Surface roughness and correlated enhanced field emission investigations of electropolished niobium samples

A. Navitski[1], S. Lagotzky[1], G. Müller[1], D. Reschke[2], X. Singer[2]

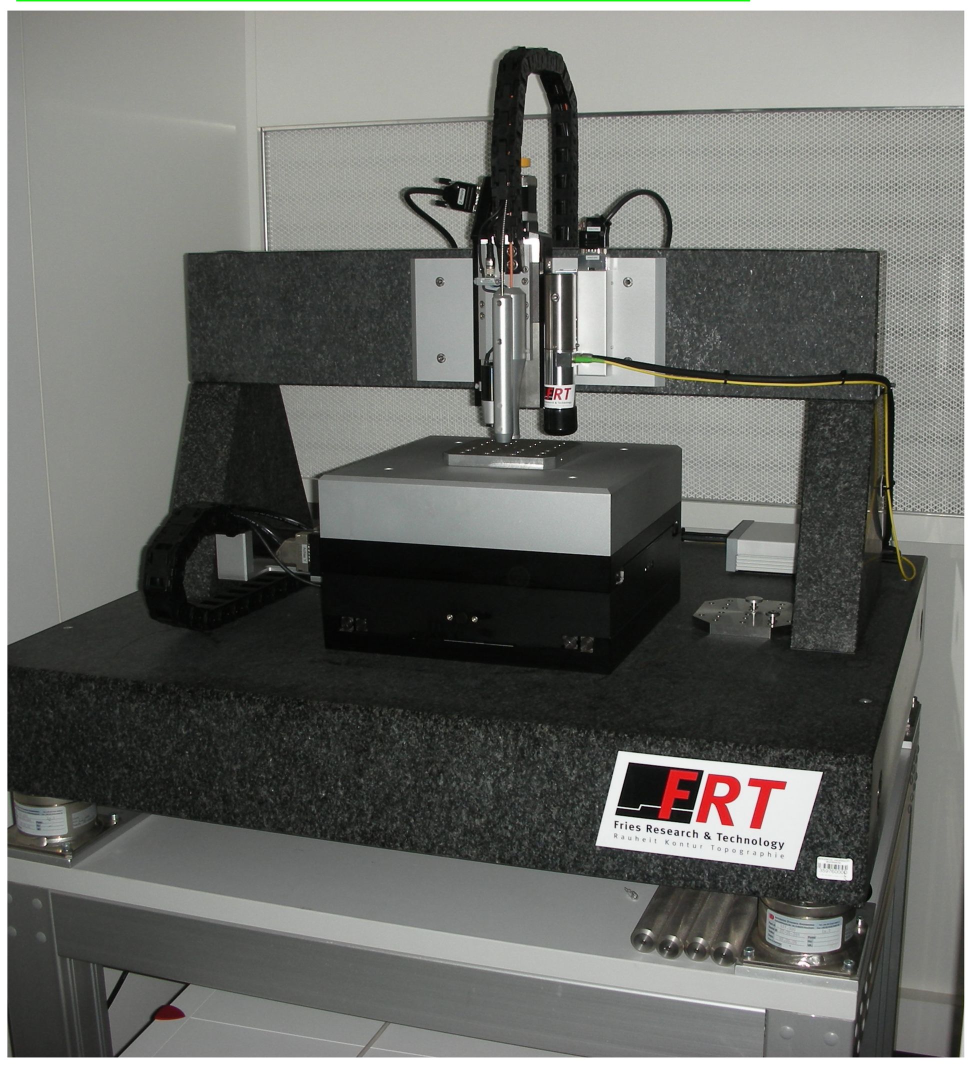
[1] University of Wuppertal, Physics Department, 42119 Wuppertal, Germany, navitski@physik.uni-wuppertal.de
[2] DESY, 22603, Hamburg, Germany

Motivation

Enhanced field emission (EFE) from particulate contaminations or surface irregularities is one of the main field limitations of the high gradient superconducting niobium cavities required for XFEL and ILC [1]. While the number density and size of particulates on metal surfaces can be much reduced by high pressure water rinsing [2], dry ice cleaning [3] and clean room assembly of the accelerator modules, the influence of surface defects of the actually electropolished and electron-beam-welded Nb surfaces on EFE has been less studied yet. Therefore, we have systematically measured the surface roughness of typically prepared Nb samples, some of which were cut out of a nine-cell cavity, by means of optical profilometry and AFM. Pits up to 800 µm diameter with crater-like centers and sharp rims as well as scratch-like protrusions were found even on mirror-like surfaces. An average surface roughness, step height of grain boundaries will be given with respect to magnetic field enhancement [4] which might cause high-field Q-drop and quenches. Electrical field enhancement factor of defects will be also derived.

Measurement techniques:

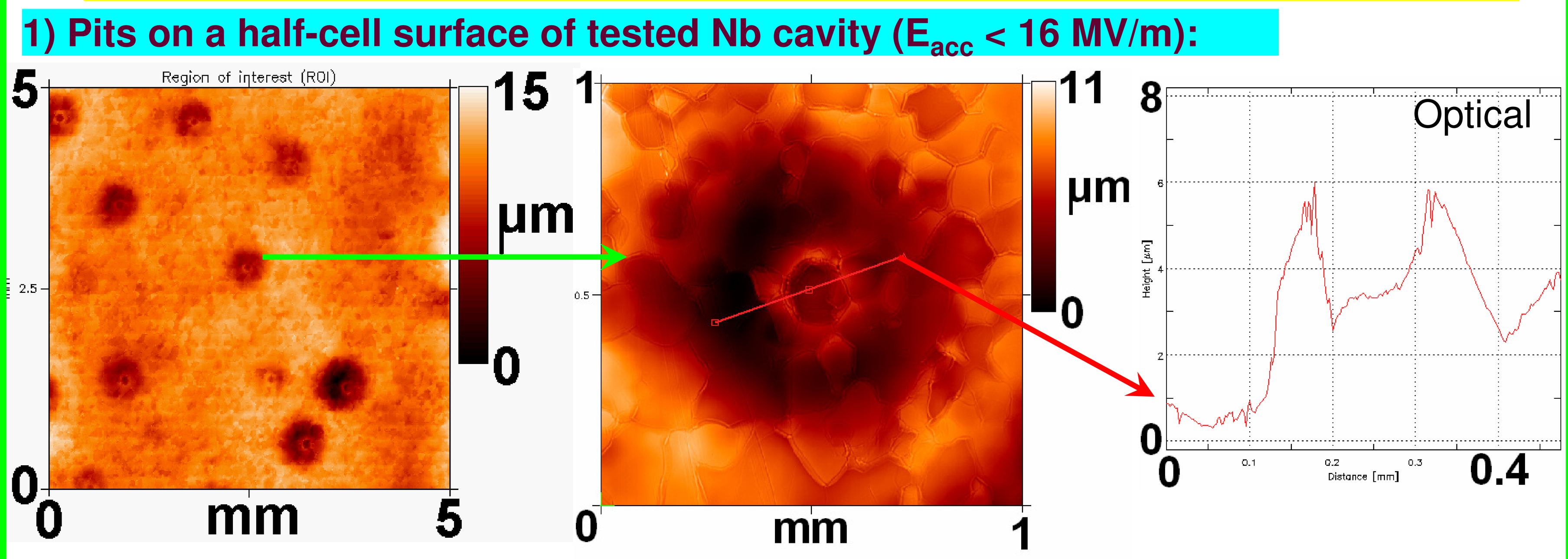
FRT optical profilometer with AFM



- granite plate with active damping system for nm measurement
- CCD camera for positioning control
- Optical profilometer:
  - white light irradiation and spectral reflection (chromatic aberration)
  - scanning range up to 20×20 cm² and 5 cm height difference
  - 2 µm lateral resolution
  - 3 nm vertical resolution
- further zooming by AFM:
  - 1 µm precision of positioning with respect to the optical profilometer
  - 34×34 µm² scanning range
  - 3 (1) nm lateral (height) resolution
  - contact or non-contact modes.
- clean laminar air flow from the back to reduce particulate contamination

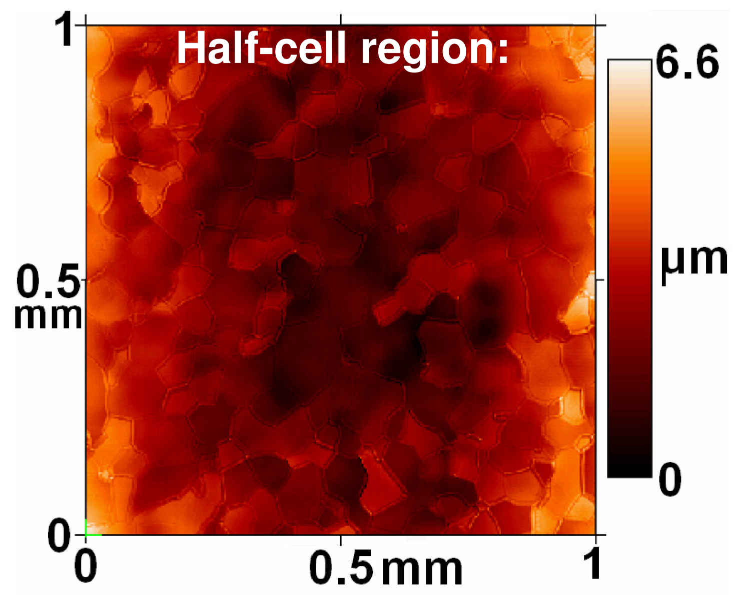
Investigations of 5 curved samples from nine-cell Nb cavity:

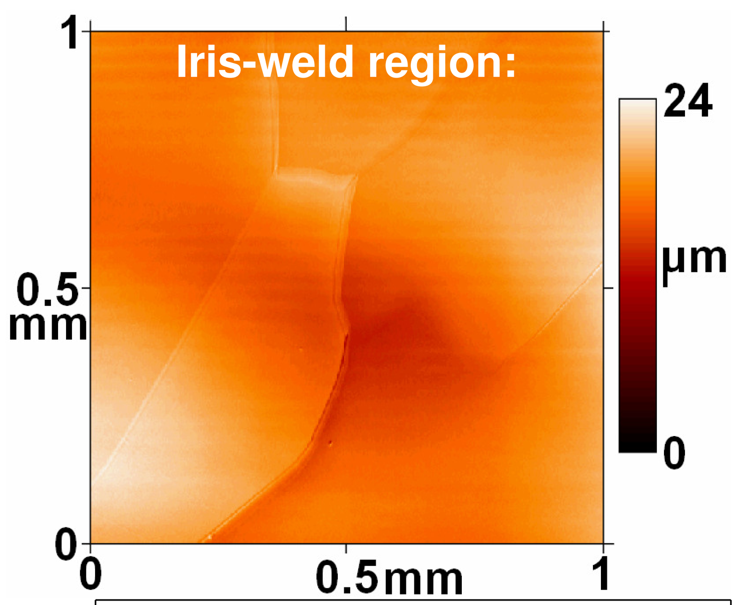
1) Pits on a half-cell surface of tested Nb cavity (E_{acc} < 16 MV/m):



⇒ ≤ Ø 800 µm with crater-like centers (~Ø 100µm) and sharp rims (5-10 µm height)
⇒ R_a = 0.418 µm, R_q = 0.557 µm, β_{max} ≈ 9.6
⇒ Hints for problems with washing off the acid solution after electropolishing

2) Comparison of grain boundaries:





Half-cell region	Iris-weld region
average grain size ≈ 152 µm	average grain size ≈ 640 µm
step height < 1.964 µm	step height < 1.917 µm
r ≈ 0.45 µm → β_{max} = 4	r ≈ 0.41 µm → β_{max} = 4.67
R_a = 0.180 µm	R_a = 0.115 µm
R_q = 0.250 µm	R_q = 0.159 µm

⇒ Welds have factor of ~4 larger grains but similar R_a, R_q and β values

Investigations of 6 flat Nb samples:

4 types of surface defects:
- particles,
- scratches,
- grain boundaries
- round hills and holes

Field enhancement factor β of all defects have been extracted from height h and curvature radius r and **maxima β_{max}** found

$$\beta = \frac{h}{r}$$

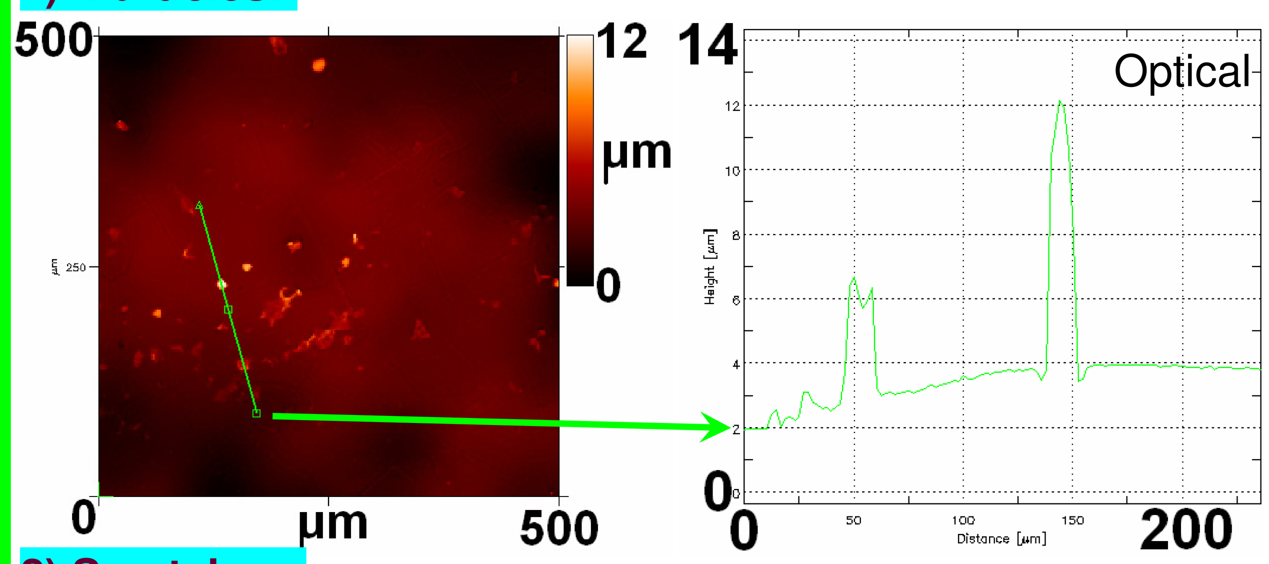
Definitions of surface roughness:

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

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

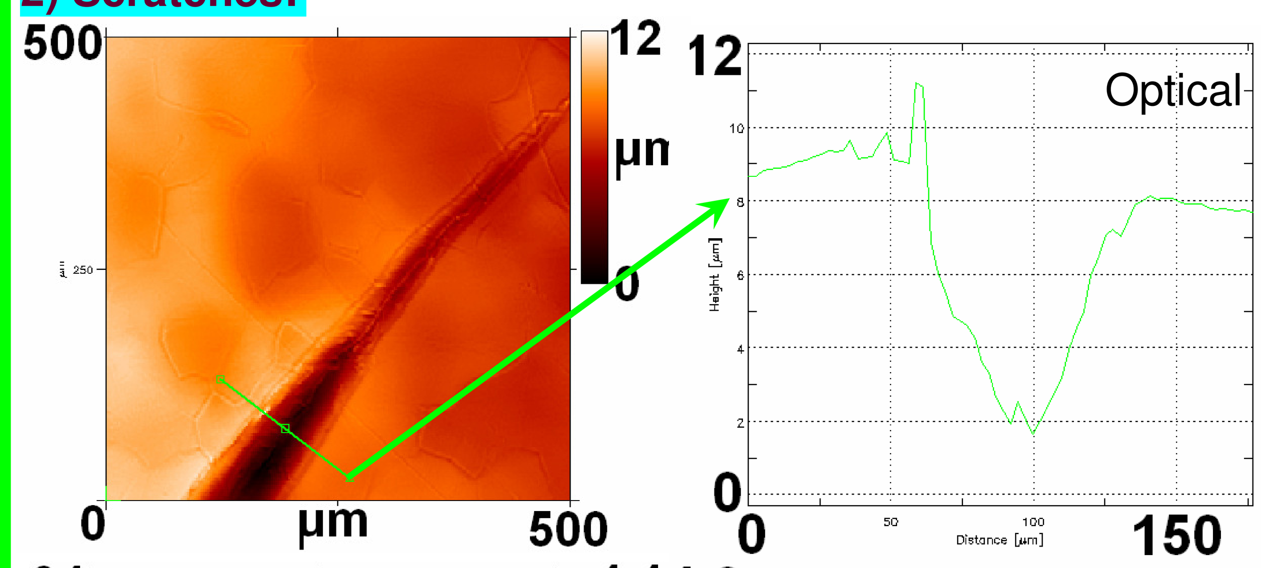
$z(x_i, y_j)$ = actual height value of profile
n, m = # of points in x and y direction
$\bar{z}$= average height value

1) Particles:

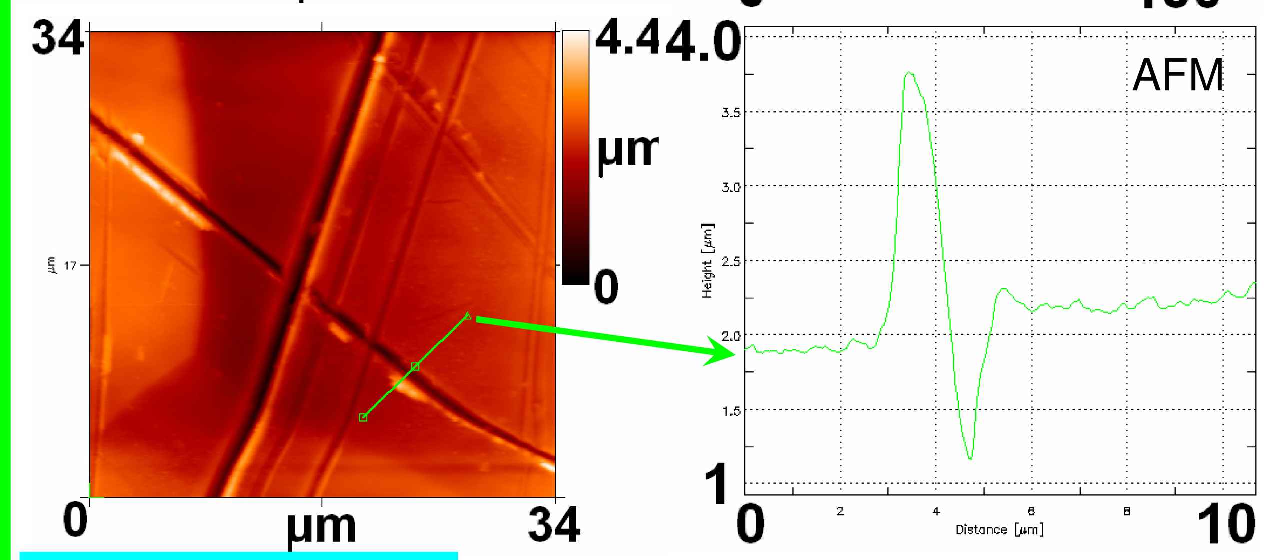


< 5 µm	43 %
5 - 15 µm	48.4 %
15 - 25 µm	6.1 %
> 25 µm	2.5 %
R_a = 0.276 µm	
R_q = 0.548 µm	
β_{max} = 14.55	

2) Scratches:

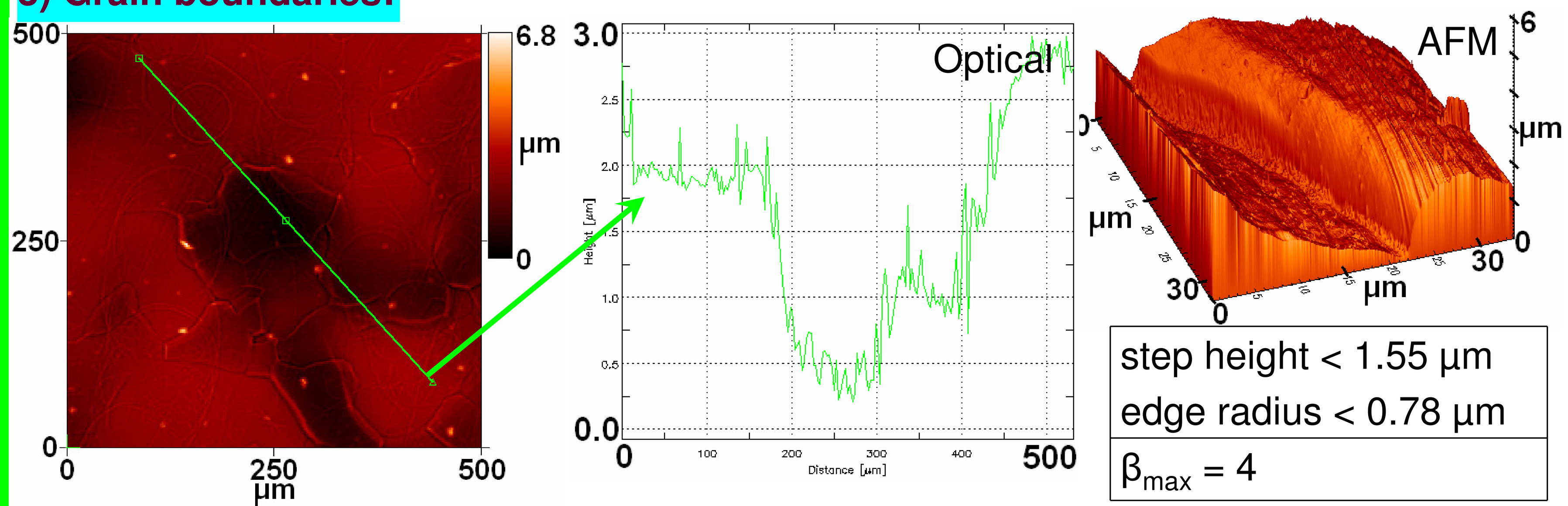


4 - 100 µm width
11 µm - 2.7 mm length (on average 326 µm)
ridge height < 10 µm



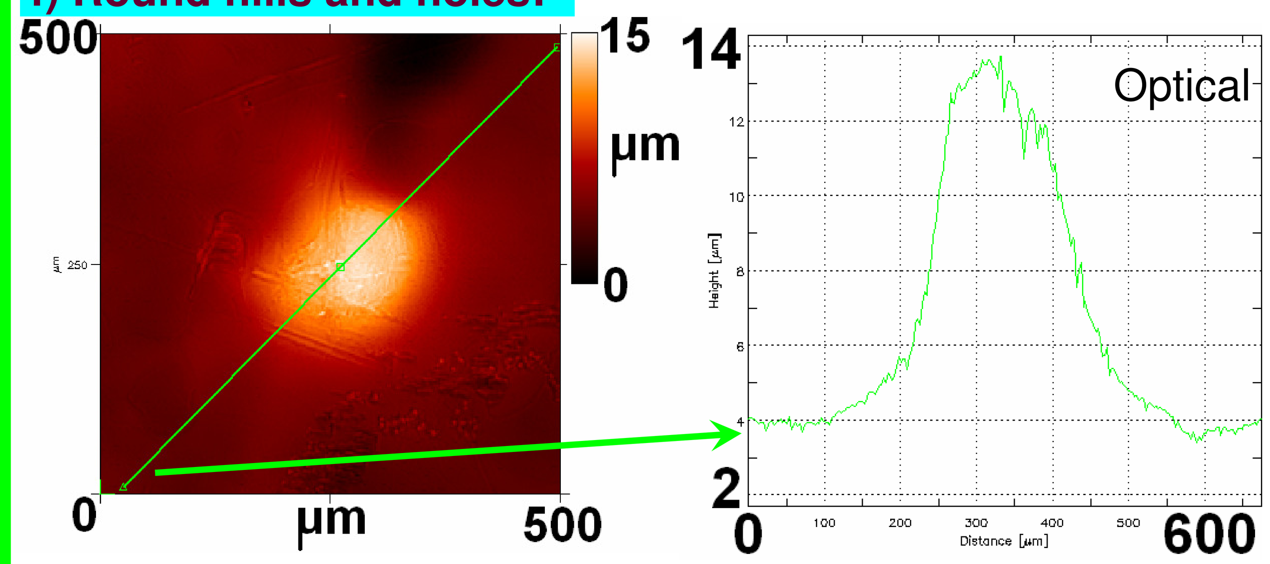
R_a = 0.466 µm
R_q = 0.646 µm
r < 0.77 µm
β_{max} = 12.94

3) Grain boundaries:



step height < 1.55 µm
edge radius < 0.78 µm
β_{max} = 4

4) Round hills and holes:



height < 17 µm
size 10 - 440 µm
R_a = 0.295 µm
R_q = 0.489 µm
β_{max} < 4

⇒ created most probably due to foreign material inclusions leading to modified chemical reactions during electrochemical polishing
⇒ small β → only weak EFE expected due to smooth edges

Conclusion and outlook

1. Combination of optical profilometry and AFM is suitable as fast quality control of electropolished Nb surfaces in terms of roughness and defects.
2. Remaining particles with β_{max}< 15 have to be removed by HPR and DIC.
3. Scratch-like protrusions with β_{max}< 13 must be prevented by a more careful handling.
4. Grain boundaries with step heights < 1.55 µm might reduce the magnetic field limit?
5. Round hills and holes with smooth edges cause less EFE but probably quench.
6. Pits with crater-like centers and sharp rims have been found on real cavity surfaces and hint for problems with the speed of acid removal after electropolishing.
7. Correlated field emission scanning microscopy will be performed after HPR (and DIC) of these samples especially in the localized surface defect regions.

References and Acknowledgements

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PHYSICS AT THE TERA SCALE Helmholtz Alliance