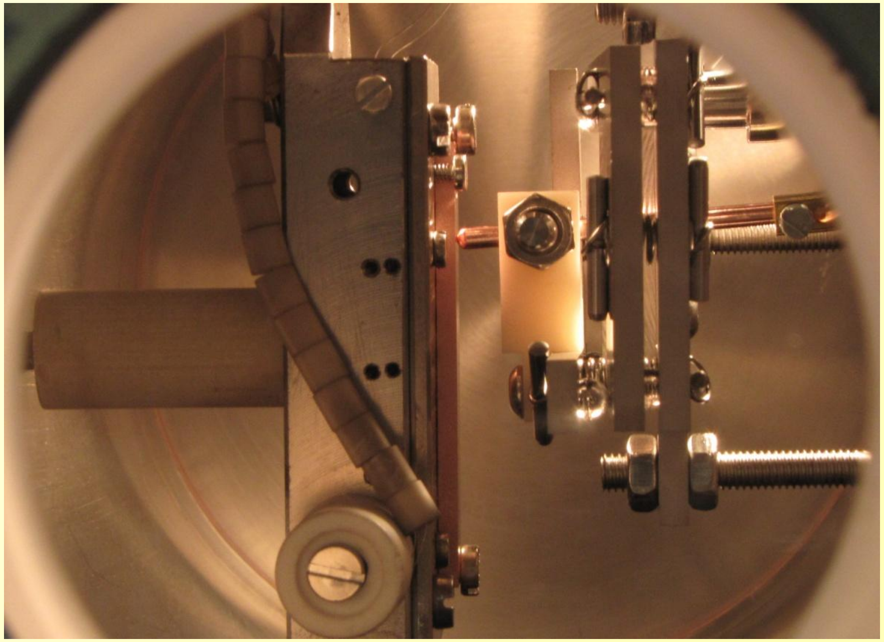
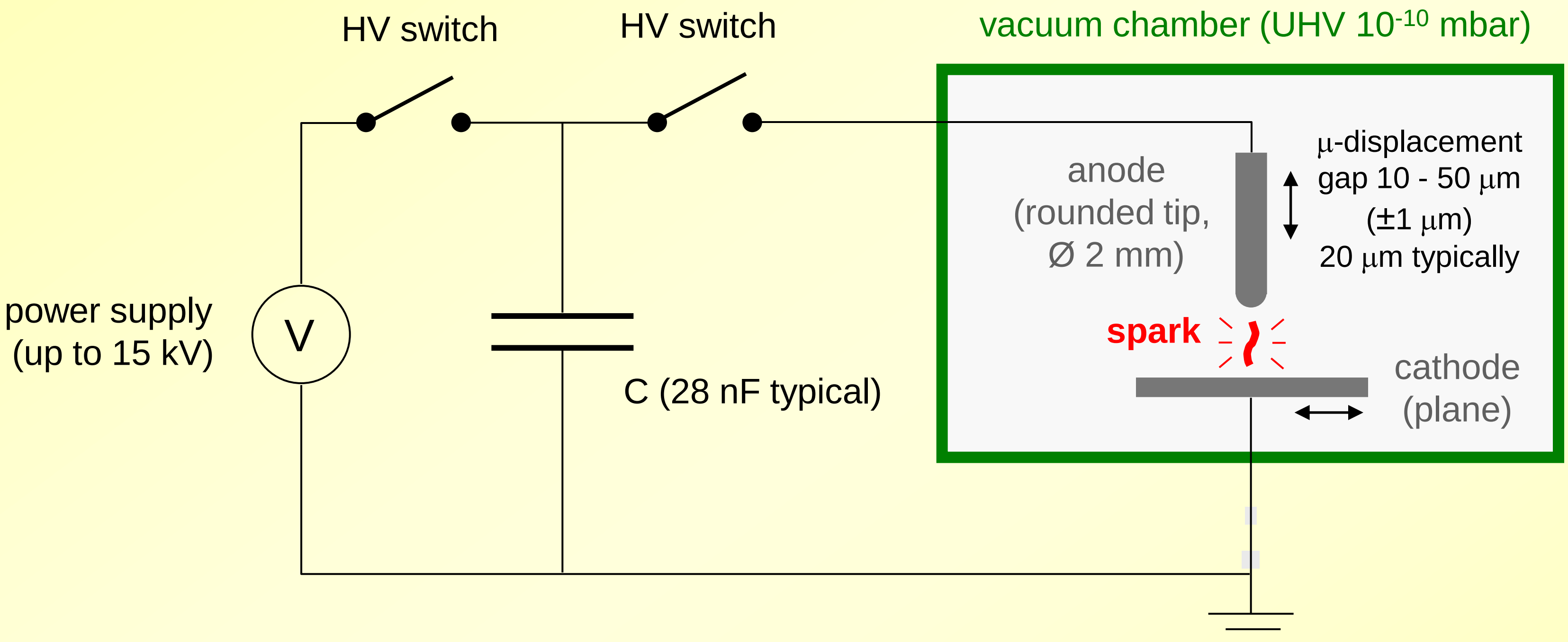
Outline

- Experimental setup
- Typical measurements
- Materials and surface preparations
- Time delays before breakdown
- Gas released during breakdown
- Evolution of β and Eb
- Effect of spark energy
- Future

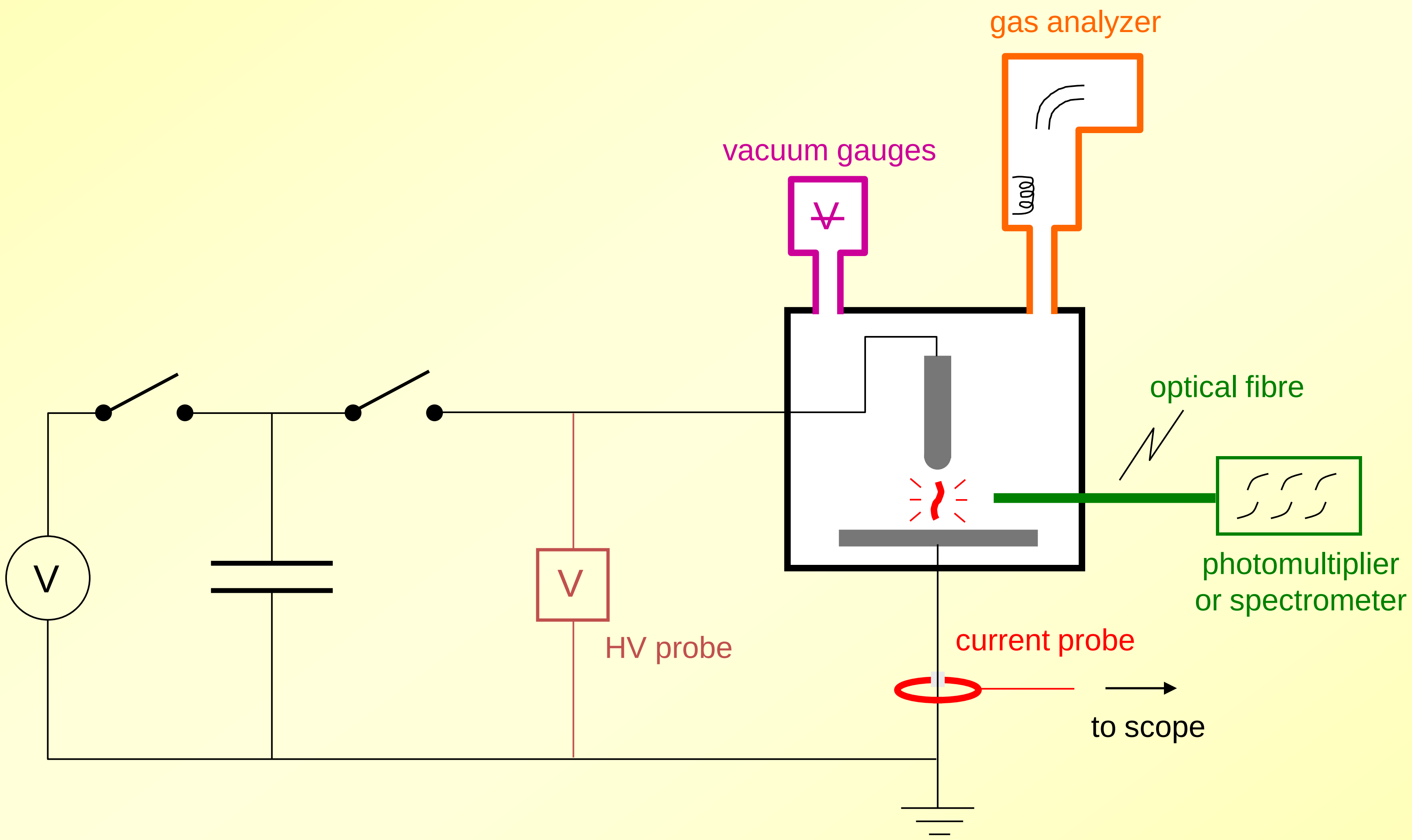


Experimental set-up : " the spark system "



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

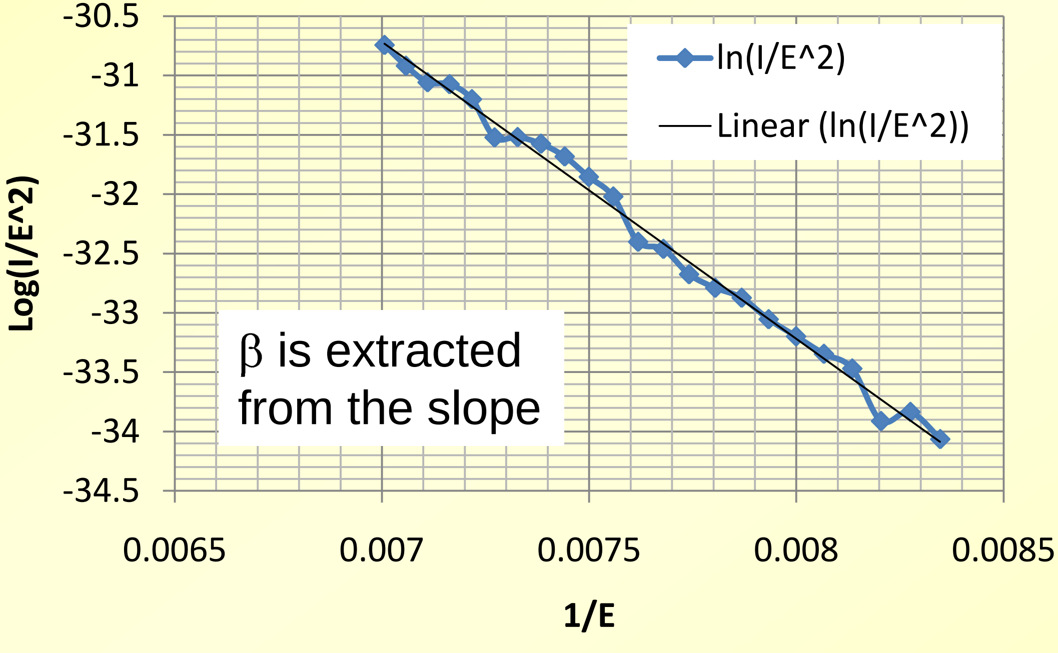
Experimental set-up : diagnostics

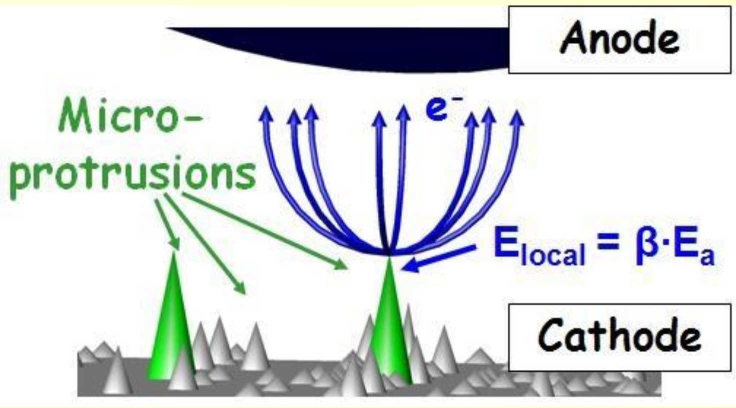


Field emission - β measurement

- An I-V scan is performed at limited current, fitting the data to the classical Fowler-Nordheim formula, where $[j_{FE}] = A/m^2$, $[E] = MV/m$ and $[\phi] = eV$ (usually 4.5 eV).

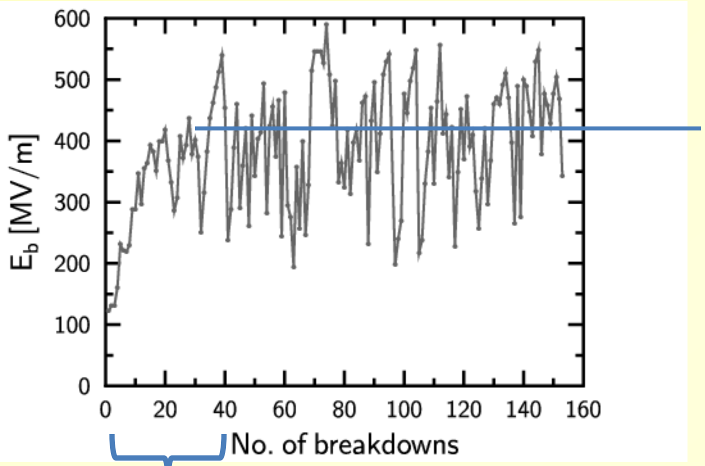
$$j_{FE} = \frac{1.54 \cdot 10^{6} (\beta \cdot E)^{2}}{\phi} \exp(10.41 \cdot \phi^{-1/2}) \exp\left(\frac{-6.53 \cdot 10^{3} \phi^{3/2}}{\beta E}\right)$$





Conditioning – average breakdown field

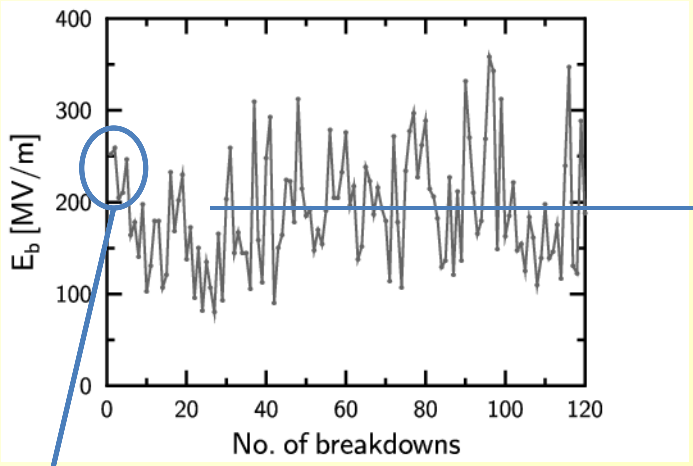
Molybdenum



Eb

Conditioning
phase: 40 sparks

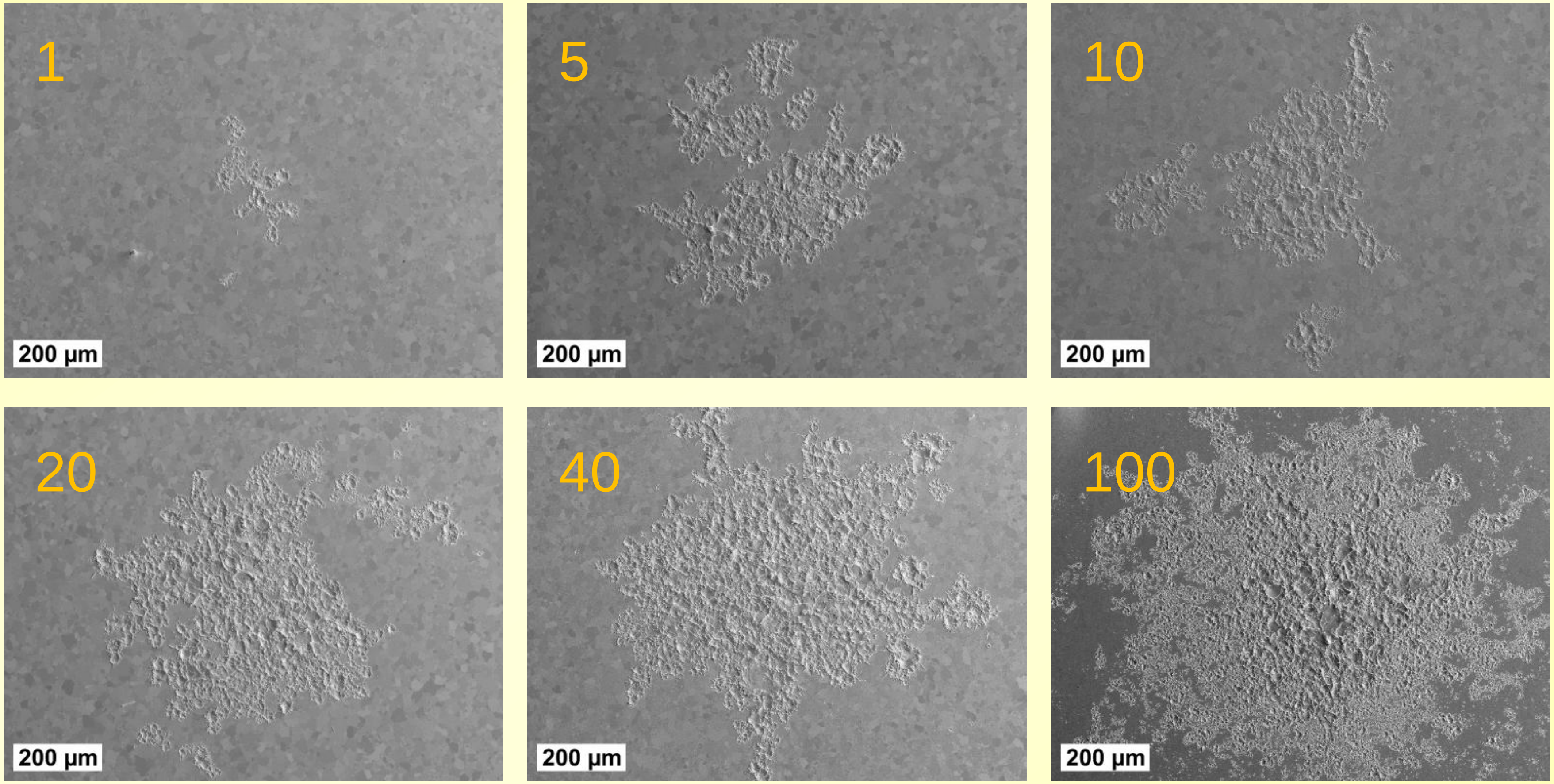
Copper



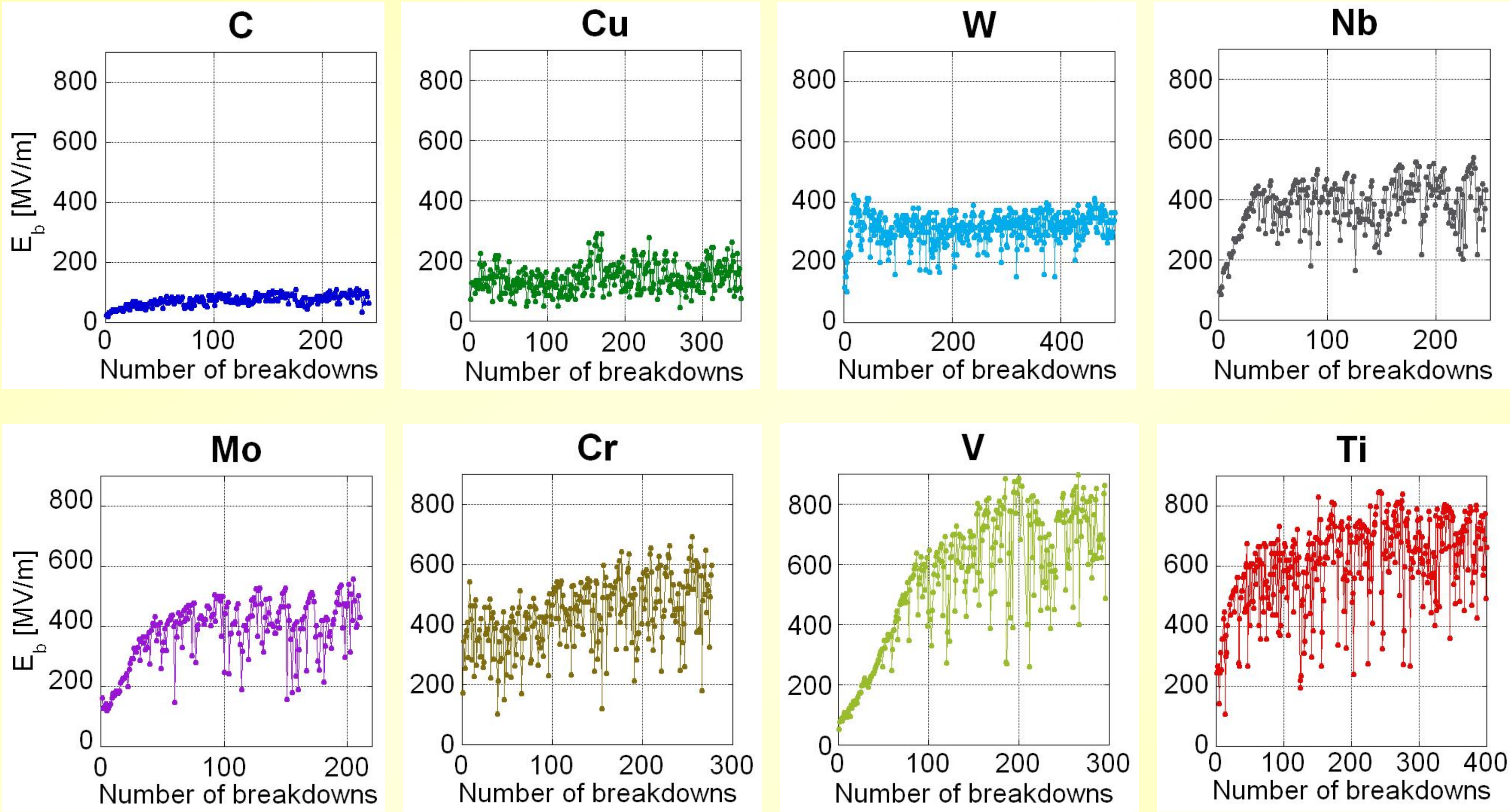
Eb

Deconditioning 1-5 sparks
or no conditioning

Surface damage (Mo)

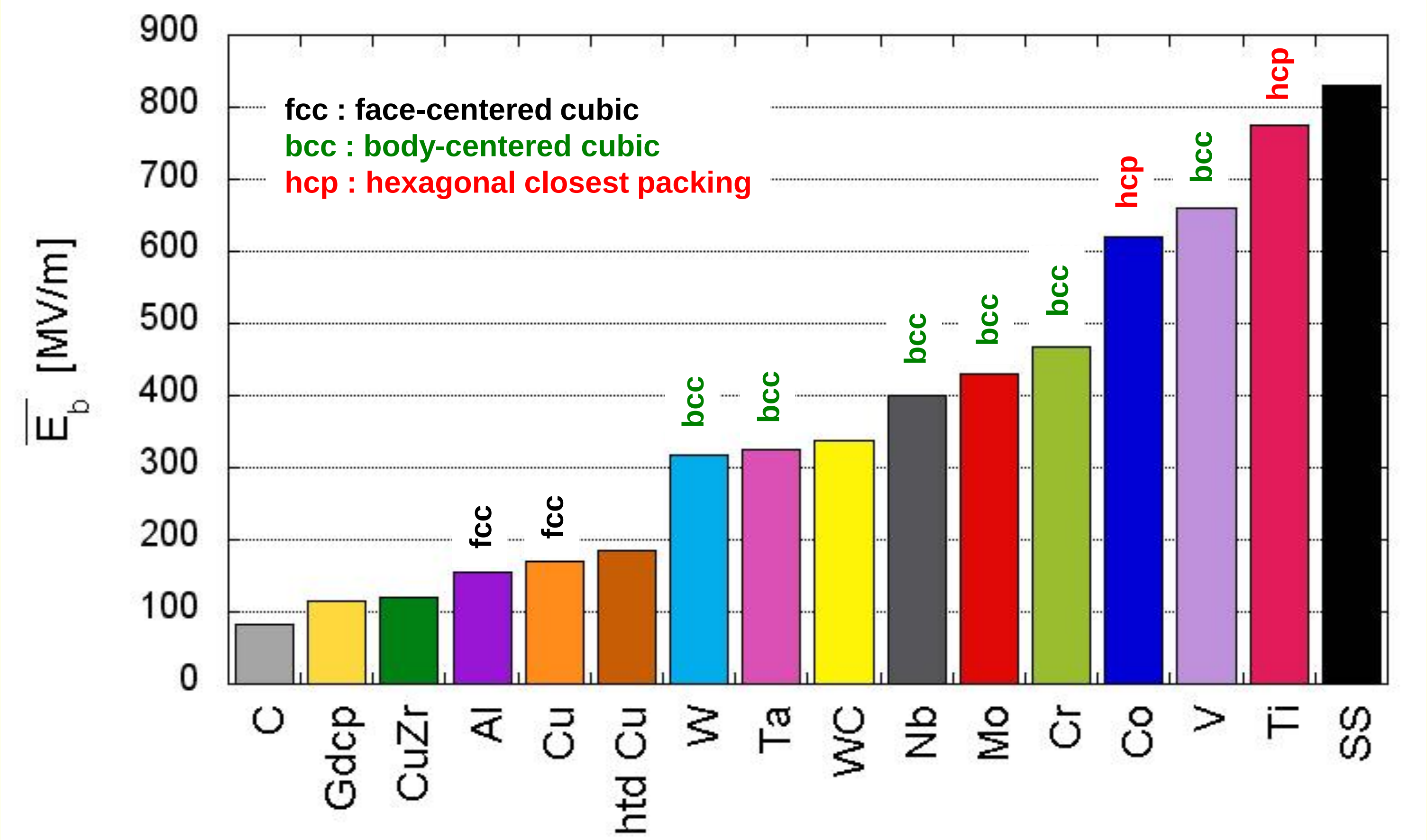


Conditioning curves of pure metals



Selection of new materials for RF structure fabrication was the original purpose of the experiment

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)

Surface treatments of Cu

- Surface treatments on Cu only affects the very first breakdowns

	rolled sheet / heat treatm.	milling	Subu	electro-polishing
β before 1st spark	~ 15 - 20	~ 20	~ 25 - 30	~ 15 - 20
1st brkd field [MV/m]	~ 200 - 400	~ 300 - 500	~ 150 - 200	~ 300 - 400

- After a few sparks: ~ 170 MV/m, β ~ 70 for every samples

The first sparks destroy rapidly the benefit of a good surface preparation and result in deconditioning. This might be the intrinsinc property of copper surface

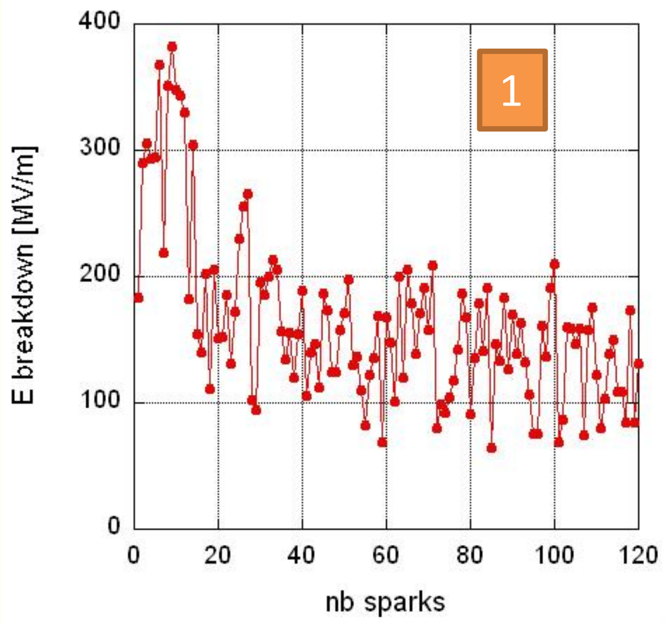
In RF, sparks are distributed over a much larger surface, and conditioning is seen. Might be due to extrinsic properties.

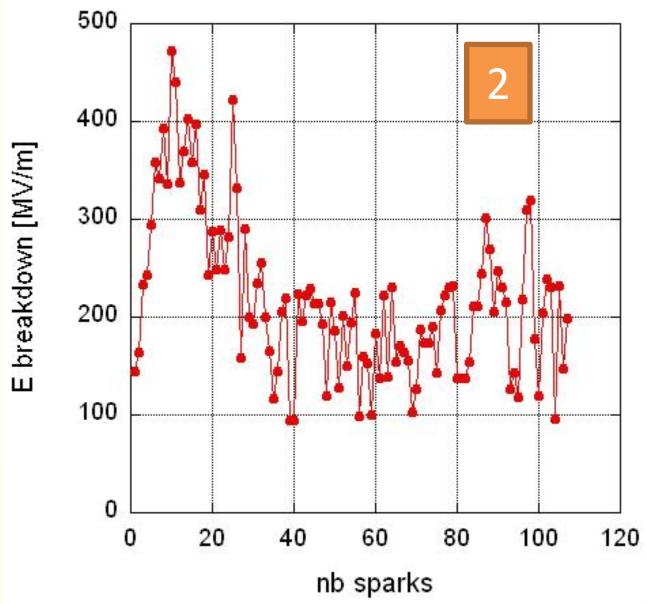
- More foreseen in the near future to assess the effect of etching, brazing, etc.

Oxidized copper

Cu_2O is a p-type semiconductor, with a higher work function than Cu : 5.37 eV instead of 4.65 eV

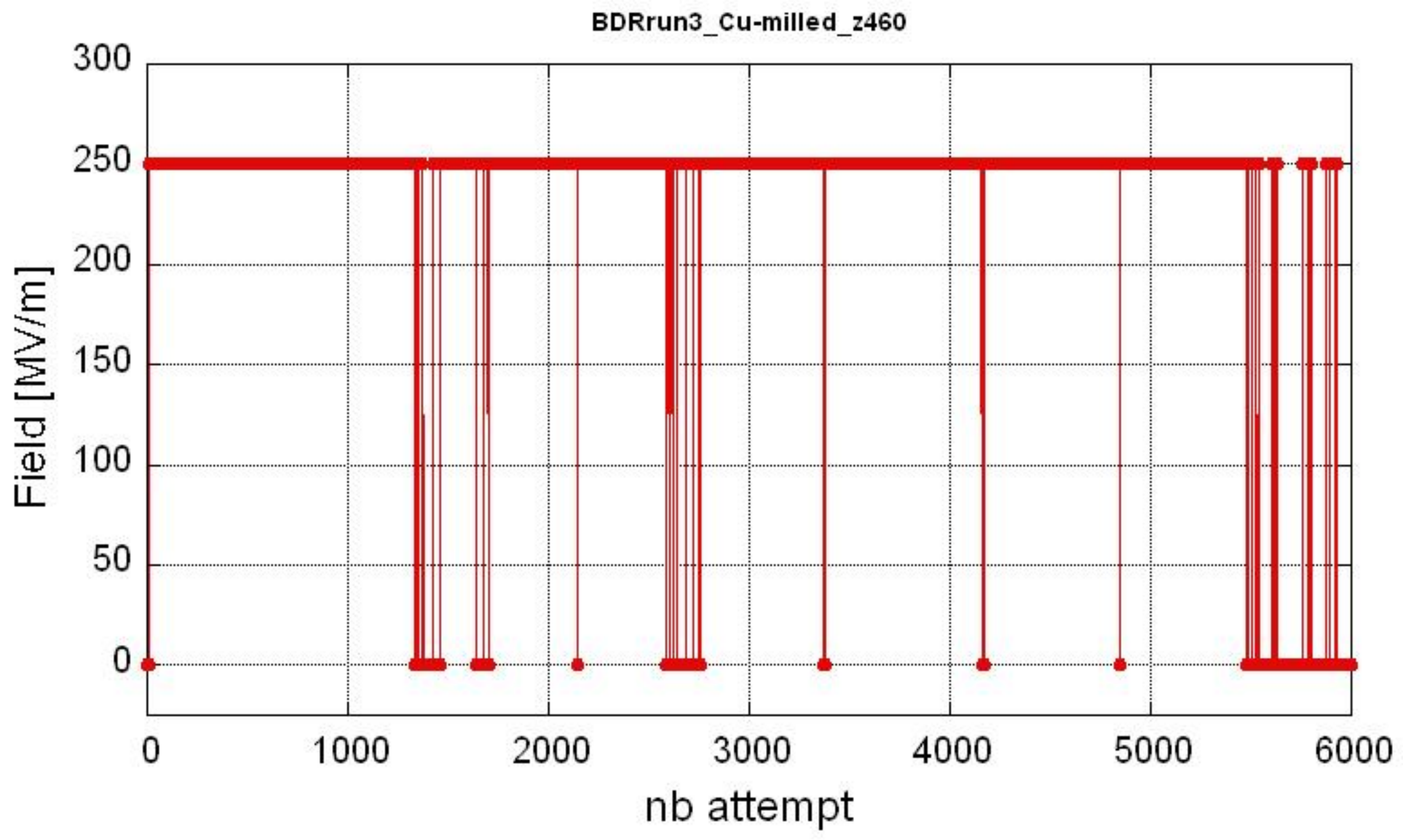
1. Cu oxidized at 125°C for 48h in oven (air): purple surface ↔ Cu_2O layer ~15 nm
2. Cu oxidized at 200°C for 72h in oven (air):





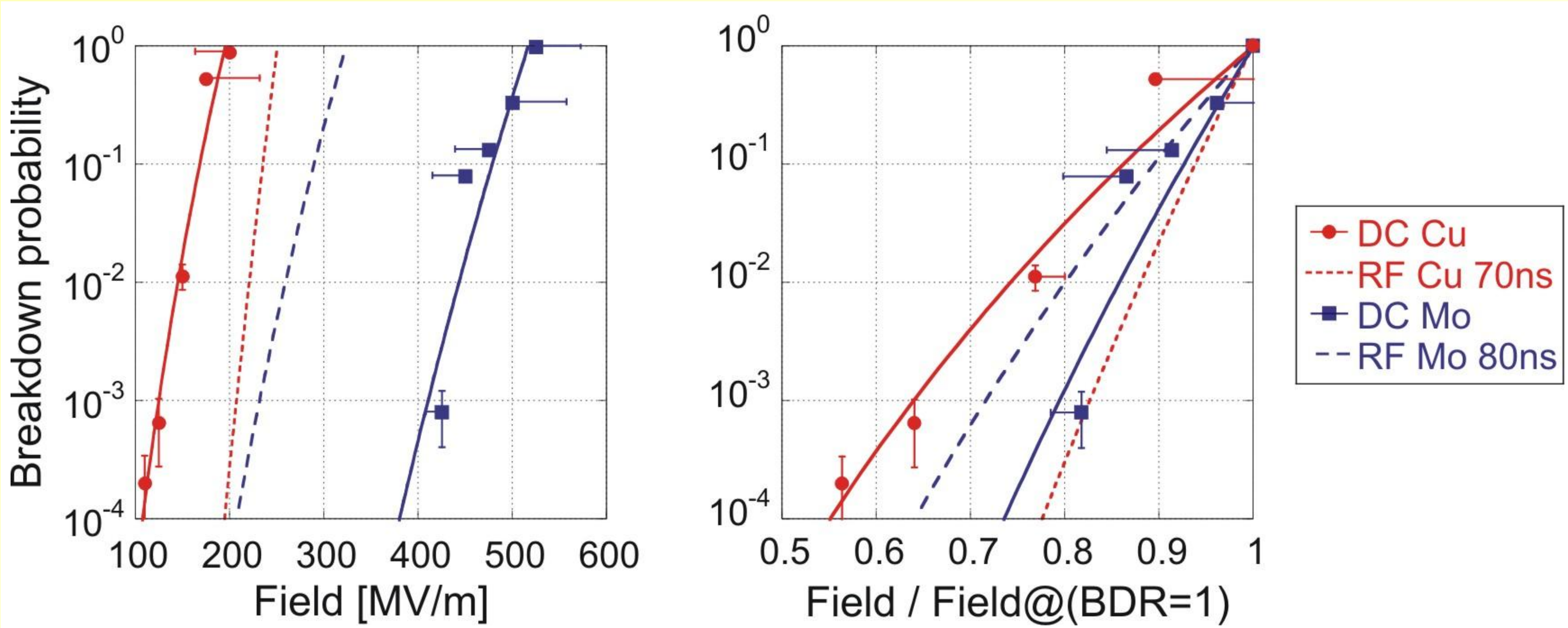
- BDR = 1 for standard Cu @ 300 MV/m
- BDR = $10^{-3} - 10^{-4}$ for oxidized Cu @ 300 MV/m, but last only a few sparks

Breakdown rate experiments



- A target field value is selected and applied repeatedly for 2 seconds
- BDR is as usual: #BD / total attempts
- Breakdown do often appear in clusters (a simple statistical approach can account for this)

Breakdown Rate : DC & RF (30 GHz)



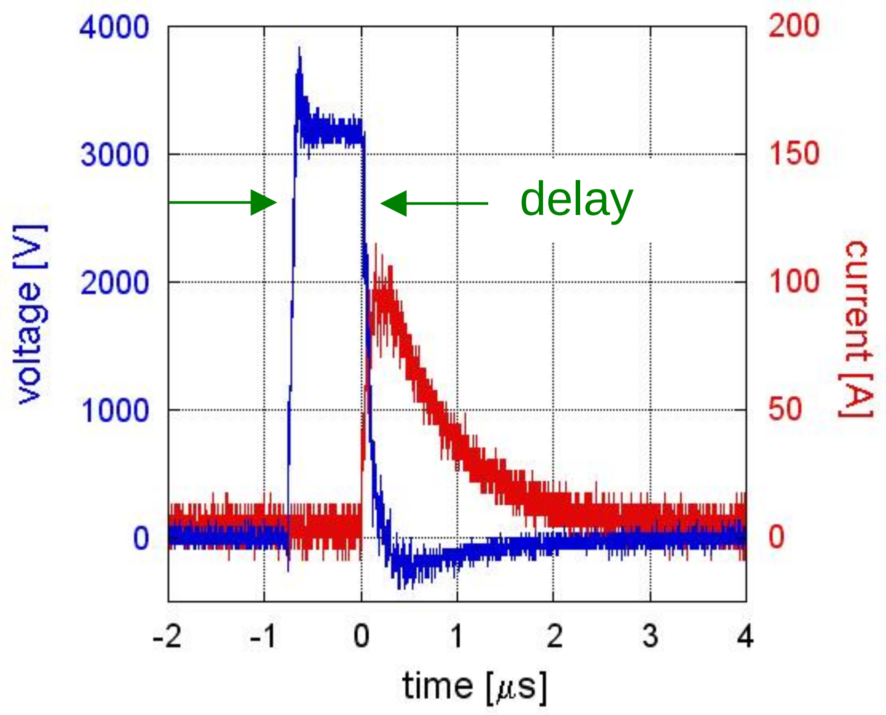
$BDR \sim E^{\gamma}$

γ	DC	RF
Cu	10 - 15	30
Mo	30 - 35	20

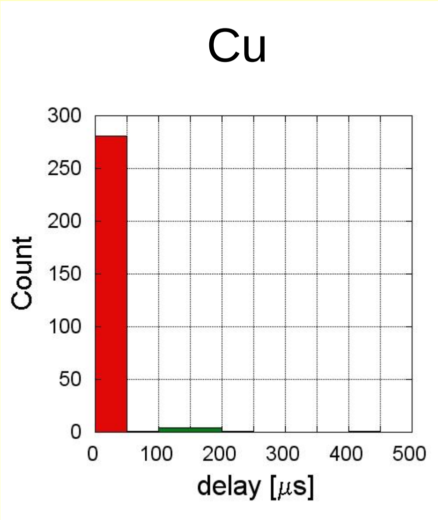
Same trend in DC and in RF, difficult to compare 'slopes'

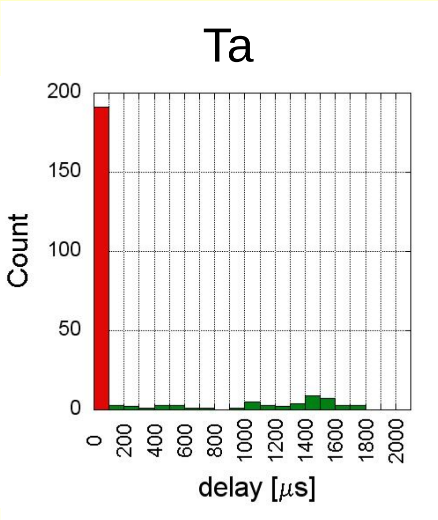
Time delays before breakdown

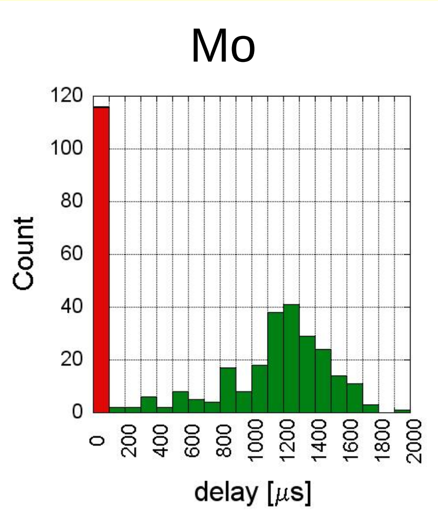
- Voltage rising time : ~ 100 ns
- Delay before spark : variable
- Spark duration : ~ 2 μs

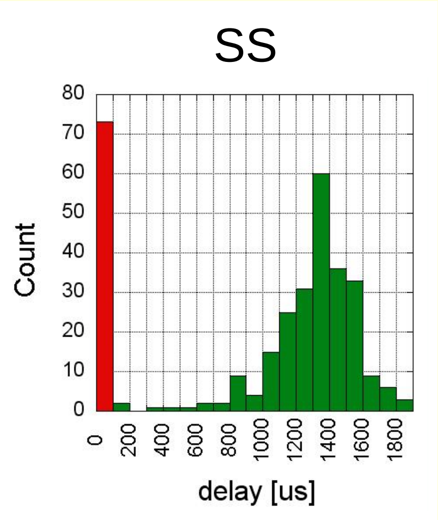


Time delays with different materials









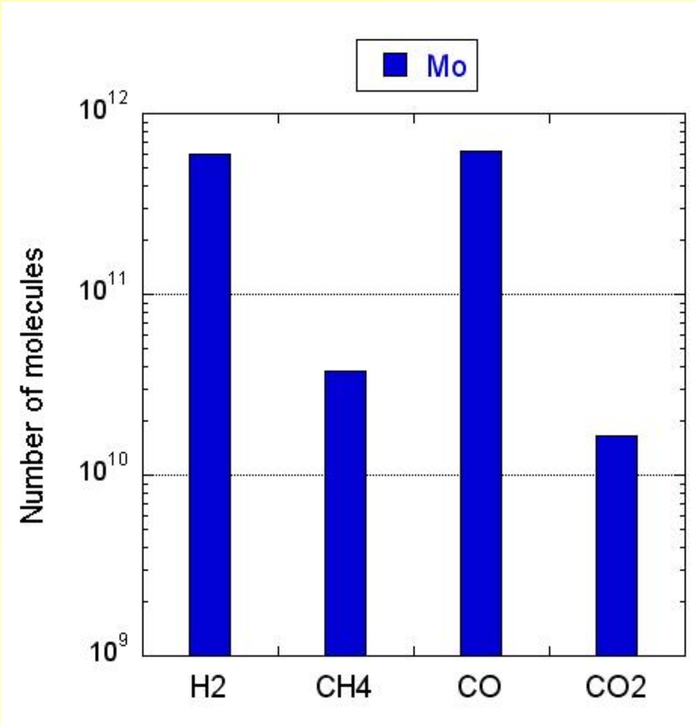
$\overline{E}_b$ = 170 MV/m | $\overline{E}_b$ = 300 MV/m | $\overline{E}_b$ = 430 MV/m | $\overline{E}_b$ = 900 MV/m

R = 0.07 | R = 0.29 | R = 0.76 | R = 0.83

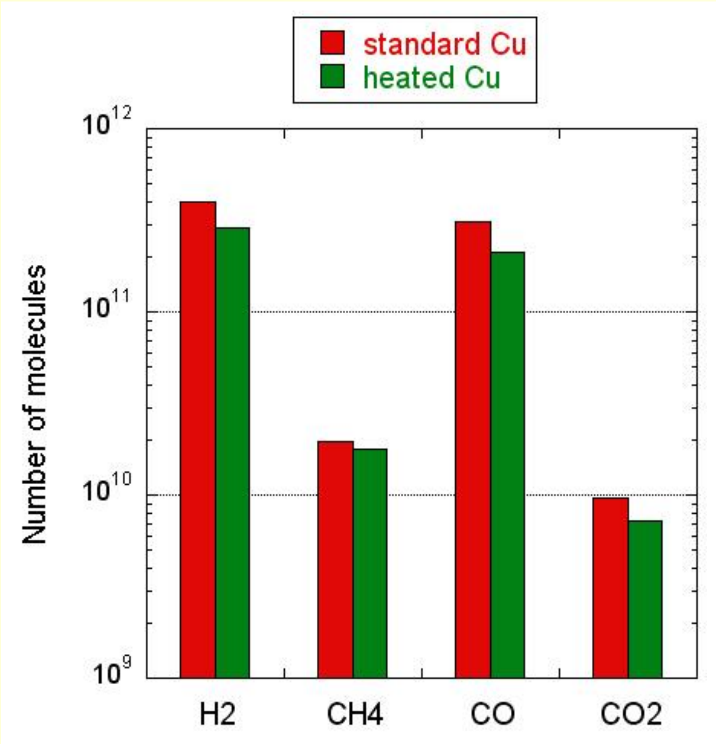
R = fraction of delayed breakdowns (excluding conditioning phase, where imediated breakdowns dominate)

→ R increases with average breakdown field *(but why ?!?)*

Gas released during a breakdown



0.95 J / spark



0.8 J / spark

(heat treatment: ex-situ, 815°C, 2h, UHV)

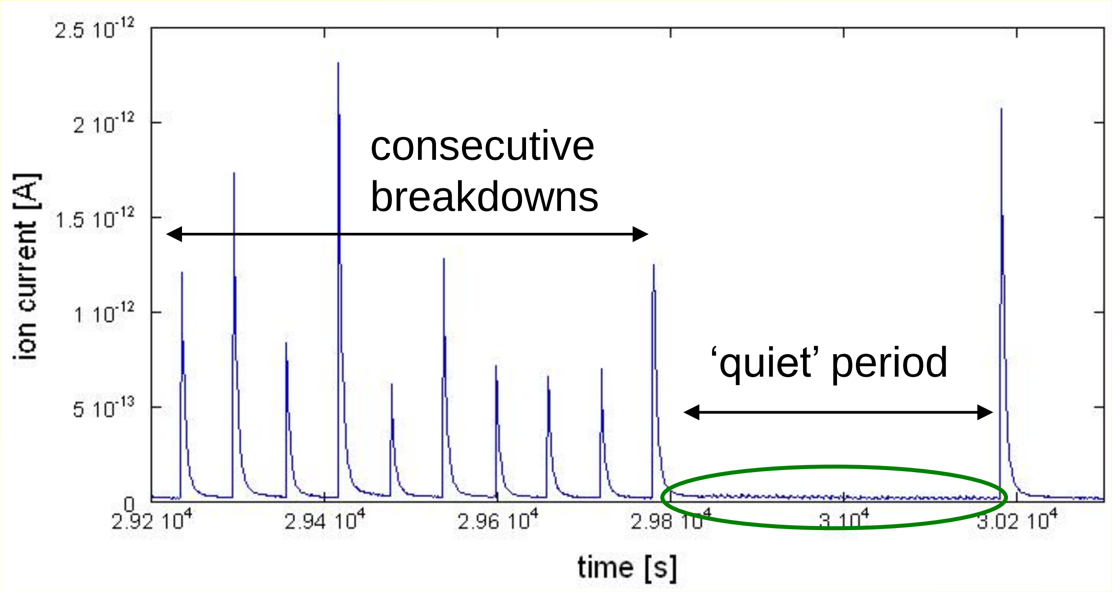
- Same gases released, with similar ratios
  - ➢ Outgassing probably dominated by Electron Stimulated Desorption (ESD)
- Slight decrease due to preliminary heat treatment
- Data used for estimates of dynamic vacuum in CLIC strucures

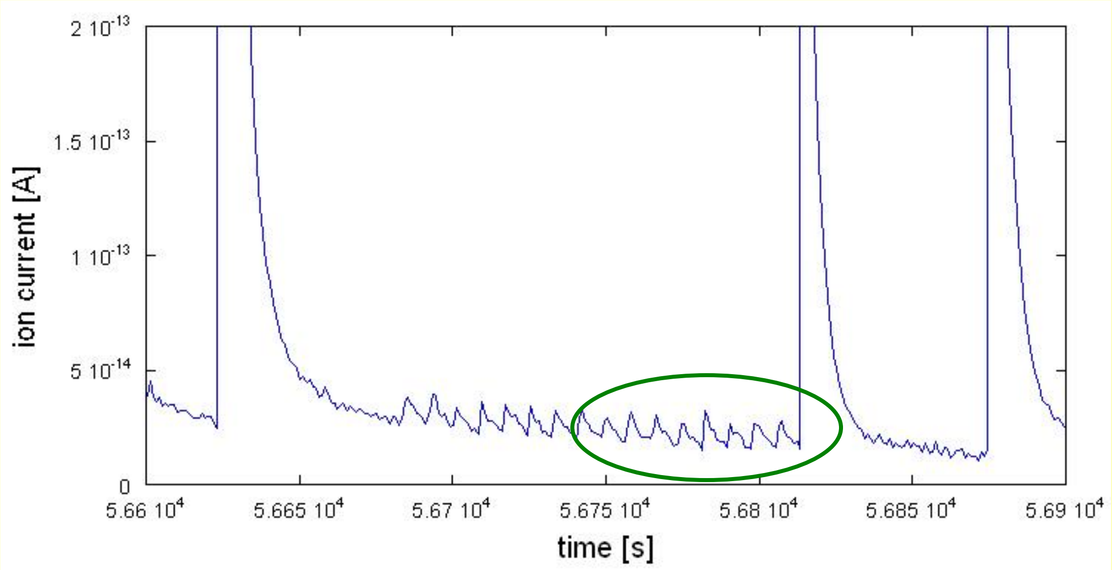
H_2 outgassing in Breakdown Rate mode (Cu)

Outgassing peaks at breakdowns

Slight outgassing during 'quiet' periods
→ ESD with FE e^- at the anode

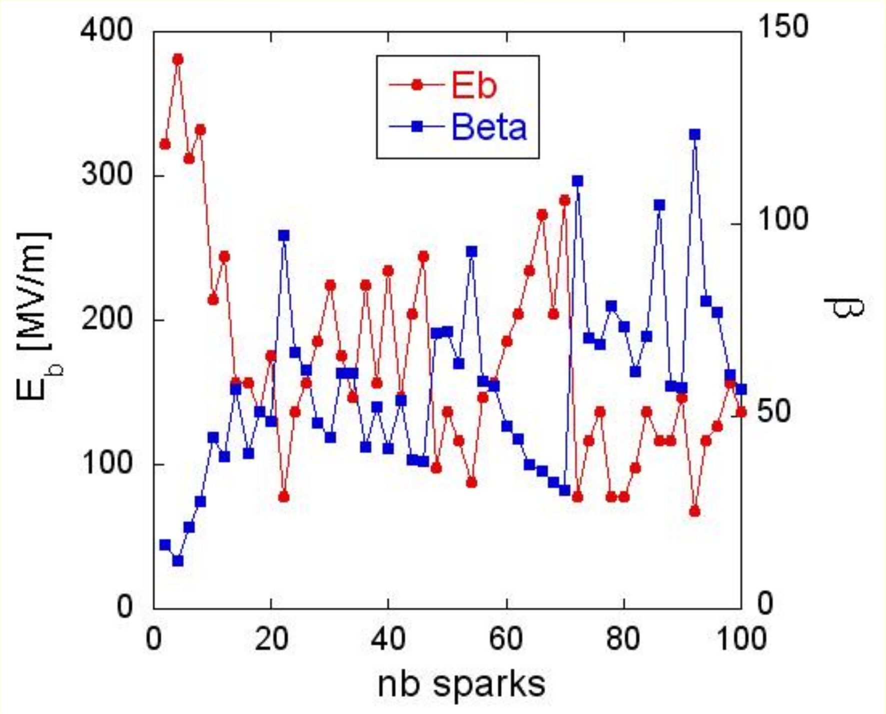
No visible increase in outgassing just before a breakdown



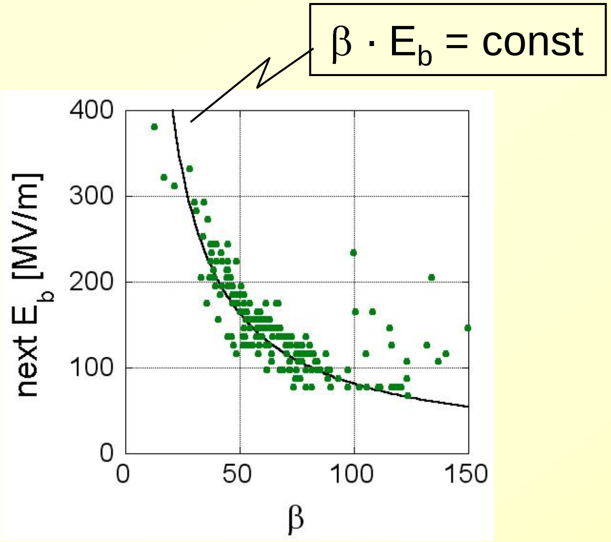


Local field: β· Eb (Cu)

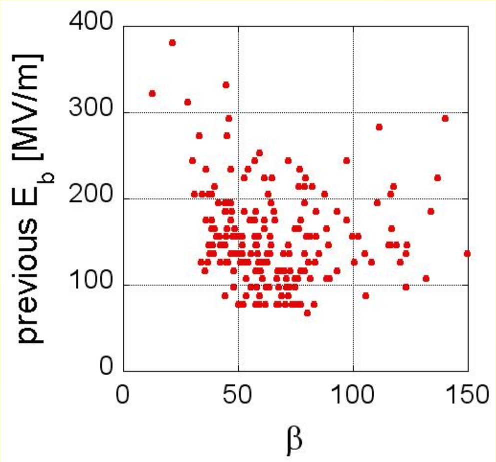
- Measurements of β after each sparks (Cu electrodes)



$\beta \leftrightarrow$ next E_b
correlation



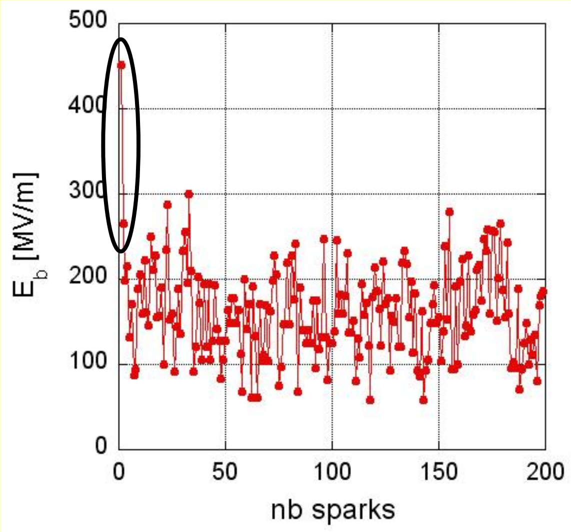
$\beta \leftrightarrow$ previous E_b
no correlation



→ $\beta \cdot E_b$ is the constant parameter

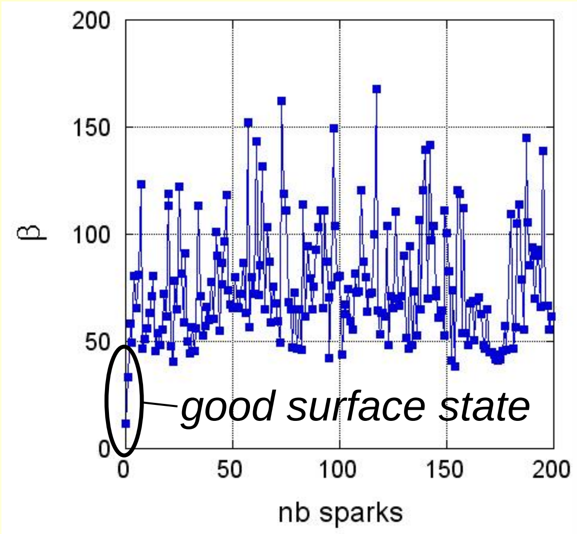
(cf. Alpert *et al.*, J. Vac. Sci. Technol., **1**, 35 (1964))

Evolution of β & Eb during conditioning experiments



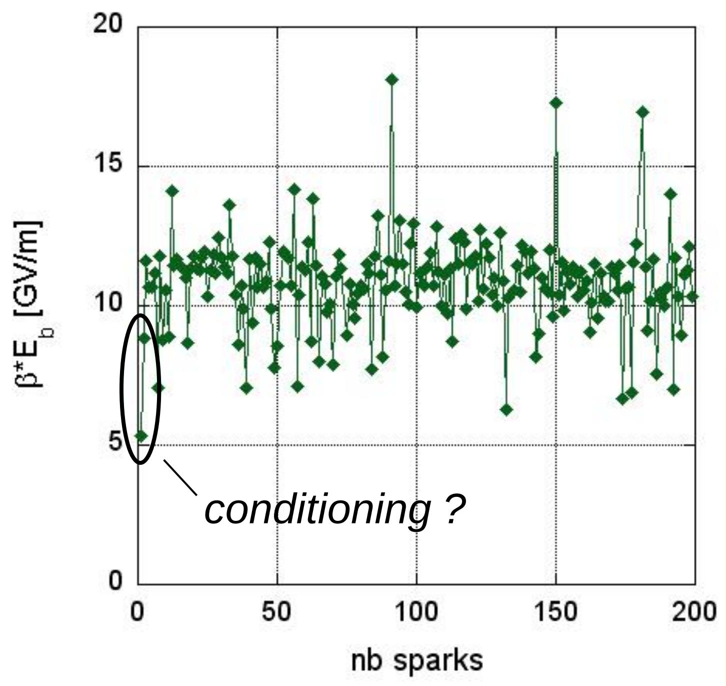
$\overline{E_b}$ = 159 MV/m

(± 32%)



$\overline{\beta}$ = 77

(± 36%)

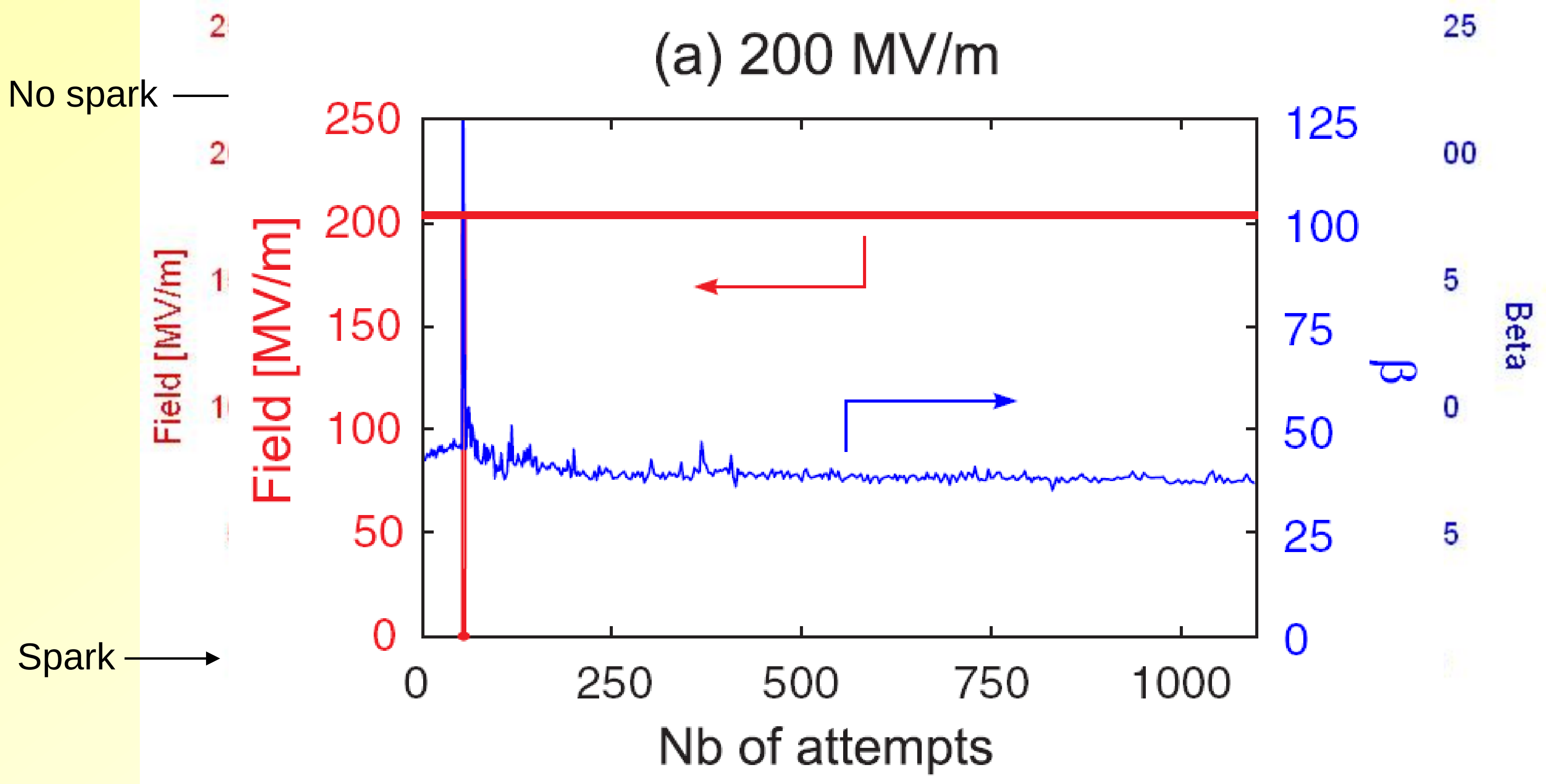


$\overline{\beta \cdot E_b}$ = 10.8 GV/m

(± 16%)

→ Local field = const = 10.8 GV/m for Cu

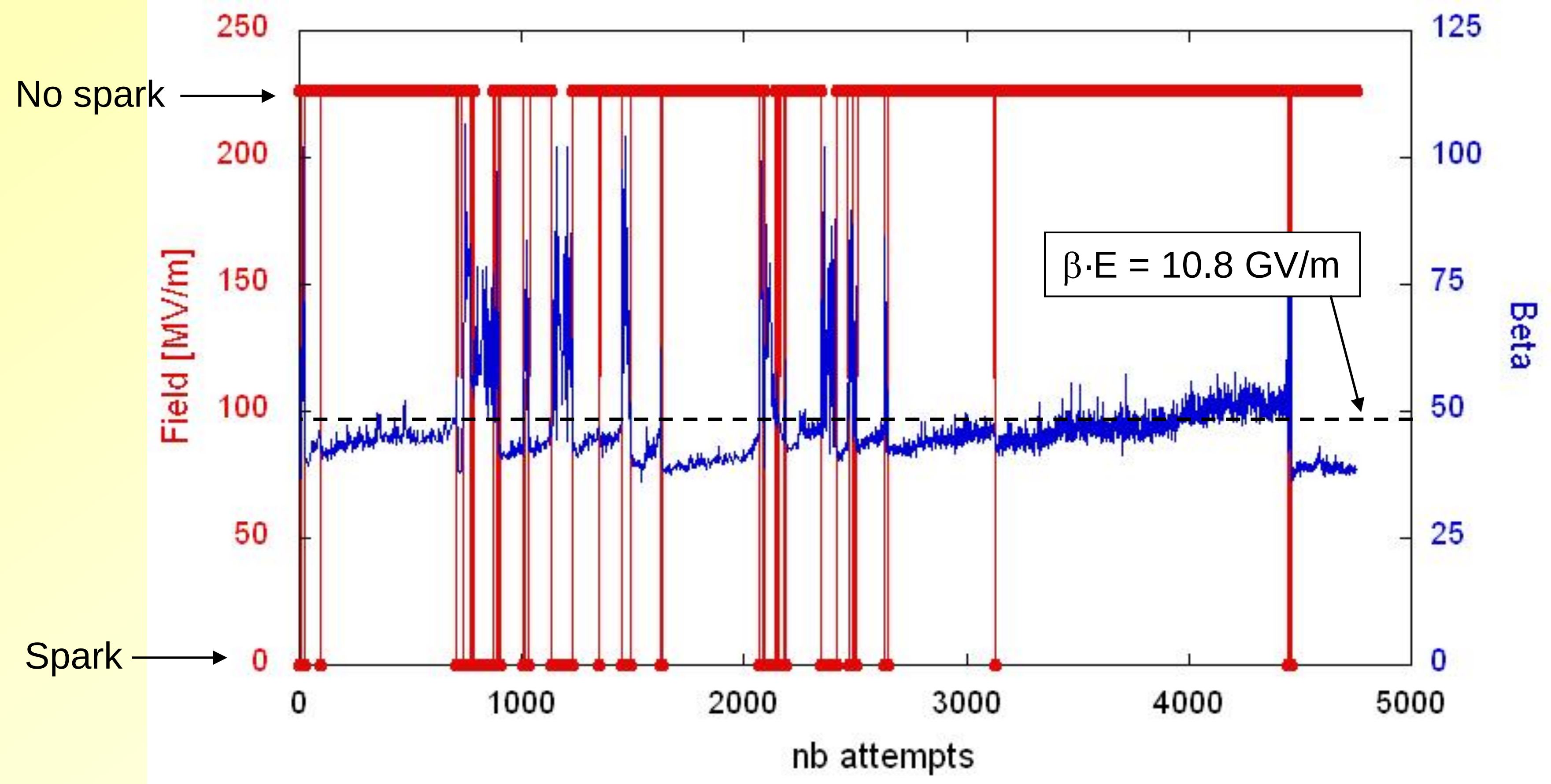
Evolution of β during BDR measurements (Cu)



- General pattern : clusters of consecutive breakdowns / quiet periods (here BDR = 0.11)
- β slightly increases during a quiet period ***if E is sufficiently high***

The surface is modified by the presence of the field (are « tips » pulled?)
Probably the single most important result from DC-spark

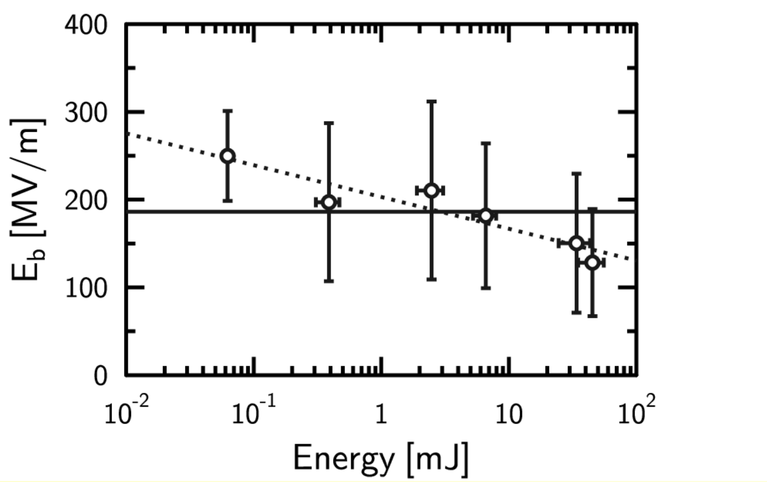
Evolution of β during BDR measurements (Cu)

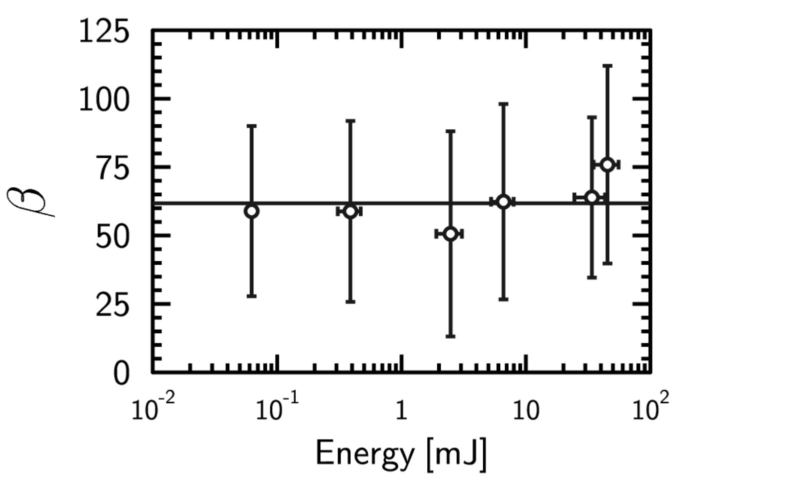


- Breakdown as soon as $\beta > 48$ (↔ $\beta \cdot 225$ MV/m > 10.8 GV/m)
- Consecutive breakdowns as long as $\beta > \beta_{threshold}$

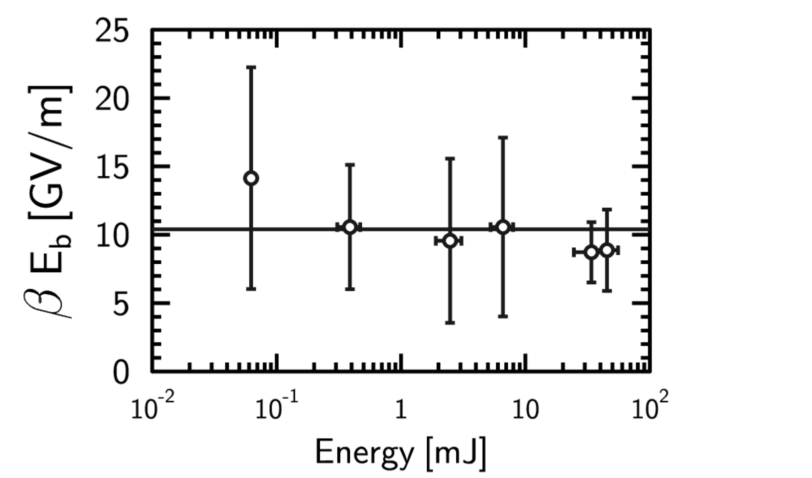
length and occurence of breakdown clusters ↔ evolution of β

Effect of spark energy - Cu

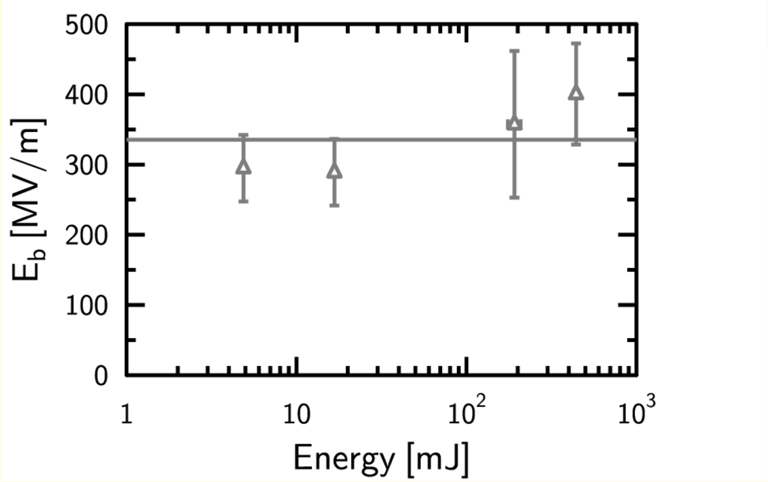


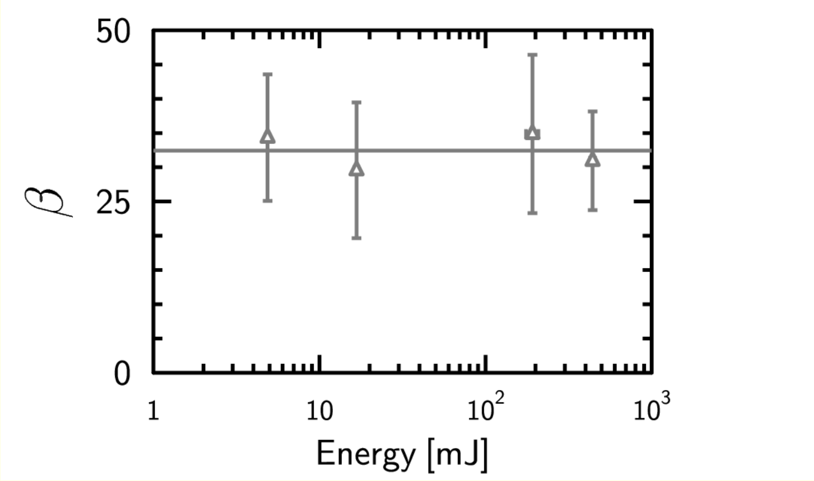


- E_{BRD} increases with lower energy (less deconditioning is possible)
- Local breakdown field remains constant

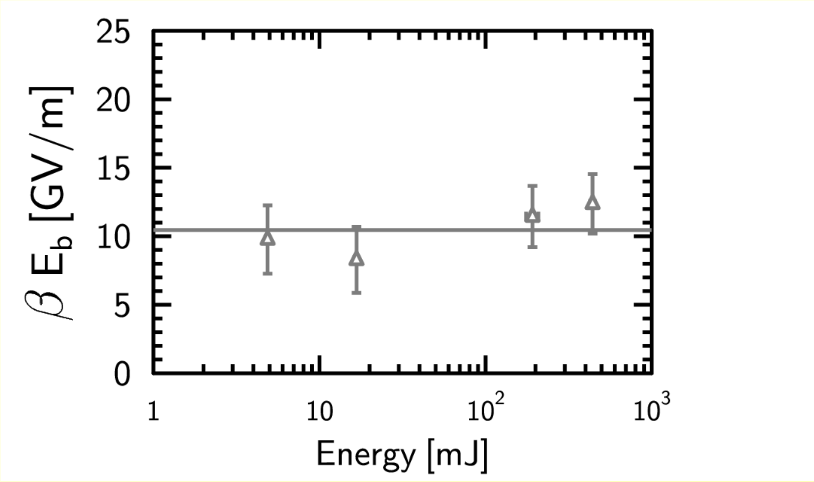


Effect of spark energy - Mo



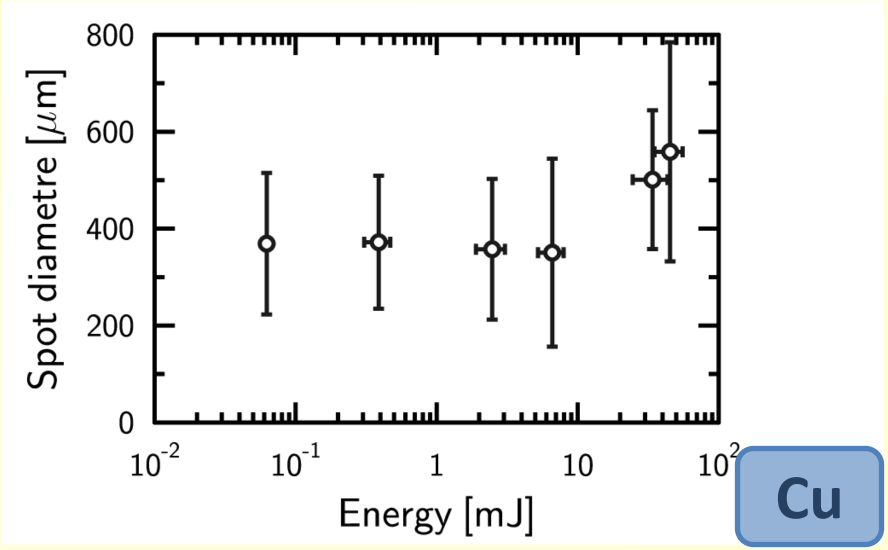


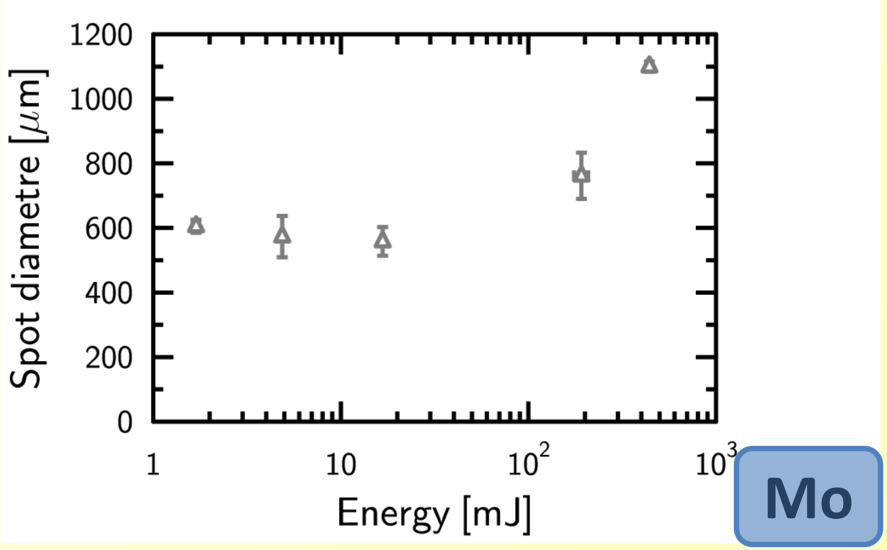
- E_{BRD} seems to increase with higher energy (better conditioning possible)
- Local breakdown field remains constant
- However, we have doubts on representative the β measurement is in this case



Energy scaling of the spot size

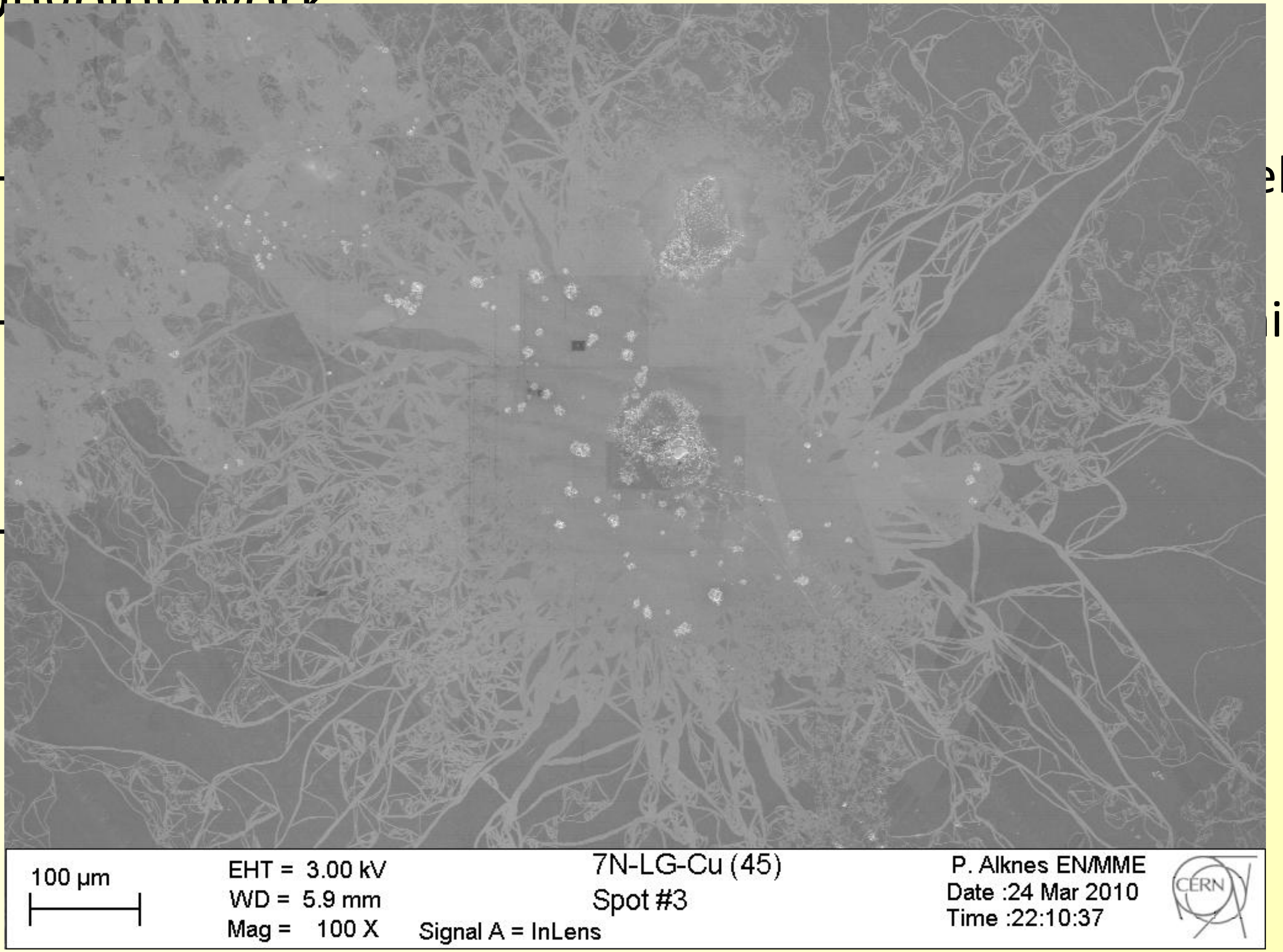
- The diameter of the damaged area depends on the energy available
  - Area mostly determined by the conditioning phase
  - Decreases with decreasing energy; saturates below a given threshold





The future

- Ongoing work:



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The future

- Effect of temperature on β evolution and other properties

  – To verify the dislocation motion in c ngle crystals

The future

- Effect of surface treatment and in general of the fabrication process on BD
  - To study the influence of etching and its link with machining (preferential etching at dislocations, field enhancement or suppression, smoothening etc.)
  - To study the influence of H_2 bonding (faceting, etc)
  - (In parallel, ESD studies on the same samples)

The end

Many thanks to all those who participated in the years