Preliminary experimental evidence for the protrusion hypothesis on CuO forest

Sven Oras, Salvador Barranco Cárceles, Andreas Kyritsakis, Sergei Vlassov, Veronika Zadin

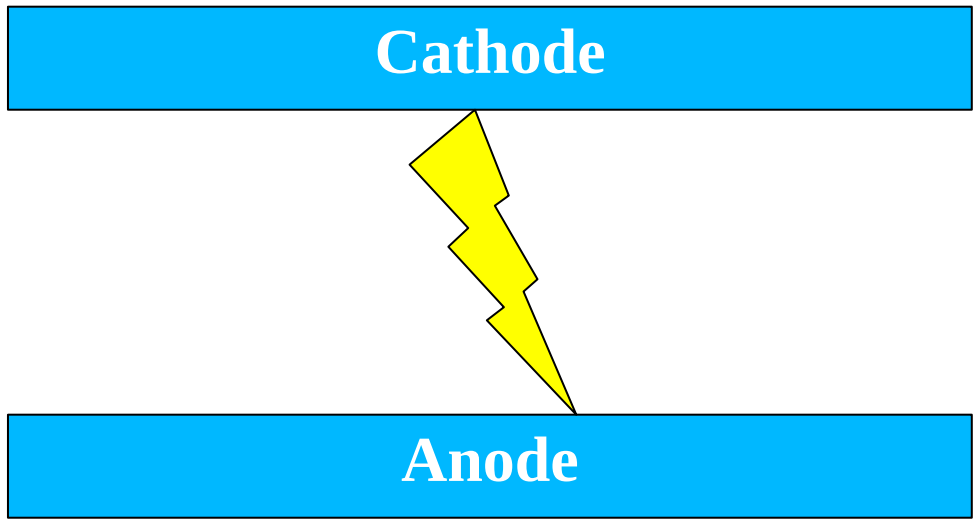
Tartu University, Institute of Technology

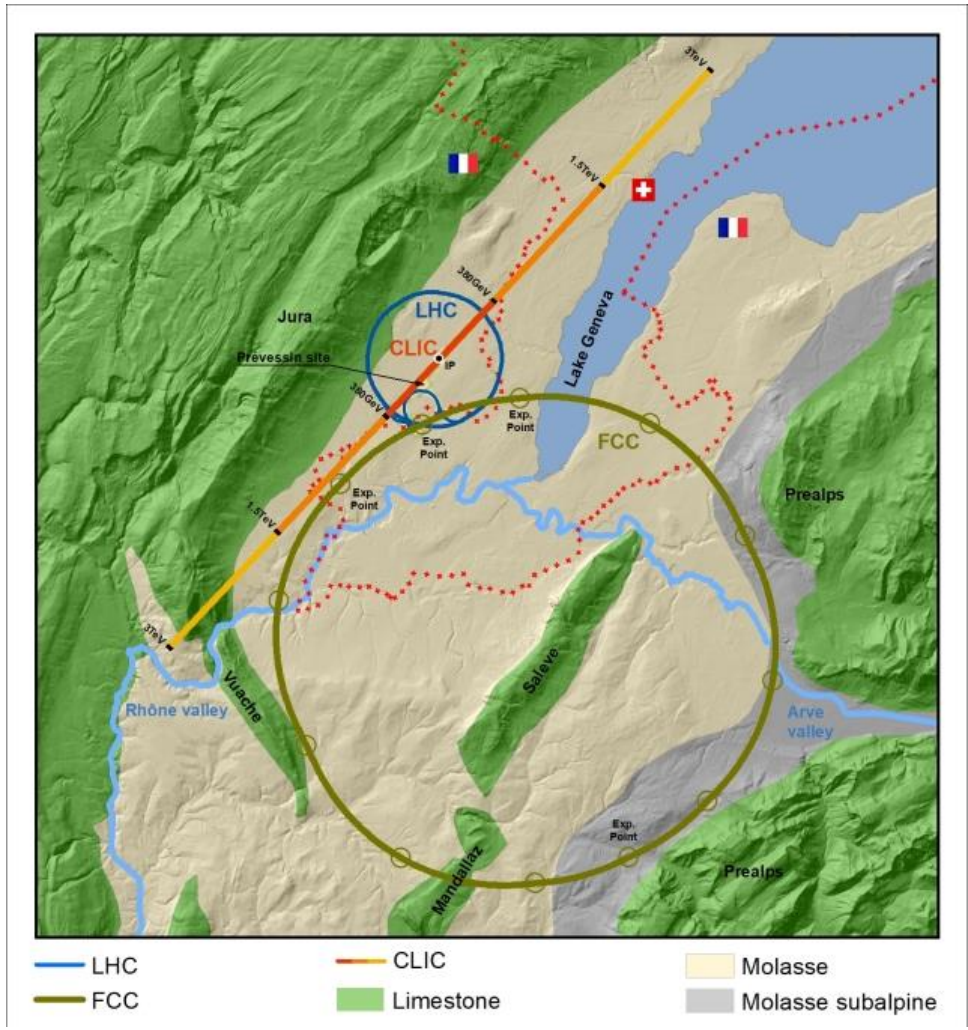
MATTER

CERN, 11.10.2023

Introduction

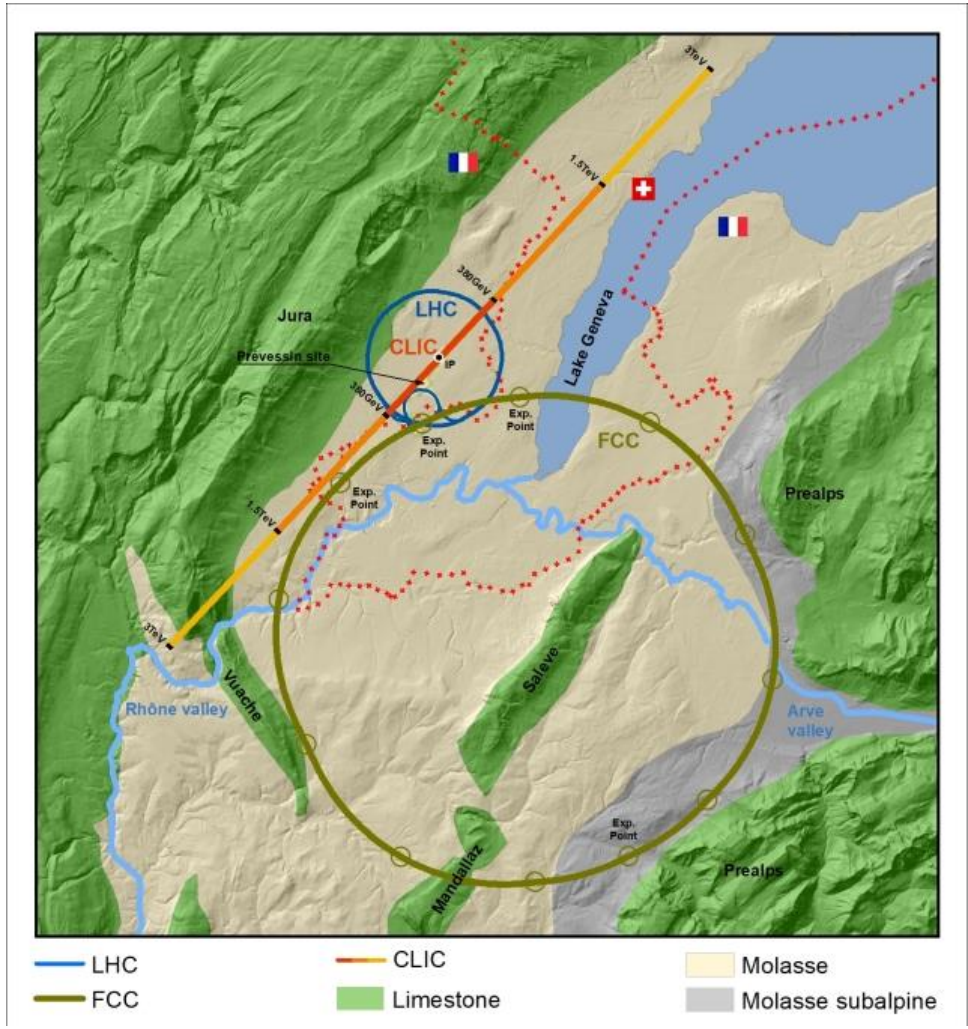
- Our collaboration is with CLIC and FCC
- We deal with the vacuum breakdown phenomenon present in linear accelerators (not only problem in particle phyics).





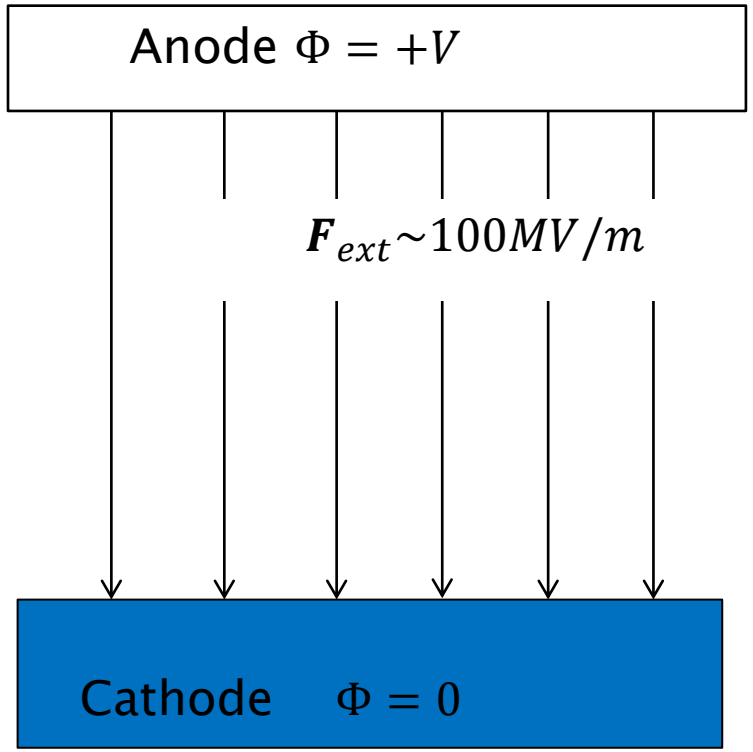
Introduction

- Our collaboration is with CLIC and FCC
- We deal with the vacuum breakdown phenomenon present in linear accelerators.
- There are a few hypothesis how breakdowns happen.
  - Dislocations reaching the electrode surface
  - Plasmons on the surface
  - **Formation of nanoprotrusions**

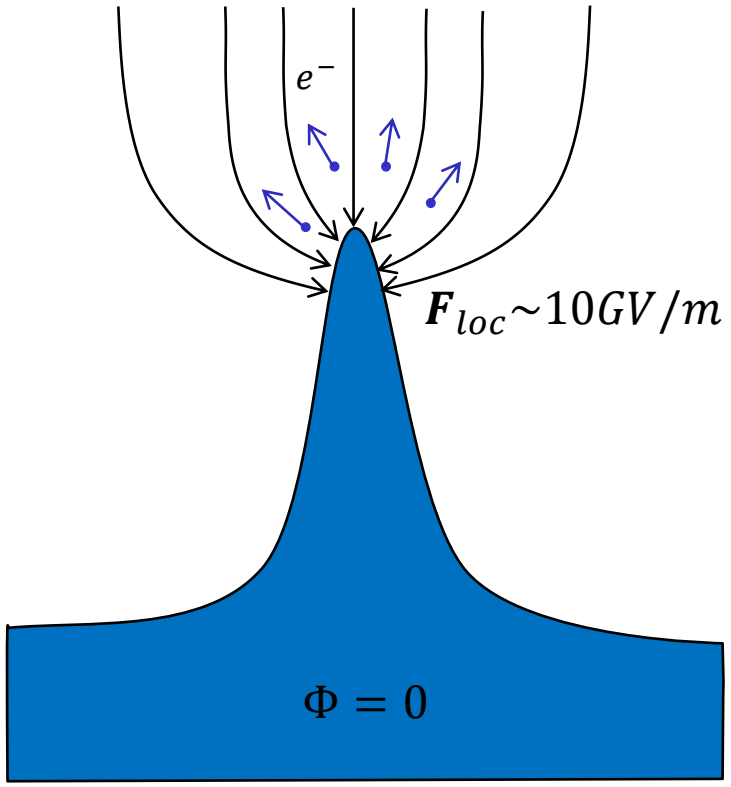


Vacuum breakdown

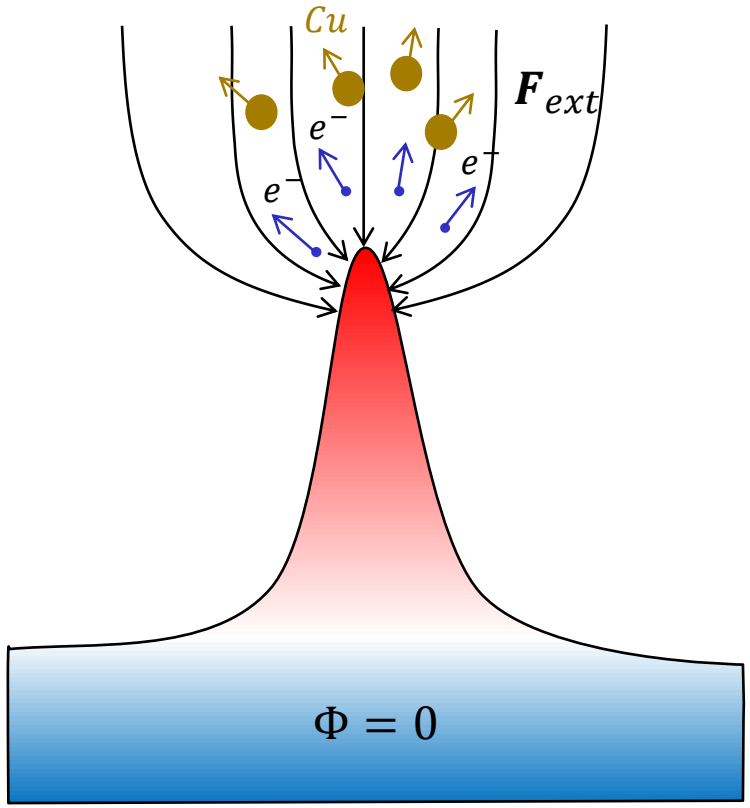
Stage 0: Flat surface



Stage 1: Field emission



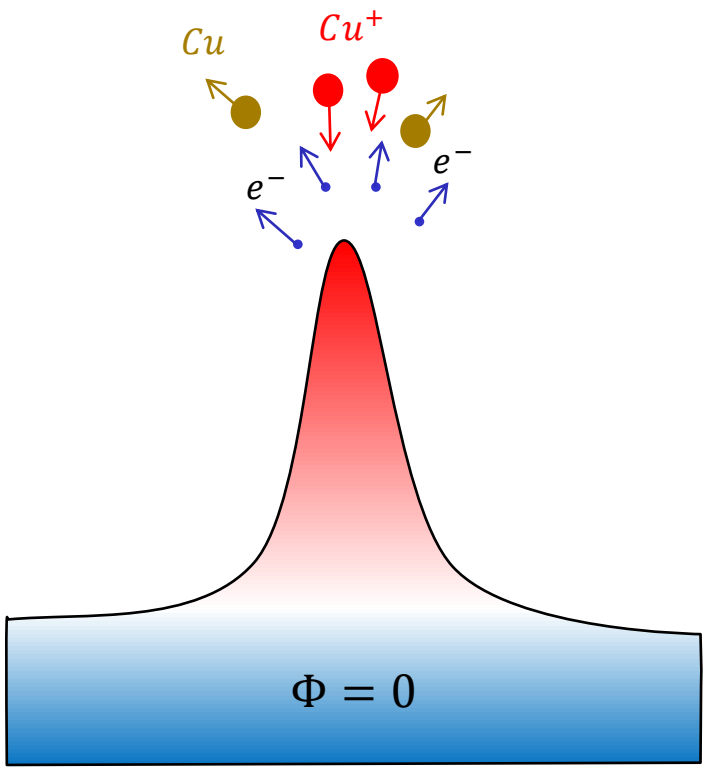
Stage 2: Field emitter
Thermal Runaway



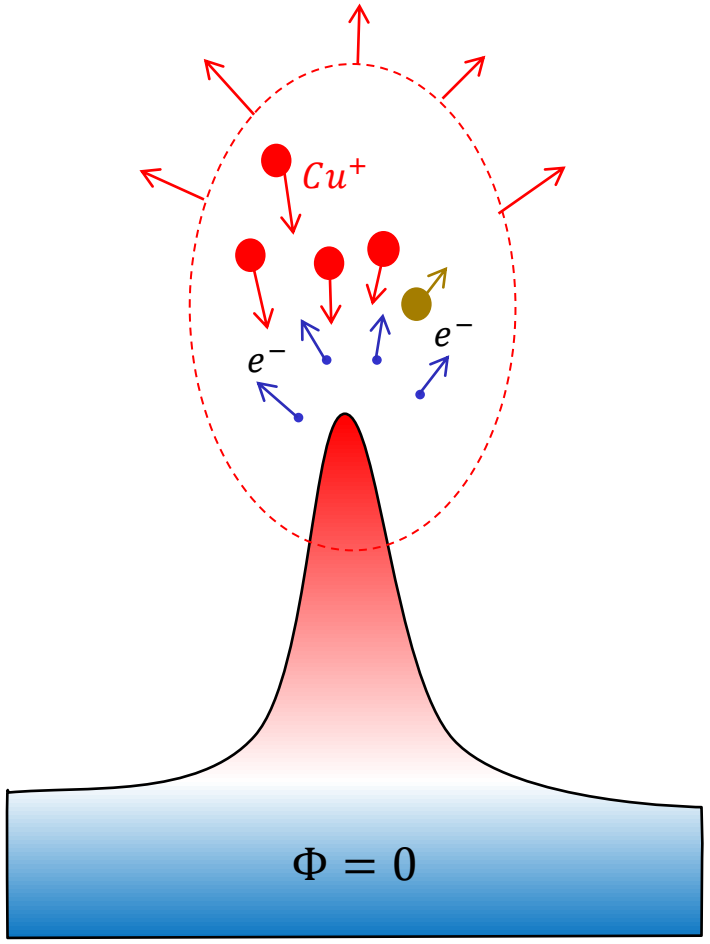
Images by Andreas Kyritsakis

Vacuum breakdown

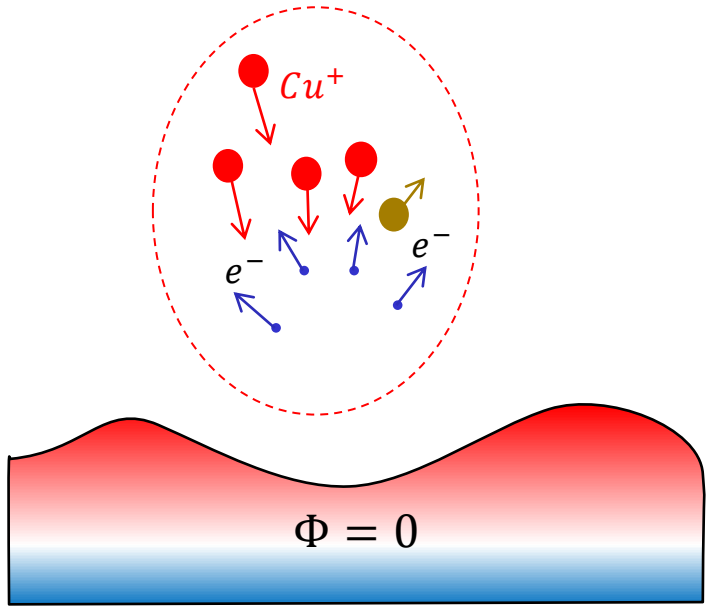
Stage 3: Ionization runaway & Plasma onset



Stage 4: Plasma expansion



Stage 5: Burning arc, crater formation



Images by Andreas Kyritsakis

Problem

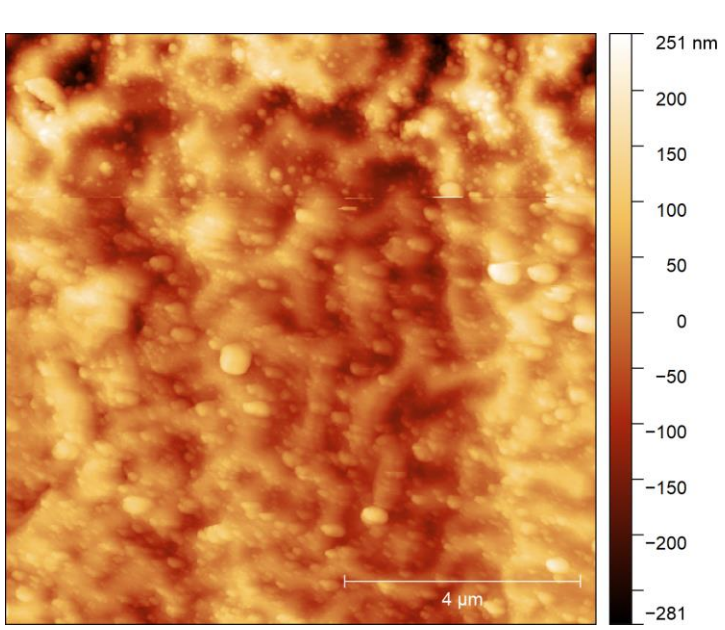
We don’t know yet if the protrusions exist as nobody has seen them.

We try to find them.

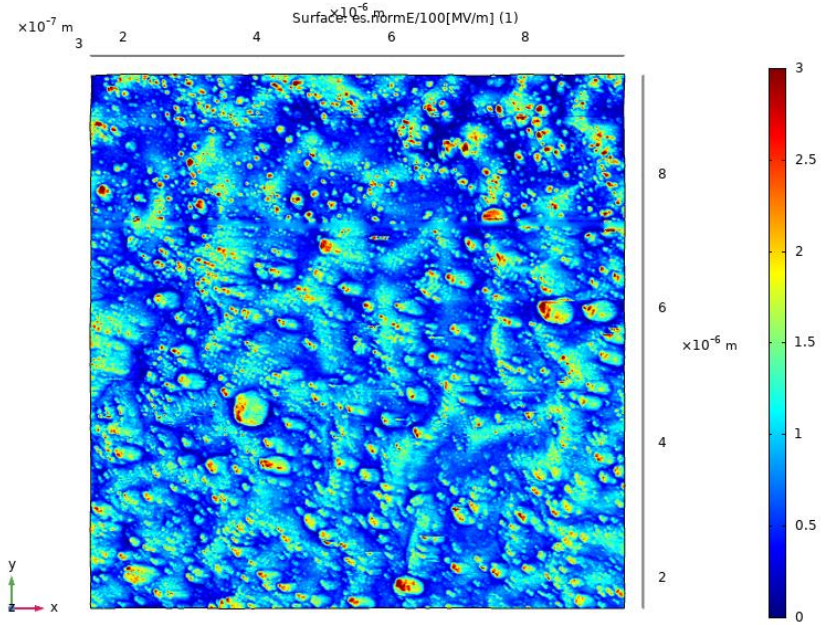
But how to see them?

Previous experiments

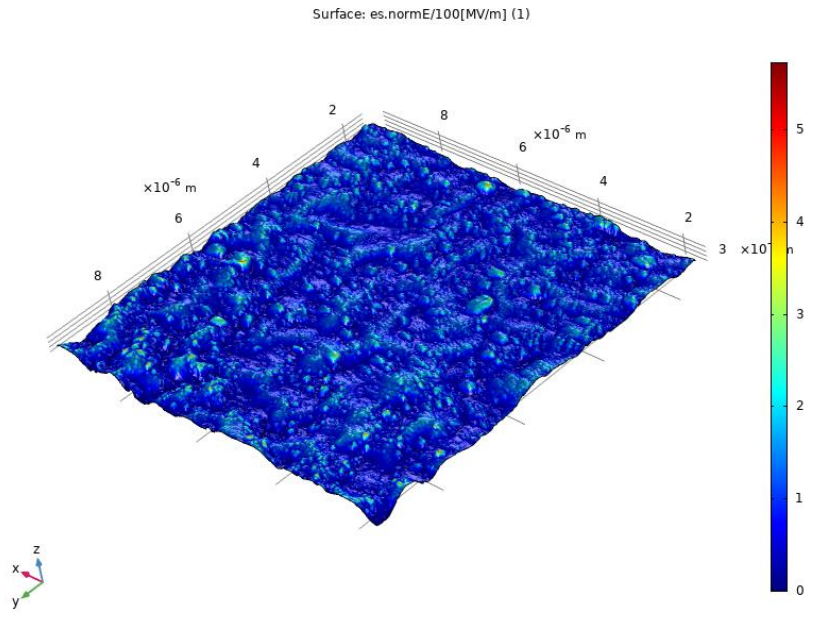
Field enhancement up to 5 times due to topology.



Topography image



Field enchancement capped at 3



Field enhancement modeling

Previous experiments

- Previous experiments were done in Uppsala.
- A needle and a flat sample inside SEM and a tungsten tip is approaching the Cu sample.
- Field emission is mesured.

- No proof of protrusions was found.

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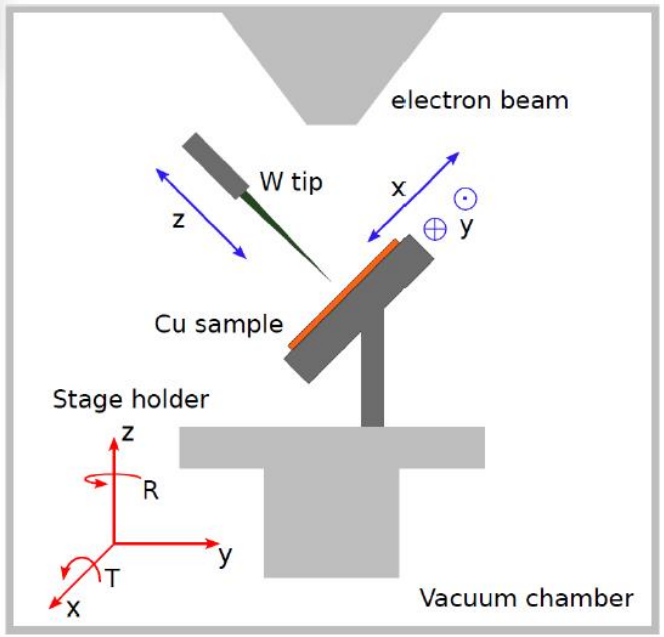
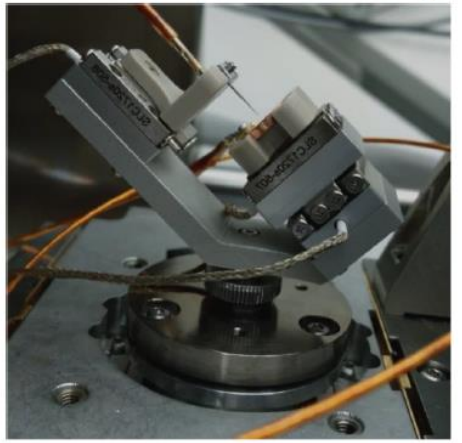
In-SEM Setup





Stage
W tip, radius of curvature 5 µm
nm precision piezo-motors

Environmental SEM
Field emitting gun, 10-30 kV
Vacuum ~7×10^{-5} mBar

Keithley 6517a Electrometer
FE currents from sub-pA to mA
Applied V = up to 1 kV, 50 Hz

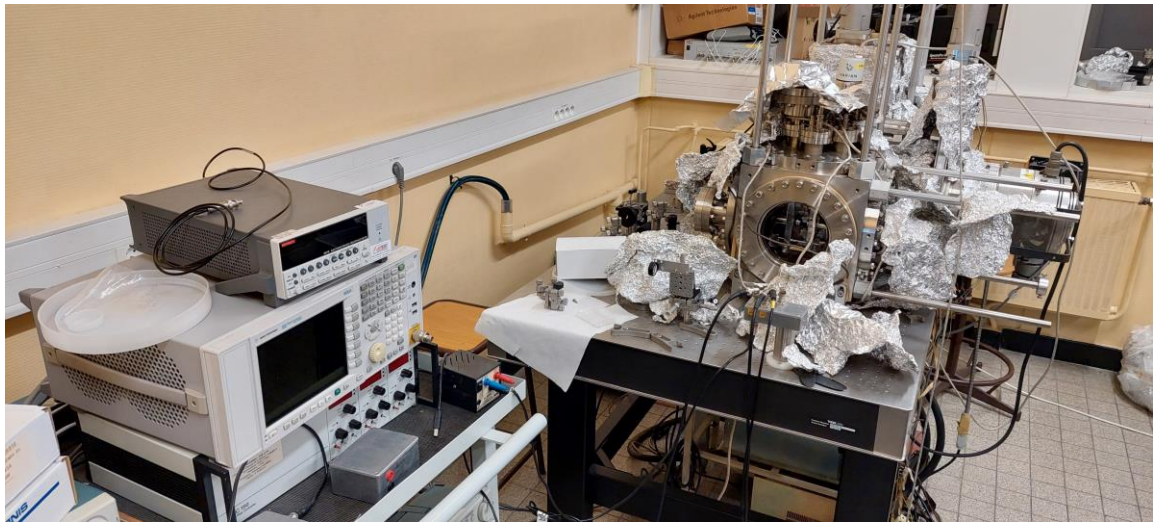
Typical gap distance → 700 nm
Surface search procedure:
Low voltage, approach surface in steps (2 nm) while measuring current until threshold breech (done 2 times just left and right to the area-of-interest)

3

Slide from MeVArc 2018, *Marek Jacewicz*

Setup in Lyon

- There is a similar setup in Lyon at Claude Bernard University Lyon 1
- We went there to do get to know the setups and plan future experiments.



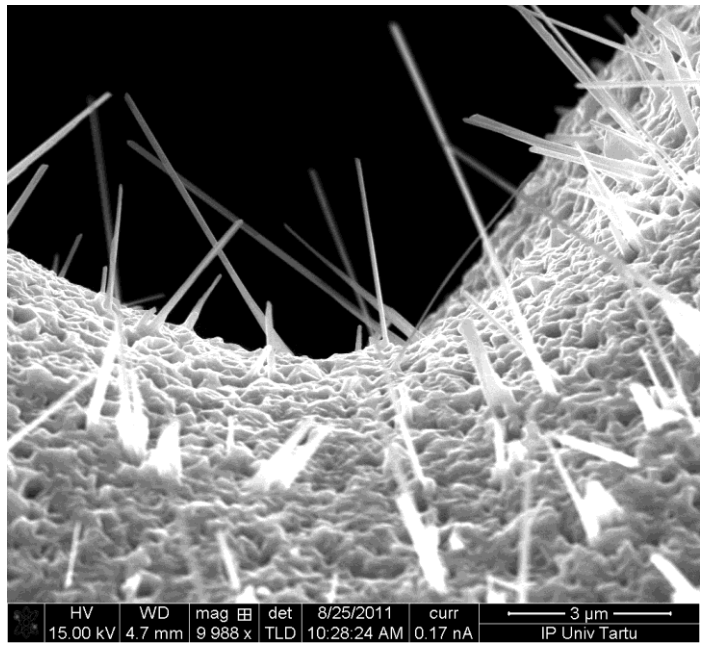
Growth of CuO nanowires

CuO NWs can be synthesized by heating Cu in air. **Nano Lett., Vol. 2, No. 12, 2002**

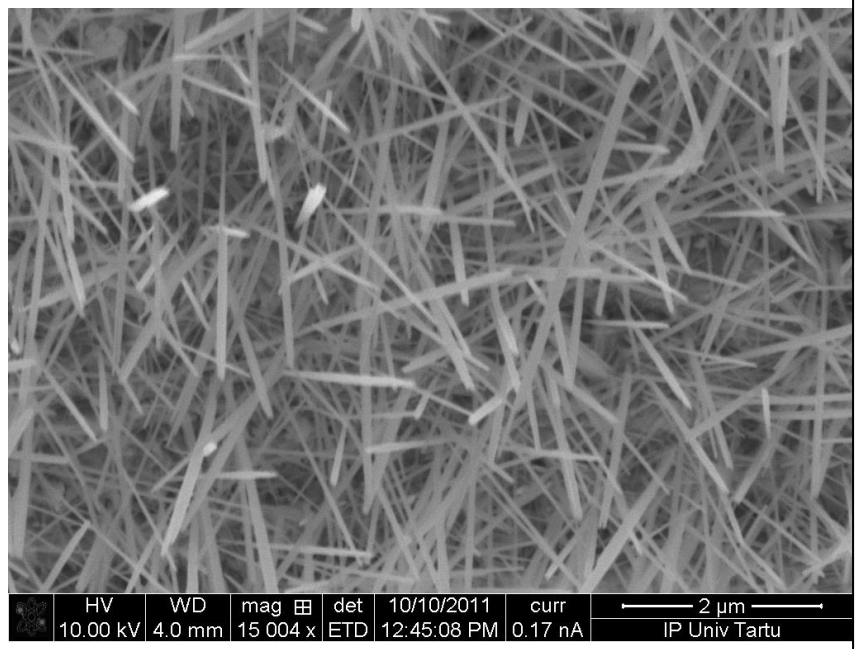
Temperatures 400°C-700°C results in NWs.

Higher temperatures produces particles.

Copper Oxide



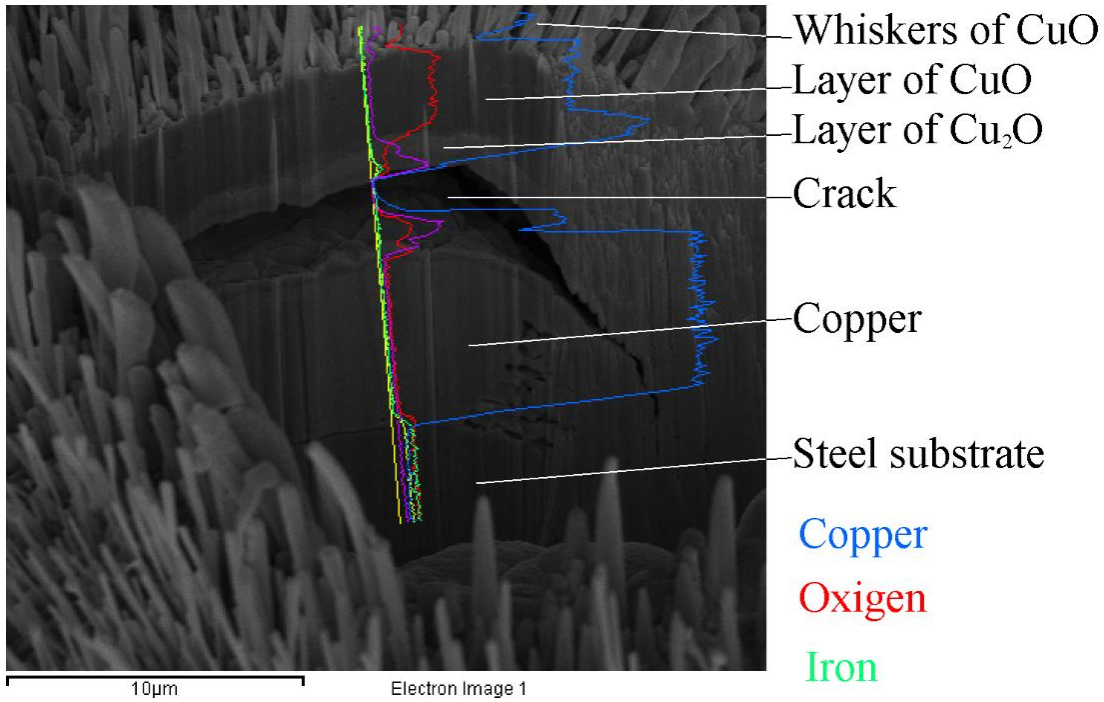
Tungsten Oxide

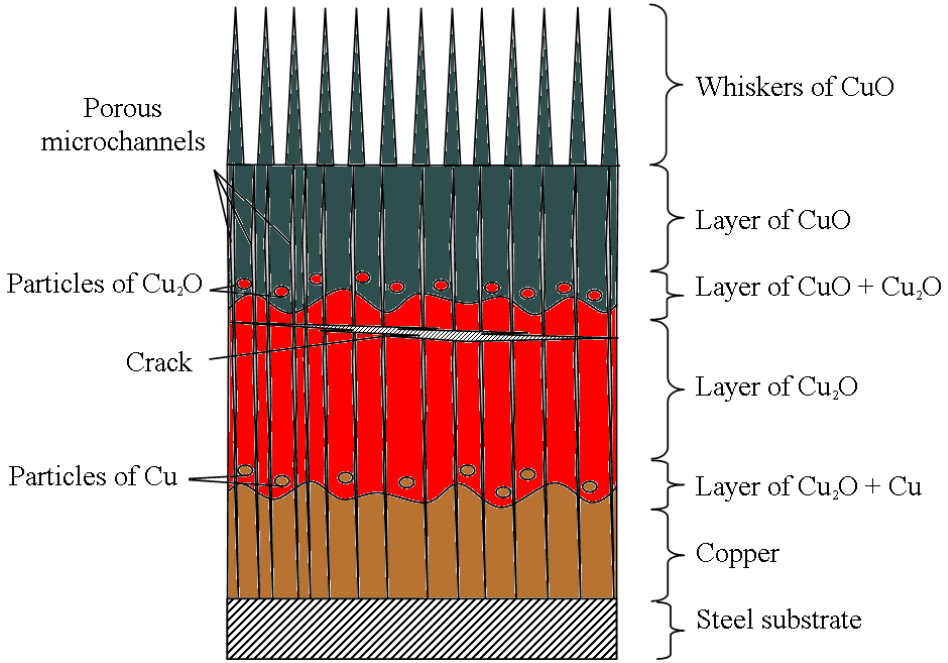


Cu sample with CuO nanowires:

inner structure after heat-treatment

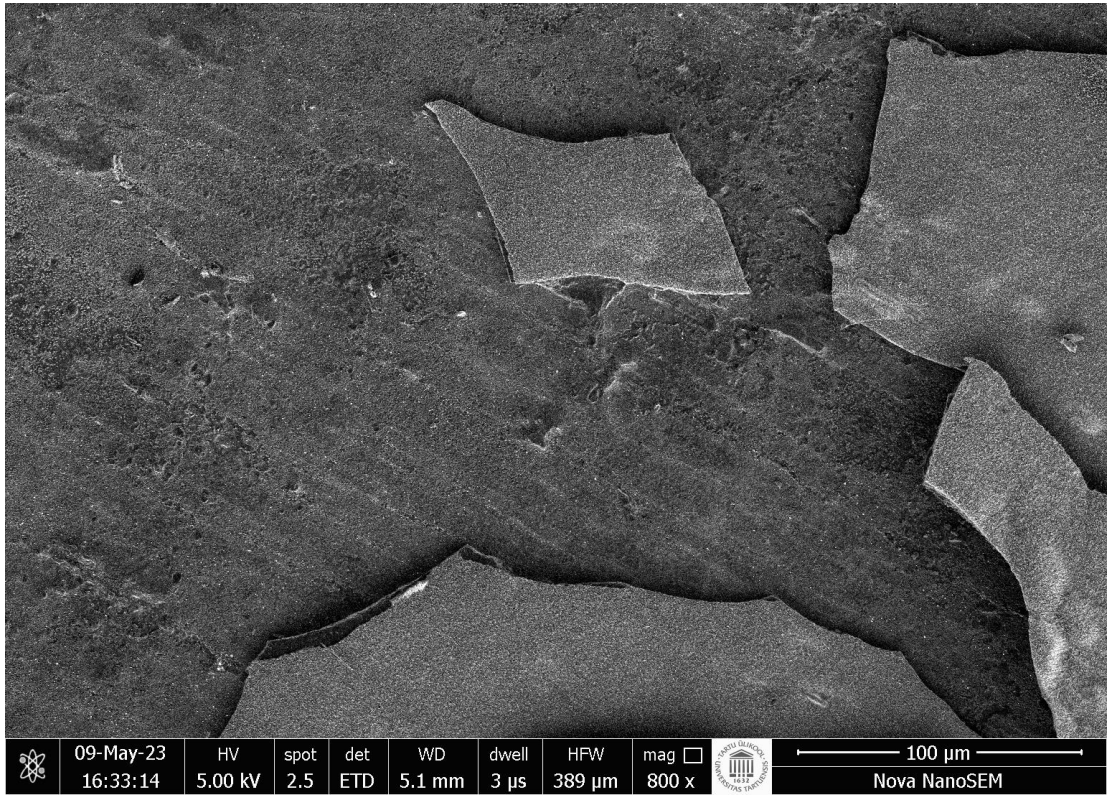
Cut by FIB, analysed by EDX (NSFL, IPUT)

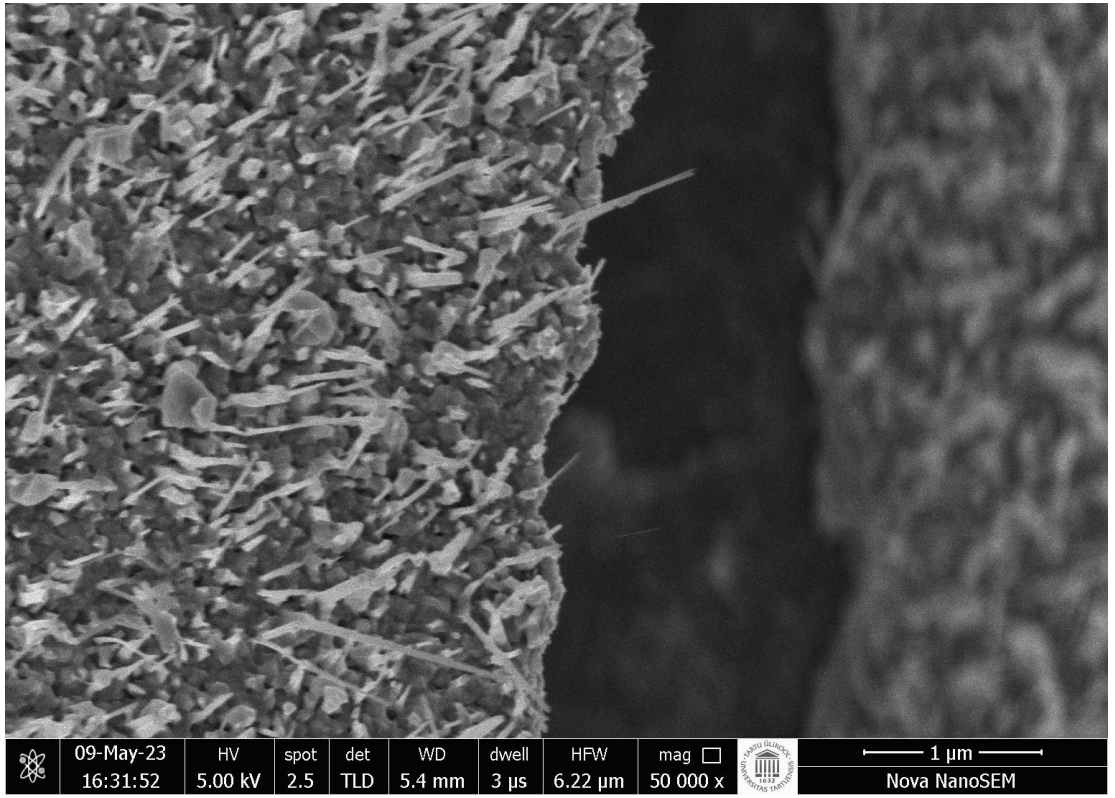




Dorogov, et. al, Appl. Surf. Sci. ***246****, 423 (2015).*

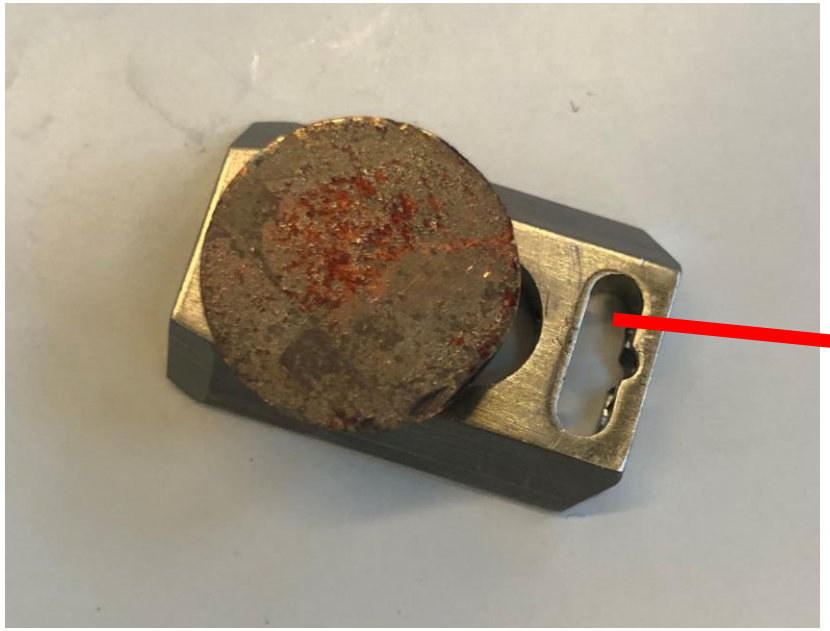
Cu samples

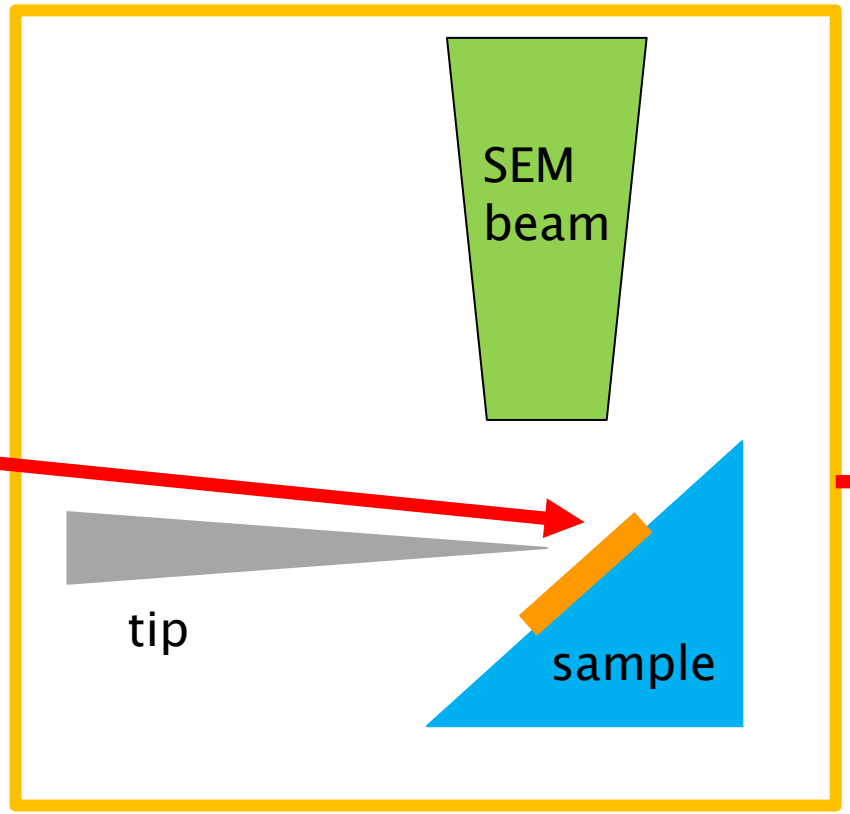

09-May-23
16:33:14
HV
5.00 kV
spot
2.5
det
ETD
WD
5.1 mm
dwell
3 µs
HFW
389 µm
mag
800 x
100 µm
Nova NanoSEM


09-May-23
16:31:52
HV
5.00 kV
spot
2.5
det
TLD
WD
5.4 mm
dwell
3 µs
HFW
6.22 µm
mag
50 000 x
1 µm
Nova NanoSEM

Setup

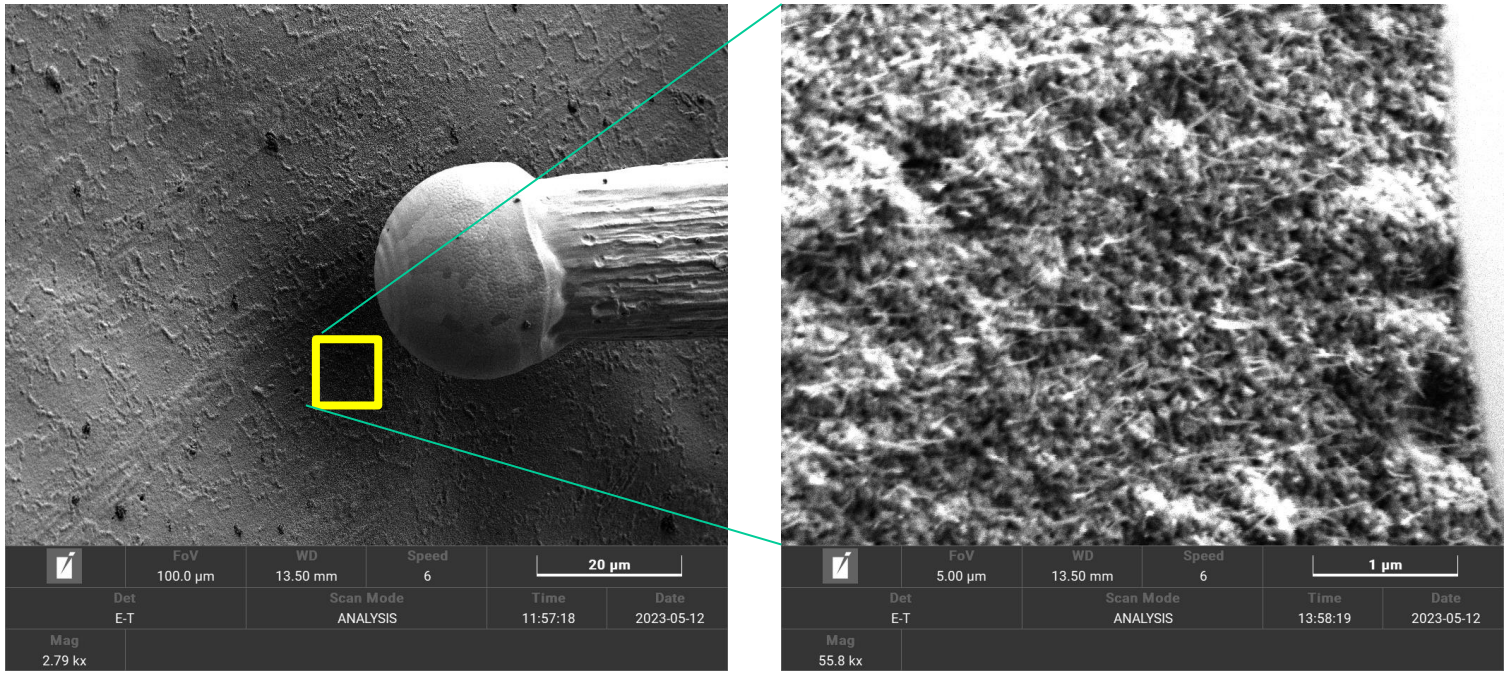
- Cu plate with CuO forest grown on it.

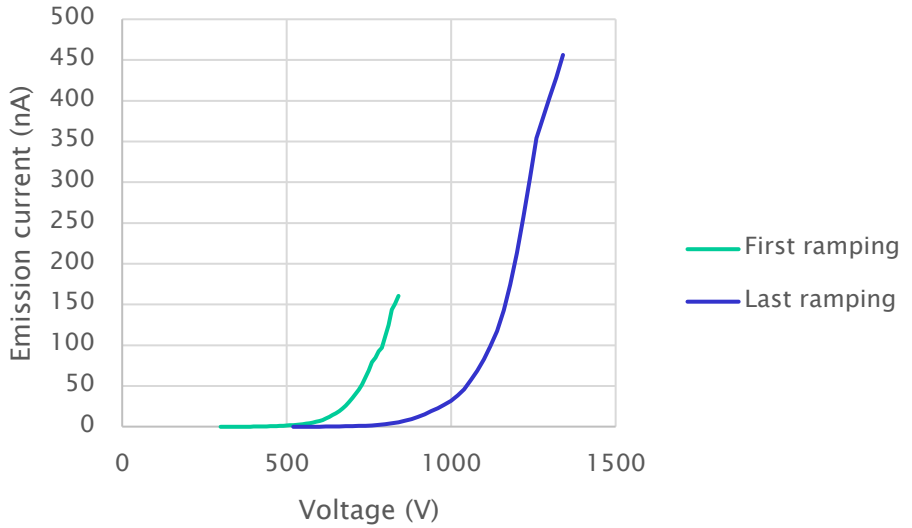




CuO forest

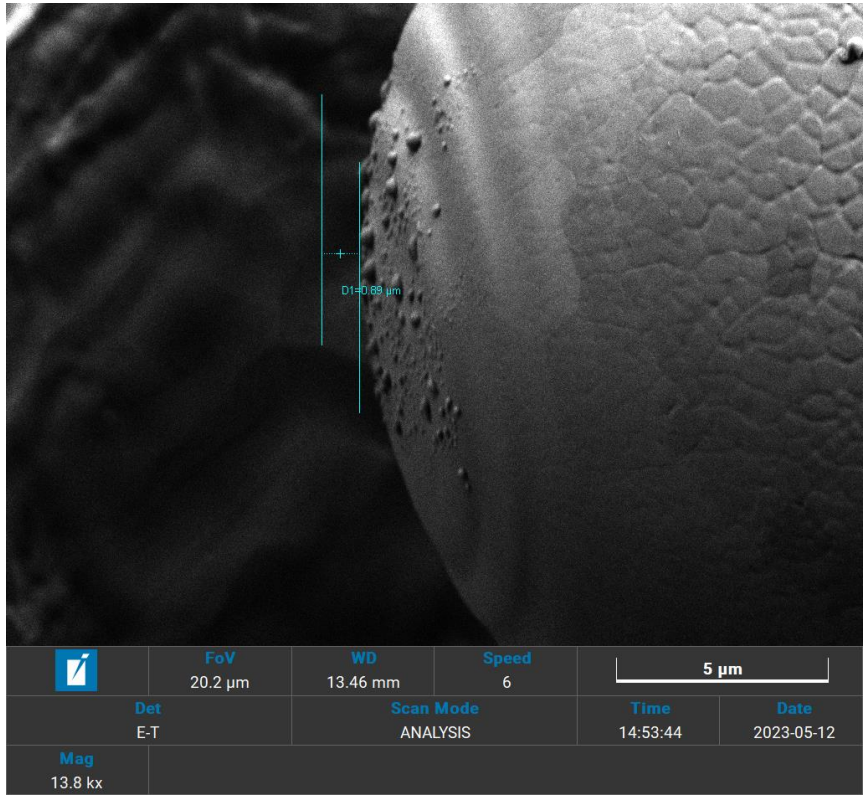
- Unexpectedly stable field emission all over the forest.
- Ramped up the voltage until breakdown ocurred.

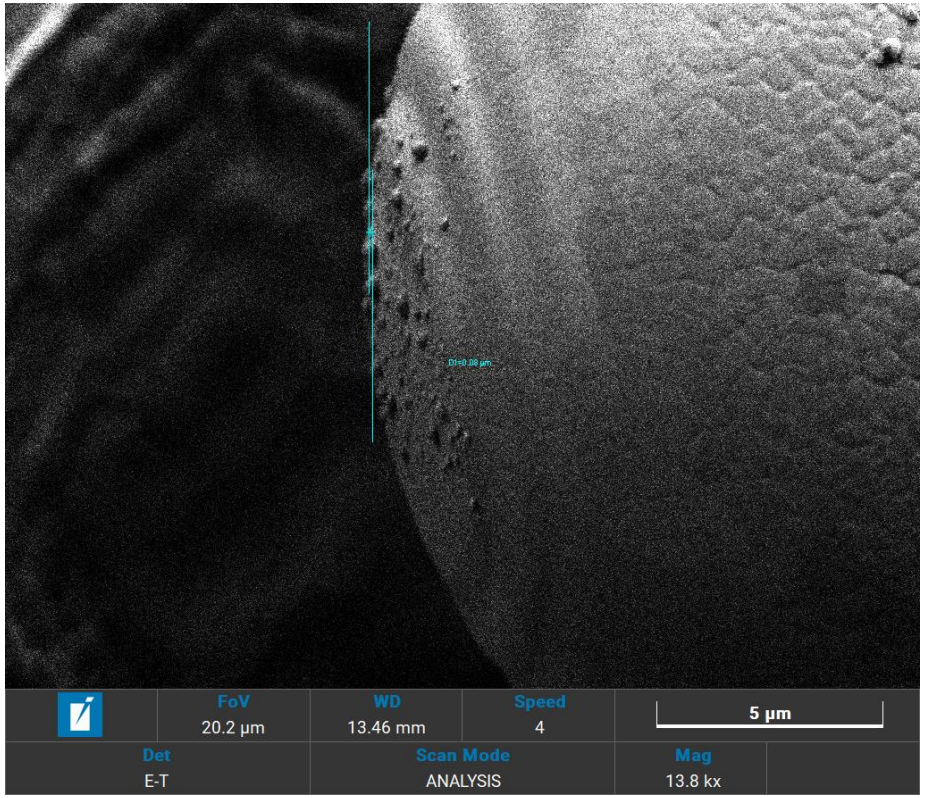


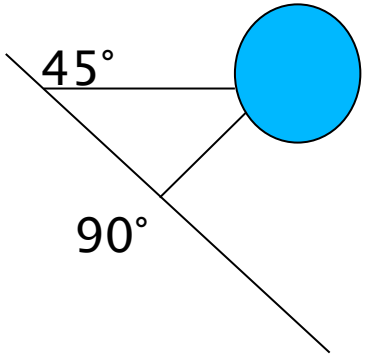


Estimating the distance

- No good way to get the field strength.
- We made some rough estimations in the next experiment.

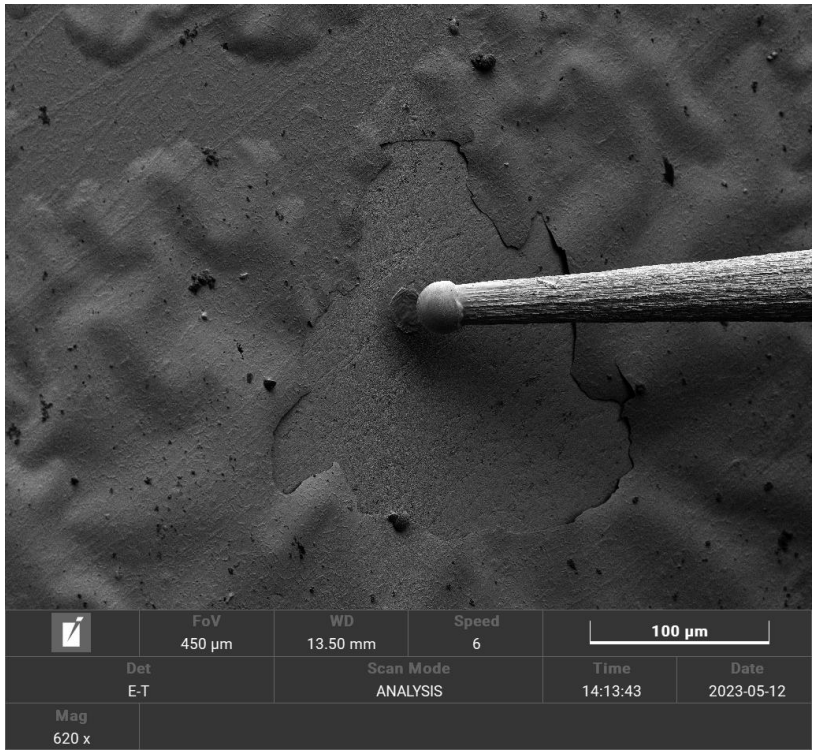


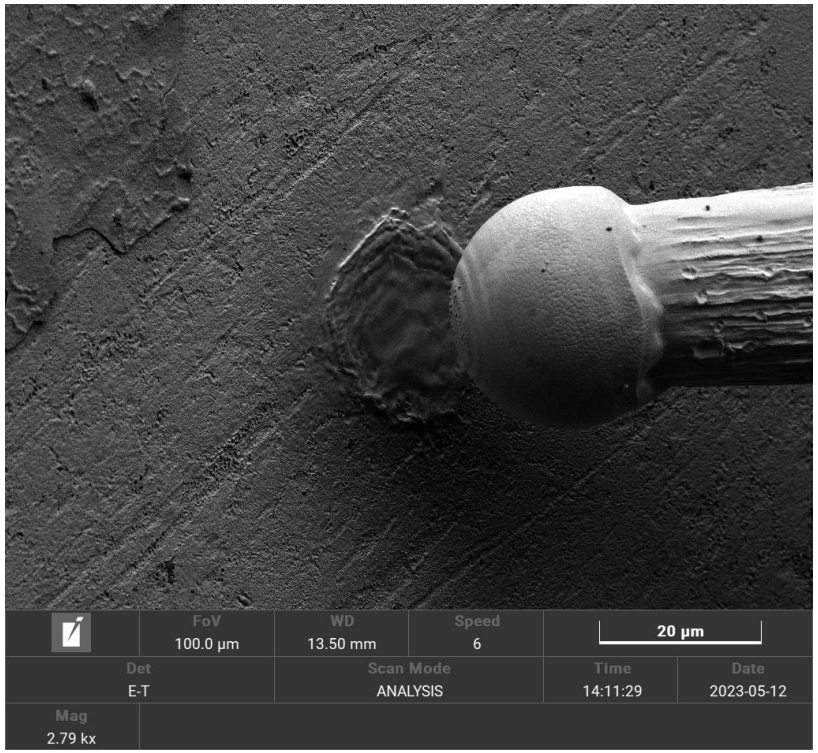


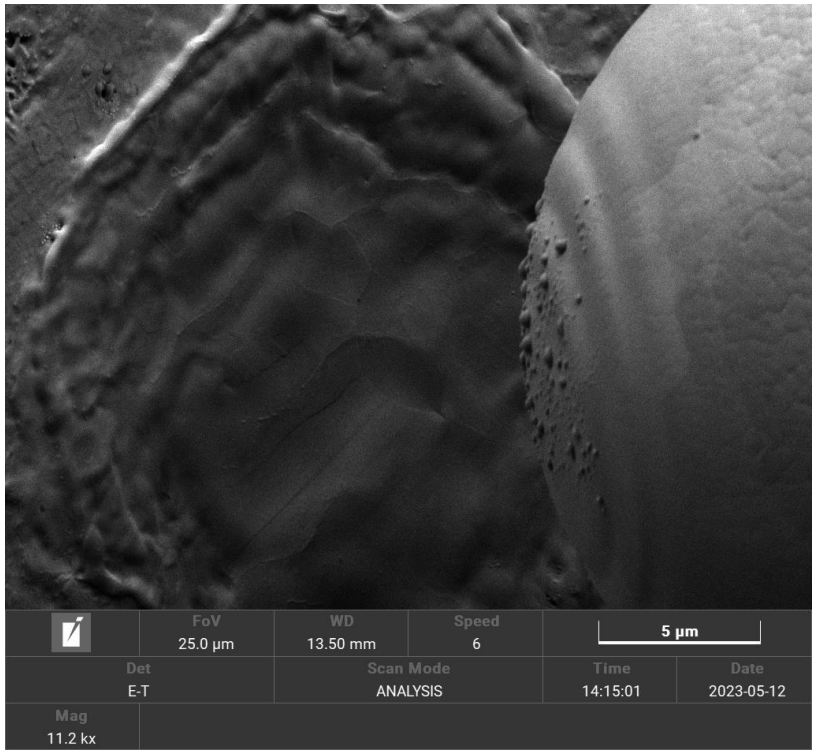


After breakdown

- Pieces of CuO layer is thrown away.
- Result is a fresh Cu surface.
- Now we went closer with same voltage.

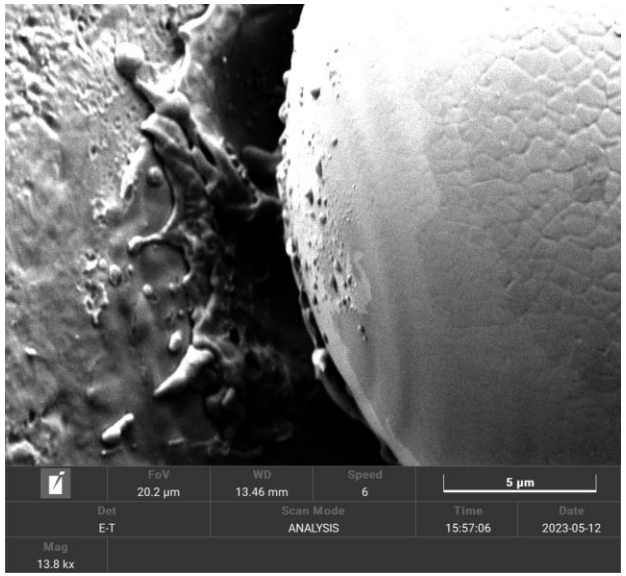


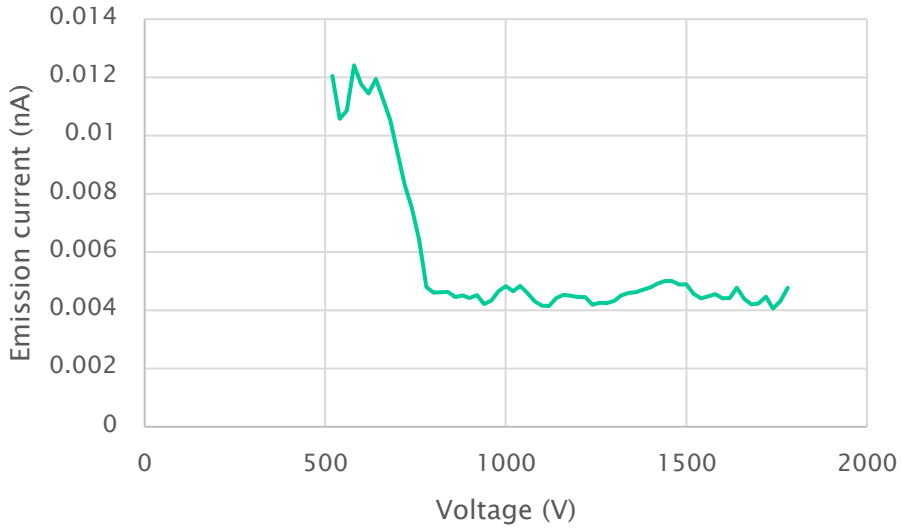




Breakdown on fresh Cu surface

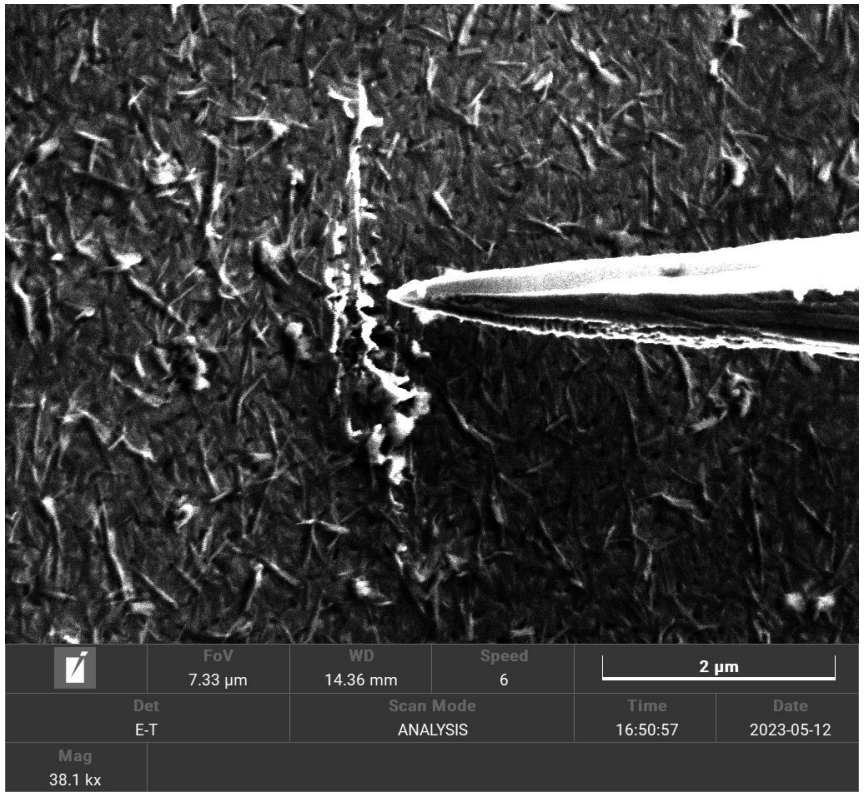
- We achieved no field emission or breakdown on fresh surface at first.
- Then we bumbed into the surface (by accident).
- We changed the conditions allowing for breakdown
- Theory: we probably introduced deformations (sharp tips and edges) on the surface.

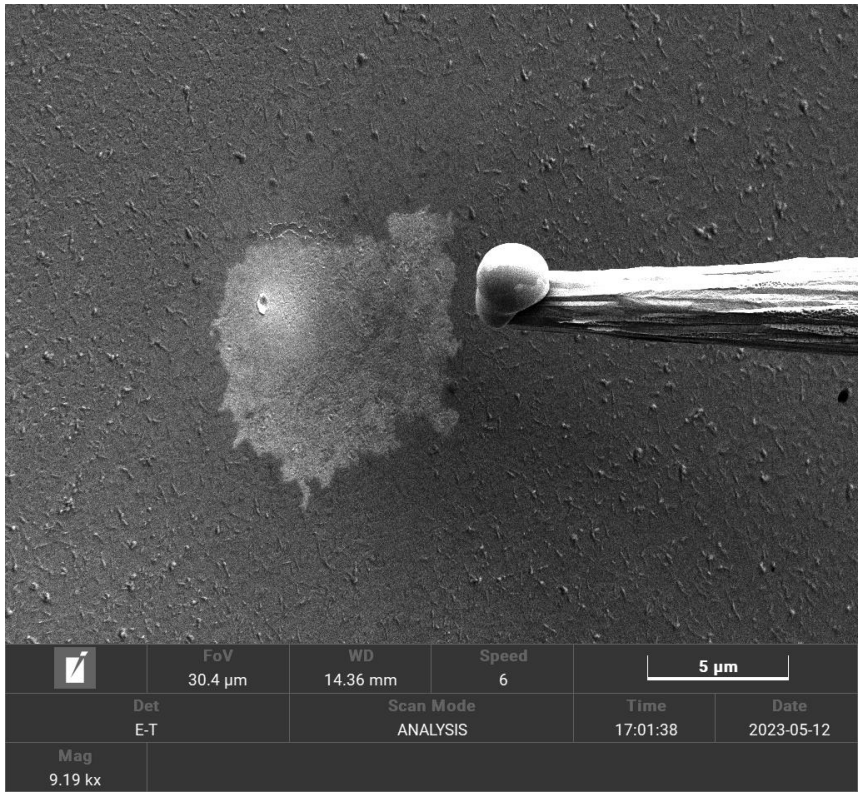




Old sample from CERN

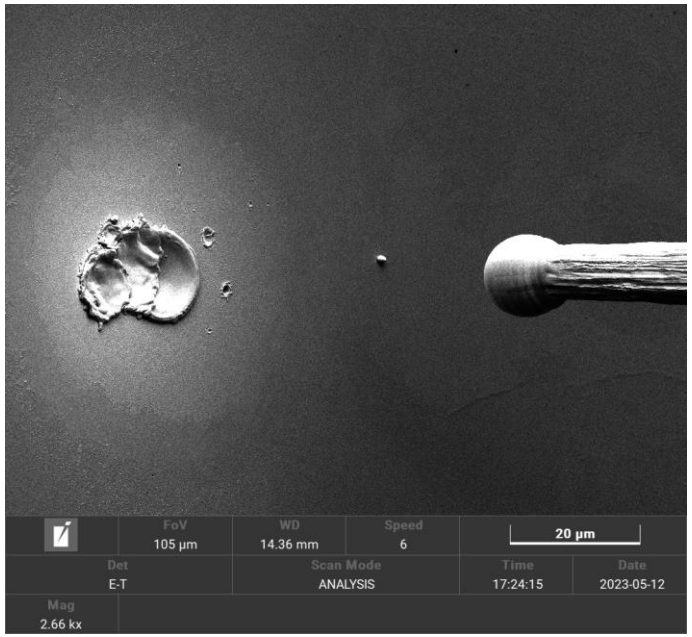
- We also had a Cu sample from CERN.
- Same type of Cu used in electrode production but very old.
- We had a little extra time, so we tried this sample as well with a new tip.

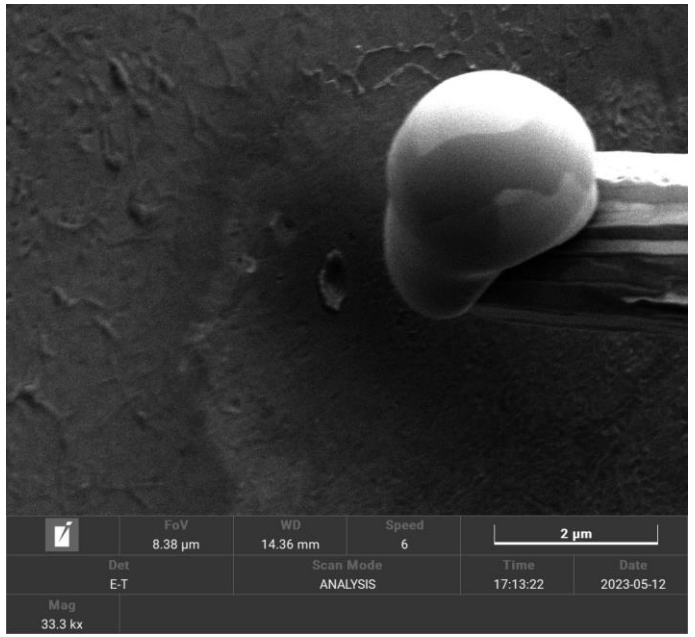


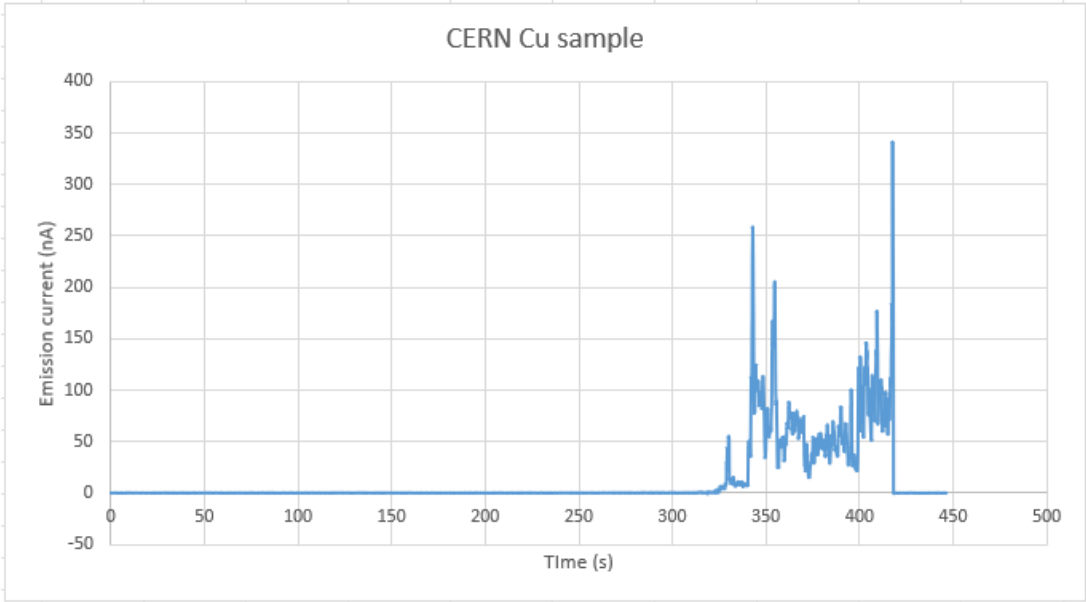


Breakdown on old sample

- Emission began right away and followed by breakdown.
- Probably due to the rough surface.





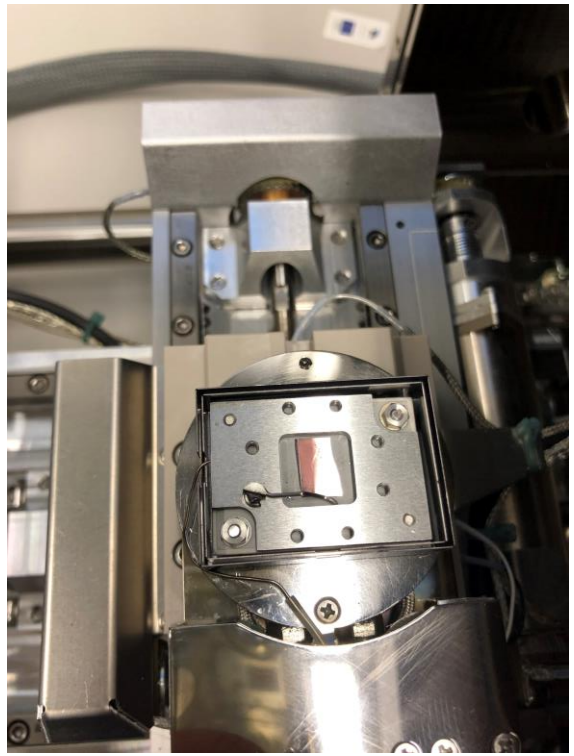


Summary & future plans

- CuO forest turned out to be a stable field emitter, but it is quite fragile.
- Cu surface on the same sample was a bad field emitter.

- We still don't know how (if) the protrusions grow.
- A forest of CuO nanowires on an electrode is unreasonable. A single wire?

- Future
- We can now try growing CuO wires in SEM vacuum and observe the growth in real time.



Achnowledgments

Thanks to the ILM team in Lyon.

ERA Chair ”MATTER”