Surface Roughness Investigations on Nb Samples using Optical Profilometry

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- **Motivation and strategy**
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Nb samples from: A. Matheisen, D. Reschke, X. Singer, J. Ziegler (DESY)
P. Kneisel (TJNAF)
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Motivation and strategy

- Enhanced field emission (EFE) is caused by particulates or scratches [1]
- Quenches and high-field Q-drop might depend on surface roughness [2]
- Number density of particulates can be much reduced by HPR [3], DIC [4] and clean room assembly, but influence of surface irregularities on EFE and quenches of poly/single crystalline EP/BCP Nb has been less studied

[1] A. Dangwal et al., Phys. Rev. ST Accel. Beams 12, 023501 (2009).

[2] J.Knobloch et al., Proc. 9th Workshop on SRF (1999), p.77.

[3] P. Kneisel et al., Proc. 7th Workshop on SRF (1995), p.311.

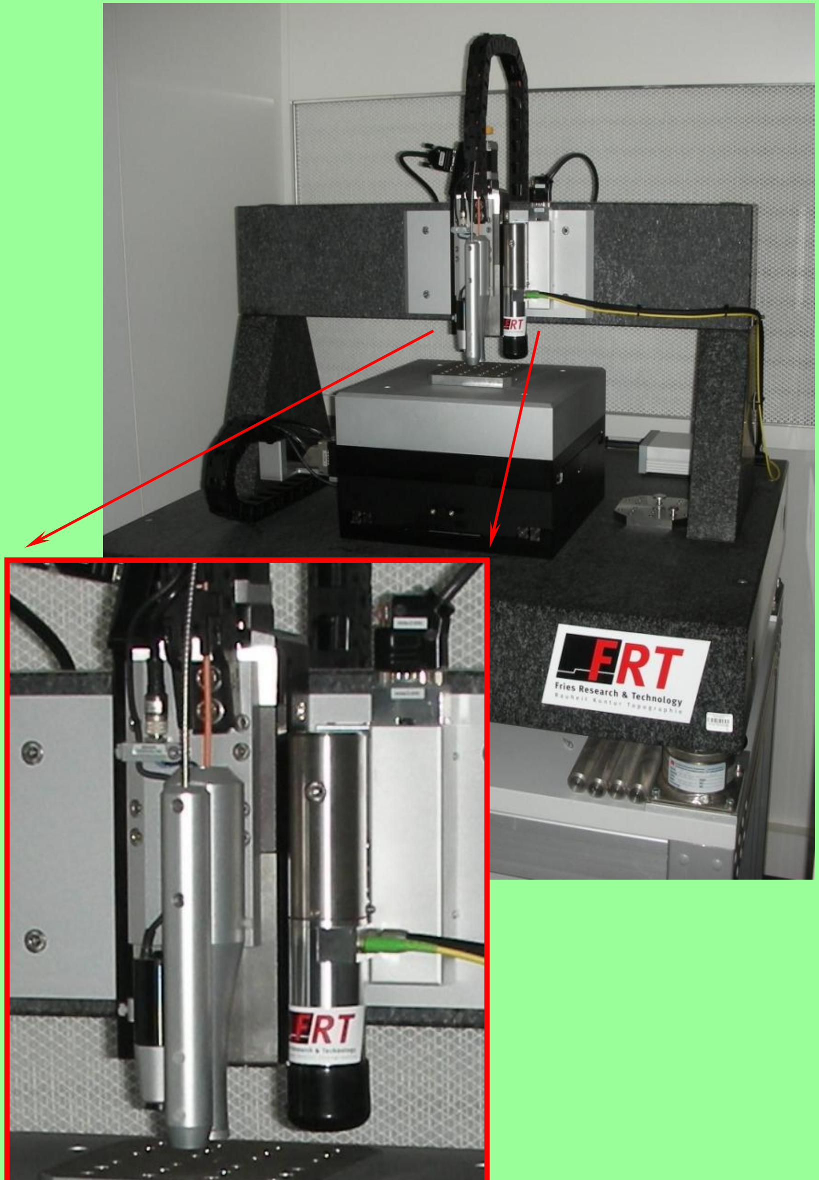
[4] A. Dangwal et al., J. Appl. Phys. 102, 044903 (2007).

1-st step Systematic measurements of average surface roughness and local defect geometry for typical Nb samples by means of optical profilometry and AFM

2-nd step Localization and characterization of effective field emitters (E_{on} *(1 nA)*, β, S) on the same Nb samples after HPR with FESM and in-situ SEM imaging

3-rd step Ex-situ HRSEM/EDX identification of emitting defects and investigation of the correlation between EFE parameters and geometry of defects

Surface roughness measurement techniques



- Optical profilometer (OP)
  white light irradiation and spectral reflection
  - fast scanning speed (100×100 pixel per min)
  - samples up to 20×20 cm^2 and 5 cm height
  - 2 µm lateral and 3 nm height resolution
- atomic force microscope (AFM)
  operated in contact or non-contact mode
  - 2 µm positioning accuracy within OP scan
  - 34×34 μm^2 scanning range
  - 3 nm lateral and 1 nm height resolution
- CCD camera for positioning control
- granite plate with an active damping system for undisturbed measurement at nm scale
- clean laminar air flow from the back to reduce particulate contamination

Average surface roughness and electric field enhancement

Definition of average surface roughness

$$R_a = \frac{1}{n \cdot m} \sum_{i=1}^{n} \sum_{j=1}^{m} \left| z(x_i, y_j) - \bar{z} \right|$$

$$R_q = \sqrt{\frac{1}{n \cdot m} \sum_{i=1}^{n} \sum_{j=1}^{m} \left(z(x_i, y_j) - \bar{z} \right)^2}$$

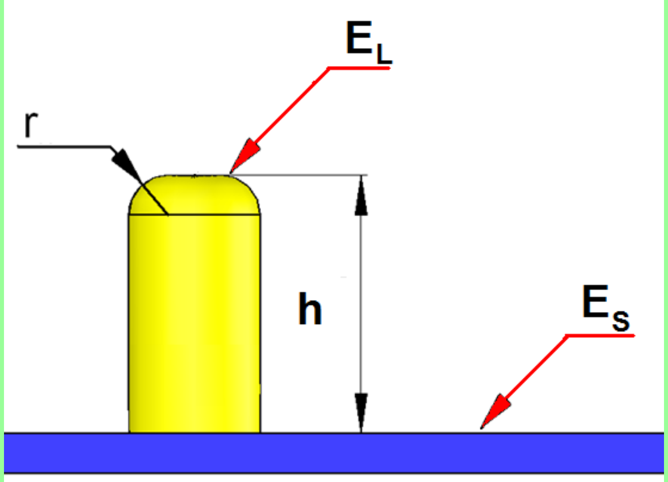
$z(x_i,y_j)$ = actual height value of profile
n, m = pixel number in x and y direction
$\bar{z}$ = average height value

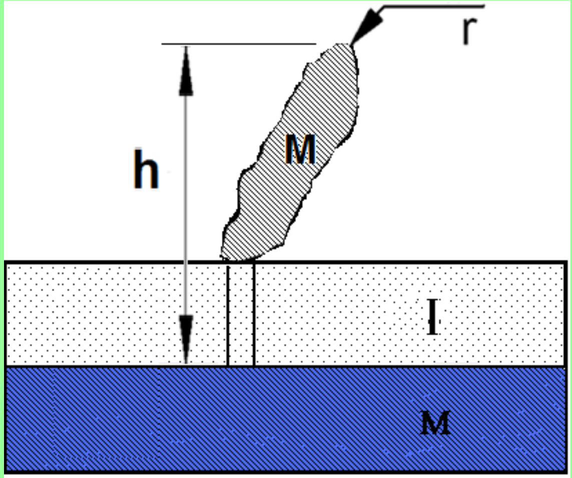
Estimated electric field enhancement for protrusions, activated particulates (initially MIM) and scratches:

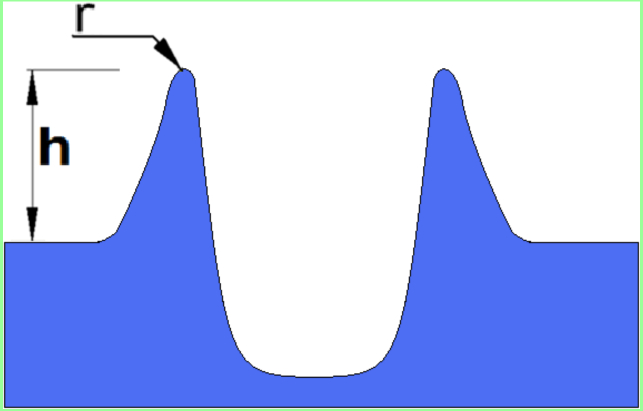
$$\beta_E = \frac{E_L}{E_S} \approx \frac{h}{r}$$

→ emission area $S \approx 2\pi r^2$

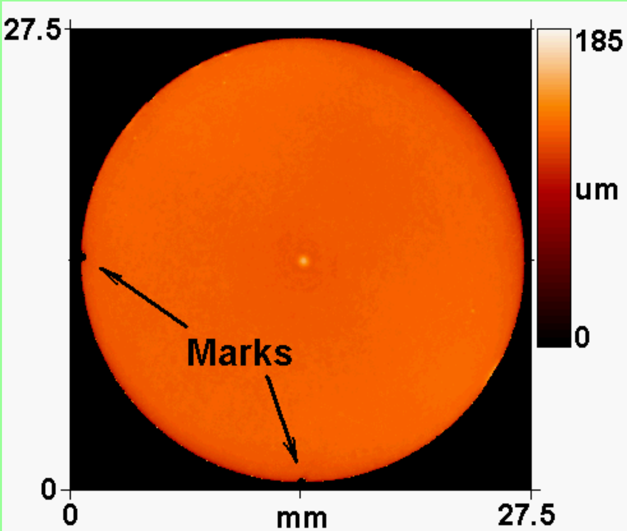
E_L = local electric field on defect
E_S = electric field on flat surface
h = height of defect
r = curvature radius







Results on polycrystalline Nb samples from DESY

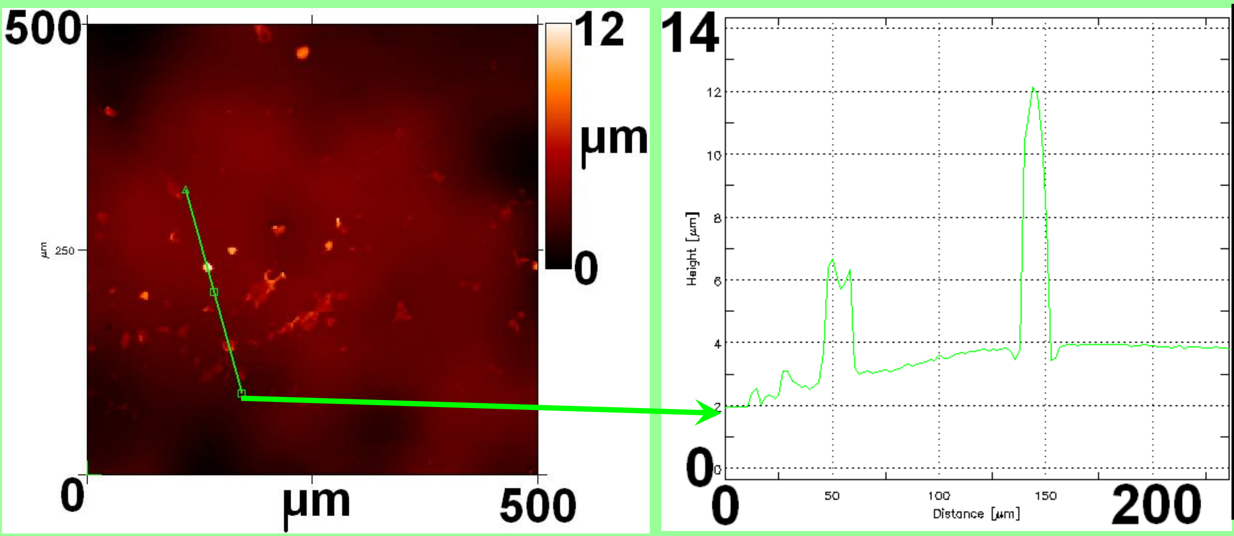


Nb samples were assembled into the coupler port and BCP/EP/HPR processed with 9-cell cavities

4 types of surface irregularities found with OP:

- **particulates**
- **scratches**
- **grain boundaries**
- **round hills and holes**

Particulates

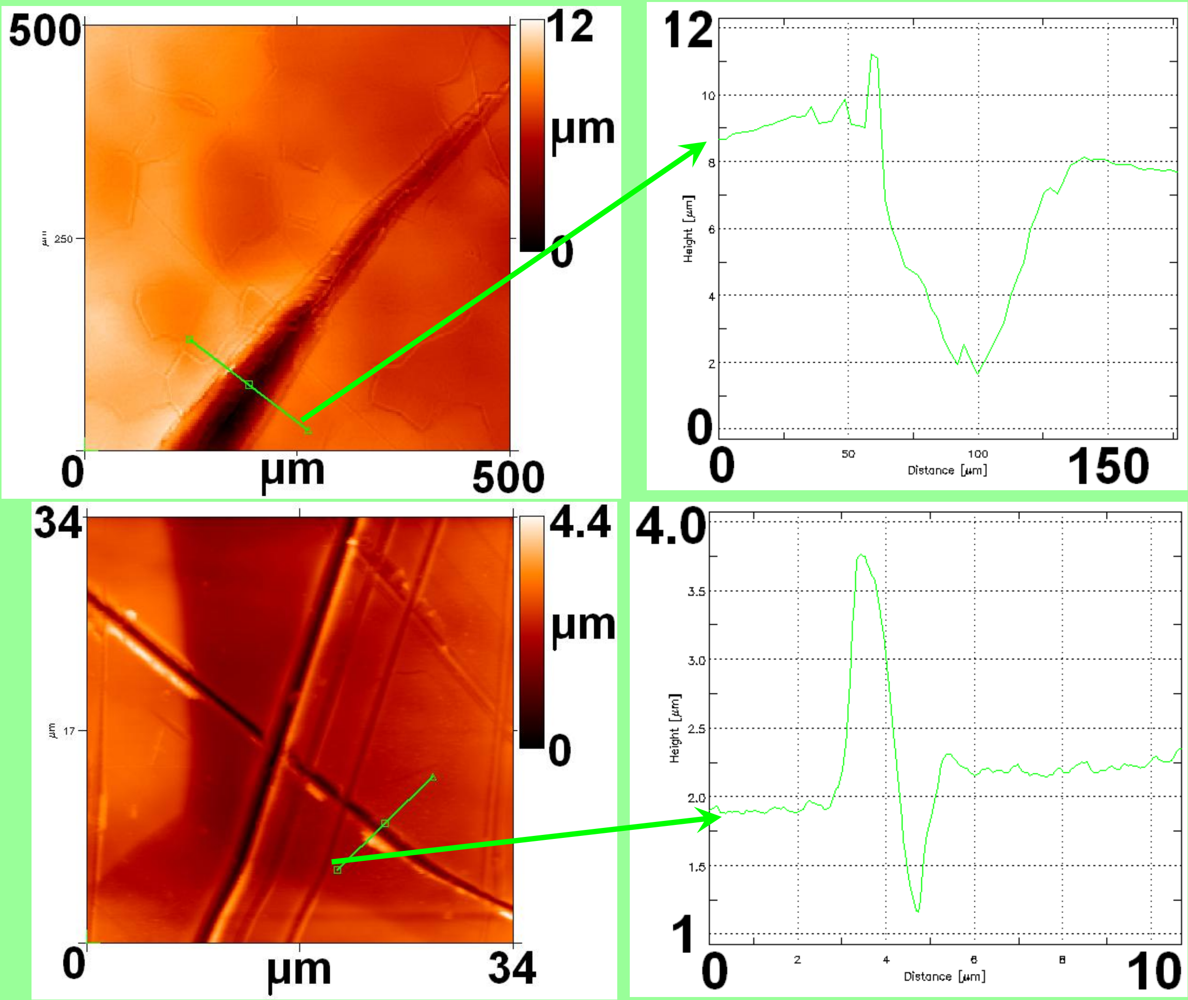


< 5 µm	43 %
5 - 15 µm	48.4 %
15 - 25 µm	6.1 %
> 25 µm	2.5 %

R_a = 0.276 µm
R_q = 0.548 µm
$\beta_{E,max}$ = 15

OP results on polycrystalline Nb samples from DESY

Scratches



4 - 100 µm width

11 µm - 2.7 mm length (on average 326 µm)

ridge height < 10 µm

$\beta_{E,max}$ = difficult

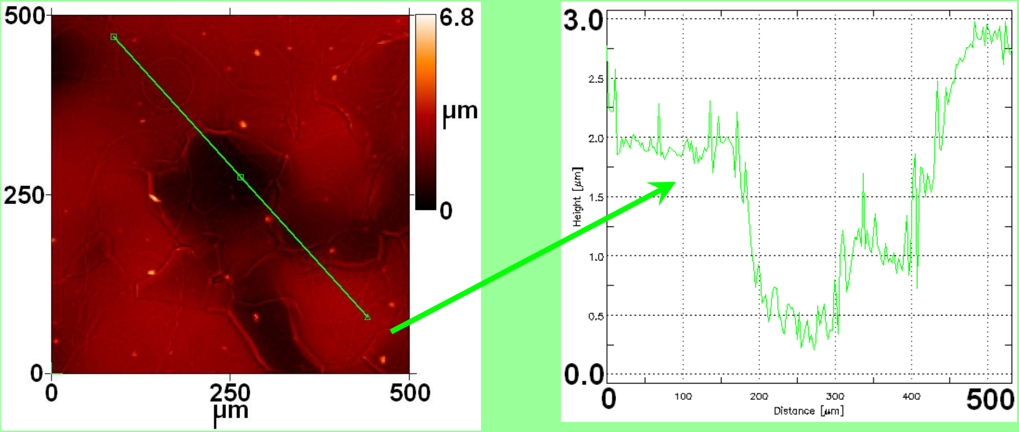
R_a = 0.466 µm

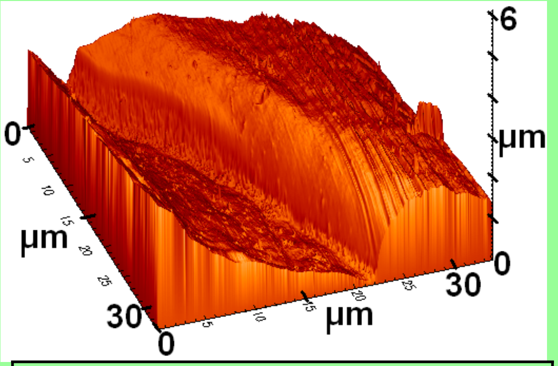
R_q = 0.646 µm

$\beta_{E,max}$ = 13

OP results on polycrystalline Nb samples from DESY

Grain boundaries

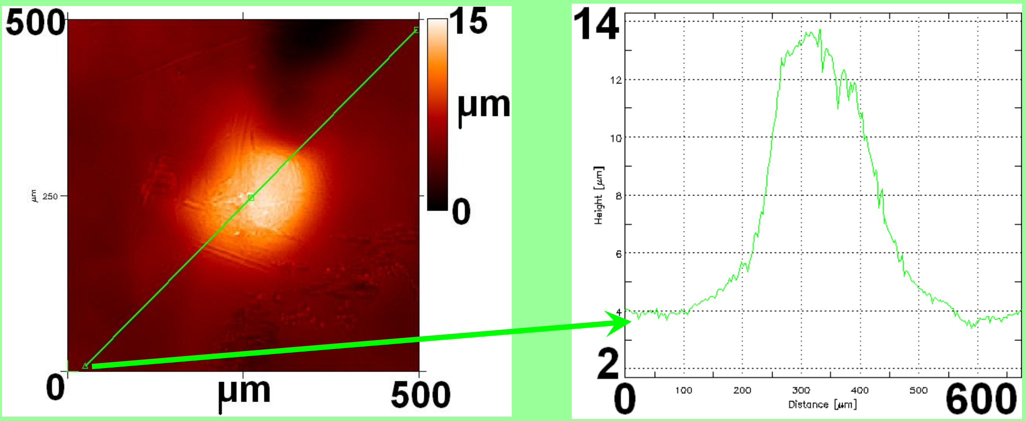




step height < 1.55 µm
edge radius < 0.78 µm

$\beta_{E,max} = 4$

Round hills and holes



height < 17 µm
size 10 - 440 µm

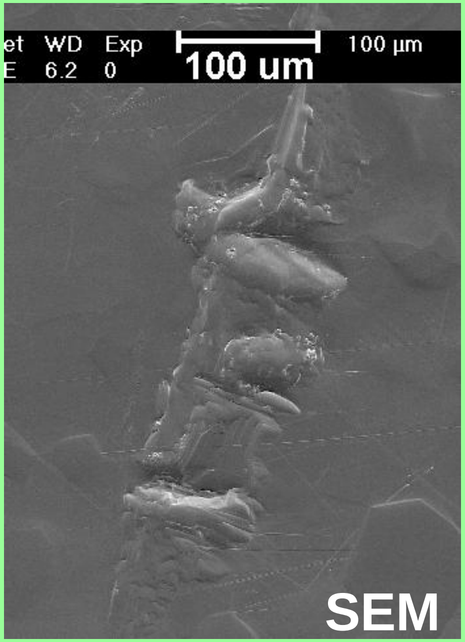
$R_a = 0.295$ µm
$R_q = 0.489$ µm
$\beta_{E,max} < 4$

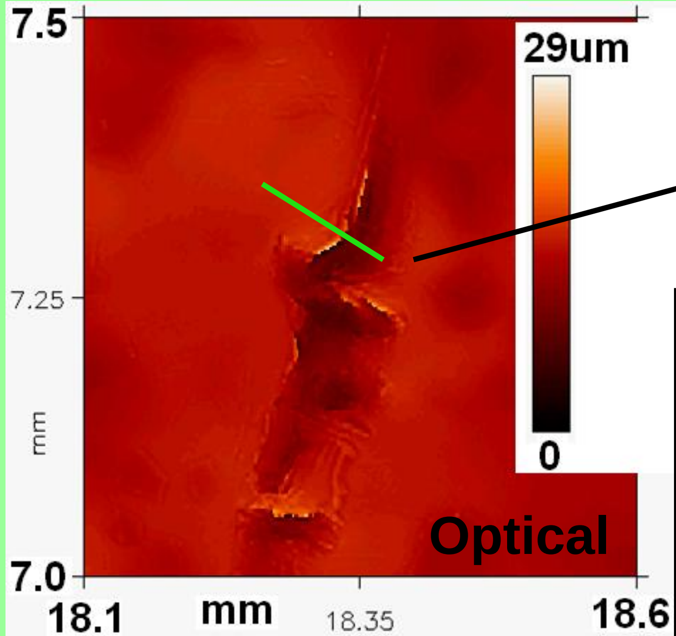
Probably caused by foreign material inclusions and modified chemical reactions during EP

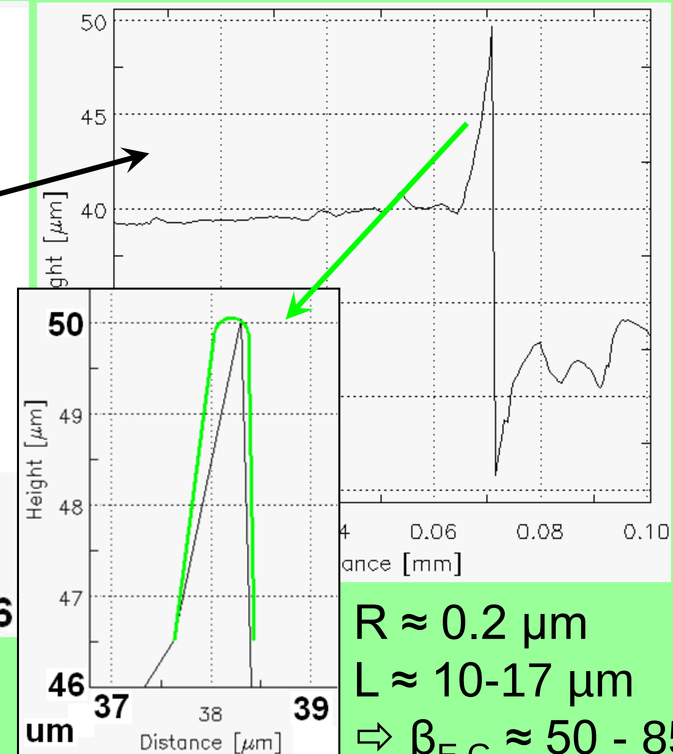
only weak EFE expected

but probably high magnetic field enhancement β_M ?

EFE/SEM/OP results on polycrystalline HPR-Nb samples



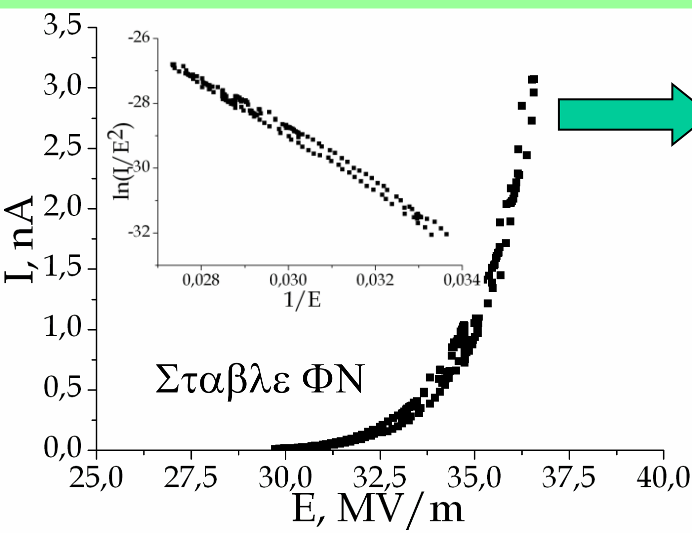




R ≈ 0.2 µm

L ≈ 10-17 µm

⇨ $\beta_{E,G}$ ≈ 50 - 85



E_{act} ≈160 MV/m

E_{on} = 35 MV/m

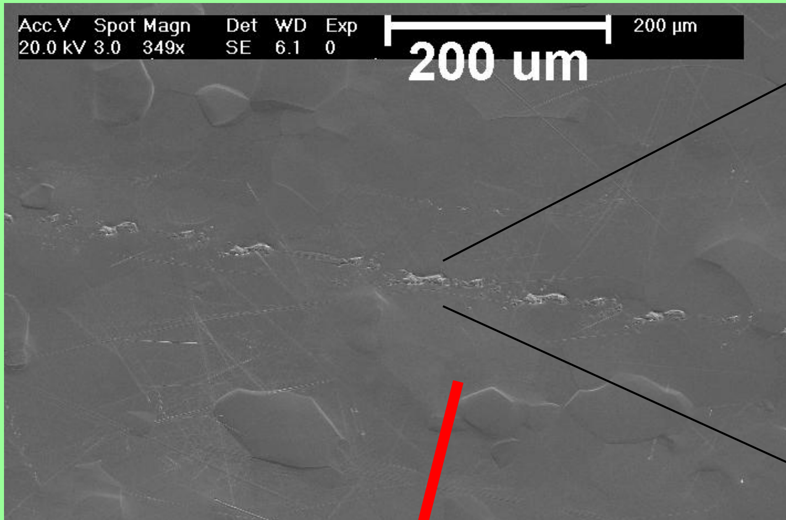
S ≈ 70 nm²

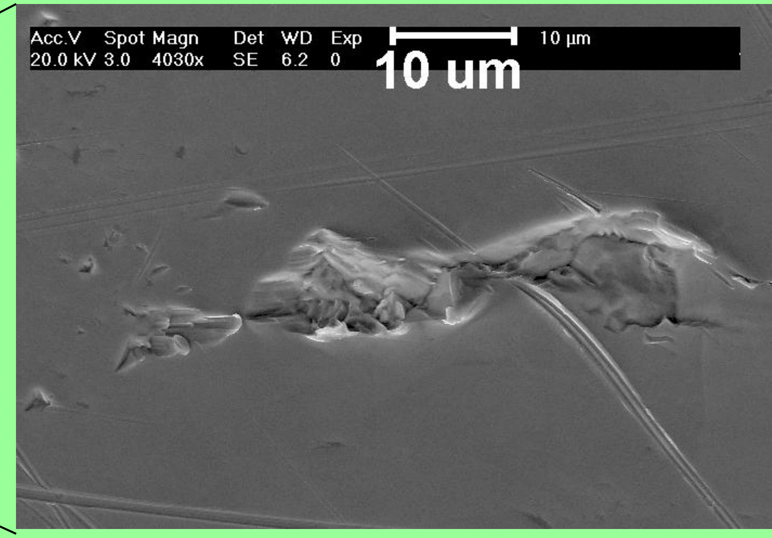
$\beta_{E,FN}$ ≈ 60

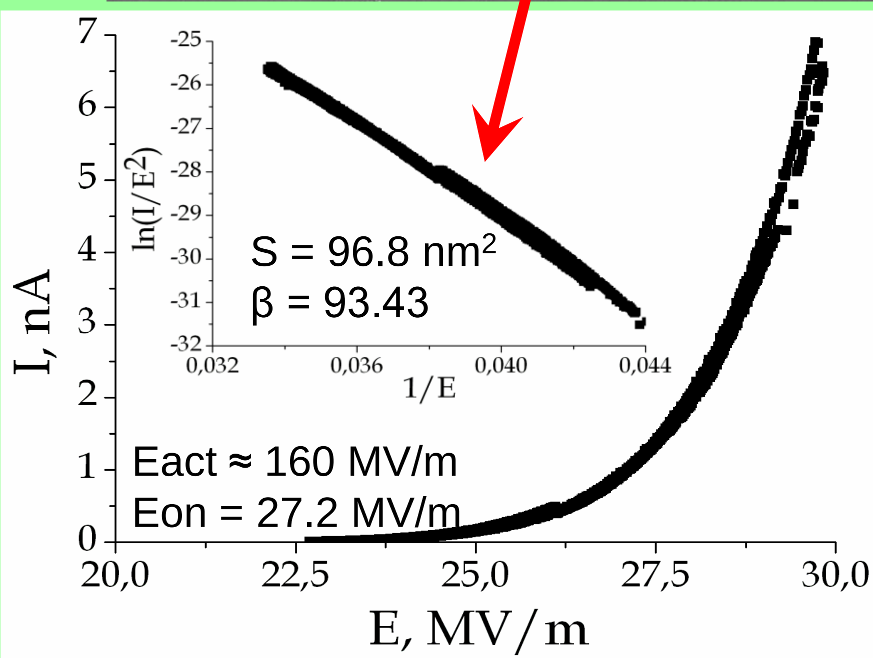
Large scratches ⇒ good correlation

$\beta_{E,FN} \approx \beta_{E,G}$

EFE/SEM results on polycrystalline Nb samples





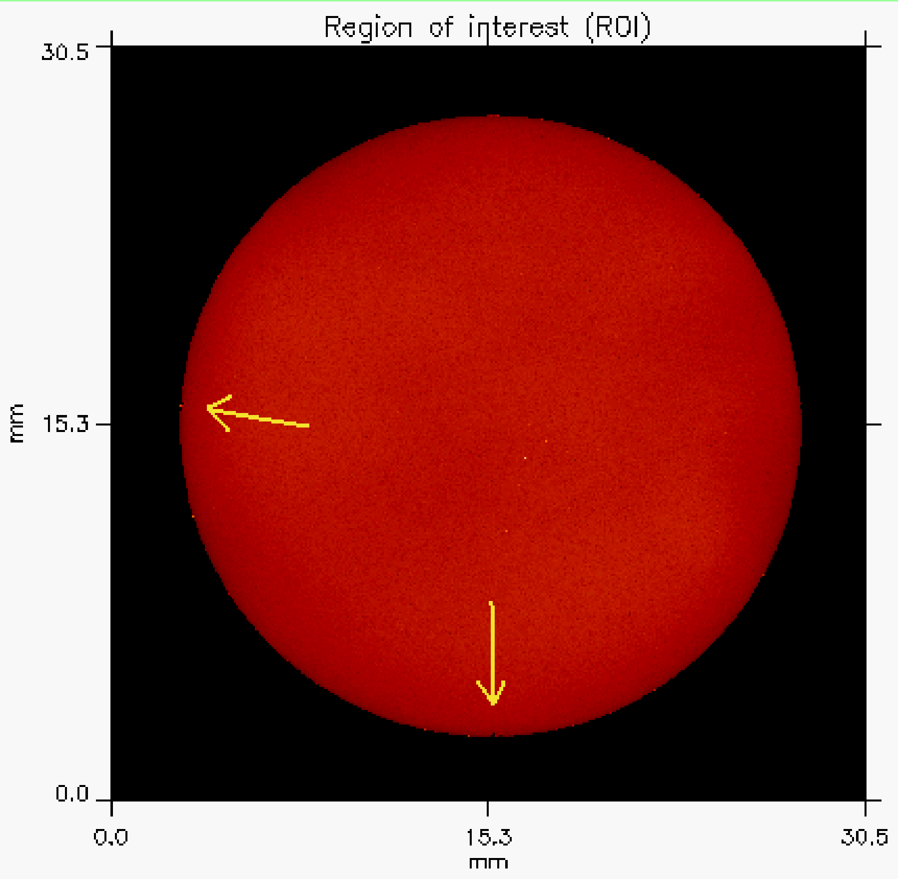


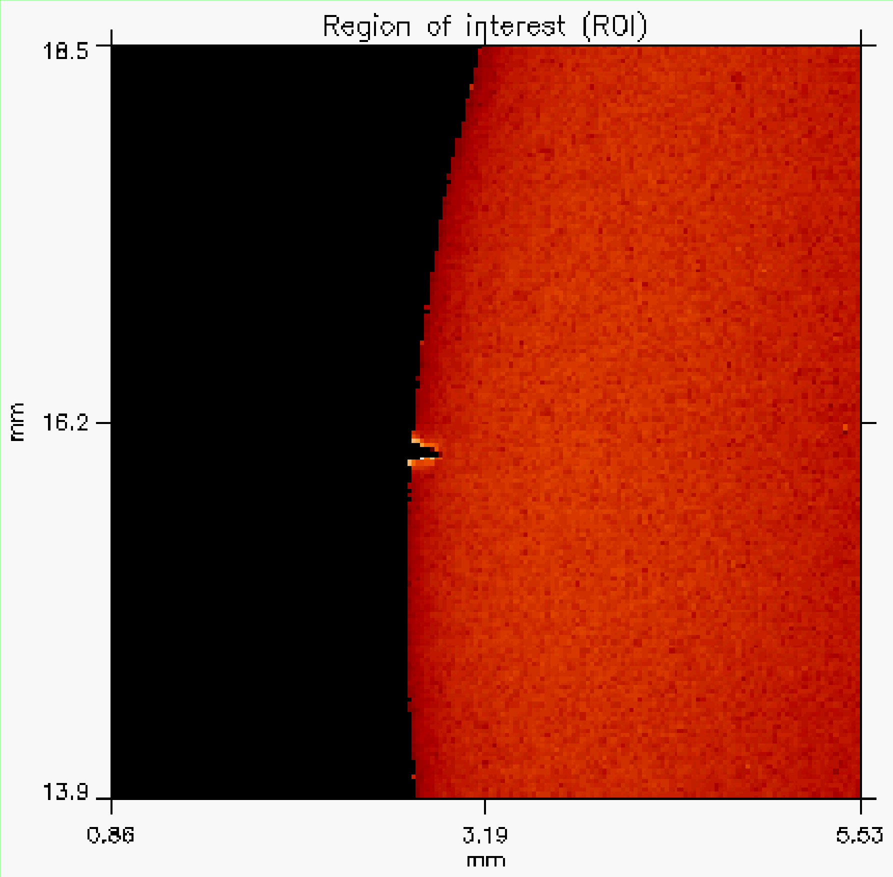
In most EFE locations it is difficult to identify the exact emitter position due to complex geometry of defects

AFM measurements are required for β_{geo} estimation of small structures

Results on single crystalline Nb samples from TJNAF

In order to investigate the possible advantages of single crystalline Nb for SRF, 4 round samples with varying BCP damage layer removal (20, 40, 80, 120 µm) and two marks at the edge for clear orientation have been measured with OP.

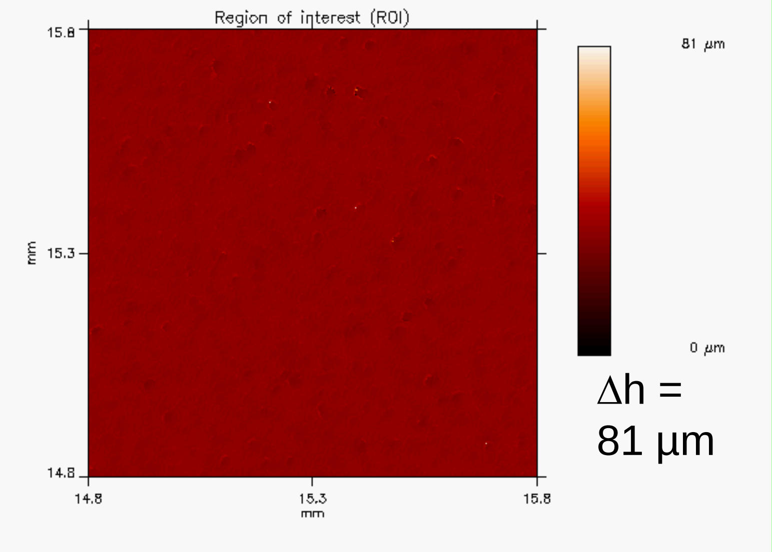




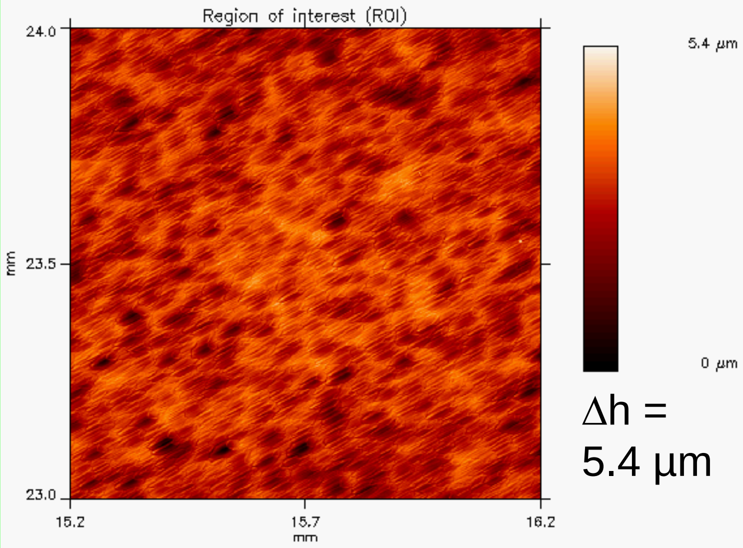
OP of single crystal Nb for different BCP layer removal

scanned area 1×1 mm^2

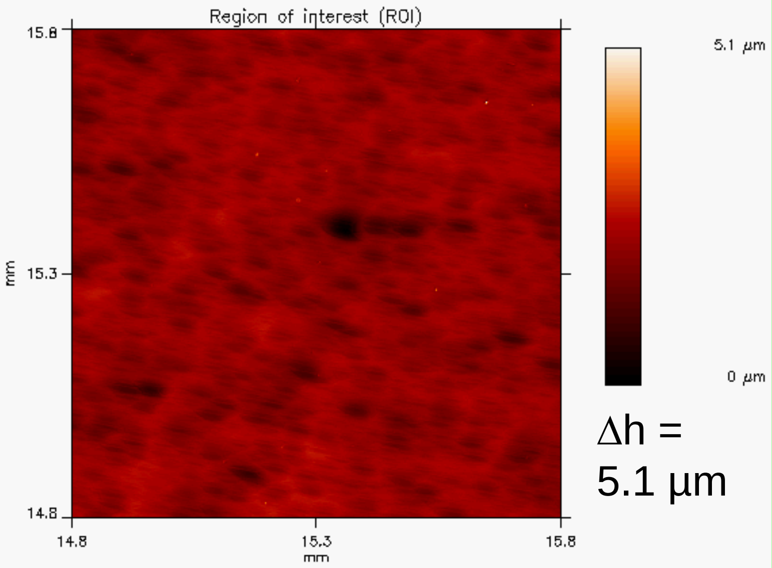
BCP 20 µm



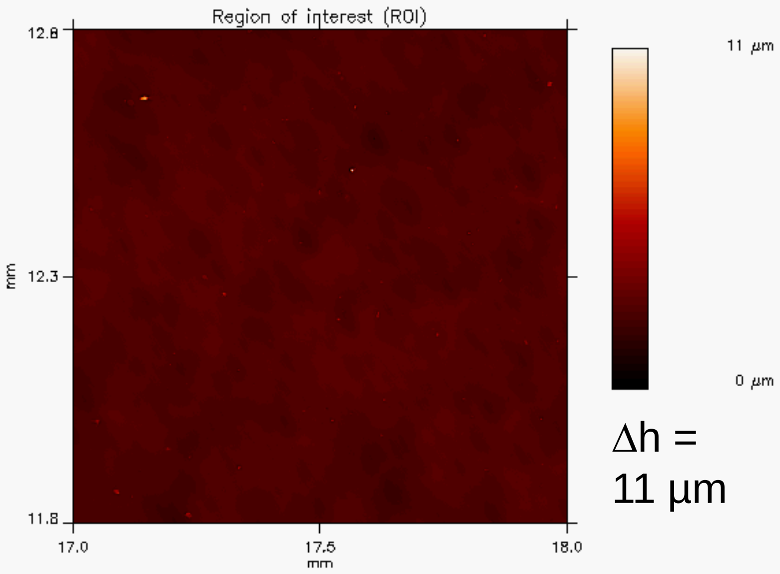
BCP 40 µm



BCP 80 µm

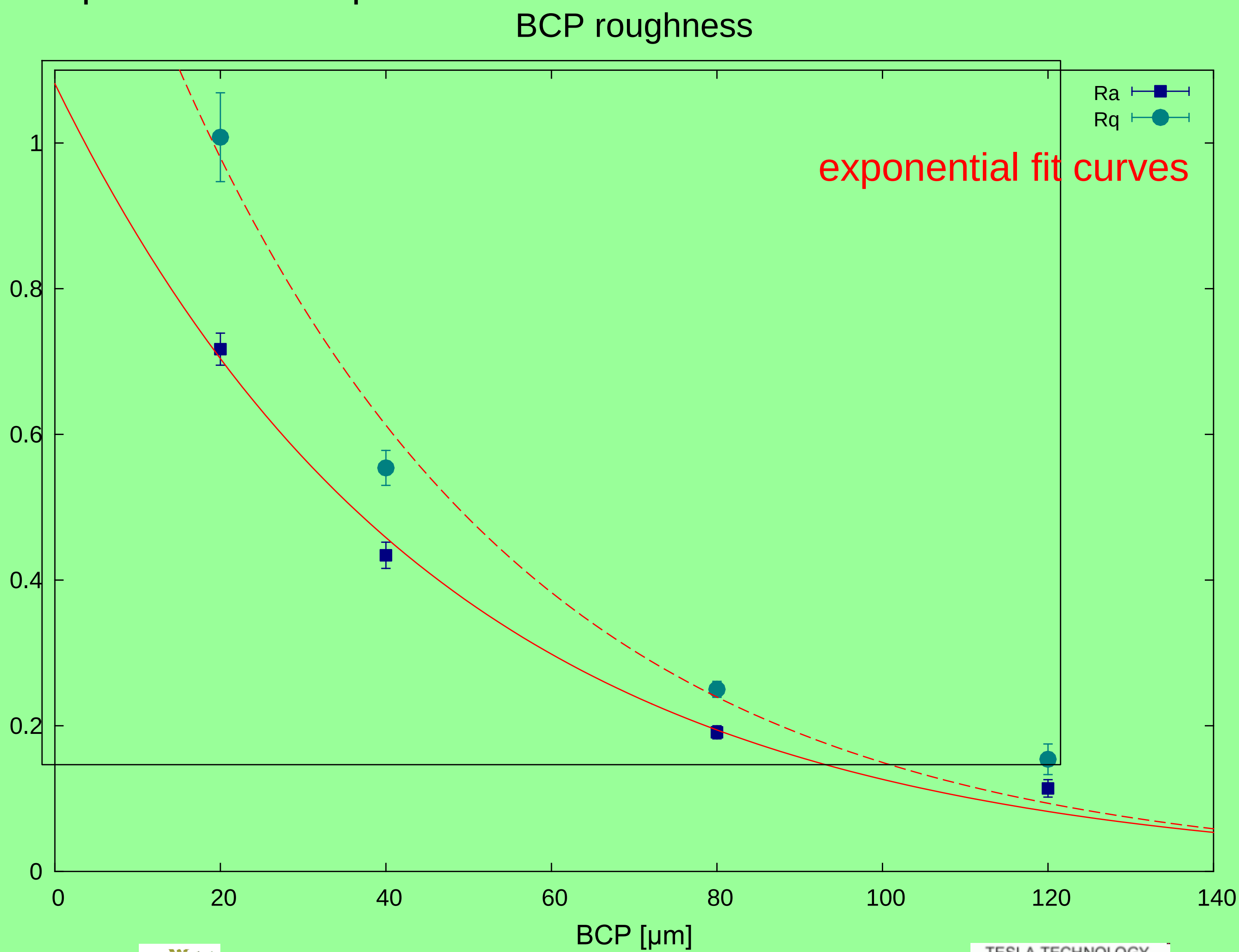


BCP 120 µm



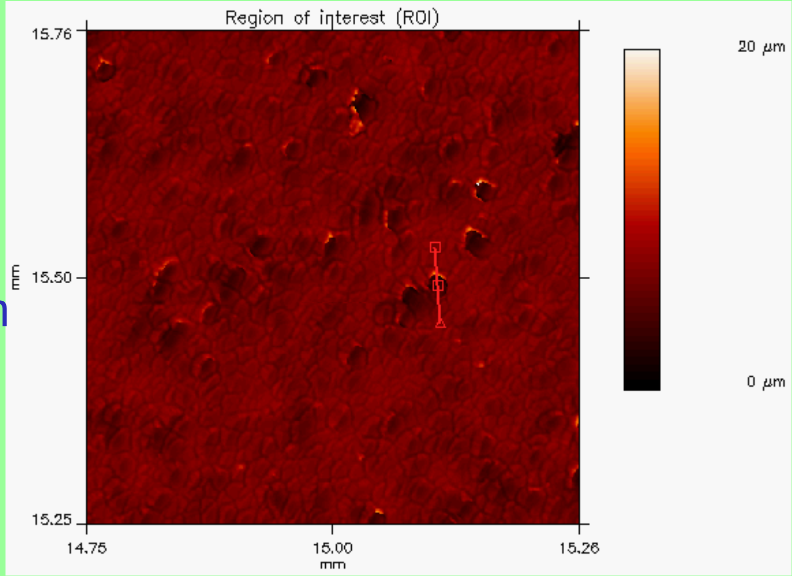
Average surface roughness of single crystal BCP-Nb

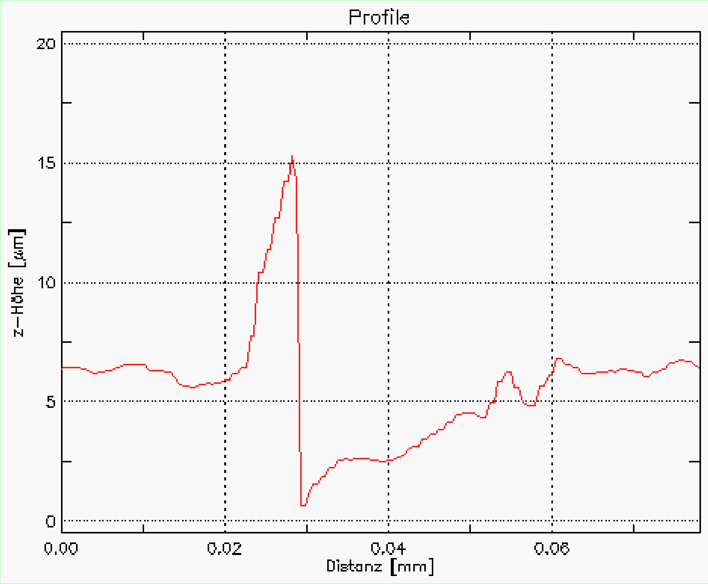
Each point based on profiles in 10 different defect-free areas of 1 mm^2



Regular pit-like features on single crystal BCP-Nb

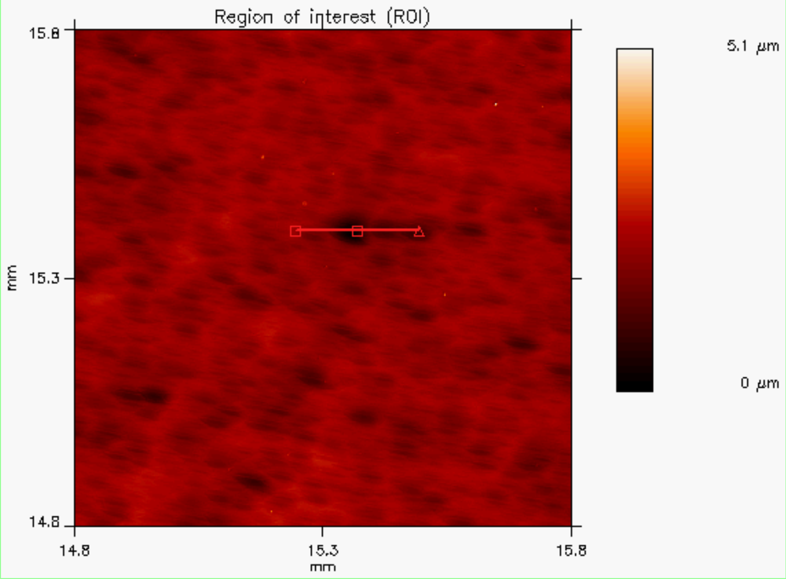
BCP
20 µm

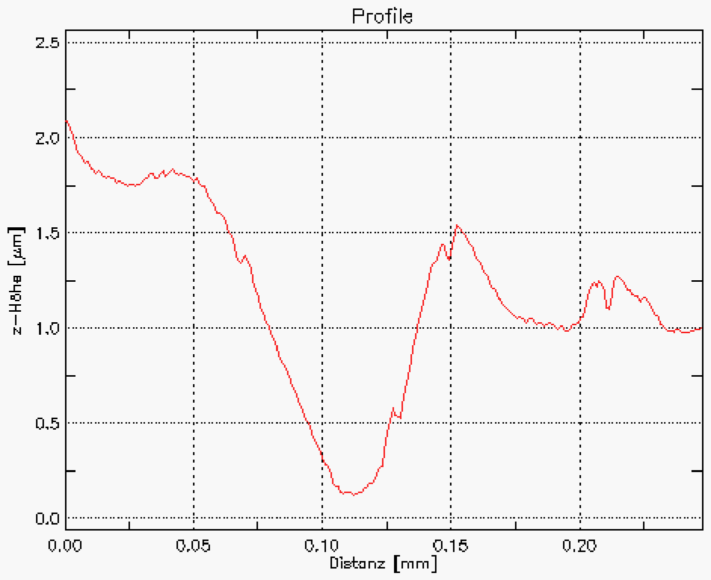




~ circular
sharp rim
average
∅ 30 µm
Δh 5 µm

BCP
80 µm

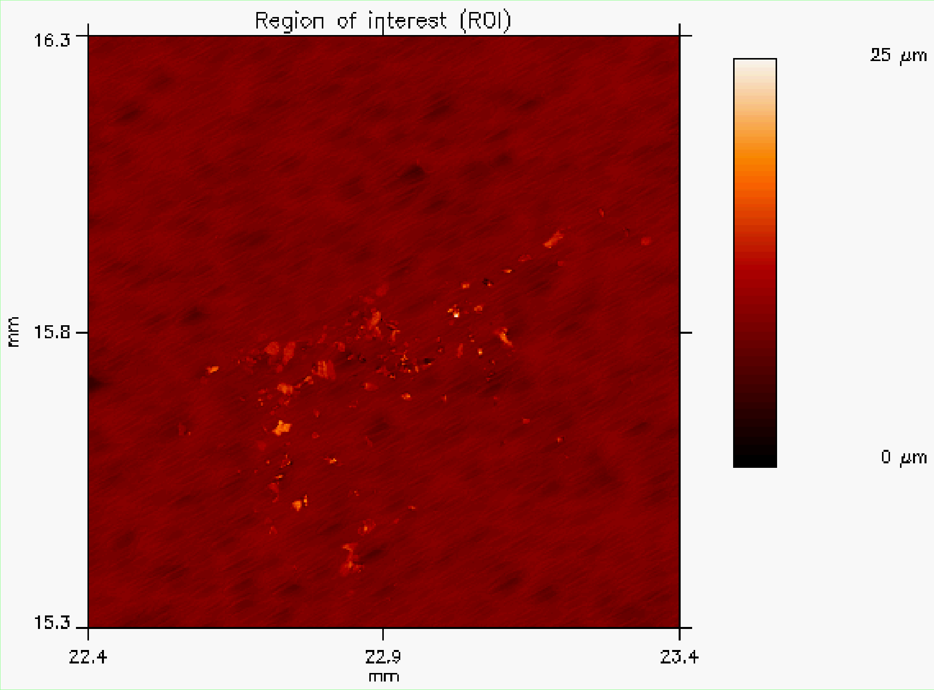




elliptic
no rims
average
∅ 60 µm
Δh 1.5 µm

Few local defects found on single crystal BCP-Nb

All samples showed a few local defects (> 5 µm) which might cause EFE

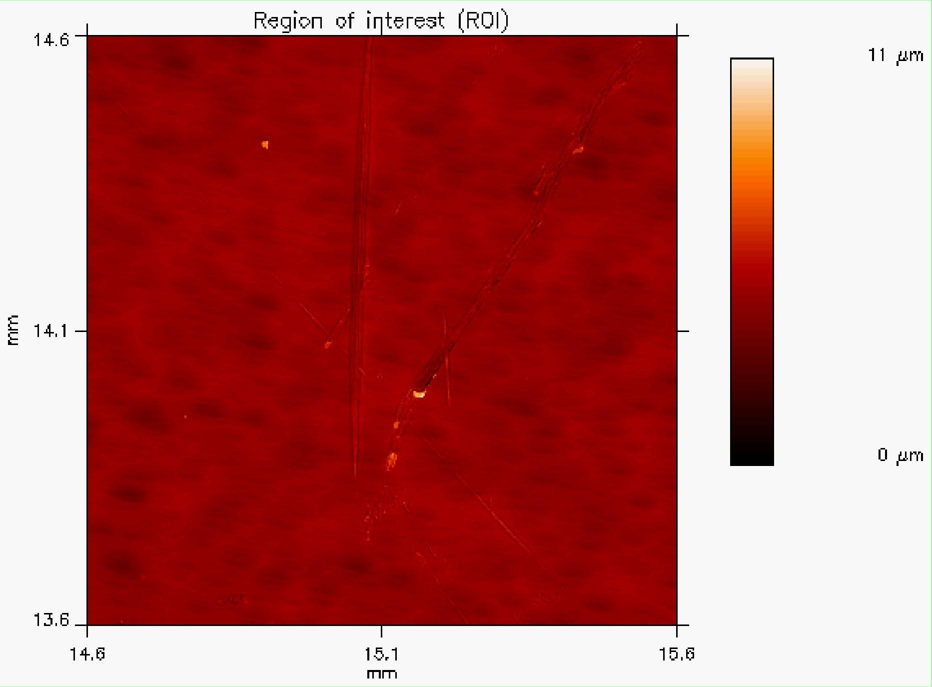


BCP 40 µm

accumulated particulates

average size ~ 22 µm, Δh 5 = µm

resistant against nitrogen blow



BCP 80 µm

long scratch (~ 0.8 mm)

mean width 100 µm, depth 1-2 µm

at one end peak Δh = 10 µm

Conclusion and outlook

- OP of Nb samples (> µm) is suitable for fast quality control of processes

Results for polycrystalline samples:

- Particulates with $\beta_{E,max}$> 15 must be removed by HPR and DIC
- Scratches with $\beta_{E,max}$> 13 must be prevented by a more careful handling
- Grain boundaries (Δh ≈ µm), hills and holes are not harmful for EFE but probably cause magnetic field enhancement and limitation?
- Emitter density of EP/HPR Nb samples increases exponentially with field
- Correlation between EFE, SEM and OP of localized emitters difficult

Results and outlook for single crystalline samples:

- Mean surface roughness decreases exponentially with BCP layer removal
- Regular pit-like features and few defects found, influence on EFE ?
- Correlation between EFE, SEM and OP of localized emitters will be easier
- Activation of various types of emitters by heating will be investigated soon