Performance of electrical vacuum breakdown under cryogenic temperatures

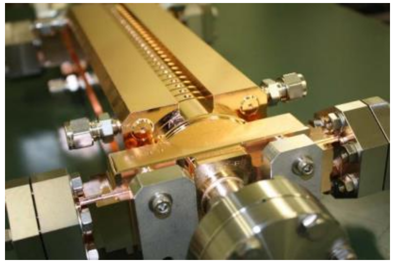
Iaroslava Profatilova, Marek Jacewicz, Piotr Szaniawski from Uppsala University (Sweden)
Inna Popov, Yinon Ashkenazy from Recah Institute of Physics, The HUJI (Israel)
Ruth Peacock, Sergio Calatroni, Walter Wuensch from CERN (Switzerland)

MeVArc 2022

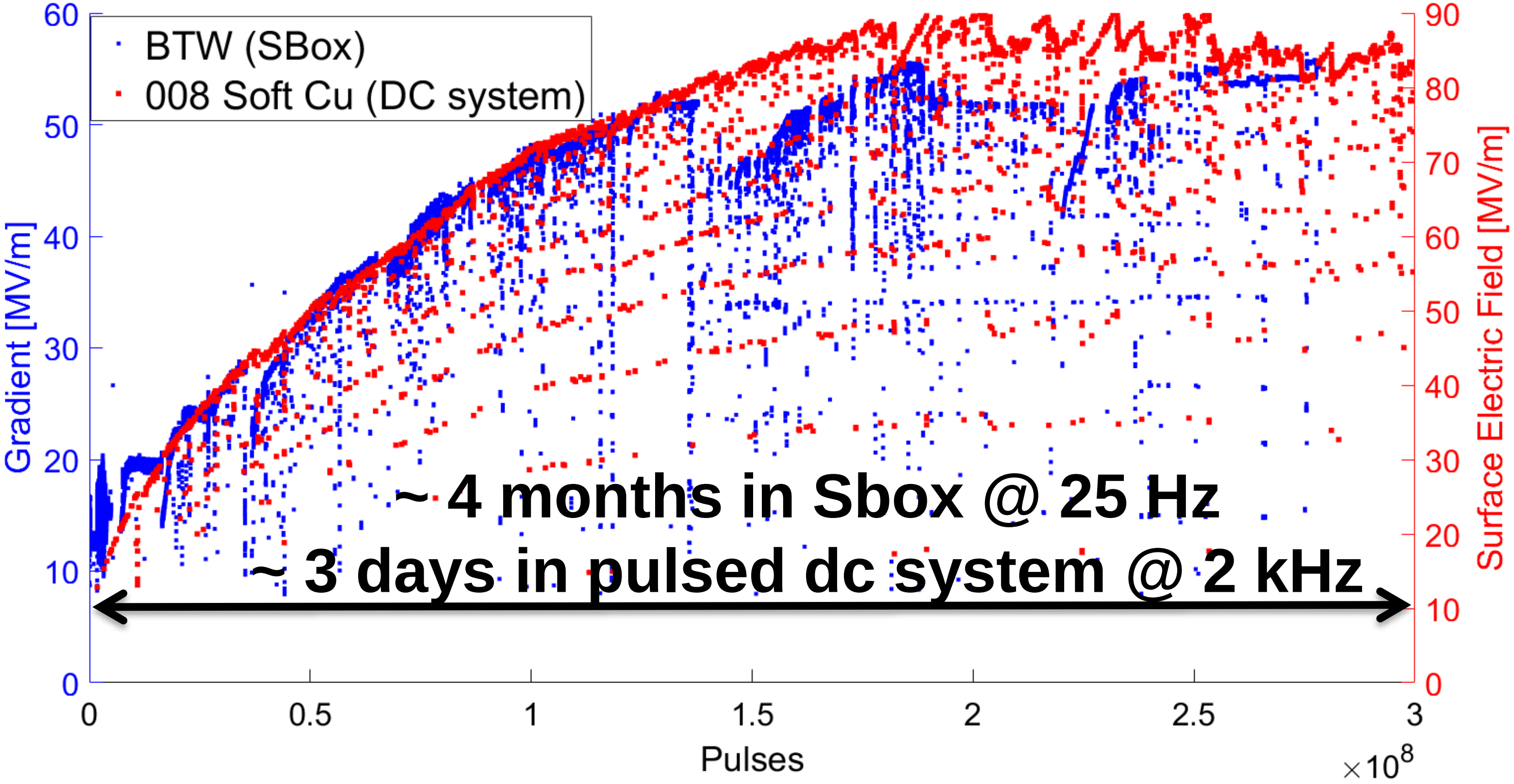
Outline

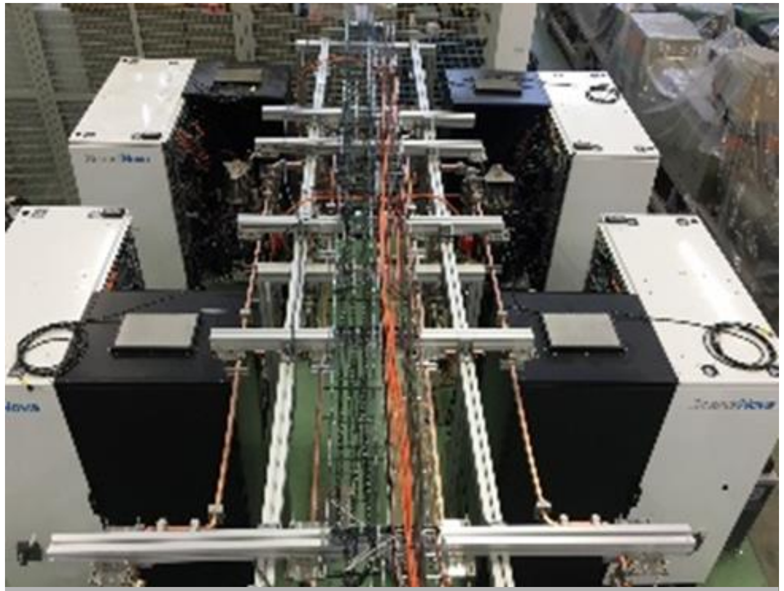
- Motivation and background.
- Cryo DC pulsed system experimental equipment.
- Achievements of Cryo DC system
- Microscopic observation of the BD features. Their differences on Anode and Cathode sides.
- Characterisation of Cryogenic BD features and investigation of their conditions.
- Conclusion and future plan.

Conditioning in RF and DC



Marx generator, up to 6 kHz





XBox-3: 6 MW, 400 Hz!

…courtesy of Xboxes team

Comparison of heat-treated and as-machined copper

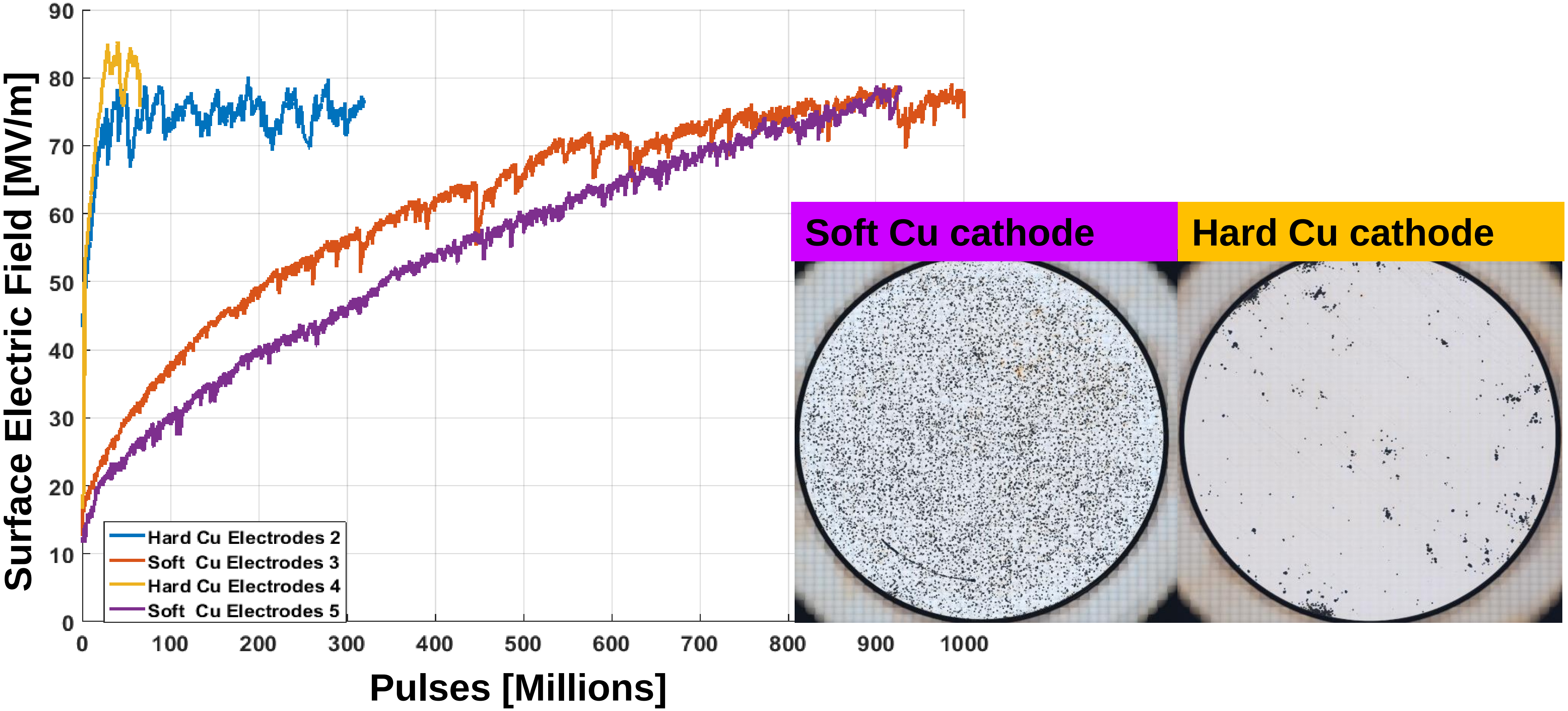
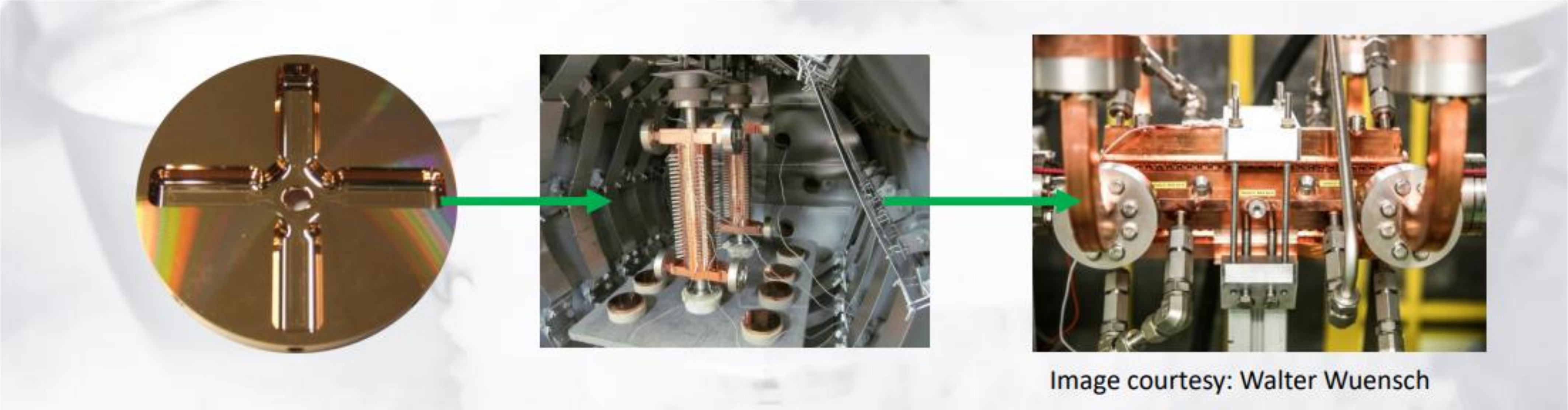
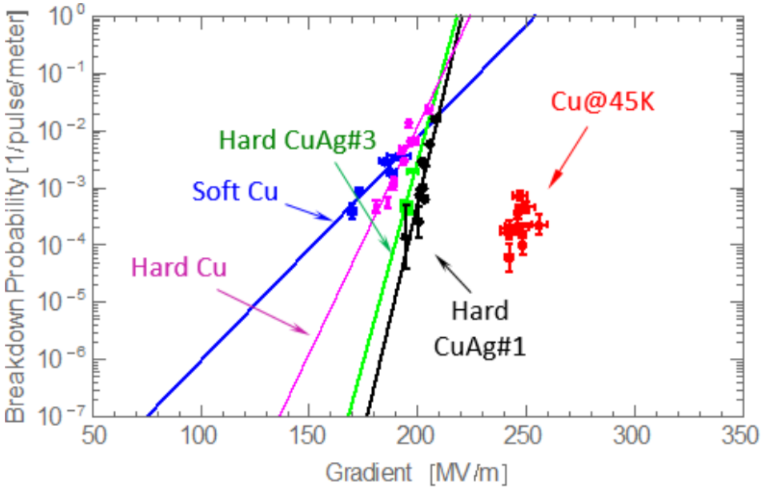


Fig. 4. Conditioning curves from tests at Pulsed DC System taken with HRR circuit, 16.7 µs pulse lengths and 60 µm gap distances.

Motivation for cryogenic pulsed dc system



Cryo experiments provide new information for vacuum arc theories.
Cryogenic setting reduces BDR (SLAC's results).
Possible approach to ultra-compact linac.



Pulsed DC system and their differences

Switzerland | Finland | Sweden

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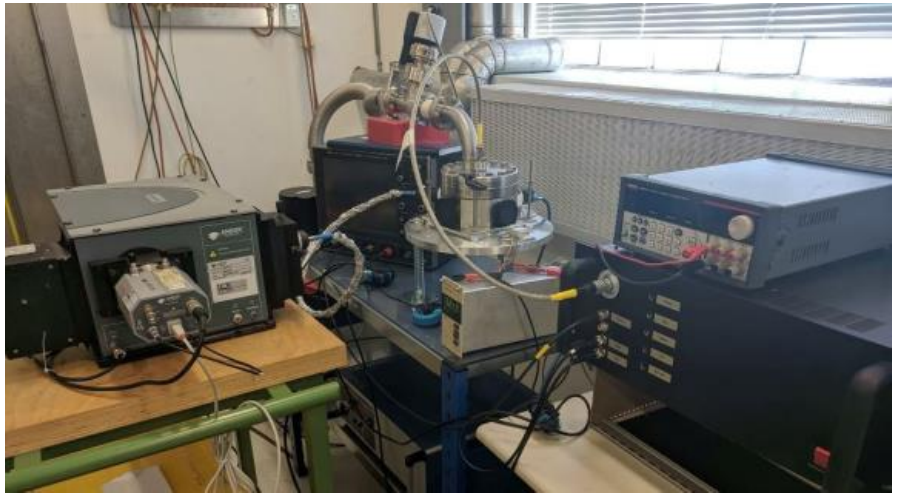
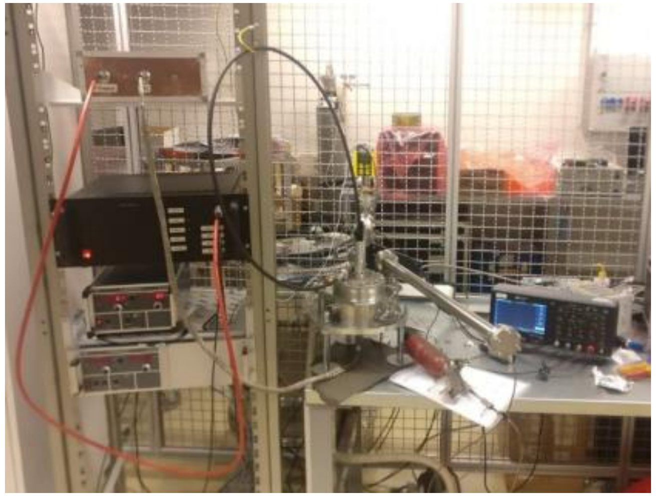




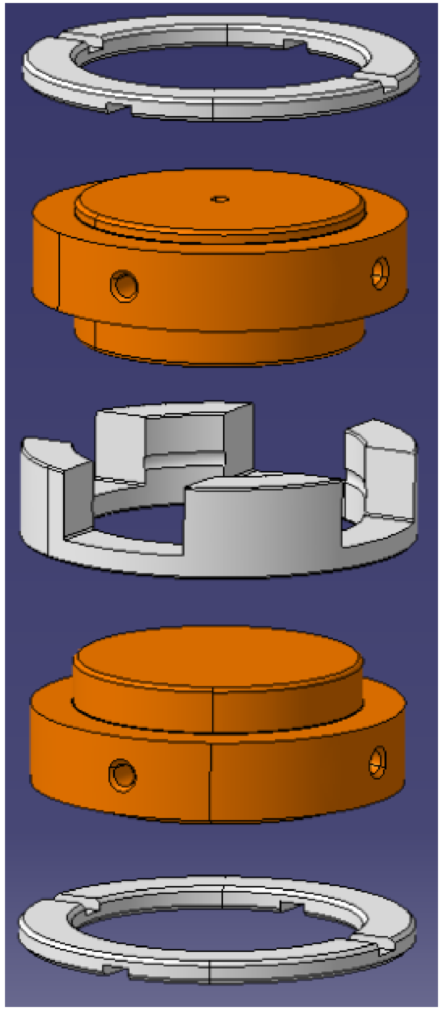
All these systems use the same electrodes geometry and generator type.

- BD localization technique;
- Optical spectroscopy.

- Plasma treatment without exposition to air.

- Cryogenic temperatures

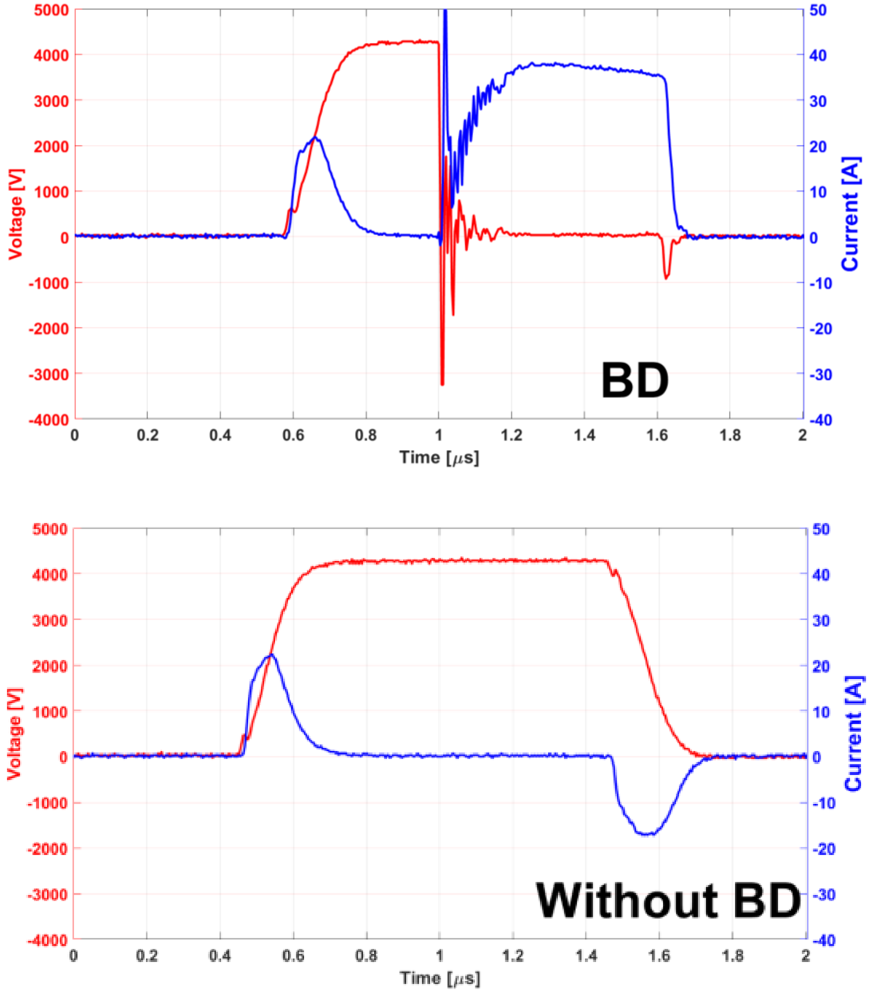
Pulsed DC systems main configuration



Electrodes configuration:
40 mm diameter of surface (40 mm – anode, 60 mm cathode)

The interelectrode distance is varied by ceramic ring (nominal size of the rings is 20, 40, 60 or 100 µm)

HV generator parameters:
Voltage: up to 10 kV
Repetition rate: up to 6 kHz
Pulse length: 500 ns – 1 ms.



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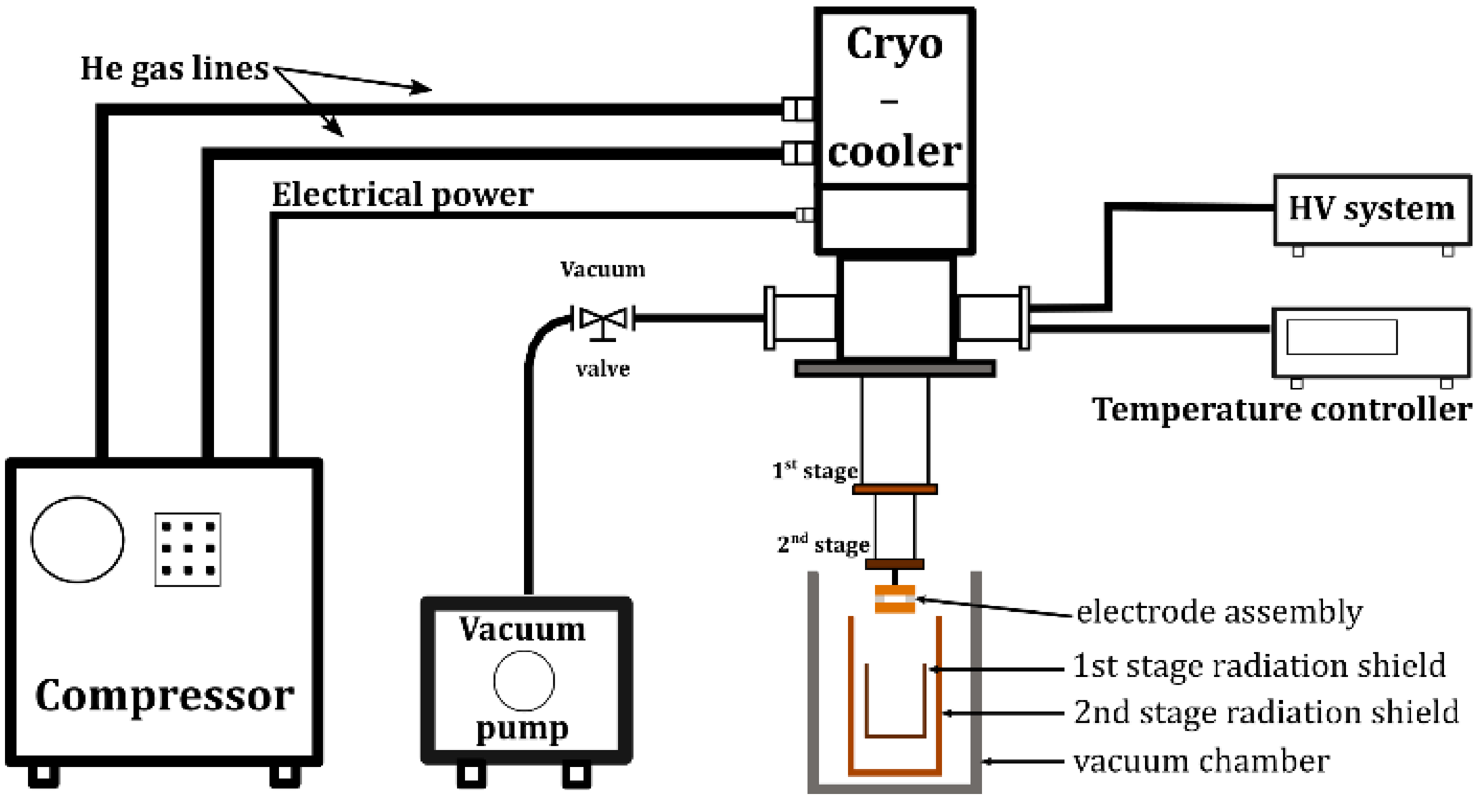
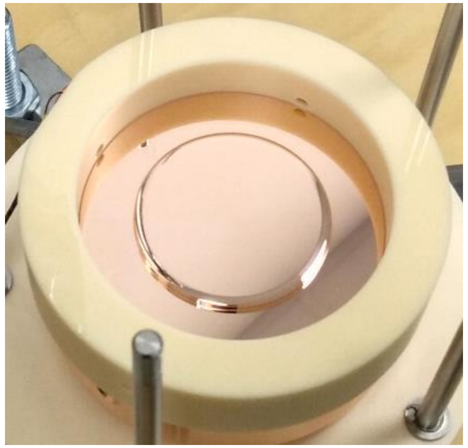
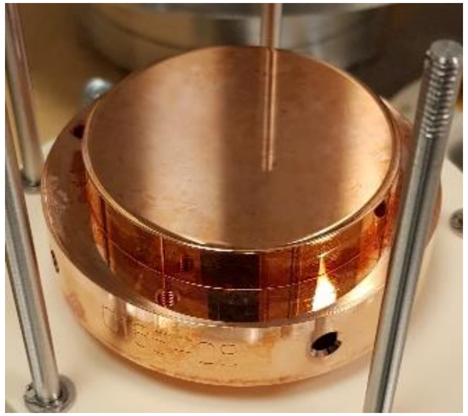
Cryo DC pulsed system



Anode



Cathode



Pressure value:
@ room temperature: < 1e-7 mbar
@ cryo temperatures: ~ 5e-9 mbar
Temperature: min 5 K.

60 mm diameter **cathode**
40 mm diameter **anode**
Gap: 40 or 60 µm at warm,
i.e. **59 or 79 µm at 30 K**.

Previous results from cryo dc system

PHYSICAL REVIEW APPLIED **14**, 061002 (2020)

Letter

Temperature-Dependent Field Emission and Breakdown Measurements Using a Pulsed High-Voltage Cryosystem

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http://doi.org/10.1103/PhysRevApplied.14.061002

TABLE I. Field holding capacity compensated for gap-size effect. Estimated saturation field E_{sat}^{est}, measured saturation field E_{sat}, and relative change $\Delta E/E$ between them, for conditioning runs at different temperatures T.

	Electrode set 1			Electrode set 2		
T (K)	E_{sat}^{est} (MV/m)	E_{sat} (MV/m)	$\Delta E/E$ (%)	E_{sat}^{est} (MV/m)	E_{sat} (MV/m)	$\Delta E/E$ (%)
30	67.4	96.7	43	78.3	117.1	50
60	67.7	93.6	38	78.6	115.0	46
90	...	...	...	78.9	109.4	39
300	72.2	72.2	0	83.9	83.9	0

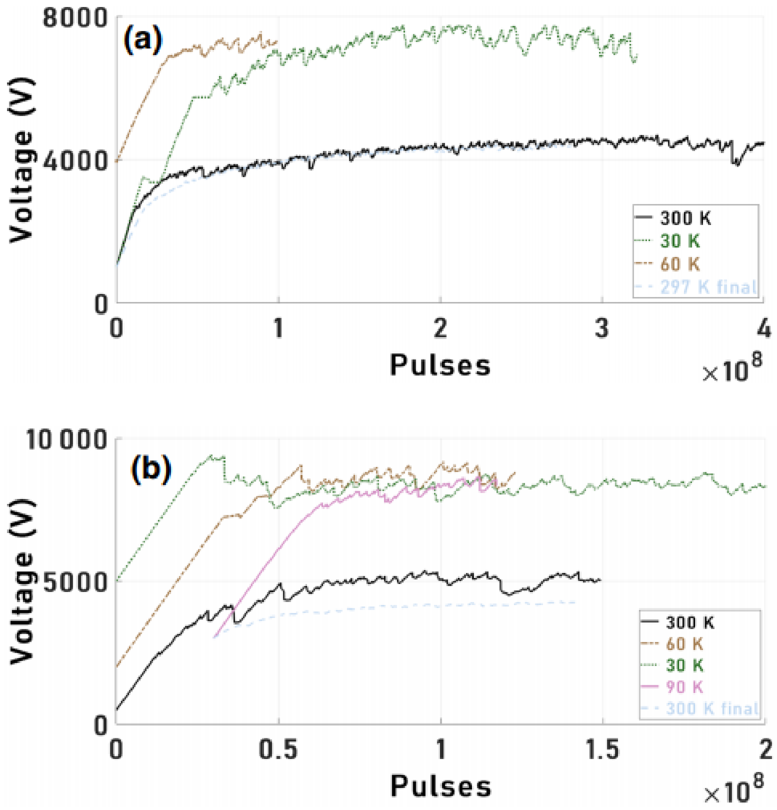
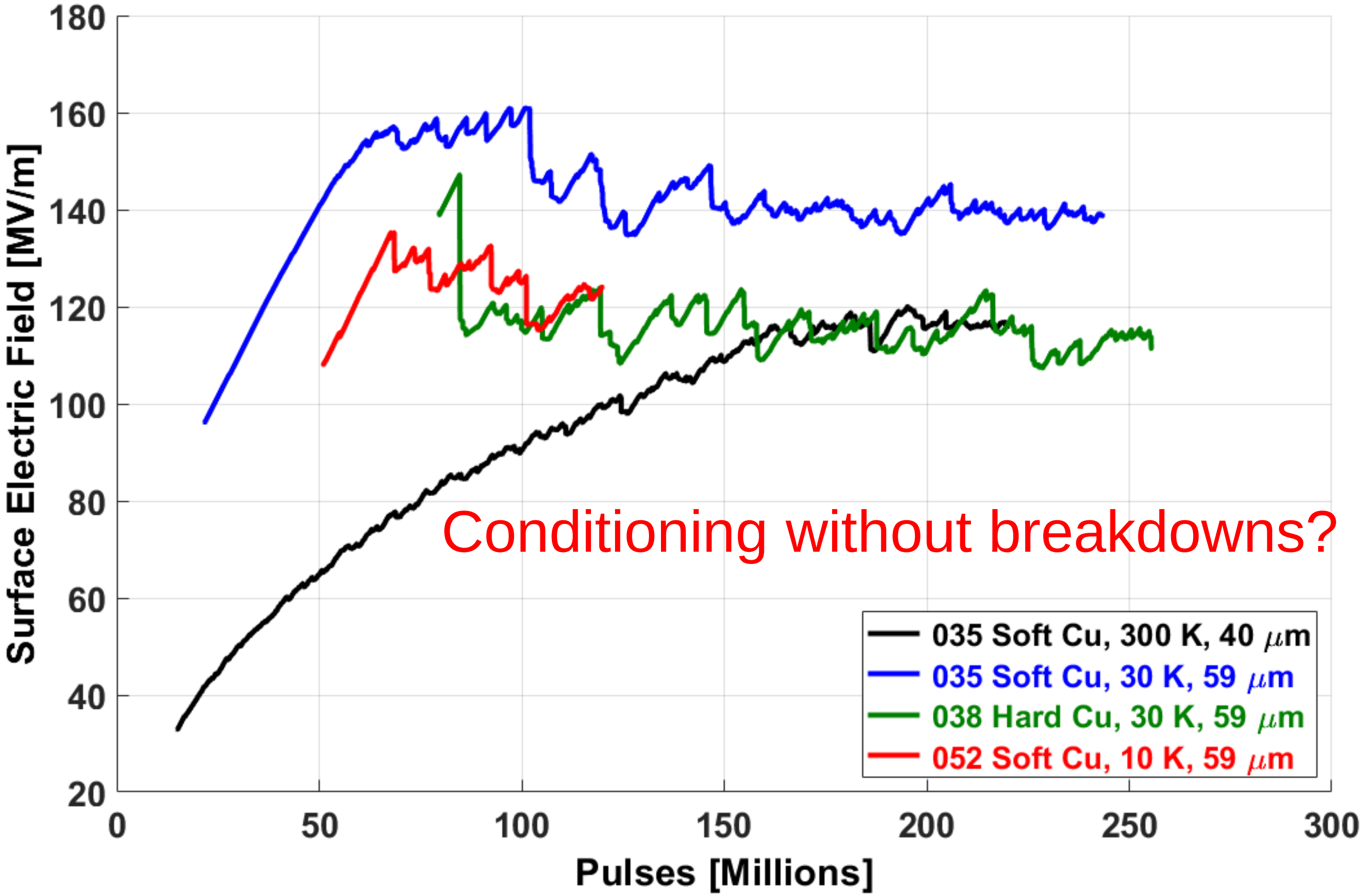


FIG. 1. Conditioning curves for all runs. Data from (a) the first set of electrodes and (b) the second set of electrodes.

Conditioning at cold



Conditioning algorithm started to apply pulses from 10 MV/m. Figure shows the cases where breakdowns are happened. First BD occurs much later at cold temperature. Also after some period surface electric field does not increase and very often even degrades.

Post-mortem microscopic analysis

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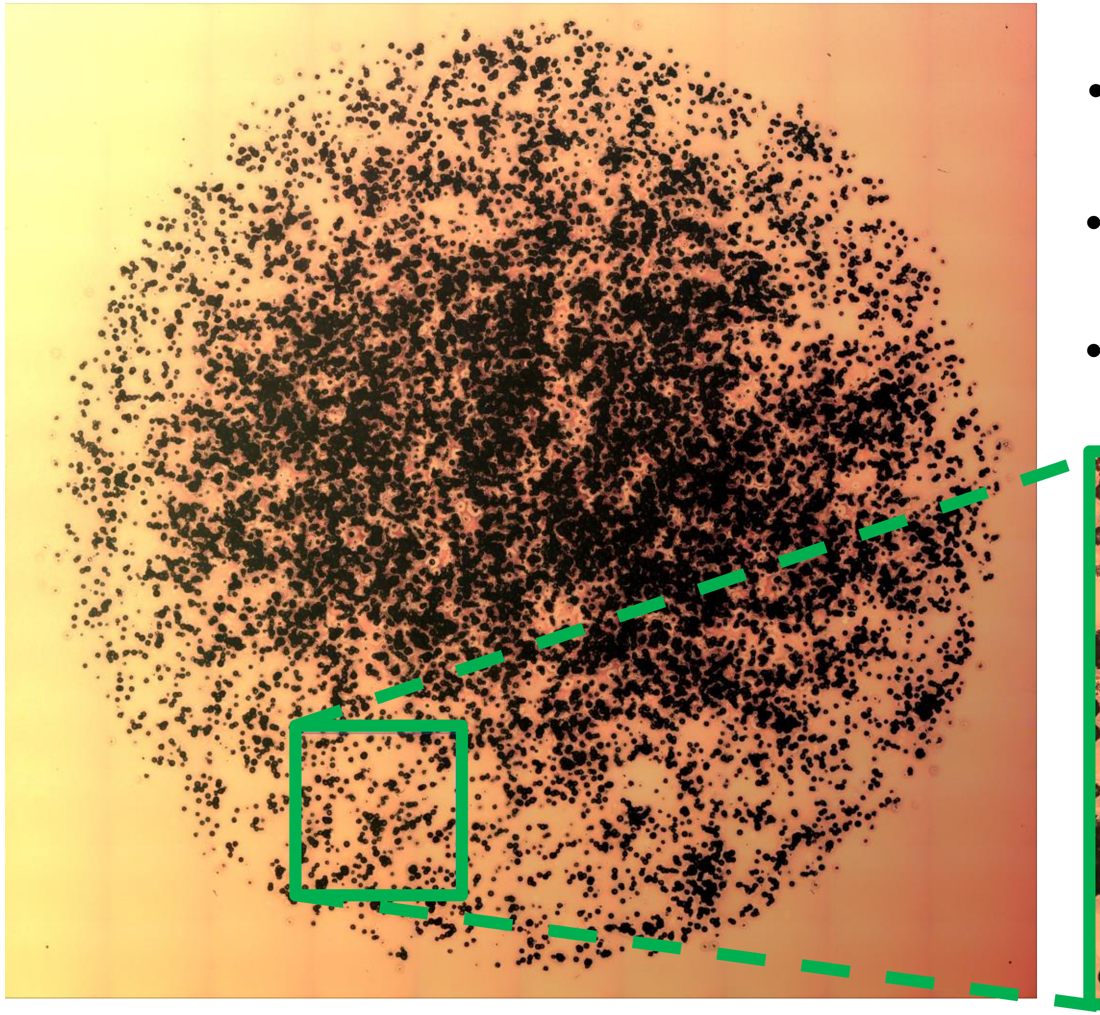
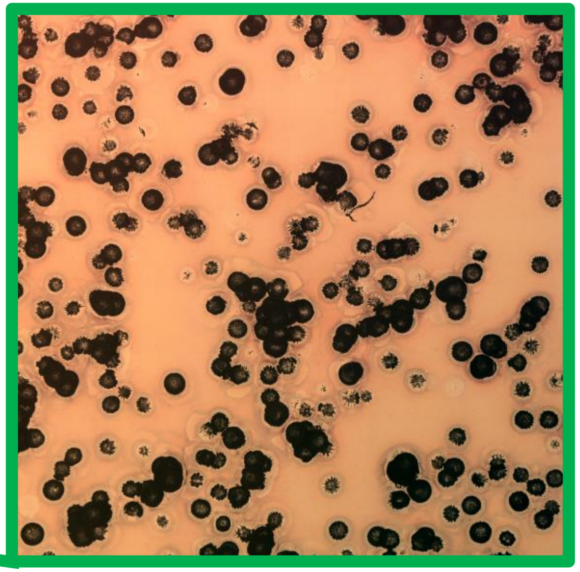
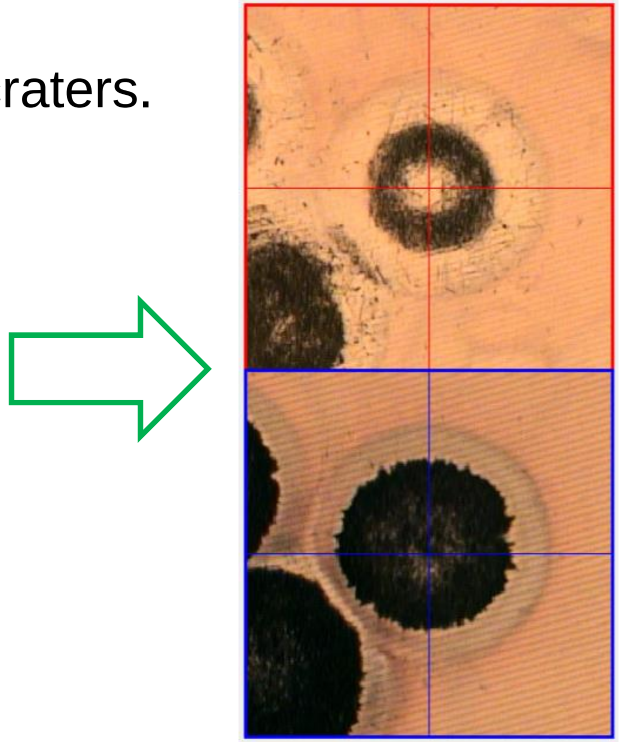
Procedure:

- Make a scan with microscope for anode and cathode;
- Found the same area and transformation factors;
- Match the craters as a BD couple;
- Fit the circles around craters.

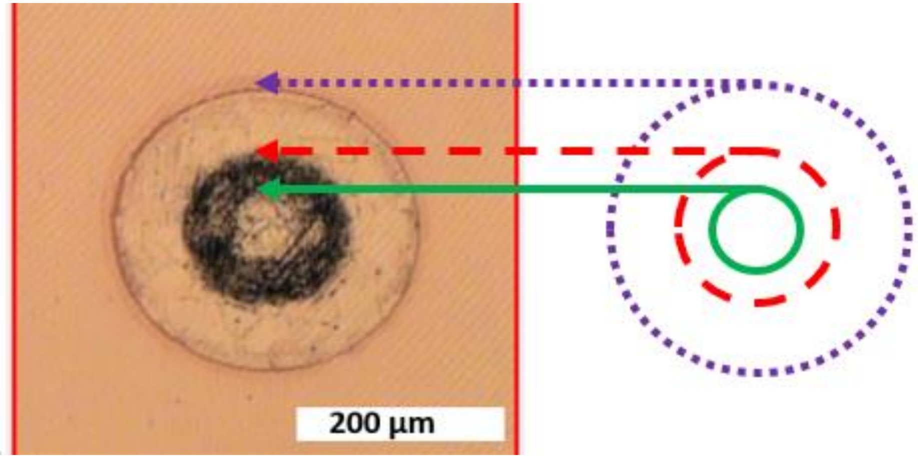




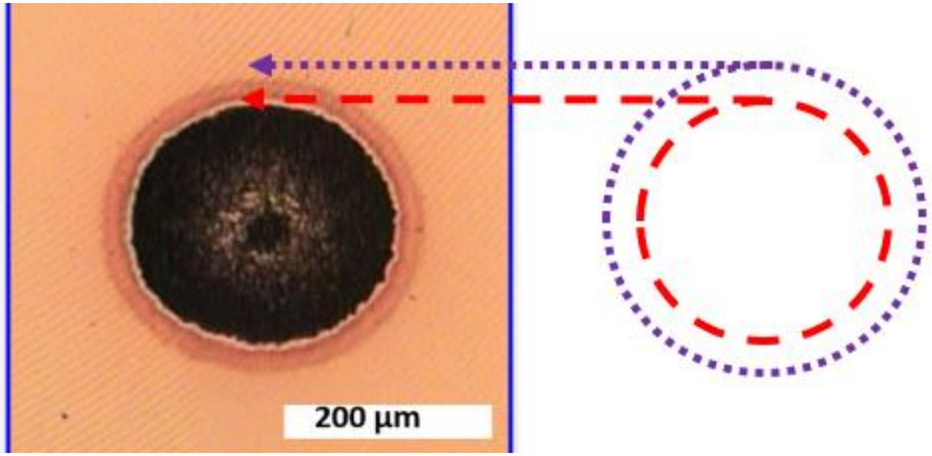


Anode versus Cathode breakdown features

…courtesy of Inna Popov



a) Anode



a) Cathode

Typical BD features:

(a) a typical round-shape anode BD feature is composed of a reflective central part (r_a) surrounded by a wavy circumference (w_a) with a thin lighter ring (tlr_a) around;

(b) a typical cathode BD feature has a wavy dark major part (w_c) and a thin lighter ring (tlr_c).

Anode versus Cathode breakdown features

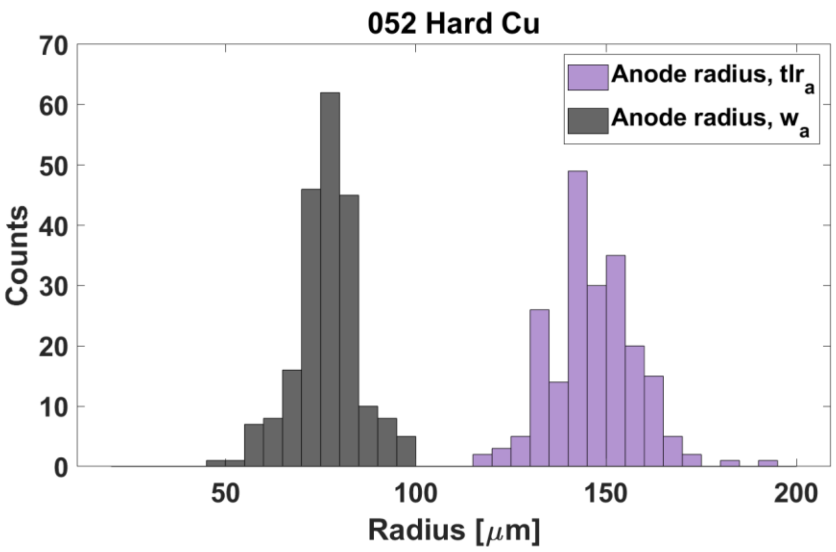
…courtesy of Inna Popov

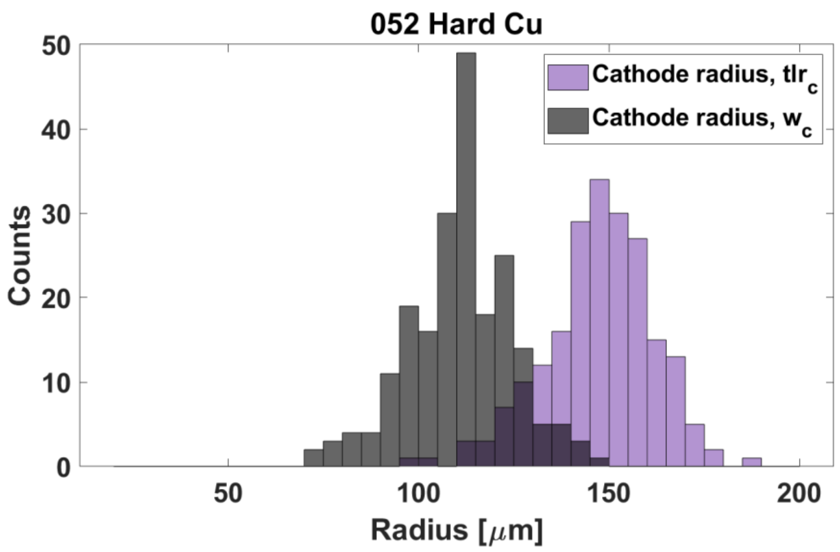
a) Anode

a) Cathode

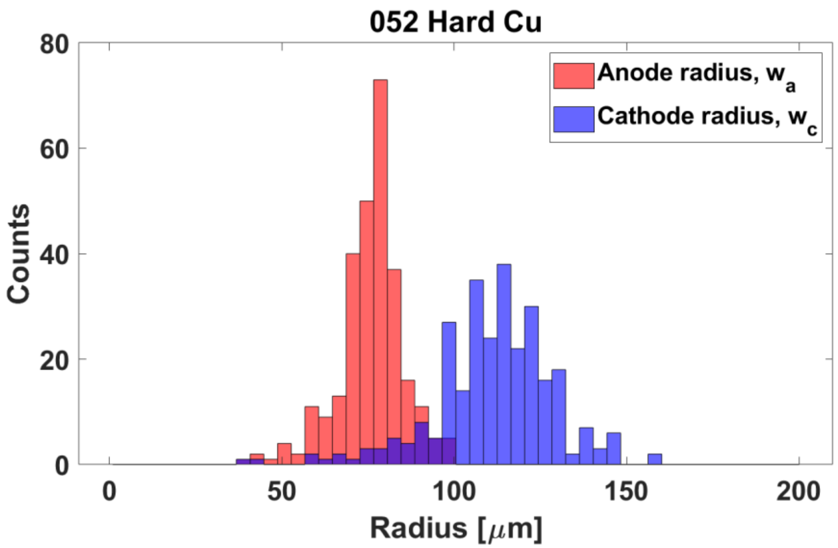
The traces from mashining is visible over anode's thin lighter ring, but now over wavy dark part. The same for cathode's BD spot. It means the depth of wavy part is deeper than at another BD areas. Also jets are common around the cathode BD feature.

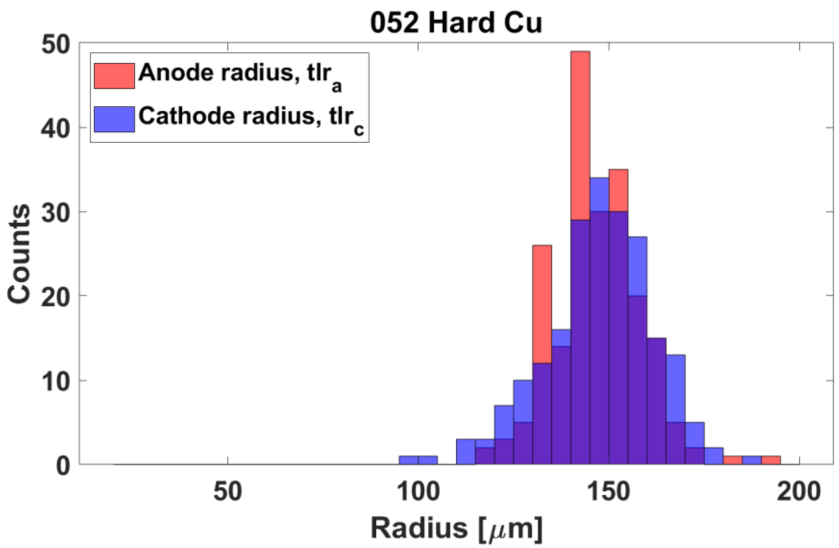
Anode versus Cathode breakdown features

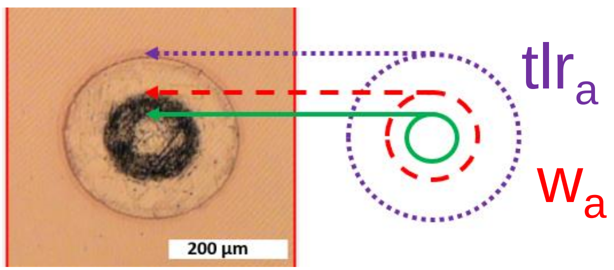


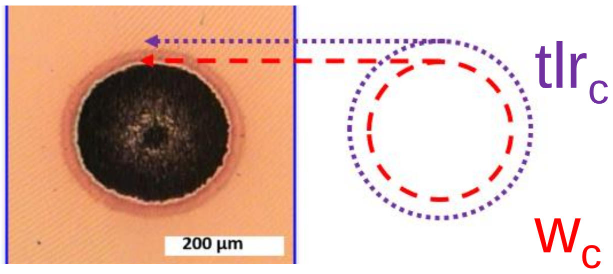


No.	Ratio name	Number
1.	tlr_a/w_a	1.93 ± 0.21
2.	tlr_c/w_c	1.33 ± 0.11
3.	w_c/w_a	1.46 ± 0.17
4.	tlr_c/tlr_a	0.99 ± 0.08

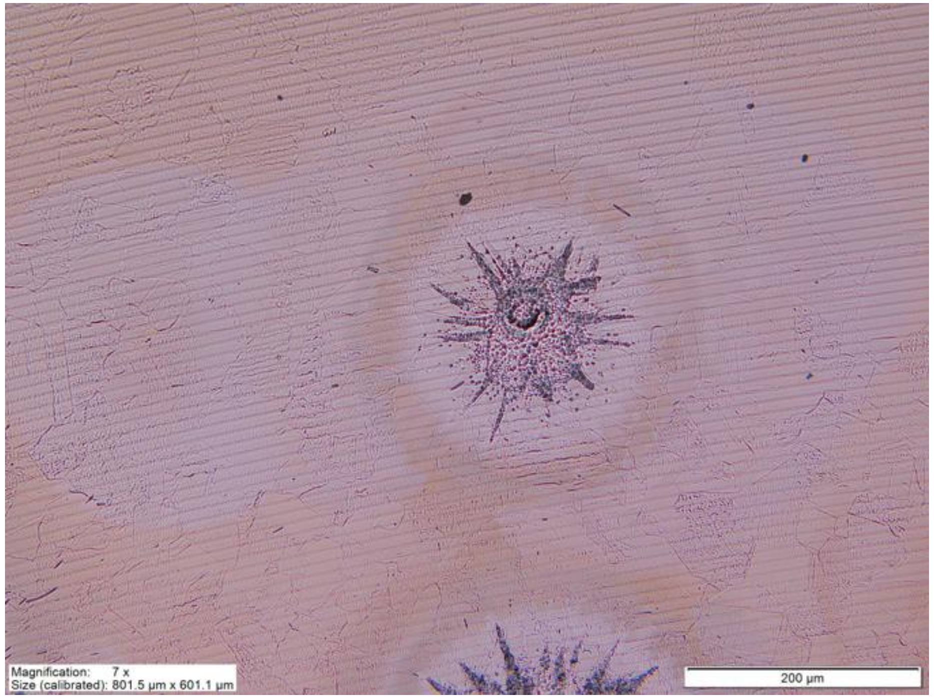


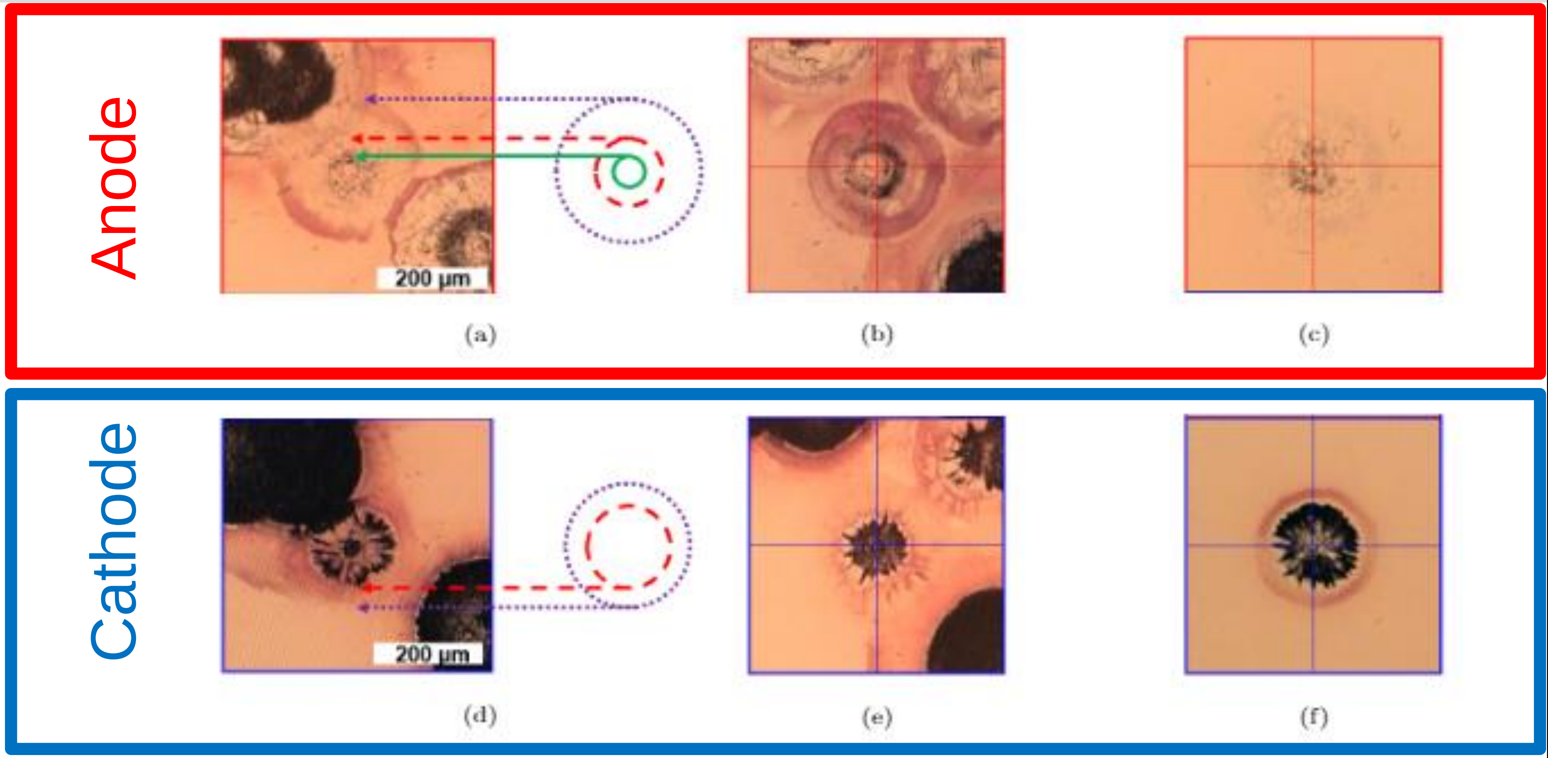






Star-like features



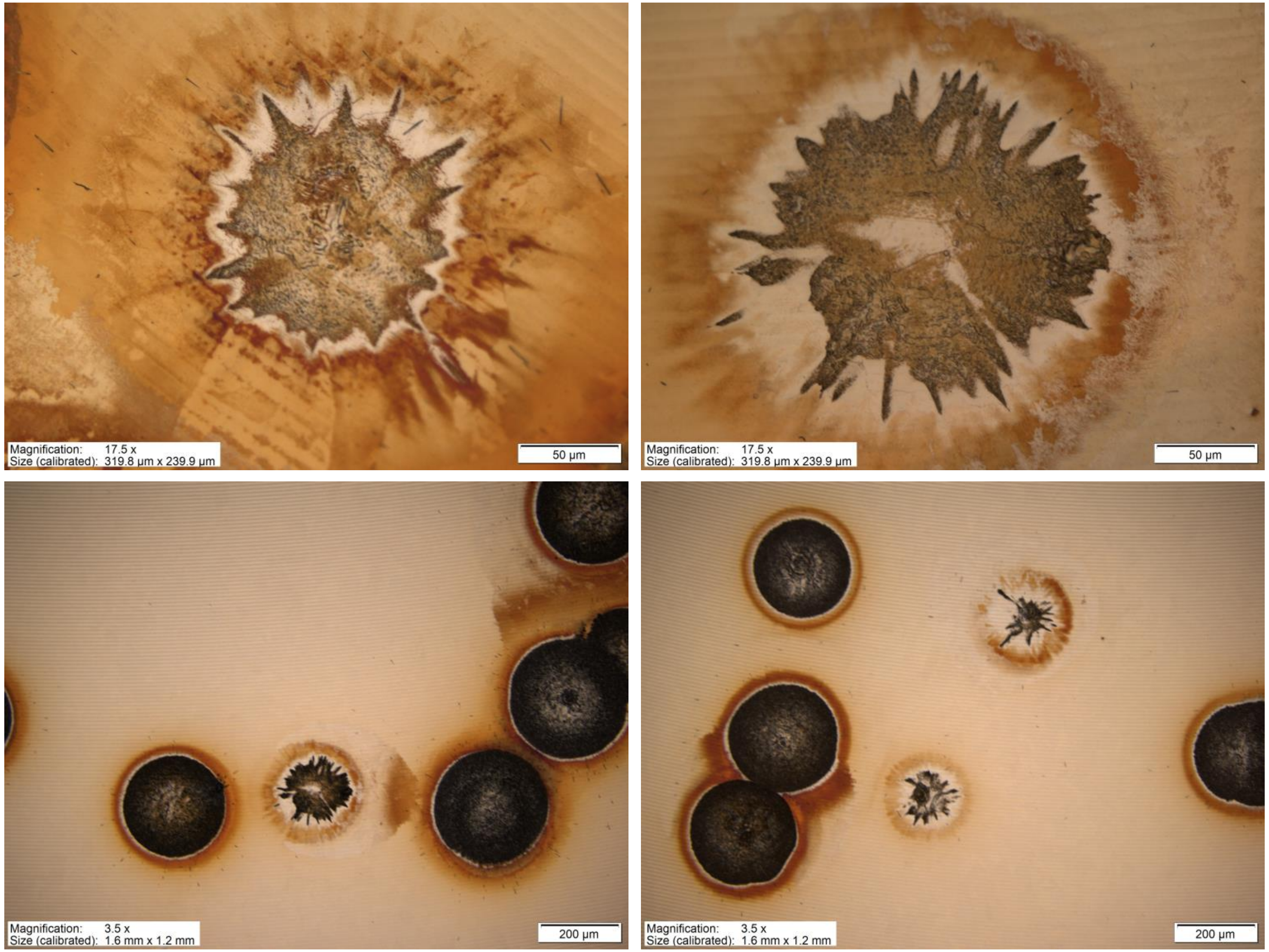


A typical round-shape anode BD feature is composed of a reflective central part (r_a) surrounded by a wavy circumference (w_a) with a thin lighter ring (tlr_a) around;
A typical cathode BD feature has a wavy dark major part (w_c) and a thin lighter ring (tlr_c).

No.	Samples	Temperature	Number of BDs	Number of star-like couples
1.	015 Cu	300 K	516	8 (1.6 ± 1 %)
2.	035 Soft Cu	300 and 30 K	232	31 (13 ± 3 %)
3.	038 Hard Cu	30 K	145	37 (26 ± 5 %)
4.	052 Hard Cu	10 K	280	149 (53 ± 7 %)

*Counted on the area 6 x 6 mm for 035, 038, 052, and full area for 015 Cu

Star-like features



- Star-like BD features found only at cathode side.
- They are do not have jets around.
- Star-like distributed more individually, separated from other BD craters.

Post-mortem microscopic analysis

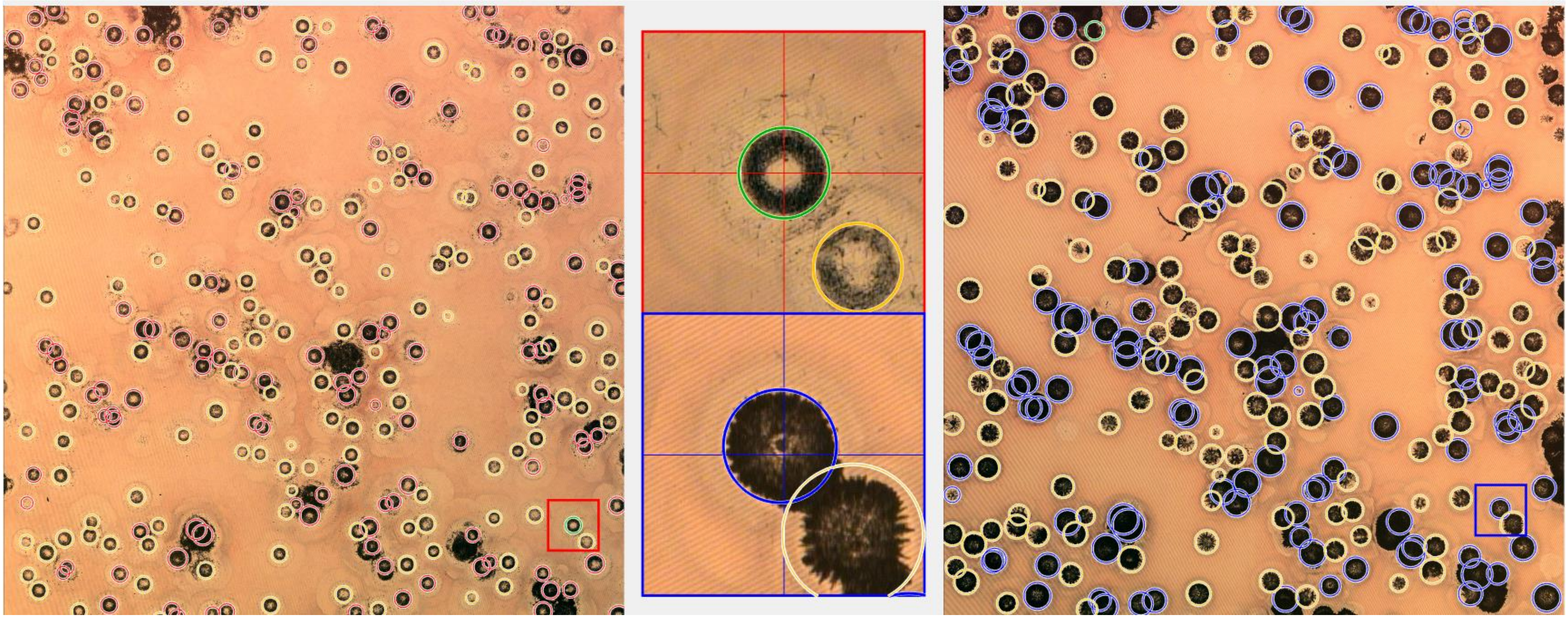
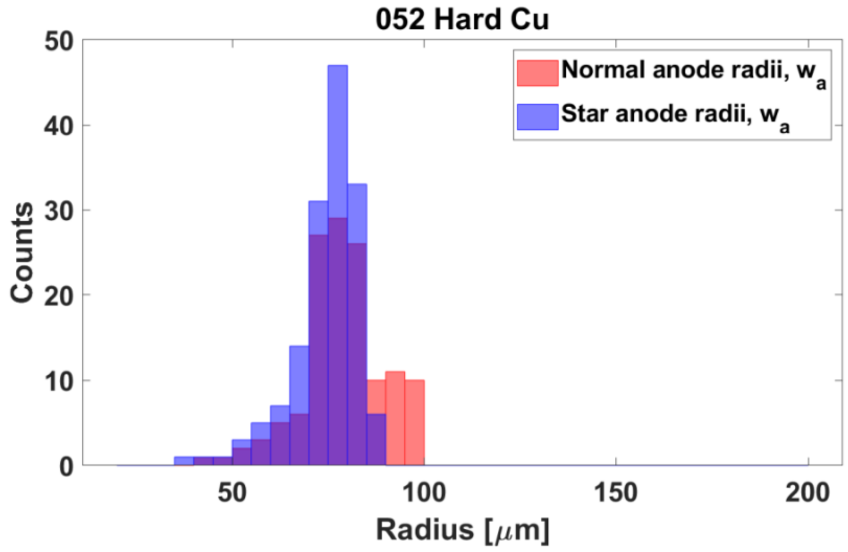
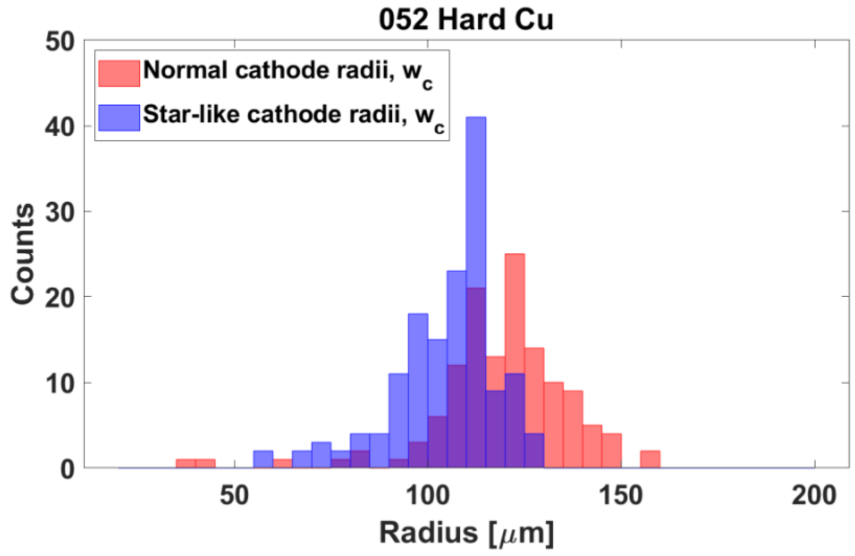


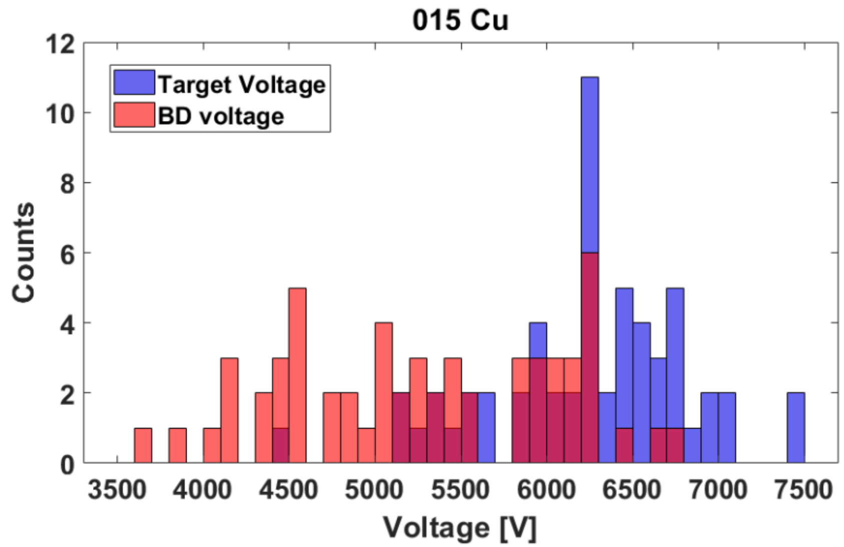
Fig. 17. Part of Cu electrode: anode on the left, cathode on the right. By yellow circles marked the couples where ”star-like” features on cathode are found. Regular BDs are in clusters, while star-like BD features more individual and separated.

Sizes of Star-likes vs Normal BD features



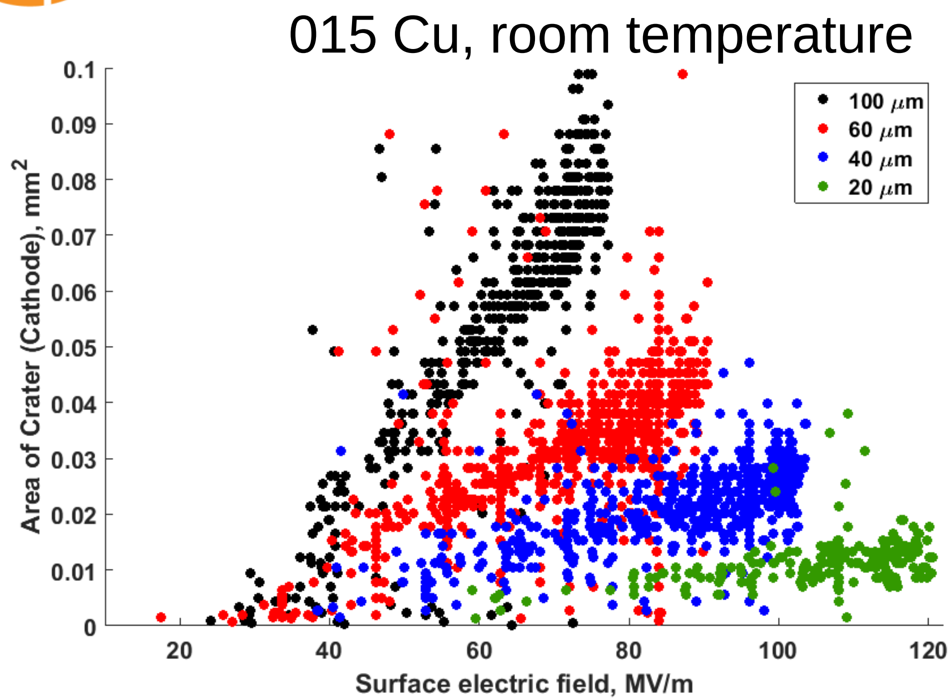


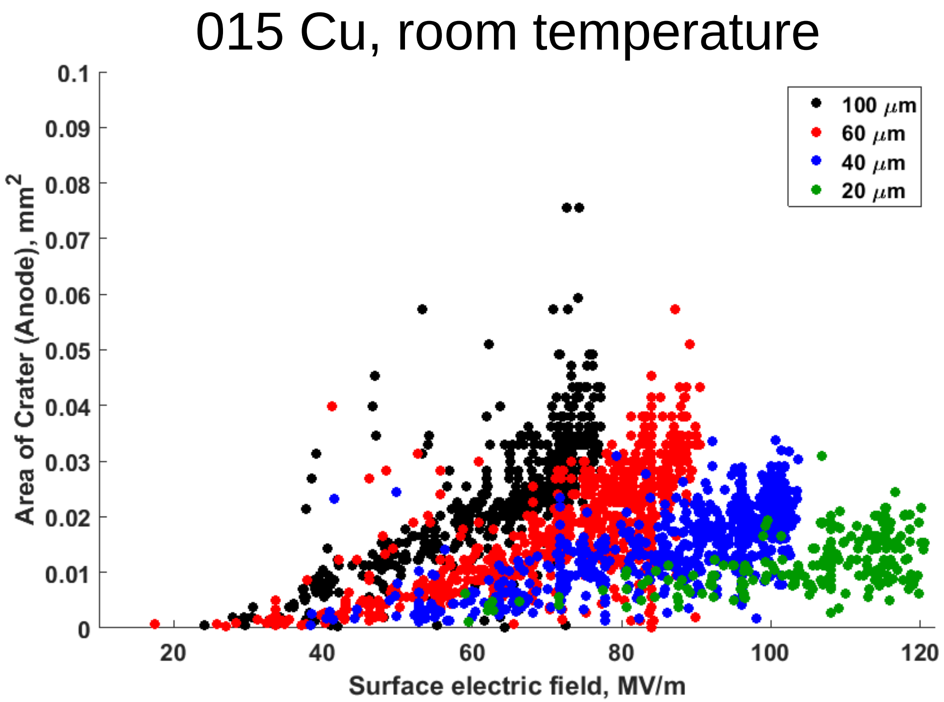
*052 Hard Cu tested at 10 K
*015 Soft Cu tested at room temperature, at CERN, where BD localisation is avaiable.



- The size of star-like features on cathode is smaller than for normal BDs, while the anode features have similar size.
- The voltage for the start-like is lower than should be for those conditions of the test.

Cathode/Anode craters



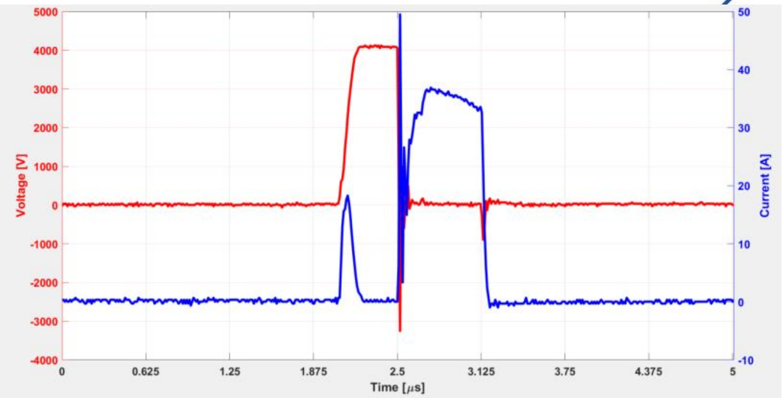


Gap, µm	Average area of the craters, mm²			Average diameter of the craters, µm		
	Cathode	Anode	Ratio C/A	Cathode	Anode	Ratio C/A
100	**0.055**	**0.023**	**2.39**	**255**	**164**	**1.55**
60	0.034	0.02	1.7	204	152	1.34
40	0.022	0.016	1.38	165	137	1.2
20	0.011	0.012	0.92	118	119	0.99

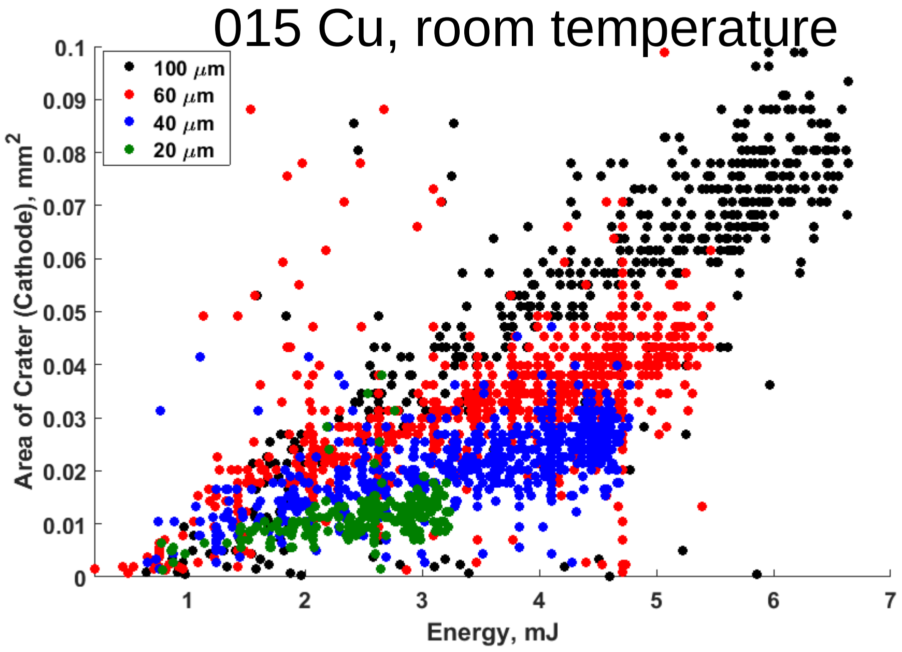
From MeVArc 2019

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.



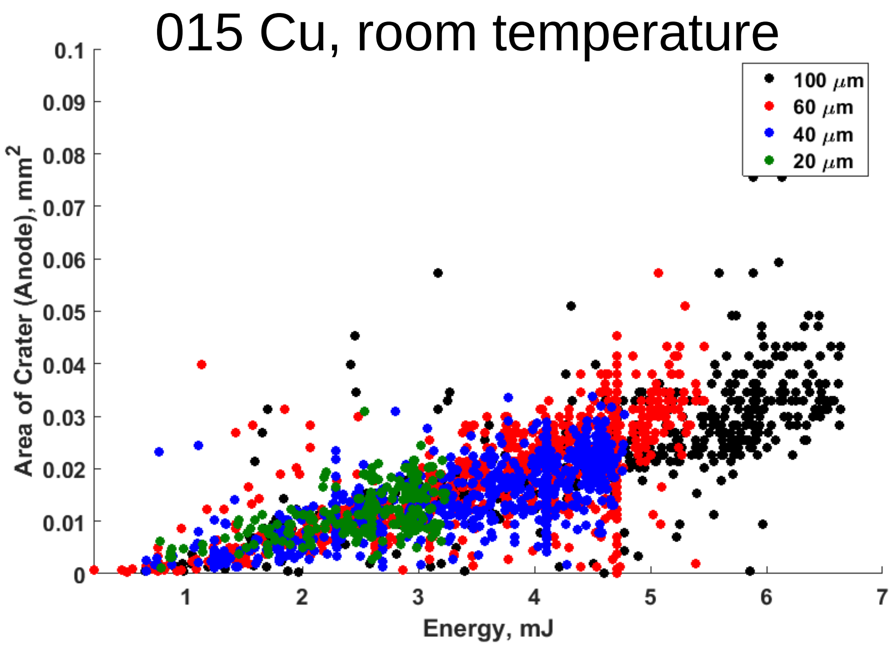


Fig. 20. The relation between crater area and energy (counted by using only first part of the formula).

From MeVArc 2019

Summary and future plans

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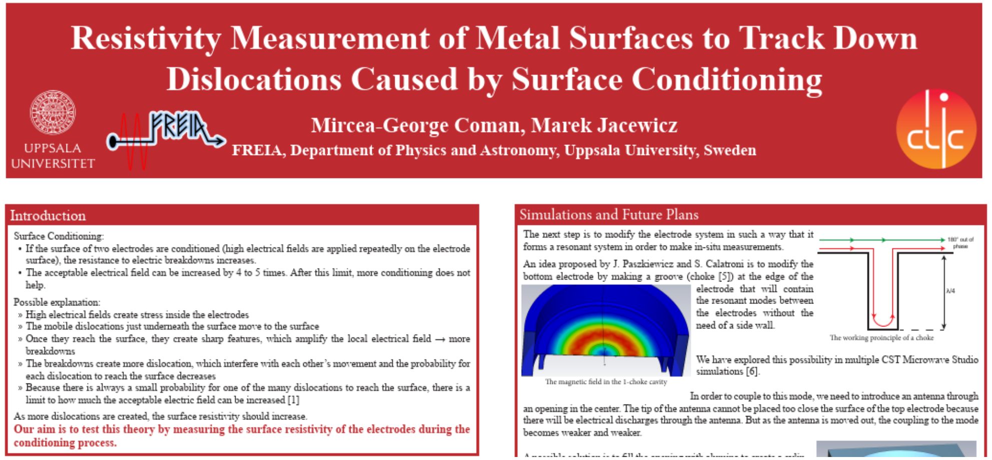
- Cathode and anode BD spots have different morphology:
  - the cathode has a deeper crater and, typically, the machining traces are destroyed by the BD. At the outer parts, in star-like BD spots traces remain visible.
  - the anode BD features usually have a reflective central part, a wavy deep circle and a shallow halo. The machining traces are destroyed only under the wavy circle.
- BD features have characteristics radii and demonstrate similarity in radii ratios for anode and cathode.
- We identified a quarter of the BD spots as star-like after HV dc test @ 30 K (26%, 37 from 145 BD spots in the analysed region) and around half – for the test @ 10 K (53%, 149 from 280 BD spots). The inter-electrode gap size was 59 µm.
- During the room temperature test less than 2% (8 from 485) of star-like BDs are found for the test with 100 µm gap between electrodes and none for the test with smaller gap.
- Star-like features were found only on cathode side with radii smaller than typical BD spot.
- The BD voltage for 95 % star-like BD features is 10 - 40% lower than expected BD voltage for the same conditions.
- Star-like BD features more separated from another BDs, than normal BDs.

Plans:

- Improve the system by recording voltage waveforms also for non-breakdown cases.
- Implement resistivity measurements of surface to track down the dislocations caused by surface conditioning (see Mircea poster).
- Test Nb and CuAg electrodes.

Related talks



Resistivity Measurement of Metal Surfaces to Track Down Dislocations Caused by Surface Conditioning

Mircea-George Coman, Marek Jacewicz

FREIA, Department of Physics and Astronomy, Uppsala University, Sweden

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Introduction

Surface Conditioning:

- If the surface of two electrodes are conditioned (high electrical fields are applied repeatedly on the electrode surface), the resistance to electric breakdowns increases.
- The acceptable electrical field can be increased by 4 to 5 times. After this limit, more conditioning does not help.

Possible explanation:

» High electrical fields create stress inside the electrodes
» The mobile dislocations just underneath the surface move to the surface
» Once they reach the surface, they create sharp features, which amplify the local electrical field → more breakdowns
» The breakdowns create more dislocation, which interfere with each other's movement and the probability for each dislocation to reach the surface decreases
» Because there is always a small probability for one of the many dislocations to reach the surface, there is a limit to how much the acceptable electric field can be increased [1]

As more dislocations are created, the surface resistivity should increase.

Our aim is to test this theory by measuring the surface resistivity of the electrodes during the conditioning process.

Simulations and Future Plans

The next step is to modify the electrode system in such a way that it forms a resonant system in order to make in-situ measurements.

An idea proposed by J. Paszkiewicz and S. Calatroni is to modify the bottom electrode by making a groove (choke [5]) at the edge of the electrode that will contain the resonant modes between the electrodes without the need of a side wall.

The magnetic field in the 1-choke cavity

The working proinciple of a choke

We have explored this possibility in multiple CST Microwave Studio simulations [6].

In order to couple to this mode, we need to introduce an antenna through an opening in the center. The tip of the antenna cannot be placed too close the surface of the top electrode because there will be electrical discharges through the antenna. But as the antenna is moved out, the coupling to the mode becomes weaker and weaker.

Tue 20/09

Time	Session	Speaker	Location	Time slot
	Coffee Break		*Chania, Crete*	09:30 - 10:00
10:00	**Recent results from the CERN pulsed DC systems**	*Ruth Peacock*	*Chania, Crete*	10:00 - 10:30
	Microscopy investigation on different materials after pulsed high field conditioning and low energy H- irradiation.	*Catarina Serafim*		
16:00	HV Discharges Monitoring at HVPTF: Perspectives from X-ray Spectroscopy	*Matteo Hakeem Kushoro*	*Chania, Crete*	16:05 - 16:15
	Plasmonics manipulation of Photoemission	*Victoria Bjelland*	*Chania, Crete*	16:20 - 16:30
	Elemental Theory of Photoemission and Nanoplasmonics	*Victoria Bjelland*	*Chania, Crete*	16:35 - 16:45
	Resistivity Measurement of Metal Surfaces to Track Down Dislocations Caused by Surface Conditioning	*Mircea-George Coman*		

Thank you for attention!

Extra slides

Soft and Hard Cu features

Table 8: Hardness of copper, HV.

Material	Reference	**Conditioned non-BD site**		**Conditioned BD site**	
Place		center	edge	center	edge
Hard Cu	116.04 ± 3.64	107.74 ± 3.48	109.54 ± 3.27	97.29 ± 6.33	93.19 ± 3.26
Soft Cu	47.08 ± 1.0	48.57 ± 1.47	46.3 ± 1.10	76.46 ± 7.07	78.8 ± 6.9

Bibliography

- M. Jacewicz, J. Eriksson, R. Ruber, S. Calatroni, Ia. Profatilova, W. Wuensch, **Temperature-dependent field emission and breakdown measurements using a pulsed high-voltage cryosystem**, Phys. Rev. Applied 14, 061002 – 2020. (http://doi.org/10.1103/PhysRevApplied.14.061002)
- Ia. Profatilova, X. Stragier, S. Calatroni, E. Rodriguez Castro, A. Kandratsyeu, W. Wuensch, **Breakdown localisation in a pulsed DC electrode system**, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 953, 163079 – 2020. (https://doi.org/10.1016/j.nima.2019.163079)
- Marek talk on MeVArc 2019: https://indico.cern.ch/event/774138/contributions/3507926/
- Elias talk on MeVArc 2020: https://indico.cern.ch/event/966437/contributions/4245442/

Anode / cathode BD features

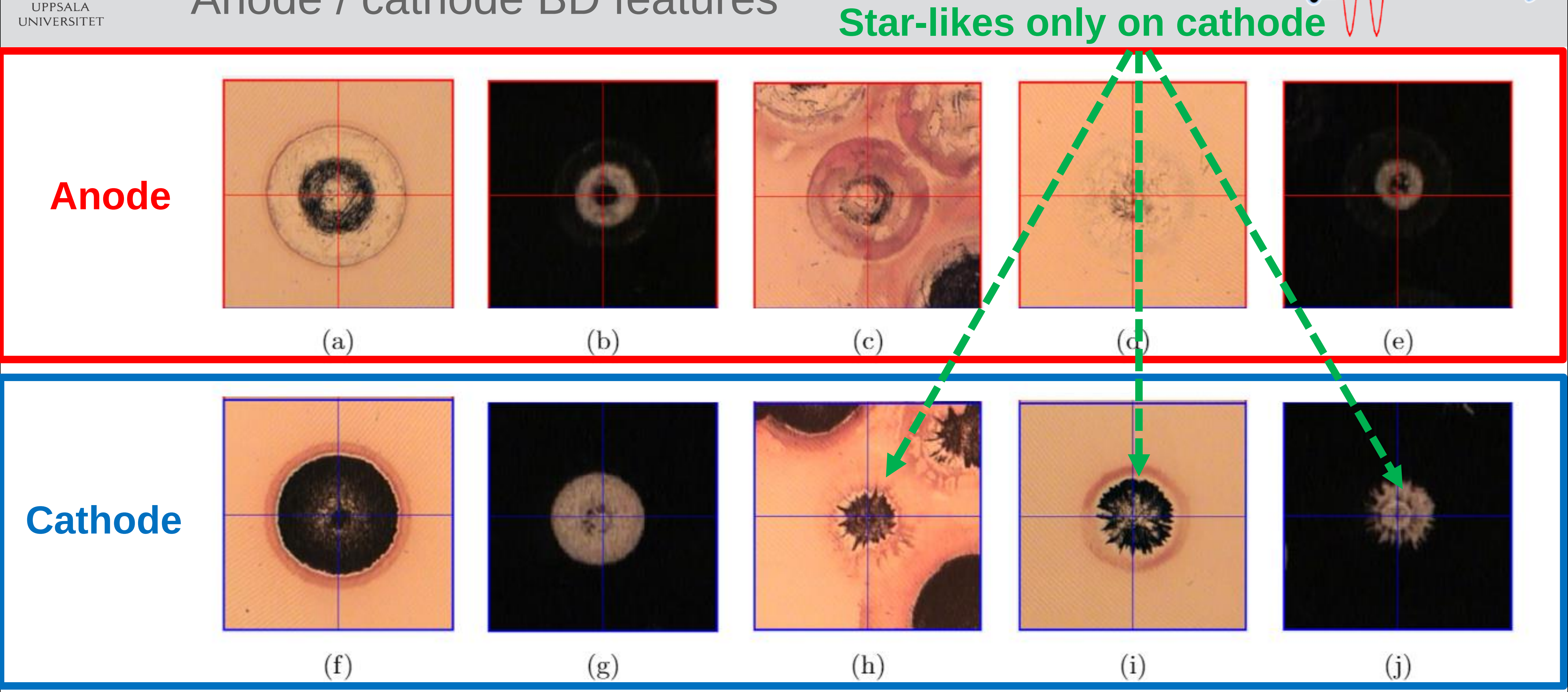

Fig. 6. BD features on the anode and cathode, matched by couples.