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Detection of magnetic particles by magnetoresistive sensors

D2 PHYSICS

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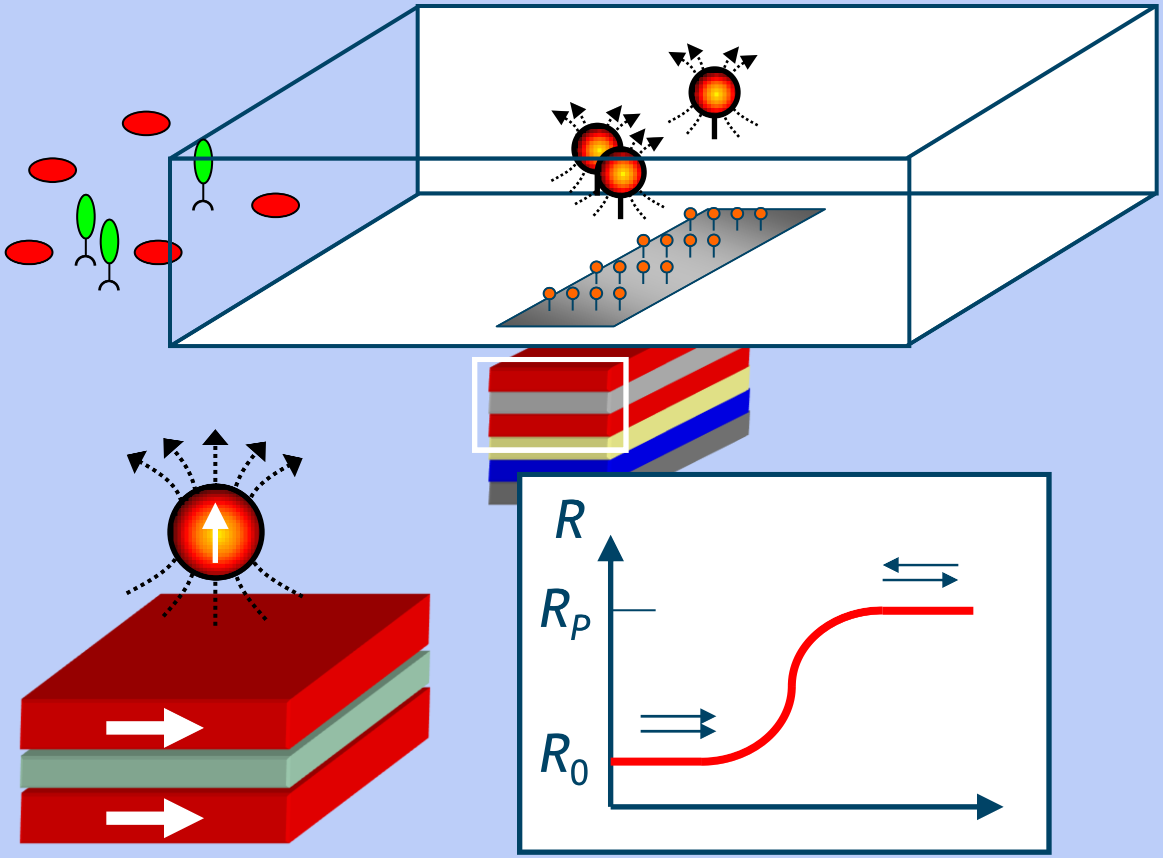
Motivation

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



$$TMR = \frac{R_P - R_0}{R_0}$$

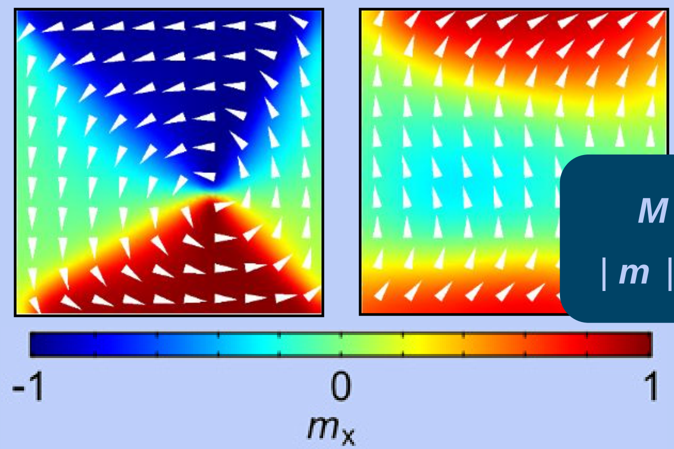
Questions:

- 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:



$$\mathbf{M} = M_S \mathbf{m}$$

$$|\mathbf{m}| = 1$$

$$\frac{\partial \mathbf{m}}{\partial t} = \underbrace{-\gamma \mathbf{m} \times \mathbf{H}_{\mathrm{eff}}}_{\text{precession}} + \underbrace{a \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}}_{\text{damping}}$$

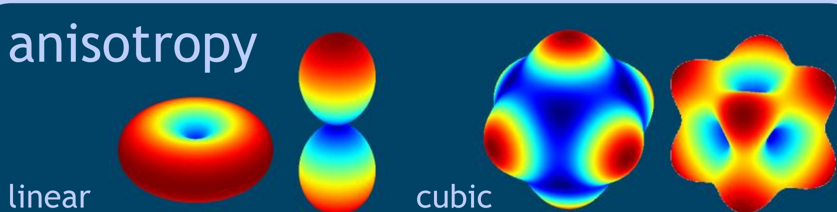
damping

precession

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

exchange

anisotropy



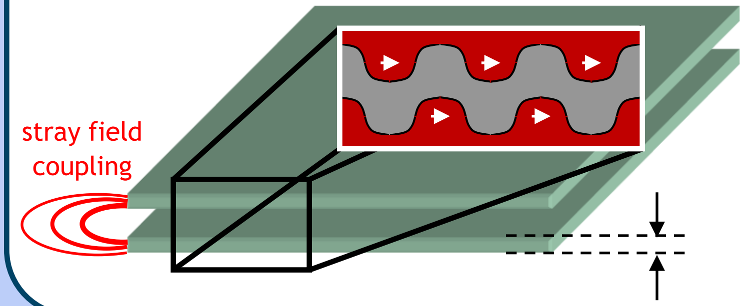
demagnetization

$$\mathbf{H}_{\mathrm{demag}} = -\nabla \phi_{\mathrm{mag}}$$

$$\Delta \phi_{\mathrm{mag}} = M_S \nabla \mathbf{m}$$

How to describe ferromagnetism?

Thin films



High aspect ratio!!

Find effective two-dimensional system, if possible.

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

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

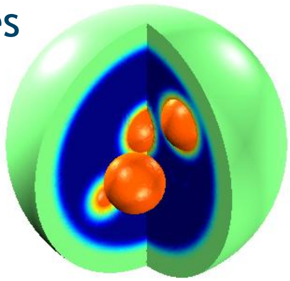
$$\boldsymbol{H}_{\text{eff}}=\frac{2A}{\mu_0M_S}(\nabla\boldsymbol{m})^2+\frac{\delta f_{\text{ani}}(\boldsymbol{m})}{\delta\boldsymbol{m}}+\boldsymbol{H}_{\text{demag}}+\boldsymbol{H}_{\text{ex}}$$

Superparamagnetic particles

magnetic nanoparticles

polymer matrix

shell



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

System simplifies to set of ODEs

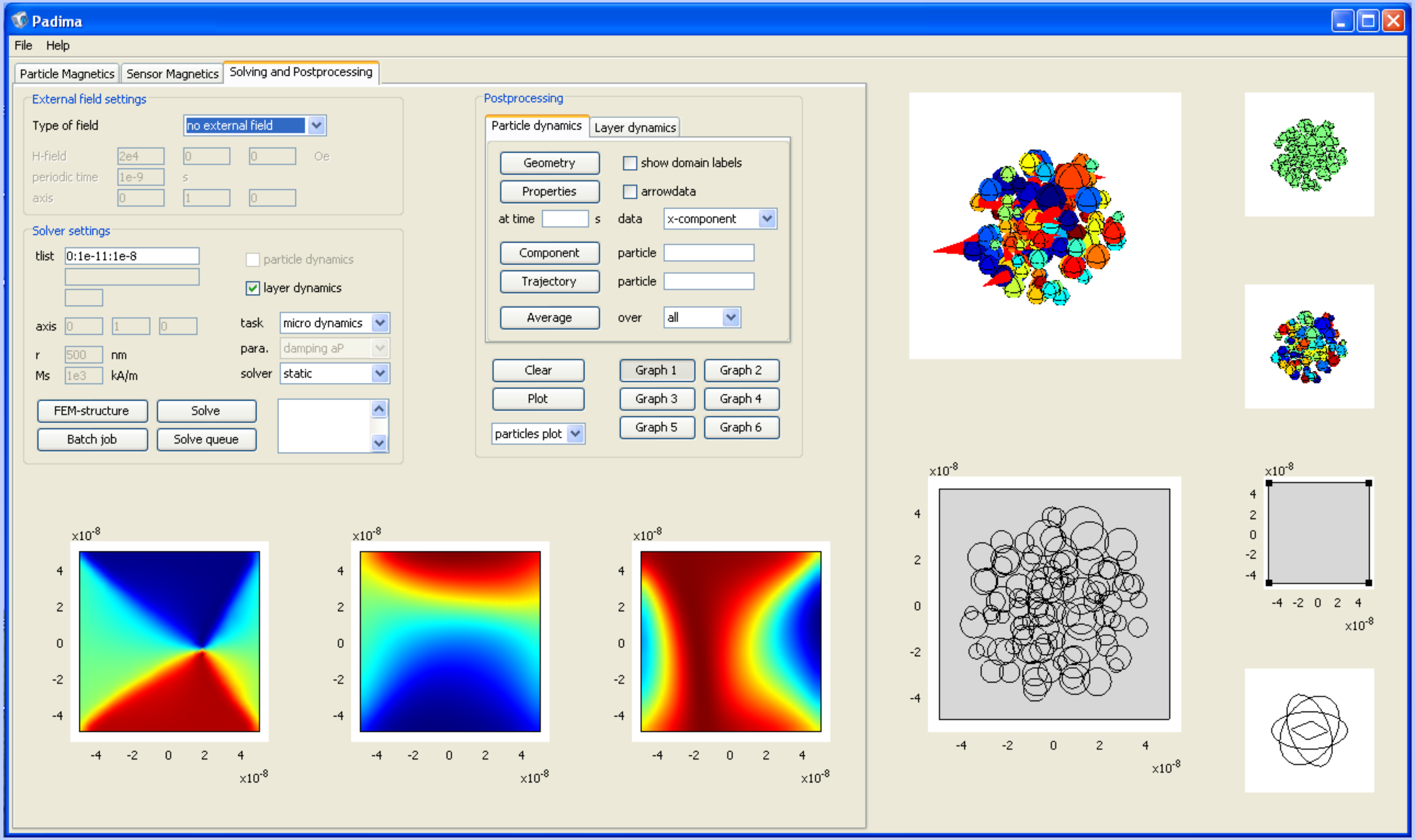
$$(Id-aA)\frac{\partial\tilde{\boldsymbol{m}}}{\partial t}=\gamma A\tilde{\boldsymbol{H}}_{\text{eff}}\qquad A=\begin{pmatrix}A_1 & & 0\\ & \ddots & \\ 0 & & A_N\end{pmatrix}$$

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

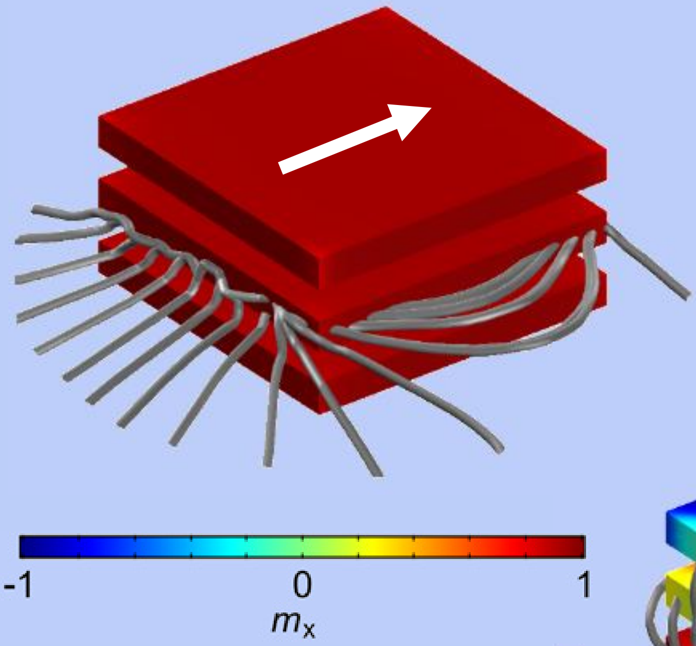
$$\tilde{\boldsymbol{H}}_{\text{eff}}=(H_{\text{eff},x,1},H_{\text{eff},y,1},H_{\text{eff},z,1},H_{\text{eff},x,2},\ldots)^T\qquad A_n=\varepsilon_{ijk}m_{n,j}$$

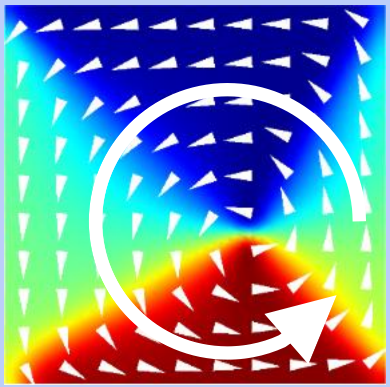
Implementation into COMSOL

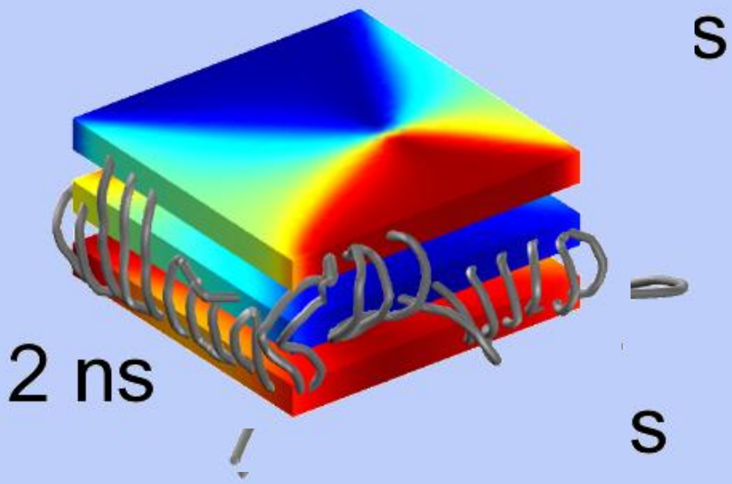
Self generated GUI

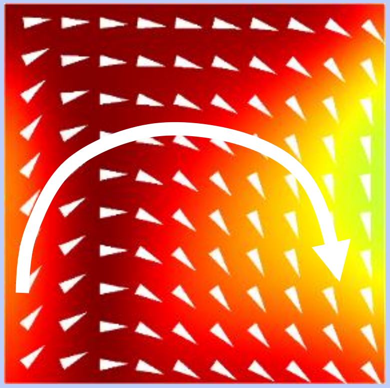


Examples



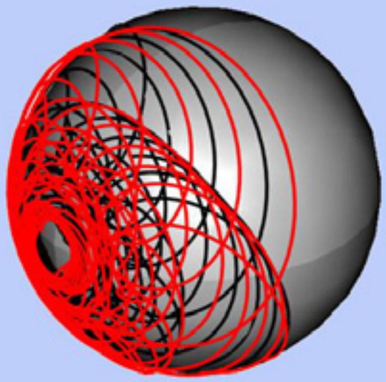


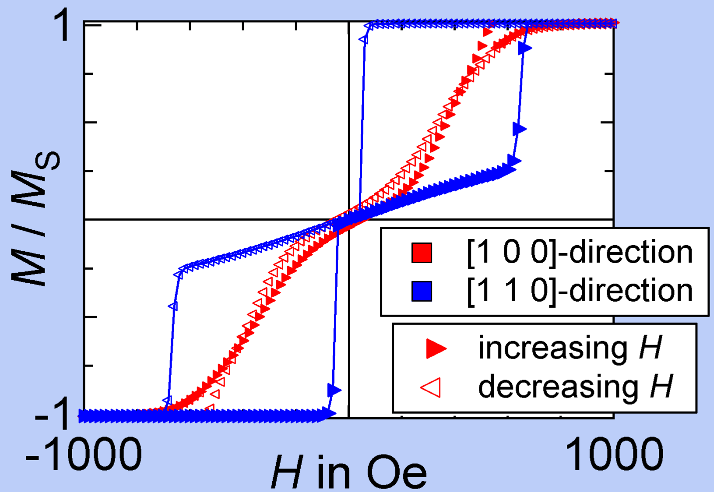


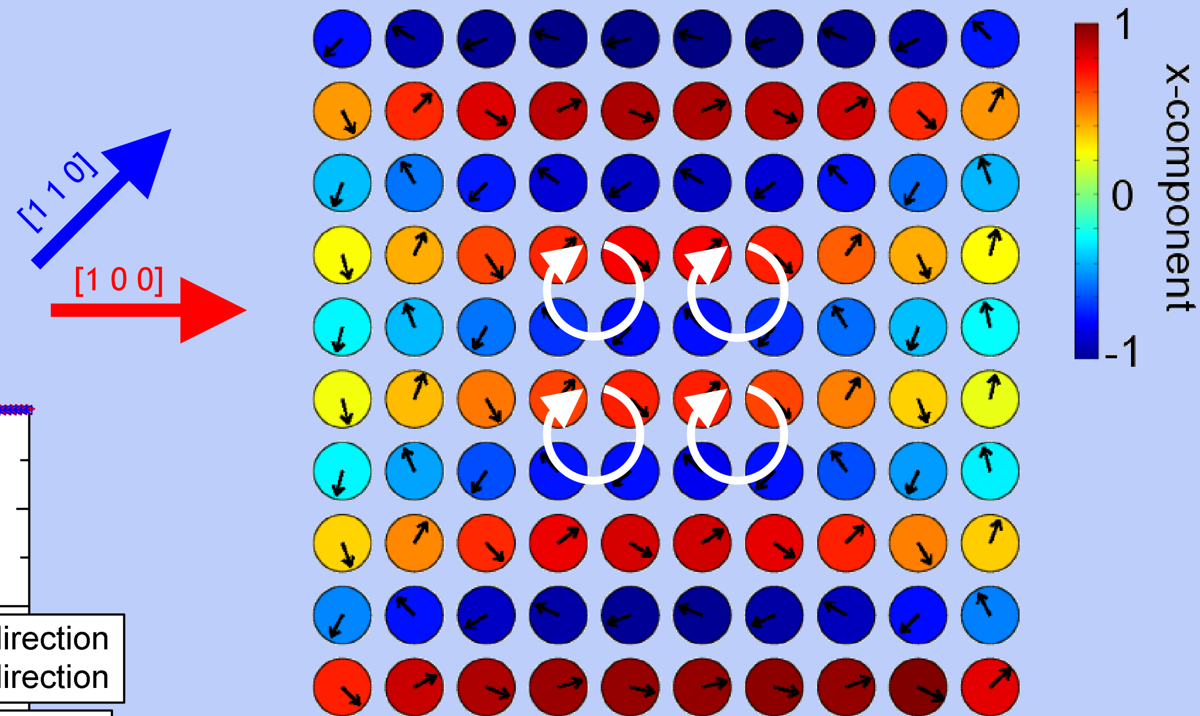


Examples

Dynamics of particles can be complex:

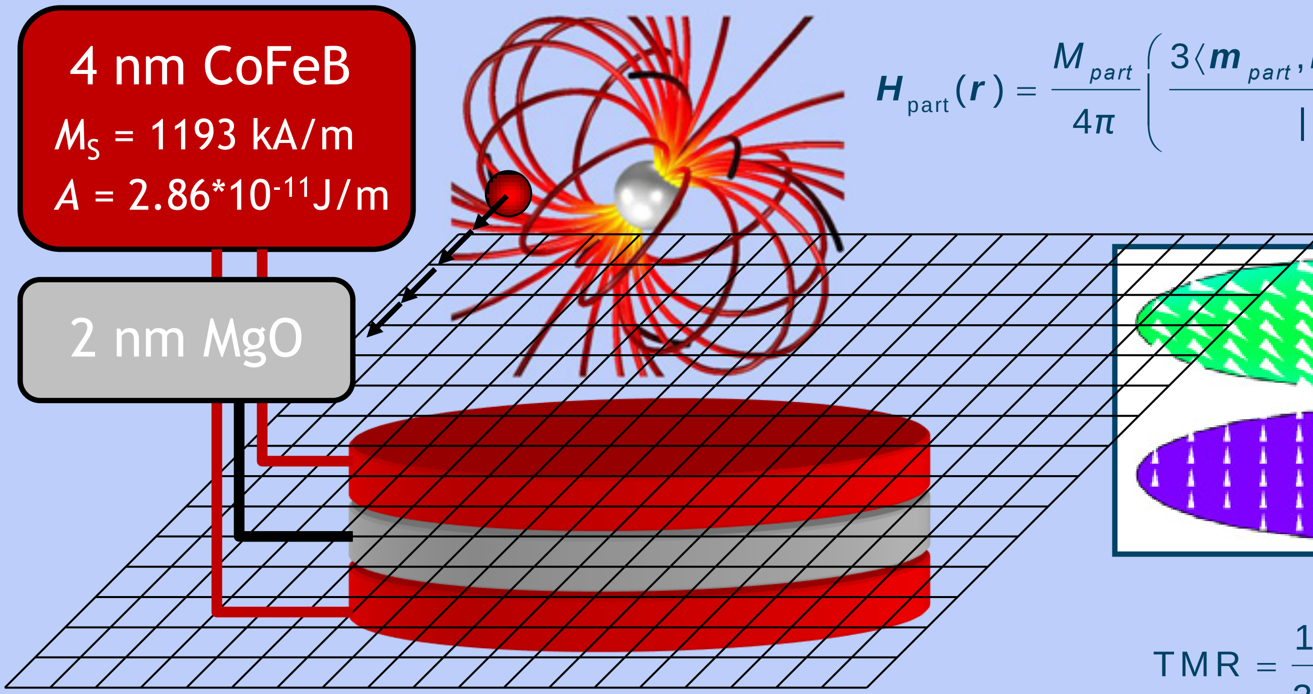




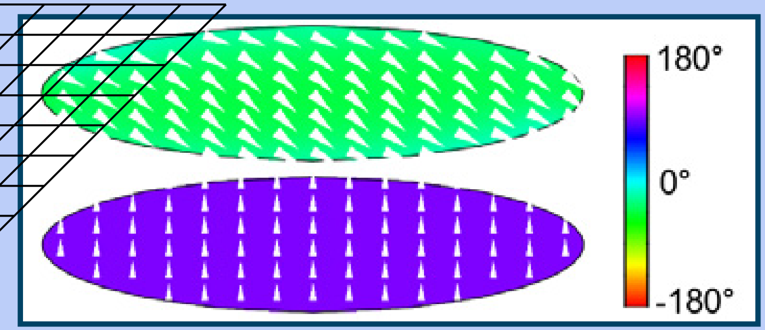


- antiferromagnetic vortex equilibrium state
- anisotropic hysteresis effects

Measuring tasks



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



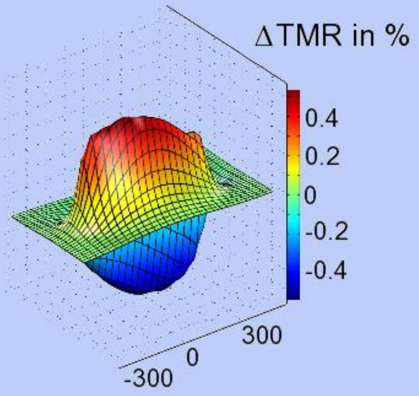
$$\mathrm{TMR} = \frac{1}{3}\frac{1-\langle \delta \boldsymbol{m}\rangle}{1+\langle \delta \boldsymbol{m}\rangle/3}$$

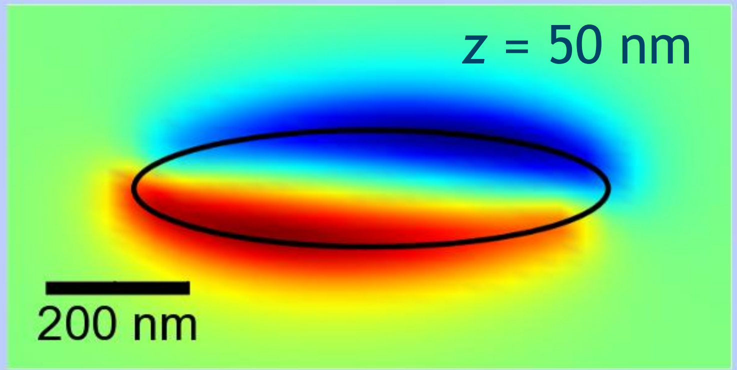
$$\langle \delta \boldsymbol{m}\rangle = \frac{1}{A_{\mathrm{layer}}}\int_{A_{\mathrm{layer}}} \langle \boldsymbol{m}_1, \boldsymbol{m}_2\rangle \, d\boldsymbol{r}$$

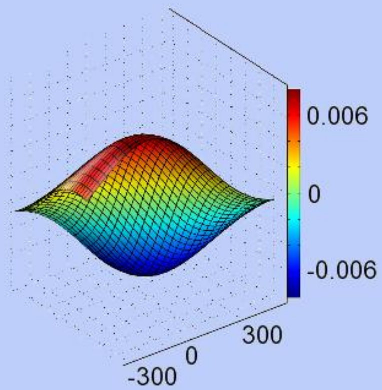
- determine position of a single particle
- measure number of particles in range

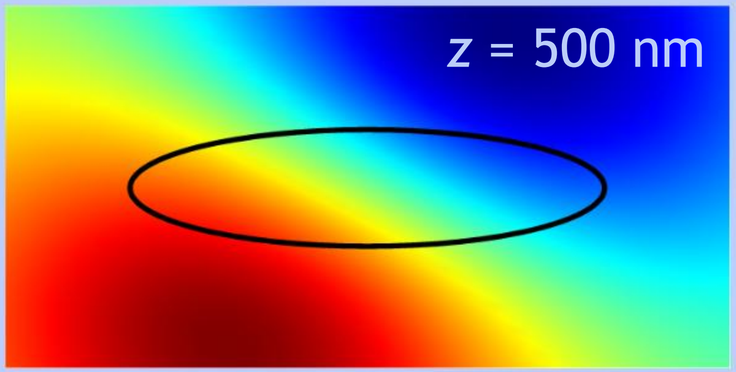
Measuring single particles

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







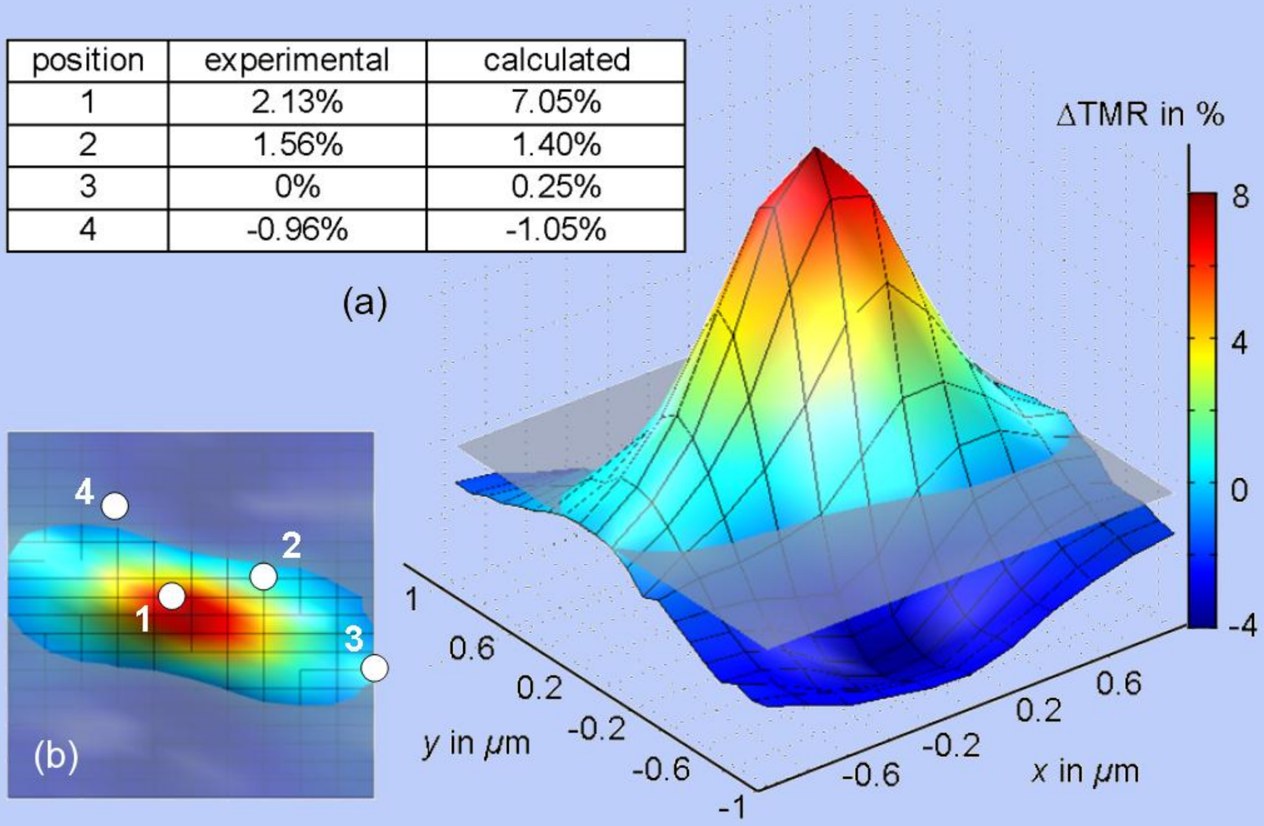


Rapid decrease in respect to particle sensor distance

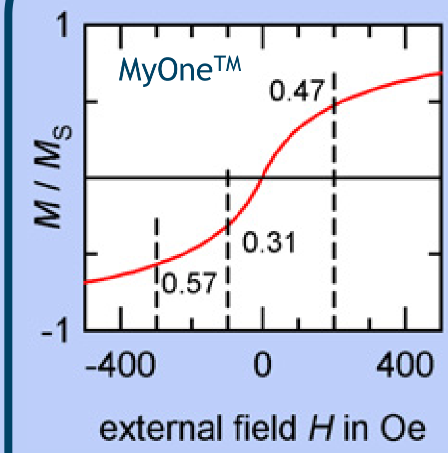
Measuring single particles

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%



particle properties

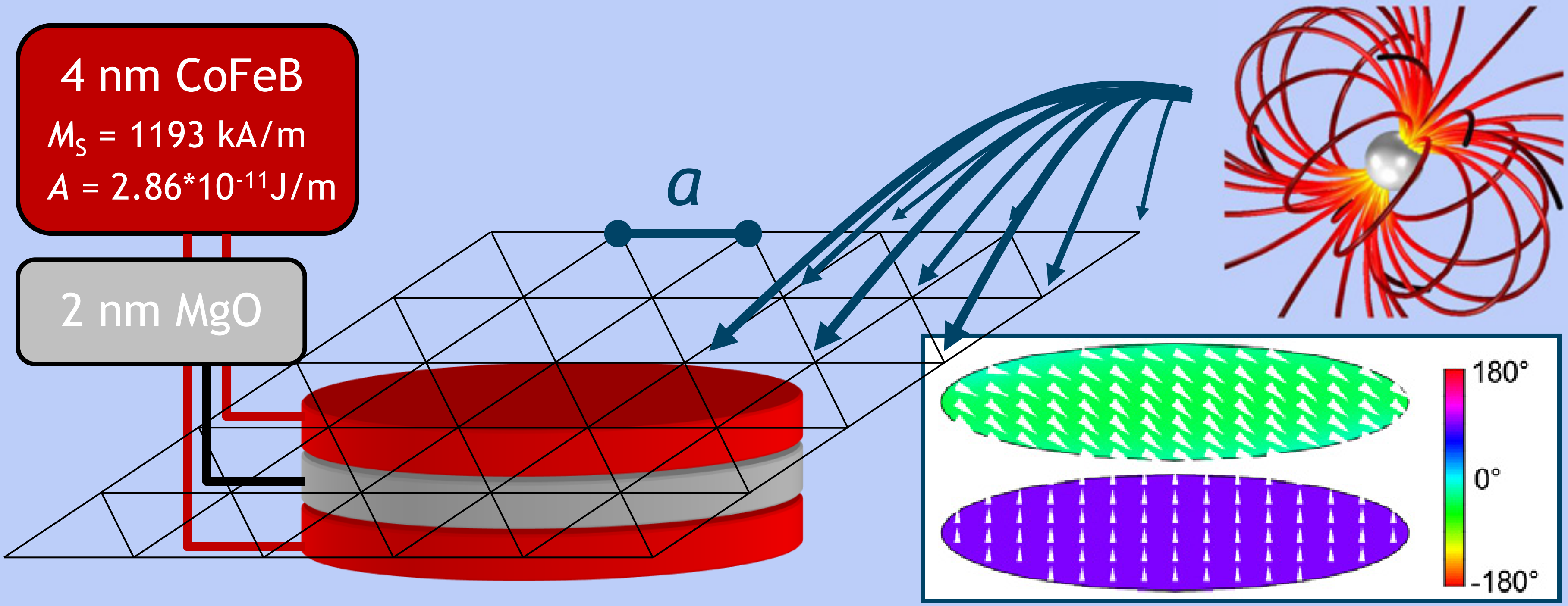


M_S = 120 kA/m

r = 0.5 μm

z = 0.562 μm

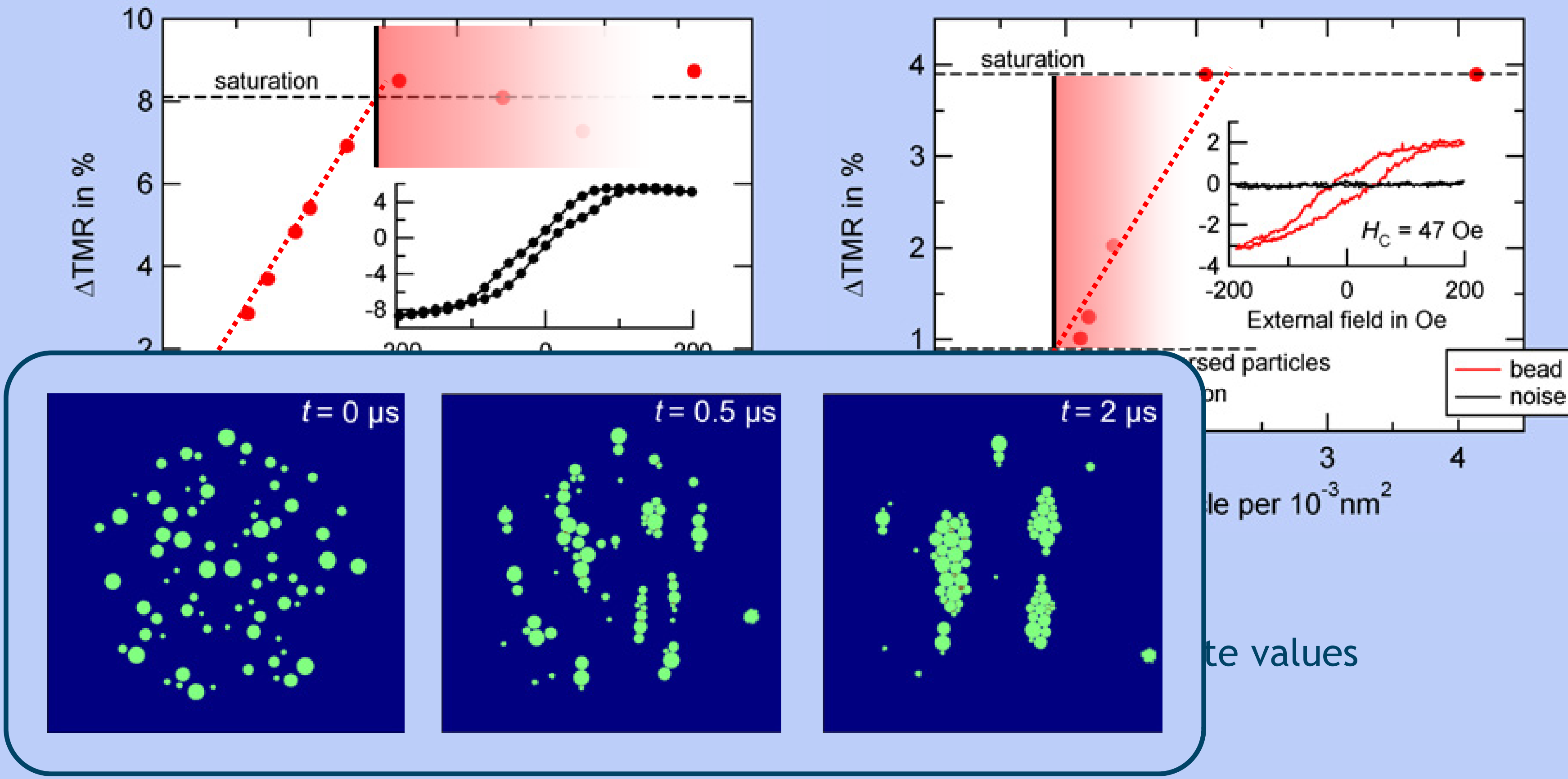
Measuring tasks



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

Measuring several particles

Influence of sensor coverage:



Conclusion & Outlook

Conclusion

- We have successfully implemented micromagnetic equations for the calculation of ferromagnetic thin film systems
- Theoretical predictions on spatial and number resolutive 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 resolutive particle detecion*, 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.