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Detection of magnetic particles by magnetoresistive sensors

D2 PHYSICS

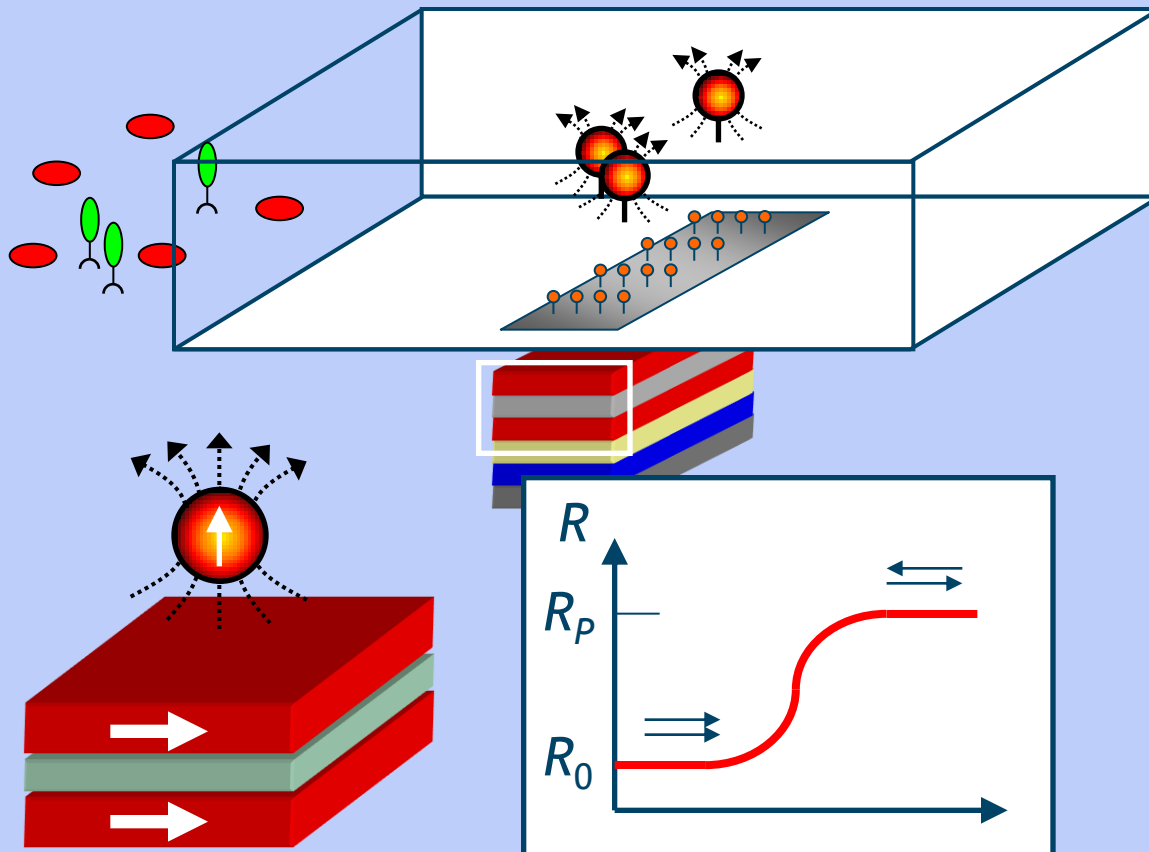
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Motivation

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Tunneling magnetoresistance sensors

Detection of biomolecules, e.g. in point-of-care-diagnostics



$$\text{TMR} = \frac{R_p - R_0}{R_0}$$

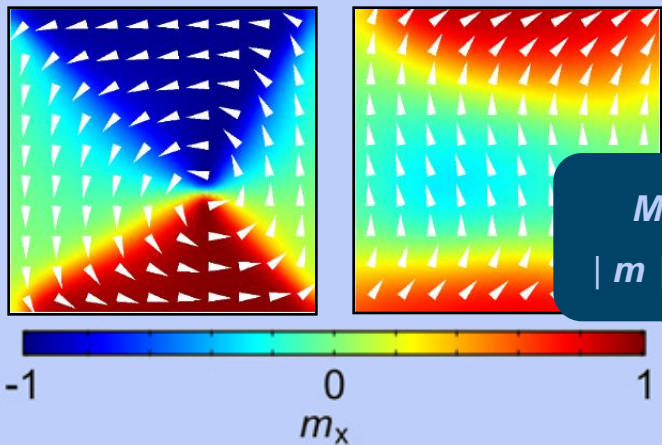
Questions:

- yes / no-answer
- particle position
- particle number

Good understanding of the relation between particle properties and signal necessary.

How to describe ferromagnetism?

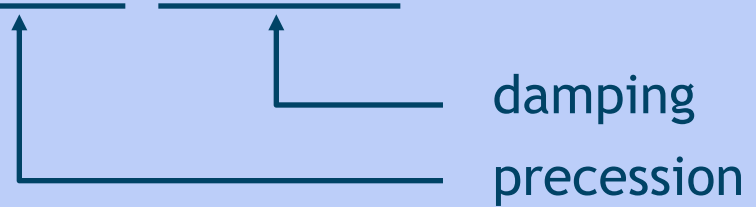
Governing equation is Landau-Lifshitz Gilbert:



$$M = M_s m$$

$$|m| = 1$$

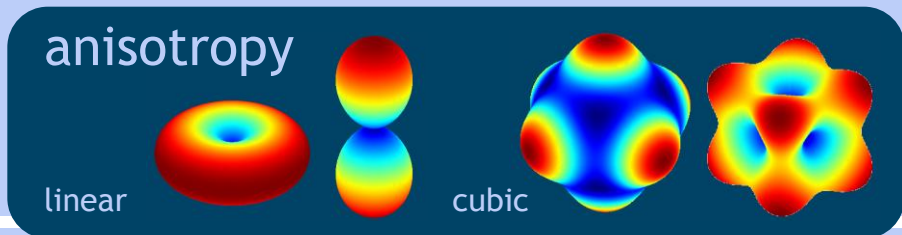
$$\frac{\partial m}{\partial t} = -\gamma m \times H_{\text{eff}} + a m \times \frac{\partial m}{\partial t}$$



$$H_{\text{eff}} = \frac{2A}{\mu_0 M_s} (\nabla m)^2 + \frac{\delta f_{\text{ani}}(m)}{\delta m} + H_{\text{demag}} + H_{\text{ex}}$$

exchange

demagnetization



$$H_{\text{demag}} = -\nabla \phi_{\text{mag}}$$

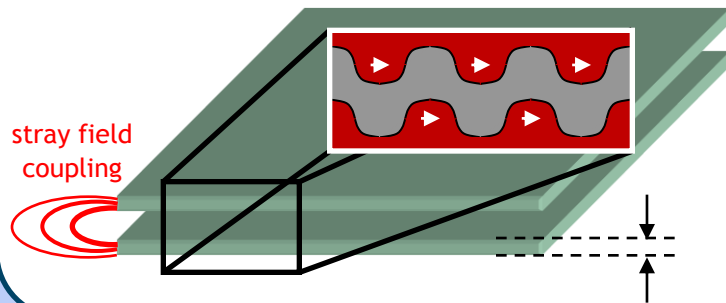
$$\Delta \phi_{\text{mag}} = M_s \nabla m$$

How to describe ferromagnetism?

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Thin films and superparamagnetic particles

Thin films



High aspect ratio!!

Find effective two-dimensional system, if possible.

$$\mathbf{m}(x, y, z) = \mathbf{m}(x, y)$$

$$J_{\text{Néel}} = -M_S^2 \langle \mathbf{m}_1, \mathbf{m}_2 \rangle \frac{\mu_0 \pi^2 h^2}{\sqrt{2} \lambda^2} \exp\left(-\frac{2\pi\sqrt{2}d}{\lambda}\right)$$

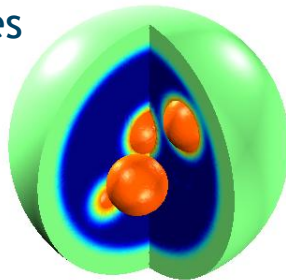
Superparamagnetic particles

magnetic nanoparticles

polymer matrix

shell

$$\mathbf{m}(x, y, z) = \mathbf{m}$$



System simplifies to set of ODEs

$$(Id - aA) \frac{\partial \tilde{\mathbf{m}}}{\partial t} = \gamma A \tilde{\mathbf{H}}_{\text{eff}}$$

$$\tilde{\mathbf{m}} = (m_{x,1}, m_{y,1}, m_{z,1}, m_{x,2}, \dots)^T$$

$$\tilde{\mathbf{H}}_{\text{eff}} = (H_{\text{eff},x,1}, H_{\text{eff},y,1}, H_{\text{eff},z,1}, H_{\text{eff},x,2}, \dots)^T$$

$$A = \begin{pmatrix} A_1 & & 0 \\ & \ddots & \\ 0 & & A_N \end{pmatrix}$$

$$A_n = \varepsilon_{ijk} m_{n,j}$$

$$\mathbf{H}_{\text{eff}} = \frac{2A}{\mu_0 M_S} (\nabla \mathbf{m})^2 + \frac{\delta f_{\text{ani}}(\mathbf{m})}{\delta \mathbf{m}} + \mathbf{H}_{\text{demag}} + \mathbf{H}_{\text{ex}}$$

Implementation into COMSOL

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Self generated GUI

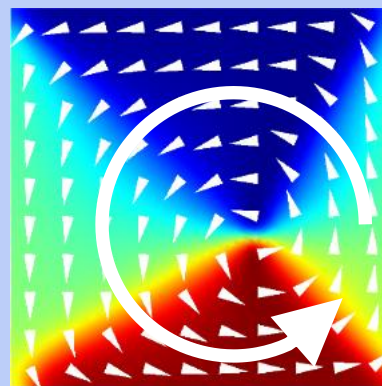
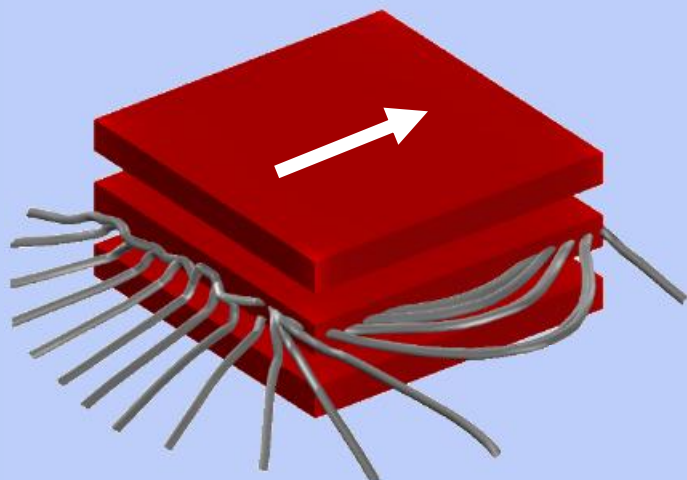
The screenshot displays the Padima software interface, which is a self-generated GUI for COMSOL. The window title is "Padima" and it includes a menu bar with "File" and "Help". The main interface is divided into several sections:

- External field settings:** Includes a dropdown for "Type of field" (set to "no external field"), input fields for "H-field" (2e4), "periodic time" (1e-9), and "axis" (0, 1, 0).
- Solver settings:** Includes a "tlist" field (0:1e-11:1e-8), checkboxes for "particle dynamics" (unchecked) and "layer dynamics" (checked), and a "task" dropdown (set to "micro dynamics").
- Postprocessing:** Includes tabs for "Particle dynamics" and "Layer dynamics", buttons for "Geometry", "Properties", "Component", "Trajectory", and "Average", and a "particles plot" dropdown.
- Plots:** The bottom section contains six plots. Three are heatmaps showing field distributions, and three are particle plots showing particle trajectories and positions. The axes for the plots are labeled with $\times 10^{-8}$.

Examples

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Micromagnetics - A trilayer system

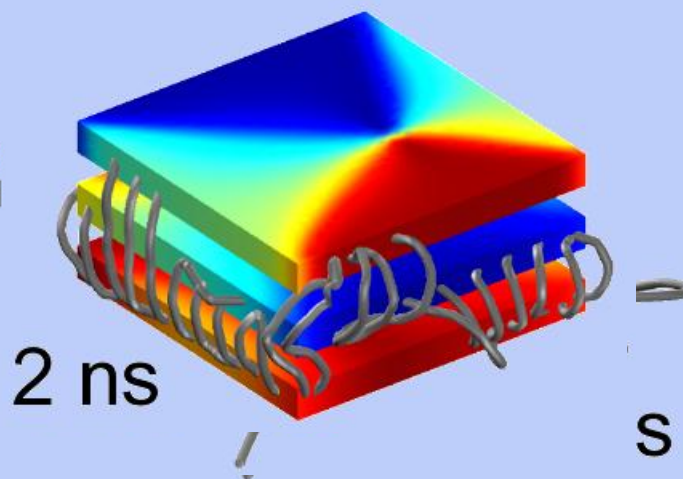
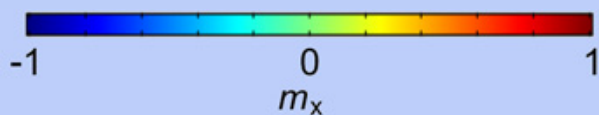
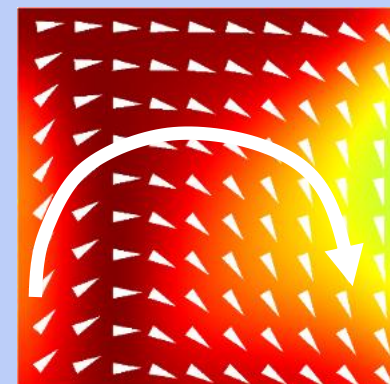


vortex

S-state



C-state



S

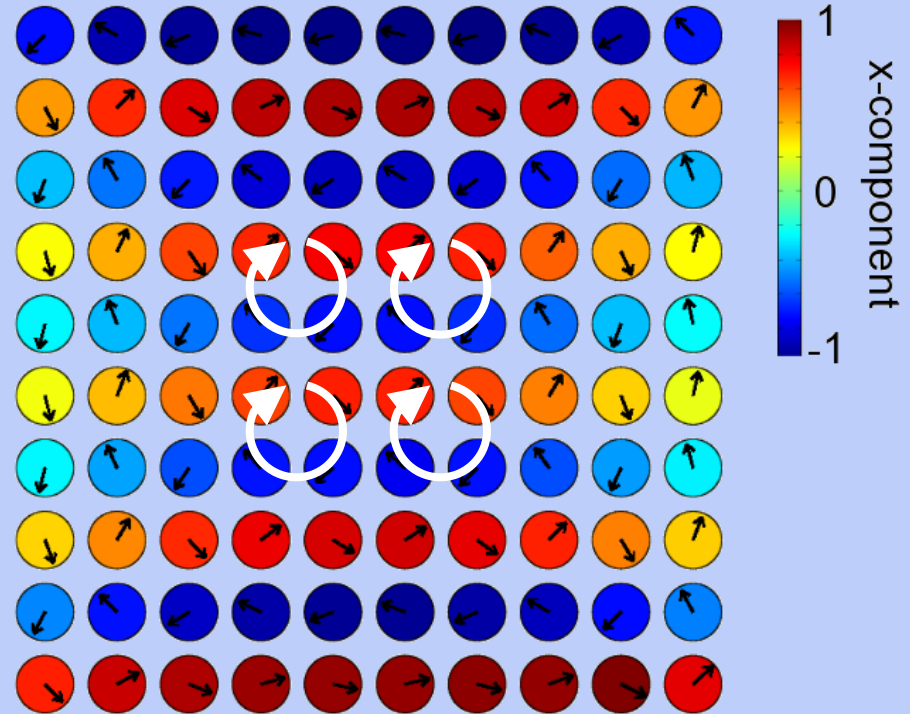
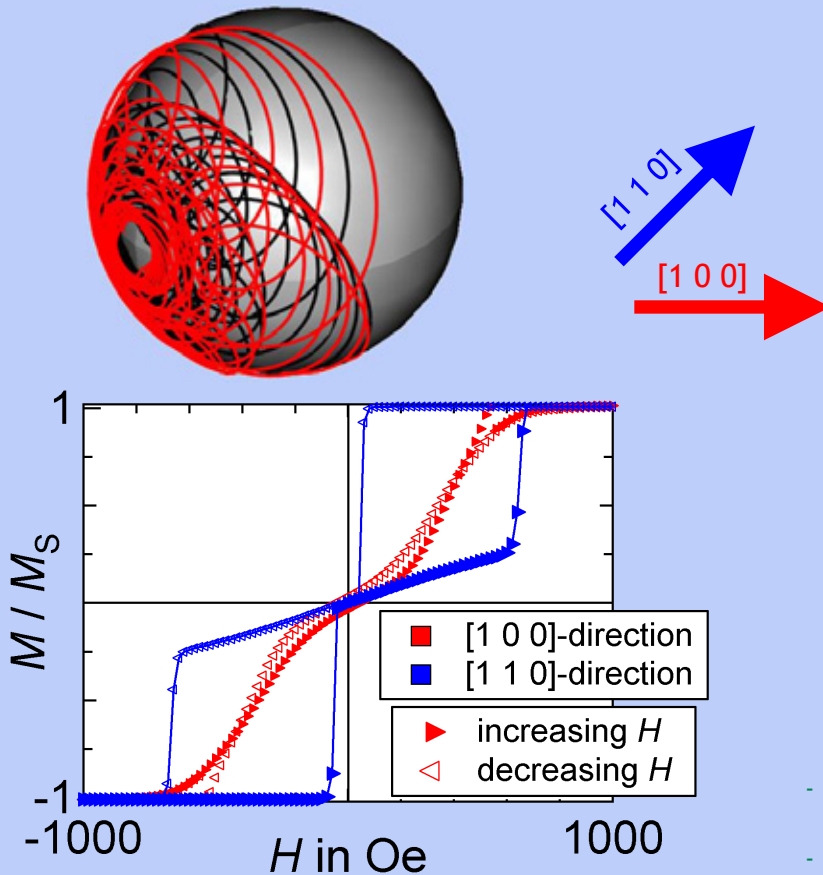
S

Examples

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Particle dynamics - Two-dimensional particle assemblies

Dynamics of particles can be complex:



- antiferromagnetic vortex equilibrium state
- anisotropic hysteresis effects

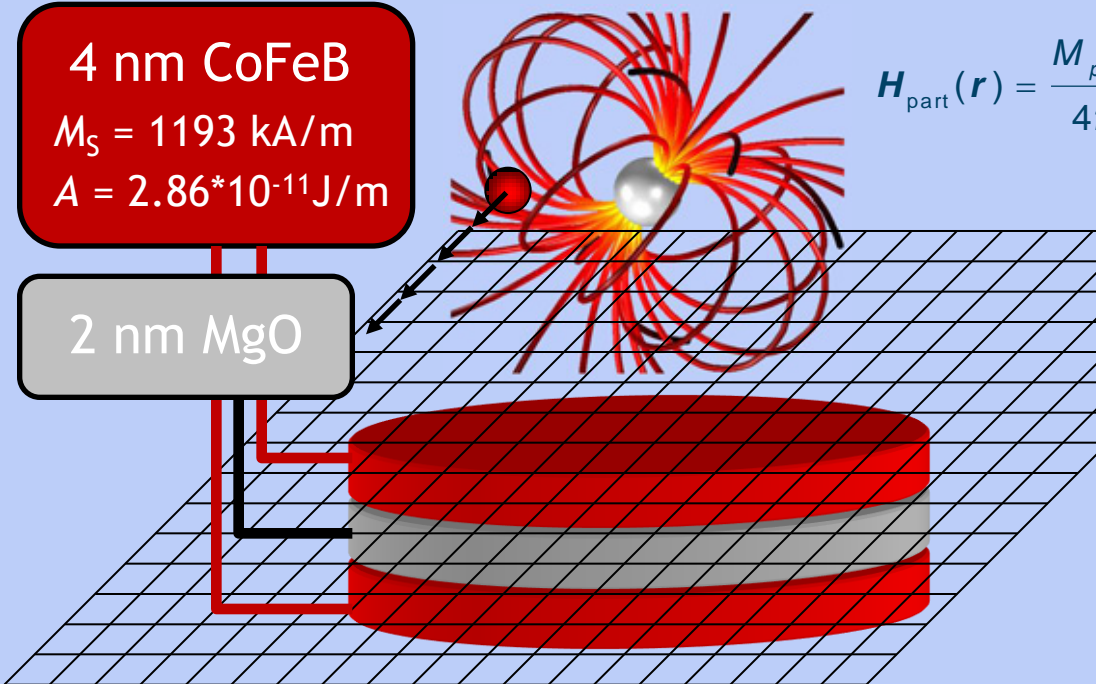
Measuring tasks

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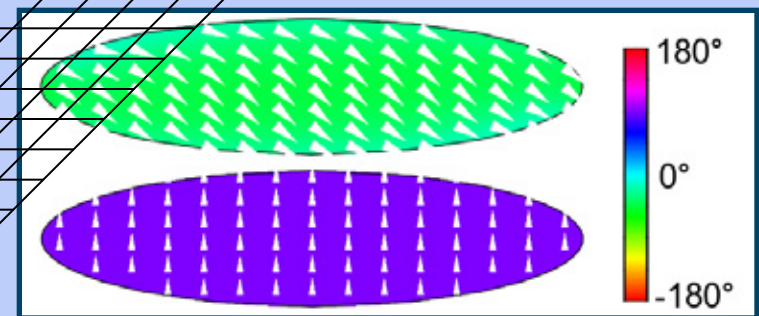
Model system

4 nm CoFeB
 $M_S = 1193 \text{ kA/m}$
 $A = 2.86 \cdot 10^{-11} \text{ J/m}$

2 nm MgO



$$H_{\text{part}}(\mathbf{r}) = \frac{M_{\text{part}}}{4\pi} \left(\frac{3\langle \mathbf{m}_{\text{part}}, \mathbf{r} - \mathbf{r}_{\text{part}} \rangle (\mathbf{r} - \mathbf{r}_{\text{part}})}{|\mathbf{r} - \mathbf{r}_{\text{part}}|^5} - \frac{\mathbf{m}_{\text{part}}}{|\mathbf{r} - \mathbf{r}_{\text{part}}|^3} \right)$$



- determine position of a single particle
- measure number of particles in range

$$\text{TMR} = \frac{1}{3} \frac{1 - \langle \delta \mathbf{m} \rangle}{1 + \langle \delta \mathbf{m} \rangle / 3}$$

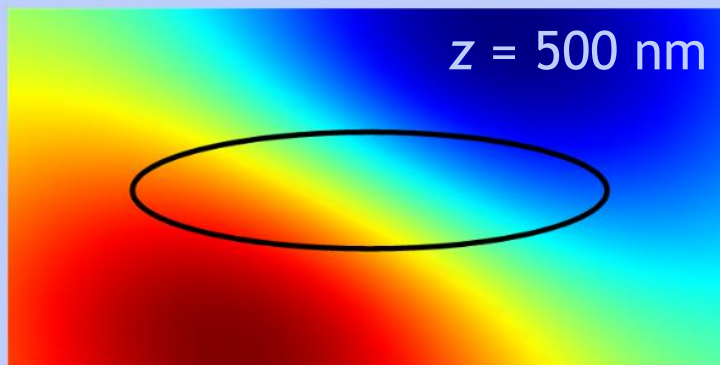
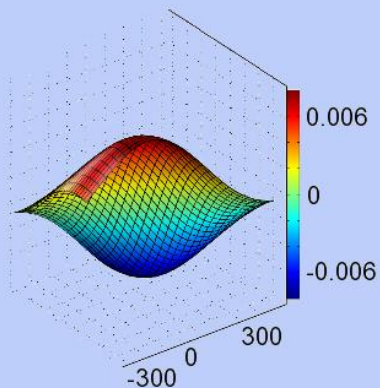
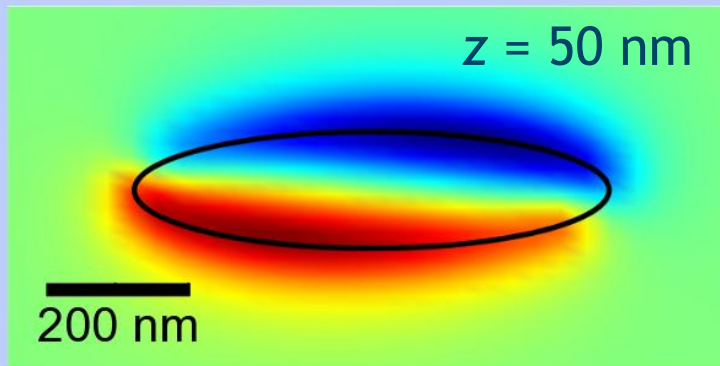
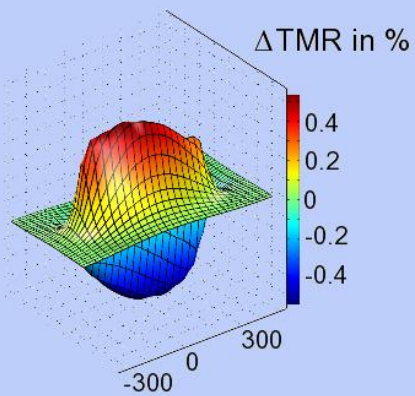
$$\langle \delta \mathbf{m} \rangle = \frac{1}{A_{\text{layer}}} \int_{A_{\text{layer}}} \langle \mathbf{m}_1, \mathbf{m}_2 \rangle d\mathbf{r}$$

Measuring single particles

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TMR-maps

Probe particle of $r = 20$ nm and $M_s = 1000$ kA/m at different heights



Rapid decrease in
respect to particle
sensor distance

Measuring single particles

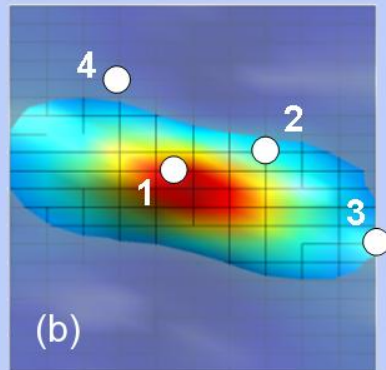
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Comparison to experiment

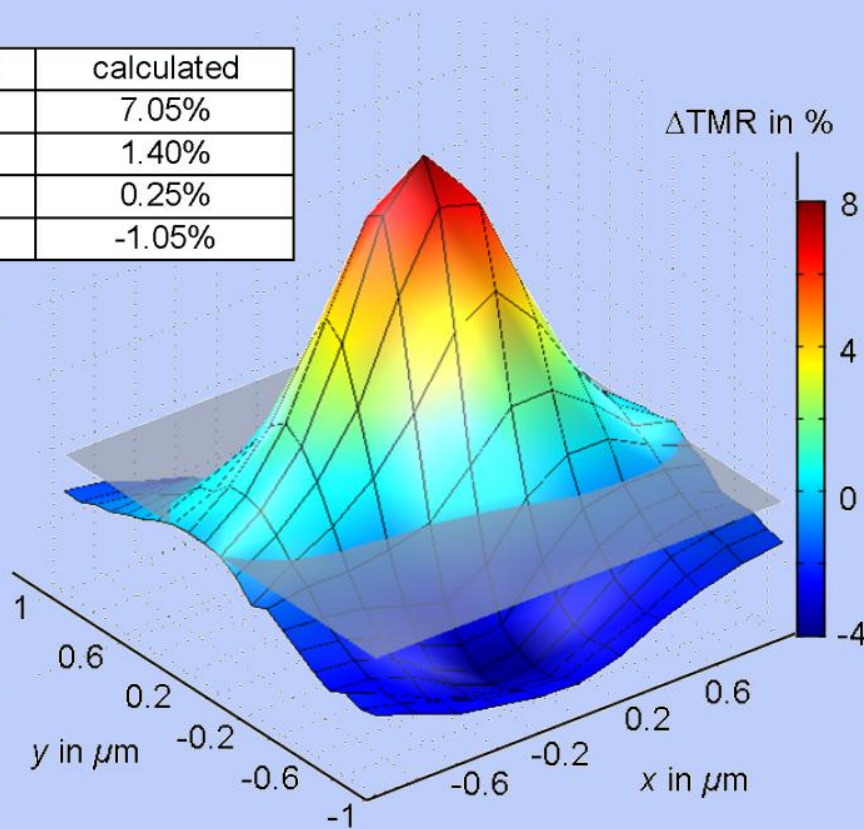
Frequency dependence for different particle diameters:

position	experimental	calculated
1	2.13%	7.05%
2	1.56%	1.40%
3	0%	0.25%
4	-0.96%	-1.05%

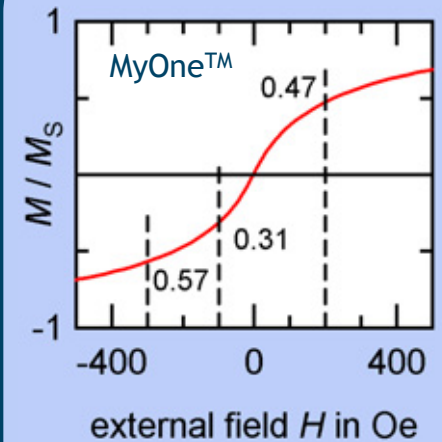
(a)



(b)



particle properties



$$M_S = 120 \text{ kA/m}$$

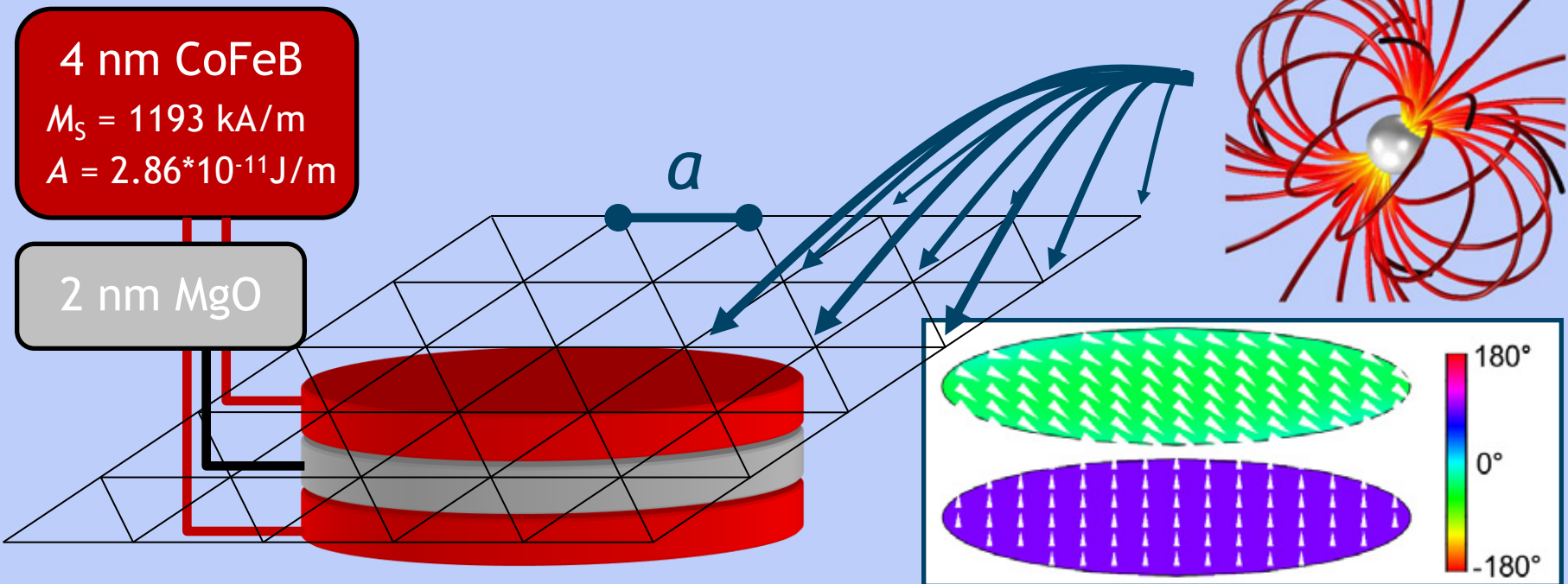
$$r = 0.5 \text{ } \mu\text{m}$$

$$z = 0.562 \text{ } \mu\text{m}$$

Measuring tasks

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Model system



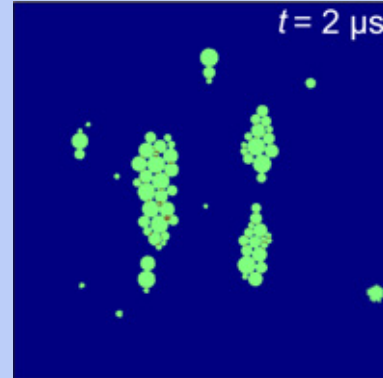
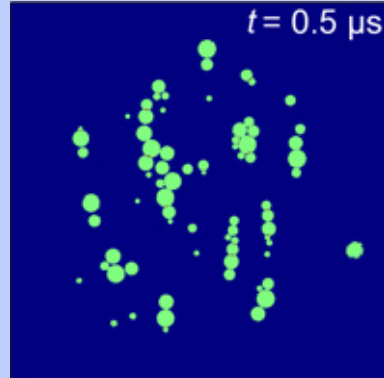
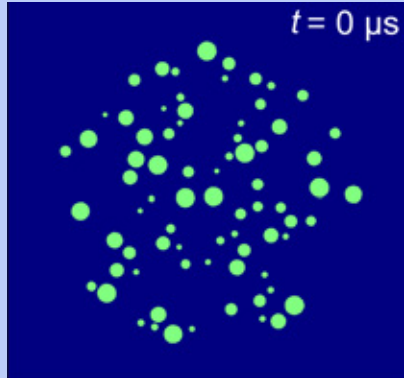
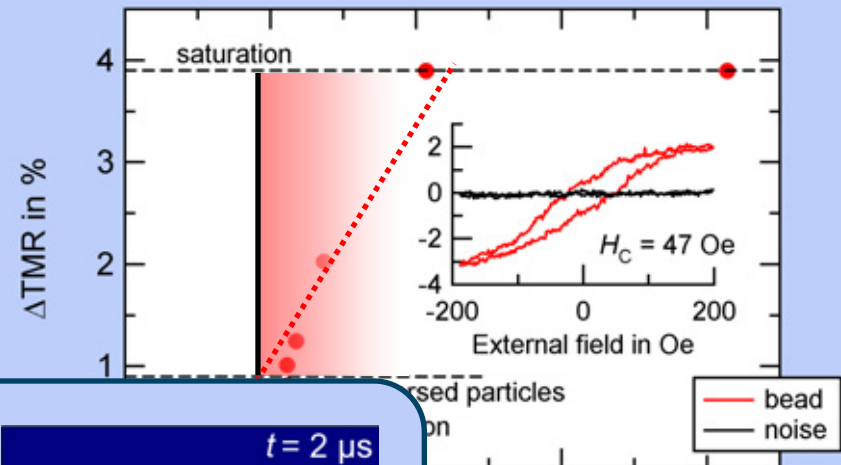
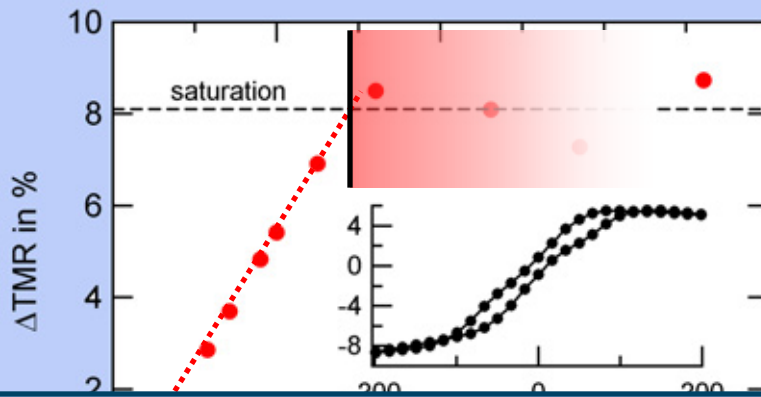
- measure number of particles in range
 - varying a leads to different sensor coverage

Measuring several particles

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Comparison to experiment

Influence of sensor coverage:



used particles
on
le per 10^{-3} nm^2
te values

Conclusion & Outlook

Conclusion

- We have successfully implemented micromagnetic equations for the calculation of ferromagnetic thin film systems
- Theoretical predictions on spatial and number resolute detection are in very good agreement with experimental findings

Outlook

- Better quantification of cluster detection
- Use this model to guide the design of new sensor layouts (see also Poster session)

Further reading:

- [1] A. Weddemann et al., *A hydrodynamic switch: microfluidic separation system for magnetic beads*, Appl. Phys. Lett. **94**, 173501 (2009)
- [2] A. Auge et al. *Magnetic ratchet for biotechnological applications*, Appl. Phys. Lett. **94**, 183507 (2009)
- [3] A. Weddemann et al., *Particle flow control by induced dipolar particle interactions*, submitted to Lab-Chip
- [4] A. Weddemann et al., *Dynamic simulations of the dipolar driven demagnetization process of magnetic multi-core nanoparticles*, subm. to JMMM
- [5] A. Weddemann et al., *On the resolution limits of tunnel magnetoresistance sensors for particle detection*, submitted to New Jour. Phys.
- [6] C. Albon et al., *Tunneling magnetoresistance sensors for high resolute particle detection*, Appl. Phys. Lett. **95** (2009)
- [7] C. Albon et al., *Number sensitive detection and direct imaging of dipolar coupled magnetic nanoparticles by tunnel magnetoresistive sensors*, accepted for publication in Appl. Phys. Lett.
- [8] A. Weddemann et al., *Towards the detection of single nanoparticles: new strategies by adjustment of sensor shape*, subm. to Appl. Phys. Lett.