Surface roughness and field emission measurements on diamond turned Cu samples

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- Motivation and strategy
- Measurement techniques and samples
- Surface quality
- Field emission (FE) results
- Conclusion and outlook

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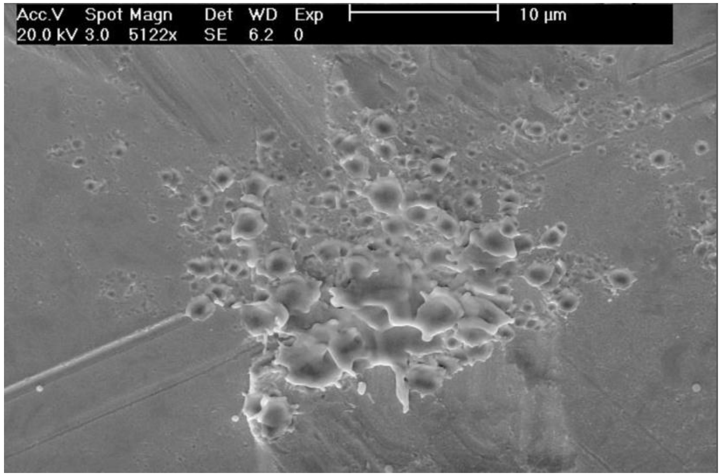
Motivation and strategy

- Dark current/Electric **Breakdown** is the main field limitation of accelerating structures for CLIC (E_{acc}=100 MV/m, E_{pk}=243 MV/m)
- Deep and quantitative understanding of the origins of breakdown processes is important
- Investigation of the Cu surface quality after different fabrication procedures



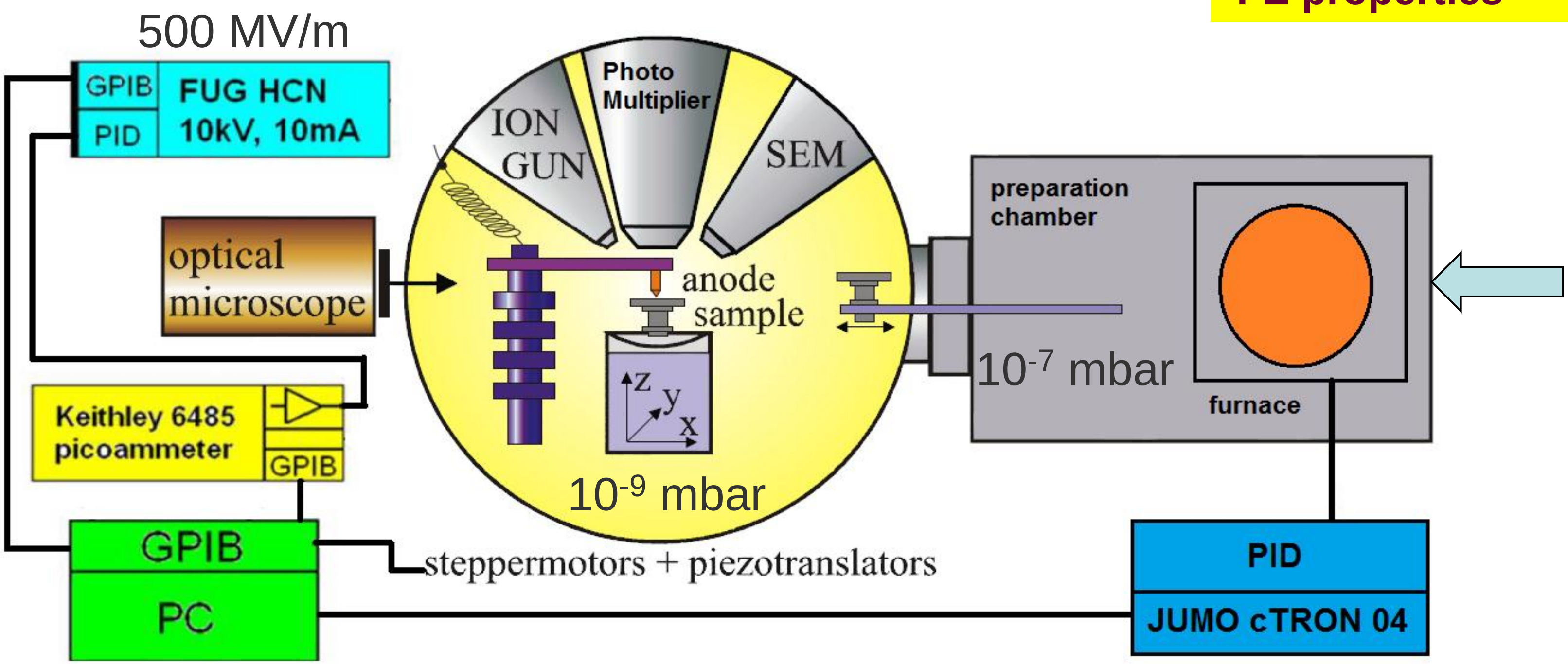
Strategy

1. Preparation of Cu samples with all/selected preparation steps
2. Investigation of the actual surface quality. Roughness? Cleanliness?
3. **Measuring** of the initial enhanced field emission (EFE, dark currents) of the samples after the preparation
4. Investigation of the EFE from single emitters. Stability?
5. High resolution SEM **identification** of the emitting defects (if possible)

Presenting here: First results of surface quality measurements and EFE measurements

FE & SEM measurement techniques

Field emission scanning microscope (FESM): → **- localisation of emitters**
- FE properties

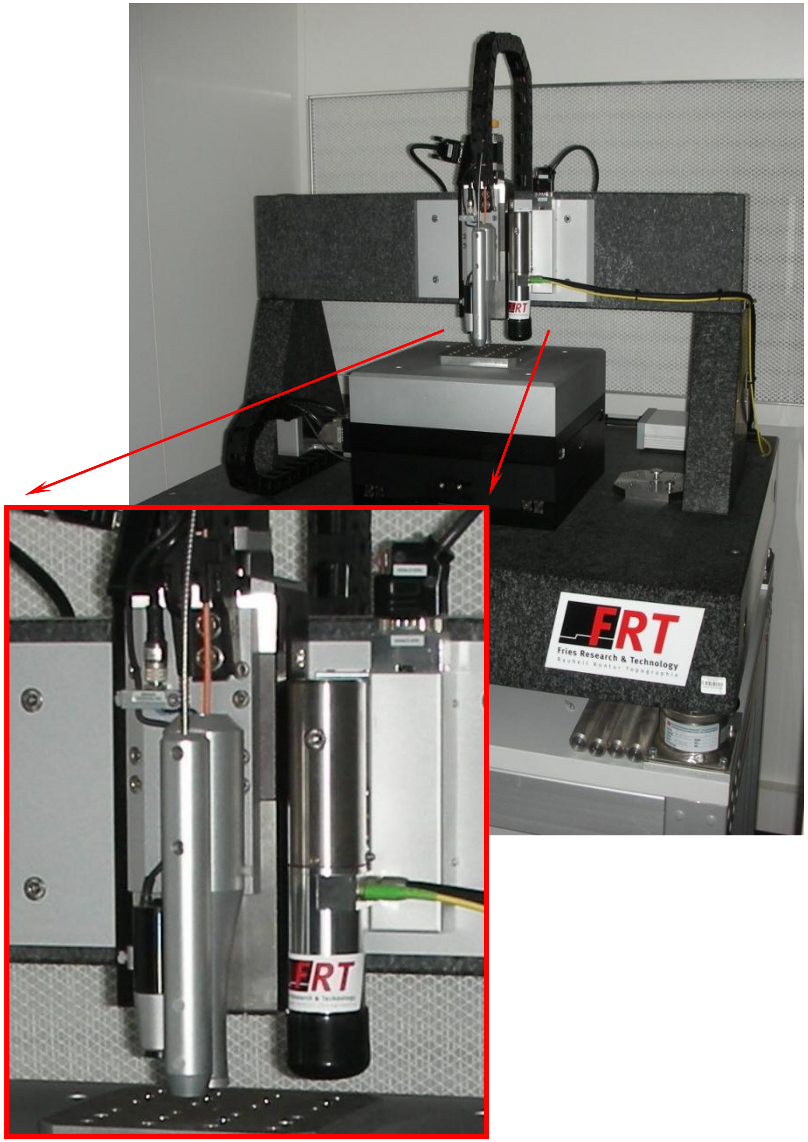


- Regulated V(x,y) scans for FE current I=1 nA & gap Δz $\Rightarrow$ emitter density at $E=U/\Delta z$
- Spatially resolved I(E) measurements of single emitters $\Rightarrow$ E_{on}, β_{FN}, S
- Ion bombardment (**Ar,** E_{ion}= 0 – 5 kV) and SEM (low res.)
- In-situ heat treatments up to 1000°C

Ex-situ SEM + EDX → **Identification of emitting defects**

Correlation of surface features to FE properties (positioning accuracy ~ ±100 µm)

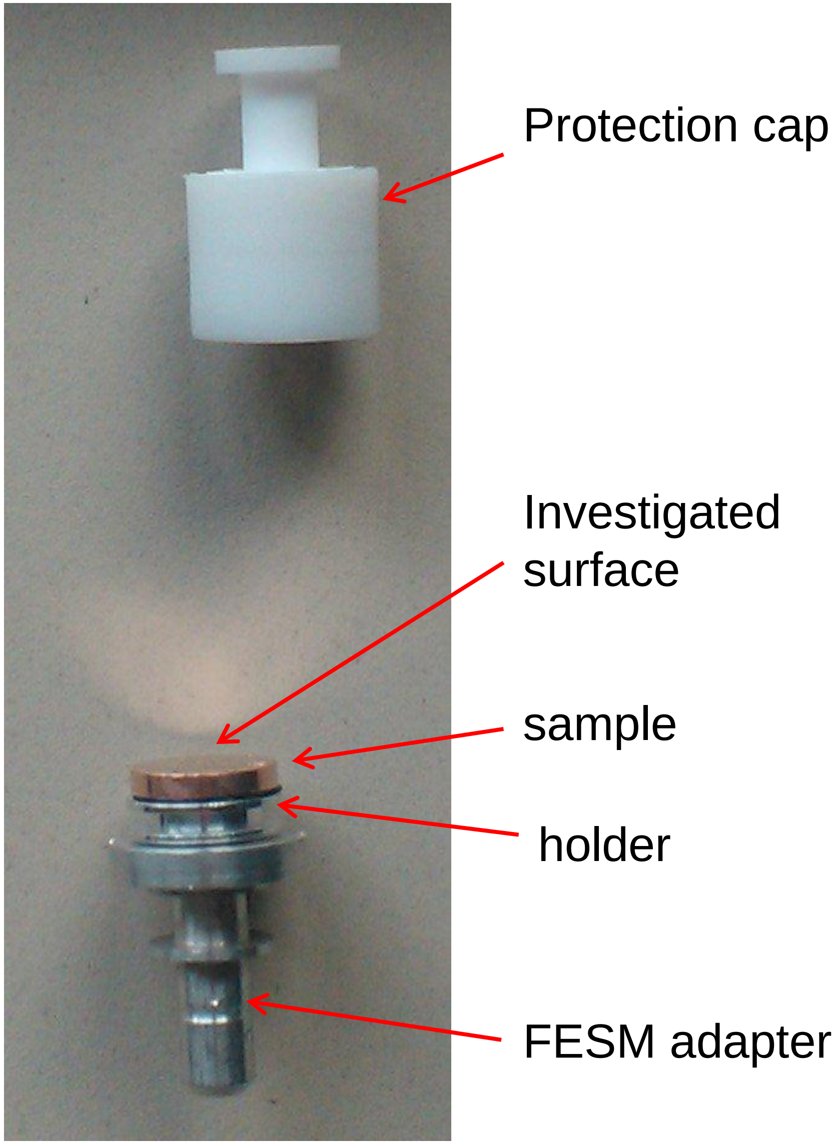
Optical profilometer (OP) with atomic force microscope (AFM):



- Full surface quality scans by OP:
  - white light irradiation and spectral reflection (chromatic aberration)
  - up to 20×20 cm^2 and 5 cm height difference
  - 2 µm (3 nm) lateral (height) resolution
- further zooming by AFM:
  - ±2 µm precision of positioning with respect to the optical profilometer
  - 95x95 $µm^2$ scanning range
  - 3 (1) nm lateral (height) resolution
  - contact or non-contact modes
- CCD camera for positioning control
- granite plate with an active damping system for undisturbed nm measurement
- clean laminar air flow from the back to reduce particulate contamination

→ - surface roughness
- defect geometry

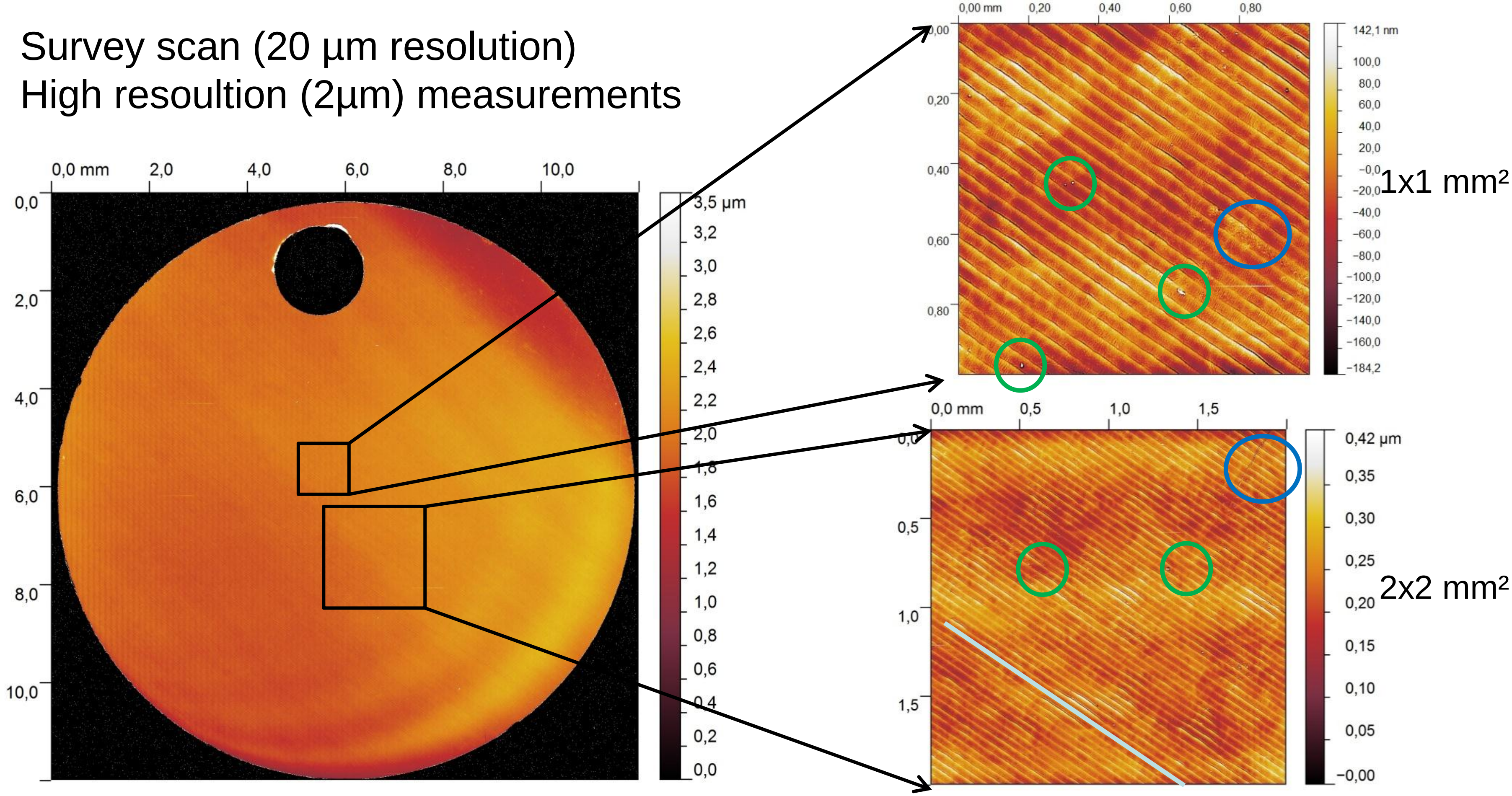
Samples



- Two flat **Cu** samples
- Diameter: ~11 mm
- One hole as mark to identify the position in different systems
- Diamond turned and glued to a sample holder at CERN
- Mounted to an adapter for the FESM at BUW
- Surface cleaned with **ionized N_2**, cleanroom condition (class 100) with 5 bar pressure
- **Teflon protection cap** to avoid damage and contaminations after polishing and cleaning
- Only 1 sample measured yet

Surface quality (OP)

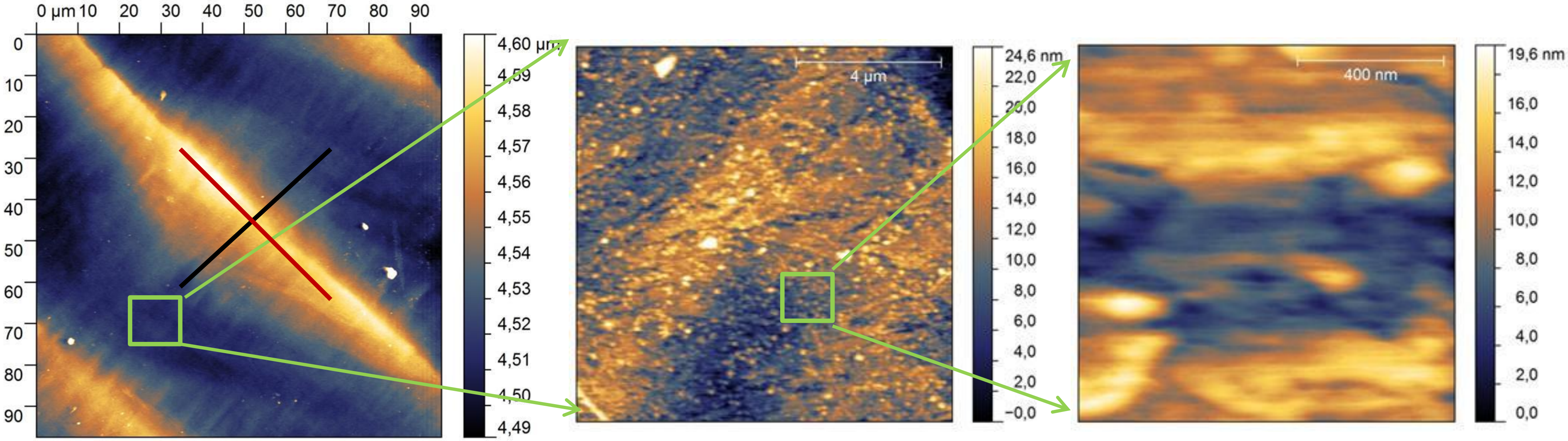
1. Survey scan (20 µm resolution)
2. High resoultion (2µm) measurements

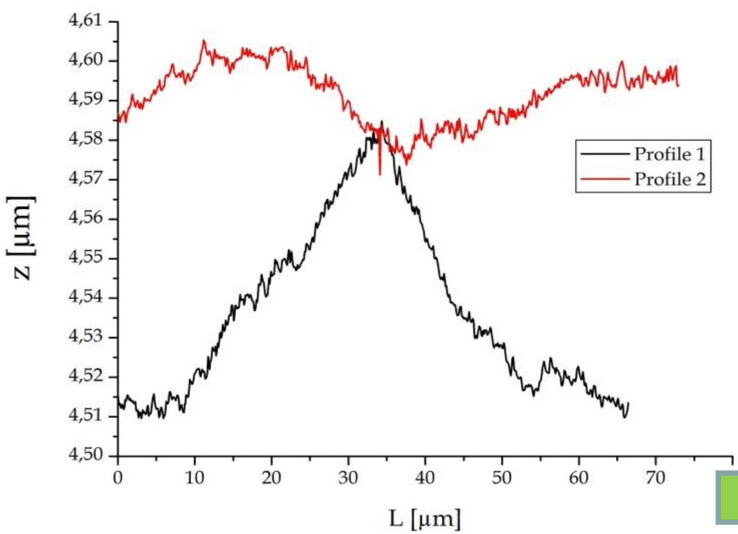


- Few **particles**/**scratches** can be found (d ≥ 1 µm)
- **Ridges** as result of diamond turning?
- Slightly waved surface (λ~ 0,5 – 1 mm)

Surface quality (AFM)

AFM scan of ridges





- More particles (Ø = 0.6 – 3 µm) observed
- Polycrystalline structure? (d_{grain} ~ 60 nm)
- Ridges:
  - Height h = 70 nm
  - Curvature radius r = 30 – 50 nm

Calculation of roughness and estimation of geometric field enhancement factor for FE

Roughness and geometric field enhancement

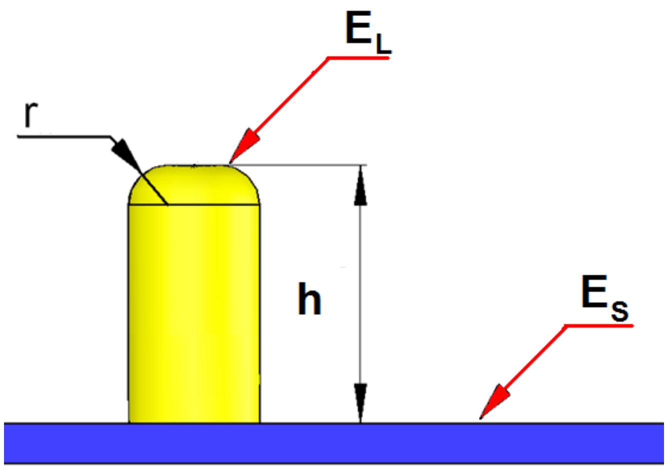
Surface roughness:

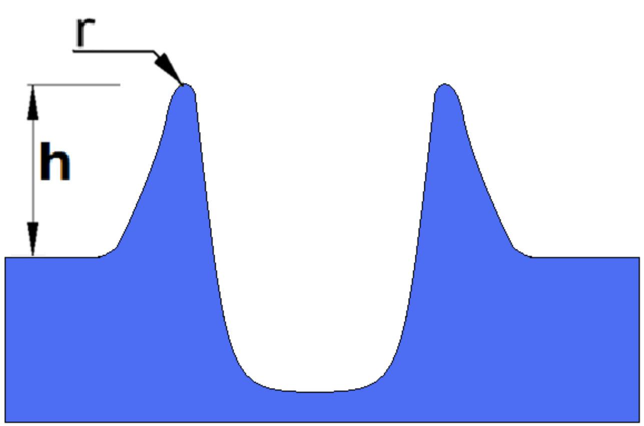
$$R_a = \frac{1}{n \cdot m} \sum_{i=1}^{n} \sum_{j=1}^{m} \left| z(x_i y_j) - \bar{z} \right|$$

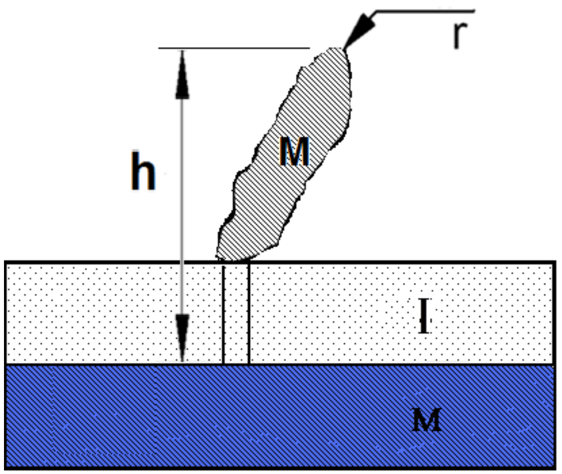
$$R_q = \sqrt{\frac{1}{n \cdot m} \sum_{i=1}^{n} \sum_{j=1}^{m} \left(z(x_i y_j) - \bar{z} \right)^2}$$

$z(x_i, y_j)$ = actual height value of profile
n, *m* = No. of points in *x* and *y* direction
$\bar{z}$ = average height value

particles / protrusions: **scratch:** **metal-insulator-metal (MIM):**







Electric field enhancement factor:

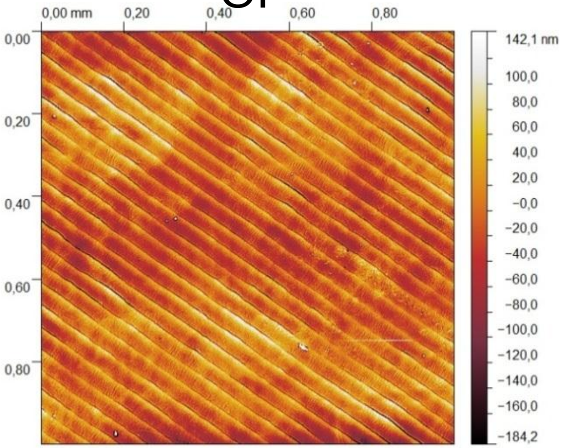
$$\beta_E \approx \frac{h}{r} + 2{,}5 \Rightarrow E_L = \beta_E E_S$$

$$S \approx 2\pi r^2$$ → emission area

h = height of defect
r = curvature radius
E_L = local electric field on defect
E_S = electric field on flat surface

Surface roughness

OP



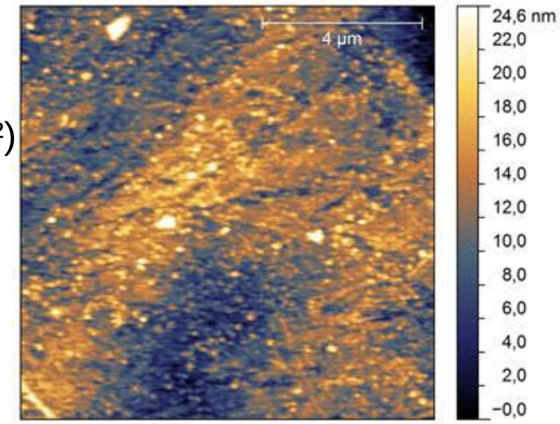
R_a=126 nm
R_q=145 nm
(2x2 mm²)

R_a=43 nm
R_q=54 nm
(1x1 mm²)

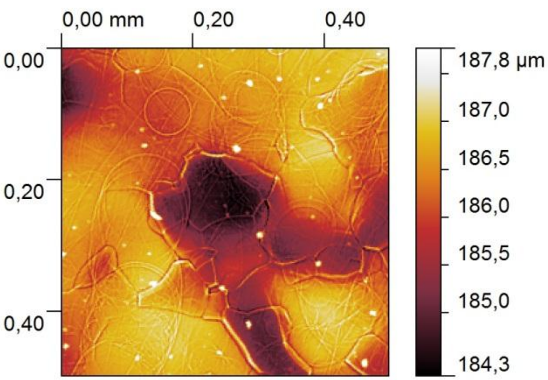
AFM

R_a=20 nm
R_q=24 nm
(100x100 µm²)

R_a=3 nm
R_q=4 nm
(10x10 µm²)

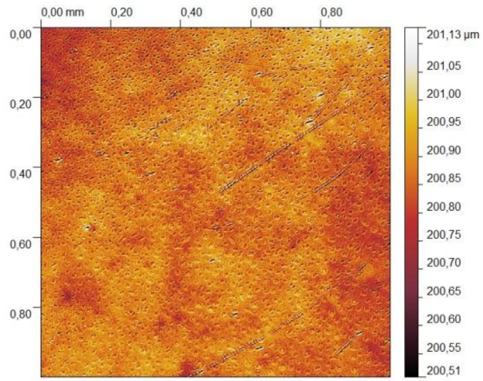


Comparison with Nb (OP):



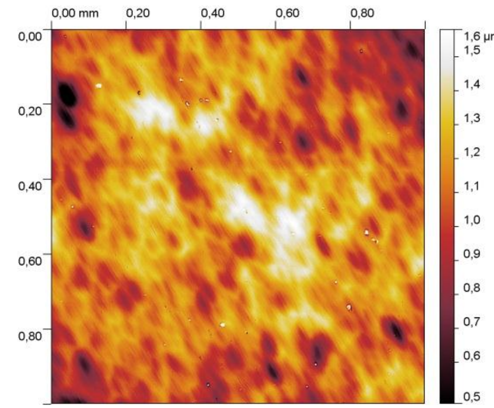
100 µm EP, polycrystalline

R_a=518 nm, R_q=646 nm, (0,5x0,5 mm²)



40 µm BCP, single crystal (DESY)

R_a=57 nm, R_q=77 nm, (1x1 mm²)

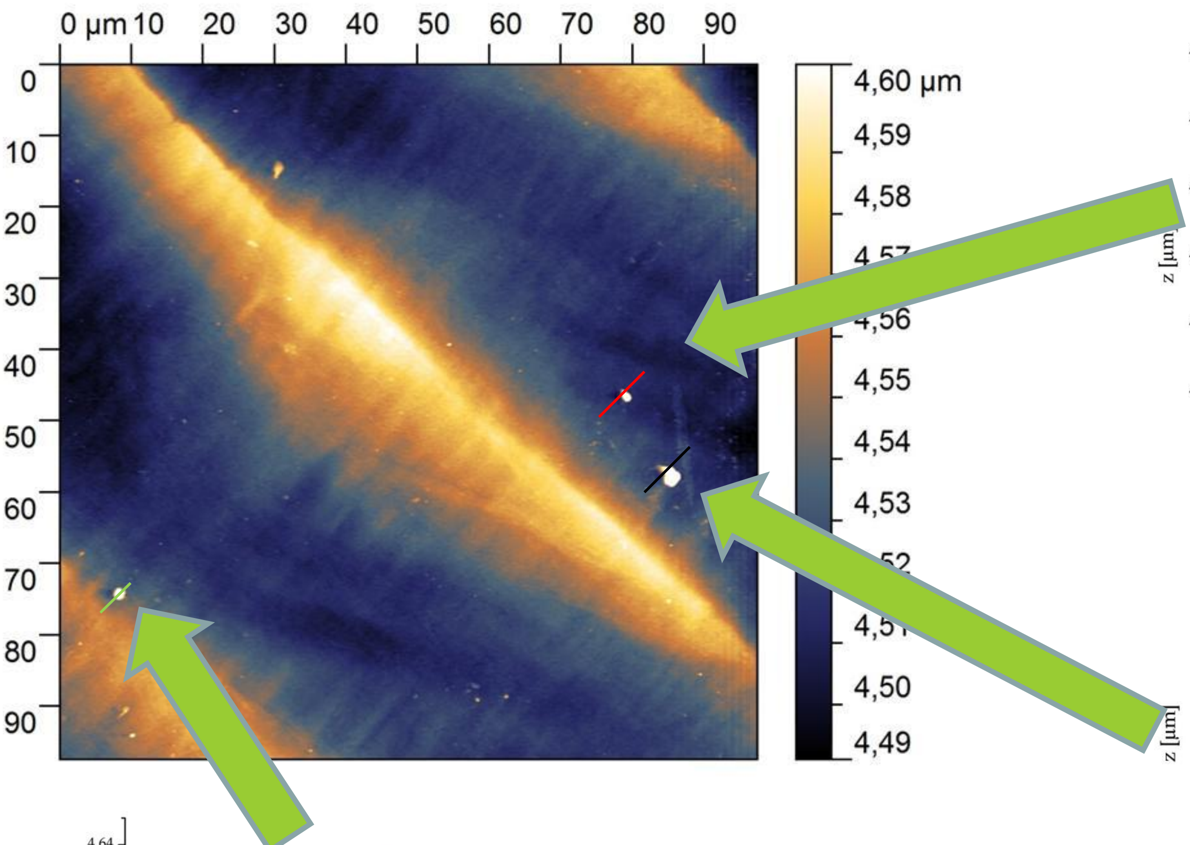


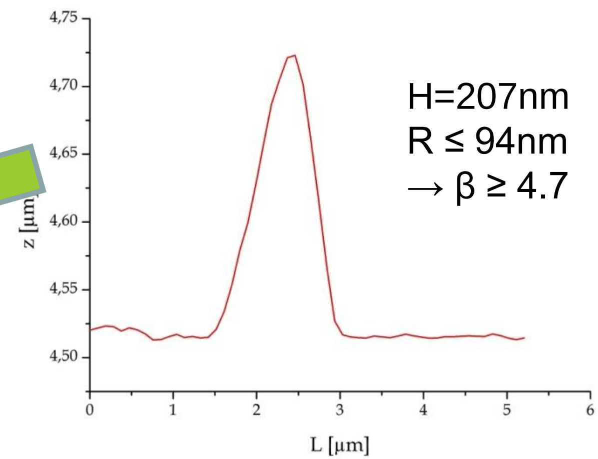
120 µm BCP, single crystal (JLAB)

R_a=126 nm, R_q=165 nm, (1x1 mm²)

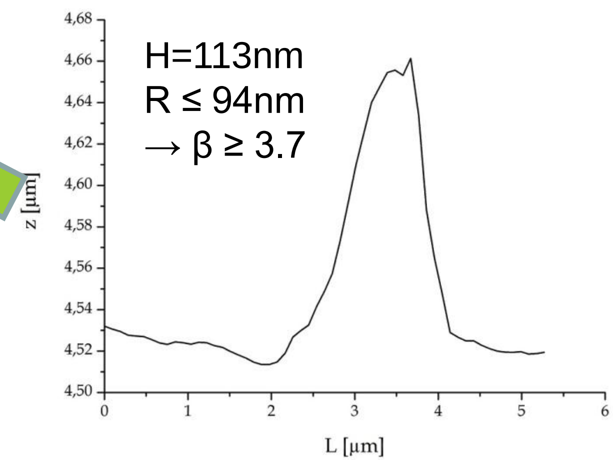
Even without electrochemical polishing: very flat surface!

Estimation of β_{geo} for particulets

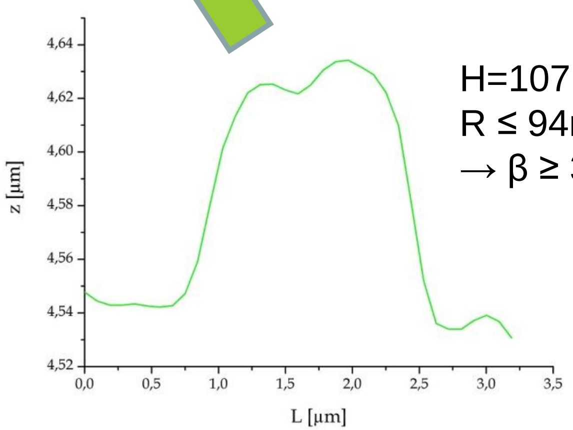




H=207nm
R ≤ 94nm
→ β ≥ 4.7



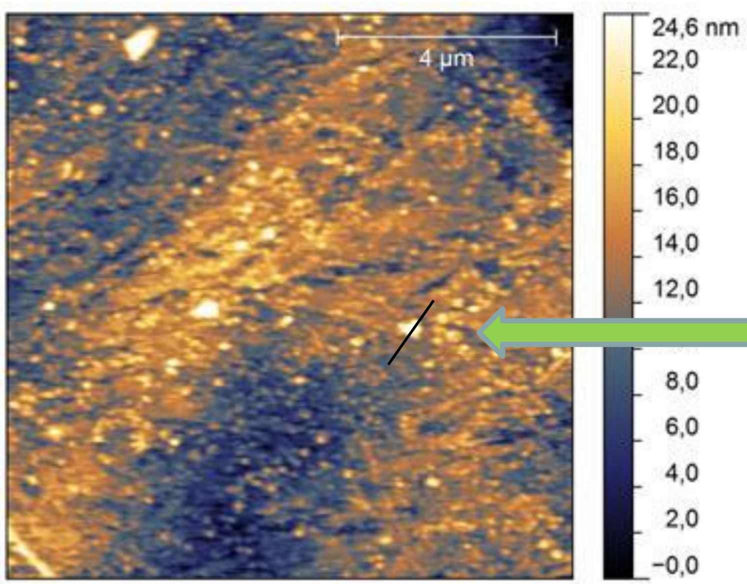
H=113nm
R ≤ 94nm
→ β ≥ 3.7

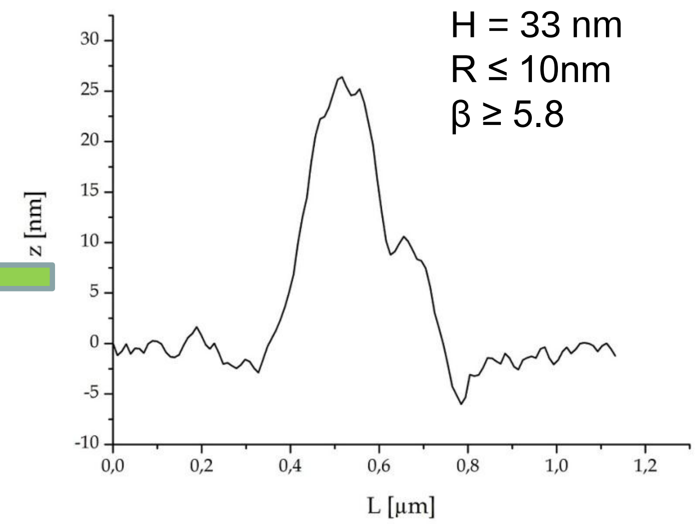


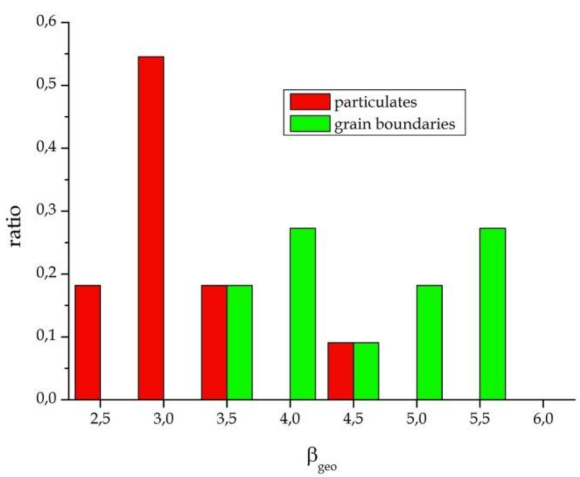
H=107nm
R ≤ 94nm
→ β ≥ 3.6

- Many particles: H < R, only few with β > 2.5
- Only low values for β_{geo}
- What about polycrystalline structure?

Estimation of β_{geo} for grain boundaries







- Grain boundaries: slightly higher β_{geo}
- Altogether only low β values
- At which field EFE sets in?

$$j(E) = \frac{A(\beta E)^2}{\phi t(y)^2} e^{-\frac{B\phi^{3/2}\nu(y)}{\beta E}}$$

Modified Fowler-Nordheim (FN) law

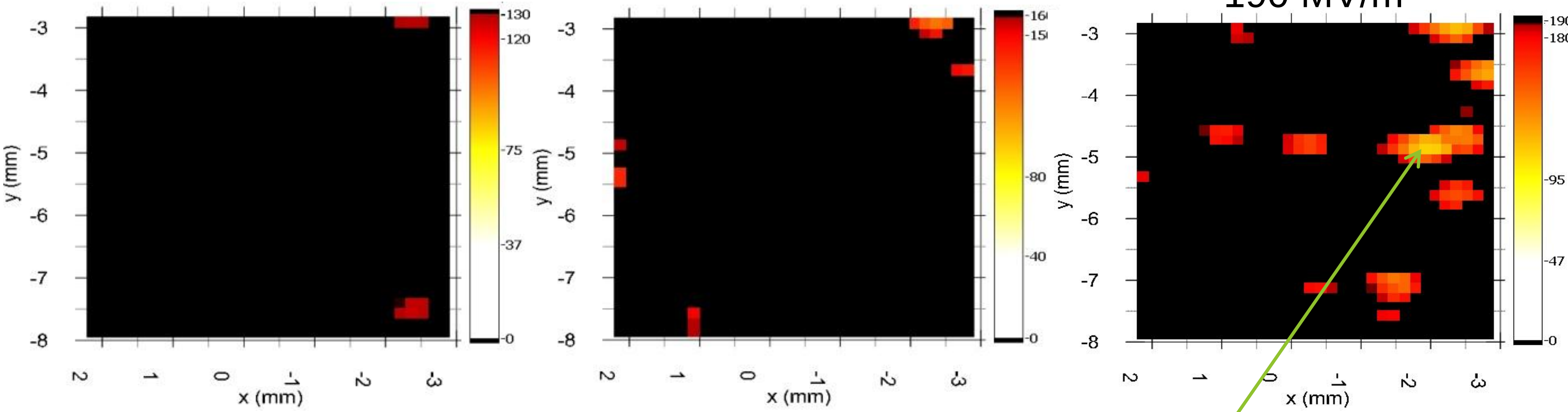
$$\nu(y) = t(y) \approx 1$$
$$y = \Delta\phi/\phi$$
$$A = 154, B = 6830$$

With β = 5,8: 1 nA/µm² at ~500 MV/m (Φ=4,4 eV)

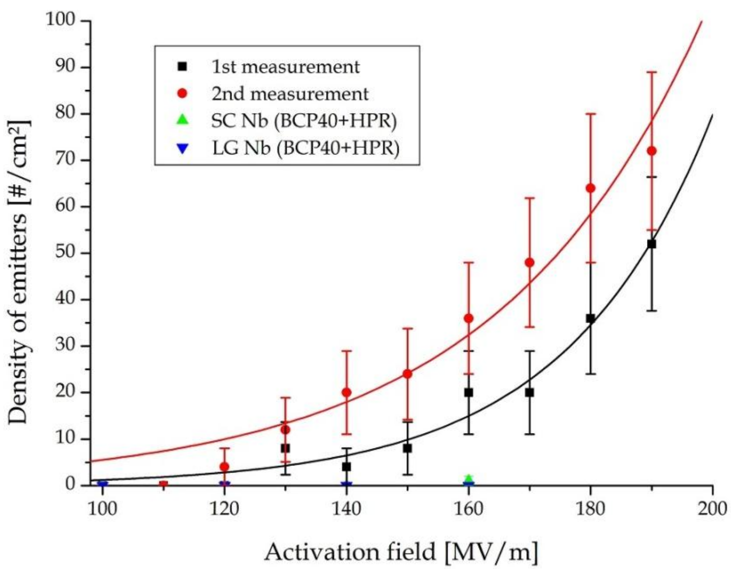
FESM results

Regulated E(x,y) maps for I = 1 nA , Δz ≈ 50 µm of the same area

130 MV/m | 160 MV/m | 190 MV/m



E_{on} = 120 MV/m



- **EFE starts at 130MV/m and not 500MV/m**
- Emitter density increases exponentially with field
- Activated emitters: E_{act}=(1,2 – 1,4)·E_{on}

→ 2nd measurement: shifted to lower fields

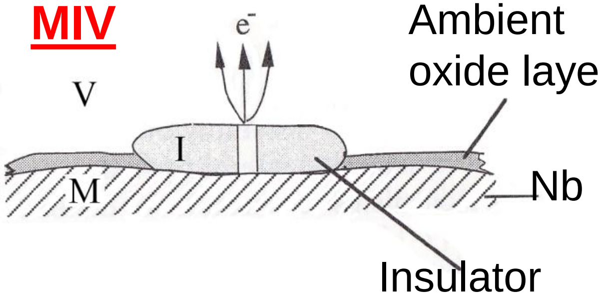
Possible explanations:
- Surface oxide
- adsorbates

FE due to oxides and adsorbates

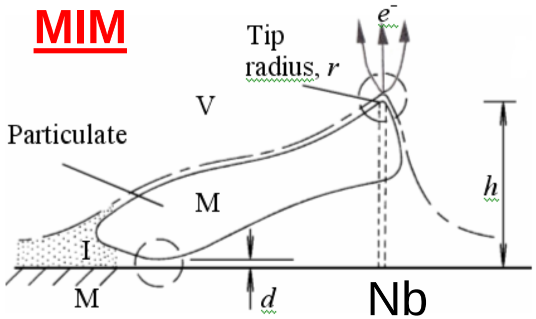
(1) Nb surface oxide:

→ activation by burning of conducting channels:

MIV



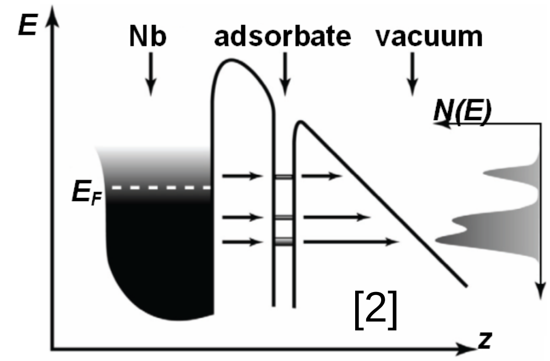
MIM



Switch-on state persists! for a long period without E under UHV at RT → permanent formation of conducting channels [1]

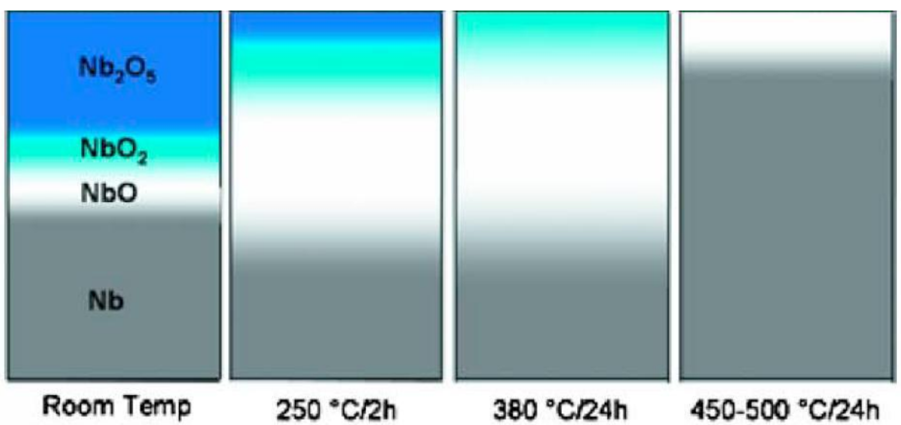
(2) Adsorbates:

- ad- or desorption lead to enhancement or reduction of field
- resonance tunneling can occur:



(3) Reduction of isolating Nb_2O_5 layer by heat treatment [3]:

Heating of a Nb surface can activate EFE



- Enhance **MIM-activation** of particles
- Enhance **MIV-activation** or surface defects

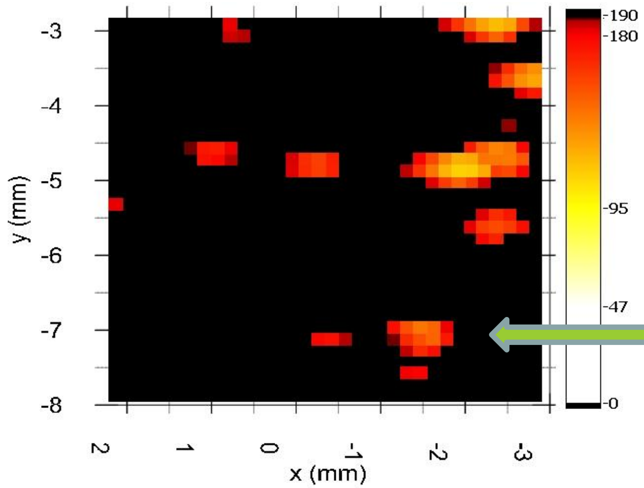
Nb_2O_5 natural (~5nm) isolating
NbO_2 semiconducting
NbO metalic

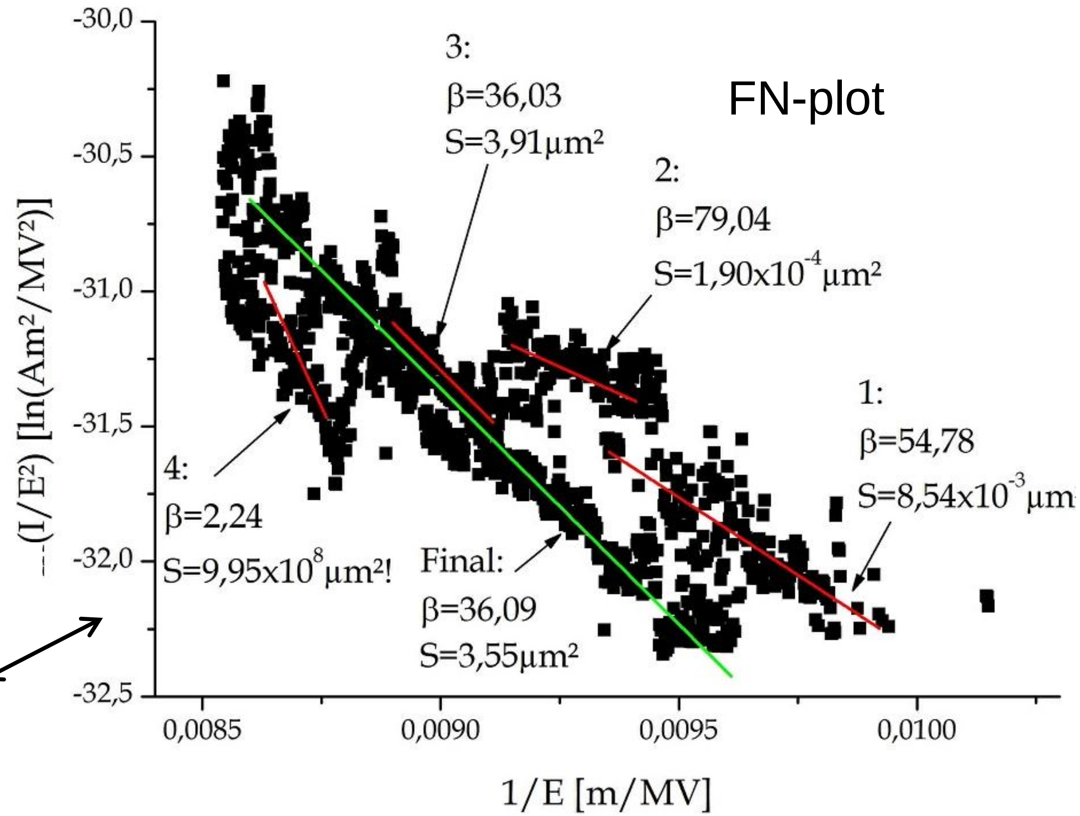
Impact for cavities:

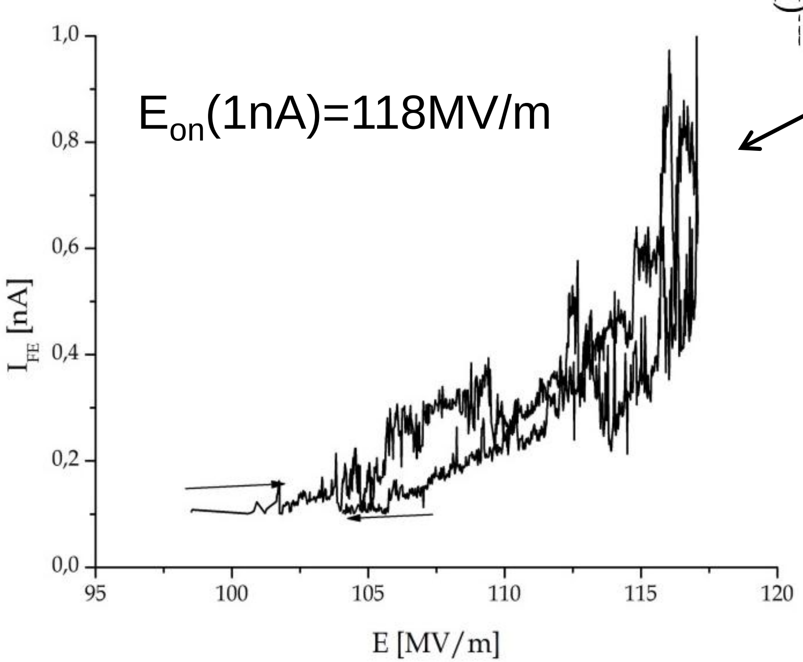
⇨ **Heating** or **rf power** ? [4] activate emitters

[1] R. V. Latham, "High vacuum insulation," (1995)
[2] J. D. Jarvis, et al. IFEL 2010, WEPB46 (2010)
[3] T. Proslier et.al. Appl. Phys. Let., 93, 192504 (2008)
[4] J. W. Wang, et al. SLAC-PUB-7684 (1997)

Local measurements of a typical emitter on Cu





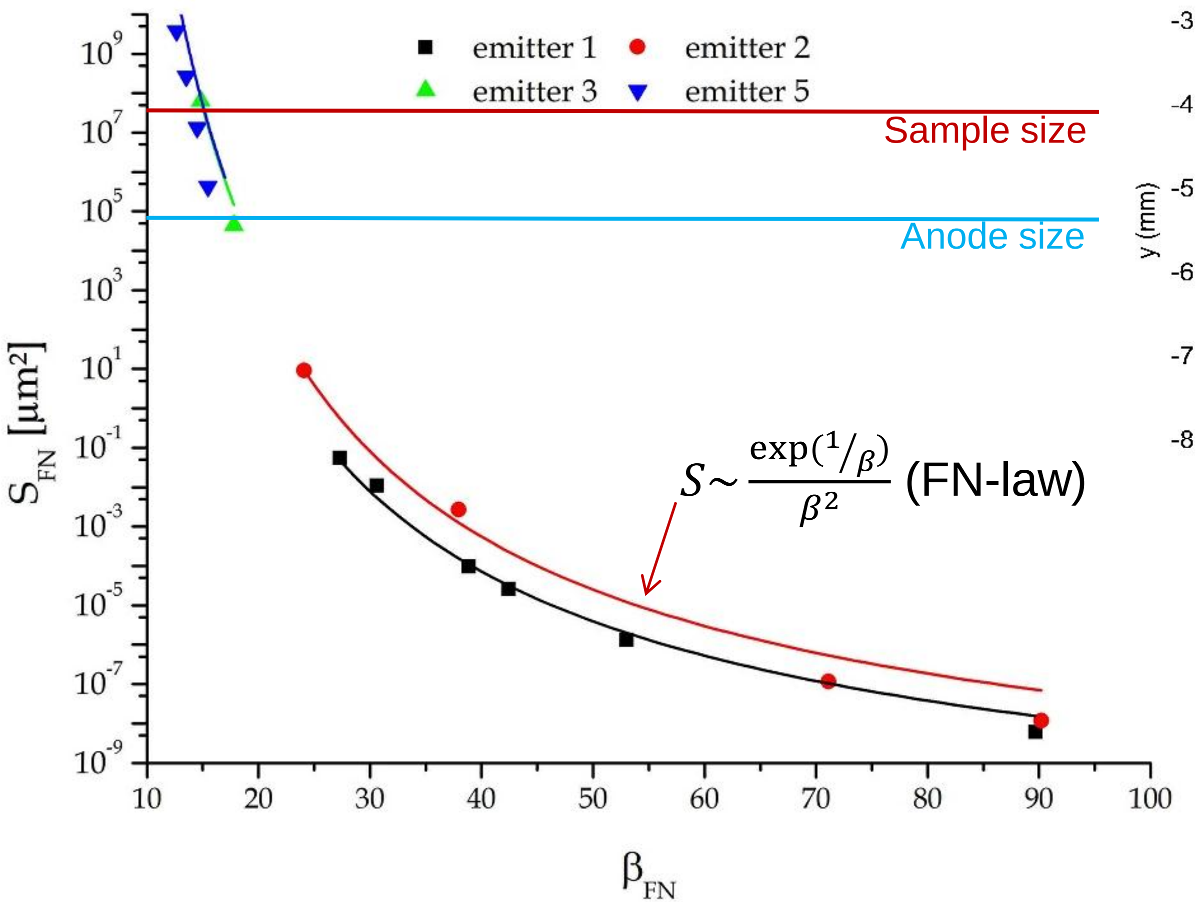


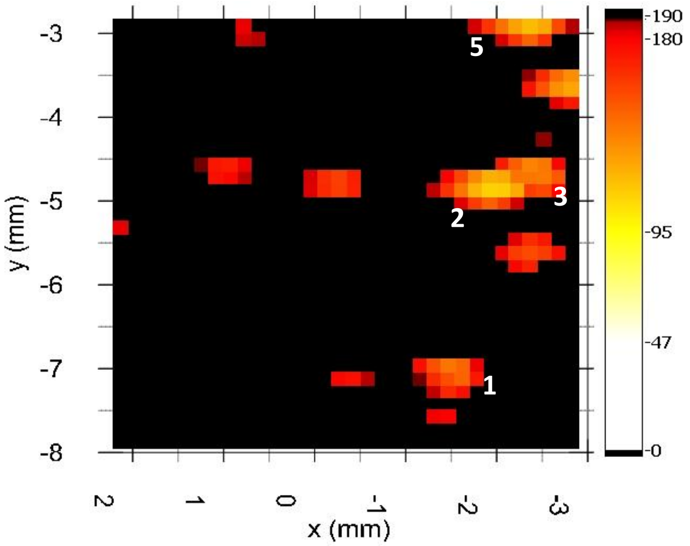
- Field calibrated via U(z)
- β and S: Calculation from FN-law

$$I(E) = \frac{AS(\beta E)^2}{\phi t(y)^2} e^{-\frac{B\phi^{3/2}\nu(y)}{\beta E}}$$

- Local measurements of the strongest emitters

Results of β and S of strongest emitters

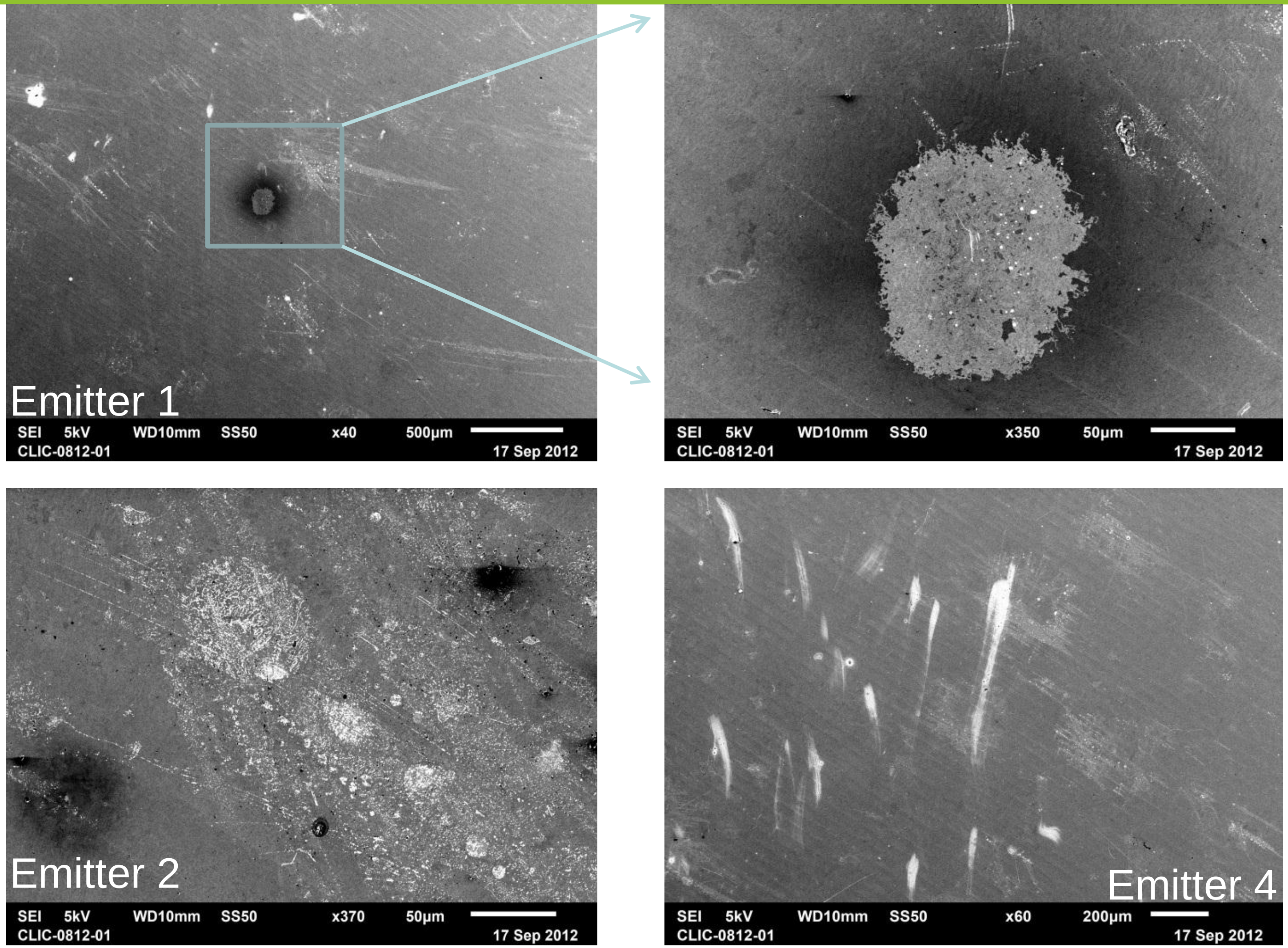




- Strong fluctuation of EFE
- Fit for FN law reflects nearly const. current range
- **But**: FN analysis provides impossible S values

- **Random current switching and S values of single emitters cannot only be described by FN law.**
- **Influence of surface oxides and adsorbates is important, too (MIM and MIV).**

SEM correlations



Too many surface features and particles near the emission sites

→ Impossible to give a clear correlation

→ Surface features = inclusions after diamond turning? Damage layer?

Conclusions and Outlook

Conclusions:

- The Cu surface is **very flat** (even after diamond turning)
- Remaining particulates and grains revealed the **highest** β_{geo} (≥ 5.8)
- EFE sets in between 120MV/m and 130 MV/m, earlier than expected from β_{geo}
- EFE from single emitter: very unstable with **impossible** values of S
- Emission cannot be described by FN-law, but other mechanism are involved
- No correlation to SEM images, too many particulates and surface features

→ Electrochemical polishing and **Dry Ice Cleaning** (DIC) of the surface should improve the EFE of the samples

Outlook:

- Measuring additional samples with the same fabrication
- Measuring samples after the standard CLIC manufacturing procedure (diamond turning, slight chemical etching, vacuum firing in H2 atmosphere)
- Installing a DIC system at the BUW and application to Cu samples