Advances in Investigations of clean Nb surfaces

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- Motivation
- Enhanced field emission of Nb surfaces
- Preparation and measurement techniques
- Statistical distribution of field emitters
- FE properties and nature of emitters
- Conclusions and outlook

Motivation

- Accelerating fields E_{acc} in SC Nb cavities are limited by NC defects and protrusions and surface impurities

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local quenches   electron loading due to field emission

- Improved Nb purity and surface preparation techniques are required to achieve E_{acc}>25 MV/m at $Q_0>10^{10}$ reliably
- Advanced surface investigation of clean Nb samples by profilometry, scanning FE microscopy and SEM/EDX

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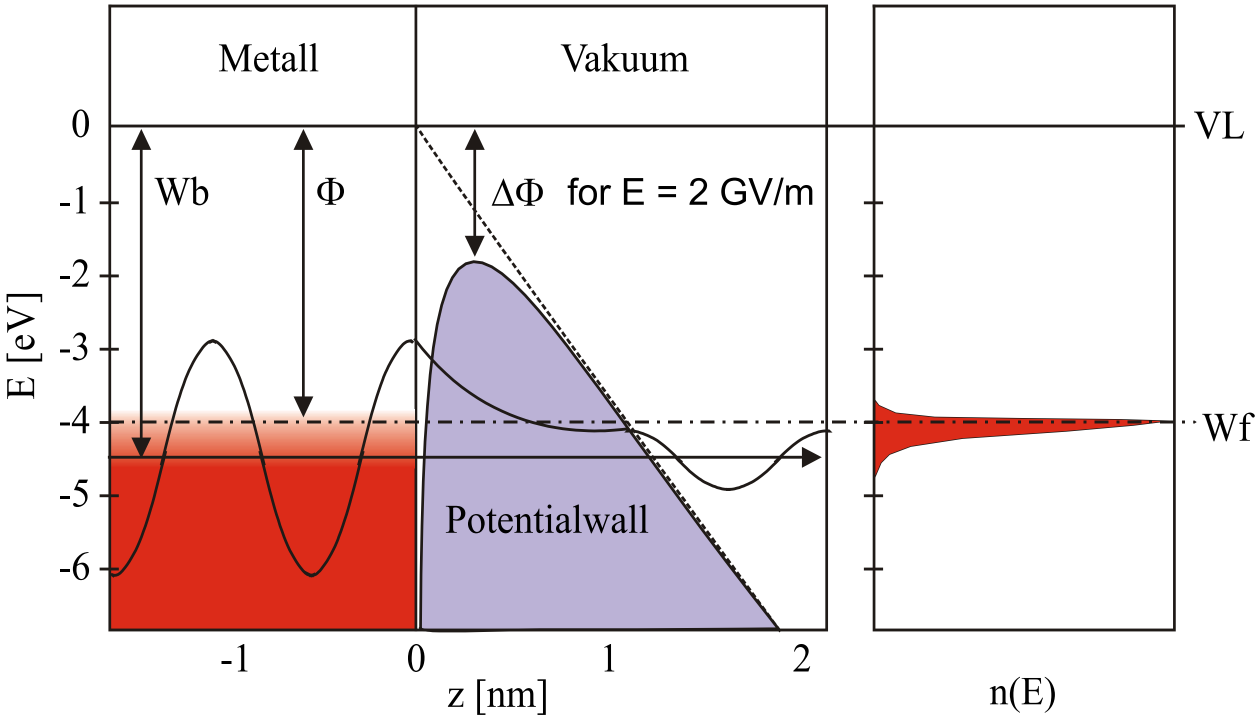
Identification of relevant features for field limitation

Systematic improvement and control of surface quality

Field emission of electrons from flat metal surfaces

Electron waves of bound states in a metal can tunnel through the potential barrier V(z) at the solid surface into vacuum by means of the quantum mechanical tunnelling effect



$V(z) = -e\cdot E\cdot z - e^2/(16\pi\varepsilon_0\cdot z)$

work function Φ of metal

applied field E on surface

image charge correction

$\Delta\Phi = (e^3E/\ 4\pi\varepsilon_0)^{1/2}$

Calculation of the current density j(E) within the Fowler-Nordheim theory results in

$$j(E) = \frac{AE^2}{\Phi t^2(y)} \exp\left(-\frac{B\Phi^{3/2} v(y)}{E}\right)$$

with constants A=154 and B=6830 and slight correction functions t(y) and v(y)

Φ=4eV at E=2000 MV/m ⇒ j= 1nA/µm²

Enhanced field emission of electrons from real surfaces

For real metal surfaces, i.e. broad area cathodes with some roughness and pollution, nA currents occur at much lower fields (<100 MV/m) than predicted by FN theory

⇒ modified FN theory with **field enhancement factor β** describes at least the slope of locally measured I(E) curves quite well:

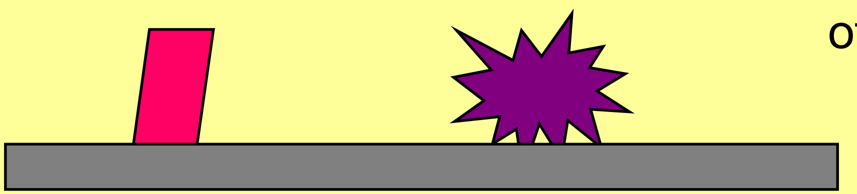
$$I(E) = S\,\frac{A(\beta \cdot E)^2}{\Phi}\exp\left(-\frac{B\Phi^{3/2}}{\beta \cdot E}\right)$$

with emitting surface S as fit parameter

Theoretical models for enhanced field emission of real surfaces:

- Geometric field enhancement for metallic protrusions/rough particulates of height h and edge radius r_k

  ⇒ **$\beta \approx h/r_k$**

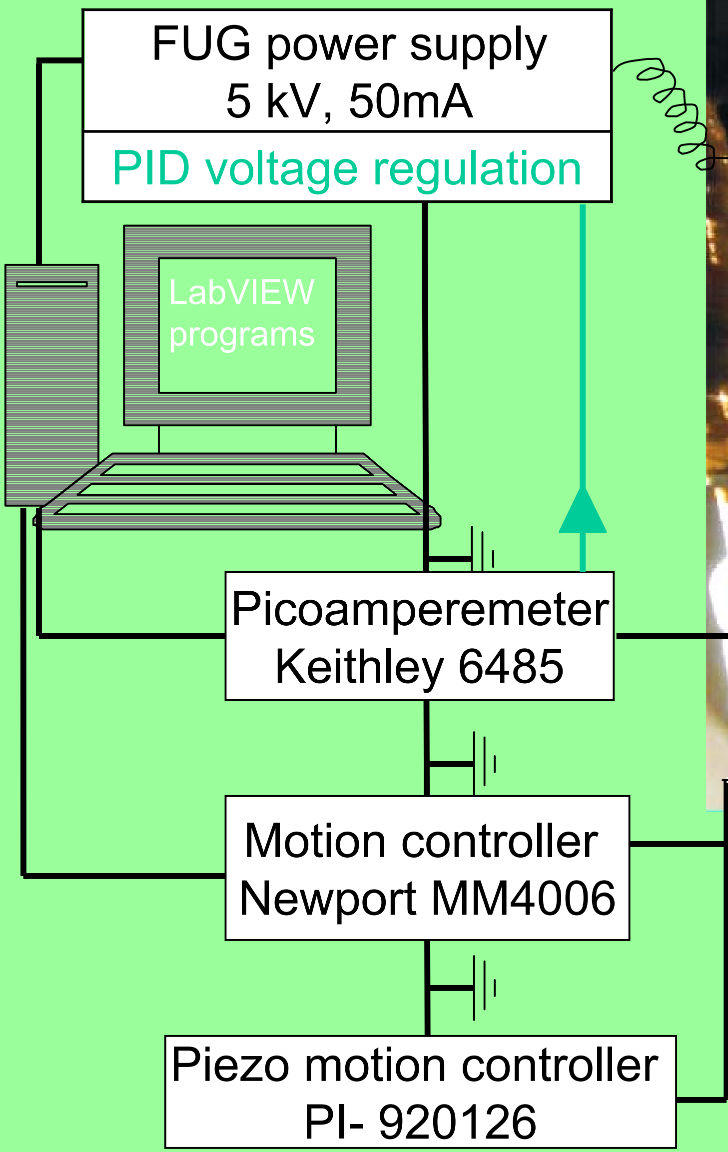


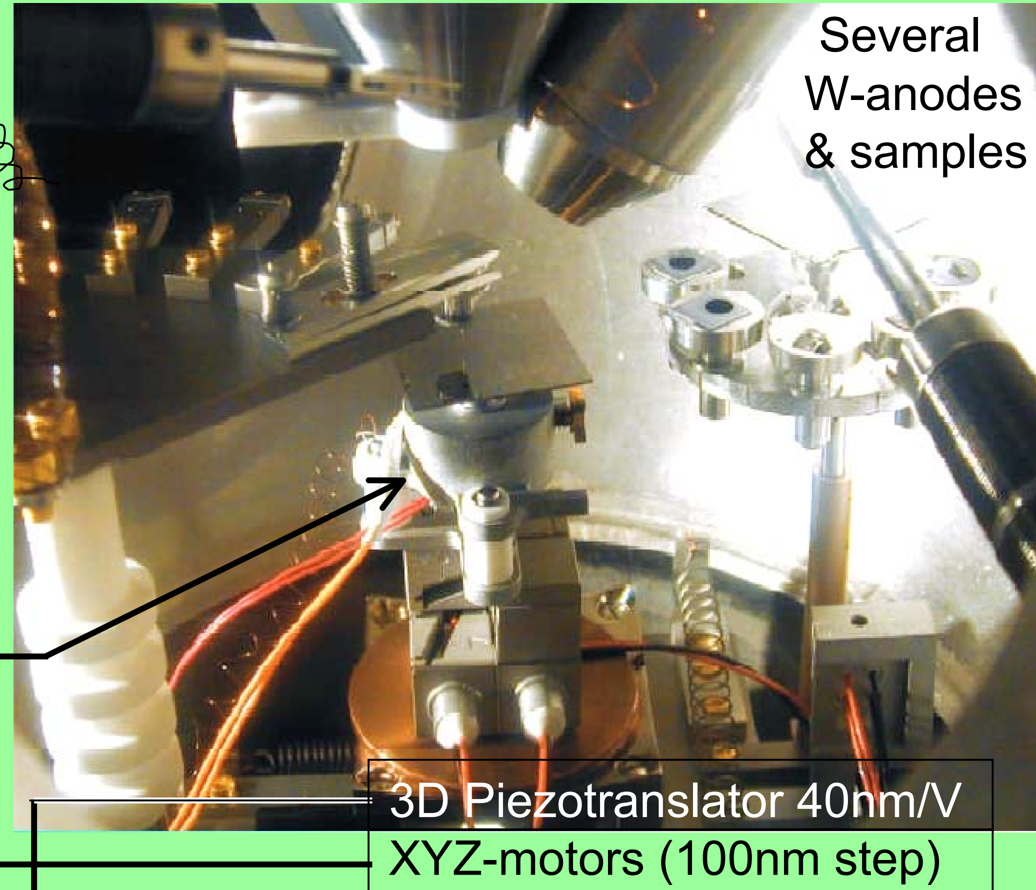
- Metal-Isolator-Vacuum for metals with oxide layers (d < 10 nm)

  ⇒ irreversible creation of conducting channels ⇒ switch-on effect
- Antenna or Metal-Isolator-Metal for particles on oxidized metals

  after switch-on at $\beta \approx h/d$ geometric field enhancement as above
- Resonant tunneling through localized states in adsorbates and oxides

Field emission scanning microscope (FESM)





UHV system typically at $2 \cdot 10^{-7}$ Pa

LabVIEW automated scans of U(x,y) for 2 nA

Scanning speed: (100×100) pixels in 1 hr

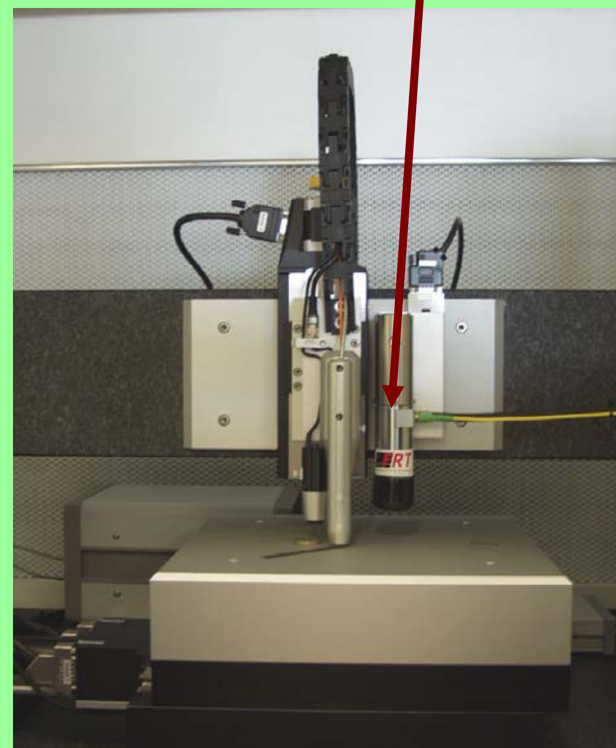
I/V curves and localization of stable emitters

Profilometer with AFM and SEM with EDX

Additional surface analysis of whole samples and relocalized areas of enhanced FE

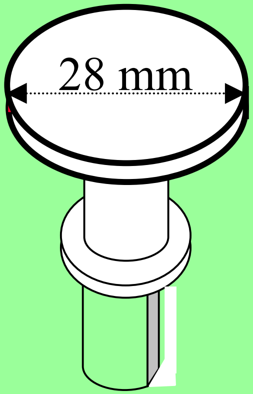
Optical profilometer with lateral resolution of 2 µm and height resolution of 3 nm combined with atomic force microscope AFM

Scanning speed: (100×100) pixels in 1 min

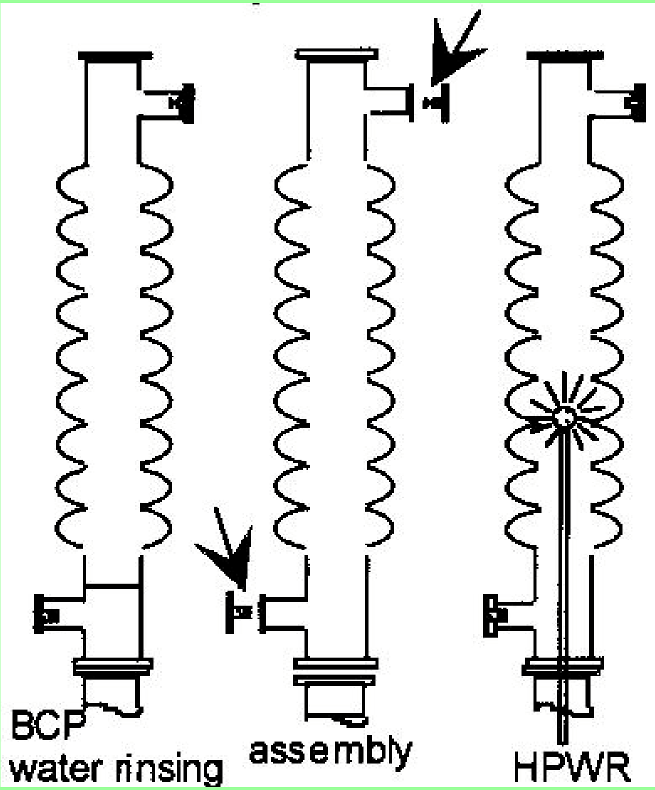


Scanning electron microscope SEM (XL-30) with energy dispersive X-ray analysis EDX

Preparation techniques for Nb samples



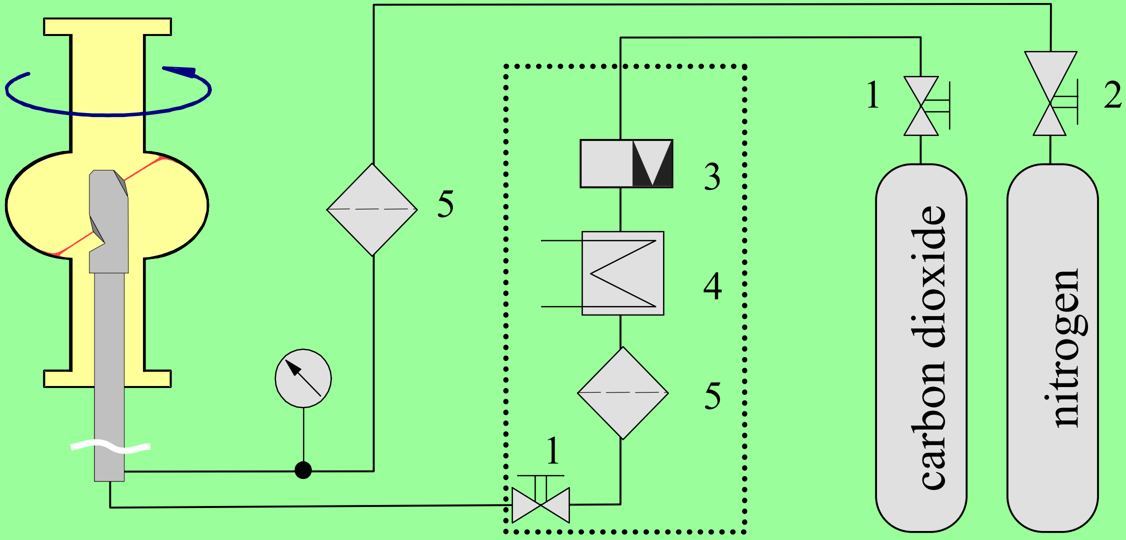
Nb samples prepared like cavities at DESY
Buffered chem. BCP or electropolished EP
and high pressure rinsed HPR with water
mostly in single cells, few in 9-cell cavities



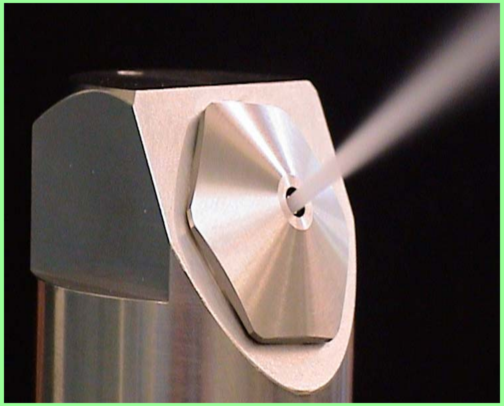
Ultra pure water	ρ > 18MΩcm
Water flow	7 - 20 l/min
Water pressure	80-150 bar
Rotation speed	4-5 rpm

Dry ice cleaning of Nb samples (DIC)

Process developed at FH Stuttgart and adapted for cavities at DESY



1 valve
2 pressure reducer
3 gas purifier
4 chiller
5 filter

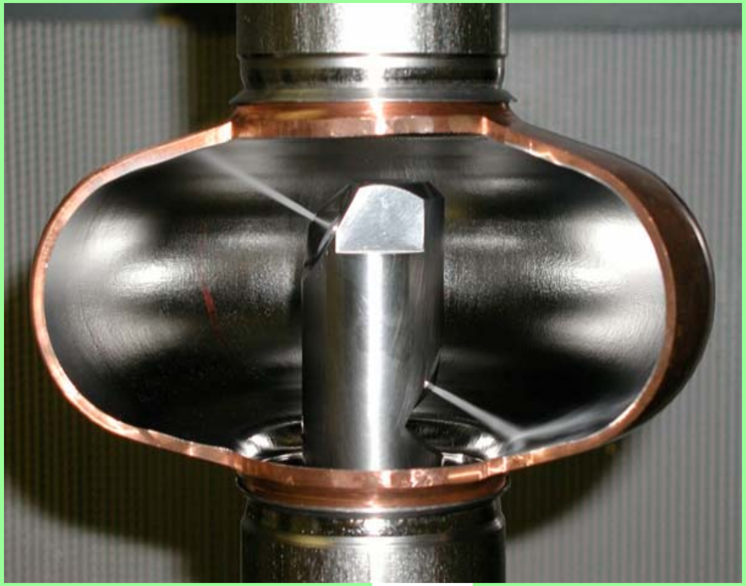


CO_2 pressure ~ 50 bar

N_2-pressure: 12 - 18 bar

Particle filter < 0.05 µm

CO_2 temperature > -40°C



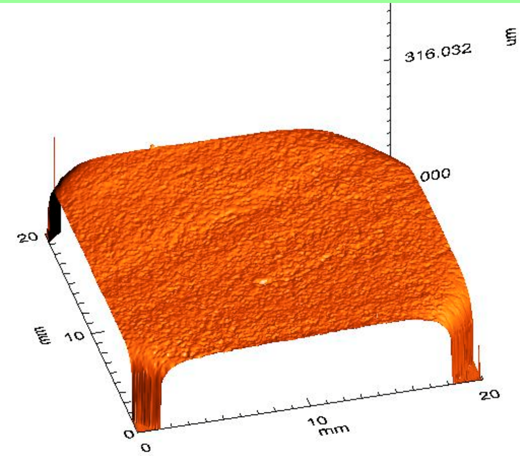
3 cleaning effects:

- Mechanically
  - impact of snow crystals ⇒ shearing forces
- Chemically
  - liquid CO_2 is good solvent for hydrocarbons
- Thermally
  - rapid cooling ⇒ brittling of contaminants
  - sublimated volume increase × 500

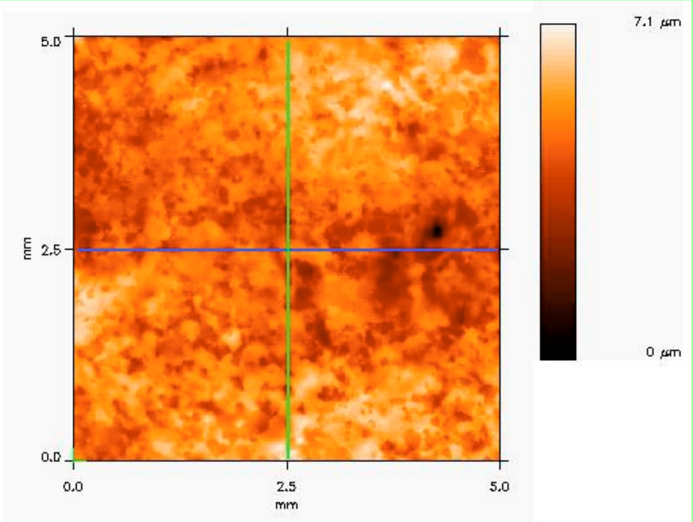
Quality control scans of EP/HPR-Nb prepared in 9-cell cavity

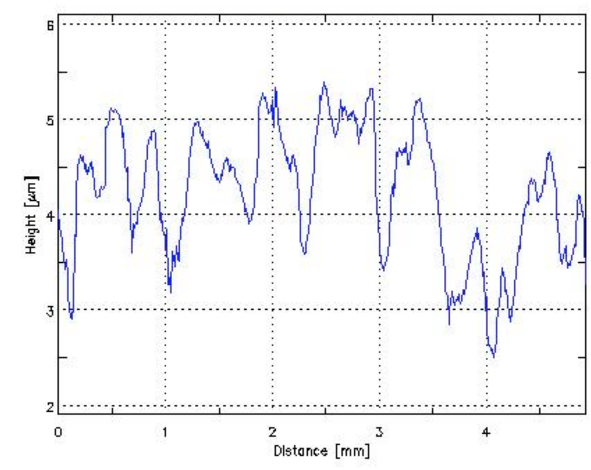
Profiles of whole sample and central part of sample

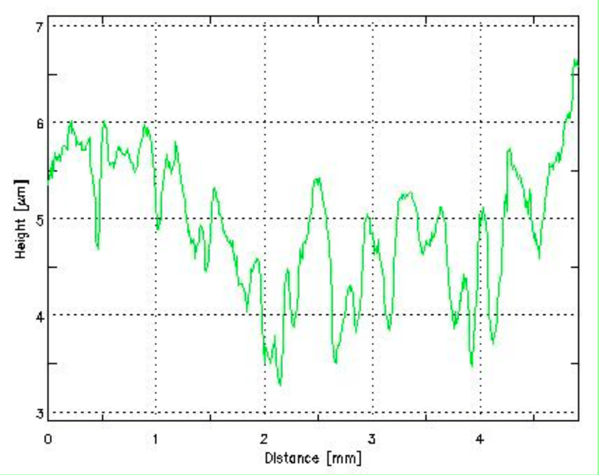
scanned area 20×20 mm^2 5×5 mm^2



7 μm curvature/20 mm







Line scans ⇒ grooves < 2 μm, roughness < 0.2 μm

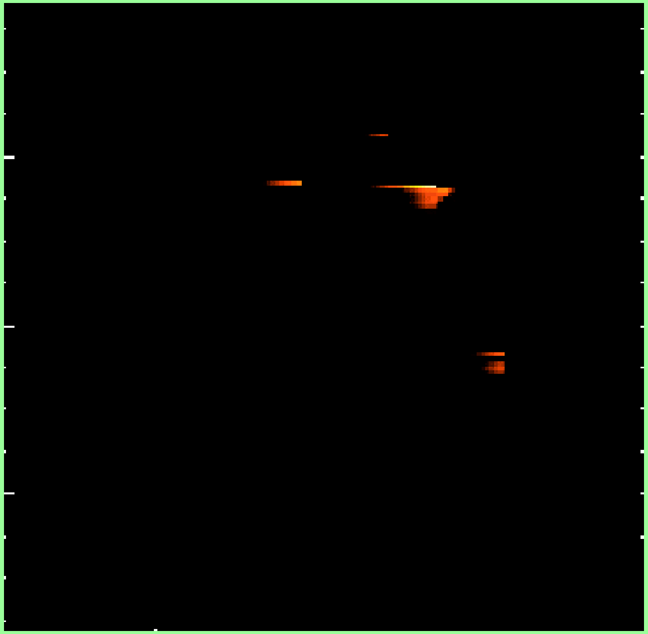
PID-regulated U(x,y) for 1 nA

scanned area = 7.5×7.5 mm^2

flat W-anode $Ø_a$= 100 μm

anode voltage U = 4800 V

electrode spacing Δz = 32 μm



no emission @ 120MV/m

5 emitters @ 150MV/m

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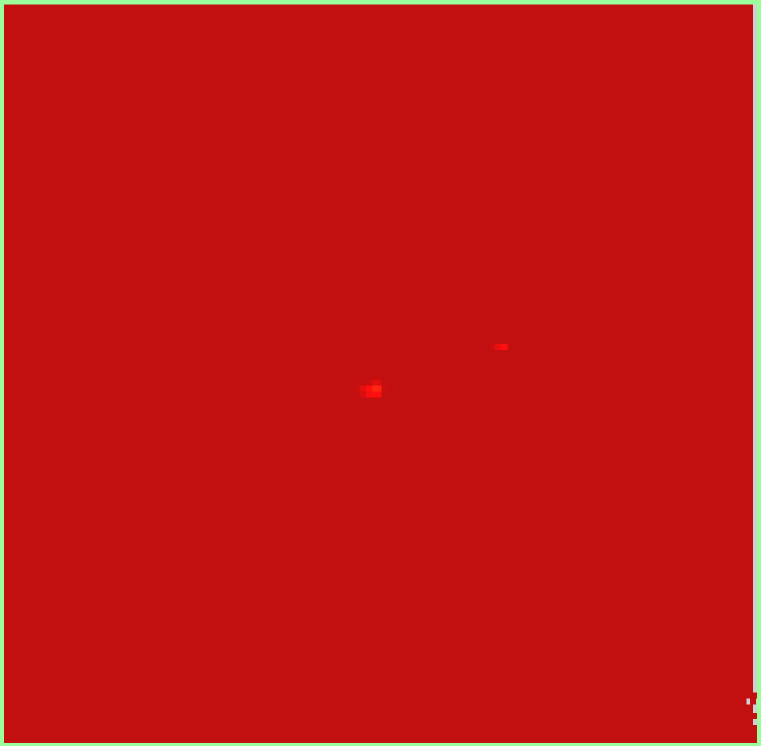
best EP/HPR sample yet

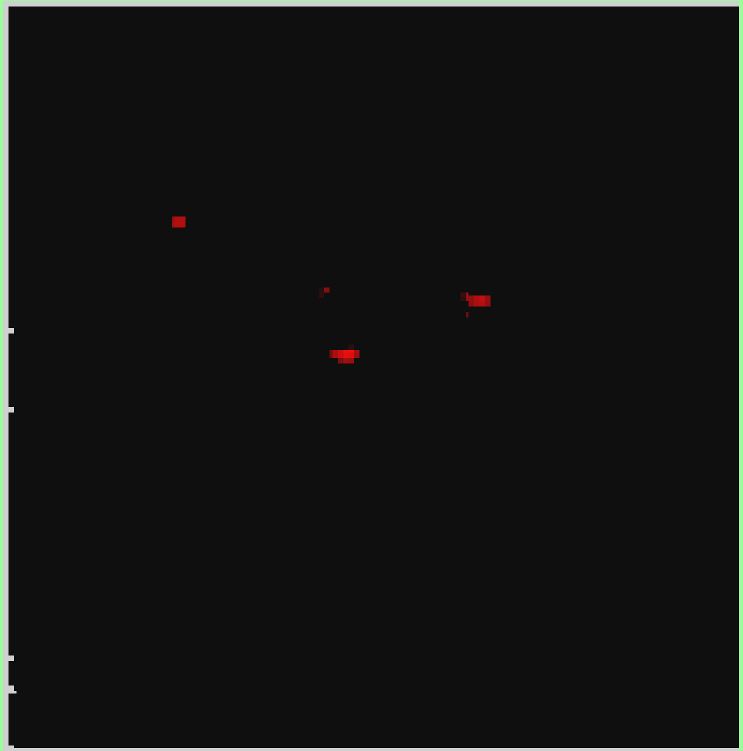
Emitter distribution on single crystal Nb after BCP/HPR

Alternative approach for mirror-like surfaces: large crystal Nb+BCP30µm/HPR

PID-regulated voltage maps U(x,y) for 1 nA
flat W-anode $\varnothing_a$ = 100 µm
electrode spacing Δz = 32 µm

scanned area = 7.5×7.5 mm^2
anode voltage U = 4800 V
Δz = 24 µm





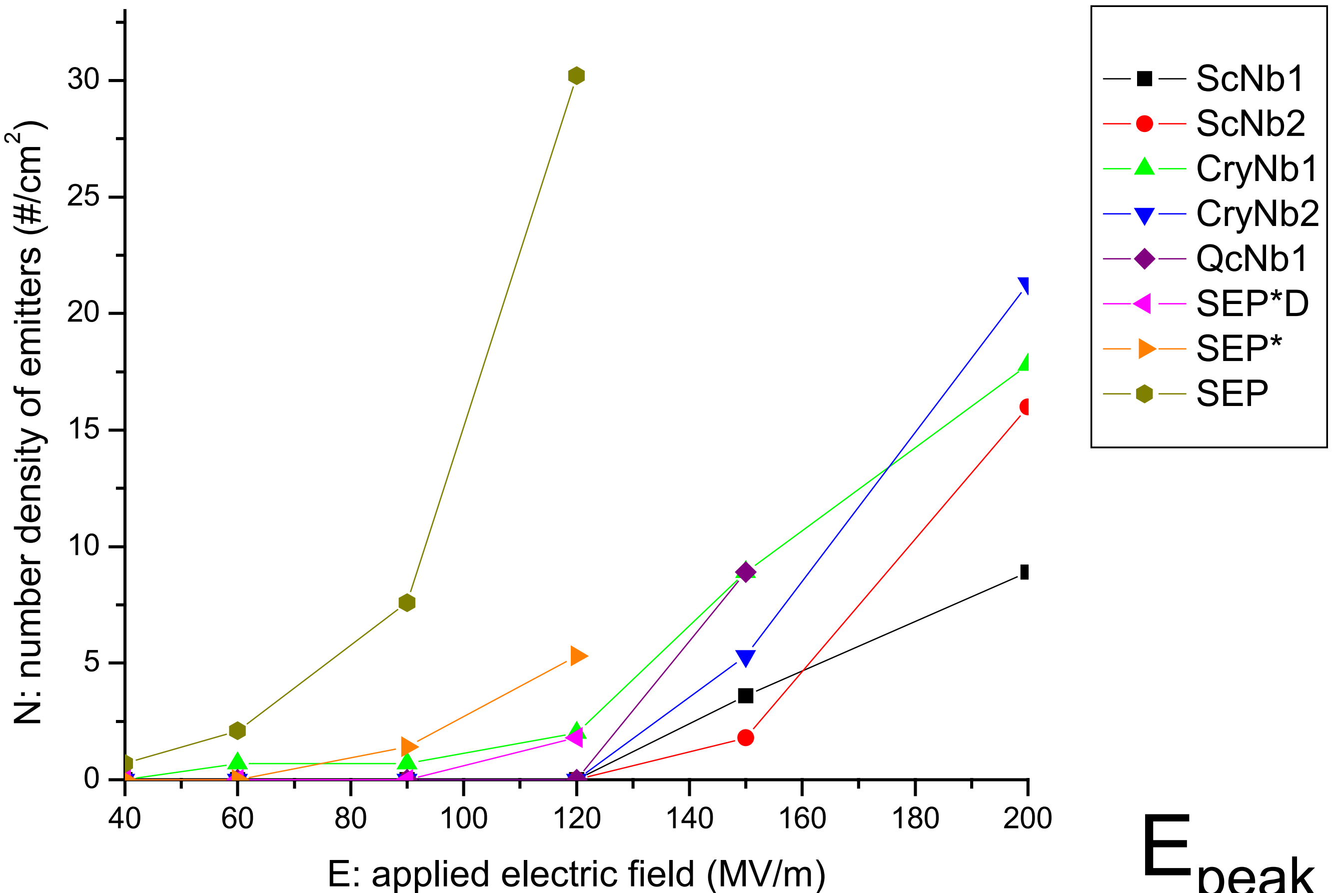
no emission @ 120MV/m

2 emitters @ 150MV/m

5 emitters @ 200MV/m

⇒ **best FE performance of all Nb samples yet**

Emitter statistics for various types of Nb samples



single crystal #1
& #2, BCP30HPR
3 large grains #2
& #1, BCP30HPR
EP+HPR at DESY
EP+HPR+DIC
EP+HPR
EP at Saclay

$$E_{peak} = 2 \times E_{acc}$$

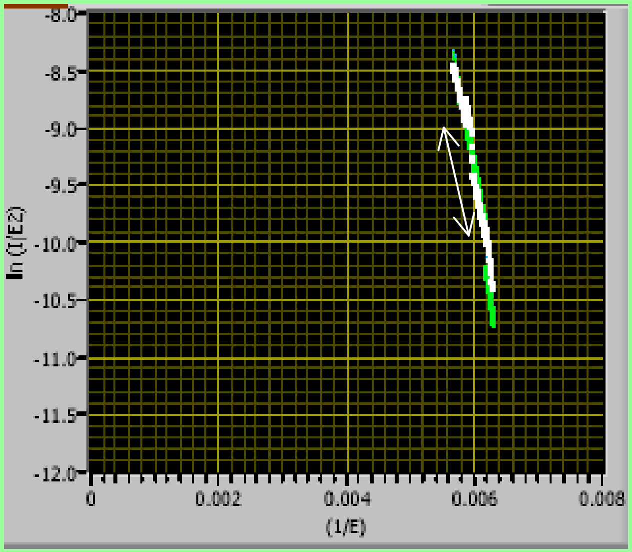
Systematically reduced FE by EP+HPR, DIC and large crystal Nb

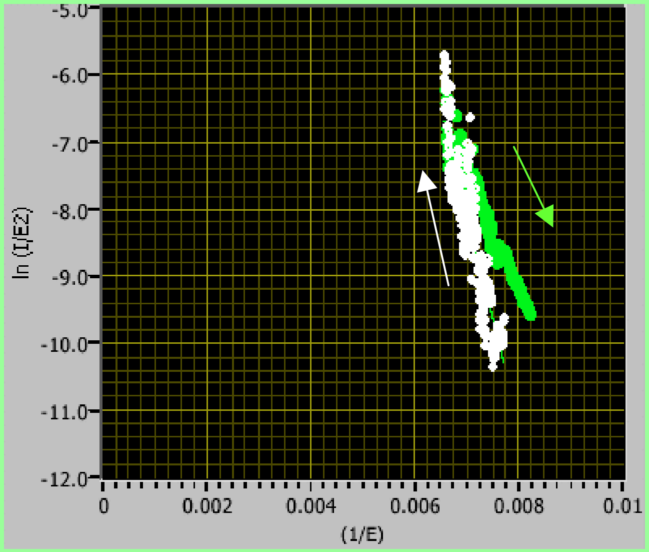
BCP+HPR of large crystal Nb is probably sufficient

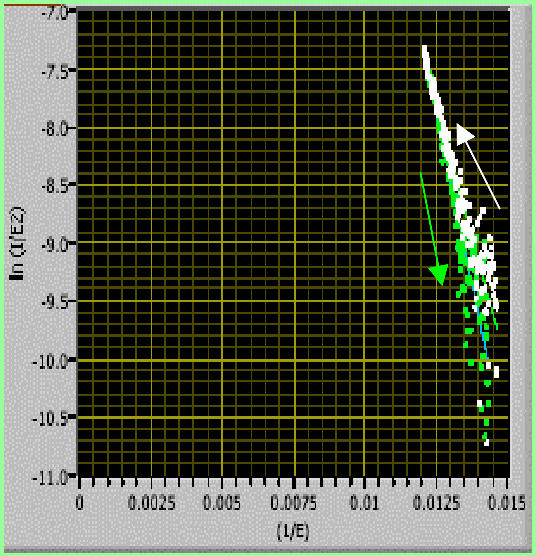
Locally measured I/V-curves and FN-Analysis of emitters

$$\ln\left(I(E)/E^2\right) = \ln\frac{S\cdot A\cdot\beta^2}{\Phi} - \frac{B\cdot\Phi^{3/2}}{\beta}\frac{1}{E}$$

Typical FN-plots of a stable | activated | deactivated emitter







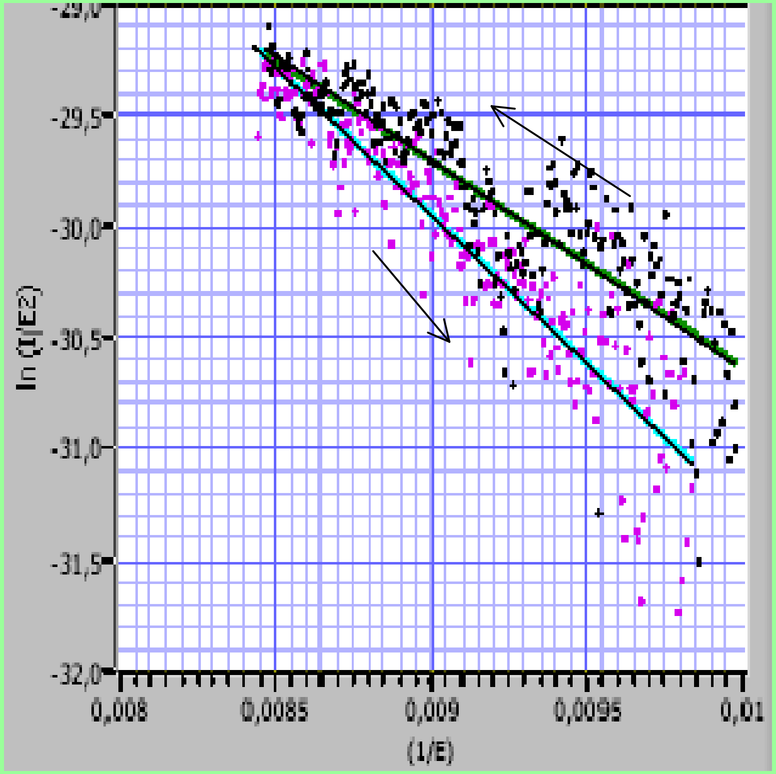
E_{on}(1 nA) = 76.9 MV/m
$\beta_{\uparrow} = 19.3$ $S_{\uparrow} = 1\times10^{-13}$ m²
$\beta_{\downarrow} = 17.9$ $S_{\downarrow} = 5\times10^{-13}$ m²

E_{on}(1 nA) = 103.3 MV/m
$\beta_{\uparrow} = 17.4$ $S_{\uparrow} = 1\times10^{-11}$ m²
$\beta_{\downarrow} = 31.2$ $S_{\downarrow} = 3\times10^{-16}$ m²

E_{on}(1 nA) = 54.3 MV/m
$\beta_{\uparrow} = 67.4$ $S_{\uparrow} = 2\times10^{-17}$ m²
$\beta_{\downarrow} = 61.2$ $S_{\downarrow} = 1\times10^{-15}$ m²

After first processing, most emitters are stable up to 100 nA

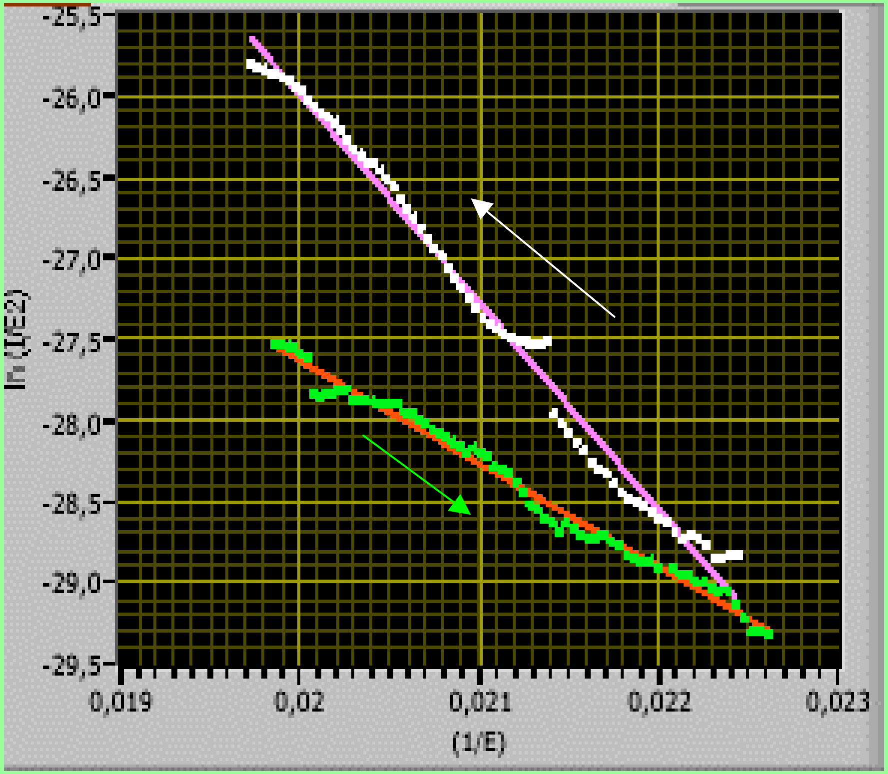
Current processing of instable emitters



E_{on}(1 nA) = 33 MV/m

$\beta_\uparrow = 231$ $S_\uparrow = 3\times10^{-19}$ m^2

$\beta_\downarrow = 160$ $S_\downarrow = 2\times10^{-17}$ m^2



E_{on}(1 nA) = 44.6 MV/m

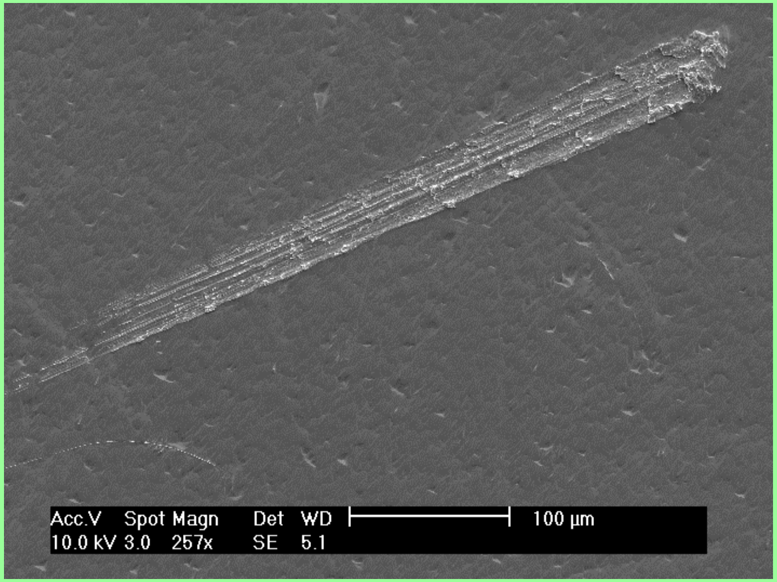
$\beta_\uparrow = 59.5$ $S_\uparrow = 8\times10^{-10}$ m^2

$\beta_\downarrow = 119$ $S_\downarrow = 1\times10^{-16}$ m^2

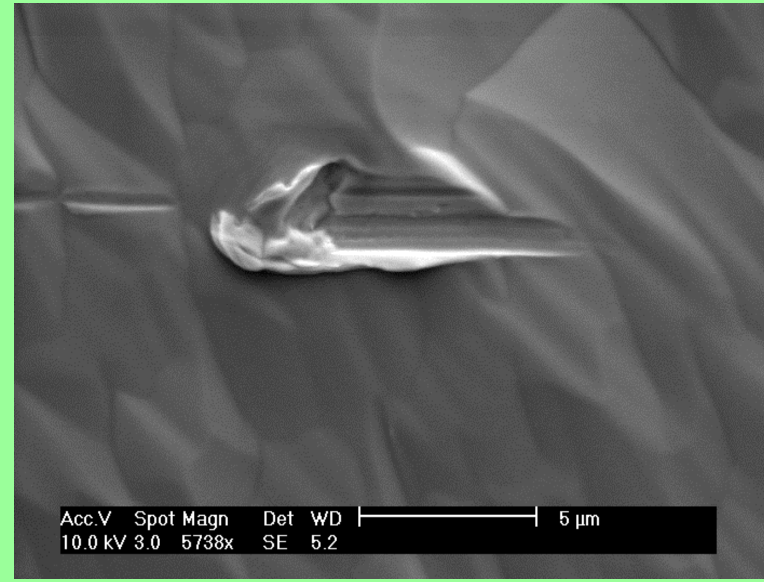
Fluctuations / oscillations most probably caused by adsorbates

Understanding of instabilities and nature of emitters very difficult

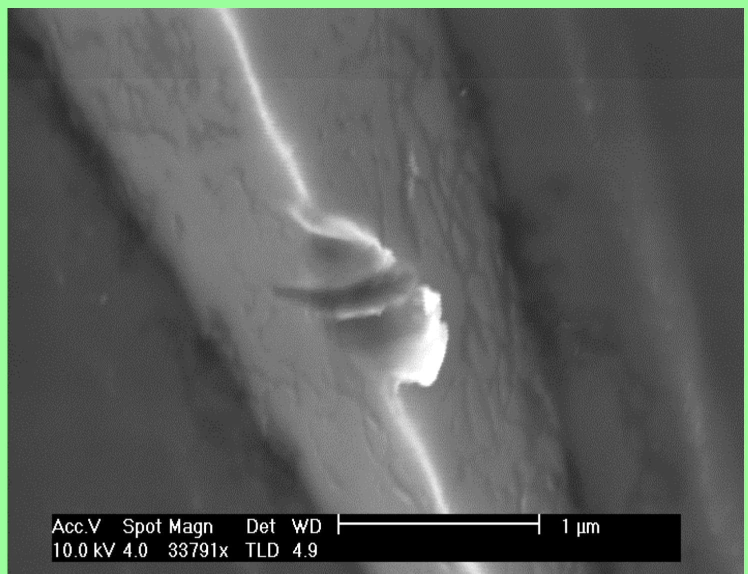
Typical protrusion emitters containing only Nb (+ O?)



E_{on}(2nA) < 60 MV/m
~500 µm long scratch
(mishandling of sample)

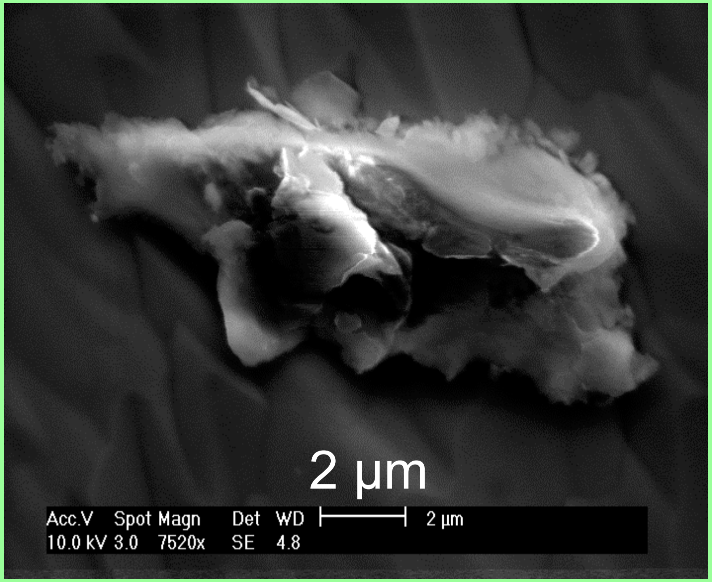


E_{on}(2nA) = 90 MV/m
~5 µm long groove
$\beta = 71$, $S = 2.3 \cdot 10^{-6}\ \mu m^2$

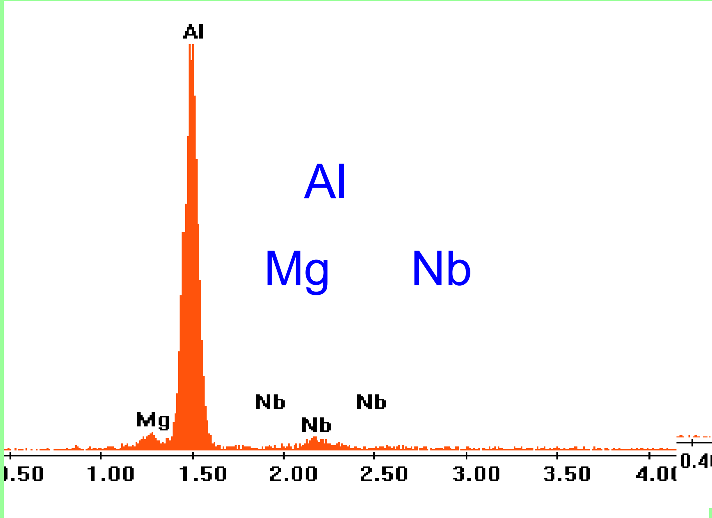


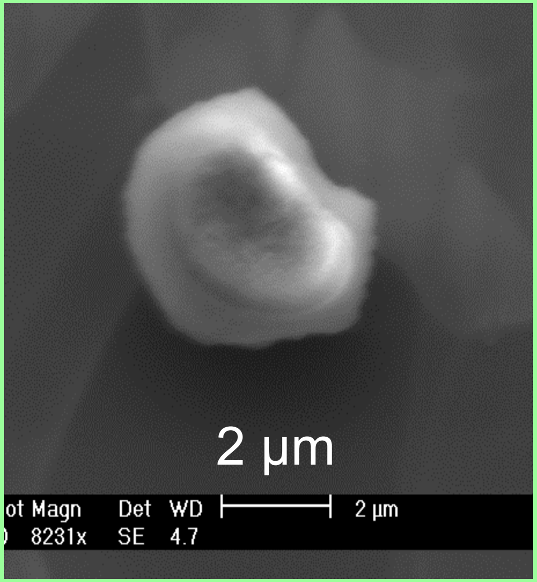
E_{on}(2nA) > 140 MV/m
~1 µm small defect
$\beta = 59$, $S = 7 \cdot 10^{-8}\ \mu m^2$

Typical particulate emitters containing impurities

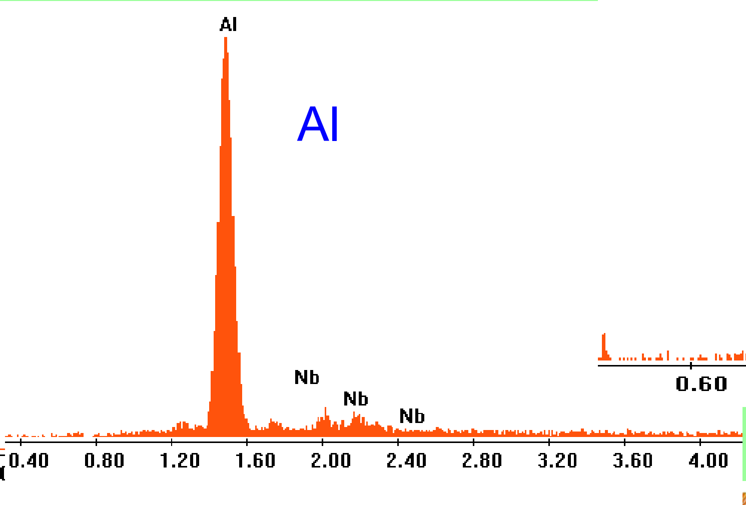


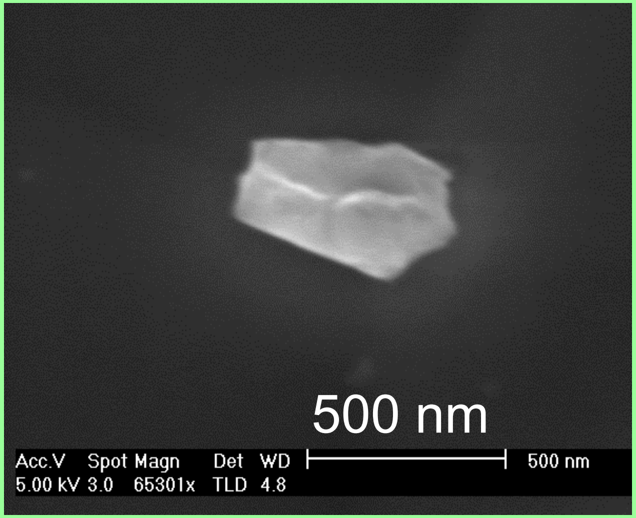
E_{on}(2nA) =140 MV/m
β= 31, S = $6.8\cdot10^{-6}$ µm²



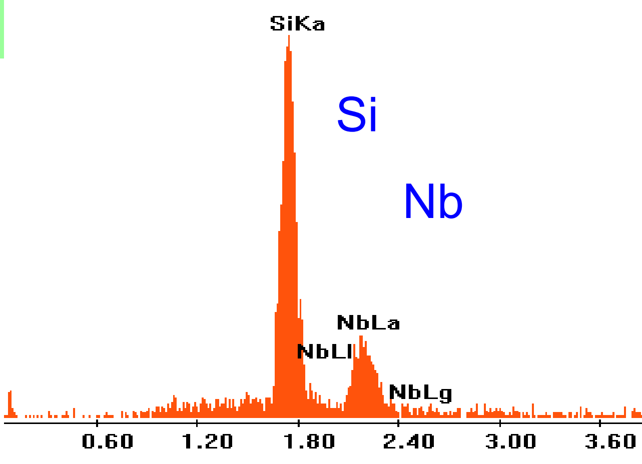


E_{on}(2nA) = 132 MV/m
β = 27, S = $7\cdot10^{-5}$ µm²

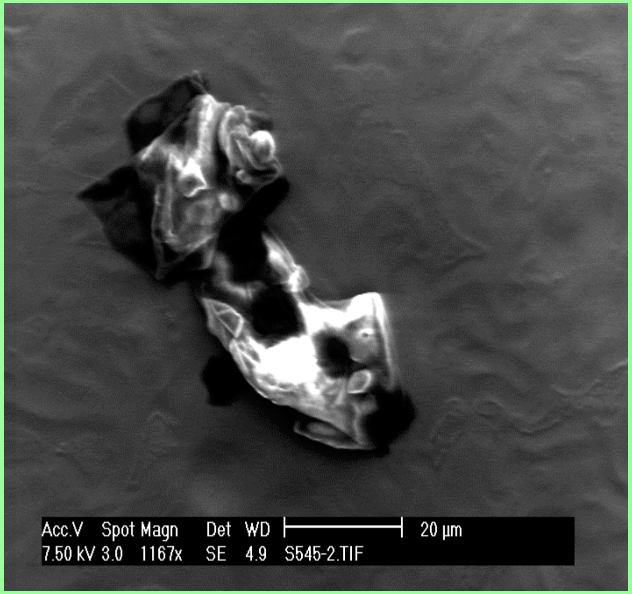




E_{on}(2nA) > 120 MV/m
β = 46, S = $6\cdot10^{-7}$ µm²

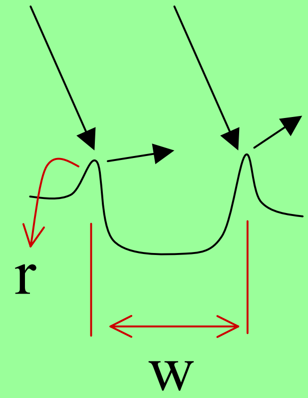


Effect of DIC on particulate and protrusion emitters



E_{on}(1nA) = 77 MV/m

S particulate removed by DIC



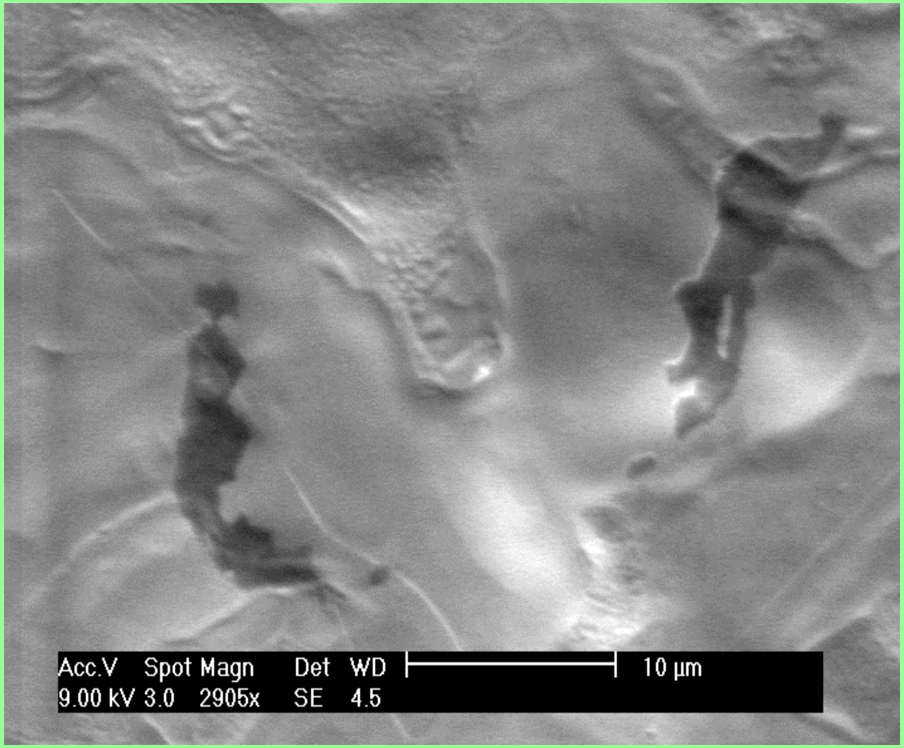
$\Rightarrow \beta = h/r \sim w/r$

$S \sim r^2$

Protrusion	HPR	HPR+DIC
E_{on} (MV/m)	48.5	103.3
$\beta_\uparrow$	166.7	17.4
$\beta_\downarrow$	147	31.2
$S_\uparrow$ (m^2)	1.6×10^{-20}	9.6×10^{-12}
$S_\downarrow$ (m^2)	7.2×10^{-20}	3.3×10^{-16}

FE of protrusion much reduced by DIC

Effect of DIC on a flake-like emitter with exposed edge



emitter of ~ 20 µm size destroyed by DIC

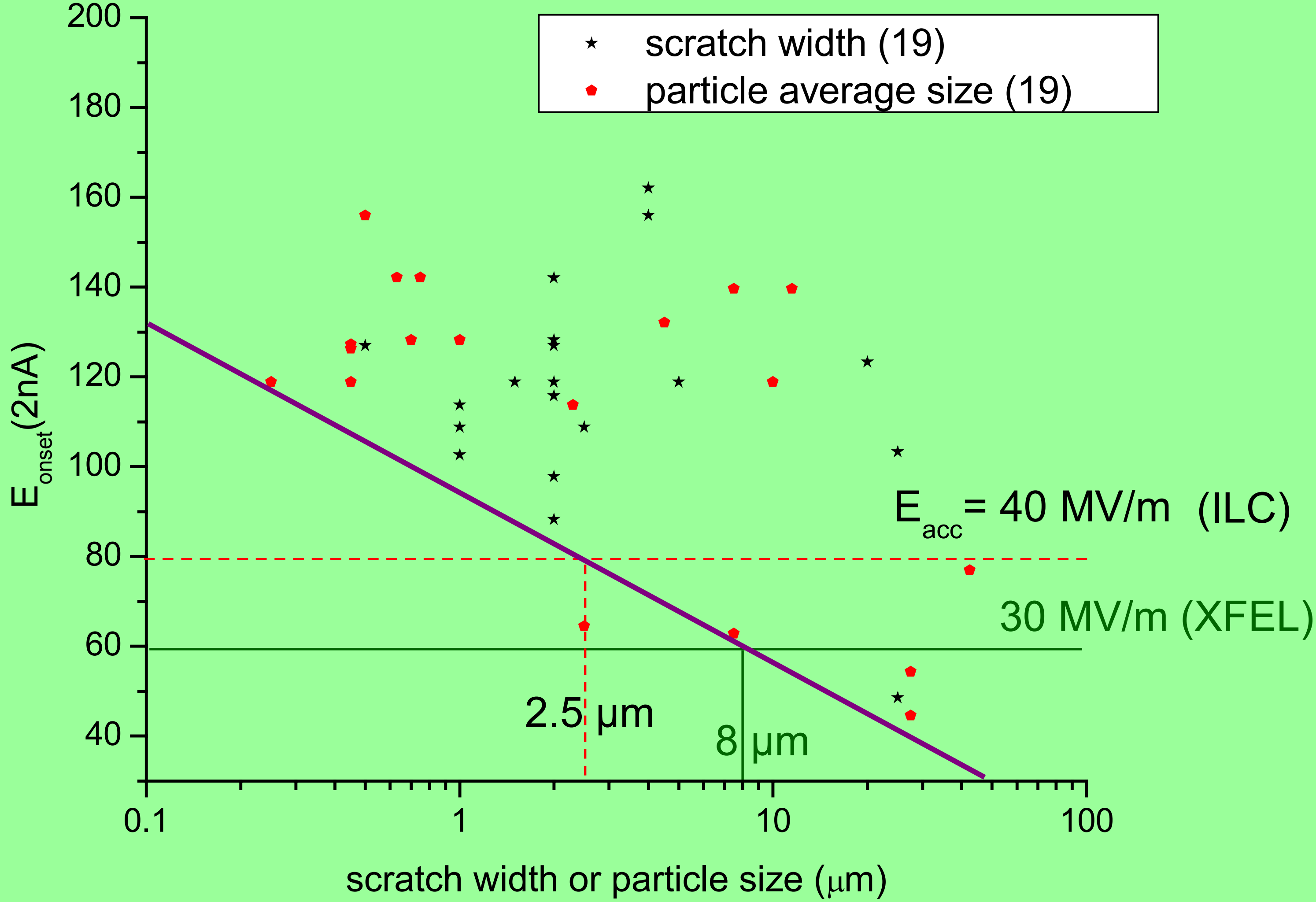
remnants emitting at higher E_{on}!

EDX: no foreign element detected
(probably oxide of Nb)

emitter	HPR	HPR+DIC
E_{on} (MV/m)	54.3	62.8
$\beta_{\uparrow}$	67.4	35.4
$\beta_{\downarrow}$	51.2	38.0
$S_{\uparrow}$ (m^2)	2×10^{-17}	8.3×10^{-13}
$S_{\downarrow}$ (m^2)	1.2×10^{-15}	2.4×10^{-13}

Correlation between FE onset field and emitter size ?

based on FE measurements and SEM analysis of 38 field emitters



Evidence for correlation ⇒ fast FE quality control by emitter size

Conclusions and outlook !

- Standard EP+HPR Nb sample provides good FE performance
  no field emission up to E_{on} = 120 MV/m ⇒ E_{acc} = 60 MV/m
- Large Nb crystal BCP+HPR samples show best FE results
  ⇒ **interesting alternative for cavity fabrication !**
- Particulates and protrusions identified as relevant emitters
- DIC effectively removes particulates and weakens protrusions
- After first processing, most emitters are stable up to 100 nA
  ⇒ **instabilities and nature of emitters challenging !**
- Evidence for correlation between onset field and emitter size
  ⇒ **fast FE quality control on samples for XFEL !**

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