Laser polishing in the field of SRF cavities

Super Surfer project meeting in Wuppertal

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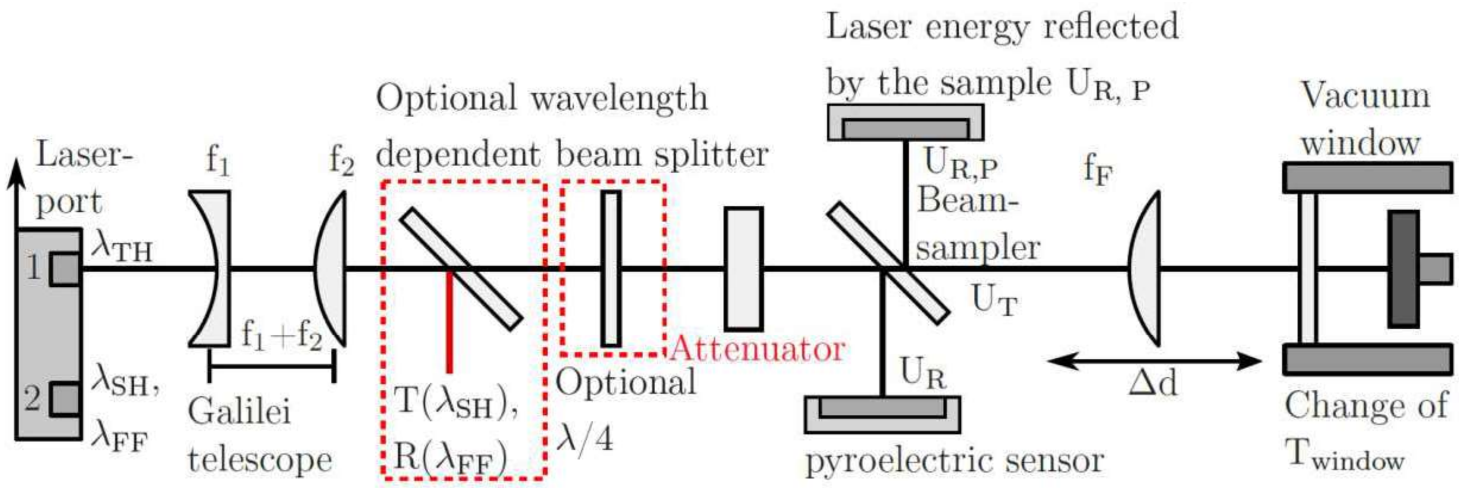
Project plan

Project plan

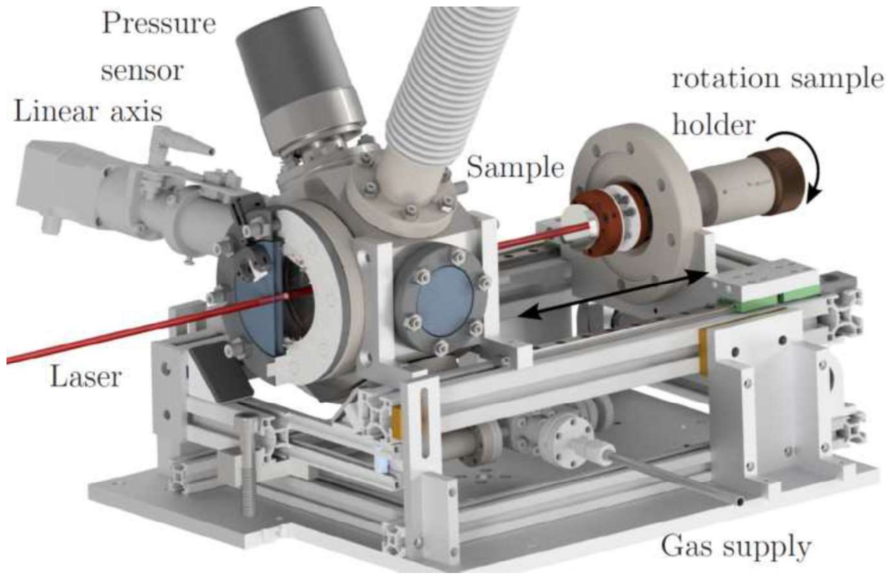
Work packages / milestones	2024		2025				2026				2027	
	III	IV	I	II	III	IV	I	II	III	IV	I	II
Modifications to the setup (laser), new hardware / software; first investigation of laser polishing of niobium and copper	x	x	x	o								
Modification + commissioning of scanning tunnelling microscope; first measurements of tunnelling spectroscopy on niobium, at low T	x	x	x	x	o							
Publication: Polishing of niobium with circularly polarised radiation; DPG-Spring + IPAC 2025			x	o								
Measurement of parasitic field emission of laser-polished material samples (Nb, Cu, layer systems); Publication + DPG-Spring		x	x	x	x	x	x	x	x	x	x	o
Field emission measurements, tunnelling microscopy and tunnelling spectroscopy in the cooperation Joint publication(s)		x	x	x	x	x	x	x	x	x	x	o

Experimental setup for laser polishing BUW

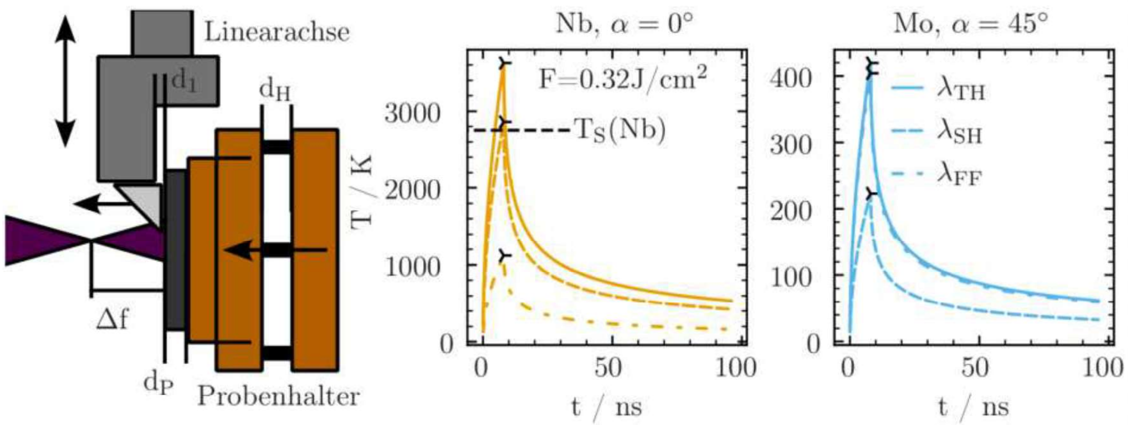


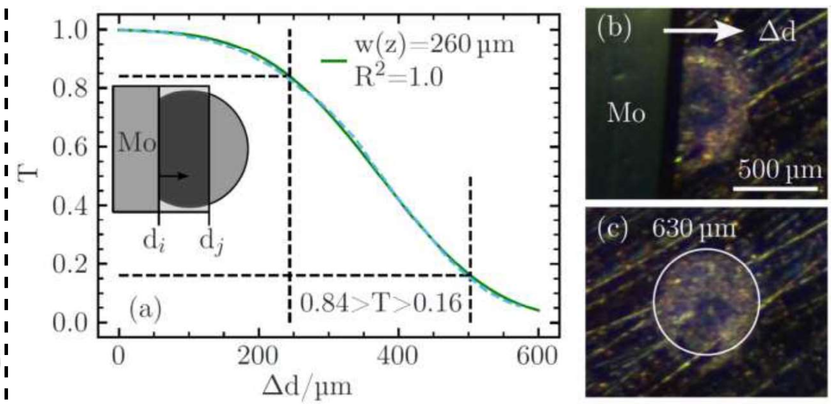
- **Telescope:** Change of laser diameter, d
- **Beamsampler:** Energy measurement, $U_{R,P}$, U_R
- **Focus lens (ΔA)** / **Beam attenuator (ΔU)**
  Change of F=U/A
- **$U_{R,P}/U_R$**: Influence of the transmission of the window + change in the reflectivity of the sample + Influence of surface waviness
  ⇒ Changes observable as a result of the LP
- **Pressure measurement:** ΔP Indication of the modification of the surface
- **Electrical signals:** Charge emission as a result of the laser pulse
- **Beam profile camera:** Measurement of the beam profile ⇒ better alignment, more precise determination of F
- **Long-range microscope:** Insitu inspection of surface modification
- **Beam shaper:** Convert Gaussian profile to top hat profile

Vacuum chamber



- Extension of the vacuum chamber by a movable cutting edge to determine the beam diameter at the sample surface
- Beam diameter unclear ⇒ so far only possible indirectly by measuring the damage by SEM or optical microscope
- Selection of the material of the cutting edge with analytical solution of the heat conduction equation , W, Ta, Mo
- Measurement shows discrepancy between beam diameter and size of surface damage

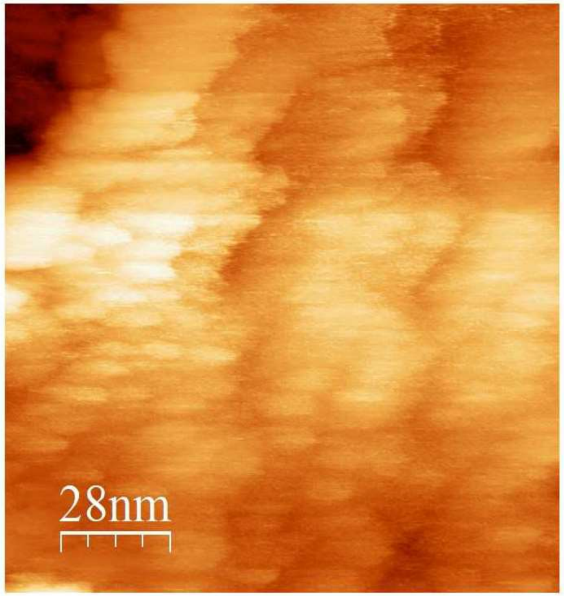


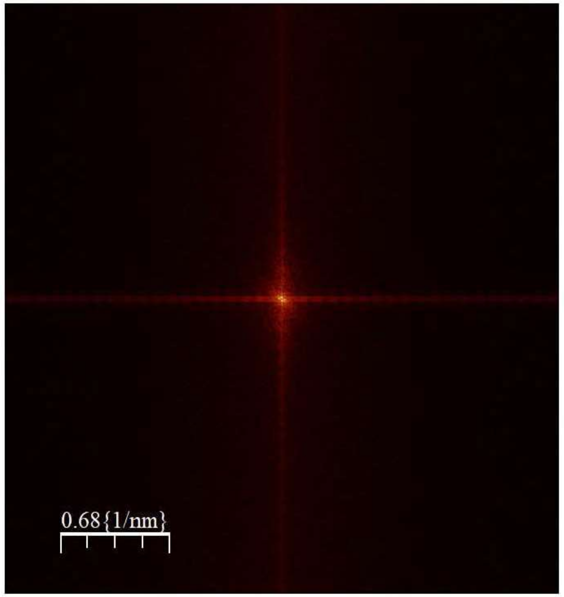


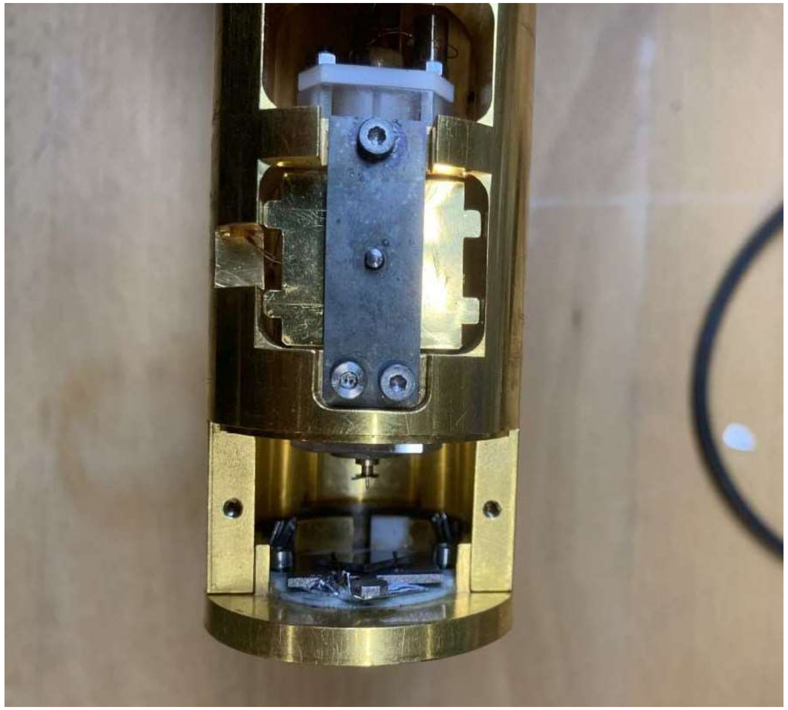
First results of the STM measurements

Low temperature STM measurements

- Large grain, (110)-oriented Nb-samples, standard DESY treatment, mirror-like polish
- Dip-stick STM, temperatures down to 4 K with LHe-cooling ($\Delta E \approx 1.5 - 1.8$ meV)
- Topography + tunneling spectroscopy (at low T, i.e. 4 – 7 K)







$\Rightarrow$ no atomic resolution at 4 K. FT does not provide (periodic) interatomic distances

BSc. Thesis T. Köster, Wuppertal (2025)

Low temperature STM measurements

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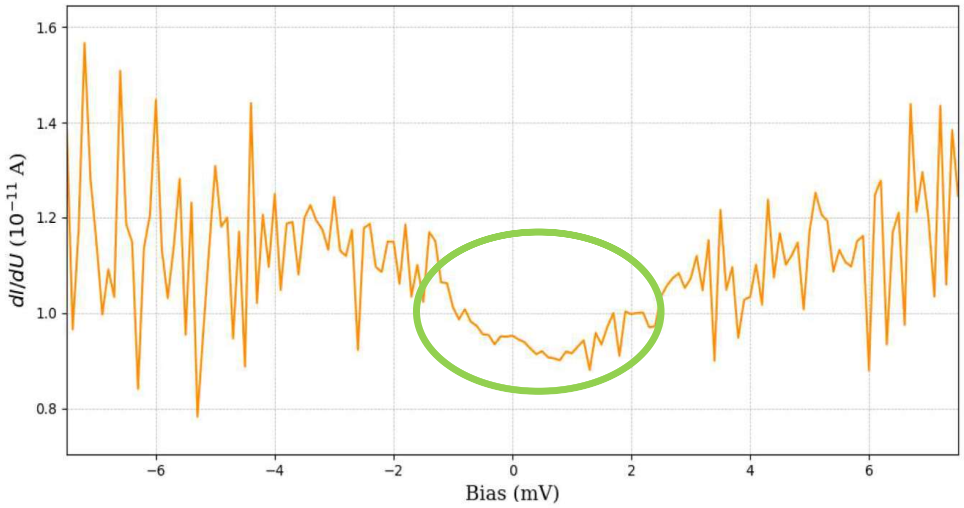
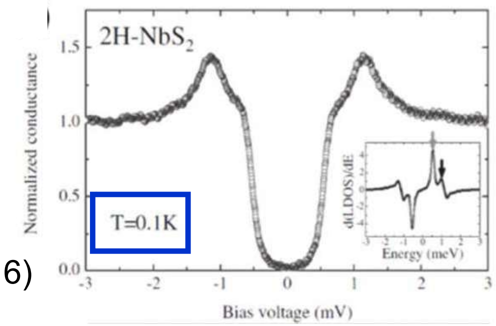
- Tunneling spectroscopy (T = 4.7 K):



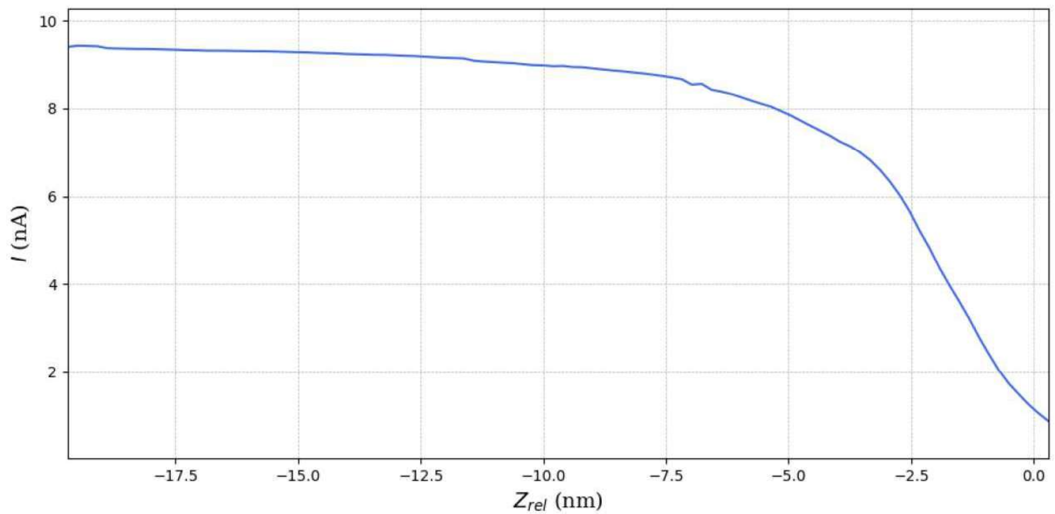
⇒ No indications for superconducting gap (Nb: $E_g \approx 2.3$ meV)



(Quantum Frontiers 3 (2024) 6)

Compare Sci. Rep. 10 (2020) 3794

- Z-spectroscopy (T = 4.7 K): Variation of tunneling distance (z) below the working point (z=0)



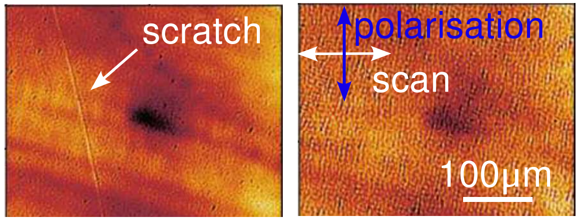
⇒ Exponential increase of tunneling current down to z=-2.5 nm

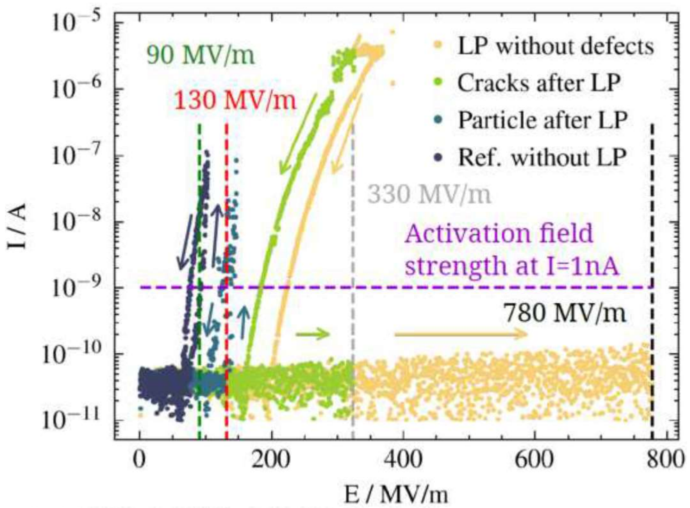
⇒ Then saturation *below* I_{max} (10 nA): Point contact with high resistance.

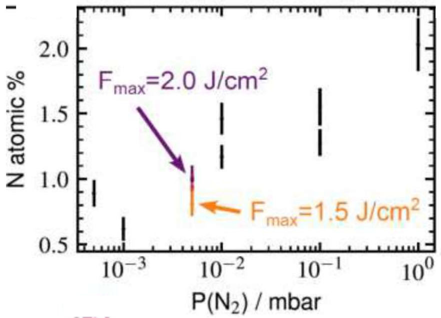
⇒ Influence of oxide layer (passive layer) on Nb due to contact with air?

BSc. Thesis T. Köster, Wuppertal (2025)

Laser material treatment of copper wafers with Nb_3Sn layers (HZB)







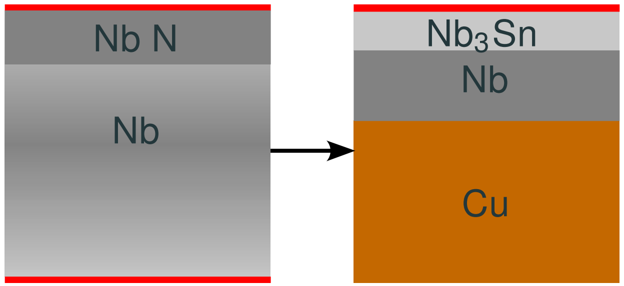
Previously: Examination of Nb

- Polishing (macro / micro)
- Suppression of field emission
- Oxide removal
- Nitrogen incorporation
- Recrystallization

⇒ from bulk to thin-film

In the future

natural oxide



Different thin-film systems possible

Laser material processing

Near-surface treatment

⇒ Depth approx. < 2 µm (depending on the process parameters)

⇒ Positive influences on thin films

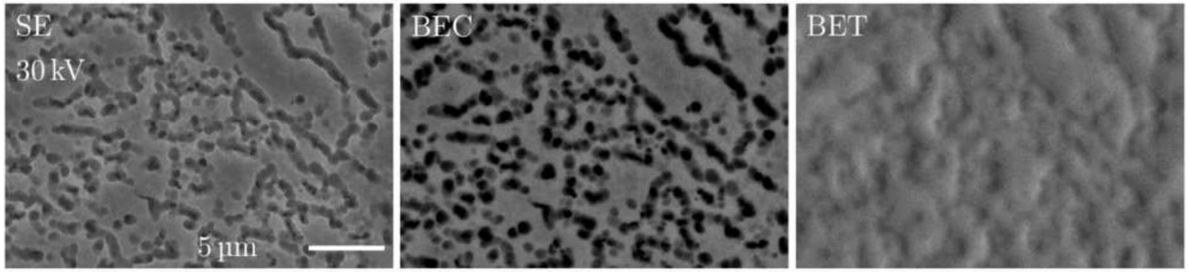
⇒ Polishing (?) Remelting (?) Crystal growth (?)

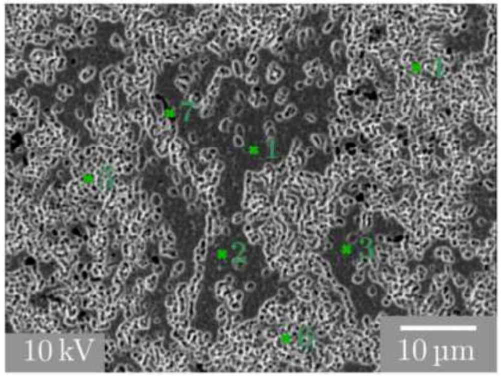
Laser material processing of alloys very challenging

Nb_3Sn ⇒ Material parameters differ greatly

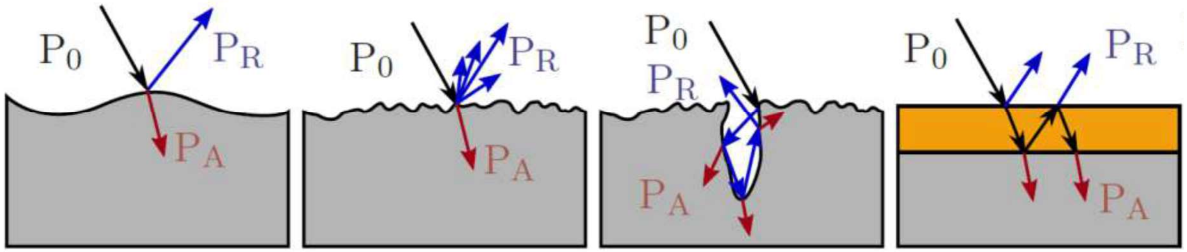
	T_M / K	T_V / K	λ_F / W/(kg·K)	c_p / J/(kg·K)	H_f kJ/mol	H_v kJ/mol
Nb	2750	5014	54	260	26.8	694
Sn	505	2859	66.8	229	7.03	296.1

Initial state of the Nb_3Sn layers





	O Atom %	C Atom %	Sn Atom %
P_1	5.65	13.7	21.38
P_2	7.28	11.8	20.59
P_3	8.05	15.78	22.49
P_4	10.69	11.74	11.7
P_5	6.54	16.56	13.33
P_6	7.88	0.0	8.97
P_7	7.52	38.22	9.86



(a) (b) (c) (d)

Nb_3Sn:

- $Nb_{1-\beta}Sn_\beta$ (approx. $0.18 < \beta < 0.25$)
- Surface roughness must be in nm range

⇒ superconducting coherence length 4 nm

Sample:

⇒ Nb_3Sn on Cu from HZB

⇒ Produced via bronze route

Initial state

- EDX measurement A=0.2 mm^2:

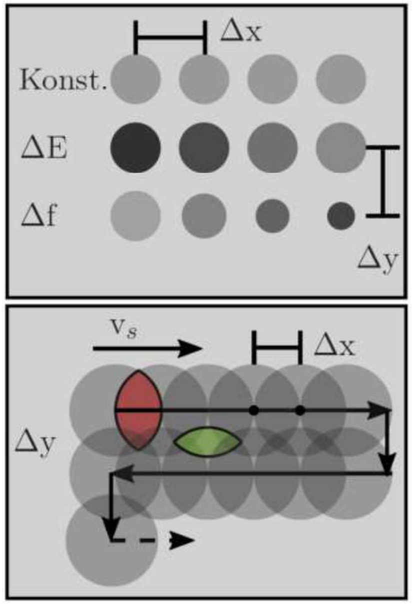
⇒ Sn(min/max)=(5.4/20.8) atom / %, $\overline{Sn}$=14.7±4.1 atom / %

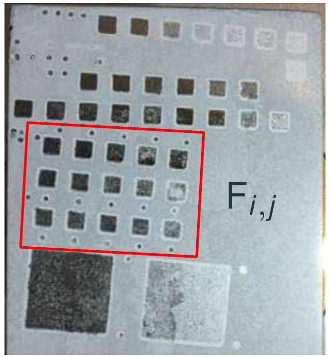
⇒ porous surface reason for fluctuating tin concentration

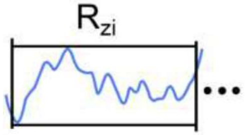
Laser material processing

Inhomogeneous composition and texture are problematic

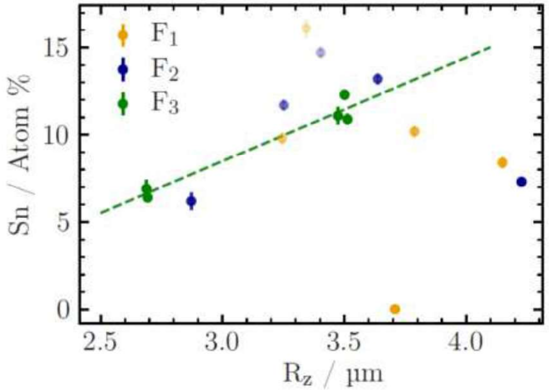
First results of Nb_3Sn laser polishing

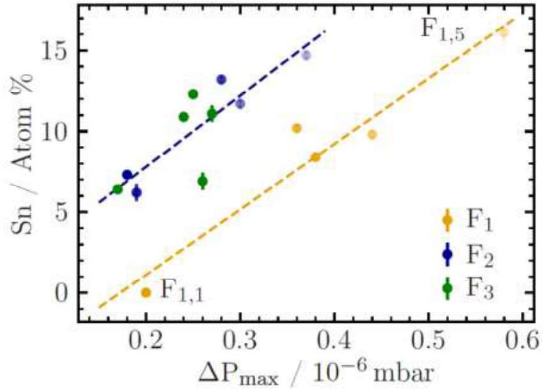




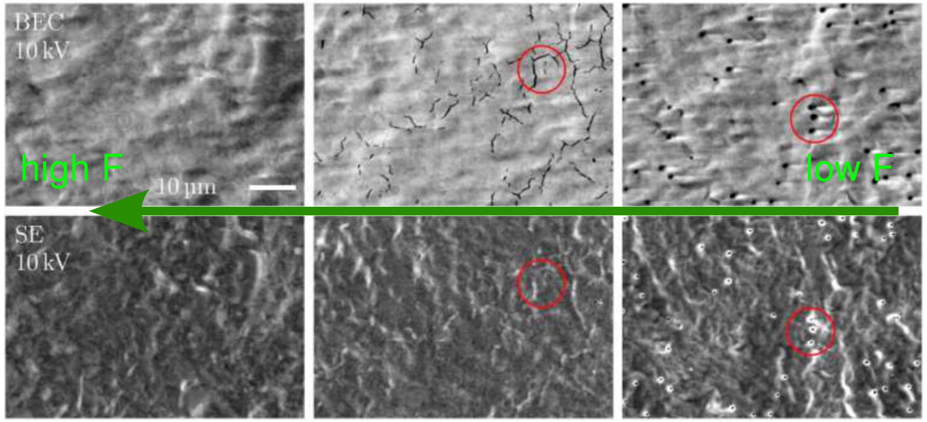


R_z Sensitive to peaks





	konst.	Change	$F_{i,1}$	$F_{i,2}$	$F_{i,3}$	$F_{i,4}$	$F_{i,5}$
$F_{1,j}$	Δf=3.5 mm	Δ(x,y) / µm	62.5	50	40	31.25	20
$F_{2,j}$		Δ(x,y) / µm Δf / mm	62.5 4.5	50 5.5	40 6.5	31.25 7.5	20 8.5
$F_{3,j}$	Δf=6.5 mm, Δ(x,y)=40 µm	/					



$F_{1,5}$ $F_{2,1}$ $F_{2,4}$

Point and area measurements

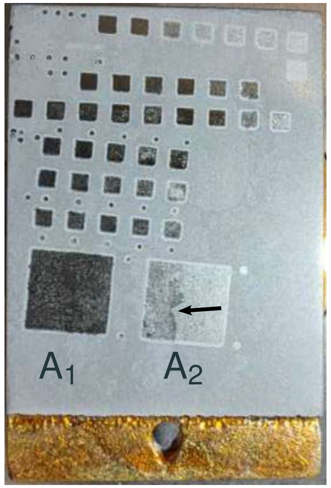
⇒ Correlation Sn R_z

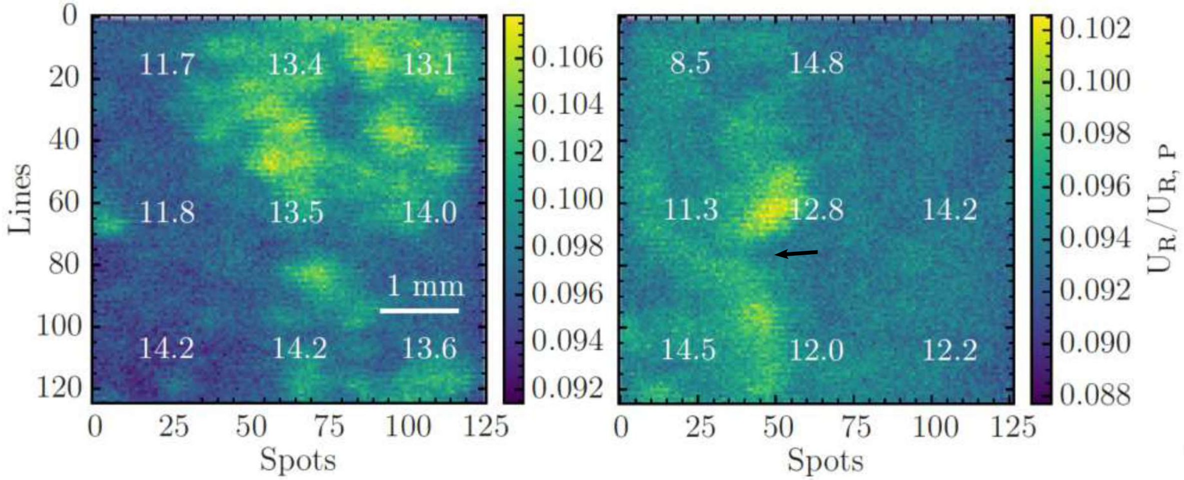
⇒ Correlation Sn ΔP

⇒ Higher Sn losses and R_z at higher F and lower $\Delta(x, y)$

⇒ Surface artefacts at low F

First results of Nb_3Sn laser polishing





EDX measurement

Sn in atom %

↓

Measurement at different locations

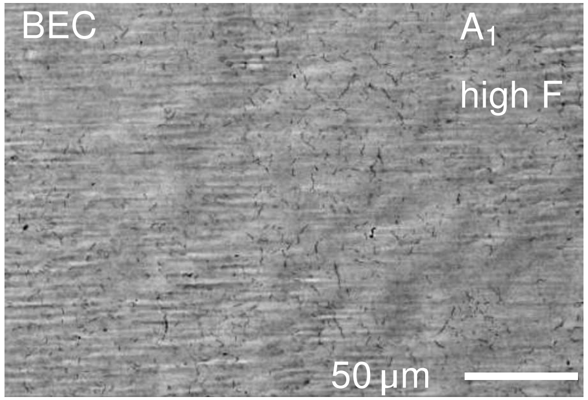
Constant laser parameters over the entire areas $F(A_1)>F(A_2)$

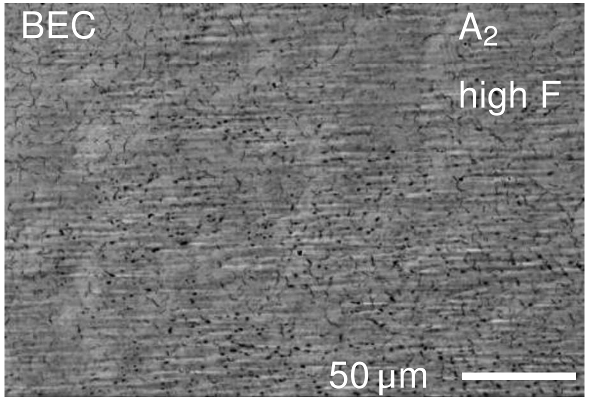
⇒ Differences in reflectivity

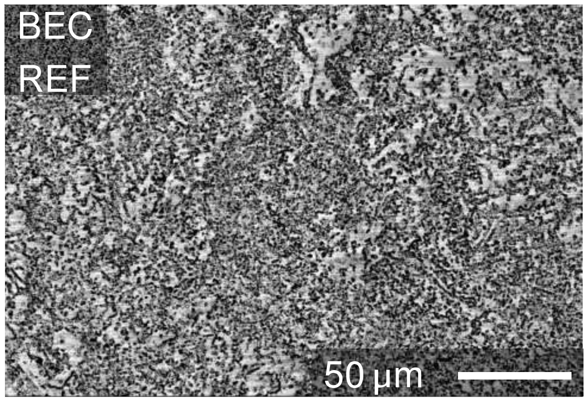
⇒ Change in reflectivity measurable in the reflected laser energy

⇒ Origin unclear

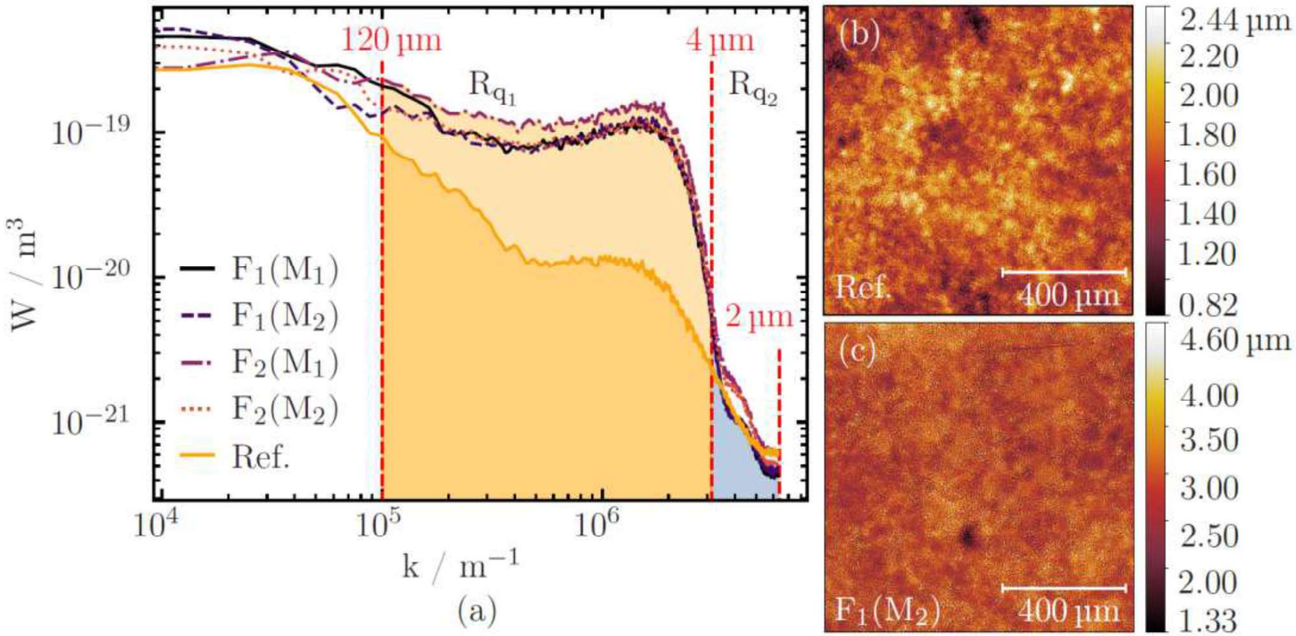
⇒ Further measurements necessary







PSDF analysis



	$F_1(M_1)$	$F_1(M_2)$	$F_2(M_1)$	$F_2(M_2)$	Ref.
R_{q_1} (120 µm, 4 µm) / nm	518	517	591	514	242
R_{q_1} (4 µm, 2 µm) / nm	56	56	69	64	55

PSDF analysis and calculation of R_q in defined frequency range

$F(F_1)>F(F_2)$

⇒ higher roughness with lower F

⇒ Sn effect

No wavy structures due to laser treatment

Roughness increased by laser treatment in the entire frequency range

⇒ No significant increase for low roughness

⇒ Decide on micro-roughness for field emission

First results of Nb-thin film / Cu laser polishing

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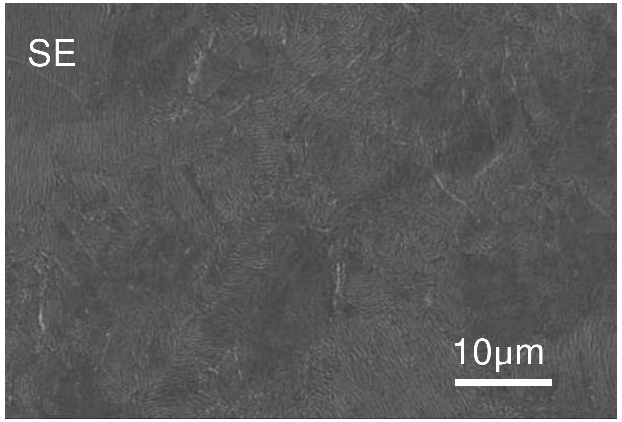
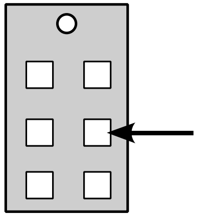


Characterize before laser polishing

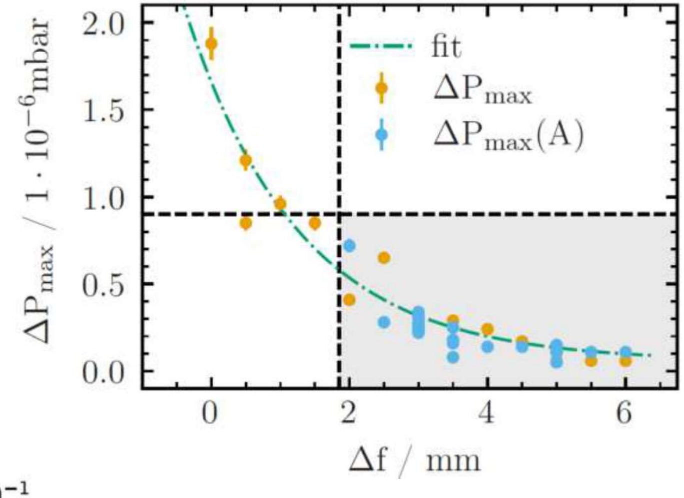
R_z=0.56±0.06 µm

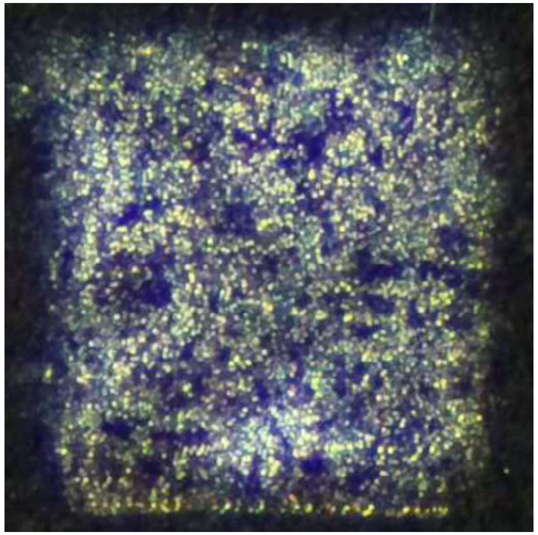
O Atom



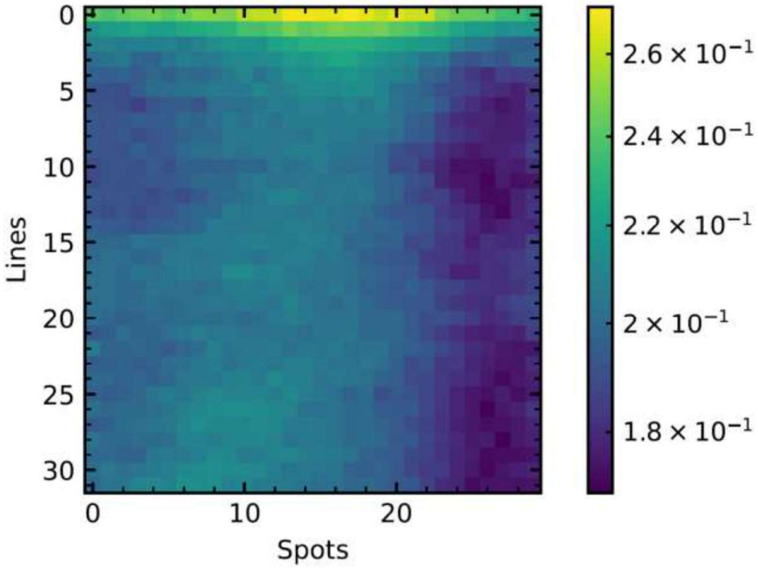
First characterize

then laser





Optical microscope



U_R / $U_{R,P}$

Spot and area measurements

1x1mm^2 measurements with

change of polishing parameters

Goal:

Remelting + crystal growth

Δf=3 mm, Δx=Δy=31.25 µm

⇒Further analyses +

Nb_3Sn coating

Summary & Outlook

Summary & Outlook

- Commissioning of the new hardware
  ⇒ Beam profile camera, long-range microscope, beam attenuator
- Extension of the vacuum chamber to enable the beam diameter at the sample surface to be determined
- First investigations of Nb_3Sn layers on Cu
  ⇒ porous surface, fluctuating Sn concentrations and very different material parameters are a challenge

⇒ Sn loss due to laser treatment and increase in roughness

⇒ Polishing of Nb_3Sn layers questionable but remelting, Crystal growth, homogenization possible

1. **Idea:** Creation of layers with higher Sn concentrations to compensate Sn loss
2. **Idea:** Polishing of Nb layers on Cu ⇒ then Nb_3Sn coating
   ⇒ Prevention of porous coating
   ⇒ First results but further investigations necessary

Thank you very much for listening!

Thanks for support by

HZB:
Cooperation by Nb_3Sn

HZB Helmholtz Zentrum Berlin

DESY:
Measurements at Petra III and extensive cooperation

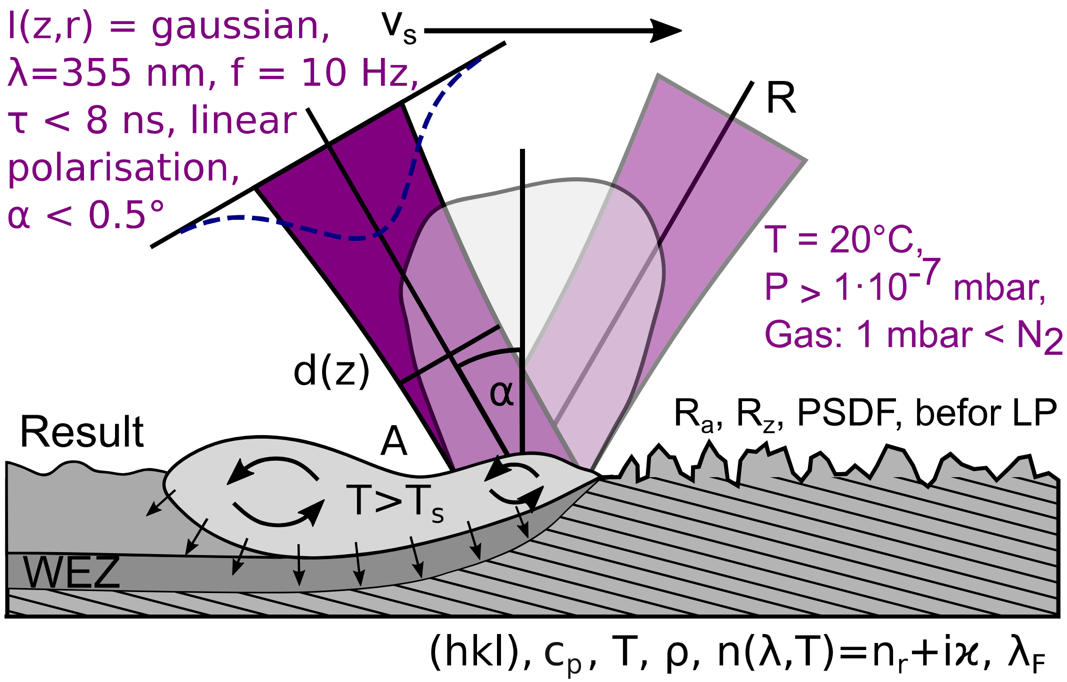
DESY.

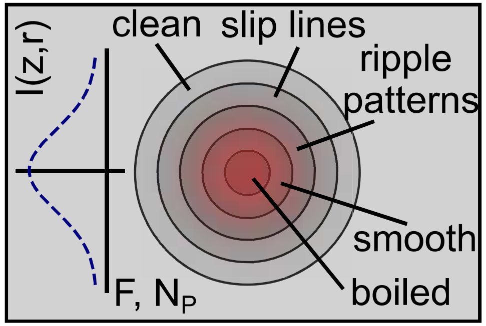
BMBF (BMFTR):
Financial Support by the BMBF, projects no: 05H18PXRB1 and 05H21PXRB1 (ErUM Pro)

Bundesministerium für Forschung, Technologie und Raumfahrt

Questions?

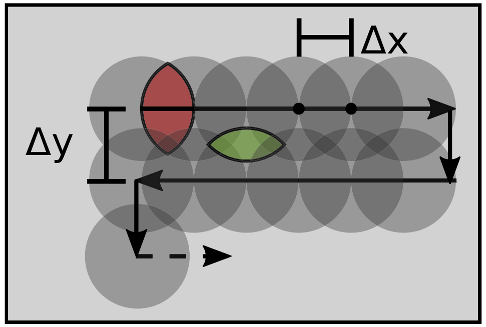
Theory of laser material processing





Point measurements

- Investigation of the influence of F, N_p, pressure, surface defects, ...

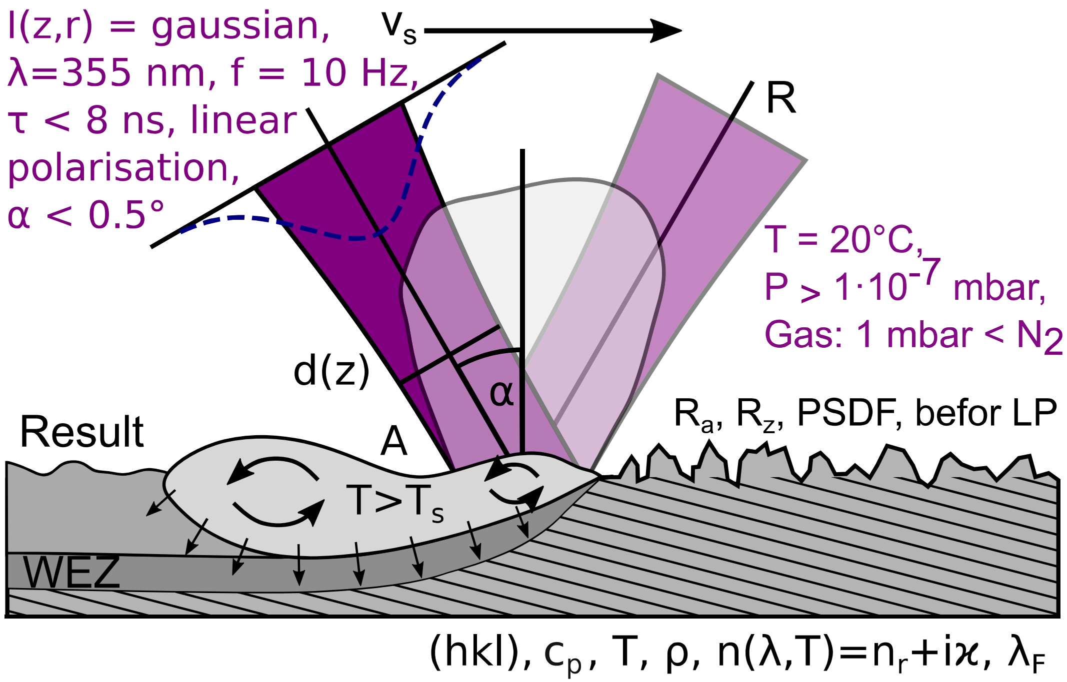


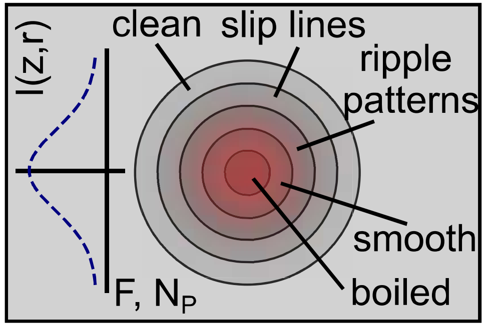
Area measurements

- Investigation of the influence of the overlap of the spots and the rows, ...

- The result of the LMB is influenced by many parameters:
  - **Laser:** λ, τ, f, polarization
  - **Process:** α, Δx, Δy, v_s, N_p, atmosphere/vacuum, ...
  - **Sample:** material, roughness, grain size and orientation

⇒ Highly complex optimization problem





Point measurements

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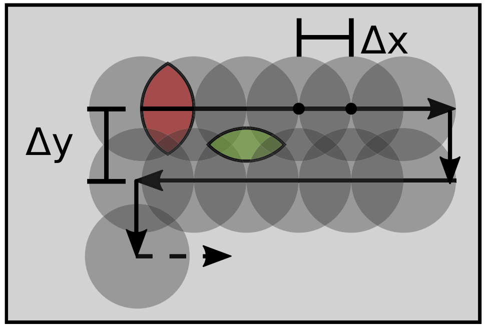

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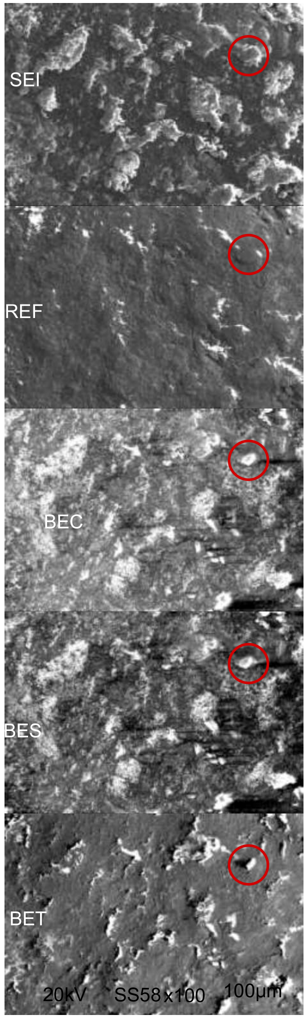
$\Rightarrow$ Highly complex optimization problem

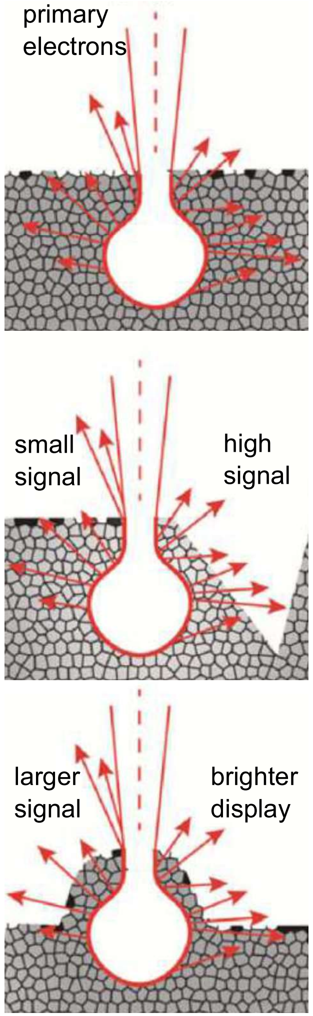
- Carrying out point and area measurements

$\Rightarrow$ Change Δx, Δy, ΔF

$\Rightarrow$ Examination of the results by SEM/EDX/OP/XRD

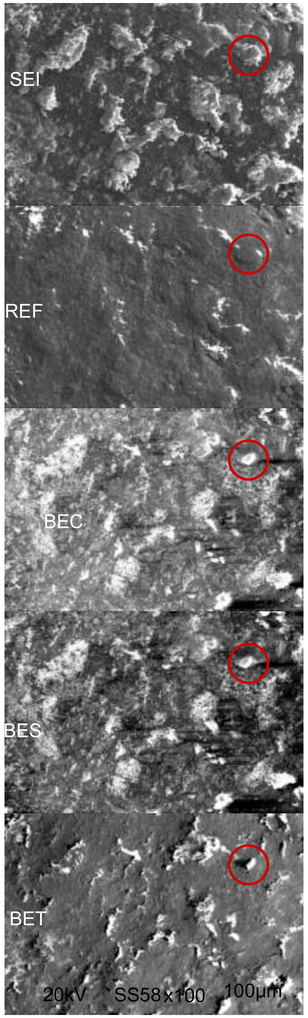
SEM - Different signals during electron microscopy

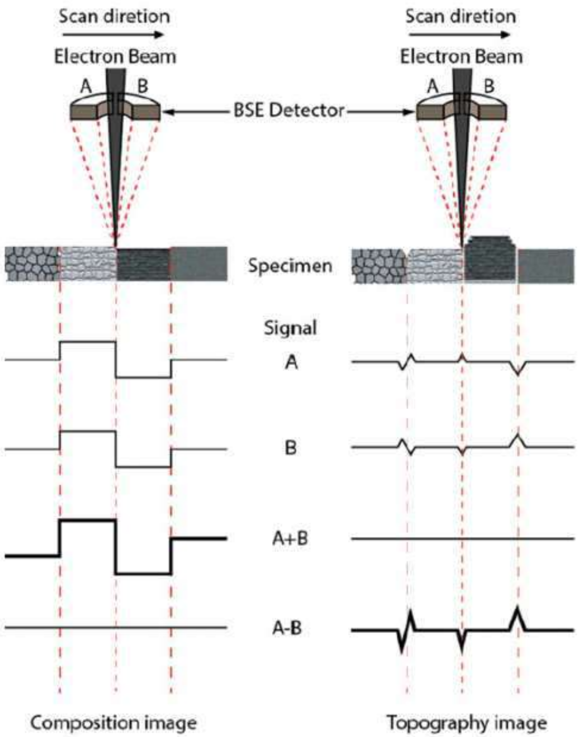




- **SEI - Secondary electrons**: Contrast due to the topography of the surface
- **REF - Reflect electrons**:
- **BE - Backscattered Electron:** Contrast by compositional or atomic number (Z), two elements $\Rightarrow$ heavy elements are displayed lighter than lighter ones
  - **BEC - COMPO mode** Signal = sum of both detector halves (A + B), Differences in the composition (Z-contrast) of the sample become visible
  - **BES - SHADOW mode** Combined signal from two detectors, first detector above the sample as in COMPO mode, second detector at an oblique angle $\Rightarrow$ Combination of both signals leads to shadowing effects $\Rightarrow$ 3-dimensional morphology and topography of the surface features of the surface features become visibl
  - **BET Backscatter Electron Topo**: Highlight surface topography $\Rightarrow$ Signal is the difference between the detector halves (A-B)

SEM - Different signals during electron microscopy





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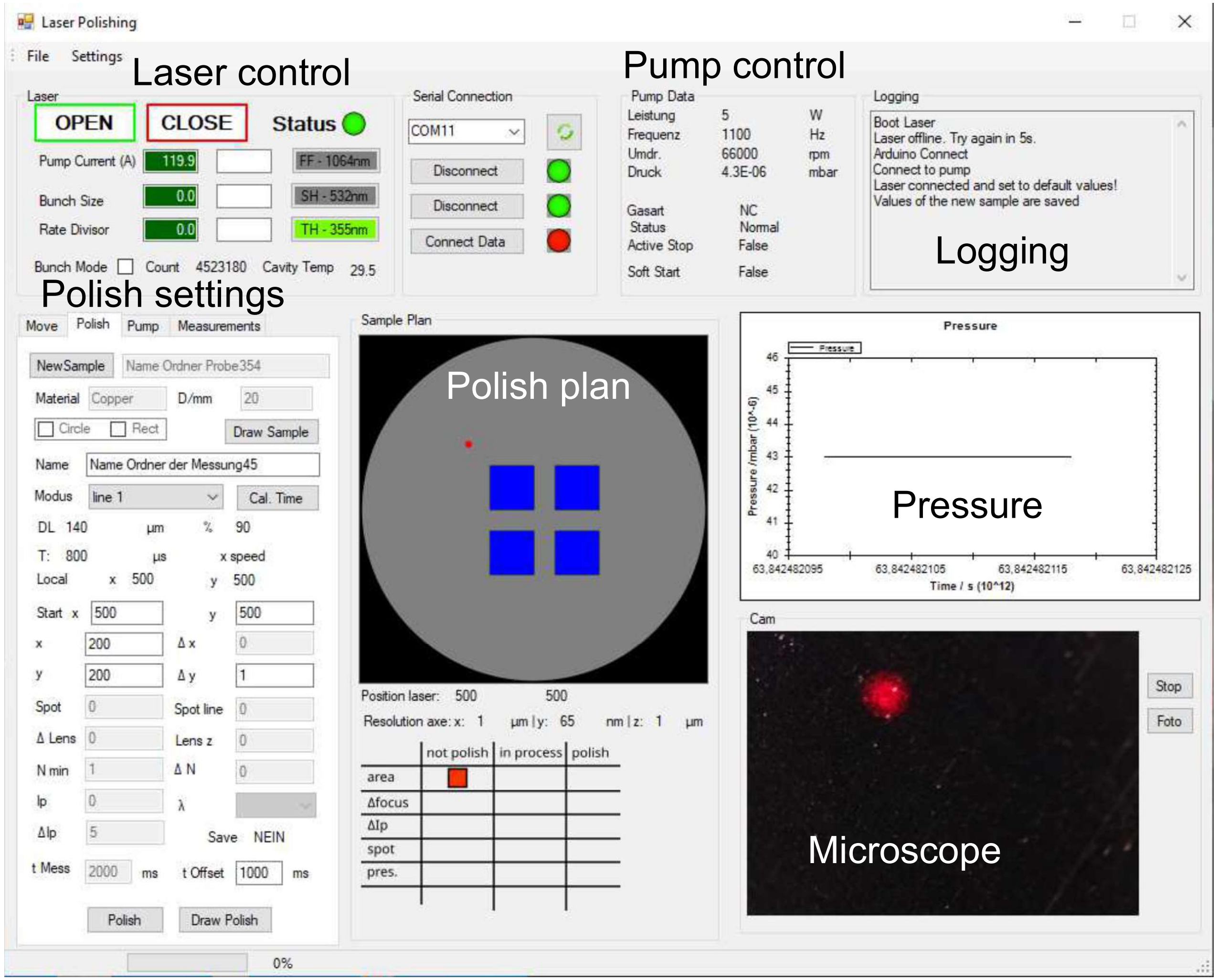
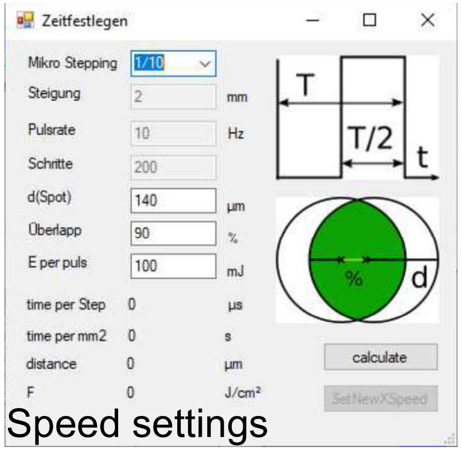
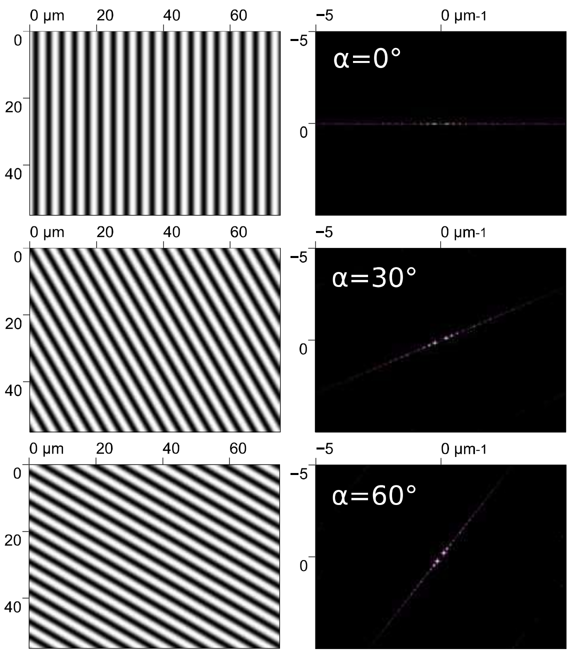
New GUI

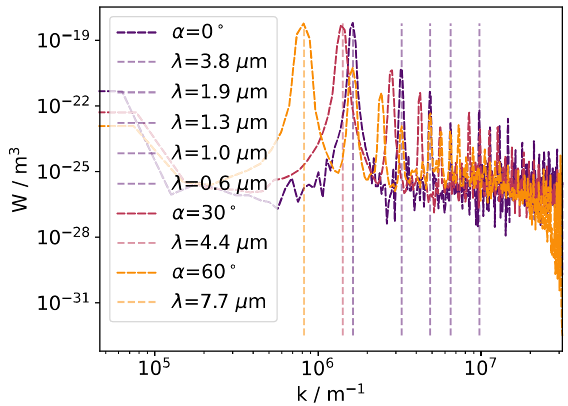


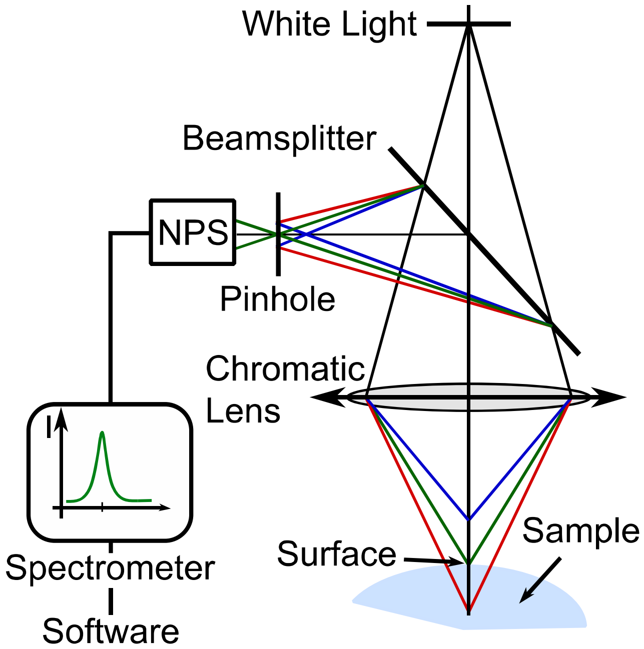


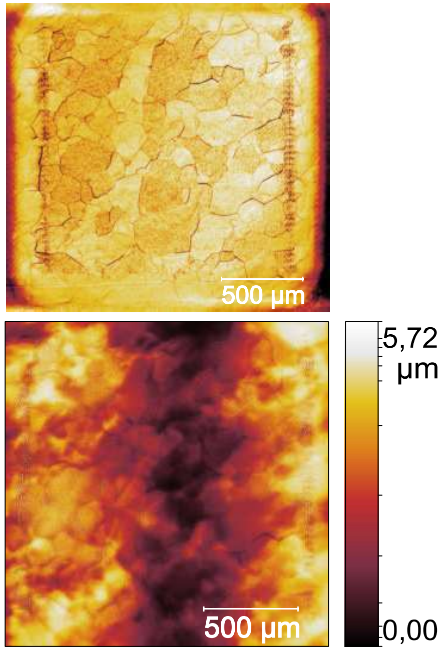
New laser software

- Control of the new pumping station (oil-free)
- Stepper motors are controlled via an Arduino so that the motor speeds can be changed
  ➔ 30 % faster polishing speed, 10 min/mm, limit f=10Hz
- visualisation of the polished areas









- $PSDF(\omega) = PSDF(-\omega) = \int_{-\infty}^{\infty} R(\tau_A)\exp(-i\omega\tau_A)d\tau_A$
- $R_q^2(k_{\min}, k_{\max}) = \int_{k_{\min}}^{k_{\max}} PSDFdk$
- $F(k,l) = \sum_{n=0}^{N-1}\sum_{j=0}^{N-1} f(n,j)\exp\left[-2\pi i\left(\frac{kn+lj}{N}\right)\right]$

⇒ Characterization of the surface by optical profilometry + PSDF + 2d FFT calculation