Cryogenic discharge system at FREIA Laboratory

Status of high gradient studies at Uppsala

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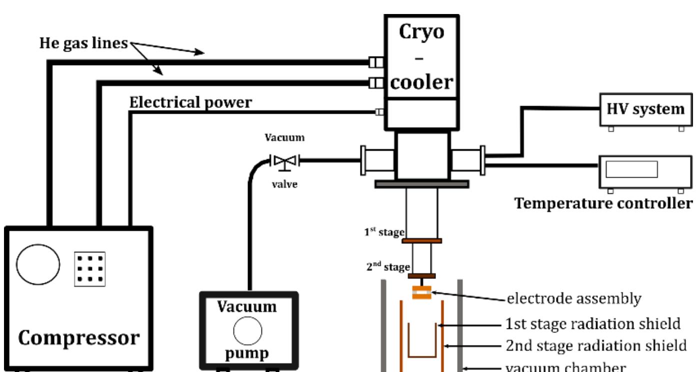
CLIC Meeting 2023, 11-13/12/2023

Cryo DC pulsed system

- Focus on fundamental understanding of conditioning process and ultimate limit on accelerating gradient
- Help theoretical models of vacuum breakdown nucleation: strong dependence on temperature
- Behavior of different, NC and SC, materials, and thin-films
- Interest in cryogenic copper applications

Field emission and BDR as a function of temperature



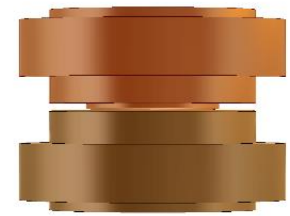
Pressure : ~ 5e-9 mbar (@cryo)

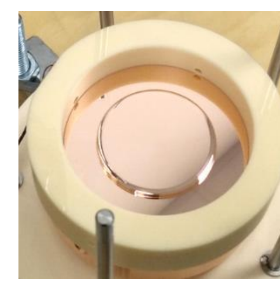
Temperature: flexible down to 4 K.

Electrodes (CERN std):
60 mm diameter cathode
40 mm diameter anode

Gap: 40 or 60 µm at warm,
(increasing **at cold**)

High voltage generator:
- Up to 12 kV voltage
- Pulsed DC
- Pulse width **1 µs** (up to 1 ms)
- Rep rate: **1 kHz** (up to 6 kHz)





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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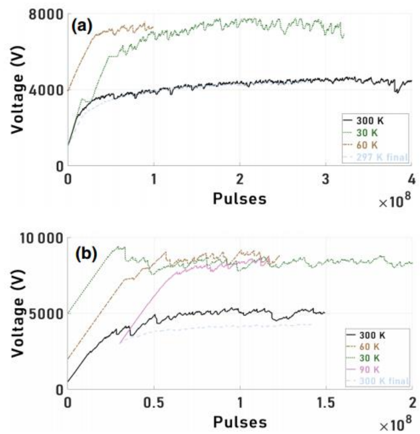
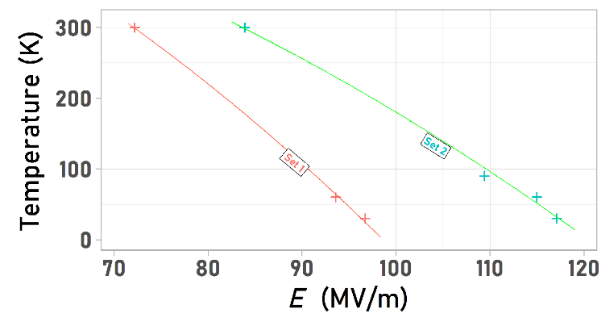
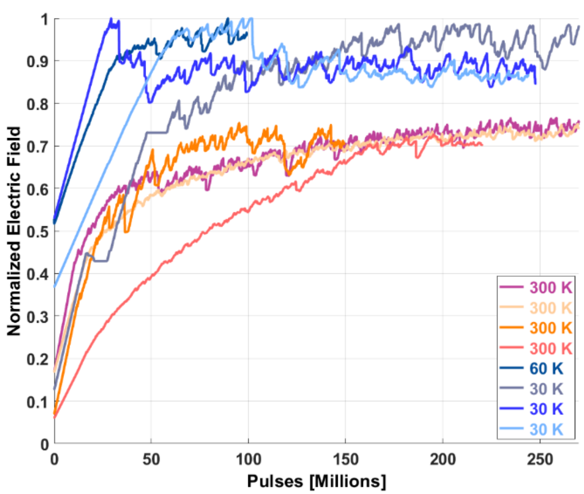
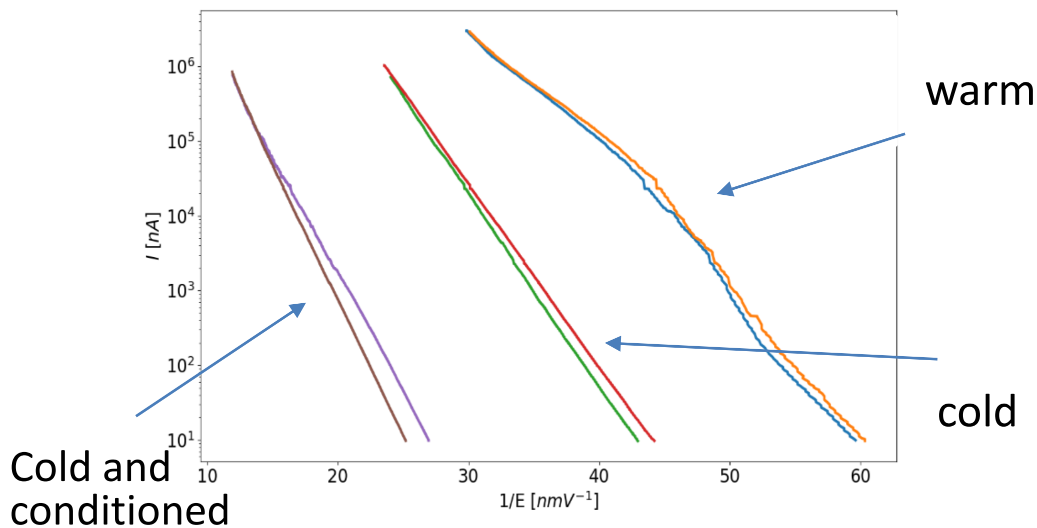




Recent results confirm the previous findings
Highly reproducible results from Field Emission (FE) – becoming valuable tool for diagnostics

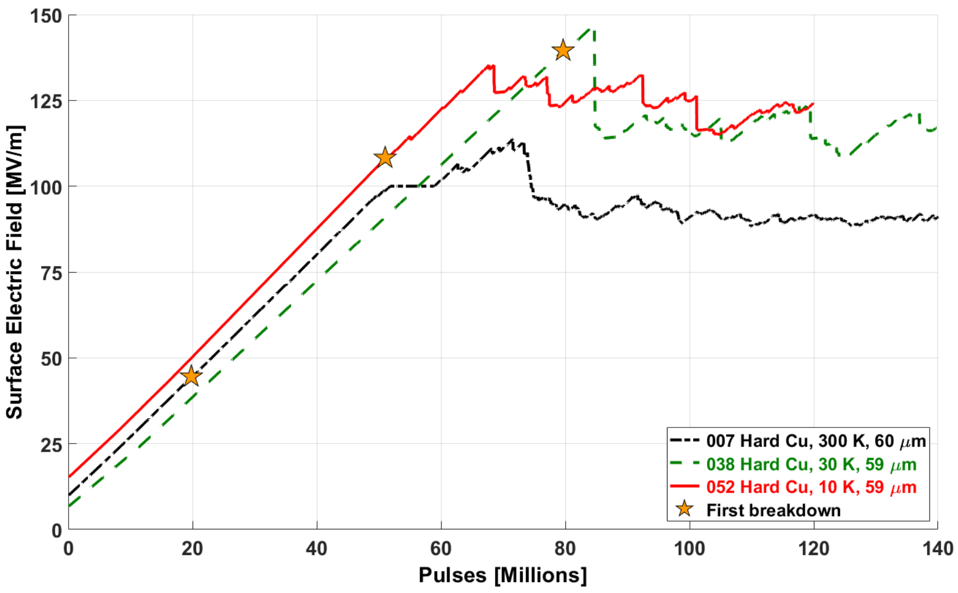




Hard copper: warm vs cold

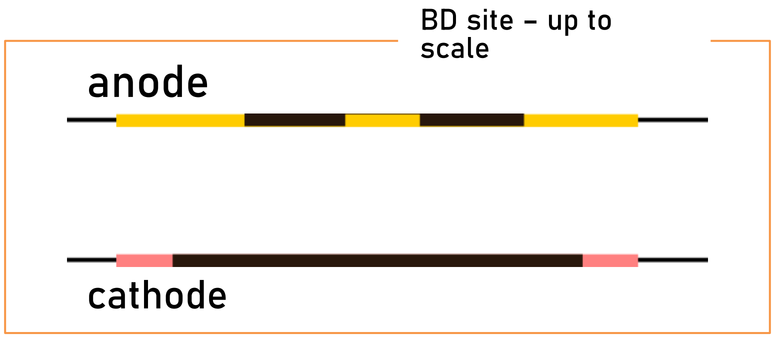
Electrodes and conditioning history:

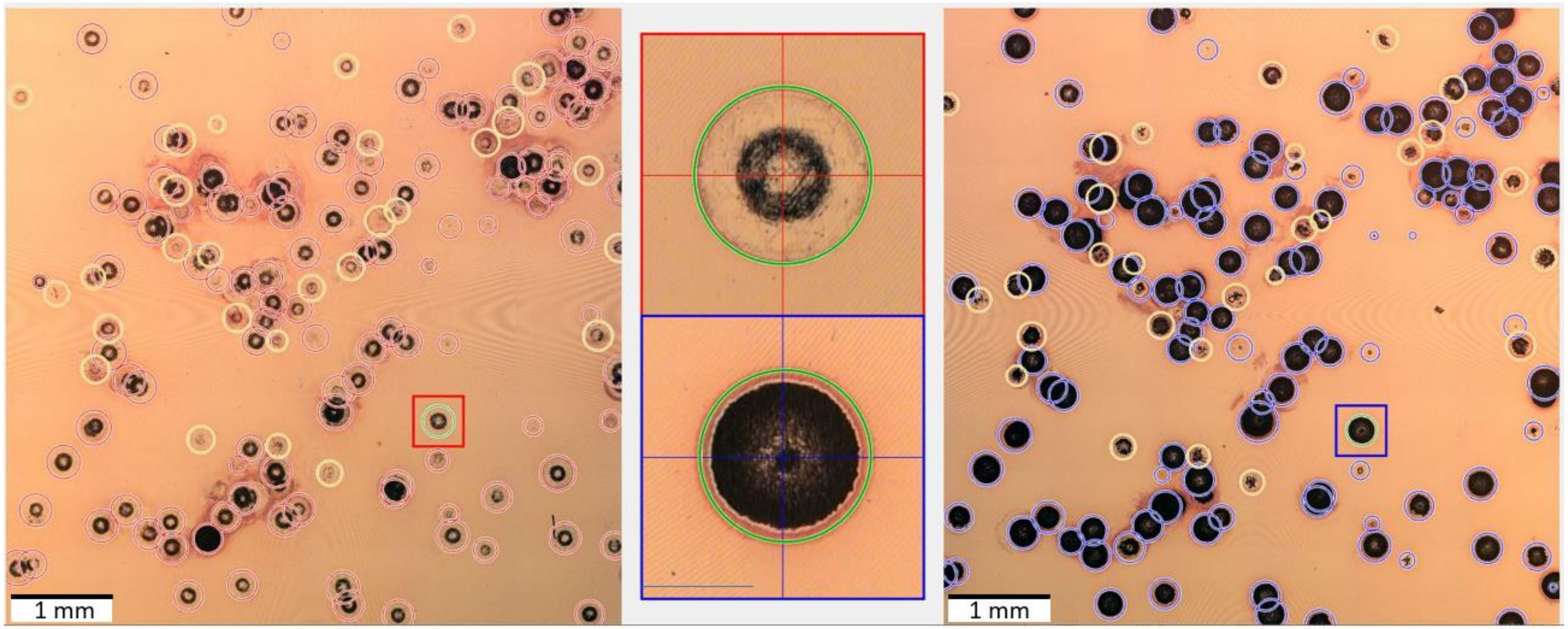
Temperature	Gap size	First BD E_{field}	Max E_{field}	Saturated E_{field}	#BDs to max E_{field}
300 K	60 µm	45 MV/m	114 MV/m	90 MV/m	94
30 K	59 µm	140 MV/m	147 MV/m	120 MV/m	7
10 K	59 µm	108 MV/m	135 MV/m	123 MV/m	27



Surface morphology "post-mortem"

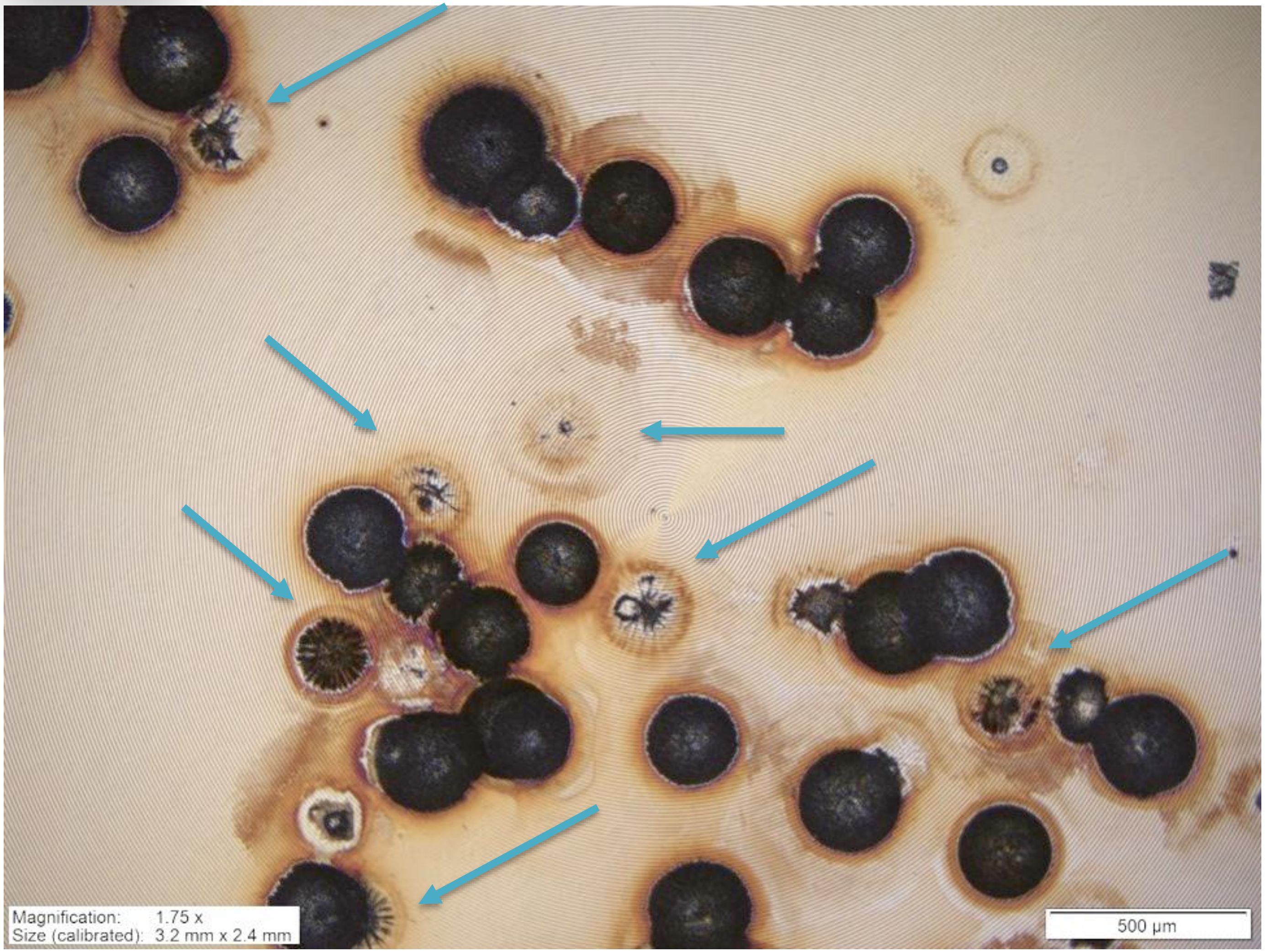
HiRes optical scan with anode-cathode matching





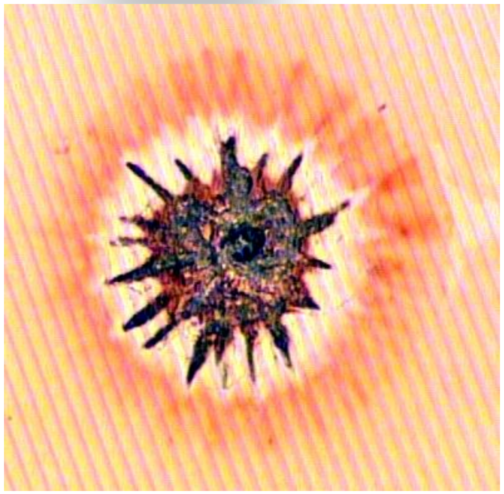
Atypical BD features

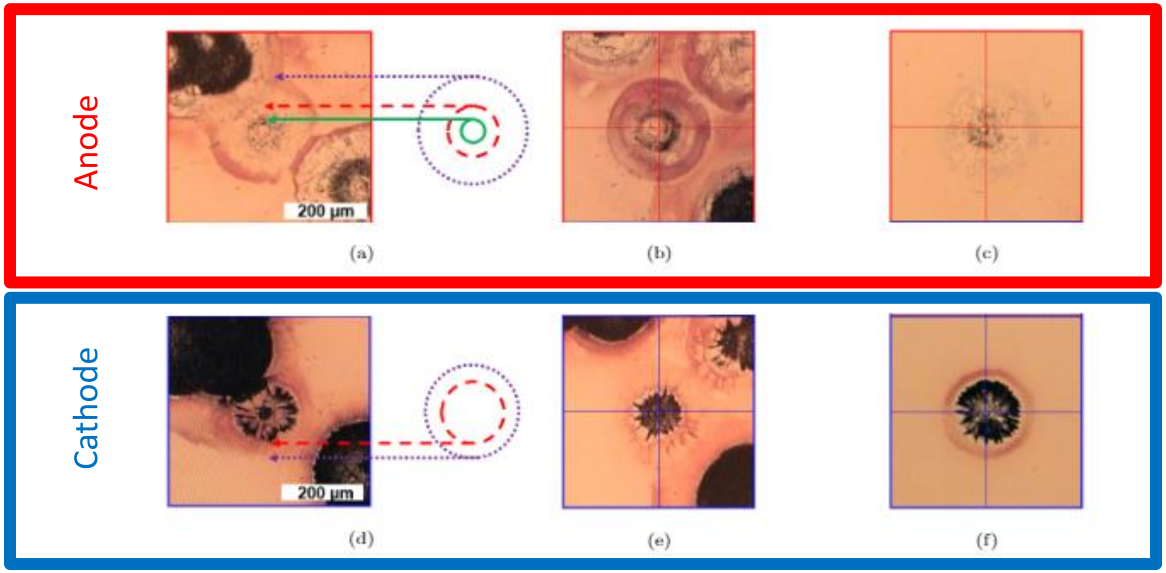
cathode surface after high field conditioning at 30K and 10K



Courtesy Inna Popov, The Hebrew University of Jerusalem

Star-like features created during cryo test





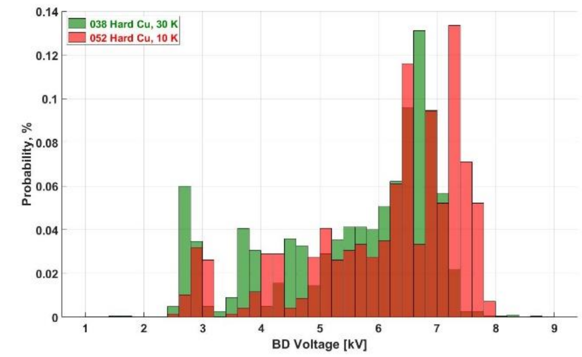
Found only on cathode

Features on anode similar to regular ones, but ”weaker”

Temperature	Nb of BDs	Nb of star-like	Fraction
30K	145	37	**26**±5%
10K	280	149	**53**±7%

Temperature dependence

The data taken at 30K and 10K are at very similar field conditions, giving large confidence in feature comparison

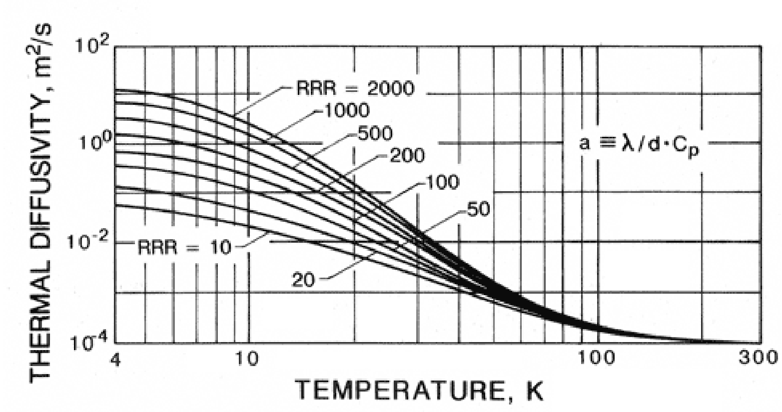


BD sites show therefore clear the temperature dependence:

- Formation of star –like features and
- their percentage, doubling in number when going from 30K → 10K

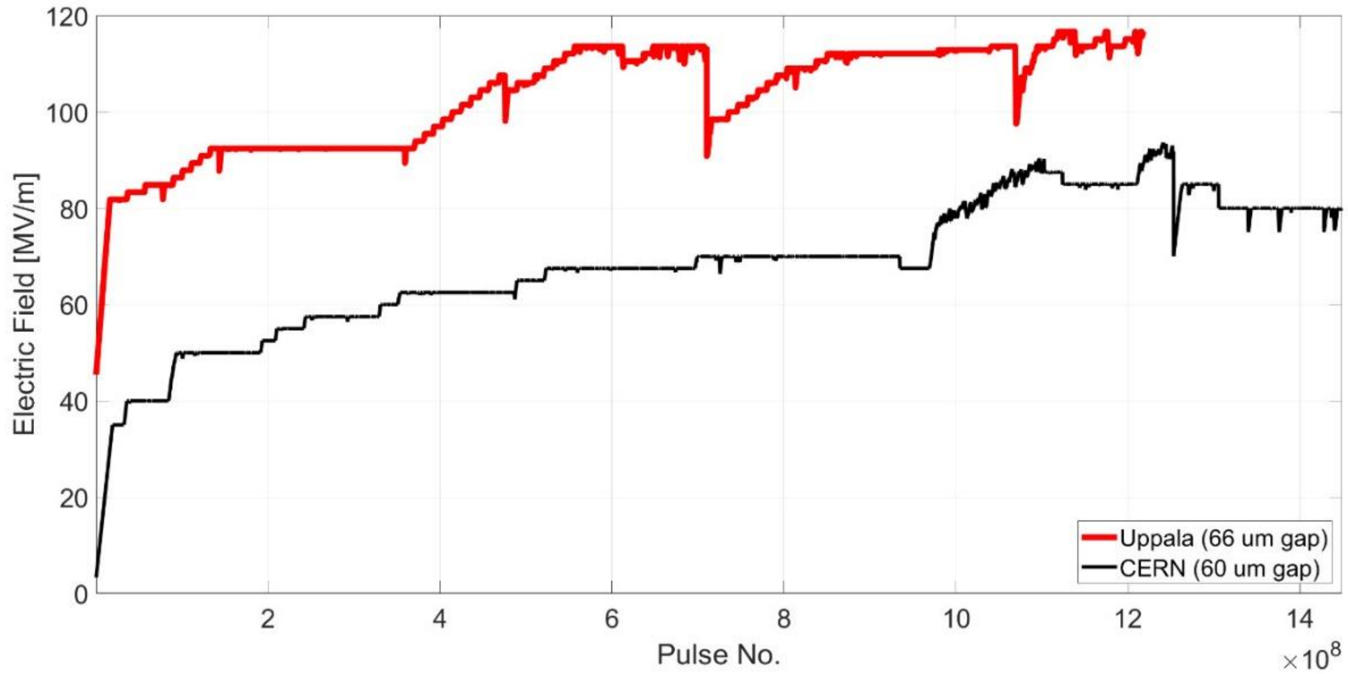
Our interpretation:

- Unstable tip ejects molten material in random direction, lands on the cold(er) surface and freezes
- If the melting continues, the regular circle around the crater will form and expand → features created by plasma instabilities will be covered
- In the room temperature experiments we see therefore no star-like traces left
- In cryo temperatures, the heat is dissipated more efficiently, and we can get a glimpse to the first stages of the thermal runaway of the tip



Source: https://www.copper.org/resources/properties/cryogenic/

Nb conditioning at 4K – first run
(preliminary results)



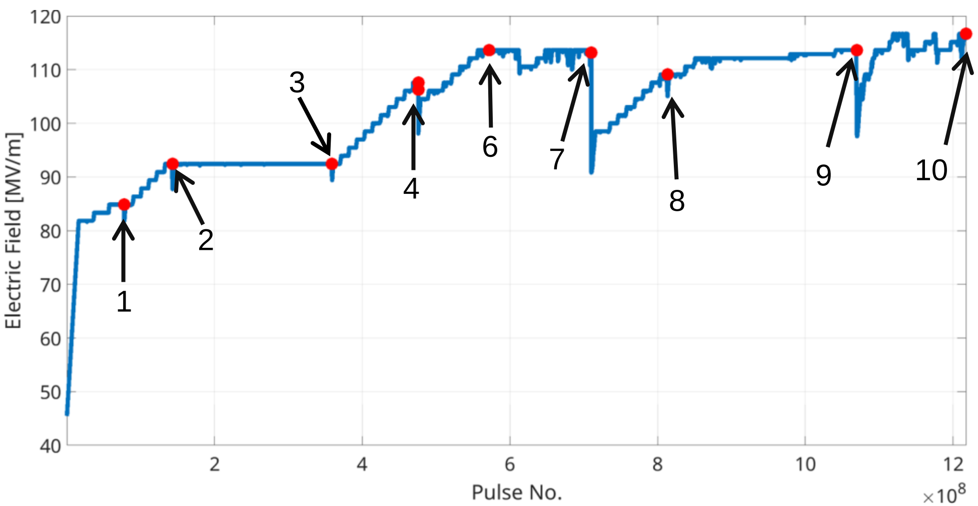
Saturation field: 116 MV/m, BDR ~ few 10^{-6}

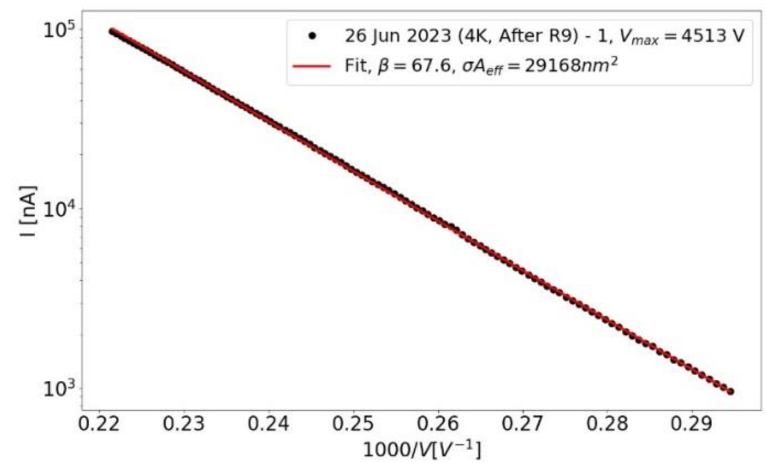
Room temperature (CERN), saturation field: 84 MV/m

Nb conditioning – first run
(preliminary results)

Conditioning accompanied by a regular FE measurments

β and the emitter area are extracted from the data

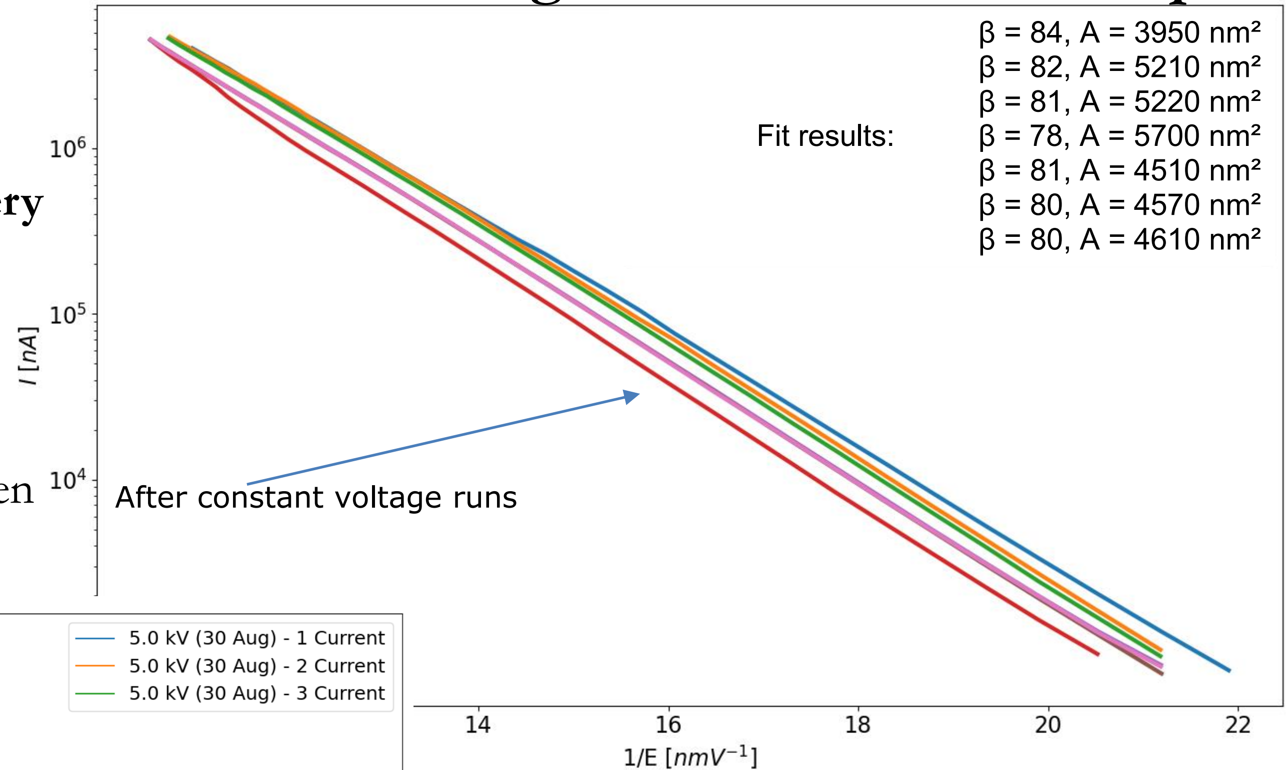




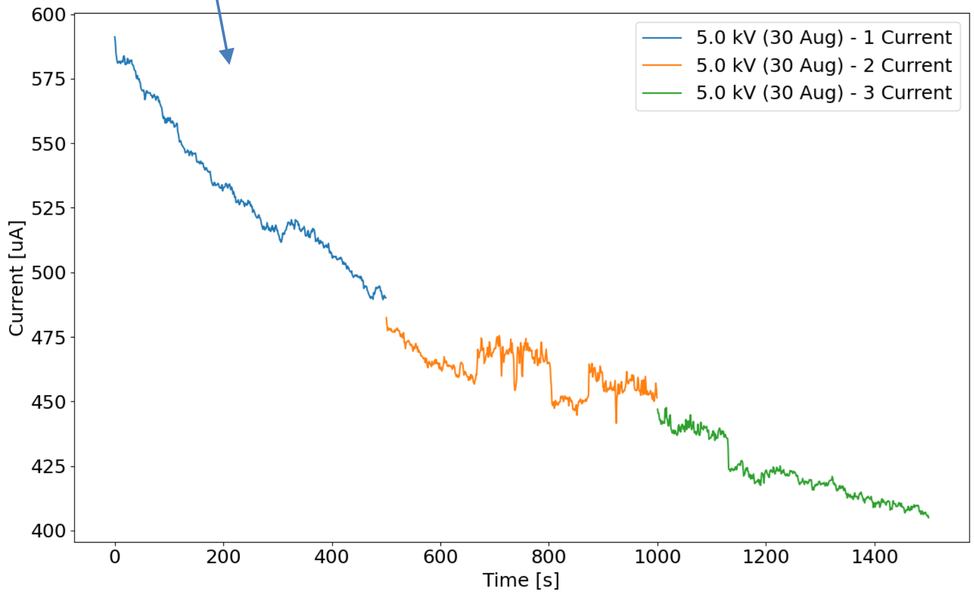
Typical FE scan data with F-N type fit

Nb conditioning – field emission examples

Field emission scans show very stable surface



Small effect of conditioning even for constant voltage runs

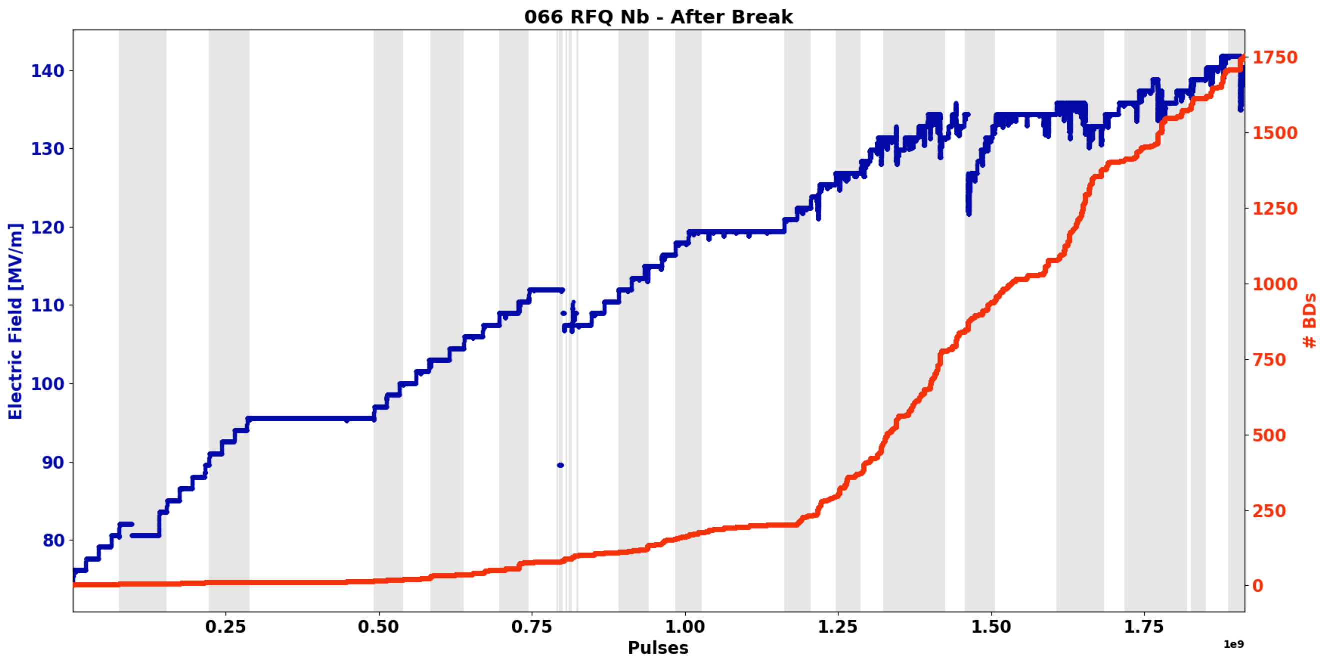


Temperature slowly increases on anode, then stabilizes

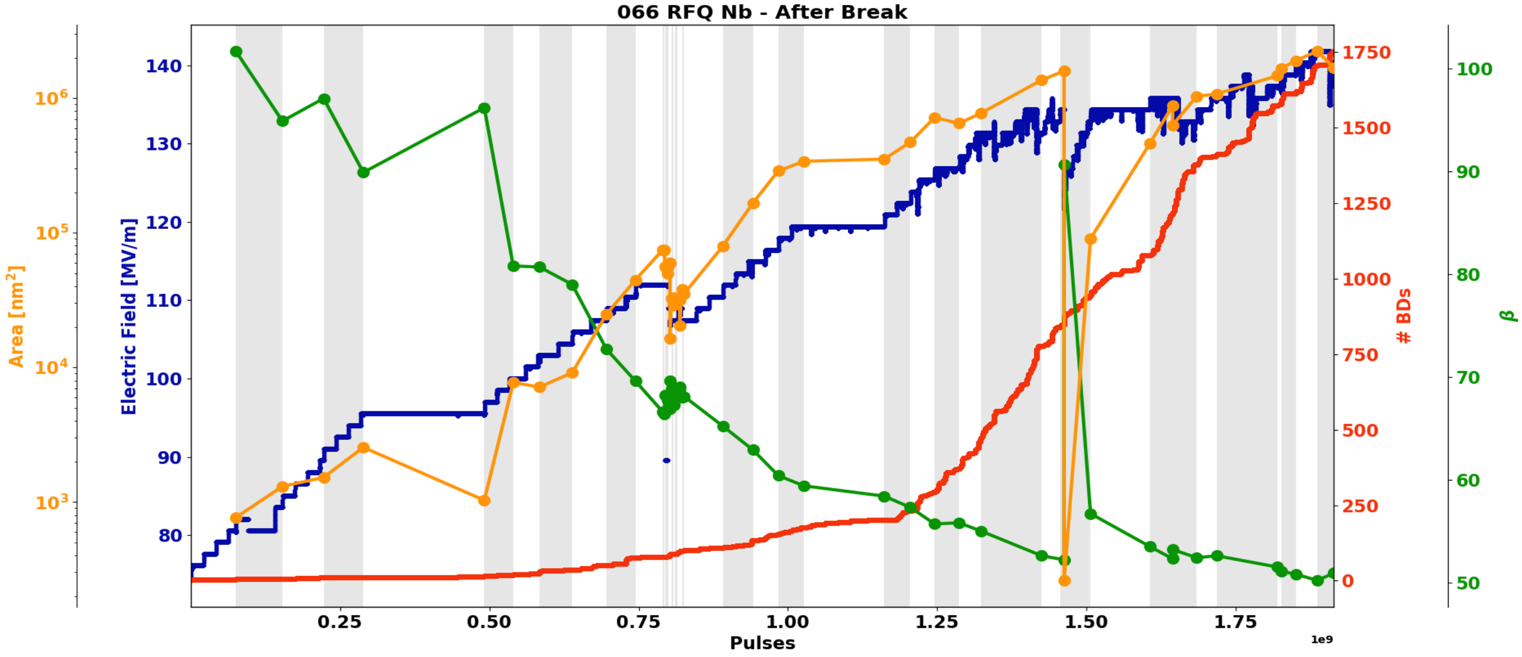
If stopped, after a pause to cool down, FE picks up from the same value

Nb conditioning – second run (preliminary results)

Saturation field: 144 MV/m, BDR ~ few 10^{-6}



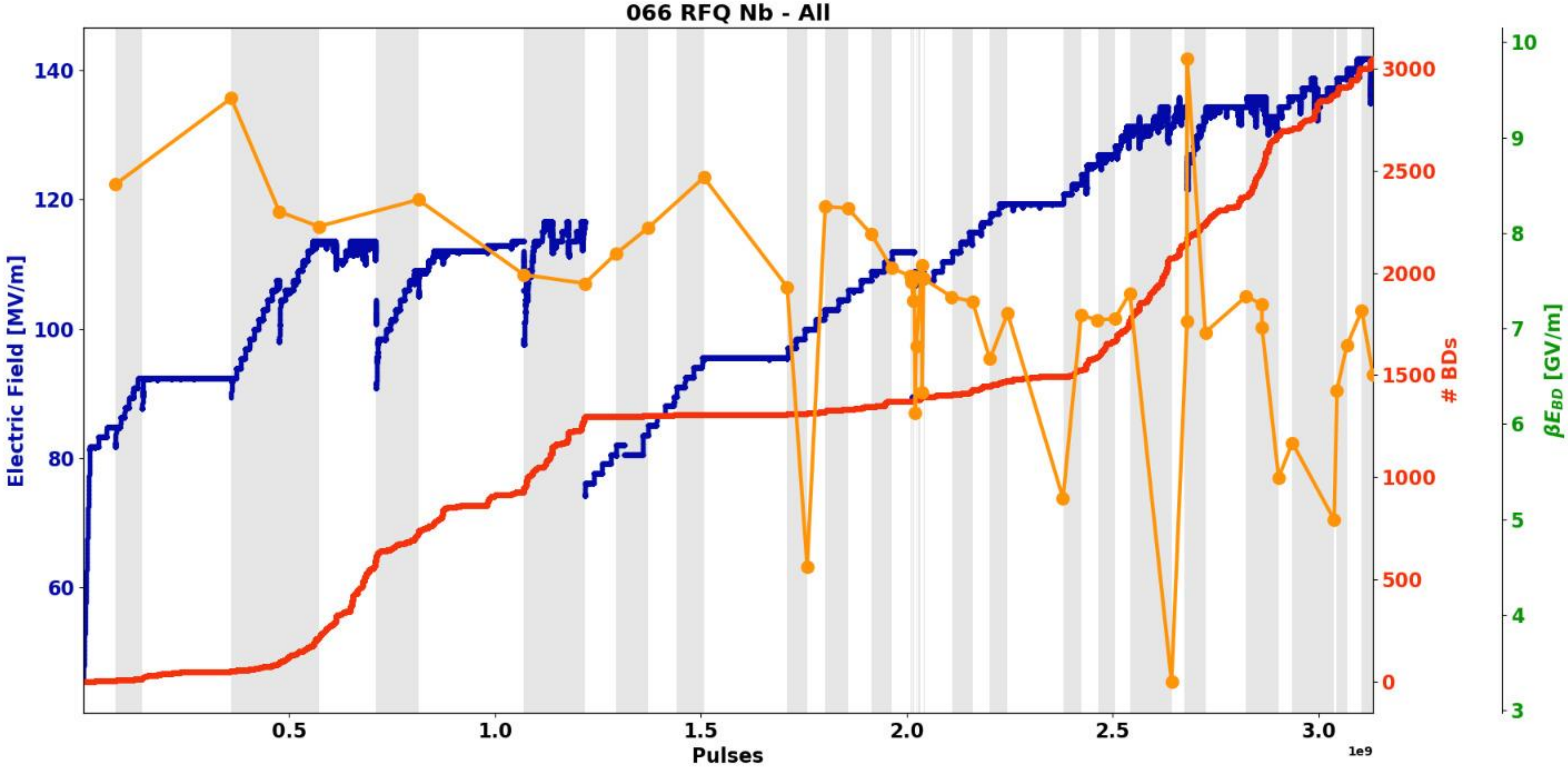
Nb conditioning
Emitting area and field enhancement factor



Conditioning curve and the fit parameters from the FE curves
(the first measurement immediately after a portion of a conditioning run)

Beta stopped decreasing is a sign that we are towards the end of the conditioning

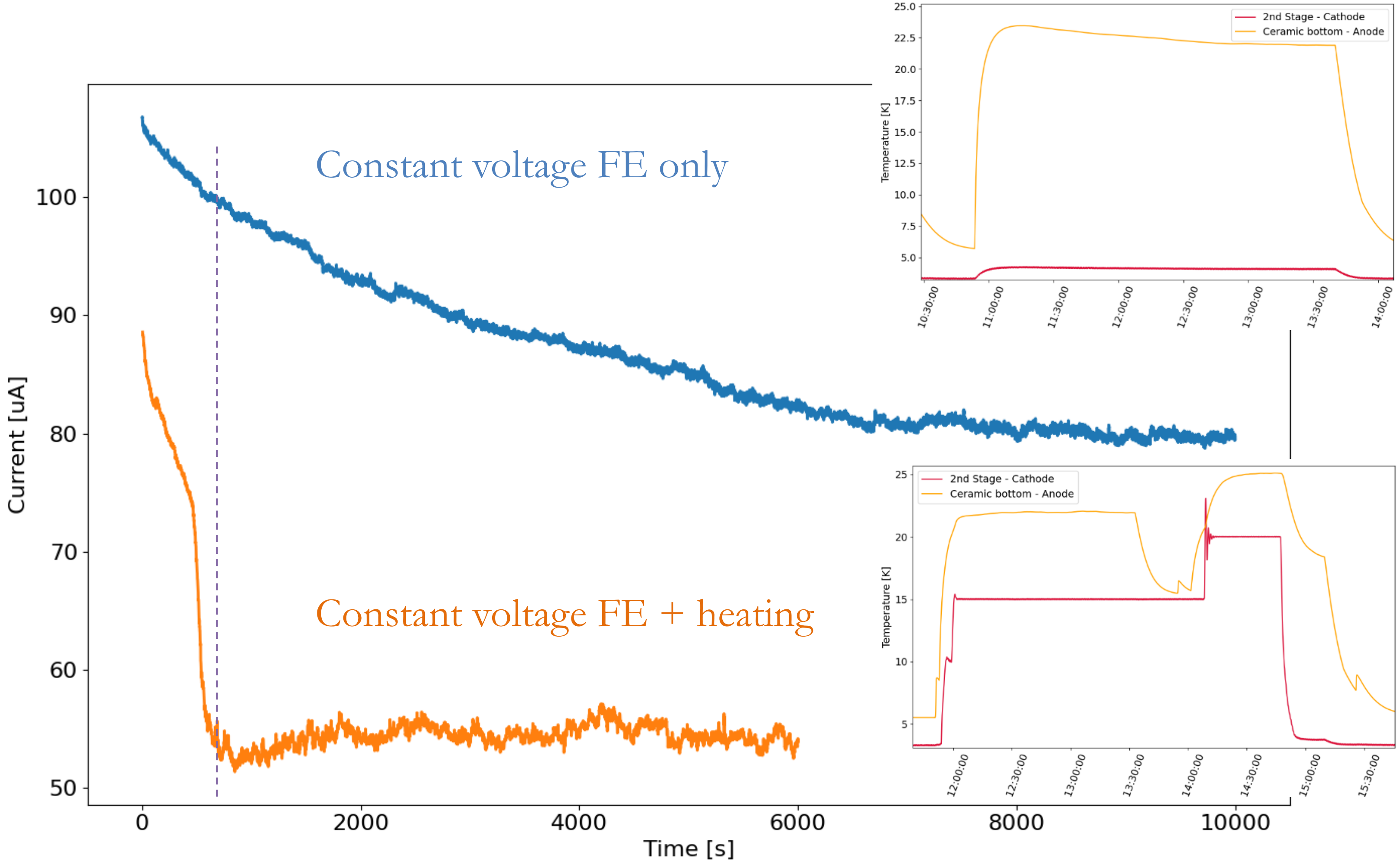
Nb conditioning
Local Electric field



$$E_{BD}^{Local} = \beta E_{BD} \cong 7\frac{GV}{m}$$

Field emission studies

Temperature dependance



Surface resistivity measurements during high-field conditioning

Main motivation: Test the dislocation hypothesis

How?

- Cryogenic environment + DC conditioning + RF resistivity measurement

The electrode system needs to be **modified**:

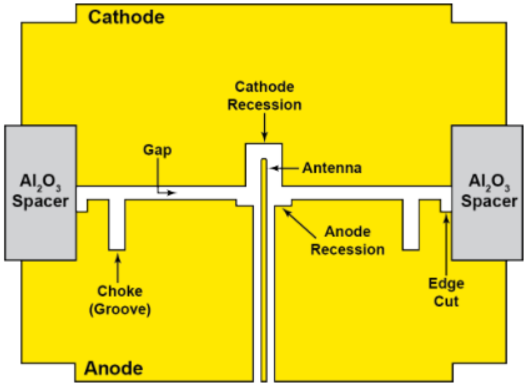
- Anode: a groove (choke) to contain a resonant mode between electrodes) (idea thanks to J. Paszkiewicz and S. Calatroni)
- Cathode: for better/safer antenna coupling

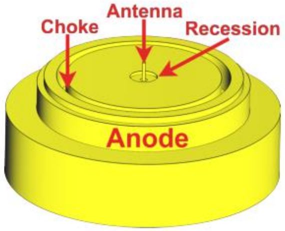
We have tested a prototype to confirm the concept (at room temperature)

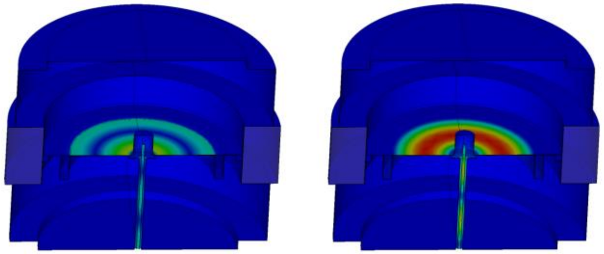
First set in production at CERN

We are getting ready for first measurements

BONUS: RF antenna inside the system = new methods of investigating breakdowns.







"*In Situ Resistivity Measurement of Metal Surfaces to Track Down Dislocations Caused by High Field Conditioning*", Manuscript accepted (DOI: 10.1017/S1759078723001411) Cambridge University Press

Summary and plans

The temperature "knob" is a great way to further explore the limits on accelerating gradient

Cathode and anode surface morphology → may shed light on process that dominates BD formation, e.g. pre-BD phase, instabilities during thermal runaway and initial explosion ; simulations needed

Field emission is an invaluable tool for diagnostics of the conditioning process

- Very clean data at cryo, highly reproducible

We aim to fully utilize our setup with further tests and diagnostics:

- Characterization of Nb electrodes with the same methods
- Other materials, Ti electrodes in the pipeline
- Measure changes in surface resistivity during conditioning with microwave method
- RF antenna as additional tool for BD diagnostics
- Upgraded Marx power supply with build-in FE capabilities
- Regular use of RGA for diagnostics

UPPSALA UNIVERSITET

Thank you for attention