Status of high gradient studies at Uppsala

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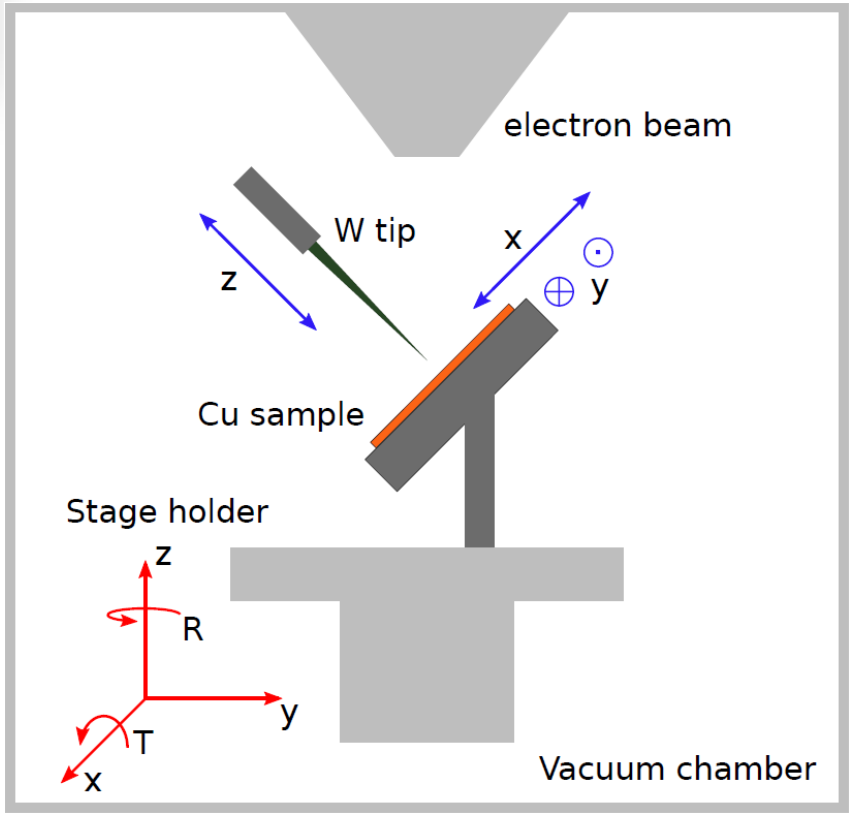
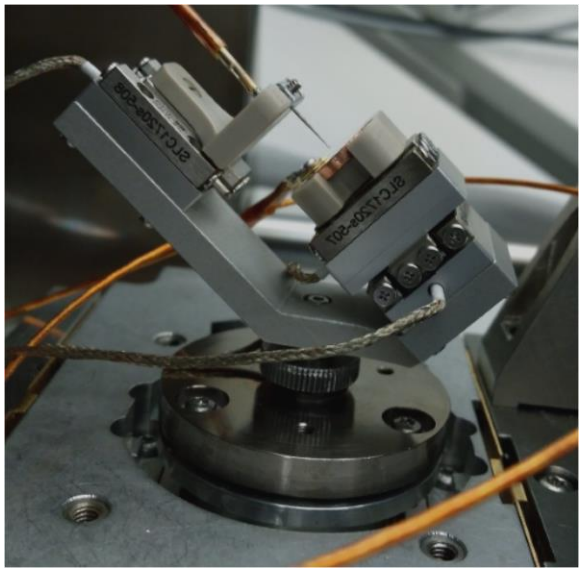
Outline

- In-SEM Field Emission Studies
  - I-V curves
  - Changes in surface composition
- Cold DC Setup
- Dark and Breakdown Currents at Xbox
- Summary and Outlook

In-SEM Setup





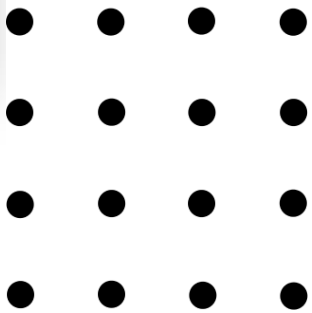
Stage
W tip, radius of curvature 5 µm
nm precision piezo-motors

Environmental SEM
Field emitting gun, 10-30 kV
Vacuum ~7×10^{-5} mBar

Keithley 6517a Electrometer
FE currents from sub-pA to mA
Applied V = up to 1 kV, 50 Hz

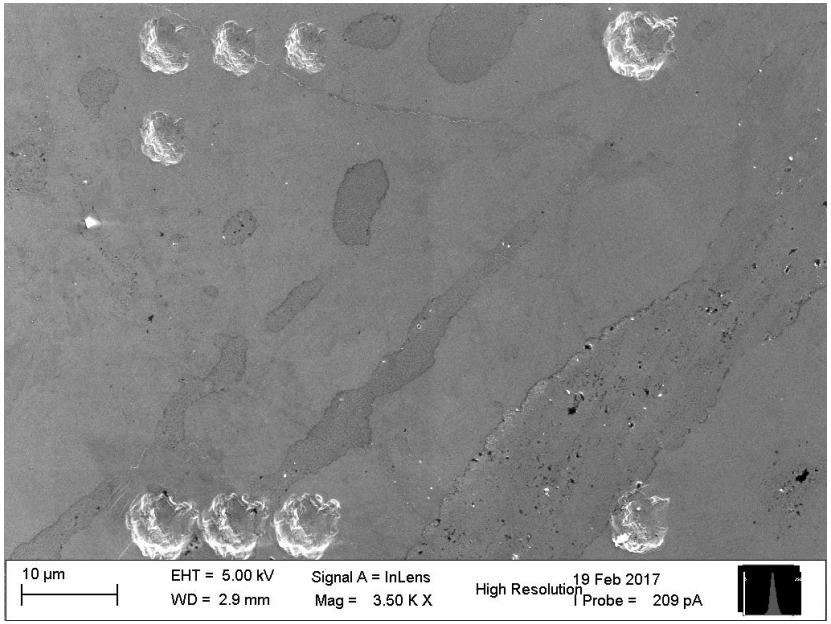
Typical gap distance → 700 nm
Surface search procedure:
Low voltage, approach surface in steps (2 nm) while measuring current until threshold breech (done 2 times just left and right to the area-of-interest)

Results of surface scan



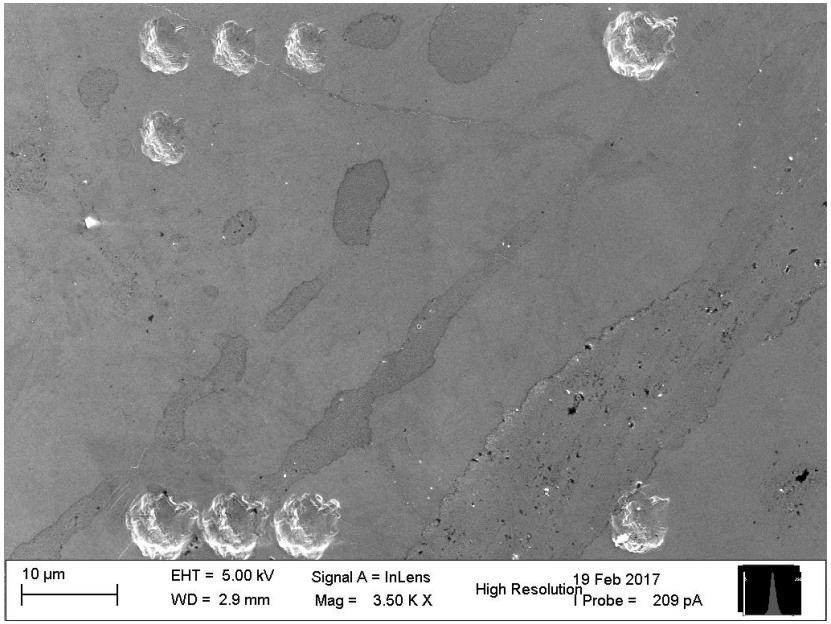
Example:
Scan pattern
16 points inside
50x50 µm

Before

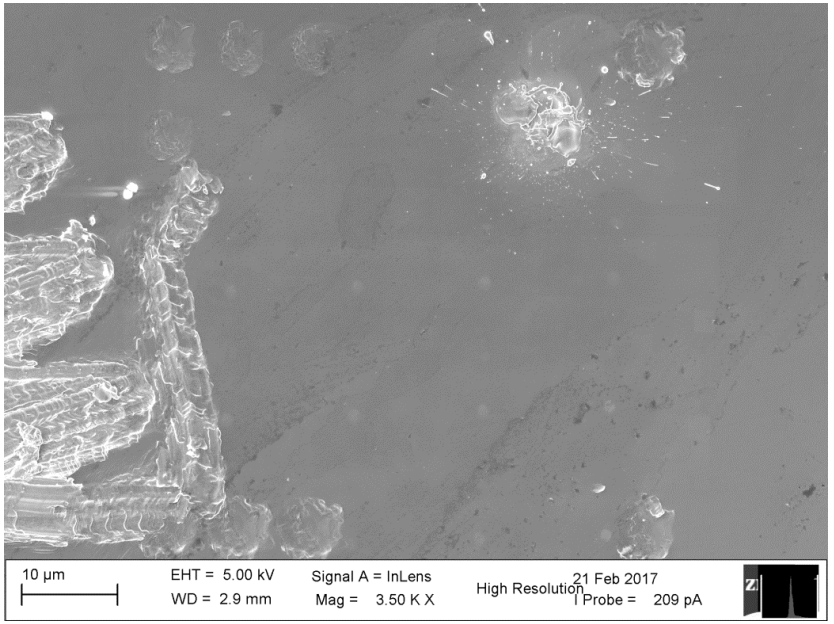


Results of surface scan

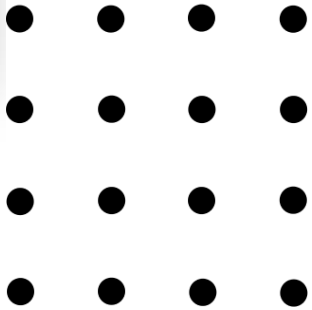
Before



After

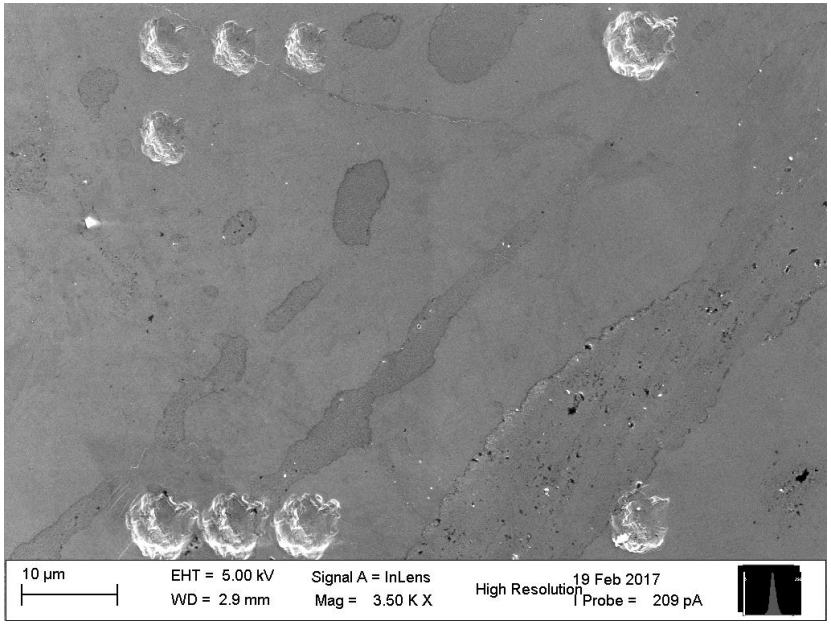


Scan pattern

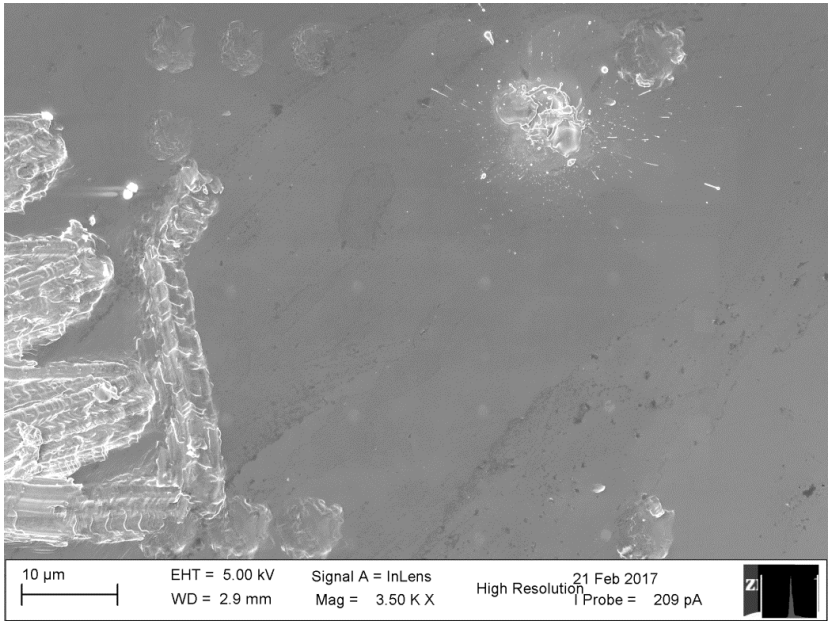


enchanced image

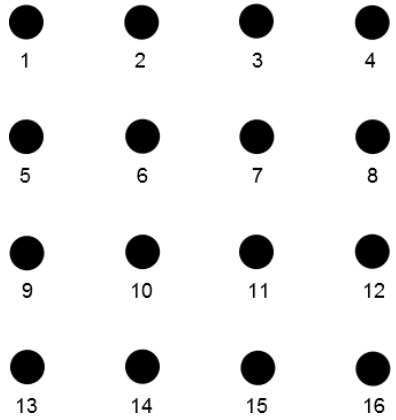
Before

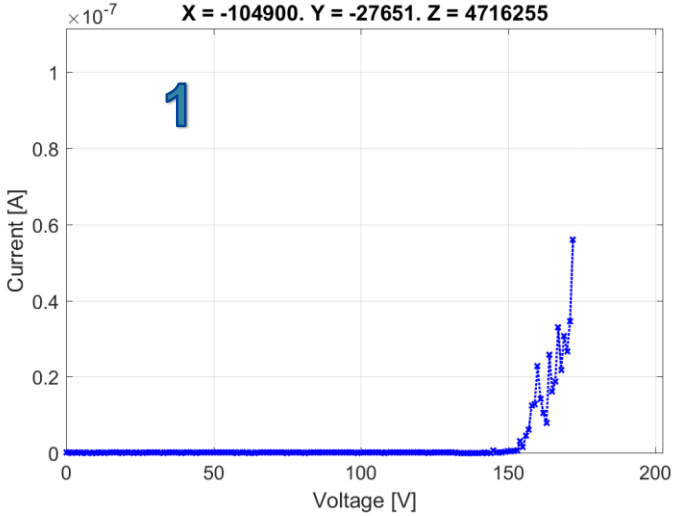


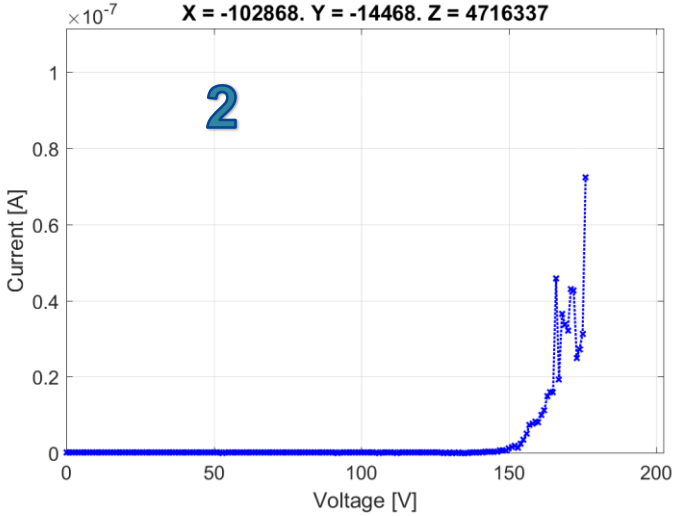
After

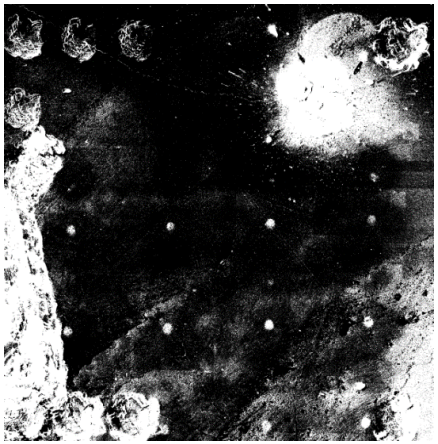


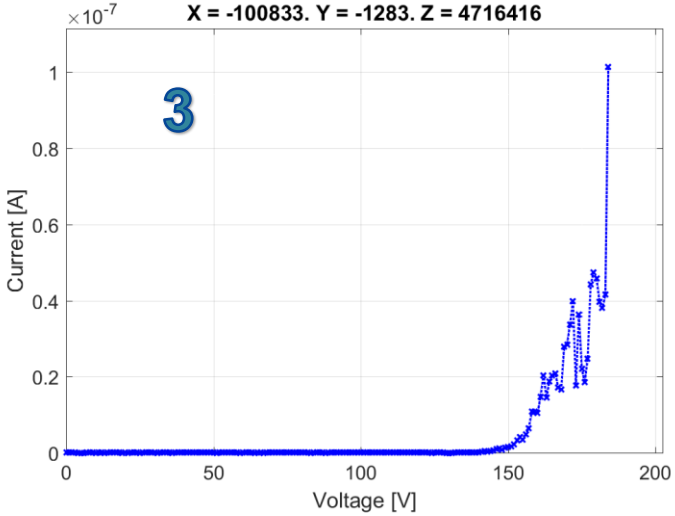
I-V curves

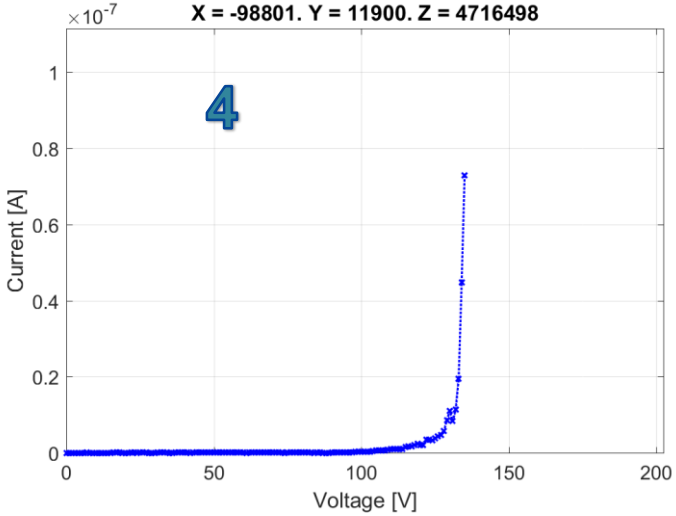

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16


X = -104900. Y = -27651. Z = 4716255
×10^-7
1
Current [A]
Voltage [V]

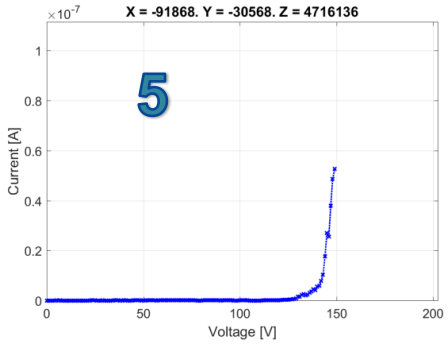

X = -102868. Y = -14468. Z = 4716337
×10^-7
2
Current [A]
Voltage [V]

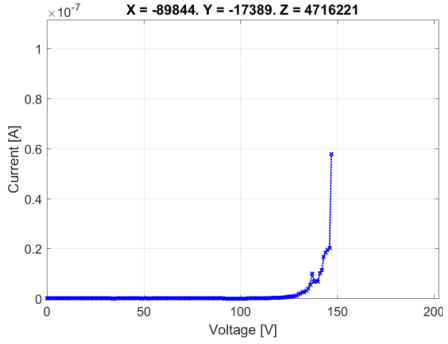


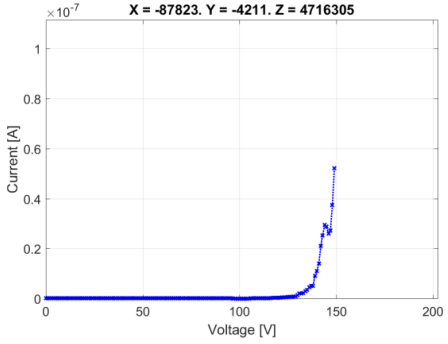

X = -100833. Y = -1283. Z = 4716416
×10^-7
3
Current [A]
Voltage [V]

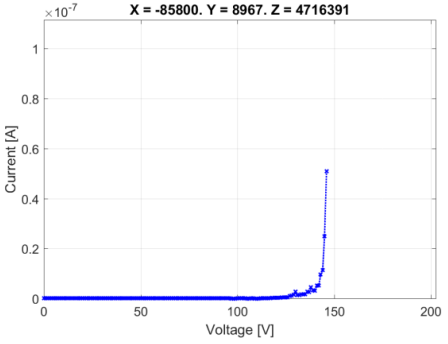

X = -98801. Y = 11900. Z = 4716498
×10^-7
4
Current [A]
Voltage [V]

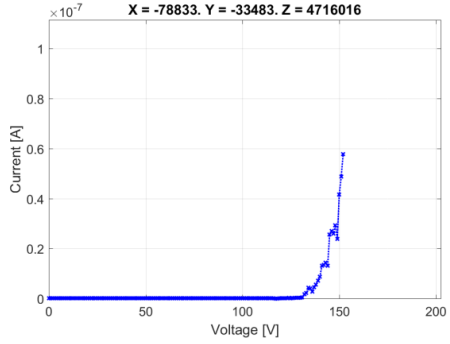
I-V curves

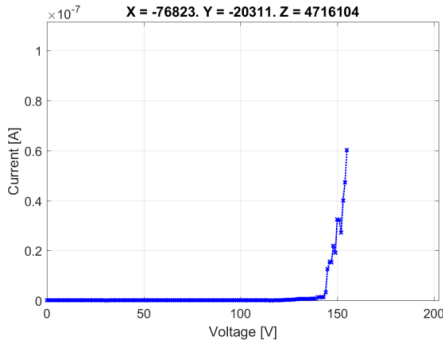

X = -91868. Y = -30568. Z = 4716136
5
Current [A]
Voltage [V]

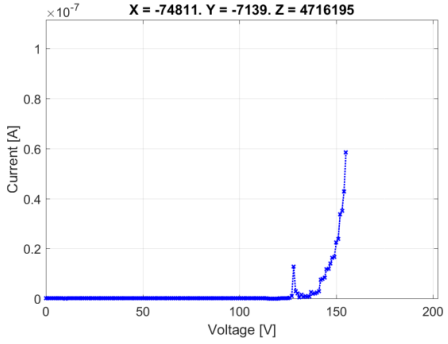

X = -89844. Y = -17389. Z = 4716221
Current [A]
Voltage [V]

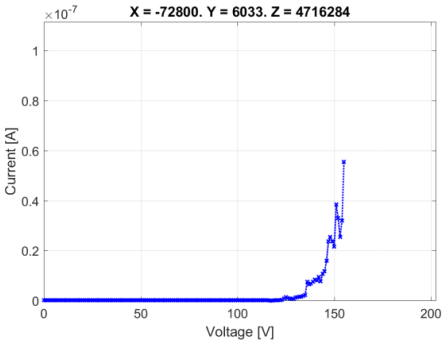

X = -87823. Y = -4211. Z = 4716305
Current [A]
Voltage [V]

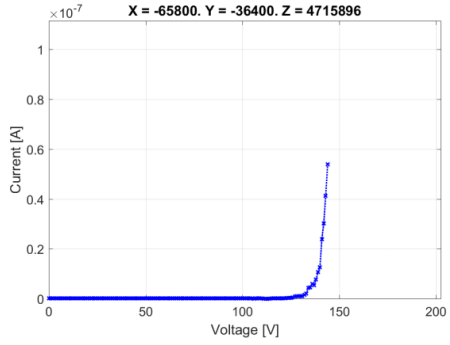

X = -85800. Y = 8967. Z = 4716391
Current [A]
Voltage [V]

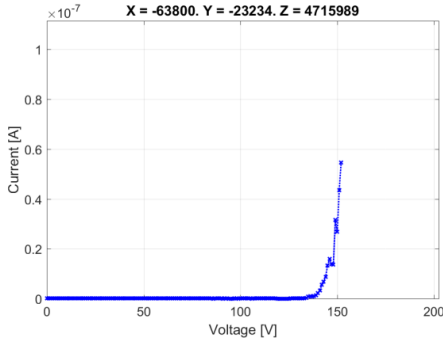

X = -78833. Y = -33483. Z = 4716016
Current [A]
Voltage [V]

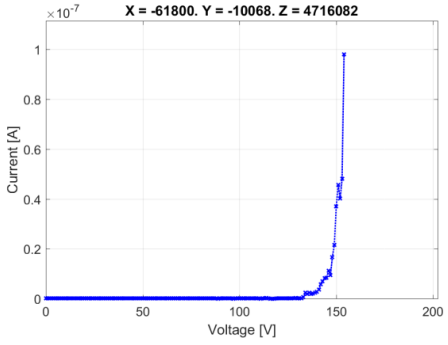

X = -76823. Y = -20311. Z = 4716104
Current [A]
Voltage [V]

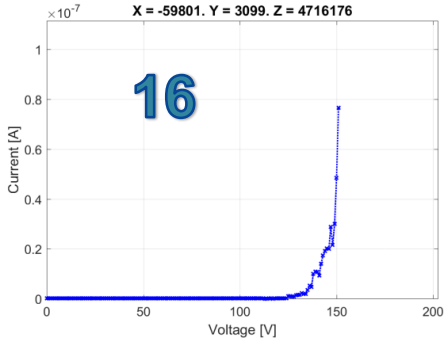

X = -74811. Y = -7139. Z = 4716195
Current [A]
Voltage [V]


X = -72800. Y = 6033. Z = 4716284
Current [A]
Voltage [V]

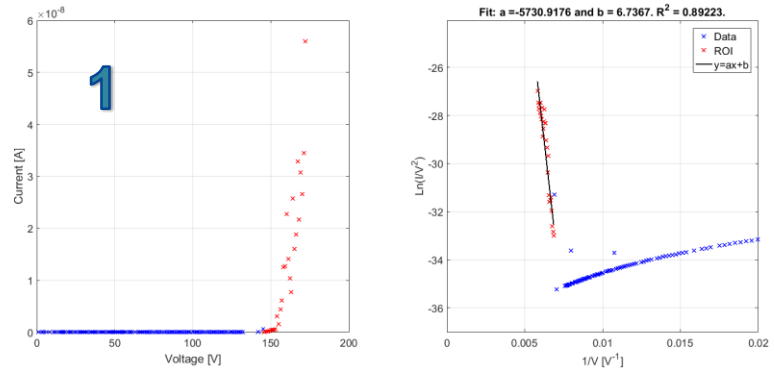

X = -65800. Y = -36400. Z = 4715896
Current [A]
Voltage [V]


X = -63800. Y = -23234. Z = 4715989
Current [A]
Voltage [V]

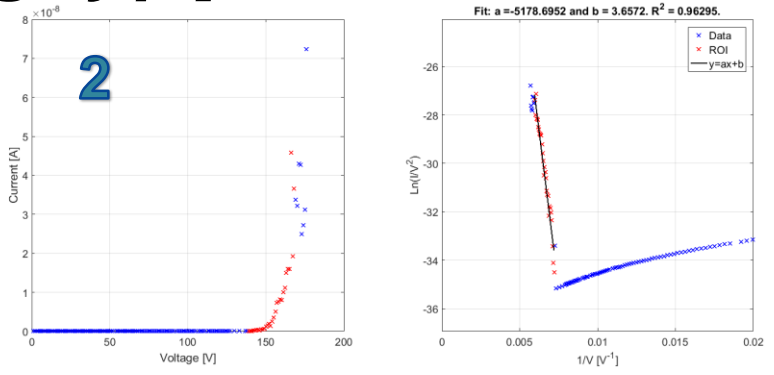

X = -61800. Y = -10068. Z = 4716082
Current [A]
Voltage [V]


X = -59801. Y = 3099. Z = 4716176
16
Current [A]
Voltage [V]

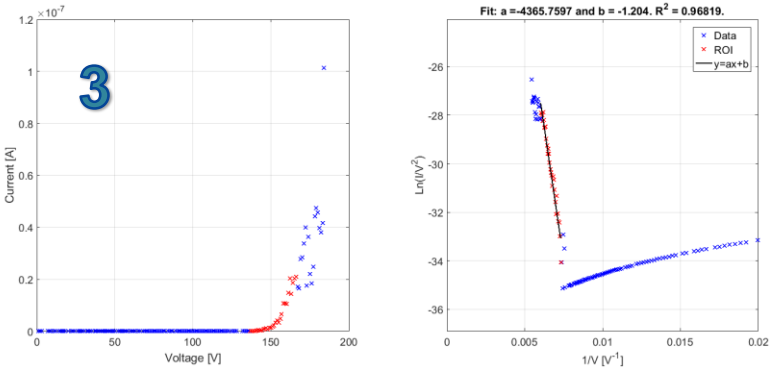
Fitting of β parameter



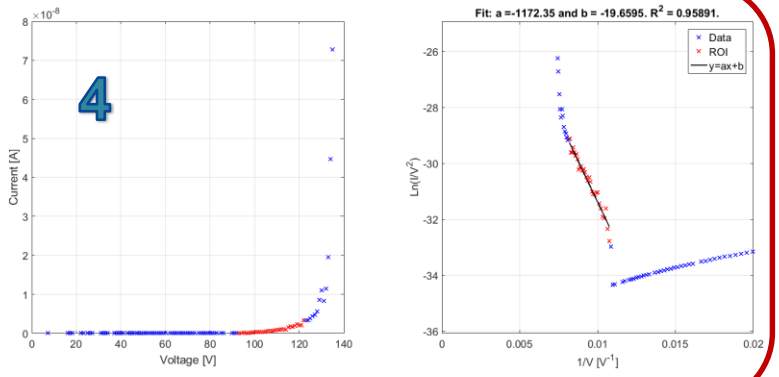
β = 15.5



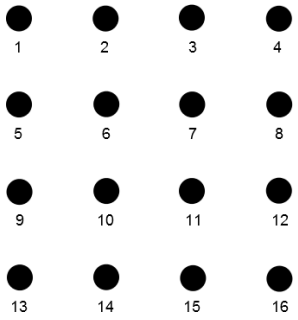
β = 17.6



β = 19.6

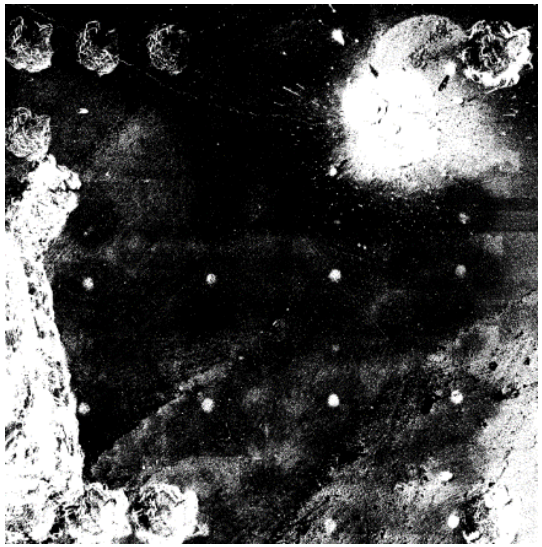


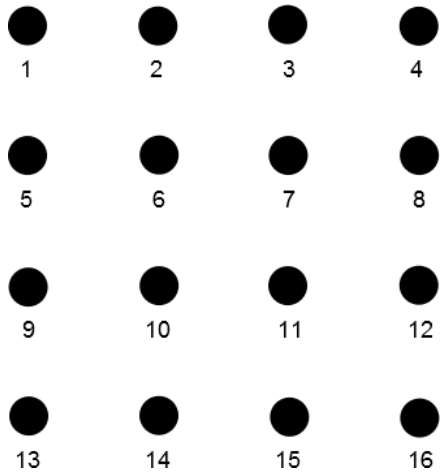
β = 75.5



Fitting of β parameter Topology

15.5	**17.6**	**19.6**	**75.5**
30.2	**38.0**	**38.8**	**37.5**
21.3	**29.6**	**27.2**	**33.2**
20.9	**13.9**	**21.1**	**22.9**





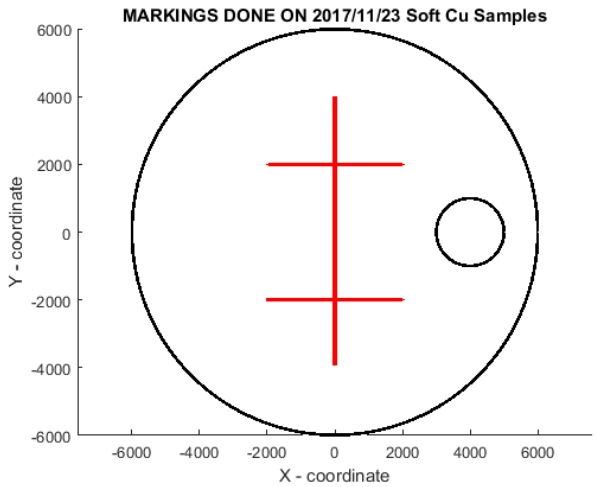
Surface composition
XPS analysis

We know that we affect the surface, but what happens?

Adding X-ray photoelectron spectroscopy information

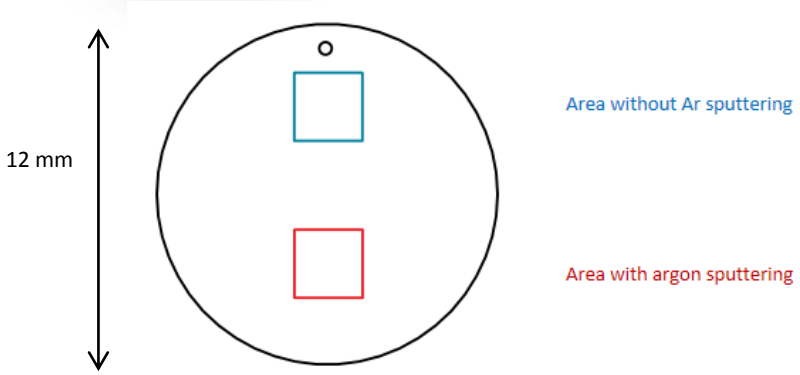
Steps *):

1. Markings
2. XPS analysis and Ar sputtering
3. HR-SEM observation
4. FE experiments
5. Final HR-SEM observation
6. Final XPS analysis

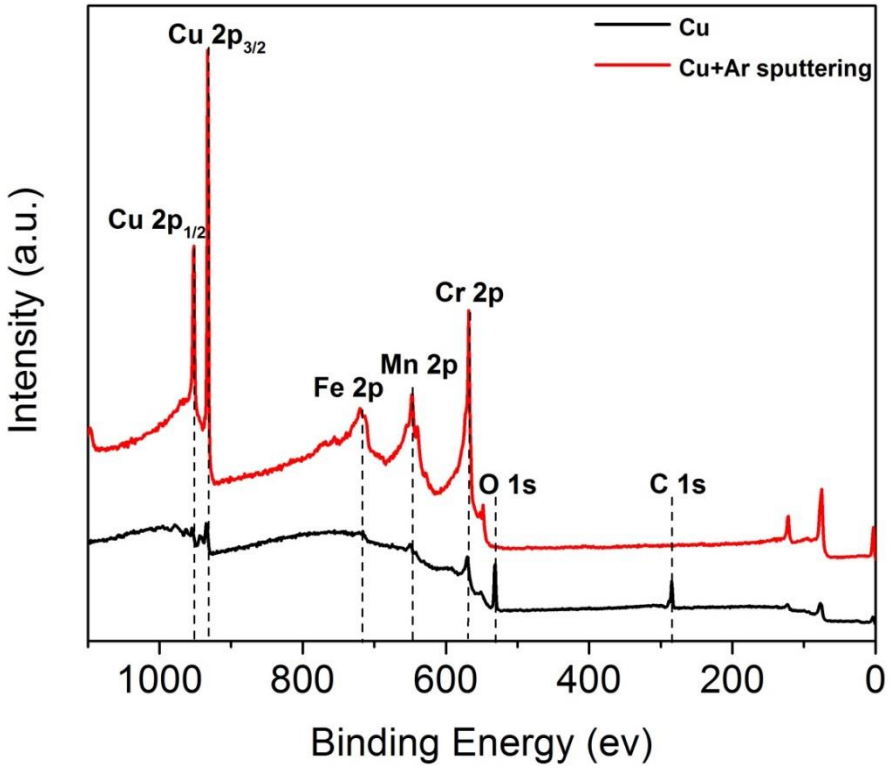


*) Between steps the sample is placed in a vacuum desiccator

Surface composition
Effect of argon sputtering



- **After Ar sputtering O and C peaks disappear.**
- **C contamination on surface equals to a thickness of 3.6 nm on top of Cu (rough estimate)**

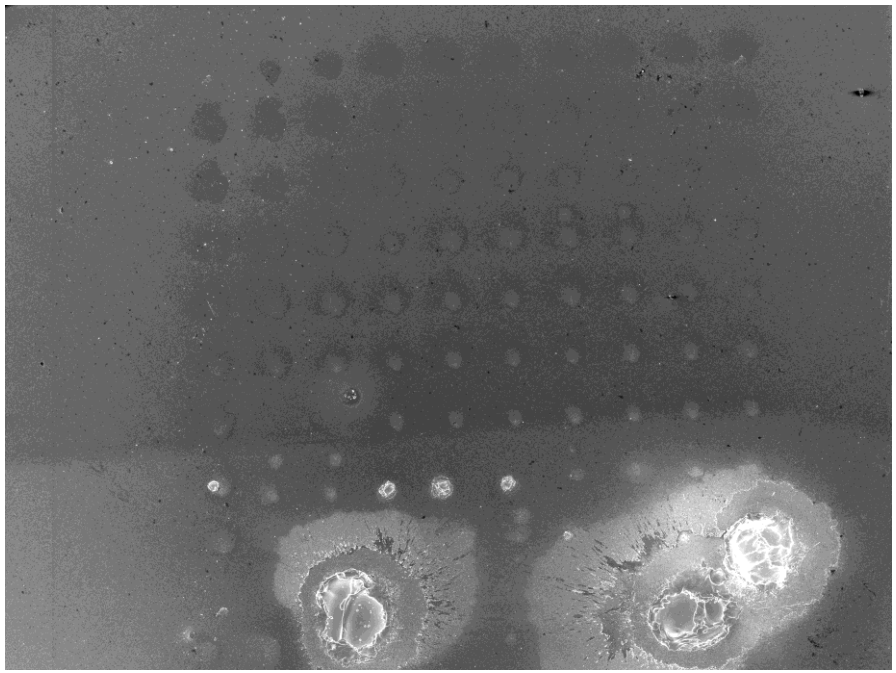


Analysis can only work on larger areas > 50 µm

Surface composition
HR-SEM images after FE experiments

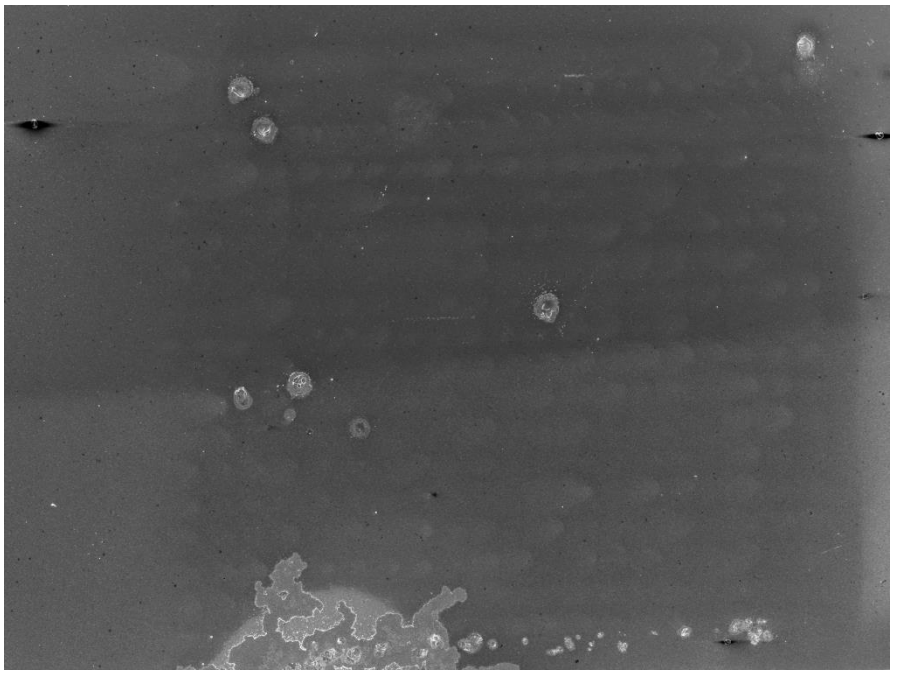
Area 1 after experiments

Pattern 10 x 10 FE points



Area 2 after experiments

Pattern 20 x 20 FE points

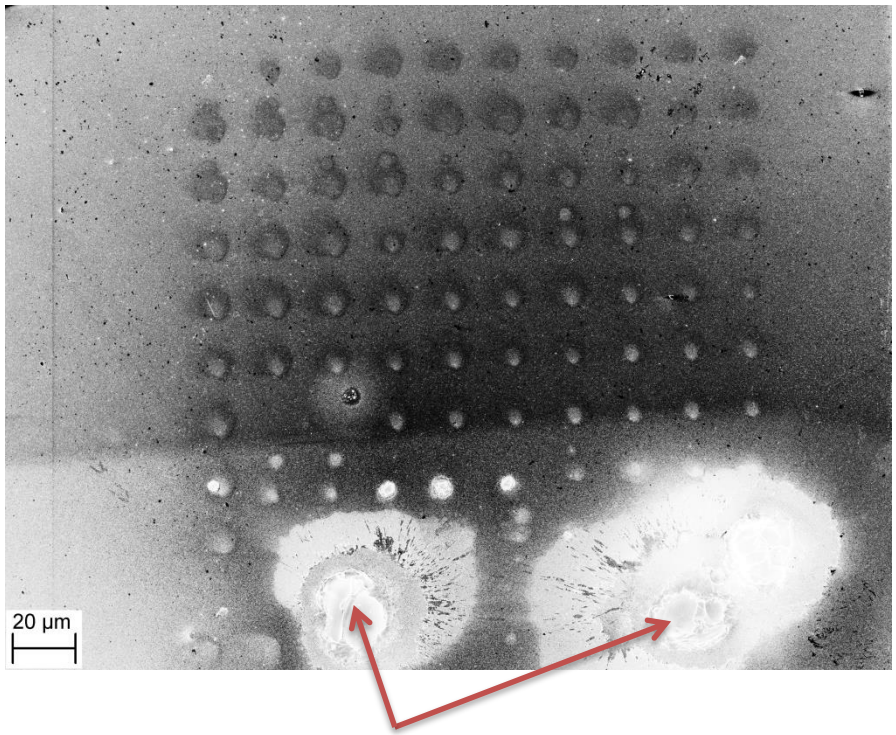


Surface composition
HR-SEM images after FE experiments

Experimental area: 200 µm x 200 µm in both cases

Area 1 after experiments

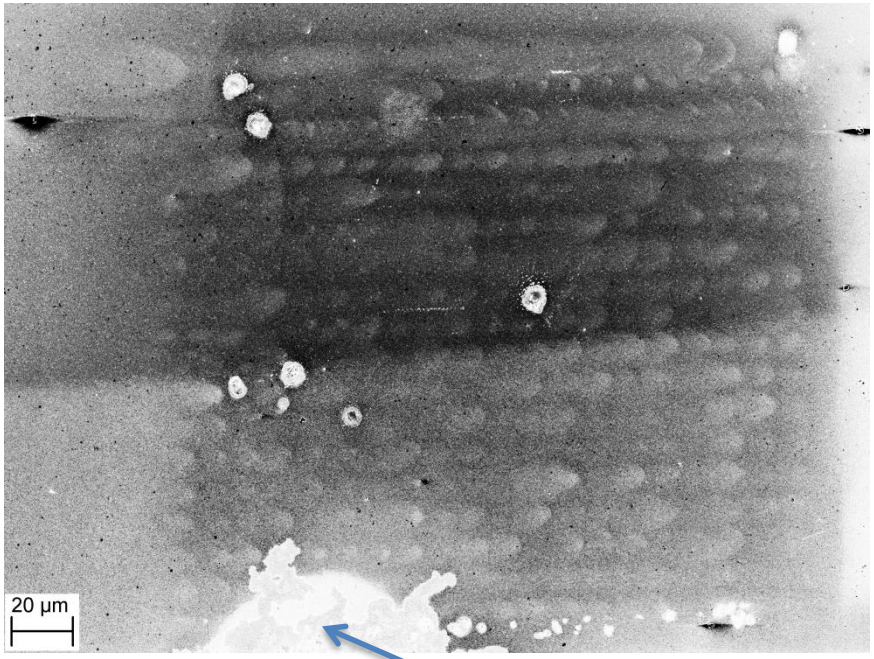
Pattern 10 x 10 FE points



Breakdowns at the end of scan

Area 2 after experiments

Pattern 20 x 20 FE points



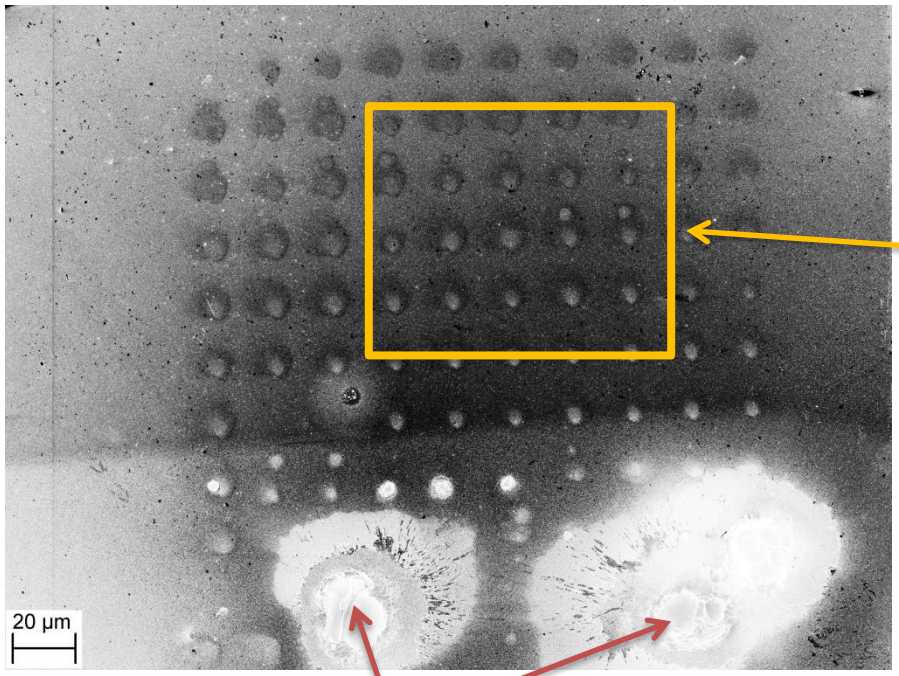
Breakdown at the end of scan

Surface composition
HR-SEM images after FE experiments

Experimental area: 200 µm x 200 µm in both cases

Area 1 after experiments

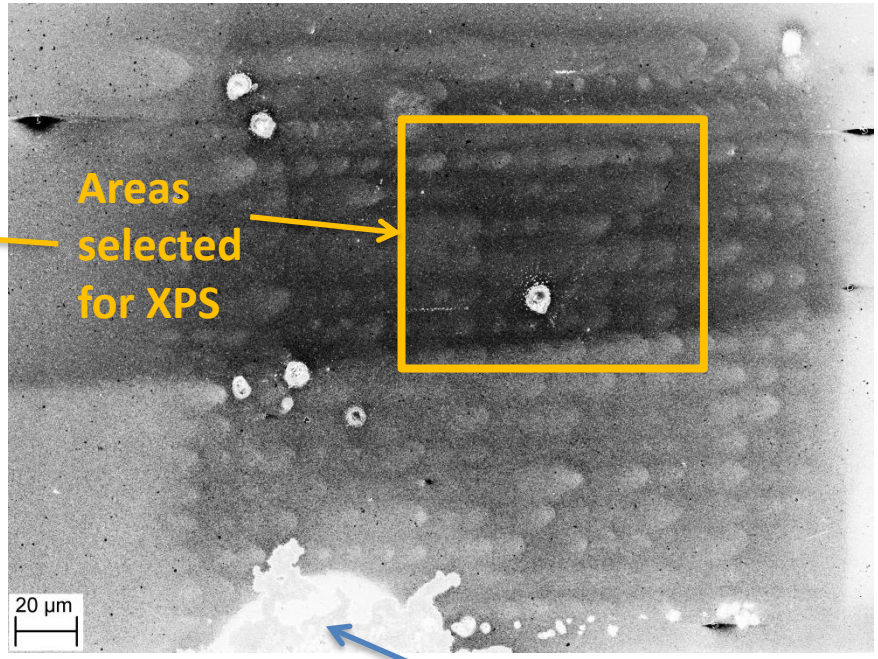
Pattern 10 x 10 FE points



Breakdowns at the end of scan

Area 2 after experiments

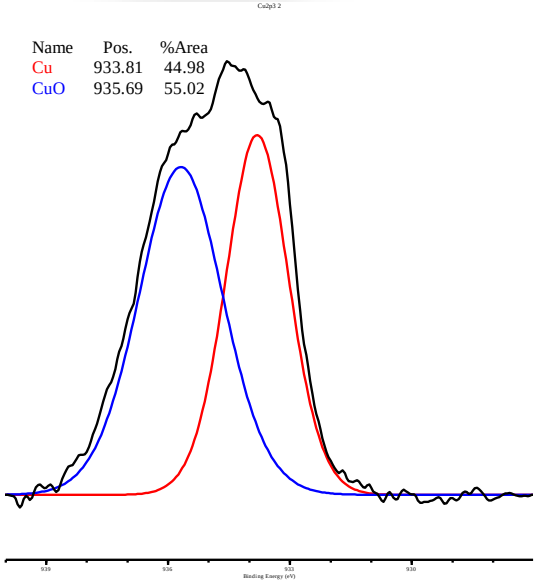
Pattern 20 x 20 FE points



Breakdown at the end of scan

Surface composition
XPS results

We see clear change in the Cu peak: significant drop in Cu-O peak after FE experiments



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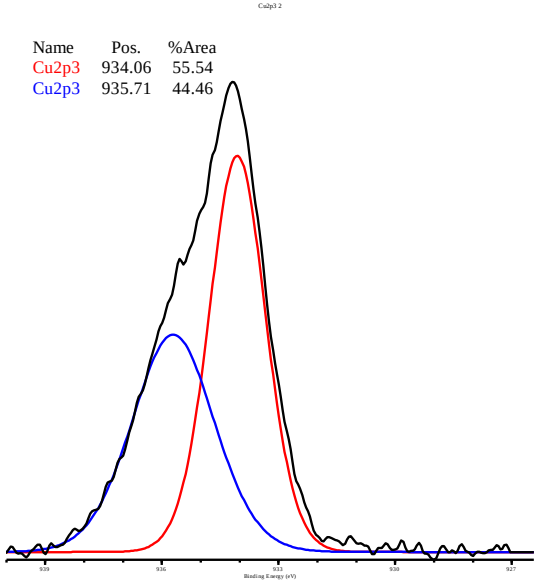
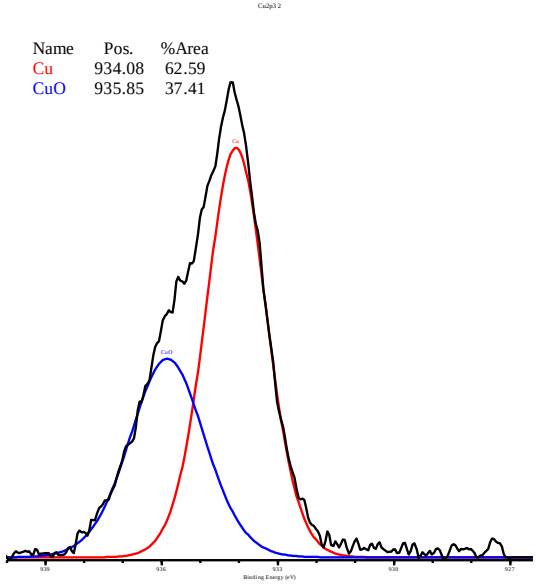


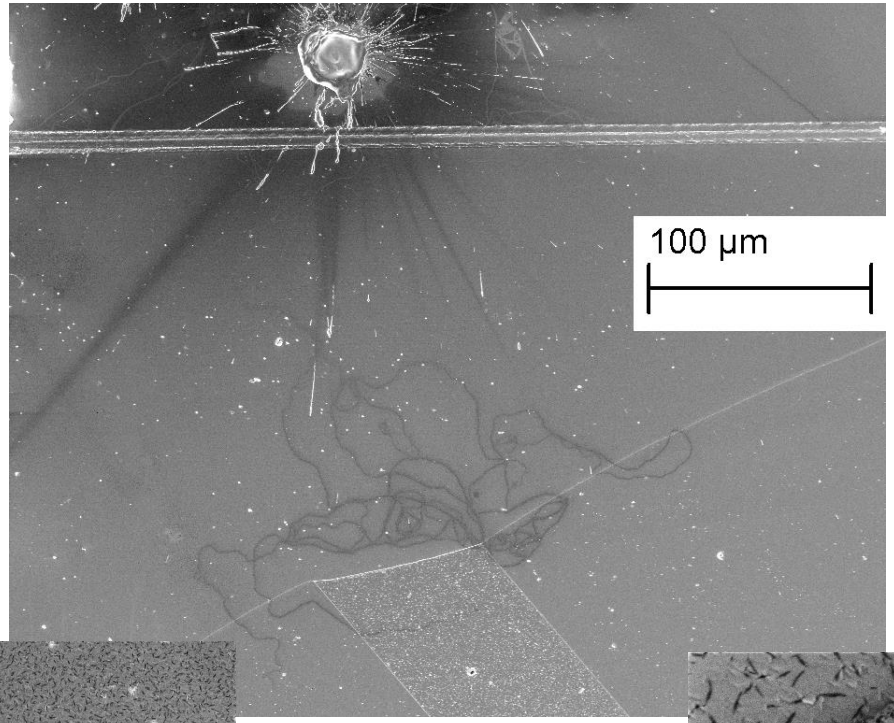
Area 1

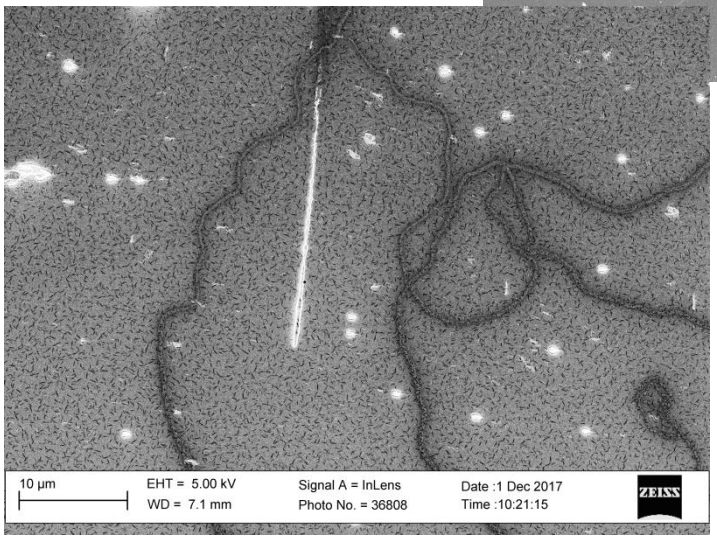


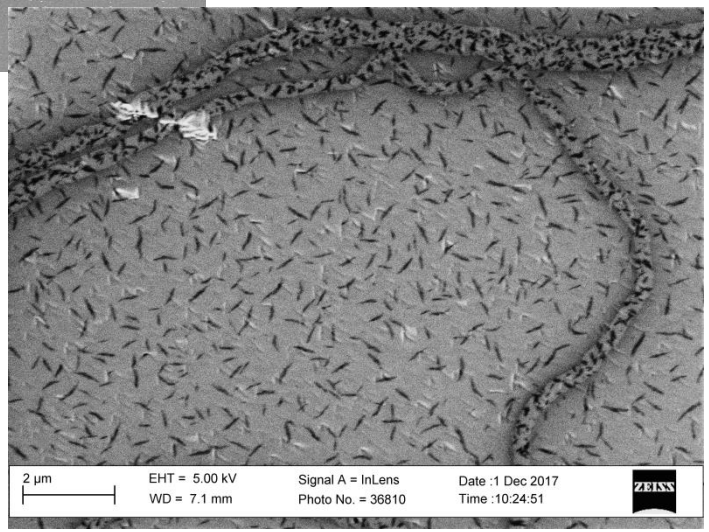
Area 2

Area	Pattern density	Cu [%]	CuO [%]	CuO thickness
Reference	0	44.98	55.01	1.13 nm
Area 1	10 x 10 FE points	55.54	44.46	0.82 nm
Area 2	20 x 20 FE points	62.59	37.41	0.65 nm

Curiosa - surface changes after a discharge







Cryo DC spark system

Field emission and BDR as a function of temperature

K. Nordlund and F. Djurabekova, *Defect model for the dependence of breakdown rate on external electric fields*, Phys. Rev. ST Accel. Beams **15**, 071002 (2012).

Model assumes that onset of electric breakdown can be associated with any kind of crystal defect

Breakdown rate is temperture dependent

$$R_{\mathrm{BD}} = a e^{\varepsilon_0 (\eta E_{\mathrm{acc}})^2 \Delta V / k_B T}.$$

ΔV is the relaxation volume of the defect

Yinon Ashkenazy et al., *Stochastic Model of Breakdown Nucleation Under Intense Electric Fields*,
6th International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2017)
https://indico.cern.ch/event/521667/contributions/2409278/attachments/1433908/2203931/eli_mevarc.pdf

High E → nucleation → Protrusions? Local effect? → Cu plasma → breakdown (arc formation)

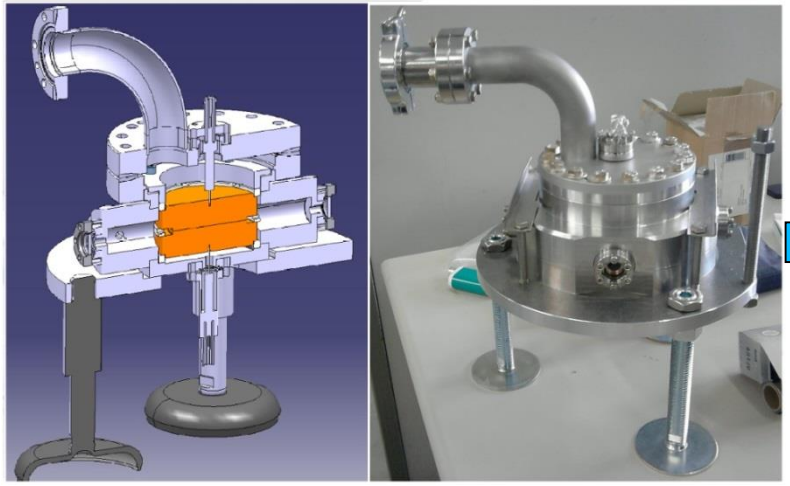
$$\dot{\rho}^{+} = \frac{25\kappa C_t}{G^2 b}(\rho + c)\sigma^2 e^{-\frac{E_a - \Omega\sigma}{k_B T}} \qquad \dot{\rho}^{-} = \frac{50\xi C_t}{G}\sigma\rho(c + \rho)$$

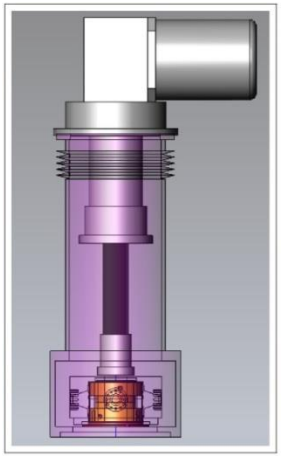
$$\sigma = \frac{1}{2}B\epsilon_0(\beta + 3.5)^2 E^2 + ZGb\rho$$

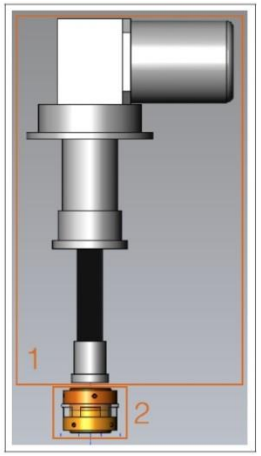
Rates:
$\dot{\rho}^{+}$ rate of mobile dislocations multiplication
$\dot{\rho}^{-}$ rate of mobile dislocations depletion,
with competing mechanisms

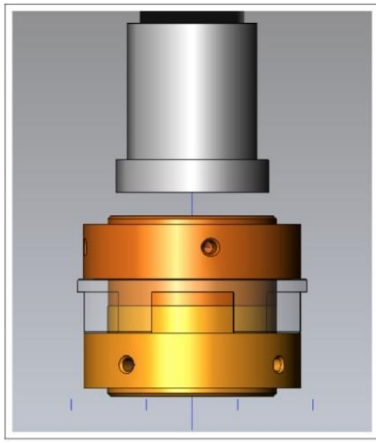
Again strong dependance on temperature

Cryo DC spark system







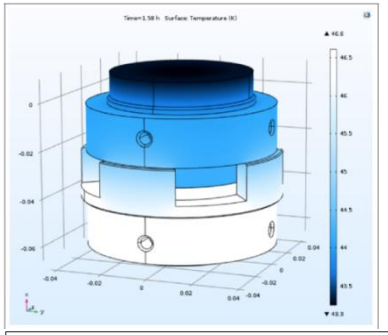


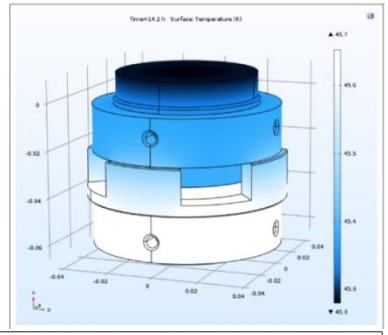
Mechanical drawings
Johan Eriksson

Cryo-DC setup – using stand-alone cryocooler
Temperatures: down to 4 K
Geometry: CERN pulsed DC large area electrodes

K-contract of UU with CERN signed by both parties

- **Cryocooler order in progress**
- **Cryostat design started**



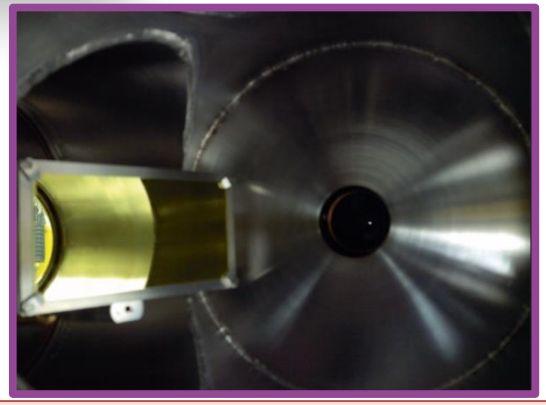


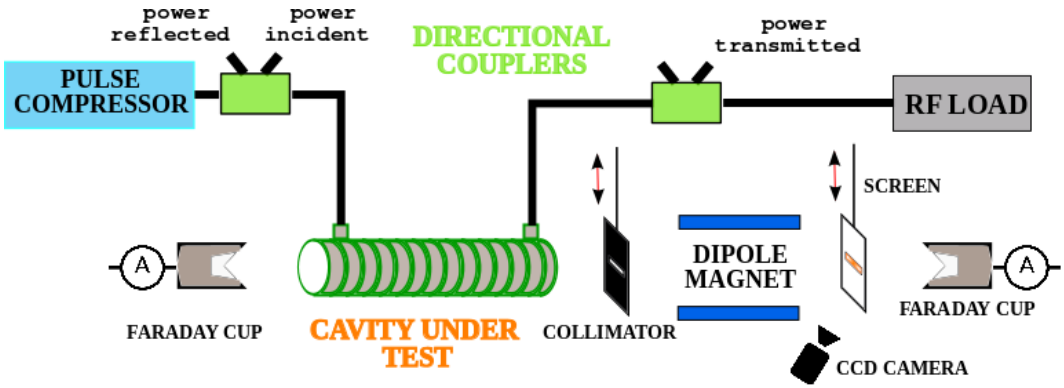
Comparison of calculations and simulations		
Cooling down from 293 K to 45 K	1.58 h 14.2 h	RDK-415D (45 W) RDK-101J (5 W)
Cooling down from 45 K to 4 K	7.8 h 58.5 h	RDK-415D (1.5 W) RDK-101J (0.2 W)

Simulations in COMSOL
Sigridur Johannsdotter

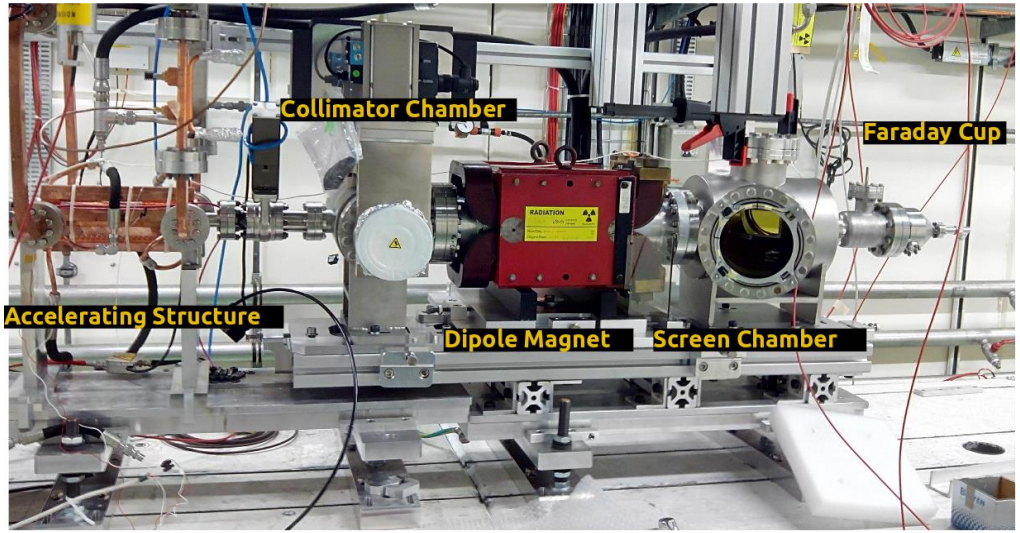
Uppsala/CLIC X-band Spectrometer (UCXS)

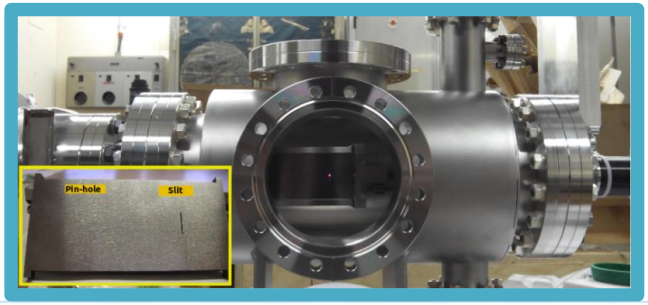
general-purpose system for detection and measurements of dark and breakdown currents during structure conditioning





Screen (100x50x0.5 mm YAG:Ce)
linear actuator (fully retractable)
30 degrees angle w.r.t. the beam axis
2M pixel, 50fps camera with focuser





Collimator (5 mm tungsten plate)
linear actuator (retractable), place for two patterns,
presently: **pin-hole** 0.5mm and **slit** 10x0.5mm

Energy resolution with dipole magnet

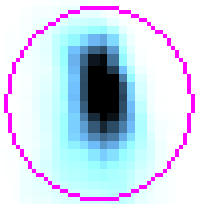
Maximum expected electron energy	~20MeV
Rel. energy spread (single slit)	10% - 25%
Full energy coverage with magnetic field scan	

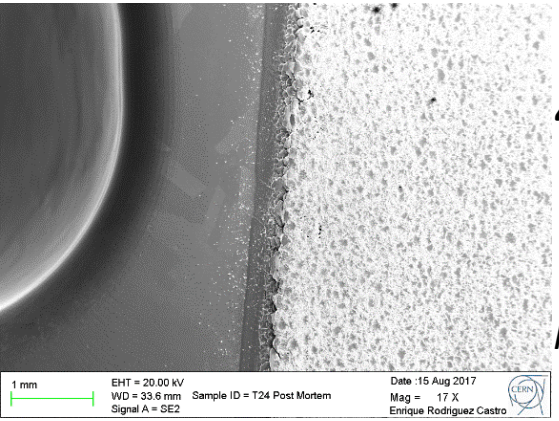
BD transverse position

Magnet OFF

- **Unique possibility to measure transverse BD position in parallel with longitudinal**
- **Works both for slit and pinhole collimator**

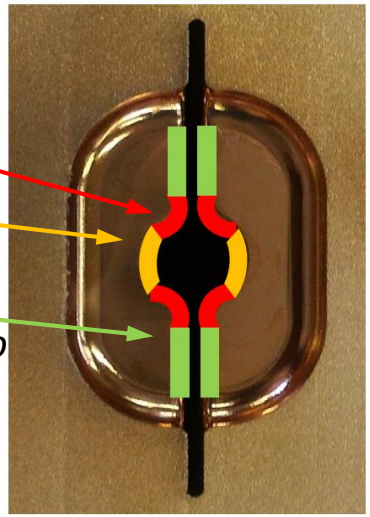
Example: Combined image from ~200 events
We measured asymmetry and excess events in vertical direction for CLIC Open structure
Later confirmed by post-mortem analysis

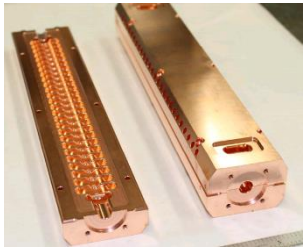




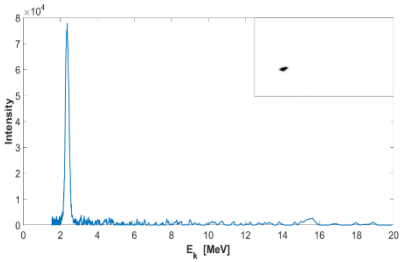
"Biggest BD accumulation on nose than centre and straight part of the iris"

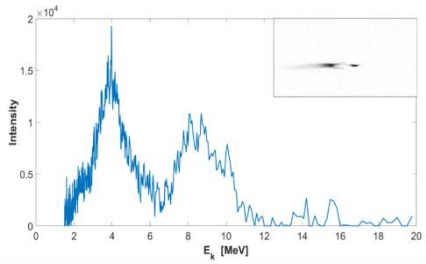
Post-mortem analysis by Enrique Castro





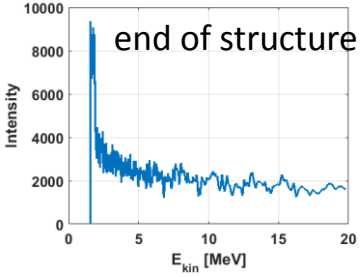
Energy spectra from the spectrometer

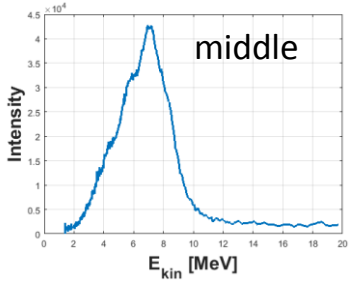


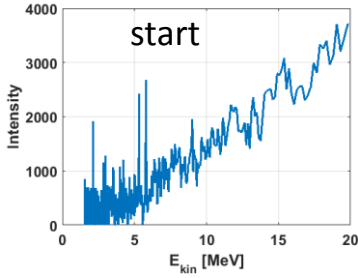


Energy spectra from BD events

- Electrons with well defined energies
- Maximum in agreement with the given power/gradient in the structure
- Good correlation with BD position from RF signals



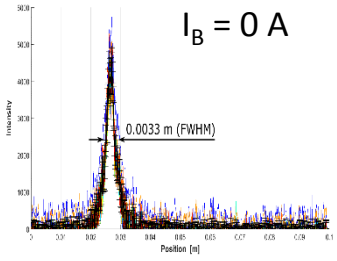


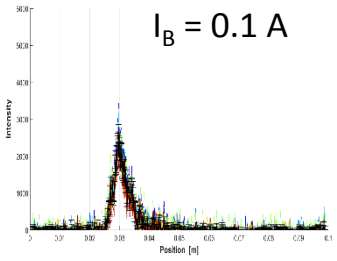


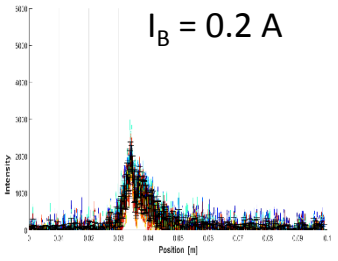
Dark current

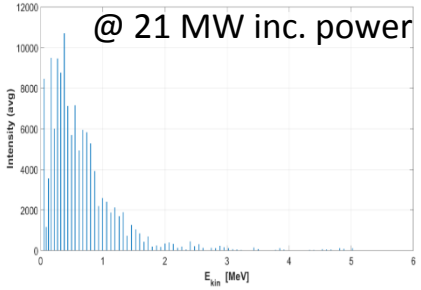
- Setup optimized for BD - weaker signals from dark current
- No indication of single emitting spot inside the cavity
- Isotropic transverse distribution
- Broad energy spectrum – continuum from electrons

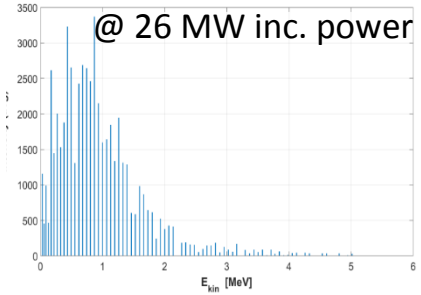
20 pulses + average

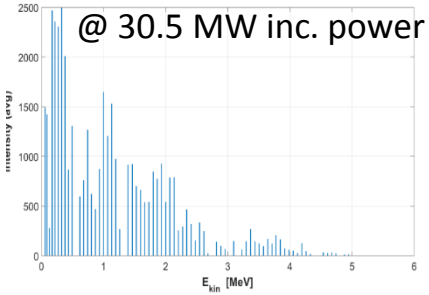












Summary and outlook

In-SEM setup

- Correlate surface features to FE-scans
  - We see effect of the FE scans directly after, however spots disappear after days
  - No conclusive proof of other, long lasting, surface changes (like e.g. melting)
- Quantify surface changes with XPS
  - Requires large surface affected by our experiments
  - We see that relative concentration of CuO is decreasing
- Conditioning in the field-emission regime (e.g. repeating scan in the same spot)
- New samples from CERN:
  - A sample characterized with EBSD (crystal orientation)
  - Soft vs hard copper

Xbox experiments status:

- Many BD and DC data from Xbox on disk - analysis in progress
  - Correlate BD RF signals with energy spectra
  - Study dark current behavior (trends and before/after breakdowns)
- Spectrometer removed from XBox2 and placed @XBox1
  - Possibility for improvements of the setup with focus on dark current, e.g.:
    - Another camera (splitter mirror) dedicated to DC measurements
    - New collimator with different patterns
- Xbox setup simulations - Goal: combine spectrometer simulation with RF simulation of CLIC cavity
- **Many thanks to XBOX team for support !**

FREIA

UPPSALA
UNIVERSITET

Thank you for attention

Simulations status

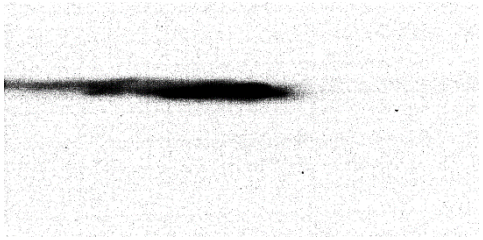
Simulations of the Electron Current Spectrometer Setup in Geant4

Exploring the Physics Limitations of Compact High Gradient Accelerating Structures

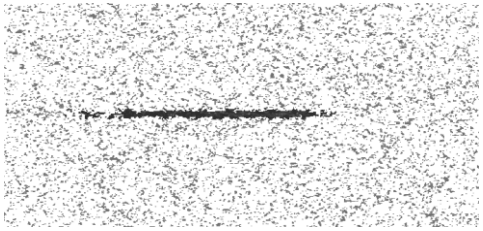
Philine van Vliet

University of Amsterdam, Netherlands

Experiment



Simulation



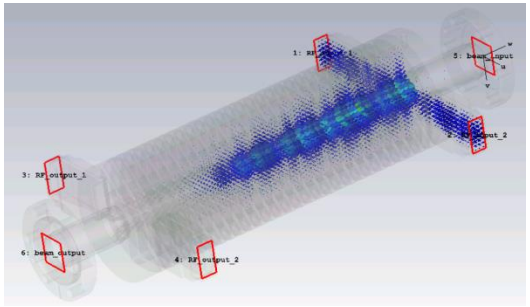
We have:

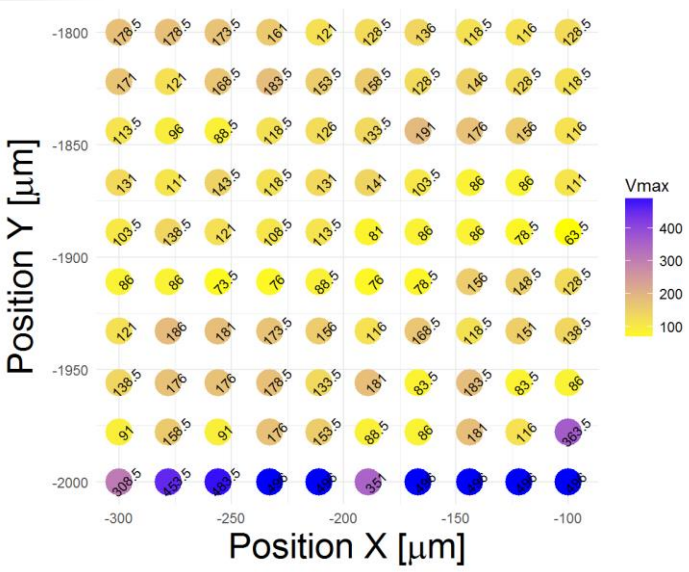
+ Faithful model of the spectrometer setup
+ Simulations with varied start conditions

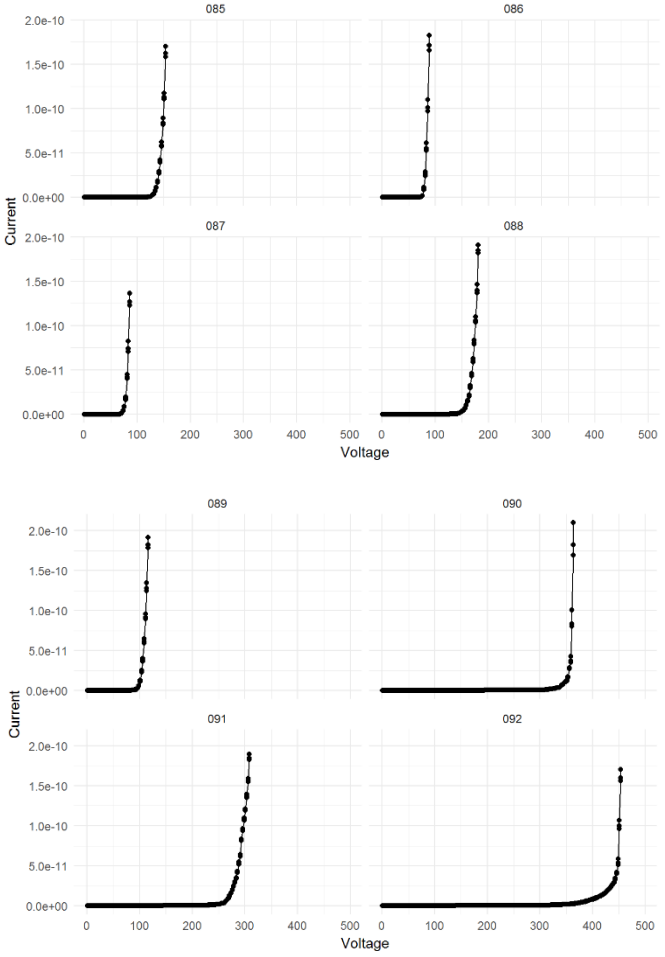
Goals:

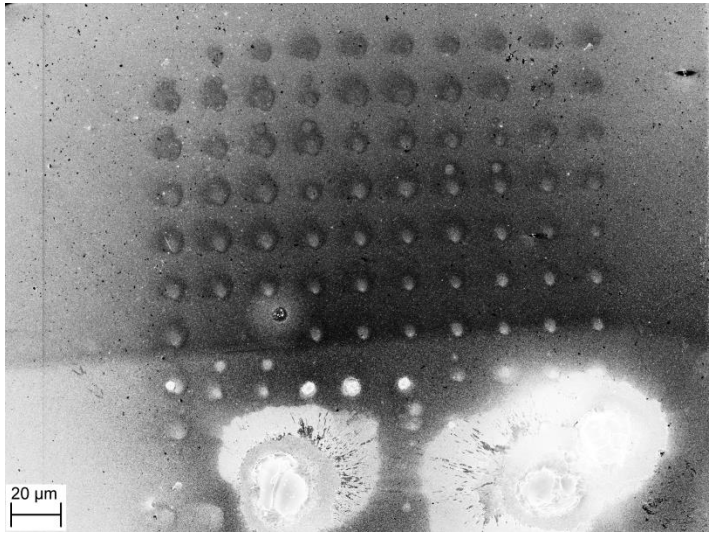
- better understanding of the experimental data
- reliable energy calibration
- energy resolution estimation
- effects of geometrical misalignment
- effects of non-uniform magnetic field

Ultimate goal:
Combine spectrometer simulation with RF simulation of CLIC cavity




Position Y [µm]
-1800
-1850
-1900
-1950
-2000
-300
-250
-200
-150
-100
Position X [µm]
Vmax
400
300
200
100


085
086
087
088
089
090
091
092
Current
Voltage
2.0e-10
1.5e-10
1.0e-10
5.0e-11
0.0e+00
0
100
200
300
400
500


20 µm

Plans

Conditioning in the field-emission regime:

Hard vs soft copper

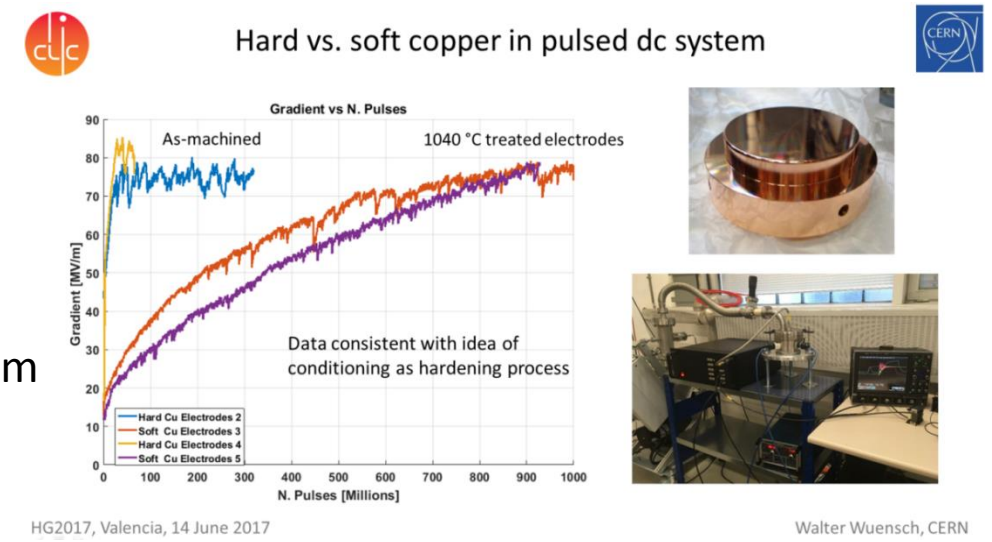
New samples from CERN:

- Soft Cu

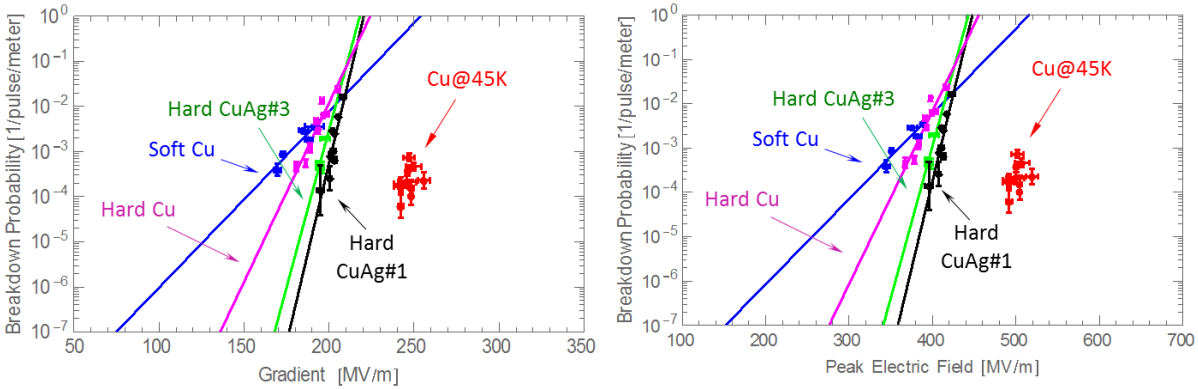
- Hard Cu

- Copper with implanted Fe ions

CERN
Large electrode system
W. Wuensch



SLAC
Accelerating Cavity
V. Dolgashev



Plans

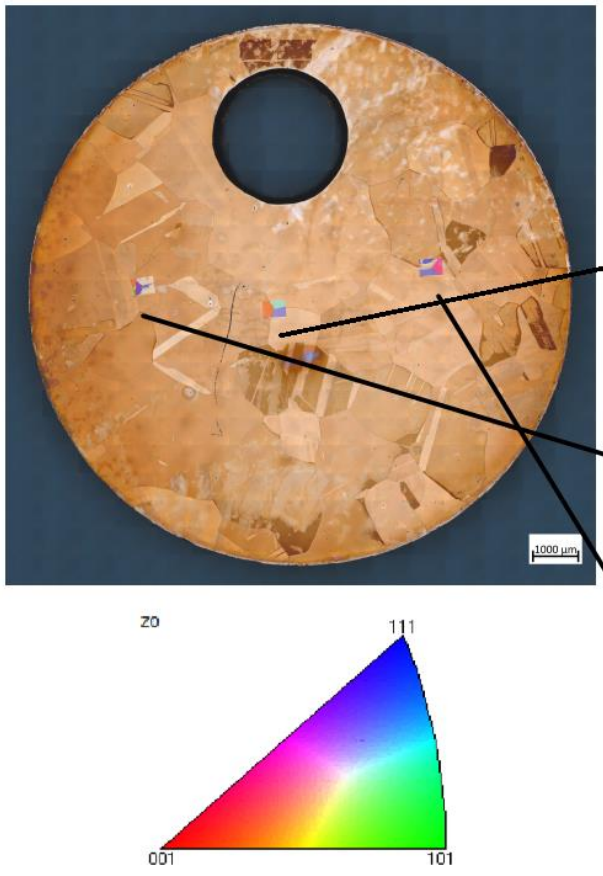
Conditioning in the field-emission regime:
crystal orientation

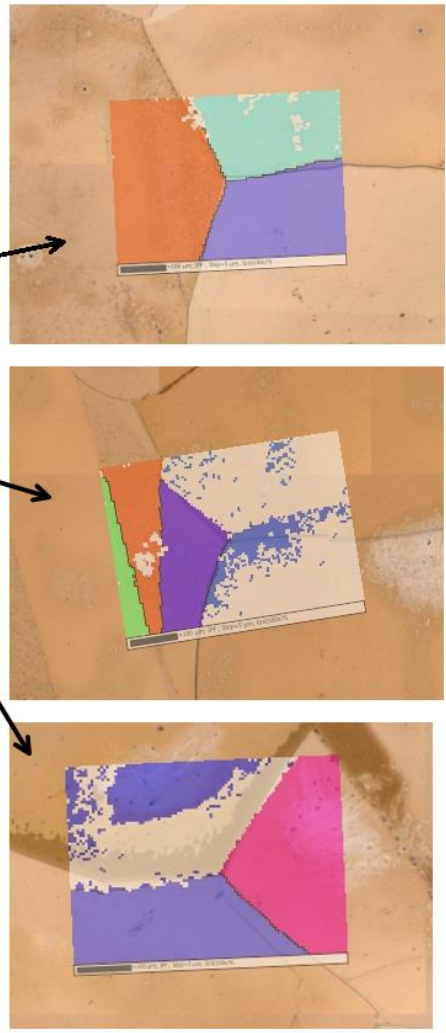
Soft Cu sample characterized at CERN with EBSD to find grain orientations in 3 separate areas (about 500x400 um each)

<u>We would like to test:</u>

- correlation between orientations and FE scans

- conditioning effect (e.g. repeating scan in the same spot) on the grains





Courtesy of Enrique R. Castro