Copper Surfaces: A Comparative Study in Cryogenic High Fields

Advanced Physics Project, 5 credits

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November 16th 2020

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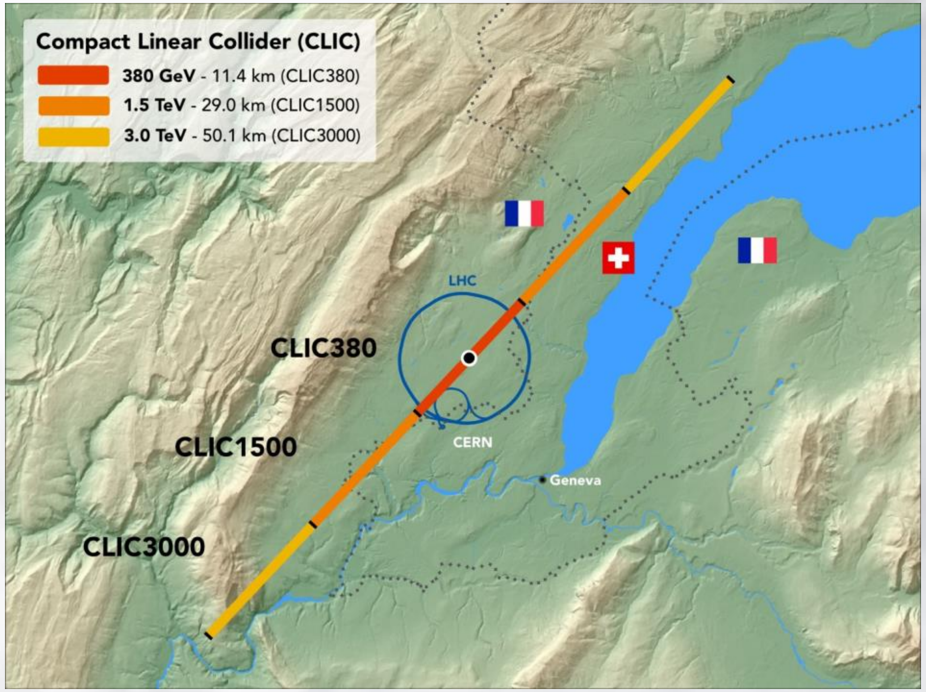
FREIA

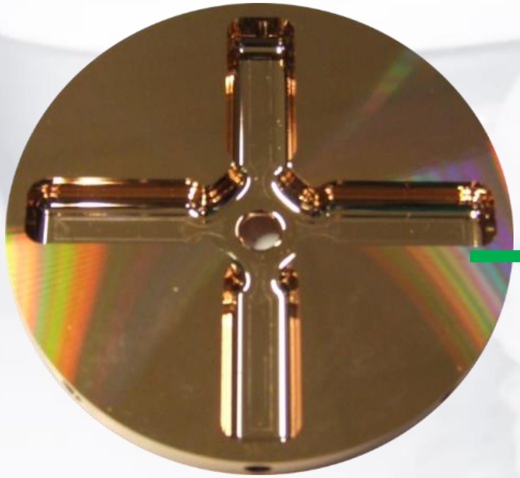
Background: Compact Linear Collider (CLIC)

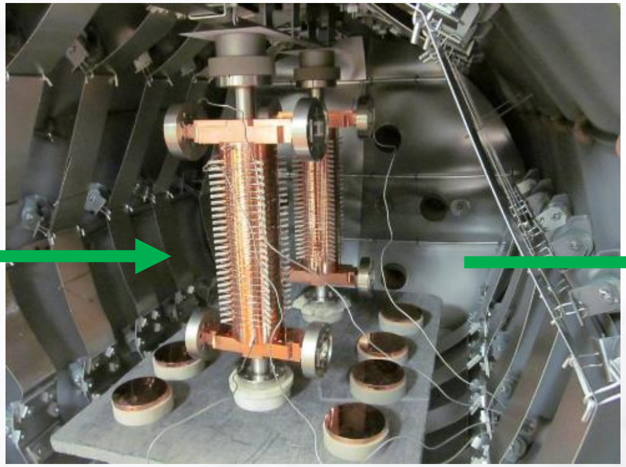
- Electron-positron accelerator using radio-frequency (RF)
- Higher gradient → shorter facilities → lower costs
- Breakdowns: main limitation to accelerating gradient

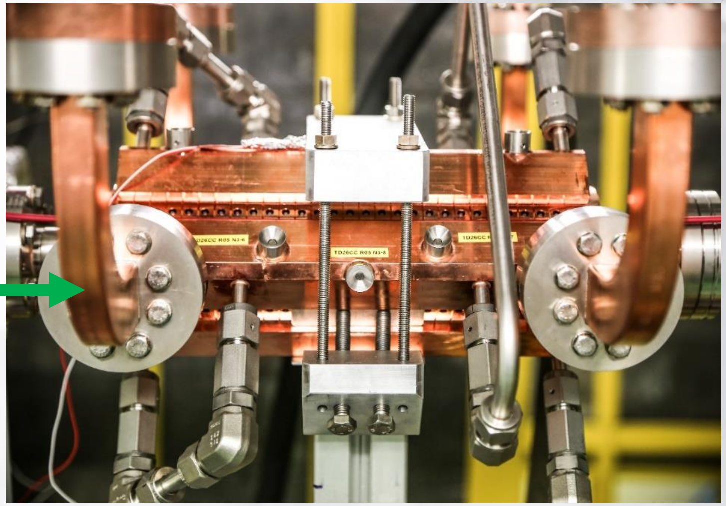


Envisioned stages of CLIC, cern.ch

Background: Copper in accelerating structures





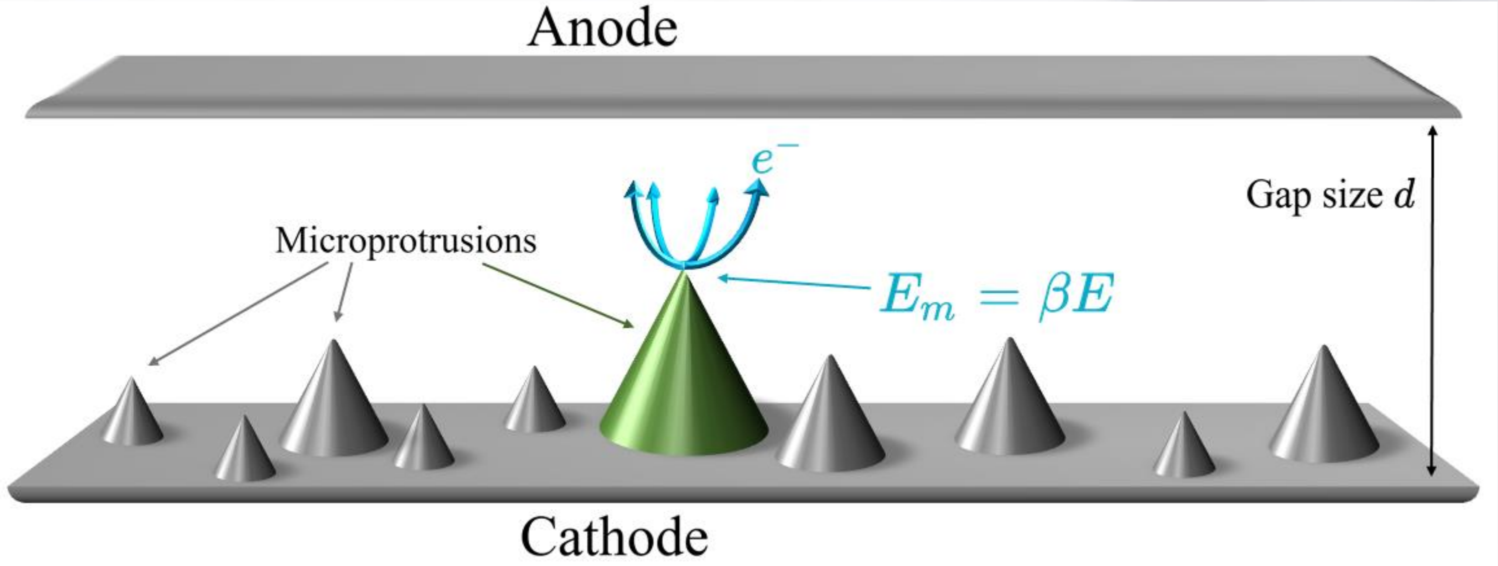


- Copper: suitable candidate material for accelerating structures (hard/soft)
- <u>Purpose of this study</u>: behaviour of soft copper at cryogenic temperatures

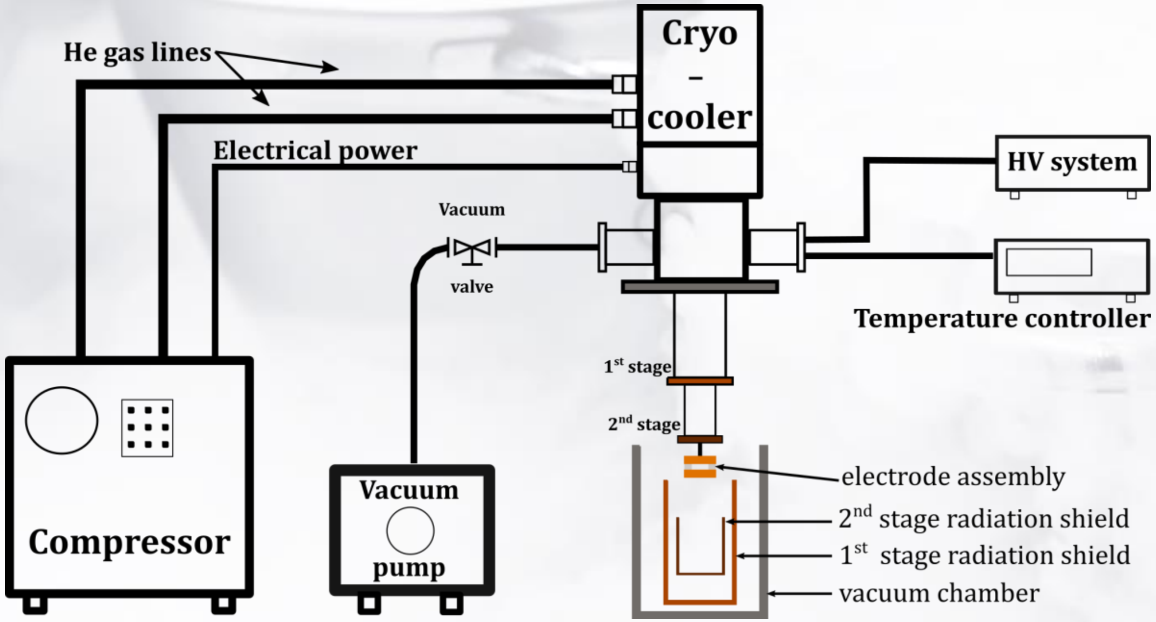
Theory: what are breakdowns?

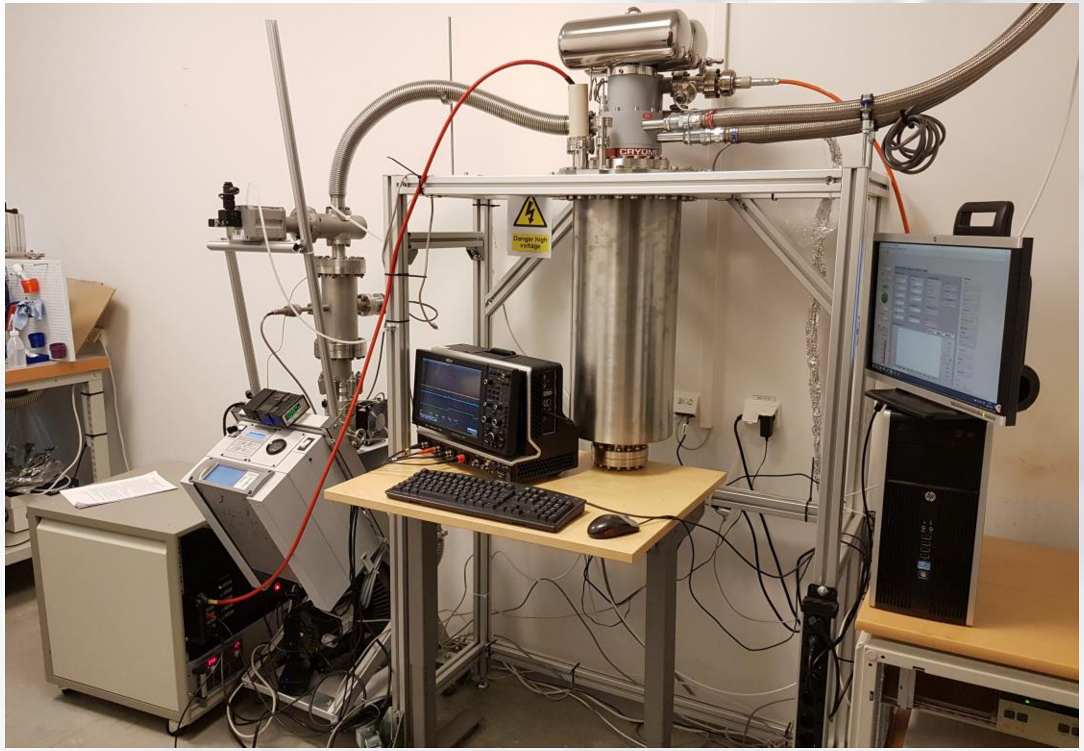
- Field emission → Plasma → breakdown
- Enhancement factor β
- Fowler-Nordheim:

$$\frac{d(\log I_F/E^2)}{d(1/E)} = -\frac{2.84\times10^9\phi^{1.5}}{\beta}$$



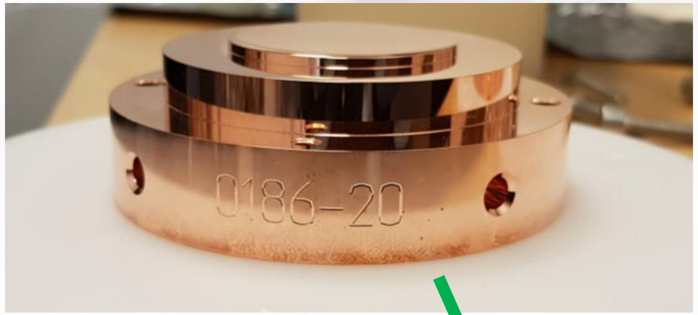
Set-up and Experimental Method



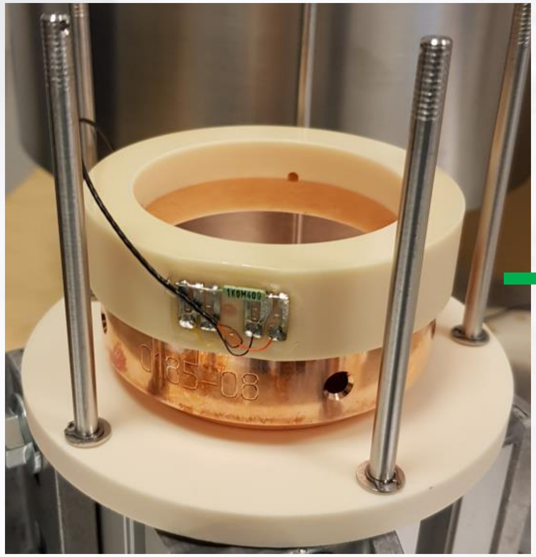


Set-up: Electrodes

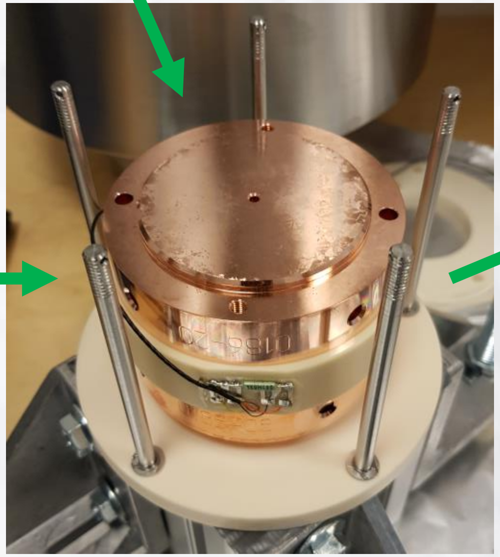
Hard Cu cathode from previous experiments

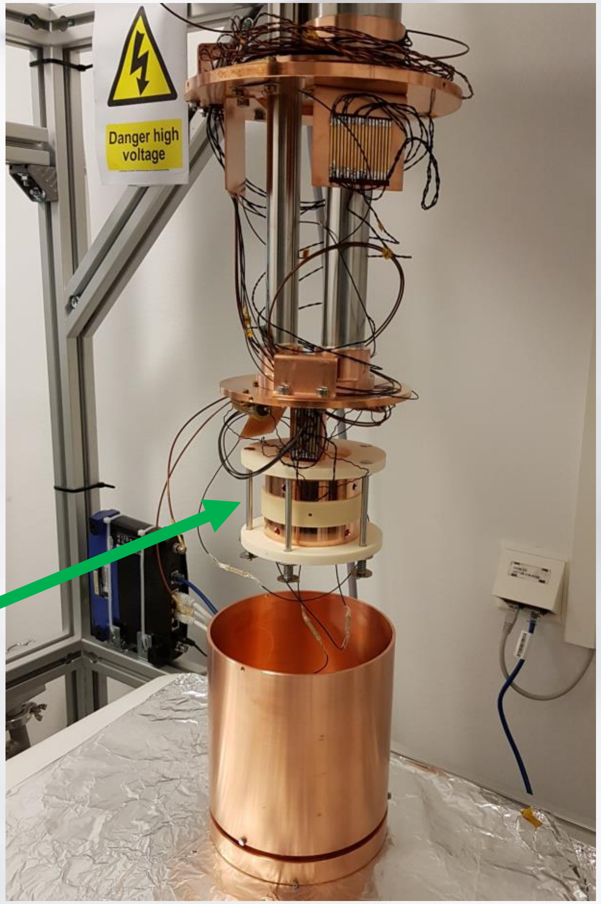


Soft Cu Anode



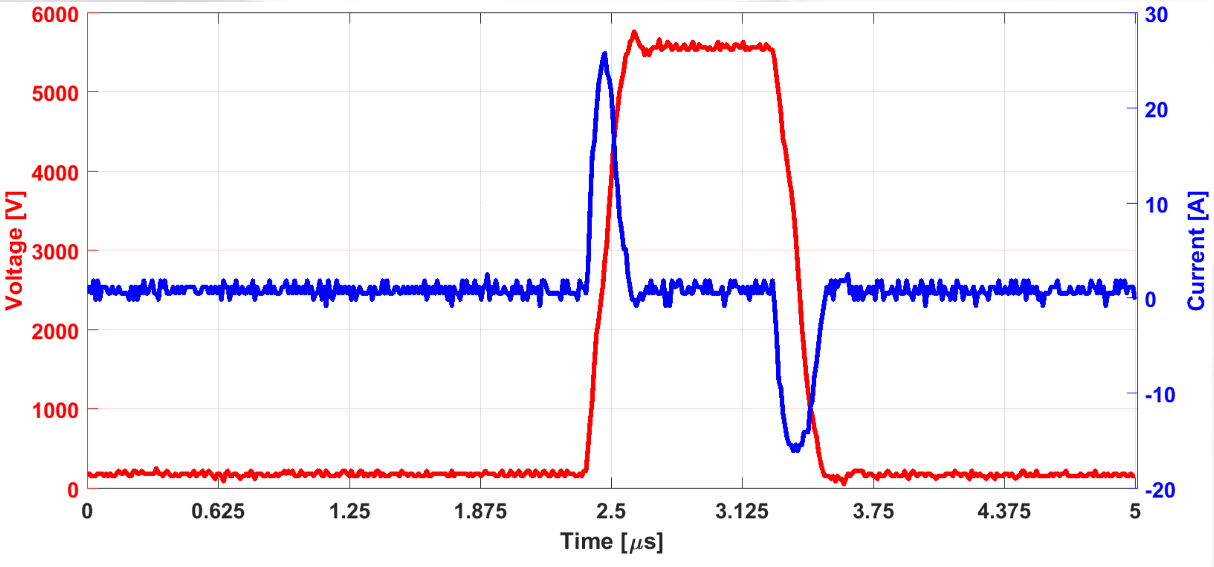
Soft Cu Cathode



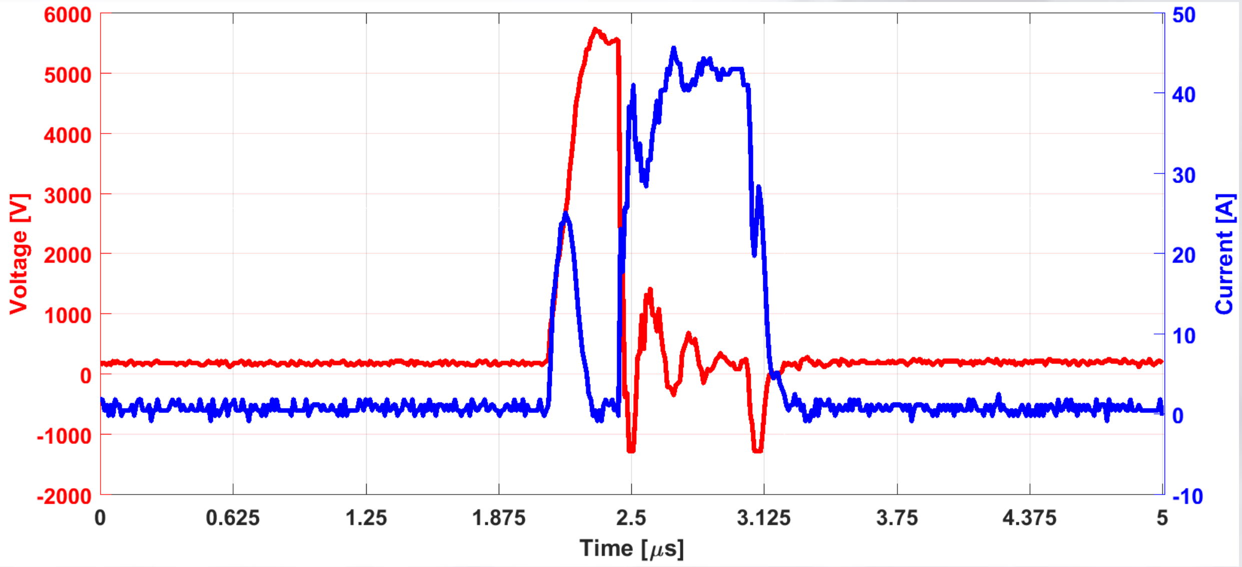


Electrodes and first stage radiation shield

Method: Pulses

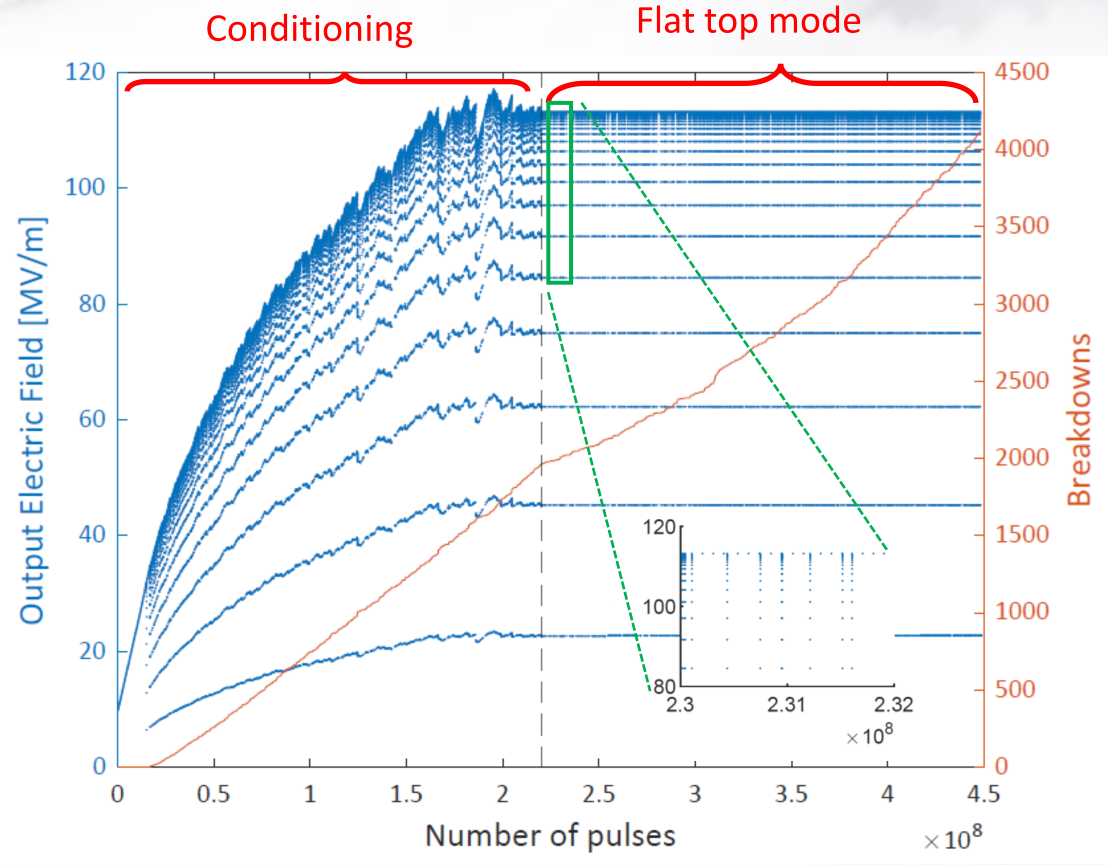


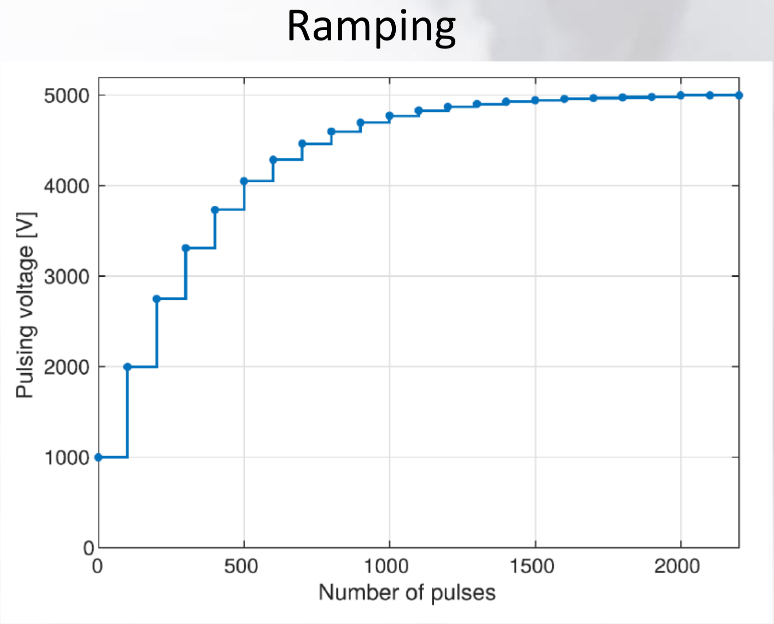
Marx generator waveform with <u>no breakdown</u>



Marx generator waveform <u>at breakdown</u>

Method: Conditioning and “flat top”





- Conditioning: process of developing resistance to breakdowns

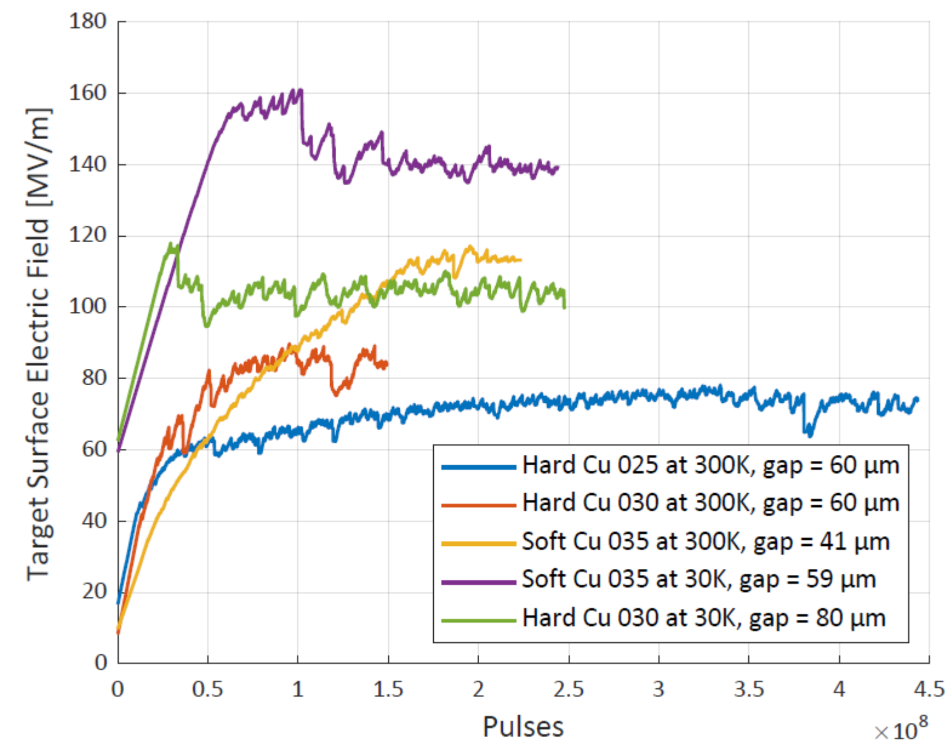
Main goals of study

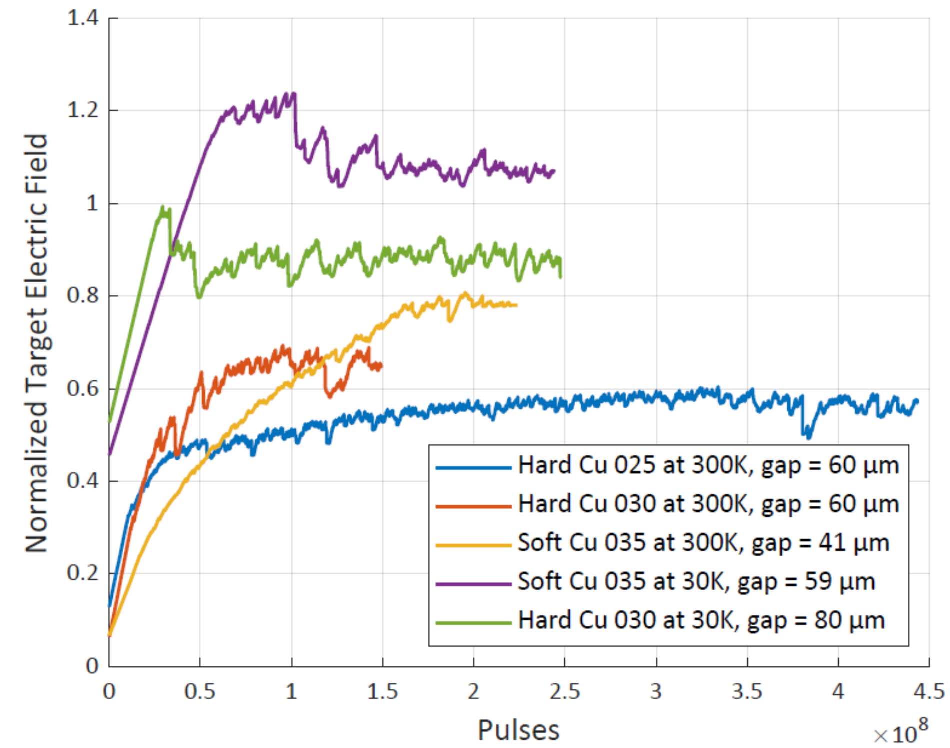
- Breakdown behaviour during conditioning phase
- Maximum electric field and normalized field

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

- Number of pulses between breakdowns during “flat top” mode
- Field emission current: Megger and Heinzinger instruments

Results: Conditioning curves

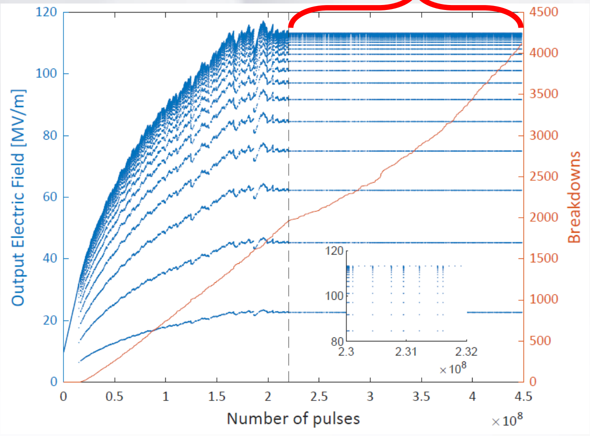


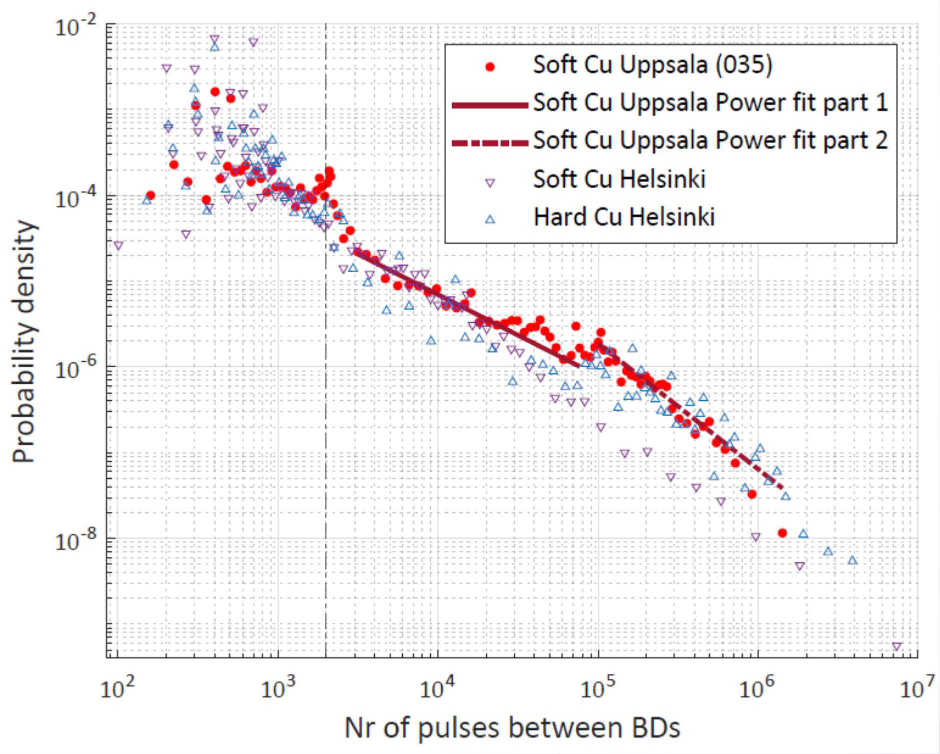


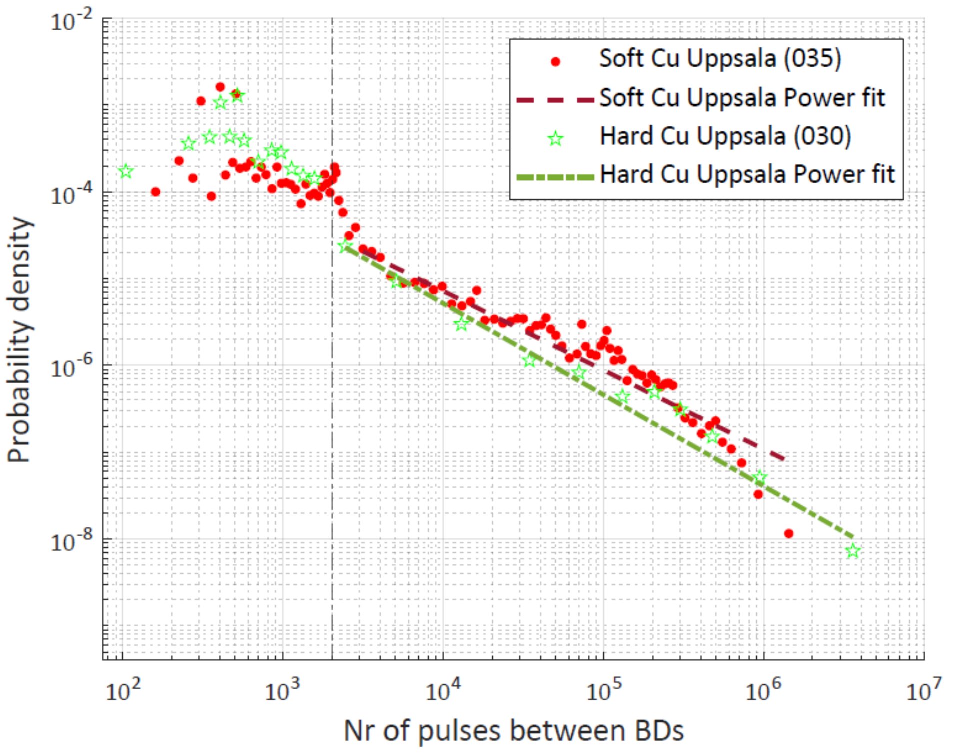
	T = 300 K			T = 30 K	
	Hard Cu 025	Hard Cu 030	Soft Cu 035	Hard Cu 030	Soft Cu 035
E_{max} [MV/m]	78.17	89.75	117.1	117.9	160.9
$E_{norm,max}$	0.604	0.693	0.808	0.994	1.24

Results: Pulses between breakdowns

During flat top mode:



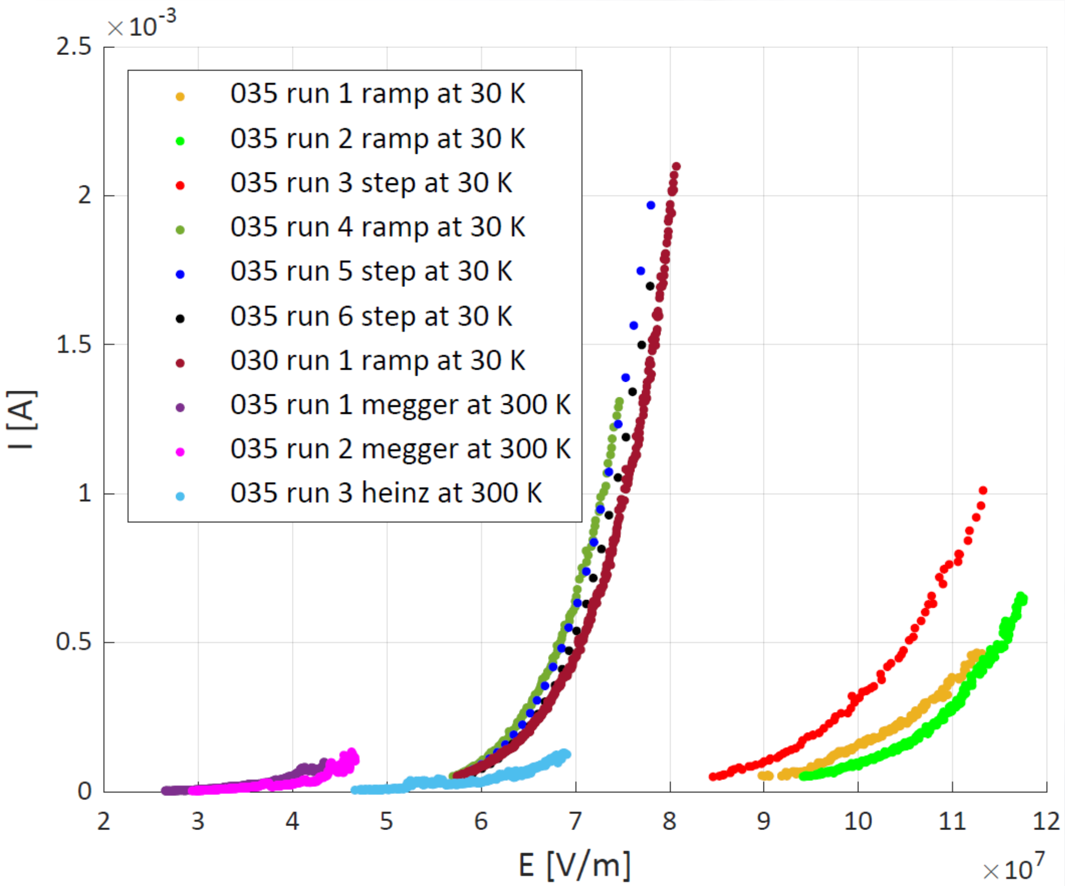




Fitting coefficients for model $P(S) = kS^{-\alpha}$

Power fit	Soft Cu Uppsala (2020)	Soft Cu Helsinki	Hard Cu Helsinki	Hard Cu Uppsala (2019)
Single	$\alpha = 0.91 \pm 0.08$	$\alpha = 1.30 \pm 0.05$	N/A	$\alpha = 1.05 \pm 0.1$
Double	$\alpha_1 = 0.95 \pm 0.1$ $\alpha_2 = 1.47 \pm 0.3$	N/A	$\alpha_1 = 1.30 \pm 0.05$ $\alpha_2 = 1.37 \pm 0.05$	N/A

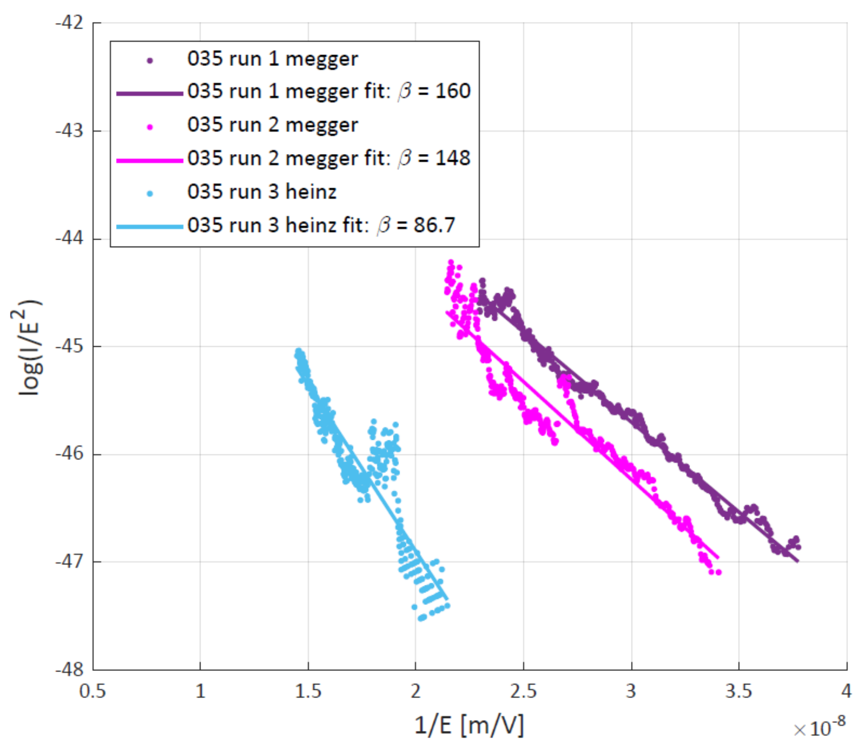
Results: Field emission



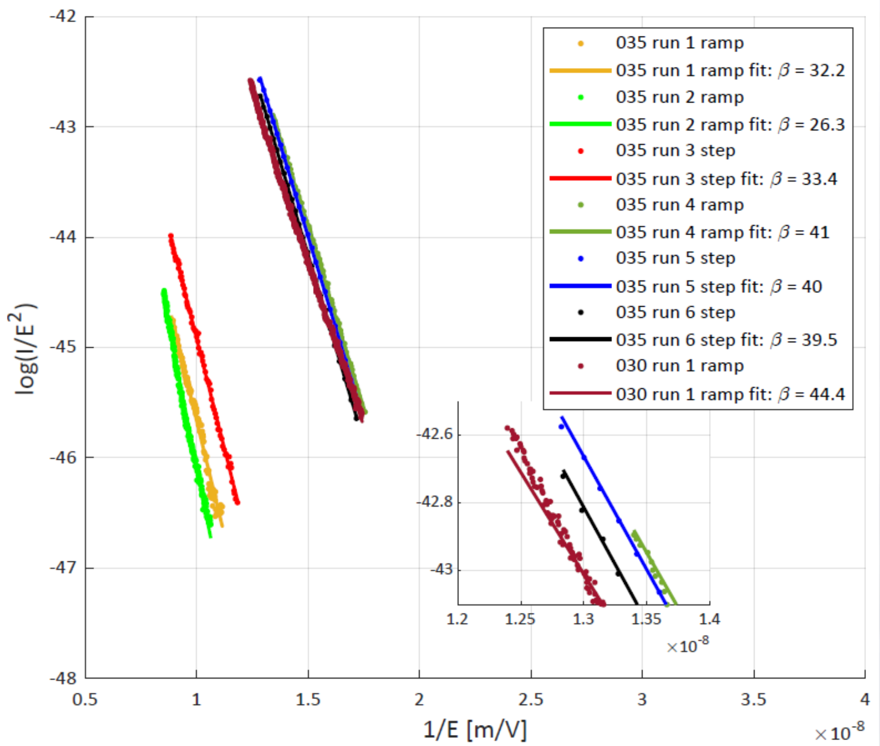
Field emission current over electric field

Results: Fowler-Nordheim plots

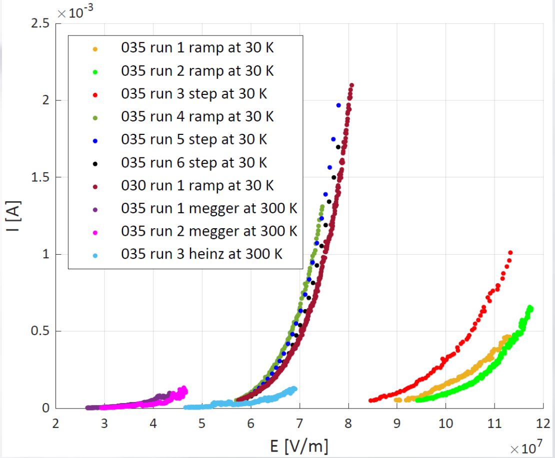
$$\frac{d(\log I_F/E^2)}{d(1/E)} = -\frac{2.84\times10^9\,\phi^{1.5}}{\beta}$$



Field emission after conditioning at 300 K

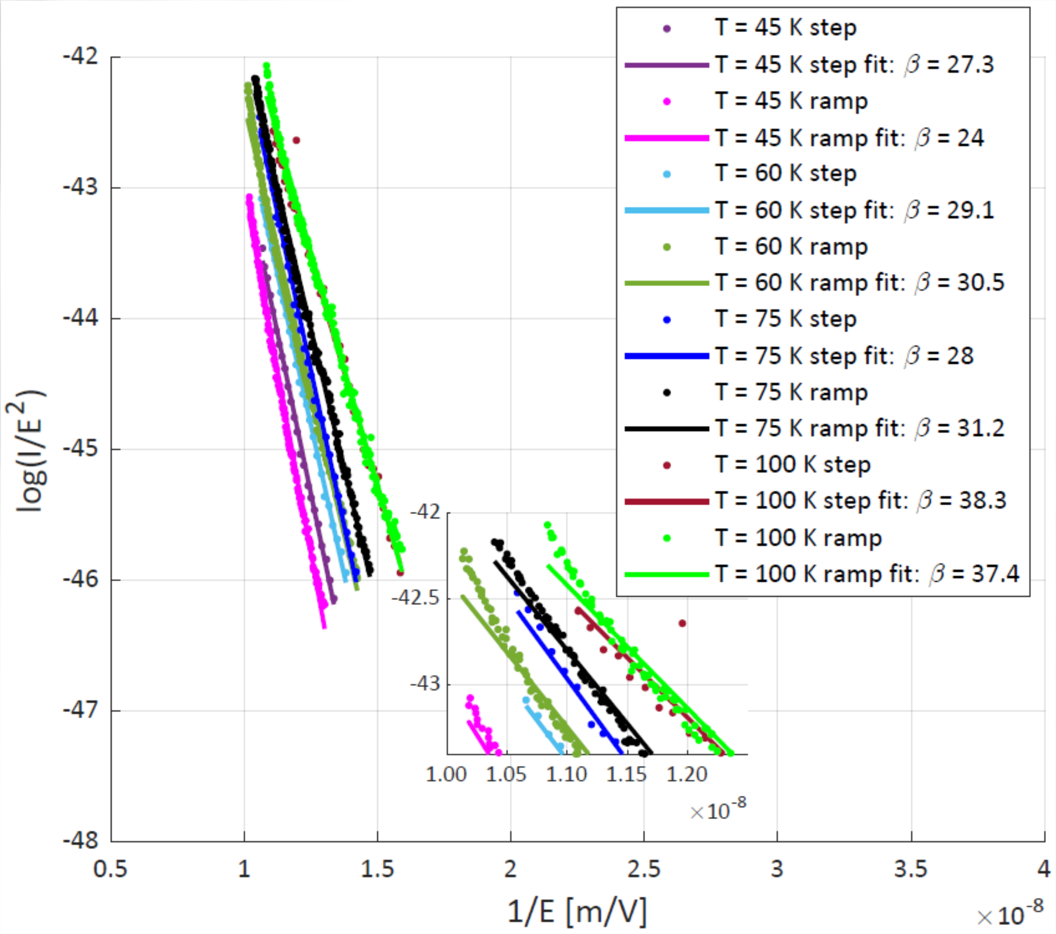


Field emission after conditioning at 300 K and cool-down to 30 K (only Heinzinger)

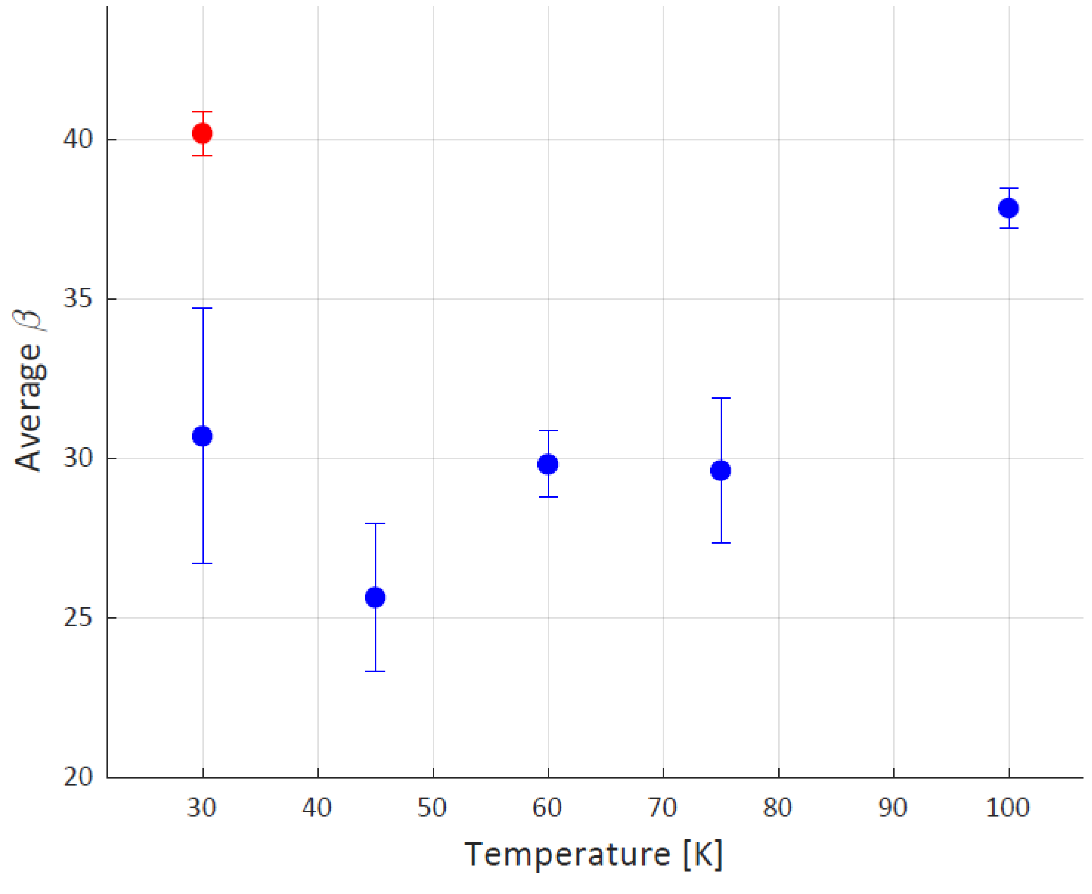


Field emission current

Results: Field emission at warm-up



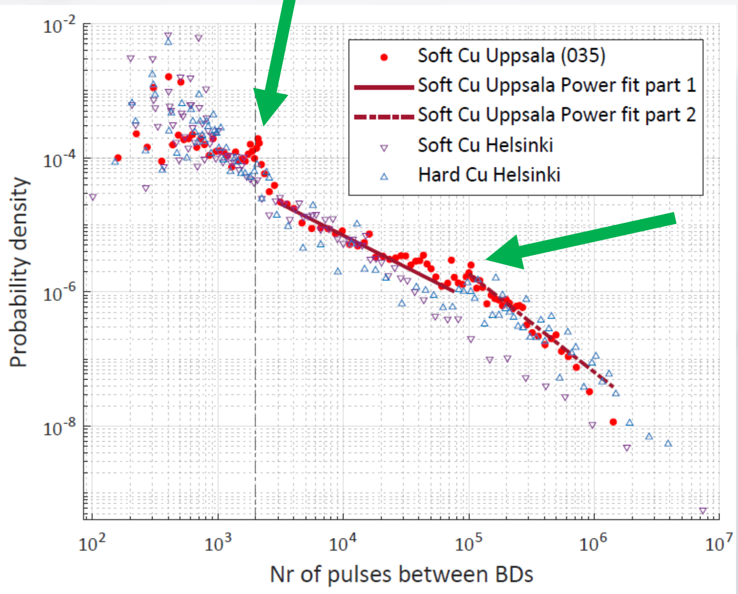
Field emission after conditioning at 300 K



Average enhancement factor β during warm-up, red dot at 30 K is after additional conditioning at that point

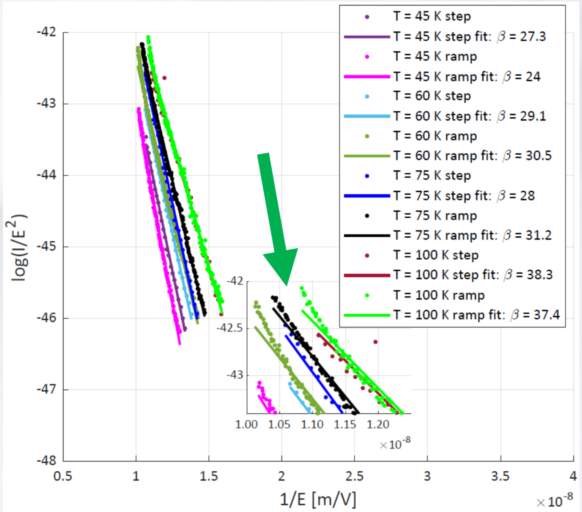
Discussion and outlook

- Conditioning
  - Successful conditioning at 300 K
  - Higher electric field for soft copper, but slower
  - Highest accelerating gradient in cryogenic setting
  - “Ricochet” effect



- Number of pulses between breakdowns
  - Could not rule out random (Poissonian) behaviour
  - Interesting peaks also in Helsinki data

- Field emission
  - Enhancement factor β increasing with temperature
  - Different order of warm-up?

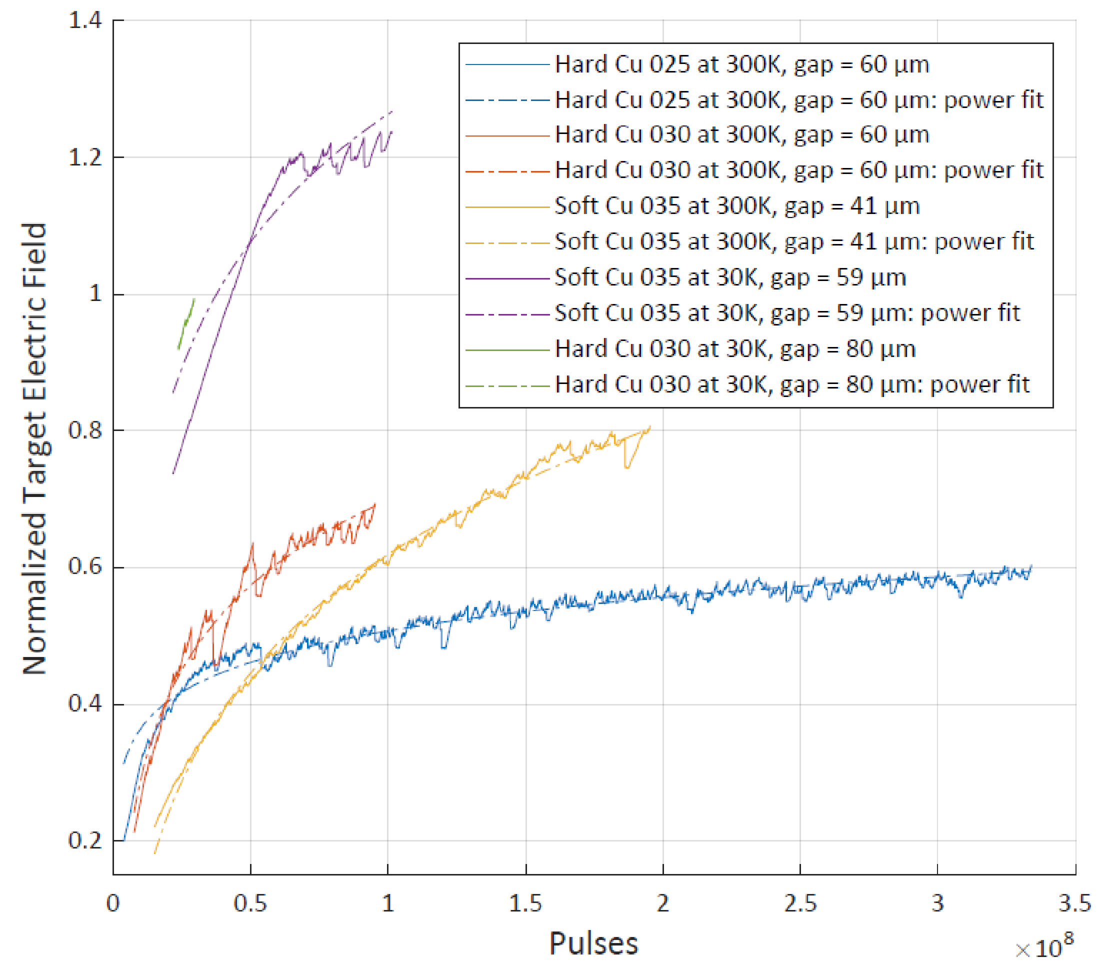


Conclusions

- Breakdowns main limitation for radio-frequency accelerators
- Soft copper in cryogenic settings
- Conditioning, breakdown behaviour and field emission
- Cryogenic experiments important for high-gradient accelerating technology!

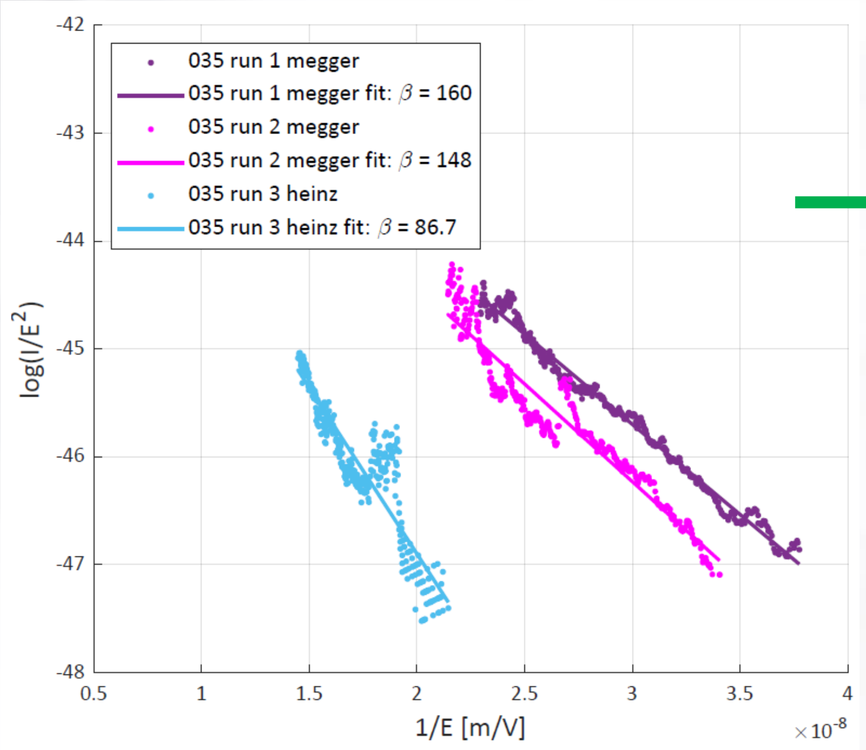
Thank you for your attention!

Results: Conditioning curve fit

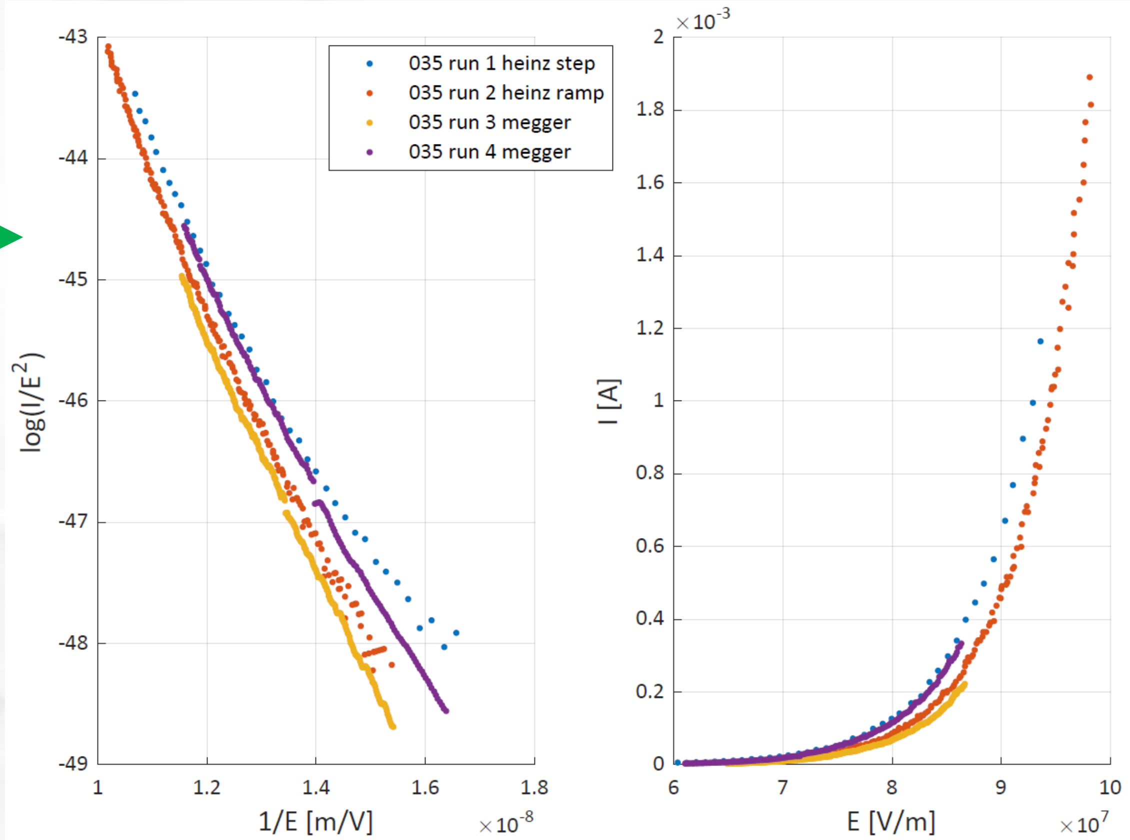


Normalized electric field with power fits

Extra slides: Field emission instrument check



Field emission at 300 K



Field emission currents at 45 K for soft copper

- No systematic difference in instruments Megger/Heinzinger