Cryogenic studies of electric vacuum breakdown and field emission

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CERN

CERN, 17/12/2019

Outline

- Motivation
- Setup
- Preliminary results:
  - Conditioning
  - Field emission
- Outlook
- Summary

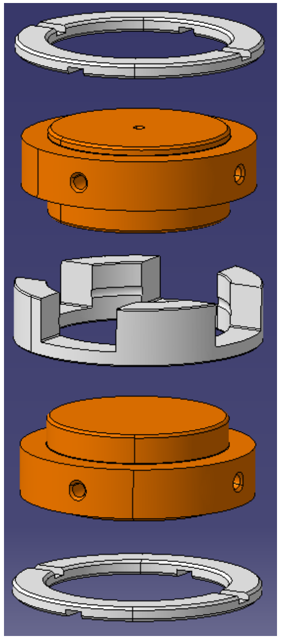
Cryo DC pulsed system
Motivations

Why DC system?

High field measurement with kHz repetition rate, μs DC pulses
Conditioning process kept as close to RF as possible
The same material treatment

- Information about breakdown physics and electrode damage
- Conditioning within days not months
- Easier for post-mortem analysis

DC system at CERN



Cryo DC pulsed system
Motivations

Why cryo?

Temperature information might help us to understand better the conditioning process:

- why the achievable gradient increases?
- why there is an ultimate limit in conditioning process?

Potentially look for connections between the high-gradient normal-conducting and superconducting fields.

Theoretical models:

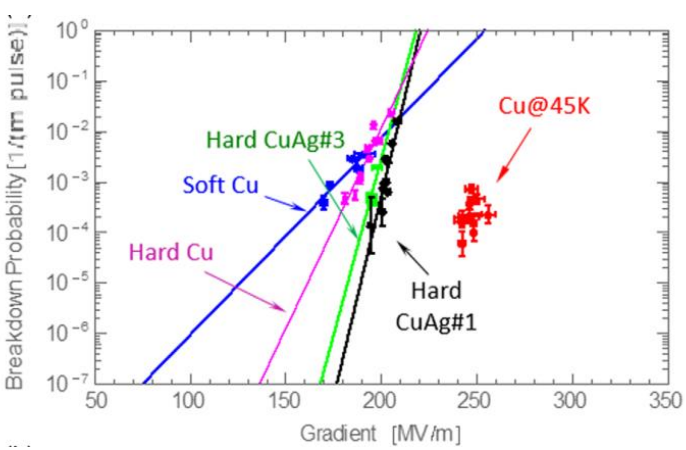
- Have strong dependence on temperature
- Agree within the range of currently available data
- Include different temperature-dependent terms

Experiments at SLAC

RF structure processed to 250 MV/m, $2 \cdot 10^{-4}$ /pulse/m with 150 ns

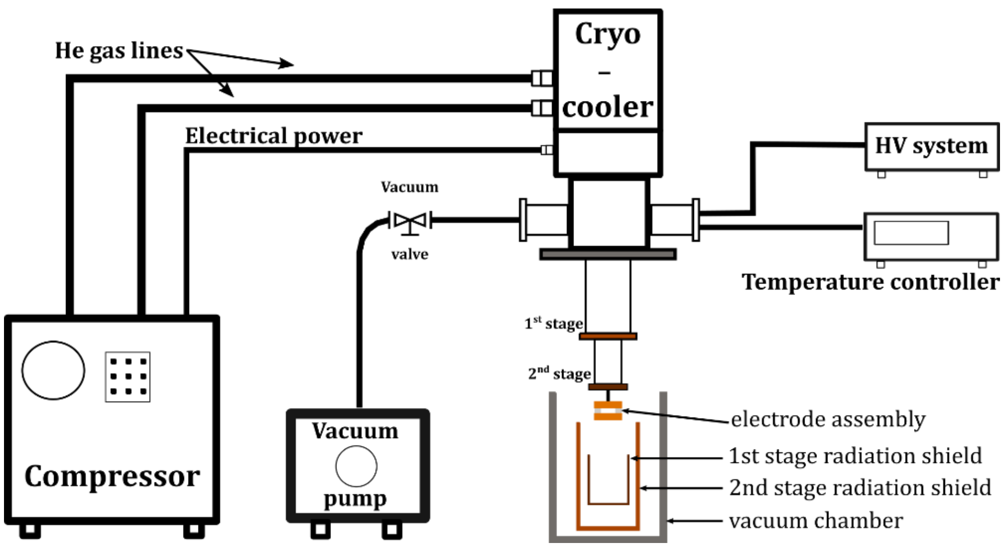
K. Nordlund and F. Djurabekova, *Phys. Rev. ST Accel. Beams 15, 071002 (2012)*

E. Engelberg, Y. Ashkenazy and M. Assaf *Phys. Rev. Lett. 120, 124801 (2018)*



Cahill et al., Phys. Rev. Accel. Beams. **21** 102002 (2018)

Cryo DC pulsed system
Setup



Typical pressure value:

@ room temperature: < 1e-7 mbar

@ cryo temperatures: < 5e-9 mbar

Cryo DC pulsed system

Cryocooler

2-stage pulse-tube type cryocooler (CRYOMECH PT415)

Compressor with inverter

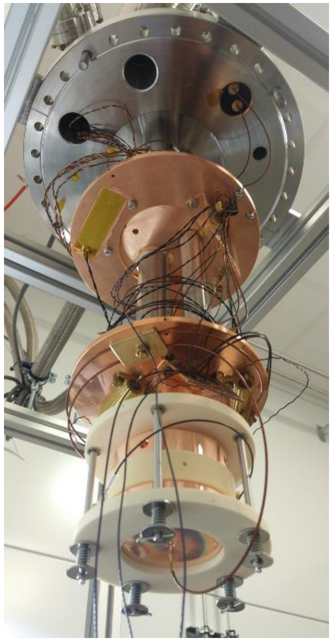
- ➢ variation of the compressor frequency
- ➢ changes cooler capacity and the electrical input power

More flexible operation and wider temperature range.

The nominal performance 1.5W @ 4.2K at second stage

Cryo DC pulsed system

Construction



Design based on experience from CERN cryo group
We minimized the use of known outgassing materials, e.g. no MLI used

Setup
HV power supplies

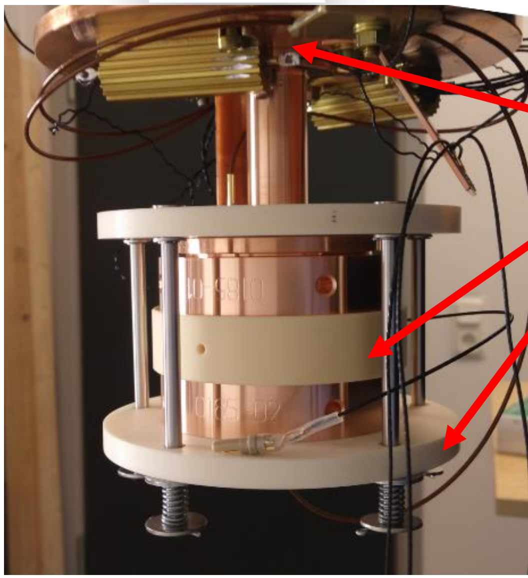
Field emission

Conditioning with MARX generator
1 μs pulses, 200Hz to 2kHz, up to 10 kV

Megger MIT525
Ramp mode up to 5 kV
Current range:0.01 nA to 3 mA
Current accuracy: ±2%

Heinzinger HNC 20.000
Programmable
Voltage up to 20 kV
Current range:0.001 to 5 mA
Current accuracy: ±0.1%

Setup
Temperature

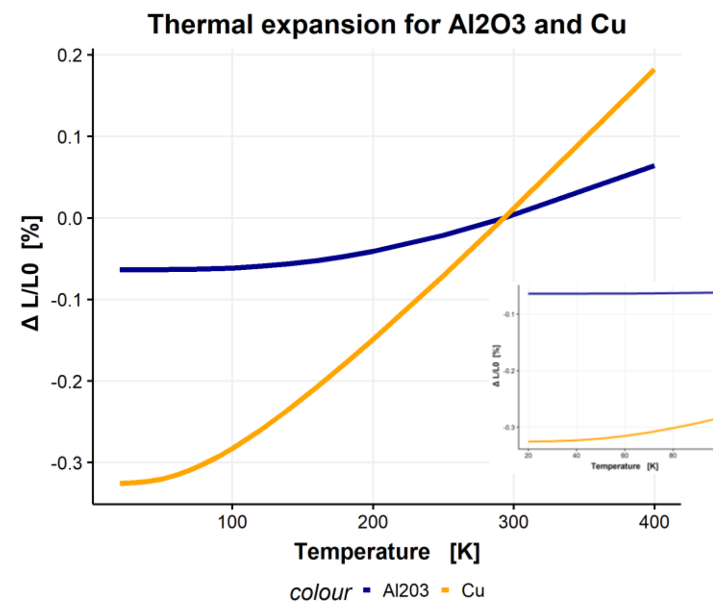


6 temperature sensors:
3 temperature sensors close to electrodes
+
1 on each radiation shield
1 at the first stage of cryocooler
+
2 heaters for temperature control

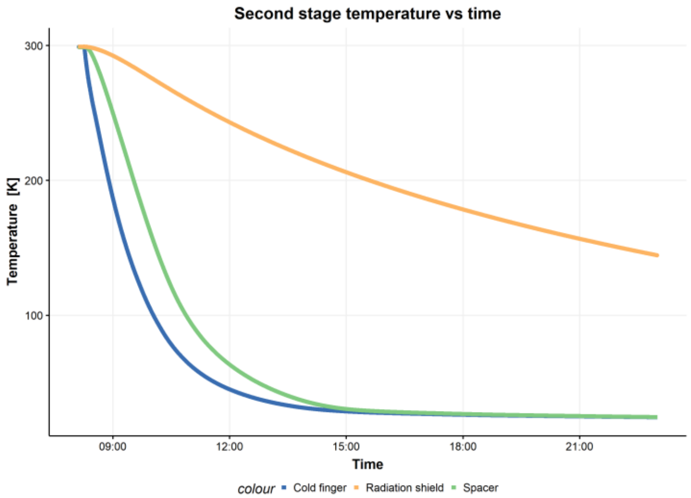
OFE Hard Cu electrodes: 60 µm gap maintaned by ceramic spacer (alumina)

Gap size increases with cooling (60 um → 80 um)
Changes monitored with:

- ➢ Direct capacitance measurments during cool-down
- ➢ Voltage and current from Marx's power supply



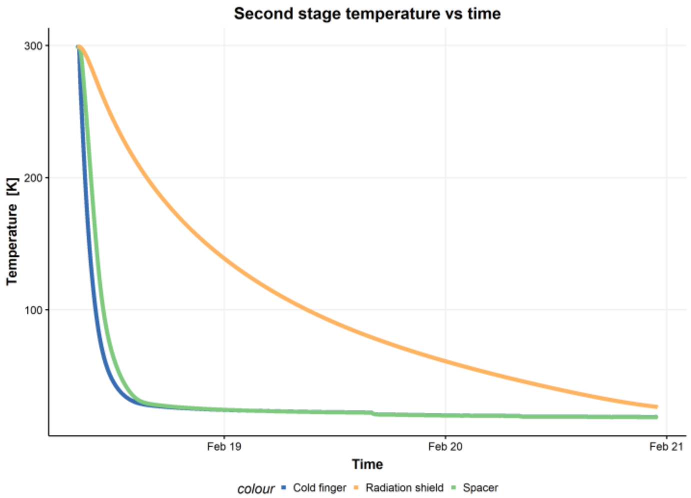
Cooling and temperature stability

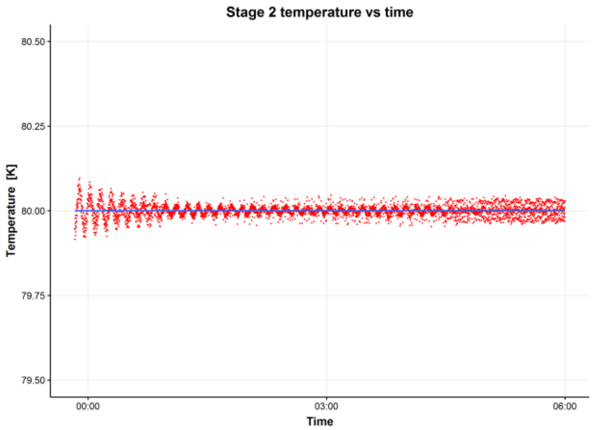


Cooling time:

Electrode system: ~10h

Radiation shield: ~3days



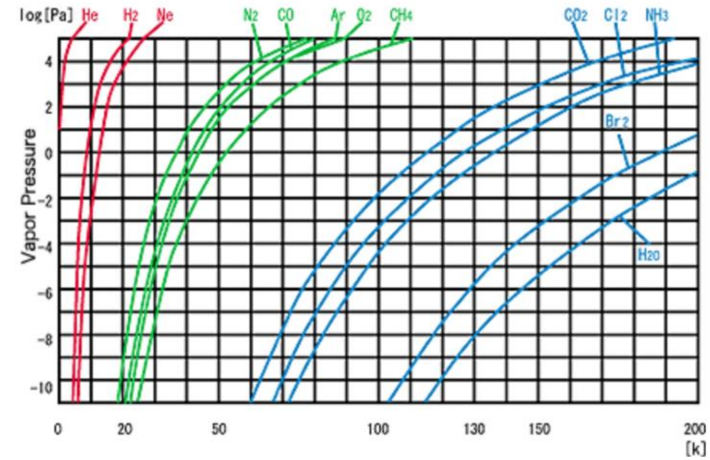


Stable temperature +/-0.1K with PID control

Cooling procedure before conditioning

Special cooling to prevent adsorption of gasses on electrodes

1) Cool down and stabilize at intermediate temperatures
2) When stable warm up electrodes
3) Gases leave electrodes and condense on colder surface (rad shield)
4) Repeat at next intermediate temperature



Temperatures to consider:

120K - H_2O, CO_2,NH_3

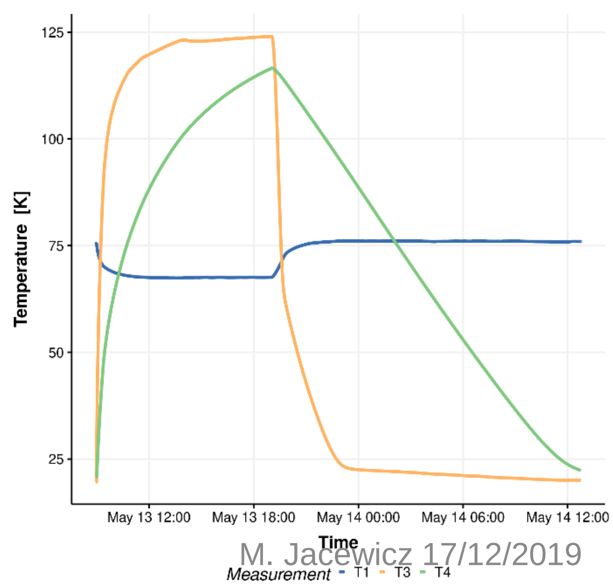
50K – CH_4, O_2, CO, N_2

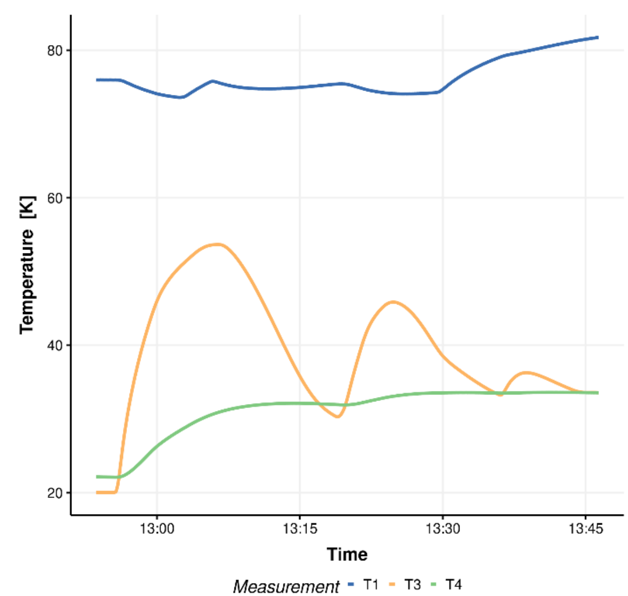
20K – H_2

Blue (T1)
1^{st} stage

Orange (T3)
spacer between electrodes

Green (T4)
2^{nd} stage rad shield





Electrodes used so far

Spring 2019

OFE Hard Cu electrodes: 60 mm diameter, 60 µm gap

Experimental timeline for conditioning:

300K → 30K → 60K → 300K

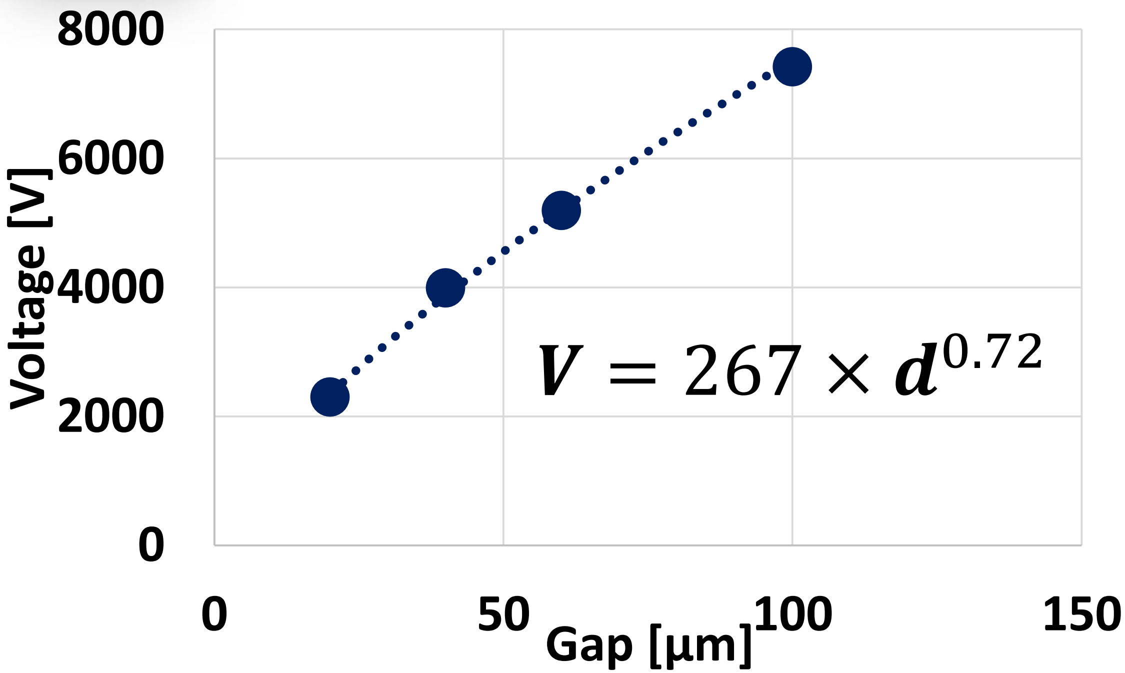
Autumn 2019

OFE Hard Cu electrodes: 40 mm diameter, 60 µm gap

Experimental timeline for conditioning:

300K → 60K → 30K → 90K → ?(300K)

Voltage dependency on gap size



Maximum voltage (voltage at the end of conditioning) vs gap distance

Field normalization based on the derived relation

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

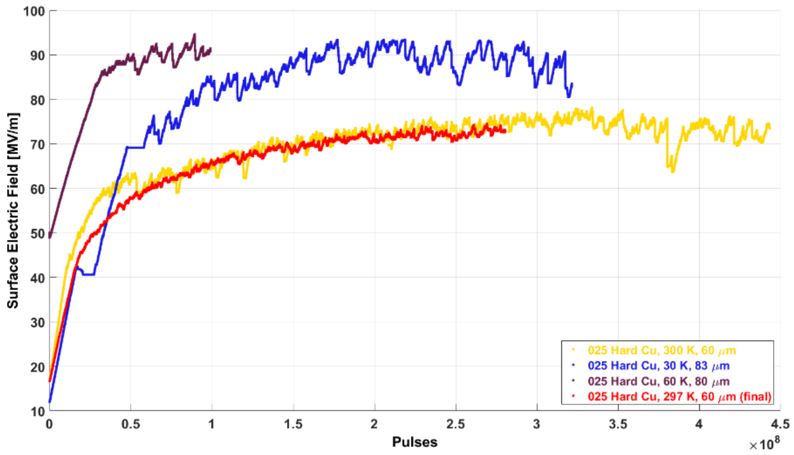
From I. Profatilova

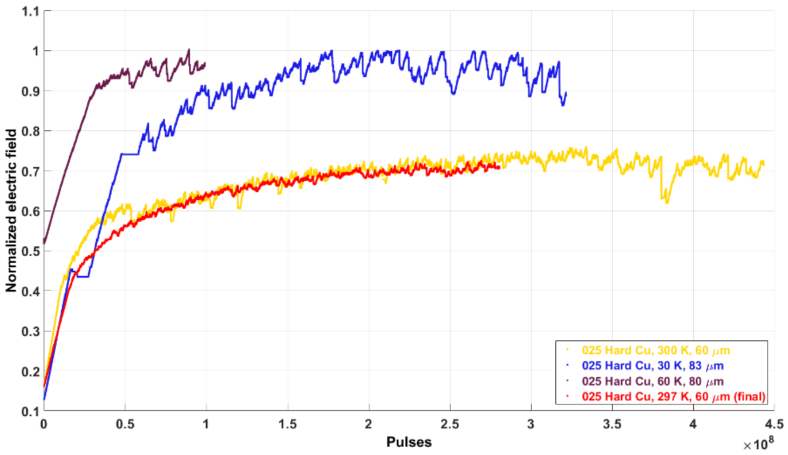
In agreement with

A. Maitland, J. Appl. Phys., vol. 32, pp. 2399-2407, 1961.

Spring results

Conditioning curves: 300K, 30K and 60K and back to 300K





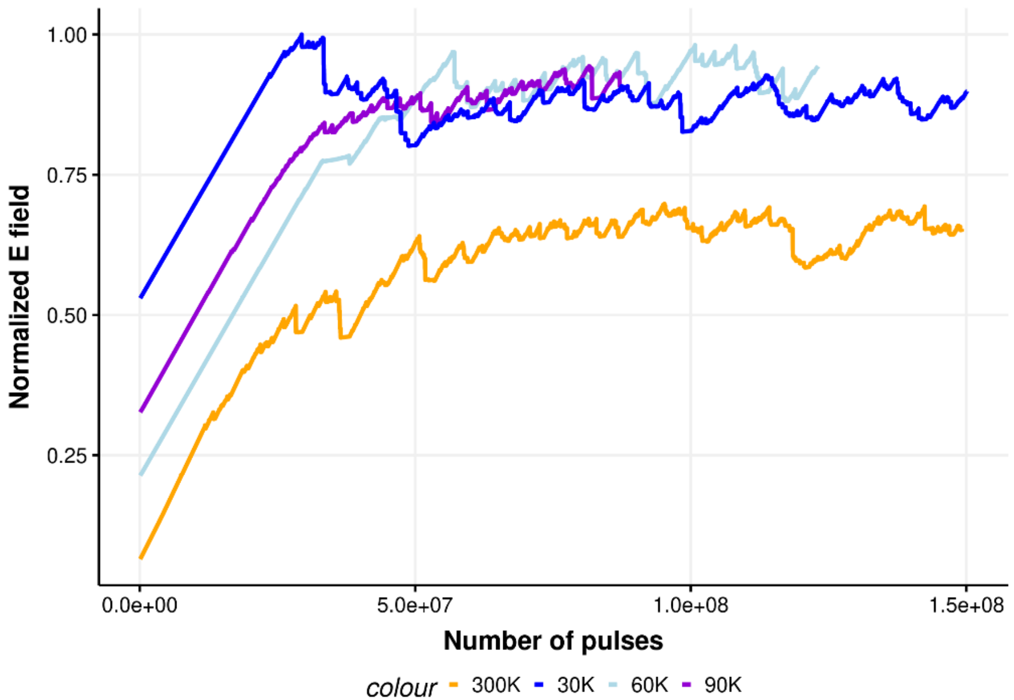
$$E_s = \frac{V}{d}$$

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

Around 23% increase in achieved gradient

Surface re-condition quicker after each cycle

Conditioning curves → 300K vs 30K, 60K, 90K



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

Around 30% increase in achieved gradient

Stable gradient at 30K dropped after period of high fields

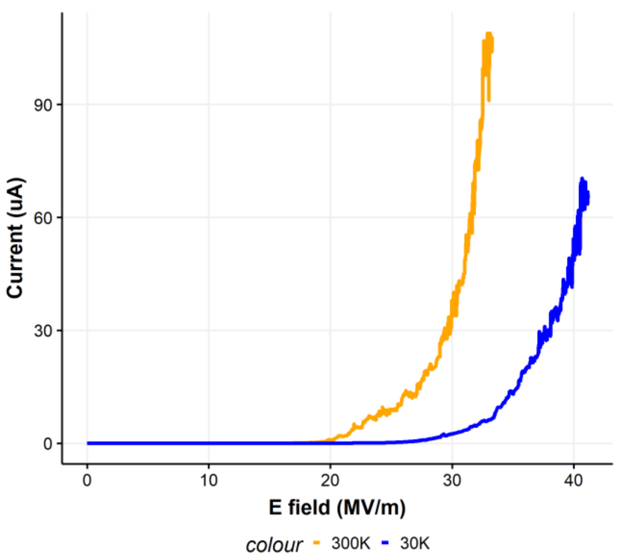
Field emission

Spring run

Field emission at two temperatures 300K and 30K

Ramping voltage with rate 100V/minute → automatic stop when breakdown detected

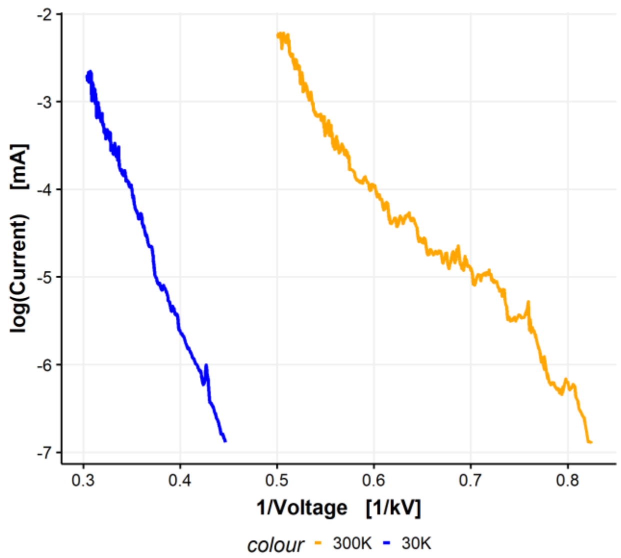
Current - Field



Orange → 300K

Blue → 30K

Current – Field – log scale



Field emission

Spring run

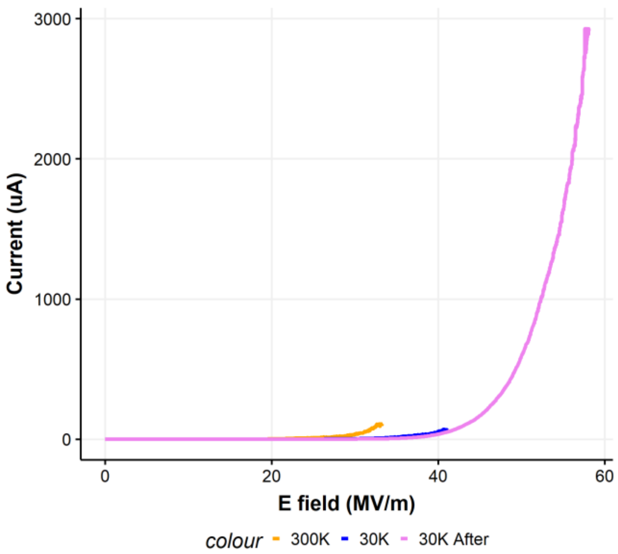
Field emission at two temperatures 300K and 30K

Ramping voltage with rate 100V/minute → automatic stop when breakdown detected

New field emission run after full conditioning

Current - Field

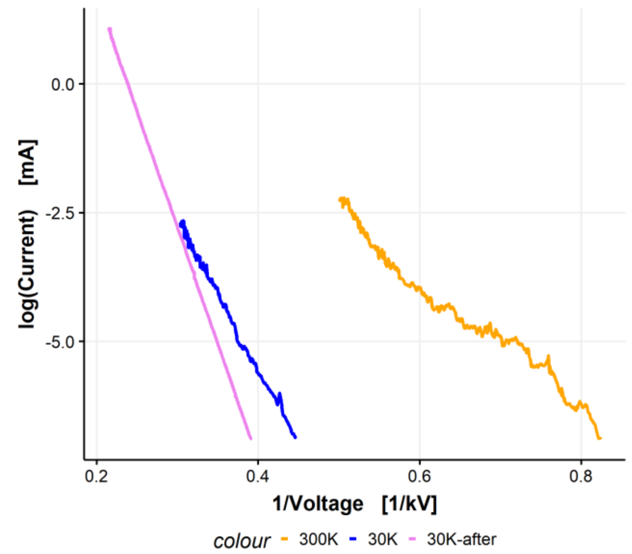
Current – Field – log scale



Orange → 300K

Blue → 30K

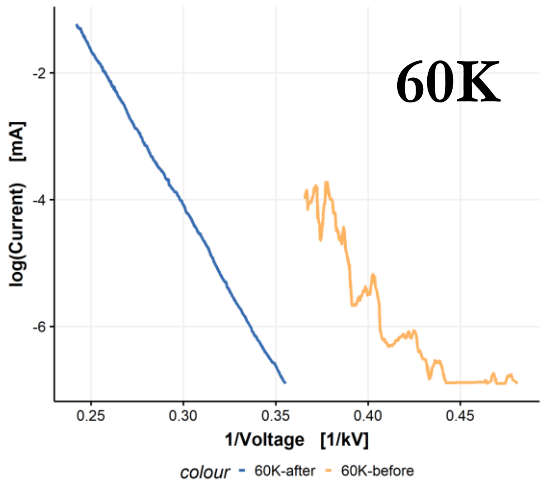
Violet → 30K conditioned



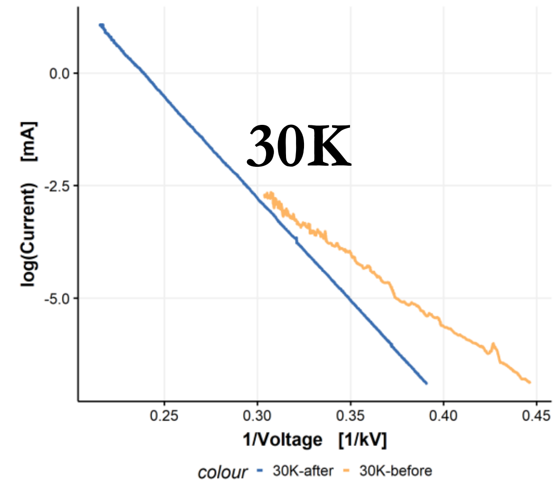
Field emission

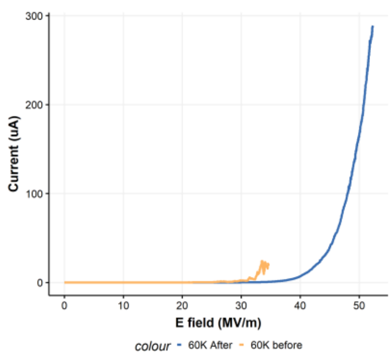
Spring run

Field emission at 30K and 60K→ before and after conditioning at 30K and 60K

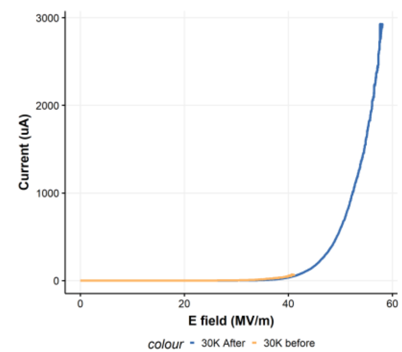


← log scale →





← linear scale →



Very high, stable current drawn, > 10W in power!

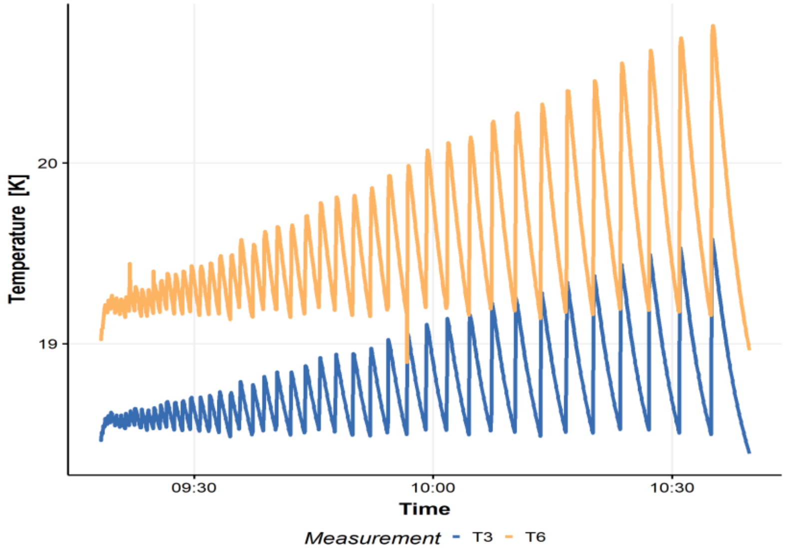
No breakdown – highest voltage reached

Field emission

Autumn run

New procedure

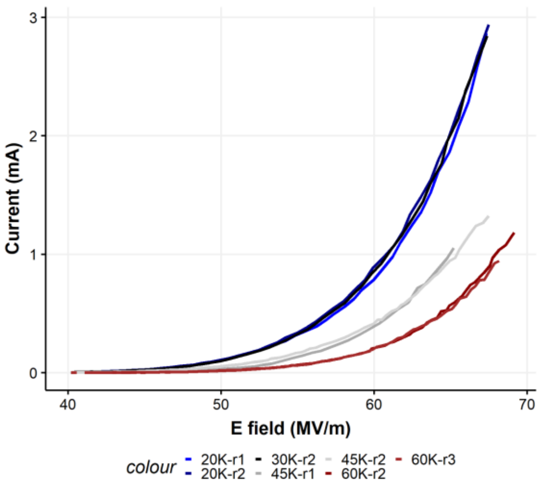
Stepping in voltage with short exposure and cool-off periodes between measurements (ignoring BDs)



Field emission

Autumn run

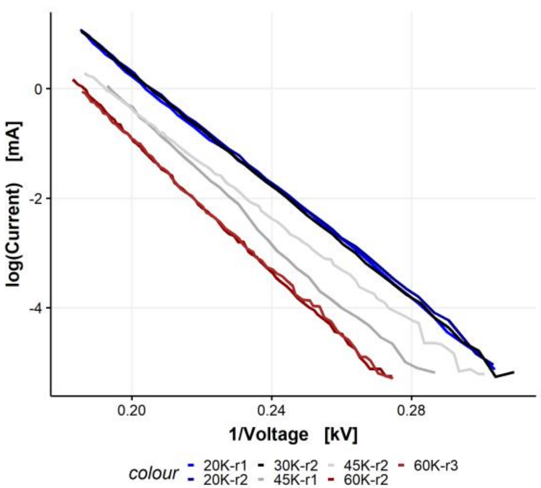
Effect of temperature on field emission curve:
surface conditioned at 30K, then FE at : 20K, 30K, 45K, 60K, 75K, 90K



20K and 30K

45K

60K



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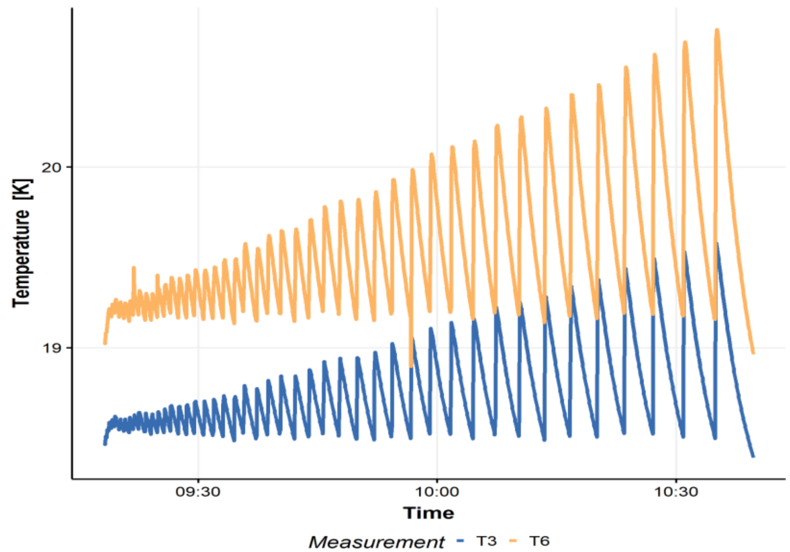

Field emission

Autumn run

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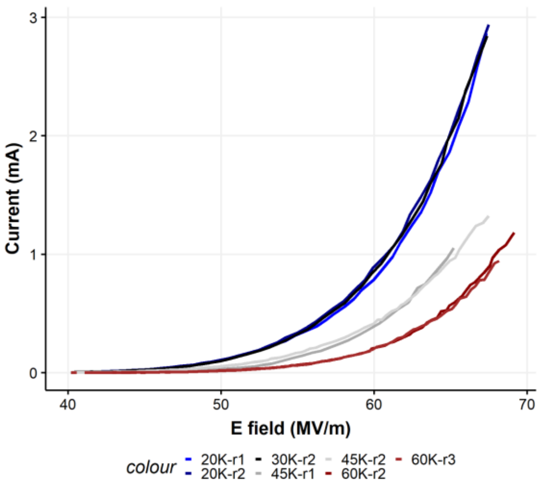
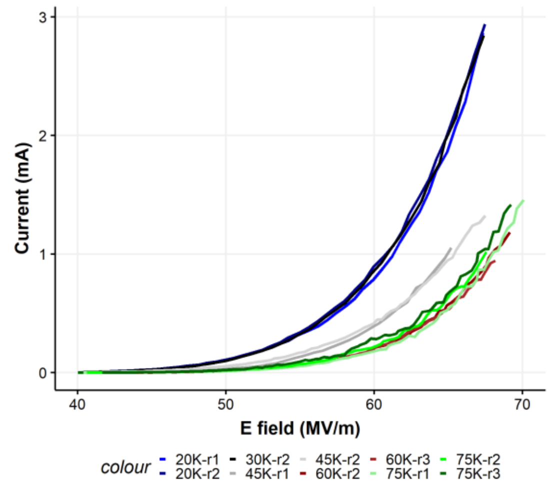
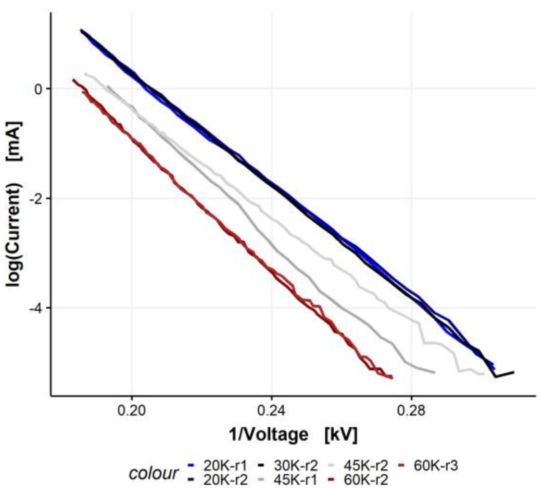
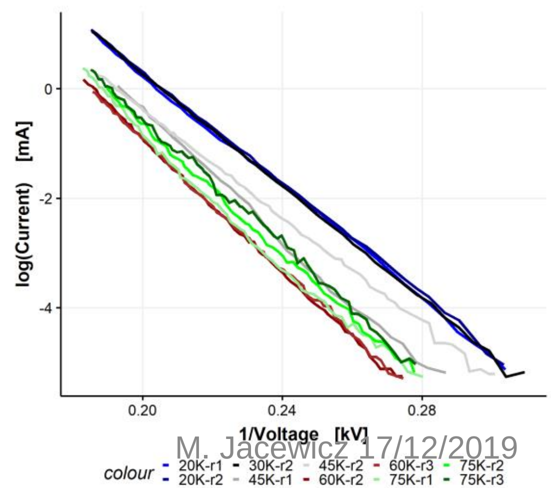




75K





Field emission

Autumn run

Effect of temperature on field emission curve:
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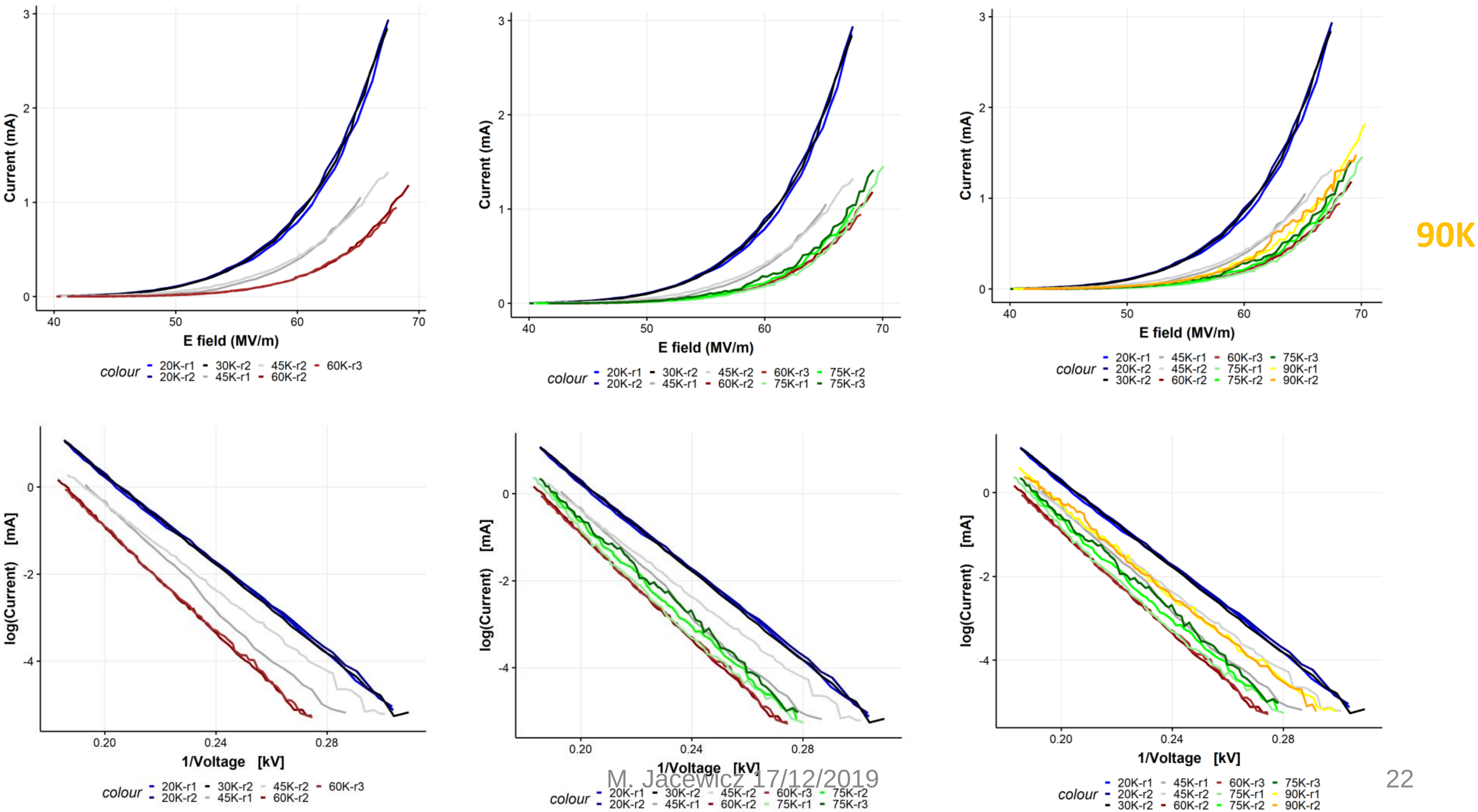
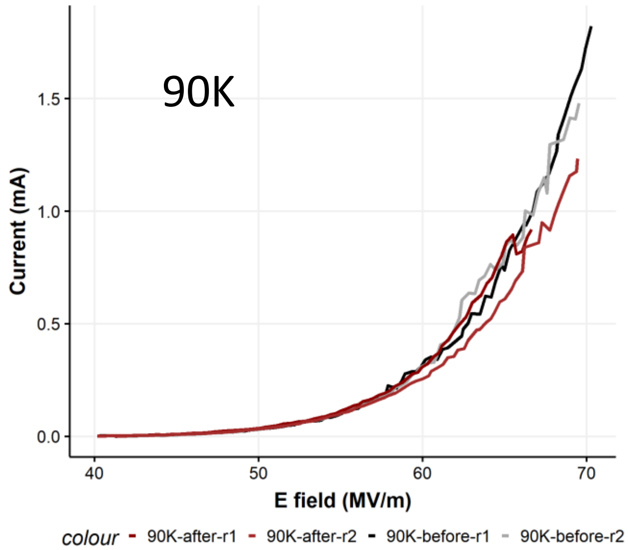
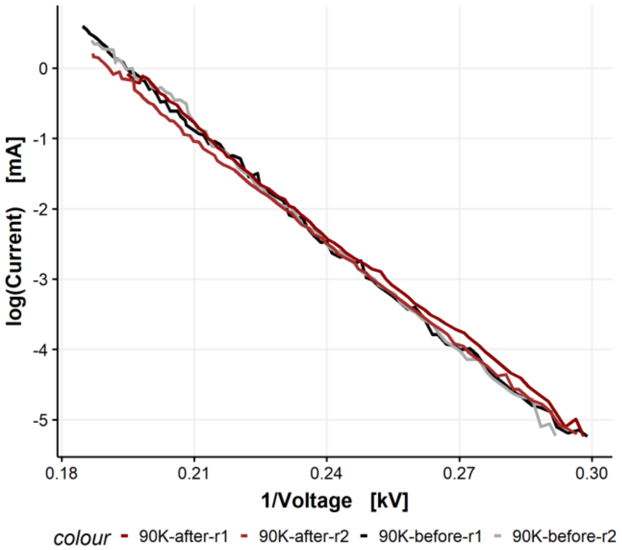


Field emission
Autumn run

Effect of conditioning on field emission curve
FE before and after conditioning at 90K

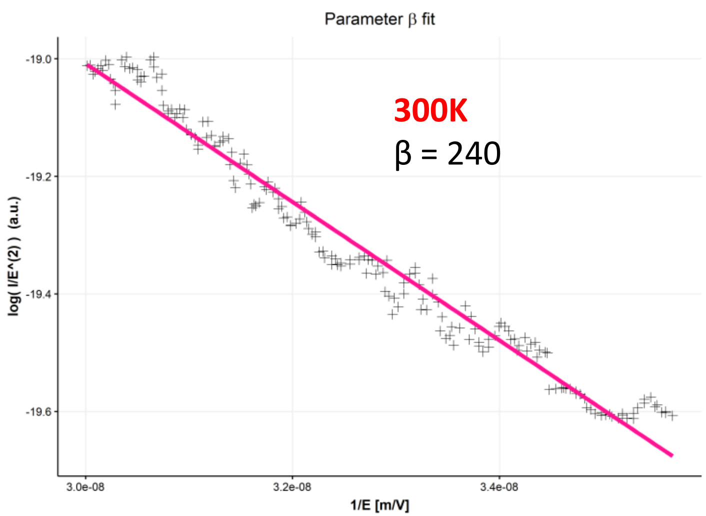


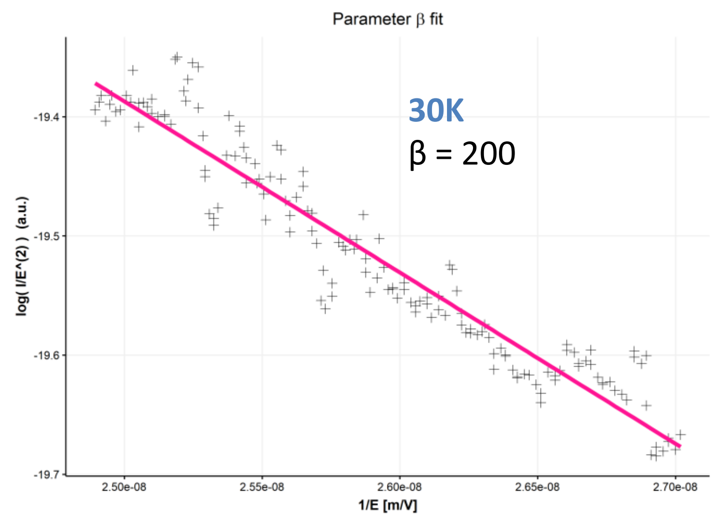


Field emission – beta parameter

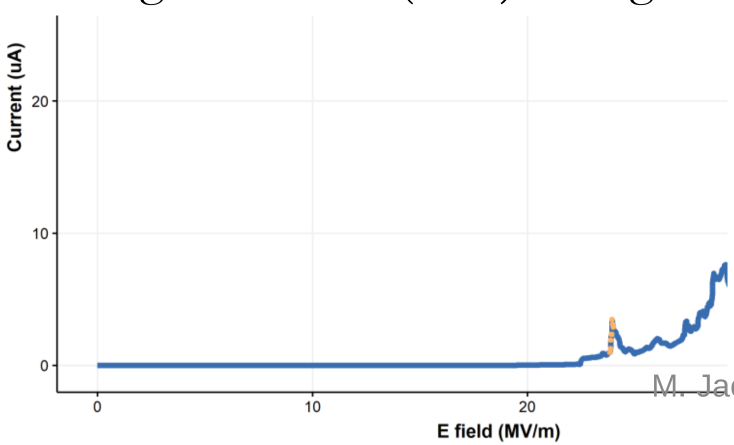
Spring run

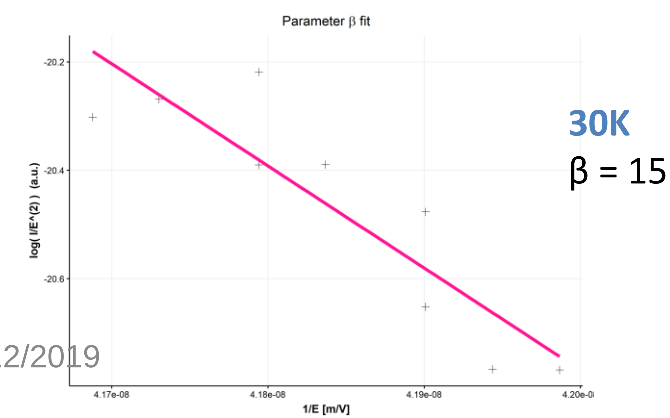
Fowler-Nordheim enhancement factor at two temperatures 300K and 30K





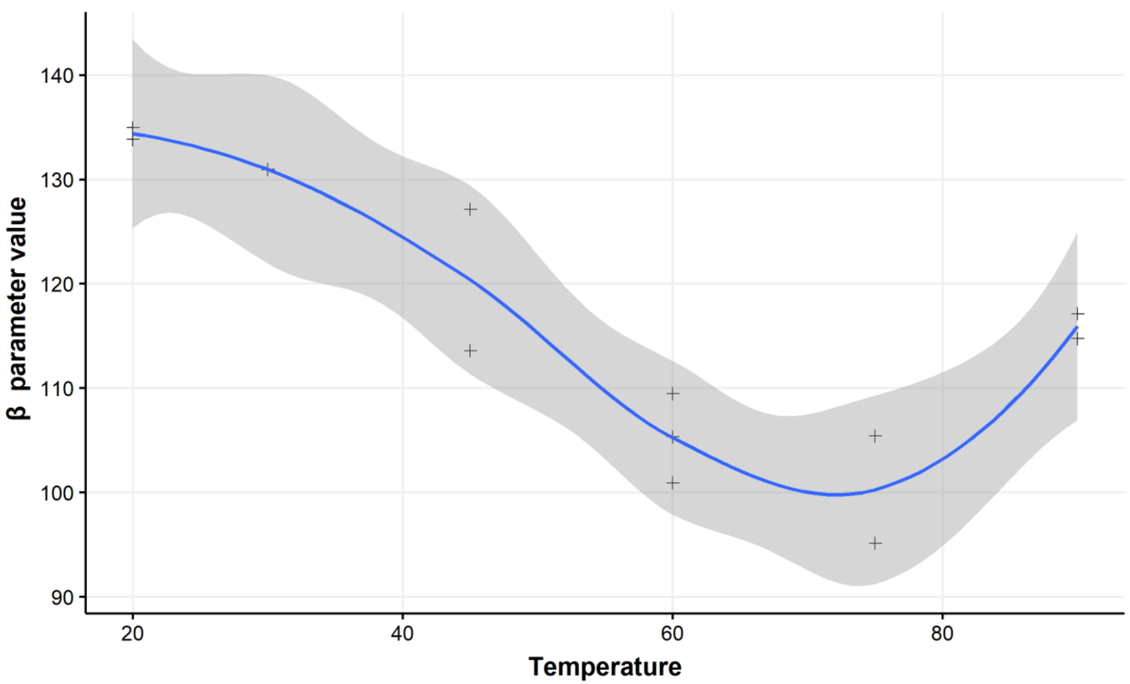
"Single" emitter (30K) – single burst of current during ramping

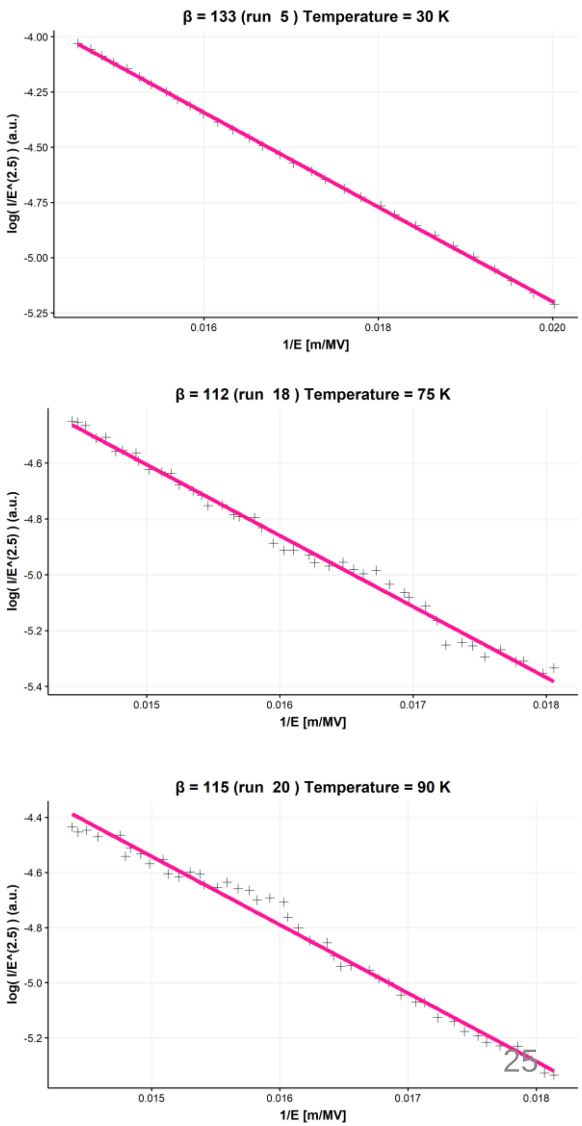




Field emission – beta parameter

Autumn run





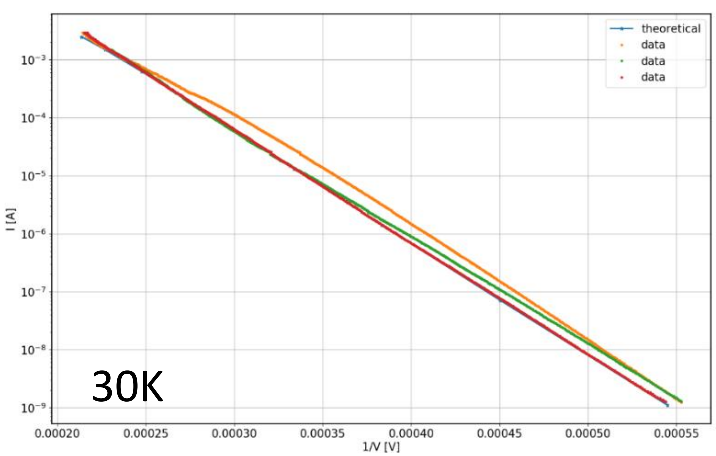
Field emission

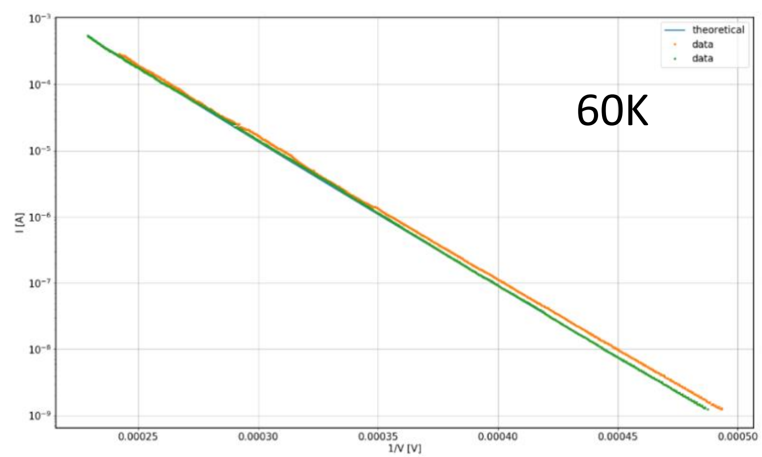
Theoretical work started: Andreas Kyritsakis, Helsinki U.

The FE data sets are very clean and wide-range → can be fitted to the FE equations with very high accuracy.

Unconditioned surfaces - extremely sharp and unstable features of the order of a few nm, very high enhancement factor (150-200), but also a very small effective emission area

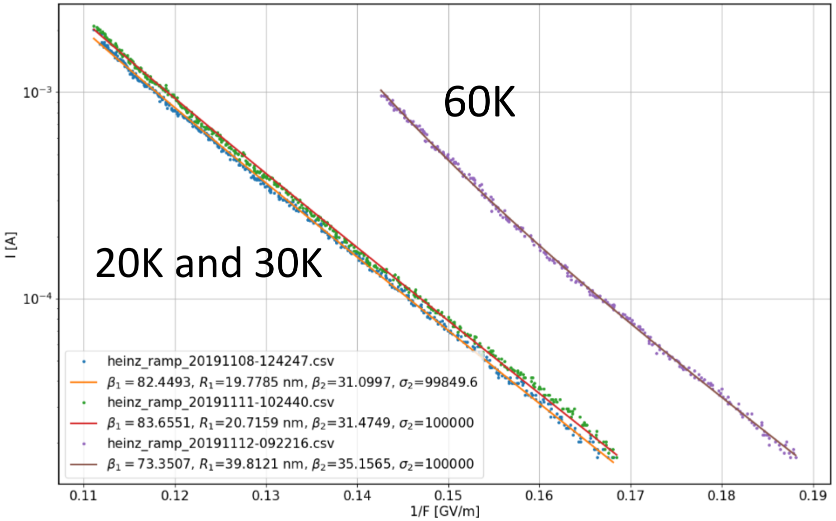
After conditioning - FE characteristics become extremely regular and very consistent with a standard big metal tip. For such conditioned system, the voltage can reach very high values, but the local field (hence the current density) don't go very high



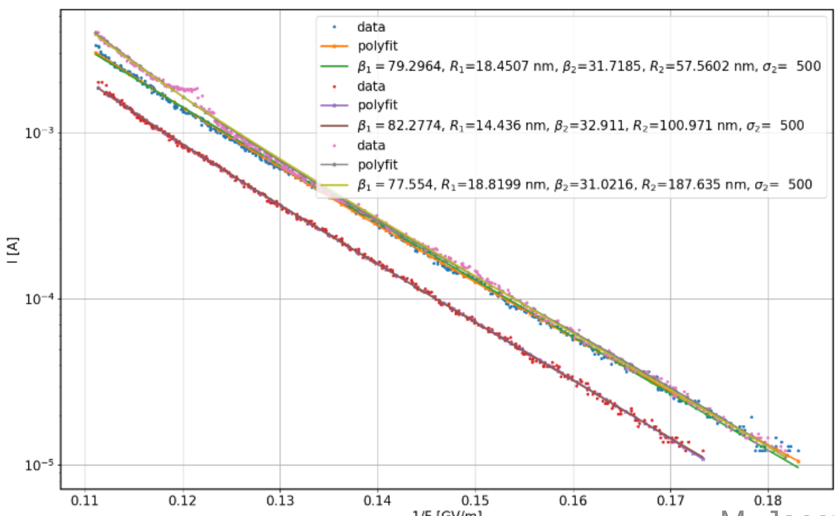


Field emission

Theoretical work started: Andreas Kyritsakis, Helsinki U.

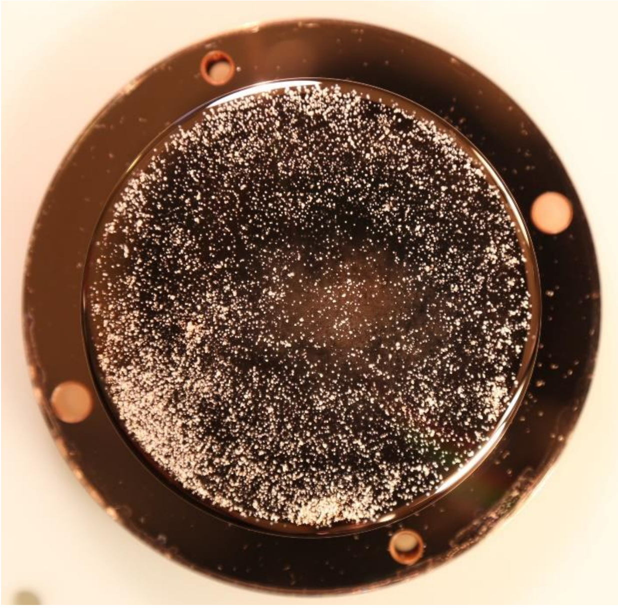


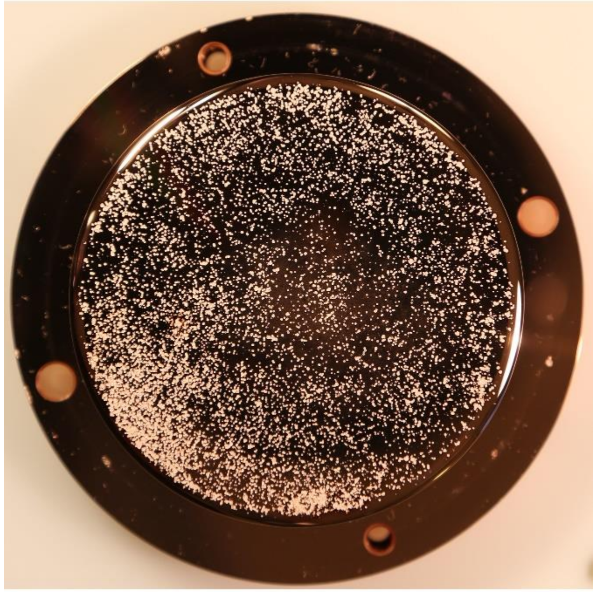
- New data consistent with hypothesis of one dominant emitter, surrounded by a "sea" of 500 small emitters with β~30 that get activated at high fields.
- This effect could explain the upward curvature for high currents.



Field emission at 60K after conditioning

Post-mortem photographs





Anode

Cathode (flipped to match)

Outlook

RF-based resistivity measurement of metal electrodes: J. Paszkiewicz/S. Calatroni and D. Dancila

- Is movement of dislocations in the crystal structure **the** underlying mechanism for breakdown phenomenon?

- Change in resistivity before and after conditioning process would give us a way to quantify movement of dislocations

- How? Use electrode system as resonance cavity and induce a high frequency (at GHz - skin depth < μm) current in the electrodes that will only flow near the surface exposed to high fields and affected by dislocations

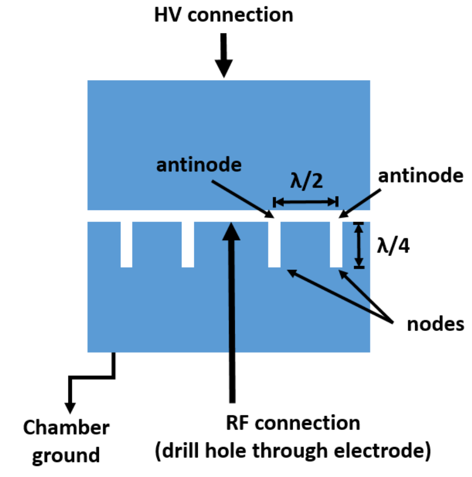
- Huge advantage of our system is the cryogenic environment since resistivity at low temperature is due only to dislocations, vacancies, impurities and all possible material defects.

Outlook

RF-based resistivity measurement of metal electrodes

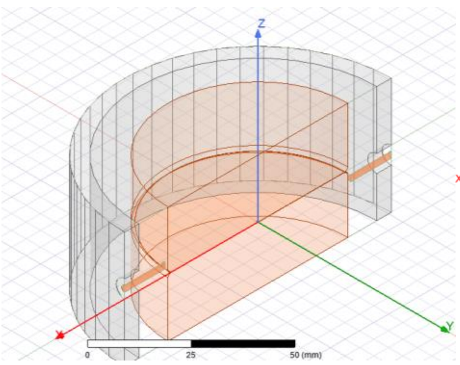
<u>First idea for CERN DC system</u>

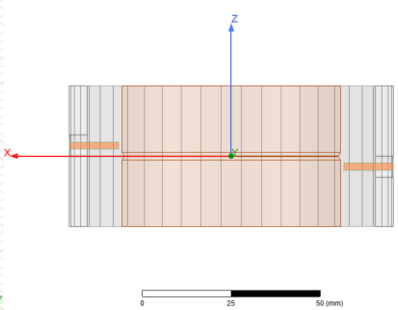
- Design should keep a resonant mode confined within the gap without a side wall so that the system will still function at DC.
- Propose the use of an RF choke (or two-choke)
- Only one electrode needs to be modified
- Challenging design of coupler

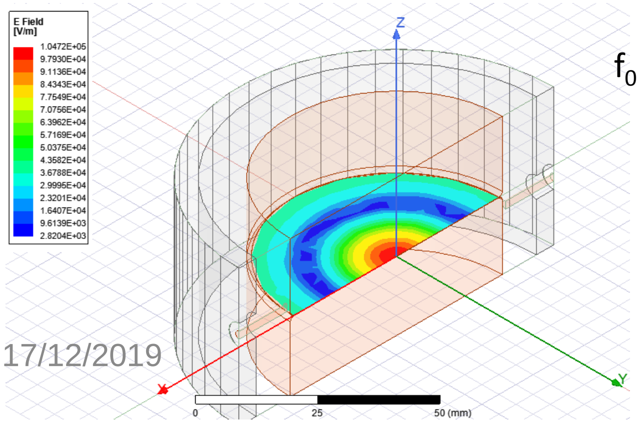


<u>The Cryo DC system is more open, more flexibility in feeding the RF</u>

Simulations show that with coaxial feeding it is possible to excite resonance modes in regular electrode arrangment. We observe then very high RF fields between the electrodes.







f_0 = 6 GHz

Outlook

Possible improvements

Reaching lower temperature (presently 17K)

- reduce mass of the electrode system
- extra radiation shields e.g. sheets of aluminum foil
- introduce additional cooling with LN
- … ?

Improved cleanliness, important for superconducting material like niobium

1) Electrode assembly in class 100 clean room in Ångström lab
2) Transport of an assembled electrode setup between Ångström clean room and Freia in vacuum container
3) Tent with unidirectional airflow built around the cryo-dc stand where we would open the vacuum container and make the final assembly

Summary

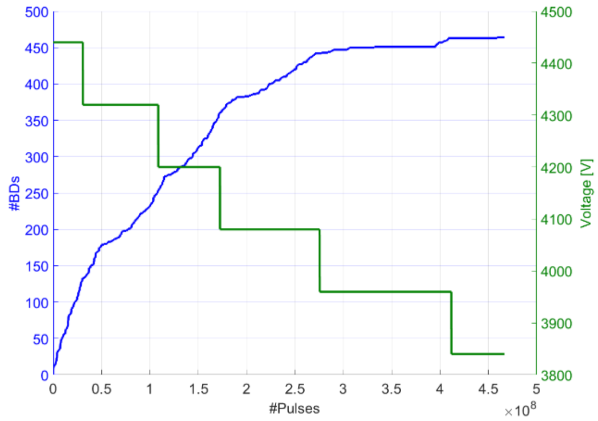
- Successful construction and commissioning of the cryo DC system
  - Two sets of Cu electrodes tested
  - Operation in wide temperature range down to ~20K
  - Set for field emission and BDR measurements
- Preliminary results indicate:
  - Higher (25-30%) gradient can be reached at 30K/60K/90K wrt 300K
  - Different field emission behaviour depending on used procedure, do we condition the surface with voltage ramping ?
  - Conditioning affects FE properties significantly at cryo temperatures. Theoretical studies in progress
- Flexible construction, ready for test with other materials/setups
  - E.g. RF-resistivity measurement

Thank You for attention!

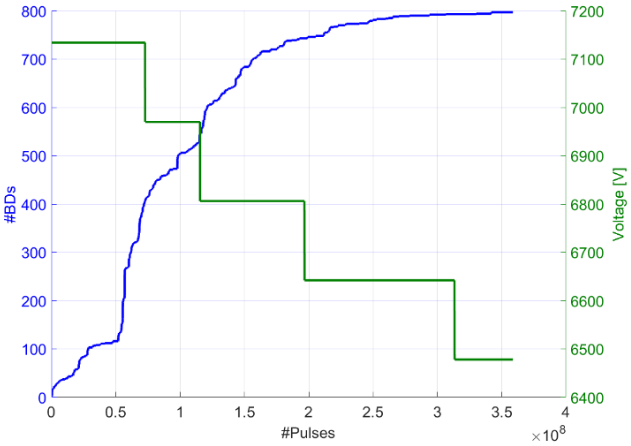
Breakdown rate

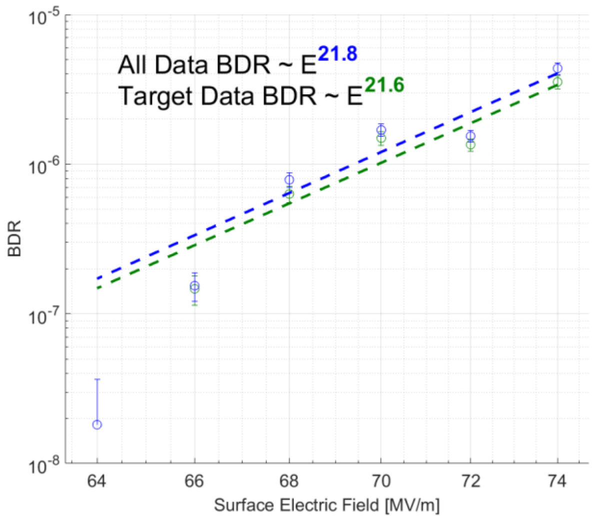
runs at constant field (flat mode) with recovering after BD

Flat mode → room temperature



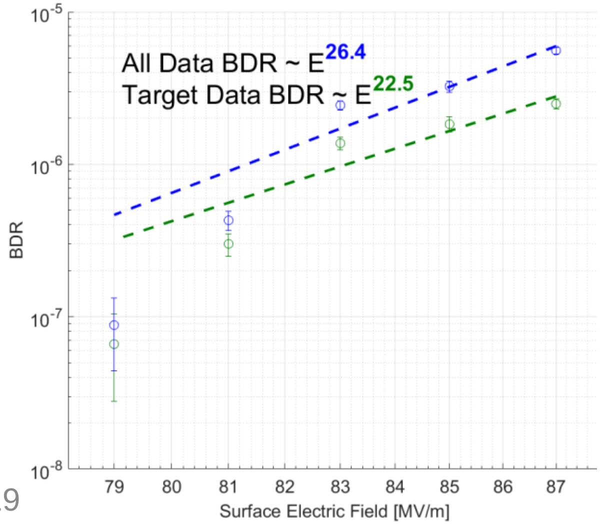
Flat mode → 30K



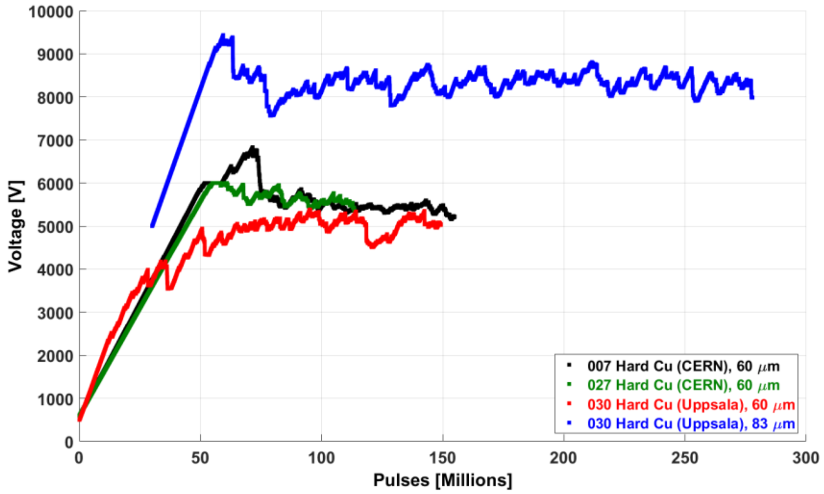


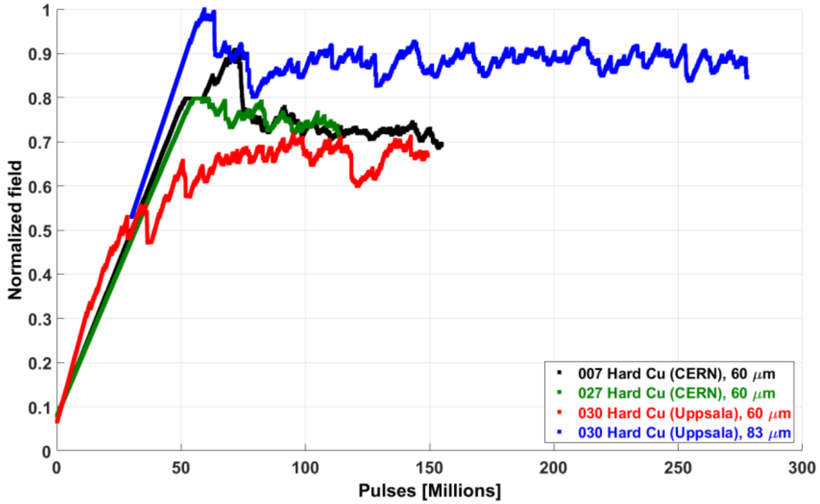
Power law fit

$$BDR \propto E^{30}\tau^{5}$$



Drop in field at 30K





Also observed previously in experiments at room temperature at CERN

Working at very high voltage, close to max specs is strenuous for the system and could have some effect

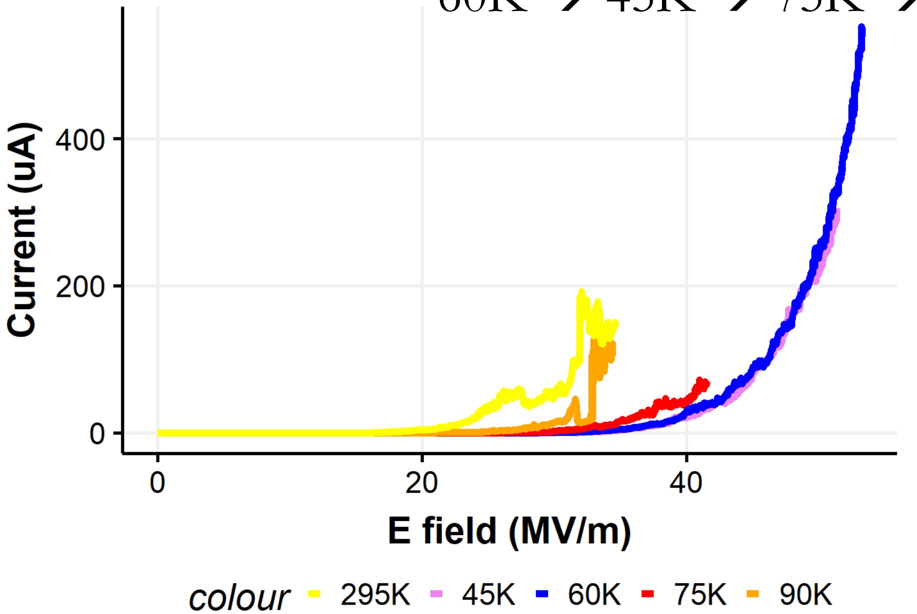
We plan to reduce the gap size to avoid these problems

Field emission

Electrodes conditioned at 60K and left for 1 week in vacuum

Temperature scan <u>without</u> re-conditioning

60K → 45K → 75K → 90K → 300K



Timeline ↓

blue → 60K
violet → 45K
red → 75K
orange → 90K
yellow → 300K

Cooling down preserves the hardened state of material
Warming up destroys arrangements → already +15K current is unstable