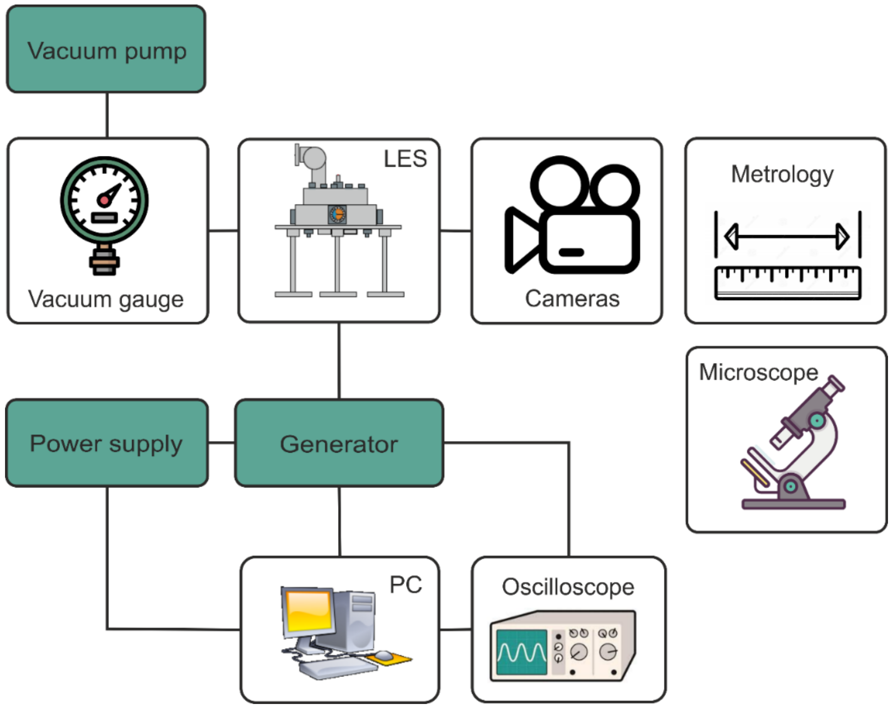
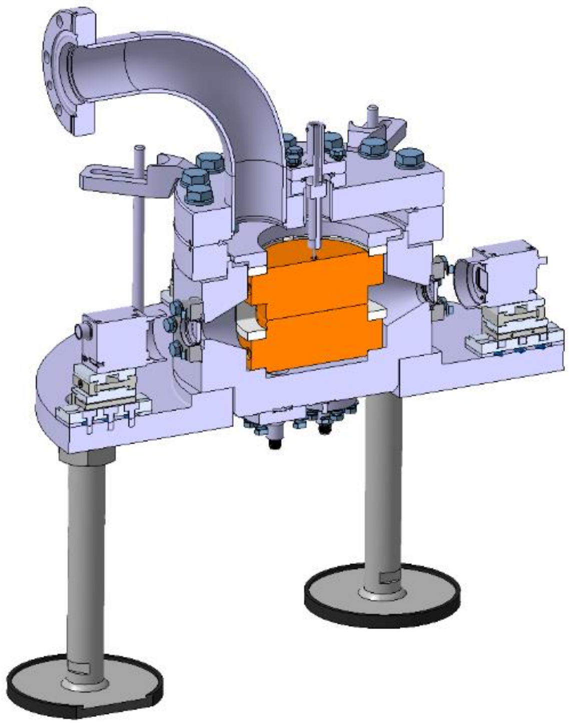
Recent progress at pulsed dc systems

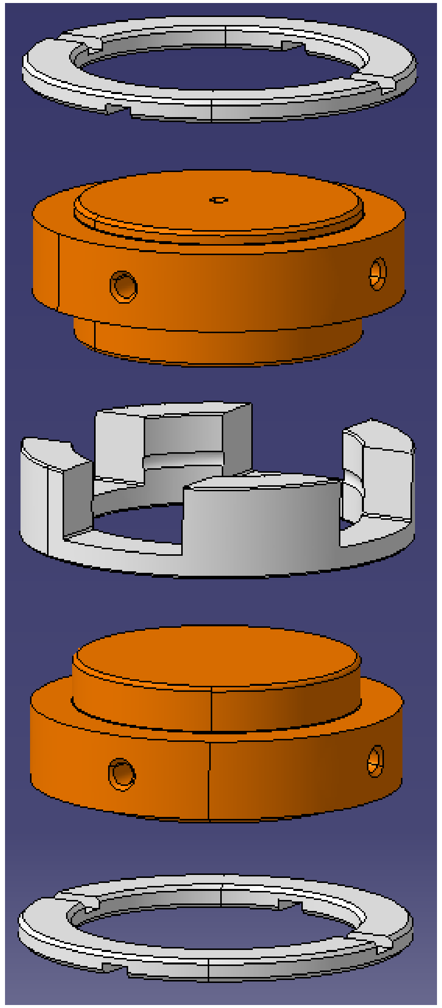
Iaroslava Profatilova

Pulsed DC System at CERN

vacuum system for high-gradient studies







a) b) c)

Fig. 2. Pulsed DC system at CERN: a) schematic of the equipment, b) 3D-model for Large Electrodes System (LES), c) electrodes assembly.

Pressure during the test less than 1E-7 mbar.

Marx generator

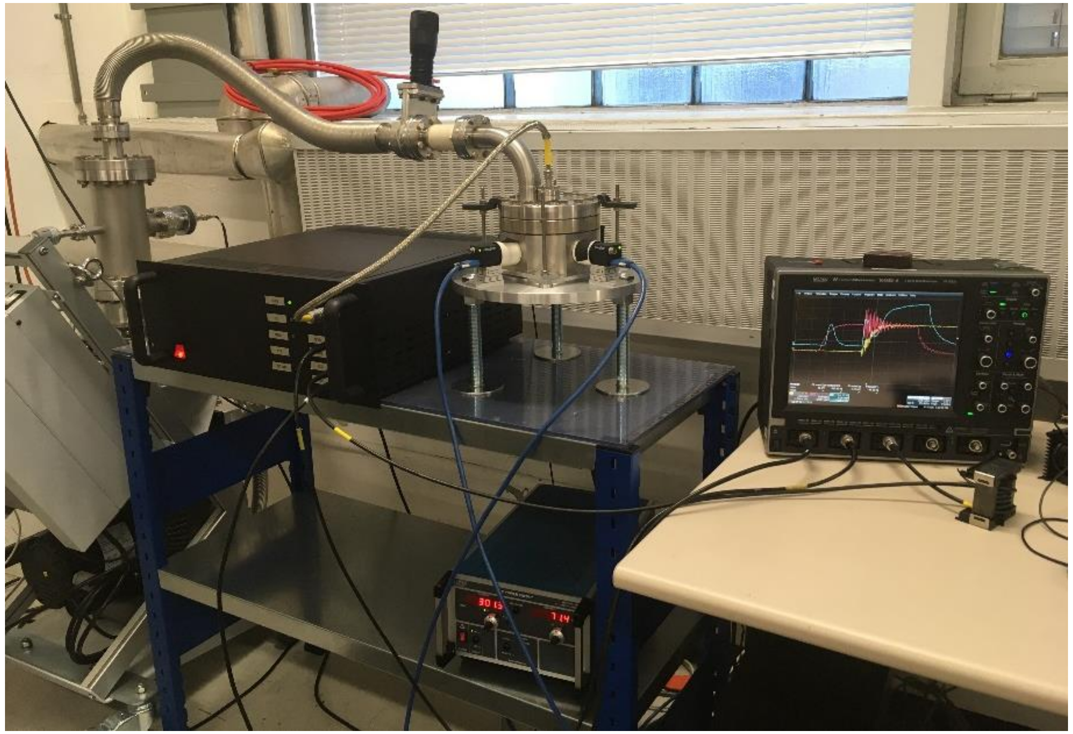


Fig. 3.1. Photo of Marx generator together with LES.

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

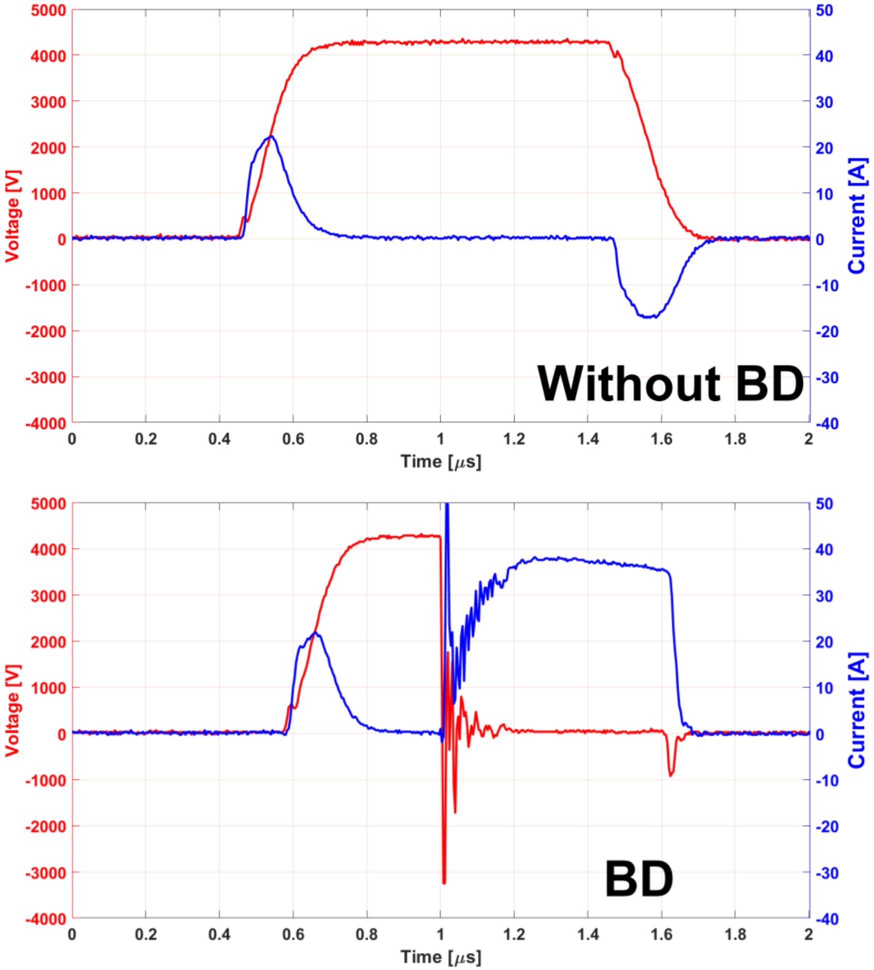
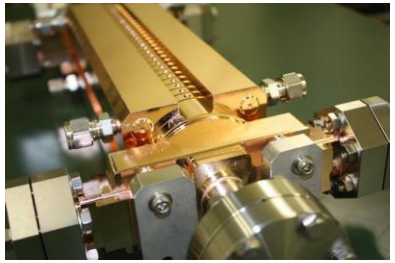
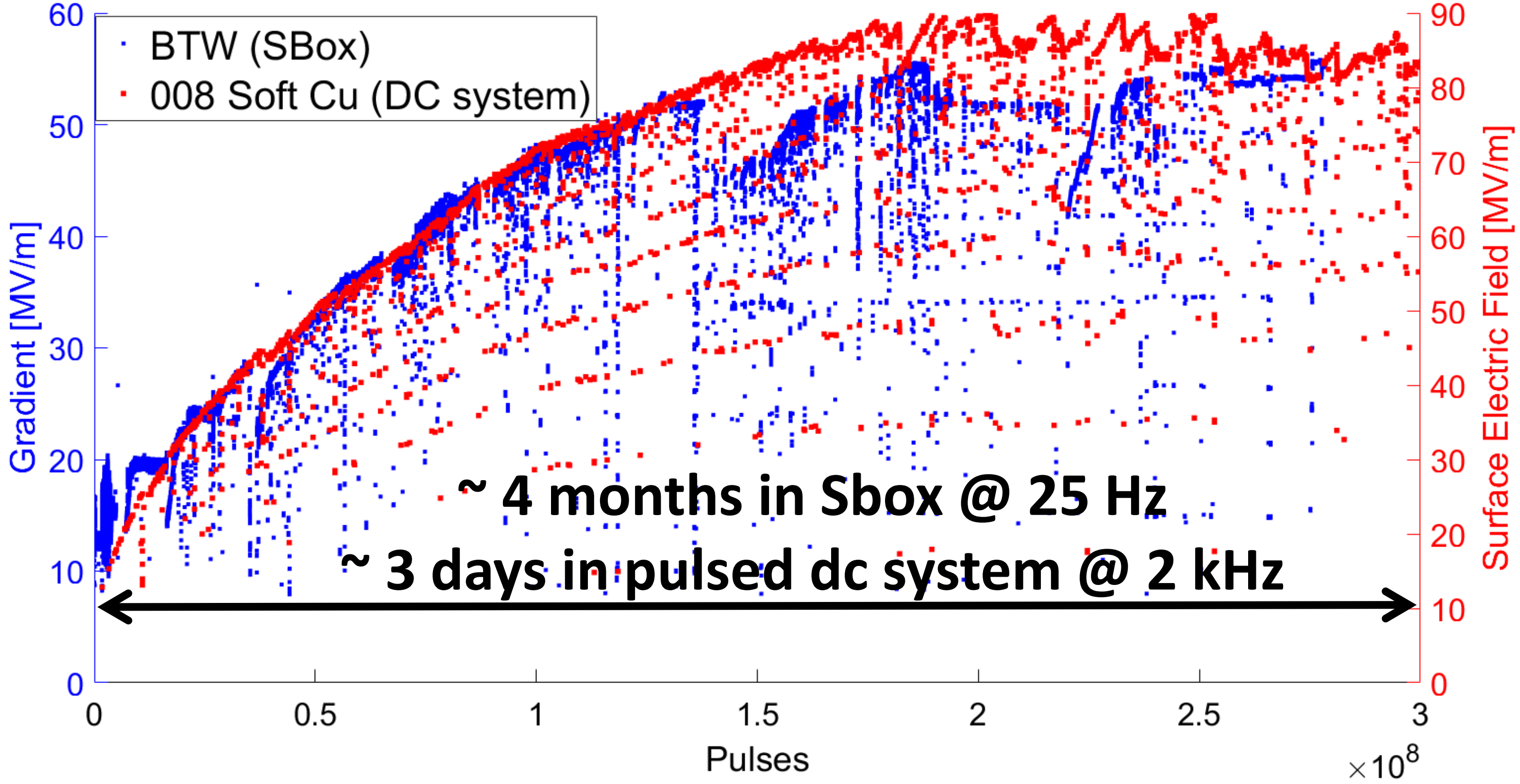


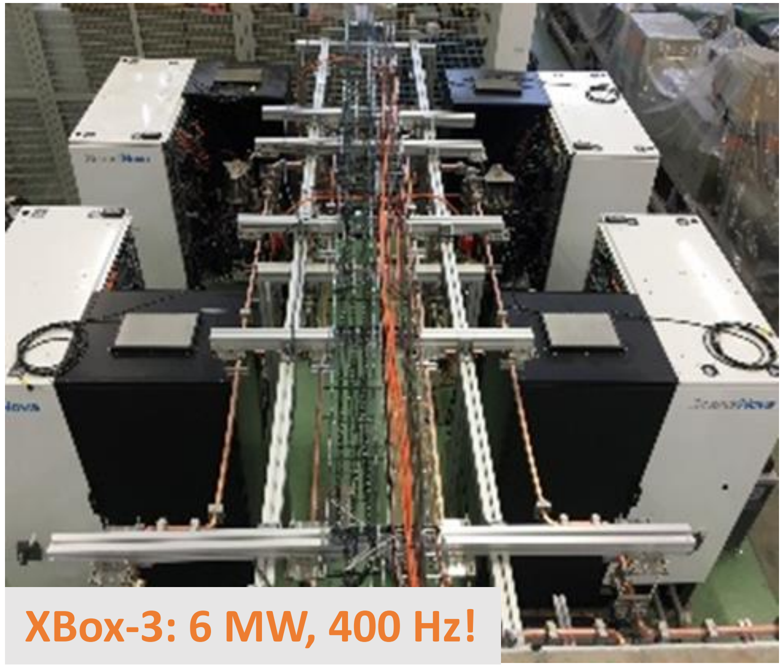
Fig. 3.2. The waveforms taken with Marx generator and LES with 1 µs pulse (0.6 µs delay is used in BD case).

Conditioning in RF and DC



Marx generator, 6kHz





XBox-3: 6 MW, 400 Hz!

...courtesy of Xboxes team

Comparison of heat-treated and as-machined copper

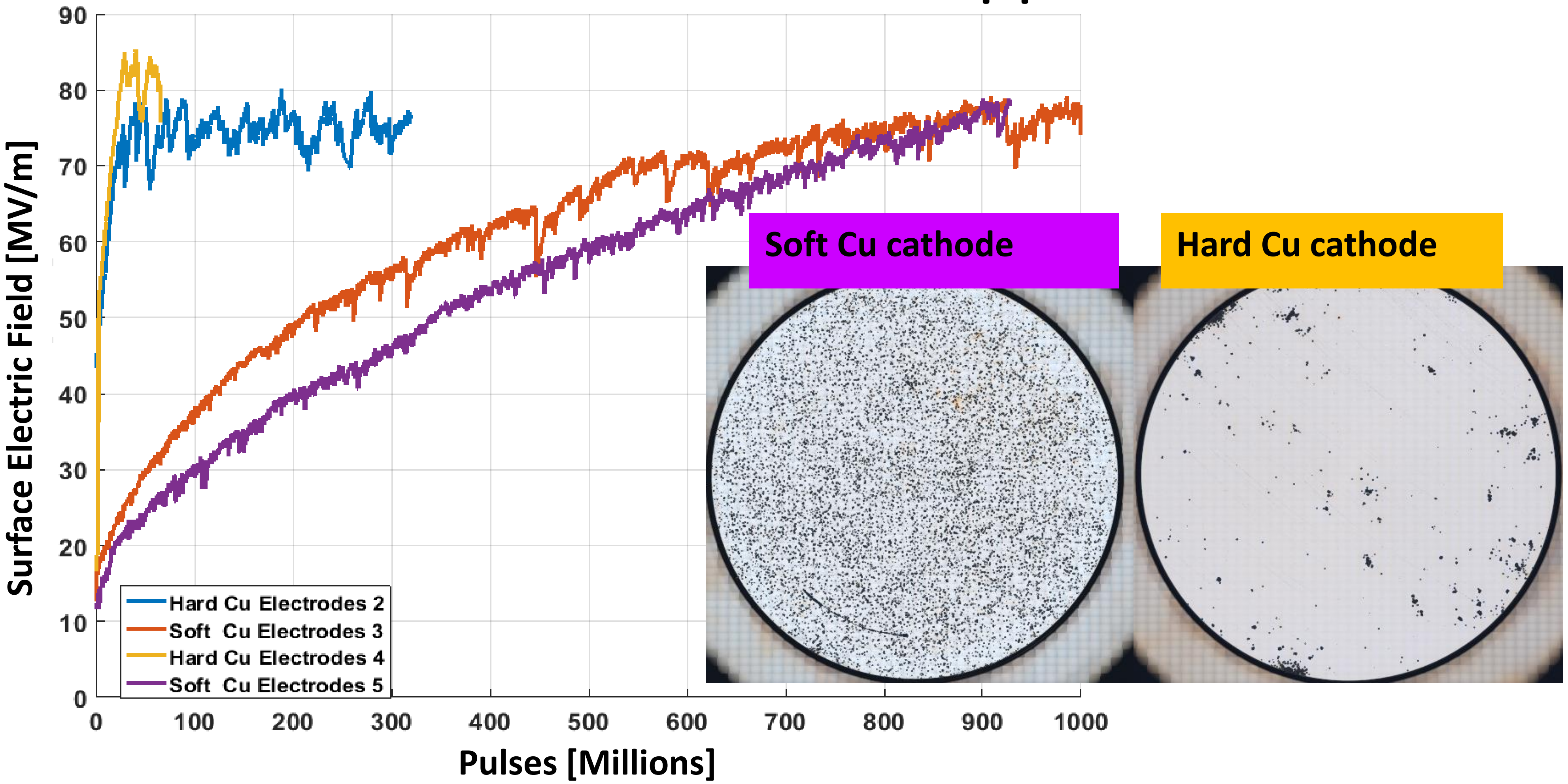


Fig. 5. Conditioning curves from tests at Pulsed DC System taken with HRR circuit, 16.7 µs pulse lengths and 60 µm gap distances.

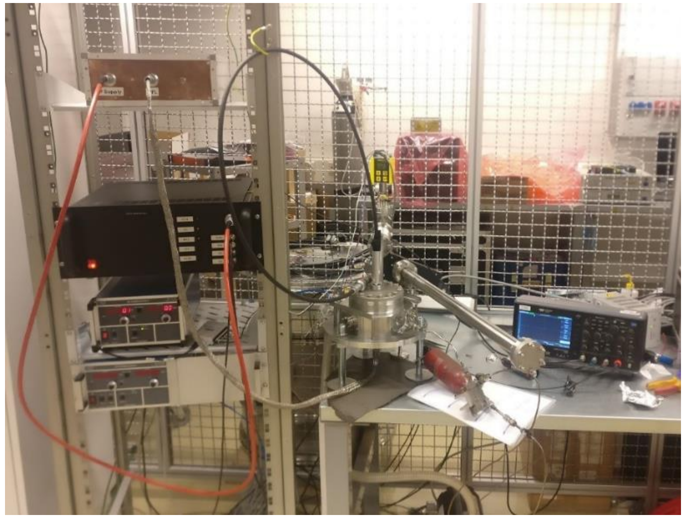
Overview of DC systems

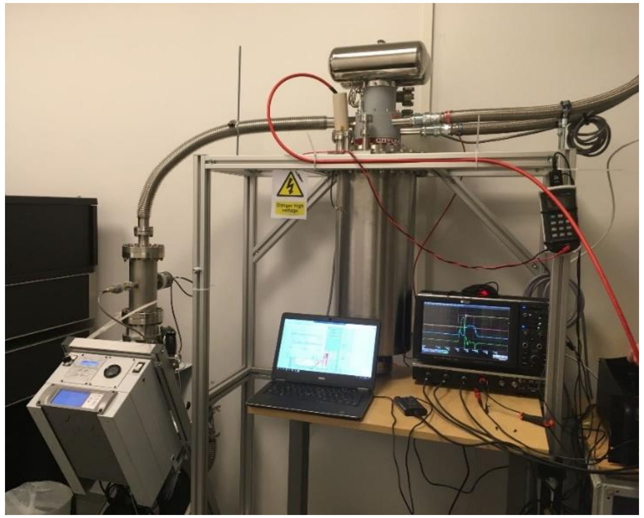
CERN systems (Yinon, Jan, Sagy talk, Ruth poster)

Helsinki (see Anton's talk)

UPPSALA UNIVERSITET

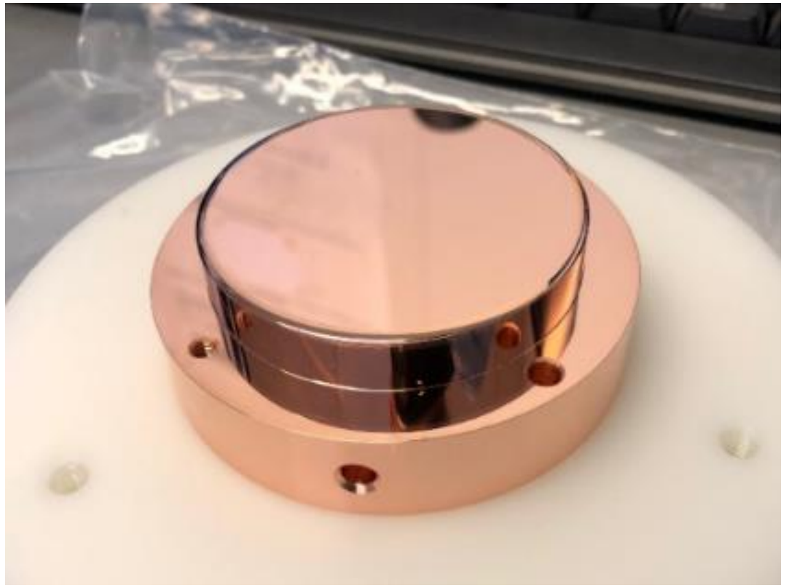
Uppsala (see Marek's talk)



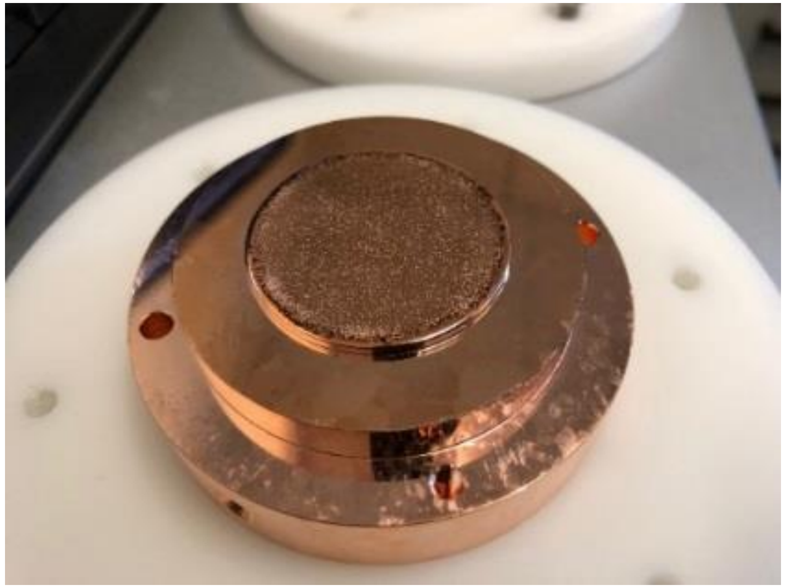


Electrodes geometry

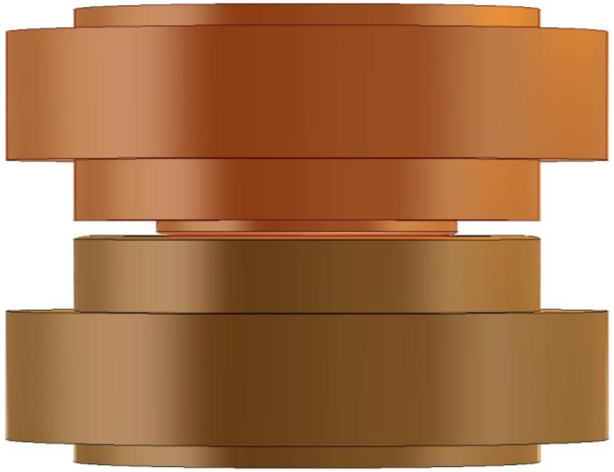
Cathode



Anode



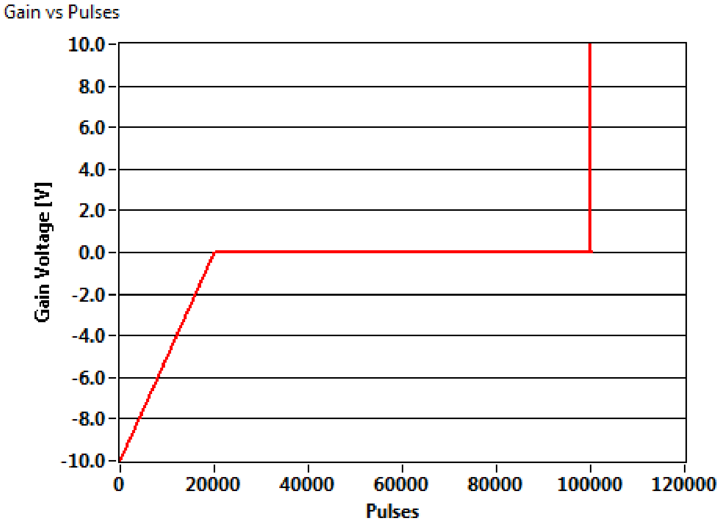
Electrodes assembly



The equal electrodes geometry for all 4 pulsed dc systems is started to be implemented.

Different tests in pulsed DC system

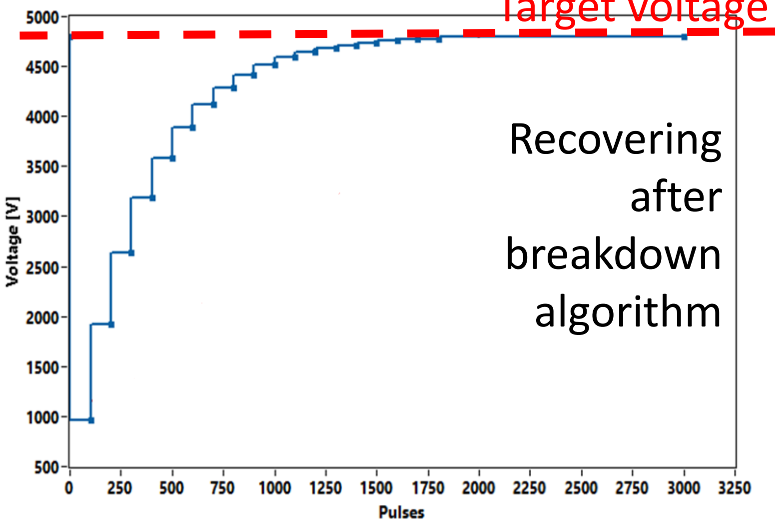
Feedback mode (initial conditioning, polarity changing, gap effect on E field)



Parameter	Value
Max number of pulses per cycle	100 000
Safe pulses	20 000
Gain voltage at 0	-0.17 MV/m
Gain after timeout	0.17 MV/m
Initial voltage	(~10 MV/m)
Max BDR	1E-5

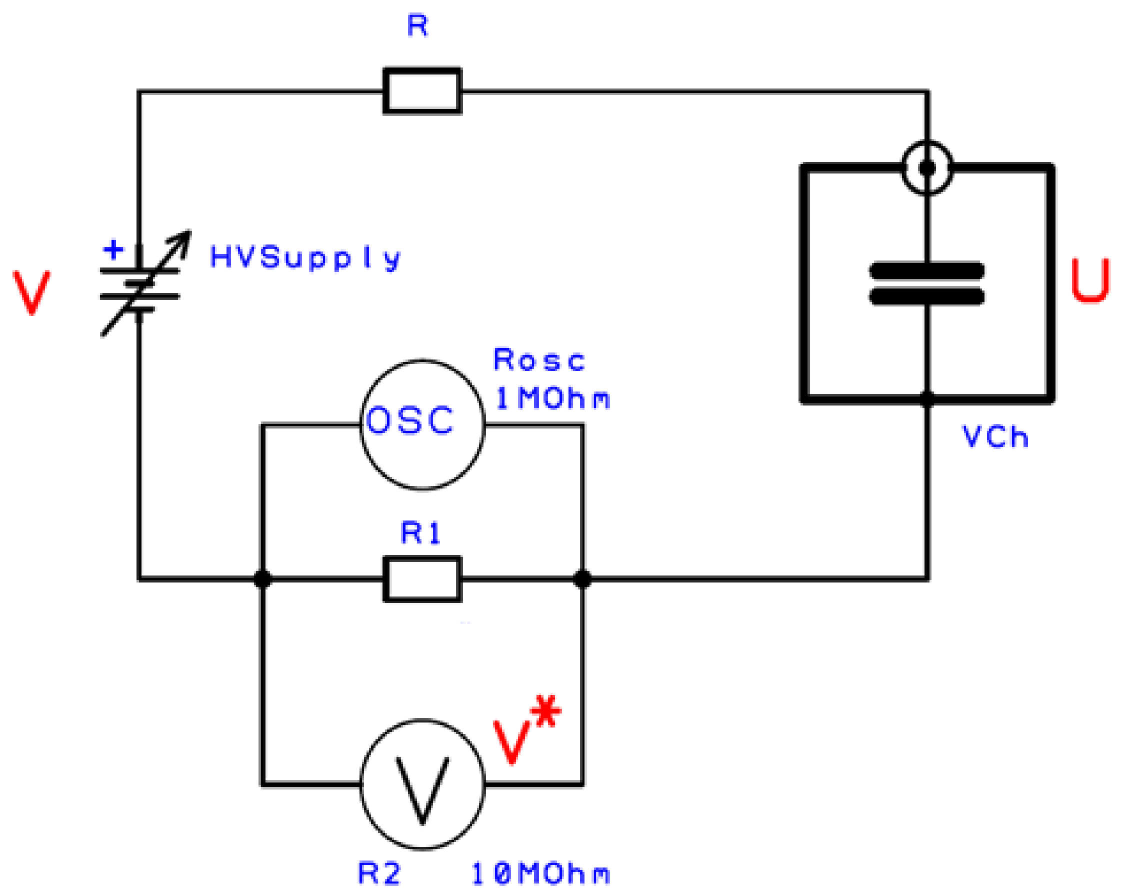
Flat mode (BDR vs Rep Rate)

Field emission measurements



Recovering after breakdown algorithm

Field emission measurement



Voltage applied to the LES (anode−cathode voltage):

$$U = V - I \times R \qquad (1),$$

V – voltage at power supply, R = 6.39 MOhm.

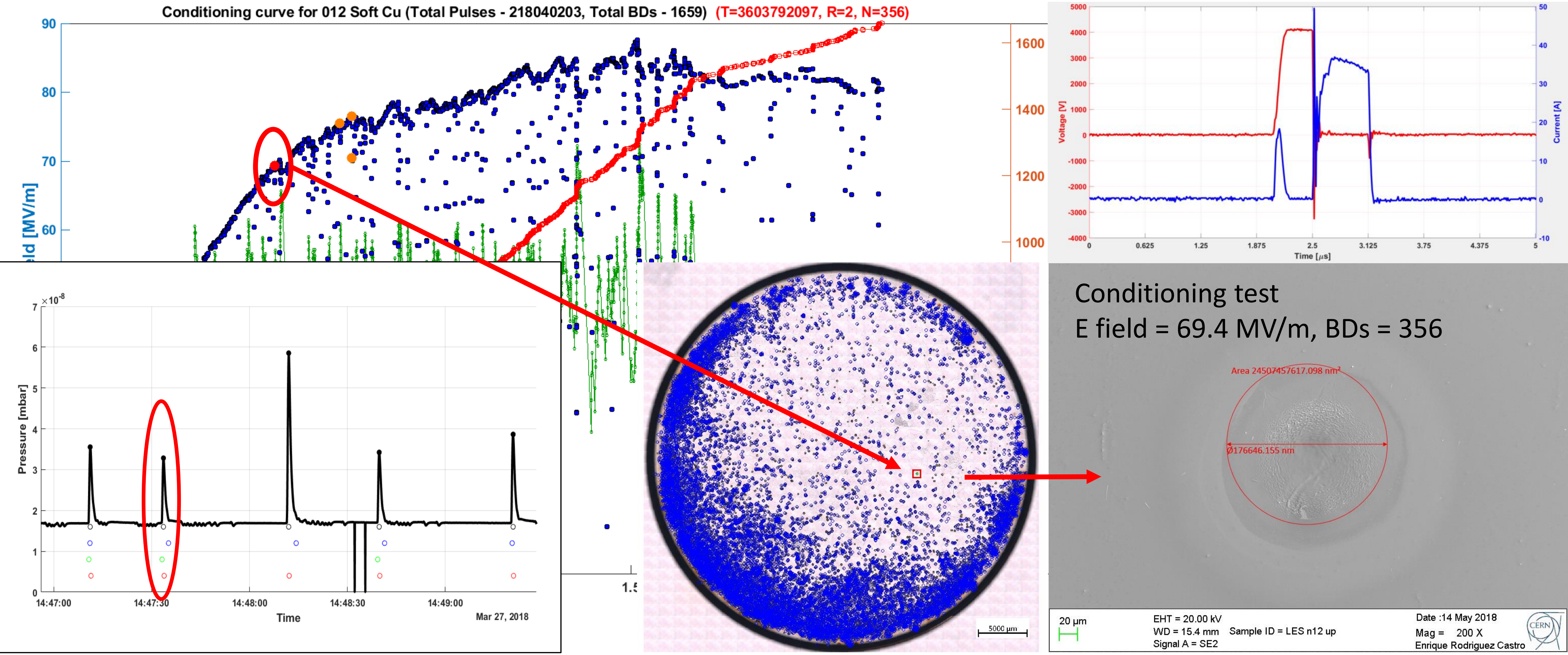
$I = \frac{V^*}{R^*}, V^*$- voltage at the multimeter.

$\frac{1}{R^*} = \frac{1}{R_{osc}} + \frac{1}{R_1} + \frac{1}{R_2}$, $R_1 = 100\ kOhm$ =>

$R^* \approx 90.1\ kOhm$

BD identification

Unique breakdown position determination.



BDs localisation

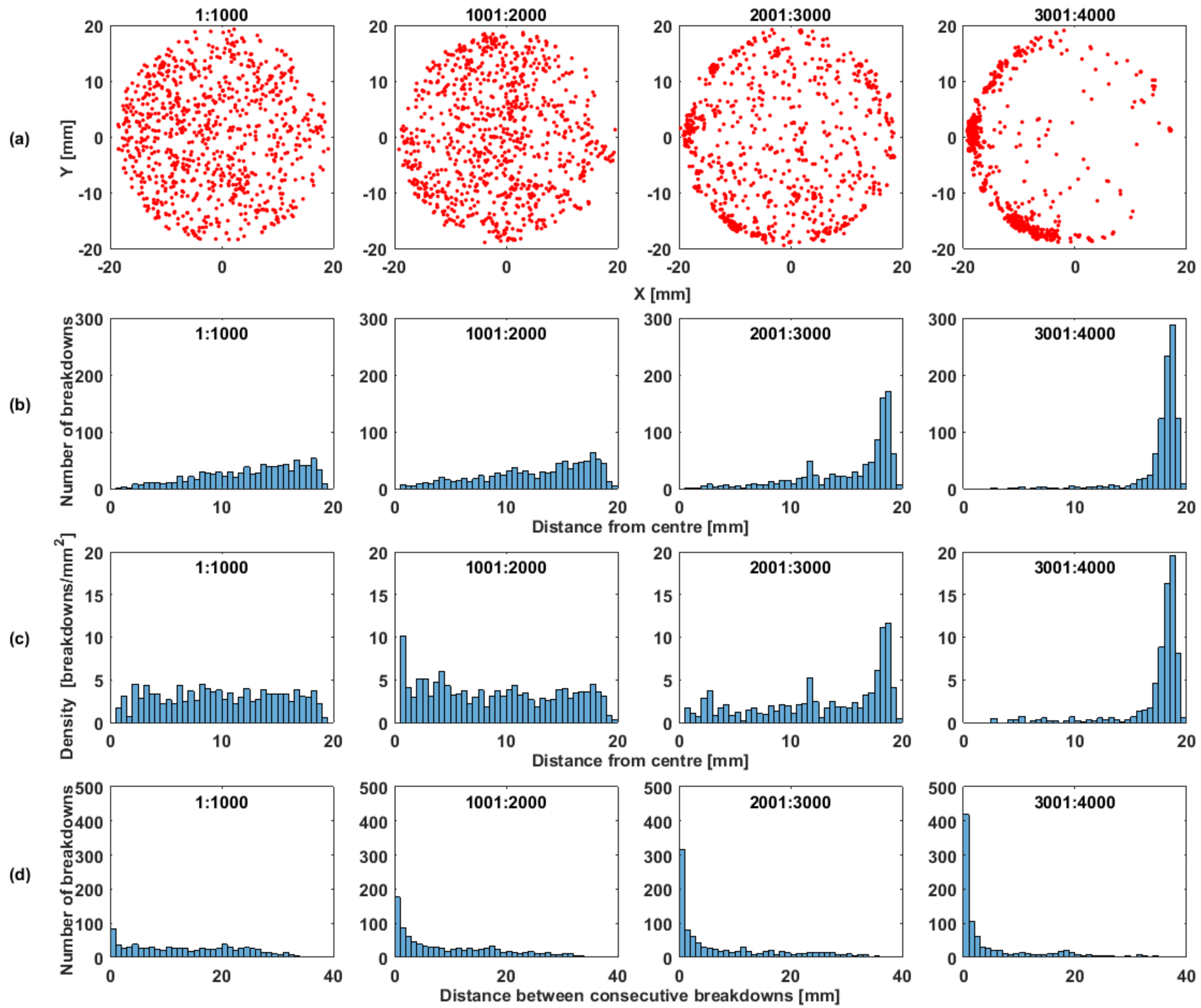
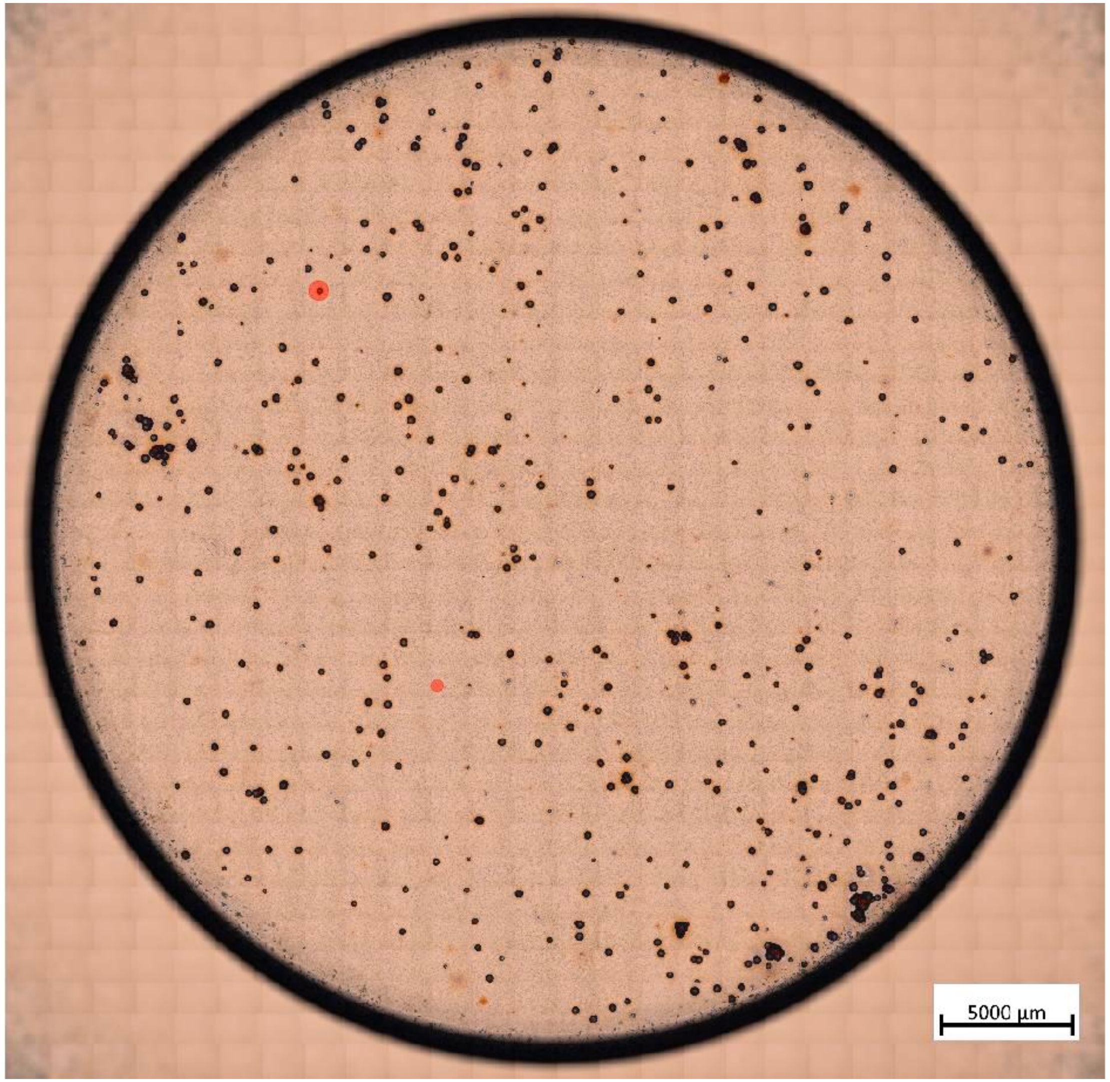
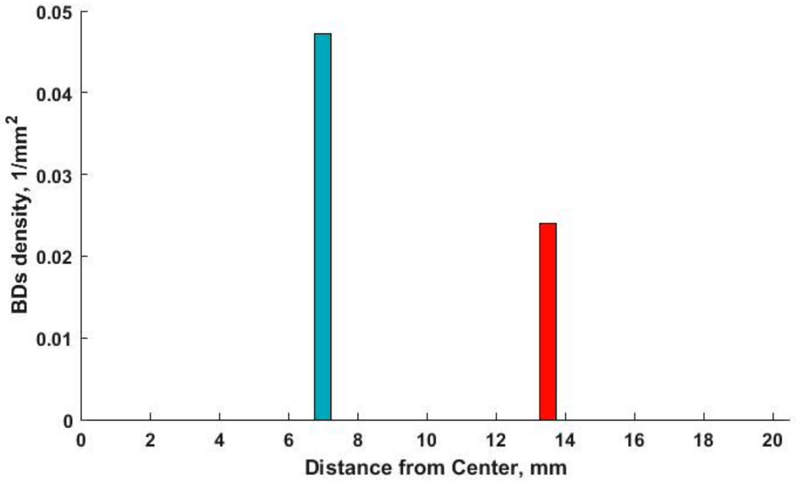
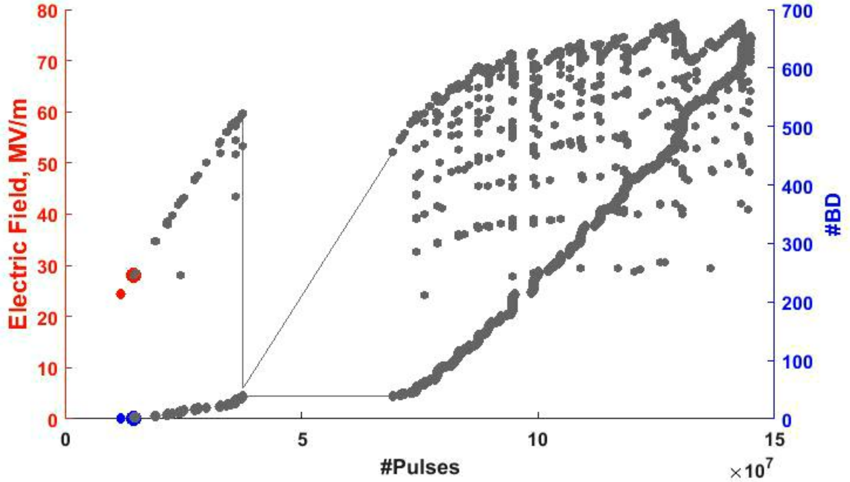


Fig. 11. Evolution of breakdowns on the surface for the Soft Cu electrodes for first 4000 events.

Evolution of breakdowns







Gap effect to the E field

Gap effect to the E field

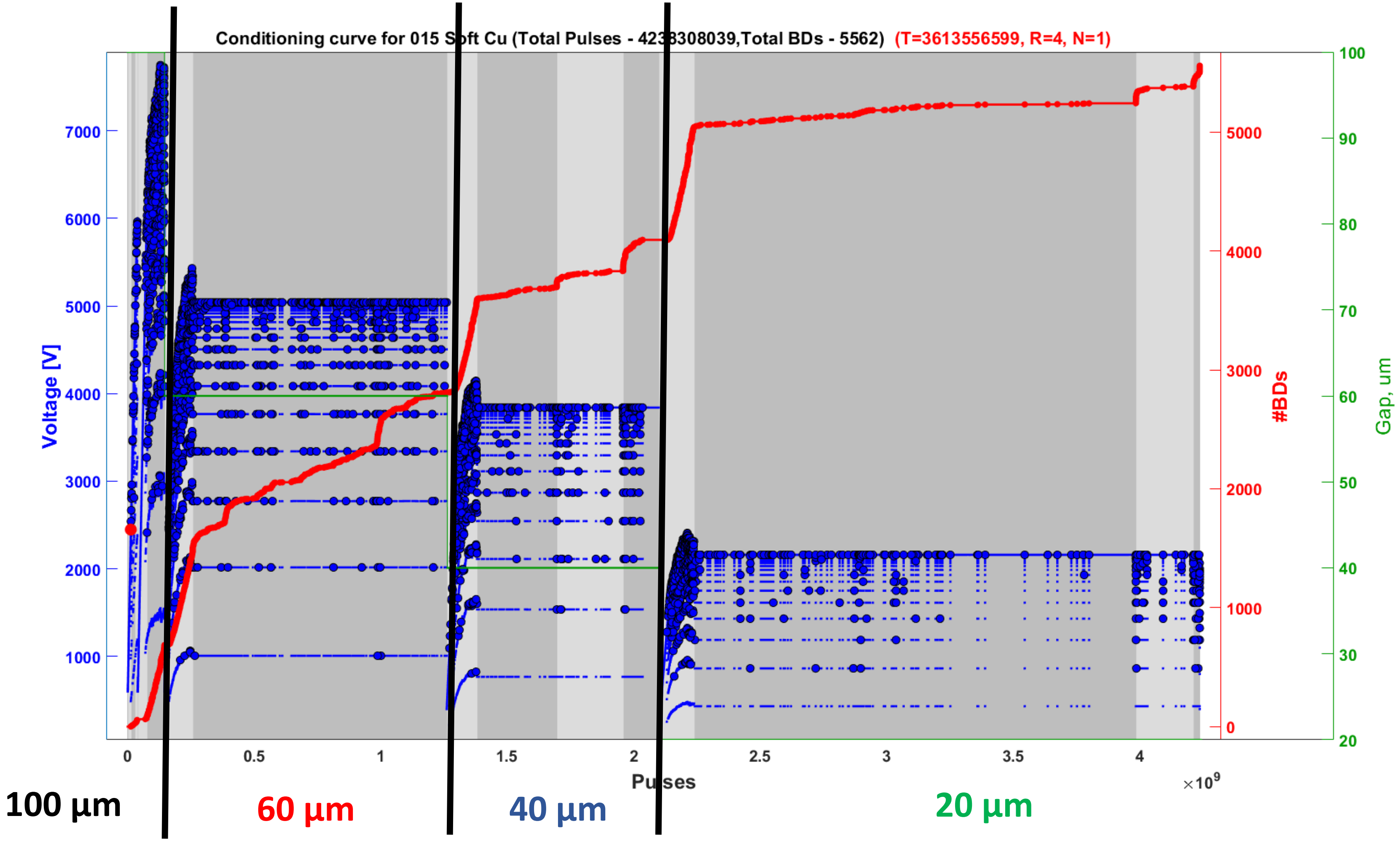
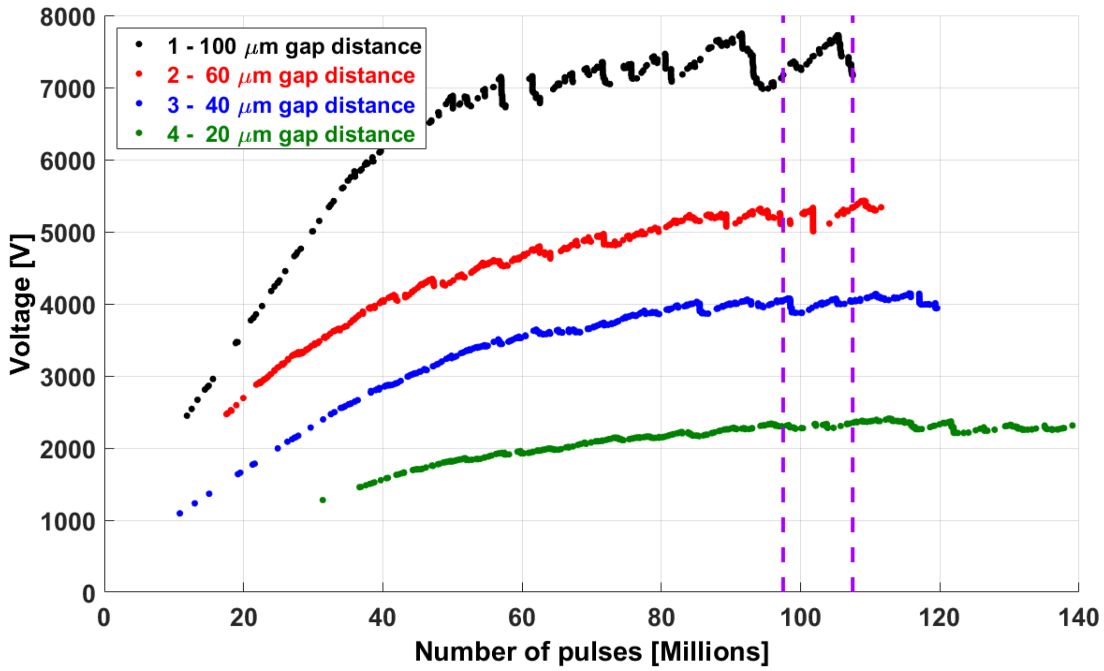
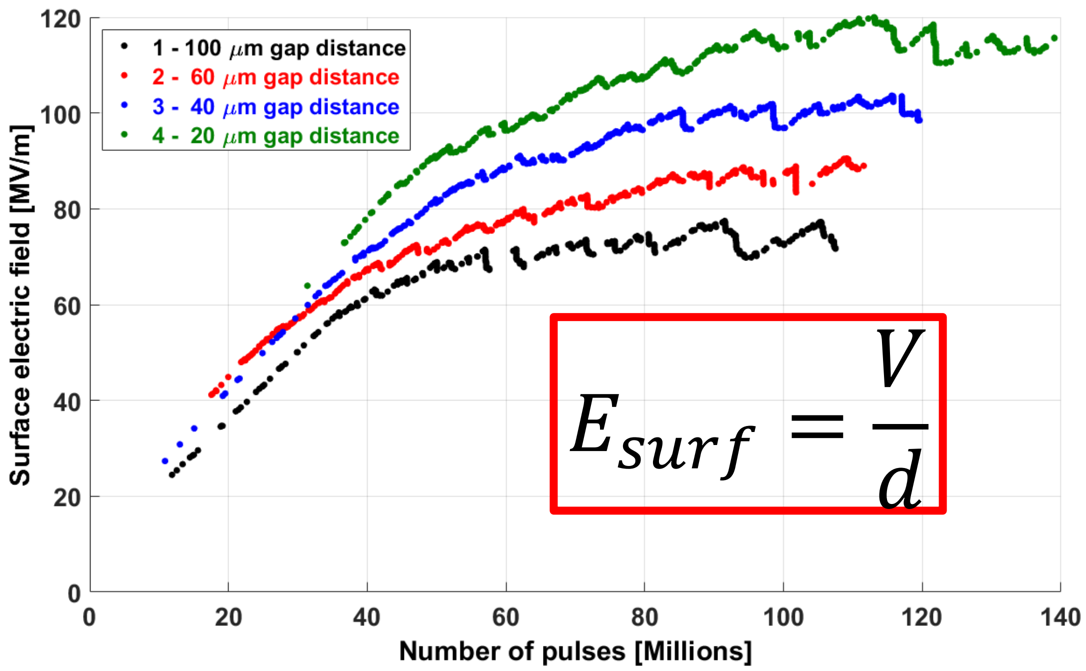


Fig. 14.
Consequence of test with different gaps in pulsed dc system.

Gap dependency

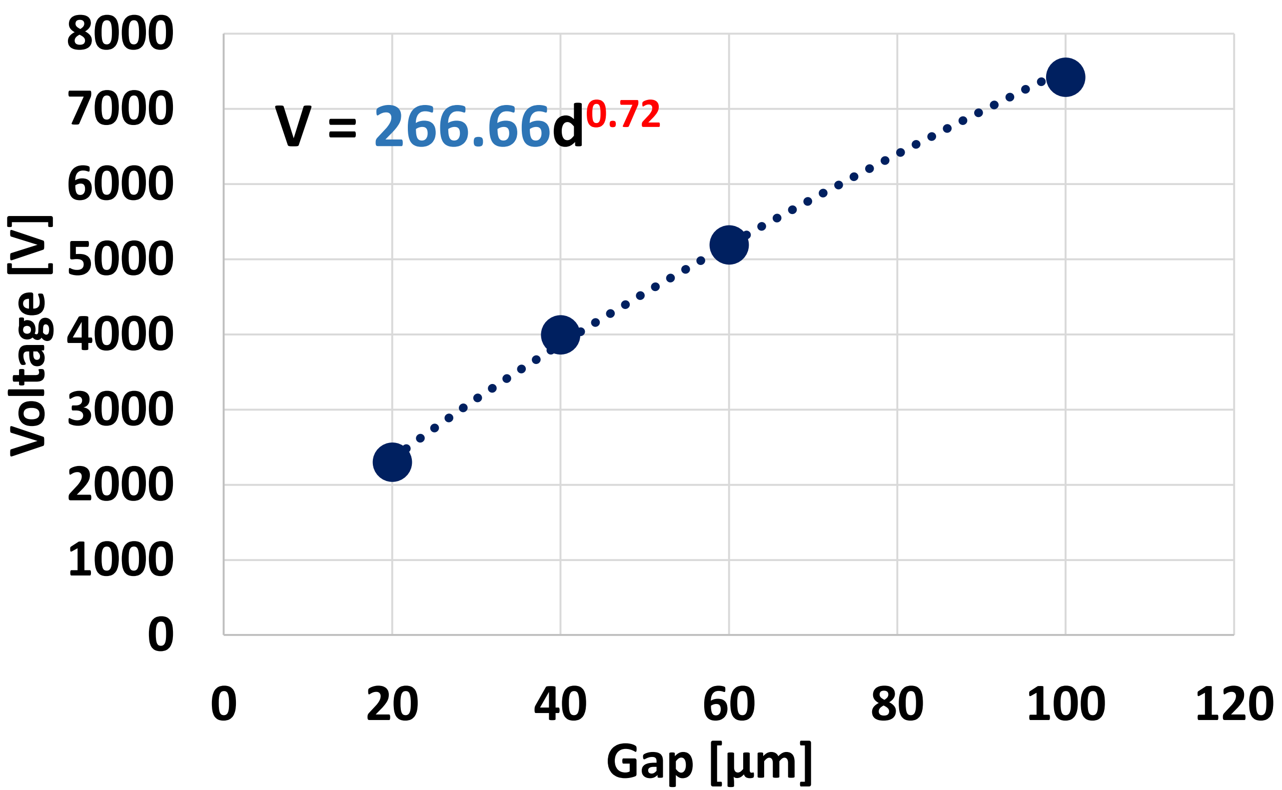




$$E_{surf} = \frac{V}{d}$$

Fig. 15. Comparison of voltages and surface electric field value for the test with the different gaps. The purple lines show the window taken for analysis.

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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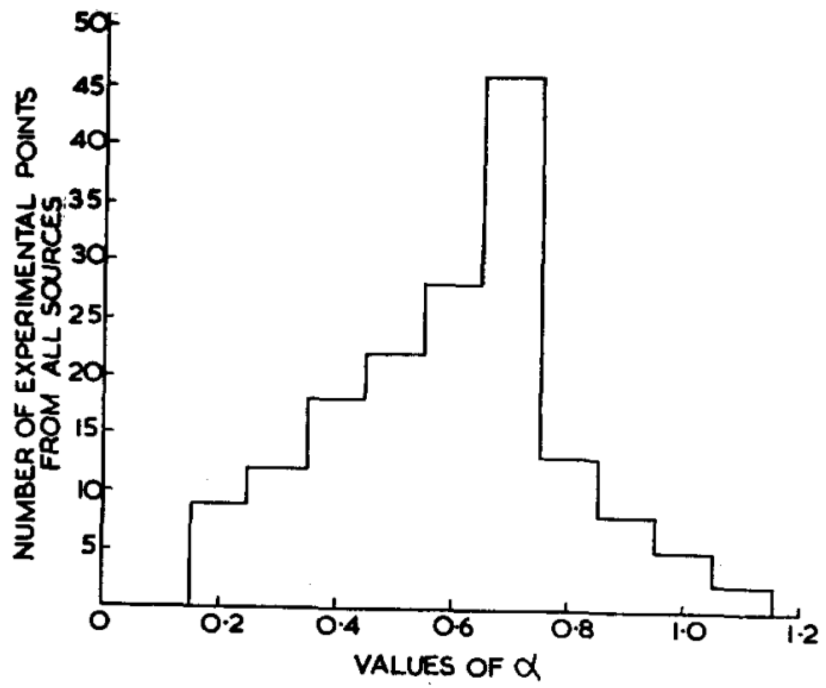
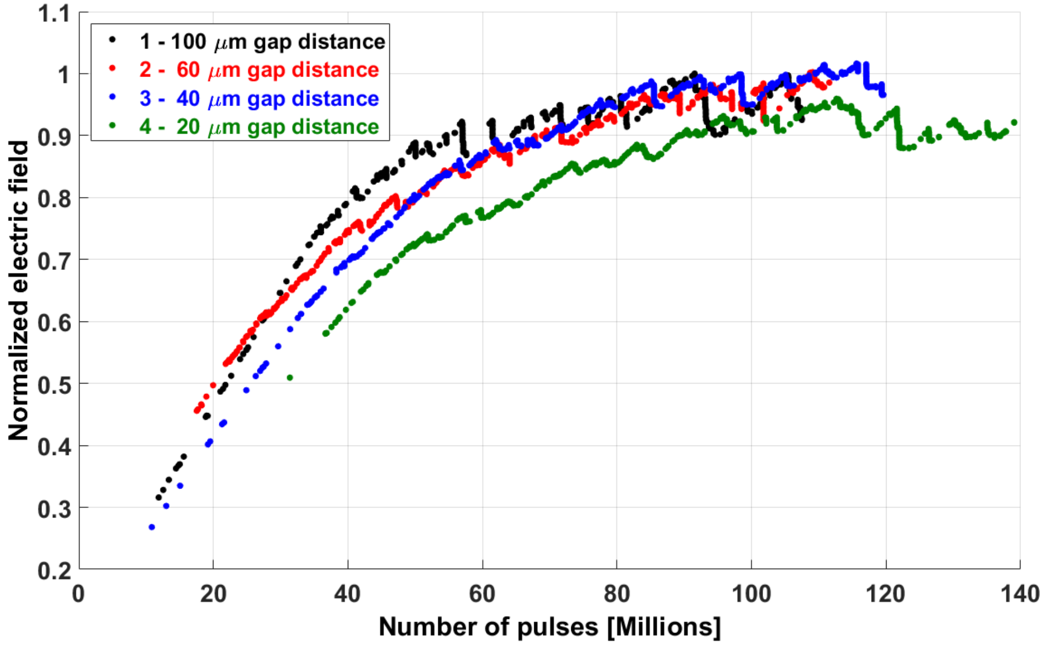


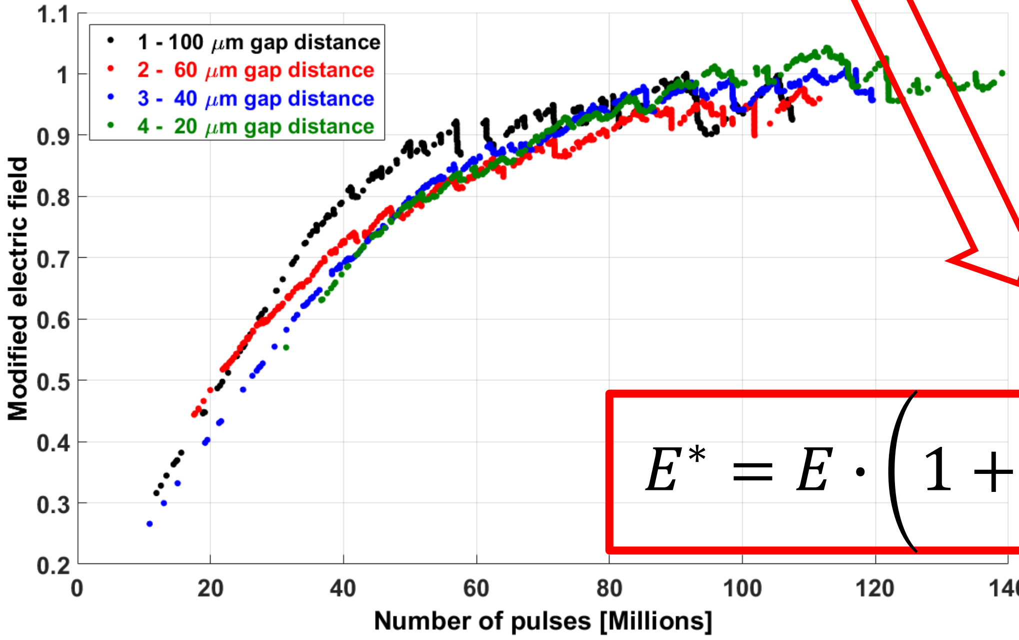
FIG. 1. Distribution of values of α obtained from publications relating to plane or near-plane geometry.

Gap dependency

$$E_{norm} = \left(\frac{V}{V_{max}}\right) \times \left(\frac{d_{max}}{d}\right)^{0.7}$$

$$E_{mod} = \frac{V}{V_{max}} \cdot \frac{d_{max}}{d} \cdot \frac{1}{1.7} \cdot \left(1 + 0.7 \cdot \frac{d}{d_{max}}\right)$$





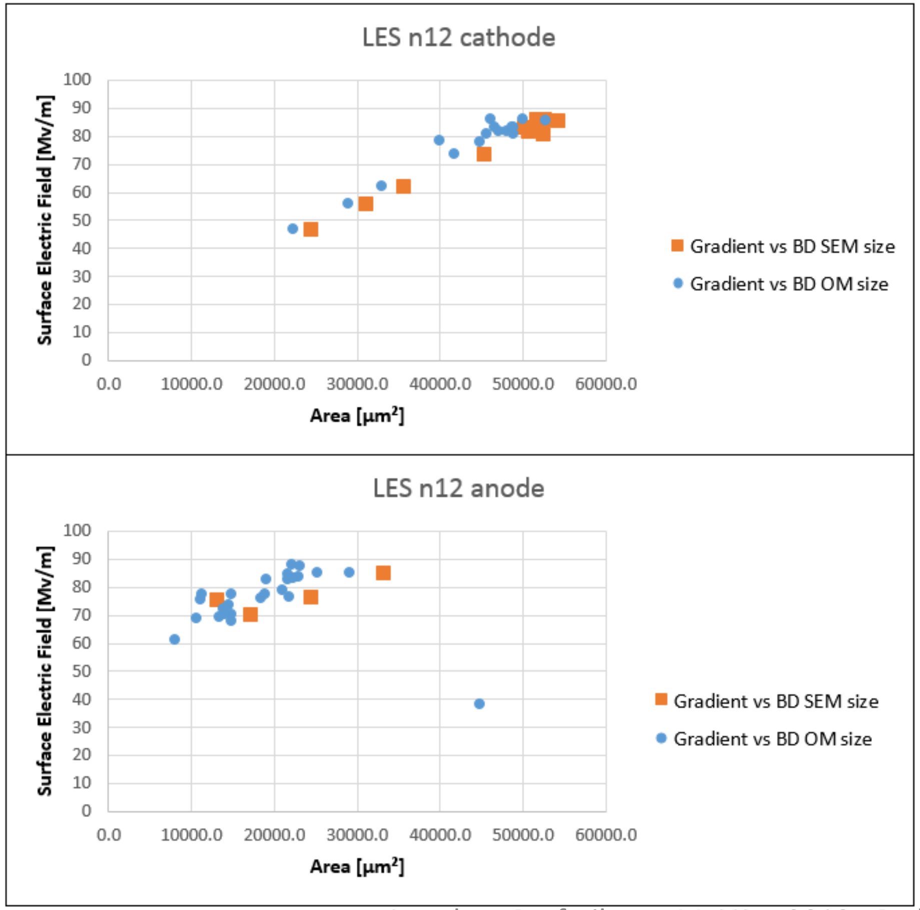
$$E^* = E \cdot \left(1 + \frac{V}{V_{ref}}\right)$$

$$V_{max} = 7747\ V$$
$$d_{max} = 100\ \mu m$$

Crater area as a function of pulsing conditioning

Large Electrode System (LES)

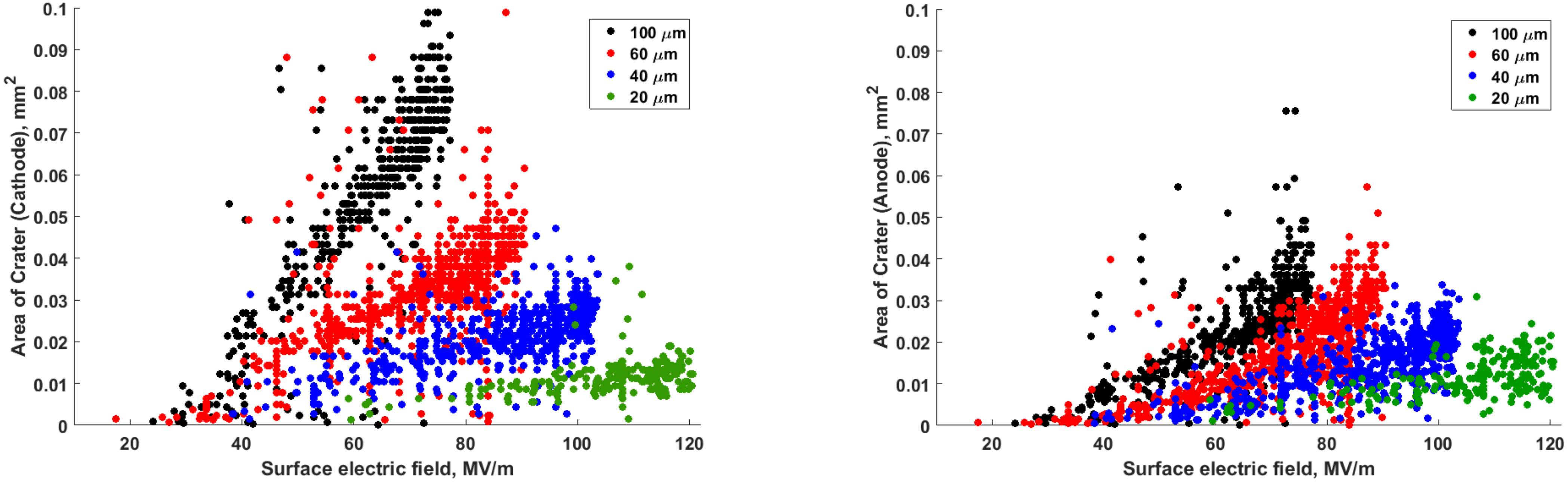
- Preliminary results show that crater size increase with surface electric field



Enrique Rodríguez Castro, MeVArc 2018

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

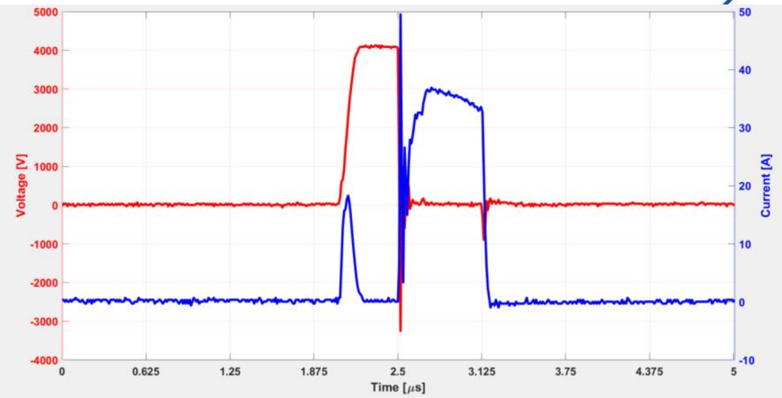
Cathode/Anode craters



Gap, µm	Average area of the craters, mm²			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

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



E – surface electric field, A – electrode area,
d – gap distance, ε_0 – permitivity for vacuum.

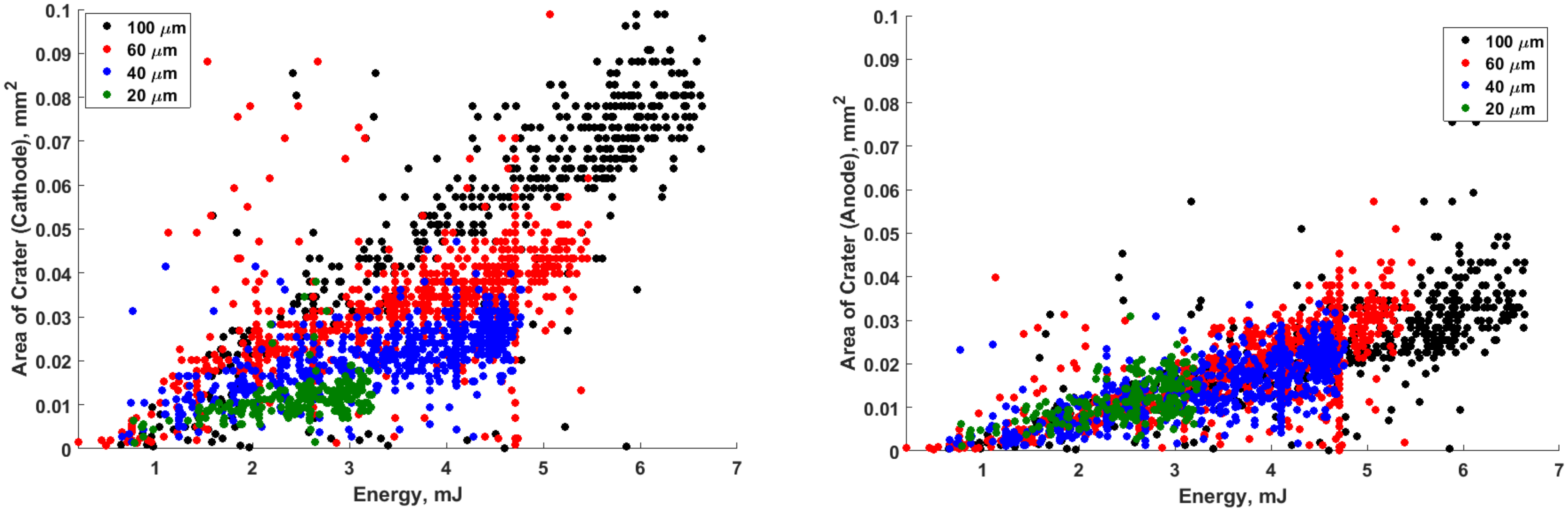
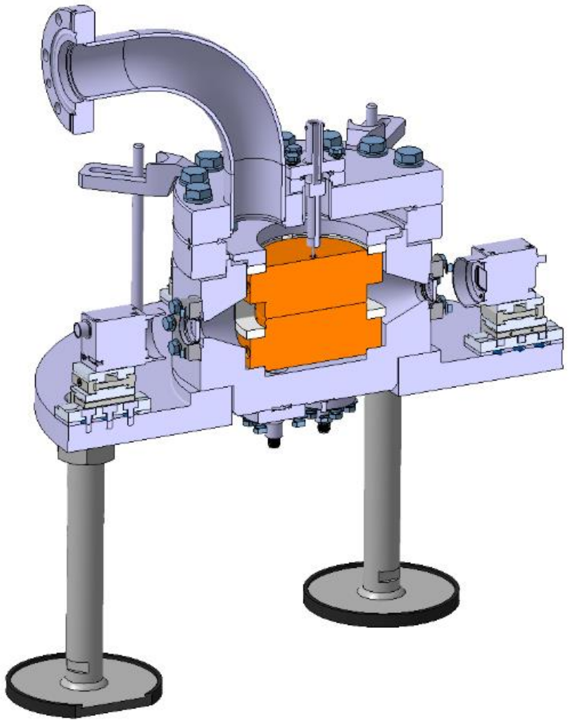


Fig. 20. The relation between crater area and energy (counted by using only first part of the formula).

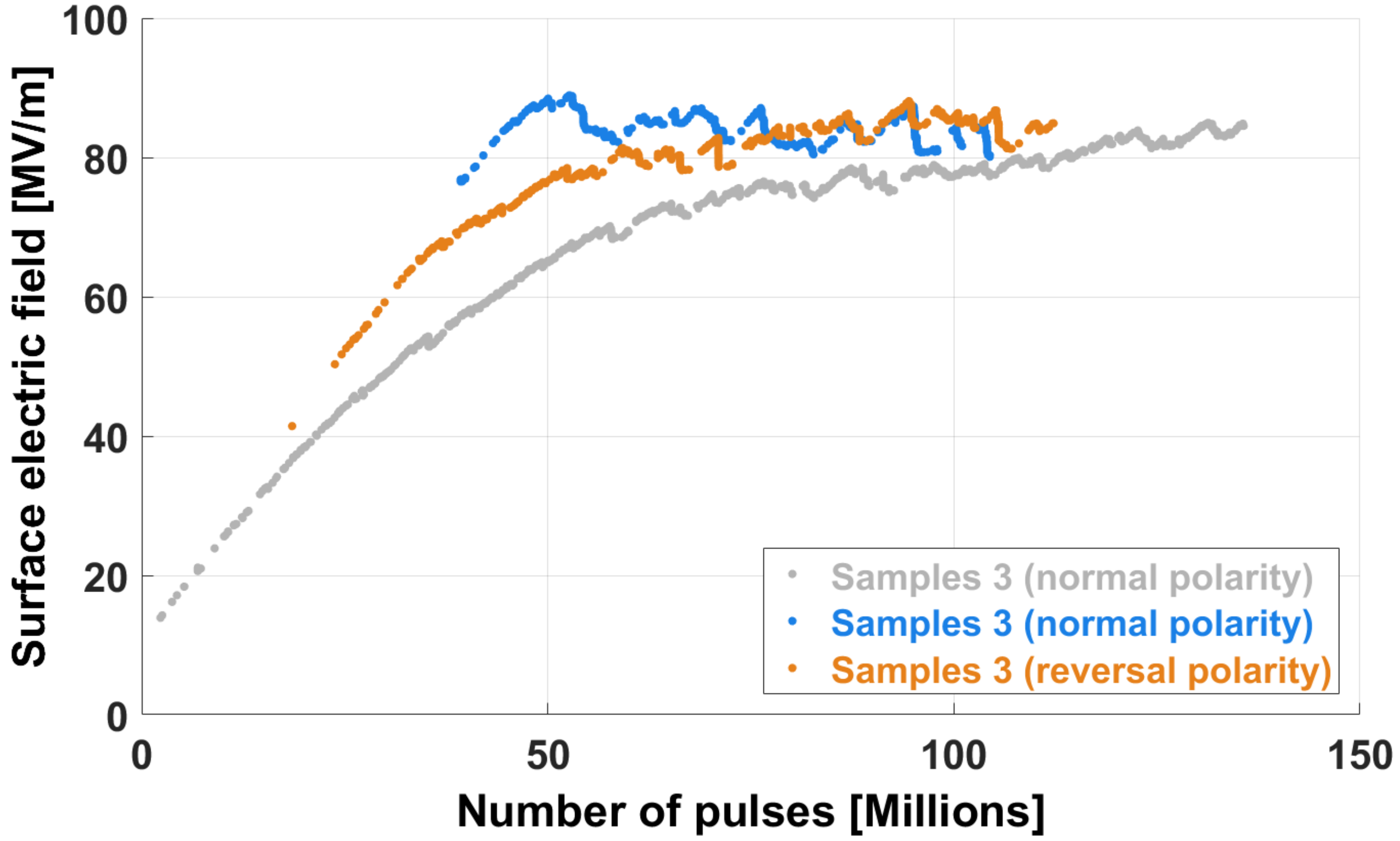
Polarity

Do anode and cathode conditioning in the same time?

For changing the polarity, the connection of the HV is changing, i.e. high-voltage generator with **a positive polarity** is connected to the bottom electrode and the top electrode is grounded, hereinafter names as **a reversal polarity**. The test is done ***in situ***, without venting and re-assembling the vacuum chamber.



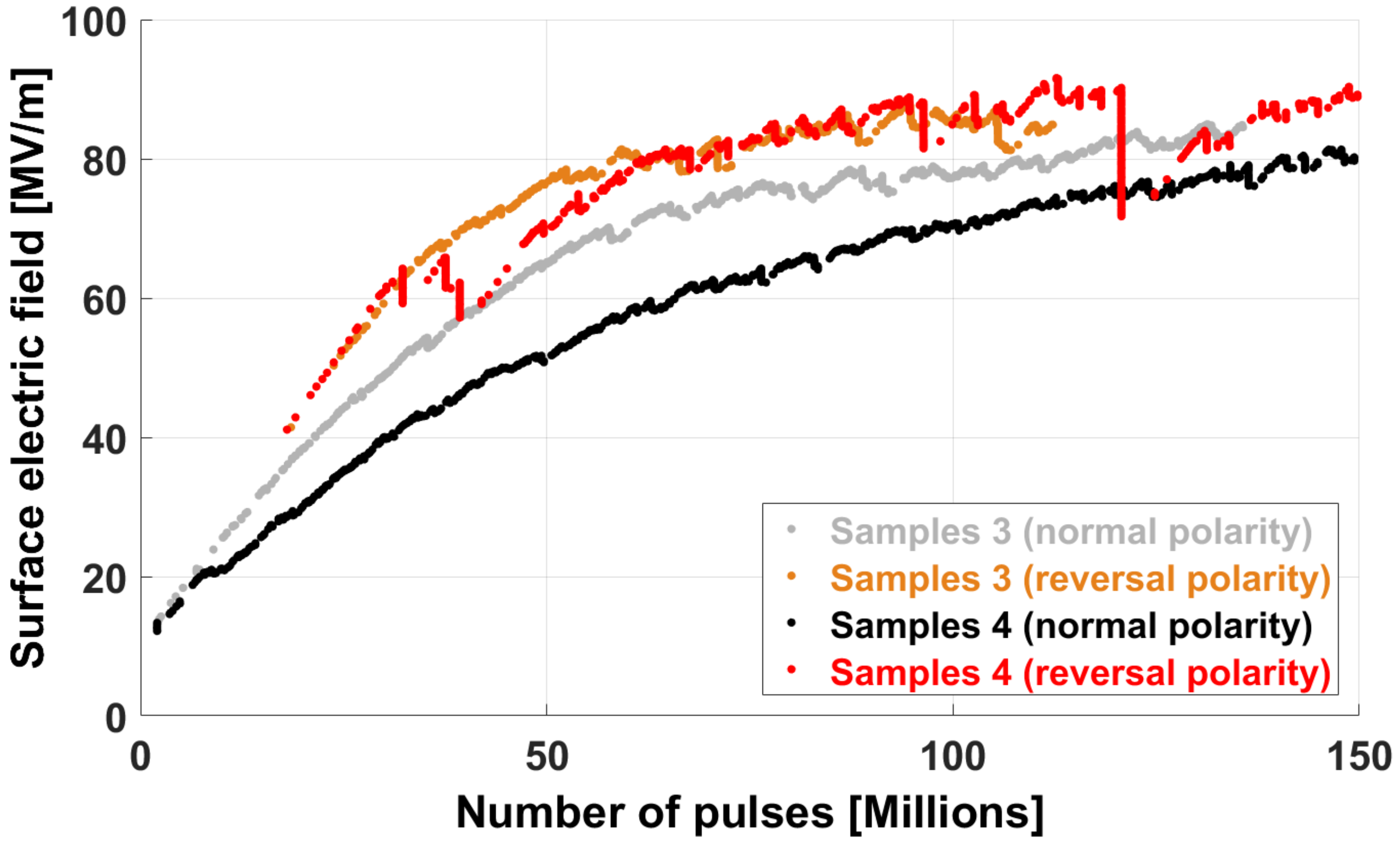
Polarity



For changing the polarity, the connection of the HV is changing, i.e. high-voltage generator with **a positive polarity** is connected to the bottom electrode and the top electrode is grounded, hereinafter names as **a reversal polarity**. The test is done ***in situ***, without venting and re-assembling the vacuum chamber.

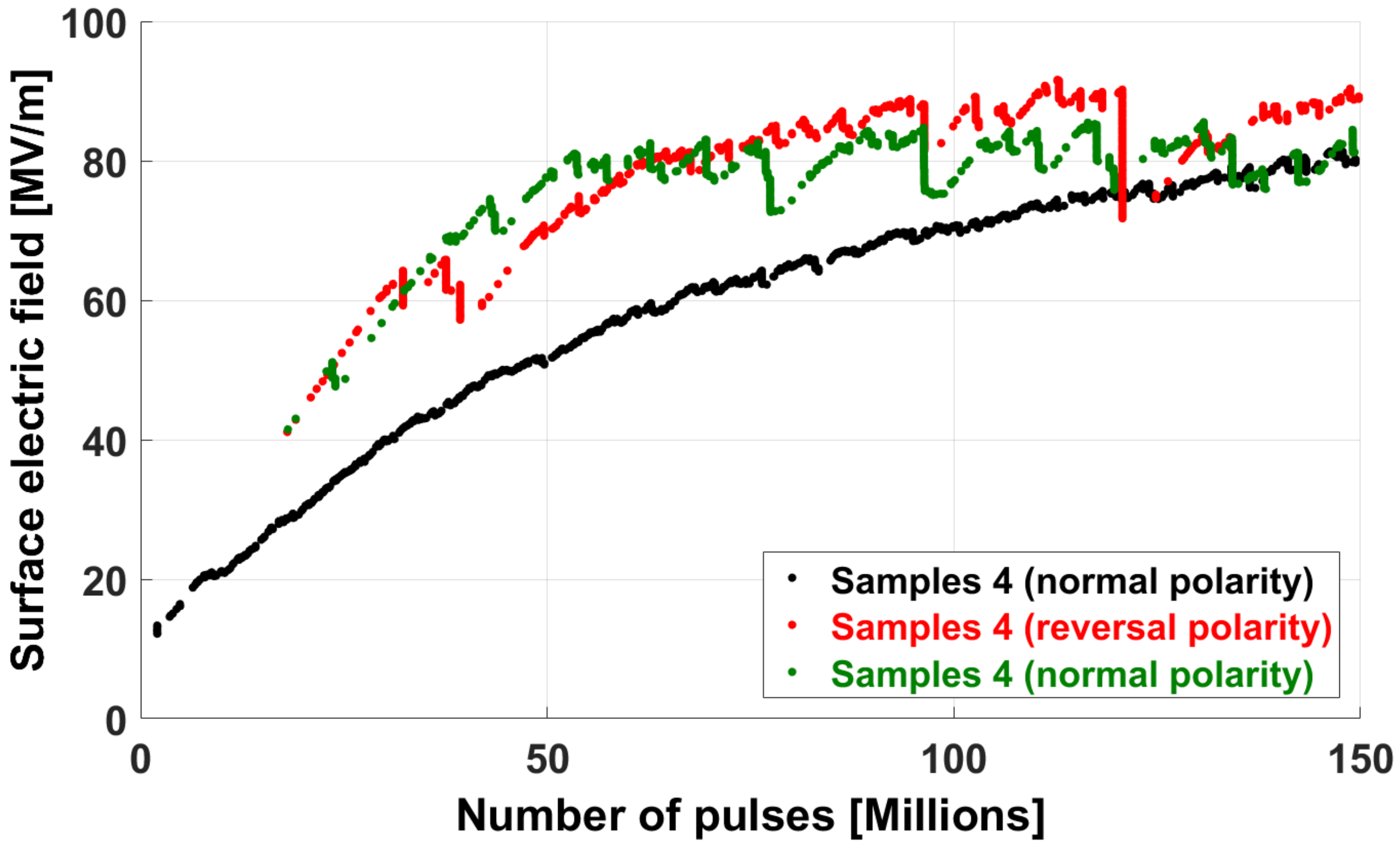
Test is done with Soft Cu electrodes and spacer for 60 µm.

Polarity



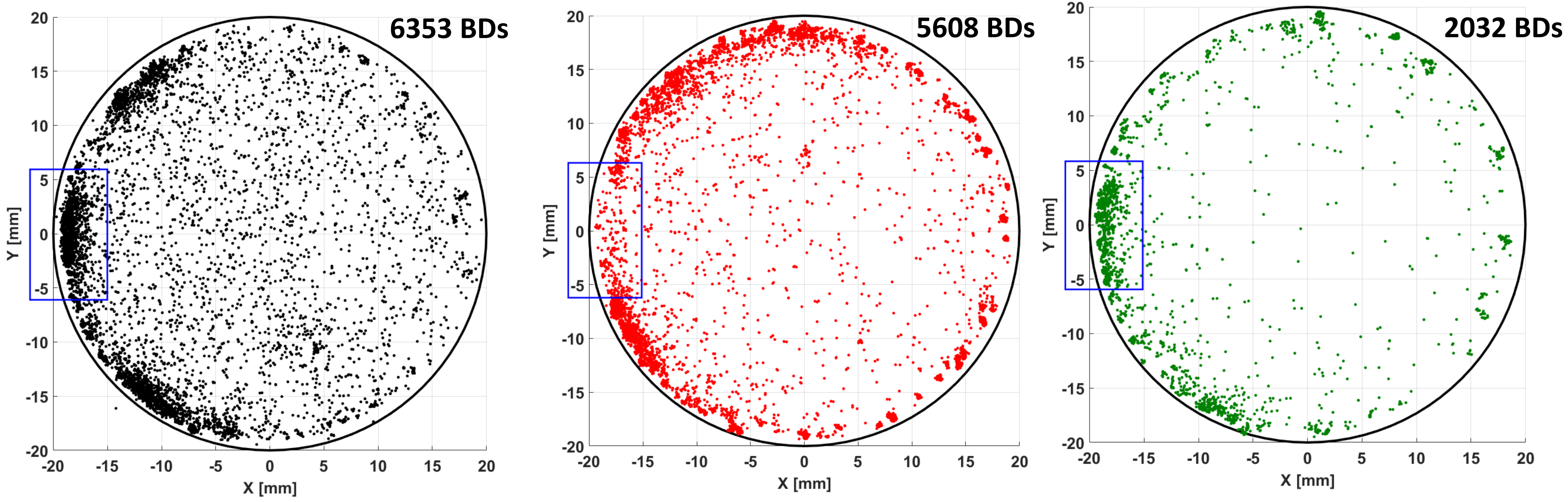
The initial conditioning curves with a normal polarity (gray and **black**) and the conditioning with reversal polarity (**orange** and **red**) for the Soft Cu electrodes tested with ceramic with 60 µm gap.

Polarity



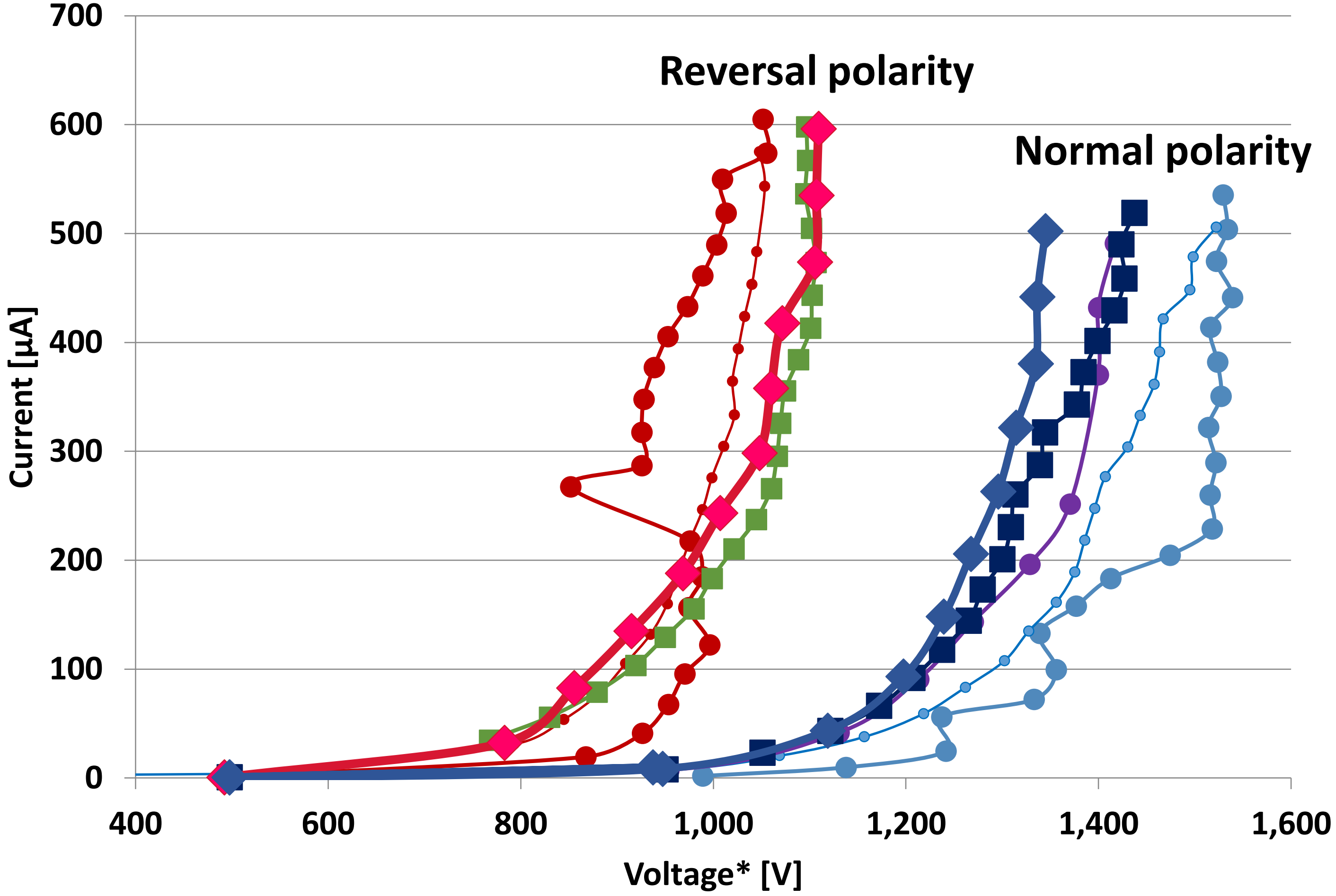
After returning to normal polarity, the reached during initial conditioning the surface electric field does not stay at the same level.

BDs localisation with different polarity



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

Field emission measurements



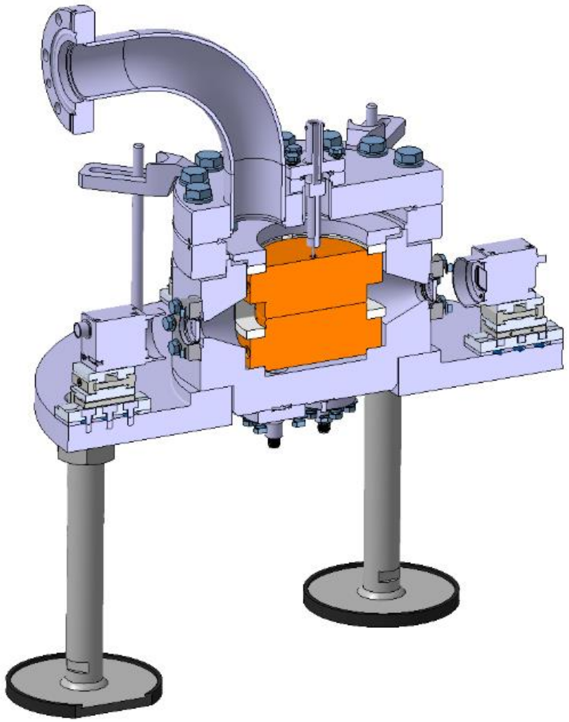
No	Direction	beta
1.	Normal Up	-----
2.	Normal Down	127
3.	Reversal Up	----
4.	Reversal Down	167
5.	Normal Up	130
6.	Reversal Up	273
7.	Normal Up	129
8.	Reversal Up	274
9.	Normal Up	116

Fig. 26. The absolute value of current vs voltage with different polarities. Measurements were done with **Cu electrodes** and spacer for 20 µm gap.

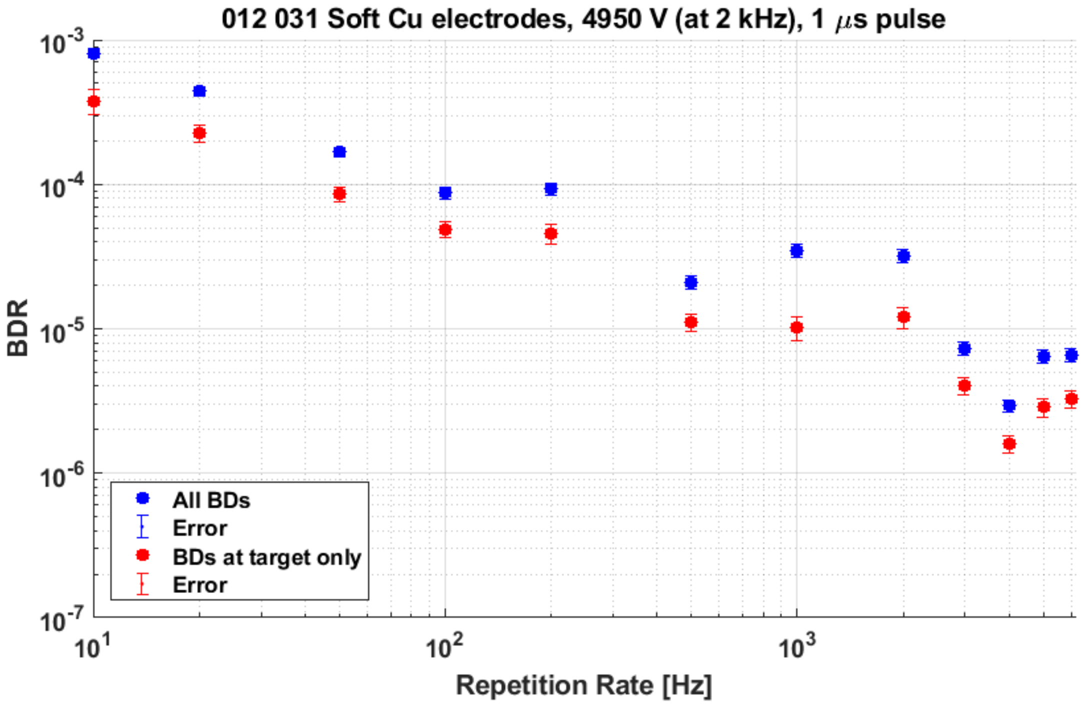
Polarity

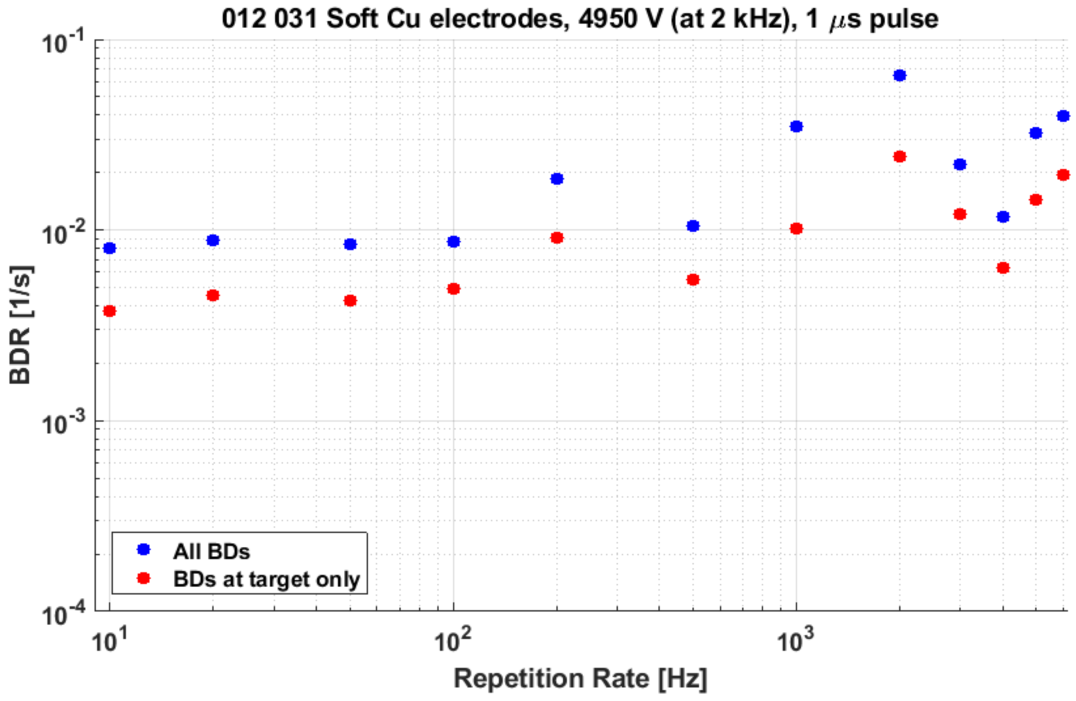
Do anode and cathode conditioning in the same time?

During conditioning of the cathode, the anode is also conditioned, but less effectively.



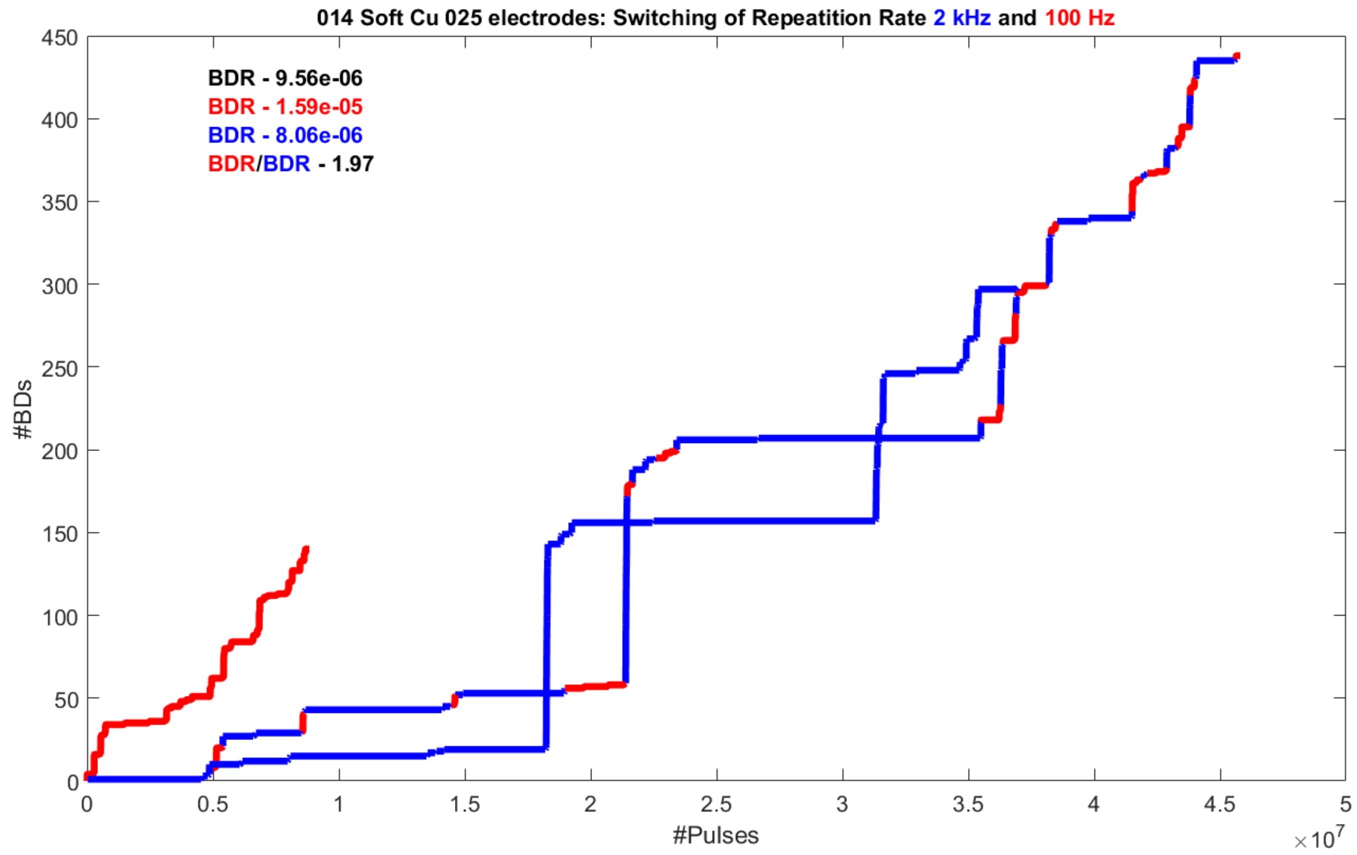
BDR vs RepRate





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

Swap RepRates

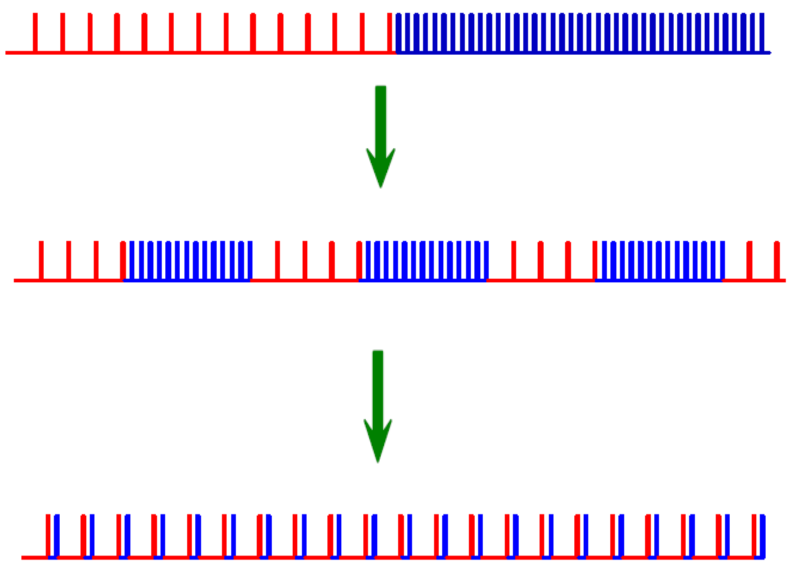


Swap Rep Rate between **100 Hz** and **2 kHz** every 3 BDs at Target voltage

Swap Rep Rates (100 Hz and 2 kHz)

Sample number	Material	Rep Rate F1/F2	V1/V2	#BDs1/ #BDs2	BDR1/ BDR2	Ratio (BDR1/BDR2)
005	SS CuAg	100/2000	5220/5220	112/16	1.12E-5/1.59E-6	7.04
005	SS CuAg		5220/5220	60/8	5.98E-6/7.99E-7	7.48
006	Nb		6000/6000	198/201	3.99E-5/3.43E-6	11.63
006	Nb		6000/6000	255/224	2.66E-5/3.59E-6	7.41
007	Hard Cu		4520/4500	145/138	2.96E-5/1.89E-5	1.57
007	Hard Cu		4440/4460	87/96	1.63E-5/1.11E-5	1.47
007	Hard Cu		4380/4400	103/102	6.34E-6/3.34E-6	1.9
008	Soft Cu		4780/4800	195/156	1.99E-4/6.56E-5	3.03
008	Soft Cu		4600/4620	130/152	2.28E-5/6.9E-6	3.3
008	Soft Cu		4510/4530	77/83	1.96E-5/7.65E-6	2.56
008	Soft Cu		**4450/4570**	89/90	1.28E-5/7.89E-6	1.62
008	Soft Cu		4400/4420	145/133	1.38E-5/1.29E-6	10.7
004	SS and Cu		3760/3780	59/137	2.11E-6/1.12E-6	1.88

Rep Rate/Pause effect



Step 1

Step 2

Step 3

Results for **009 Soft Cu** electrodes, 1 μs pulse width.

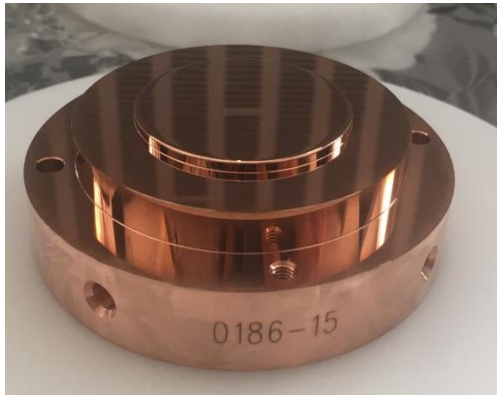
E field [MV/m]	Rep Rate, Hz	Pause before pulse, ms	BDs	BDR	BDR/ BDR
62	100	10	197	2.30E-05	**1.63**
	2000	0.5	121	1.41E-05	
61	100	10	116	9.30E-06	**1.14**
	2000	0.5	102	8.18E-06	
62	100	10	57	8.05E-06	**1.46**
	2000	0.5	39	5.51E-06	

Conclusion: Pause between high-voltage pulse matters!

Conditioning behavior for various materials

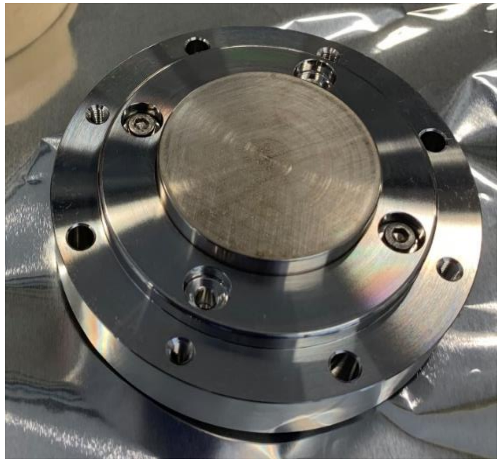
No.	Material	Information
1.	**Hard Cu**	OFE copper, as-machined using fly-cut and diamond turning, roughness 30 nm.
2.	**Cu**	OFE copper, as-machined using fly-cut and diamond turning, heated up to 800°C in hydrogen atmosphere.
3.	**Soft Cu**	OFE copper, as-machined using fly-cut and diamond turning, heated up to 1040°C in hydrogen atmosphere.
4.	**Ni**	99.5% Ni, roughness is around 400 nm.
5.	**Inox**	Steel alloy, 16.73% Cr, 10.13% Ni, 2.04% Mo, 1.54% Mn and 1.51% others.
6.	**Co**	99.9% Co, roughness is around 800 nm.

Cu



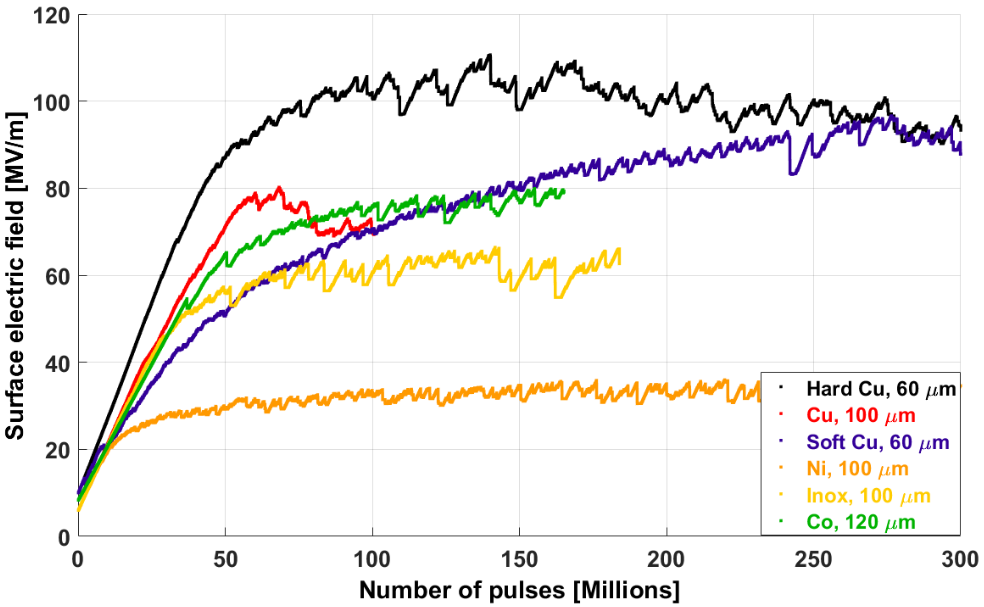
Ni

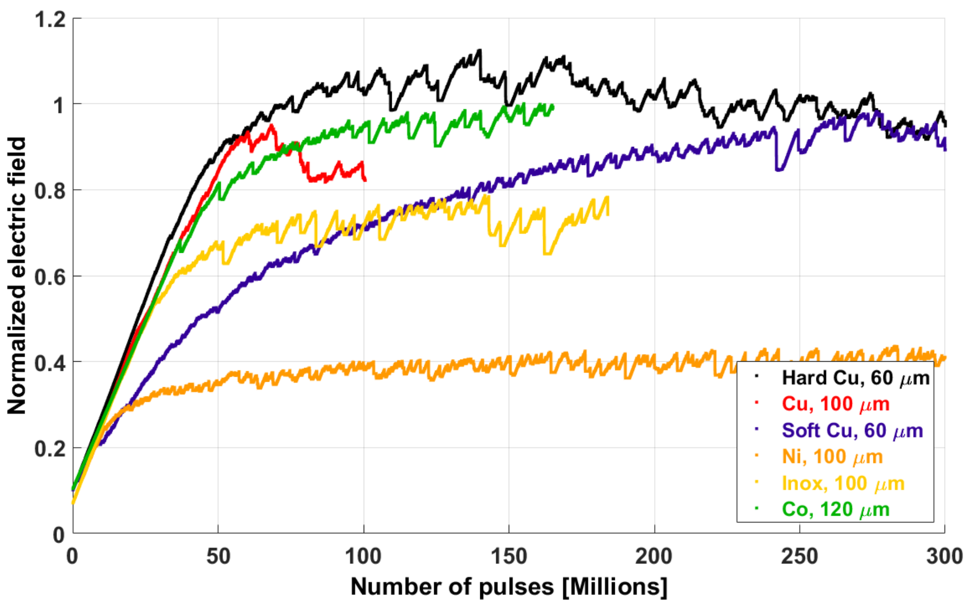
Inox



Co

Conditioning behavior for various materials





$$E_{surf} = \frac{V}{d}$$

$$E_{norm} = \left(\frac{V}{V_{max}}\right) \times \left(\frac{d_{max}}{d}\right)^{0.7}$$

Field emission measurements

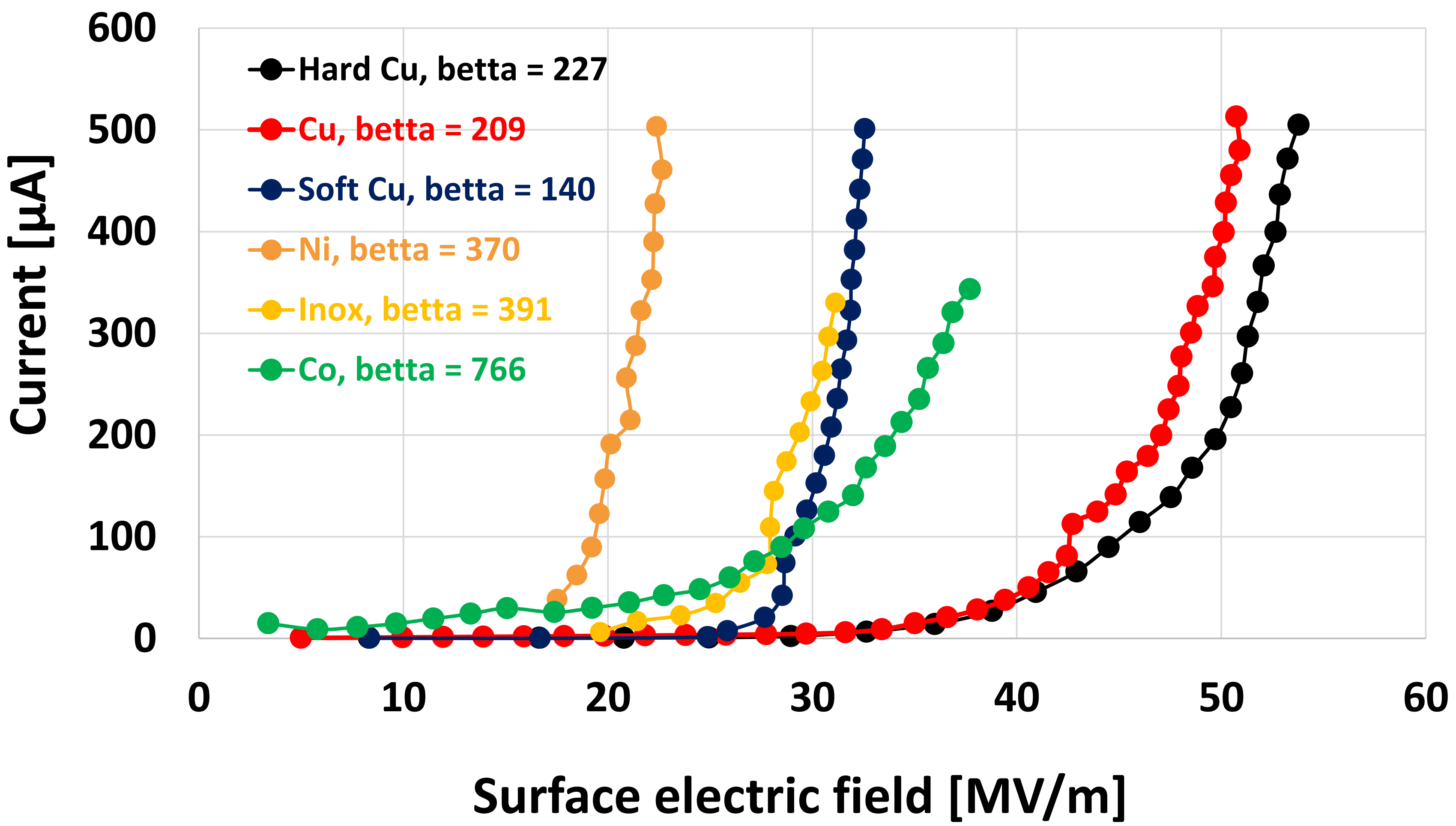


Fig. Current vs Surface electric field

$$E_{surf} = \frac{V}{d}$$

for the various materials made after initial conditioning.

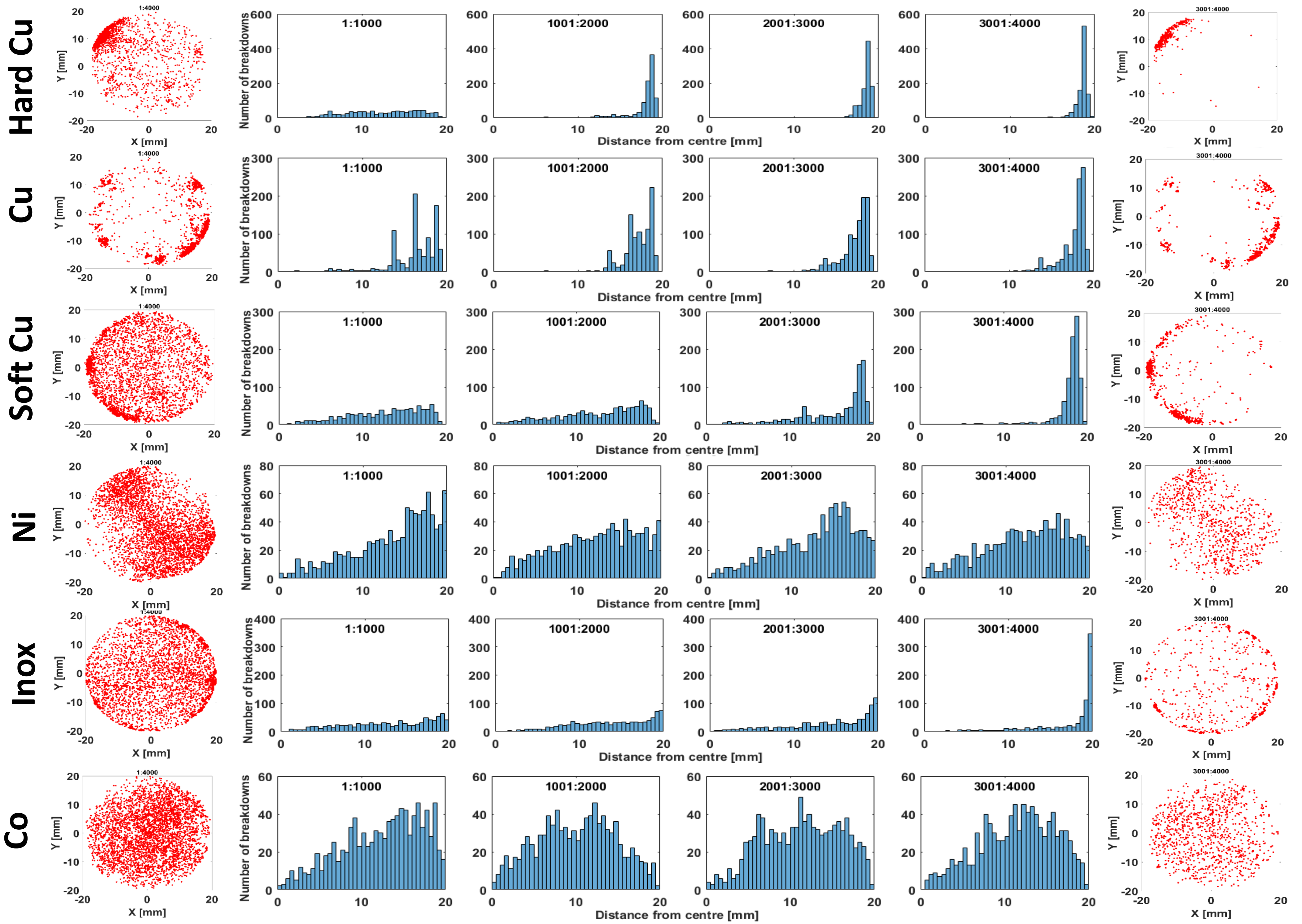


Fig. 35. Evolution of first 4000 break-downs distribution for different materials.

Material comparison

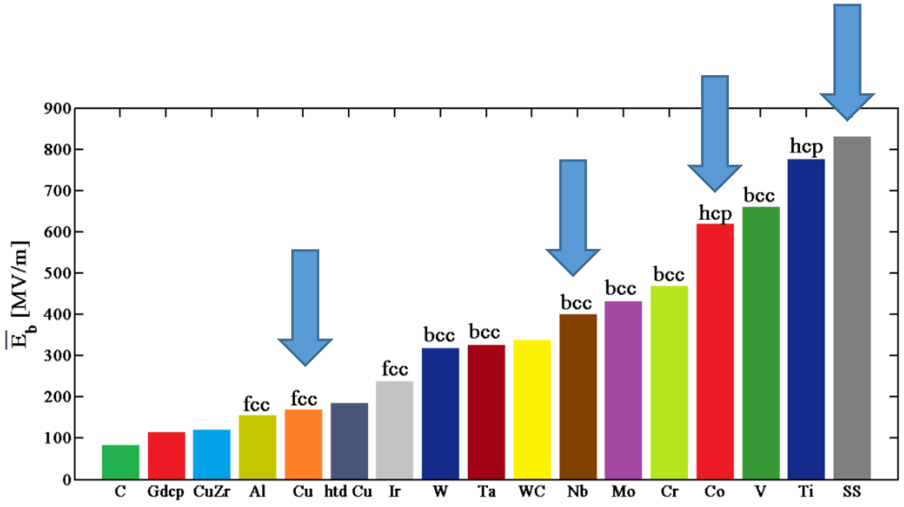


Figure 5: Average breakdown fields after conditioning of iridium shown with that of the materials previously tested in [1]. For pure metals, their crystal structures are indicated (fcc = face-centred cubic, bcc = body-centred cubic, hcp = hexagonal closest packing) on the top.

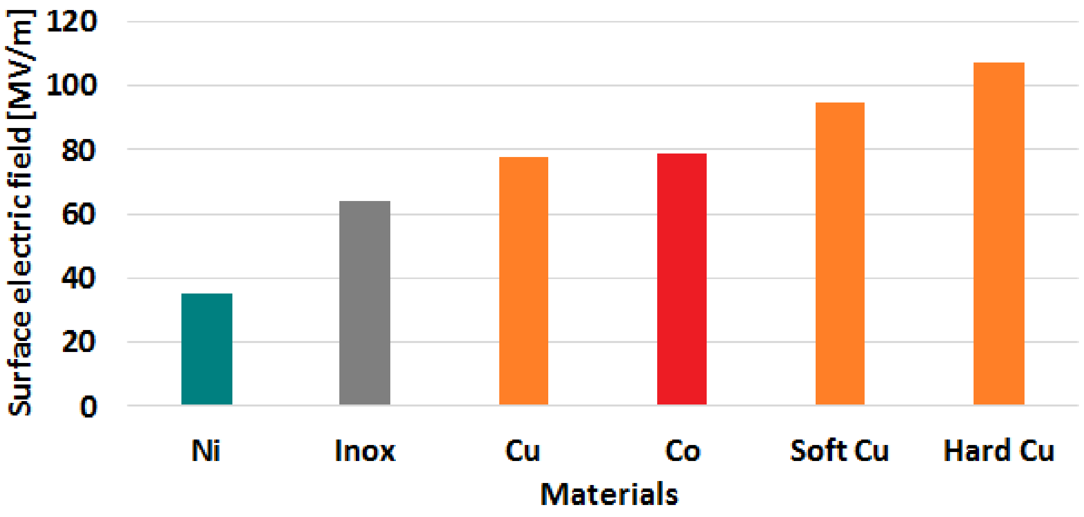
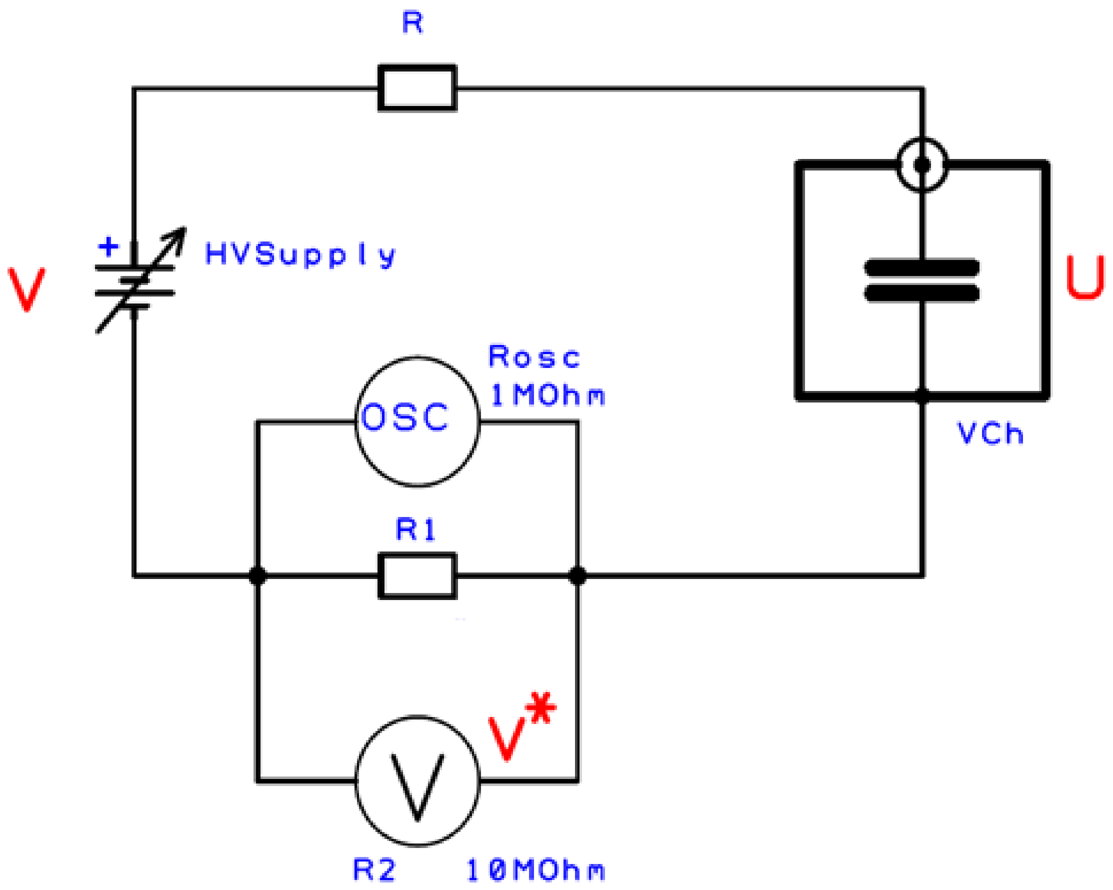


Fig. 36.1. Results from the pulsed dc system with tip plane geometry of electrodes (“DC spark system”).

Fig. 36.2. Results from the pulsed dc system with 2 plane electrodes (Large Electrodes System).

Field emission measurement (static)



Voltage applied to the LES (anode−cathode voltage):

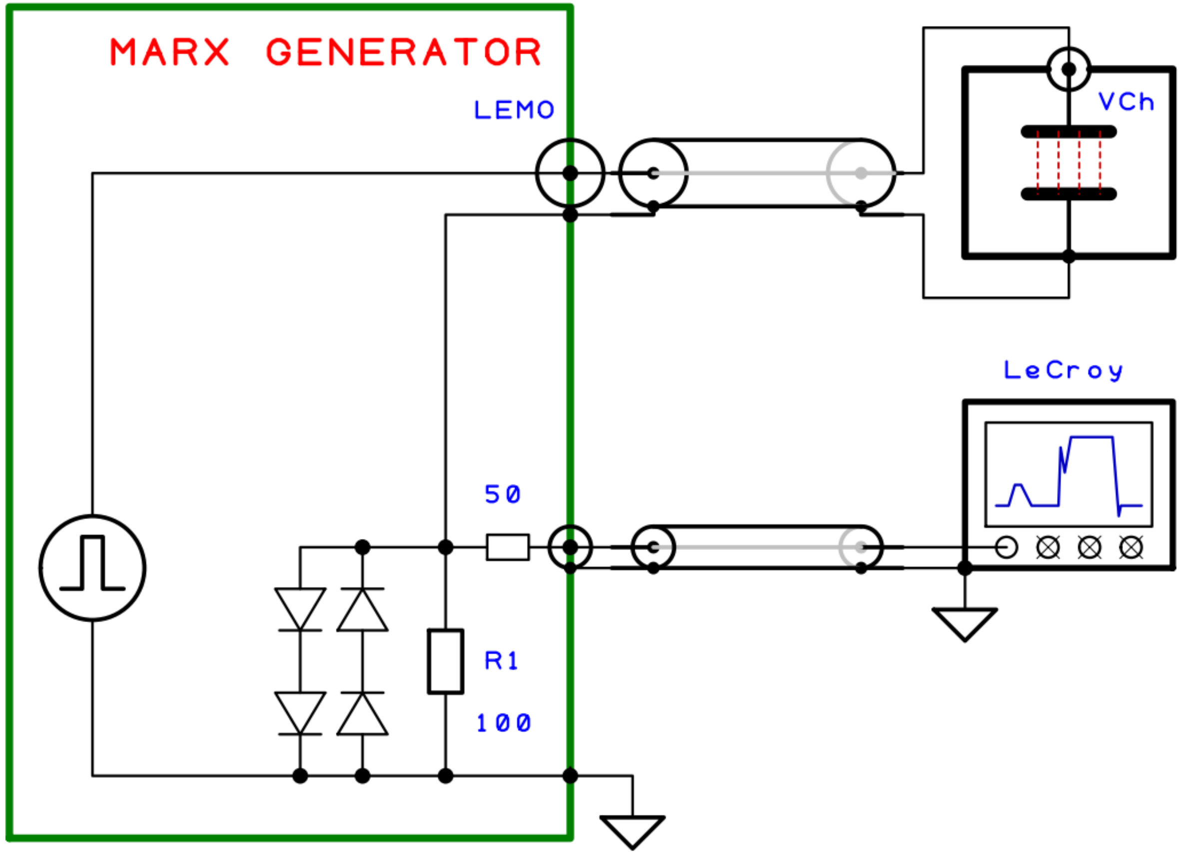
$$U = V - I \times R \qquad (1),$$

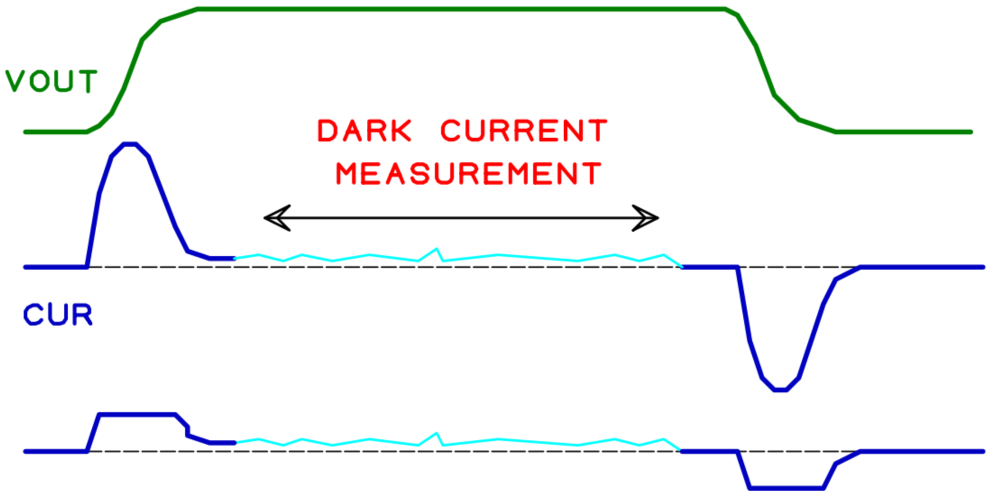
V – voltage at power supply, R = 6.39 MOhm.

$I = \frac{V^*}{R^*}$, V^*- voltage at the multimeter.

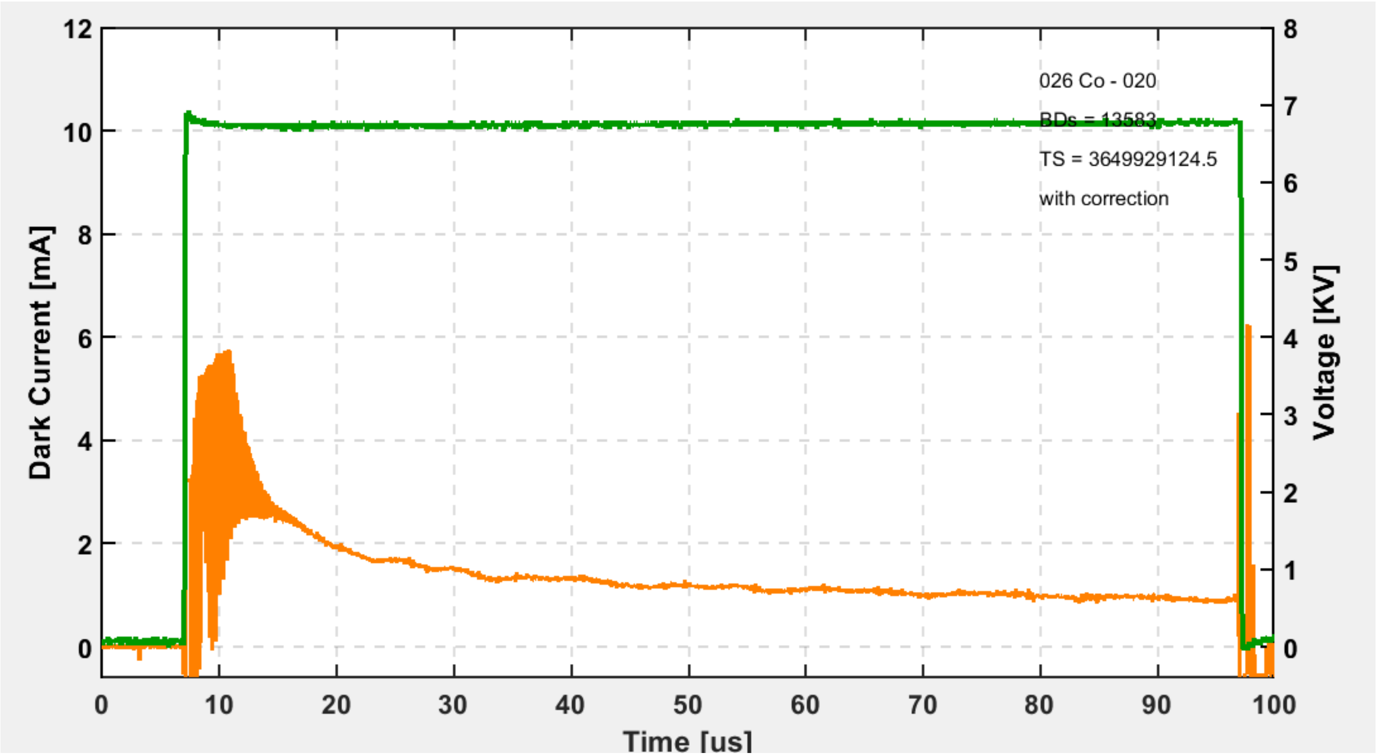
$\frac{1}{R^*} = \frac{1}{R_{osc}} + \frac{1}{R_1} + \frac{1}{R_2}$, $R_1 = 100\ kOhm$ => $R^* \approx 90.1\ kOhm$

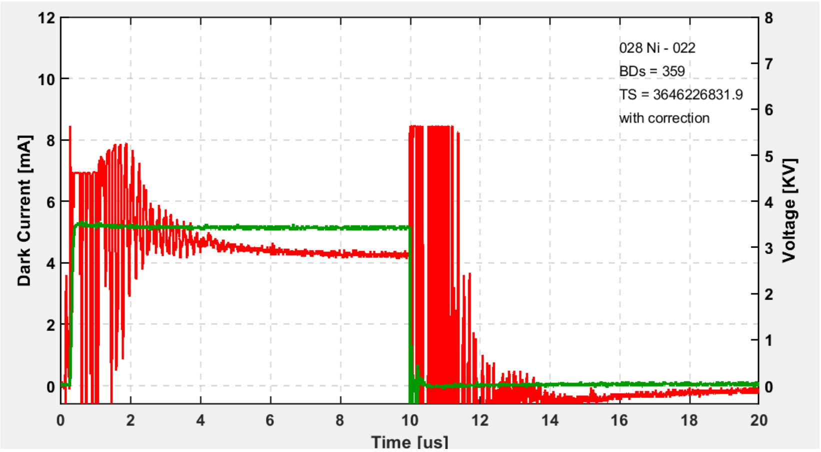
Field emission measurement (dynamic, i.e. over pulsing)

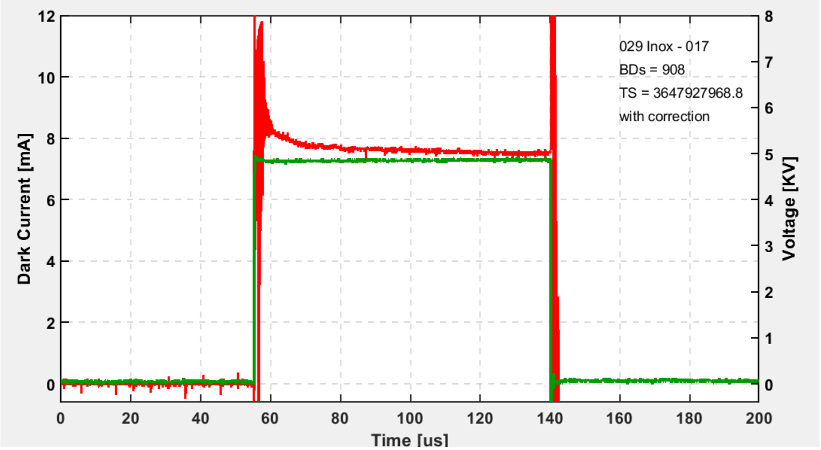




Field emission measurement (dynamic, i.e. over pulsing)

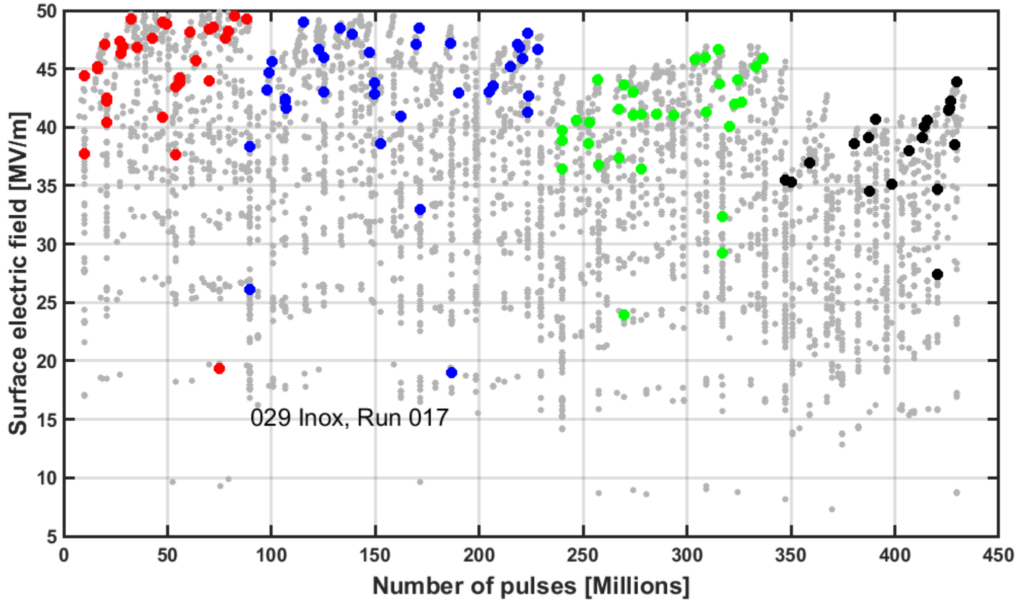




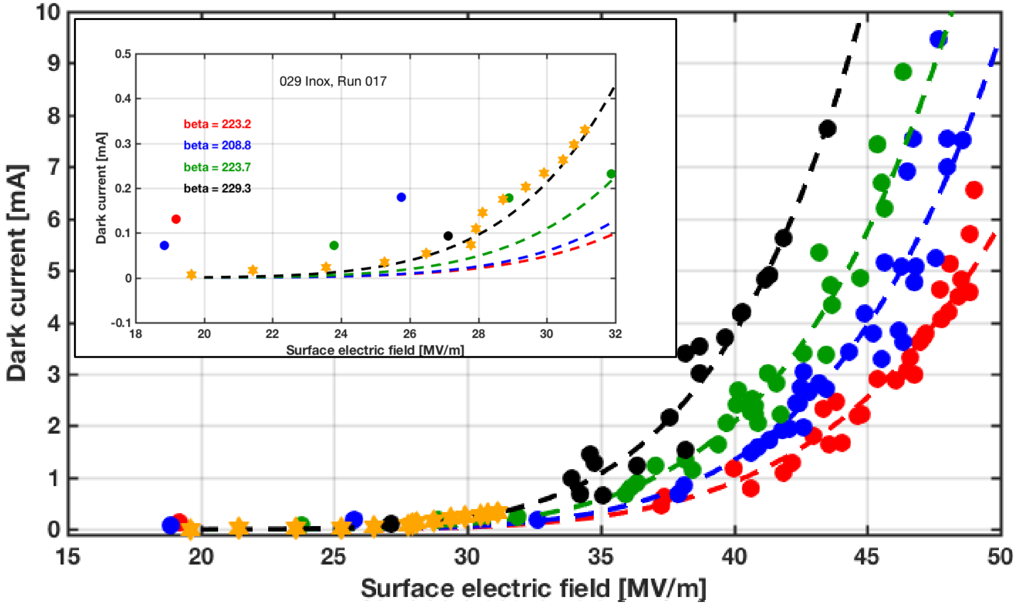


Example of waveform from the dynamic field emission measurement for Cobalt electrodes taken with 90 us pulse width and 6744 V. The next breakdown occur with 7155 V).

Field emission measurement (static vs dynamic)

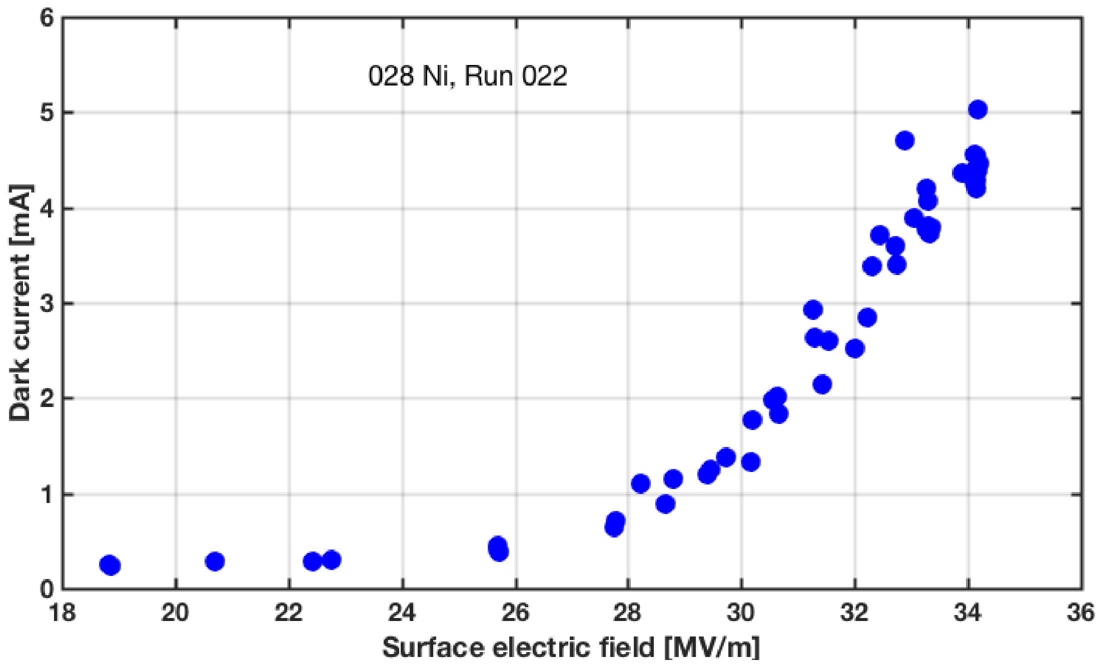


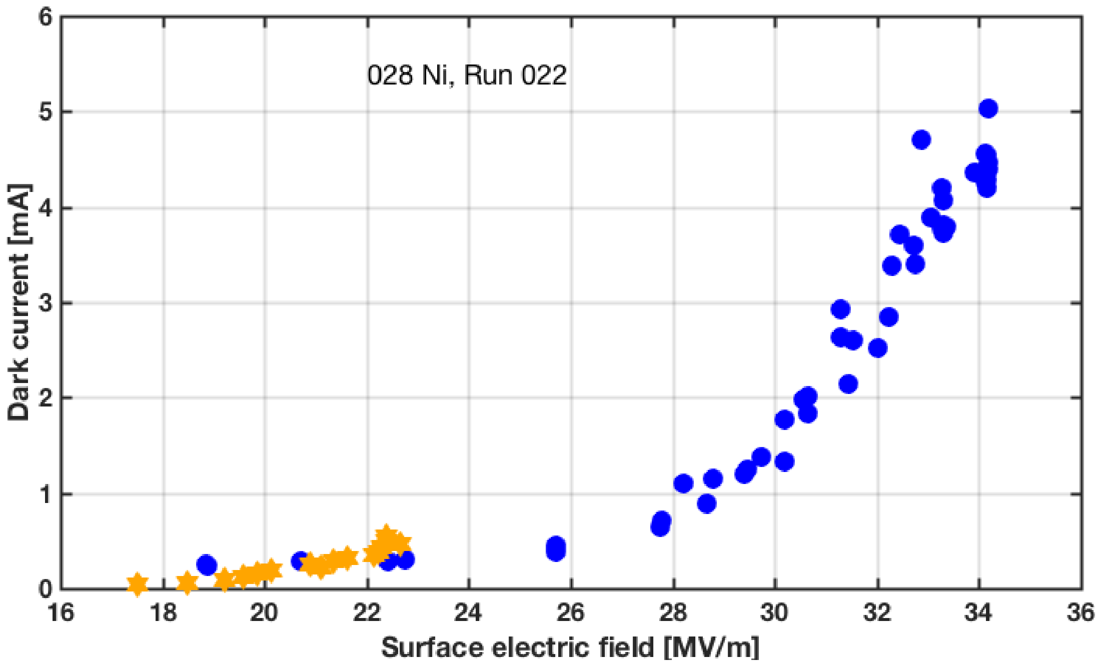
Conditioning using feedback algorithm for the Inox electrodes tested with a spacer for 100 µm gap with 90 µs pulse width.



Field emission measurement for Inox electrodes: comparison static with dynamics measurements. (orange – static field emission measurements)

Field emission measurement (static vs dynamic)





The current voltage diagram for the Ni electrodes: **blue** – during dynamic FE measurements, **orange** – during static FE measurements.

Future plans

- Optical spectroscopy of field emission (Ruth's poster).
- Dark current measurements (Jan's poster).
- Swap polarities each pulse.
- To study the effect of rise and fall times to BDR.
- Compact design of electrodes.

Engineering | Lancaster University | The Cockcroft Institute of Accelerator Science and Technology

Optical Spectroscopy in the Pulsed DC Large Electrode System at CERN

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[2]Cockcroft Institute of Accelerator Science and Technology, Daresbury, United Kingdom
[3]CERN, Geneva, Switzerland

JAI John Adams Institute for Accelerator Science | UNIVERSITY OF OXFORD

DARK CURRENT FLUCTUATIONS IN HIGH GRADIENT RF AND PULSED DC EXPERIMENTS

J. Paszkiewicz[1,2], P. N. Burrows[1,2], W. Wuensch[2]
[1]John Adams Institute, Department of Physics, University of Oxford, Oxford, United Kingdom
[2]European Organisation for Nuclear Research (CERN), Geneva, Switzerland

Recent progress at pulsed dc systems at CERN

Iaroslava Profatilova[1], Ruth Peackock[1,2], Enrique Rodriguez Castro[1], Sergio Calatroni[1], Walter Wuensch[1]
[1]CERN, Geneva, Switzerland, [2]Lancaster University, United Kingdom

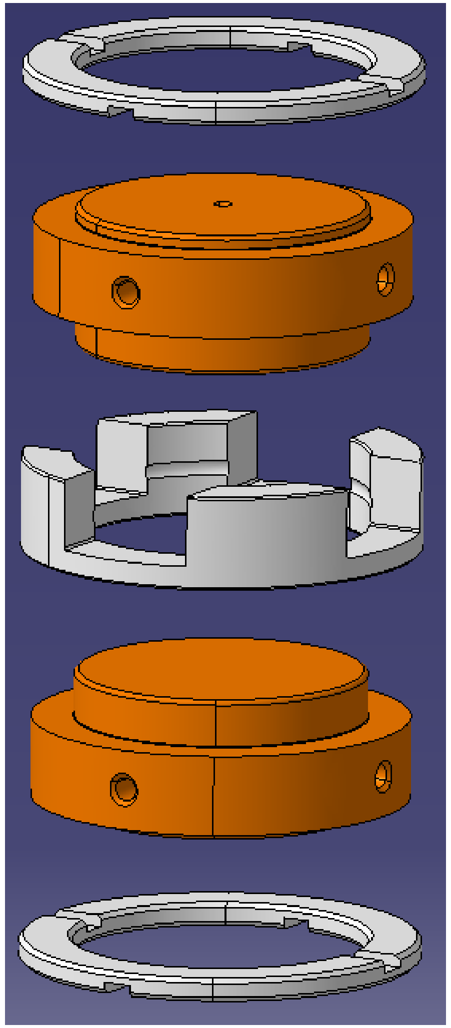
Thank you!

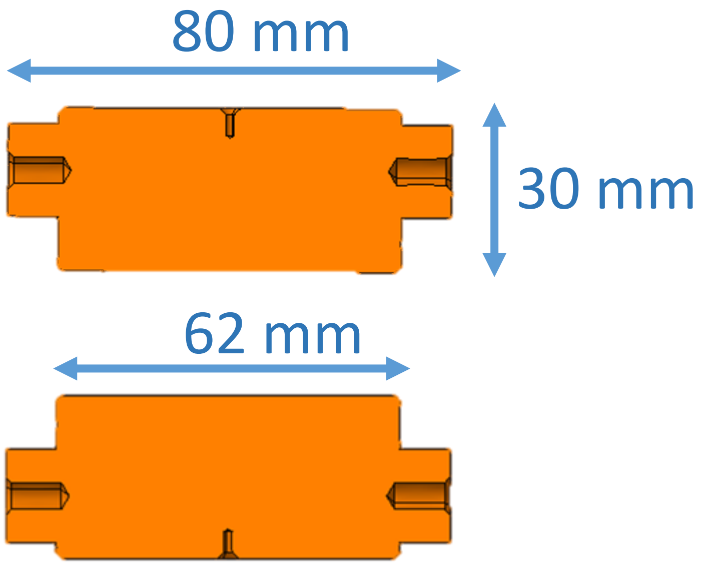
Contacts: iaroslava.profatilova@cern.ch
iaroslava.profatilova@gmail.com

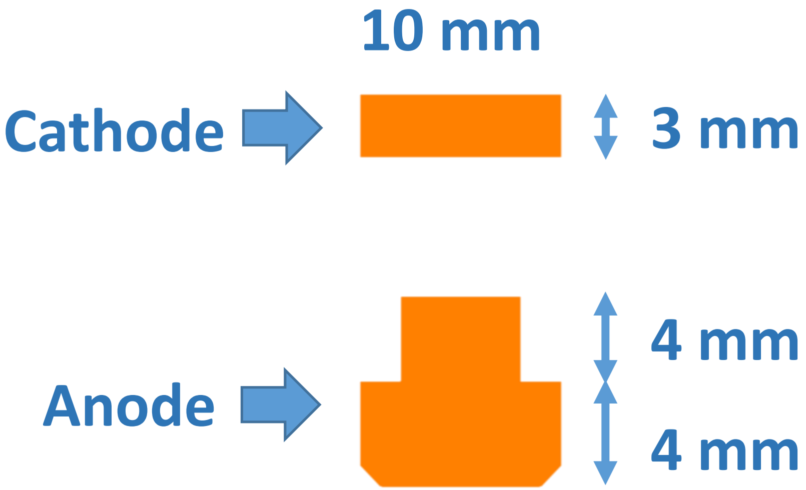
Extra slides

Large electrodes system

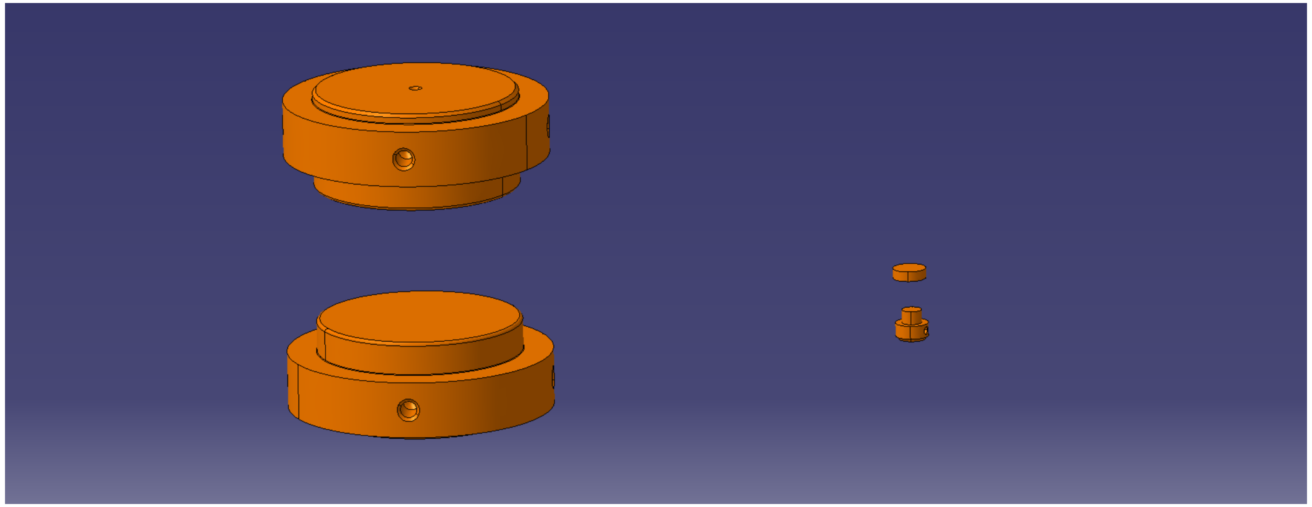
Curent model

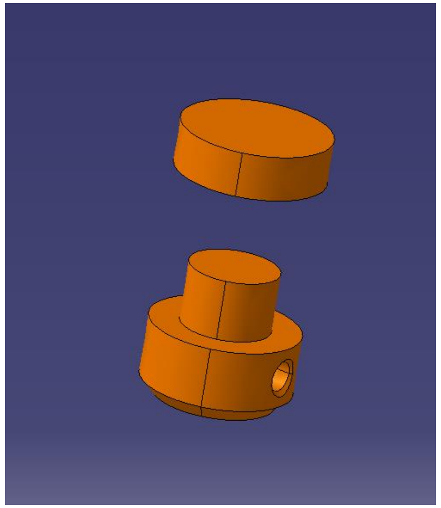






...courtesy of Enrique Rodriguez Castro





Large Electrode System (LES)