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Ferromagnetic materials for MEMS- and NEMS-devices

Towards the design of novel spintronic devices

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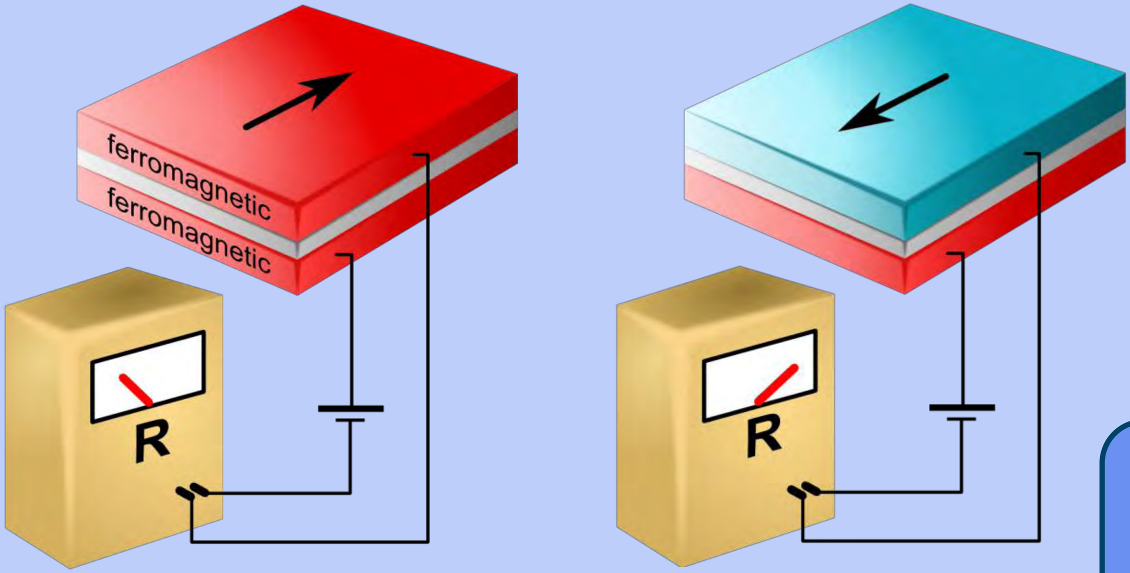
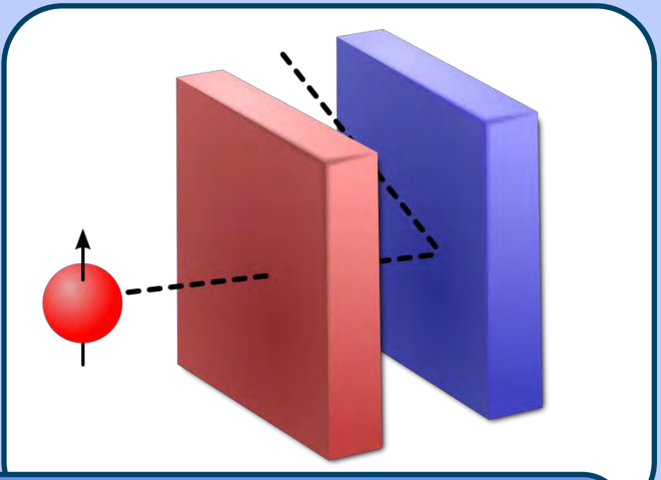
Motivation

Arrays of thin magnetic layers:





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

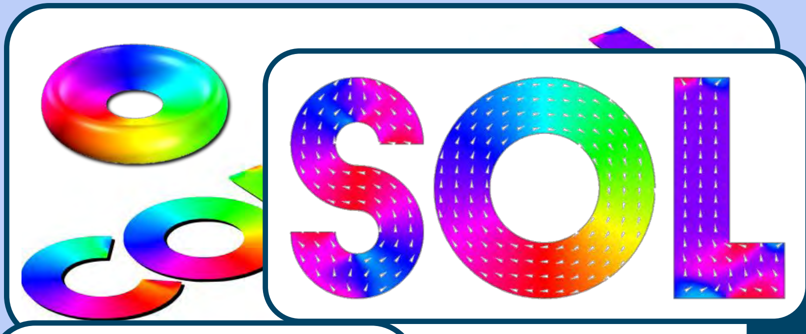
Applications:

- data storage
- magnetic field sensors

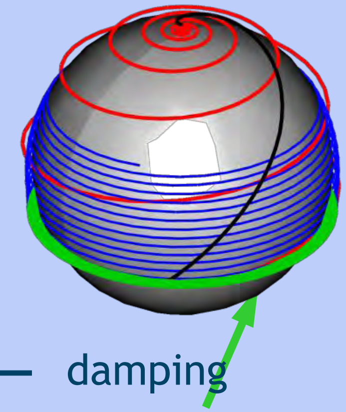
Good understanding of the dynamics of *ferromagnetic* materials necessary.

How to describe ferromagnetism?

Governing equation is Landau-Lifshitz Gilbert:



$$\frac{\partial \boldsymbol{m}}{\partial t} = -\gamma \boldsymbol{m} \times \boldsymbol{H}_{\mathrm{eff}} + a \boldsymbol{m} \times \frac{\partial \boldsymbol{m}}{\partial t}$$



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

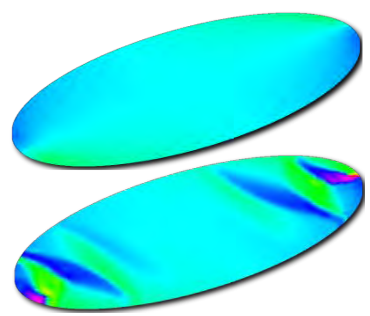
$|\boldsymbol{m}| = 1$

damping

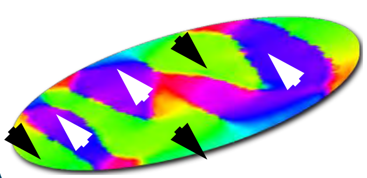
precession

$$\boldsymbol{H}_{\mathrm{eff}} = \frac{2A}{\mu_0 M_S} \Delta \boldsymbol{m} - \frac{1}{\mu_0 M_S} \frac{\delta f_{\mathrm{ani}}(\boldsymbol{m})}{\delta \boldsymbol{m}} + \boldsymbol{H}_{\mathrm{demag}} + \boldsymbol{H}_{\mathrm{ext}}$$

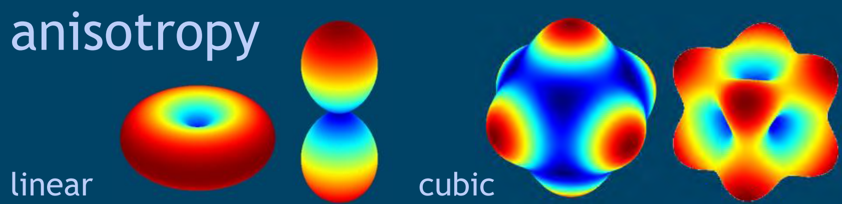
non-local contribution



exchange



anisotropy



demagnetization

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

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

Magnetic nanoparticles

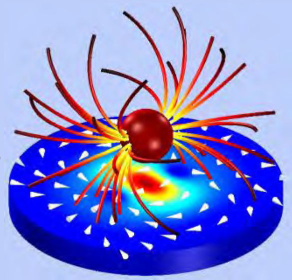
Superparamagnetic multi-core beads

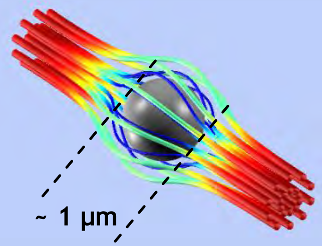
$\boldsymbol{m}(x,y,z) = \boldsymbol{m}$

$\text{LLG} \sim \boldsymbol{m} \times \boldsymbol{H}_{\text{eff}}$

$$\boldsymbol{H}_{\text{eff}} = \frac{2A}{\mu_0 M_S}\Delta\boldsymbol{m} + \frac{1}{\mu_0 M_S}\frac{\delta f_{\text{ani}}(\boldsymbol{m})}{\delta\boldsymbol{m}} + \boldsymbol{H}_{\text{demag}} + \boldsymbol{H}_{\text{ext}}$$

simplifies to set of ODEs



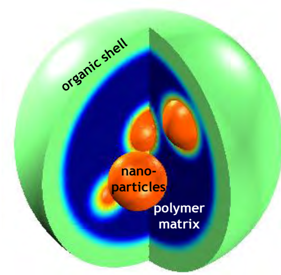


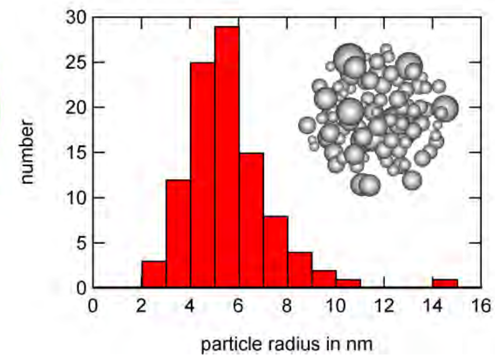
$$(Id - a\mathrm{M})\frac{\partial\tilde{\boldsymbol{m}}}{\partial t} = \gamma A \tilde{\boldsymbol{H}}_{\text{eff}} \qquad \mathrm{M} = \begin{pmatrix} \mathrm{M}_1 & & 0 \\ & \ddots & \\ 0 & & \mathrm{M}_N \end{pmatrix}$$

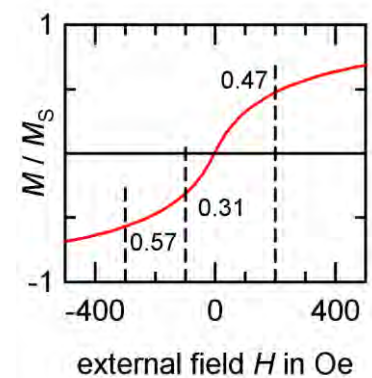
$$\tilde{\boldsymbol{m}} = (m_{x,1}, m_{y,1}, m_{z,1}, m_{x,2}, \ldots)^T$$

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

Magnetic beads

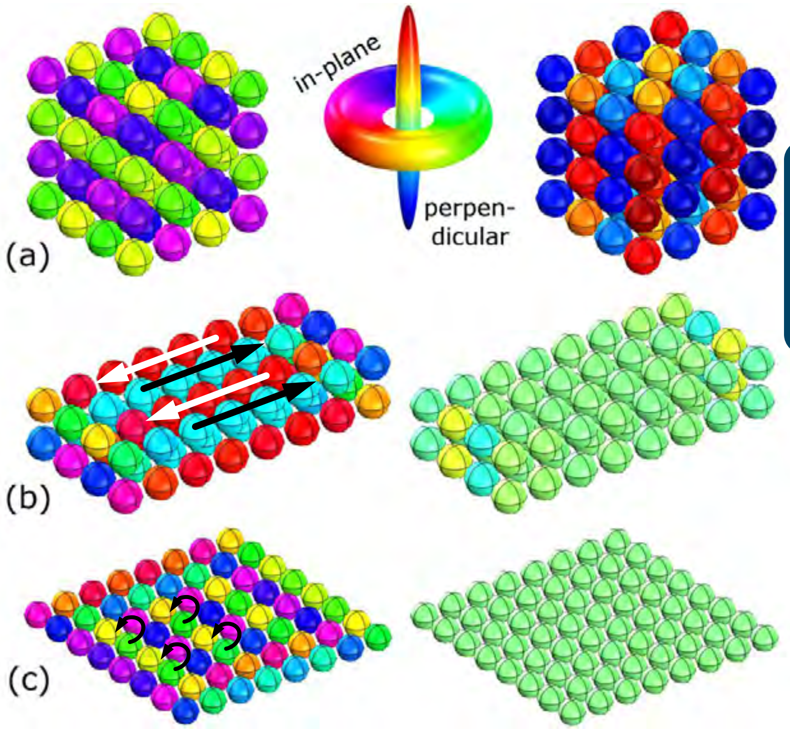






Even without consideration of temperature effects, dipolar coupling results in a vanishing magnetic moment in the equilibrium state and a superparamagnetic behaviour.

Magnetic nanoparticles

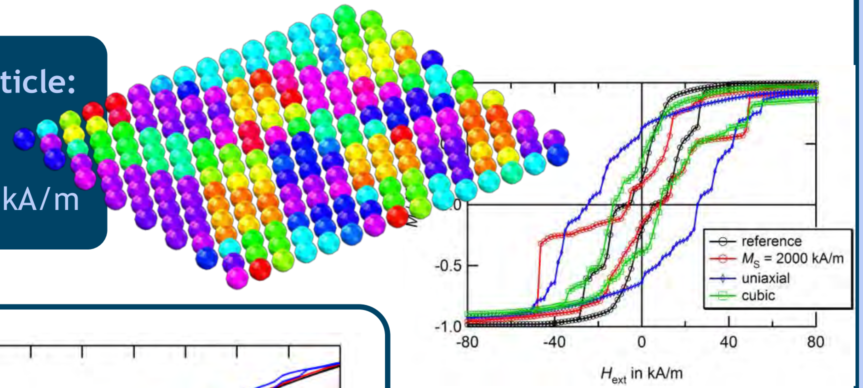


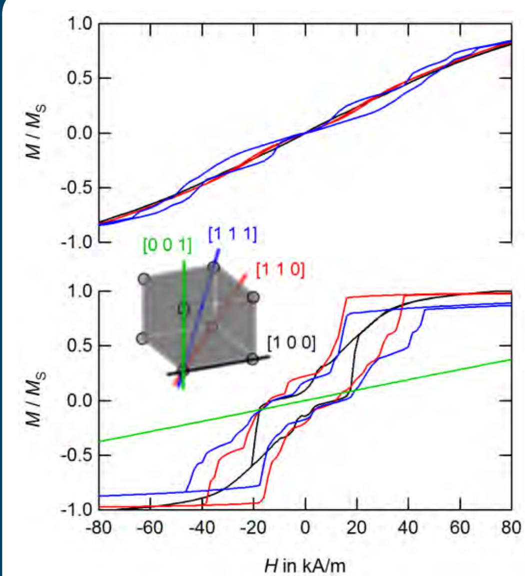
Assemblies of magnetic nanoparticles minimize their magnetic moment globally *and* locally.

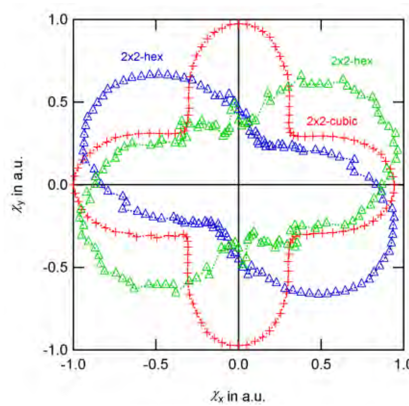
Wide range of parameters allows for adjustment of ensemble properties.

Probe particle:

- R = 8 nm
- M_S = 1000 kA/m



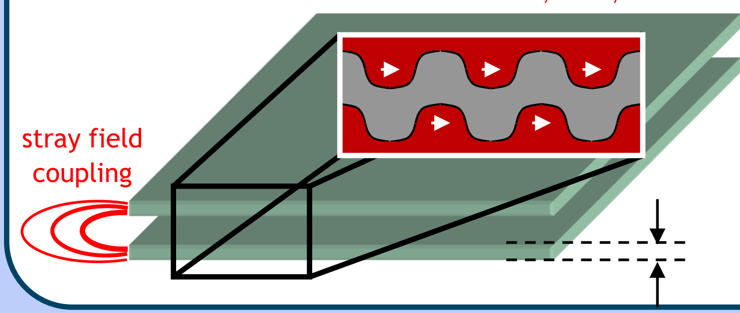




Magnetic multilayers

Thin films

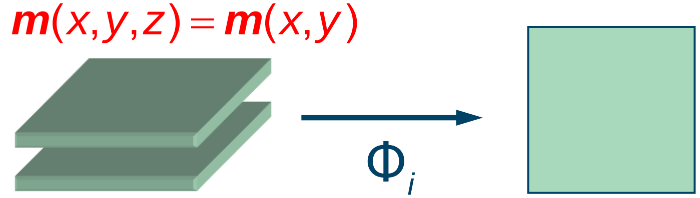
$J_{\text{Néel}} \sim -M_{S,1} M_{S,2} \langle \boldsymbol{m}_1, \boldsymbol{m}_2 \rangle$



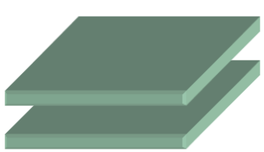
combined 2D/3D

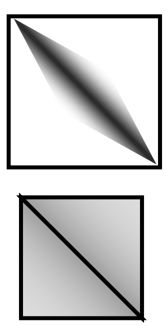
$$\boldsymbol{H}_{\text{eff}} = \frac{2A}{\mu_0 M_S} \Delta \boldsymbol{m} - \frac{1}{\mu_0 M_S} \frac{\delta f_{\text{ani}}(\boldsymbol{m})}{\delta \boldsymbol{m}} + \boldsymbol{H}_{\text{demag}} + \boldsymbol{H}_{\text{ex}}$$

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



FEM-BEM

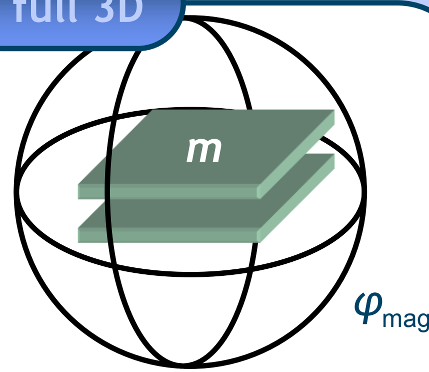




$$\varphi_{\text{mag}} = f\left(\int_{\partial\Omega} \boldsymbol{m}\, dx\right)$$

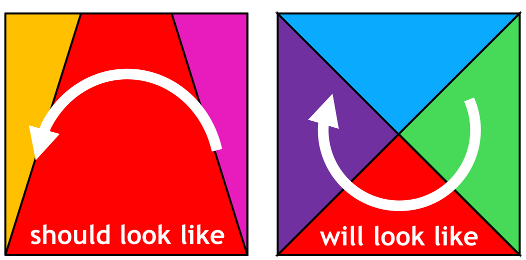
System matrix not sparse

full 3D



System matrix too large

2D-approach



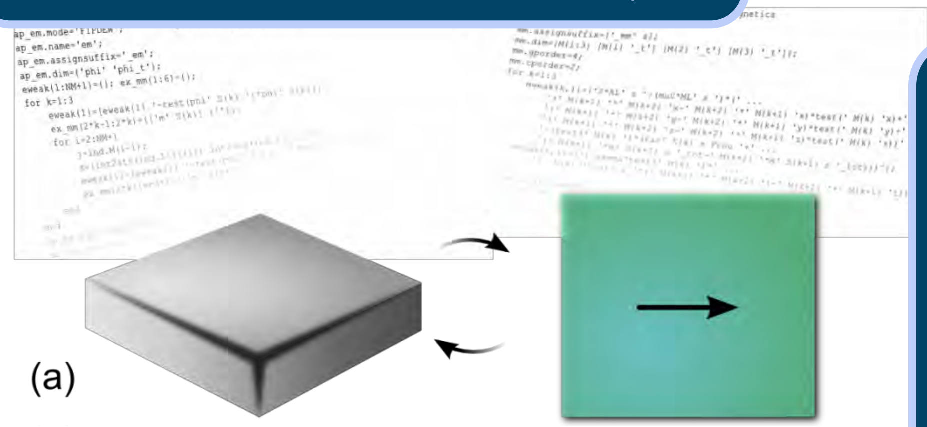
Stray field too strong

Magnetic multilayers

Weak equations for finite element discretization

Projections: $\tilde{\varphi}_{\mathrm{mag}} = \varphi_{\mathrm{mag}} \circ \Phi_i$

$$\boldsymbol{m} = \tilde{\boldsymbol{m}} \circ \Phi_i^{-1}$$



Layer stray field

$$\Delta\varphi_{\mathrm{mag}} = M_S \nabla \boldsymbol{m}$$

$$\frac{1}{\gamma}\int_{\Omega_{\mathrm{mag}}} \left\langle \boldsymbol{\psi}, \frac{\partial \tilde{\boldsymbol{m}}}{\partial t} - a\tilde{\boldsymbol{m}} \times \frac{\partial \tilde{\boldsymbol{m}}}{\partial t} \right\rangle dx$$

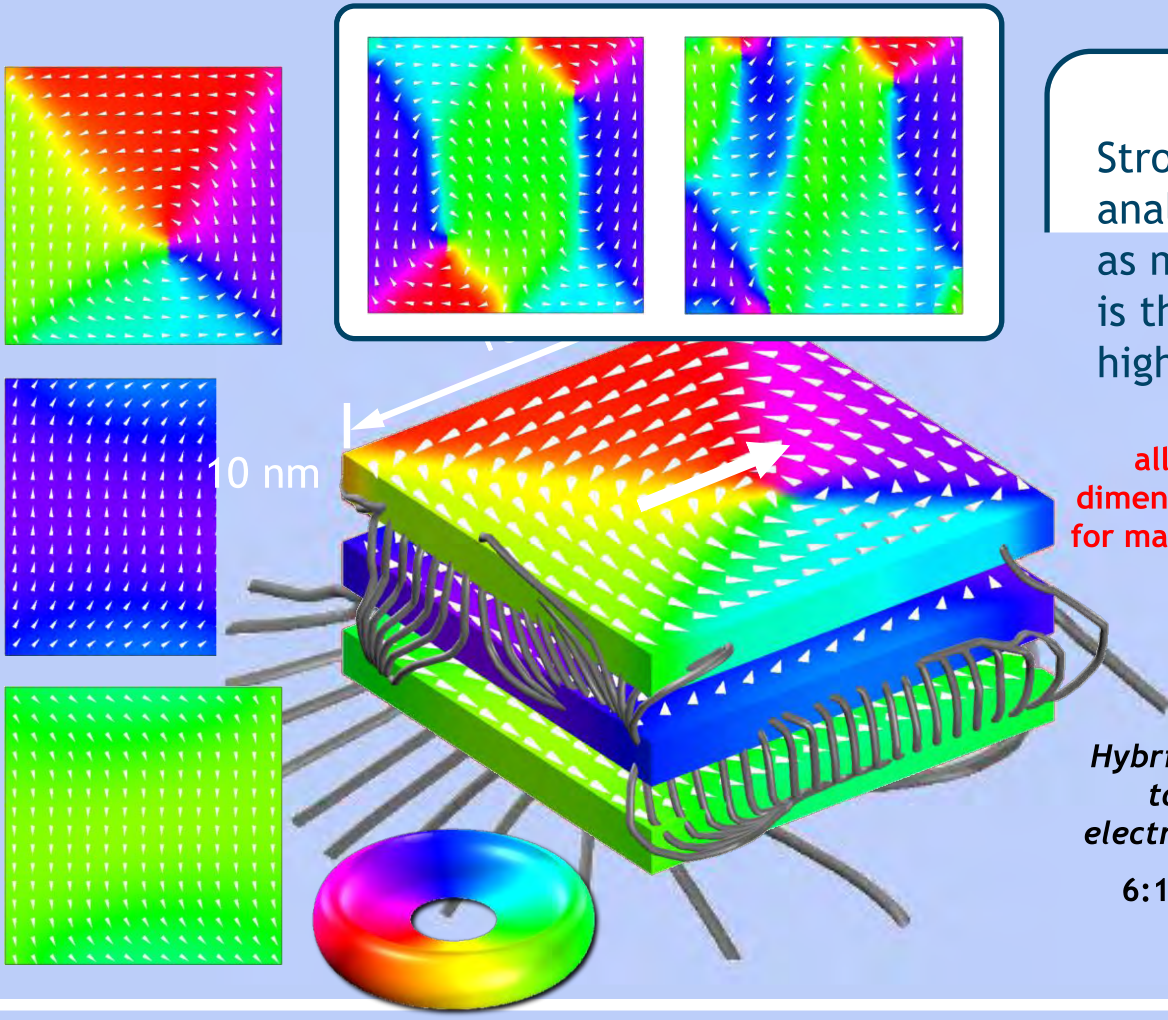
$$= -\frac{2A}{\mu_0 M_S} \sum_{x,y,z} \int_{\Omega_{\mathrm{mag}}} \left\langle \tilde{\boldsymbol{m}} \times \frac{\partial \tilde{\boldsymbol{m}}}{\partial x_i}, \frac{\partial \boldsymbol{\psi}}{\partial x_i} \right\rangle dx$$

$$+ \frac{2K_1}{\mu_0 M_S} \int_{\Omega_{\mathrm{mag}}} \langle \boldsymbol{\psi}, \tilde{\boldsymbol{m}} \times \boldsymbol{e} \rangle \langle \tilde{\boldsymbol{m}}, \boldsymbol{e} \rangle dx$$

$$+ \int_{\Omega_{\mathrm{mag}}} \langle \boldsymbol{\psi}, \tilde{\boldsymbol{m}} \times (\boldsymbol{H}_{\mathrm{ext}} - \nabla \tilde{\varphi}_{\mathrm{mag}}) \rangle dx$$

Magnetic multilayers

Micromagnetics – A trilayer system

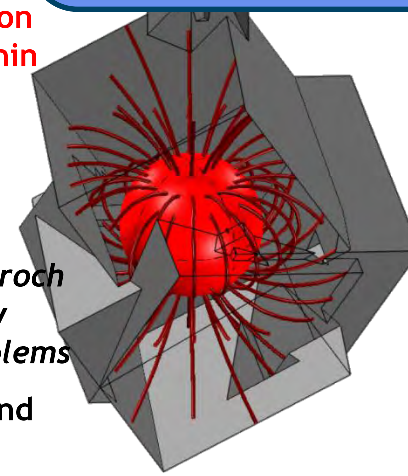


Next step?

Strongest limitation (also for analysis of additional effects such as magnetostriction, spin-torque …) is the model size together with the high aspect ratio.

FEM-BEM

allows for a two-dimensional formulation for magnetic field of thin films



Hybrid FEM-BEM approch to open boundary electromagnetic problems

6:15pm Magnetic and Electric Fields

Conclusion & Outlook

Conclusion

- We implemented the LLG-equations for:
  - thin films
  - ensembles of magnetic nanoparticles
- We designed novel magnetic field sensor based on highly ordered monolayers.
  - easy to control magnetic properties
  - increased sensitivity at the cost of inherent device noise
  - four different measurement regimes

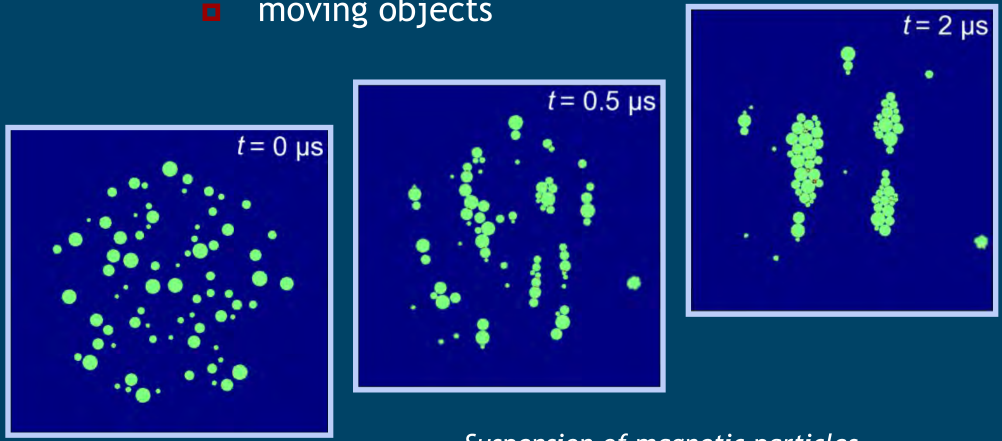
See posters:

→ Ferromagnetic materials for MEMS- and NEMS-devices

→ Magnetic nanoparticles for novel spintronic devices

Outlook

- Implementation of FEM-BEM frame
- Integration of physical phenomena:
  - magnetostriction
  - spin-torque effects
  - moving objects



Suspension of magnetic particles exposed to a magnetic field