Investigating the causes of vacuum arc breakdowns under cryogenic conditions

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Motivation

- High electrical gradients in vacuum are needed in many areas of research and in many technological applications:
  - High energy accelerators
  - Short linacs for FEL or medical applications
  - High vacuum interrupters
  - Spacecraft
  - Fusion research
  - Electron and X-ray sources
- High electric field → Electric discharge
- Electric discharges can happen even in vacuum (vacuum arc breakdown)!
- But there are no molecules to ionise in vacuum
- Metal vapours and electrons from the surface of the cavity/electrode form the conductive plasma
- The maximum acceptable electric field is given by the proprieties of the metal

Picture from Sandia National Laboratory

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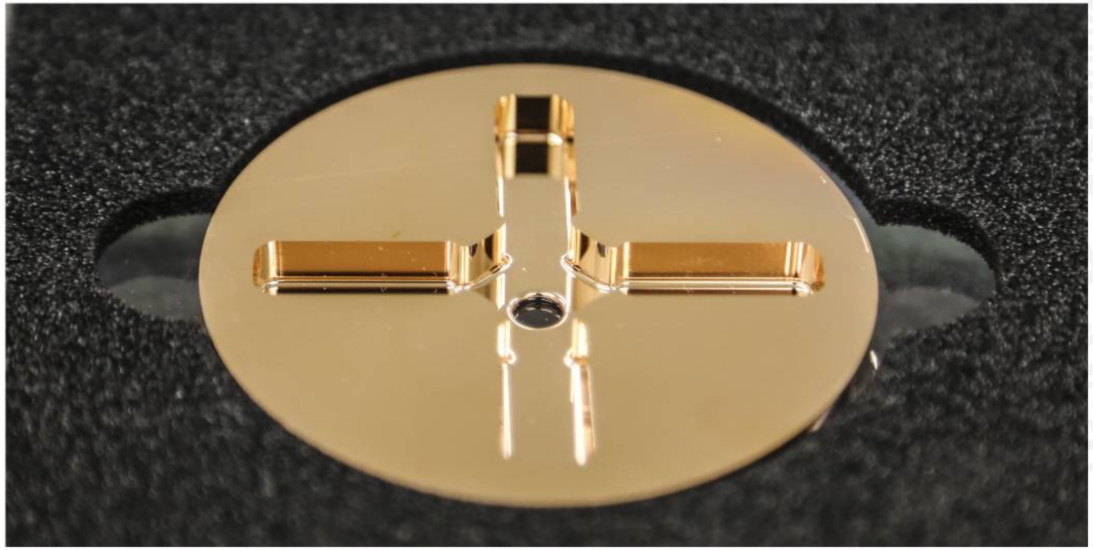
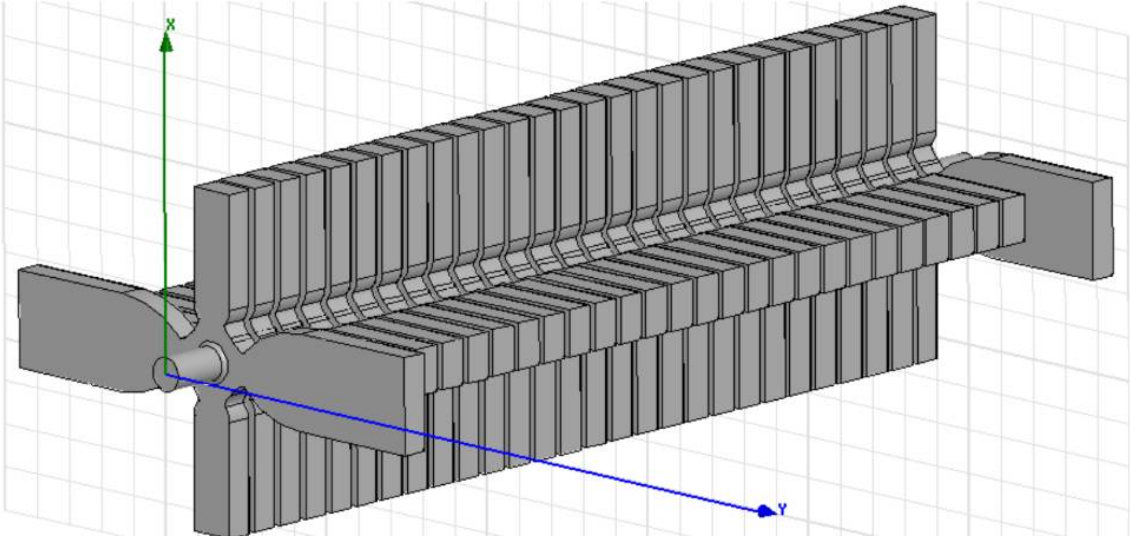
Motivation

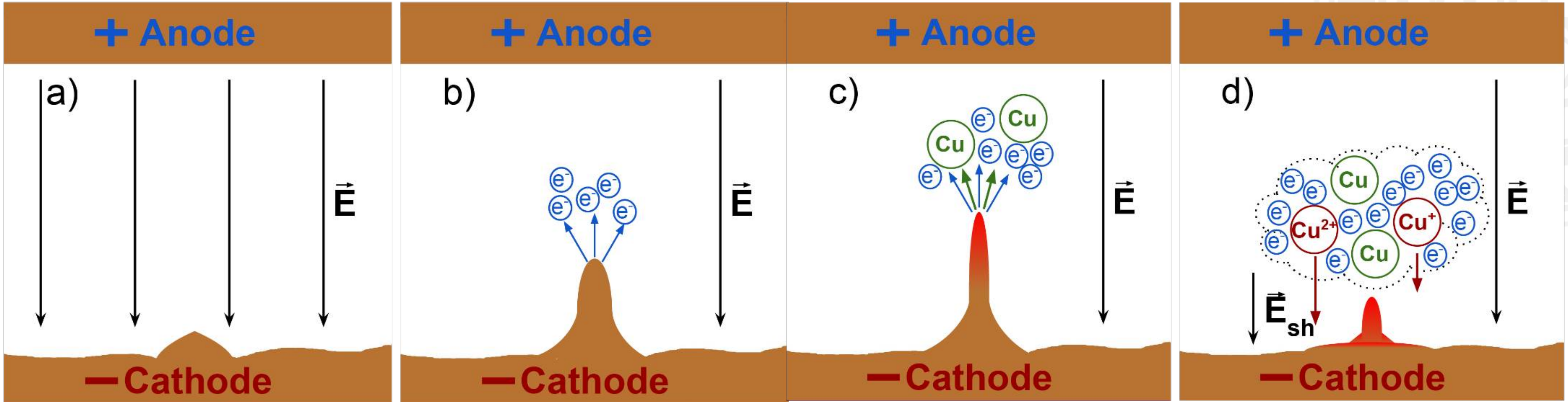
- Vacuum arc BD limit the accelerating gradient in the accelerating structures
  - CLIC: 100 MV/m
  - C3 (Cool Copper Collider): 120 MV/m – cooled by LN
- Push gradient limits while quantifying and understanding vacuum breakdown phenomena
- Provide data for benchmarking the available theories
  - Temperature dependence of the break down rate and accepted field
  - BDs are thought to start with field emission → clean field emission data is needed → cryogenic conditions

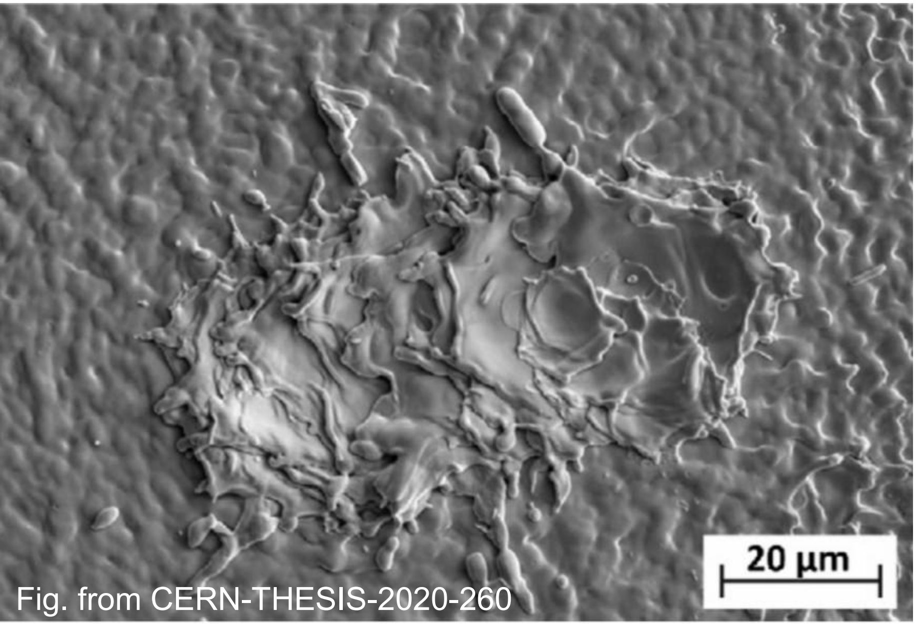


Figs. from CERN-THESIS-2020-260



How do vacuum arc breakdowns form?





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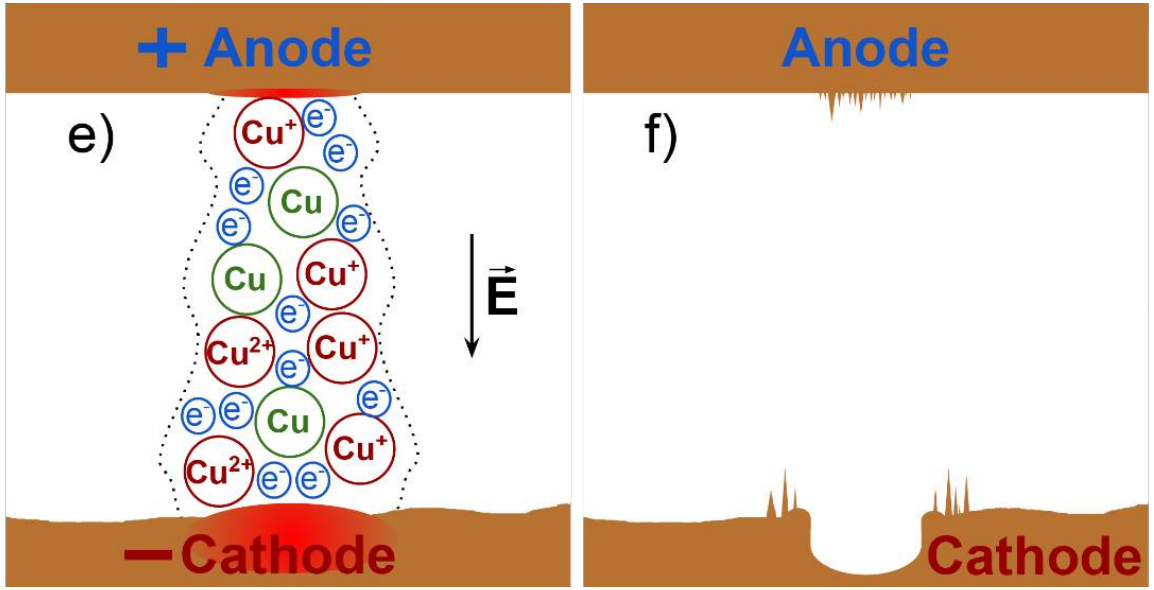
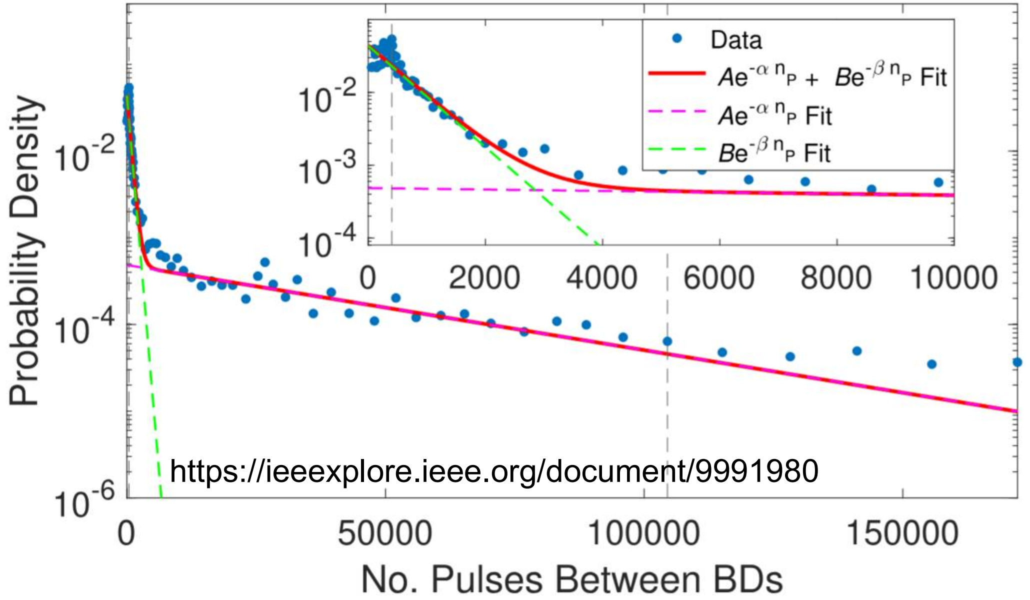


Fig. from http://hdl.handle.net/10138/336482

Introduction – Conditioning

- Conditioning the surface (applying high electric field pulses repeatedly on the surface) → higher breakdown strength
- The accepted electric field is increased by 4-5 times
- Beyond that, more conditioning does not help
- Even if the surface is rougher due to the craters, the accepted electrical field is higher!
- Two types of breakdowns:
  - Secondary – extrinsic mechanisms (surface state – impurities, geometry)
  - Primary – intrinsic mechanisms (material properties)
- Effect of temperature



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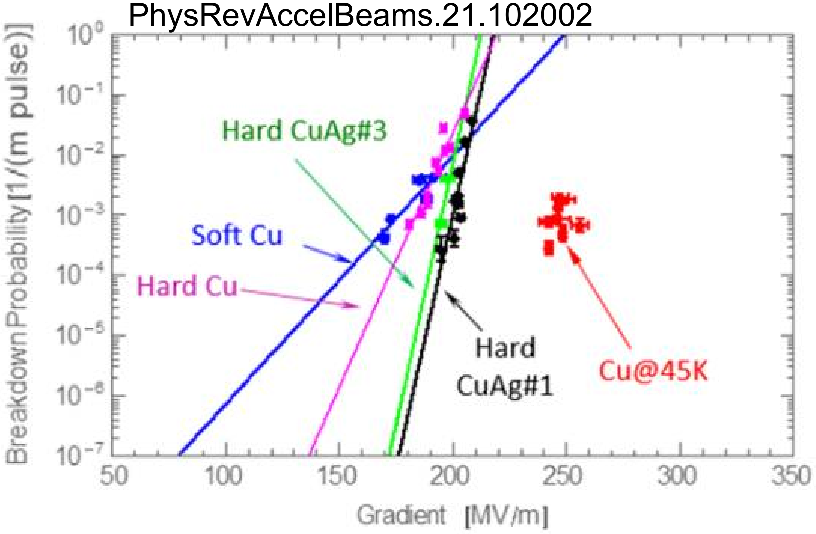

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Introduction – Material comparison

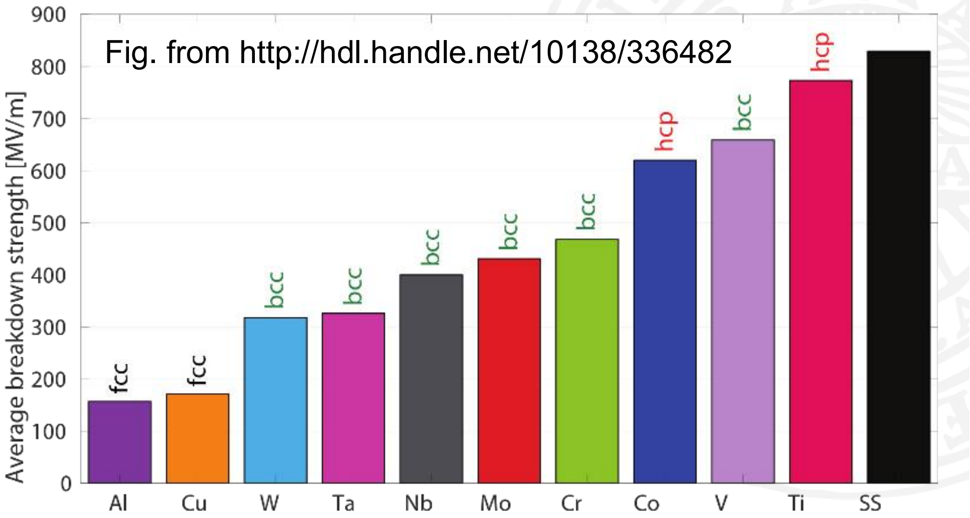
- Compare different pure metals and alloys
  - The breakdown strength correlates with crystal structure

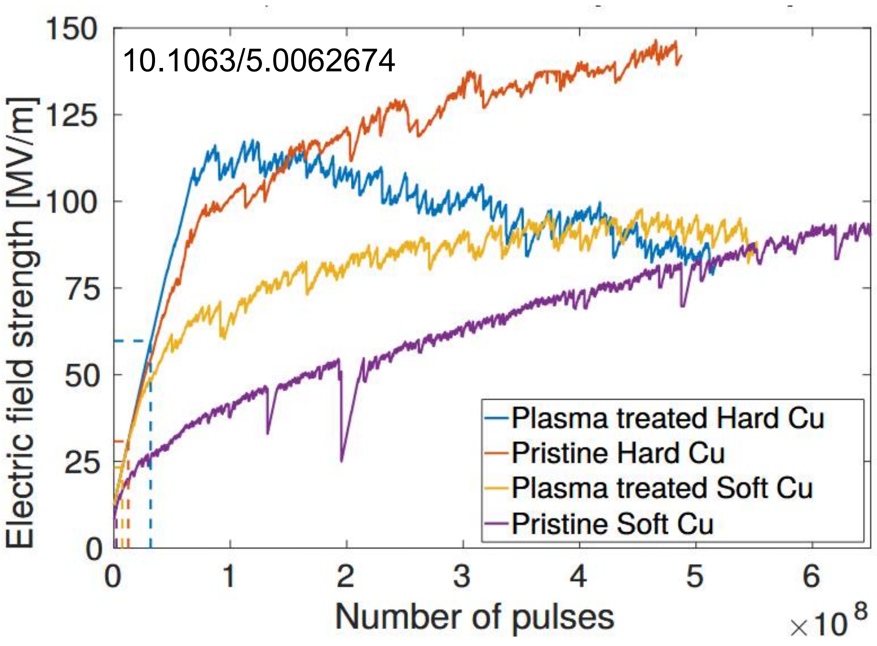
Hard Cu vs soft Cu (non-heat treated vs heat-treated)

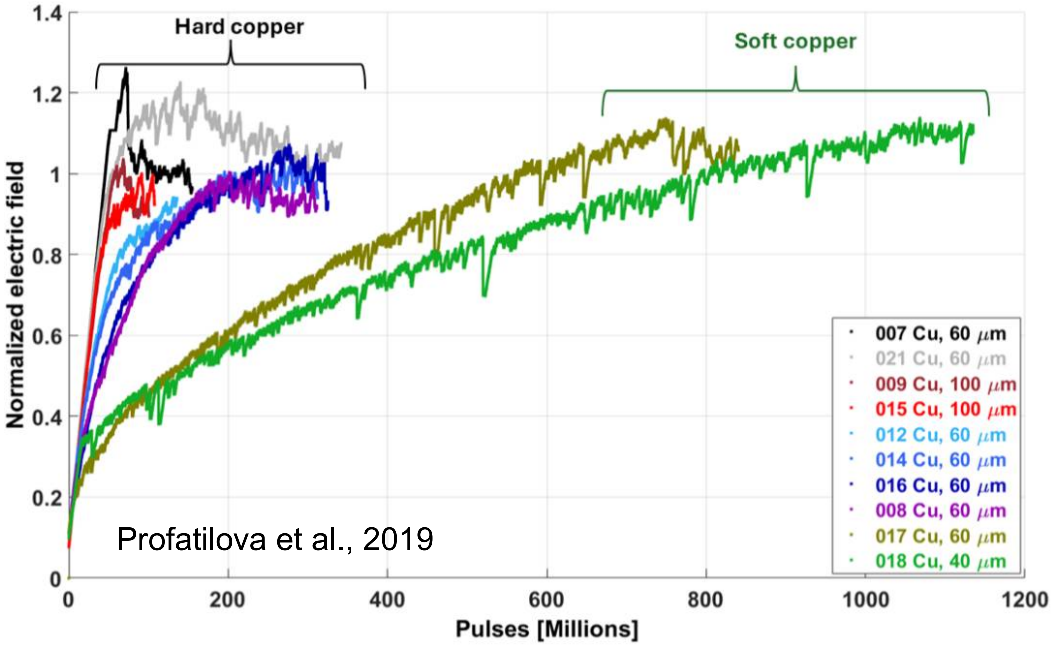
- Same final field
- But hard Cu conditions faster

Plasma treatment on Cu electrodes

- Has no effect on final field







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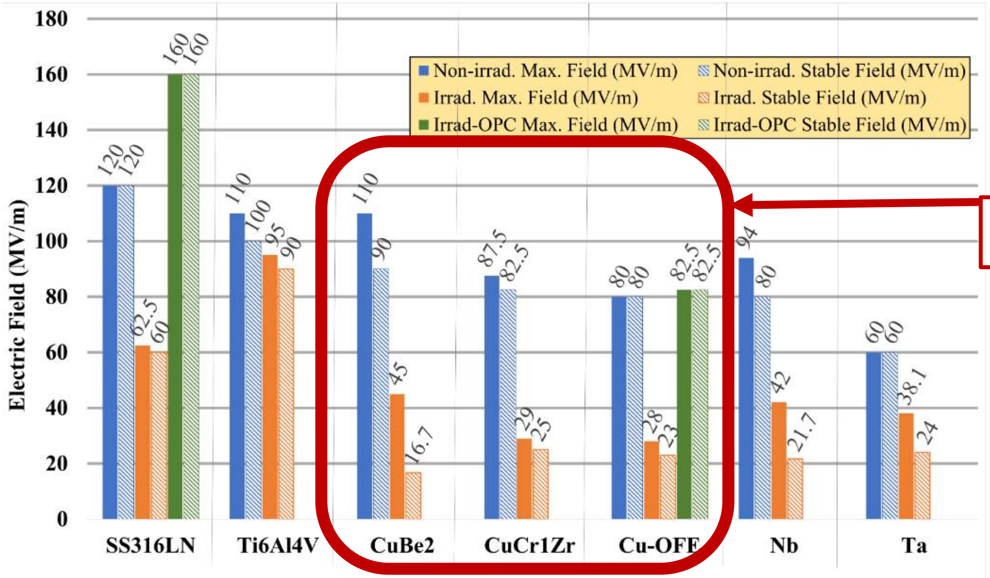
Introduction – Irradiation

- Test H- irradiated electrodes
- Motivation: surface damage due to breakdowns at LINAC4 RFQ
- All figures and data from http://hdl.handle.net/10138/595645



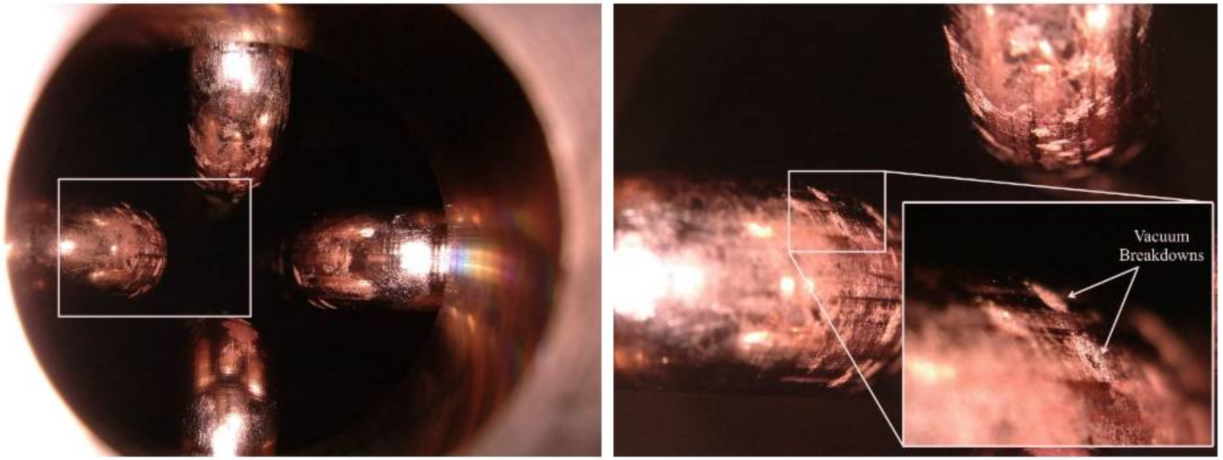
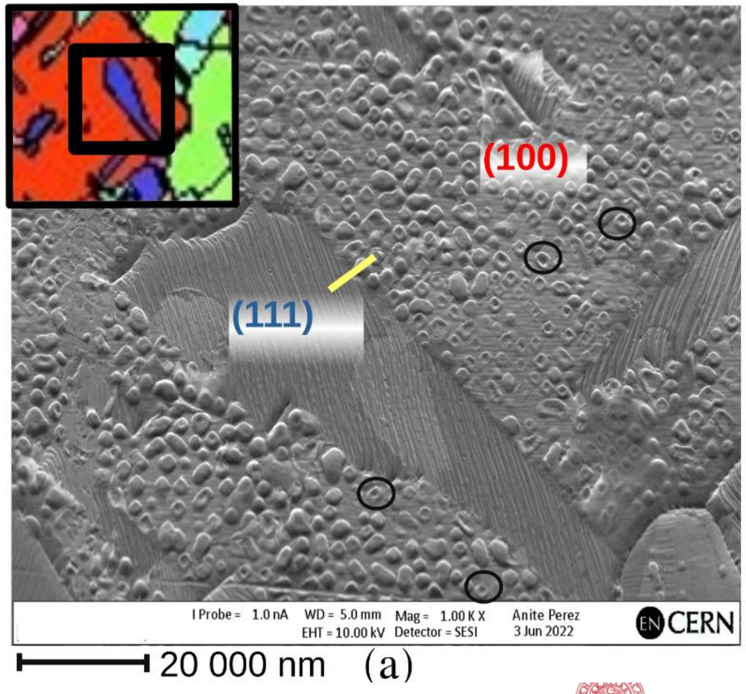
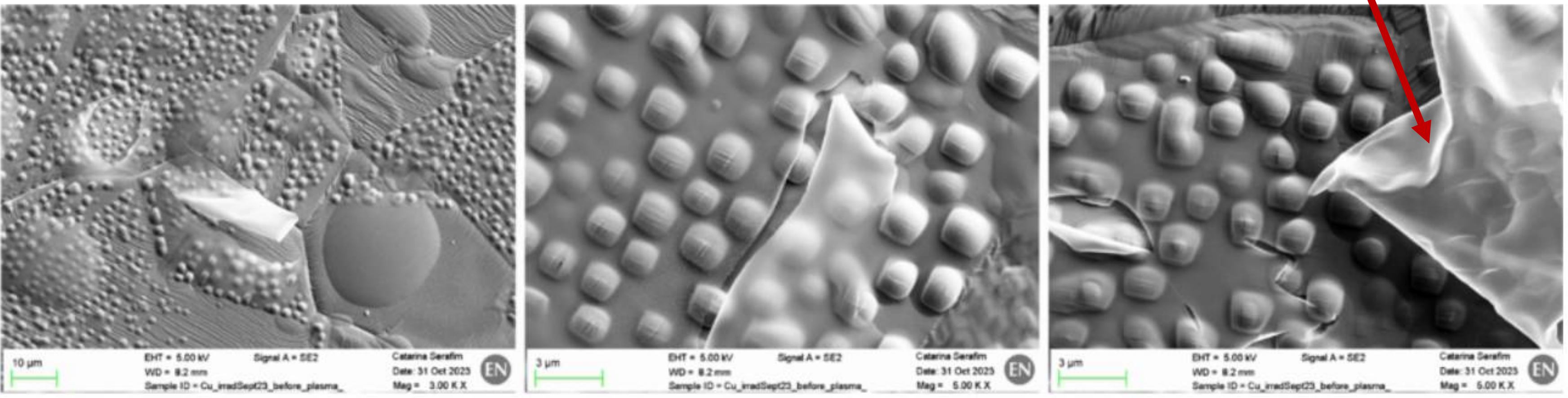


Figure 1.2: Endoscope optical images taken on the front of the LINAC4 RFQ interior vanes, at CERN.





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Introduction –Possible Conditioning Mechanism

- Under large electric fields, dislocations move to the surface, causing the sharp features
- During conditioning, new immobile dislocations are created, which block the mobile dislocations from reaching the surface → Conditioning
- Dislocations also increase surface resistivity
- Test the theory, measure the resistivity → information about the creation of dislocation underneath the surface

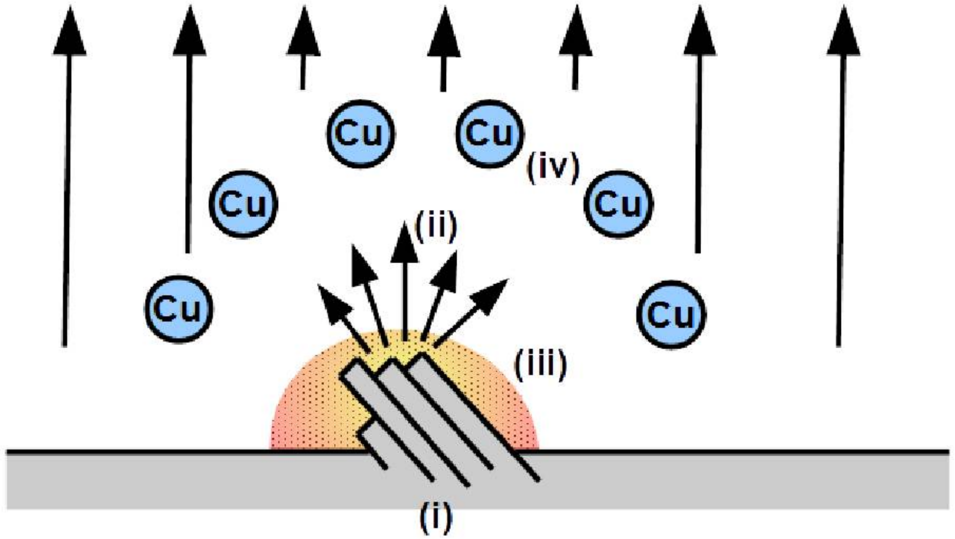


Fig. from https://arxiv.org/abs/1909.01634

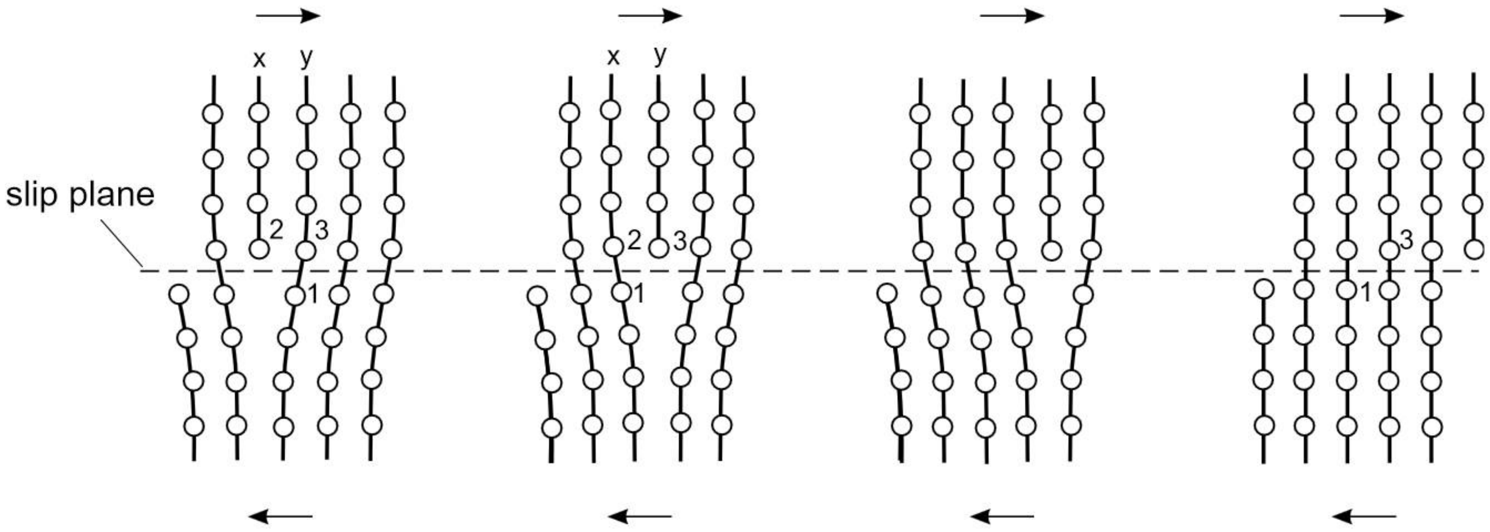
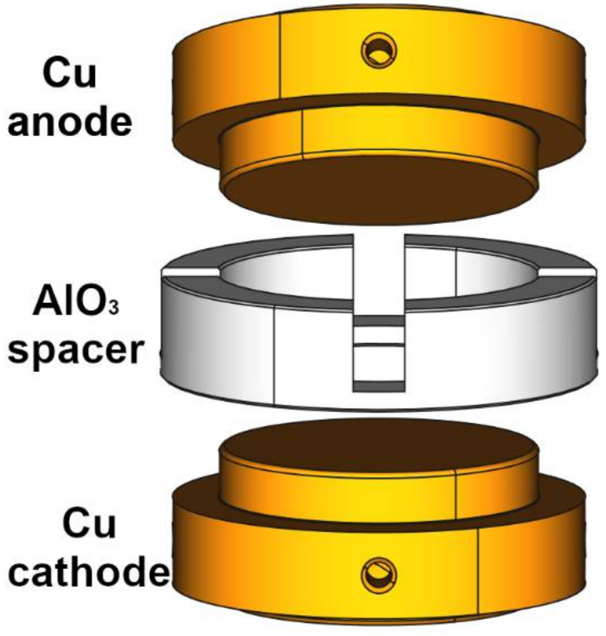
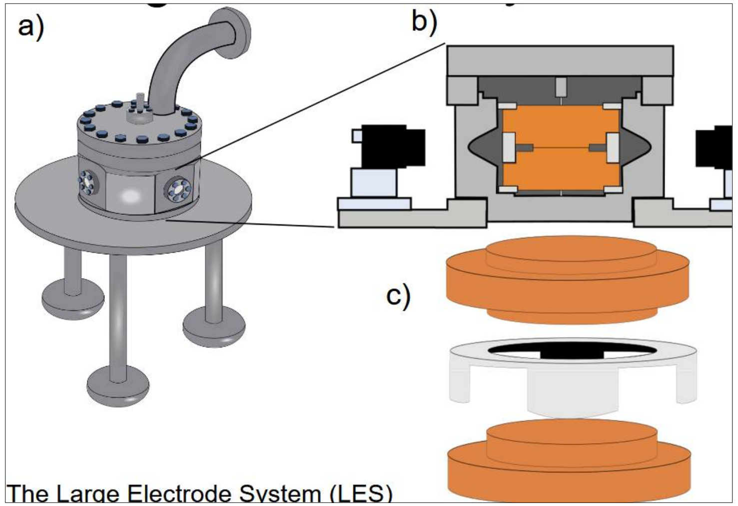


Fig. from Hull, Introduction to dislocations

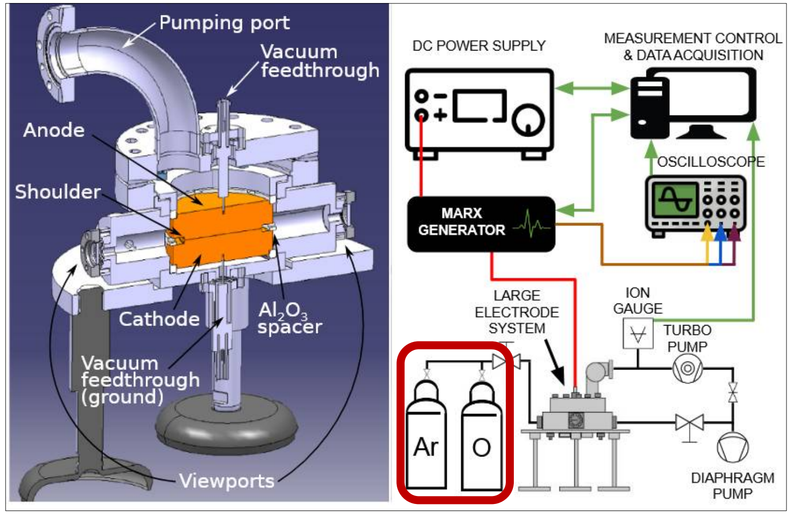
Experimental Set-Up – Pulsed DC Systems

- Cavities are conditioned using RF pulses (repetition rate < 50 Hz)
- We use high voltage pulsed DC (repetition rate ~ 1kHz)
  - Faster
  - Simpler geometry
  - Less infrastructure needed
- Maximum output voltage = 10 kV
- We condition large electrodes (LES): r = 20 mm
- Electrode gap: 40-80 µm → electric fields up to 250 MV/m

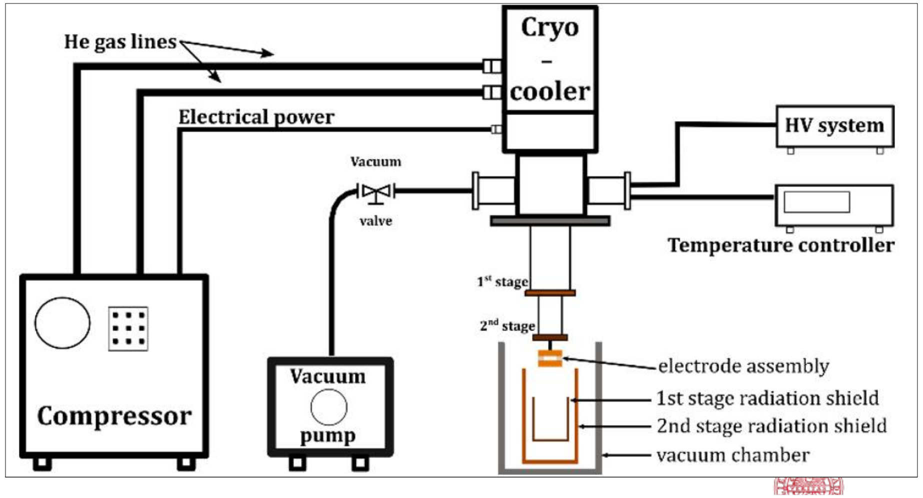




CERN, Room Temperature



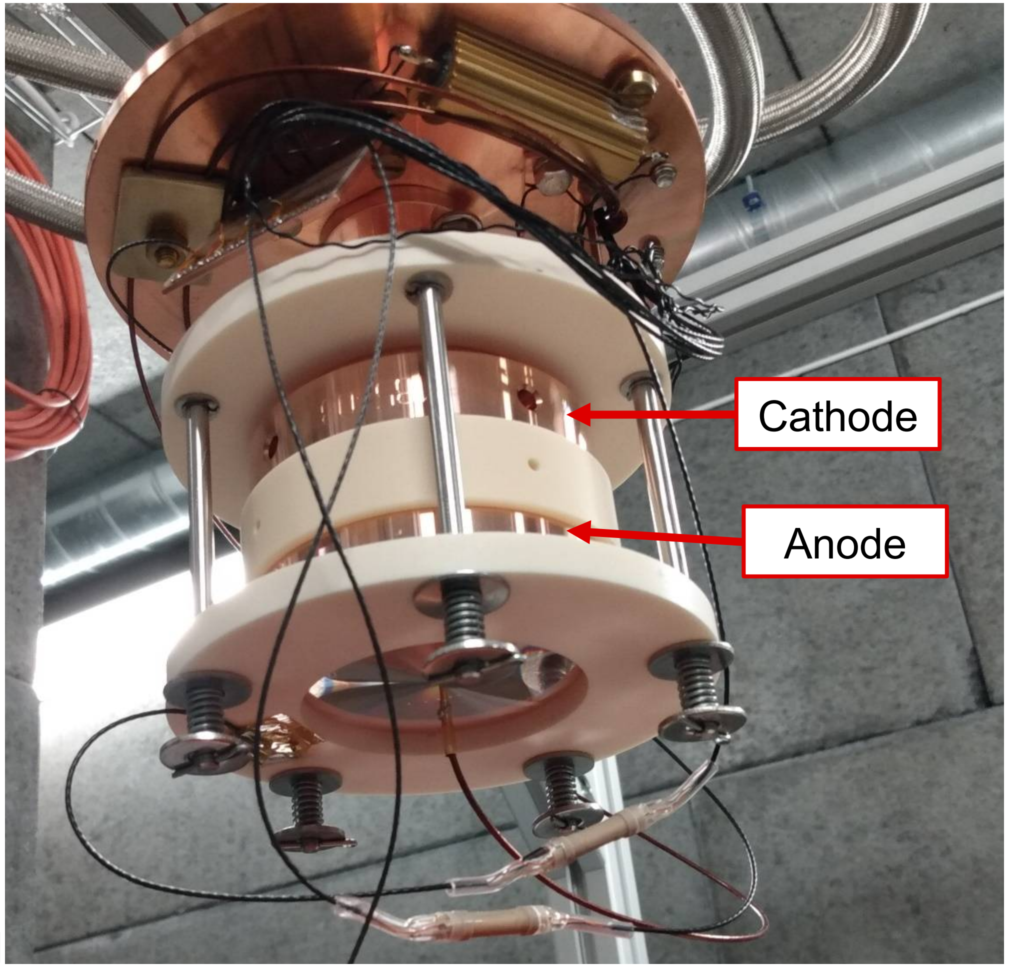
Helsinki, In-situ plasma treatment, RT

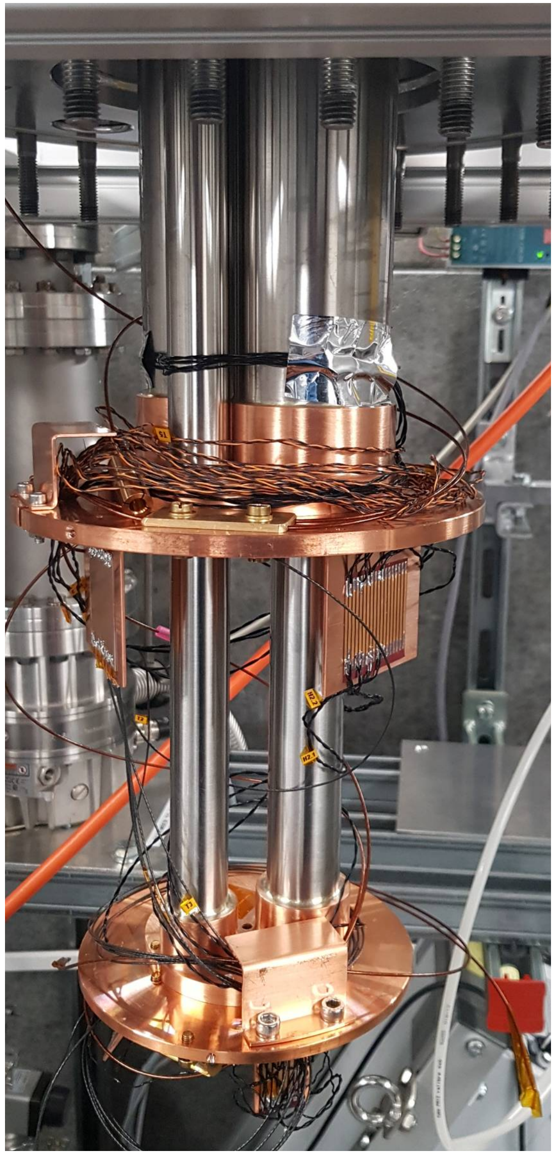


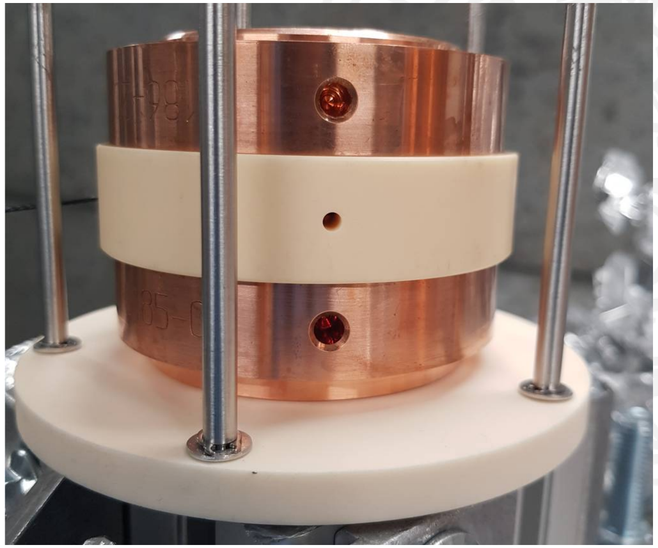
Uppsala, cryogenic (4-100K and RT)

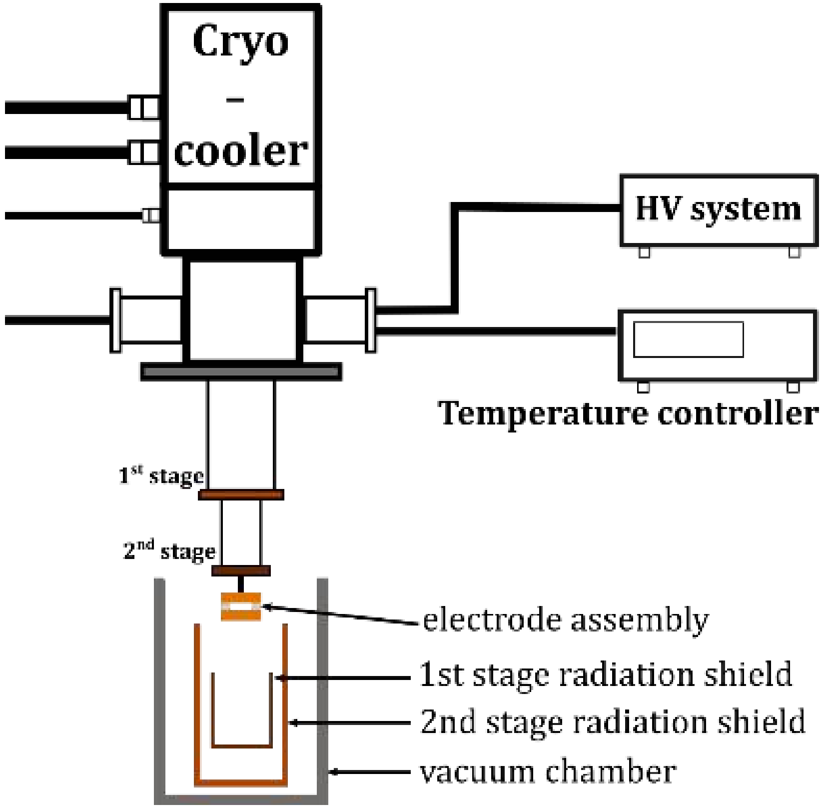
Experimental Set-Up - Uppsala

- Conditioning at cryogenic temperatures (from 4K to 100K) and at room temperatures
- Three temperature sensors
- Heater placed on 2nd stage
- Measure FE current during conditioning



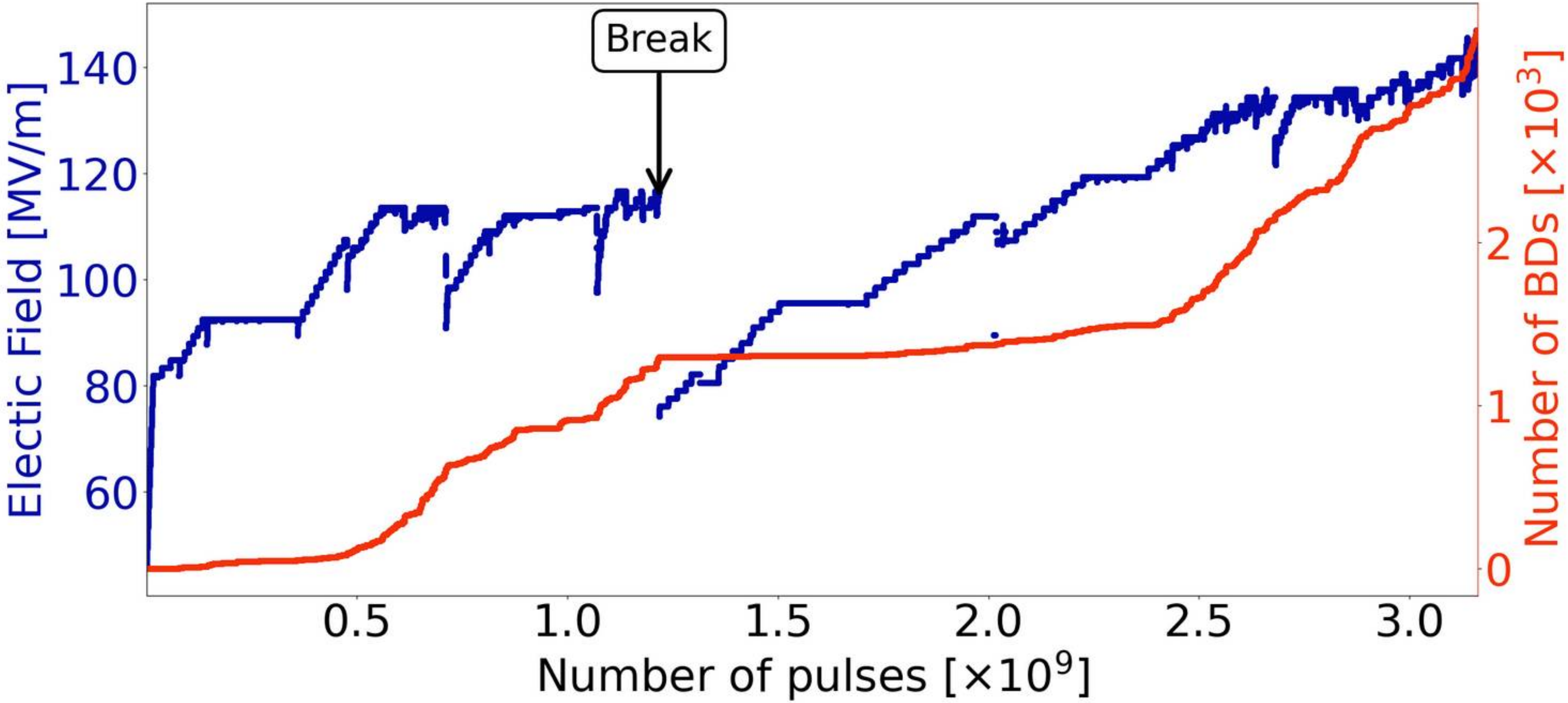






Experimental results – Nb Conditioning

- 99% pure Nb, RRR = 300
- Conditioning only at 4K
- 66 um gap



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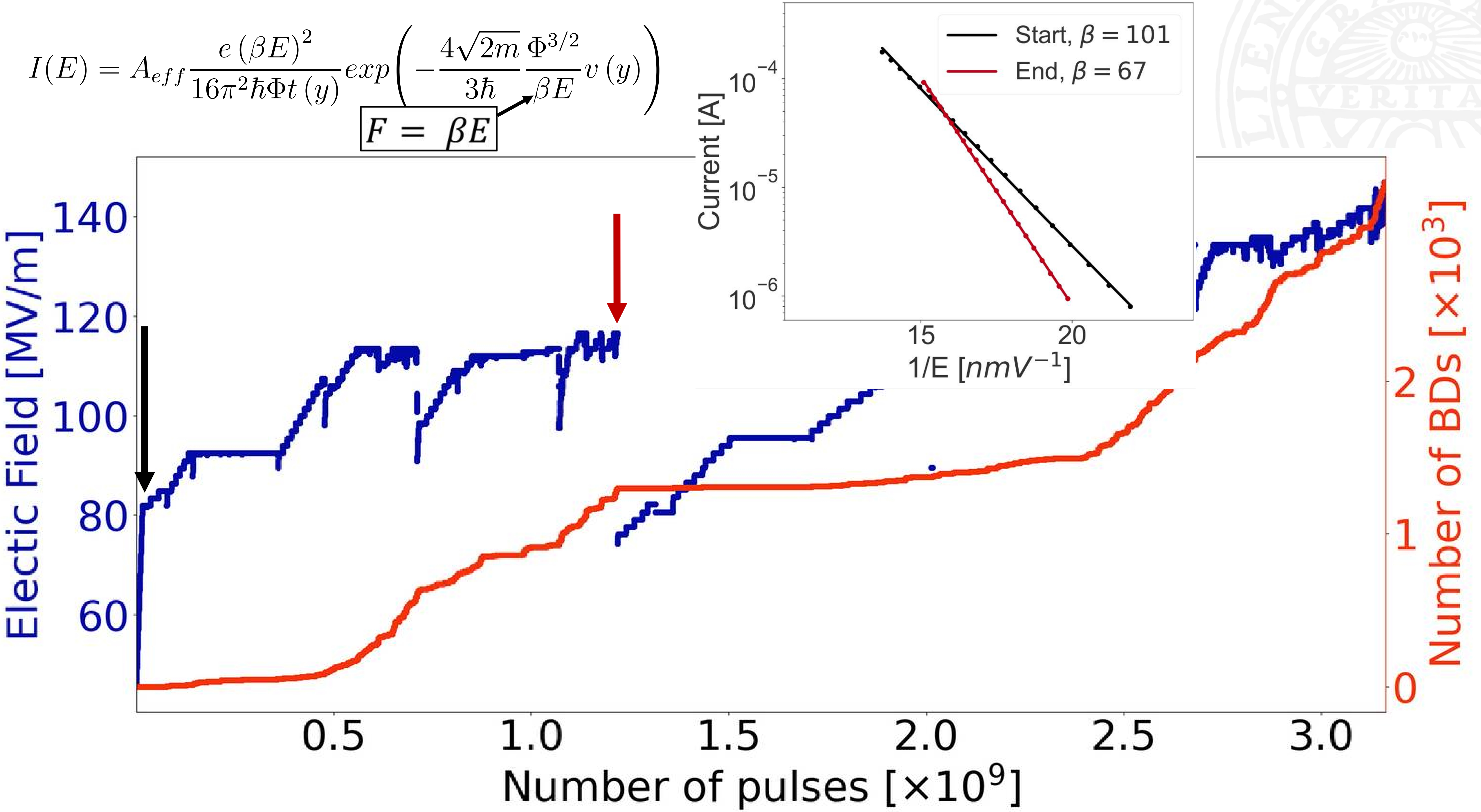
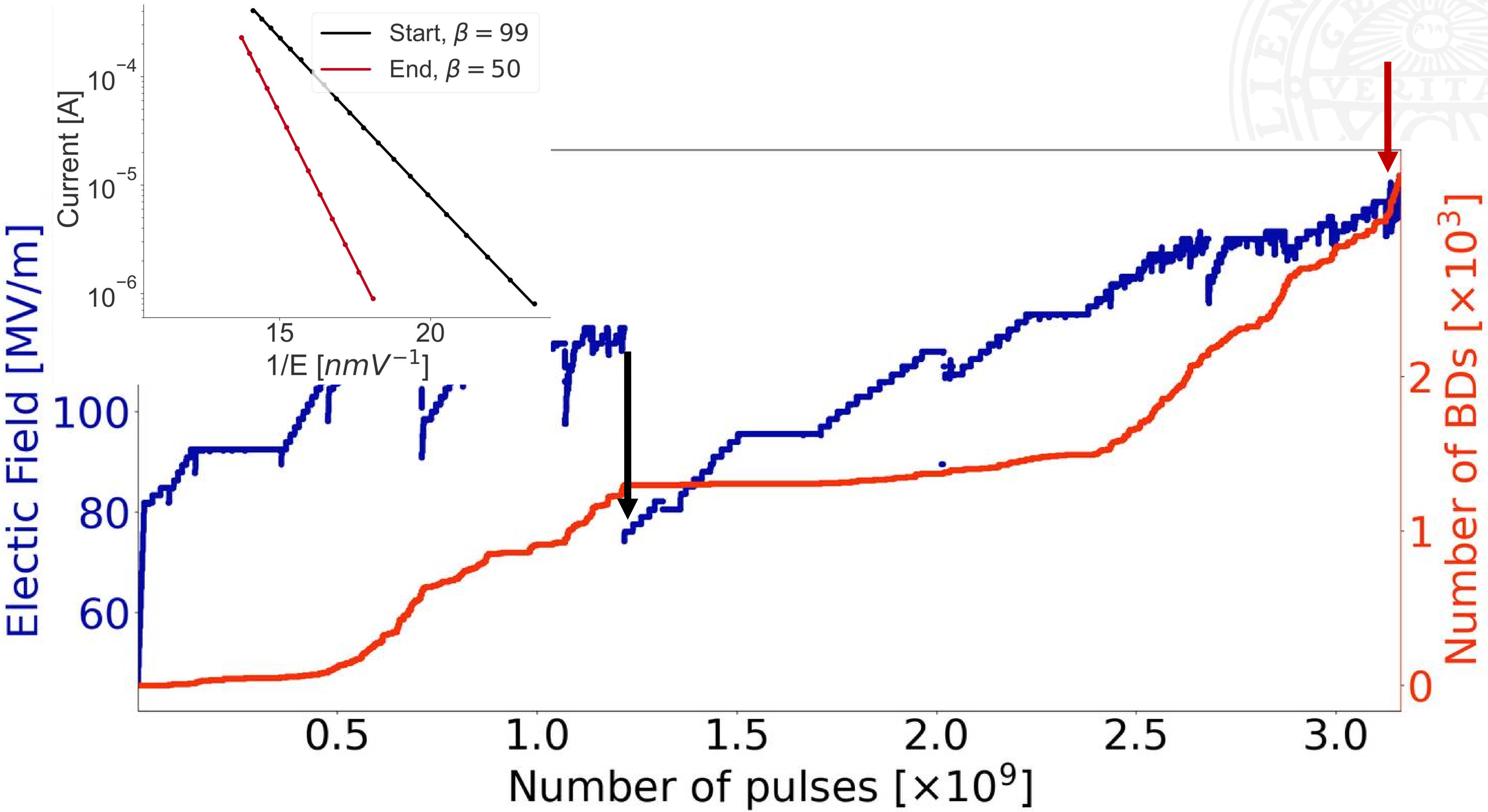
$$I(E) = A_{eff}\frac{e\,(\beta E)^2}{16\pi^2\hbar\Phi t\,(y)} exp\left(-\frac{4\sqrt{2m}}{3\hbar}\frac{\Phi^{3/2}}{\beta E}v\,(y)\right)$$

$F = \beta E$

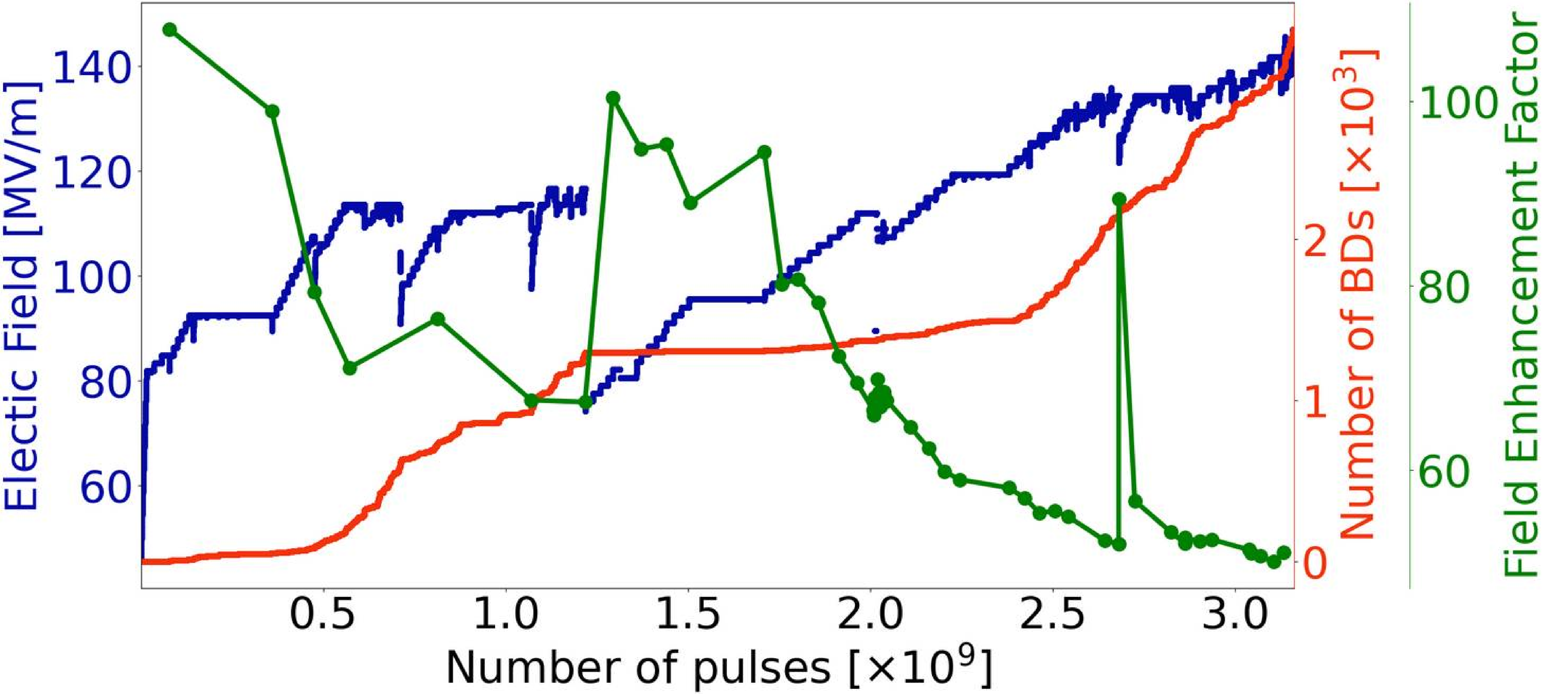




Start, $\beta = 99$
End, $\beta = 50$
Current [A]
10^{-4}
10^{-5}
10^{-6}
15
20
1/E [nmV^{-1}]
Electic Field [MV/m]
100
80
60
Number of BDs [$\times 10^3$]
2
1
0
0.5
1.0
1.5
2.0
2.5
3.0
Number of pulses [$\times 10^9$]

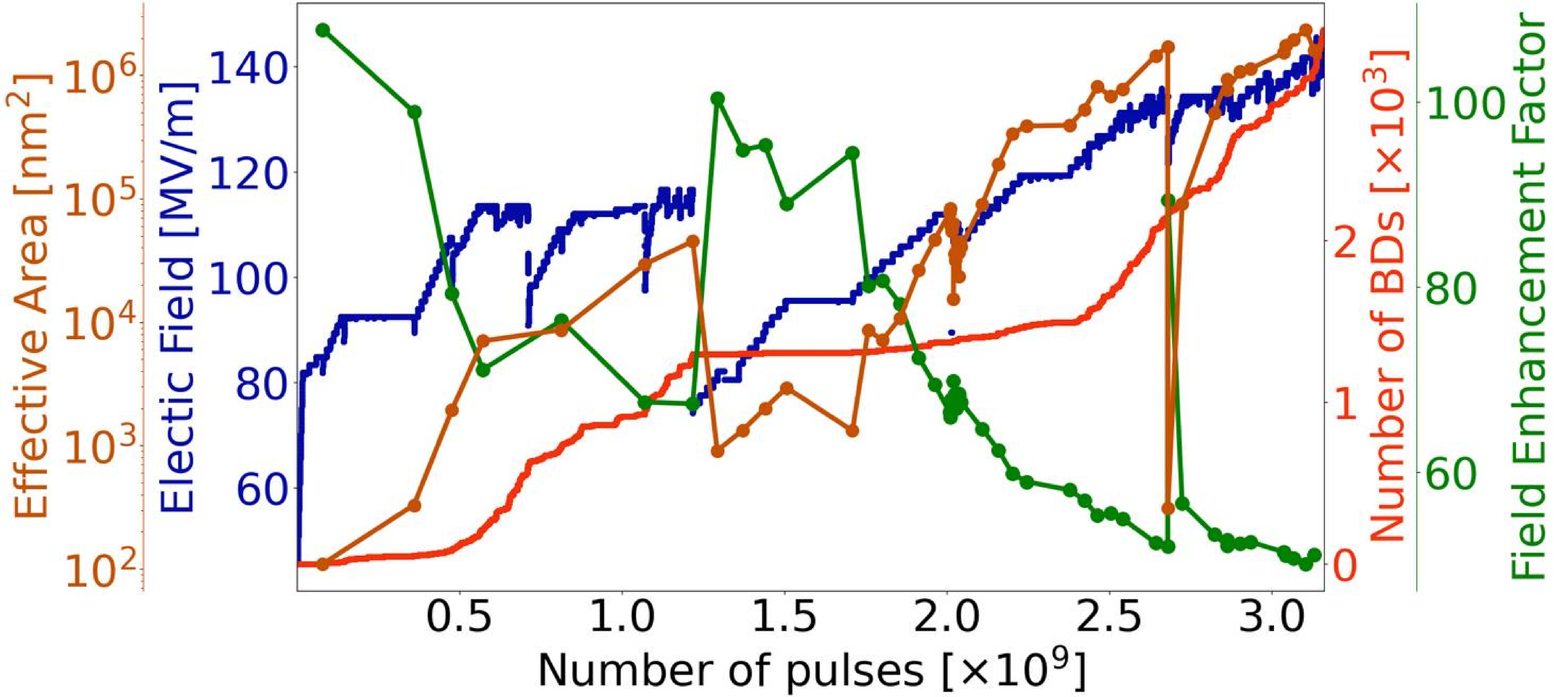
$$I(E) = A_{eff} \frac{e(\beta E)^2}{16\pi^2 \hbar \Phi t(y)} exp\left(-\frac{4\sqrt{2m}}{3\hbar}\frac{\Phi^{3/2}}{\beta E} v(y)\right)$$

Field approaches maximum
→ decrease in β slows down

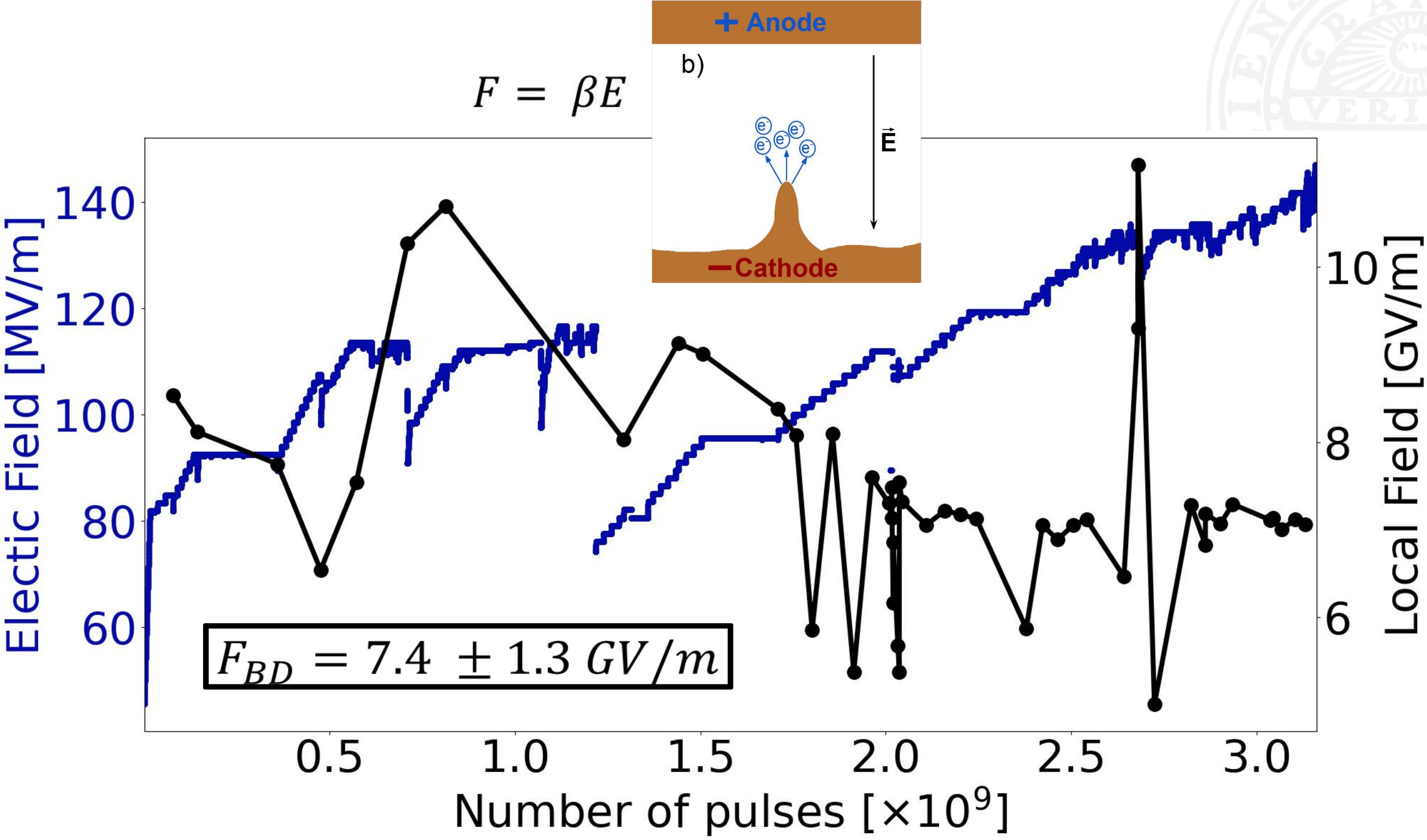


$$I(E) = A_{eff}\frac{e(\beta E)^2}{16\pi^2\hbar\Phi t(y)}exp\left(-\frac{4\sqrt{2m}}{3\hbar}\frac{\Phi^{3/2}}{\beta E}v(y)\right)$$

Field enhancement factor decreases
But area increases by 4 orders of magnitude!
New emitters are created, but with smaller β



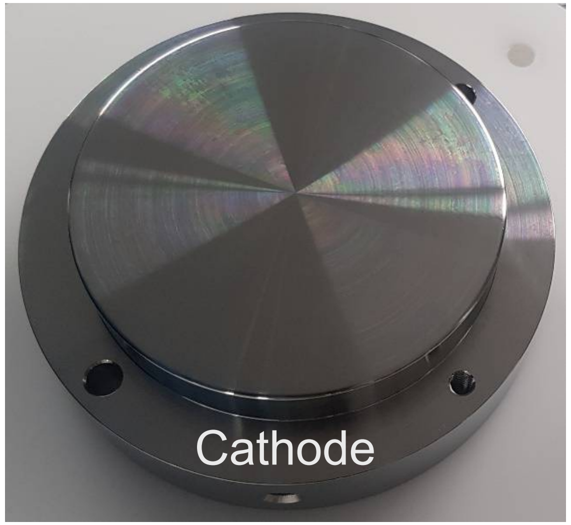
$$F = \beta E$$

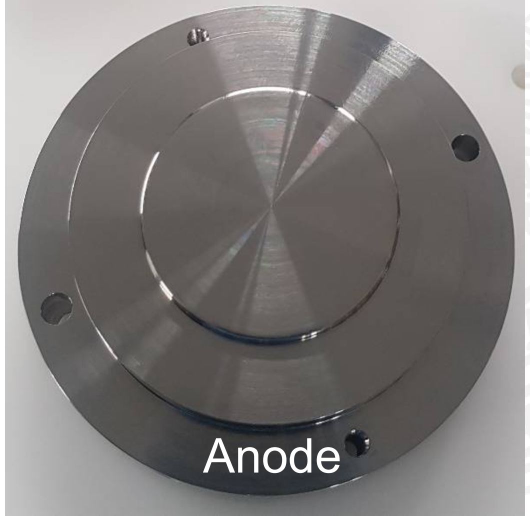


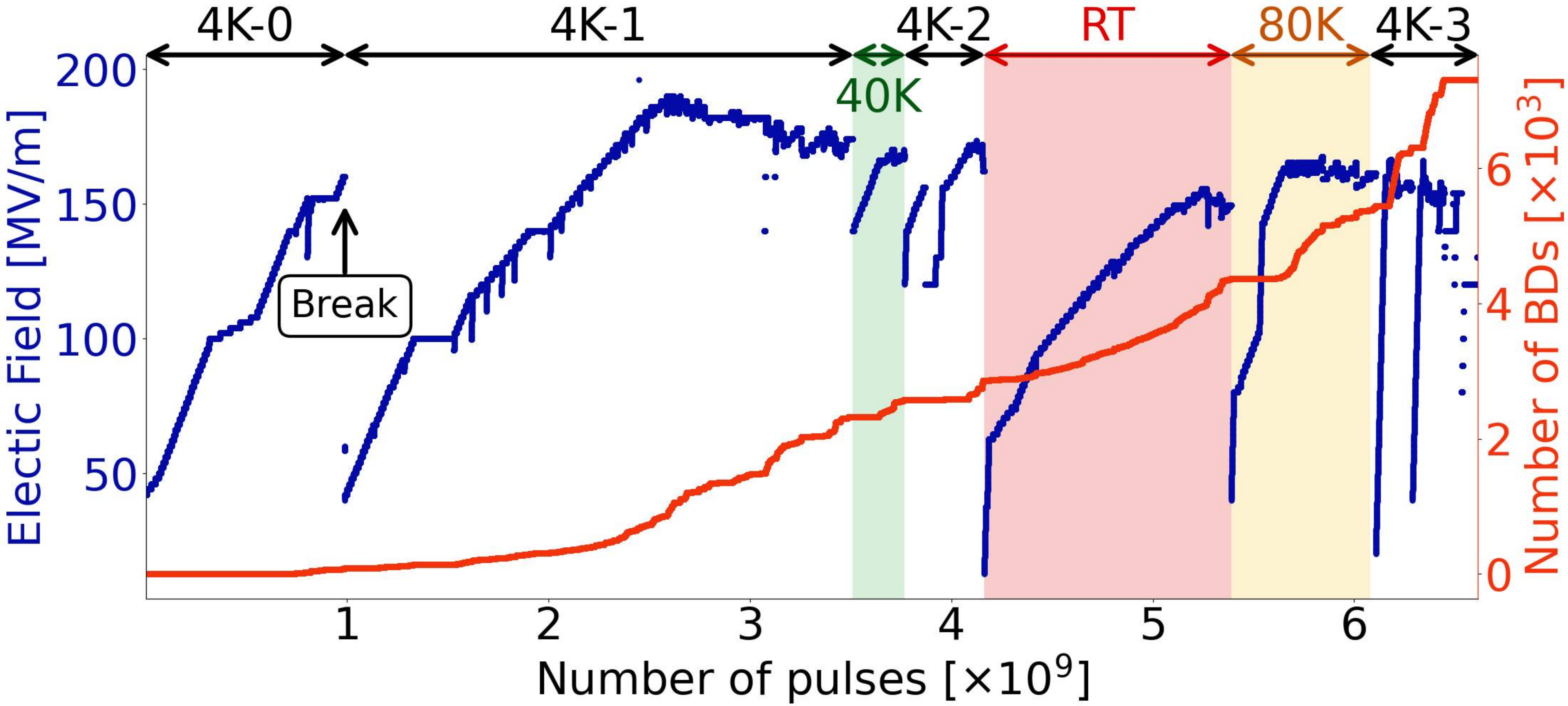
+ Anode
b)
E
e⁻
— Cathode
Electic Field [MV/m]
140
120
100
80
60
Local Field [GV/m]
10
8
6
$F_{BD} = 7.4 \pm 1.3\ GV/m$
0.5
1.0
1.5
2.0
2.5
3.0
Number of pulses [×10^9]

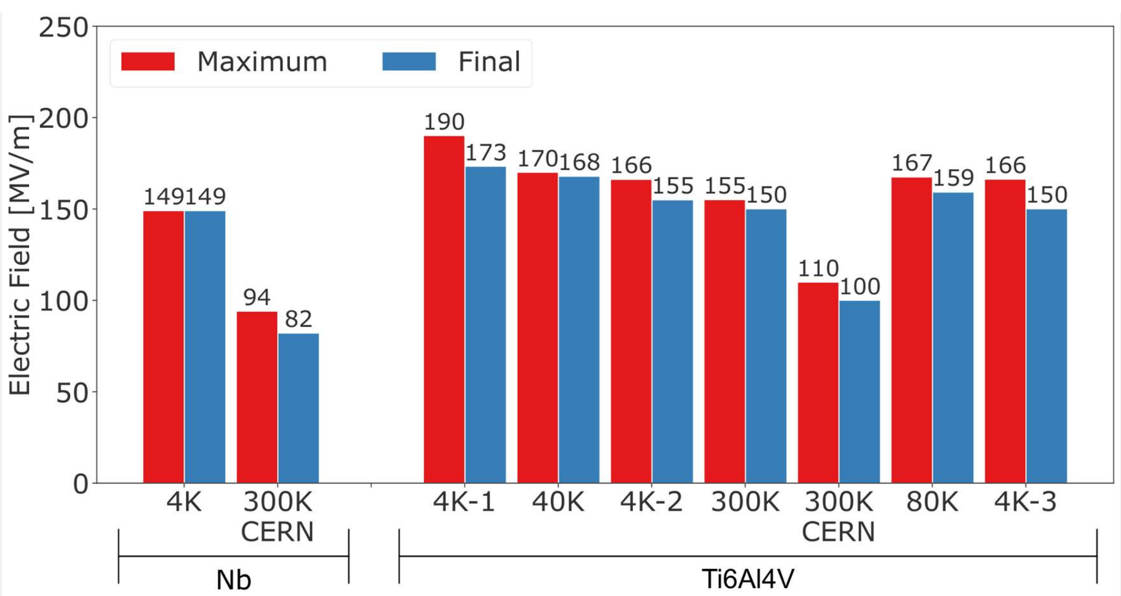
Experimental results – Ti6Al4V

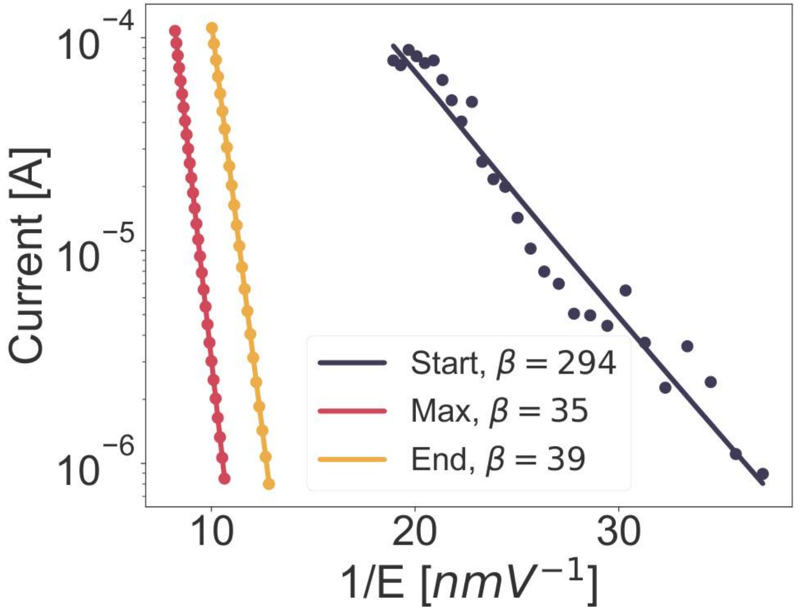
- Conditioning at 4K, 40K, 4K, RT, 80K, 4K
- Gap sizes: 40um at RT, 49um at 80K, 50um at 4-40K
- High field-holding capability
- Considered as replacement for SS in the SPS electrostatic septum

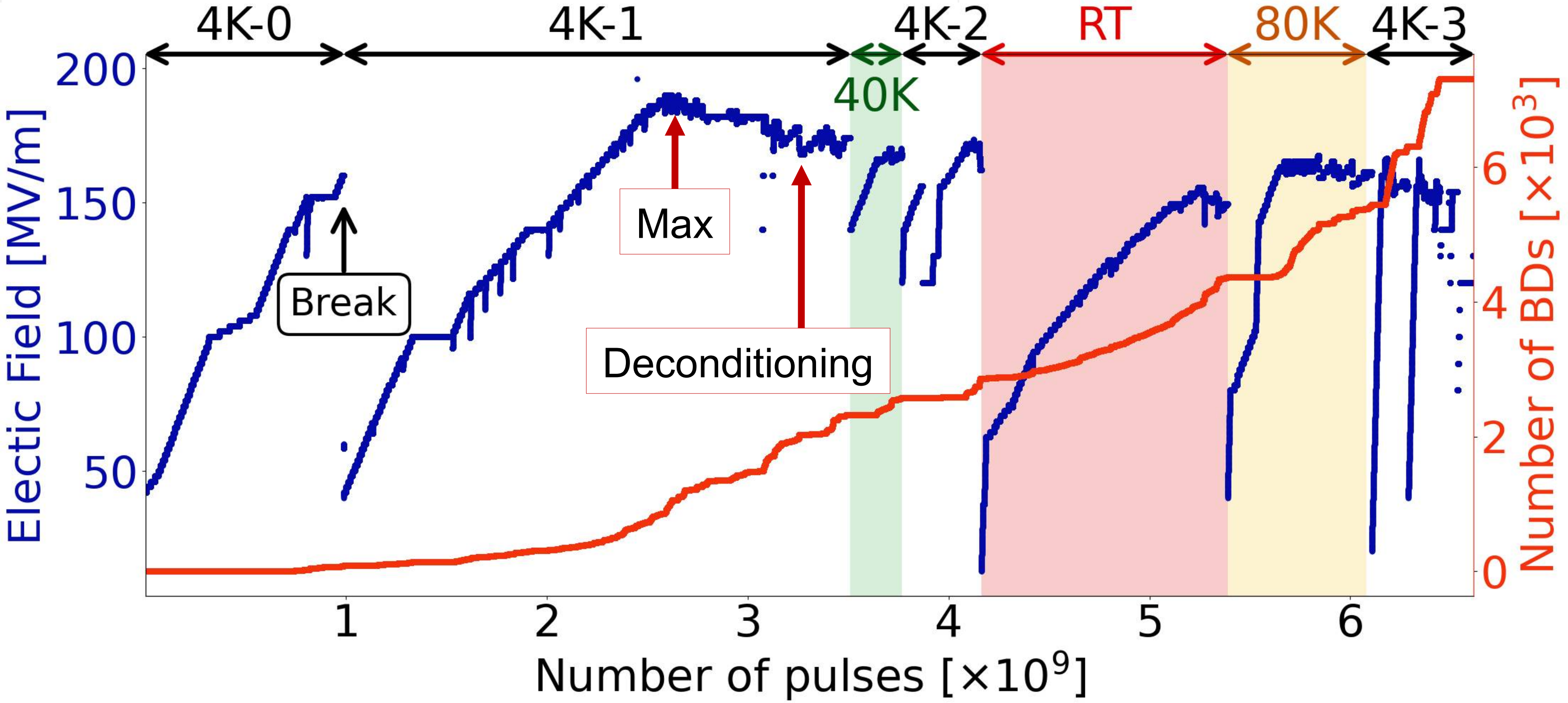












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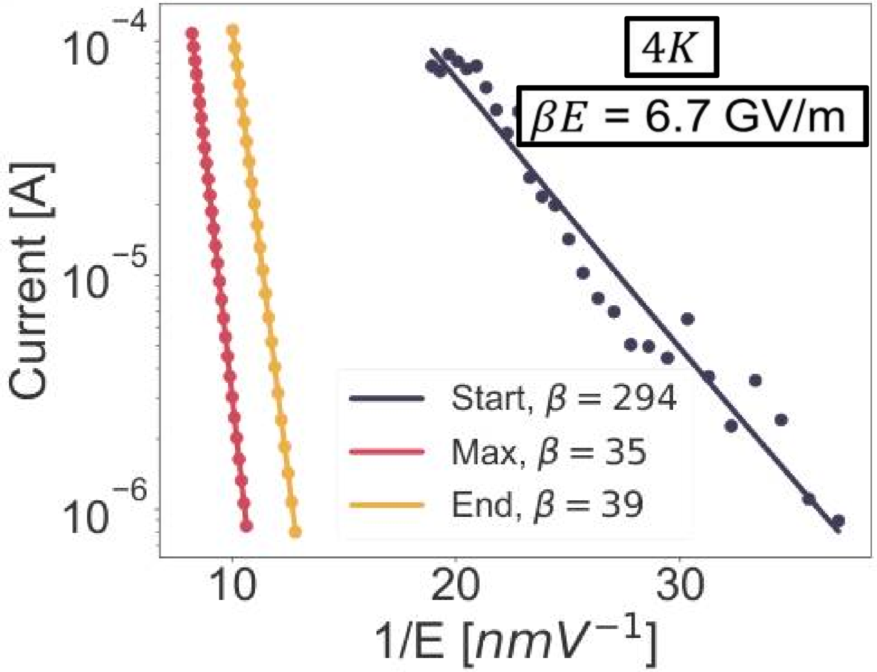

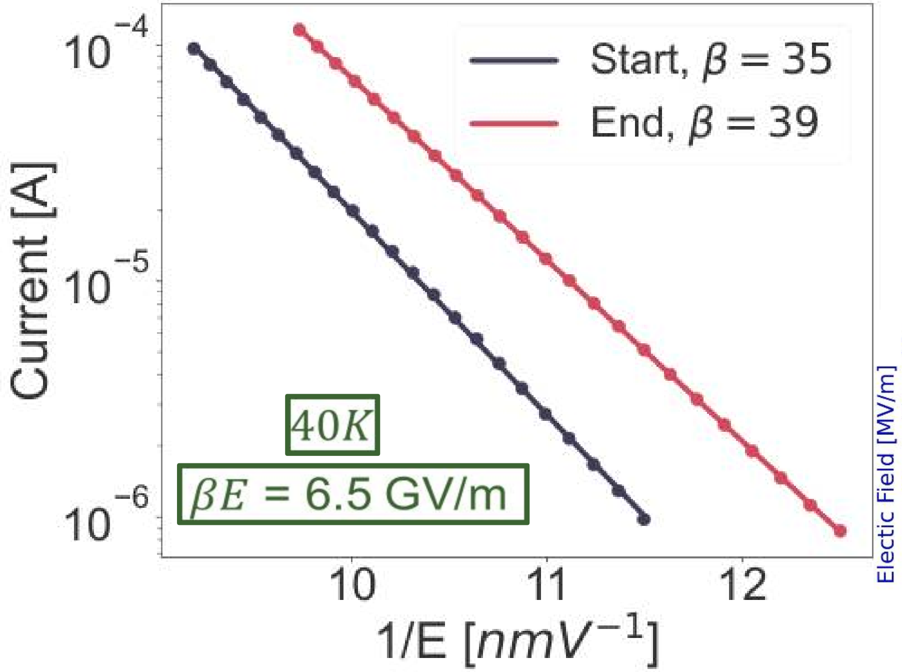

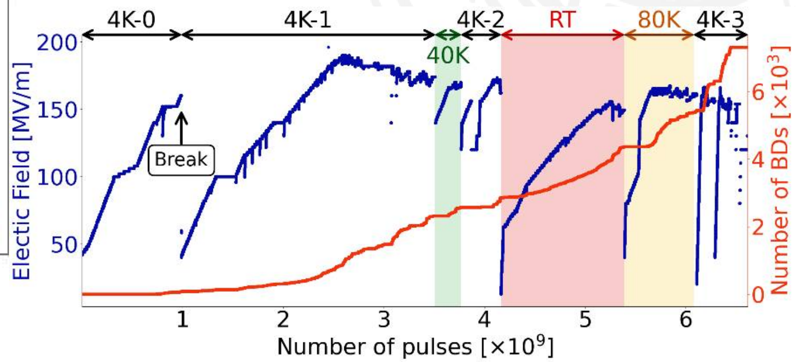

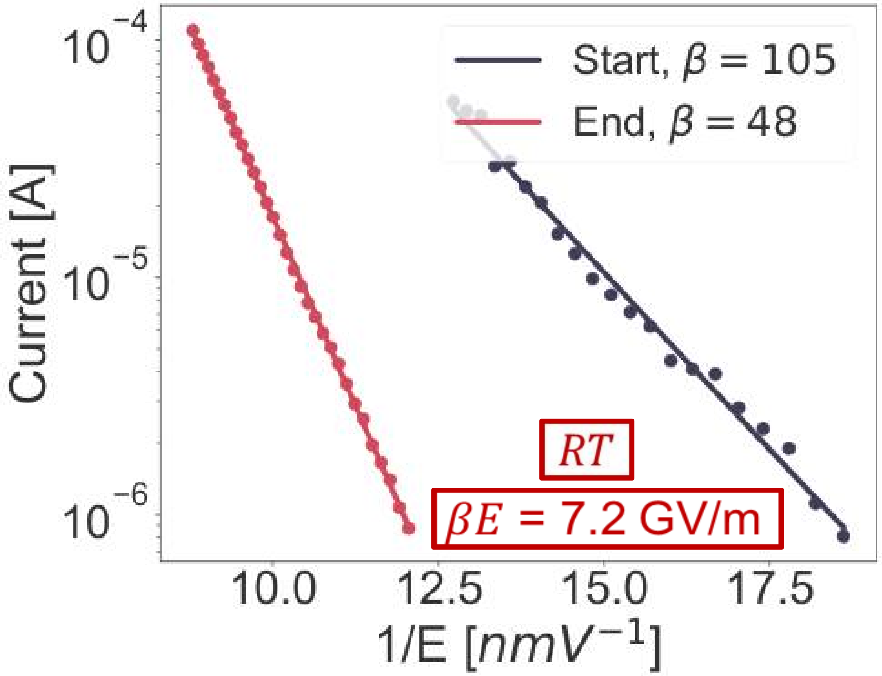

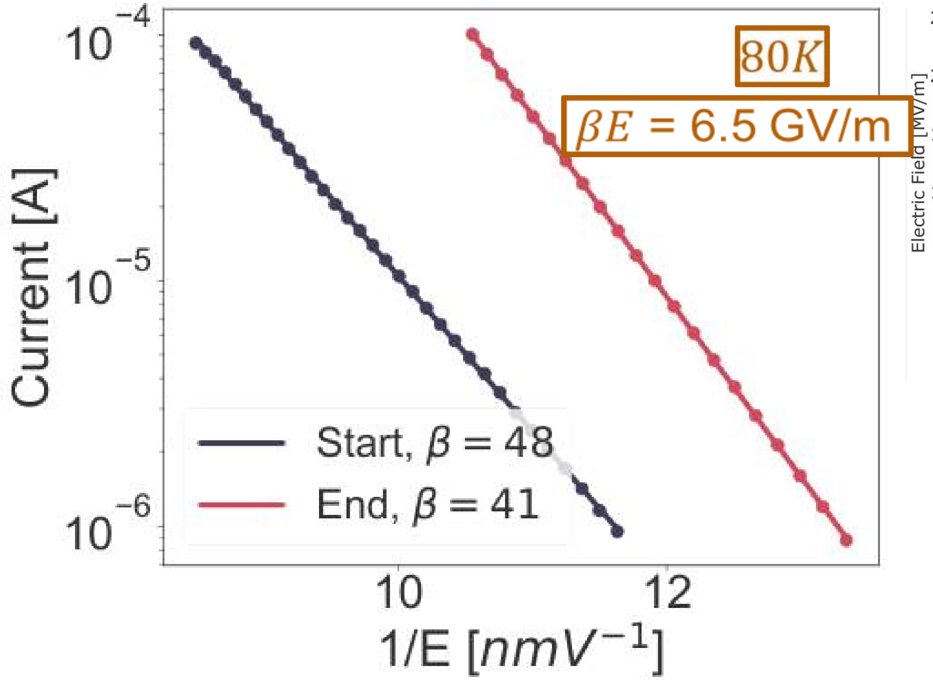

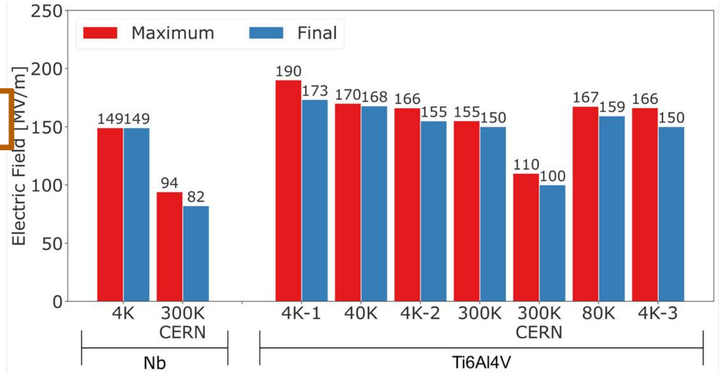

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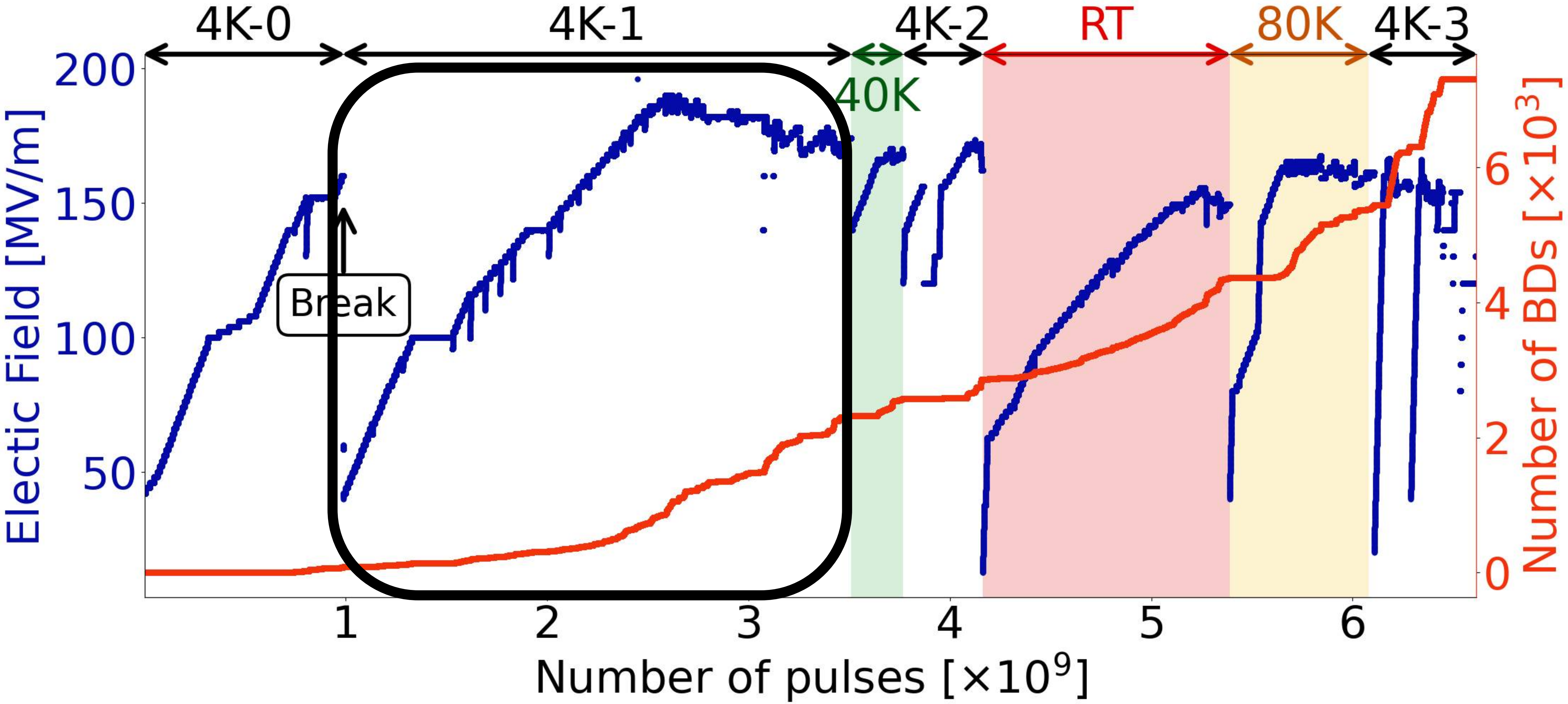

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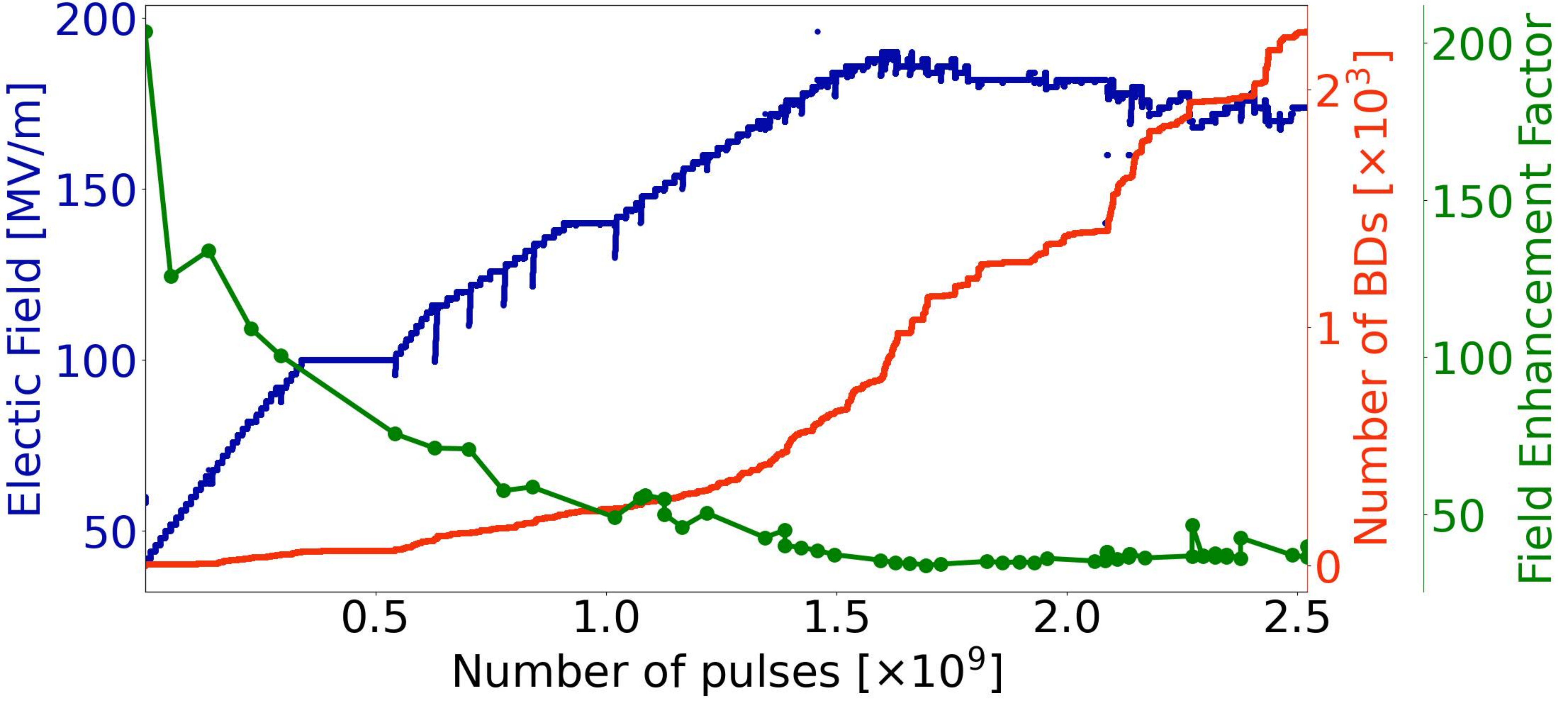
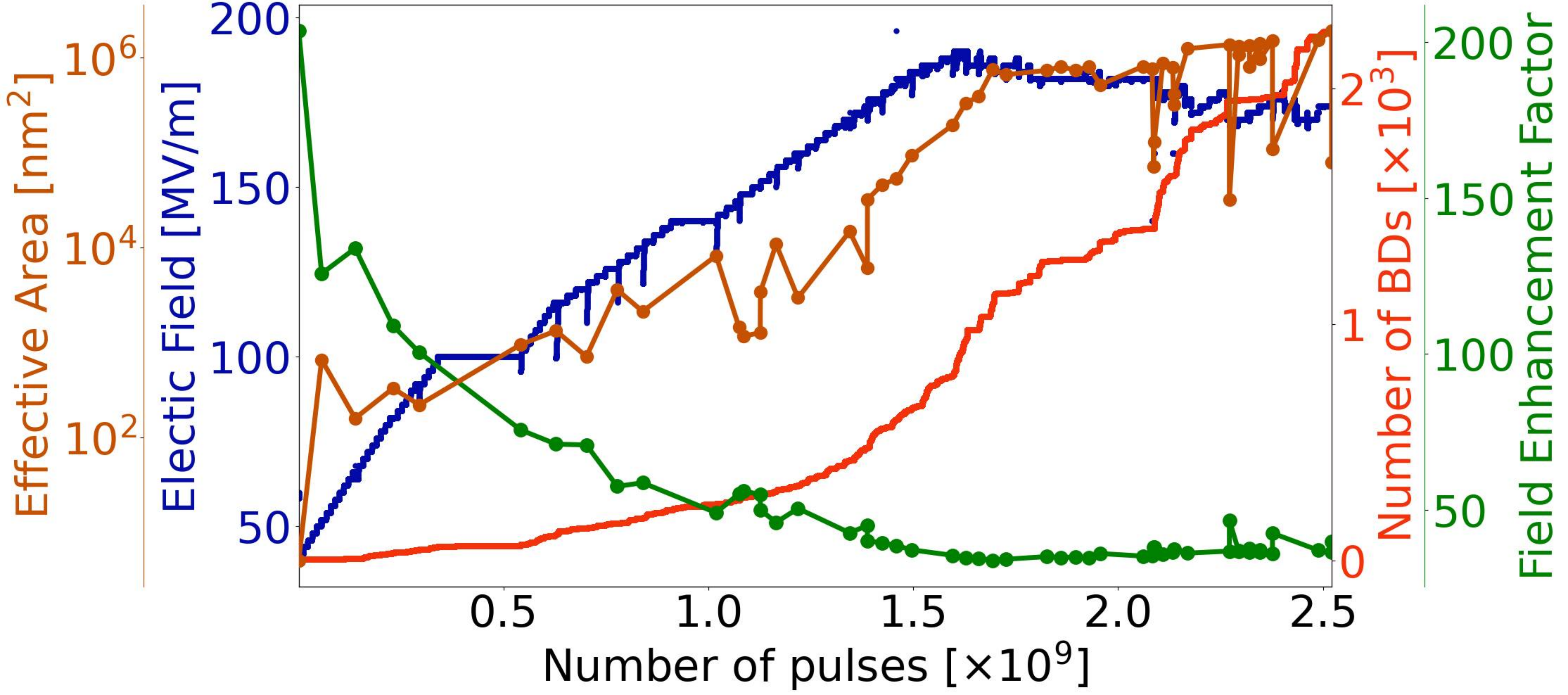
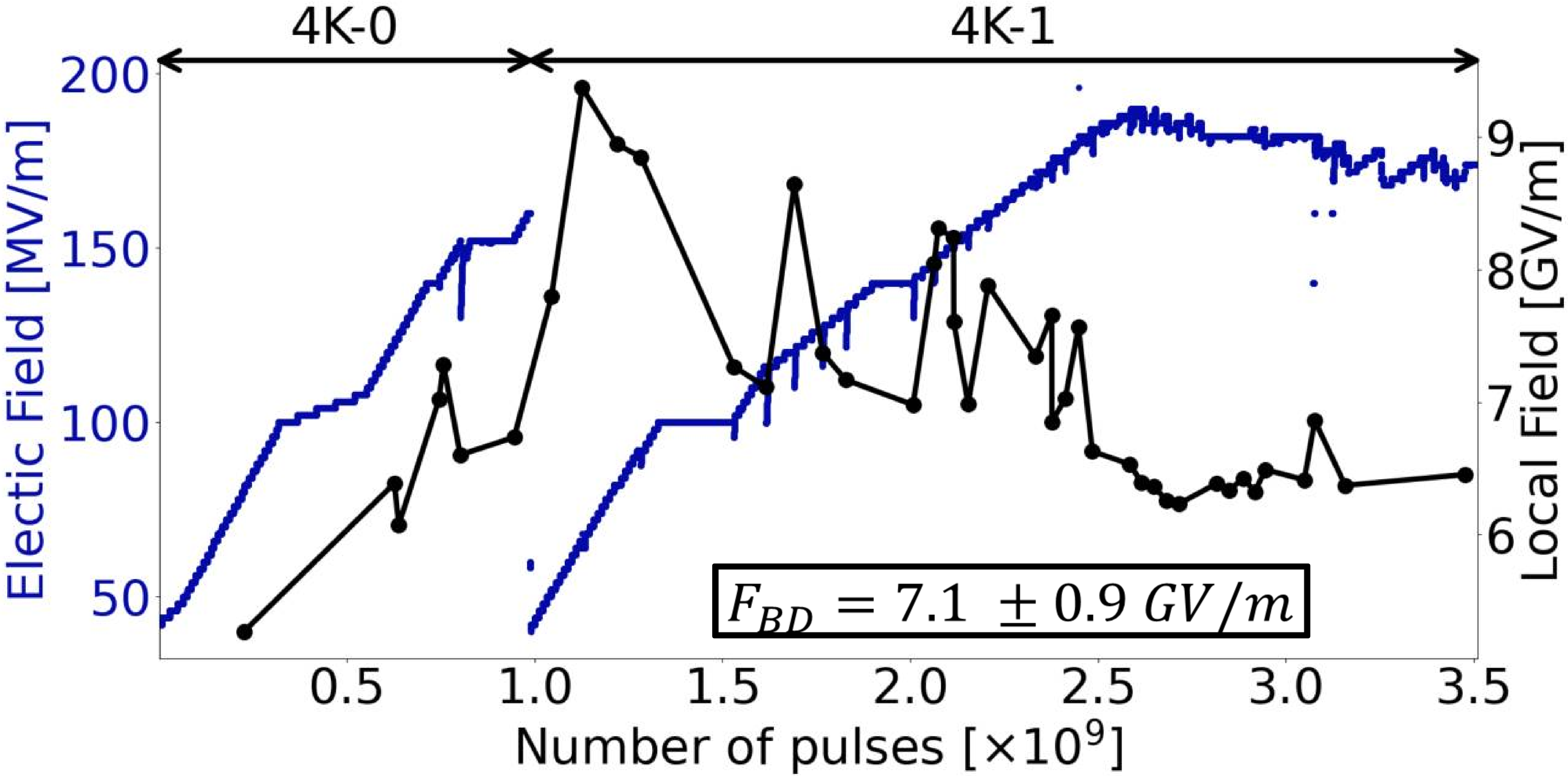
Field approaches maximum
→ decrease in β slows down
→ by tracking β, we can avoid deconditioning



Field enhancement factor decreases
But area increases by 5 orders of magnitude!
New emitters are created, but with smaller β



$$F = \beta E$$



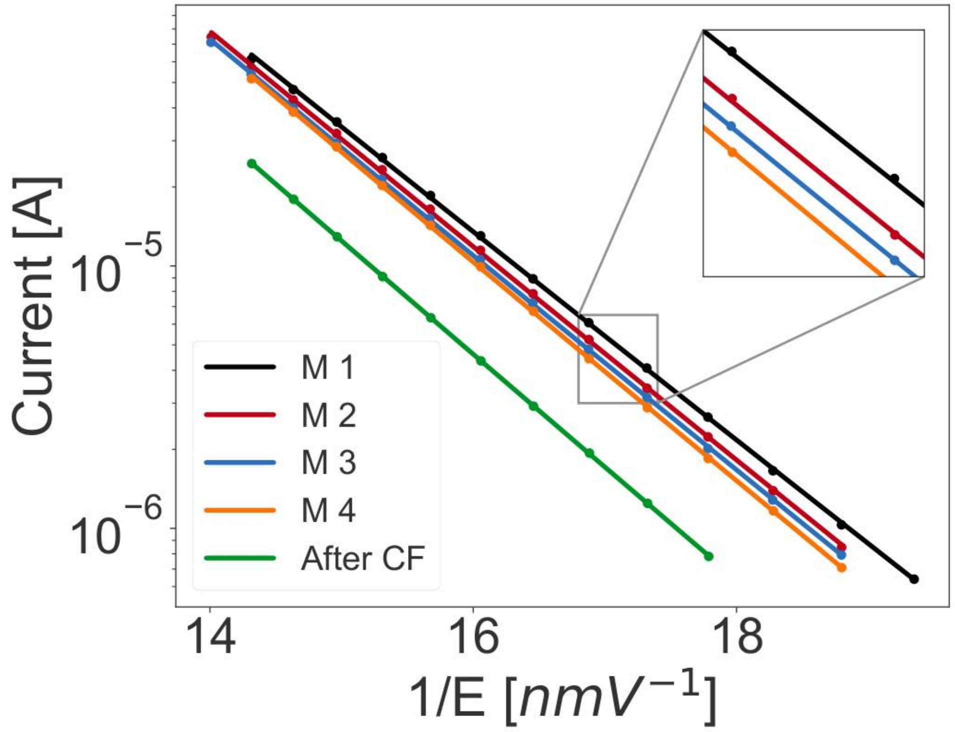
$$F_{BD} = 7.1 \pm 0.9\ GV/m$$

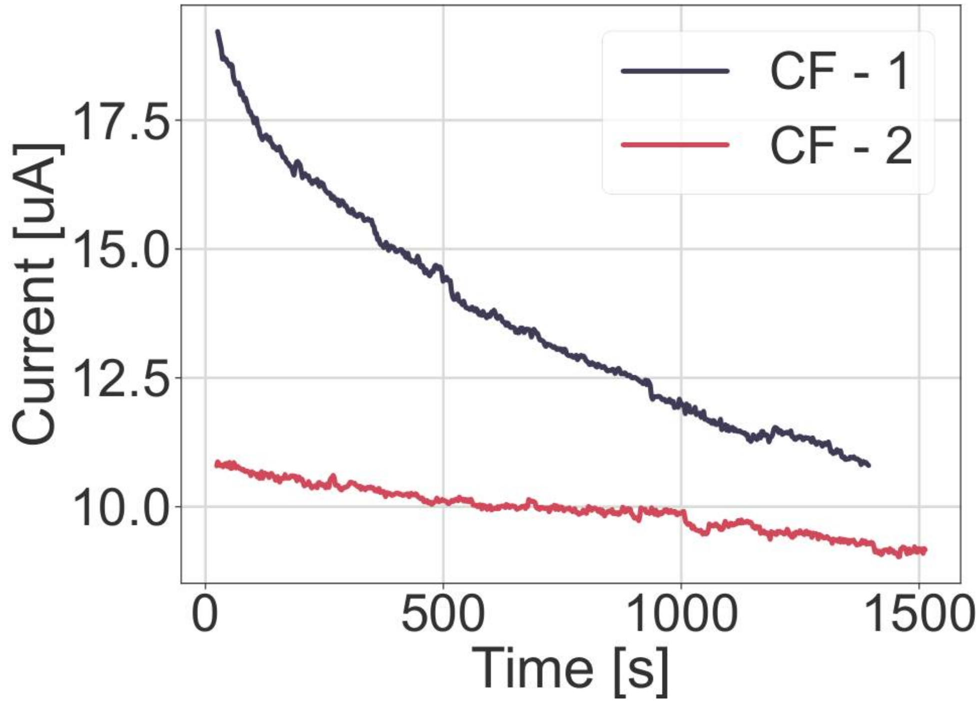
Effect of temperature variations on FE current - Nb

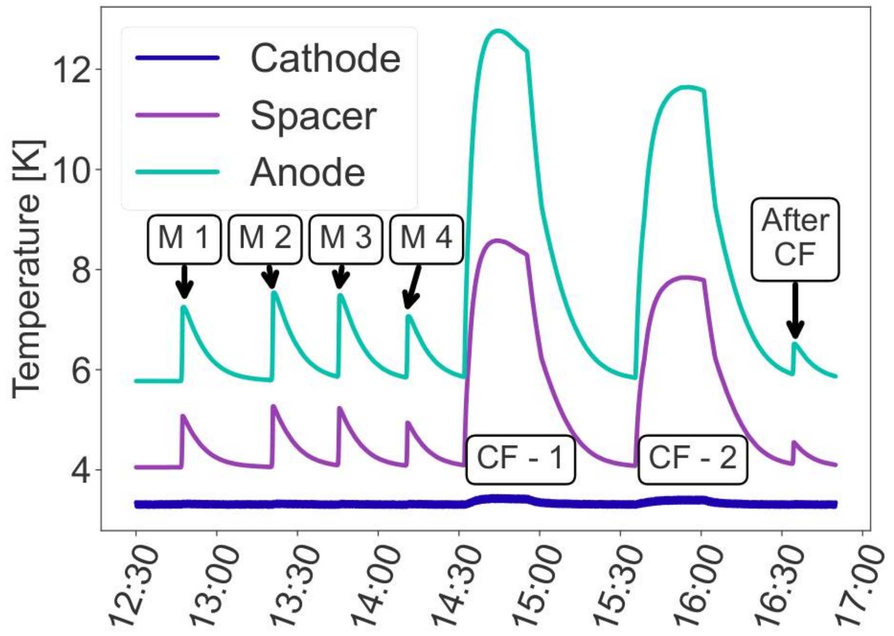
- During FE, anode temperature can increase up to 17K
- How does this change the surface?

- Stop conditioning at 102 MV/m
- 4 I-V curve measurements → current decrease
- 2x constant field measurements → ~50% current decrease

- Field or temperature effect?

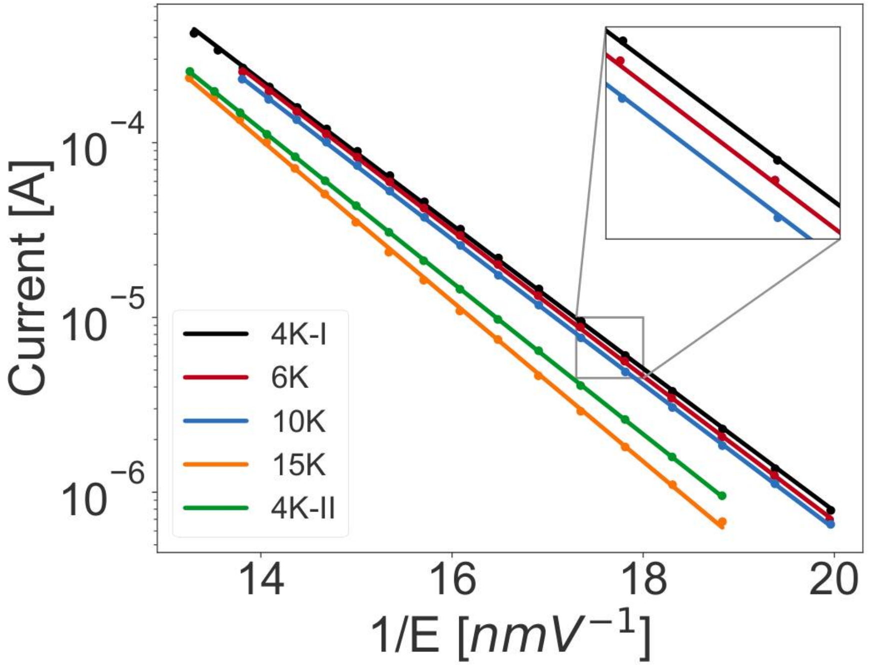


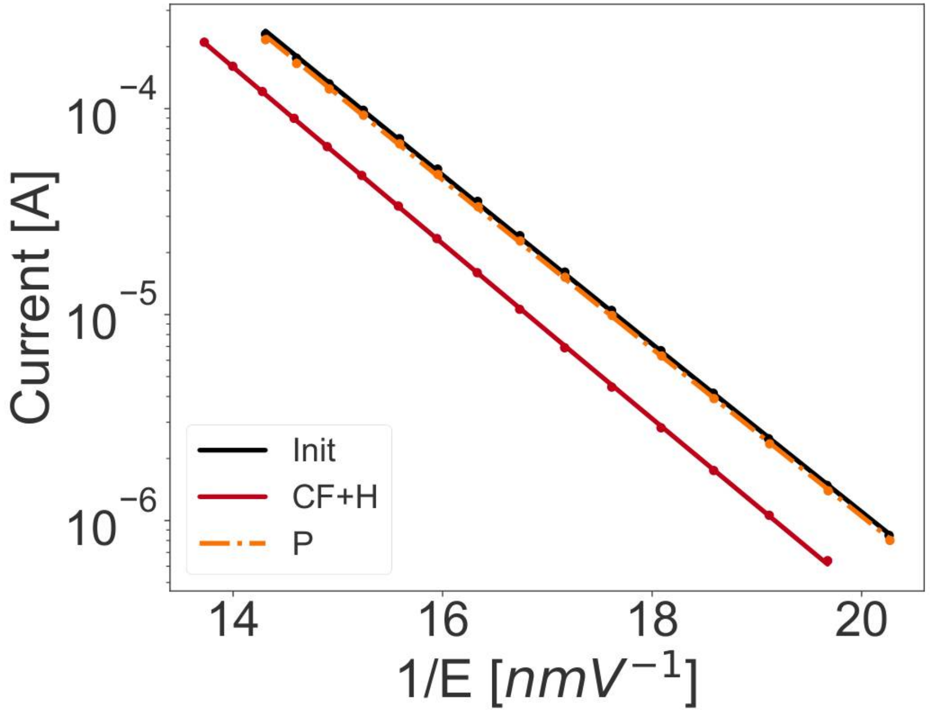


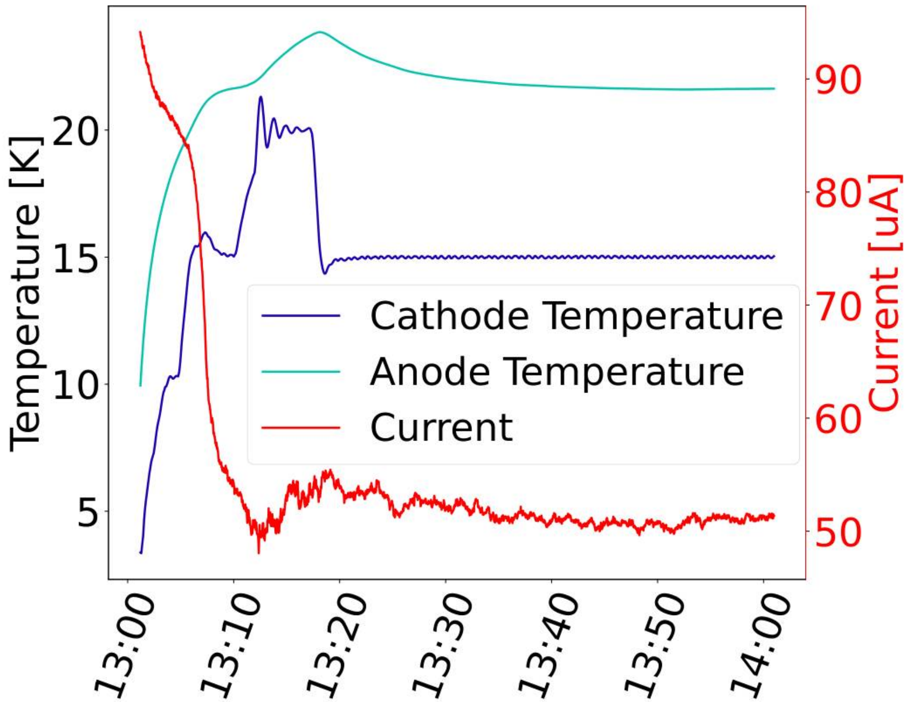


Effect of temperature variations on FE current - Nb

- Use cathode heater to heat the system
  - Now both anode and cathode heat up to same temperature
  - It is a temperature effect
- Heat the system using the external heater, probe the surface using FE current (CF+H)
- The current decrease is not reverted when cooling back down
- 3.5 million 1 us pulses at 109 MV/m, without BD → current decrease is reverted (P)







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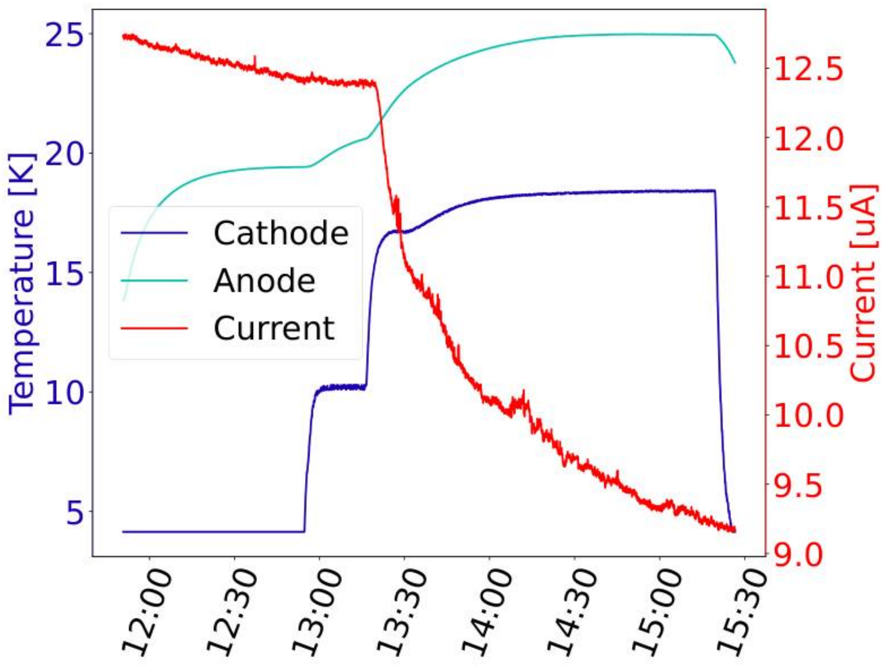
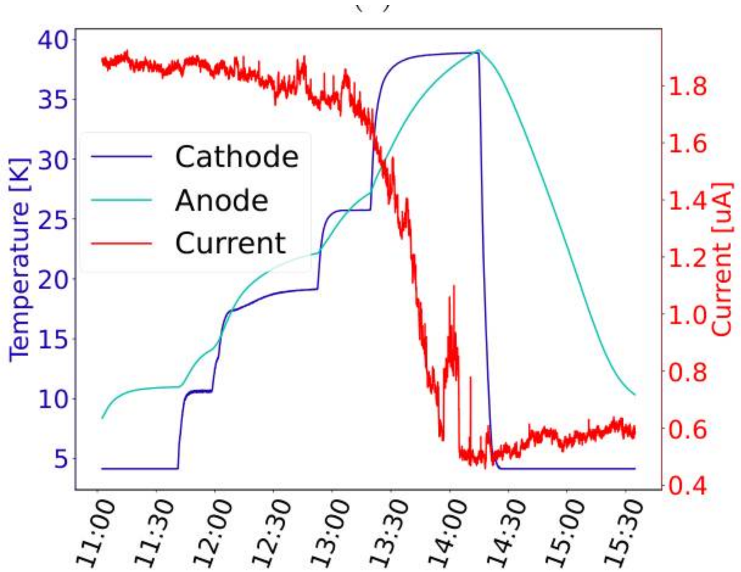
Effect of temperature variations on FE current – Ti6Al4V

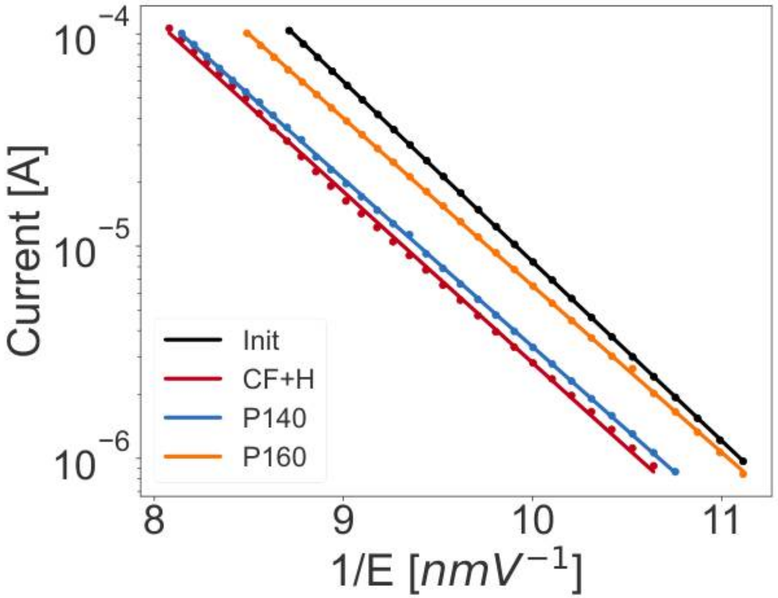
- Same experiment as previously
- Decrease in current at 17K

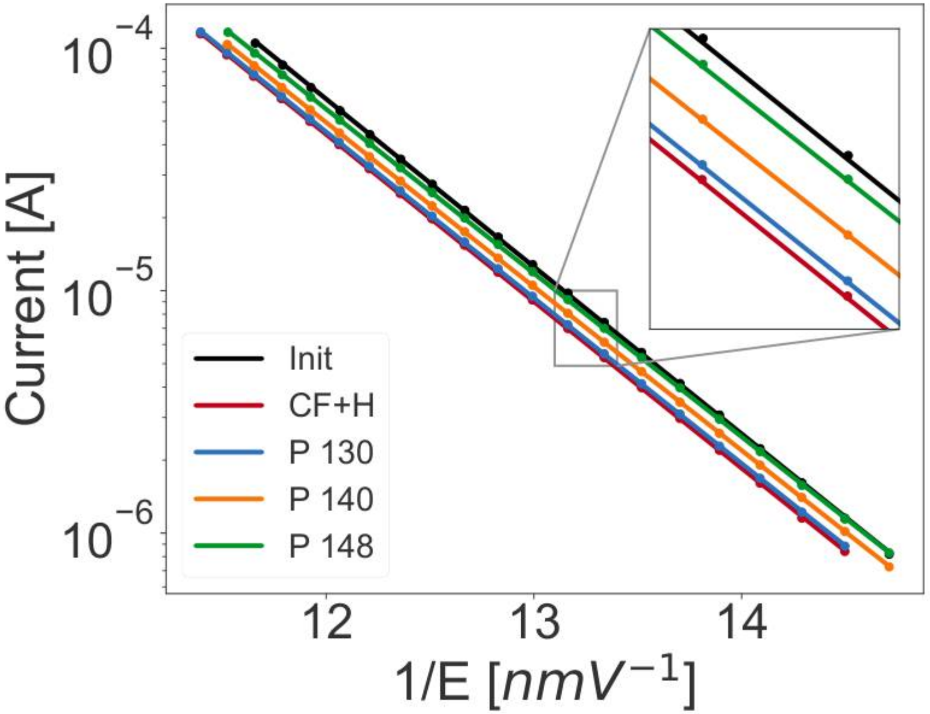
- 100 1us pulses at 80-148 MV/m, without BD
- At 130MV/m, the current decrease is not reverted
- But at 140 MV/m it is

- What about higher temperatures?





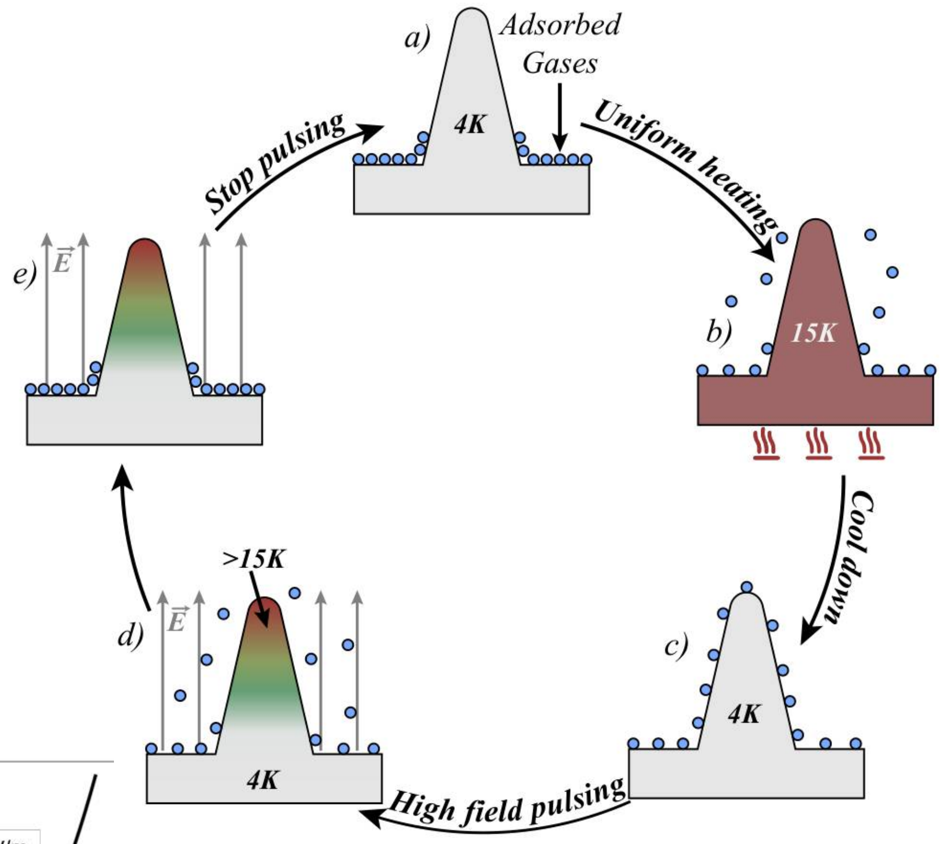




Effect of temperature variations on FE current – Explanation

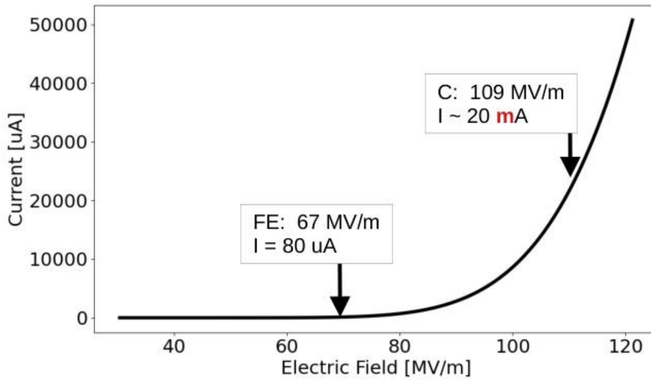
$$I(E) = A_{eff}\frac{e\,(\beta E)^2}{16\pi^2\hbar\Phi t\,(y)}exp\left(-\frac{4\sqrt{2m}}{3\hbar}\frac{\Phi^{3/2}}{\beta E}v\,(y)\right)$$

- Summary
  1. Current decreases when at least one electrode is heated to 15-17K
  2. The current is not reversed by cooling down
  3. It is reverted by pulsing at higher field (even if no BD)



- Suppose the tip theory for the field-enhancement
- Change in work function ↔ change in field enhancement factor
- Adsorbed gases → increase in work function → decrease in current
- Pulsing at high fields → only the tip is heated → gases desorb → decrease in work function

- Well-known effect in cold field emission electron sources
- First time when observed on a macroscopic surface



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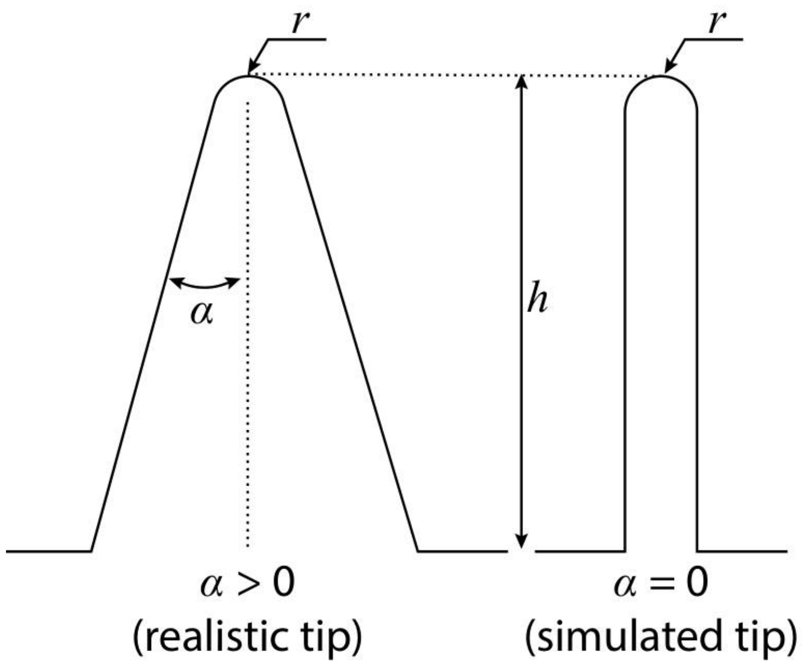
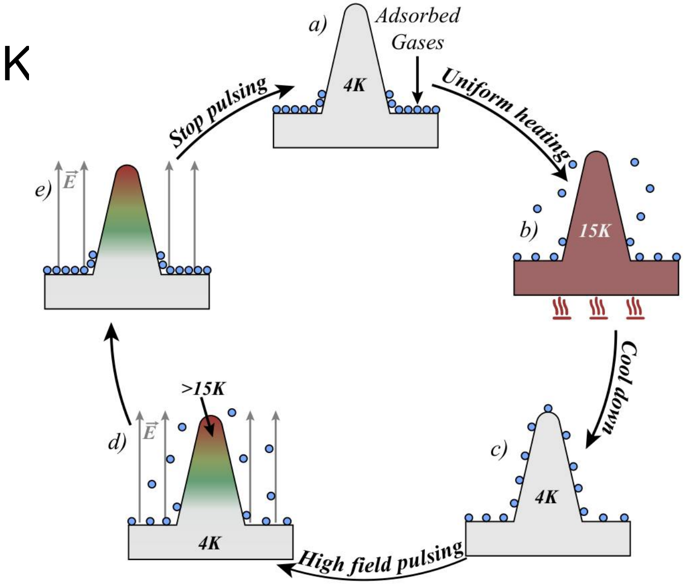
Tip size estimation from field emission data

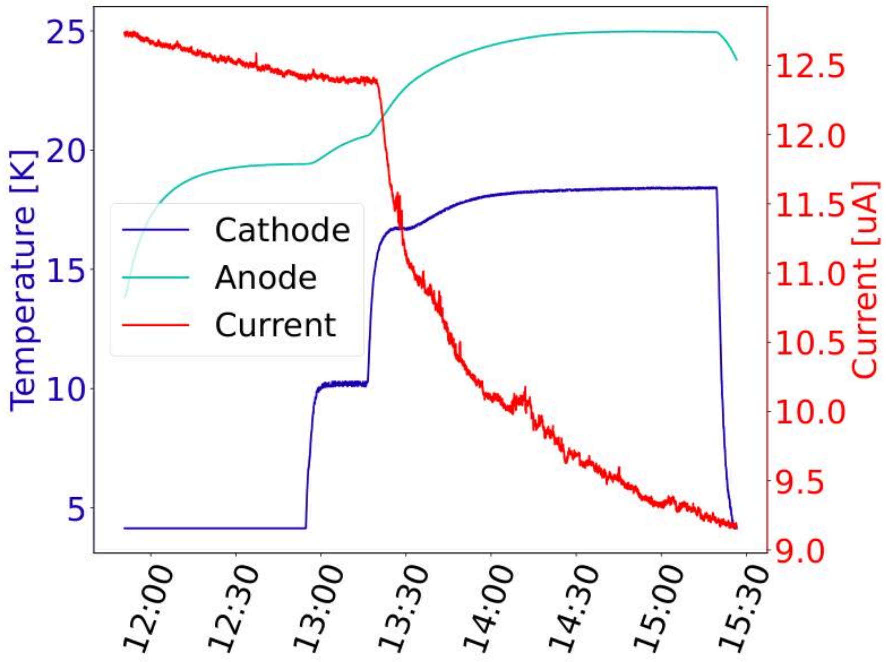
- Heating up the electrodes from 4K to ~17K → current drop
- Pulsing at high fields (>100 MV/m) → current drop is reverted

- Fitting the I-V curves → field enhancement factor → aspect ratio (h/r)
  - ➢ No information about absolute size
- Taller tip → lower apex temperature
- What temperature is needed for gas desorbtion? 15 – 17K

- Simulate tips with same field enhancement factor/aspect ratio, but with different heights
- What is the minimum tip size to reach 15K



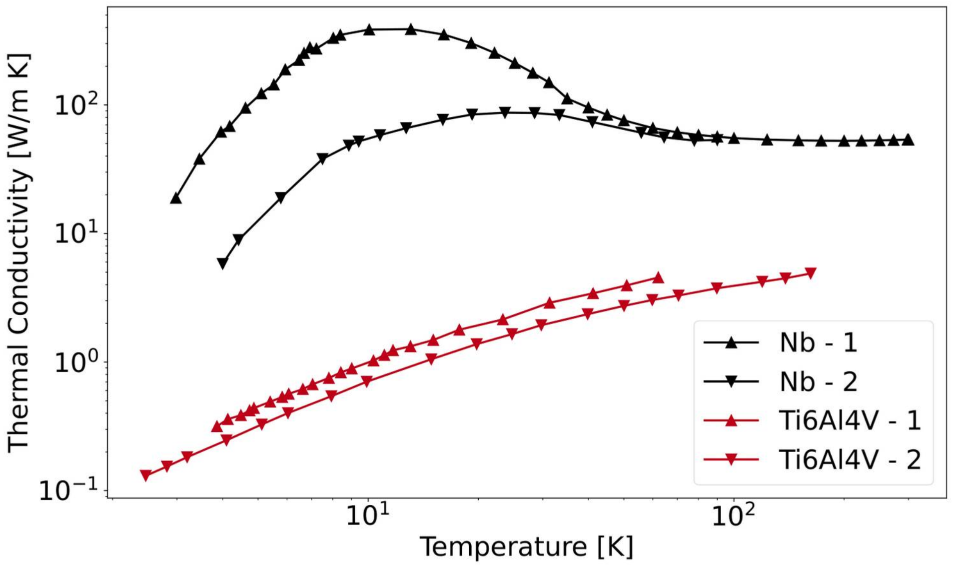


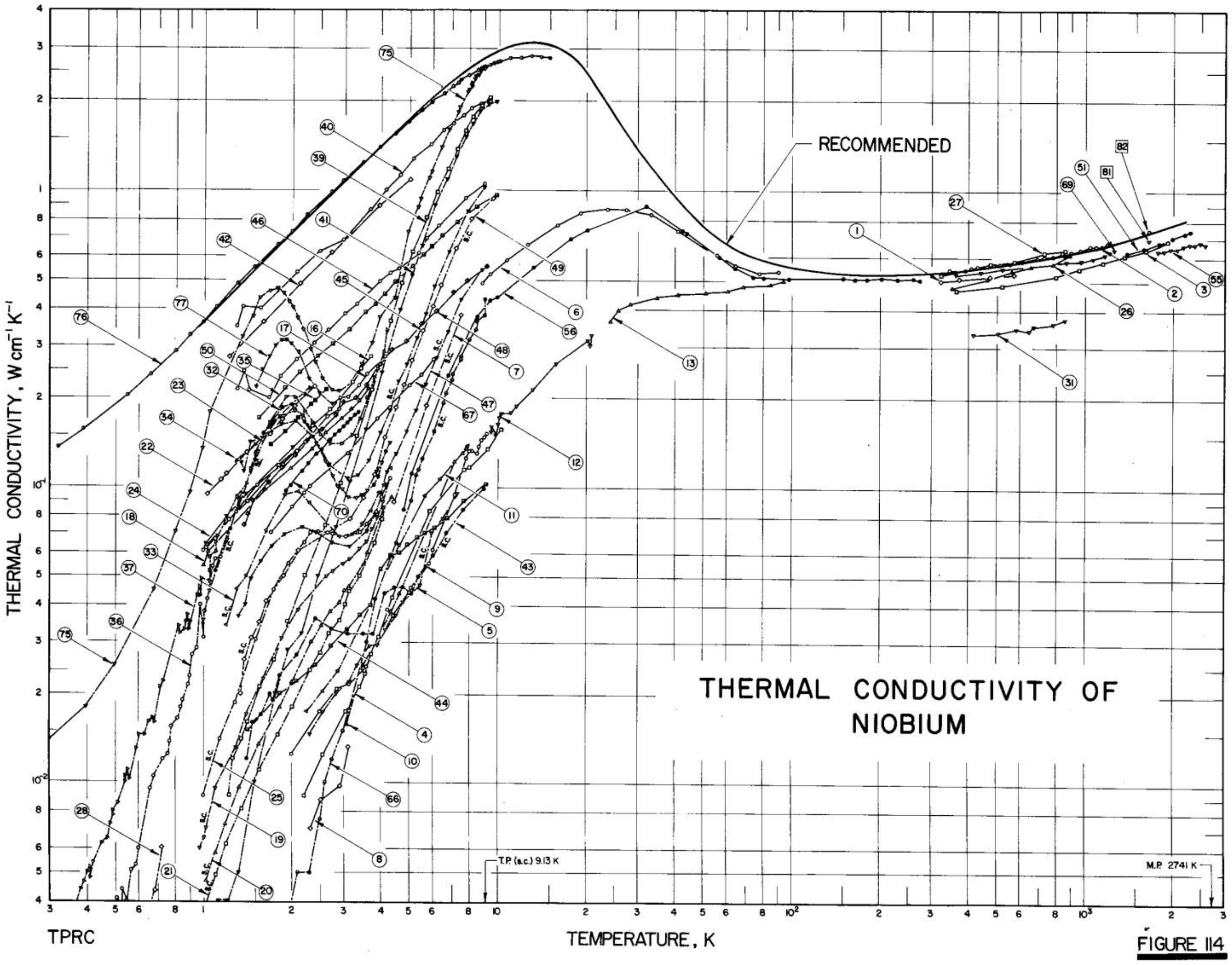


Tip size estimation from field emission data

- Large spread in Nb thermal conductivity
- Choose two curves (RRR = 382 and RRR = 300)

- Less spread for Ti6Al4V





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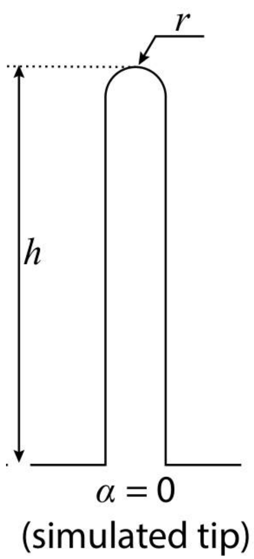
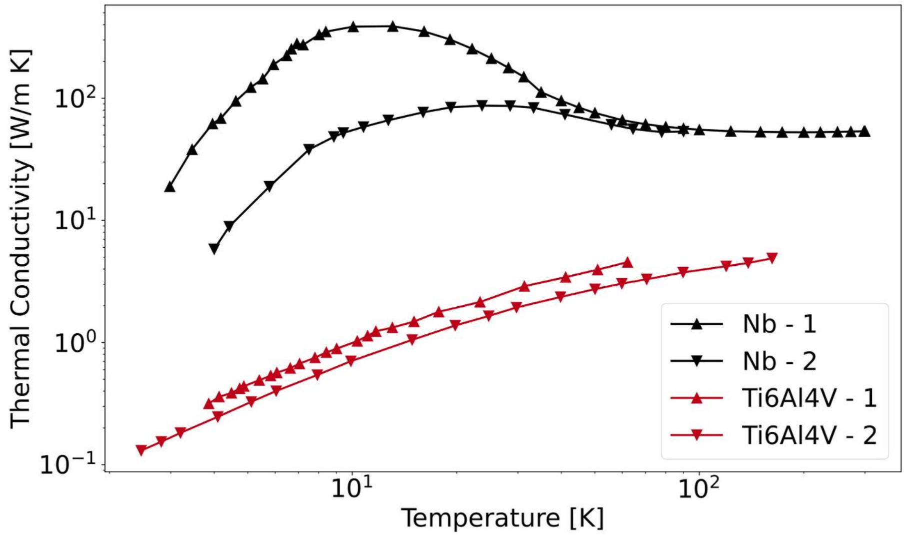
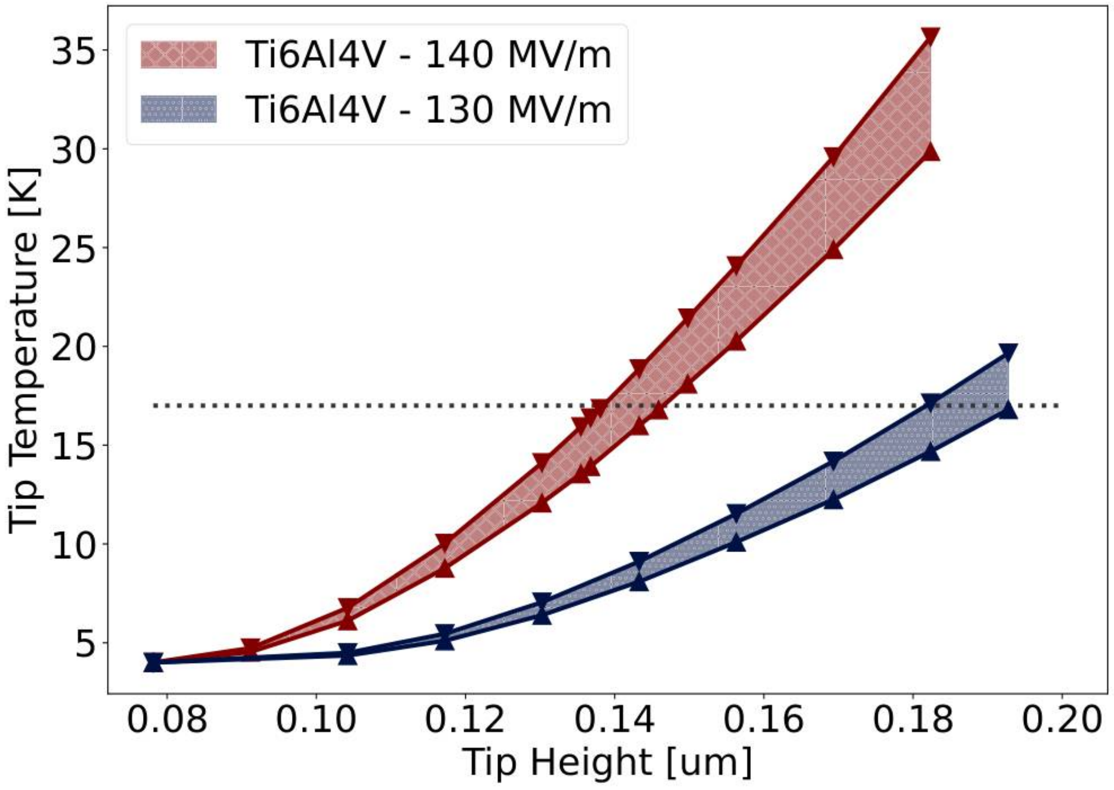
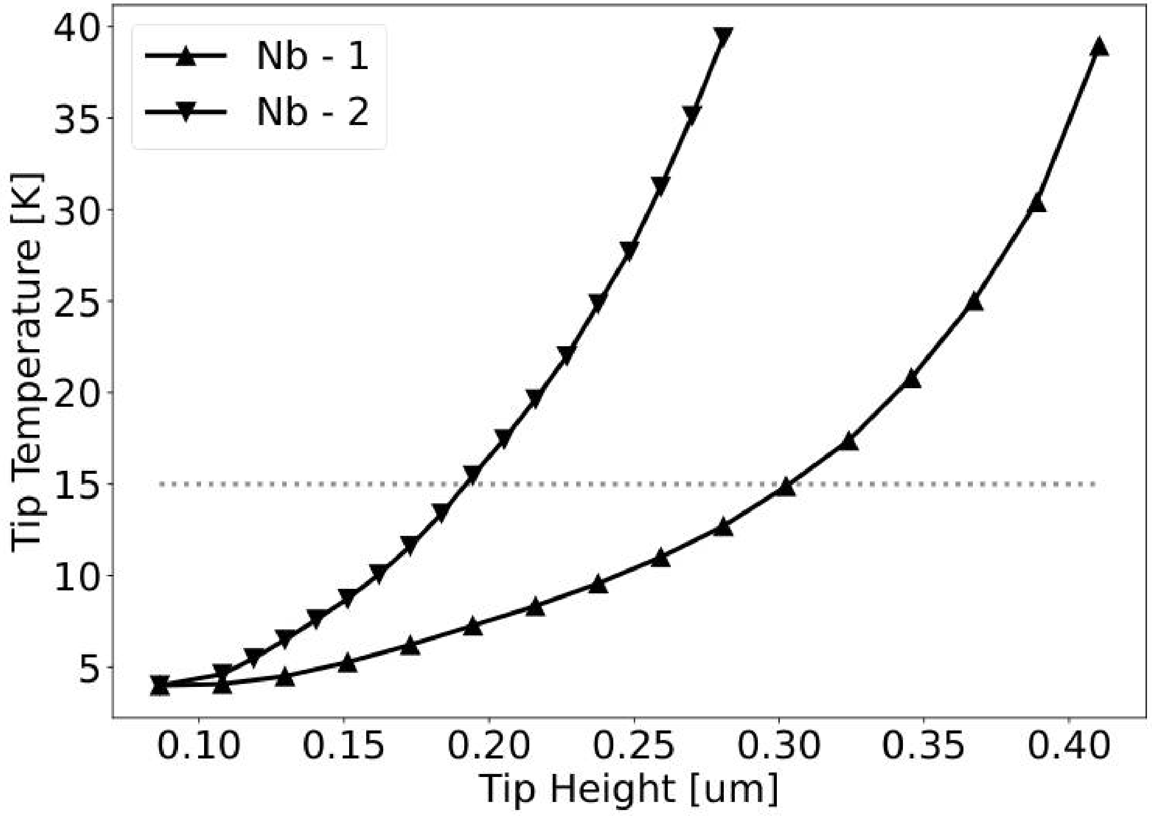
Tip size estimation from field emission data

- For Nb: h > 0.19 um
- For Ti6Al4V: h > 0.14 um
- Why haven't these tips been observed?
  - Maximum tip density: Nb: 1.1 tips/mm², Ti6Al4V: 70 tips/mm²





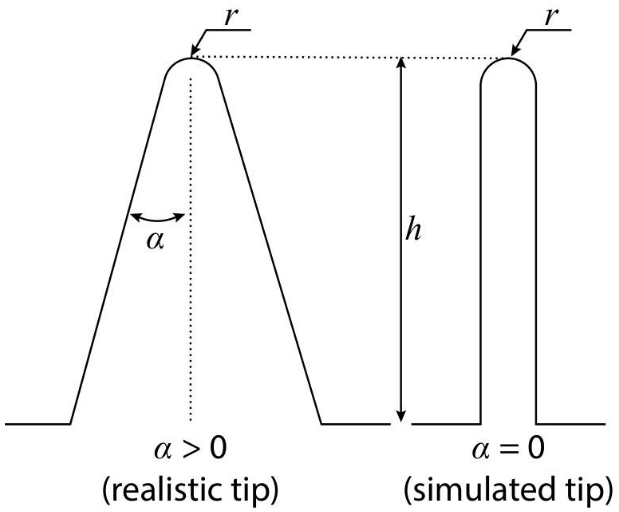




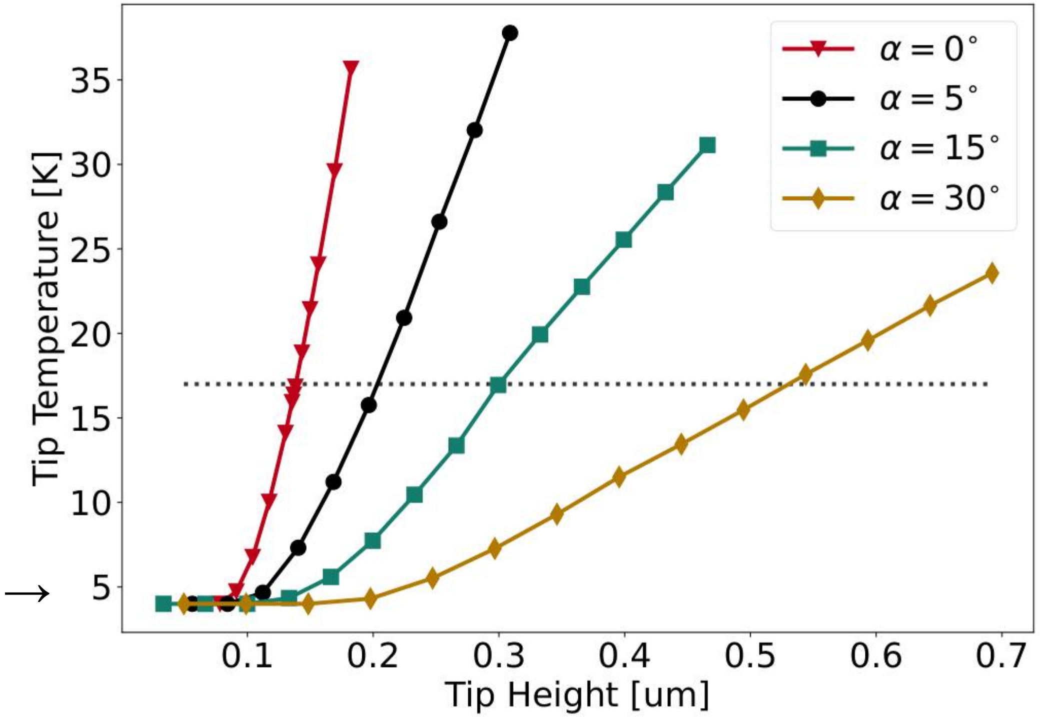
Tip size estimation from field emission data

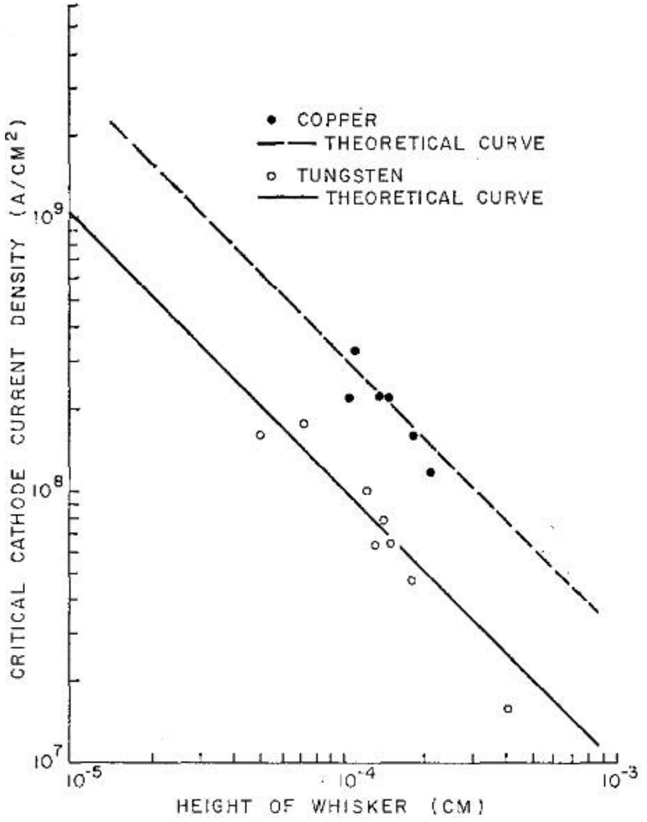
- Paper from 1967 estimated tip size from phosphor screen spot size for Cu and W (0.5-4 um)
- Same order of magnitude
- We provide additional evidence for the theory of the geometrical nature of field enhancement

- Our minimum heights are smaller:
  - Uncertainties in thermal conductivity
  - Uncertainties in opening angle
  - Different materials



For Ti6Al4V →





J. Appl. Phys. 38, 2989–2997 (1967)

Manuscript submitted to Phys Rev App

Field emission current measurements during high field conditioning of Nb and Ti6Al4V electrodes in cryogenic conditions

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(Dated: February 16, 2026)

The maximum accelerating field achievable in both normal and superconducting cavities is limited by field emission and vacuum arcs. However, this limit can be extended with a conditioning process, and significantly enhanced by operating at cryogenic temperatures. To better understand how vacuum arcs begin and how conditioning improves performance, consistent data across different materials and temperatures is needed. To support this effort, high-voltage tests were carried out on Nb and Ti6Al4V electrodes at low temperatures, demonstrating strong ability to withstand high electric fields. Nb electrodes reached fields of 149 MV/m while Ti6Al4V could sustain electric fields up to 190 MV/m at 4K with a breakdown rate less than 1×10^{-5} BDs/pulse. Ti6Al4V maintained high performance after reconditioning at room temperature, sustaining 150 MV/m.

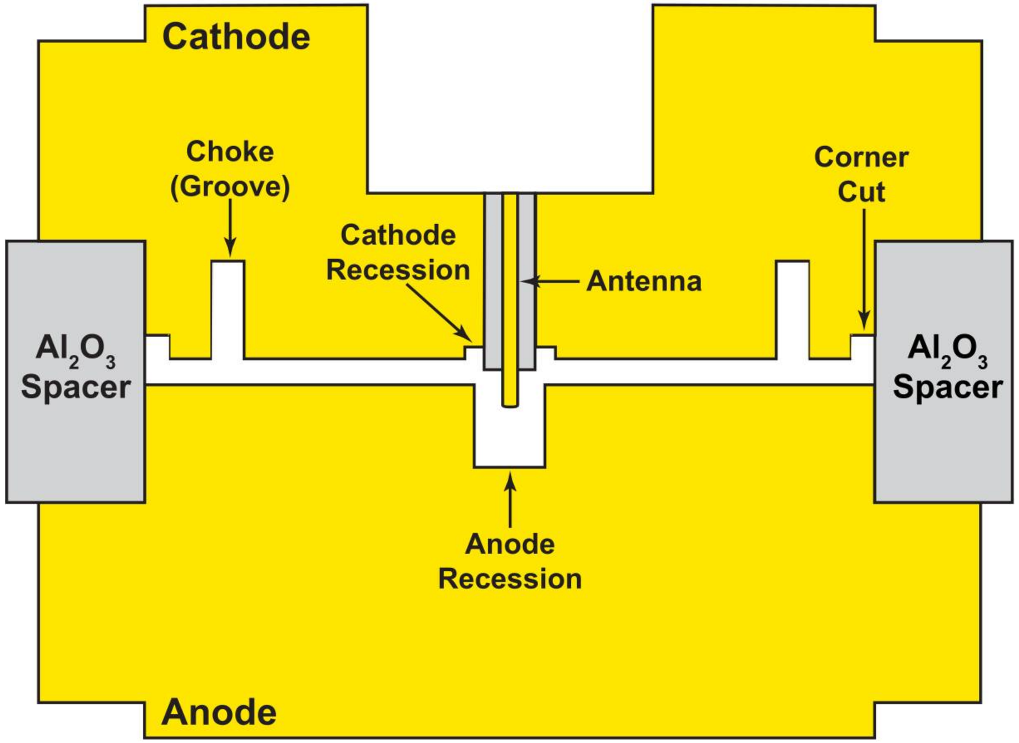
Field emission (FE) measurements enabled precise monitoring of surface evolution, especially under cryogenic conditions. High-quality I-V data obtained at cold enabled accurate extraction of surface state in form of 2 parameters: field enhancement factor and emission area. Combined with simulations, these measurements allowed estimation of required protrusion sizes needed for measured field enhancement: $\geq$0.19 µm for Nb and $\geq$0.14 µm for Ti6Al4V. Long-term conditioning showed a steady, exponential decrease in enhancement factor and a significant increase in emission area, suggesting a transition from sharp to blunt emitters. Interestingly, the product of enhancement factor and highest sustainable field was similar for both samples and nearly temperature-independent $\sim$7 GV/m. Regular field emission monitoring is proposed as a diagnostic tool for optimizing conditioning, with variations in the enhancement factor signaling approach to the material's field limit.

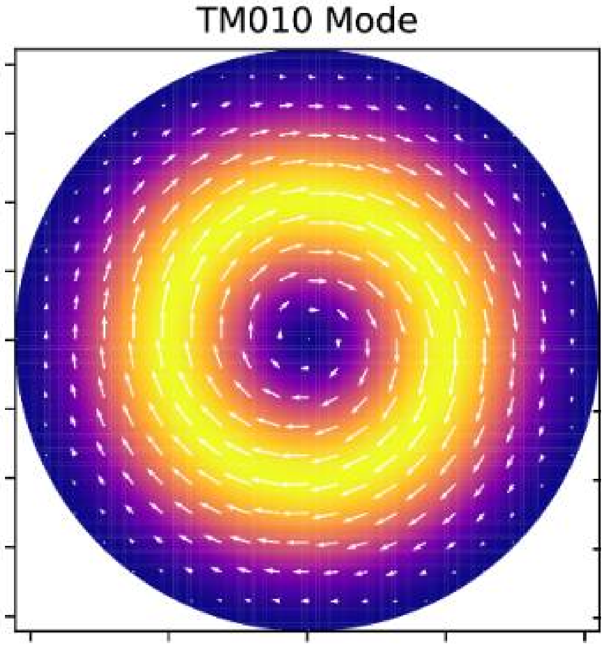
But how do the tips appear? – Future investigations

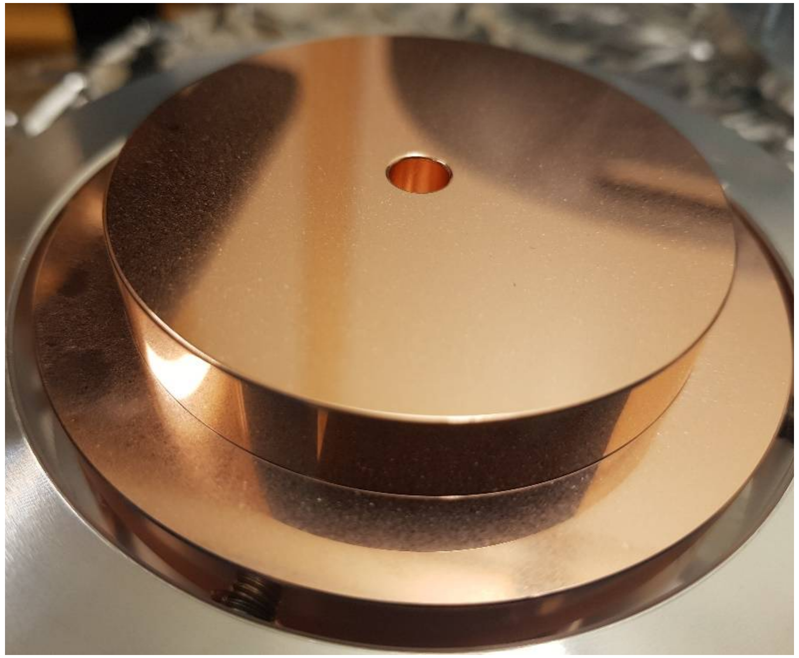
- Movement of dislocations → creation of tips
- Change in dislocation density → change in resistivity
- GHz frequency measurement → sensitivity to changes in resistivity less than a um underneath the surface
- Cryogenic measurements → resistivity due to phonons is negligible

- The electrodes need to be modified to act as a resonator
- The resistivity data is encoded in the quality factor of the system

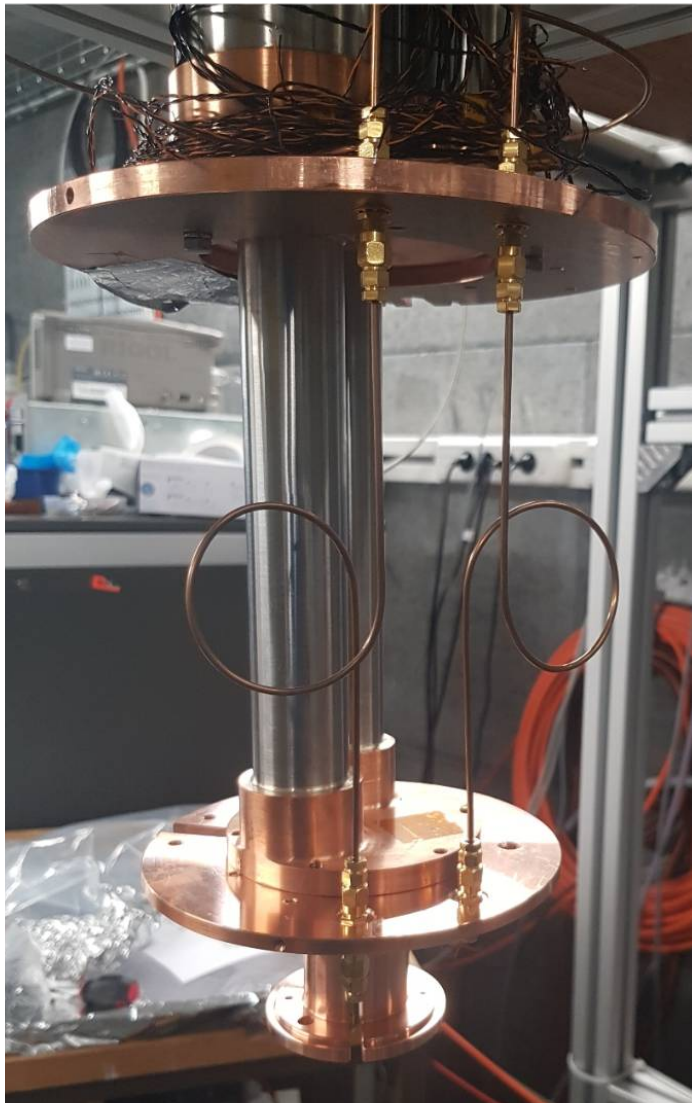
- Conditioning done by DC HV pulses
- Quality factor measured by low-power RF

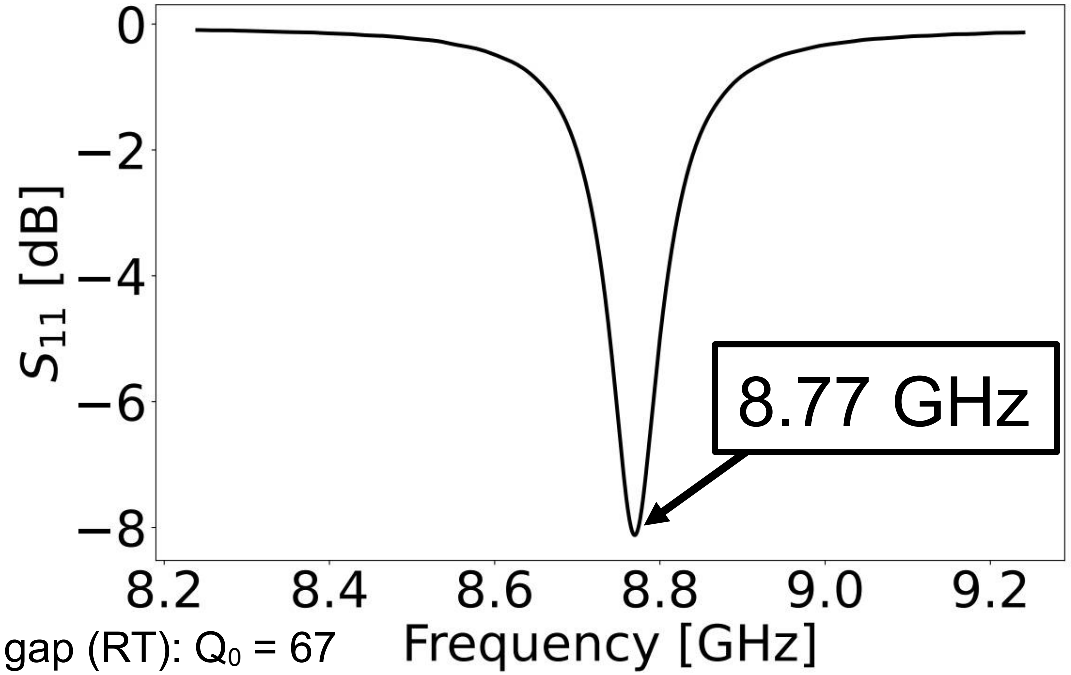






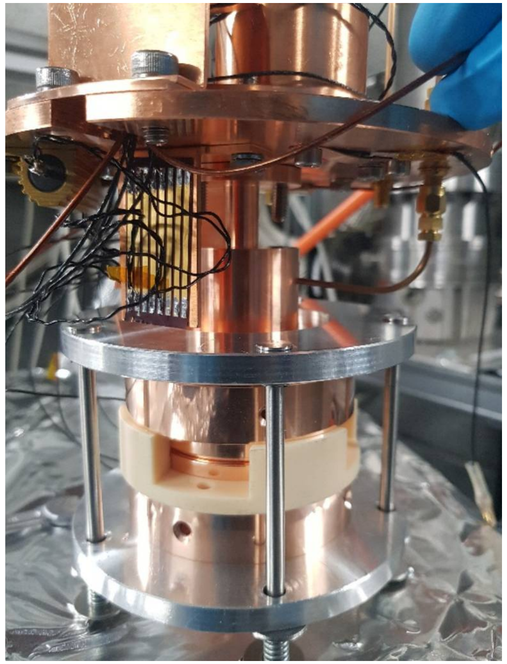
Installing the experimental set-up





40 um gap (RT): Q_0 = 67

60 um gap (RT): Q_0 = 102



International Journal of Microwave and Wireless Technologies

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In situ resistivity measurement of metal surfaces to track down dislocations caused by high field conditioning

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Research Paper

Cite this article: Coman M, Jacewicz M, Dancila D (2024) In situ resistivity measurement of metal surfaces to track down dislocations caused by high field conditioning. *International Journal of Microwave and Wireless Technologies* **16**(10), 1632–1640. https://doi.org/10.1017/S1759078723001411

Received: 22 June 2023
Revised: 20 November 2023
Accepted: 21 November 2023

Keywords:
dislocations; high gradient conditioning; quality factor; resistivity measurement

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Abstract

Conditioning of a metal surface in a high-voltage system is the progressive development of resistance to vacuum arcing over the operational life of the system. This is relevant for accelerator cavities, where high level of performance is only achievable after a long conditioning period. Beyond the accelerator research field, this is an important topic for any technology where breakdowns can cause device failure, either by directly disrupting device operation or by causing cumulative hardware damage.

We are developing a direct method to measure the surface resistivity of a metal surface that is being conditioned with a HV DC system by inducing a high frequency (GHz) radio-frequency current in the parallel-plate electrode system. If the system can function as a resonant cavity, the surface resistivity data would be encoded in its quality factor (*Q*-factor). The changes in the resistivity measured in cryogenic conditions would indicate a formation of dislocations under the surface, something that has been speculated as an important process behind the conditioning.

In this paper, we present two modified designs of the electrode system, which will act as a resonant cavity, the results of 3D EM simulations and experimental results regarding the characterization of this resonant system.

Already published: https://doi.org/10.1017/S1759078723001411

Conclusions

- Vacuum arc breakdowns are very complex processes
- Understand and quantify the phenomena → cryogenic data is valuable
- Applications in many fields of research where high gradients are needed

- So far, we have conditioned Cu, Nb and Ti6Al4V, Au platted Al electrodes electrodes at room and cryogenic temperatures
- Field emission measurements were made in order to track the state of the surface during conditioning

- Experimental results:
  - Higher fields reached at cryogenic temperatures
  - During conditioning, the field enhancement factor (β) decreases → blunter tips
  - The decrease slows down as the maximum field is reached → can be used to avoid de-conditioning
  - Area increases by 4-5 orders of magnitude → more tips are created
  - Local field at BD ~6-7 GV/m. Does not depend strongly on temperature
  - From field emission data and simulations → tip size: 0.14-0.19 um

- We are developing a method for measuring the surface resistivity during the conditioning process in cryogenic conditions
- This will help us track down changes in dislocation density underneath the surface

Future plans

- Published one paper on the design of the RF electrodes: **In situ resistivity measurement of metal surfaces to track down dislocations caused by high field conditioning**
- One paper submitted to Physical Review Applied: **Field emission current measurements during high field conditioning of Nb and Ti6Al4V electrodes in cryogenic conditions**
- We plan to have another paper about the measurements with the RF electrodes
- Now we are waiting to receive an order for a cryogenic RF cable assembly to continue building the RF system
- In the meantime, I am working on maintenance of the system and on improving the FE current measurement system
- In May, I will go to EURO-LABS Basic Training School 2026 (BTS26)
- We will start the RF electrode measurements