In-situ plasma treatment of Cu surfaces for reducing the generation of vacuum arc breakdowns

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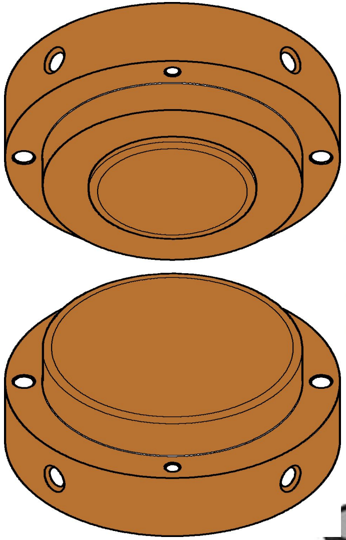
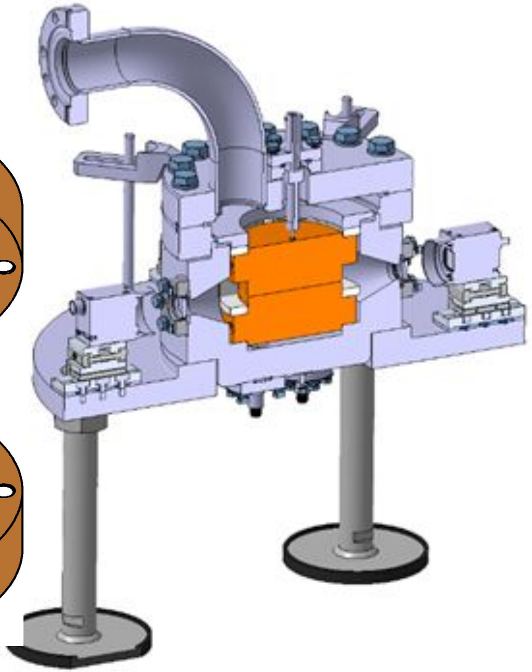
Contents

Breakdown experiments with Large Electrode System (LES)

- "Compact" system to mimic the larger RF test stands
- BD generation with electric pulses
    - Pulse width: 1 µs
    - Repetition rate: 2 000 Hz
- Two cylindrical Cu electrodes
    - 40 µm or 60 µm gap in between
    - 40 mm anode vs 60 mm cathode (contact area diameter)
- Electric fields up to 150 MV/m (up to 6 000 V)
- High vacuum (~10^{-7} mbar)

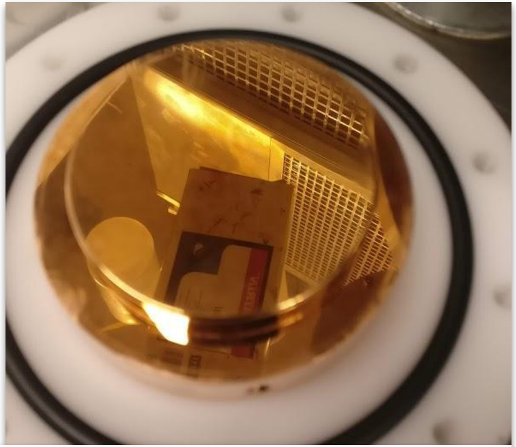


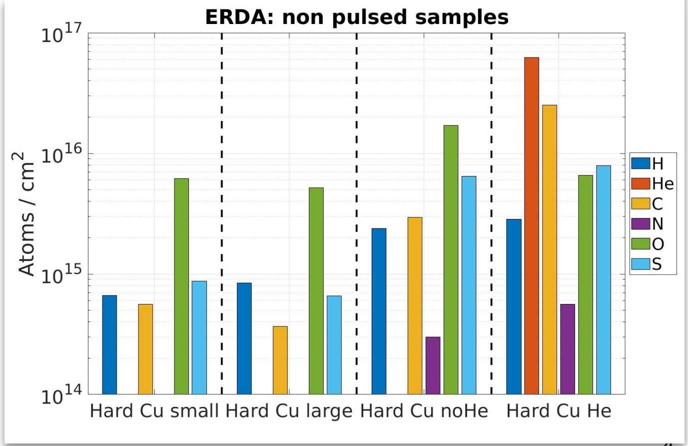


How clean are the electrode surfaces?

- New electrodes undergo a degreasing procedure after manufacturing
- Surfaces are visually very clean
- Electrodes in storage up to years before first BD experiments
  - Sometimes in nitrogen, sometimes in air
- Surface elemental analysis after the storage shows small amounts of H, C, O and S
- Our recent results show that any (vacuum) idle time increases BD probability
  - Even small amount of vacuum residuals can stimulate BDs?

Saressalo, A., Profatilova, I., Millar, W. L., Kyritsakis, A., Calatroni, S., Wuensch, W., & Djurabekova, F. (2020). Effect of dc voltage pulsing on high-vacuum electrical breakdowns near Cu surfaces. *Physical review accelerators and beams*, *23*(11), 113101.





Measurements: Kenichiro Mizohata

Implementation

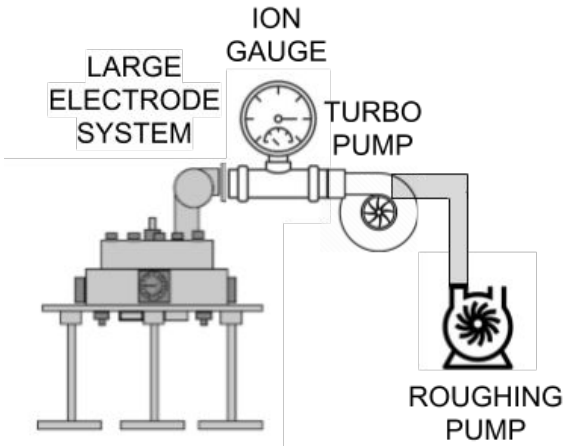
Plasma treatment with LES

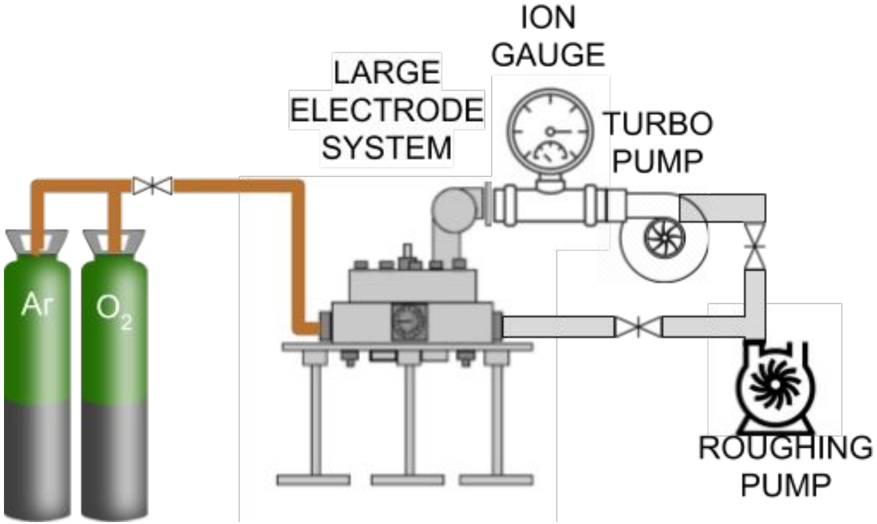
Idea

- Insert gas into the vacuum chamber
- Ionize the gas with electric field
- Ionized particles bombard the electrodes cleaning the surface
    - Oxygen to remove hydrocarbons
    - Argon to remove oxygen

Implementation

- LES already able to ionize gases!
- Gas inserted via one of the viewports
- Another viewport needed to bypass the turbo pump in order to maintain the 1-100 mbar pressure



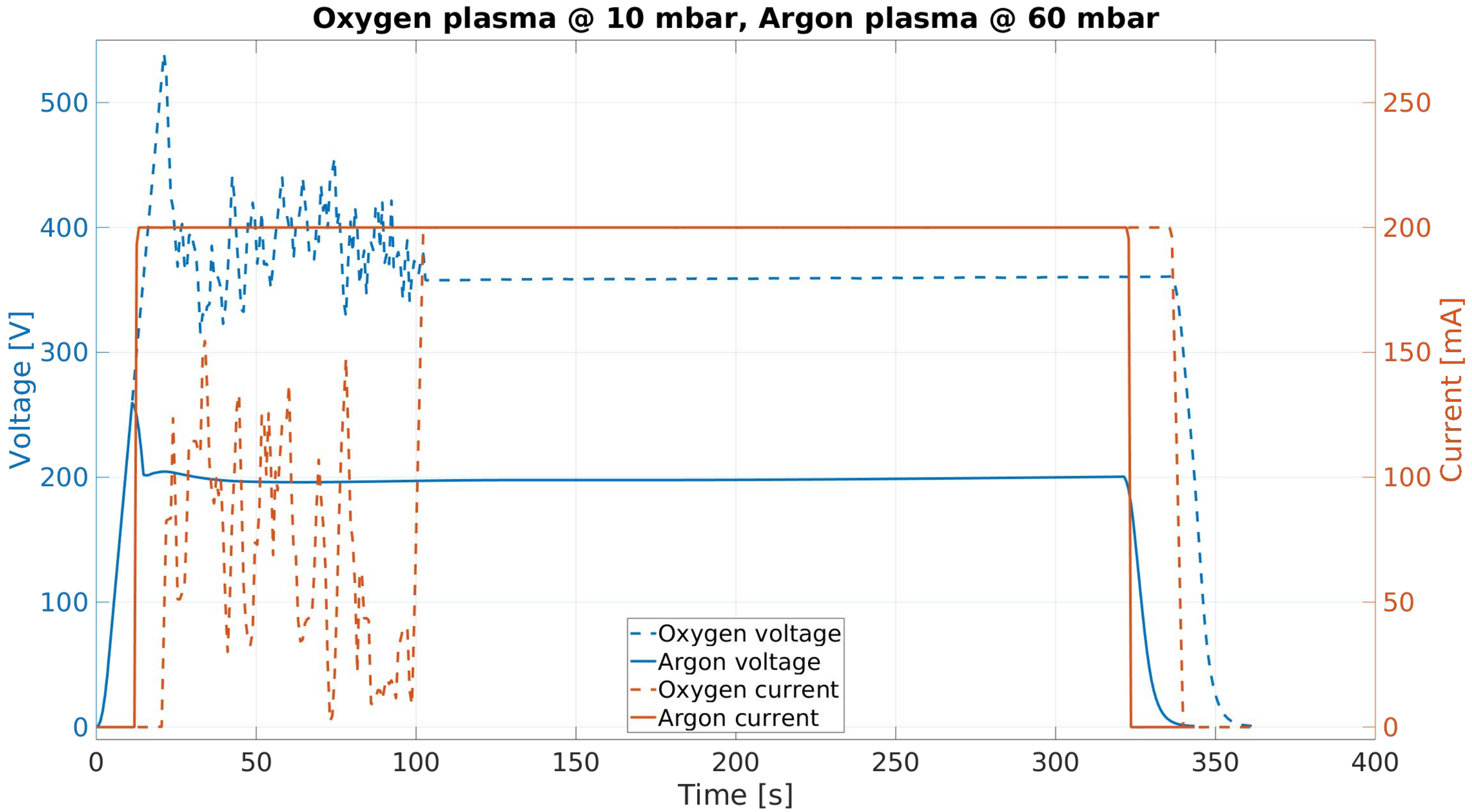


Plasma cleaning procedure

1. Pump the LES chamber into high vacuum
2. Fill the chamber with the ionizable gas (10 mbar for O and 60 mbar for Ar)
3. Apply constant DC voltage across the gap
   a. Increase the value until stable current
4. Maintain constant voltage & current for 5-10 min
5. Switch off voltage & pump back high vacuum
6. Repeat steps 2-5 with the other gas

Plasma characteristics

Plasma characteristics - Voltage stability



Plasma characteristics - Paschen curve

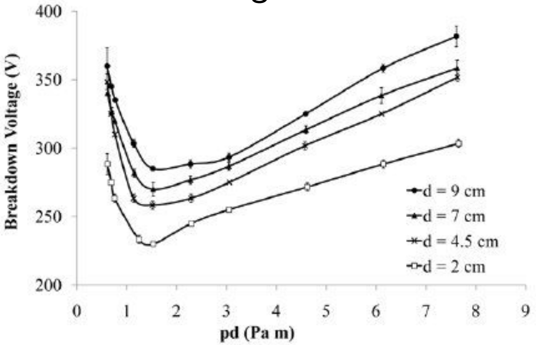
Paschen's law

- Mean free path of an electron in gas under electric field vs gas molecular density
  - If MFP is short (high pressure)
    □ no time to accelerate & ionize gas molecules
  - If MFP is long, but the gas density is small
    □ low frequency for collisions
  - Balance between electric field & pressure
    □ Ideal for ionizing molecules & forming avalanches

$$MFP \approx \frac{1}{n\sigma} = \frac{kT}{P\sigma}$$

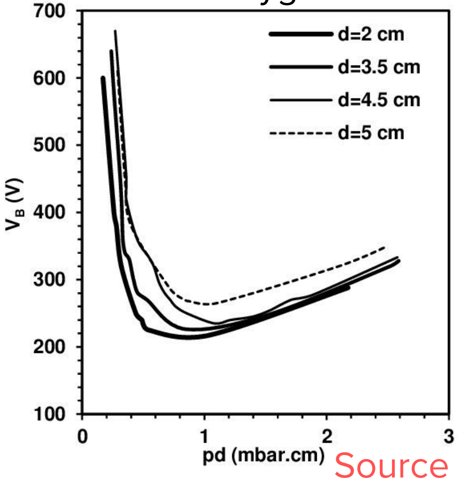
MFP(Ar, 60 mbar) ≈ 44 µm (!)
MFP(O_2, 10 mbar) ≈ 131 µm

Argon



Source

Oxygen



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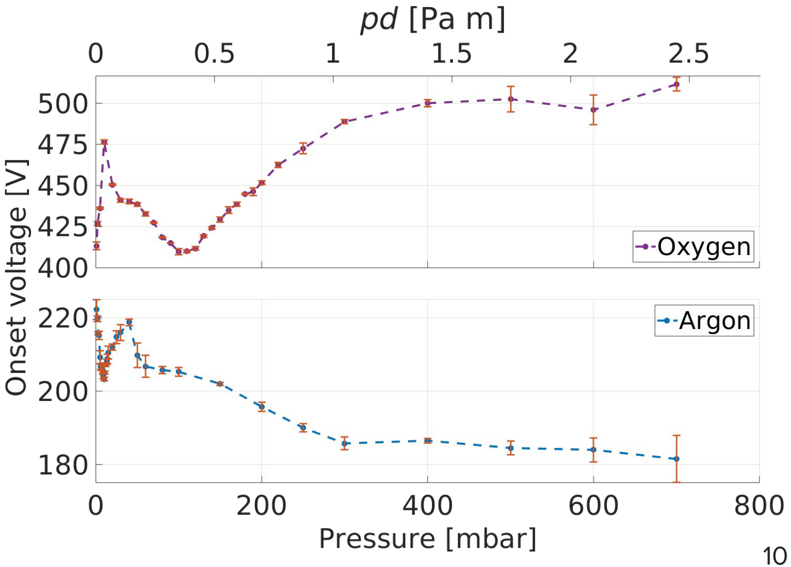
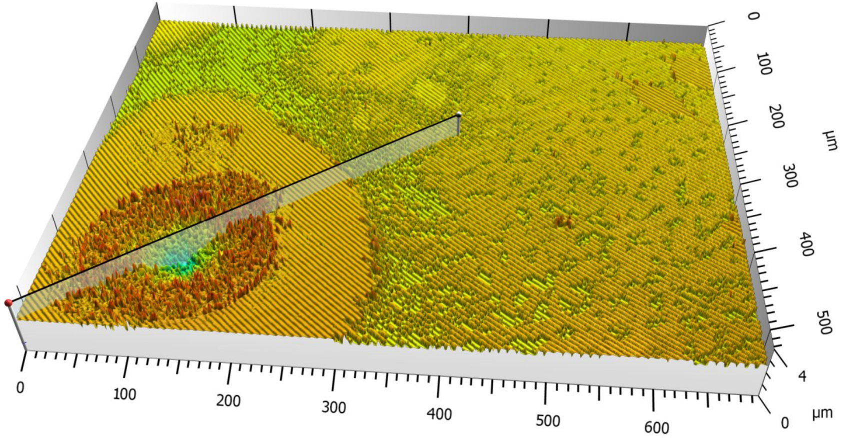
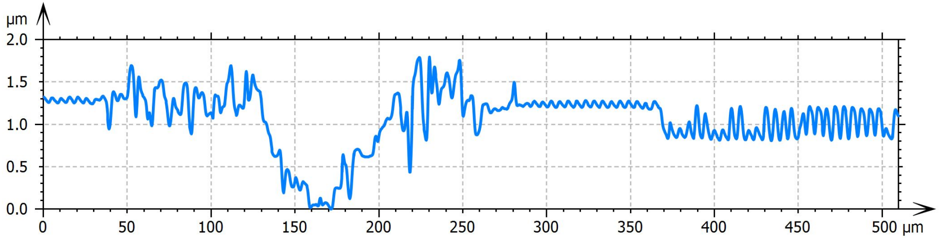


Plasma craters

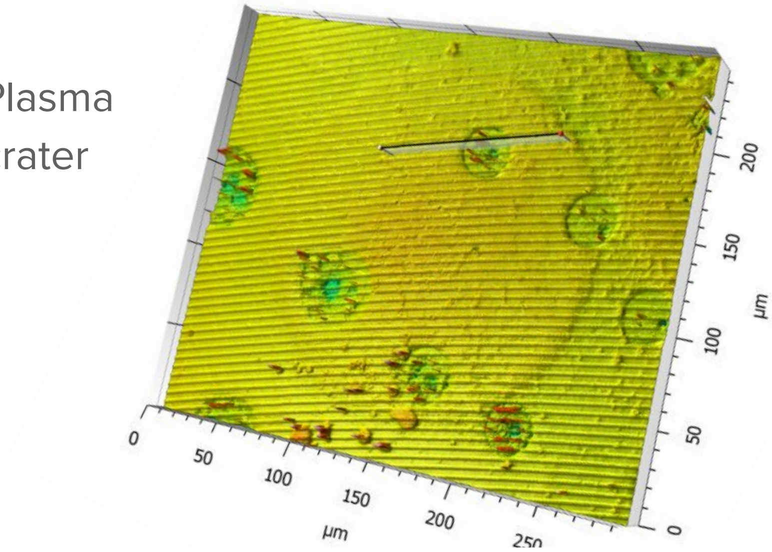
Plasma crater vs BD crater on cathode with Scanning White Light Interferometer (SWLI)

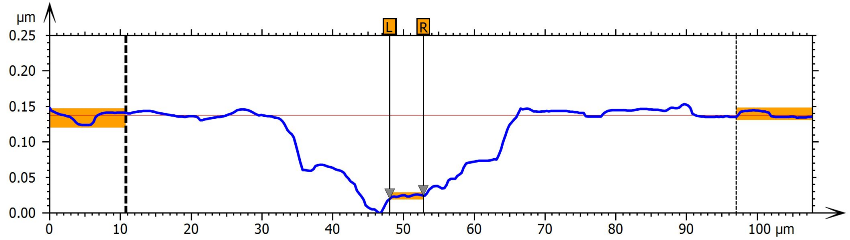
BD crater





Plasma crater





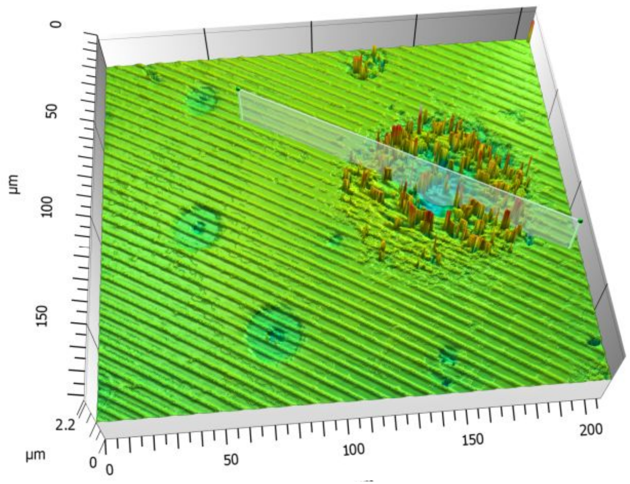
Parameters	Step 1	Unit
Mean height	0.11	µm

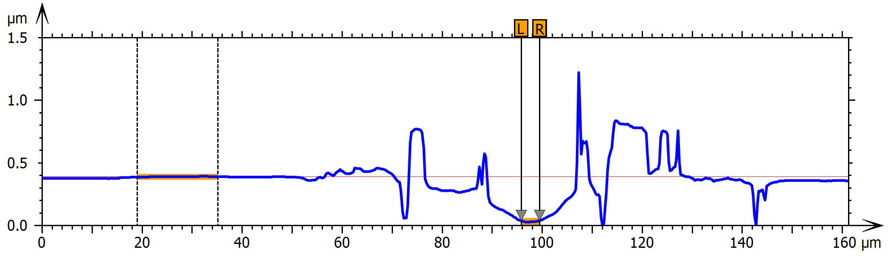
Measurements: Anton Nolvi

Plasma crater vs BD crater on anode (SWLI)

Measurements: Anton Nolvi

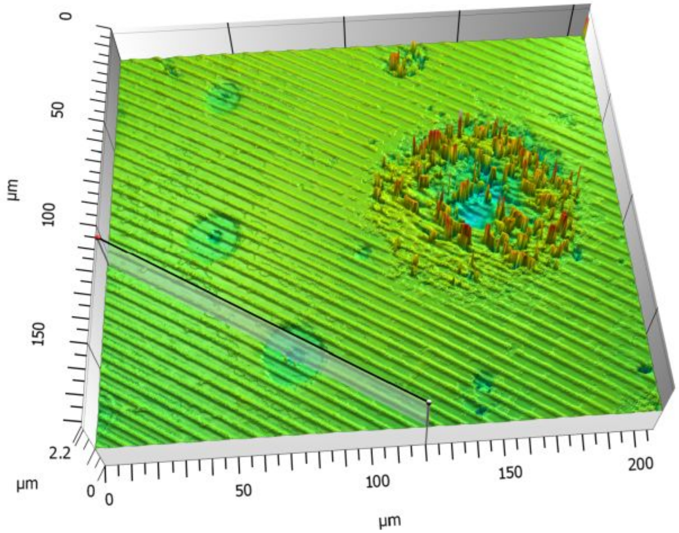
BD crater

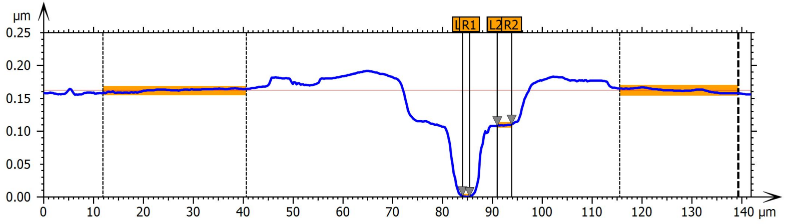




Parameters	Step 1	Unit
Mean height	0.36	µm

Plasma crater





Parameters	Unit	Step 1	Step 2
Mean height	µm	0.16	0.053

Surface elemental analysis

Surface elemental analysis with ERDA

Elastic Recoil Detection Analysis

- Measurements with the 5 MV Tandem accelerator at the University of Helsinki
- 40 MeV $^{127}I^{7+}$ ions bombarded on ~1 mm^2 area
- Elemental composition profile up to ~500 nm below surface

Hard Cu 039 history
1. ERDA measurement
2. O+Ar Plasma treatment
3. ERDA measurement
4. O Plasma treatment
5. ERDA measurement
6. Ar plasma treatment
7. ERDA Measurement
8. O+Ar plasma treatment
9. Conditioning

Unit: 1e15 at/cm^2	**Anode (40 mm, #0186)**										**Cathode (40 mm, #0185)**									
Measurement	**H**	**+-**	**C**	**+-**	**N**	**+-**	**O**	**+-**	**S**	**+-**	**H**	**+-**	**C**	**+-**	**N**	**+-**	**O**	**+-**	**S**	**+-**
Clean electrodes from packaging	1.39	0.36	1.41	0.21			6.88	0.44	0.80	0.14	1.89	0.36	1.82	0.25			7.88	0.51	1.17	0.18
After O+Ar plasma + weekend in vacuum	1.64	0.53	1.57	0.20	0.29	0.08	7.65	0.42	0.81	0.12	2.07	0.62	1.79	0.22	0.47	0.10	8.77	0.46	1.07	0.14
Right after O+Ar plasma	1.00	0.50	1.28	0.17	0.10		5.39	0.36	0.50	0.10	1.08	0.52	1.35	0.19	0.27	0.08	8.52	0.45	0.60	0.11
Right after O plasma	3.48	0.85	2.78	0.27	0.13		8.33	0.46	0.80	0.13	2.65	0.70	2.62	0.27	0.20		11.4	0.54	0.88	0.14
RIght after Ar plasma	3.56	0.71	3.83	0.29	0.49	0.09	11.2	0.61	0.85	0.16	2.18	0.78	1.82	0.26	0.17		9.85	0.58	1.30	0.19

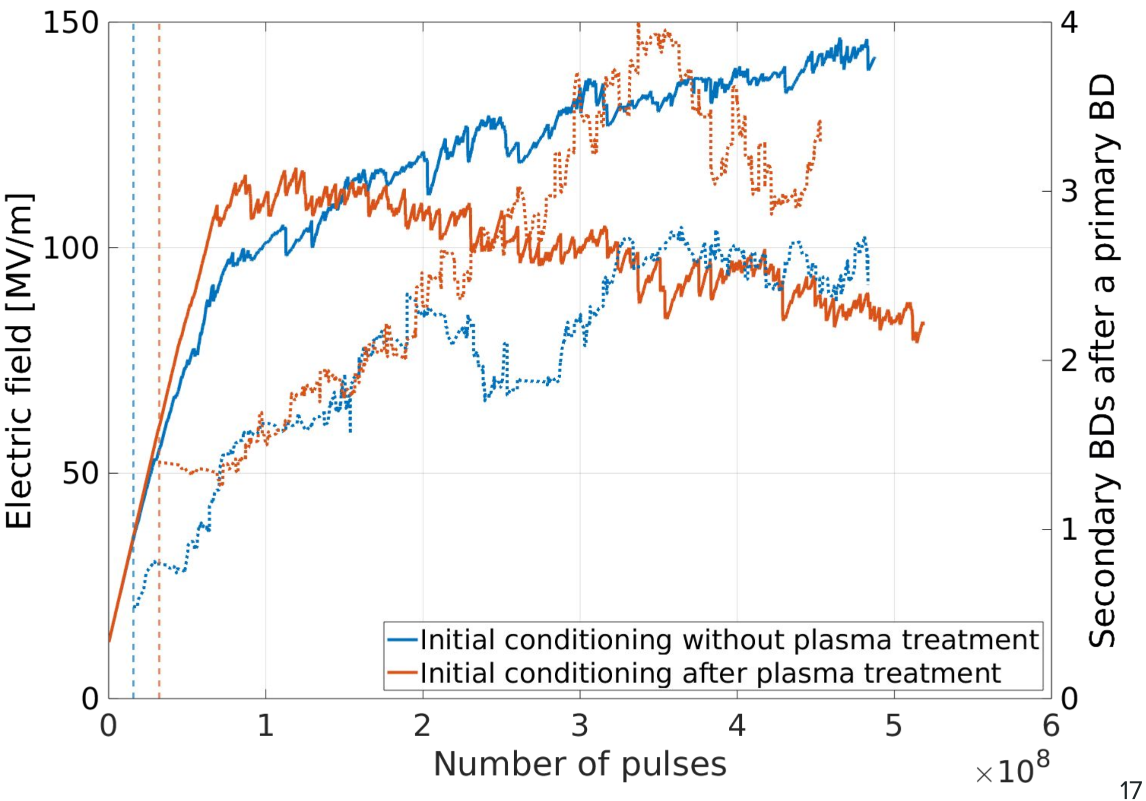
Measurements: Kenichiro Mizohata

Effects on BD generation

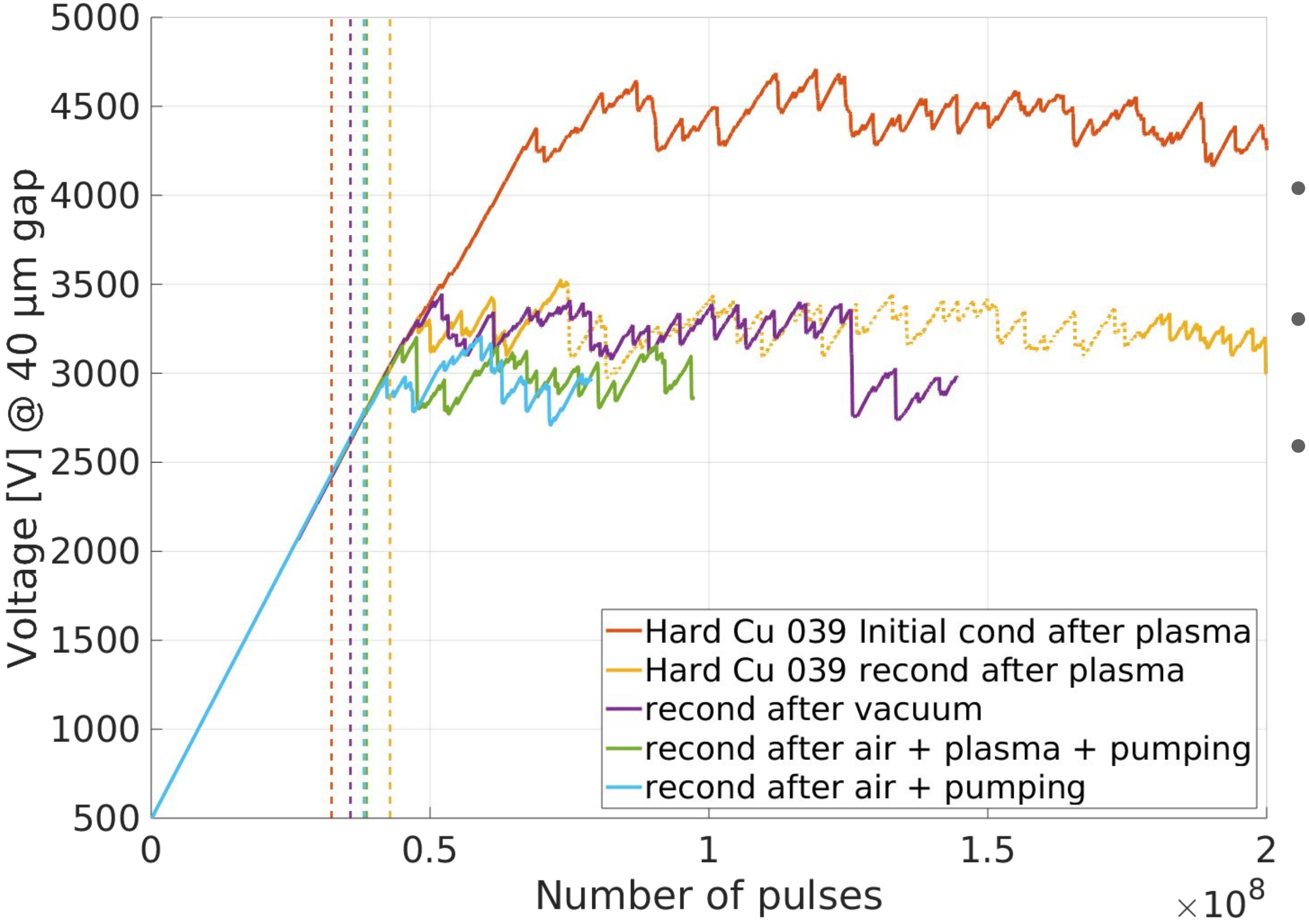
Plasma effects on BDs: First conditioning

Hard Cu 039 history
1. ERDA measurement
2. O+Ar Plasma treatment
3. ERDA measurement
4. O Plasma treatment
5. ERDA measurement
6. Ar plasma treatment
7. ERDA Measurement
8. O+Ar plasma treatment
9. Conditioning

- Initial conditioning after plasma very rapid
  - First BD at double the field (60 MV/m vs 35 MV/m)!
  - Typically between 30-40 MV/m with other electrodes & geometries
- Decline after 10^8 pulses
  - Possibly due to high pressure (5e-7 mbar vs the typical < 8e-8 mbar)
  - Similar lower saturation voltage seen with Hard 031 at such pressure
- Difference in the number of secondary BDs



Minimal effects on reconditioning runs

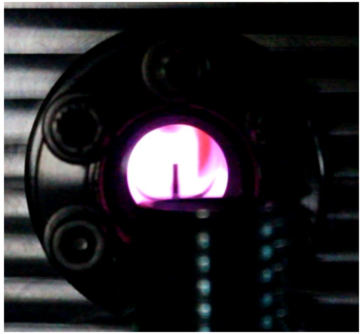


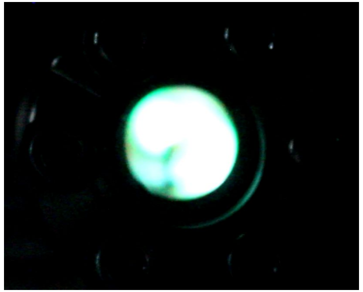
- All reconds start from 500 V & < 5 x 10^{-7} mbar
- Very similar saturation voltages regardless of the plasma
- Smaller differences in the first BD fields
  - Usually first BDs of the first cond much lower than those of reconds

Current work & conclusions

Current work

- Additional experiments on the effects of plasma treatment after 48 h exposure to air
    - Also, does different plasma pressure affect the reconditioning?
- Repeat the plasma treatment & conditioning for another pair of electrodes
    - This time carefully image the surfaces at each stage
- Continuing effort on quantifying the effect of different pressures





Conclusions

- Plasma treatment produces craters on the surfaces
- Plasma cleaning affects BD generation, especially for pristine electrodes
    - BD generation mechanism different during first 10^8 pulses or 500 BDs due to plasma?
        - Different number of secondary events
    - => Plasma “burns” away the hot spots before the conditioning starts?
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