Breakdown studies with the Pulsed DC Systems:
Optimizing the pulsing parameters & Results from He irradiation

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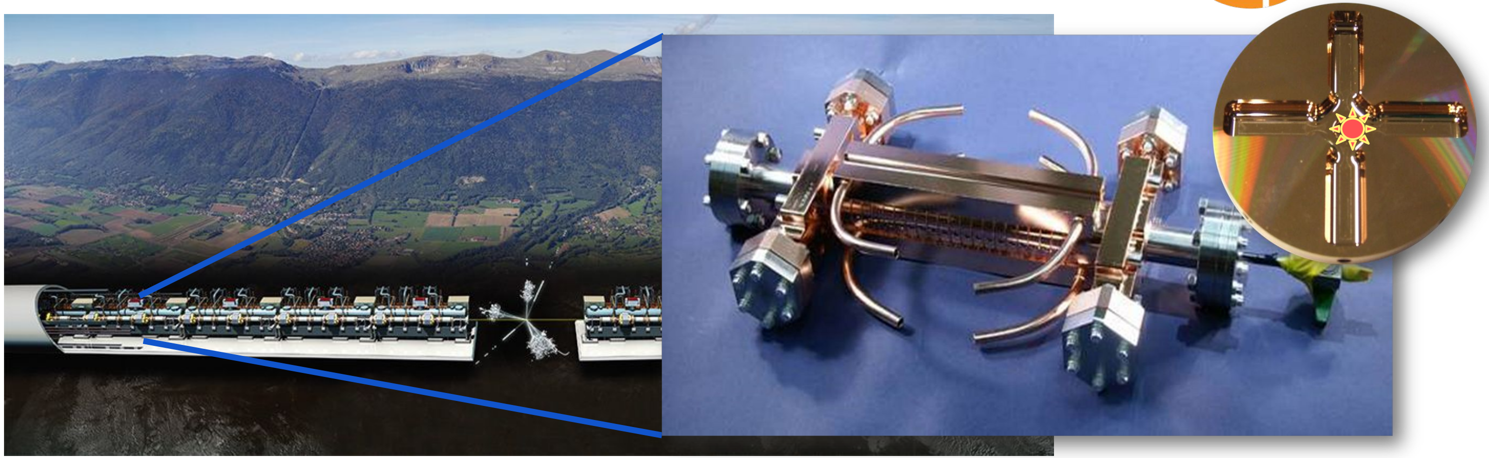
RF Development Meeting, July 15th 2020

Contents

Motivation

Breakdowns limit the efficiency of the Compact LInear Collider

Photo: CERN



- Colliding electrons and positrons
- Linear accelerator built in stages
  - 380 GeV / 11 km x 2 ➪ 70 MV/m
  - …
  - 3 TeV / 50 km x 2 ➪ 120 MV/m

- Copper accelerating structures in vacuum @ room temperature

⇒ **Breakdowns**

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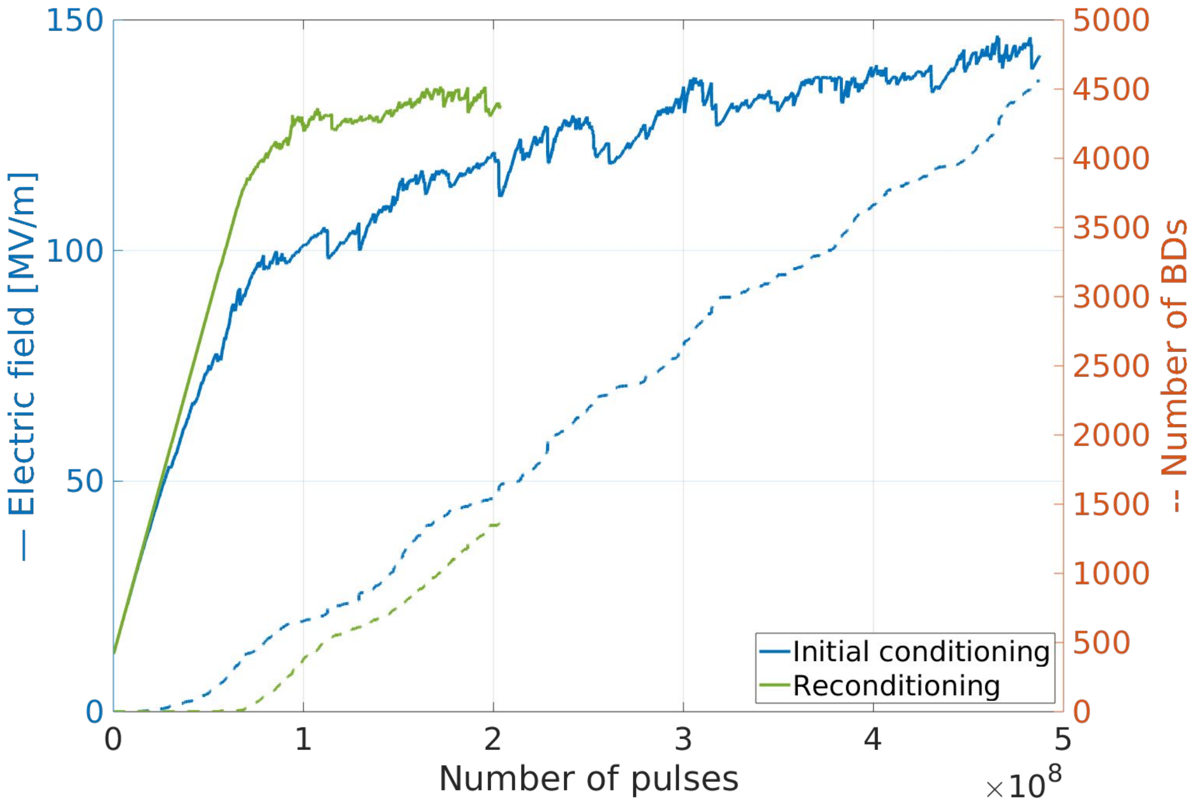
Copper requires conditioning to endure breakdowns

- Pristine electrodes vulnerable to BDs already at small fields
- After ~5x10^8 pulses & ~5000 BDs, BD field can be 5 times higher
- Long and short term conditioning?

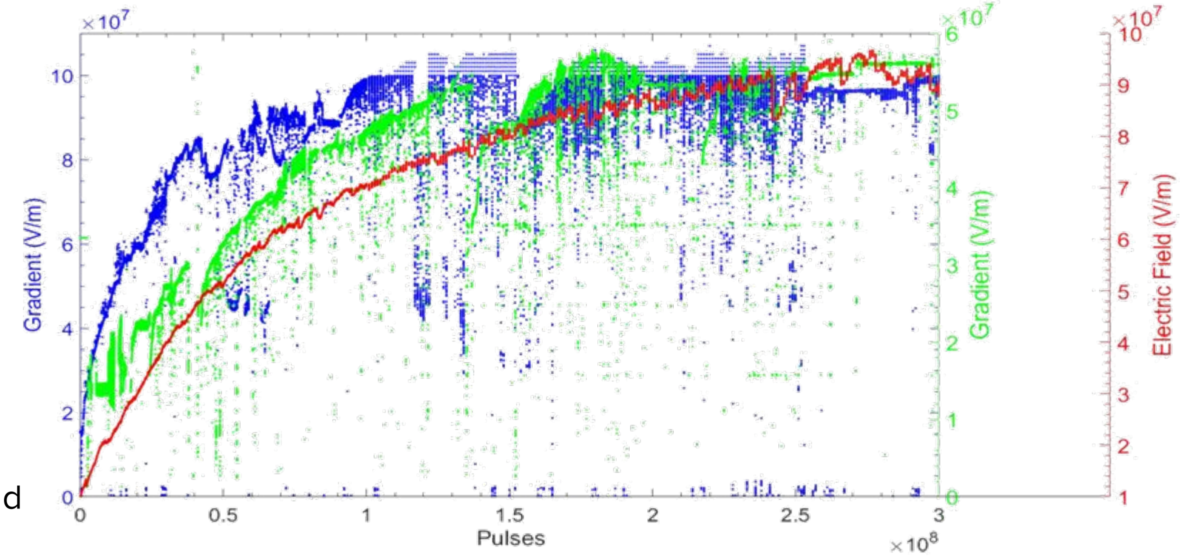


Faster conditioning with DC compared to RF

- Conditioning curves similar between Sbox, Xbox3 and Pulsed DC LES

- Huge difference in time scales
- Sbox @ 25 Hz: 4 months
- Xbox @ 200 Hz: 2 months
- Pulsed DC LES @ 2 kHz: 3.5 days

- Pulsed DC System much smaller and simpler to operate compared to Xboxes
  - Allows focus on the BDs only

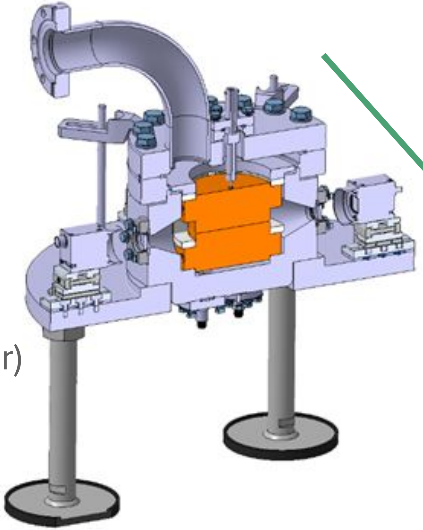


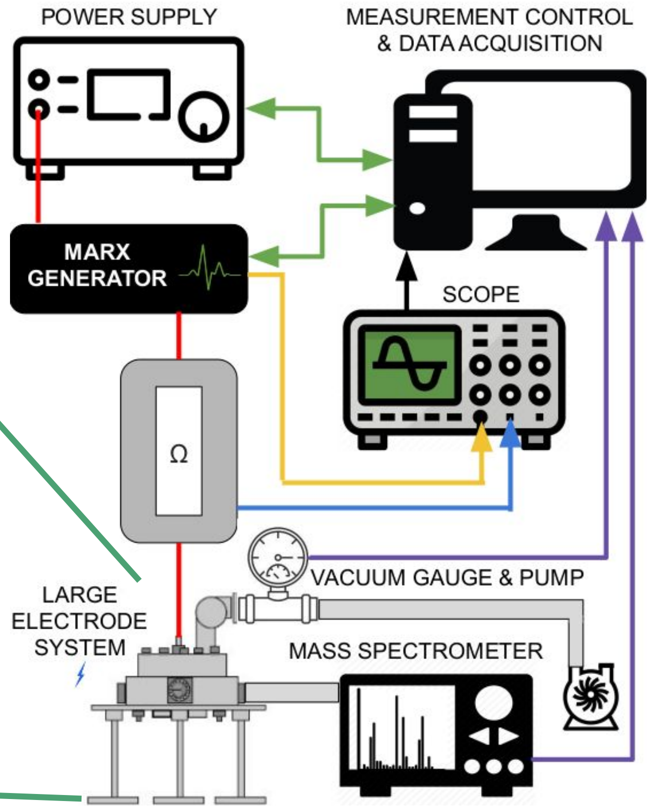
Measurements:
Lee Millar and
Iaroslava Profatilova

Experimental setup: Pulsed DC Systems

Pulsed DC Systems

- Similar systems at CERN and in Helsinki, also one in Uppsala
- Cu electrodes
  - 40-60 mm contact diameter
  - 40-60 µm gap
- Short DC pulses
  - Electric fields up to 150 MV/m
  - 1 µs pulses @ 2 kHz
  - (near) Ultra High Vacuum (< 10^{-7} mbar)
  - Room temperature
- ~ 1000 BDs / 10^8 pulses per day





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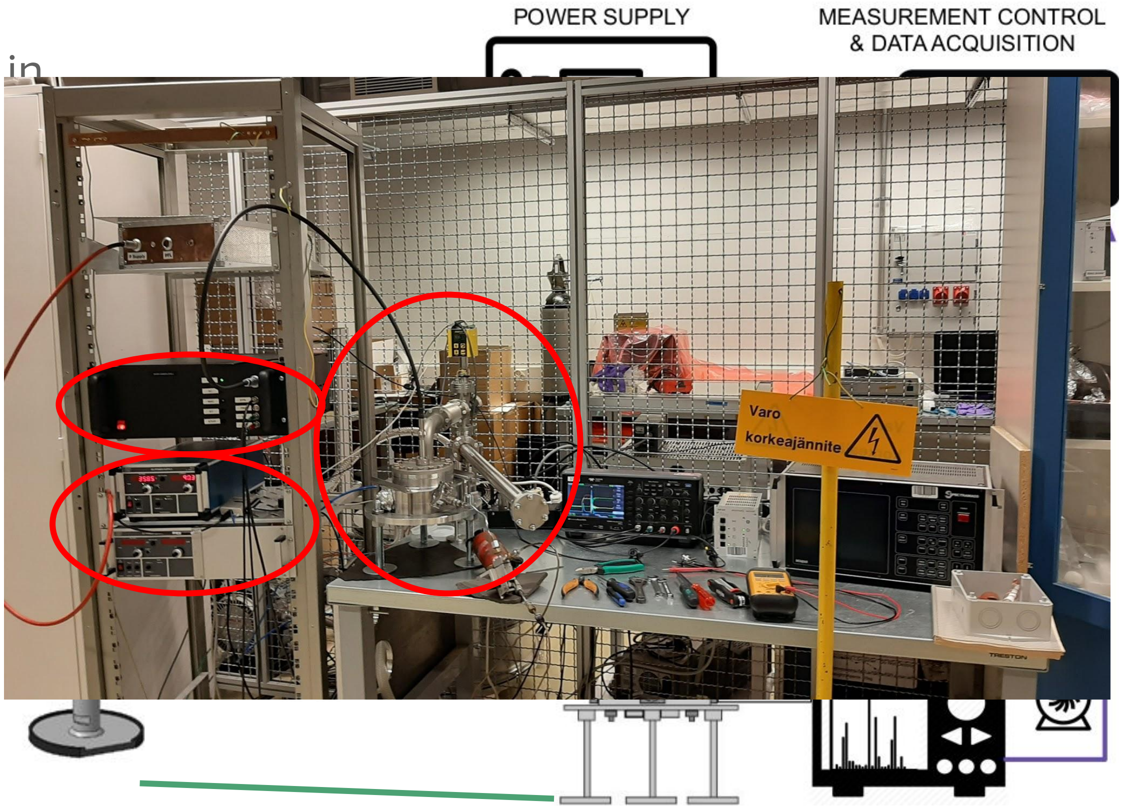
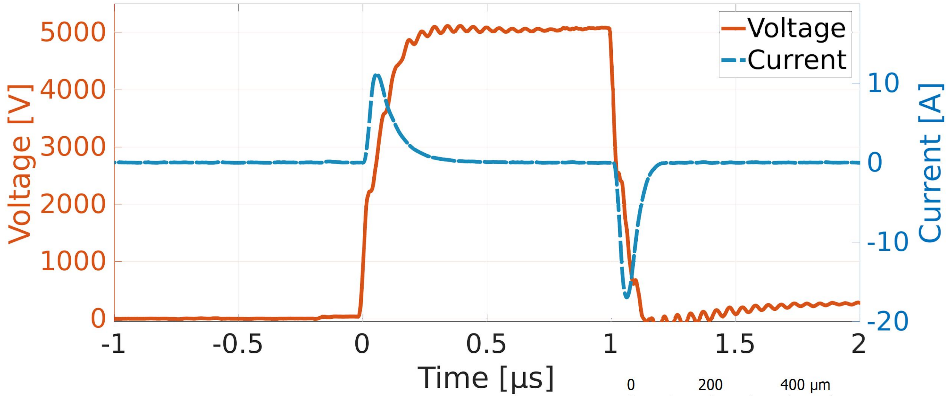
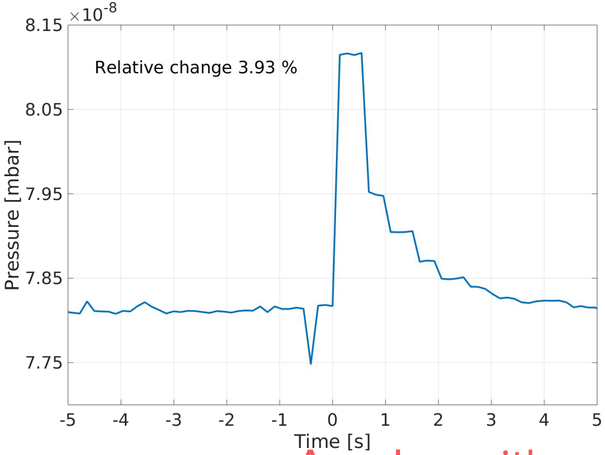


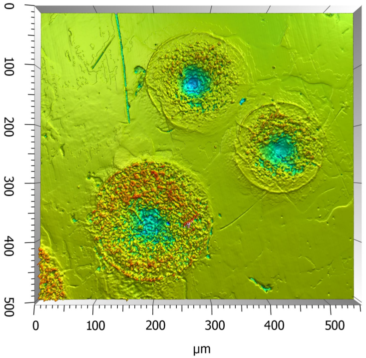
Pulse shapes: BDs are detected from current peaks

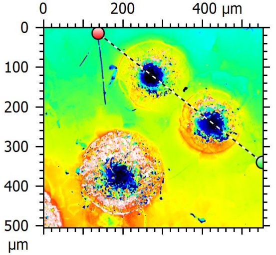
Normal pulse without a BD

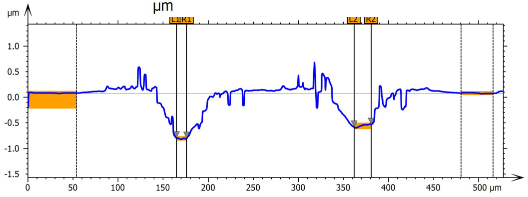




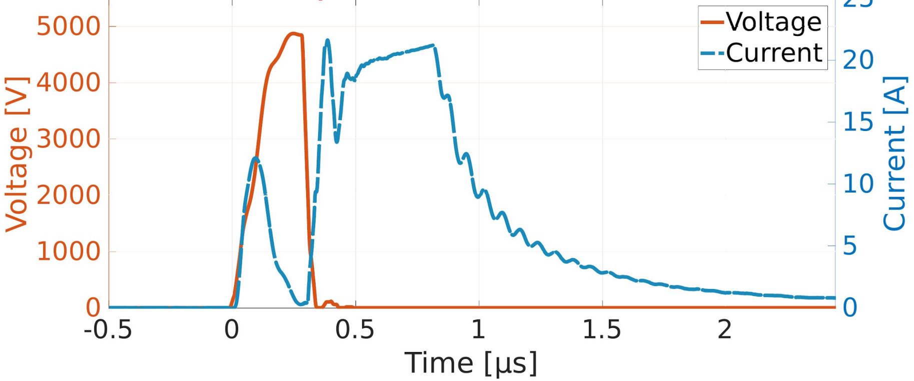
Breakdowns are also seen as pressure spikes







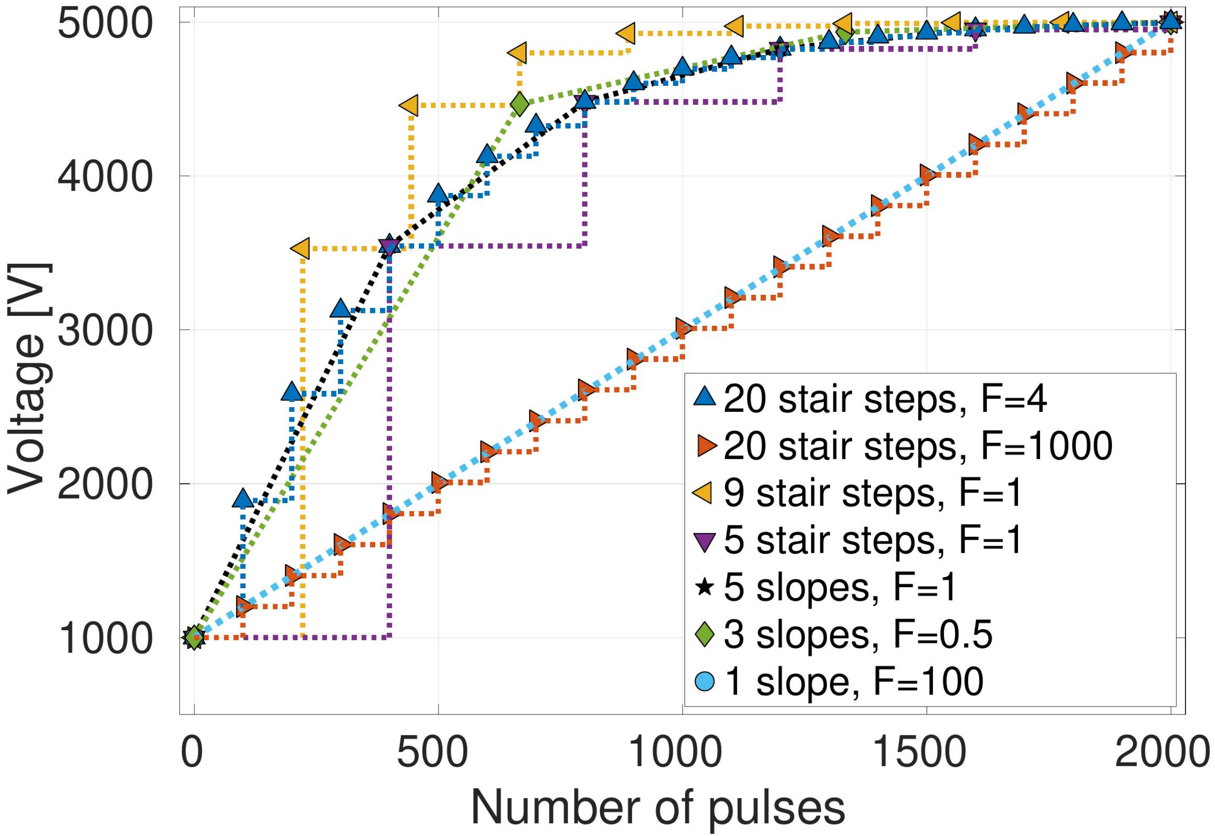
A pulse with a BD



Optimizing the pulsing parameters

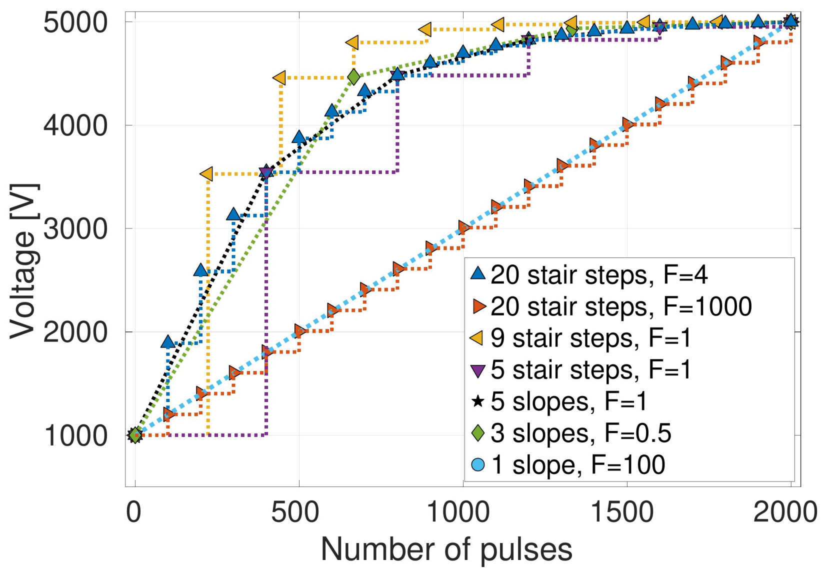
Voltage recovery after BDs - “ramping”

- “Ultra-short term conditioning”
- Voltage is ramped up from one fifth to the target value over 2000 pulses
- But the ramping itself increases BD probability
- Why? And how to ramp up causing minimum secondary BDs

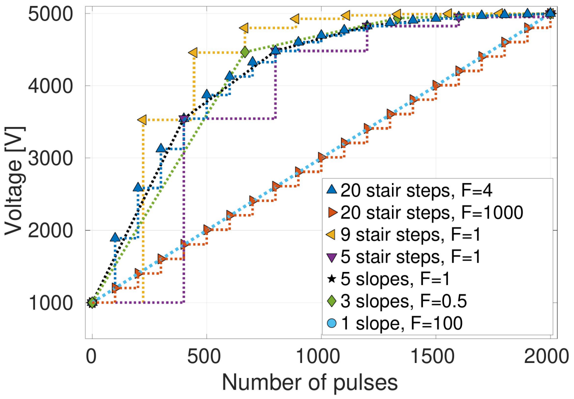


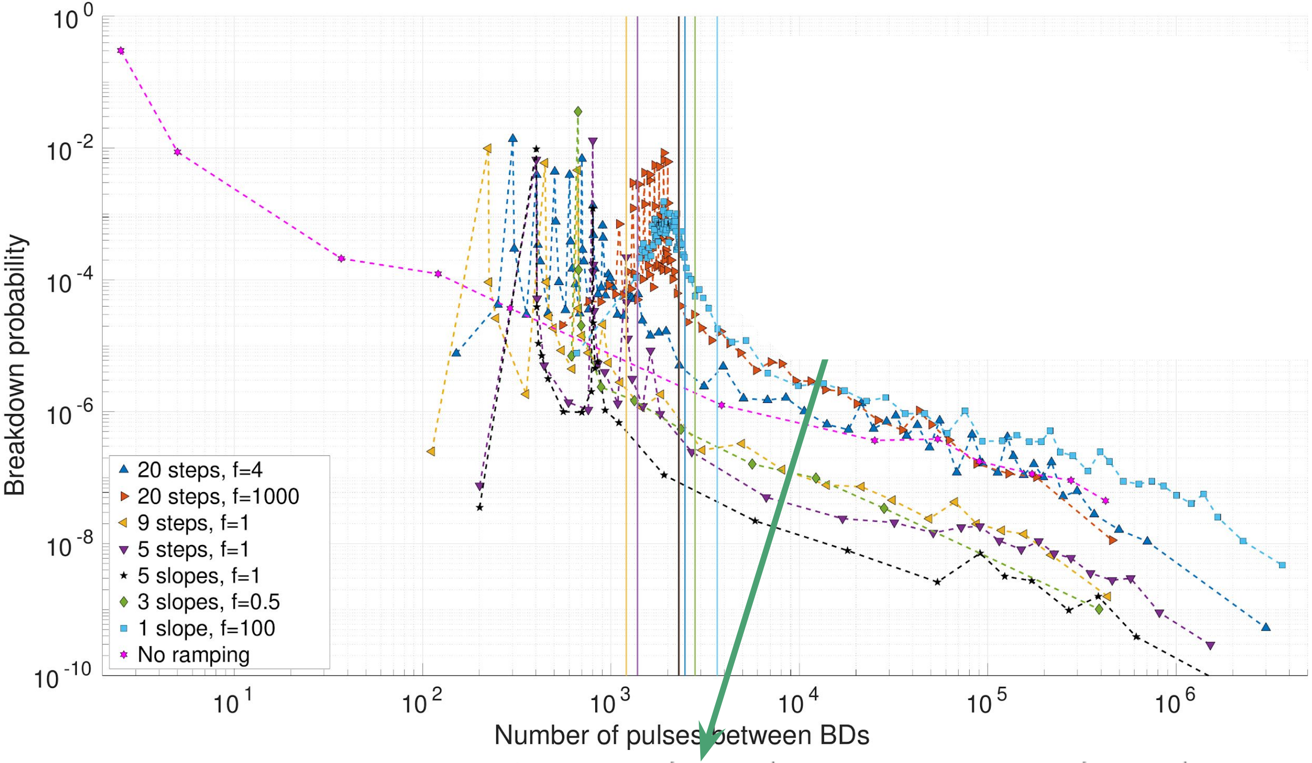
Ramping scenario comparison

	Scenario	Total BDR	Secondary BD %	BD serie length
▲	Steps, 20 steps, F=4	1.78E-05	70	3.3 ± 0.1
▶	Steps, 20 steps, F=1000	7.68E-05	82	4.3 ± 0.2
◀	Steps, 9 steps, F=1	8.18E-05	88	7.4 ± 0.6
▼	Steps, 5 steps, F=1	2.05E-05	84	5.3 ± 0.4
★	Slopes, 5 slopes, F=1	3.37E-05	90	10.6 ± 0.8
◆	Slopes, 3 slopes, F=0.5	2.98E-04	96	20.4 ± 1.1
●	Slopes, 1 slope, F=100	5.86E-06	67	3.1 ± 0.1
□	No ramping	9.60E-05	94	15.3 ± 1.3



Ramping affects BD probability





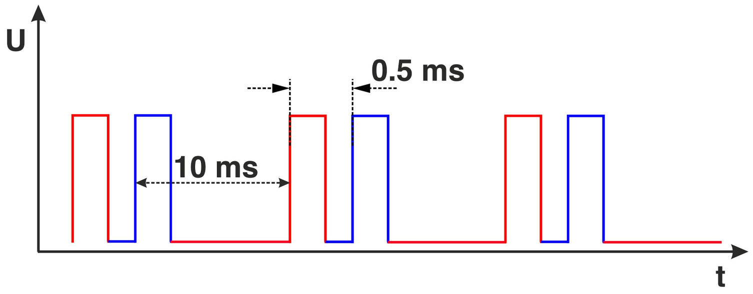
$$PDF = A\exp(\alpha n) + B\exp(\beta n)$$

Effect of the repetition rate

- What is the optimal pulsing frequency?
- Marx generator allows reprates up to 6 kHz

3 experiments:

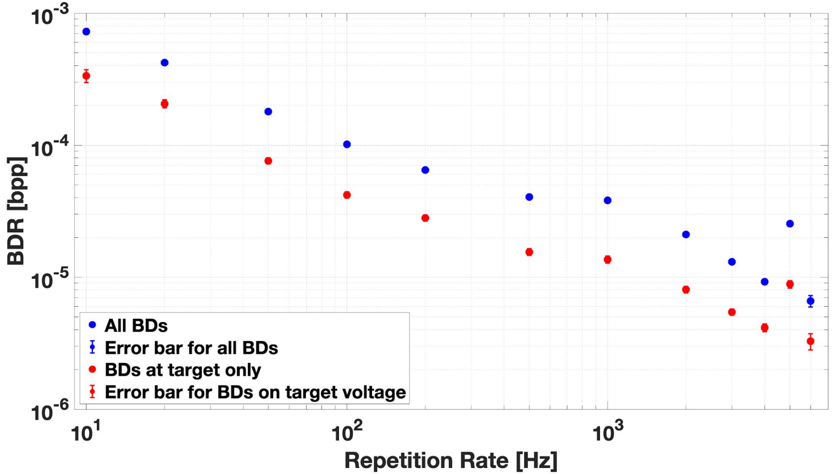
1. Variable reprate from 10 Hz to 6000 Hz
2. Swap between two reprates (100 Hz vs 2000 Hz)
3. Burst mode: change reprate after every pulse



Effect of the repetition rate

Measurements:
Iaroslava Profatilova

1.



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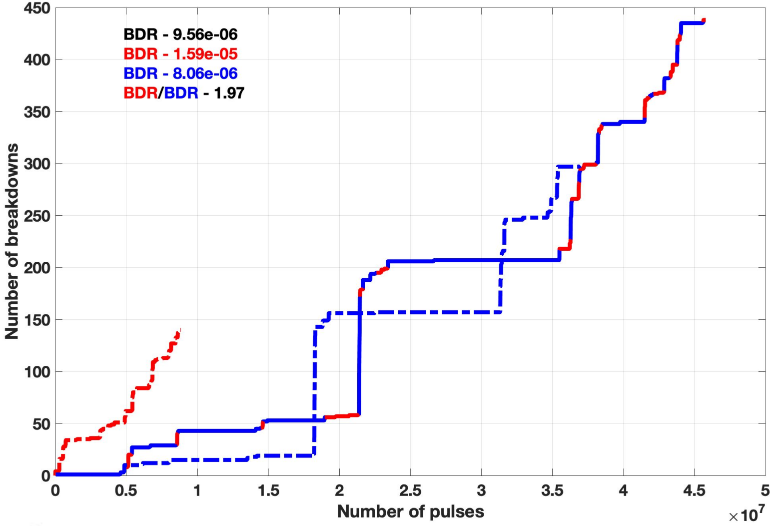
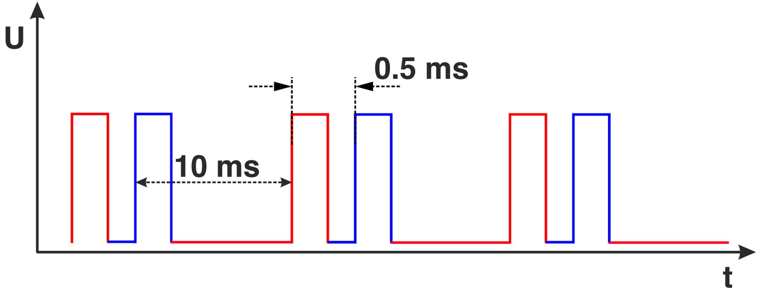


E [MV/m]	Pause [ms]	BDs	BDR [bpp]	Ratio
62	10	197	2.30×10^{-5}	1.63
	0.5	121	1.41×10^{-5}	
61	10	116	9.30×10^{-6}	1.14
	0.5	121	8.18×10^{-6}	
62	10	57	8.05×10^{-6}	1.46
	0.5	39	5.51×10^{-6}	

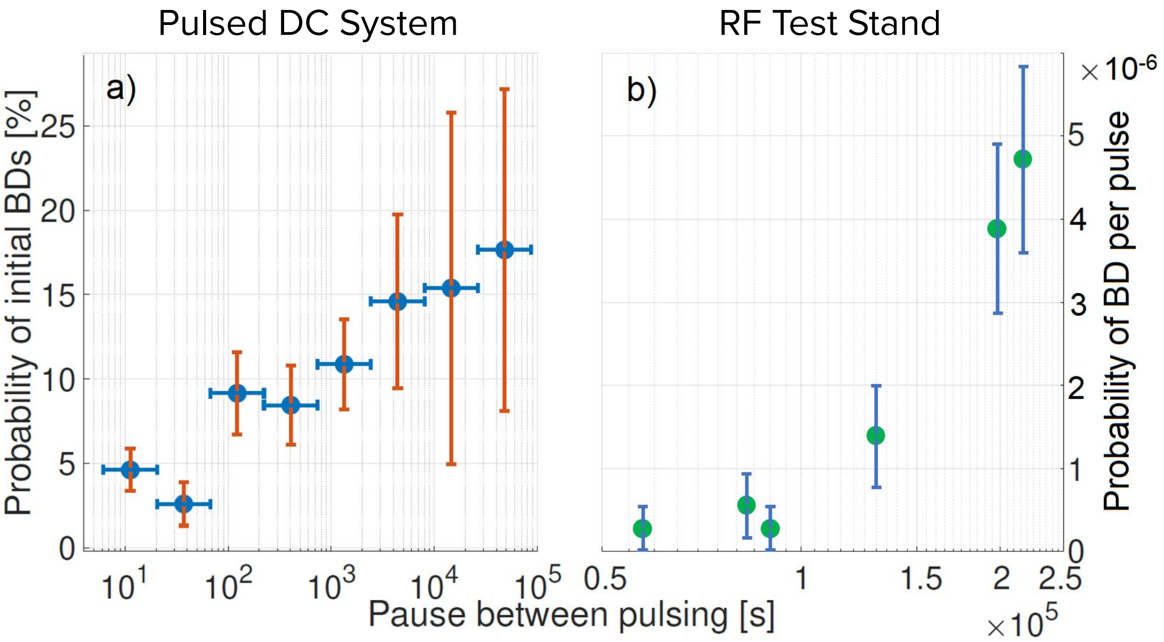
3.



Effect of a longer pause between measurements

- Previously qualitatively noticed that any pause in pulsing increases BD susceptibility
  - Both with DC and RF
  - Even when the system has been under UHV conditions

- => Needed to be measured quantitatively
  - Results both from DC and RF



- Increase in the values after ~100 s and ~10^5 pulses
  - Roughly the time of a monolayer formation

RF measurements:
Lee Millar

A longer pause increases BD susceptibility

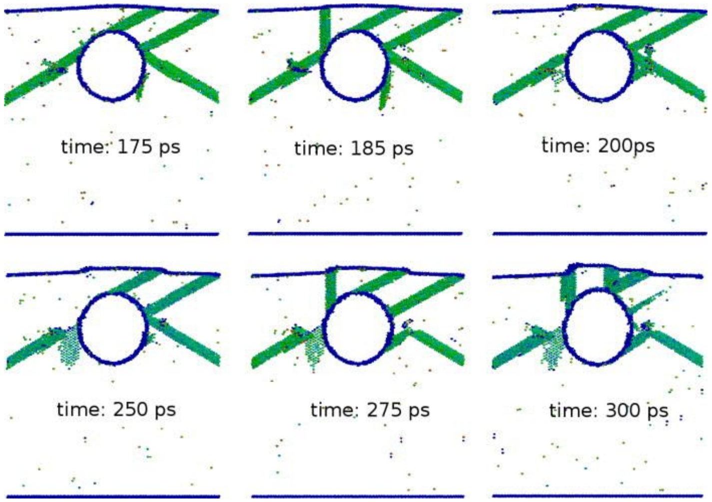
- Several different experiments agree
  - Time scales from 0.5 ms to 28 h
- Best ramping scenario was the one with no pauses
- Each reprate measurement shows a higher BDR after a longer idle time
- Initial BD probability increases with a longer pause between the measurements

- BDs after pauses linked to secondary BDs
  - I.e. events right after other BDs
  - Backed by the two-term exponential model fitted on the BD probability PDF
- => Secondary BDs mainly caused by surface impurities attaching on Cu surface from vacuum?
- However, the effect saturates at some point and is cleaned quickly with pulses and BDs

He irradiation of Cu electrodes

The hypothesis linking He irradiation to BD generation

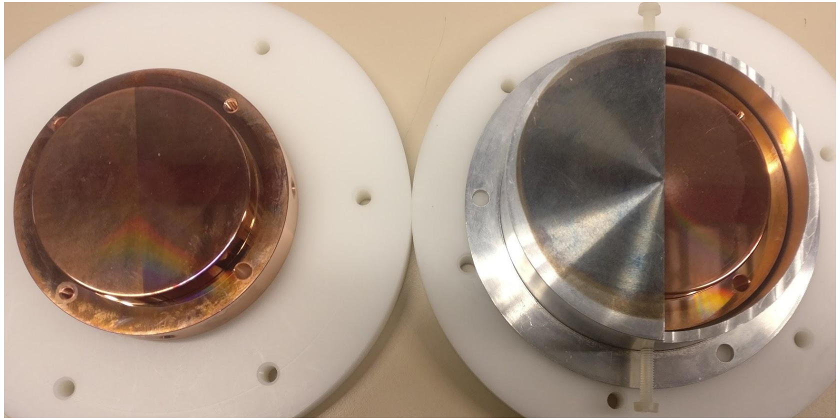
- He ions permeate the Cu surface, forming voids in the subsurface region (< 300 nm)
- These voids act as nucleation sites for dislocations
- Dislocations, moving under stress caused by the electric pulsing, migrate to the surface and cause deformations
- Higher electric field near the deformation spots nucleate BDs



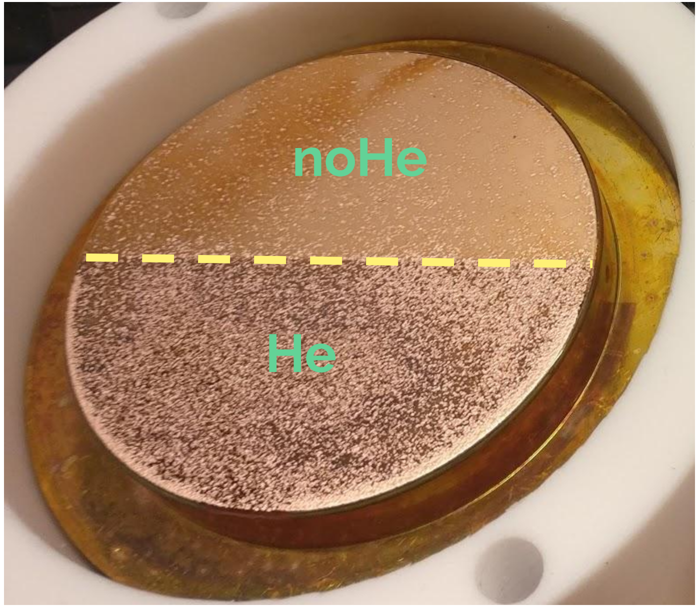
Pohjonen, A. S., et al. "Dislocation nucleation from near surface void under static tensile stress in Cu." *Journal of Applied Physics* 110.2 (2011): 023509.

He implantation - 2+1 pairs of electrodes

- Irradiation of two pairs in 2015 (Soft Cu)
  - He^+ with 30 keV
  - Fluence 6.7 x 10^{16} He/cm^2 (around 5 at.%)
  - Vacancy clusters confirmed up to 300 nm from the surface (PAS) close to the maximum depth of He ions (ERDA & SRIM)
- Another irradiation in 2018 (1 pair of Hard Cu)
  - Same parameters as in 2015
  - ERDA measurements after irradiation



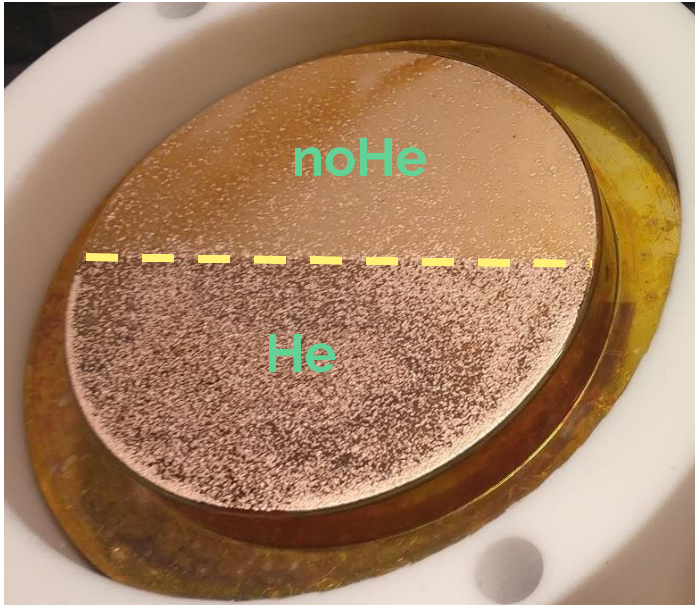
First results: He makes a difference



Cathode

Anode

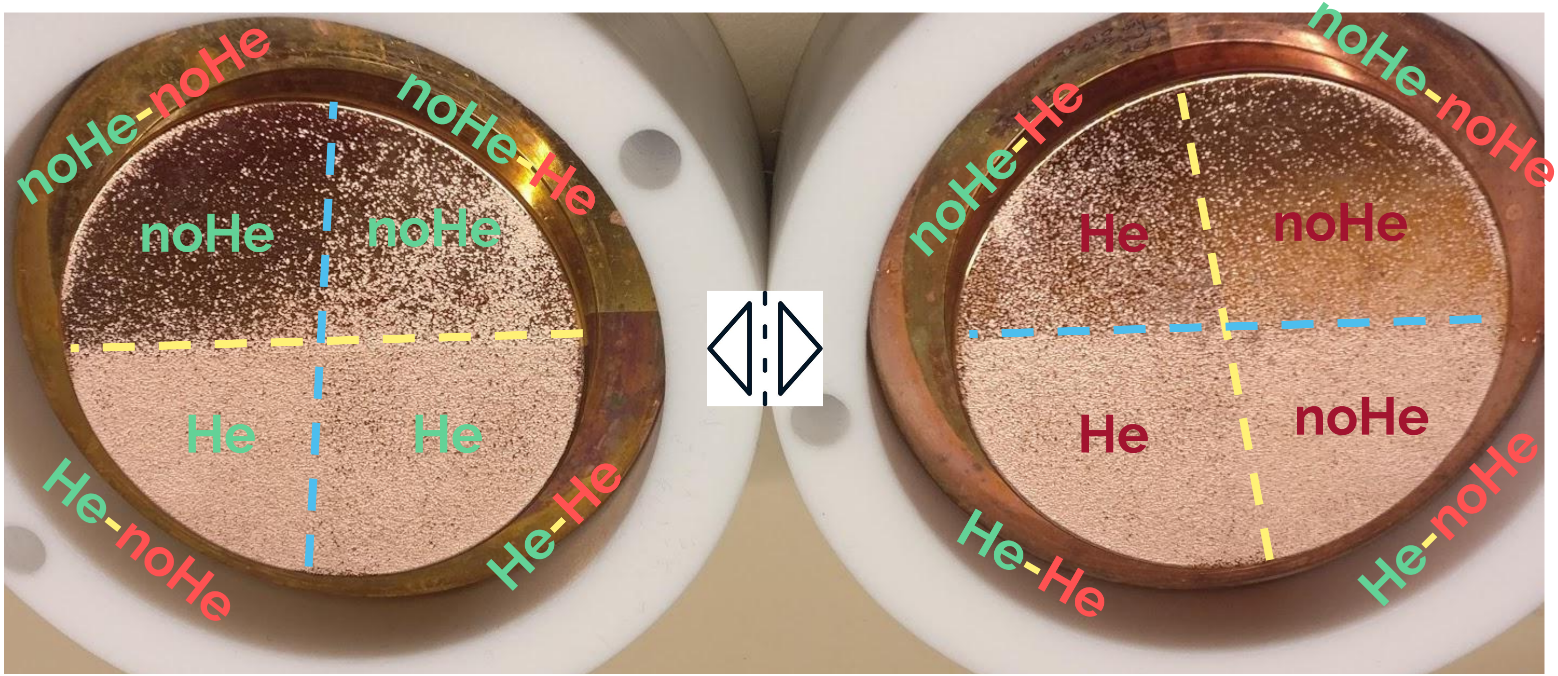
Twisting the electrodes



Cathode

Anode

Twisting the electrodes shows BDs initiating from Cathode

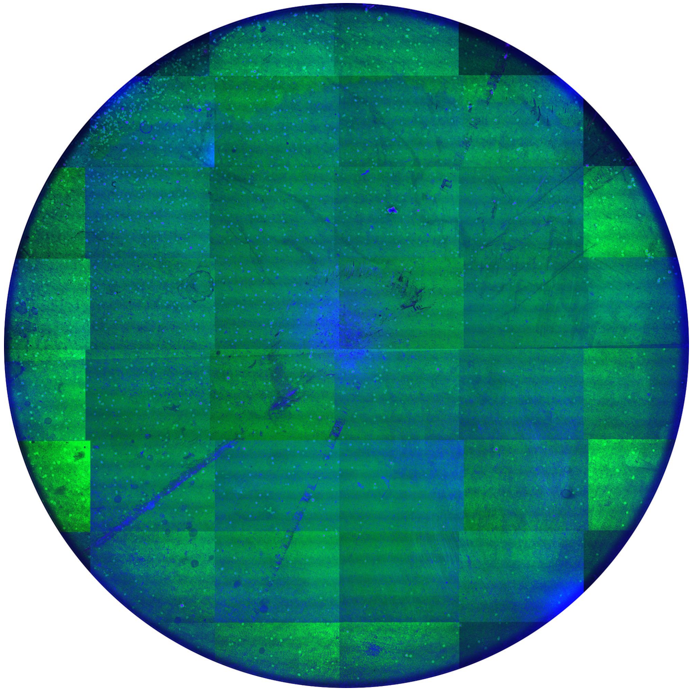


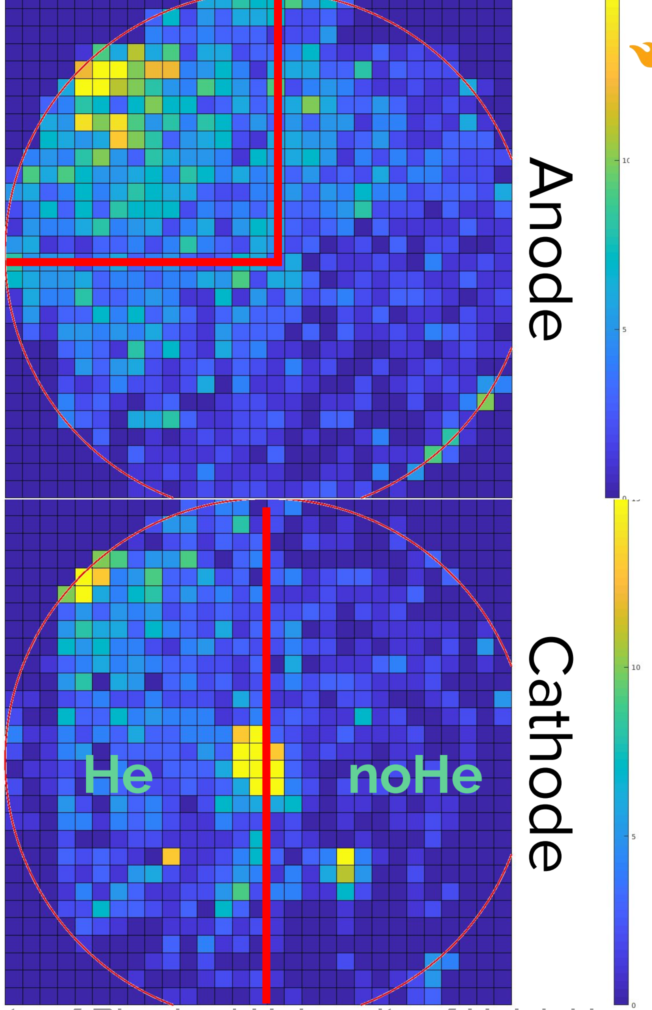
Cathode

Anode

Similar results on Hard Cu He

- Controlled amount of 3000 BDs
- DIfference between halves not so huge, but still observable

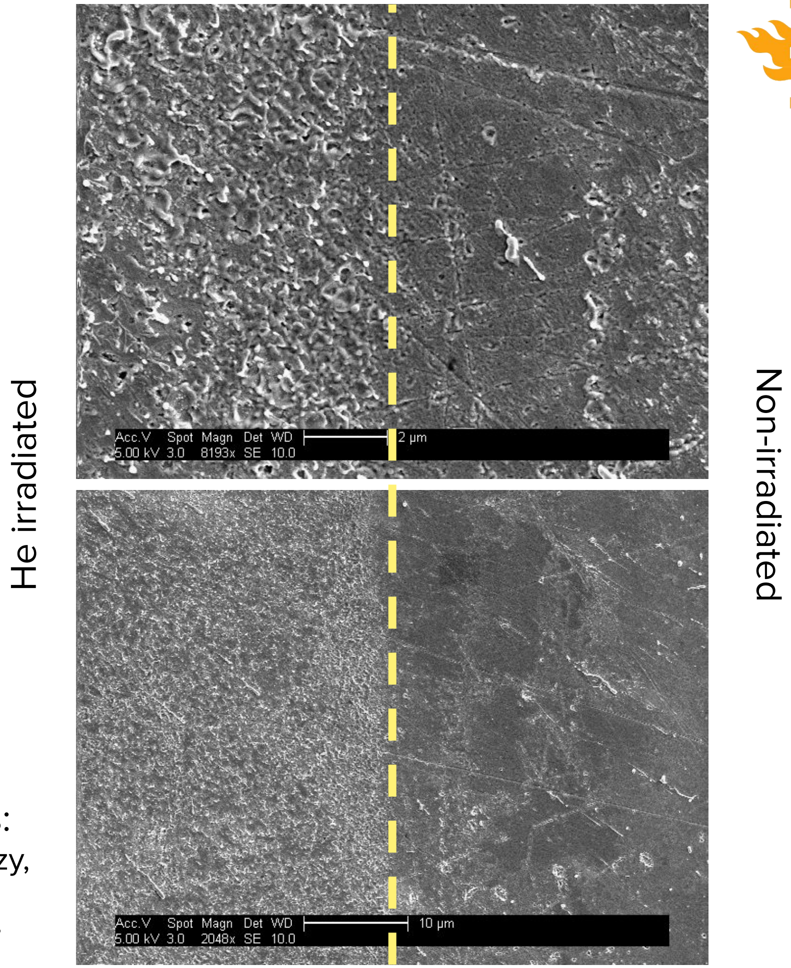




Can we trust the results?

- Closer analysis shows that the He irradiation also modifies the surface
  - Increased surface roughness
  - Increased amounts of carbon

- Not clear yet, whether the voids are fully responsible for the increased amount of BDs



SEM images:
Yinon Ashkenazy,
Inna Popov &
Ayelet Yashar

Ongoing experiments: Plasma cleaning

Conclusions

- Pause between pulses affects BD probability
- Secondary BDs linked to surface impurities
- Surface impurities rapidly cleaned by pulses & BDs
- He irradiation leads to higher number of BDs
  - ➢ Reason not fully clear

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CLIC

Thank you for your attention!

RF Development Meeting, July 15th 2020

Cleaning the Cu surfaces in-situ with plasma

- **Idea**

  "Micro sandblasting" the cathode surface with Ar+ ions to get rid of surface impurities

  ➕ Can be done in vacuum

  ➕ Minimal damage to surface

  ➕ HV equipment already there

- **Challenges**
  - Need to use also other gases than Ar?
  - Difficult to find the optimal parameters
    - Pressure, voltage, current, time
  - Methods to study effects on the Cu surface

Video:
Aarre Kilpeläinen