

A Modular Micromagnetic Platform for MFM Simulation

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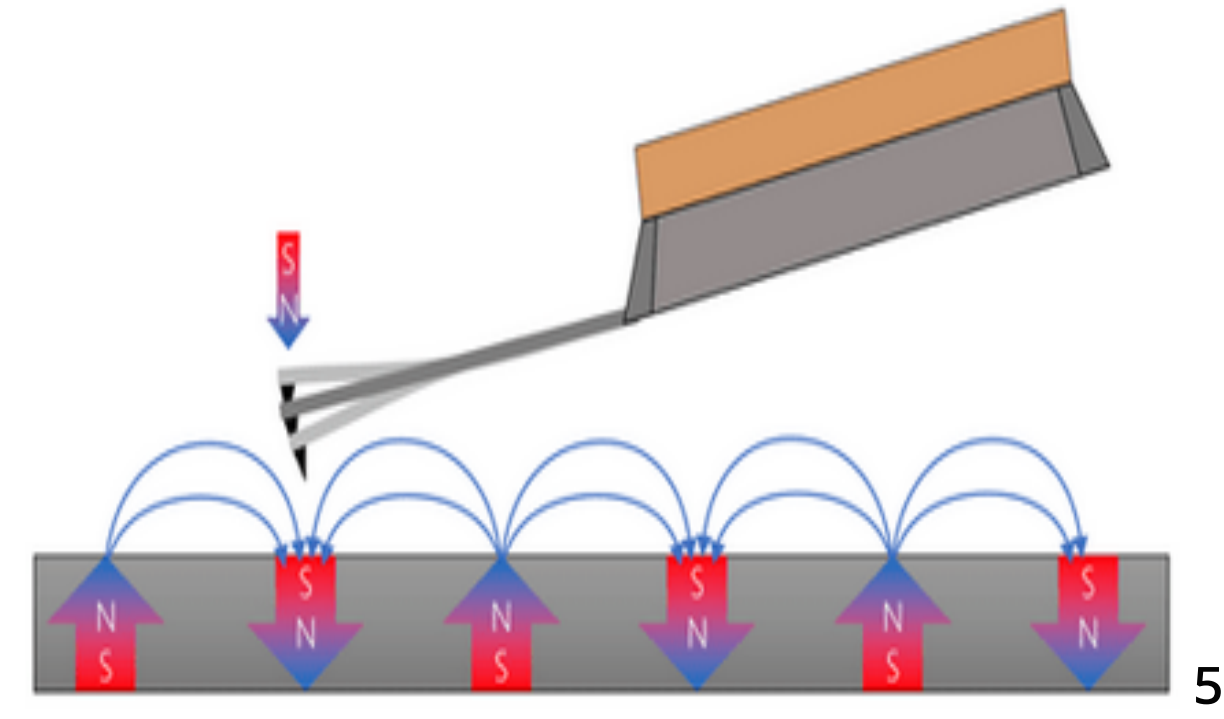
Objective

Building an comprehensive MFM simulator tool, allowing for modular inclusion of higher-order effects.

Background

How MFM works

- Cantilever **oscillating** at **resonance** with **magnetized tip** grafted to end
- Tip interacts with sample magnetization via



$$\vec{F} = \vec{\nabla}(\vec{\mu}\vec{B})$$

- Interaction **shifts** the cantilevers **oscillation phase**¹

$$\Delta\phi \approx \frac{Q}{k} \frac{dF_z}{dz}$$

Q ... Quality factor
 k ... Spring Constant

- E.g. **optical readout** of phase shift

Motivation

Magnetic Force Microscopy (MFM) is one of the most **relevant** and wide-spread measurement methods to characterize the magnetic state of a sample.

In simulation, usually stray-field **gradients** serve as **proxy** for MFM **signal**.

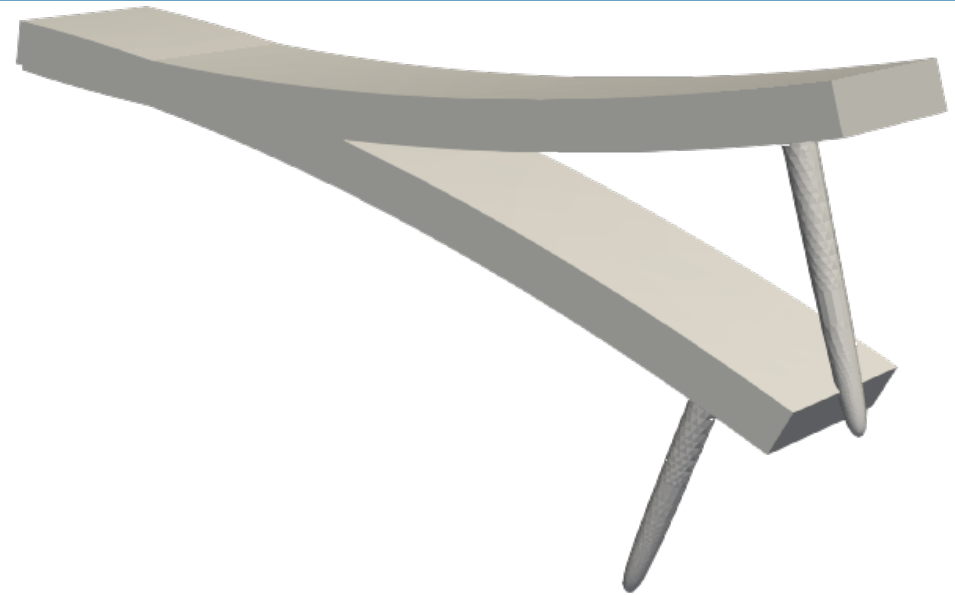
Method **imprecise**, emulates a point-like tip and neglects

- tip orientation
- tip volume
- finite oscillation path
- modulation of sample magnetization by tip

We create an MFM simulator tool built on the finite-difference and finite element frameworks NeuralMag³ and **MAGNUM**⁴ to include these effects.

This framework will allow for the optimization of non-conventional tips.

Finite Amplitude



Finite oscillation amplitudes make tip interact with **locally changing H-field**. **Averaging** of the phase becomes necessary.

$$\Delta\phi_{eff} = \langle \Delta\phi \rangle_{path}$$

Volumetric Tips

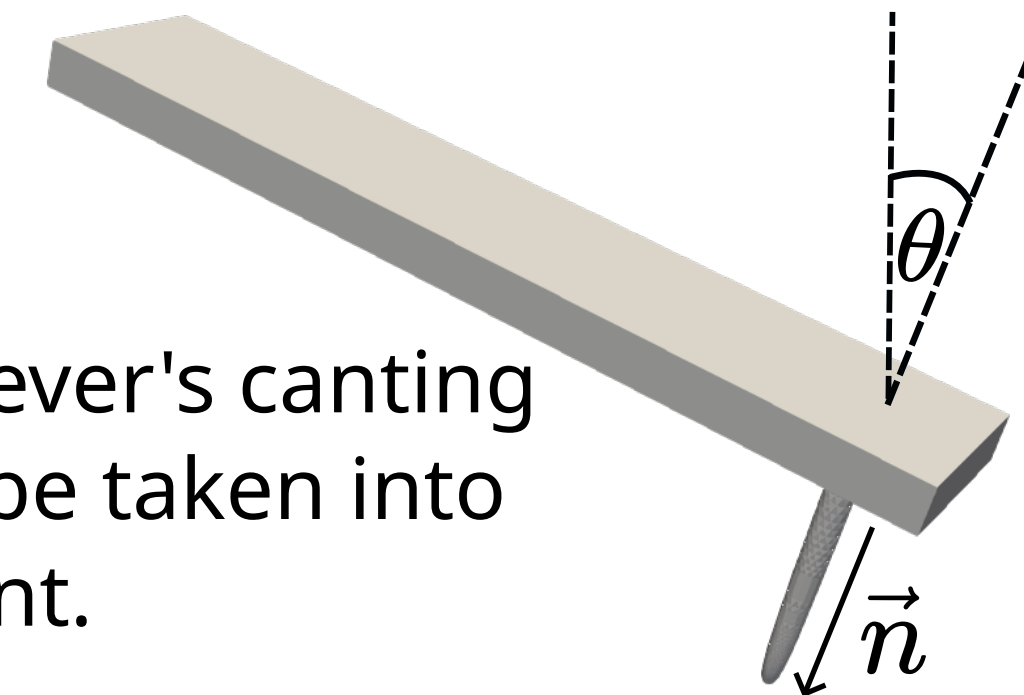


Real tips are **volumetric**. Integration over the tip-volume becomes necessary.

Correct expression for the force on the tip²:

$$\vec{F}(\vec{x}) = \mu_0 \vec{\nabla} \int_{V'} dV' m(\vec{x}') B(\vec{x} + \vec{x}')$$

Canting



Cantilever's canting must be taken into account.

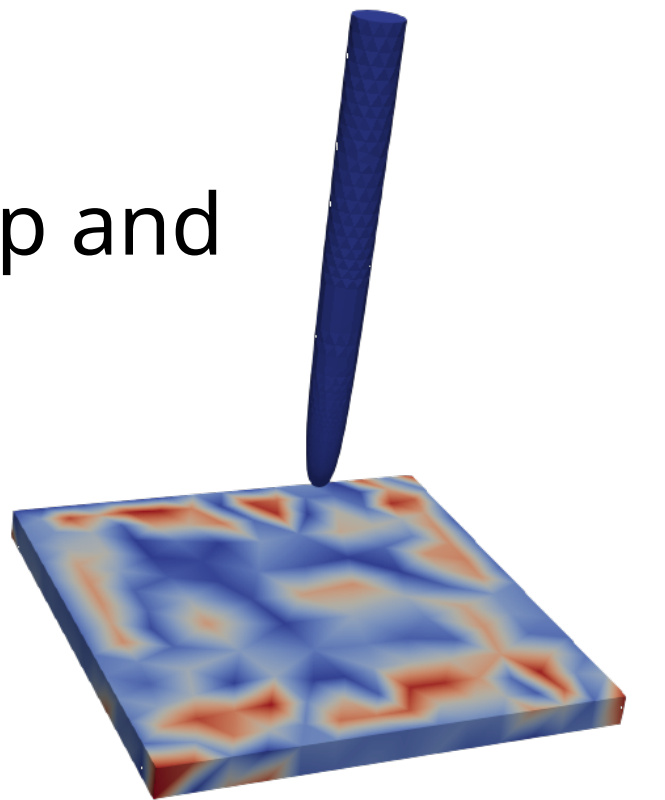
Generalize phase shift²:

$$\Delta\phi_n = \frac{Q}{k} \frac{dF_n}{dn}$$

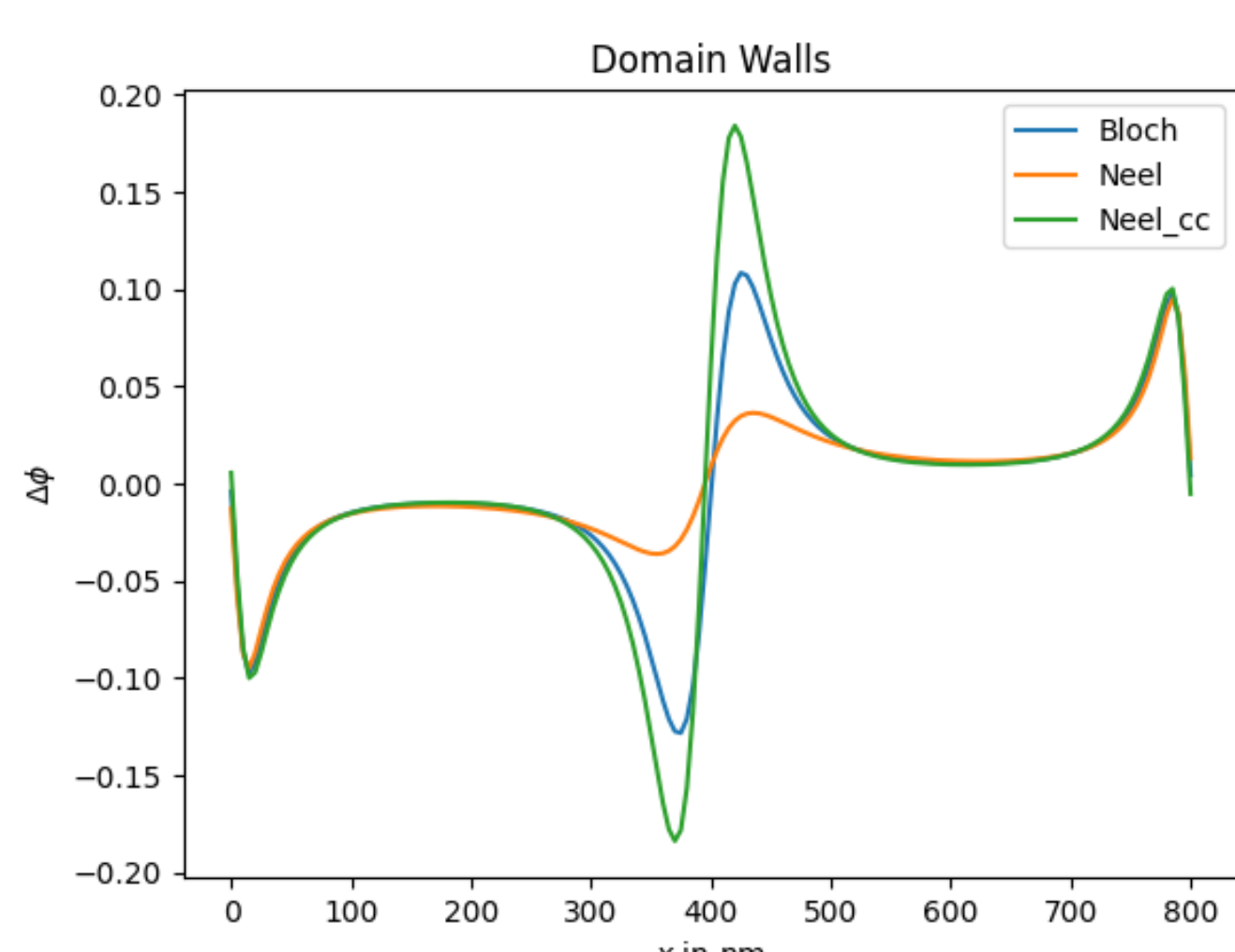
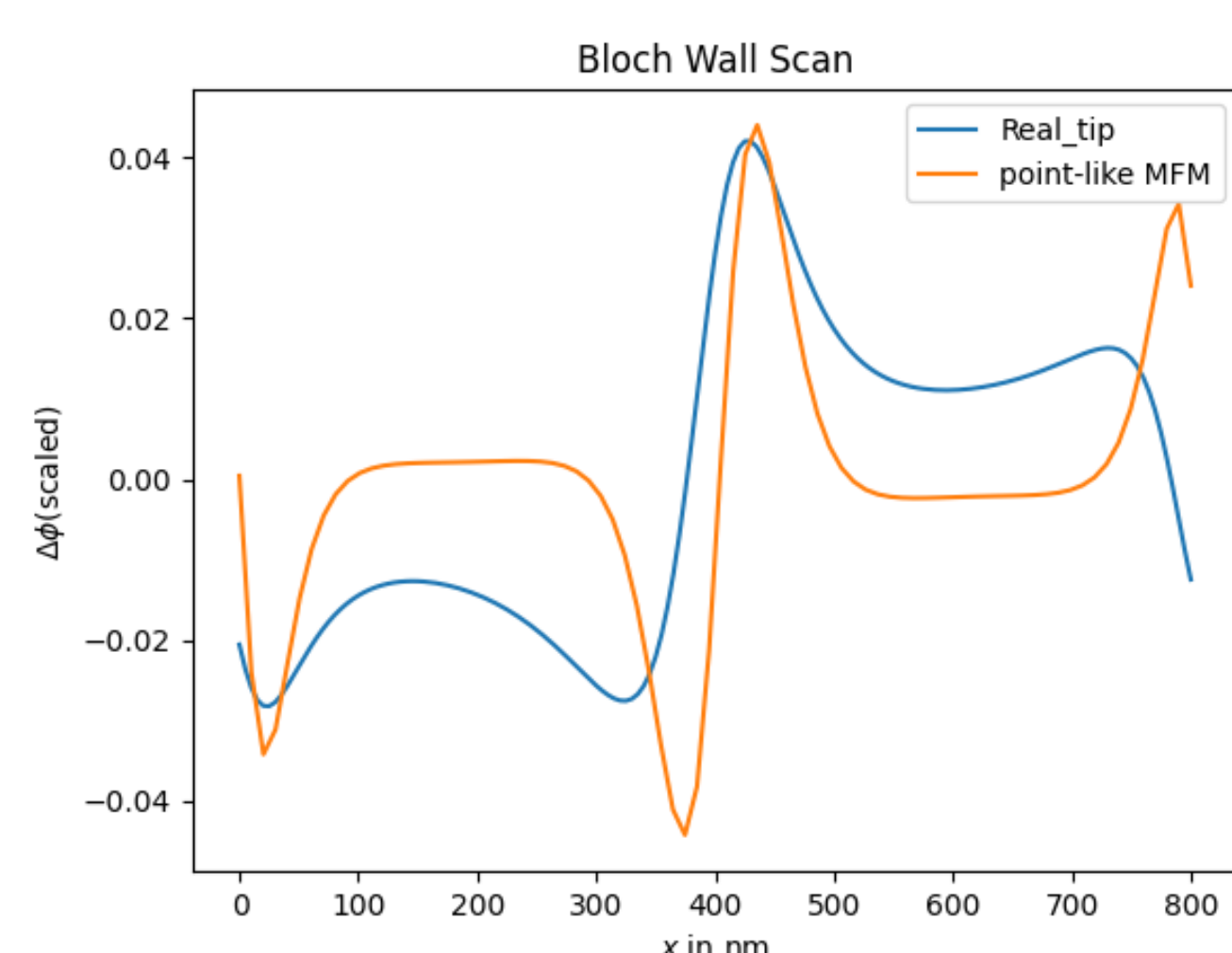
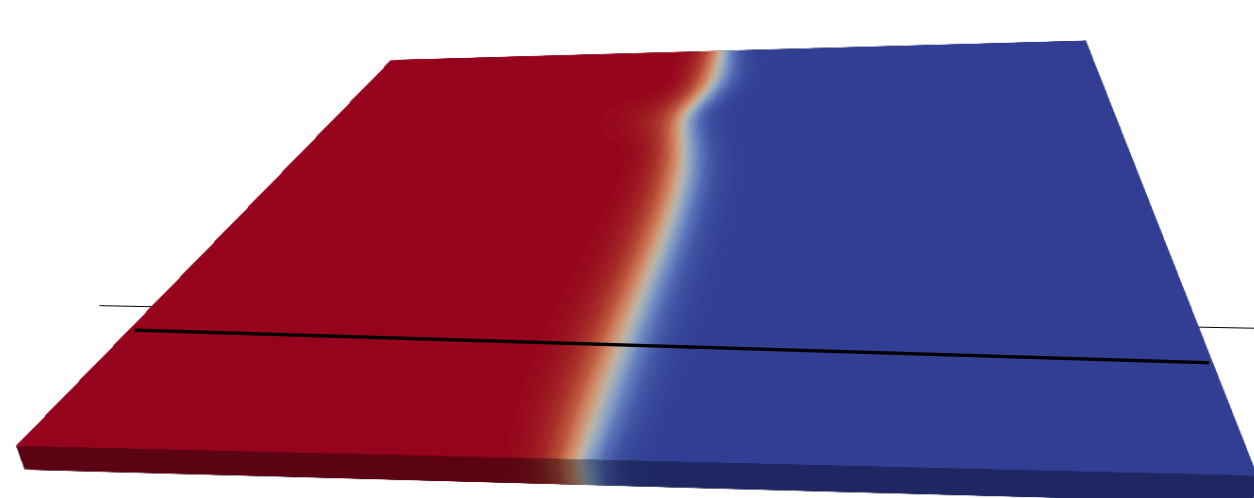
Self-Consistency

- Tip and sample magnetization **not rigid**
- Magnetization **pattern may change**
- Tip magnetization **wobbles**

Solution: Relax tip and sample together



Results



Proof of Concept

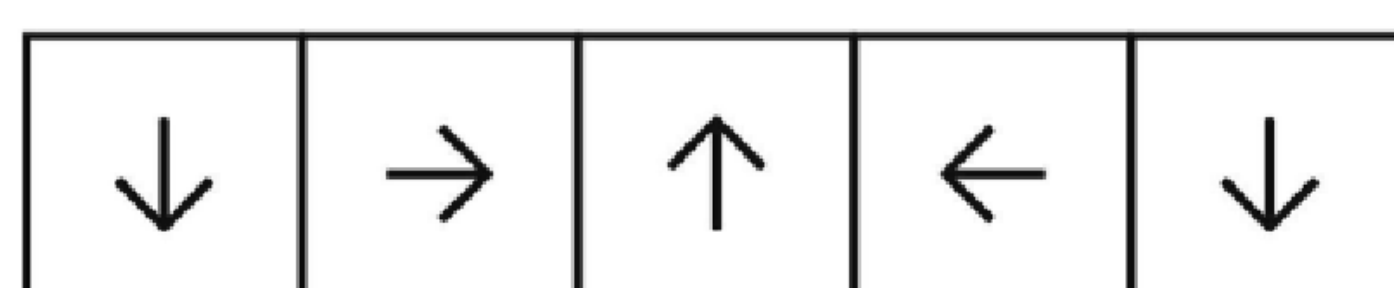
Comparison of the simulated MFM-signal obtained by a **canted, volumetric tip** with the signal obtained by a **point-like tip**.

- **Point-like** tip displays the theoretically predicted M-shaped signal
- **"Real"** tip, significantly **smears** out the signal for the chosen parameters

Sanity Check

Simulated MFM-signal of different domain walls

- Signal strength of Neel walls depends on its chirality
- Bloch wall in between



Outlook

Implemented

- arbitrary oscillatory directions
- volumetric tips

To be Implemented

- Full self-consistency
- Finite oscillation amplitudes

References

- ¹ Kazakova et al., J. Appl. Phys. 125, 060901 (2019)
- ² Feng, et al. PhysRevApplied (2022) integral force, phase shift
- ³ <https://github.com/Caiyq2019/NeuralMAG>
- ⁴ Abert et al. Journal of Magnetism and Magnetic Materials (2013)
- ⁵ credit Nanosurf AG