

Ortsaufgelöste Charakterisierung magnetischer Feldverteilungen mittels magnetischer Kraftmikroskopie im Vakuum

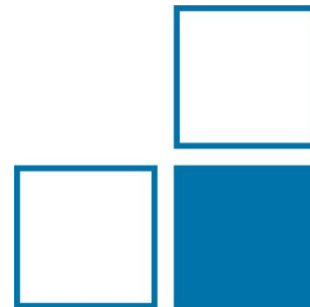
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Hans Werner Schumacher²

¹Arbeitsgruppe 2.52 Nanomagnetismus

²Fachbereich 2.5 Halbleiterphysik und Magnetismus

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Teil I

- Motivation
- MFM-Funktionsprinzip
- MFM in Vakuum

Teil II

- Quantitative MFM (qMFM)
- Kalibrierung

Weitere Techniken in 2.52:

- Nitrogen-Vacancy (Stickstofffehlstellen) Magnetometrie
- Magneto-Optischer Indikator Film (MOIF)

Rasterkraftmikroskopie

Atomic Force Microscopy (AFM)

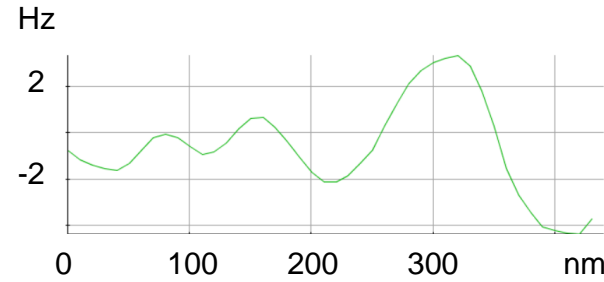
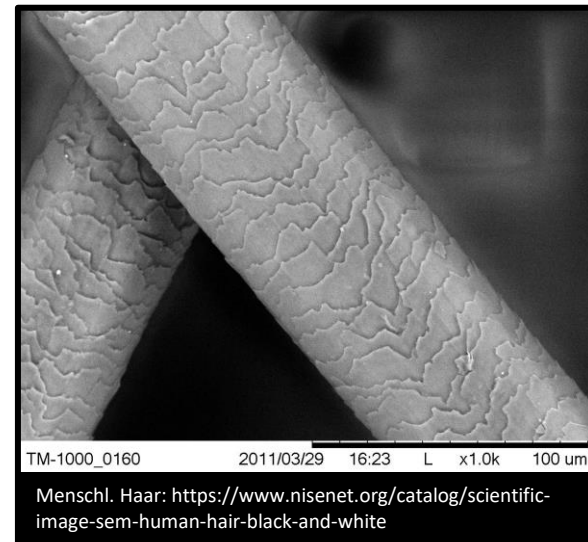
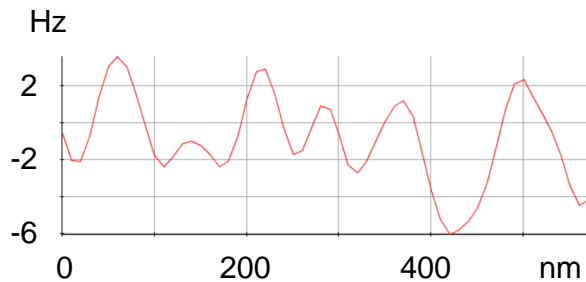
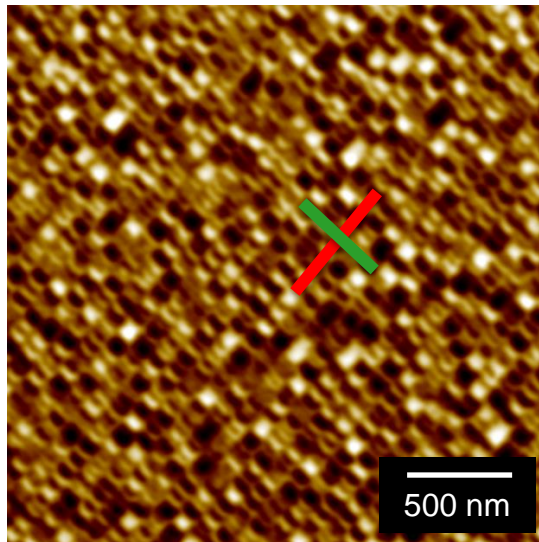
Magnetkraftmikroskopie

Magnetic Force Microscopy (MFM)

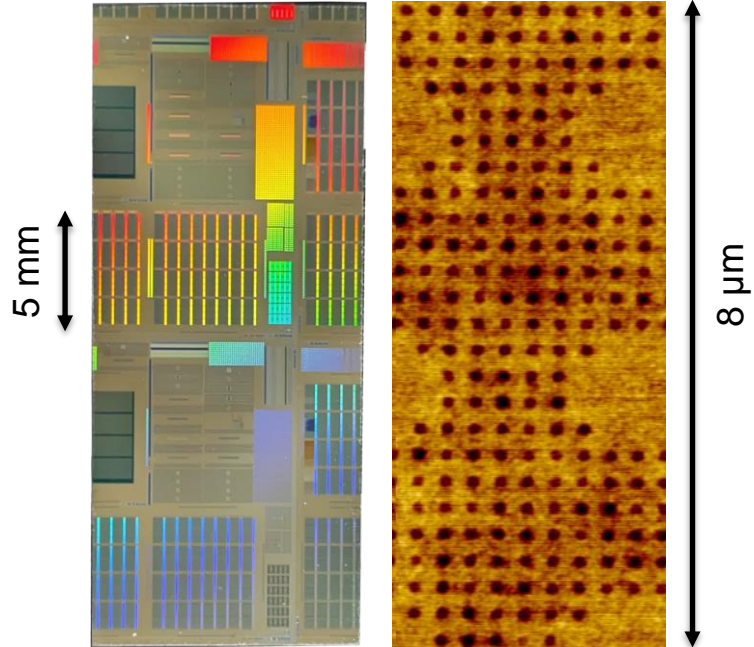
Motivation

Festplatte Hard Drive Disk (HDD)

2.5" Notebook HDD
500 GB



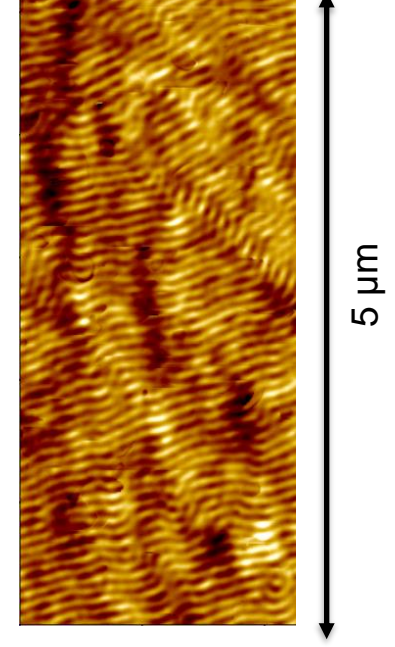
MRAM



Skymionen



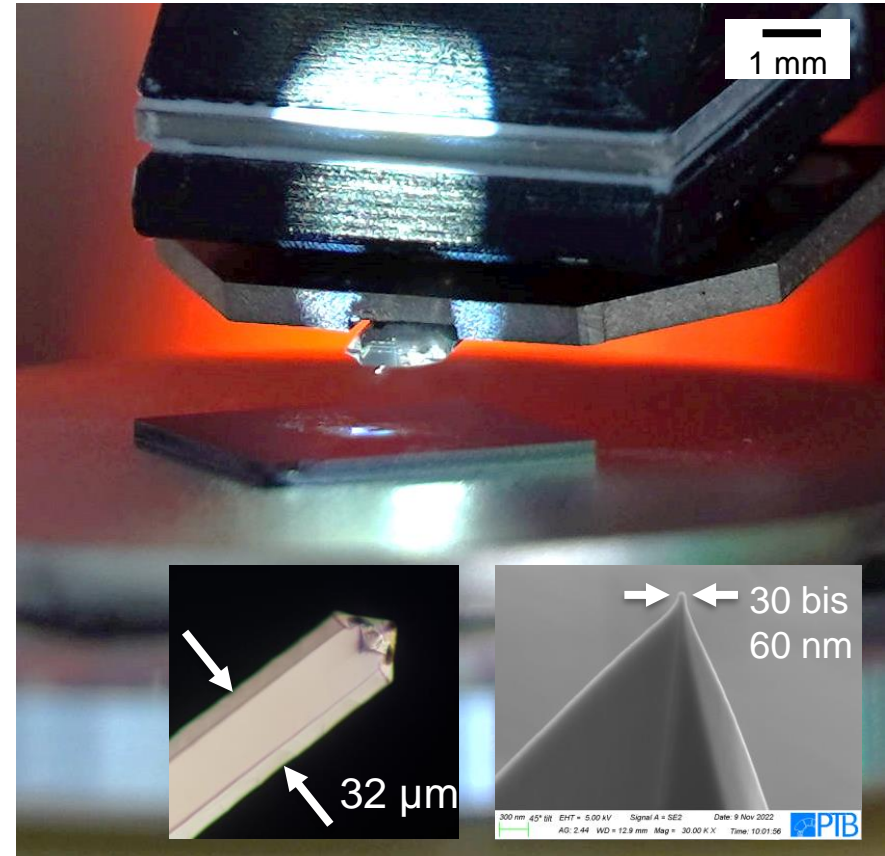
Materialien



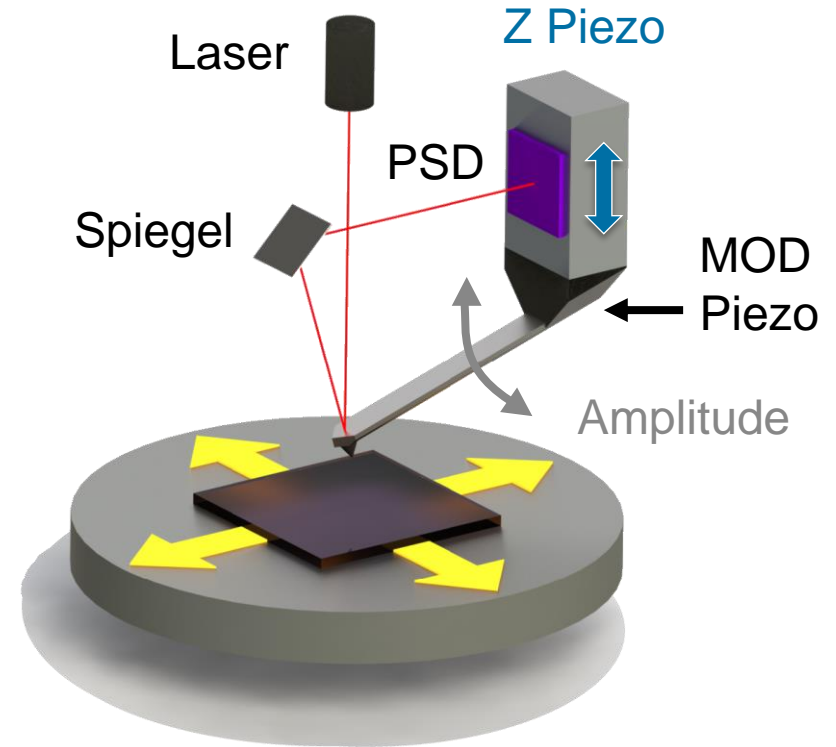
NX-Hivac Atomic Force Microscope (AFM)



NX-Hivac Atomic Force Microscope (AFM)



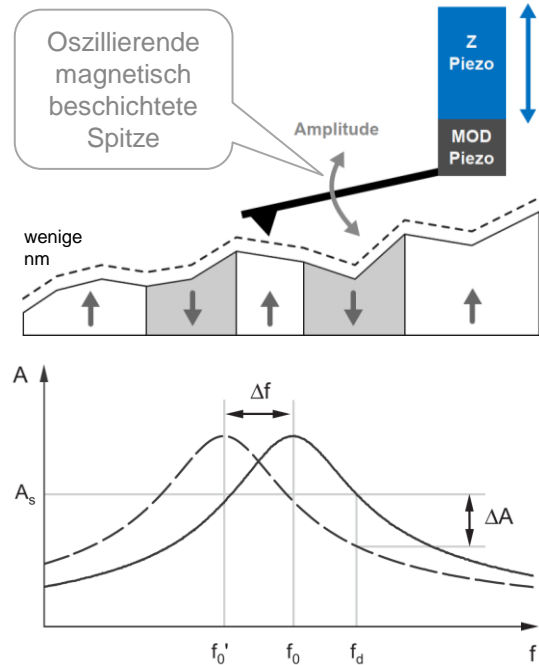
NX-Hivac Atomic Force Microscope (AFM)



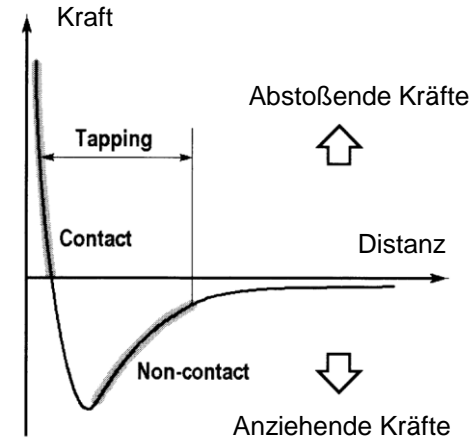
Piezo Stage (+ Motorisierte Stage)

MFM Zwei-Pass Messung (Two-Pass Mode)

1. Durchgang Topographie



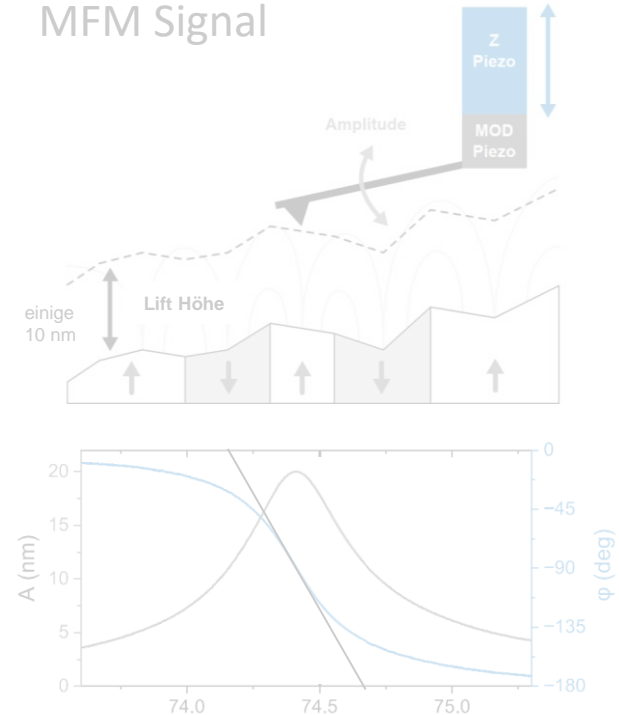
Lennard-Jones Potential



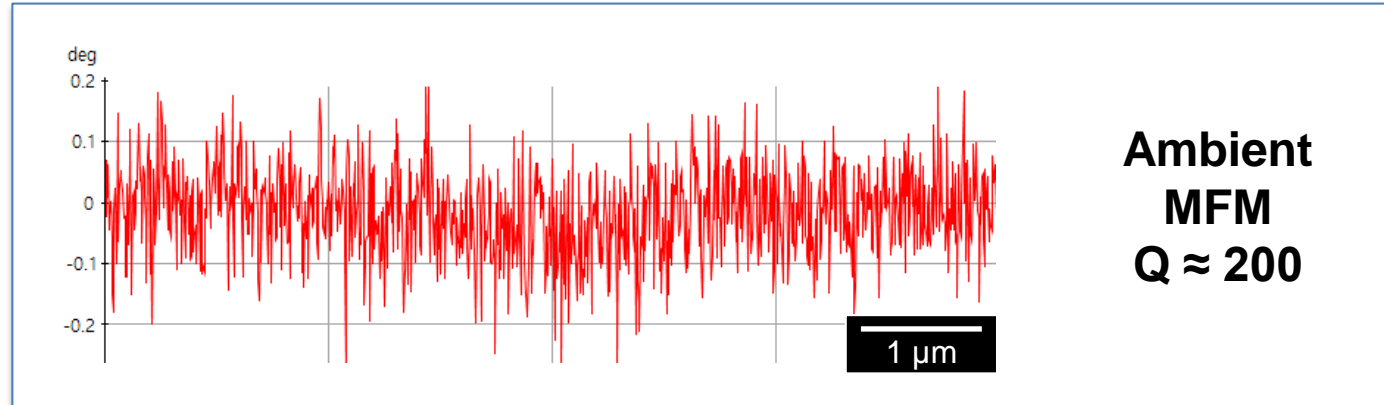
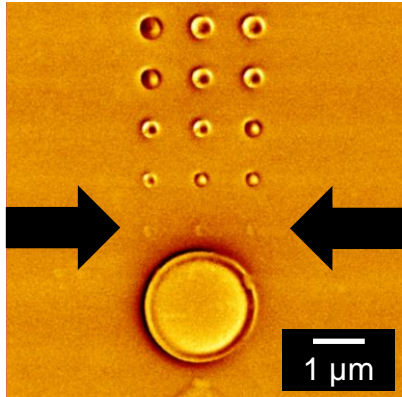
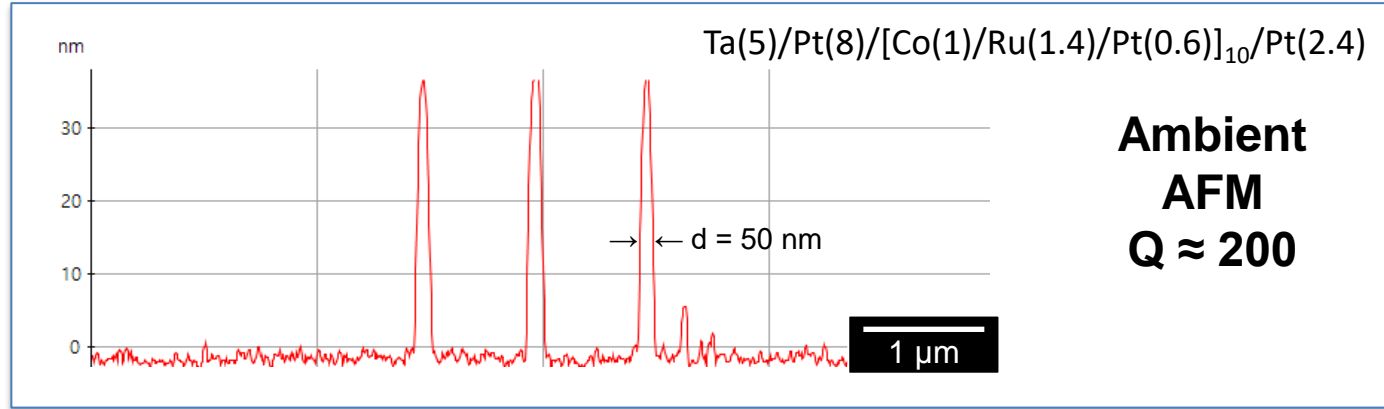
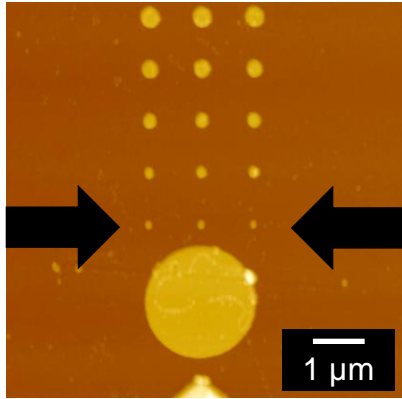
$$V_{LJ}(r) = 4\epsilon \left[\left(\frac{\sigma}{r} \right)^{12} - \left(\frac{\sigma}{r} \right)^6 \right]$$

Pauli Abstoßung Van der Waals Kräfte

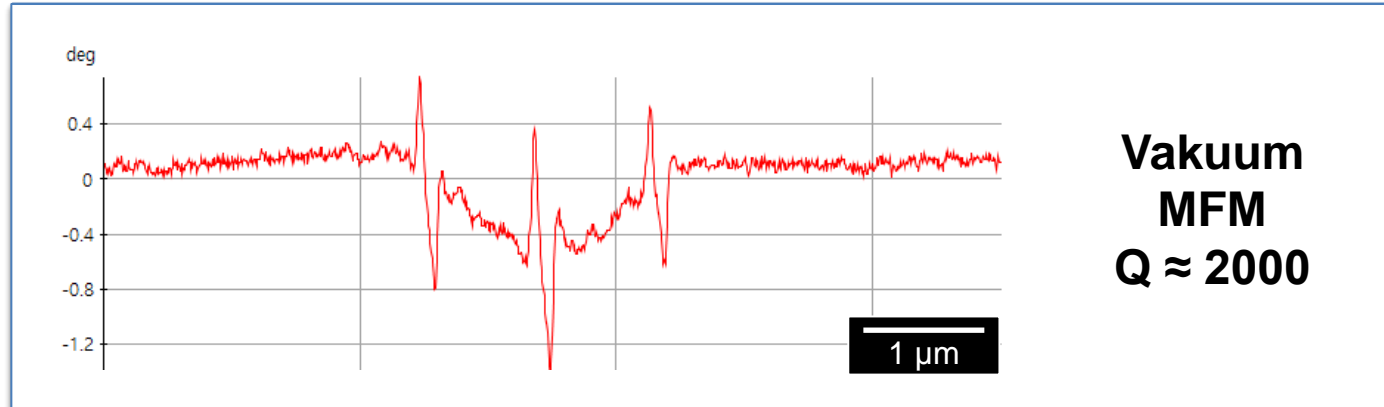
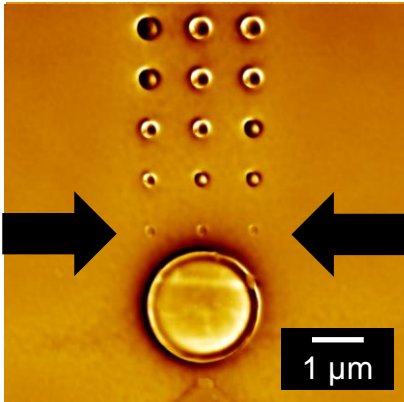
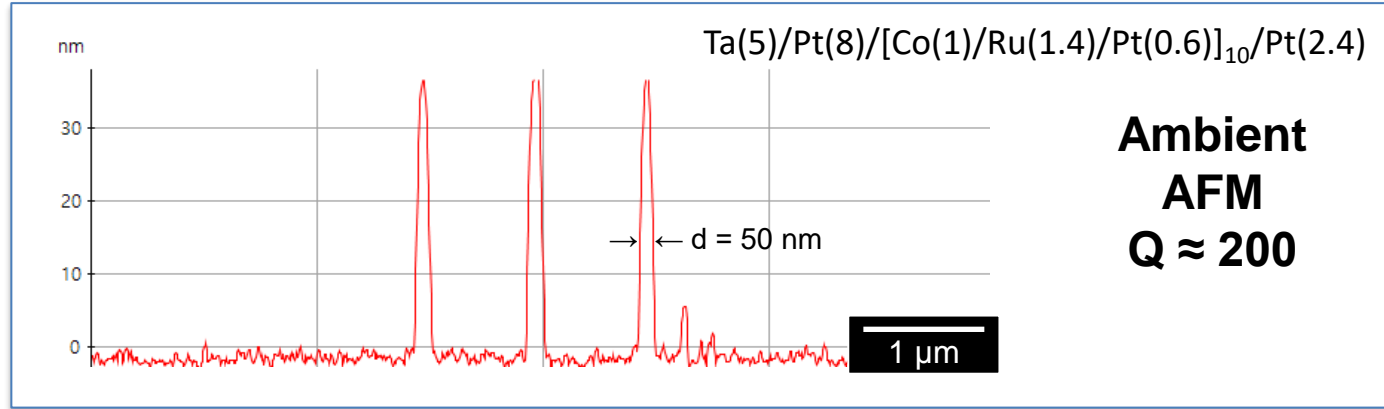
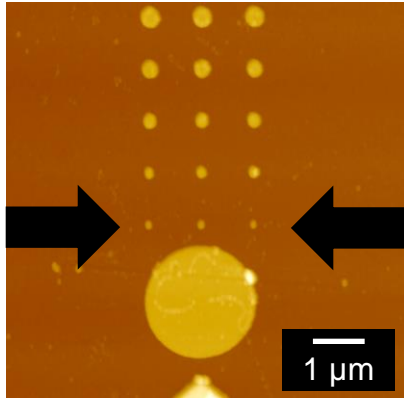
2. Durchgang MFM Signal



MFM-Signalverbesserung in Vakuum



MFM-Signalverbesserung in Vakuum



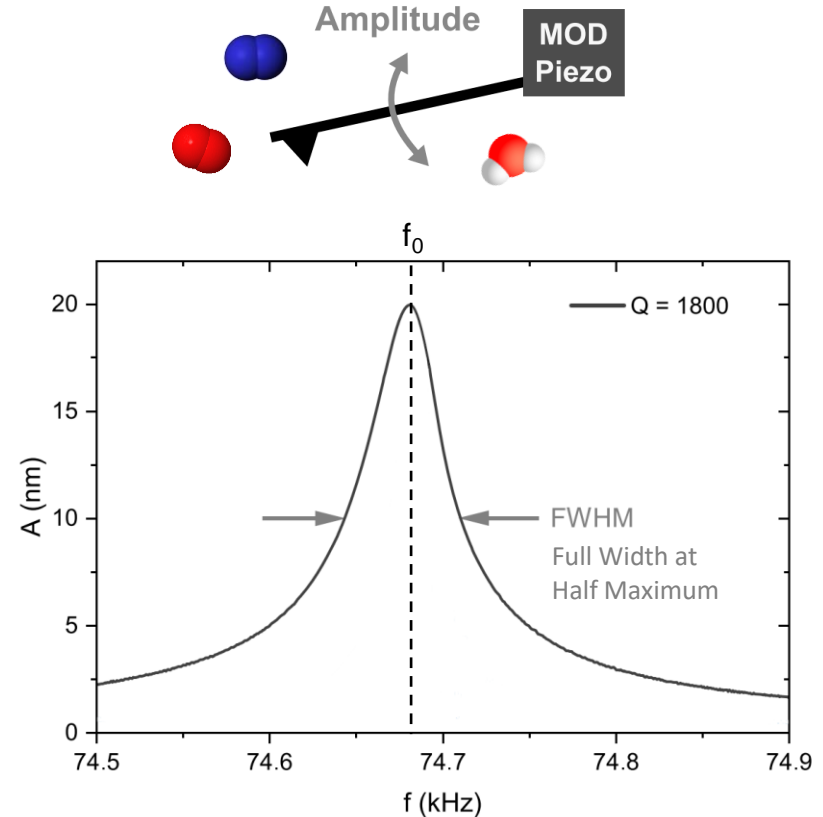
Qualitätsfaktor (Q-Faktor)

Verhältnis der in der Schwingung gespeicherten Energie zur pro Schwingungszyklus abgegebenen Energie

$$Q = \frac{f_0}{\Delta f_{\text{FWHM}}}$$

Minimal detektierbarer Kraftgradient

$$\frac{\partial F_{\text{min}}}{\partial z} \propto \sqrt{\frac{1}{Q}}$$



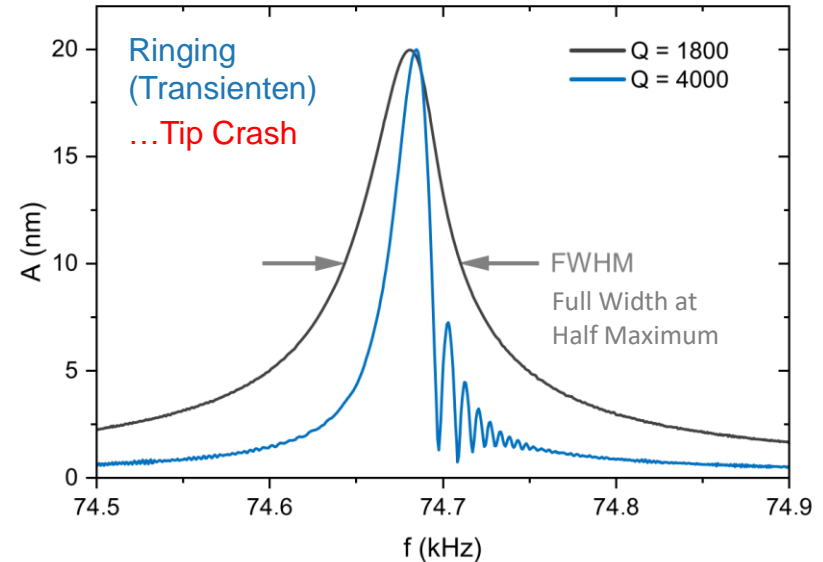
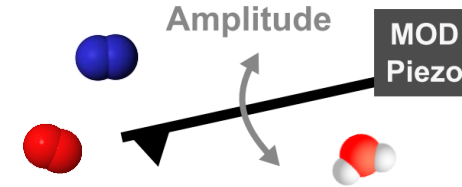
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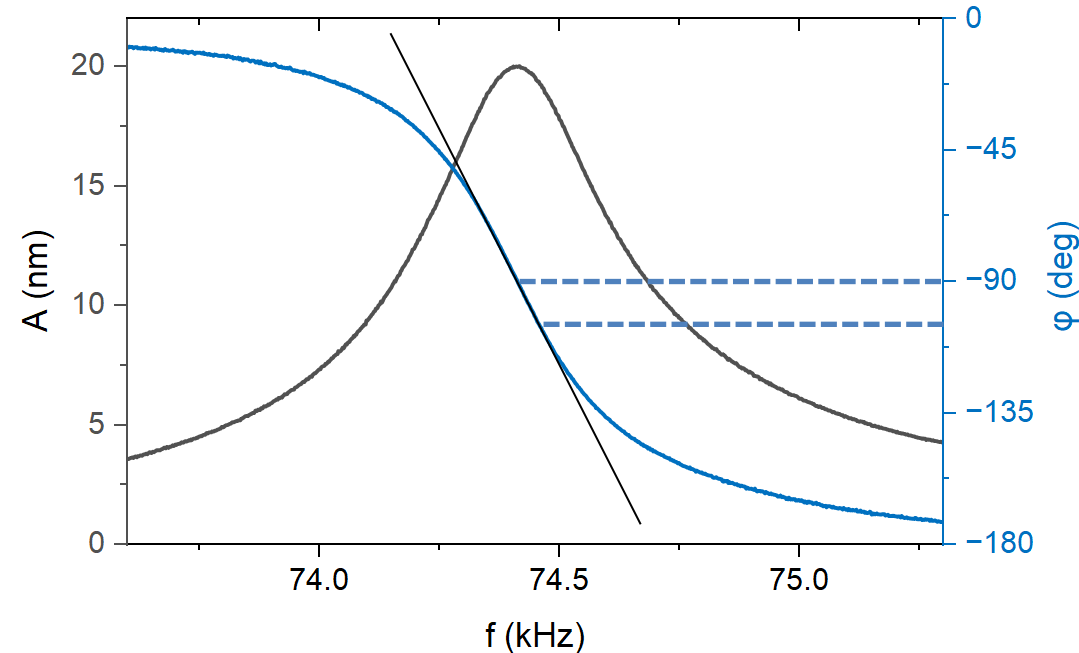


Q-Faktor und Phasenversatz

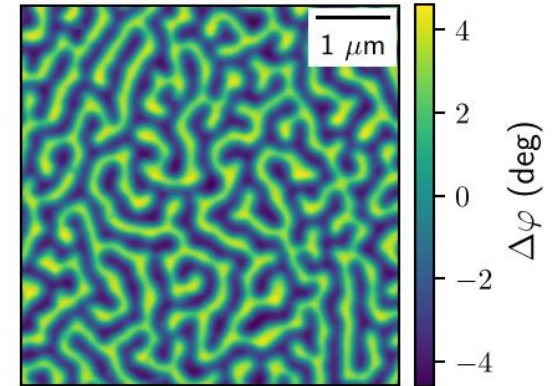
Phasenverschiebungsbasierte MFM-Signaldetektion

Pt(2 nm)/[(Co(0.4 nm)/Pt(0.9 nm)]₁₀₀/Pt(5 nm)/Ta(5 nm)

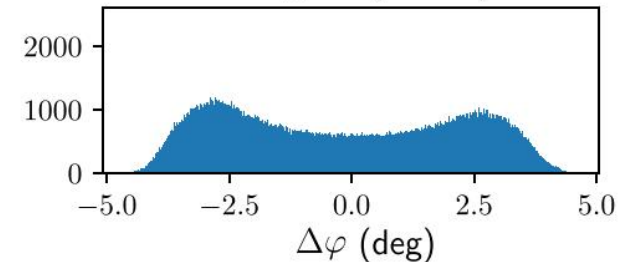
Hu, Xiukun, et al. *Journal of Magnetism and Magnetic Materials* 511 (2020): 166947.



Measured $\Delta\varphi$ (deg), $Q \approx 220$



Histogram (counts)

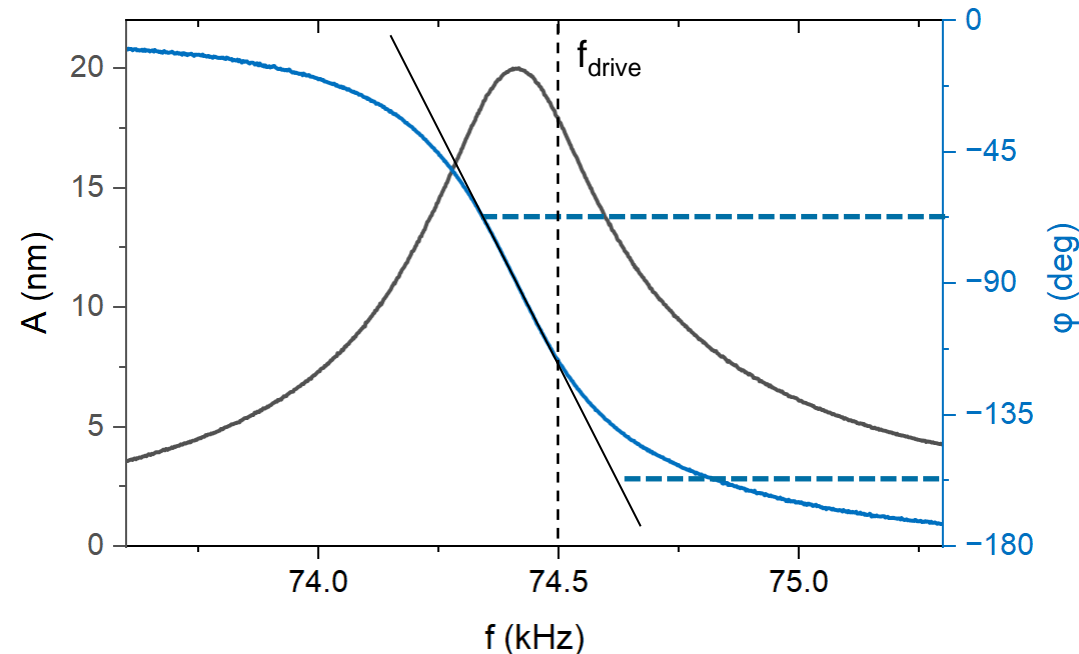


Q-Faktor und Phasenversatz

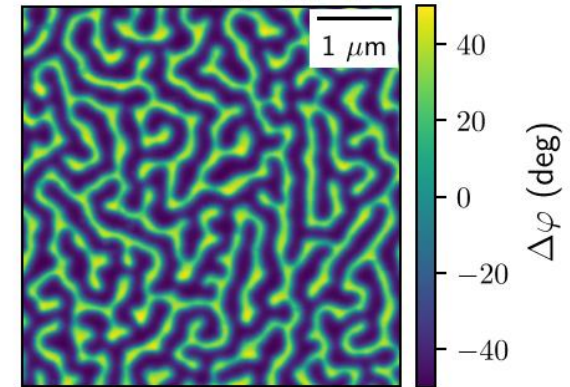
Phasenverschiebungsbasierte MFM-Signaldetektion

Pt(2 nm)/[(Co(0.4 nm)/Pt(0.9 nm)]₁₀₀/Pt(5 nm)/Ta(5 nm)

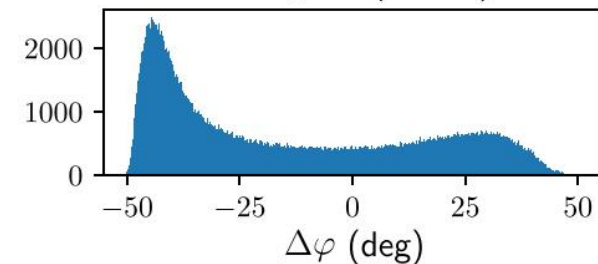
Hu, Xiukun, et al. *Journal of Magnetism and Magnetic Materials* 511 (2020): 166947.



Measured $\Delta\phi$ (deg), $Q \approx 1800$

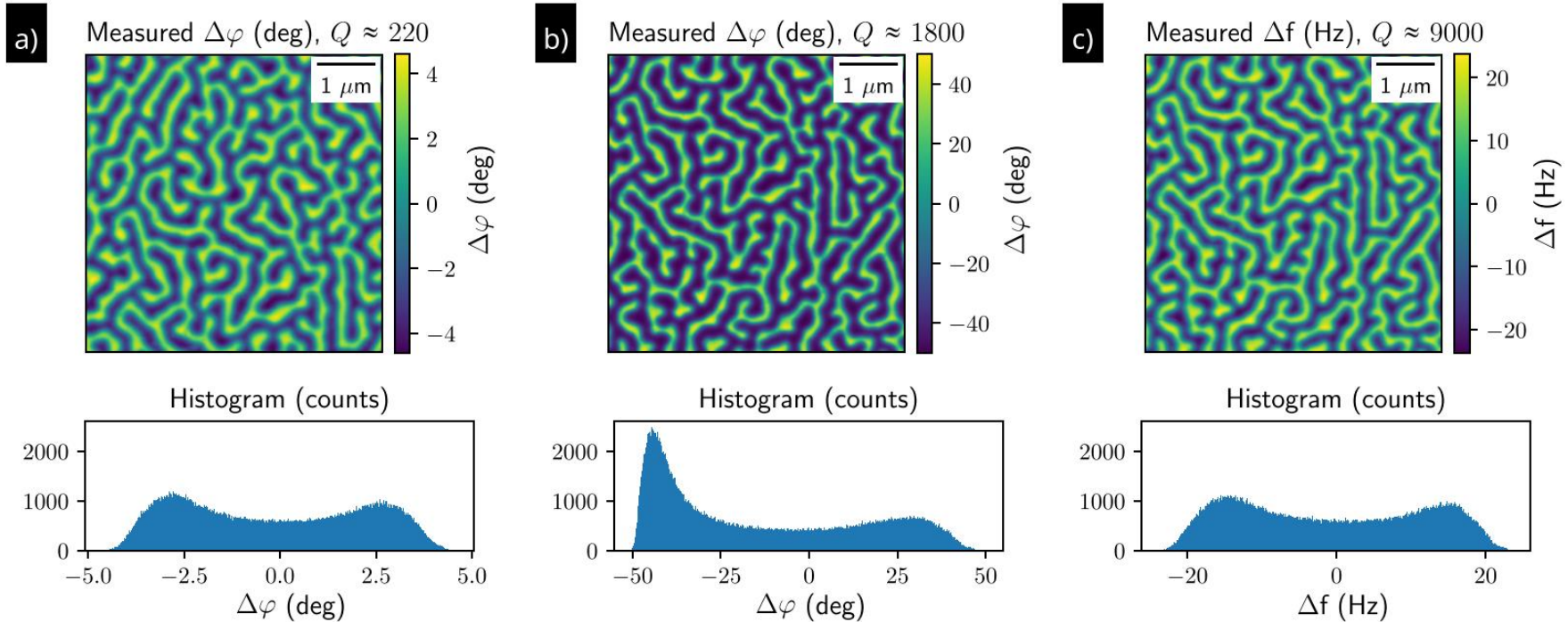


Histogram (counts)



Phase-Locked Loop (PLL) Messung von Δf

Referenzprobe: Pt(2 nm)/[(Co(0.4 nm)/Pt(0.9 nm))₁₀₀/Pt(5 nm)/Ta(5 nm)]



High Quality-Factor Two-Pass Mode

Erster Durchgang: Q-Faktor via Q-Control verringern

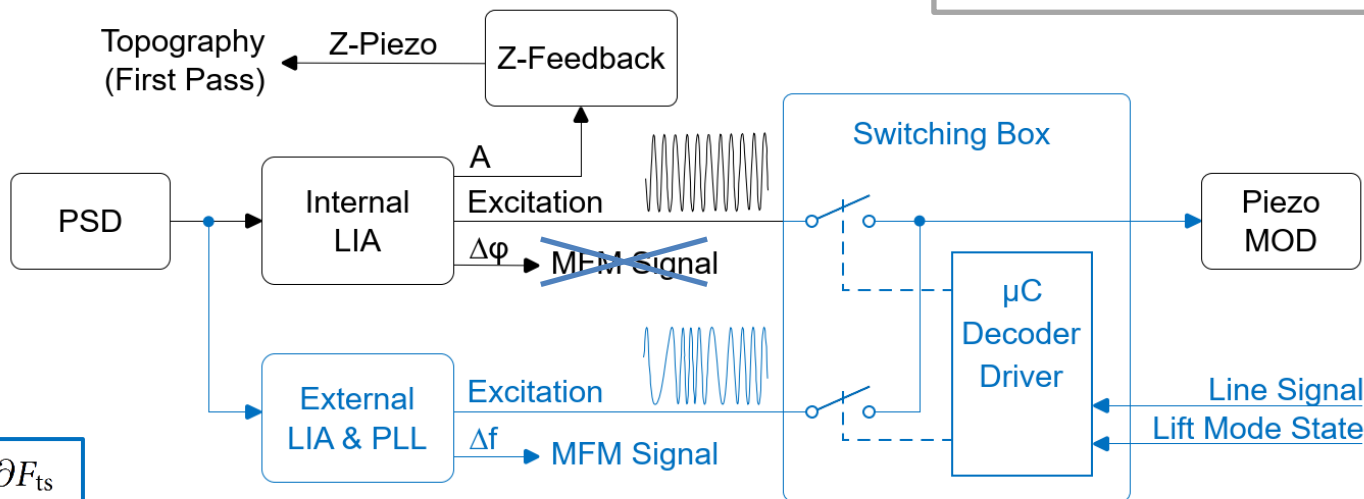
Zweiter Durchgang: **Frequenzmessung** (hoher Q-Faktor)
statt Phasenmessung



Rev. Sci. Instrum. 95,
113704 (2024)

doi.org/10.1063/5.0226633

← arXiv:2406.17664

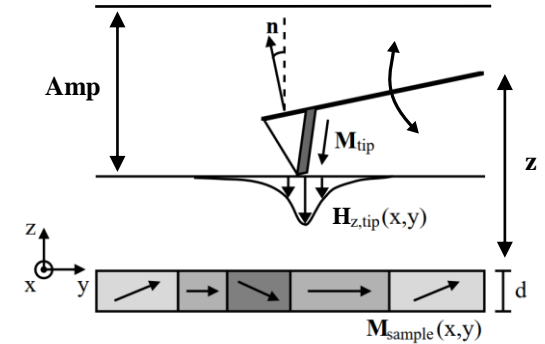
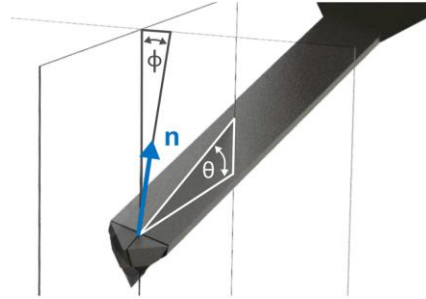


$$\Delta f = -\frac{f_0}{2k_0} \frac{\partial F_{ts}}{\partial s_z}$$

Quantitative Magnetic Force Microscopy

(qMFM)

$$\Delta f = -\frac{f_0}{2k_0} \frac{\partial F_{ts}}{\partial s_z}$$



Fourierraum

$$\Delta f(\mathbf{k}, z) = -\frac{\mu_0 f_0}{2k_0} \cdot LCF(\mathbf{k}, \theta, \phi, A) \cdot \frac{\partial H_{z,tip}^*(\mathbf{k}, z)}{\partial z} \cdot H_{z,sample}(\mathbf{k}, z)$$

Resonanz
Freq. f_0
Feder-
konst. C

Lever Correction Function
(Korrektur von Einbau-
winkeln und Amplitude)

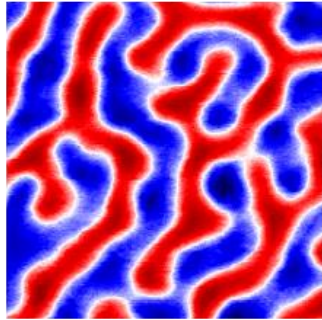
z -Ableitung der z -
Komponente des
magnetischen
Feldes der Spitze

Magnetfeldvertei-
lung in der Höhe z

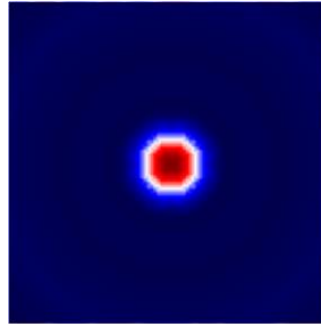
Instrument Calibration Function

$$ICF(\mathbf{k}, k_0, f_0, \theta, \phi, A)$$

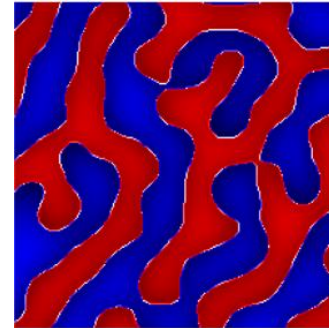
Messdaten



Unbekannt



Initial Unbekannt

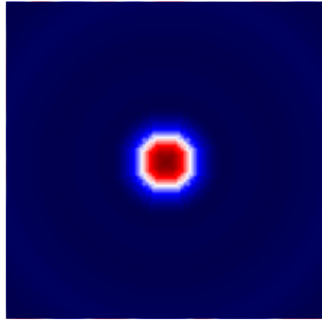


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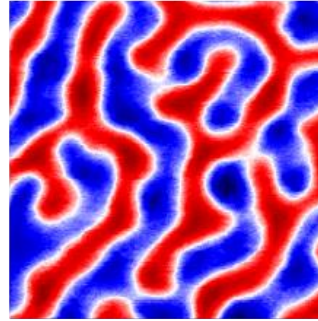
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$$\Delta f(\mathbf{k}, z) = ICF(\mathbf{k}, k_0, Q, \theta, \phi, Amp) \cdot H_{z\,sample}(\mathbf{k}, z)$$

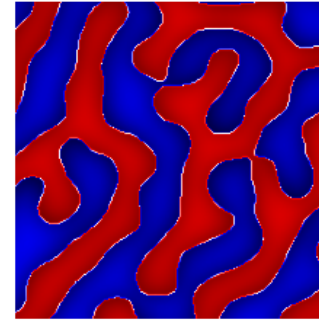
Berechnete ICF



Messdaten



Simulierte Daten



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/

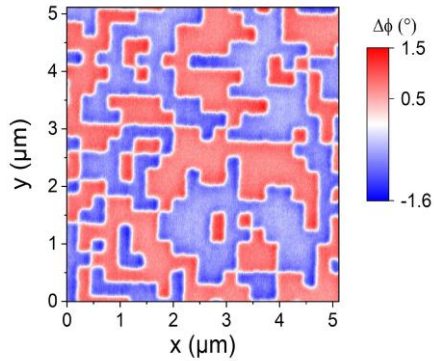
$$ICF(\mathbf{k}, k_0, Q, \theta, \phi, Amp) = \Delta f(\mathbf{k}, z) / H_{z_{sample}}(\mathbf{k}, z)$$

Referenzprobe: Pt(2 nm)/[(Co(0.4 nm)/Pt(0.9 nm))₁₀₀/Pt(5 nm)/Ta(5 nm)]

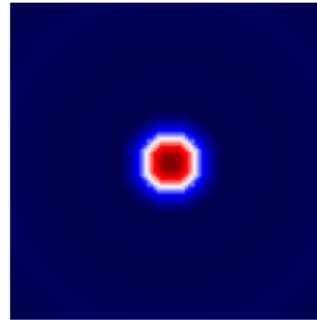
Round Robin: Hu, Xiukun, et al. *Journal of Magnetism and Magnetic Materials* 511 (2020): 166947.

Quantitative Magnetic Force Microscopy

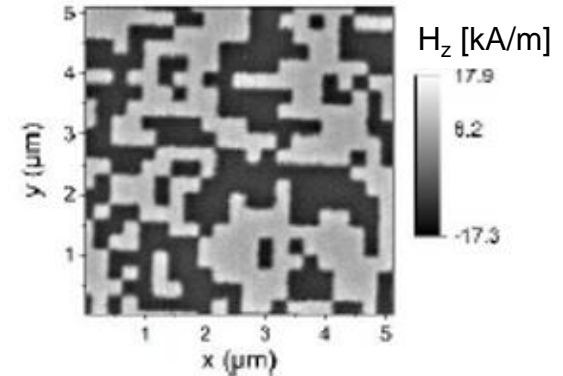
Messdaten



Berechnete ICF



Daten in SI-Einheiten



$$\Delta f(\mathbf{k}, z) \quad / \quad ICF(\mathbf{k}, k_0, Q, \theta, \phi, Amp) \quad = \quad H_{z\text{sample}}(\mathbf{k}, z)$$

$$\Delta f(\mathbf{k}, z) = - \underbrace{\frac{\mu_0 f_0}{2k_0} \cdot LCF(\mathbf{k}, \theta, \phi, A) \cdot \frac{\partial H_{z,tip}^*(\mathbf{k}, z)}{\partial z}}_{ICF(\mathbf{k}, k_0, f_0, \theta, \phi, A)} \cdot H_{z, sample}(\mathbf{k}, z)$$

Frequenz Δf

Wellenvektor $\mathbf{k} = (k_x, k_y)$
Ortsraum $(x, y) \rightarrow (k_x, k_y)$

Resonanzfrequenz f_0
Federkonstante k_0

Cantilever Einbauwinkel θ und ϕ
Cantilever Amplitude A

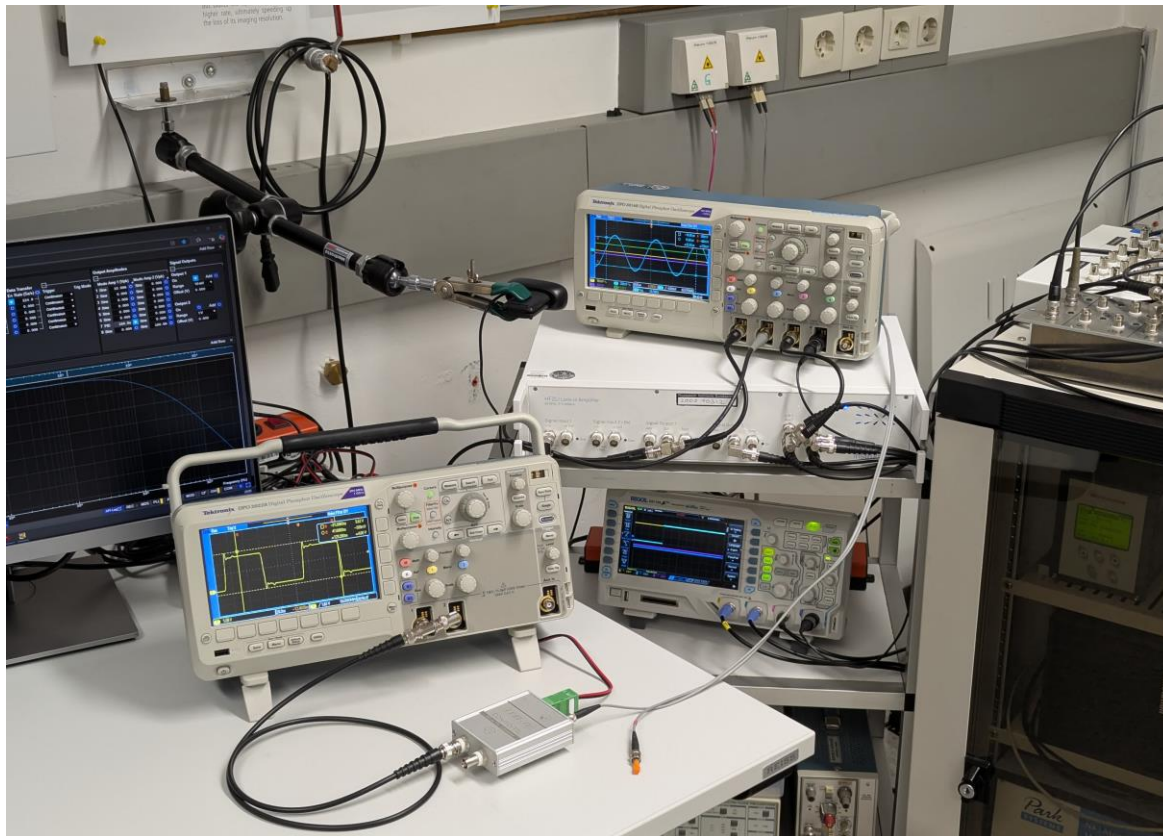
Lifthöhe z

Magn. Streufeld
in z-Richtung H_z

$[H_z] = \text{A/m}$

$B_z = \mu_0 H_z$
 $[B_z] = \text{T}$

Messung Frequenzversatz Δf



10 MHz Referenzsignal der Atomuhr (Normalfrequenz)

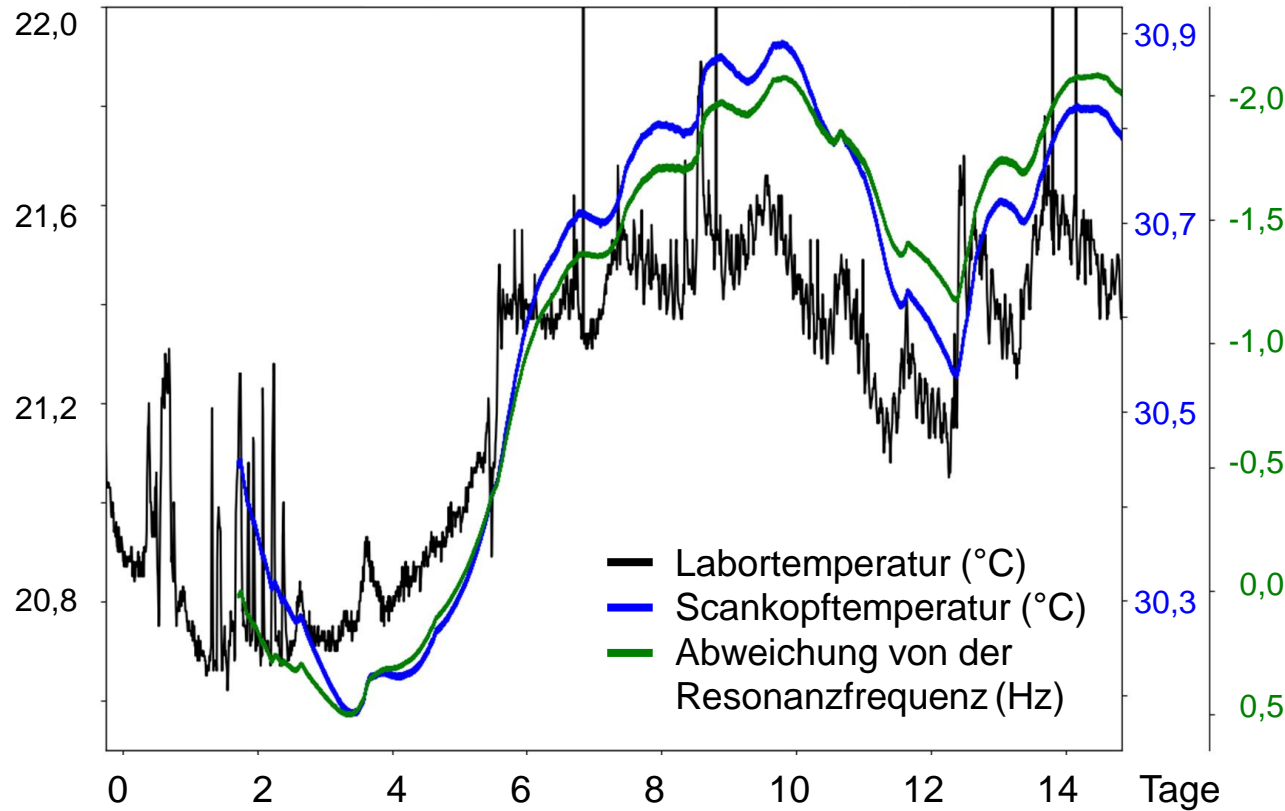
Caesium-Fontänenuhr
relativen Unsicherheit
weniger als 4×10^{-16} (CSF1)

Vergleich:
Interner Oszillator: ± 1.5 ppm ($= 10^{-6}$)
Temperaturstabilität: 0.05 ppm/°C

LWL (Glasfaser) \rightarrow TTL (5 V)
Signal-Jitter: < 1 ns

f_0 via Frequenzsweep

Resonanzfrequenz f_0 und Temperatur T

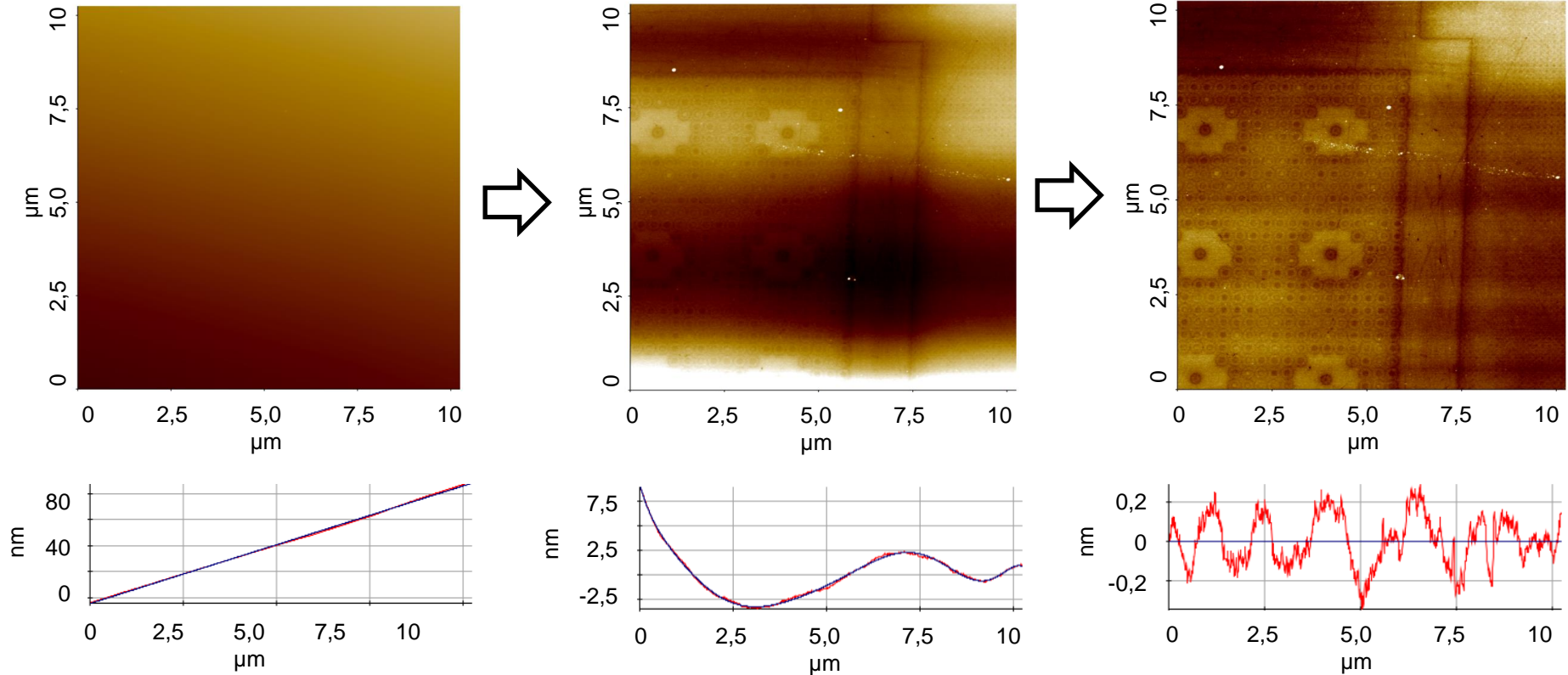


Drift um $\Delta T = 0,5^\circ\text{C}$
 \Rightarrow Drift $\Delta f_0 = 1,9\text{ Hz}$

Langsame Änderung
(Einkopplung über
Vakuum)

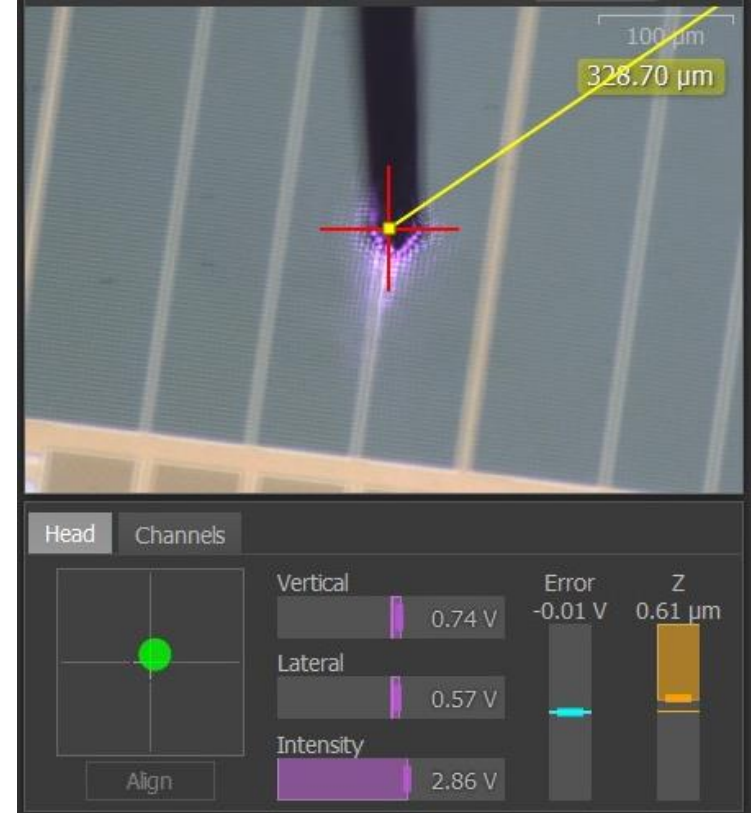
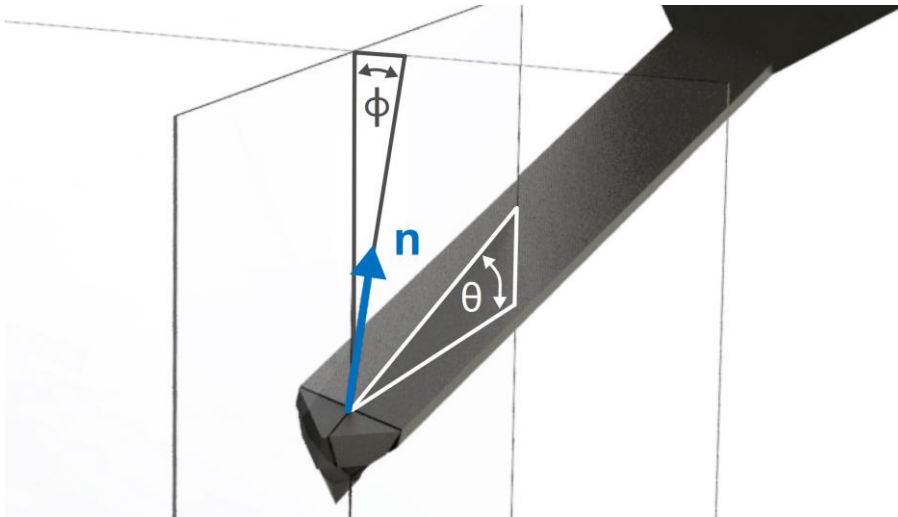
\Rightarrow Korrektur möglich

Korrektur von Temperaturdrift



Cantilever-Winkel

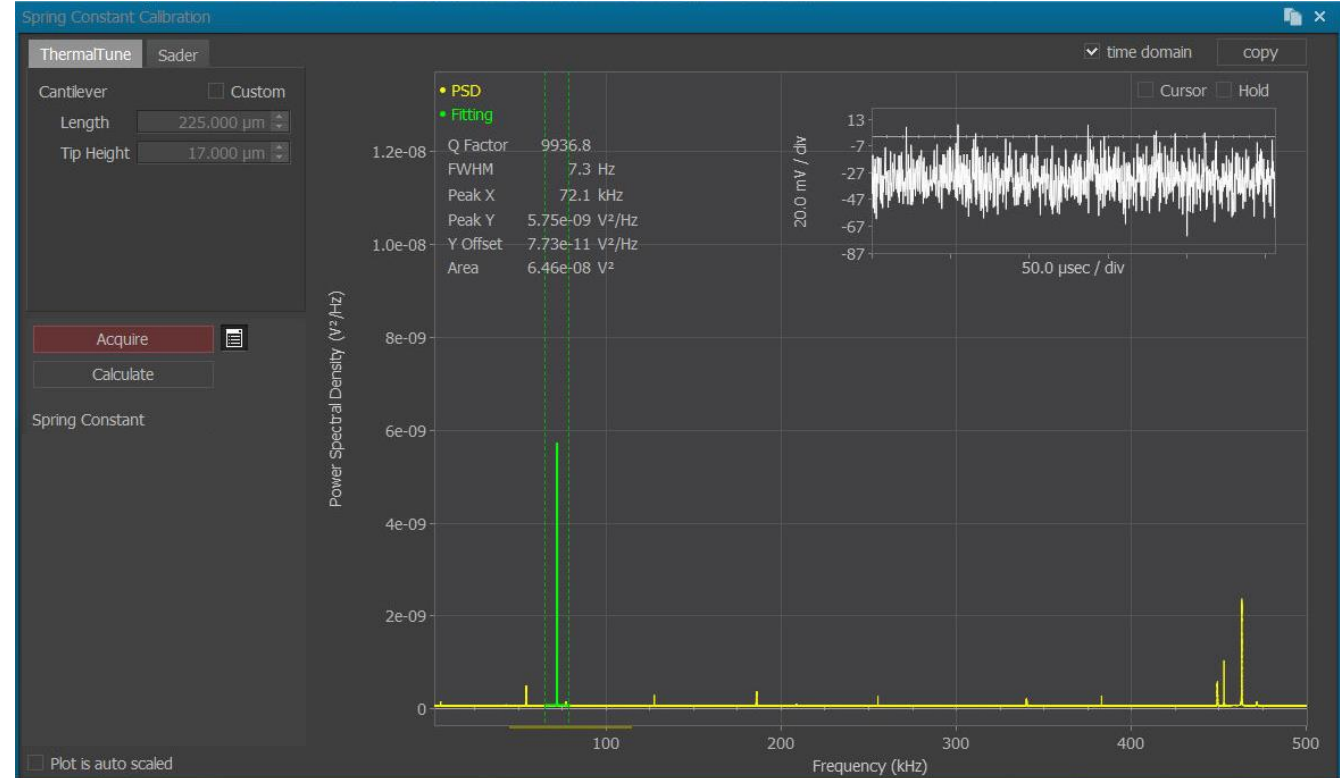
$\theta \rightarrow$ Herstellerspezifisch (hier 13°)
 $\phi \approx 0$



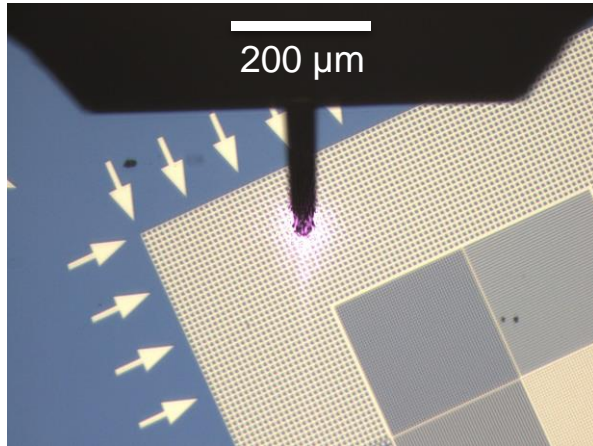
Federkonstante k_0

Thermal

$$\frac{1}{2}k_0\langle A_{\text{osc}}^2 \rangle = \frac{1}{2}k_B T$$
$$k_0 = k_B T / \langle A_{\text{osc}}^2 \rangle$$



Kalibrierung von X, Y und Z



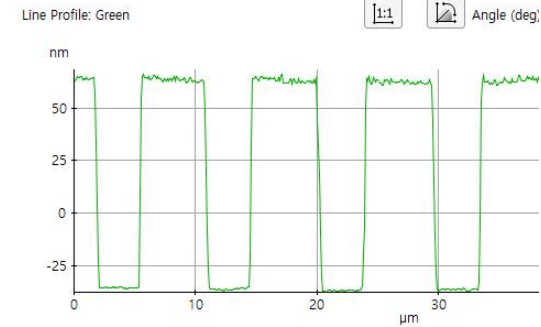
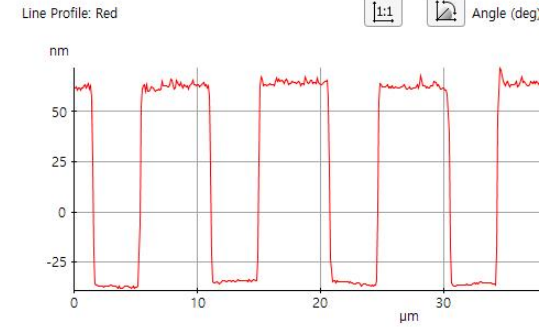
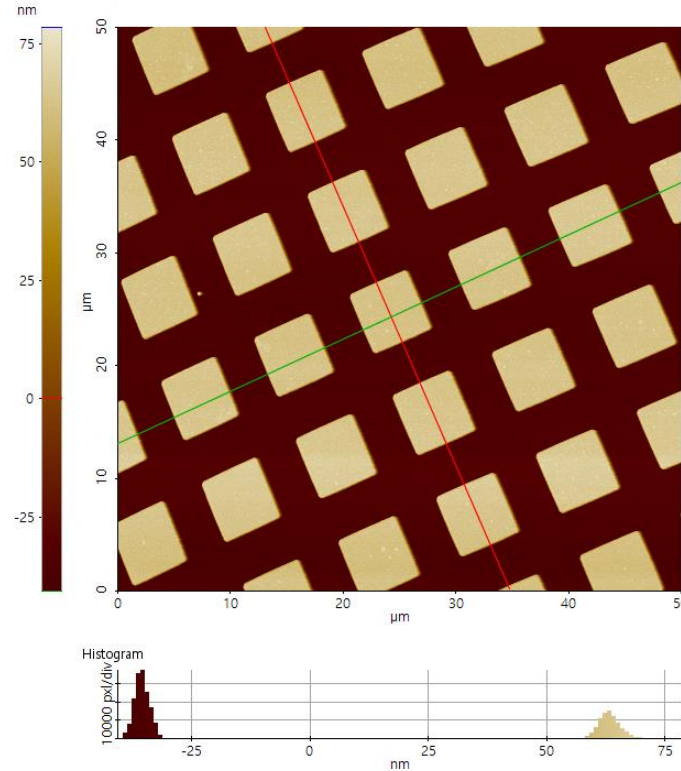
Step height:

(114) nm

It is stated on the label of each box.

Accuracy

Height accuracy is $\pm 3\%$, lateral pitch accuracy is $\pm 100\text{nm}$ for the $5\mu\text{m}$ and $10\mu\text{m}$ patterns.

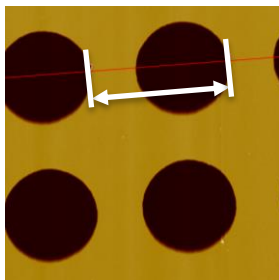


Piezo-Nichtlinearität und Vakuum



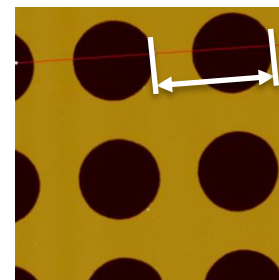
Luft

4,995 μm



Vakuum

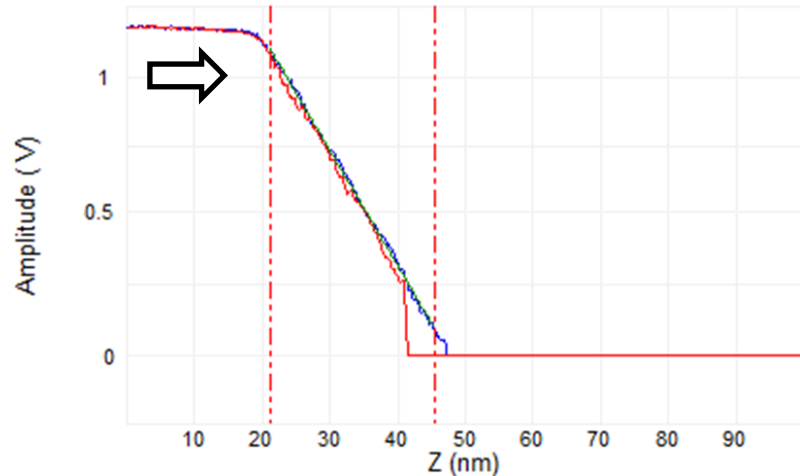
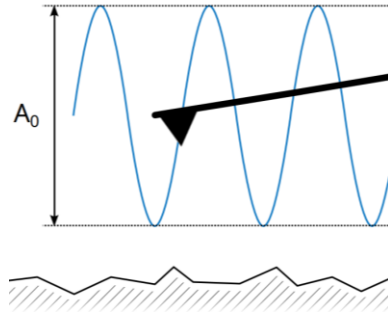
4,328 μm



Kalibrierung Amplitude

Nanoscope

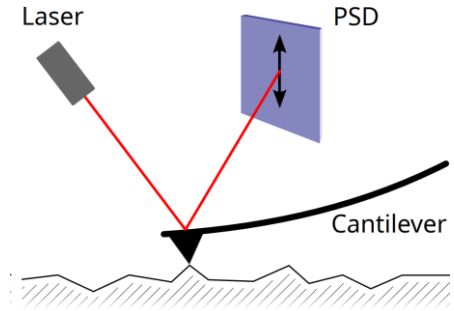
Tapping
Ambient



NX-Series

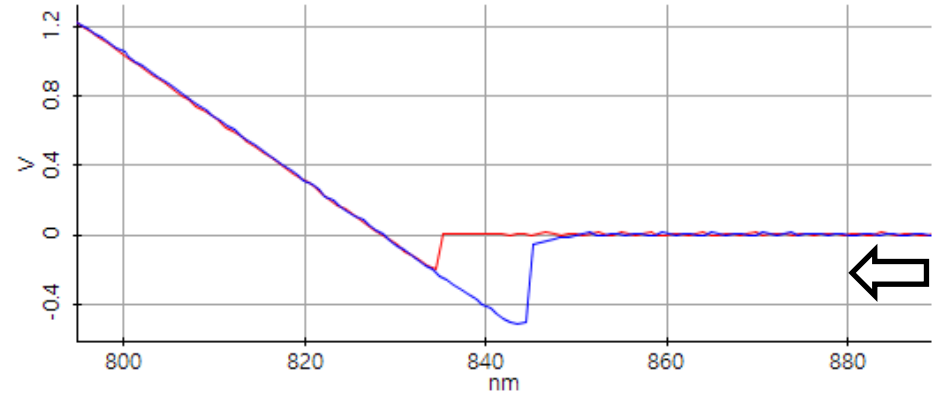
Cantilevergeometrie

⇒ Datenbank an
Cantilever



Vertical (A-B) vs. Z Height

Point : 1





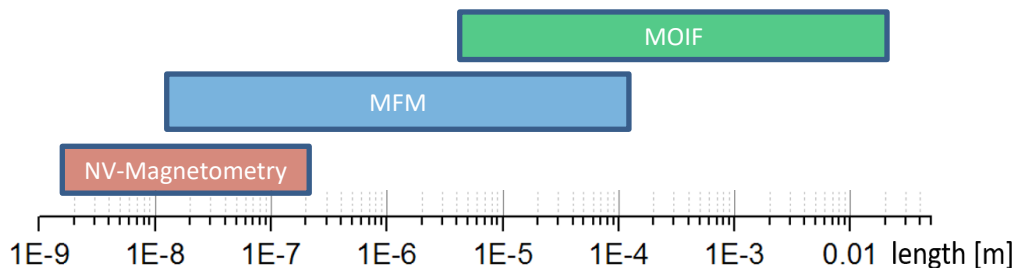
Verfahren

- **IEC TS 62607-9-1:** First IEC standard for nanomagnetic measurements – developed at PTB, Group 2.52 (JRP 15SIB06 NanoMag).
- "Round robin comparison on quantitative nanometer scale magnetic field measurements by magnetic force microscopy." *Journal of Magnetism and Magnetic Materials* 511 (2020): 166947.

Unsicherheit

- "Uncertainty analysis of stray field measurements by quantitative magnetic force microscopy." *IEEE Transactions on Instrumentation and Measurement* 69.10 (2020): 8187-8195.
- "Uncertainty propagation in quantitative magnetic force microscopy using a Monte-Carlo method." *IEEE Transactions on Magnetics* 58.5 (2022): 1-8.

NV, MFM and MOIF



	Nitrogen-Vacancy (Stickstoff-fehlstellen) Magnetometrie	Vakuum MFM	Magneto-Optischer Indikator Film (MOIF)
Sensitivität	ca. $1\text{ }\mu\text{T}$	$1\text{ mT} - 100\text{ }\mu\text{T}$	1 mT
Probengröße	Bis $100\text{ }\mu\text{m}$	üblicherweise $100\text{ }\mu\text{m}$	$\mu\text{m} - \text{cm}$
Auflösung	einige 10 nm	einige 10 nm	$> 5\text{ }\mu\text{m}$
Kalibrierung	Quanteneffekt	Referenzprobe	Externes Feld
Info	Forschungsorientiert, nicht für größere Feldstärken geeignet	Etabliertes Verfahren, weite Verfügbarkeit	Schnell und Robust

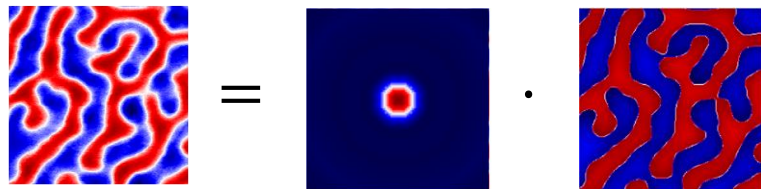
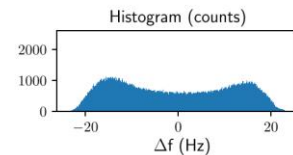
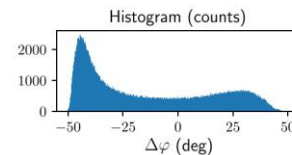
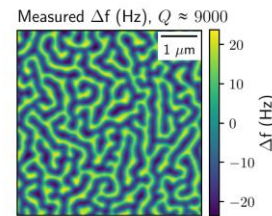
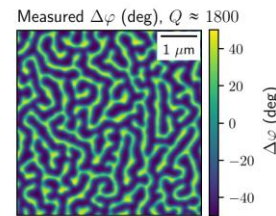
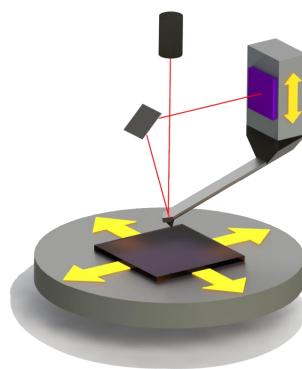
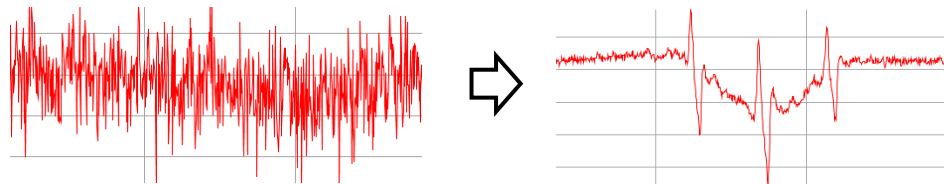
Zusammenfassung

Teil I

- Motivation
- MFM-Funktionsprinzip
- MFM in Vakuum

Teil II

- Quantitative MFM (qMFM)
- Kalibrierung



$$\Delta f(\mathbf{k}, z) = \text{ICF}(\mathbf{k}, k_0, Q, \theta, \phi, \text{Amp}) \cdot H_{z\text{sample}}(\mathbf{k}, z)$$

Kooperationspartner

Park
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