Conditioning and breakdown behavior in pulsed DC system

Iaroslava Profatilova

Overview

Plans from MeVArc 2018:

https://indico.cern.ch/event/680402/contributions/2976639/attachments/1657049/2653136/Profatilova_MeVArc_2018.pdf

- ✓ Provide fresh, half-conditioned and fully conditioned Soft Cu electrodes (for analysis @ Hebrew University of Jerusalem);
- ✓ Test with different gaps;
- ○ Dark current measurement during the pulsing and looking for dark current fluctuations.

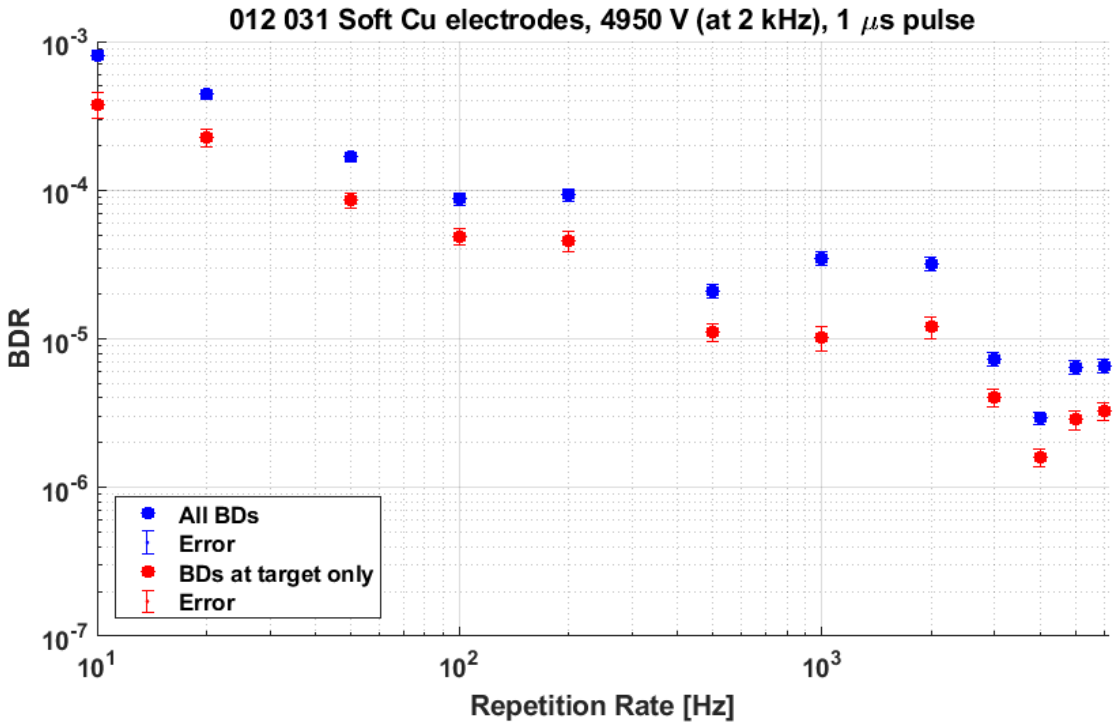
Outline for mini-MeVArc 2018

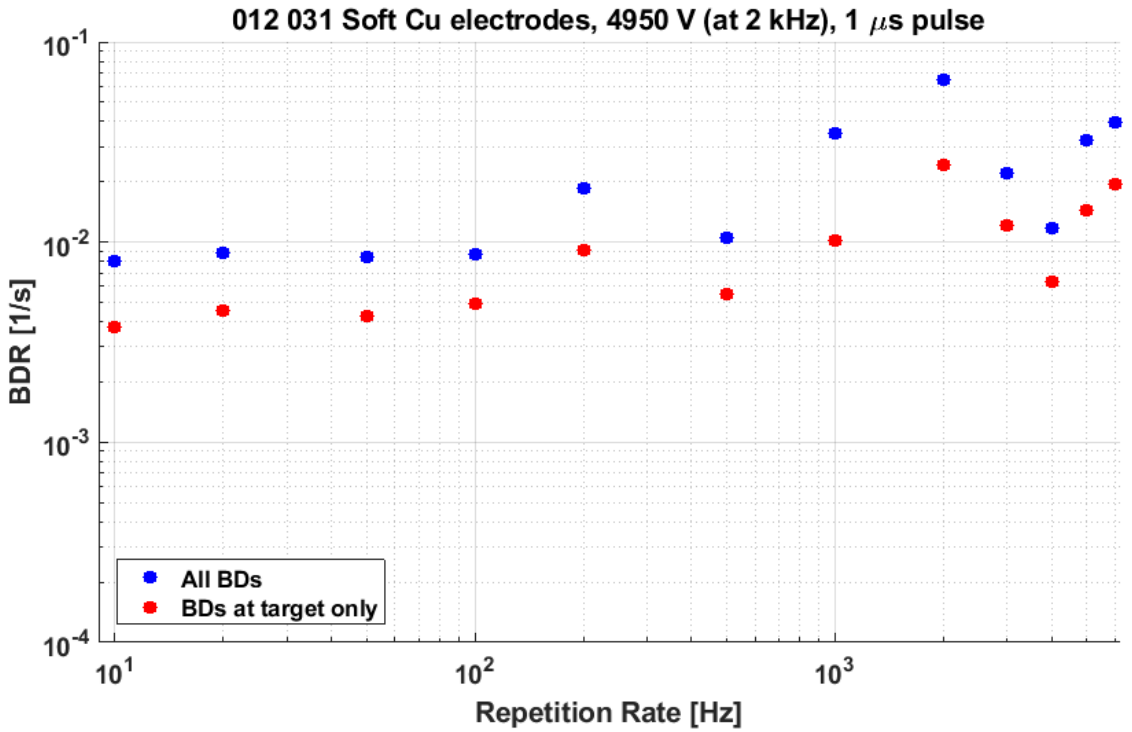
- BDR vs Rep Rates
- Polarity changing
- Gap effect

BDR vs Repetition Rates info

- 2 couples of Cu samples cleaned, heated up to 1040^{o}C in hydrogen atmosphere, unbaked (**012 Soft Cu**, **016 Soft Cu**).
- Pressure during the tests: 1E-7 – 1E-8 mbar.
- 1 µs pulse width.
- Voltages were chosen for having BDR 1E-4 – 1E-7 (BDs/pulses).
- Range of Repetition Rates is from 10 Hz to 6 kHz.

BDR vs RepRates

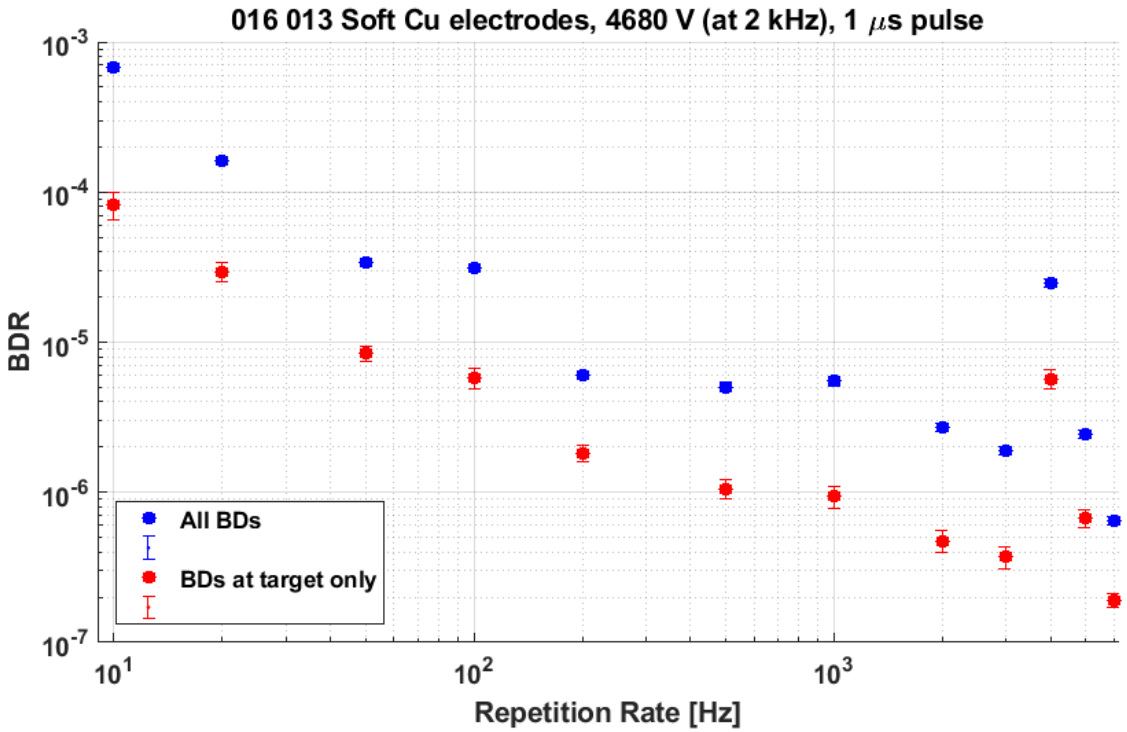


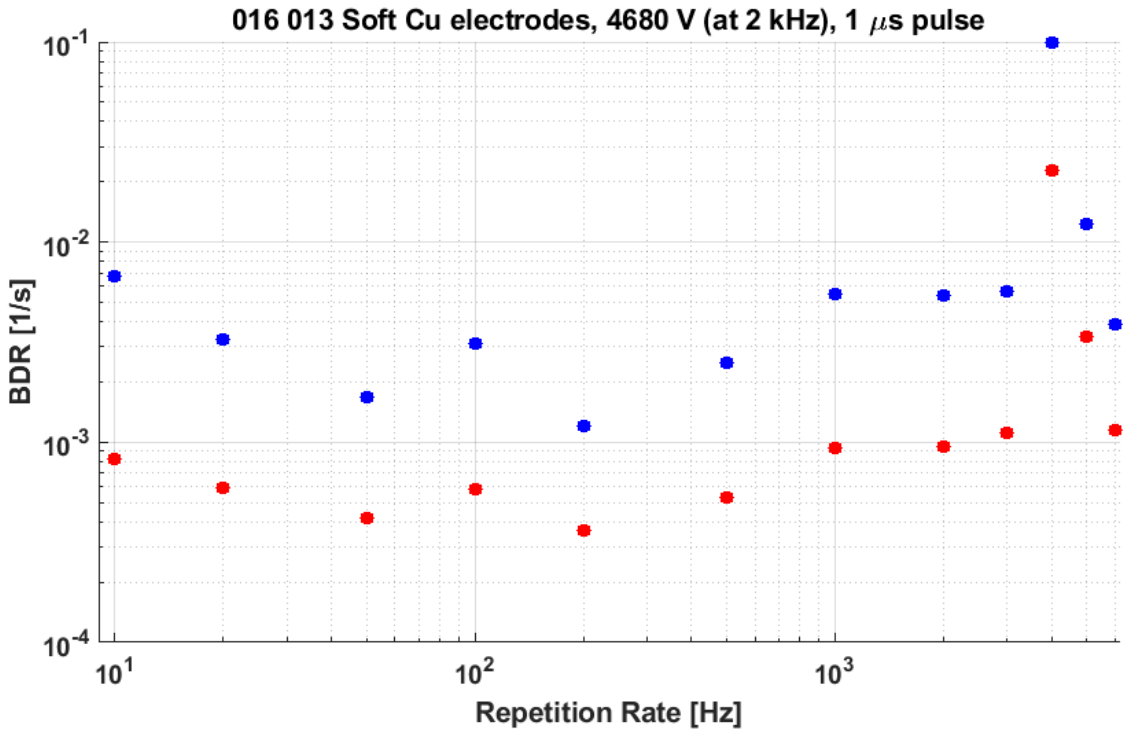


The test was done with **012 Soft Cu** electrodes (without baking), the range of Rep Rate 10 Hz – 6 kHz (increasing order). Pressure during the test ~5E-8 mbar.

More about this and other results for BDR vs RepRates at **MeVArc 2018:**
https://indico.cern.ch/event/680402/contributions/2976639/attachments/1657049/2653136/Profatilova_MeVArc_2018.pdf

BDR vs RepRates



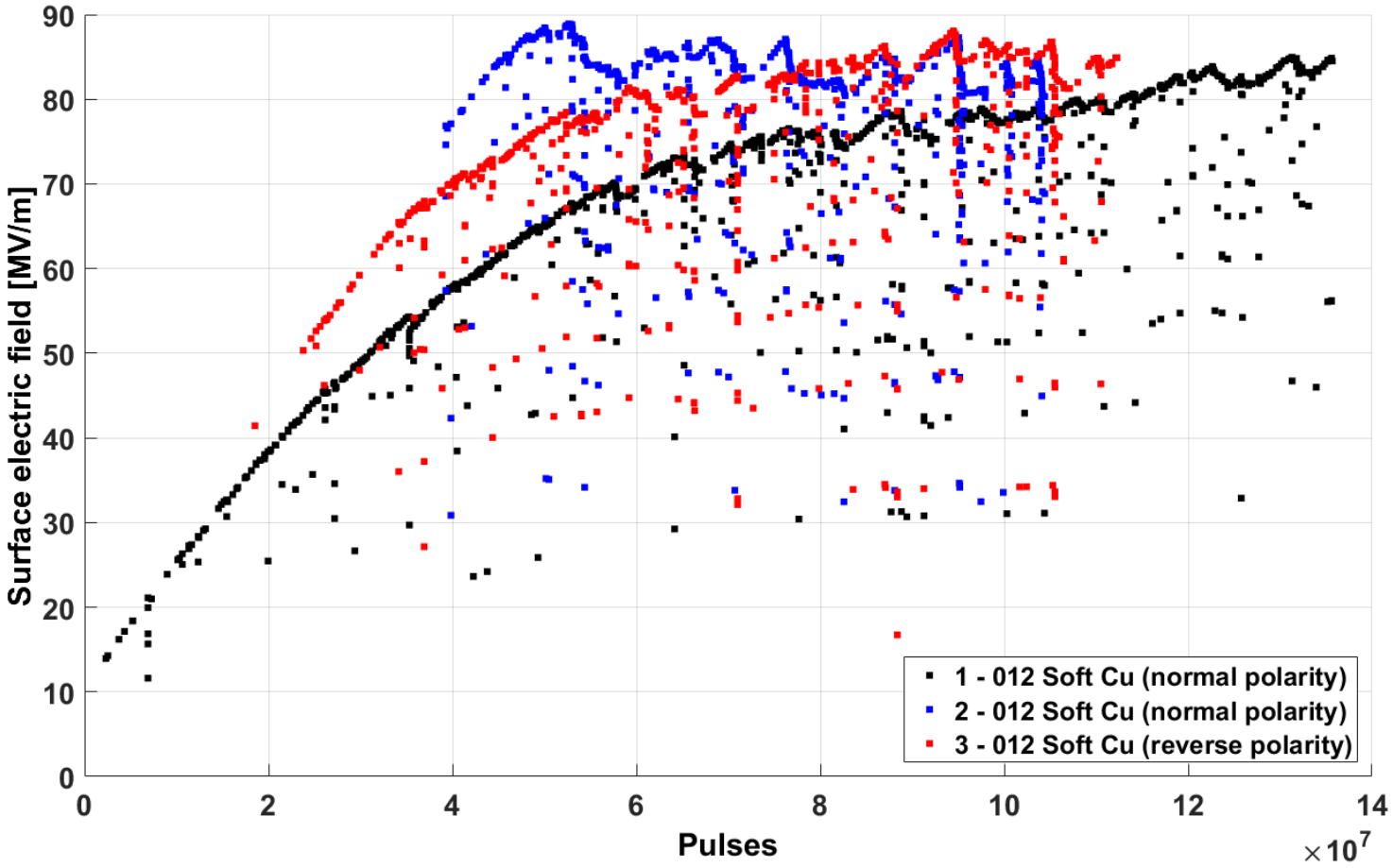


The test was done with **016 Soft Cu** electrodes (without baking), the range of Rep Rate 10 Hz – 6 kHz (increasing order). Pressure during the test ~5E-8 mbar.

Polarity changing info

- Polarities were changed without opening vacuum chamber.
- The tests were done with 3 couples of electrodes (**012 Soft Cu**, **014 Soft Cu**, **016 Soft Cu**) prepared in the same way (as-machined, heated up to 1040^{o}C in hydrogen atmosphere).
- The distance between electrodes was set by using 60 µm ceramic spacer.
- The pressure during the tests: ~ 1E-7 – 1E-8 mbar.
- The conditioning tests in feedback mode were done for comparison.

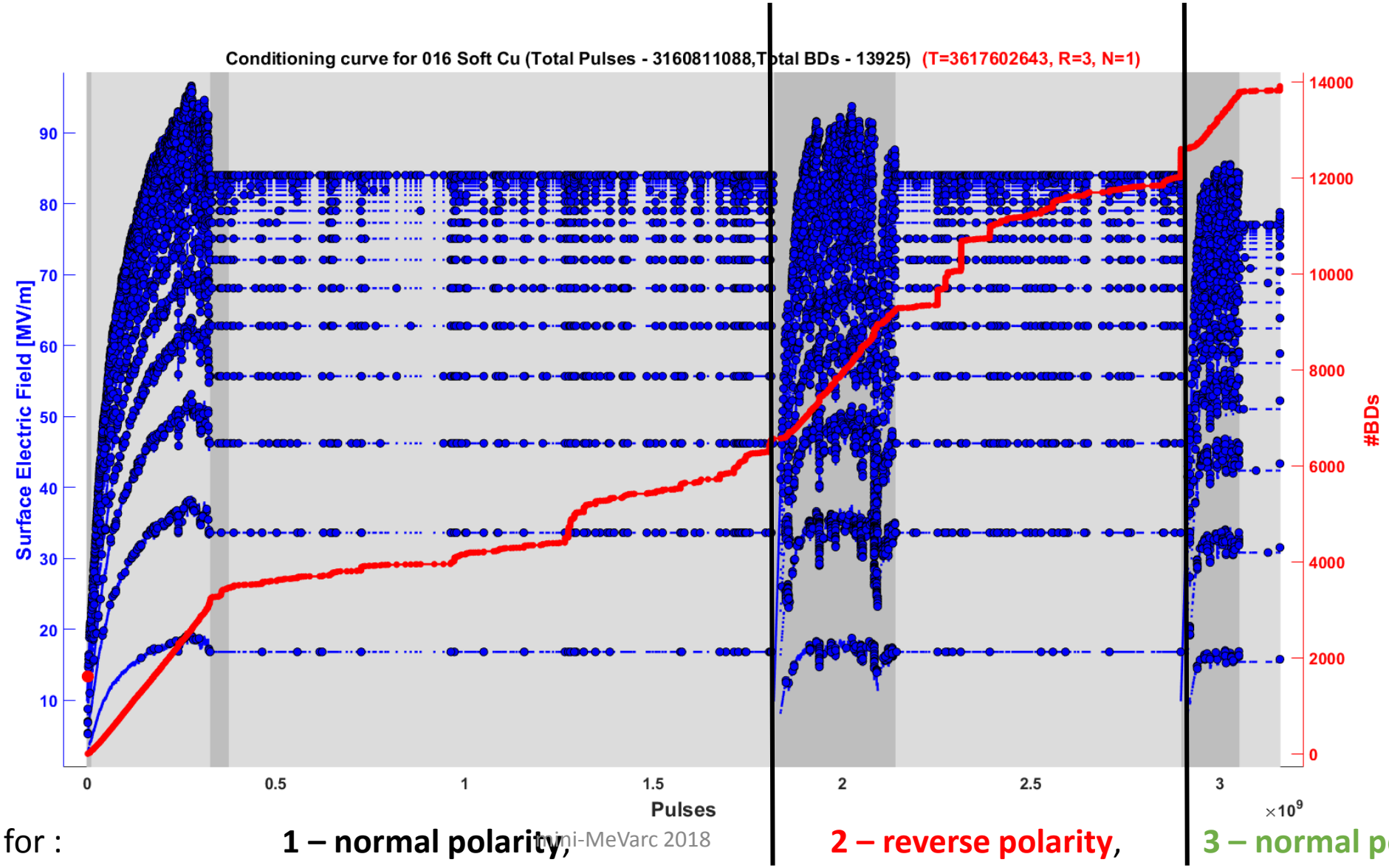
Polarity changing



1 – initial conditioning with normal polarity,
2 – additional conditioning with normal polarity,
3 – conditioning with reverse polarity

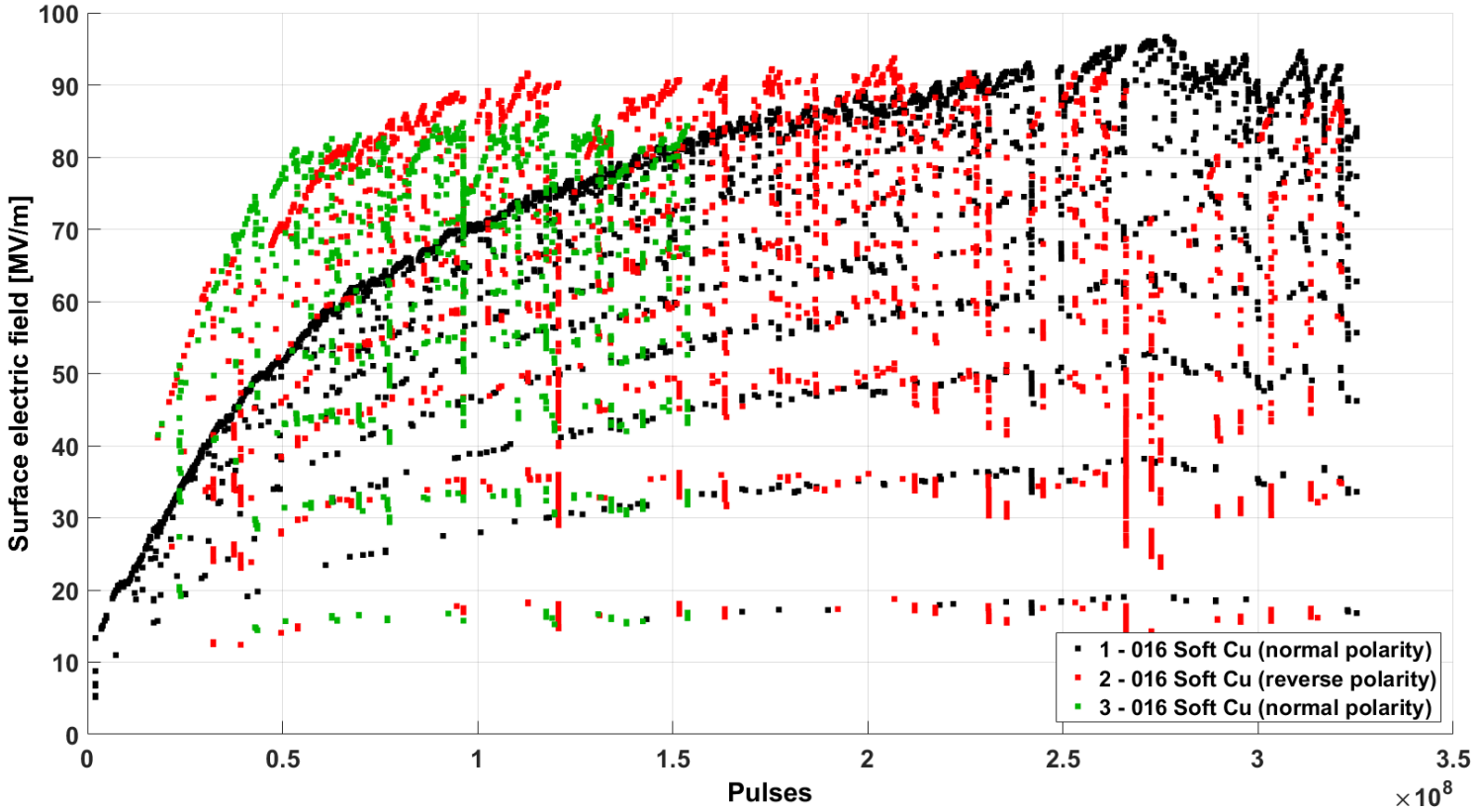
More about this and other results for BDR vs RepRates at **MeVArc 2018:**
https://indico.cern.ch/event/680402/contributions/2976639/attachments/1657049/2653136/Profatilova_MeVArc_2018.pdf

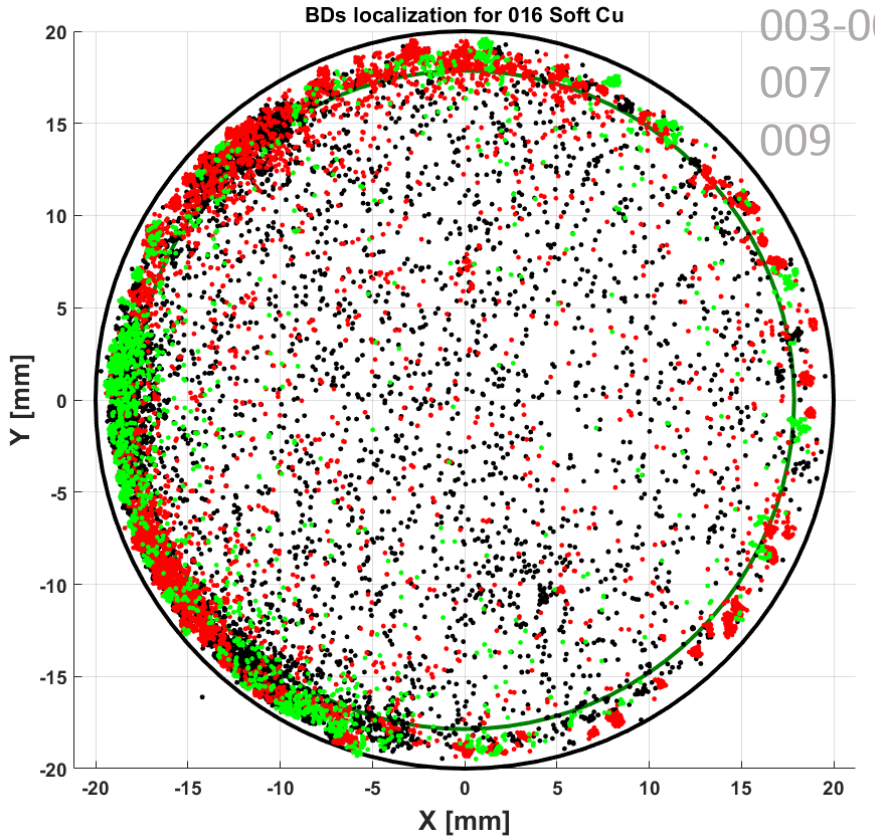
History for 016 Soft Cu



Conditioning curve for : **1 – normal polarity**, **2 – reverse polarity**, **3 – normal polarity**

Polarity changing

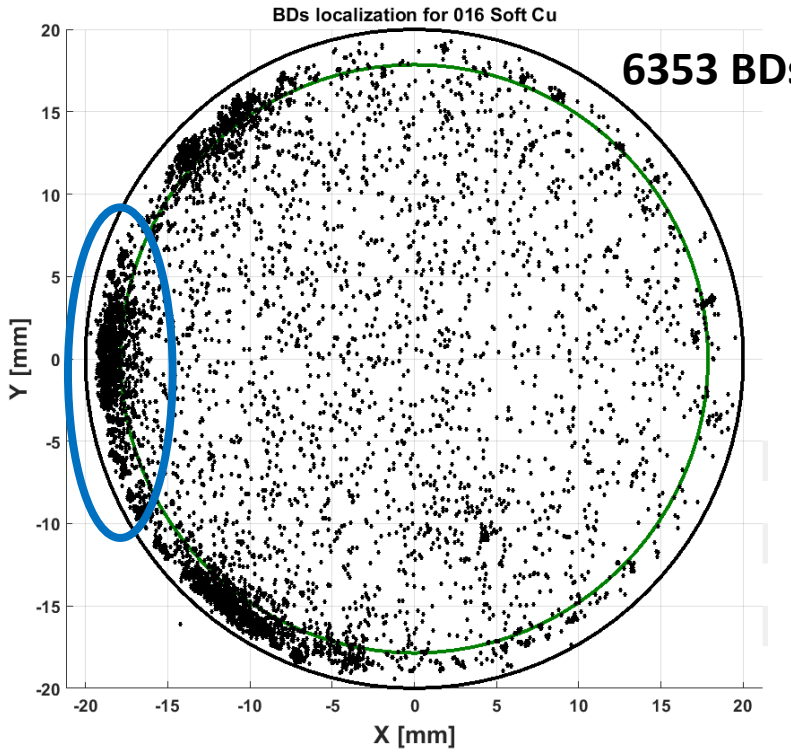


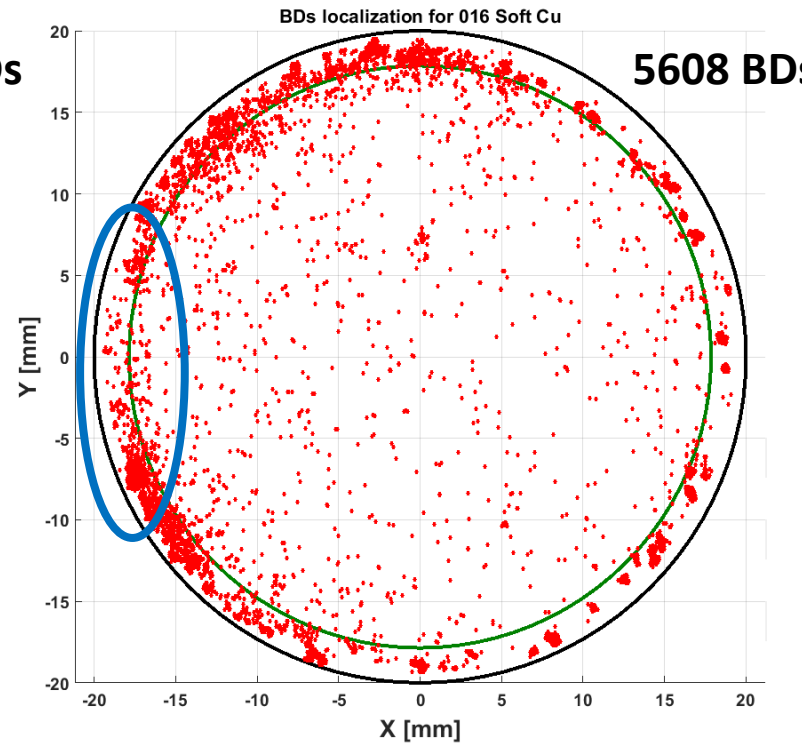


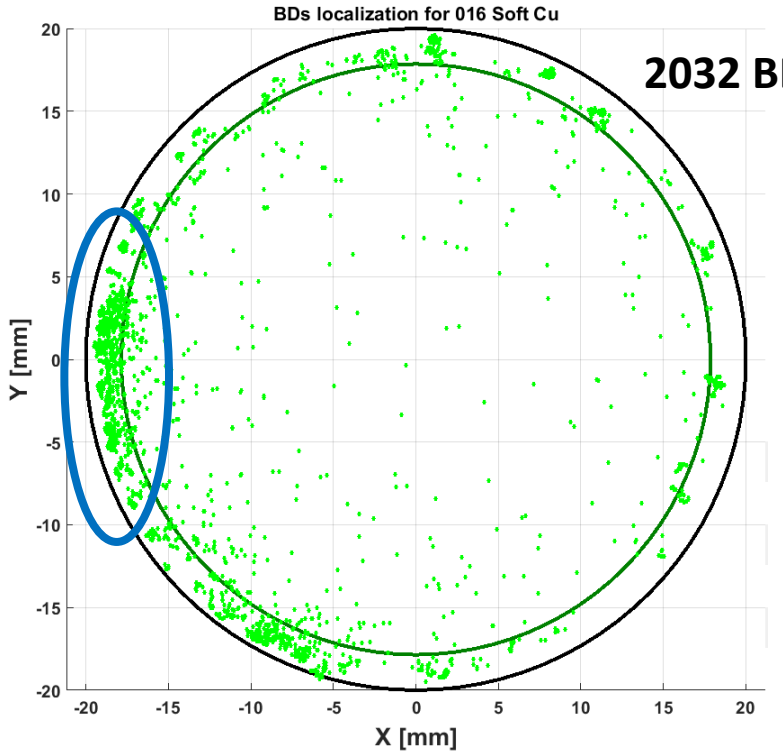
003-004,
007
009

Conditioning curves and BD localization for **016 Soft Cu**.

BDs localization

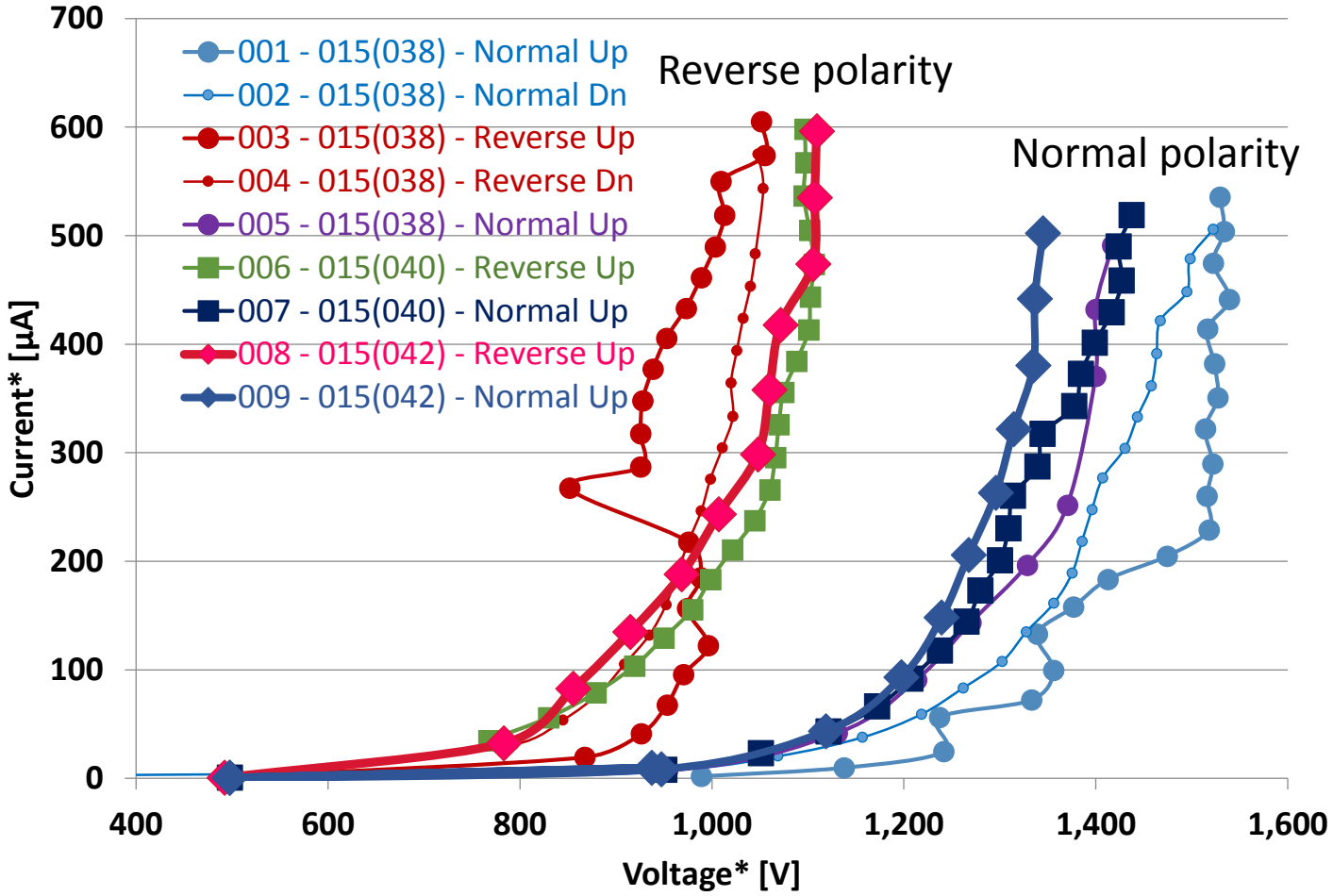






BD localization for: **1 – normal polarity**, **2 – reverse polarity**, **3 – normal polarity**

Dark current measurements



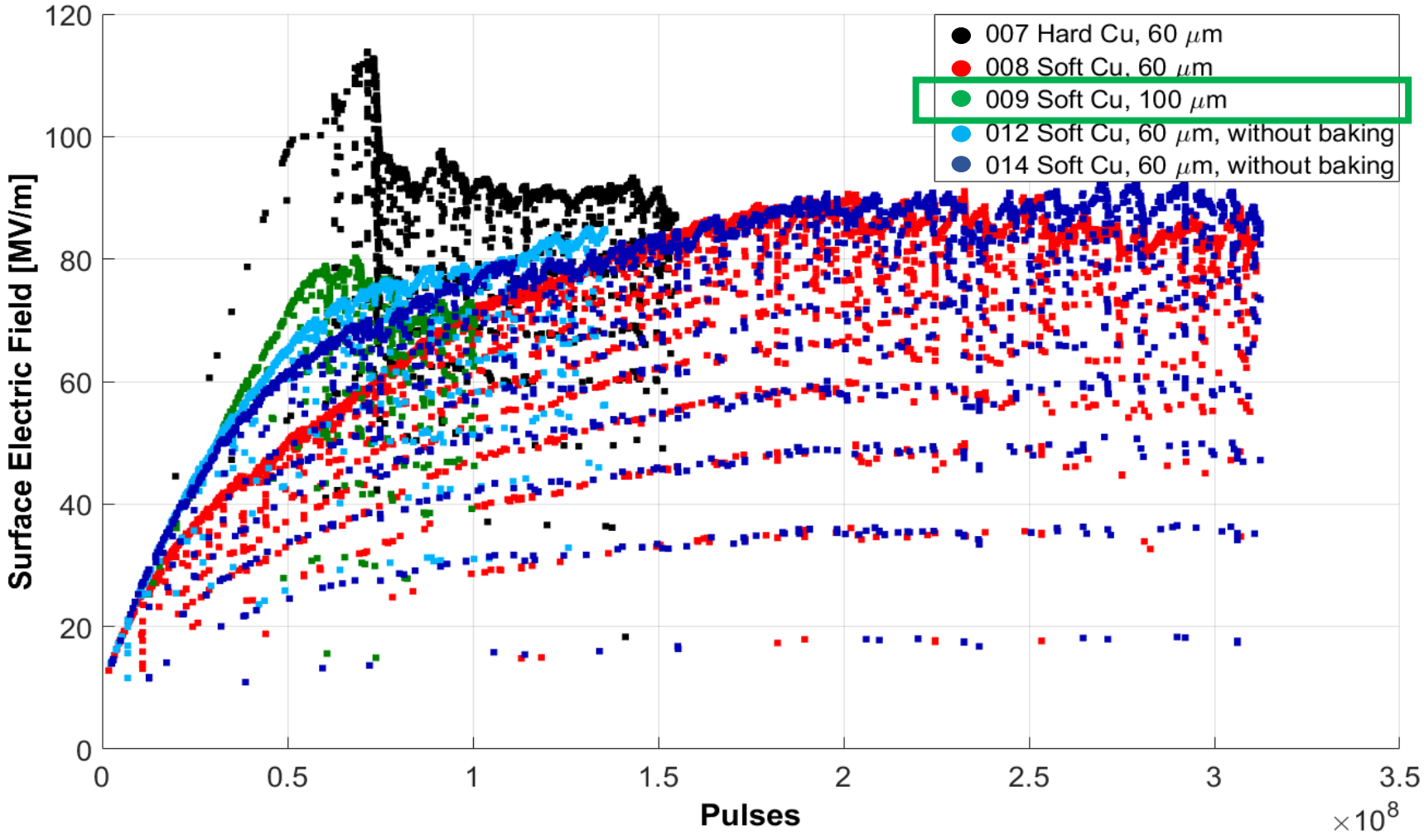
*Absolute values of current and voltage taken in different directions and polarities.

No	Direction	beta	Folder
1.	Normal Up	-----	038
2.	Normal Down	127	038
3.	Reverse Up	----	038
4.	Reverse Down	167	038
5.	Normal Up	130	038
6.	Reverse Up	273	040
7.	Normal Up	129	040
8.	Reverse Up	274	042
9.	Normal Up	116	042

Measurements were done with **015 Soft Cu** and 20 µm gap.

Gap dependency

Initial conditionings



$$E = \frac{V}{d}$$

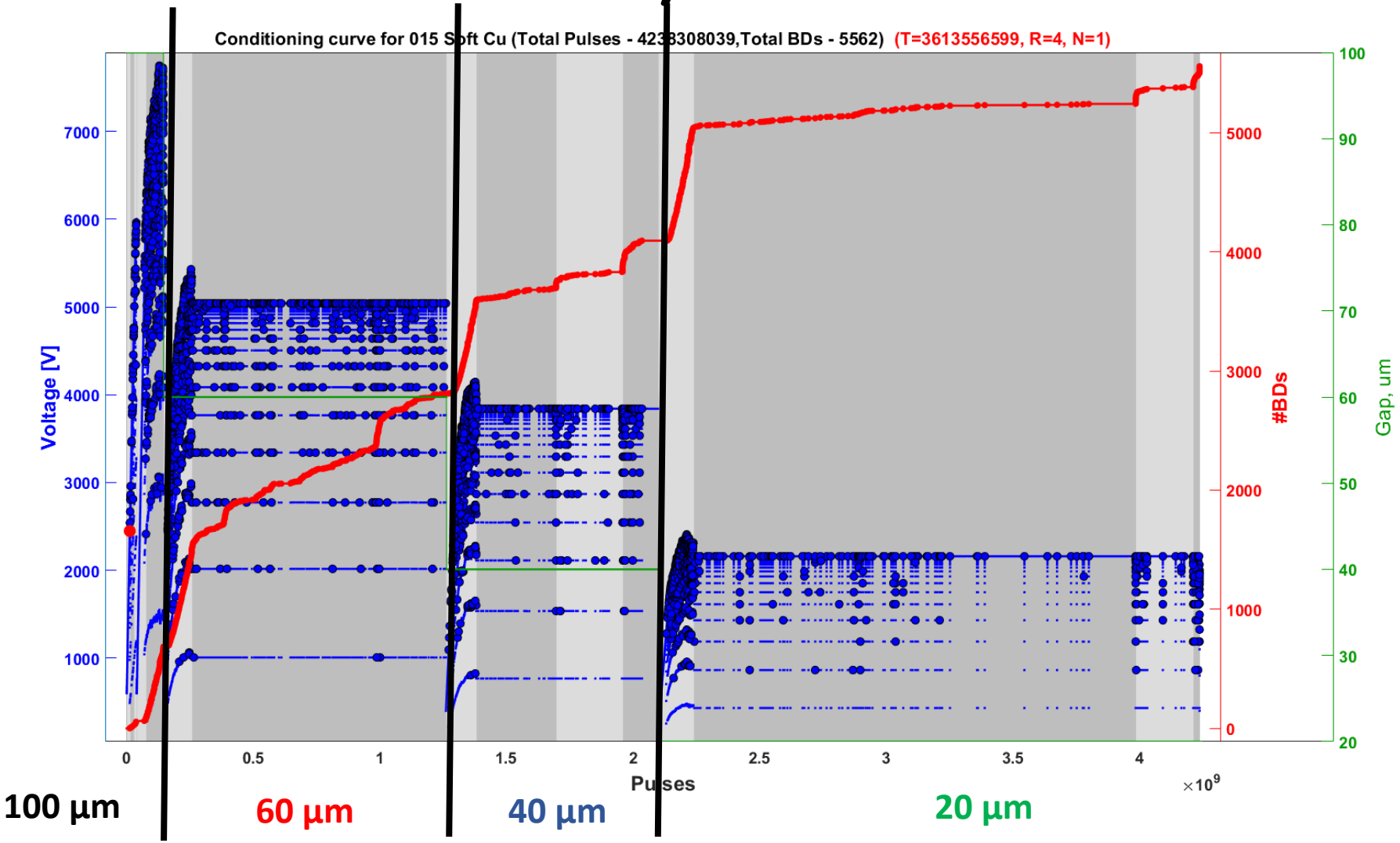
How to compare the data with another gap?

What difference between craters for different gaps?

Gap dependency info

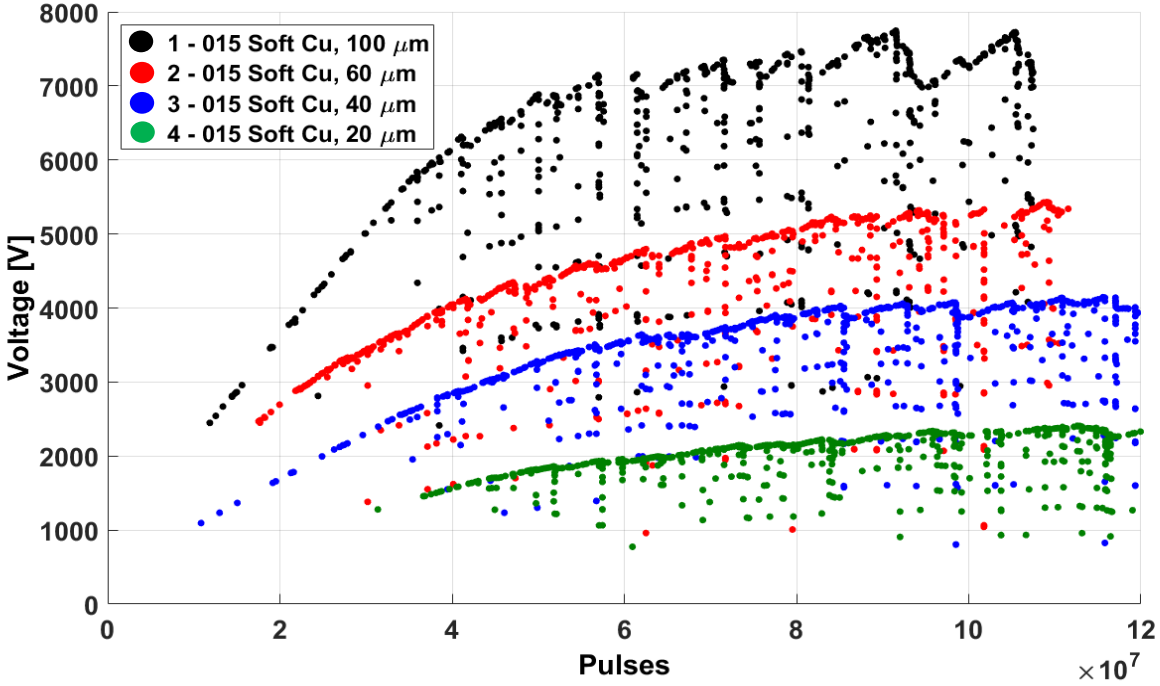
- The couple of samples was heated up to 850 ^{o}C in hydrogen atmosphere and baked up to 650 ^{o}C at CERN (named as **015 Soft Cu**).
- Test was done with spacers for **100, 60, 40, 20 µm** and again 100 µm **gap**.
- The **pressure** during the test less than $\mathbf{1 \times 10^{-7} mbar}$.
- For each gap the conditioning test was done with usual **feedback algorithm**.
- After each test the vacuum chamber was disassembled and the image with optical microscope was done.

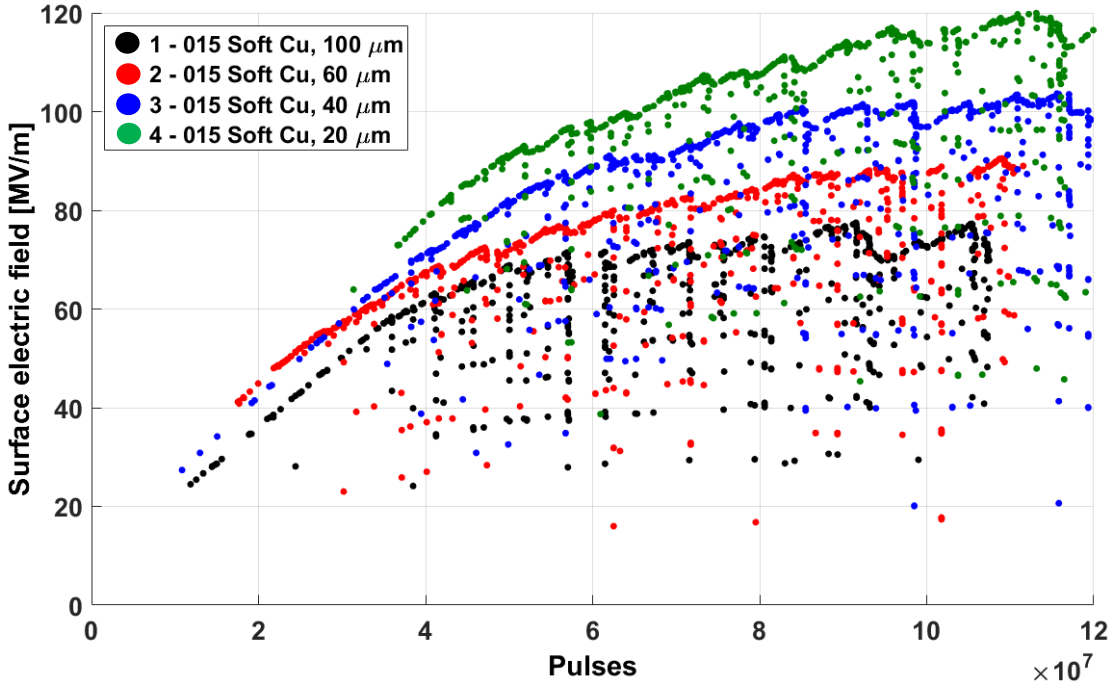
Test history for 015 Soft Cu



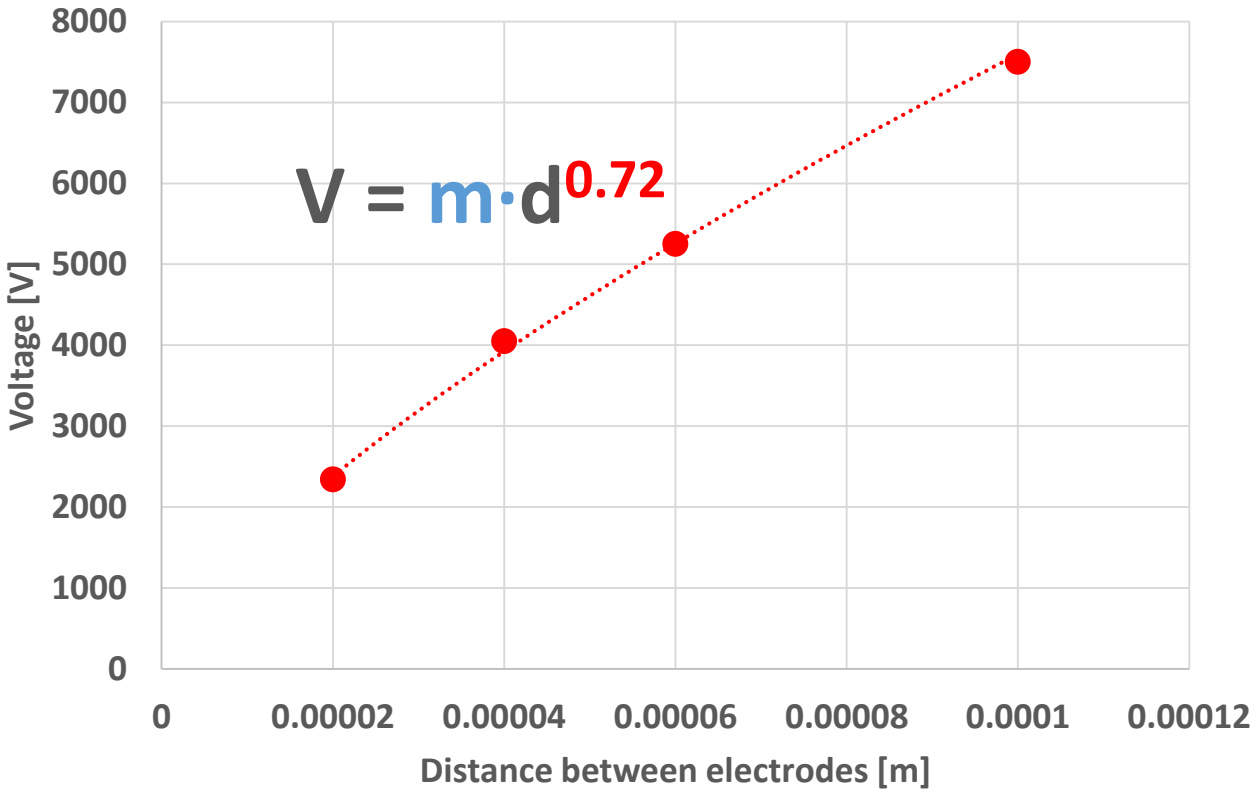
Gap dependency

$$E = \frac{V}{d}$$





Gap dependency



The averages of voltage during last 10 mlns of pulses from conditioning curves are used for the plot.

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New Derivation of the Vacuum Breakdown Equation Relating Breakdown Voltage and Electrode Separation

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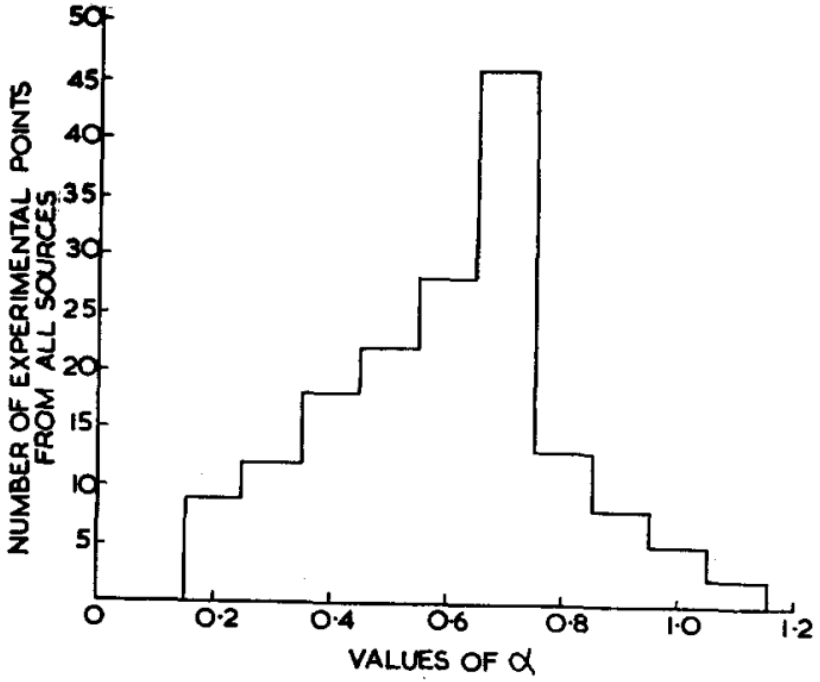
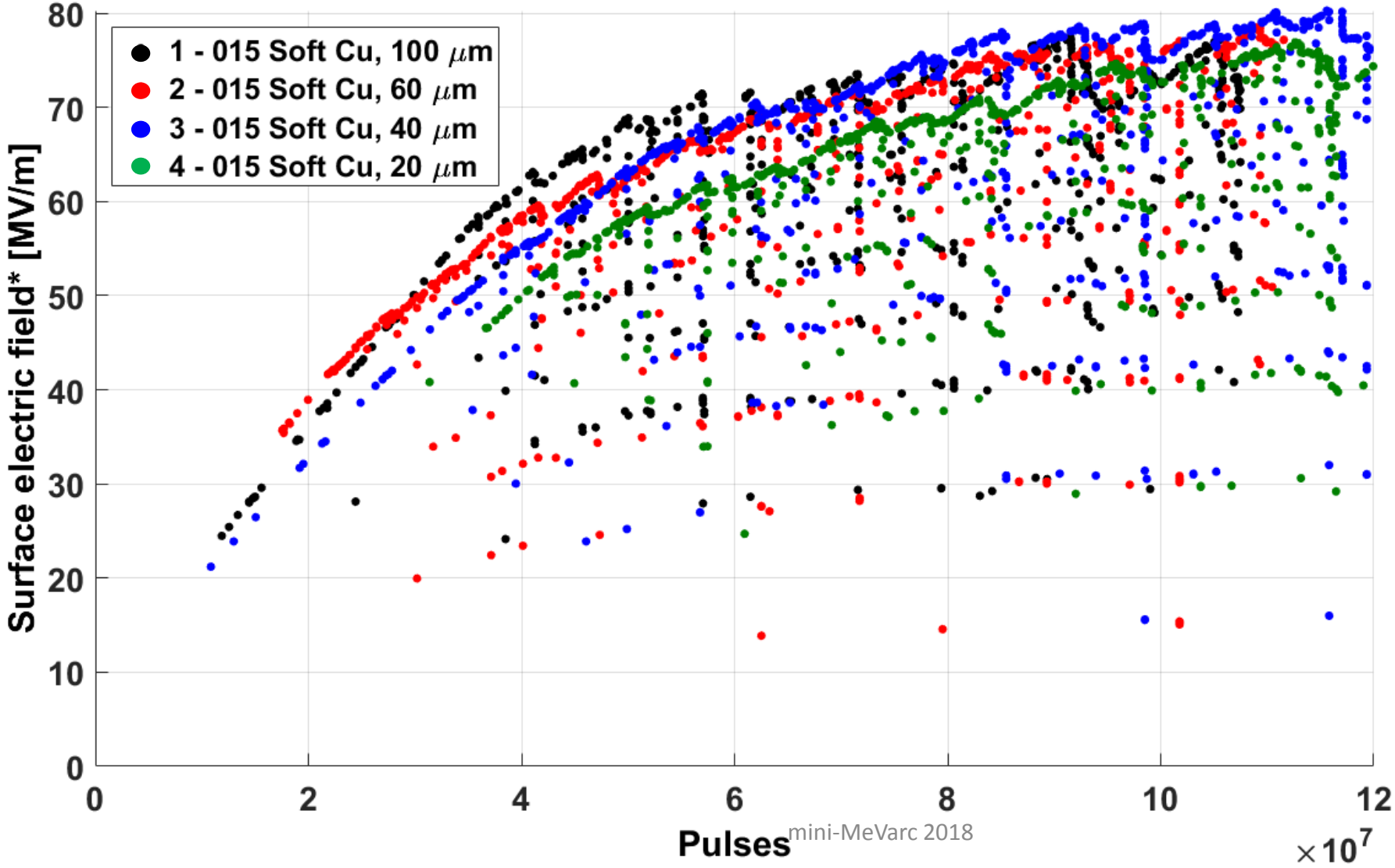


FIG. 1. Distribution of values of α obtained from publications relating to plane or near-plane geometry.

Gap dependency

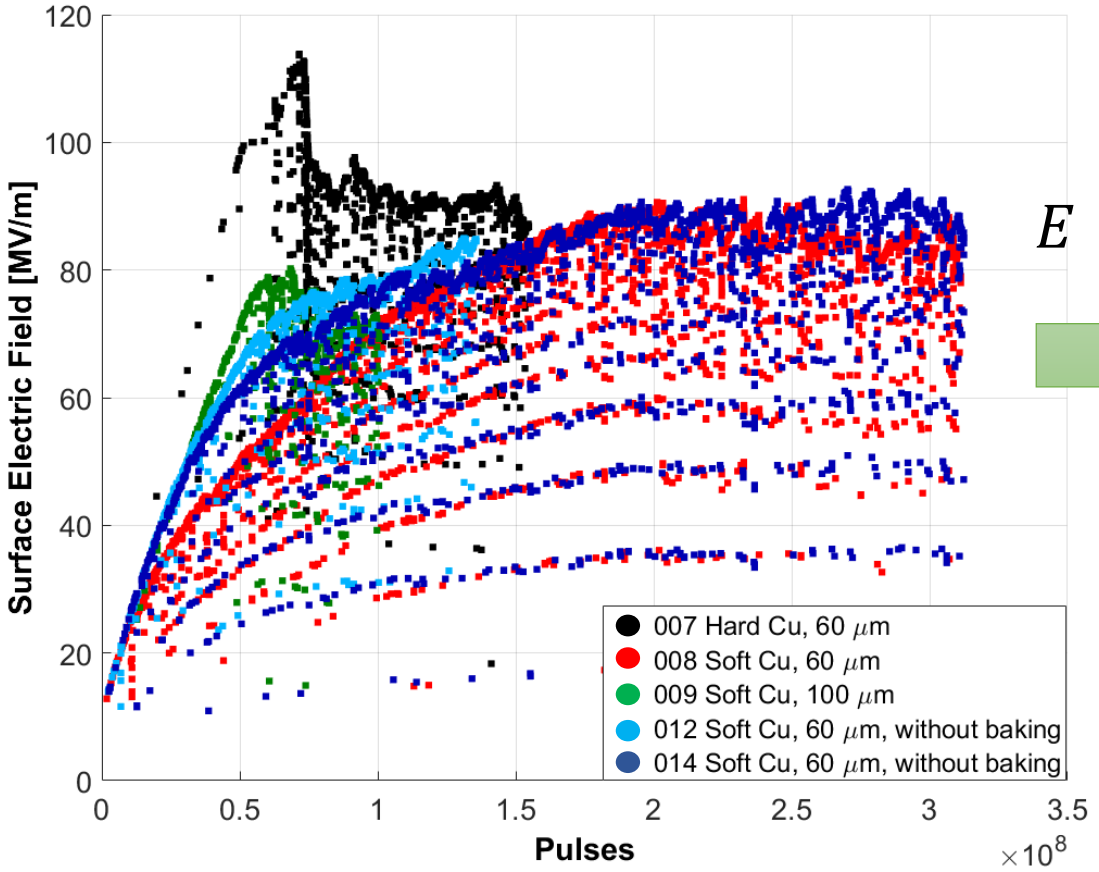


$$E = k\frac{V}{d^{\alpha}}$$

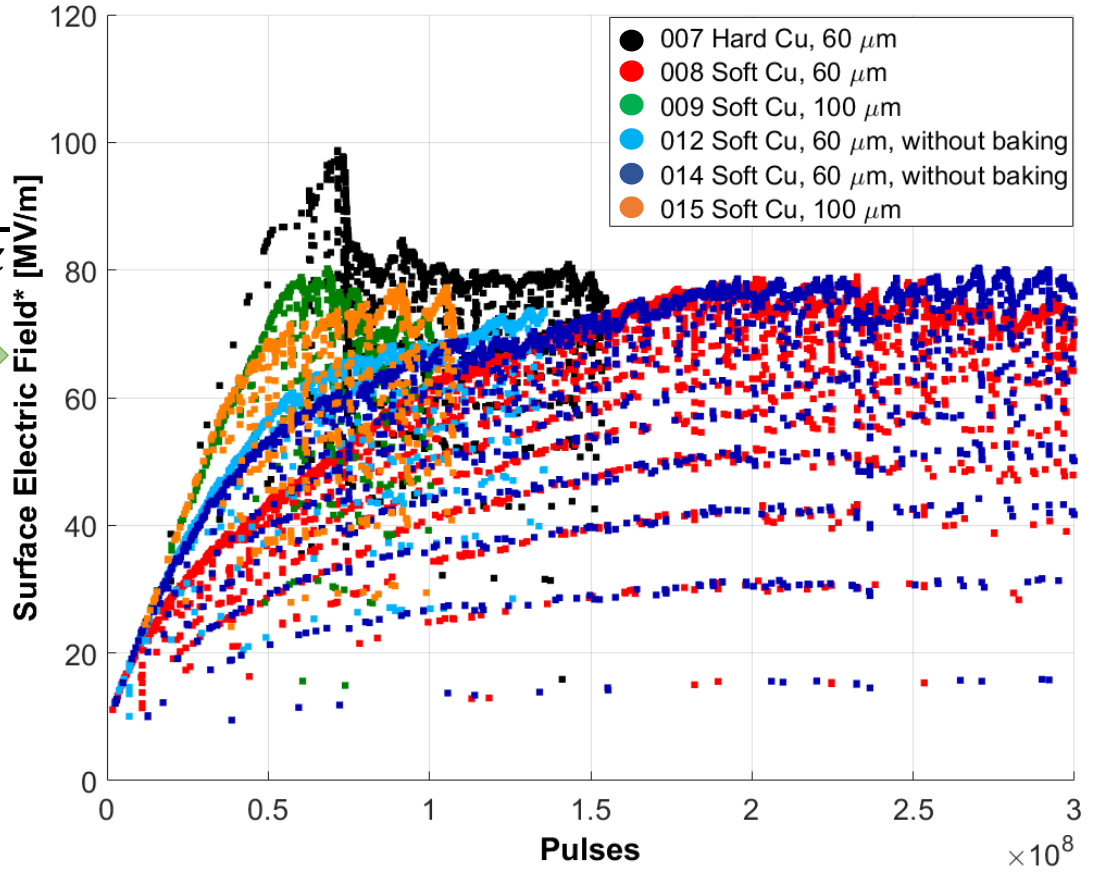
α= 0.72

*The coefficient α taken to account and the field is normalized to 100 µm

Gap dependency

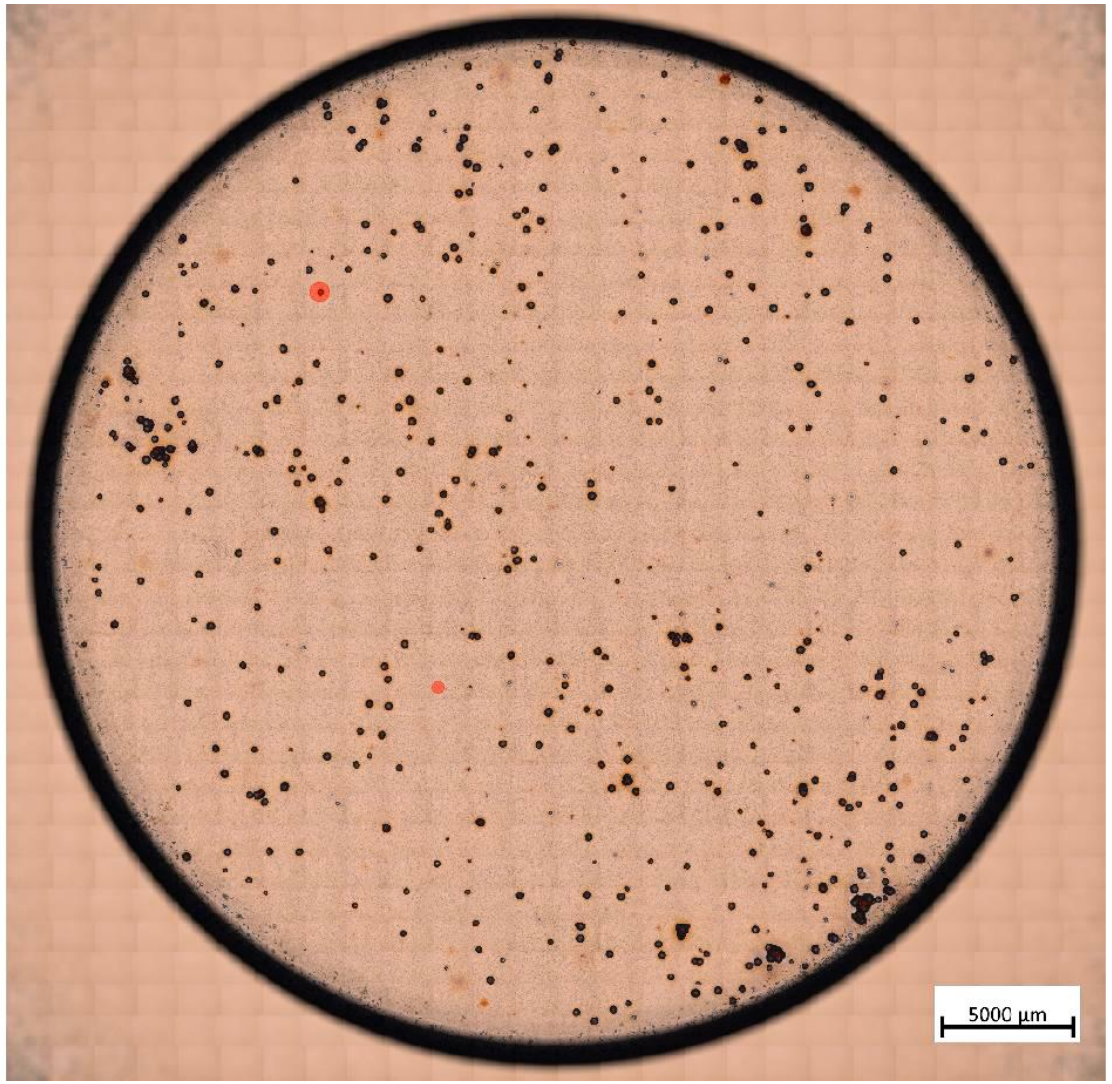


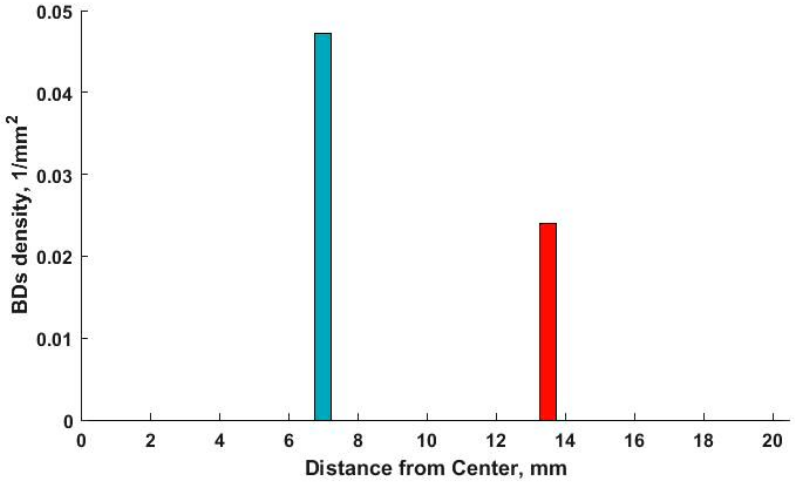
$$E = k\frac{V}{d^{\alpha}}$$

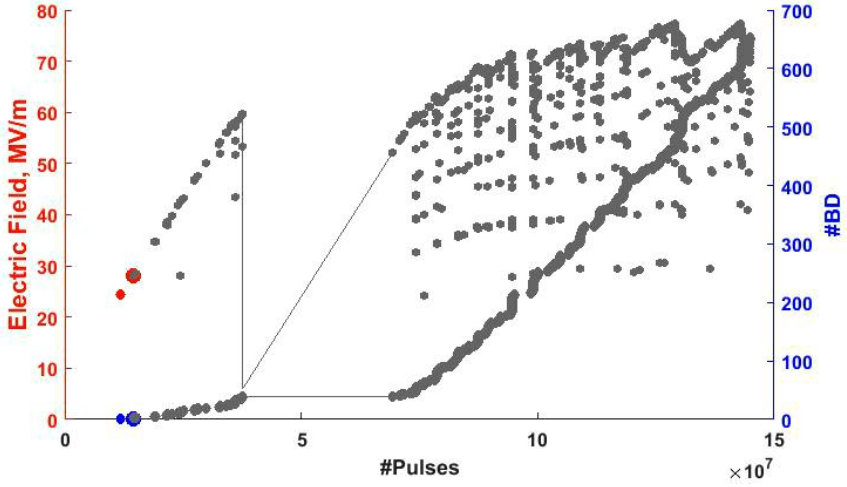


*The coefficient α taken to account and the field is normalized to 100 µm

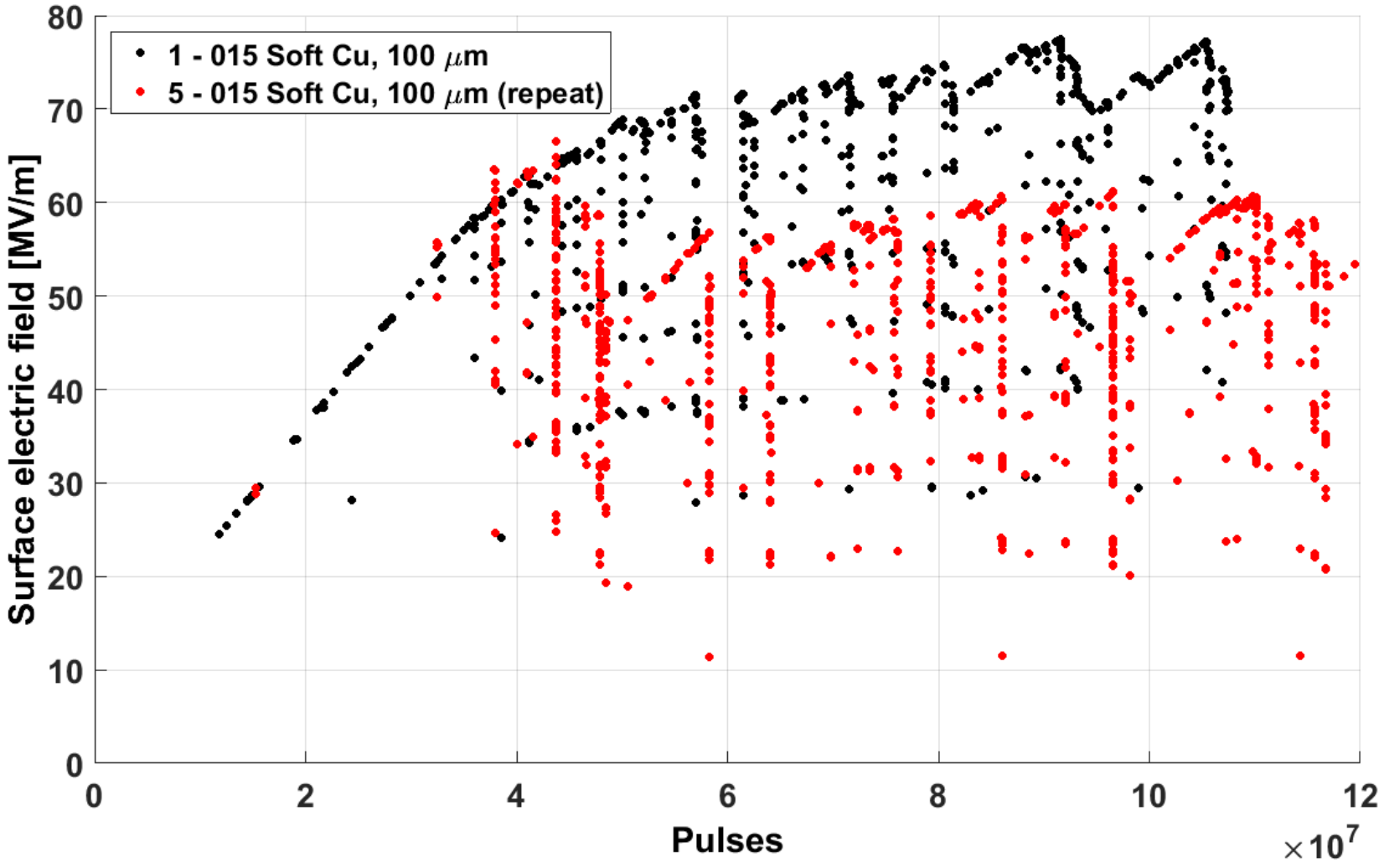
Evolution of breakdowns

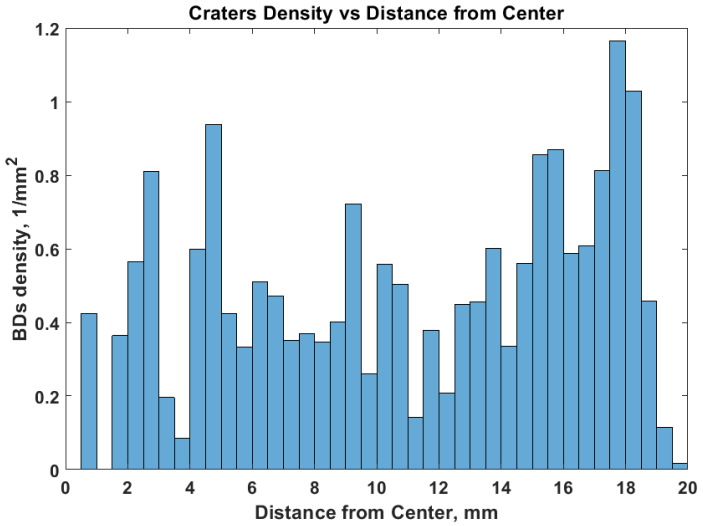


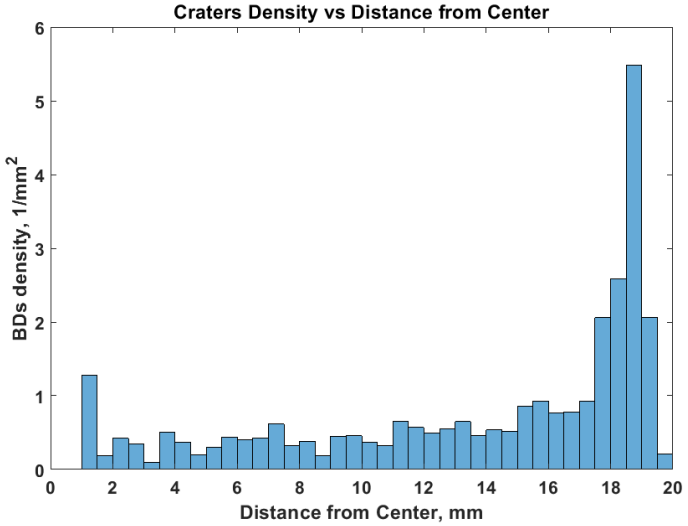




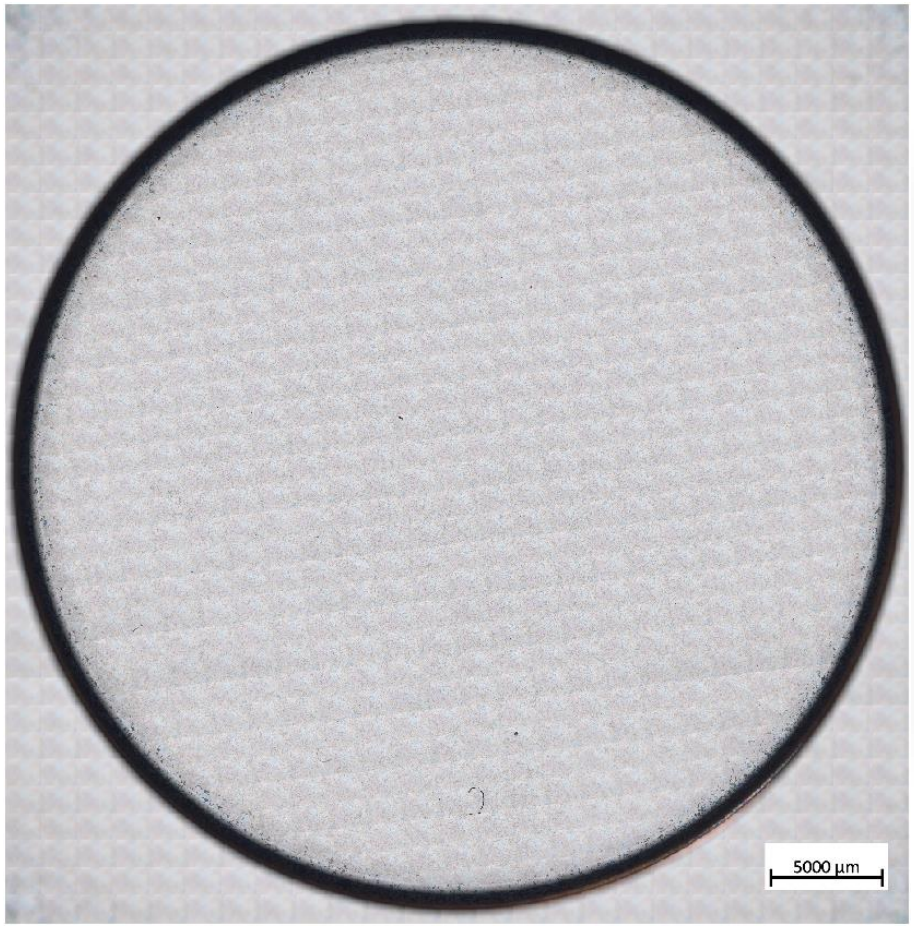
Initial and final conditionings



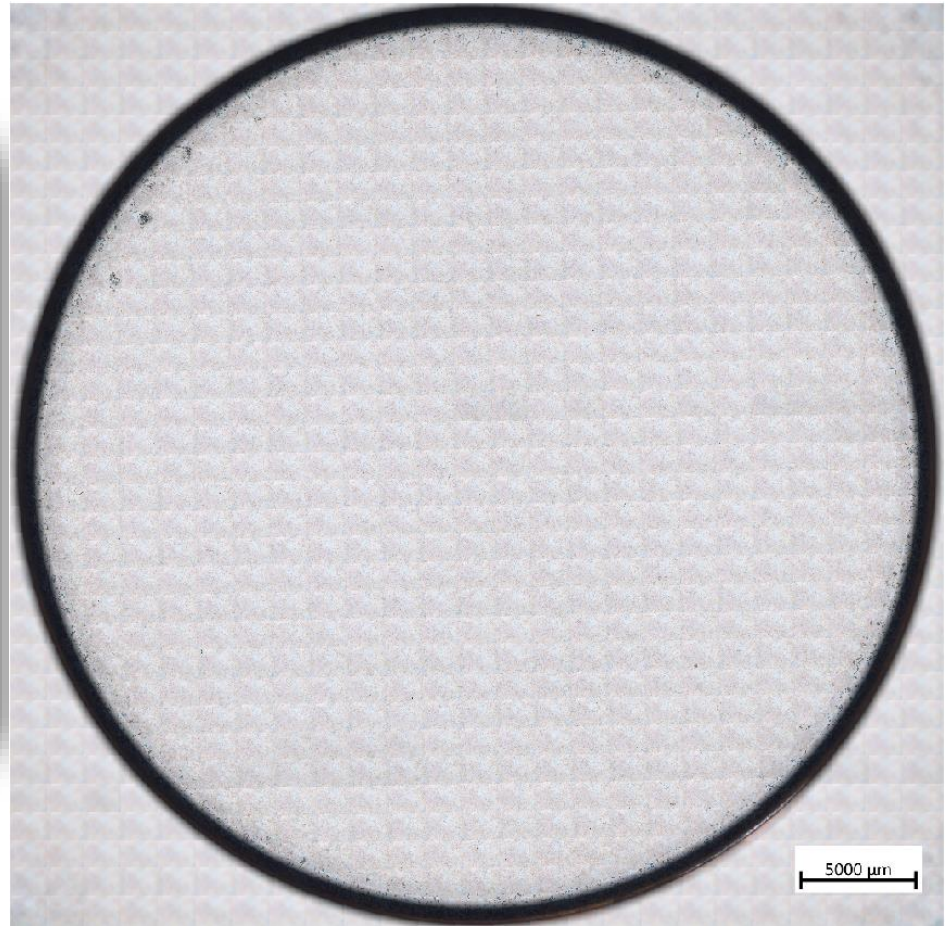




Evolution of surface



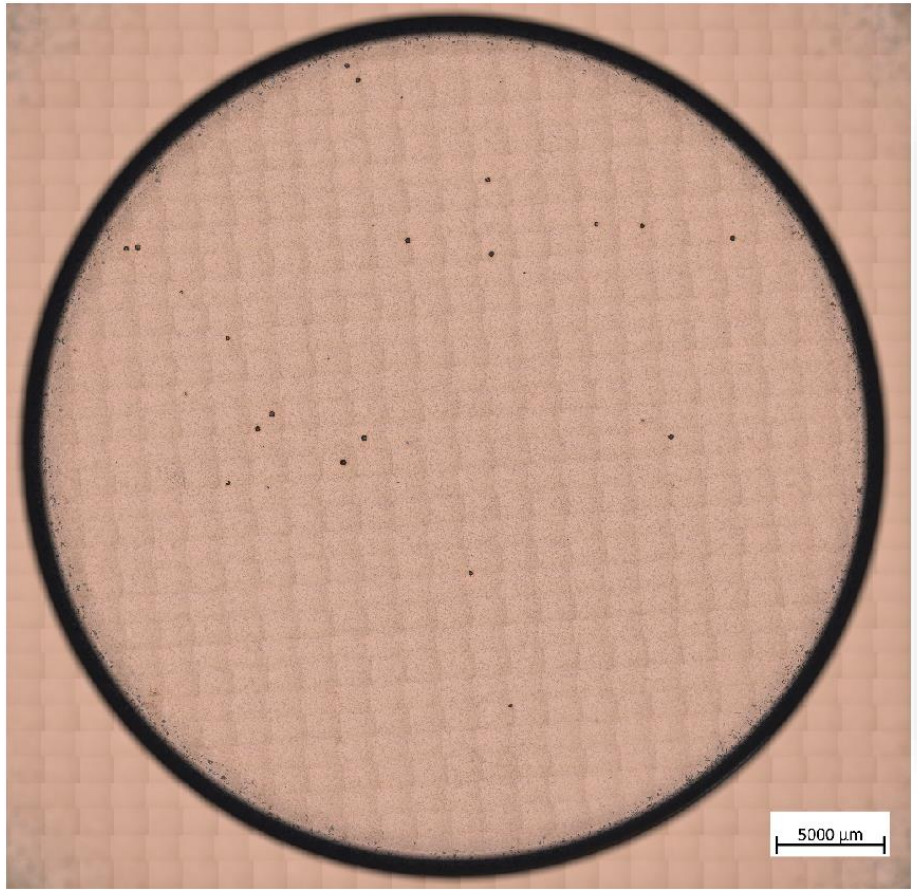
0) Before the test

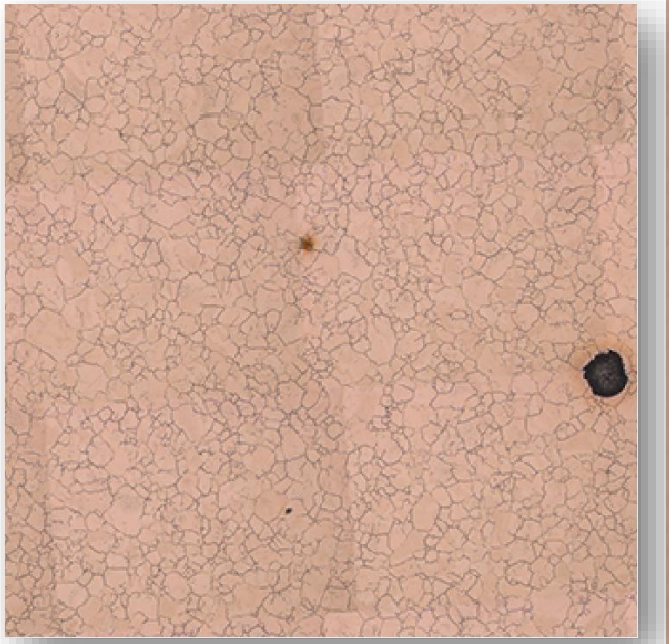


…courtesy of Enrique Rodriguez Castro

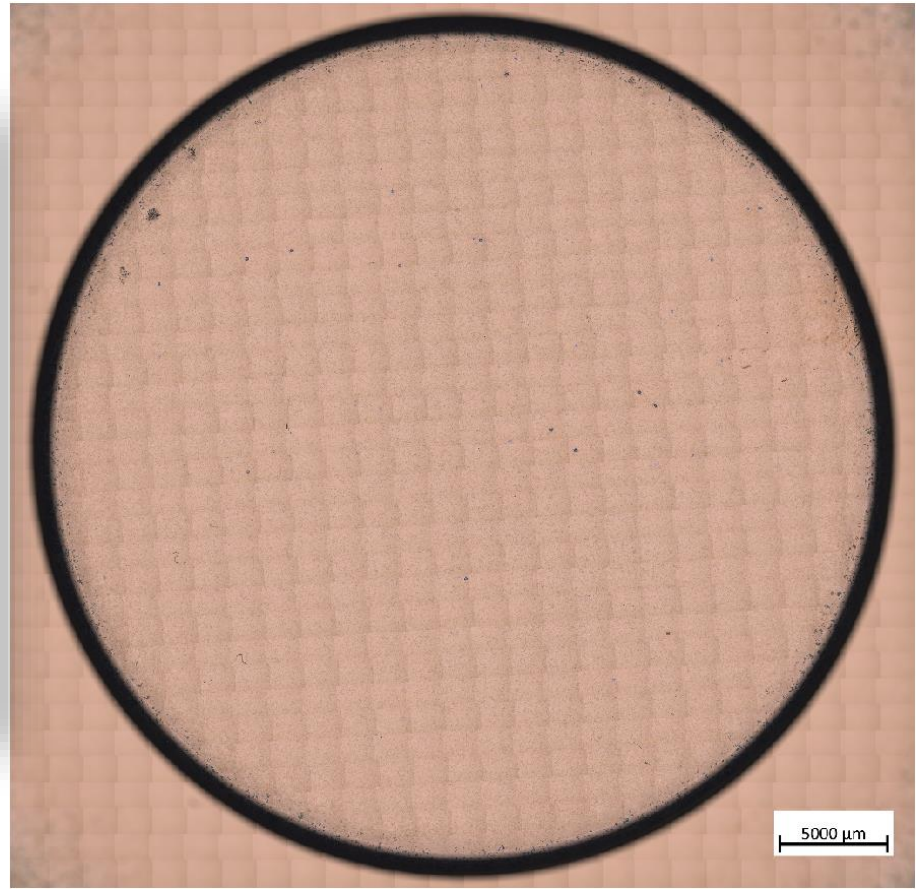
Microscopic images for **015 Soft Cu** cathode (left) and anode (right), zoom for one of the area (in the middle).

Evolution of surface





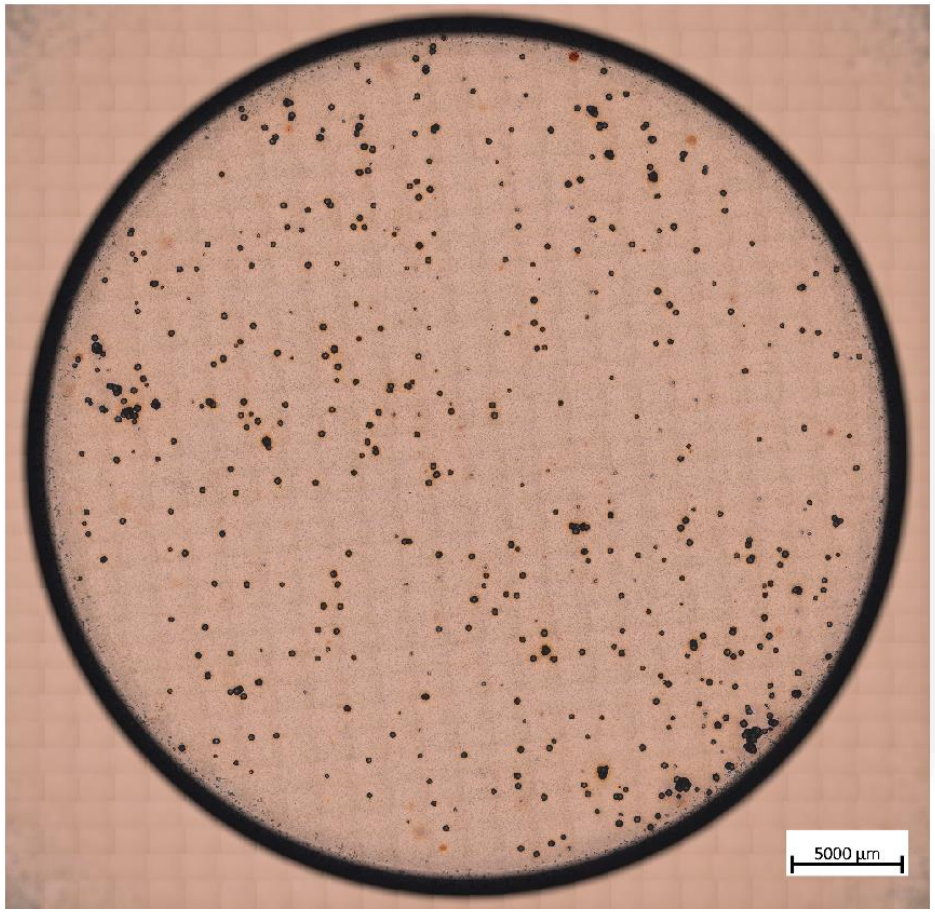
1) 100 µm

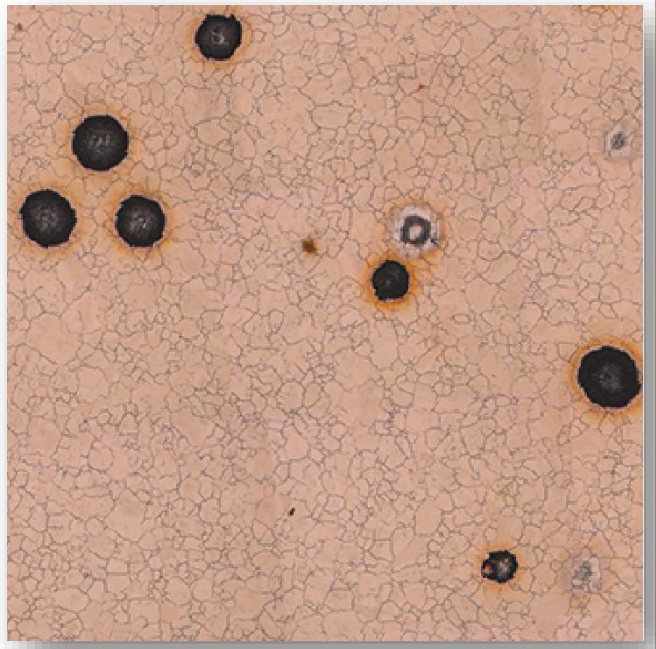


…courtesy of Enrique Rodriguez Castro

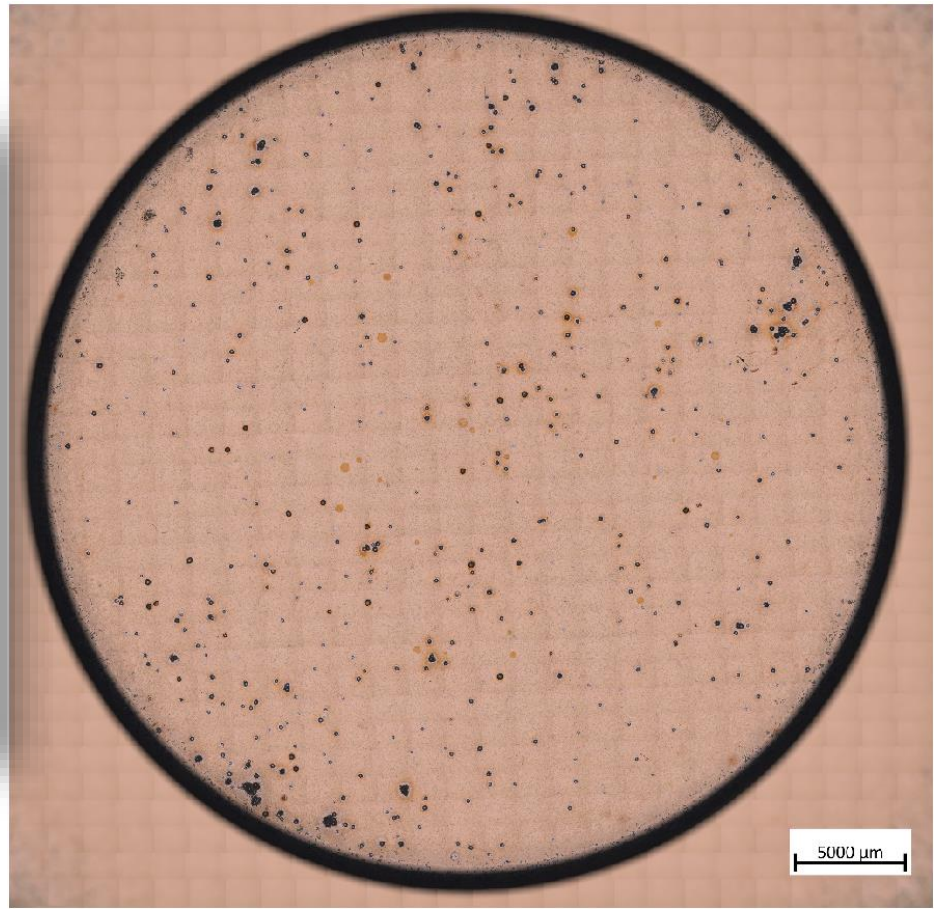
Microscopic images for **015 Soft Cu** cathode (left) and anode (right), zoom for one of the area (in the middle).

Evolution of surface





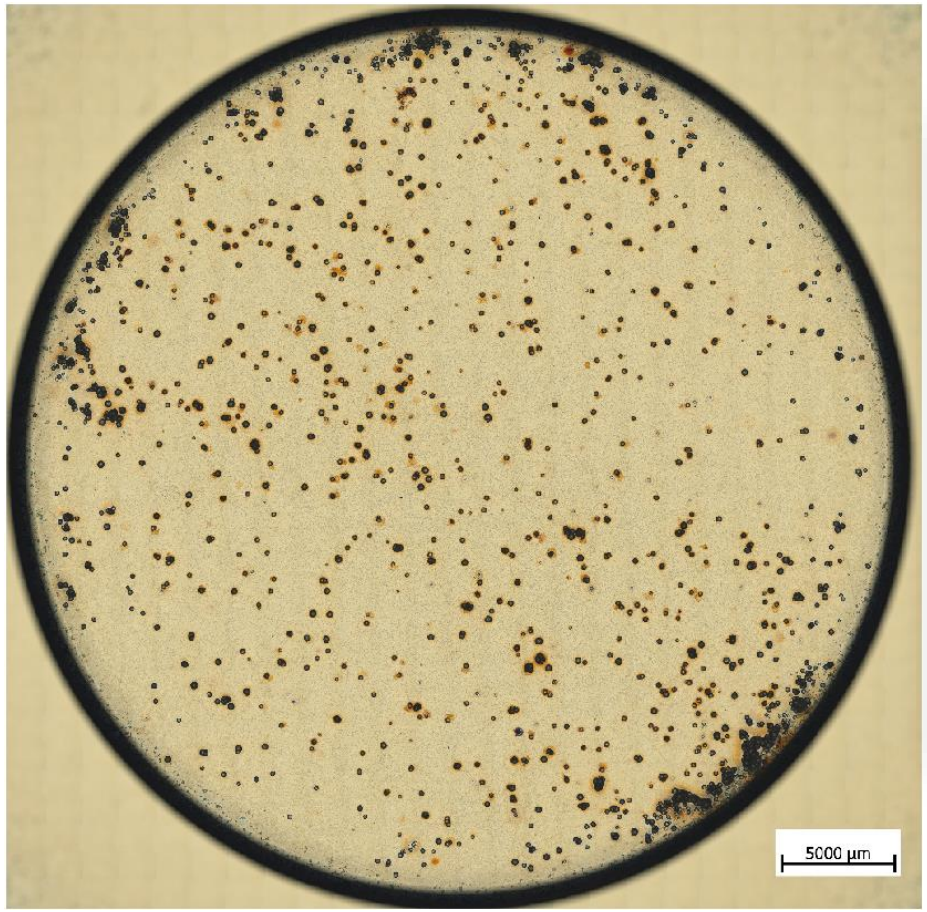
2) 100 µm

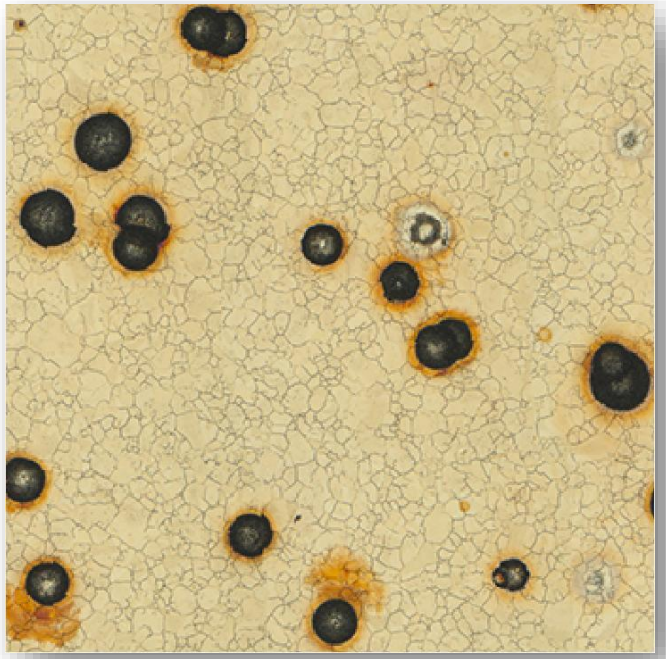


…courtesy of Enrique Rodriguez Castro

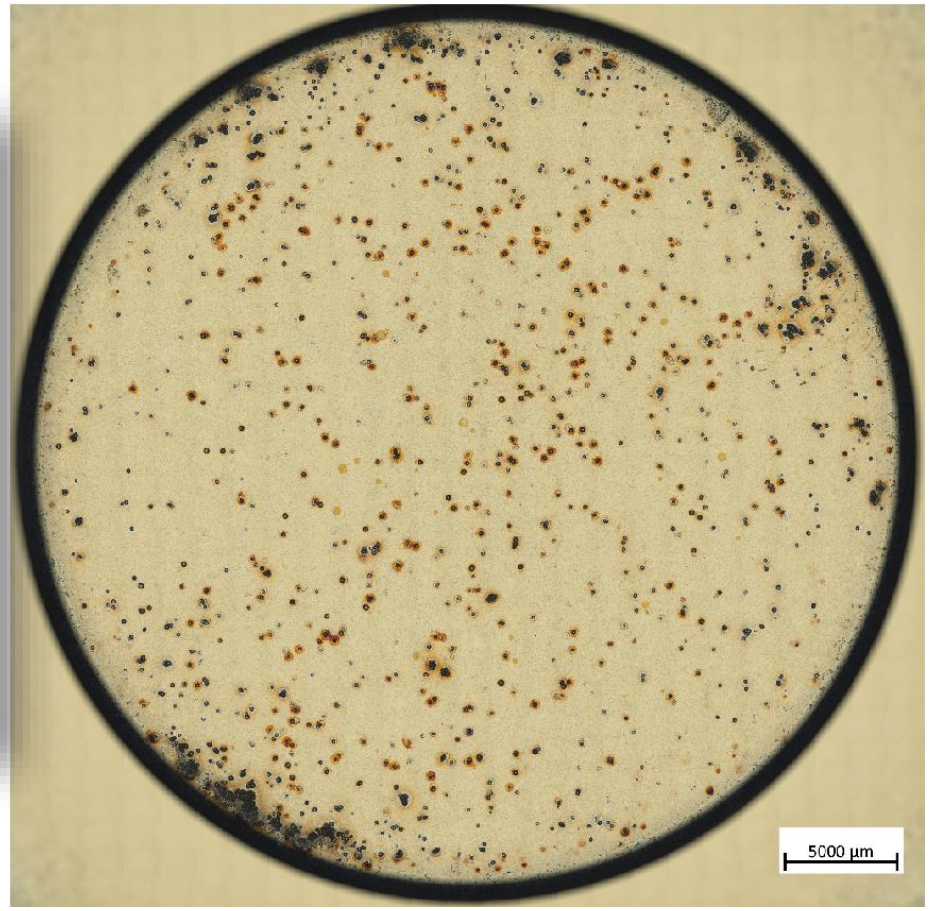
Microscopic images for **015 Soft Cu** cathode (left) and anode (right), zoom for one of the area (in the middle).

Evolution of surface





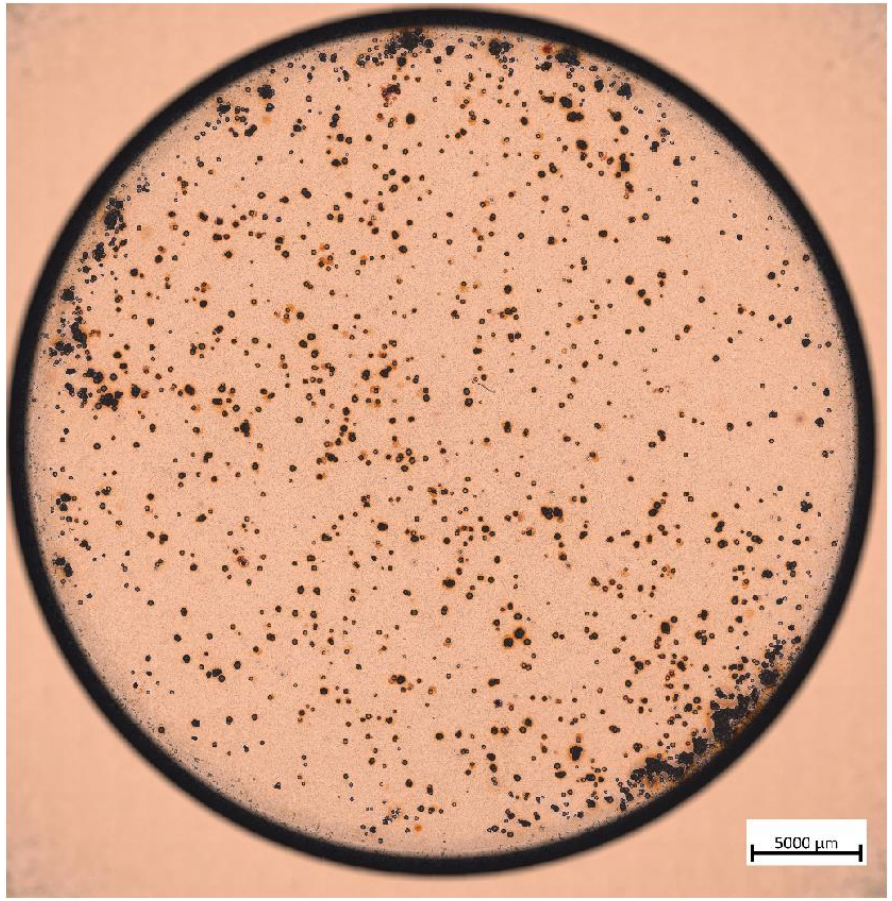
3) 60 µm

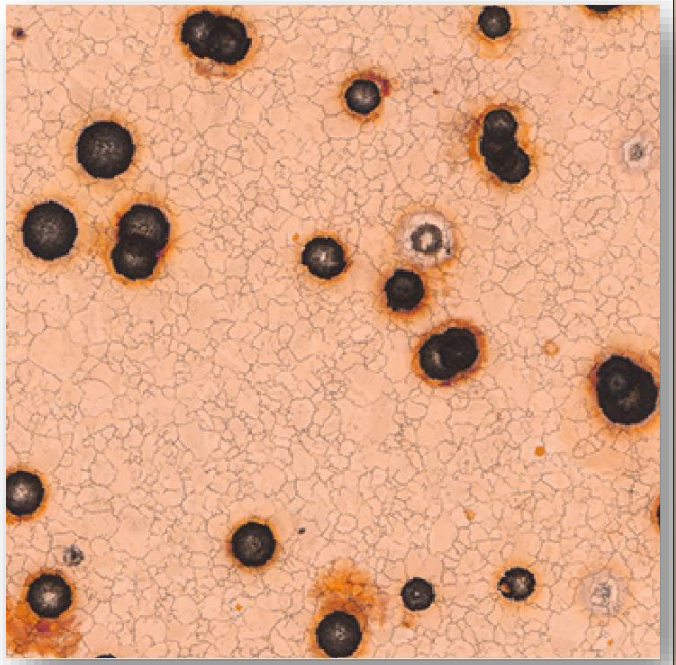


…courtesy of Enrique Rodriguez Castro

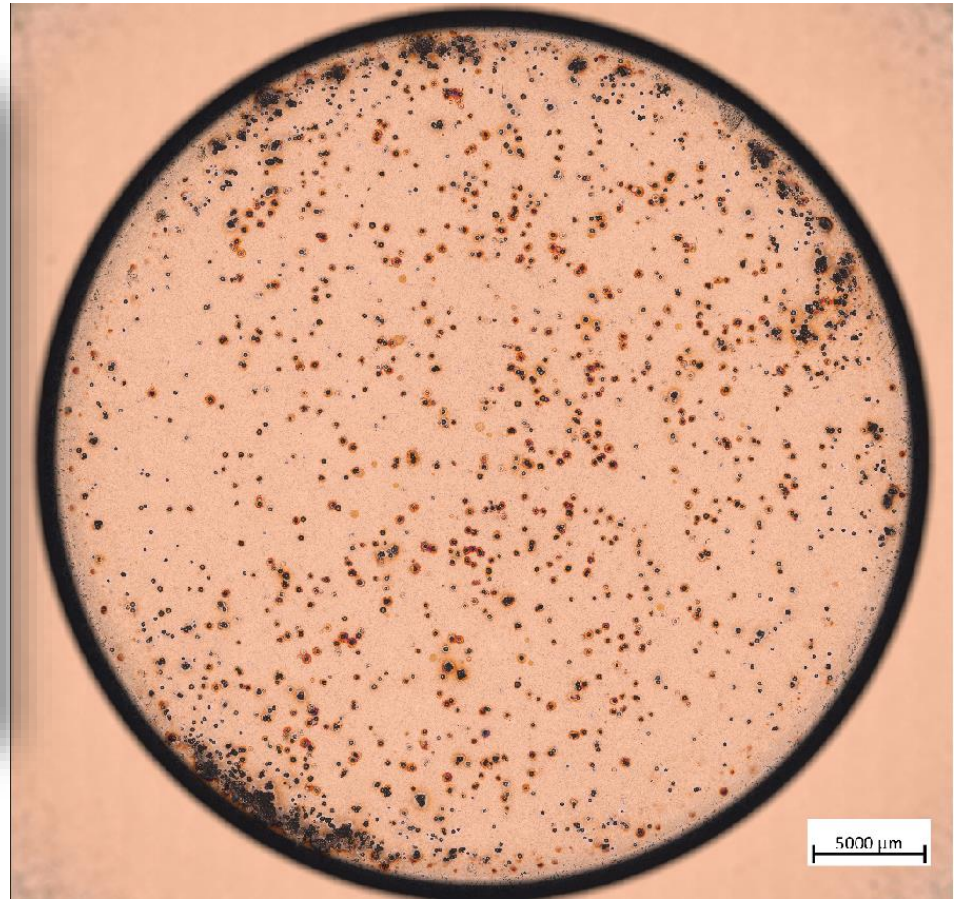
Microscopic images for **015 Soft Cu** cathode (left) and anode (right), zoom for one of the area (in the middle).

Evolution of surface





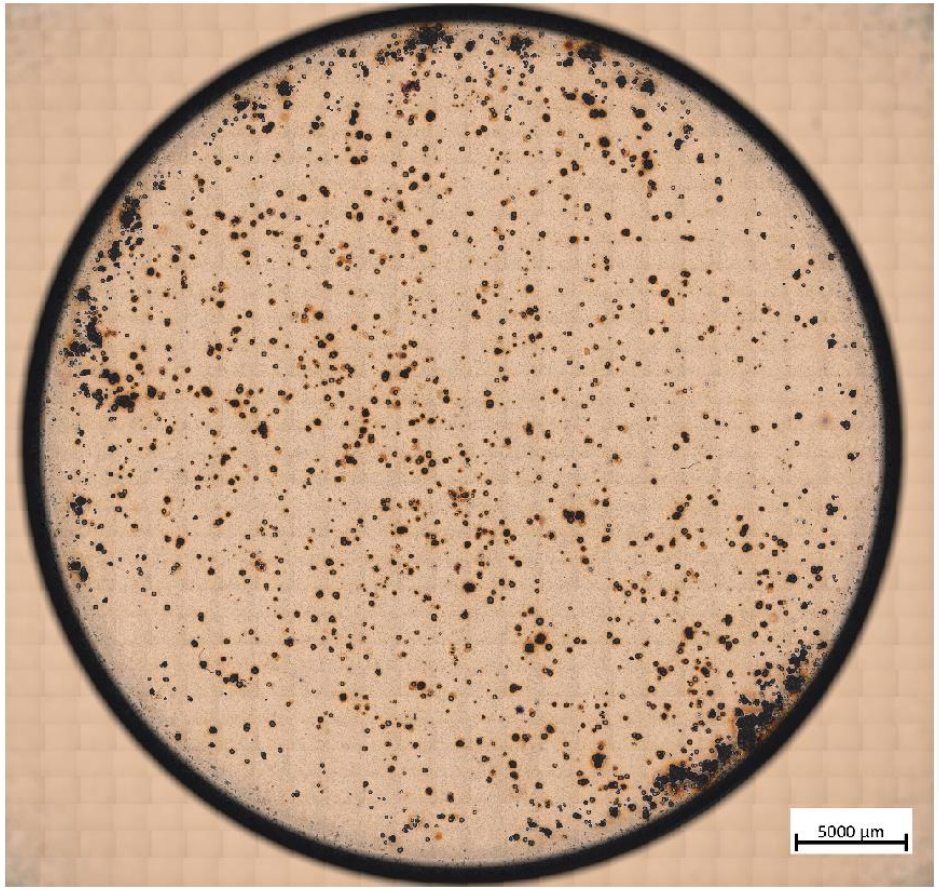
4) 40 µm

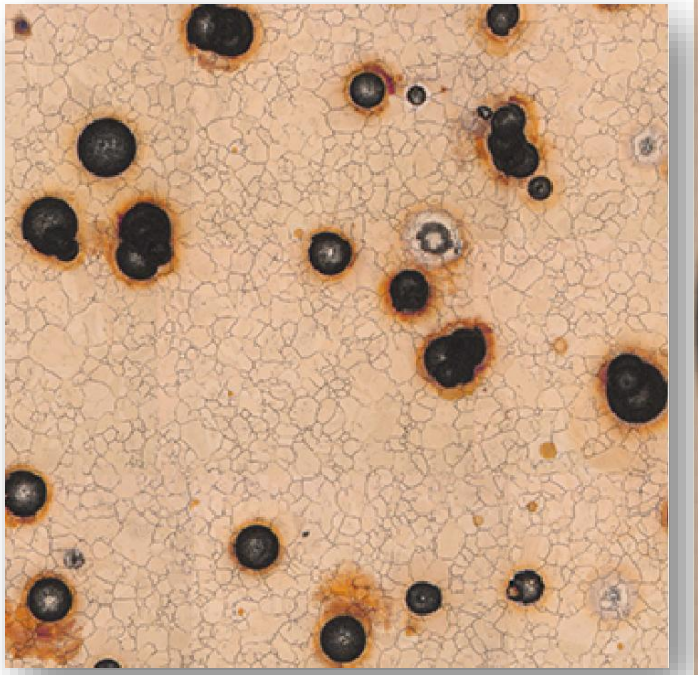


…courtesy of Ana Teresa Perez Fontenla

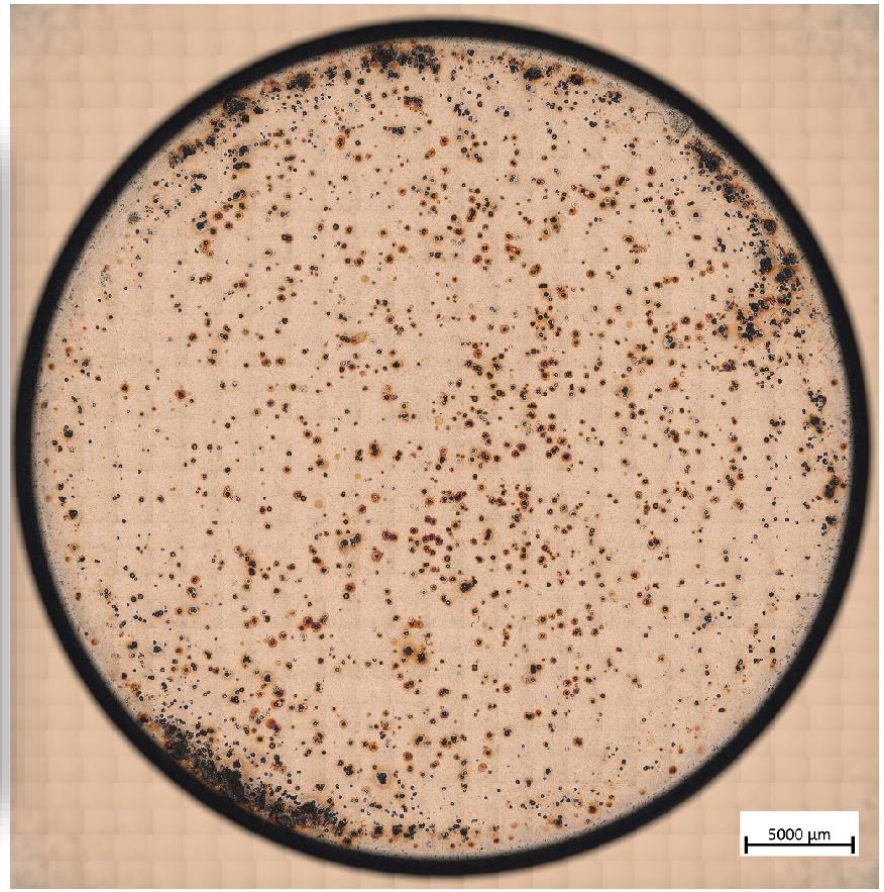
Microscopic images for **015 Soft Cu** cathode (left) and anode (right), zoom for one of the area (in the middle).

Evolution of surface





5) 20 µm



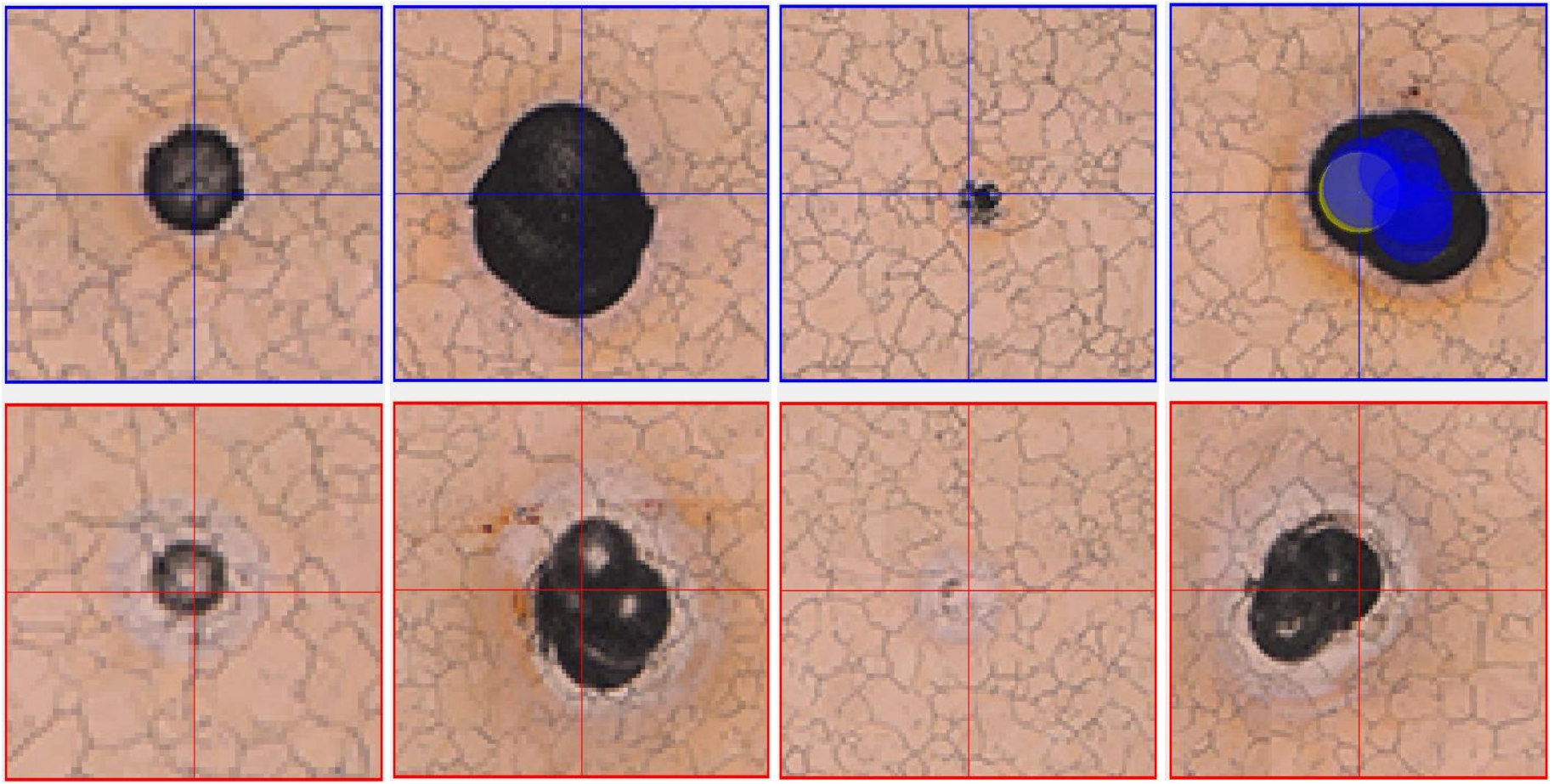
…courtesy of Enrique Rodriguez Castro

Microscopic images for **015 Soft Cu** cathode (left) and anode (right), zoom for one of the area (in the middle).

Cathode/anode craters

Cathode

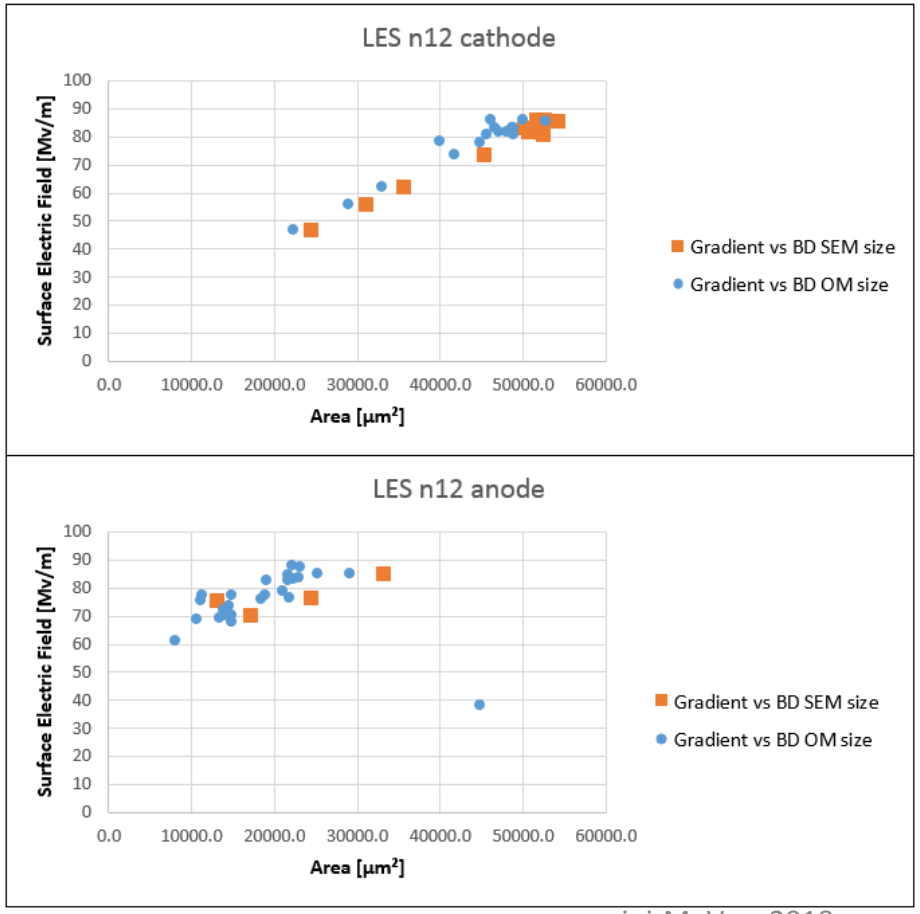
Anode



Cathode/Anode craters

Large Electrode System (LES)

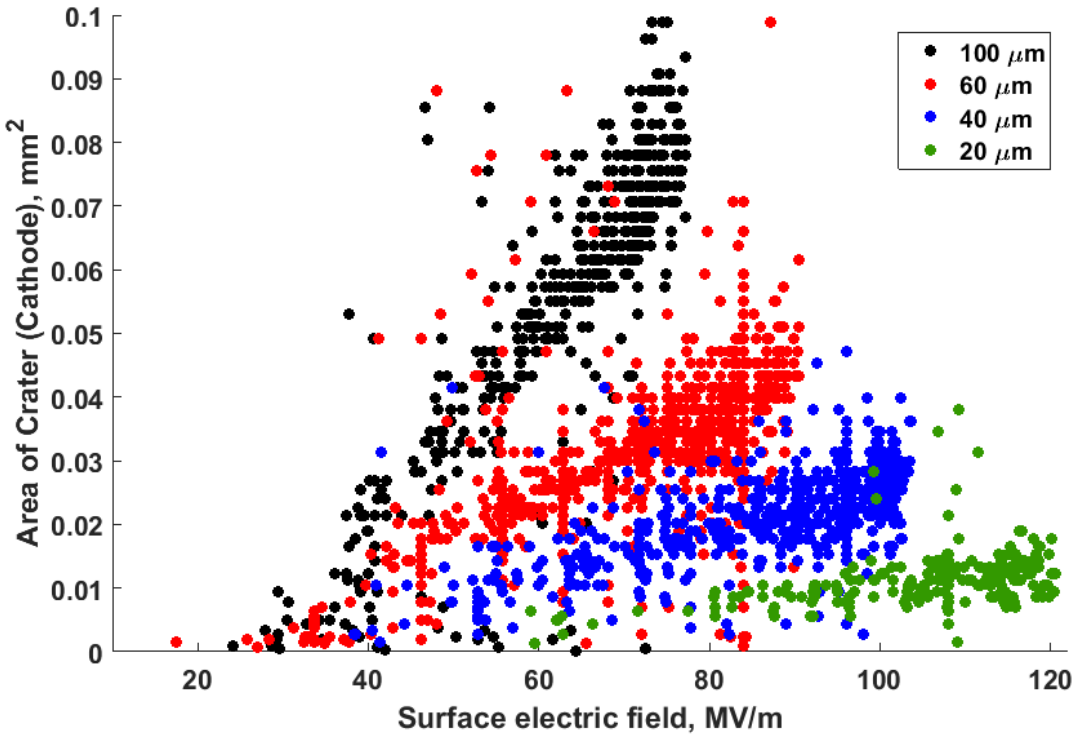
- Preliminary results show that crater size increase with surface electric field

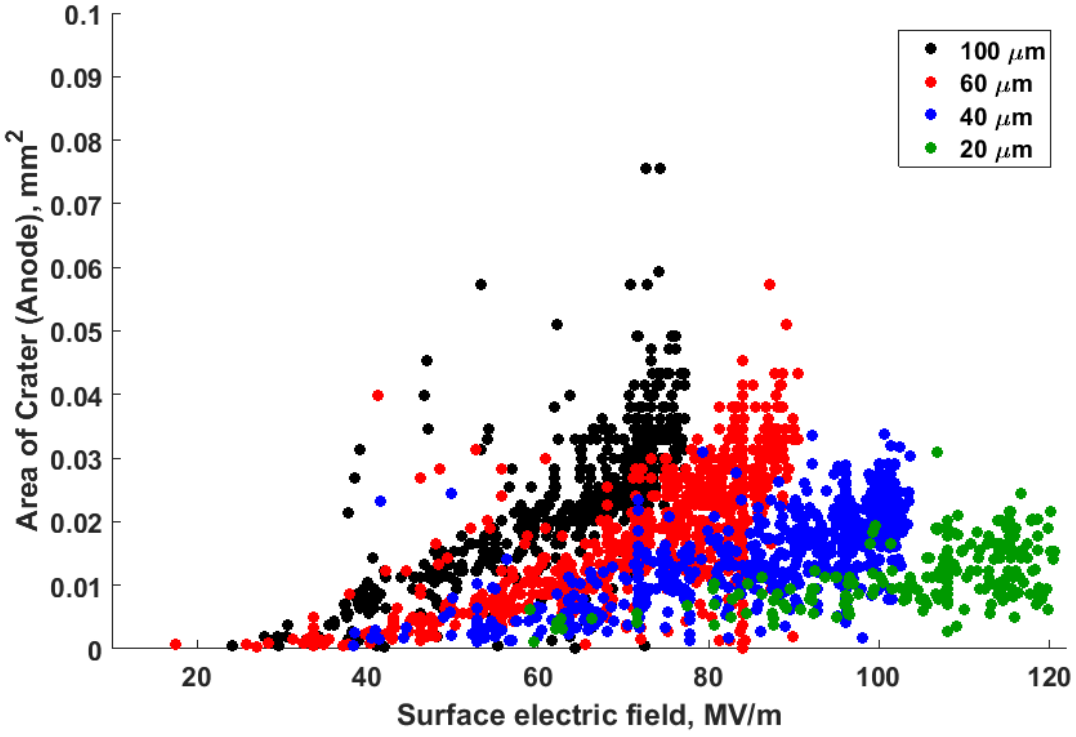


Enrique Rodríguez Castro, MeVArc 2018

https://indico.cern.ch/event/680402/contributions/2976643/attachments/1654803/2648883/MeVArc2018_ERCvIndico.pdf

Cathode/Anode craters

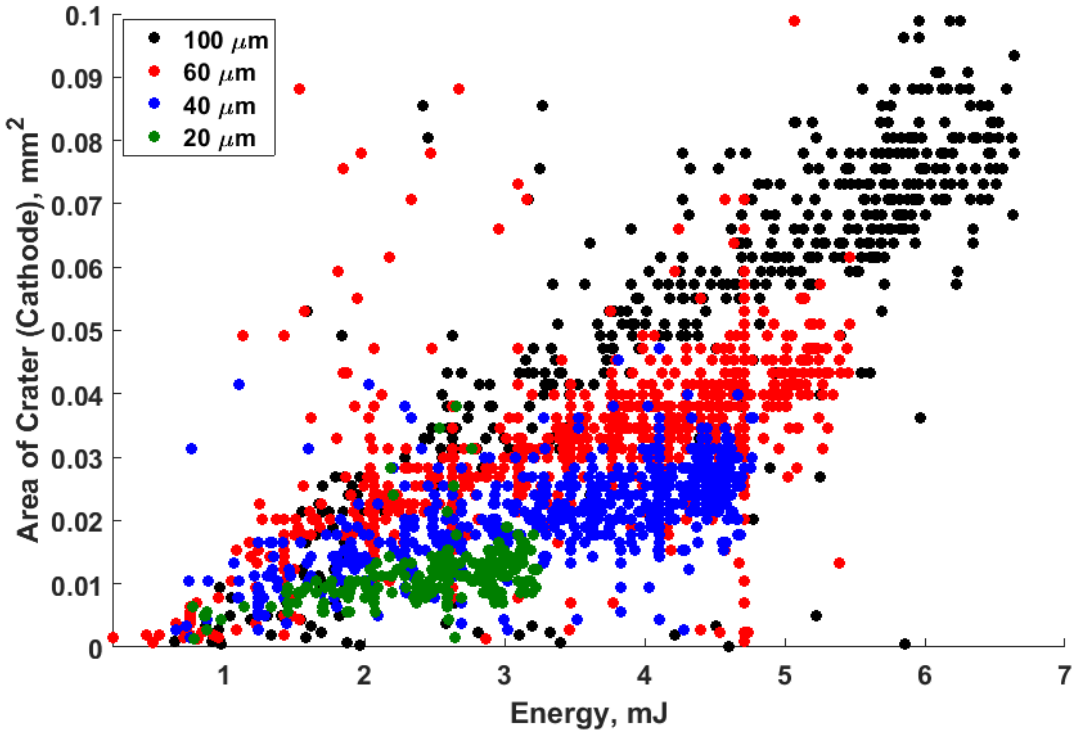


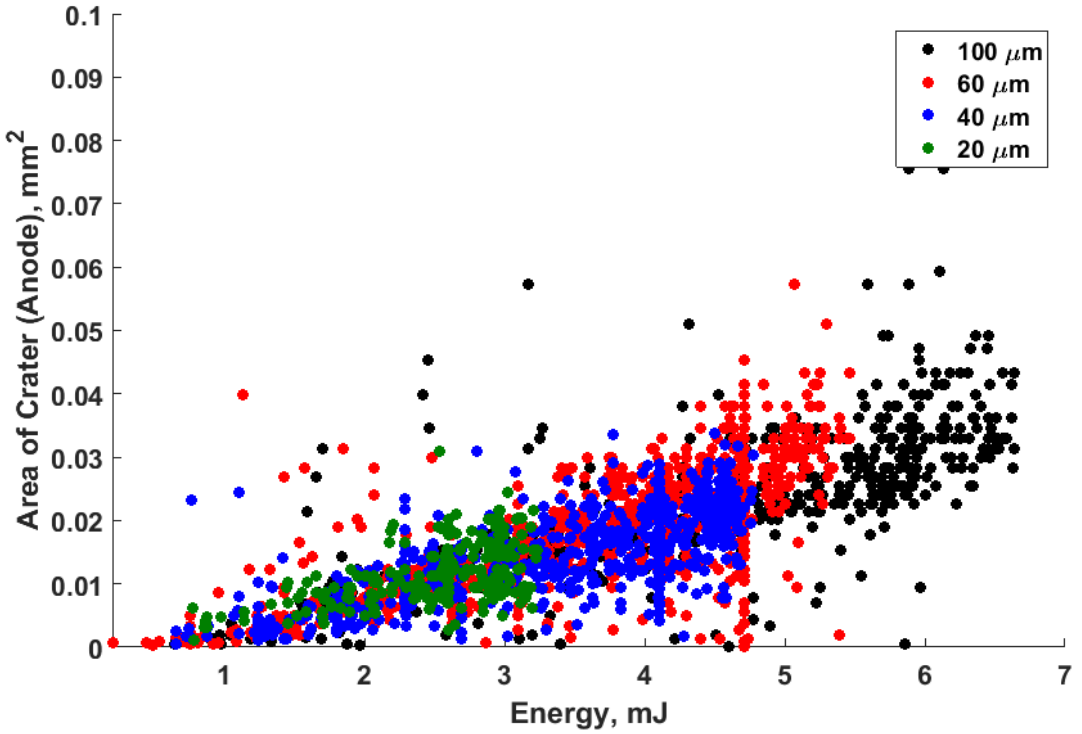


Gap, µm	Average area of the craters, mm^2			Average diameter of the craters, µm		
	Cathode	Anode	Ratio C/A	Cathode	Anode	Ratio C/A
100	**0.055**	**0.023**	**2.39**	**255**	**164**	**1.55**
60	0.034	0.02	1.7	204	152	1.34
40	0.022	0.016	1.38	165	137	1.2
20	0.011	0.012	0.92	118	119	0.99

Cathode/Anode craters

$$Energy = \frac{1}{2}\varepsilon_0 E^2 Ad + \int_{\tau_{BD}}^{\tau_{BD}+\Delta\tau} I(t)V(t)dt$$





Conclusions

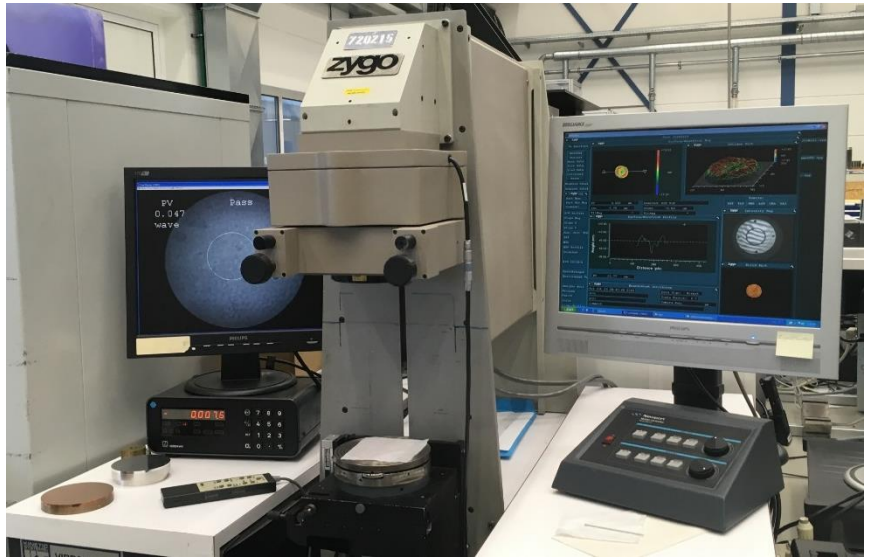
1. Additional test for studying effect of RepRates to BDR shown similar results for another couple of electrodes. The BDR is higher for lower Rep rate in value of BDs/pulses, but stable in value BDs/s.

2. Additional test with changing polarities shown that conditioning stage is no equal for both electrodes.

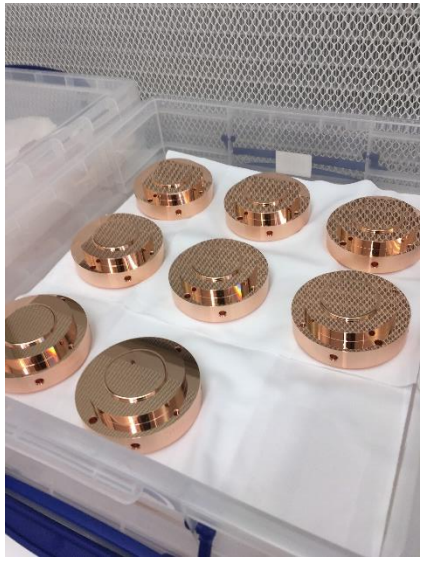
3. The studying the gap dependency was done with 100, 60 ,40 and 20 µm gap using feedback mode for conditioning. It shown a good agreement with another publications.

Electrodes production

For 2019



No	Date	Status
1.	Middle **May**	Start order in side CERN
2.	Middle **July**	Order is sent to company
3.	Begin **November**	Electrodes are produced
4.	Begin **December**	Electrodes will be at CERN



×20 pcs

×20 pcs

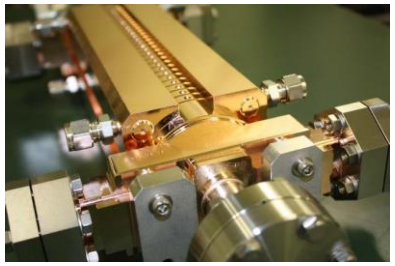
Plans

- Dark current measurement during the pulsing and looking for dark current fluctuations.
- Heat the system
- More tests with Hard and Soft Cu
- Test of single crystal Cu electrode
- Test with electron beam treated surface

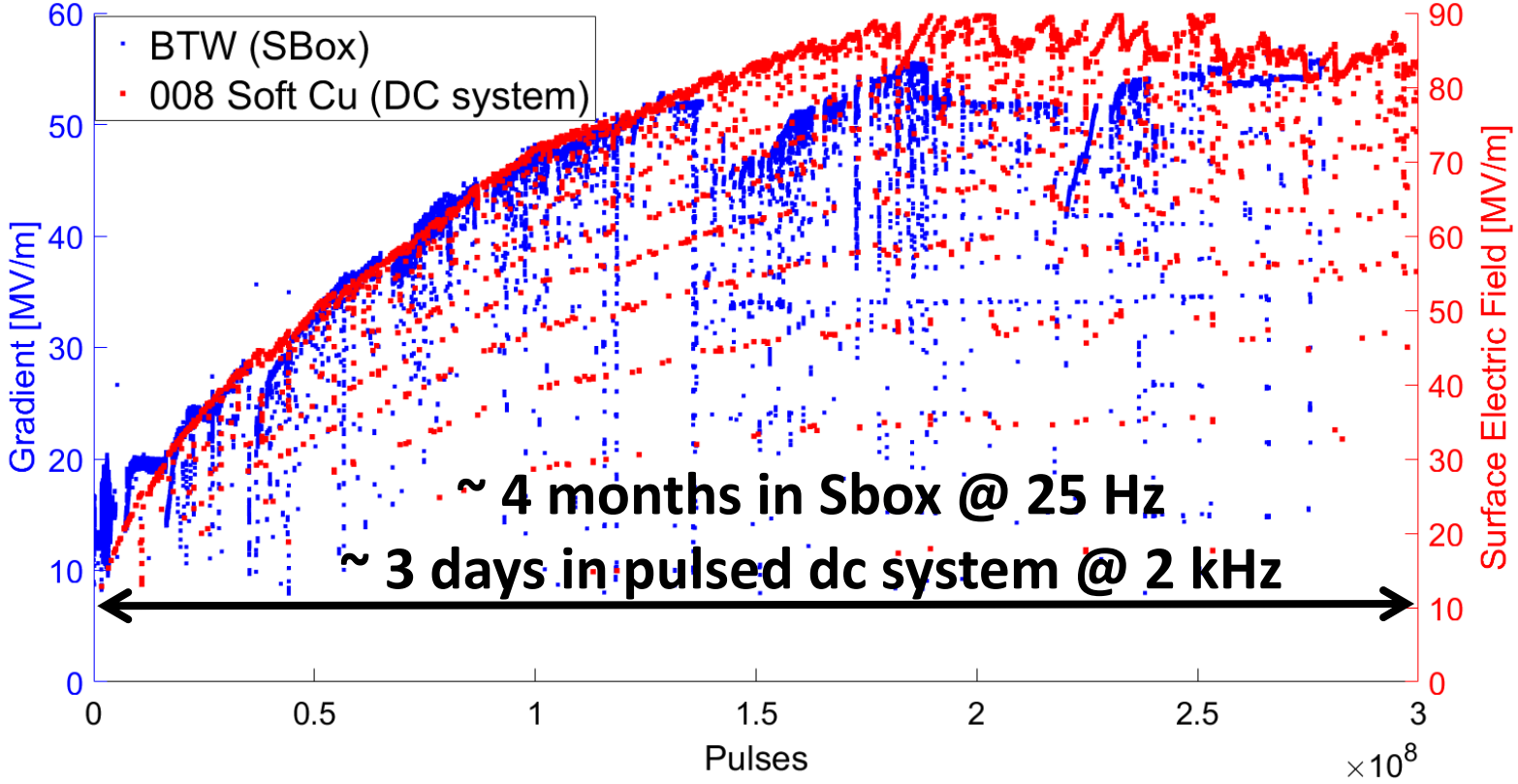
Thank you!

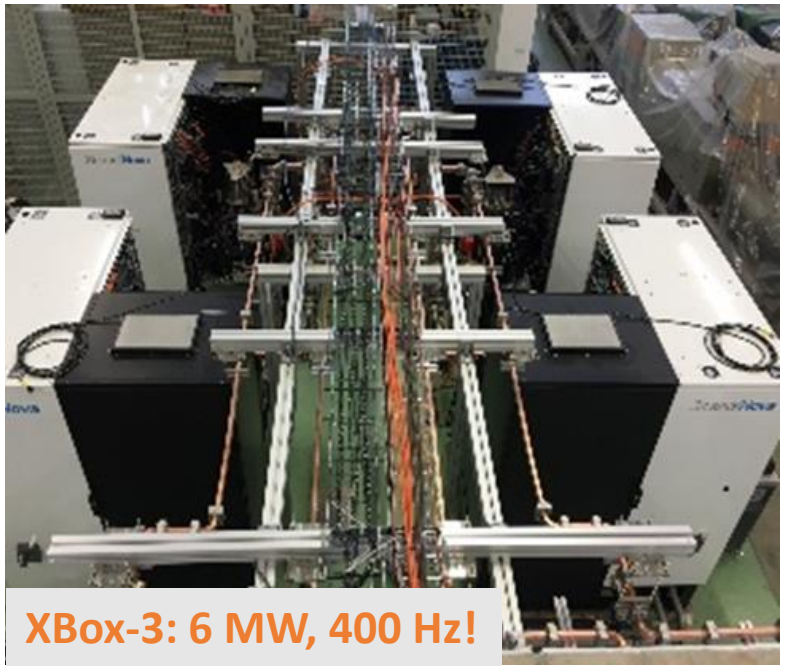
Extra slides

Conditioning in RF and DC



Marx generator, 6kHz



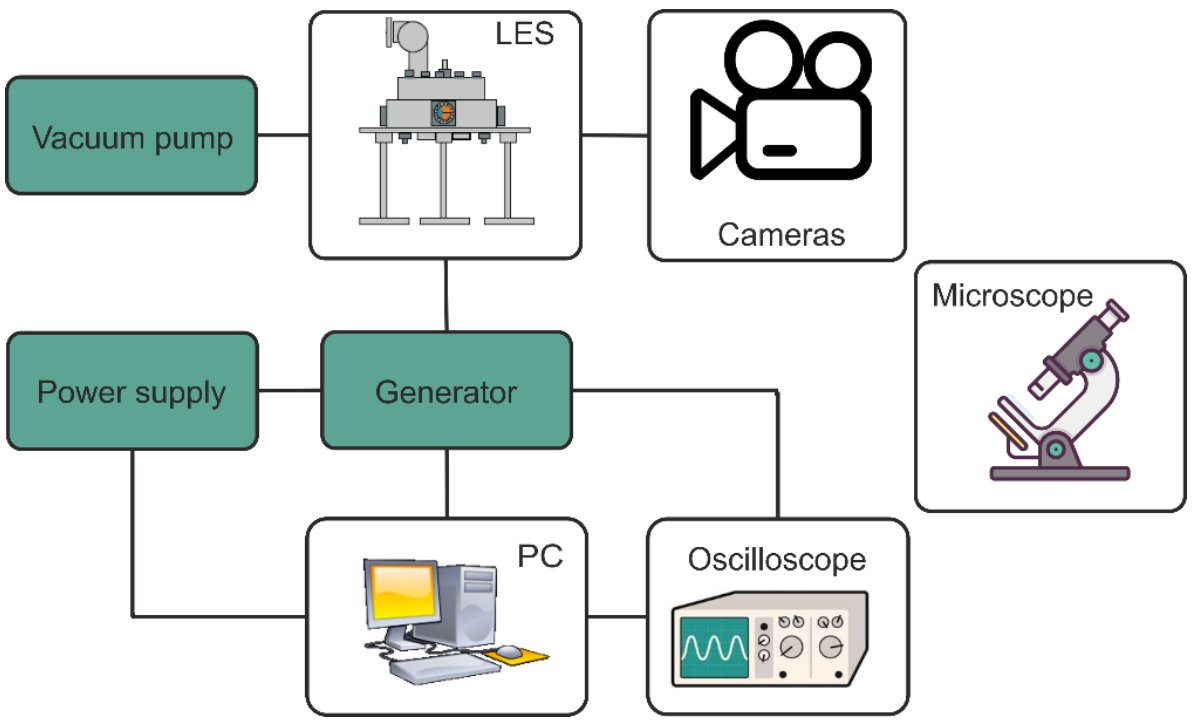


XBox-3: 6 MW, 400 Hz!

…courtesy of Xboxes team

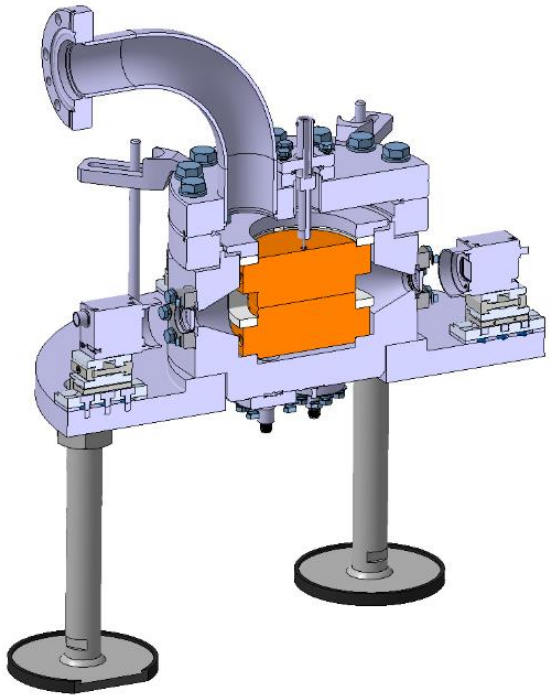
Pulsed DC System

vacuum system for high-gradient studies



a)

b)



c)

Fig. 4. Pulsed DC system at CERN: a) schematic of the equipment, b) photo of Large Electrodes System (LES), c) 3D-model for LES.

Marx generator

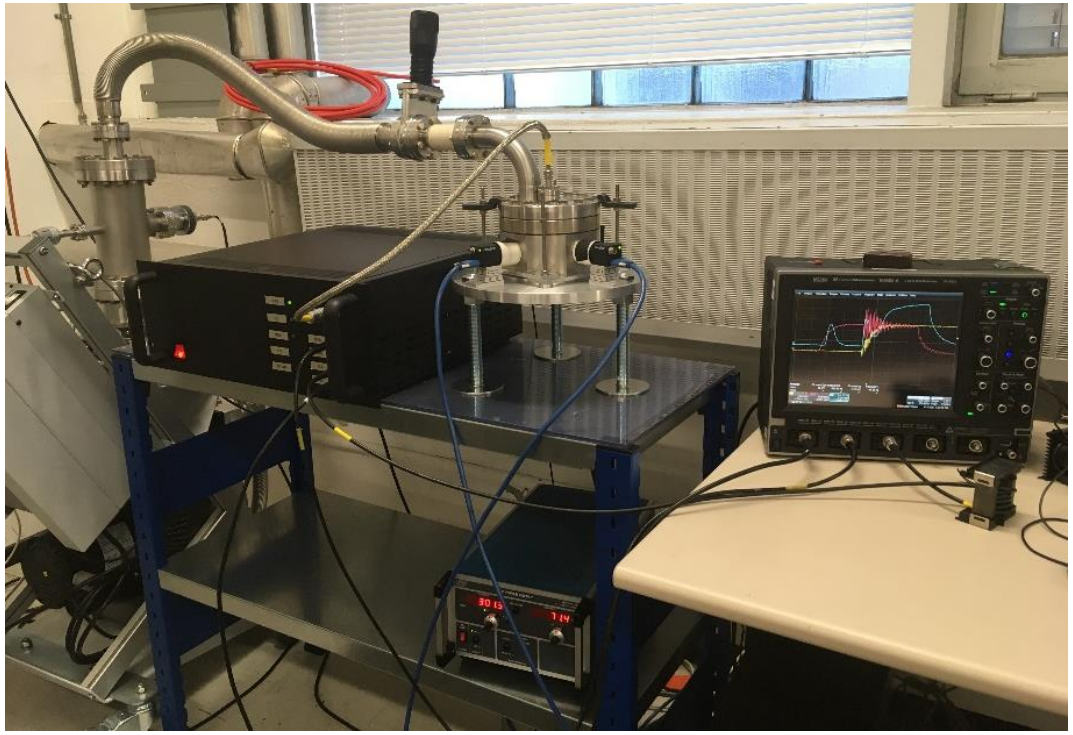


Fig. 5.1. Photo of Marx generator together with LES.

Repetition rate: up to 6 kHz
Pulse length: 500 ns – 1 ms.

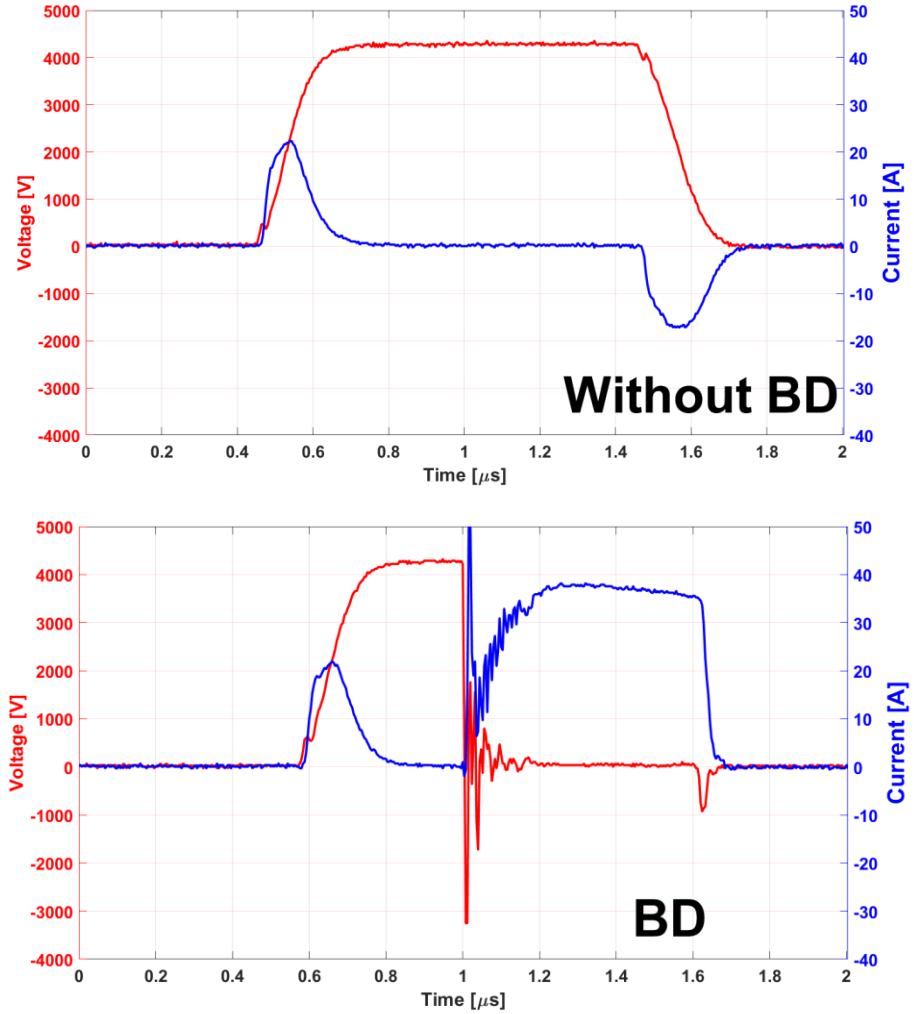
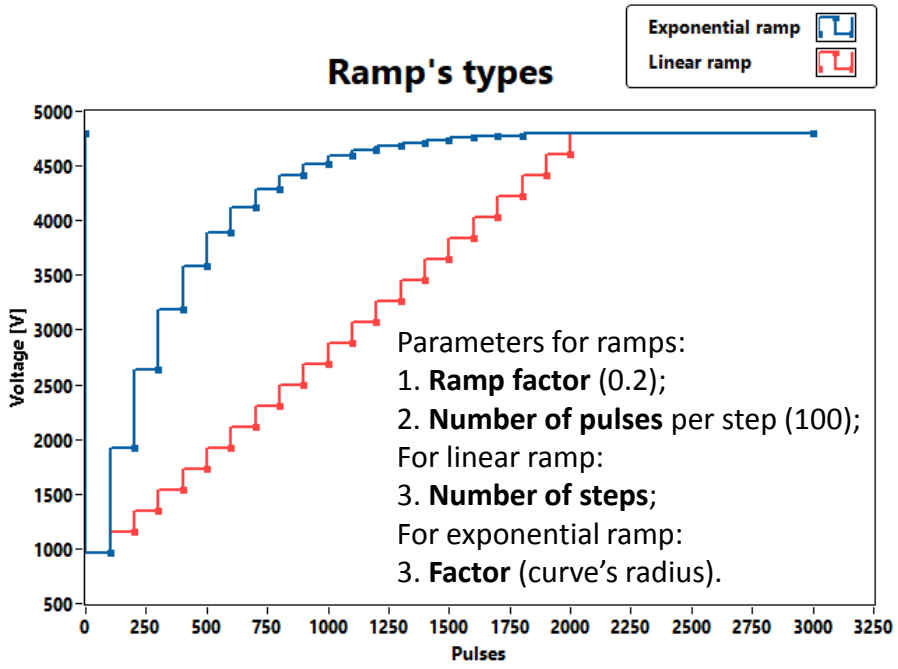


Fig. 5.2. The waveforms taken with Marx generator and LES with 1 μs pulse (0.6 μs delay is used in BD case).

Initial conditioning

No.	Parameter	Value
1.	Initial voltage	600 V
2.	Gain voltages	±15 V
3.	Max BDR	5E-5
4.	Number of pulses per cycle	100 000
5.	Safe pulses	20 000
6.	Gain voltage	8500 V
7.	Pulse length	1 µs
8.	Frequency	2 kHz
9.	Delay after BD	600 ns
10.	Recovering after BD (ramp)	exponential
11.	Ramp factor	0.2
12.	Number of pulses for ramp step	100
13.	Factor (for ramp)	4



BDR vs Rep Rate at DC-spark system

Run Num.	Rep. Rate	Starting Gap	End Gap	Num. Pulses	Num. BDs	BDR
1	1 kHz	20 μm	18 μm	1231085	150	1.22×10^{-4}
2	1 kHz	20 μm	13 μm	2028611	374	1.84×10^{-4}
3	100 Hz	20 μm	20 μm	1436455	124	8.63×10^{-5}
4	100 Hz	20 μm	17 μm	2138863	256	1.20×10^{-4}
5	10 Hz	20 μm	18 μm	621541	207	3.33×10^{-4}
6	10 Hz	20 μm	14 μm	408206	149	3.65×10^{-4}

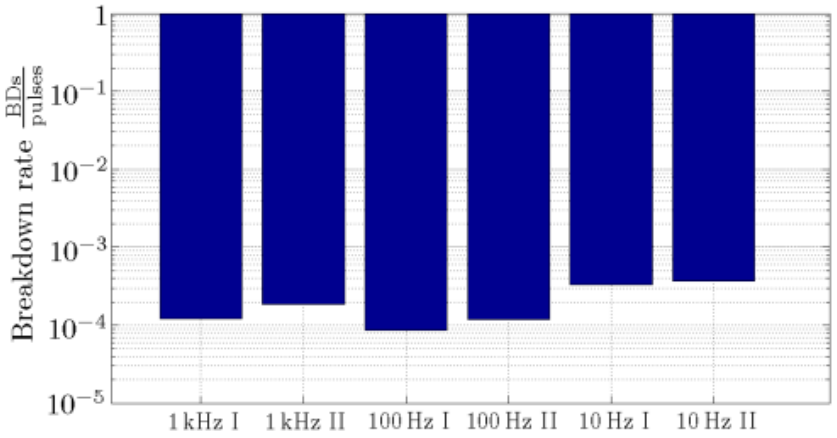


Figure 5.1: The BDR measured at three different frequencies. Two identical measurements (one labelled 'I' and the other labelled 'II') were made at each frequency.

Test is made with HRR circuit at DC spark system I (tip-plate geometry of electrodes).

From N.Shipman PhD Thesis

BDR vs Rep rate at Xbox 3

Proceedings of IPAC2018, Vancouver, BC, Canada - Pre-Release Snapshot 06-May-2018 12:00 UTC

INITIAL TESTING OF TECHNIQUES FOR LARGE SCALE RF CONDITIONING FOR THE COMPACT LINEAR COLLIDER

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[2]also at University of Oxford, Oxford, United Kingdom
[3]also at IFIC, Valencia

Table 1: BDR measured for the SiC structure for variations in the pulse repetition rate.

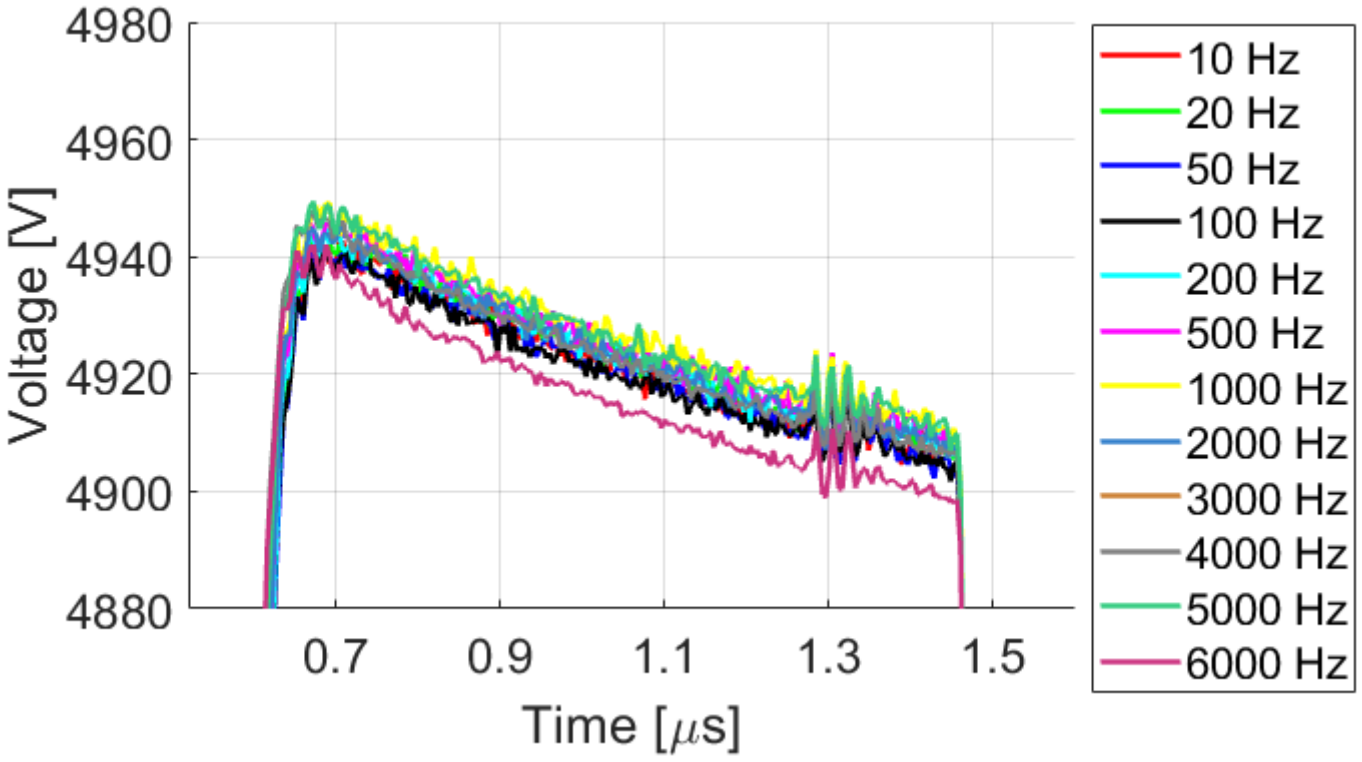
Structure	Rep. Rate [Hz]	BDR [bpp]	Uncertainty [bpp]
SiC N2	25	1.08×10^{-6}	$\pm 3.0 \times 10^{-7}$
	100	3.9×10^{-7}	$\pm 9.7 \times 10^{-8}$
	200	2.4×10^{-7}	$\pm 9.12 \times 10^{-8}$
PSI N2	25	1.66×10^{-6}	$\pm 3.73 \times 10^{-7}$
	100	7.317×10^{-7}	$\pm 1.34 \times 10^{-7}$
	200	3.1×10^{-7}	$\pm 1.03 \times 10^{-7}$

http://ipac2018.vrws.de/papers/thpmk103.pdf

PULSE REPETITION RATE VS BDR

The klystrons in Xbox 3 can operate at pulse repetition rates up to 400 Hz, allowing pulsing of the each line up to 200 Hz [8]. For pre-conditioning of the structures, it has been proposed that pulsing would operate at repetition rates well above the nominal CLIC parameters to reduce the required conditioning time. Increasing the repetition rate increases the average power dissipated in the structure and it is important to undestand how this affects the BDR. Using the damped Silicon Carbide (SiC) structure and the undamped PSI structure, pulsing at constant power and pulse length was performed at three pulse repetition rates. Figure 3 displays the cumulative breakdowns for 82 million pulses. Summarising the results, Table 1 displays the measured BDR for the three repetition rates. For the SiC structure, the BDR at 25 Hz and 100 Hz appeared to decrease despite the increased average power. For 200 Hz pulsing, the BDR remained the same as the 100 Hz repetition rate within statistical uncertainty. The BDR on the PSI structure began at the higher breakdown rate of 1.66×10^{-6} bpp at 25 Hz, expected to be the result of the initial change in power. Subsequent pulsing at 100 and 200 Hz continued to decrease in BDR due to conditioning. With the increase in average power, there was no evidence of a BDR increase for a pulse repetiton rate change.

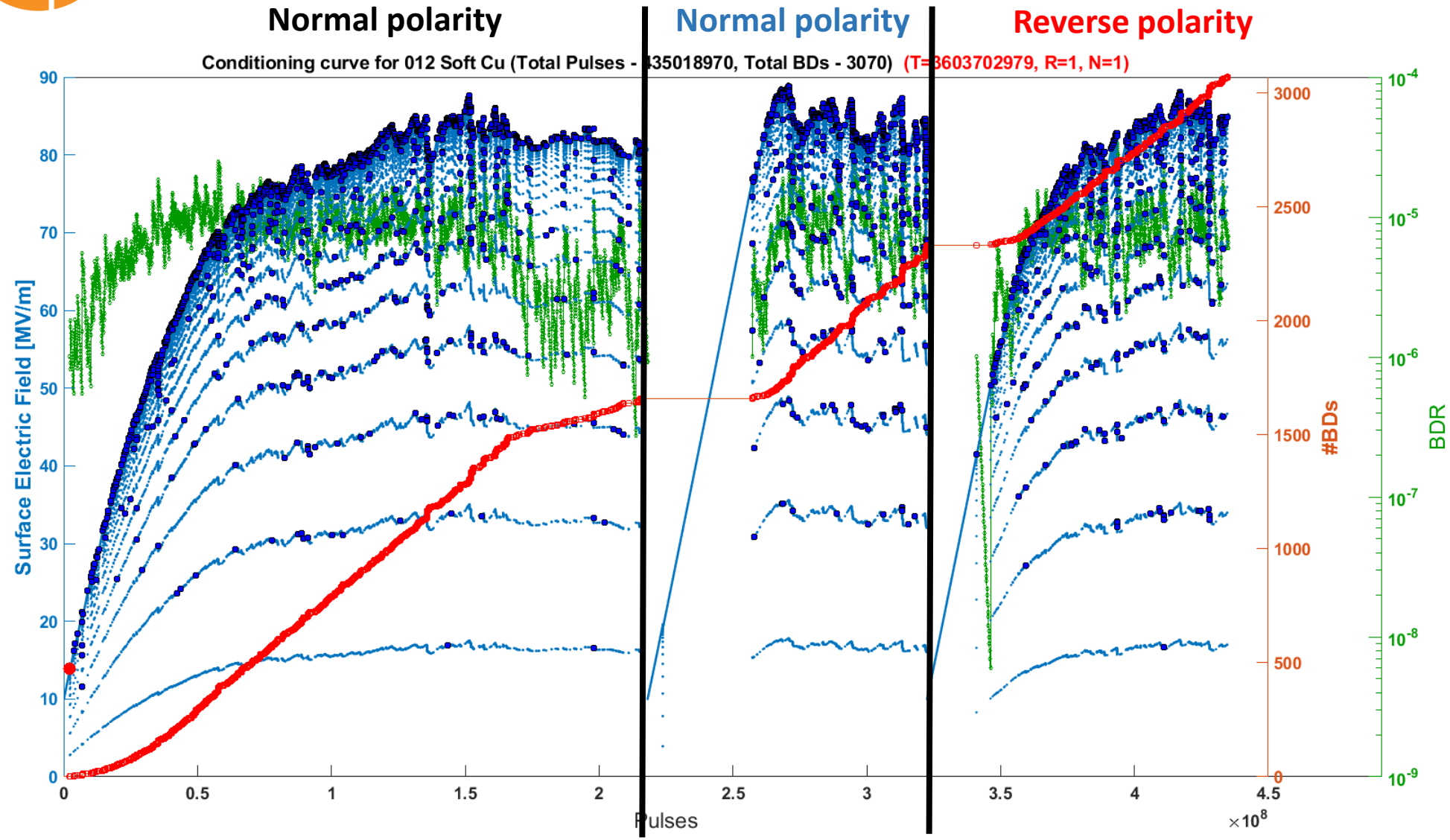
Calibration for BDR vs Rep Rate



Checking the applied correction for 4950 V.

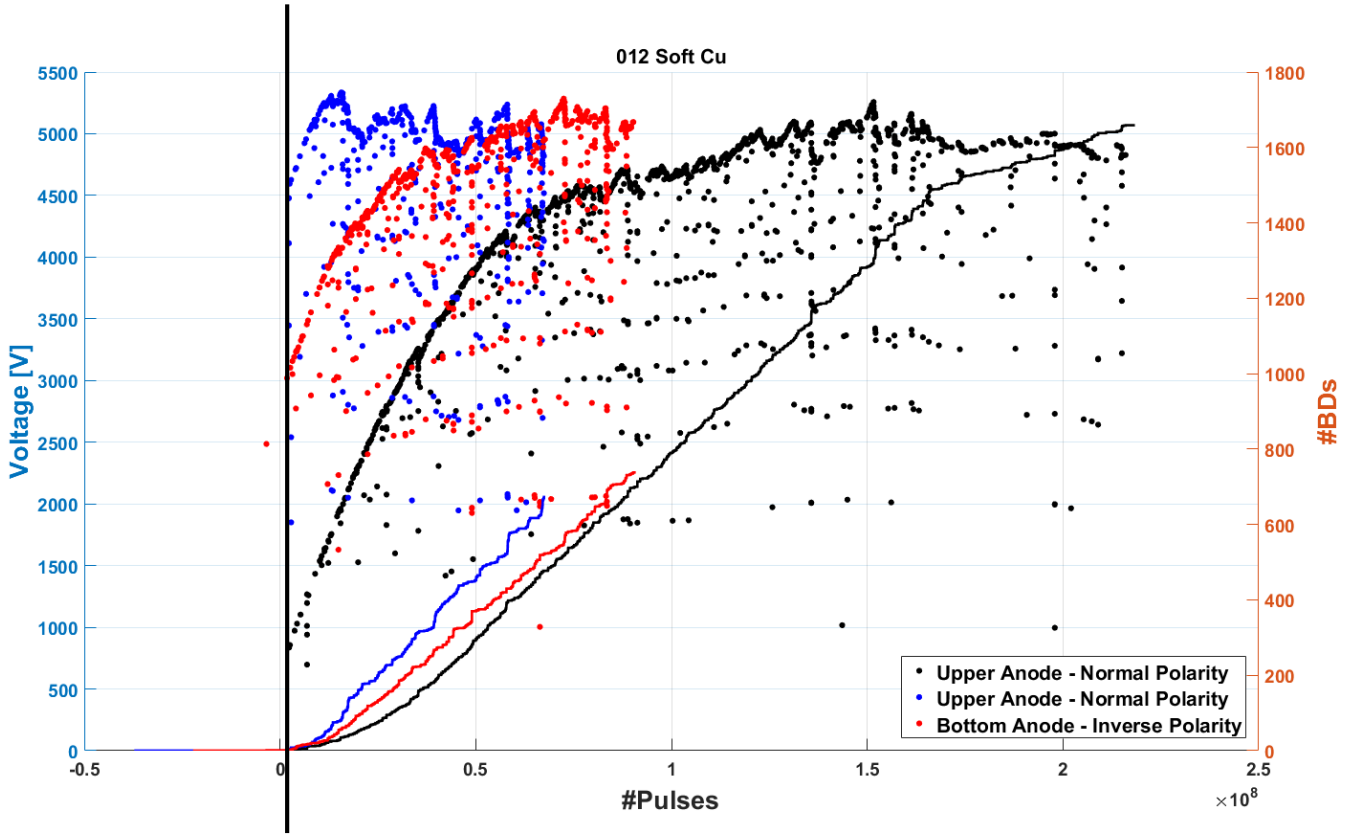
Freq	AvrV	Abs rel 2000 Hz	Rel rel 2000 Hz
10	4925	-1.7	-0.03%
20	4926	-0.4	-0.01%
50	4924	-2.7	-0.05%
100	4923	-3.6	-0.07%
200	4927	0.5	0.01%
500	4928	1.4	0.03%
1000	4930	3.3	0.07%
2000	**4926**	**0.0**	**0.00%**
3000	4929	2.6	0.05%
4000	4926	-0.8	-0.02%
5000	4929	2.6	0.05%
6000	4918	-8.5	-0.17%

History for 012 Soft Cu



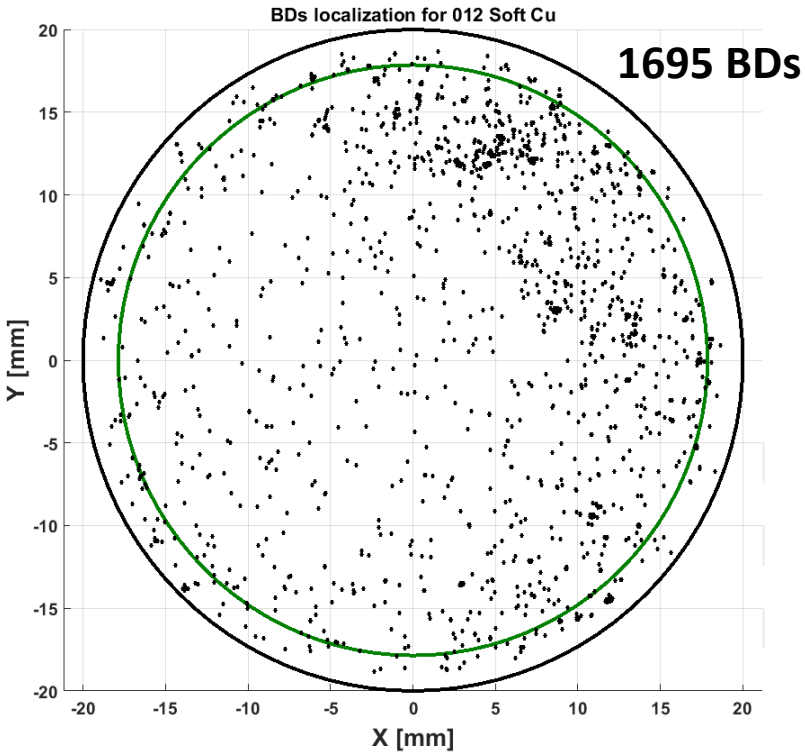
The consequence of test with different polarities. Test was done with **012 Soft Cu** electrodes, 60 um gap, 1 µs pulse width.

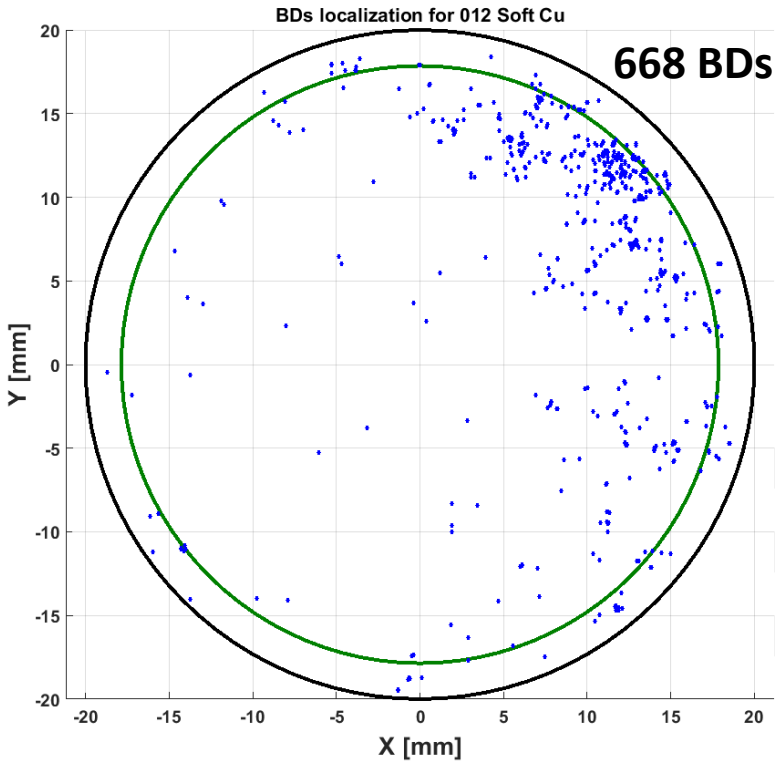
Polarity changing

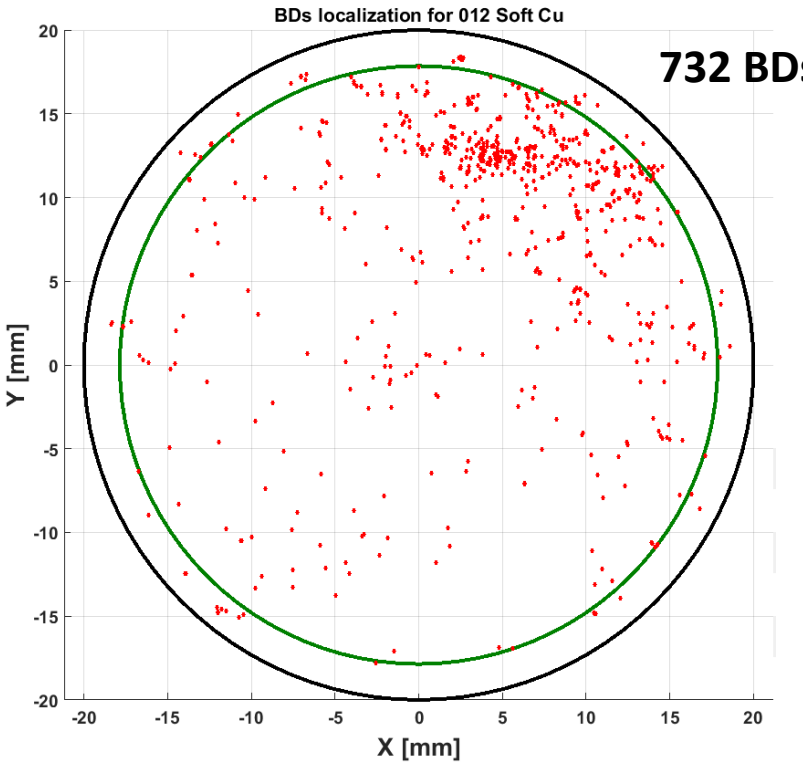


001 – 002,
005 – 006,
007

BDs localization

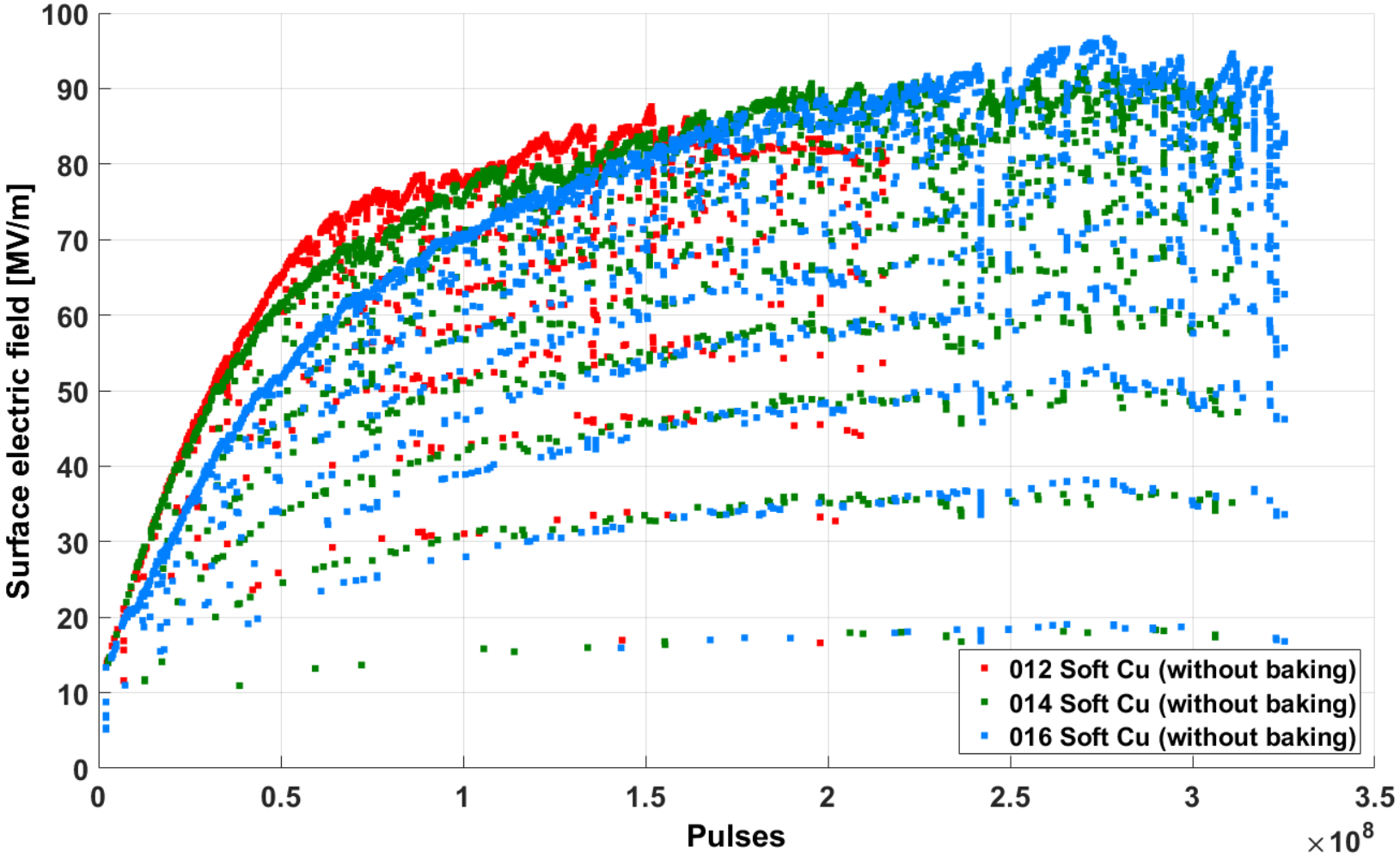






BD localization for: **1 – normal polarity**, **2 – normal polarity**, **3 – reverse polarity**

Comparison of initial conditionings



3 couples of electrodes showed similar parameters during initial conditioning

Polarity changing

001 – 021

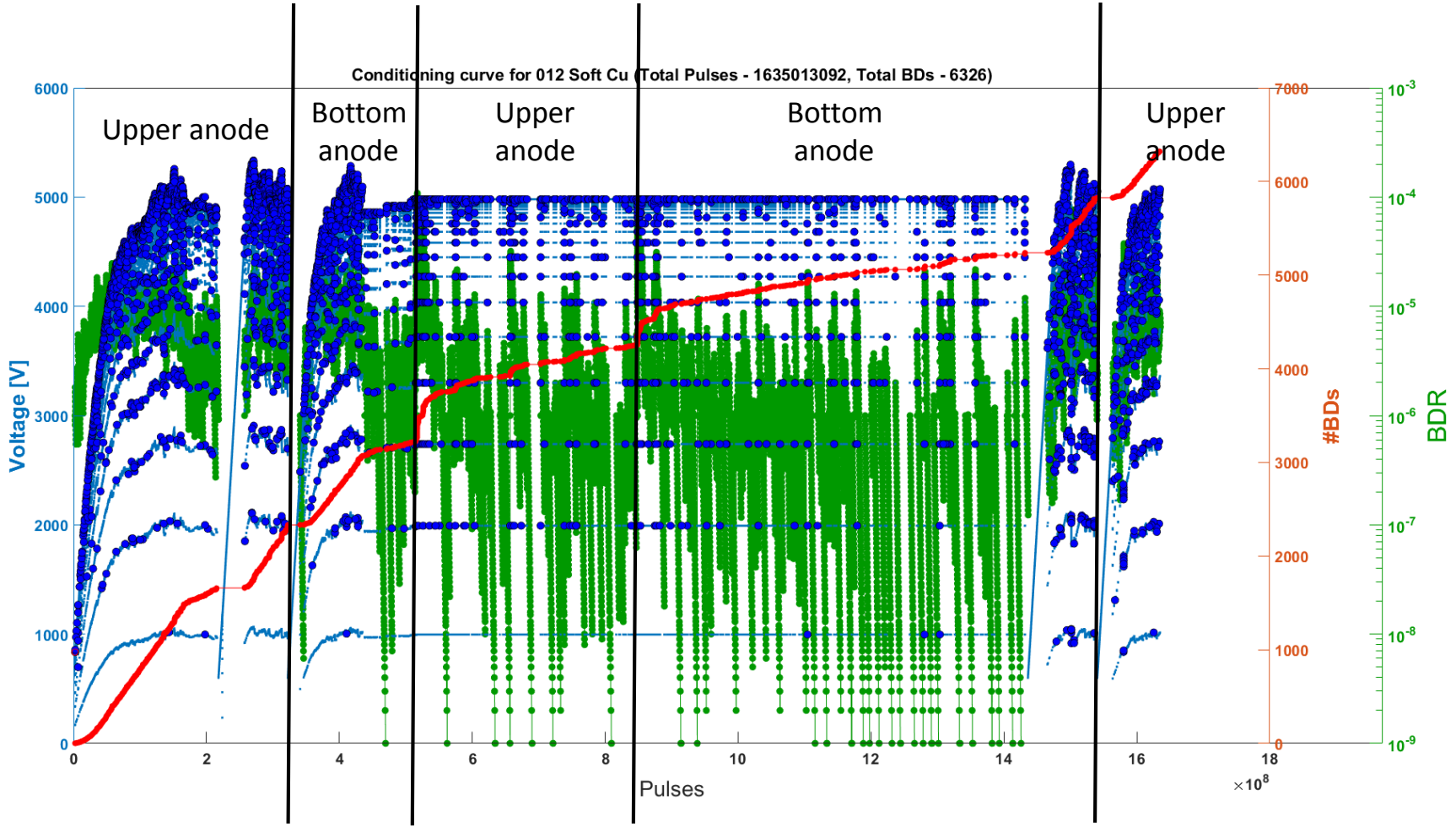
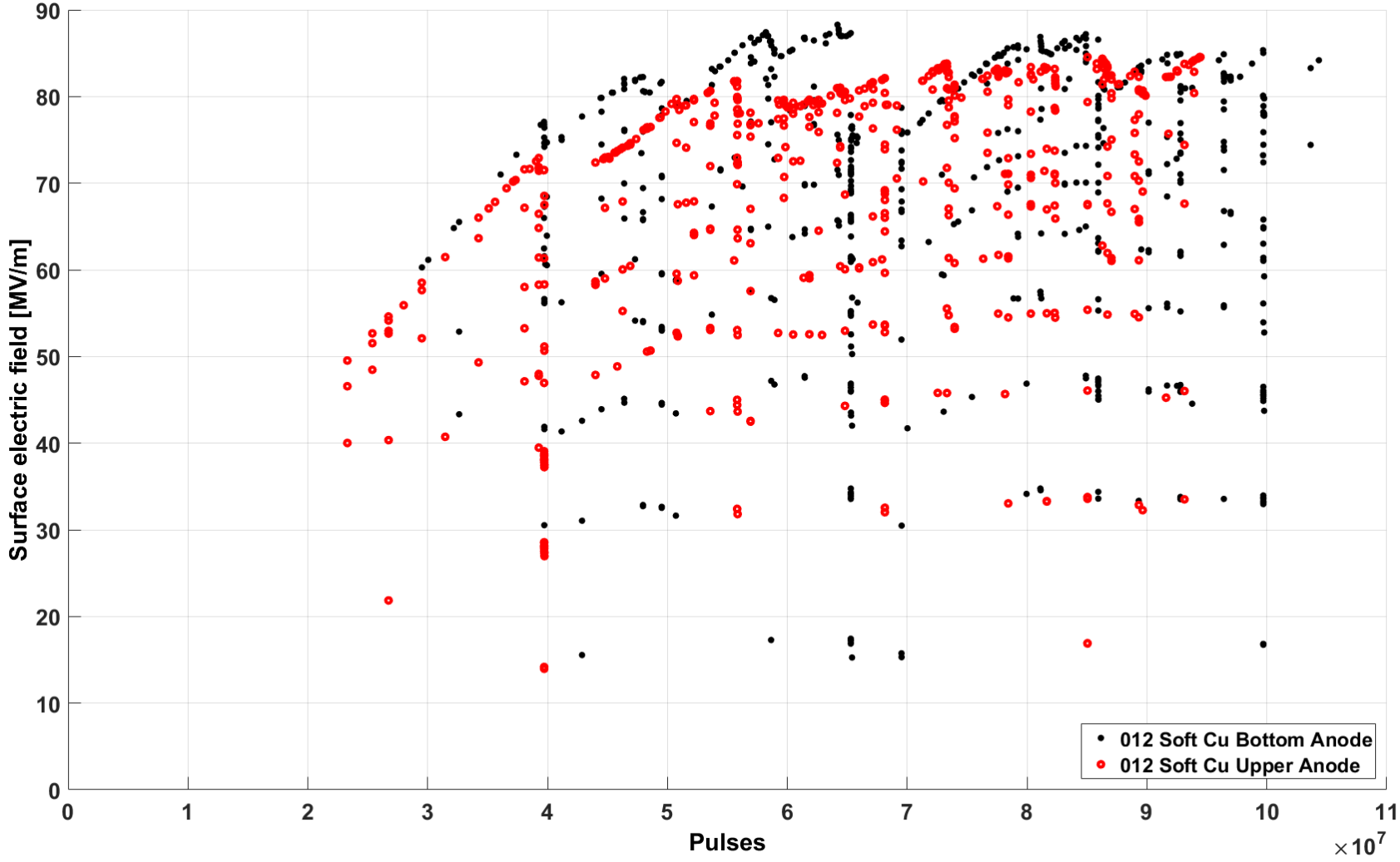


Fig. The part from the history for test with 012 Soft Cu electrodes.

Polarity changing

018 – 020, 021



Polarity changing 014 Soft Cu

001, 009

5486 BDs between (with Normal polarity)

Normal polarity

Reverse polarity

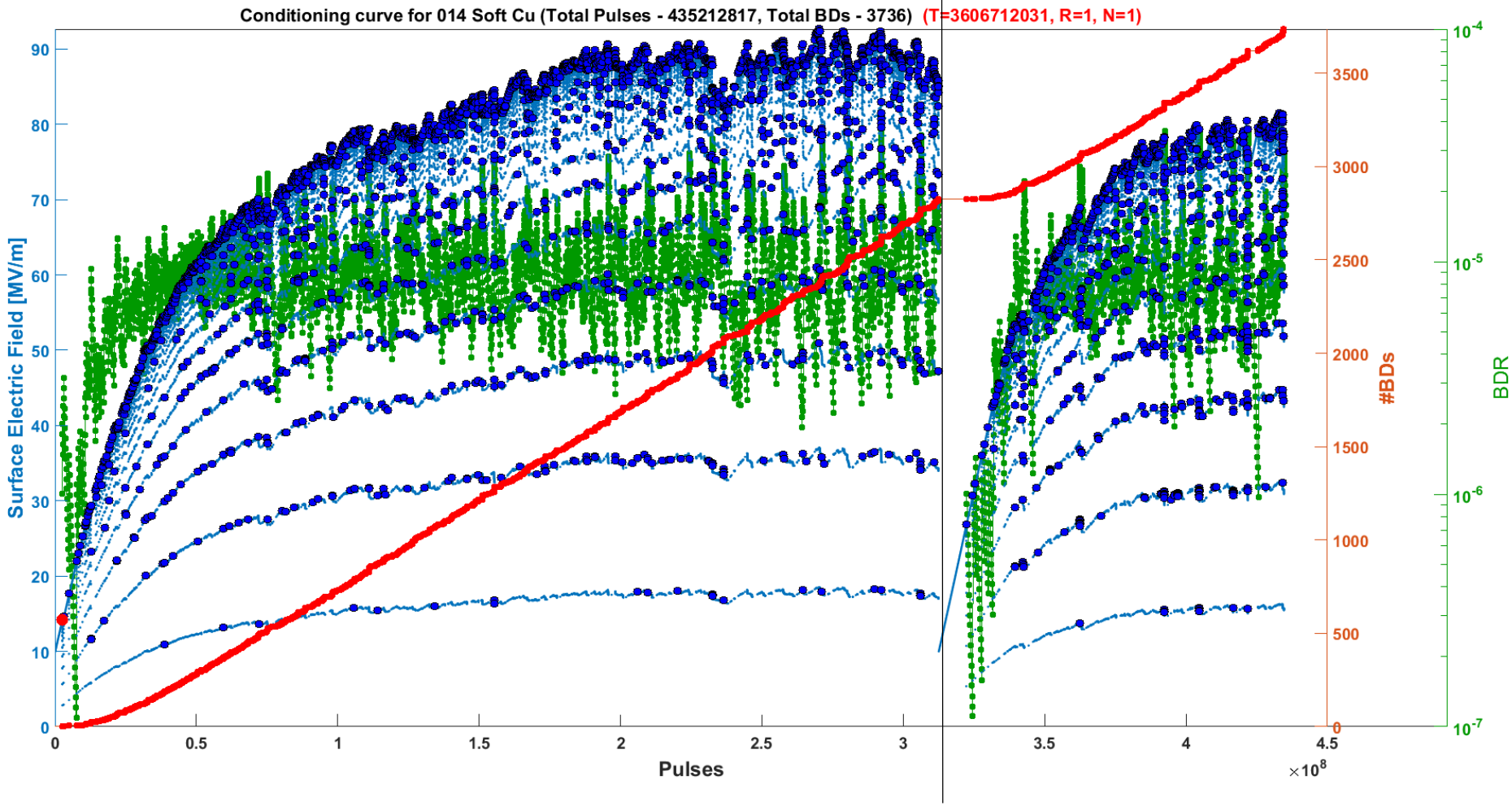
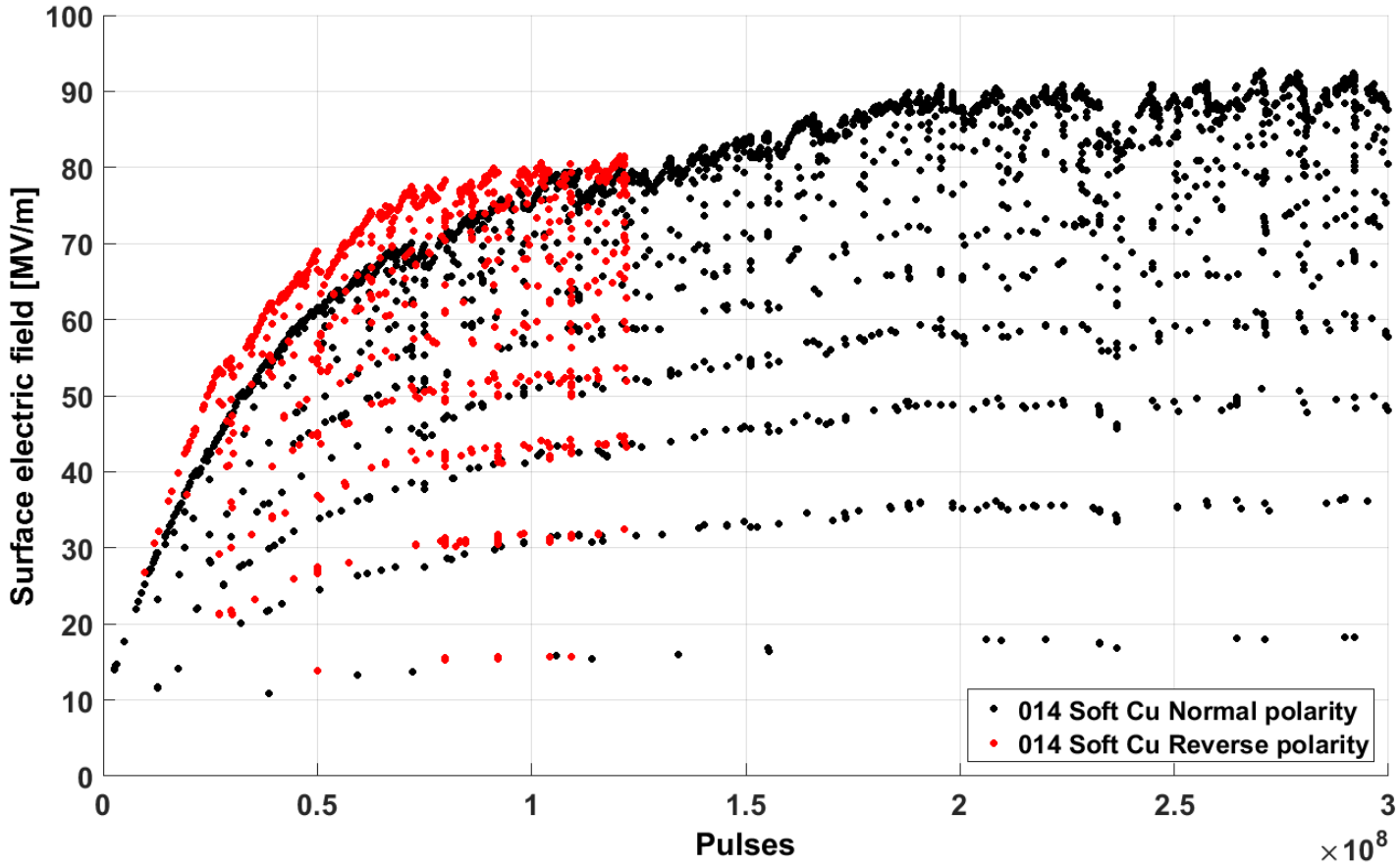
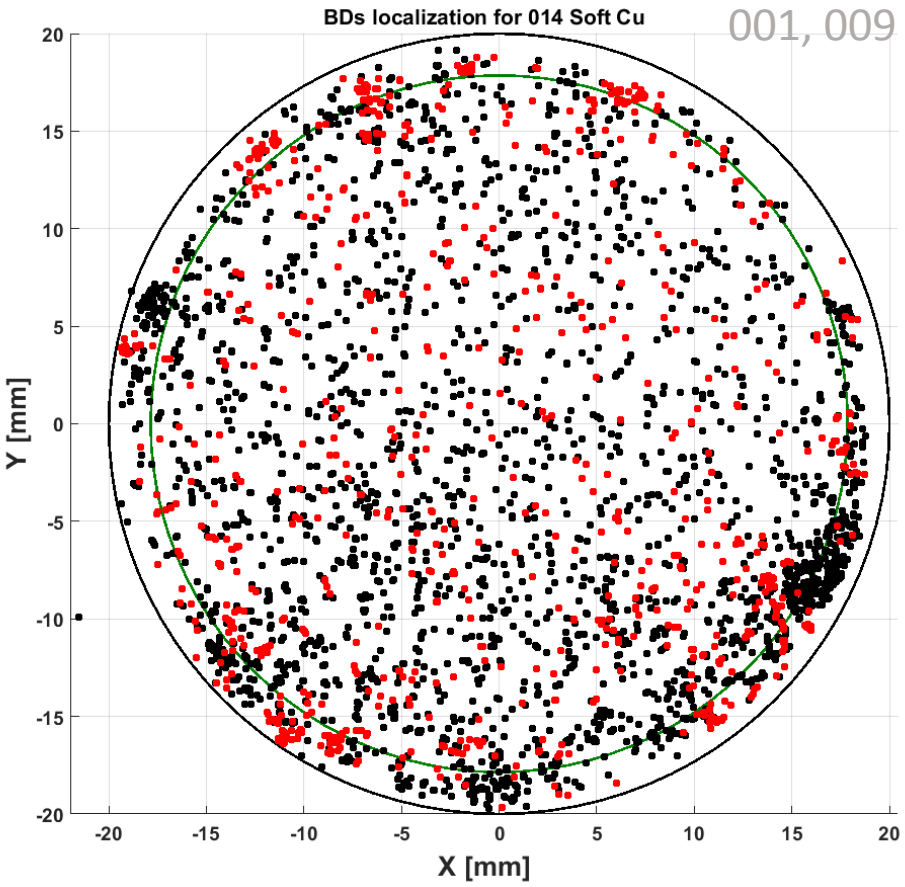


Fig. The part from the history for test with 014 Soft Cu electrodes.

Polarity changing 014 Soft Cu





Comparison of initial conditioning for 014 Soft Cu with **normal polarity** (in black) with reverse polarity (in red).