Dark and Breakdown Currents Studies with RF and In-SEM Field Emission Studies

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Outline

- Dark and breakdown currents at XBox
    - XBox2
    - Instrumentations
    - Measurements
        - BD position
            - Longitudinal
            - Transversal
        - Energy spectra
- In-SEM experiments
    - Setup
    - Scientific program
    - Recent results
- Summary and Outlook

Xbox 2 @ CERN

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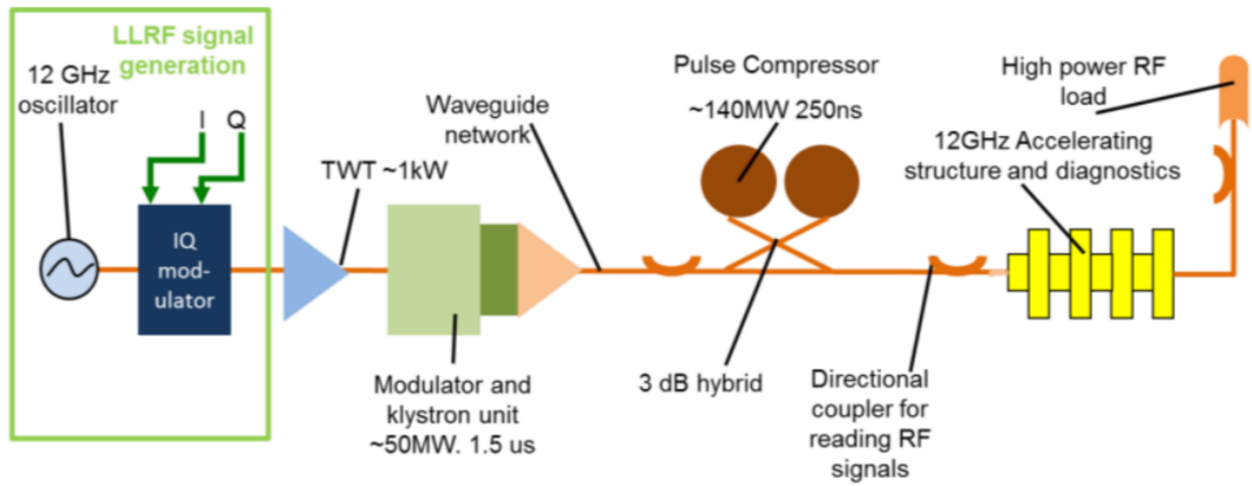
CLIC ACS tests require:

→ 40-45 MW power

→ pulse length ≤ 250 ns

Conditioning process speed related to number of pulses:

→ high rep rate ≥ 50 Hz

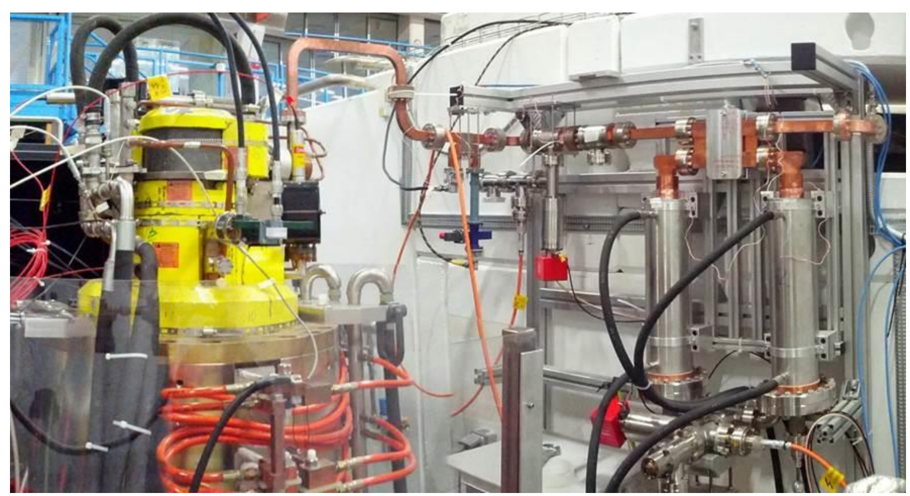


XBox2

Solid state modulator (Scandinova) +

a single 50 MW klystron +

pulse compressor



B. Woolley

Uppsala/CLIC X-band Spectrometer (UCXS)

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

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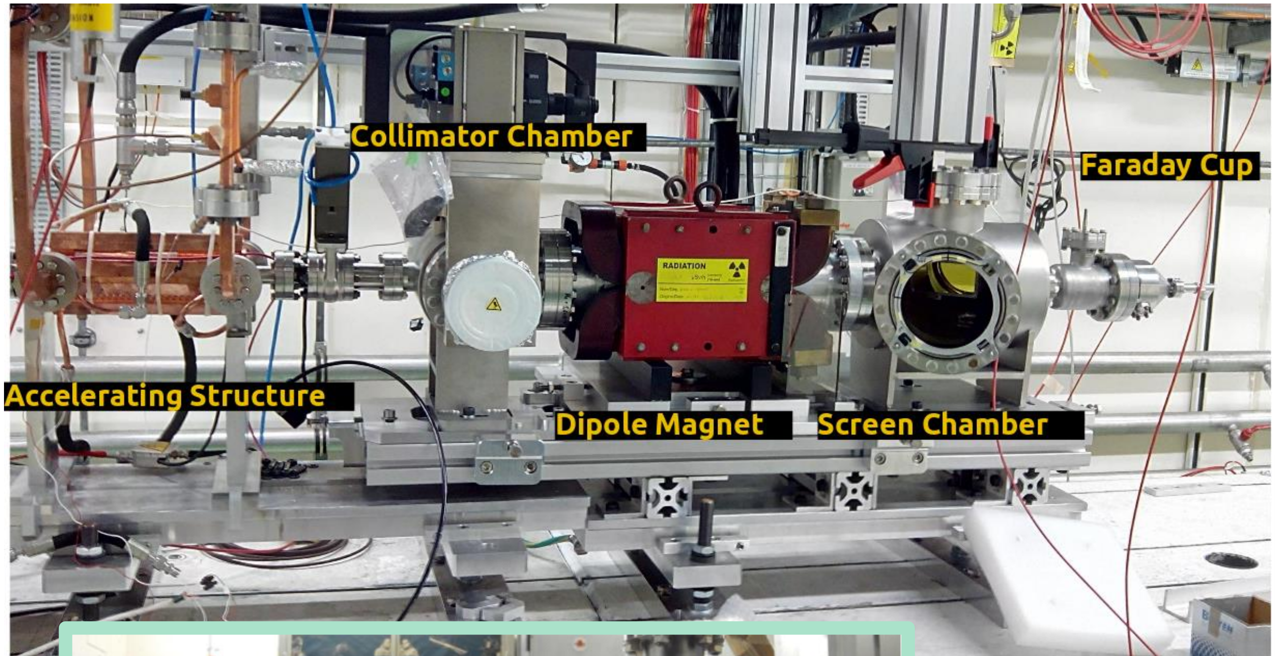
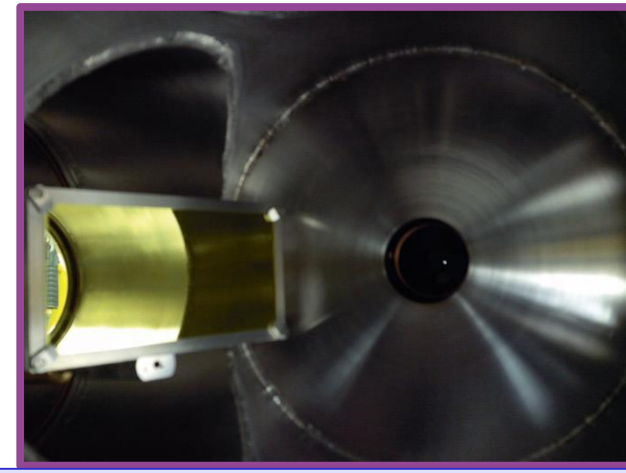
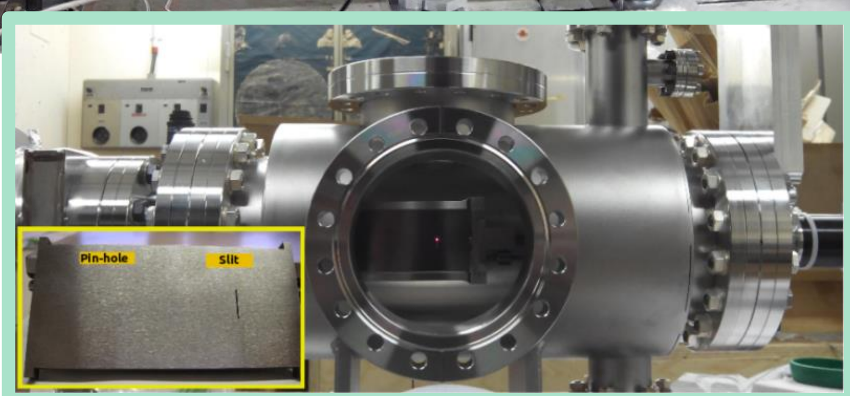




Screen (100x50x0.5 mm YAG:Ce)
linear actuator (fully retractable)
30 degrees angle w.r.t. the beam axis
2M pixel, 50fps camera with focuser



Energy resolution with dipole magnet

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

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

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Instrumentation at XBox2

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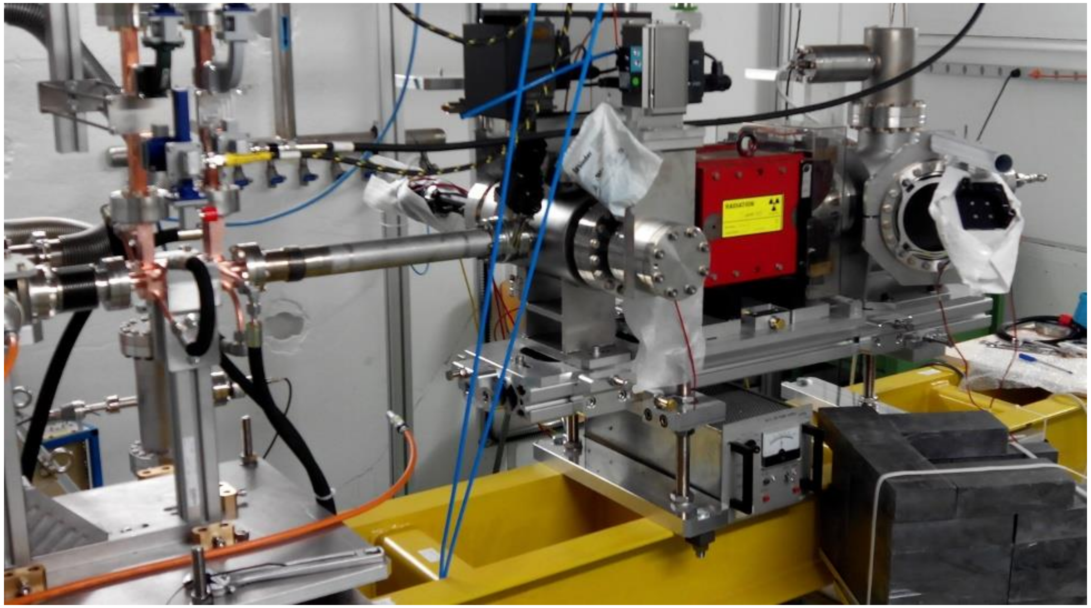
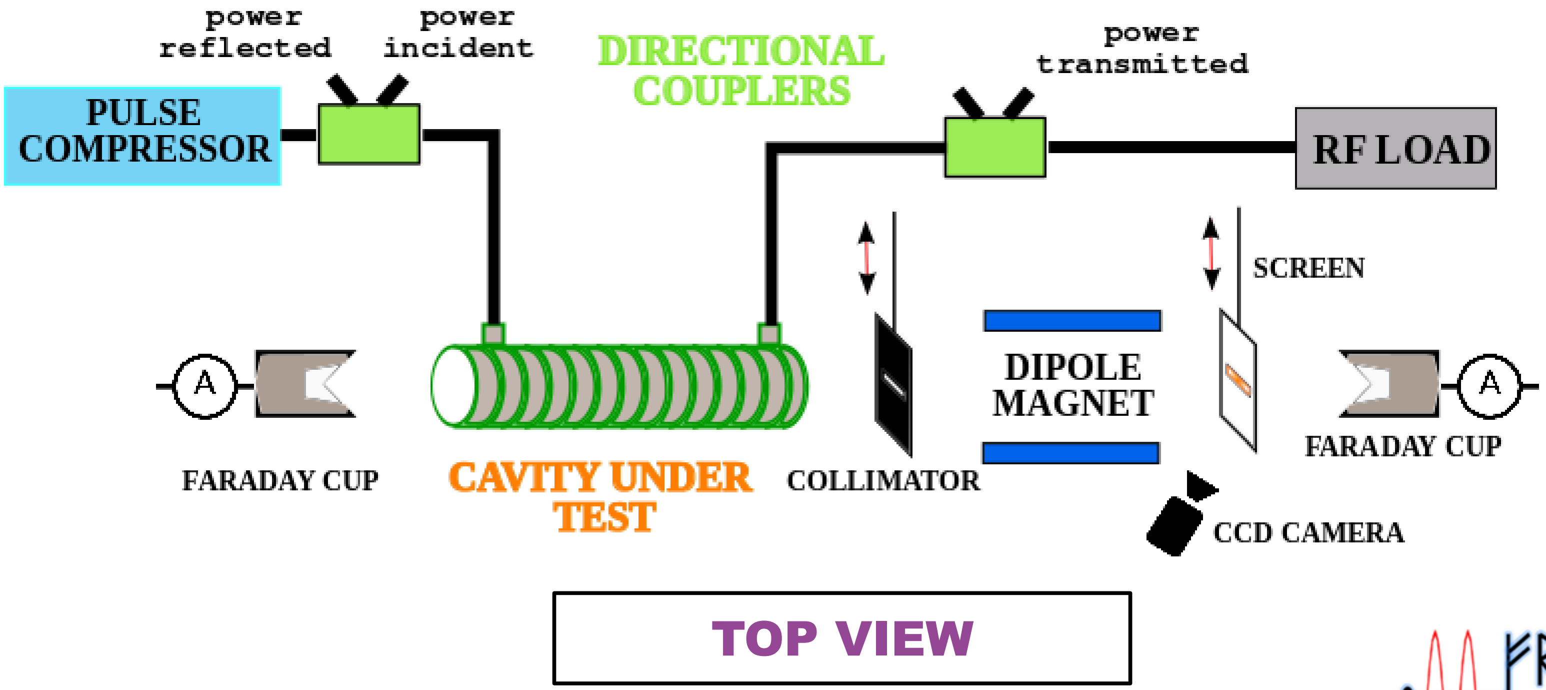


All diagnostics information available for the breakdown events is combined with images from the camera (including images from before and after BD)

50 Hz operation



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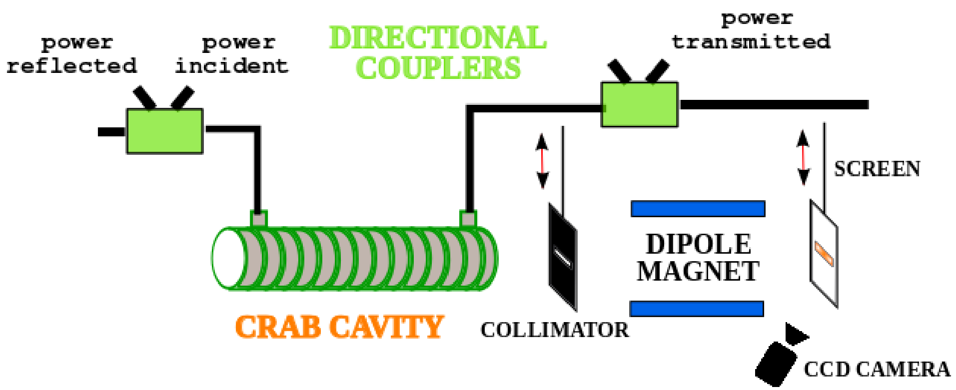
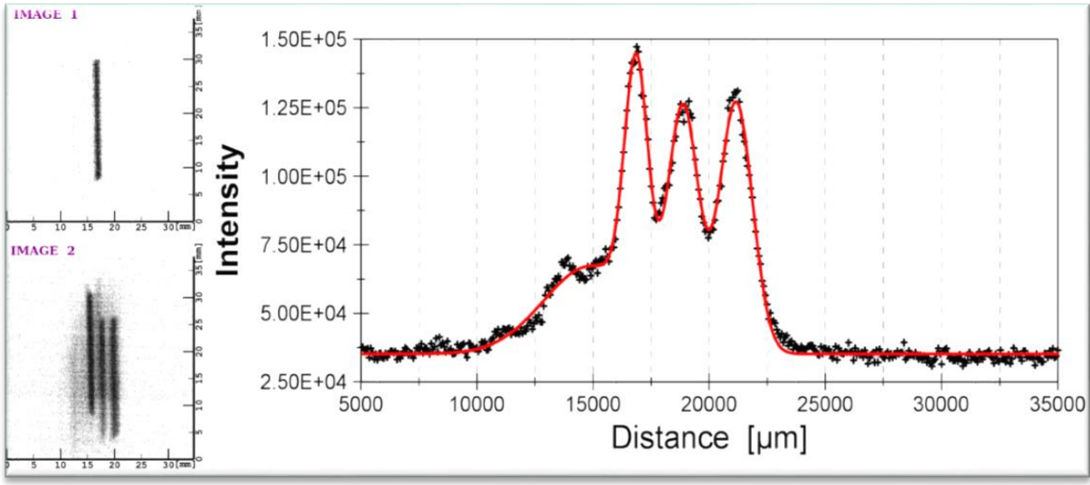
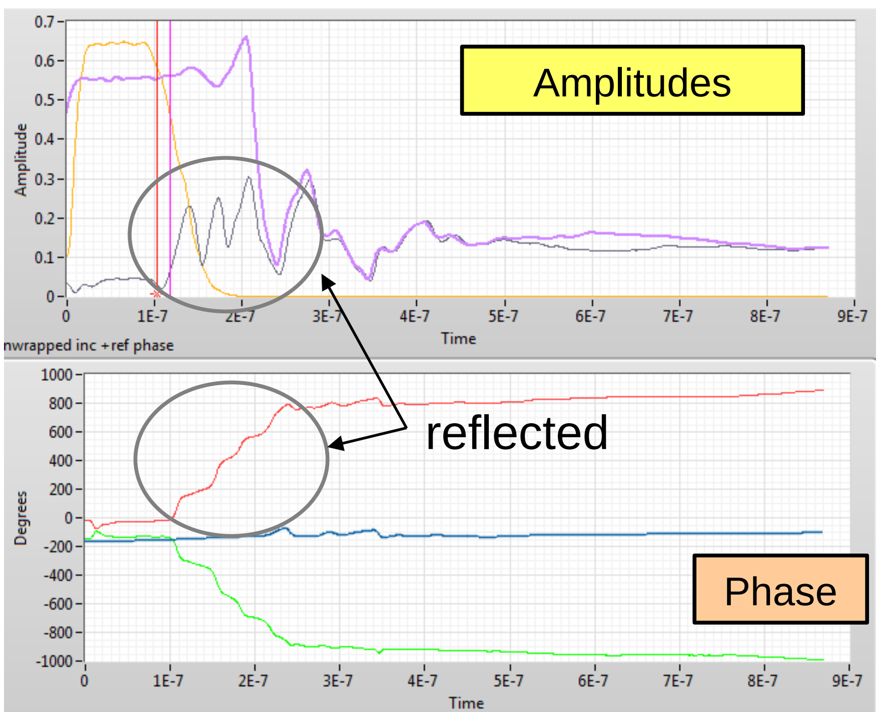
Example of collected signals – BD events



Example of images after the slit





LEGEND

Amplitudes:
- RF In
- RF Transmitted
- RF Reflected

Phase:
- RF In
- RF Reflected
- In - Reflected

Often rich structure of the reflected signal

From amplitude spectrum we conclude that the energy is lost
→ breakdown is "feeding" from the RF power

For the same events we see more features on the screen

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BD position

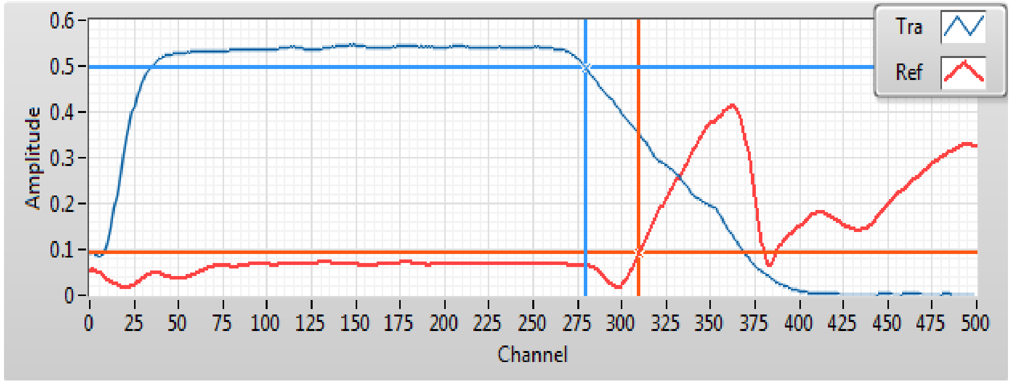
The time and phase difference can give us information about position of the BD site

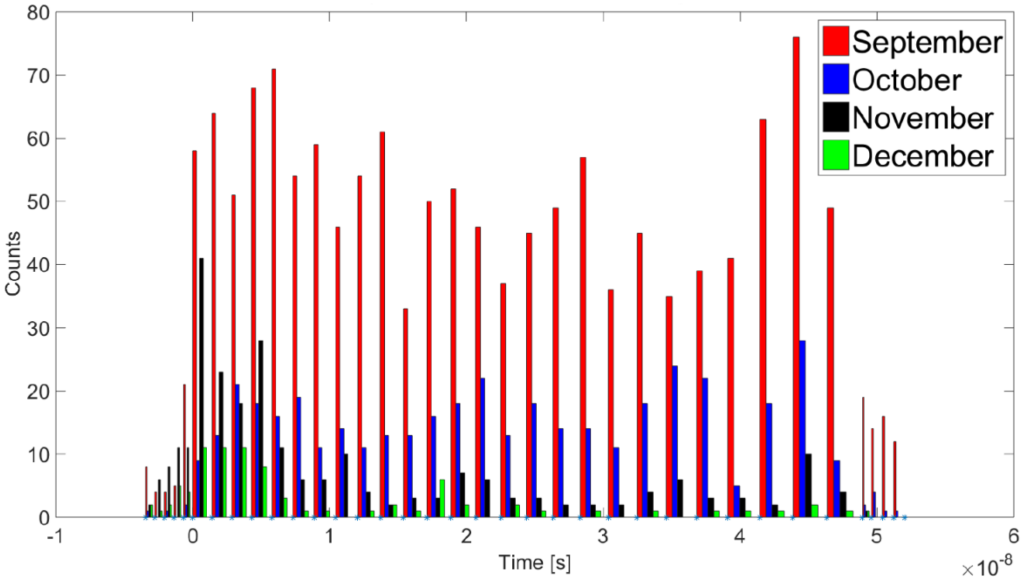
BD detected when:

1) Drop in transmitted power due to plasma formation
2) Power reflected back

Difference in time between the transmitted power falling and the reflected power increasing to find the BD cell location. *)

The phase of the reflected signal is used to pinpoint cell location.





Static information (single value), while BD is a dynamic process

Can we do better?

*)There are other methods that use RF signal timing to extract BD position.

Longitudinal discharge dynamics

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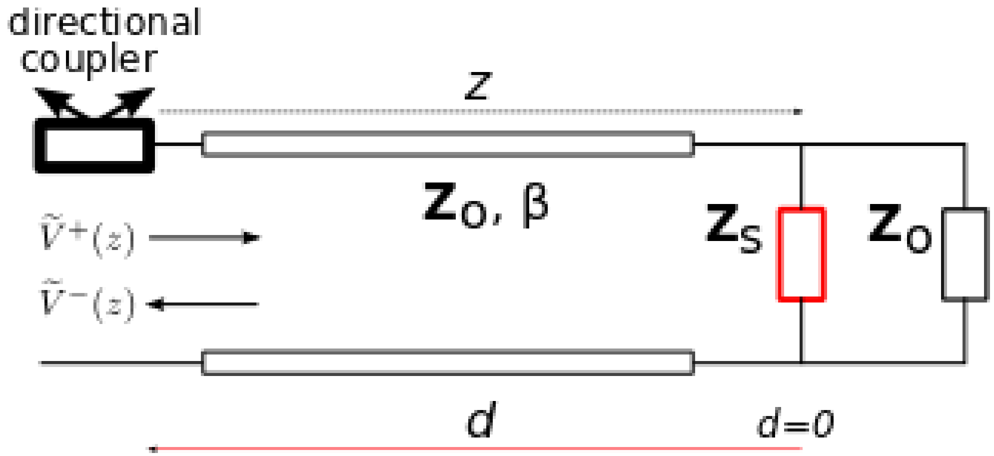
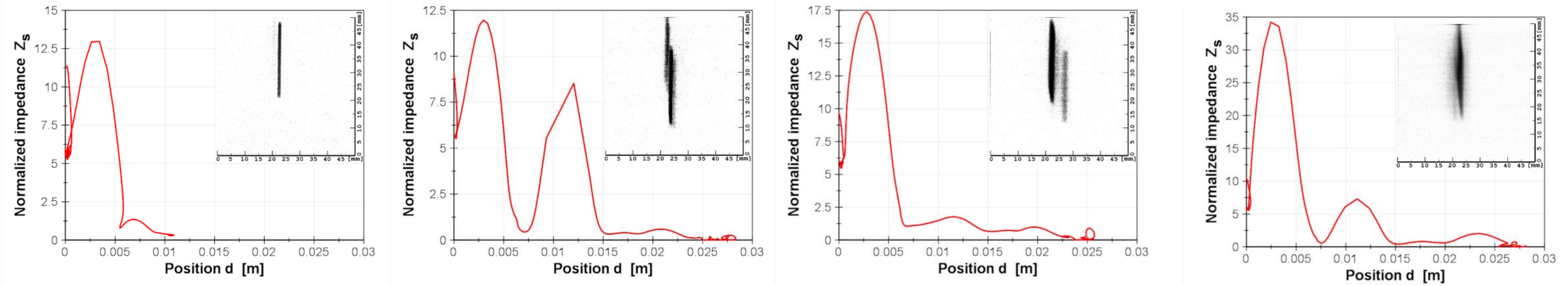


Field reflections can be seen as reflection on a mismatched load in the structure
→ In a simple model we interpret the mismatch as plasma growth
→ Combining phase and amplitude information from Incoming and Reflected waves we can get relation between position of the wave and the relative impedance



Peak separation in agreement with cell length of 8.3 mm

This supports the theory of breakdown migrations during the RF pulse

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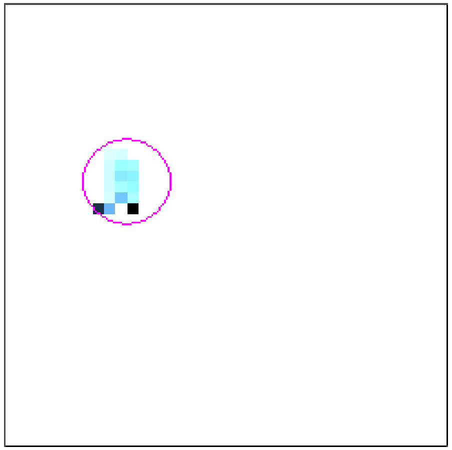
Information from the images

Breakdown transverse position – SLIT

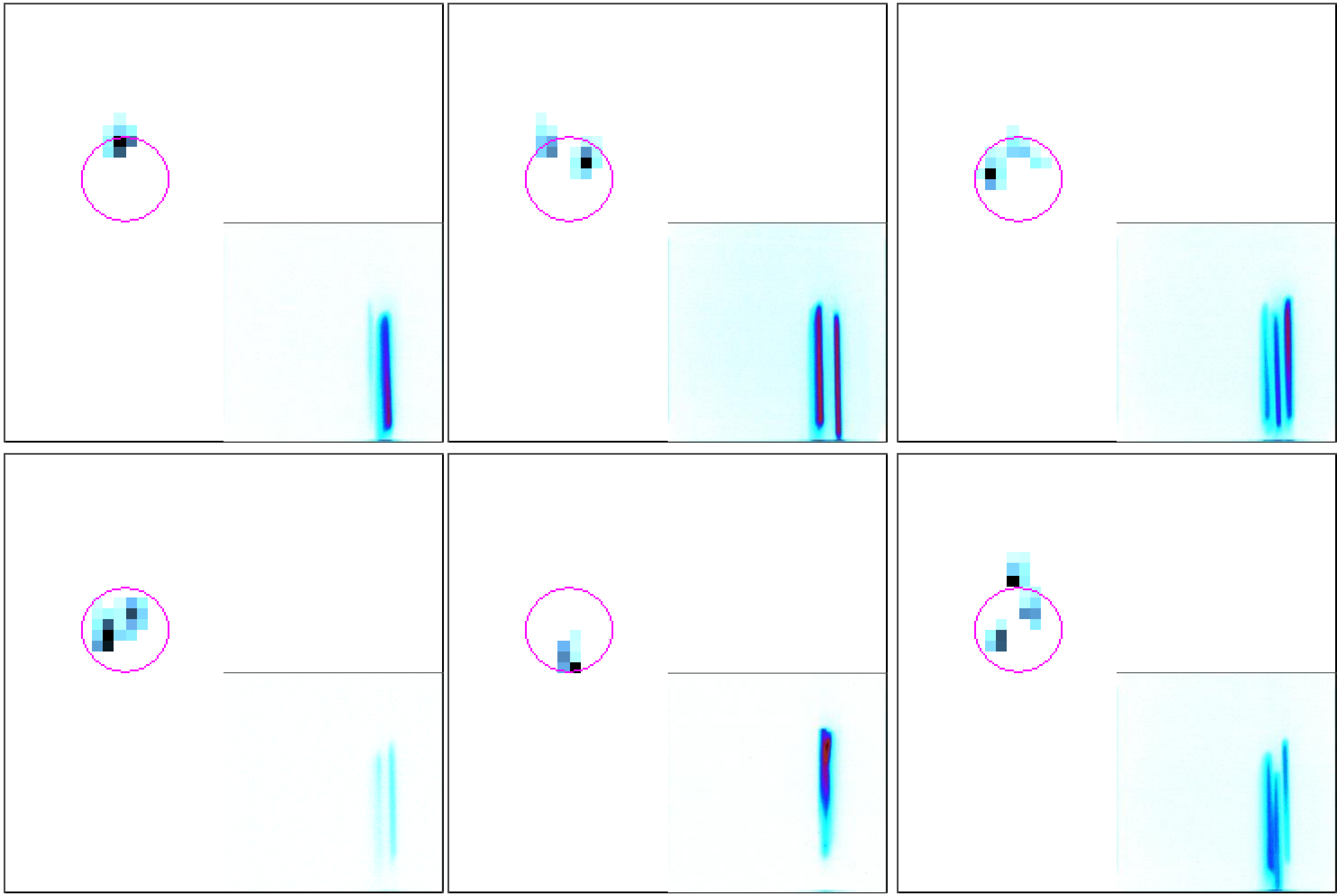
75 ns pulses

Deconvolution with slit transfer function

Single events - recorded images and reconstructed source positions



Single events (animated preview)

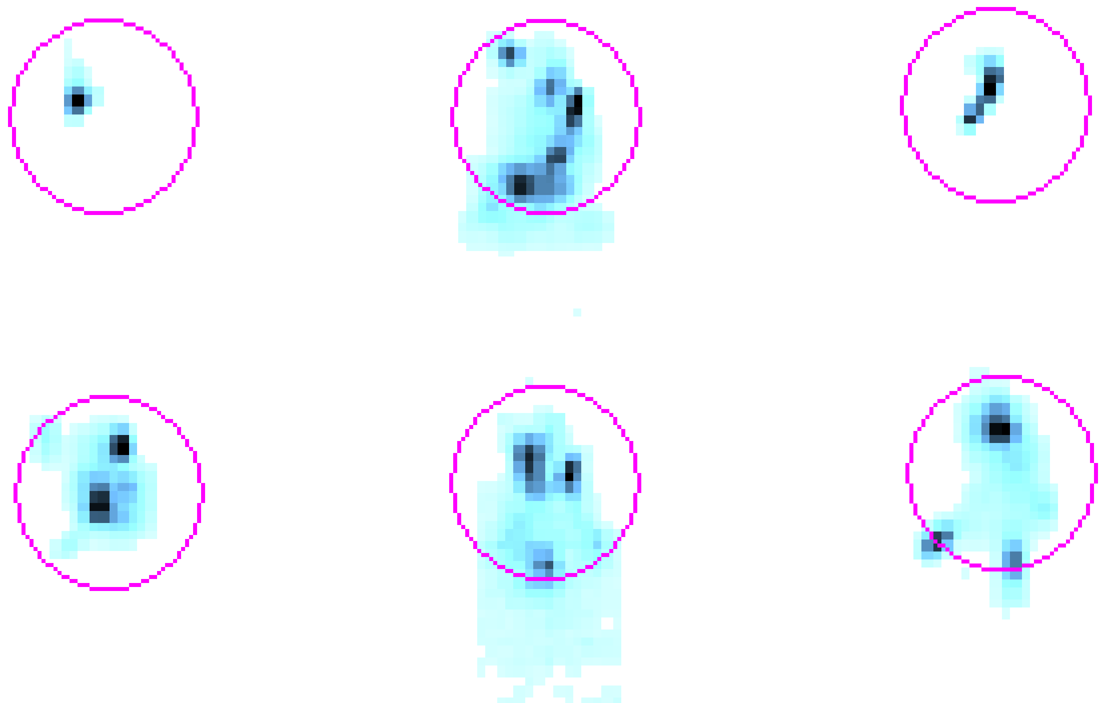


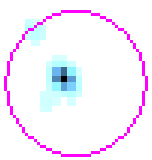
Breakdown transverse position – PINHOLE

200 ns pulses

Deconvolution with slit transfer function

Single events - recorded images and reconstructed source positions





Single events
(animated preview)

Qualitatively more features in data –
longer pulse, more time to develop new breakdown

Breakdown transverse position – PINHOLE

200 ns pulses

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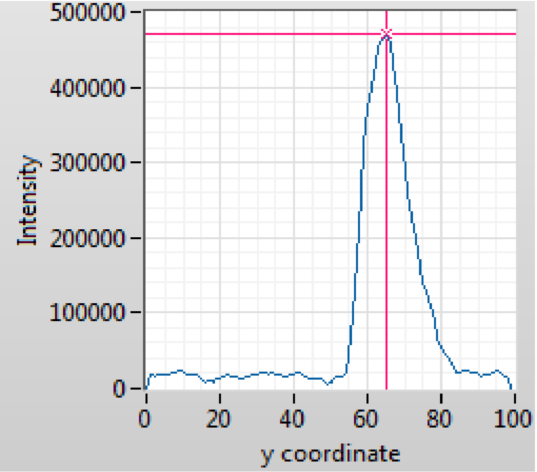
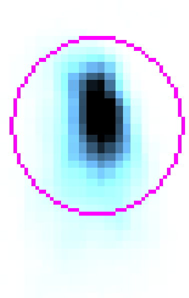
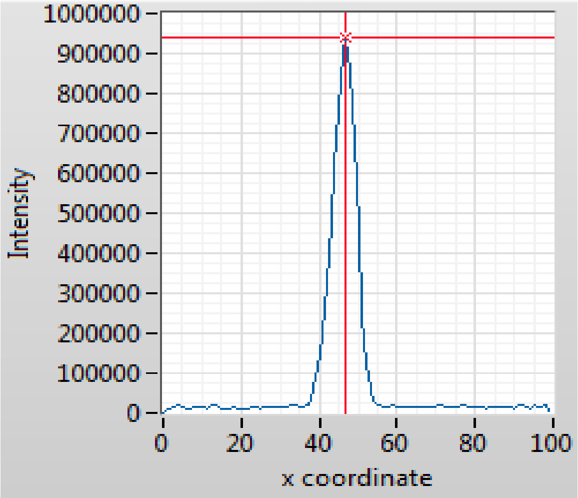
Combined image from 199 events

Asymmetry and excess events in vertical direction







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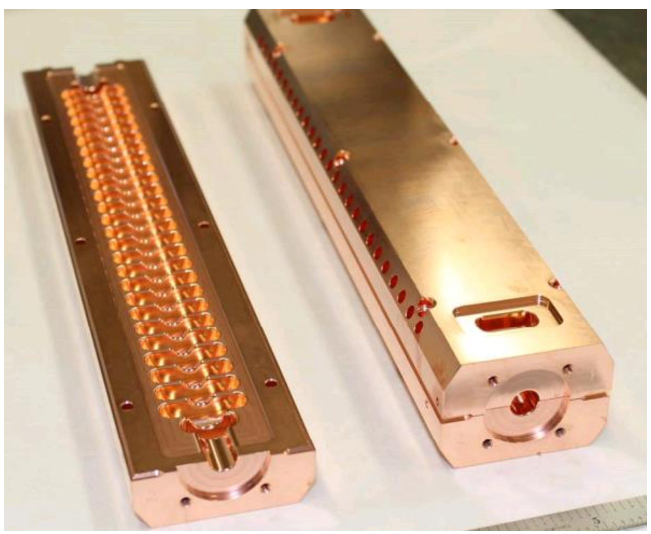
Breakdown transverse position – PINHOLE

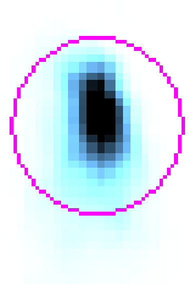
200 ns pulses

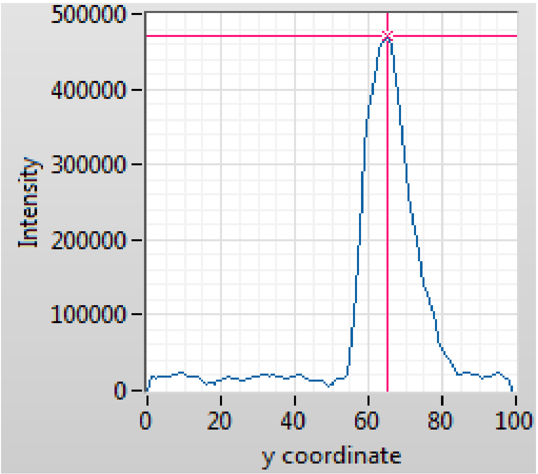
Combined image from 199 events

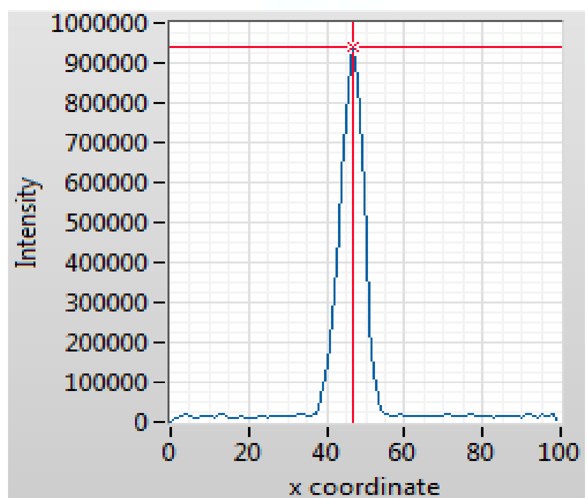
Asymmetry and excess events in vertical direction

Due to special type of structure under test?









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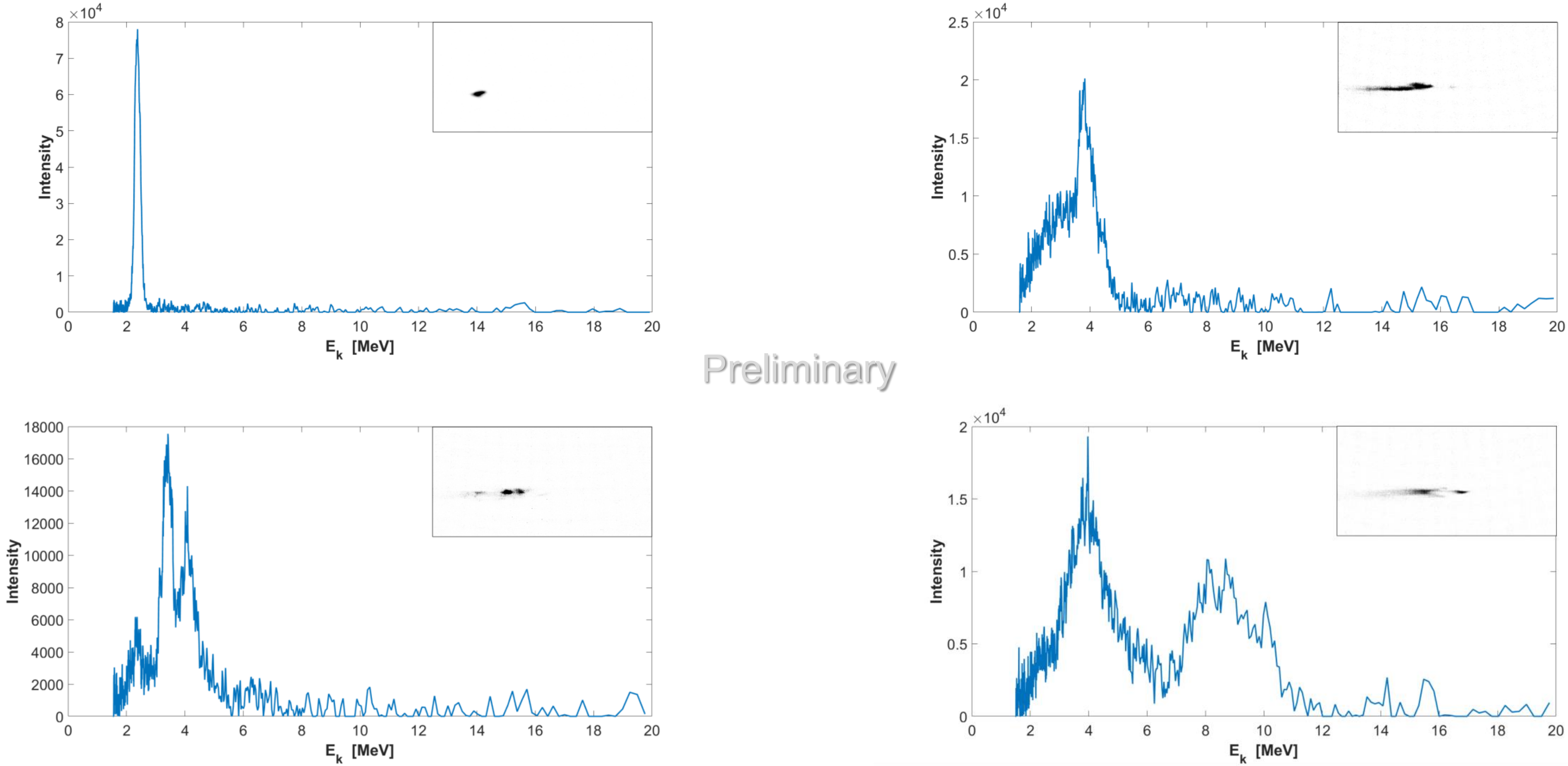
Energy spectra from BD events



Electrons with well defined energies

→ maximum in agreement with the given power/gradient in the structure

Next step: combining energy information with other signals and compare with simulation

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Dark current

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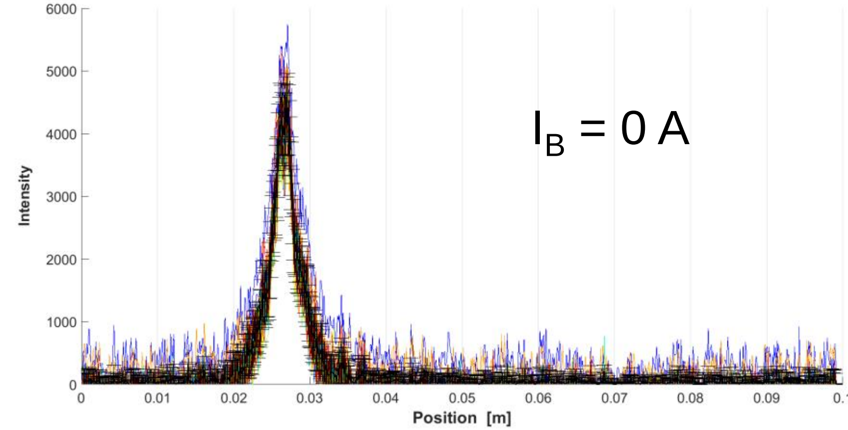
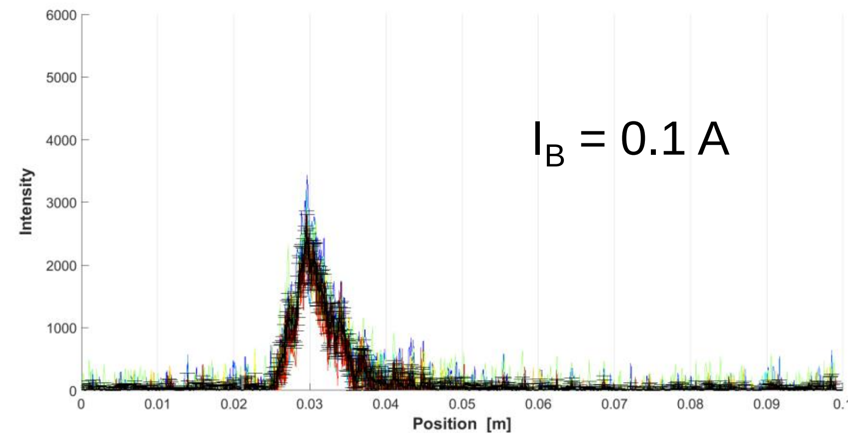
Dark current :

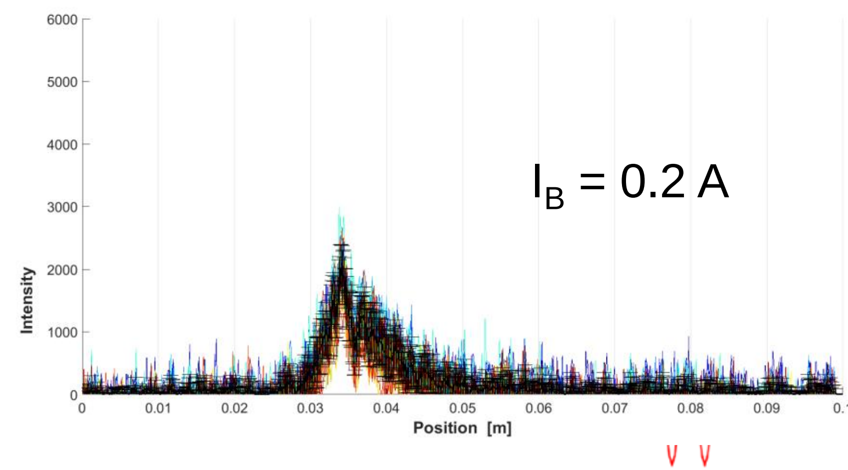
- precursor of RF breakdown, input to many models→can we predict when BD approaches?
- Information about structure hardening process
- Causes RF power loss, radiation, possible backgrounds

Preliminary

20 pulses + average







Dark current

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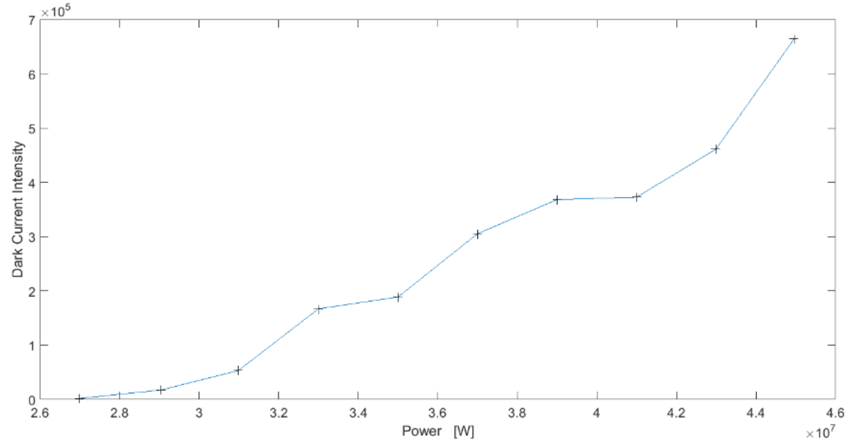
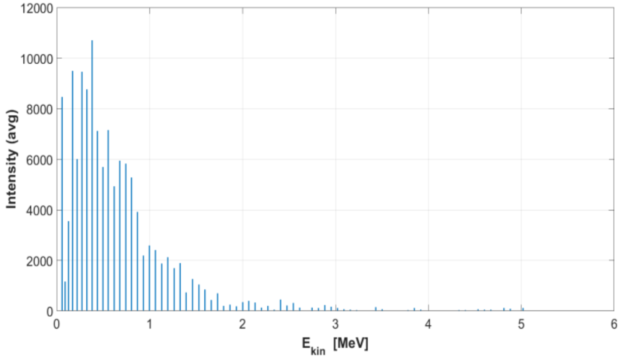
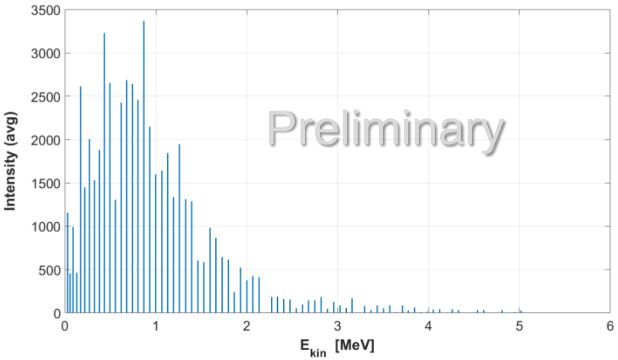
DC scan with power (done at the end of conditioning during ~ 1h)



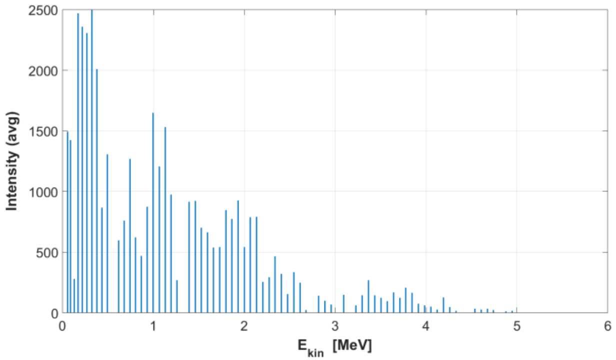
@ 21 MW inc. power



@ 26 MW inc. power



@ 30.5 MW inc. power



- No indication of single emitting spot inside the cavity
  - Isotropic transverse distribution
  - Broad energy spectrum – continuum from electrons in dark current
    example here from 50 consecutive pulses (1 second)

Next step: comparison with other detectors i.e. Cherenkov fiber detectors, Faraday cup to look at which structure parameters affect the dark current production

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In-SEM Setup

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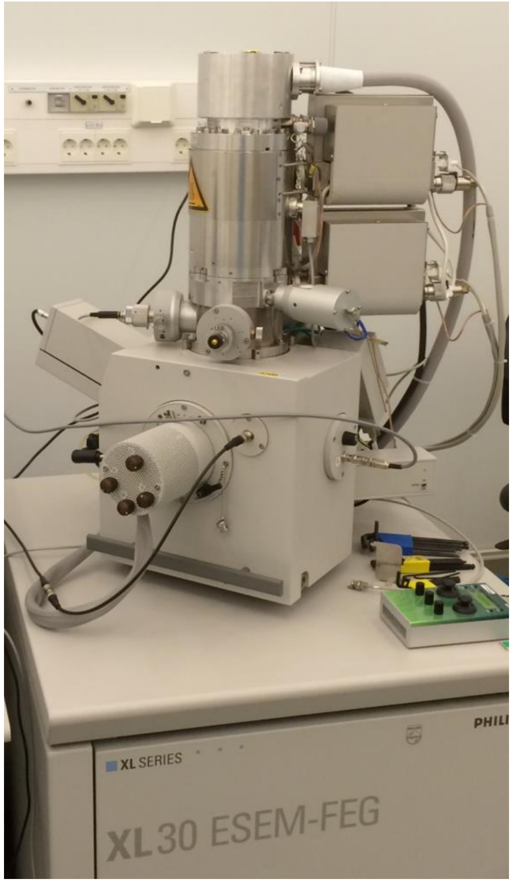

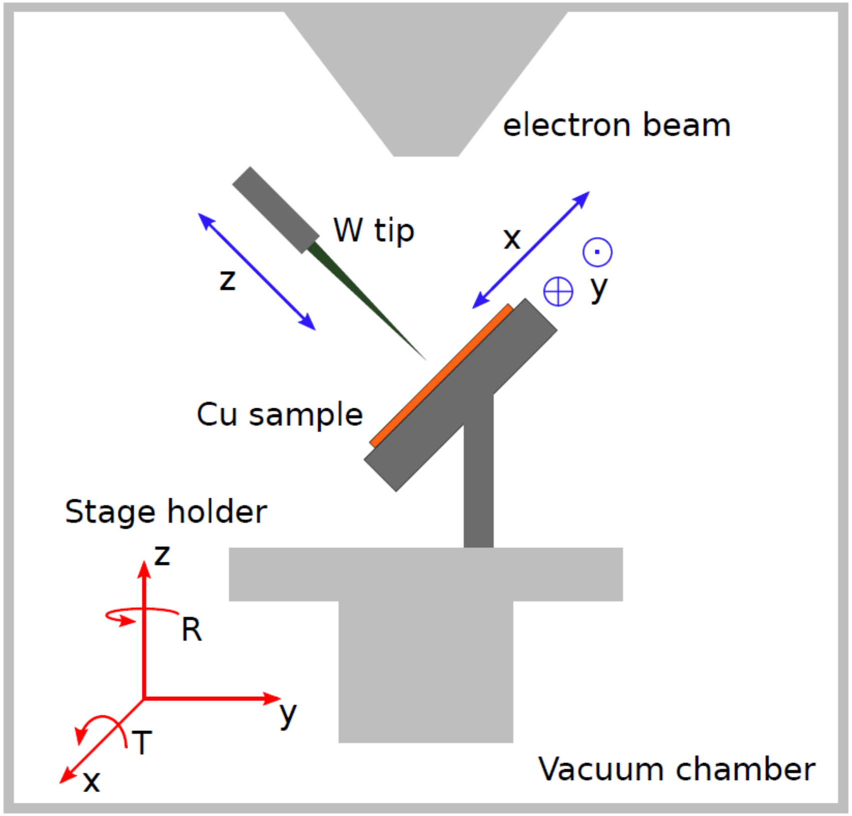

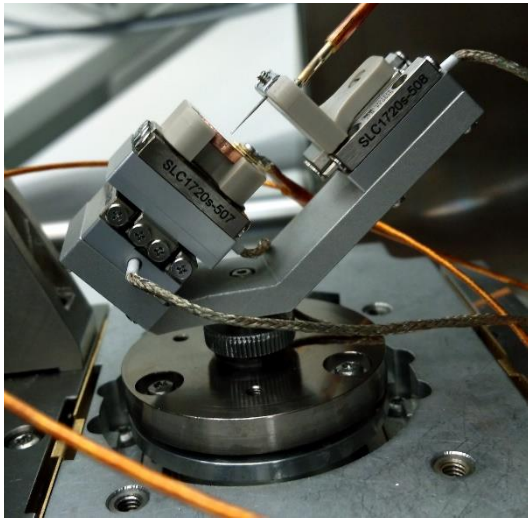

Cu sample
W tip, radius of curvature 5 µm.
nm precision Piezo-motors

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

Keithley 6517a Electrometer for measuring FE currents
- up to 1 kV
- range from sub-pA to mA
- 50 Hz sample rate

In recent experiments gap distance to 700 nm

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

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Scientific program

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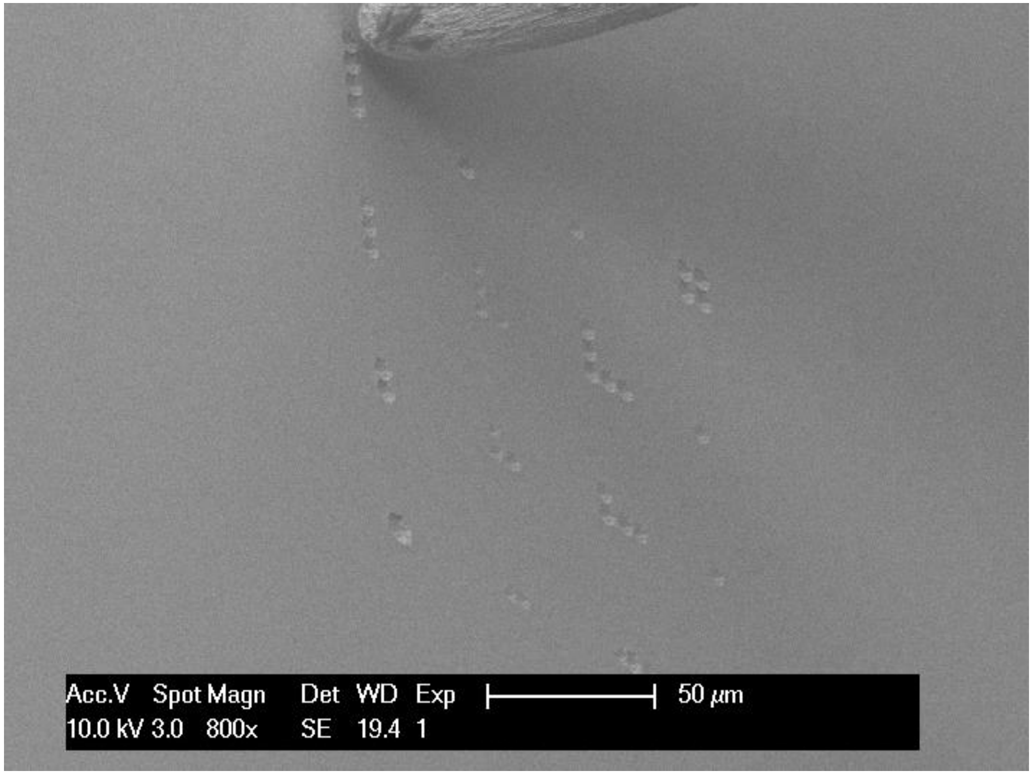
Delays due to repairs of ESEM

Activity restarted earlier this year with the following scientific program:

1. Marking an area in ESEM (for easy recognition)
2. Move sample to HR-SEM for surface microscopy of the area
3. Move back to ESEM for FE experiments
4. Move sample back to HR-SEM for post-experiment surface microscopy



Areas are marked in ESEM before initial surface analysis

Here:
150 x 150 µm ; 5µm depth
9 areas

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Scientific program

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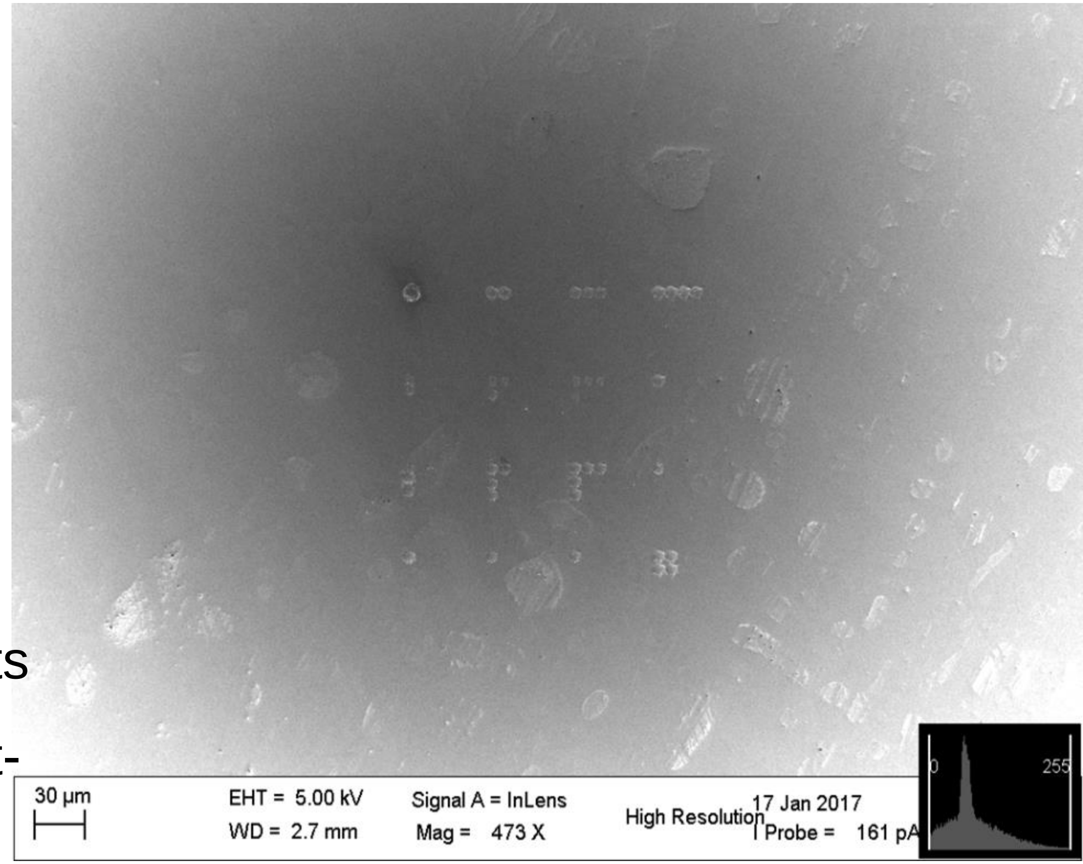

High-resolution SEM
Zeiss LEO 1550 FEG

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Scientific program

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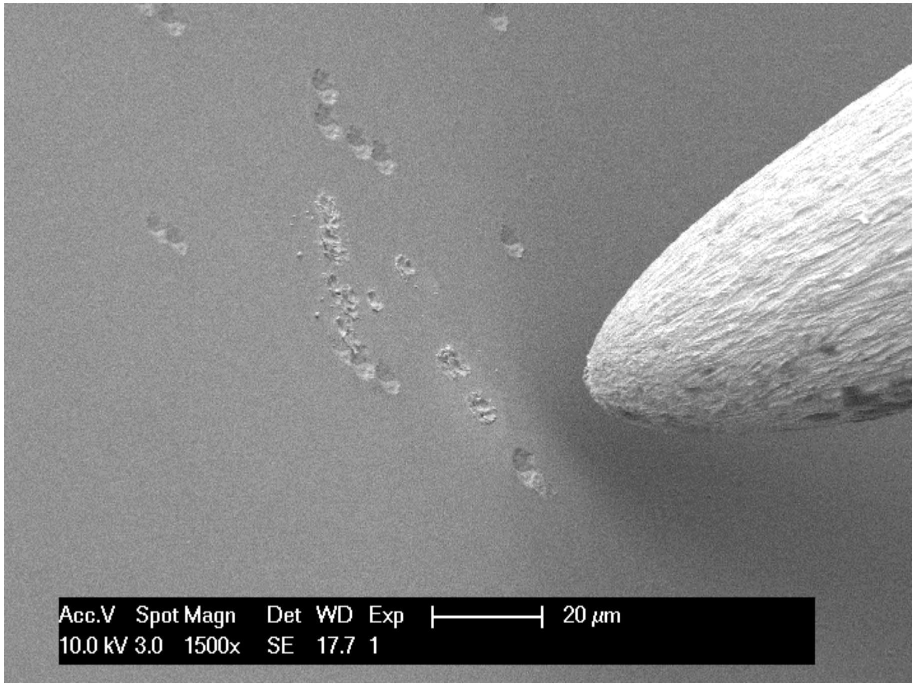
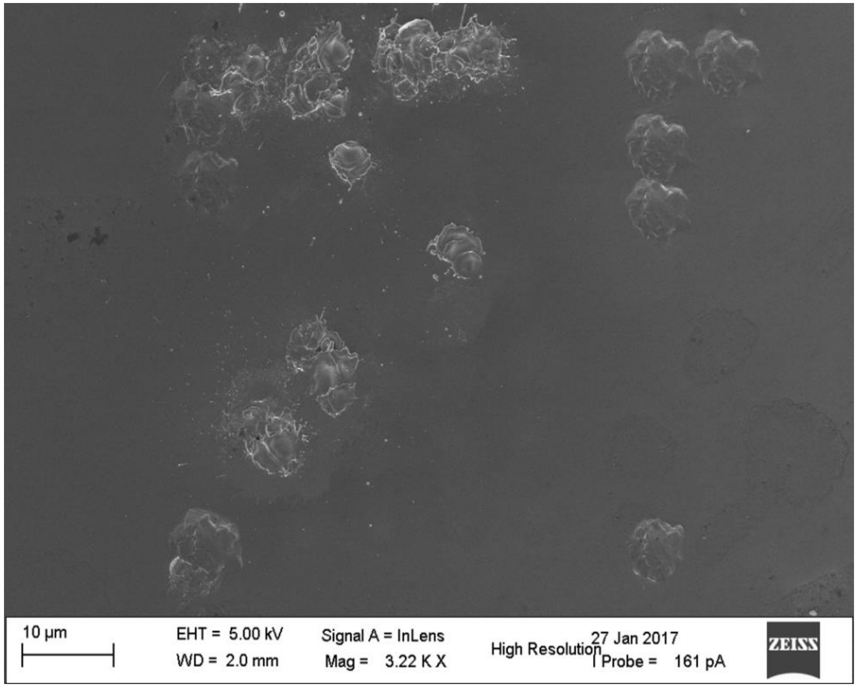


Scientific program



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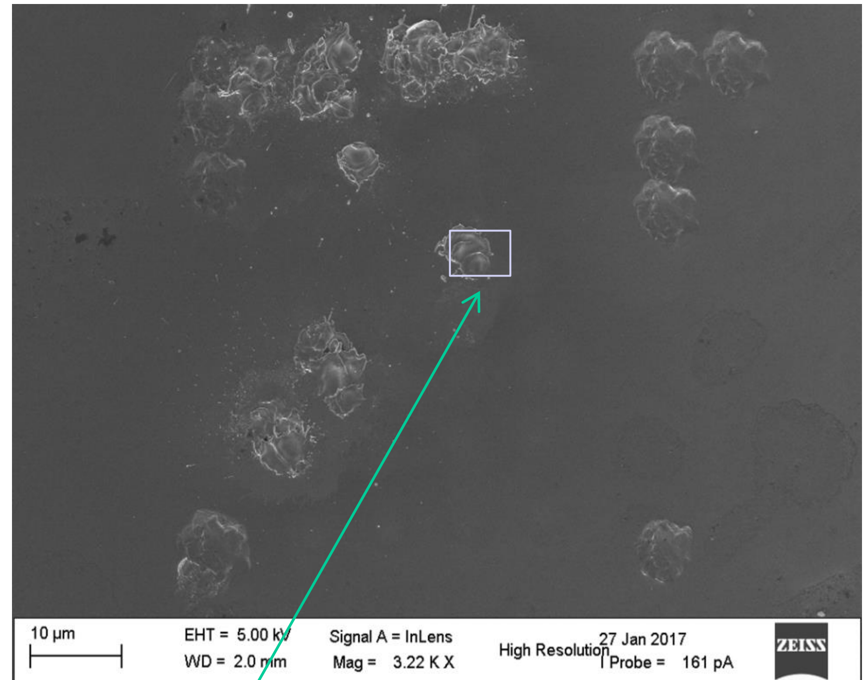
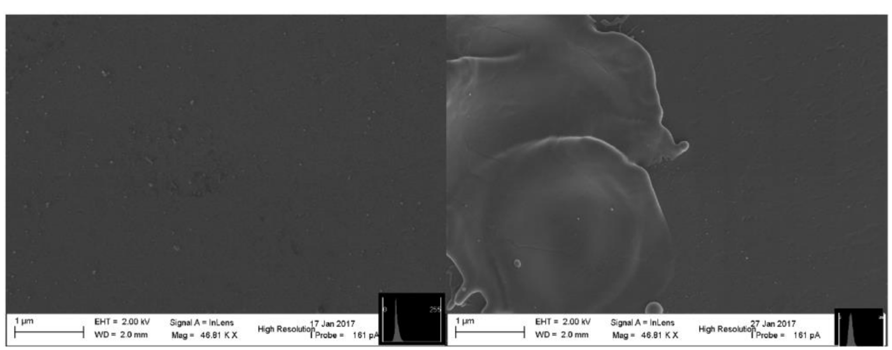
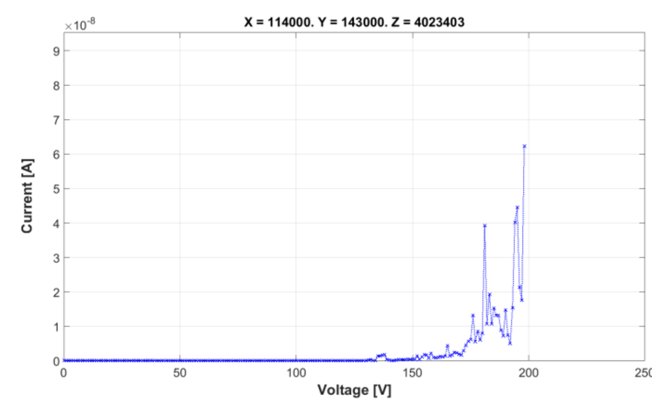


Before FN

Site 28

After FN





Results of surface scan

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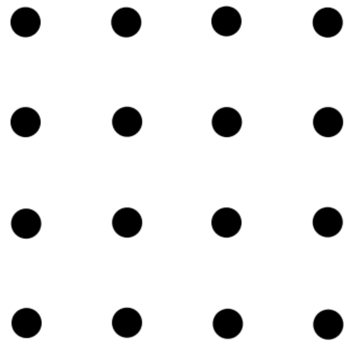
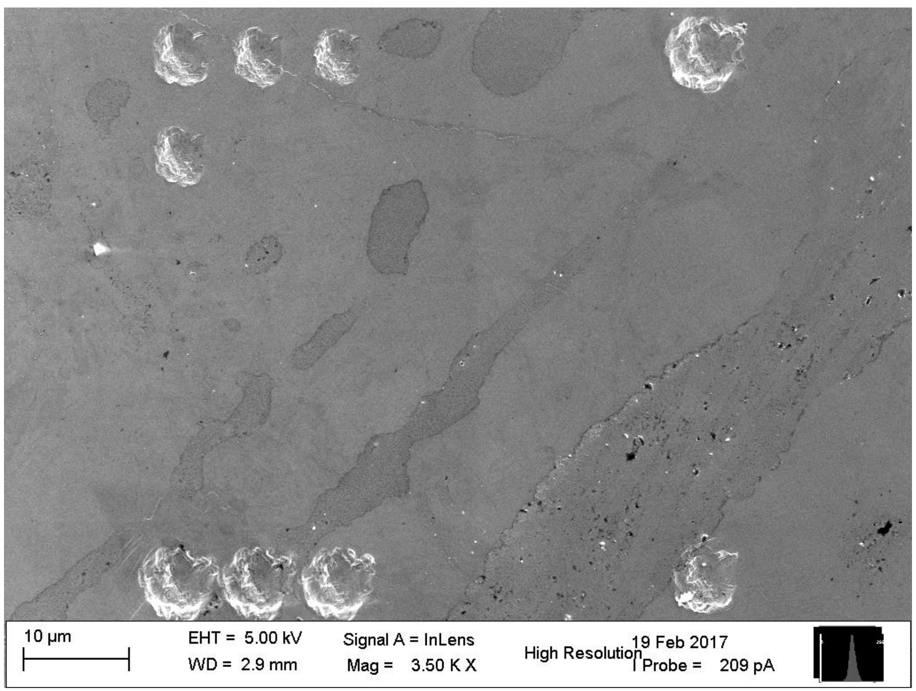
Scan pattern



Before



Results of surface scan

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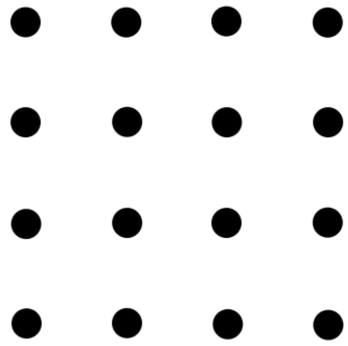
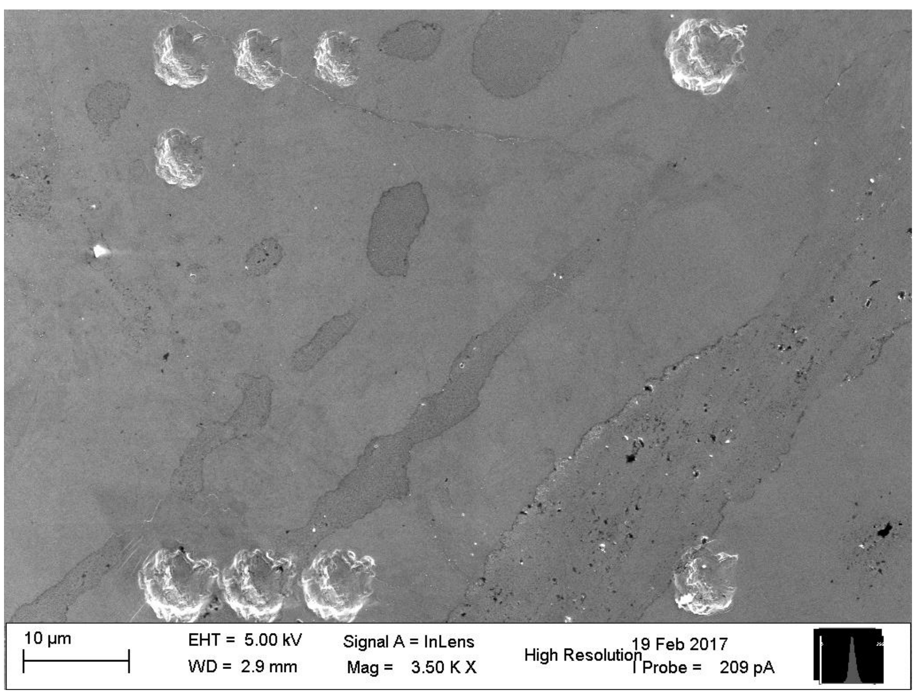
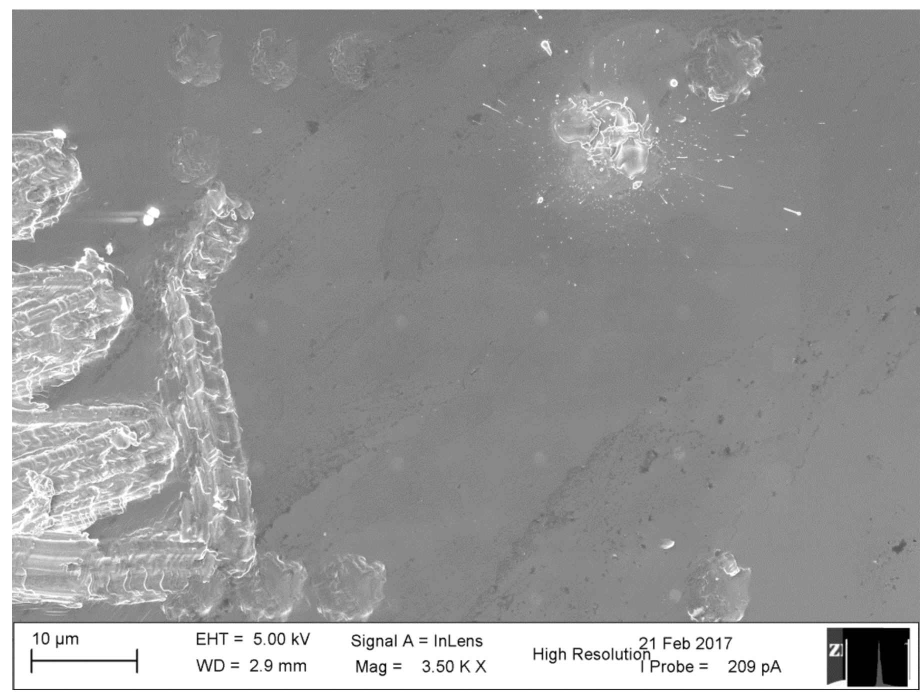


Before



After



Results of surface scan

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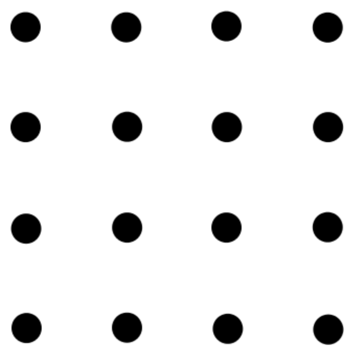
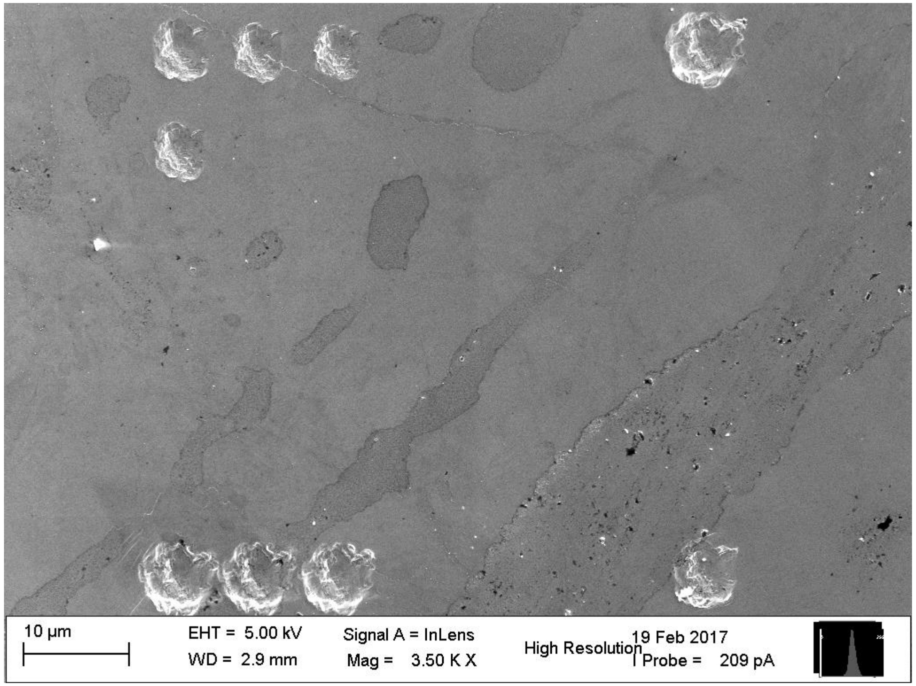
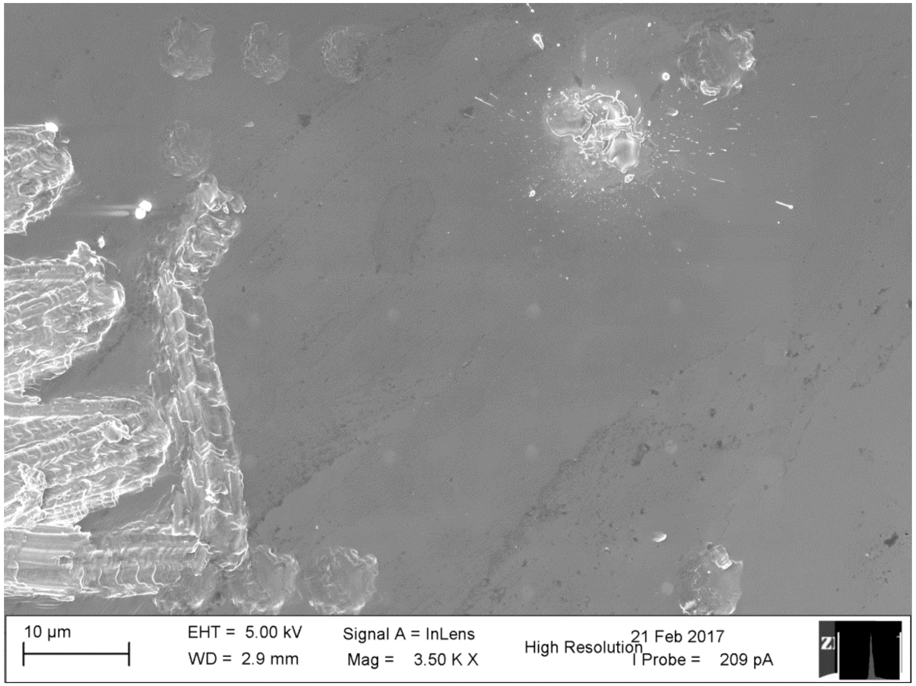


'Photoshop' enchancement

Before



After



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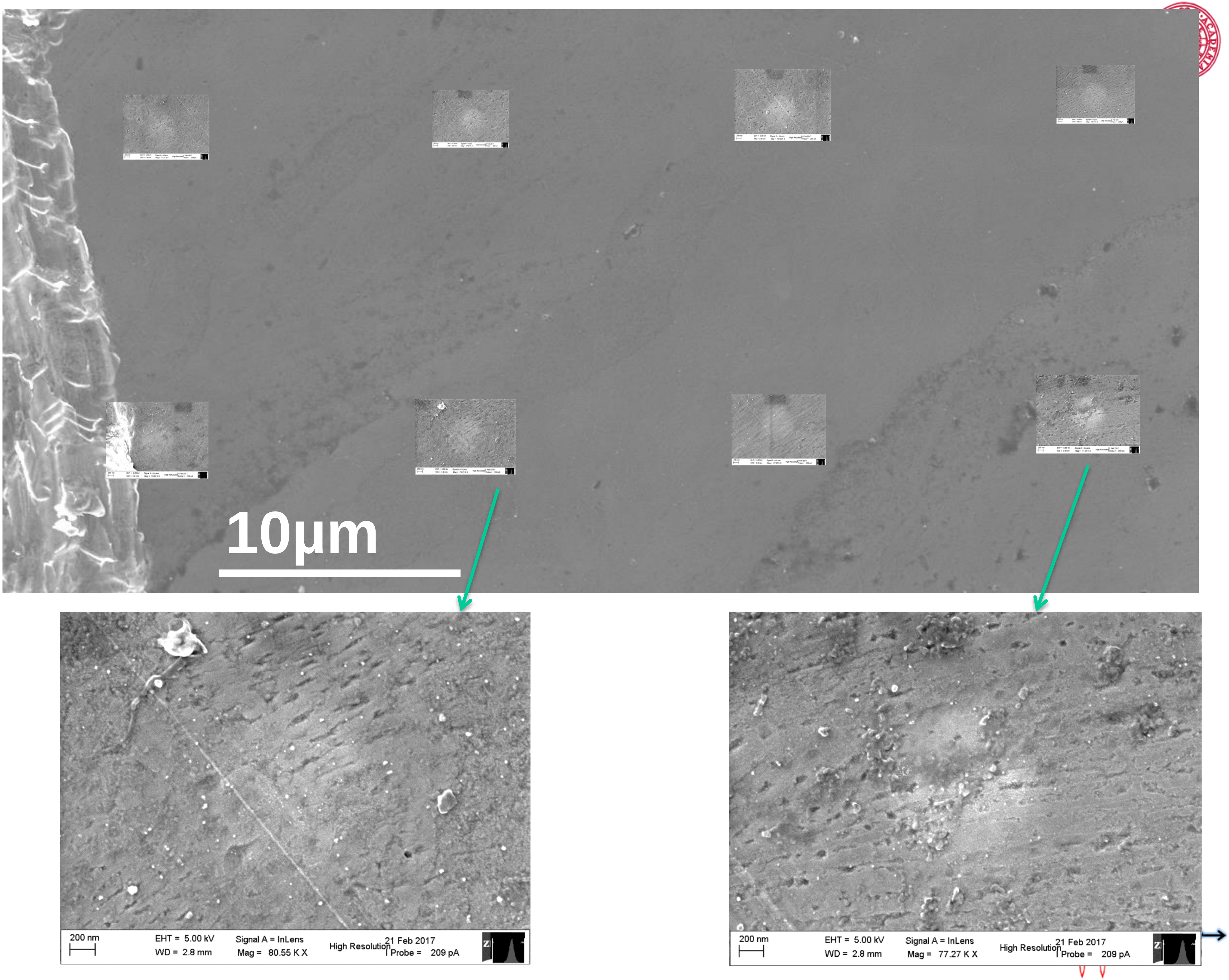
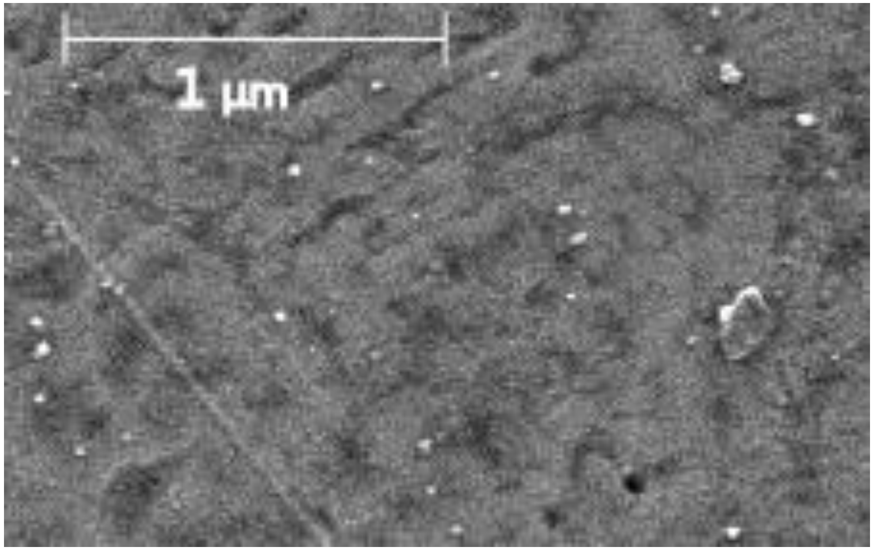
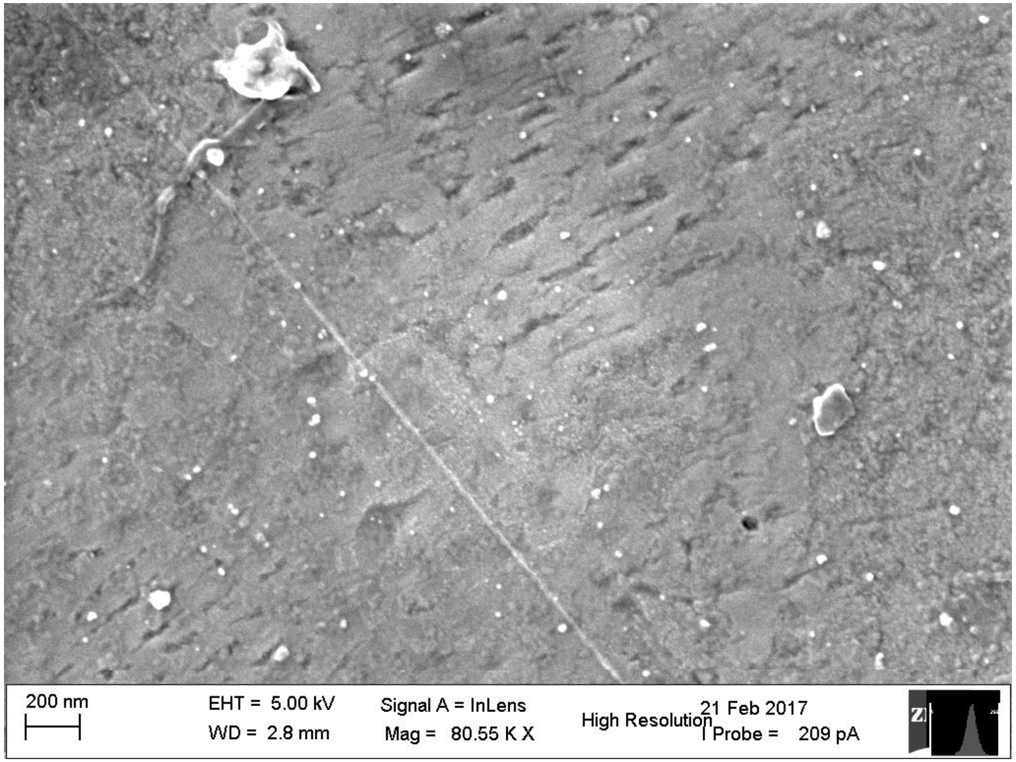

10µm
200 nm
EHT = 5.00 kV
WD = 2.8 mm
Signal A = InLens
Mag = 80.55 K X
High Resolution
21 Feb 2017
I Probe = 209 pA
200 nm
EHT = 5.00 kV
WD = 2.8 mm
Signal A = InLens
Mag = 77.27 K X
High Resolution
21 Feb 2017
I Probe = 209 pA

“Spot” area - before and after





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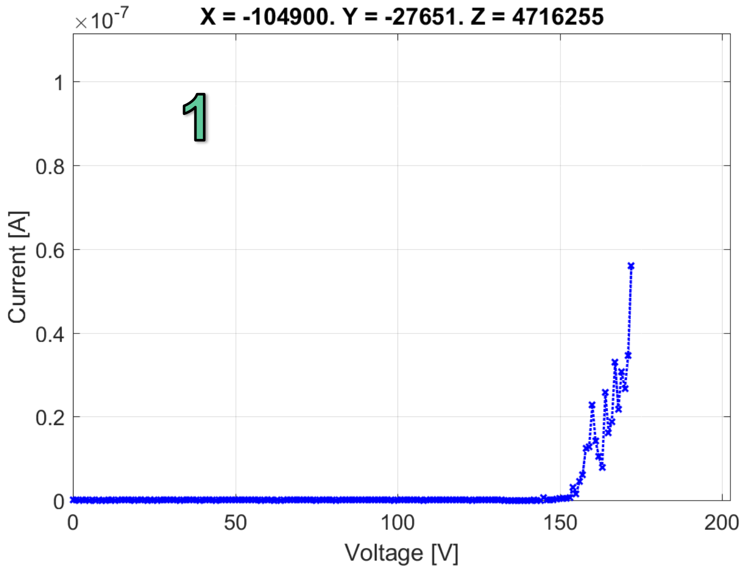
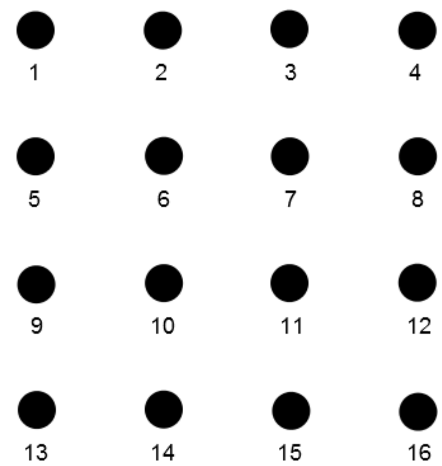
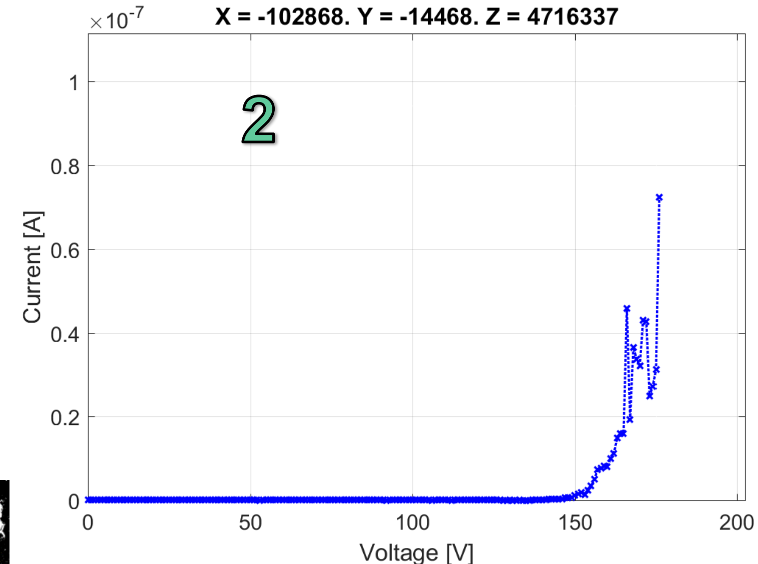
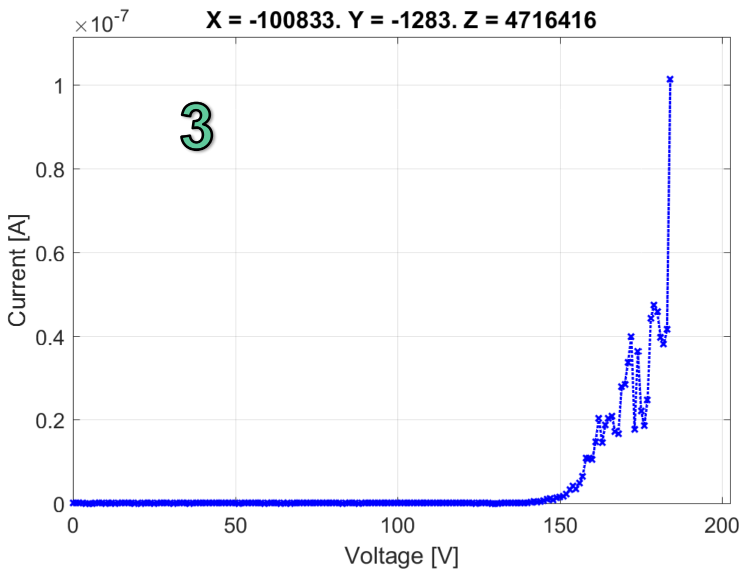
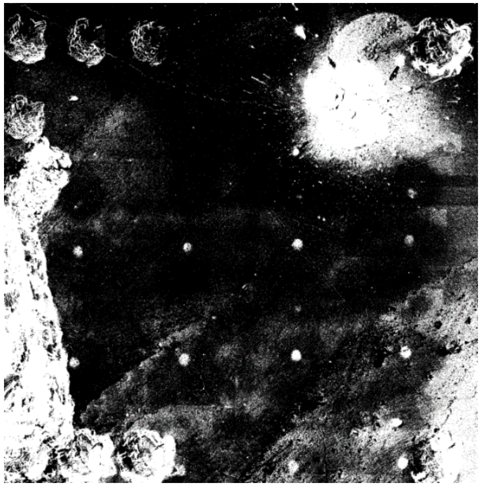
I-V curves

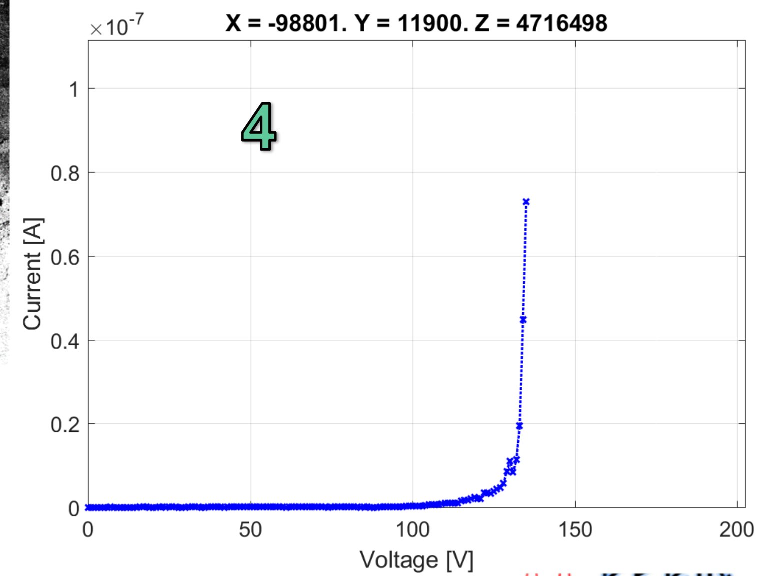












I-V curves

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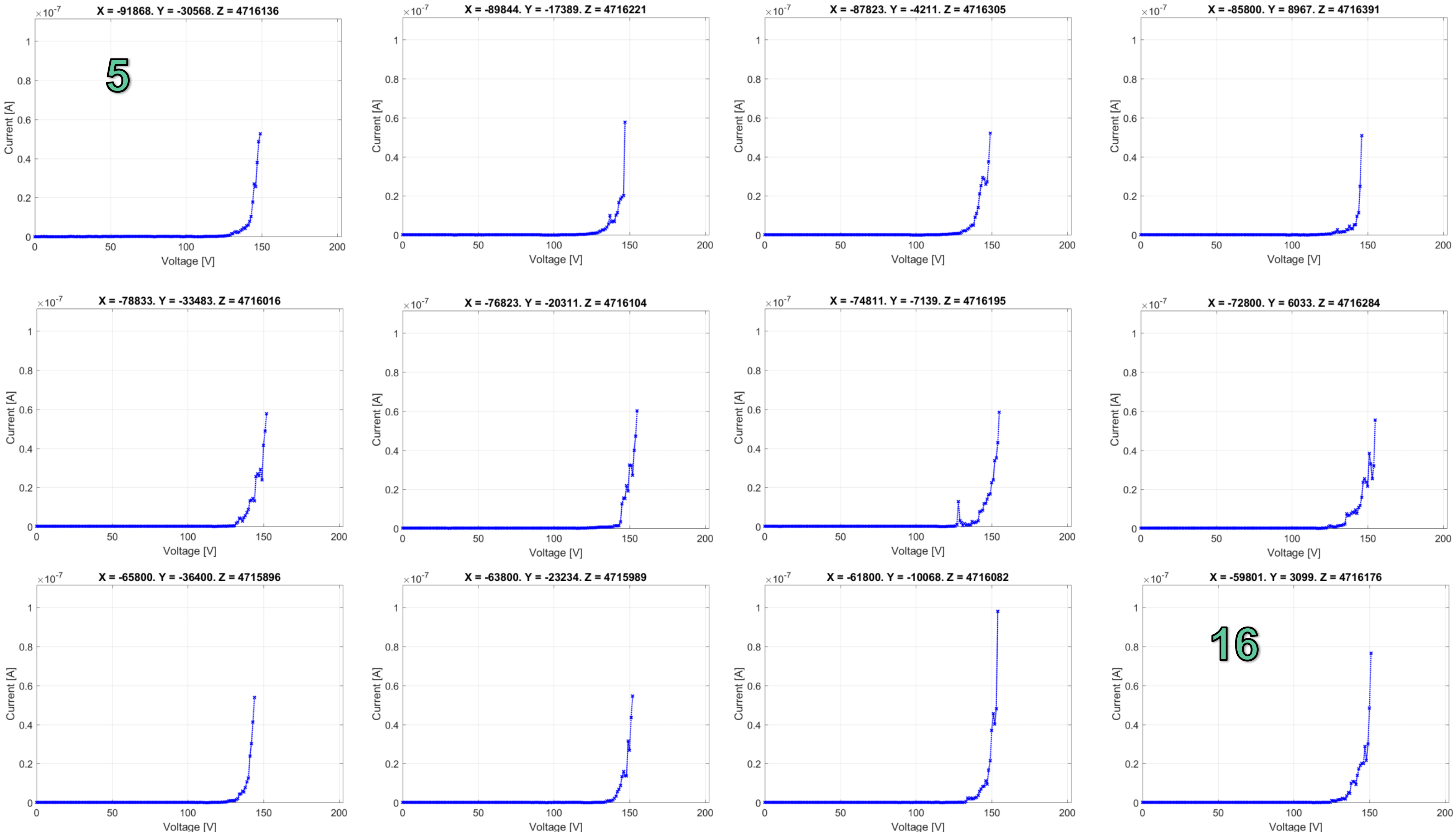

Fitting of β parameter

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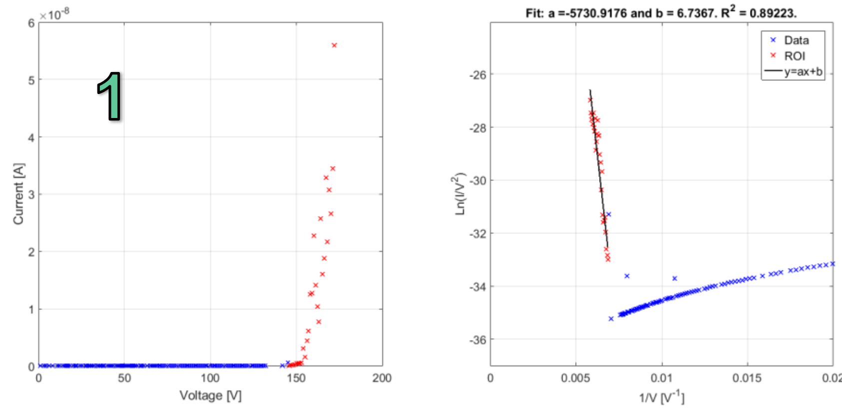
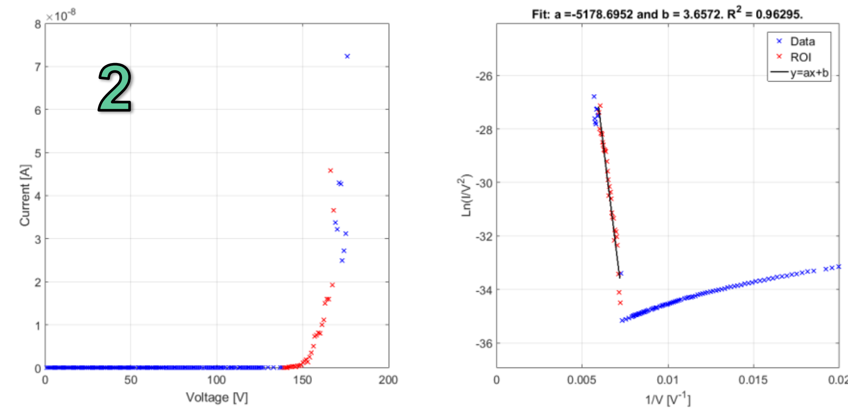
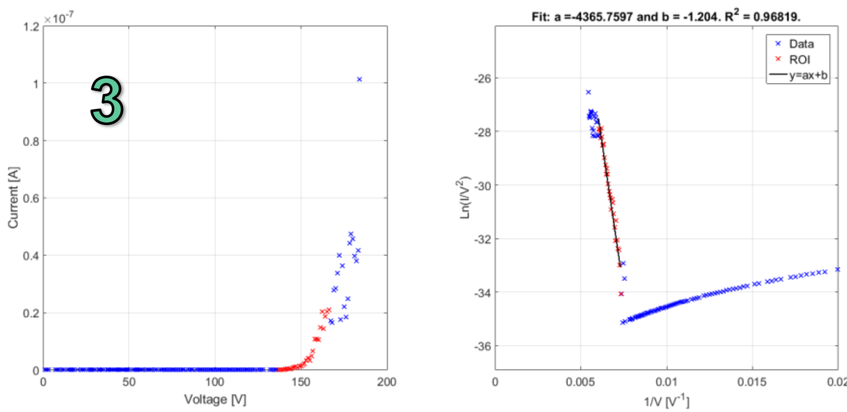


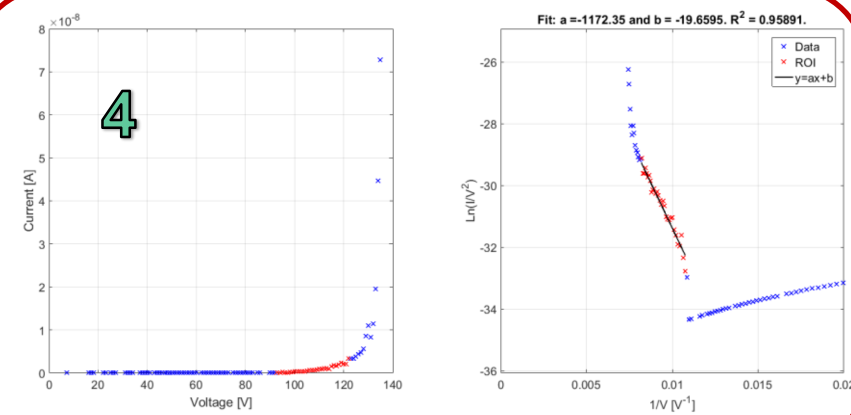
β = 15.5



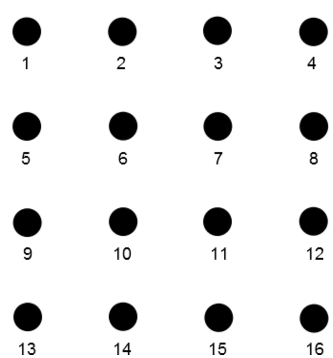
β = 17.6

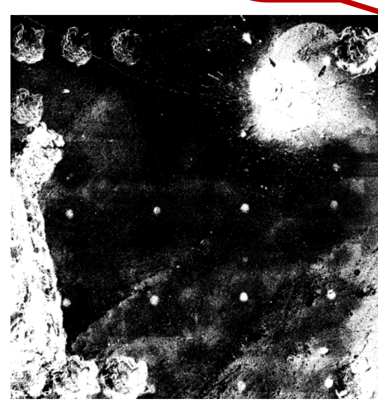


β = 19.6



β = 75.5





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Fitting of β parameter

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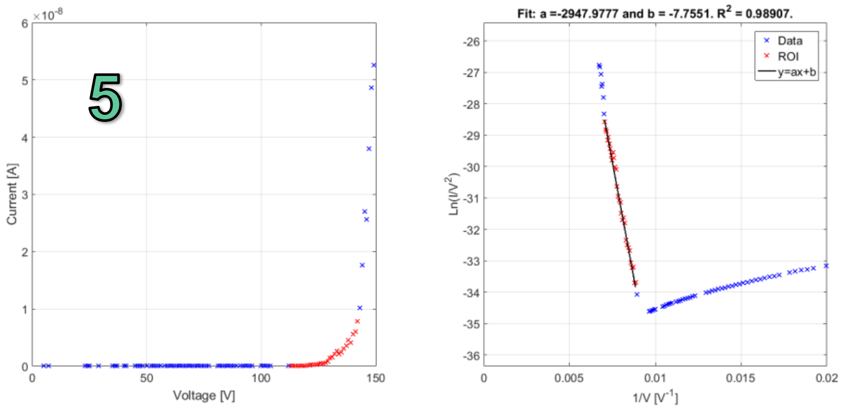
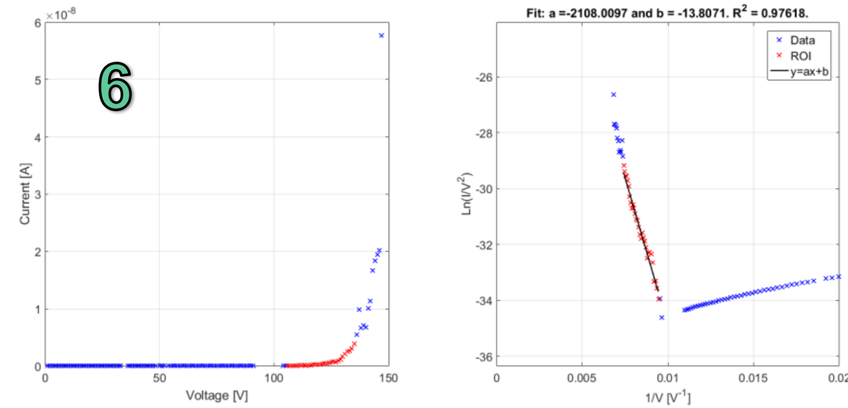
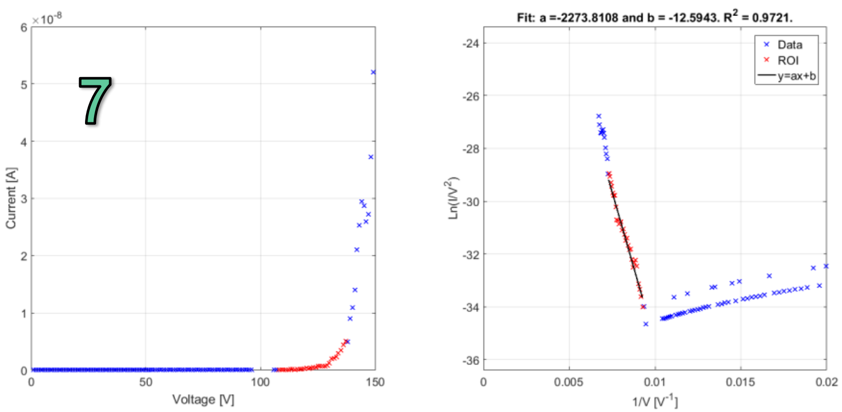


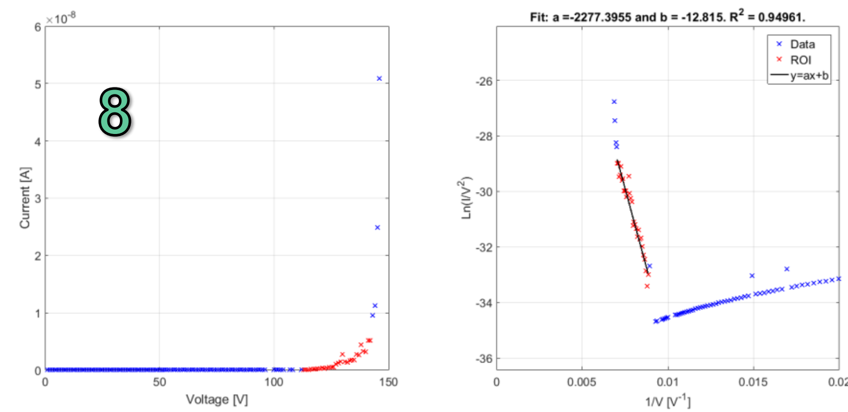
β = 30.2



β = 38.0



β = 38.8



β = 37.5

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Outlook

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Xbox experiments:

- More BD and DC data from Xbox:
    - Correlate BD RF signals with energy spectra
    - Study dark current behavior (trends and before/after breakdowns)

In-SEM experiments:

- Correlate surface features to FE-maps
- Conditioning in the field-emission regime (e.g. repeating scan in the same spot)
- EDX scan directly after
- Quantify surface changes with XPS, AFM
- Better (faster) current measurements during scans

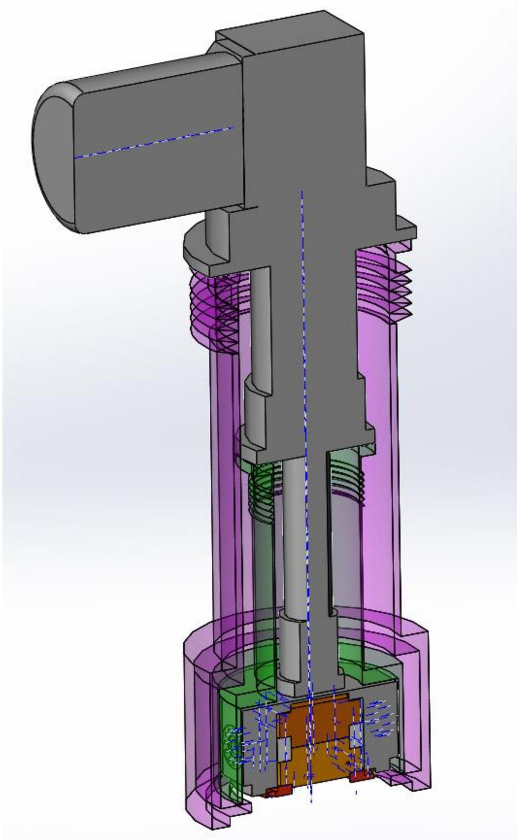
Cryo-DC setup – cryocooler, down to 4 ^{0}K, DC system with large electrodes, K contract with CERN

•Field emission and BDR as a function of temperature.

•Benchmarking for theoretical models

•Connection between high-gradient normal and

superconducting fields



Acknowledgement

Many thanks to Ben Woolley and

RF group at CERN for the efforts in

constructing and running the XBox

Fitting of β parameter

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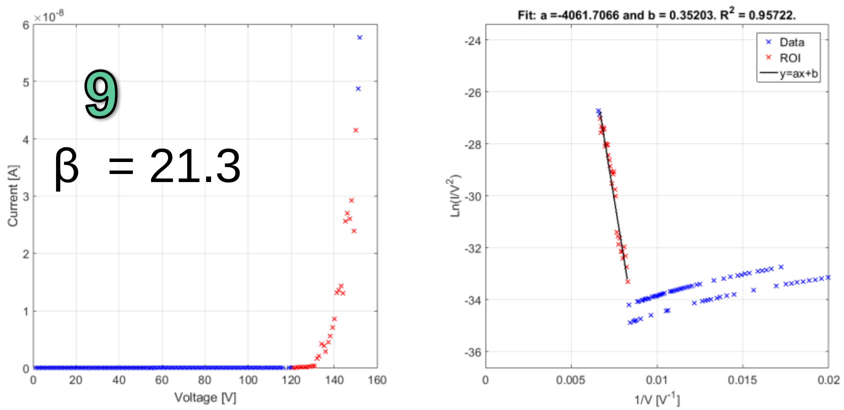

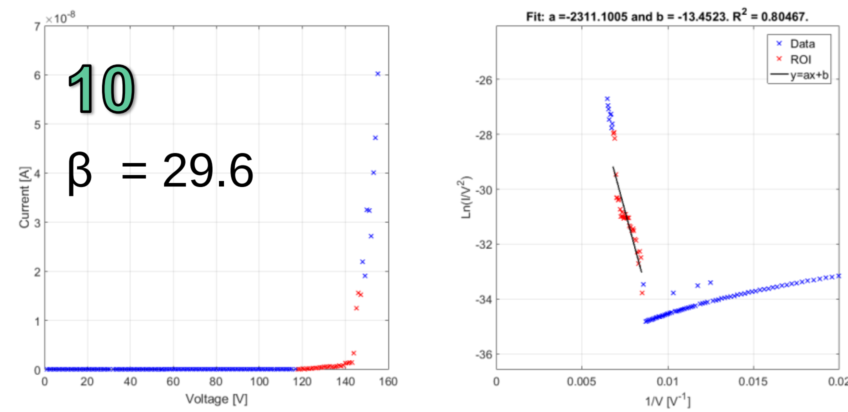

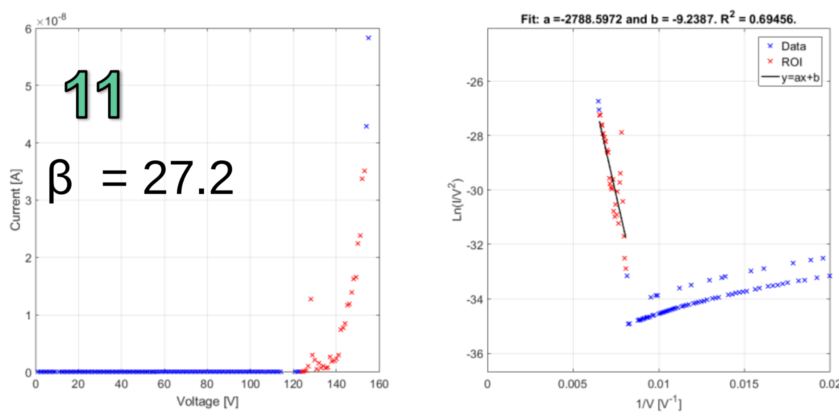

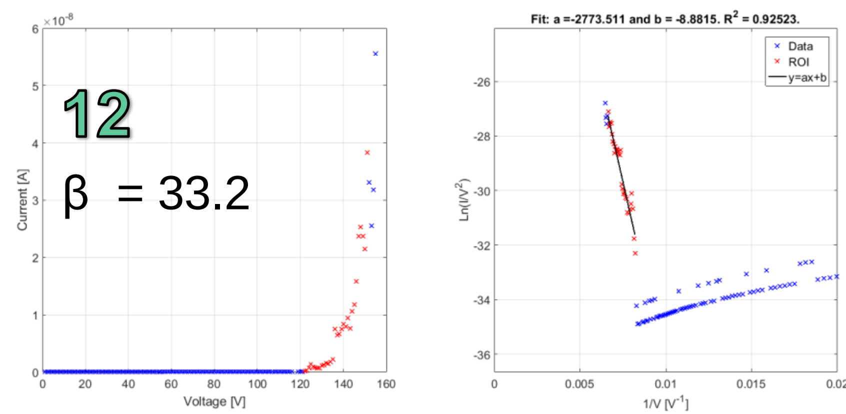

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Fitting of β parameter

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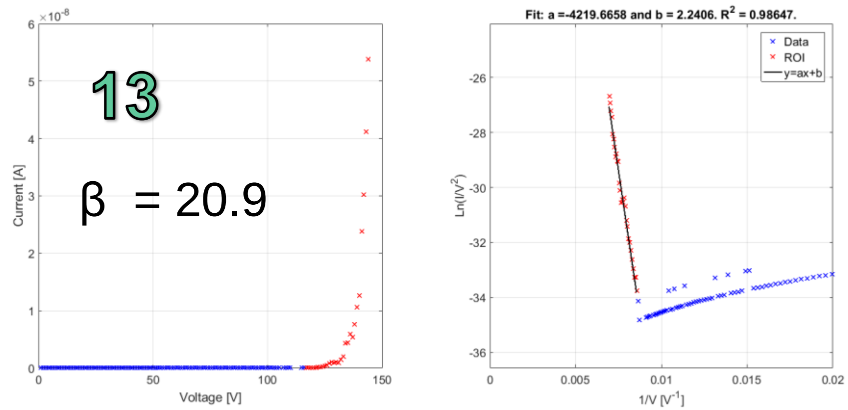

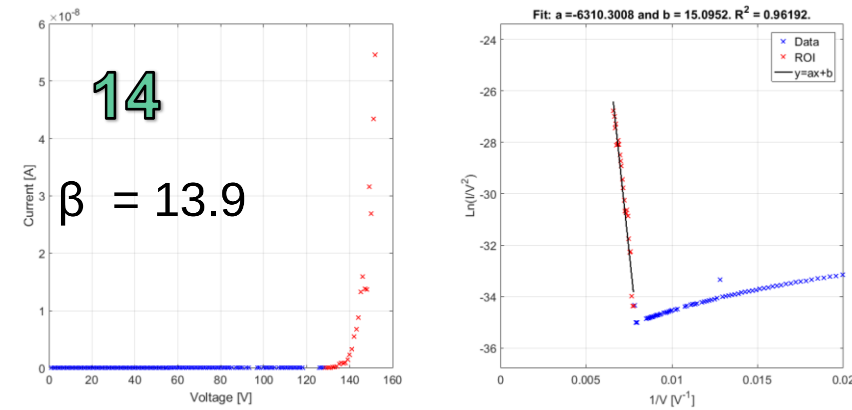

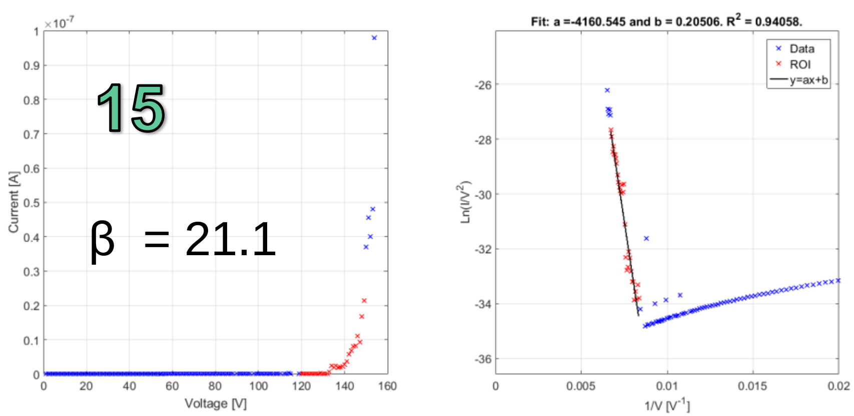

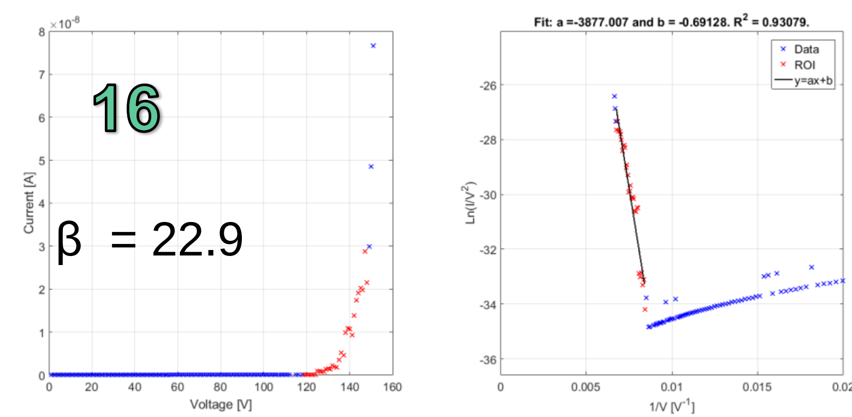

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F-N equation

- Fowler-Nordheim eq:

$$I = A_e \frac{1.54 \times 10^6 \beta^2 F^2}{\phi} \mathrm{e}^{10.41\phi^{-1/2}} \times \mathrm{e}^{-6.53\times10^3 \phi^{3/2}/\beta F}$$

$$= aF^2 \mathrm{e}^{-b/F}$$

$$\ln\left(\frac{I}{F^2}\right) = \ln(a) - \frac{b}{F}$$

Field enhancement β can be determined from the slope b:

$$\beta = \frac{6.53 \times 10^3 \phi^{3/2}}{b}$$

$$F_{loc} = \beta F$$