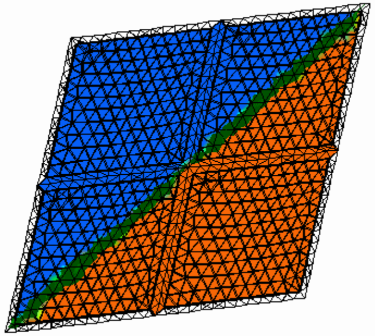
Micromagnetic Simulation of Domain Wall Pinning and Domain Wall Motion

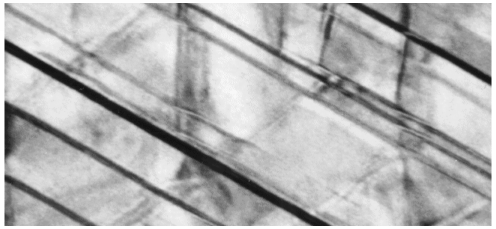
W Scholz, H Forster, J Fidler, T Schrefl
Vienna University of Technology

Outline



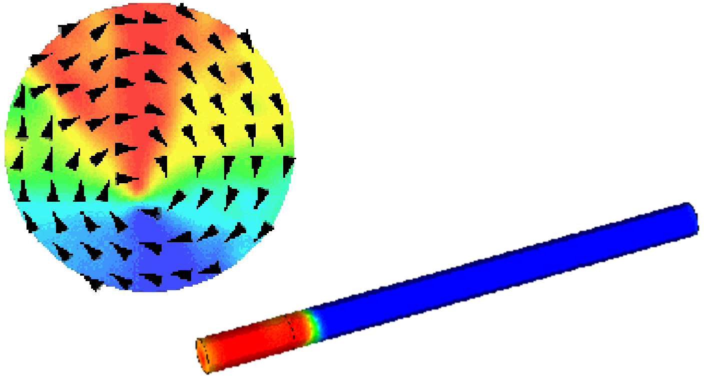
Introduction

Finite element method



Domain Wall Pinning

Pinning controlled SmCo magnets



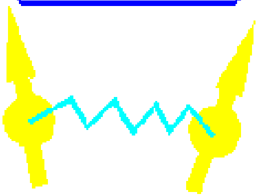
Nano-wires

Domain wall velocities

Summary

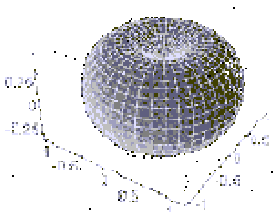
Micromagnetics

exchange



⇨ parallel spins

anisotropy



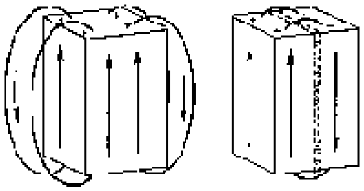
⇨ easy directions

thermal activation

⇨ fluctuations

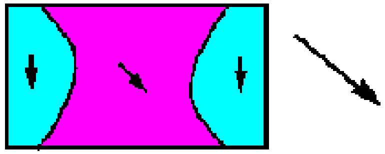
$$\frac{\partial \boldsymbol{J}}{\partial t} = -|\gamma|\, \boldsymbol{J} \times (\boldsymbol{H}_{\mathrm{eff}} + \boldsymbol{H}_{\mathrm{th}}) + \frac{\alpha}{J_s}\, \boldsymbol{J} \times \frac{\partial \boldsymbol{J}}{\partial t}$$

magnetostatic



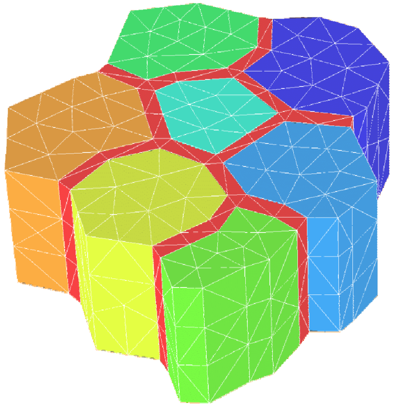
⇨ domains

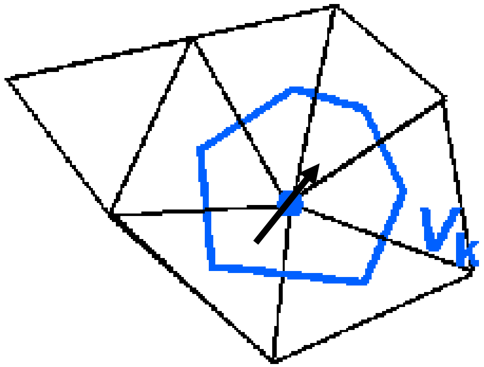
external field



⇨ rotation

Finite Element Approach





- divide particles into finite elements
  ⇨ triangles, tetrahedrons
- expand **J** with basis function φ

$$\boxed{\vec{J}(\vec{x}) = \sum_{i=1}^{nodes} \vec{J}_i \varphi_i(\vec{x})}$$

- energy as a function of $\mathbf{J}_1$, $\mathbf{J}_1$ … $\mathbf{J}_N$

$$\boxed{E(\vec{J}_1, \vec{J}_2 .... \vec{J}_N)}$$

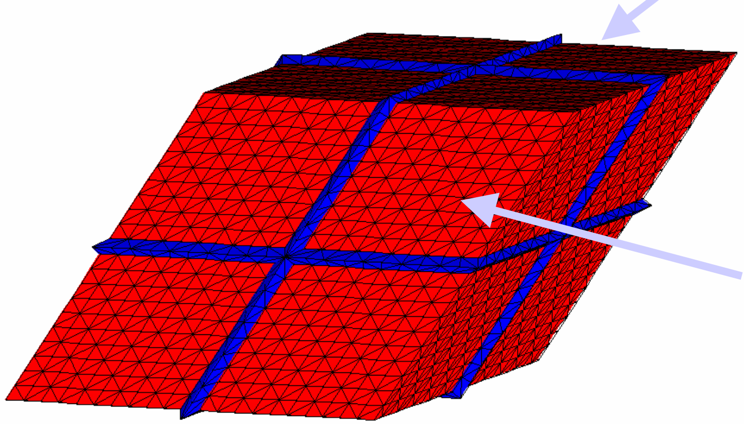
- effective field

$$\boxed{\vec{H}_k = -\frac{1}{V_k}\frac{\partial E(\vec{J}_1, \vec{J}_2 .... \vec{J}_N)}{\partial \vec{J}_k}}$$

⇨ effective field on irregular grids
⇨ rigid magnetic moment
at the **nodes**

Magnetostatic Field Calculation

- magnetic scalar potential
  $\mathbf{H} = -\nabla U$
- solve Gilbert equation *simultaneously* with
  - ⇨ Poisson equation (inside)
  - ⇨ Laplace equation (outside)



boundary element method (BEM)

finite element method (FEM)

BEM leads to a fully populated *N* x *N* matrix

- ⇨ *N* ... number of nodes at the surface
- ⇨ matrix compression using wavelets

Pinning Controlled SmCo Magnets

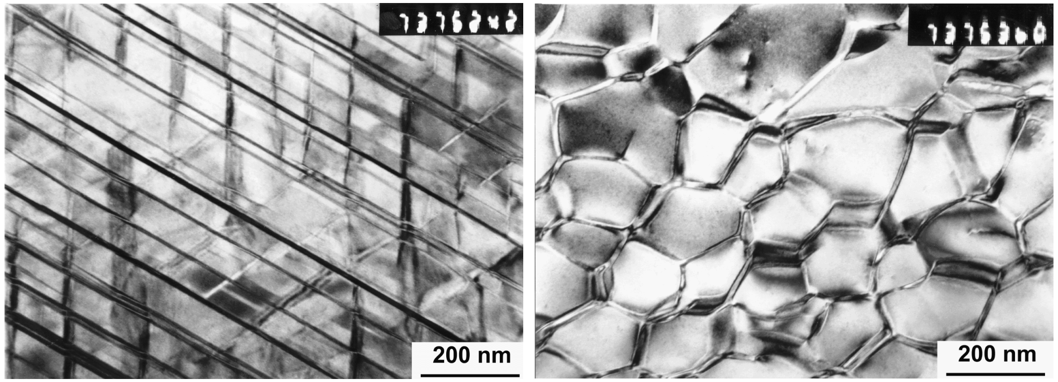
- Characterization of SmCo permanent magnets by transmission electron microscopy

Microstructure

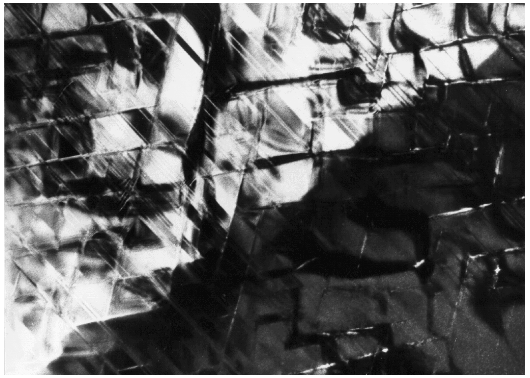
- Composition
- Heat treatment
- Additives

influence

- Precipitation structure
- Lamella phase
- Cell size



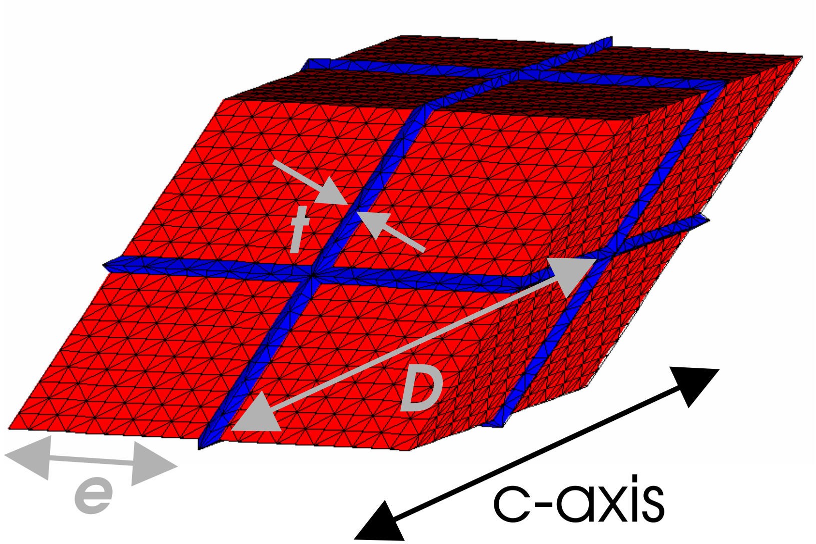
- Lorentz image of two magnetic domains

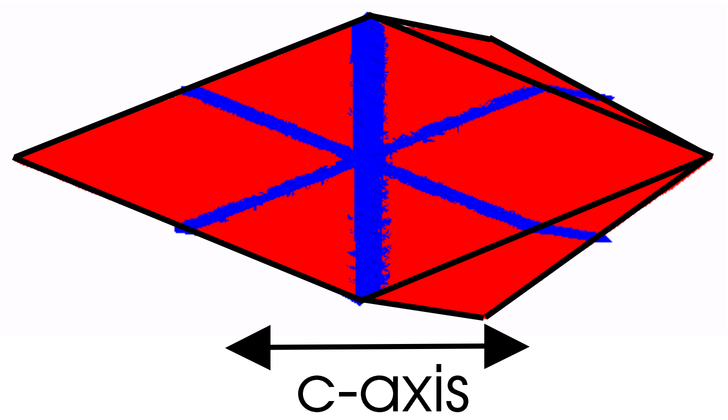


Micromagnetic Model

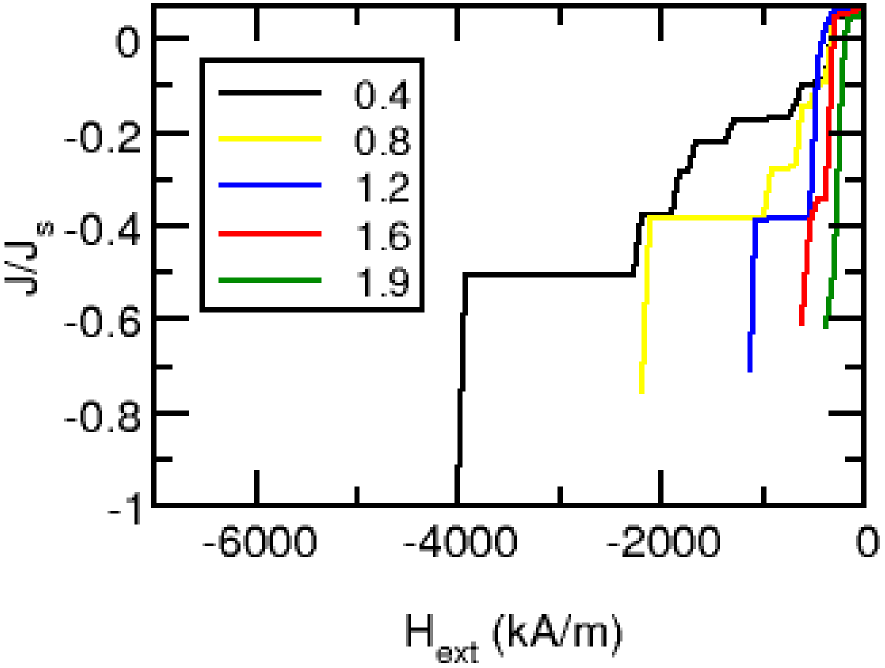
- Finite element mesh:
  15833 nodes
  84749 tetrahedral elements
  7056 surface elements

- Resolution of the mesh:
  $e/10 = D/25$
  for $D = 125$ nm: 5 nm
  $\delta(\mathrm{Sm_2Co_{17}}) = 5$ nm



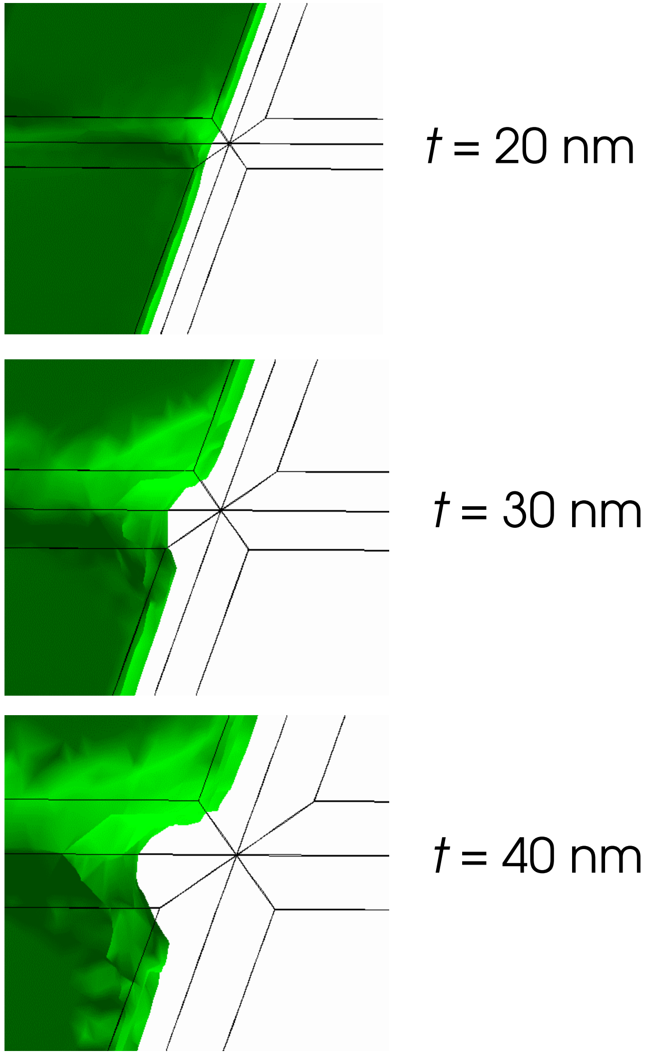


Attractive Pinning



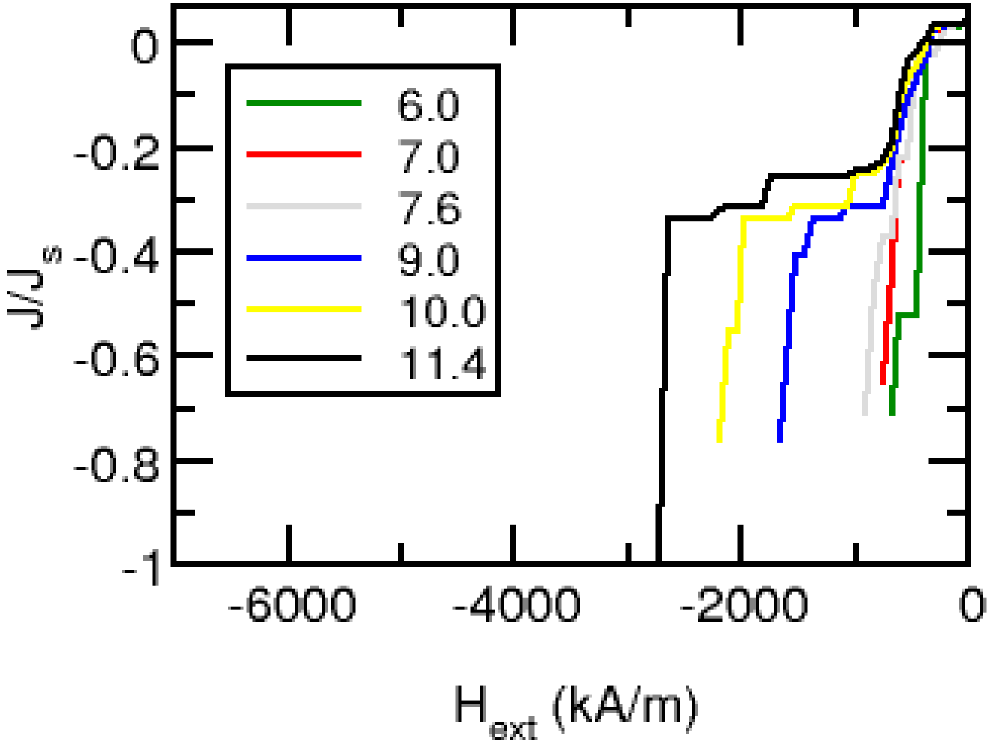
- Cells (Sm_2Co_{17}):
  Polarization: $J_s = 1.32$ T
  Anisotropy: $K_1 = 5$ MJ/m^3
  Exchange: $A = 14$ pJ/m
- Intercellular phase:
  Polarization: $J_s = 0.8$ T
  Anisotropy: $K_1 = 1.2$ MJ/m^3
  Exchange: $A = 14$ pJ/m

Domain wall bending

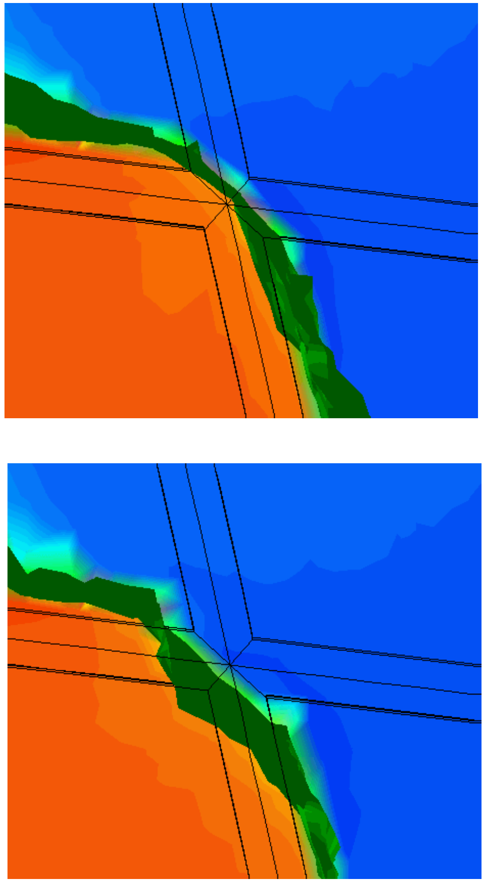


Repulsive Pinning

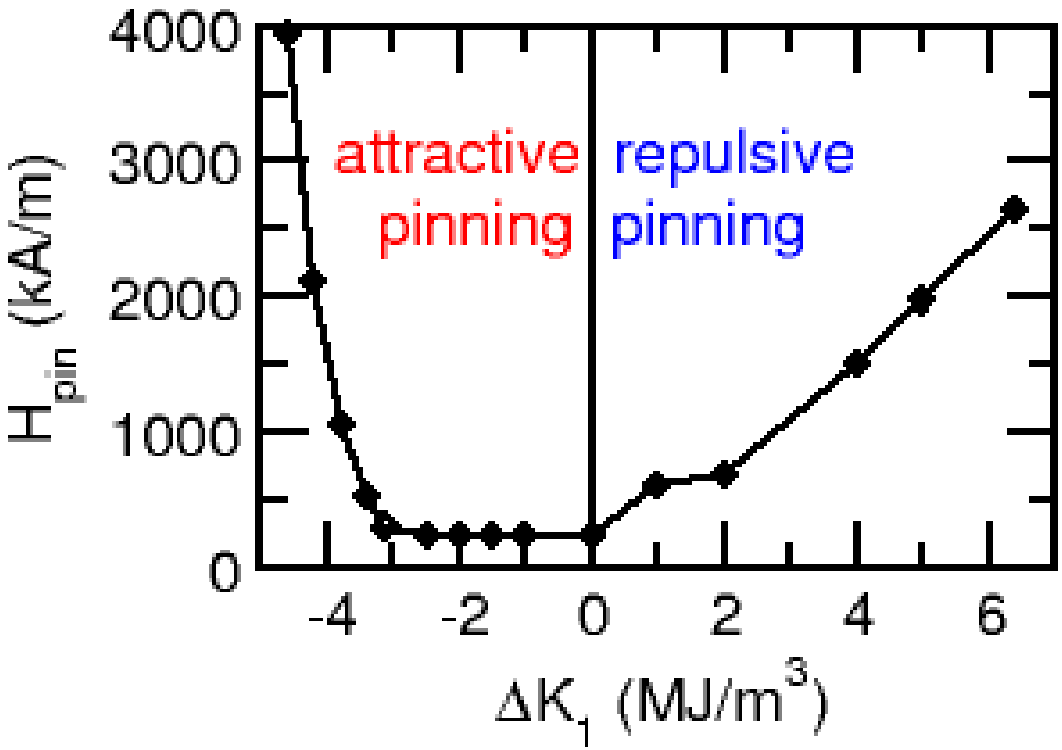
- Cells: D = 125 nm
- Intercellular phase:
  Thickness: t = 10 nm
  Anisotropy: K_1 = 9 MJ/m^3



Domain wall depinning



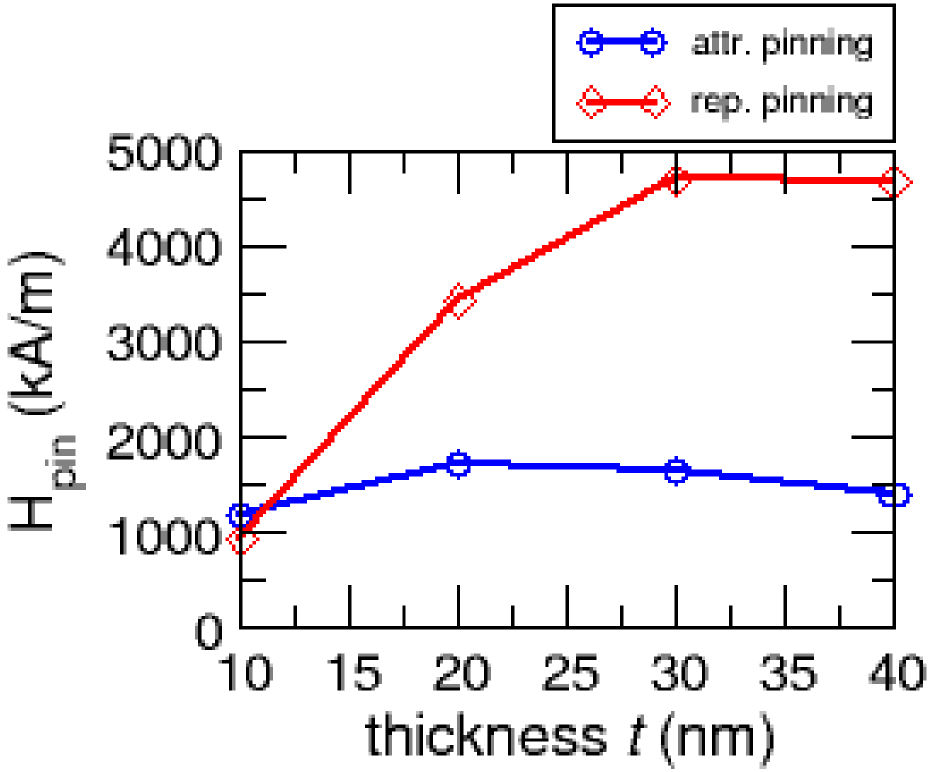
Pinning Fields



- Linear behaviour in the regime of repulsive pinning in agreement with a simple analytical 1D-model by Kronmüller (IEEE Trans. Magn. MAG-20 (1984) 1569):

$$H_c^{\max} = \alpha(K_1^{phase} - K_1^{cells}) / M_s^{cells}$$

Variation of the Phase Thickness



- Cells (Sm_2Co_{17}):
  K_1 = 5 MJ/ m^3

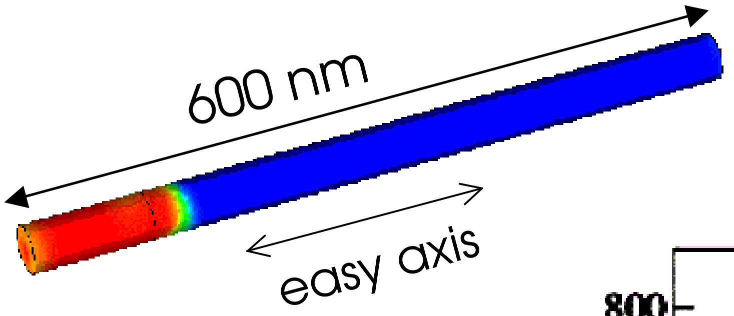
- Intercellular phase

  Attractive pinning:
  K_1=1.2 MJ/m^3

  Repulsive pinning:
  K_1=9.0 MJ/m^3

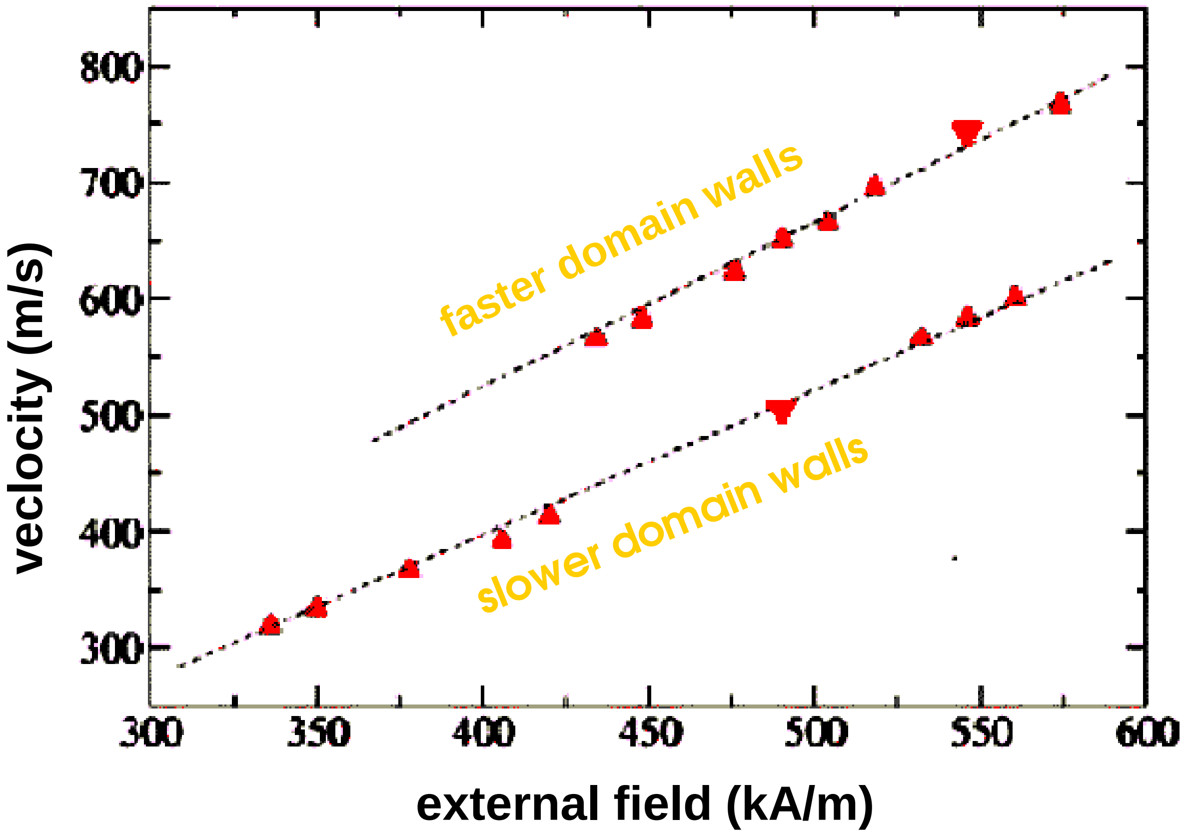
Domain Wall Motion

D = 20 nm, α = 0.1

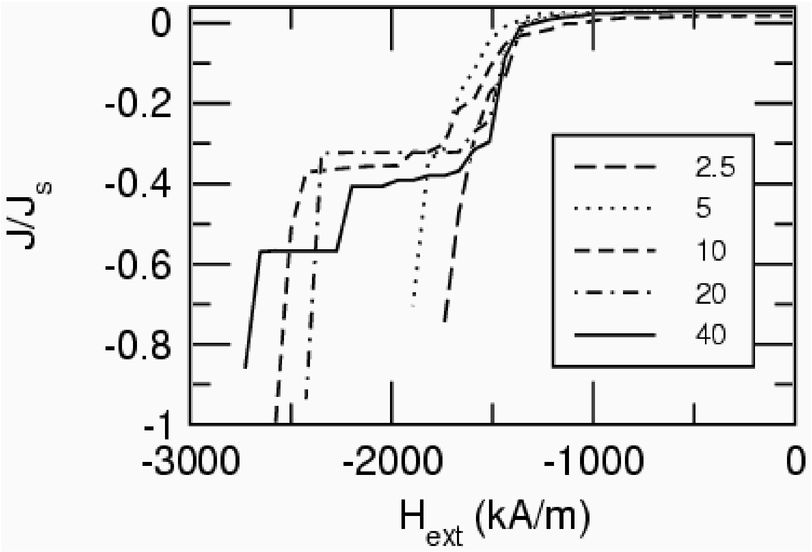


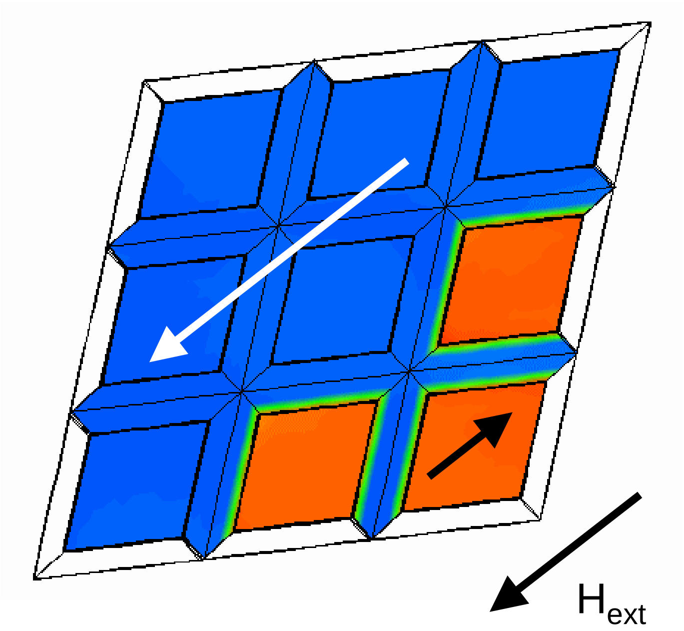
Co wire

J_s=1.76 T,
K_1=0.45 MJ/m^3
A=13 pJ/m



Thick Intercellular Phases

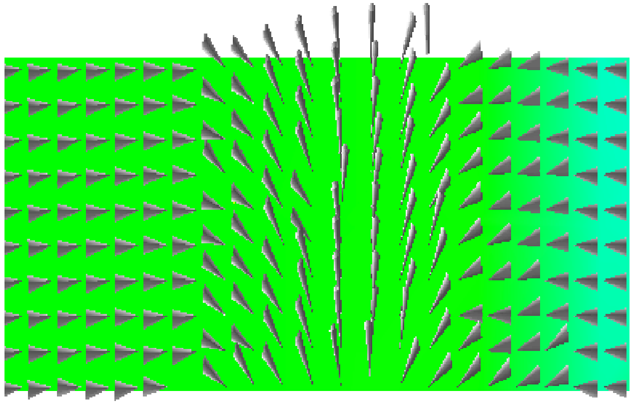


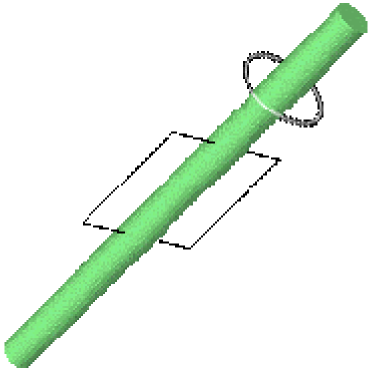


- Reversal of the whole intercellular phase
- Nucleation field of the cells determines H_c

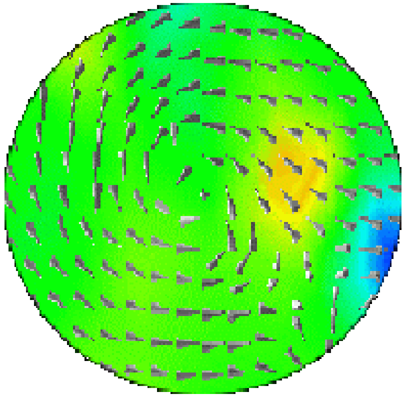
Domain Wall Structure

transverse wall





vortex wall

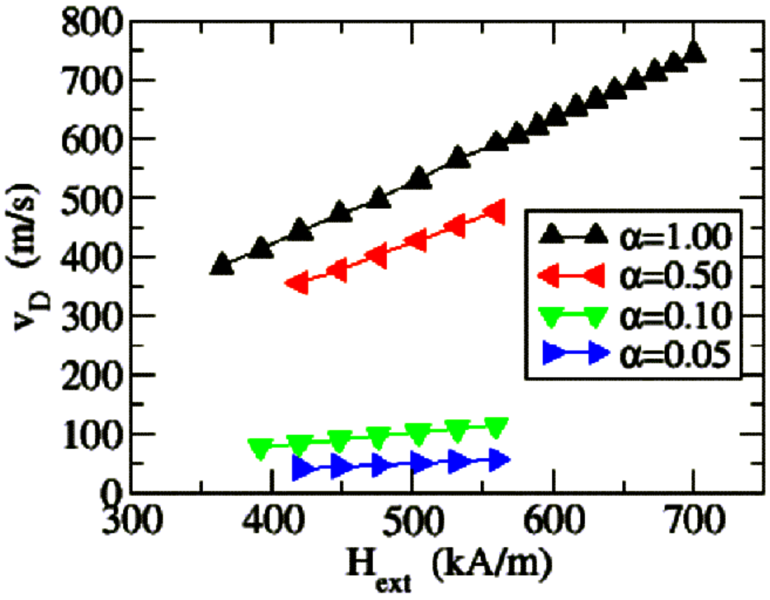


- d ≤ 20 nm
- domain wall moves slower
- velocity decreases with decreasing damping

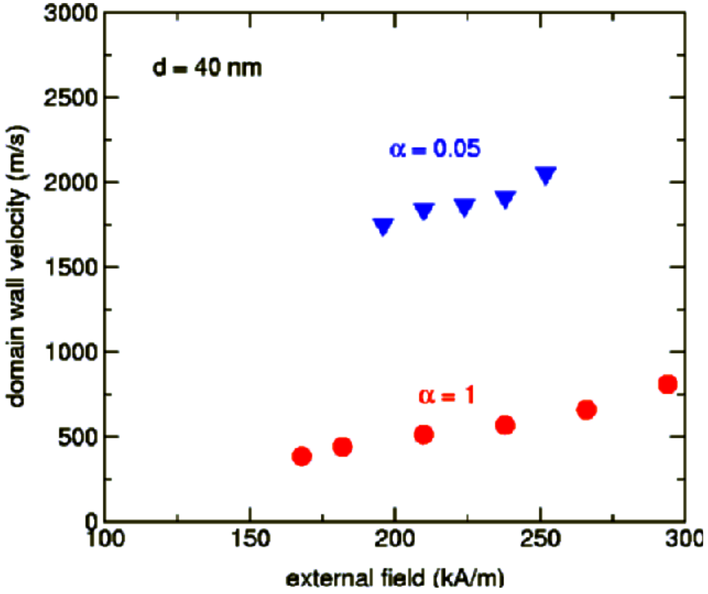
- d ≥ 20 nm
- domain wall moves faster
- velocity increases with decreasing damping

Influence of Damping

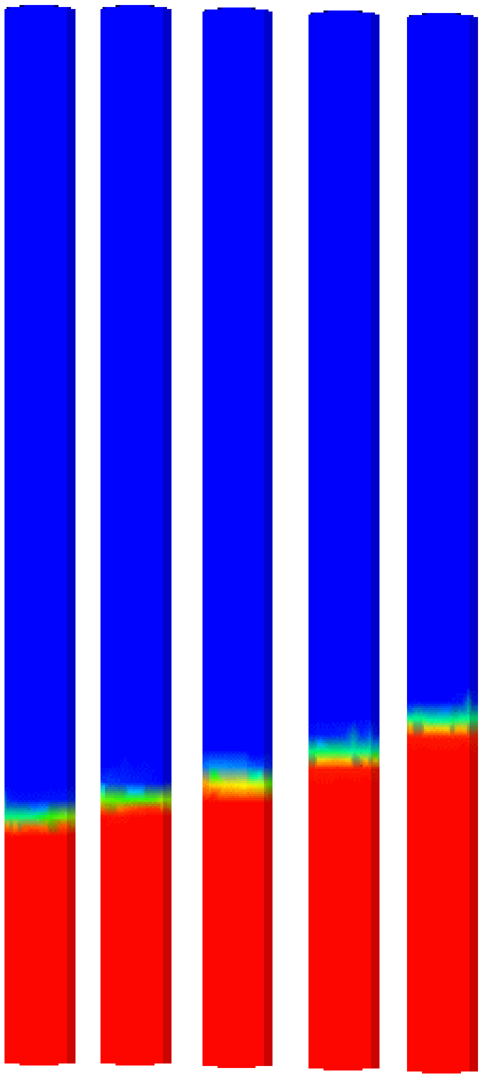
transverse wall

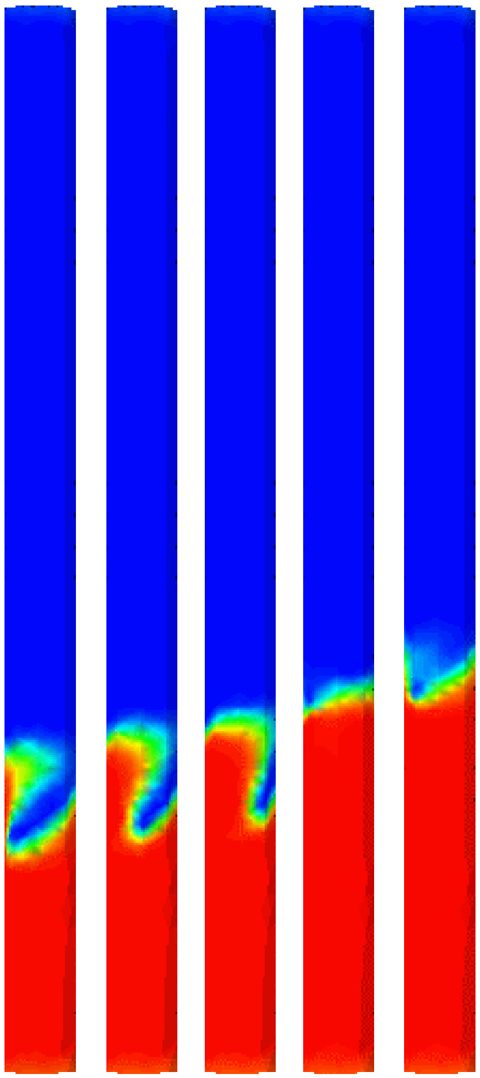


vortex wall



Domain Wall Motion


transverse wall


vortex wall

Simulation parameters:

- d = 20 nm
- $\alpha = 1$
- $H_{ext} = 490$ kA/m

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Summary

Domain Wall Pinning

- Different pinning mechanisms depending on the composition
- Repulsive pinning: linear dependence of the pinning field on anisotropy

Domain Wall Motion

- Different wall configurations depending on the wire thickness
- high domain wall velocity
  - high damping in thin wires (transverse wall)
  - low damping in thick wires (vortex wall)

Acknowledgements

- **Austrian Science Fund FWF**
  Y 132 – PHY: Advanced numerical micromagnetics
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  GRD1-1999-11125: Novel Permanent Magnets for High Temperature Applications