Micromagnetic 3D simulation of the pinning field in high temperature $Sm(Co,Fe,Cu,Zr)_z$ magnets

W. Scholz, J. Fidler, T. Schrefl, D. Suess, T. Matthias
Vienna University of Technology

MMM 2001
Seattle, Washington
November 12-16, 2001

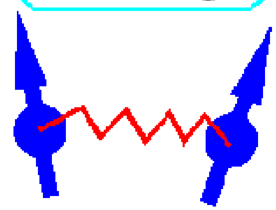
Outline

- Pinning Controlled SmCo Magnets
- Micromagnetic Model
- Attractive Pinning
- Repulsive Pinning
- Variation of the Phase Thickness
- Summary

Micromagnetics

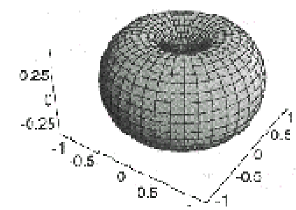
- Effective field H_{eff} :
  - exchange
  - anisotropy
  - magnetostatic
  - external field
- Find energy minimums by integration of the Gilbert equation of motion
  or direct energy minimization

exchange



⇨ parallel spins

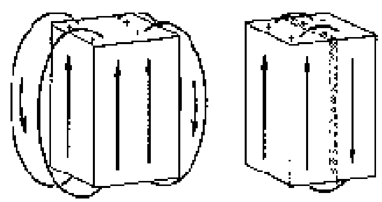
anisotropy



⇨ easy directions

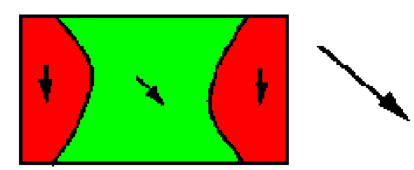
$$\frac{\partial \boldsymbol{J}}{\partial t} = -|\gamma| \boldsymbol{J} \times \boldsymbol{H}_{eff} + \frac{\alpha}{J_s} \boldsymbol{J} \times \frac{\partial \boldsymbol{J}}{\partial t}$$

magnetostatic



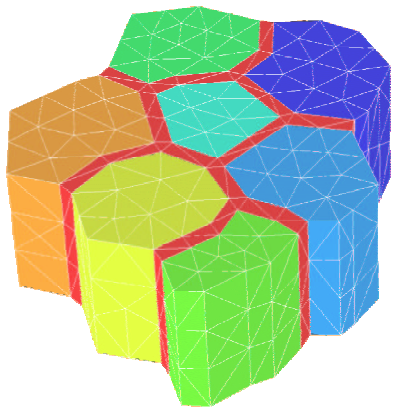
⇨ domains

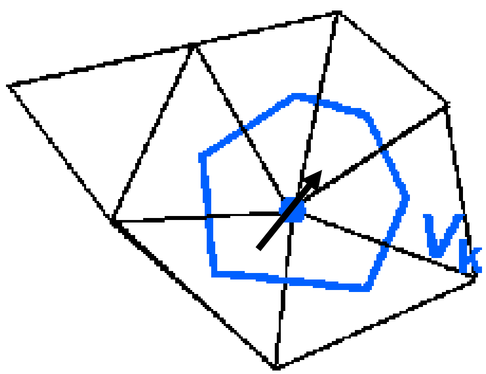
external field



⇨ rotation

Finite Element Approach





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

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

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

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

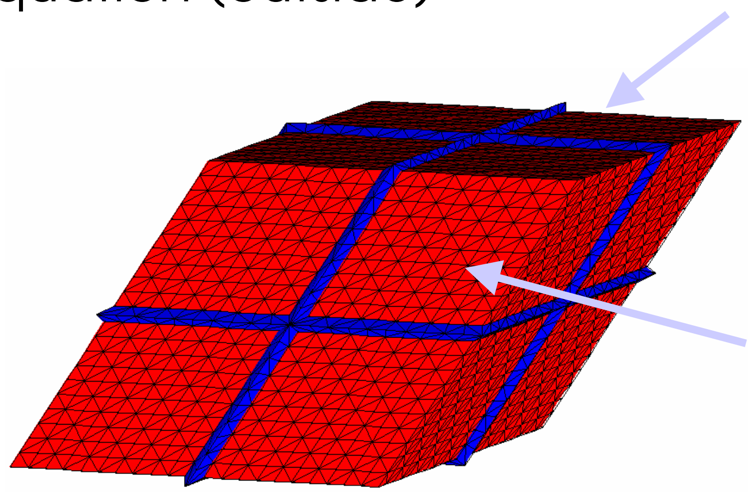
- effective field

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

⇨ 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)



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

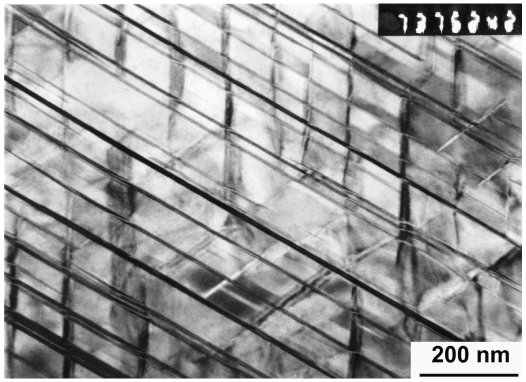
- Characterization of SmCo permanent magnets by transmission electron microscopy

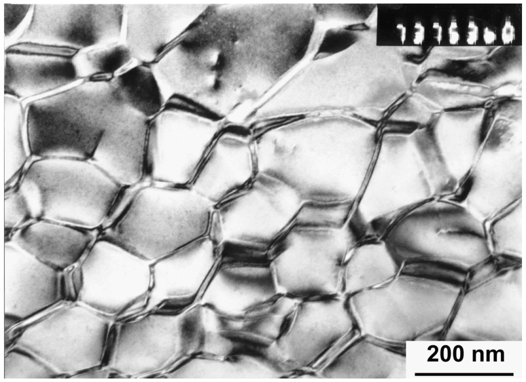
Microstructure

- Composition
- Heat treatment
- Additives

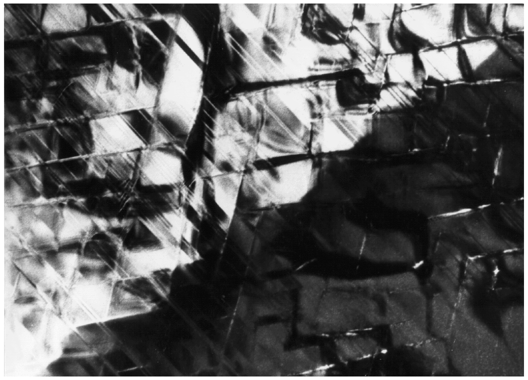
influence

- Precipitation structure
- Lamella phase
- Cell size





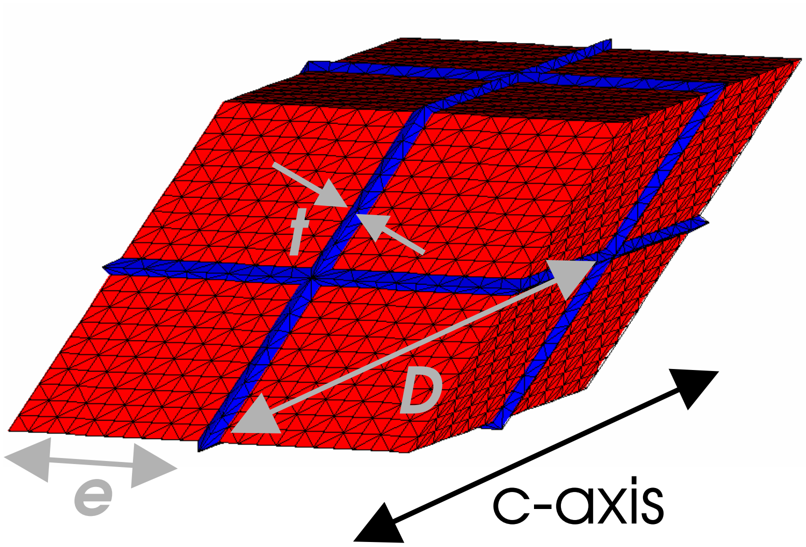
- Lorentz image of two magnetic domains

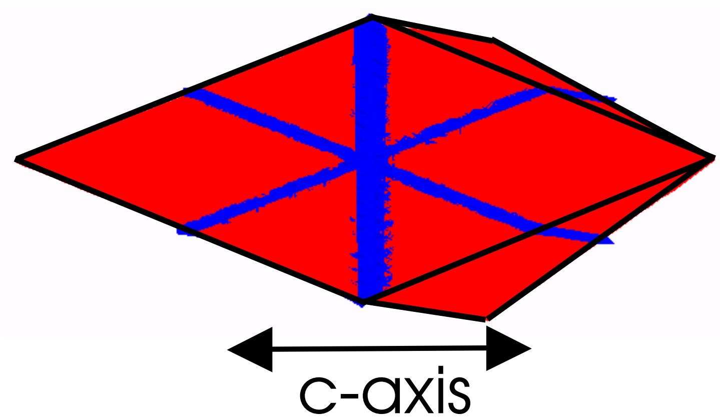


Micromagnetic Model

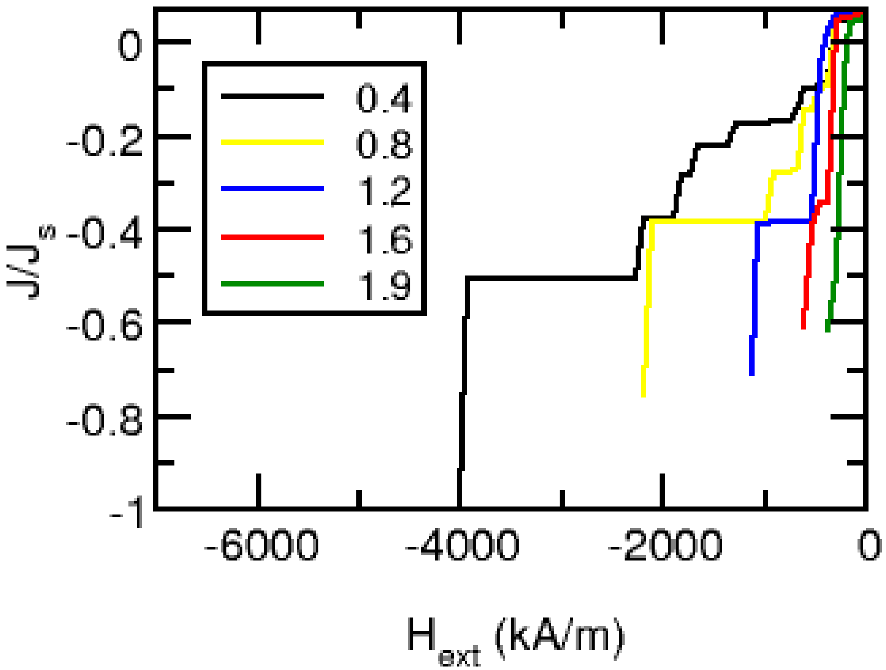
- Finite element mesh:
  15833 nodes
  84749 tetrahedral elements
  7056 surface elements

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

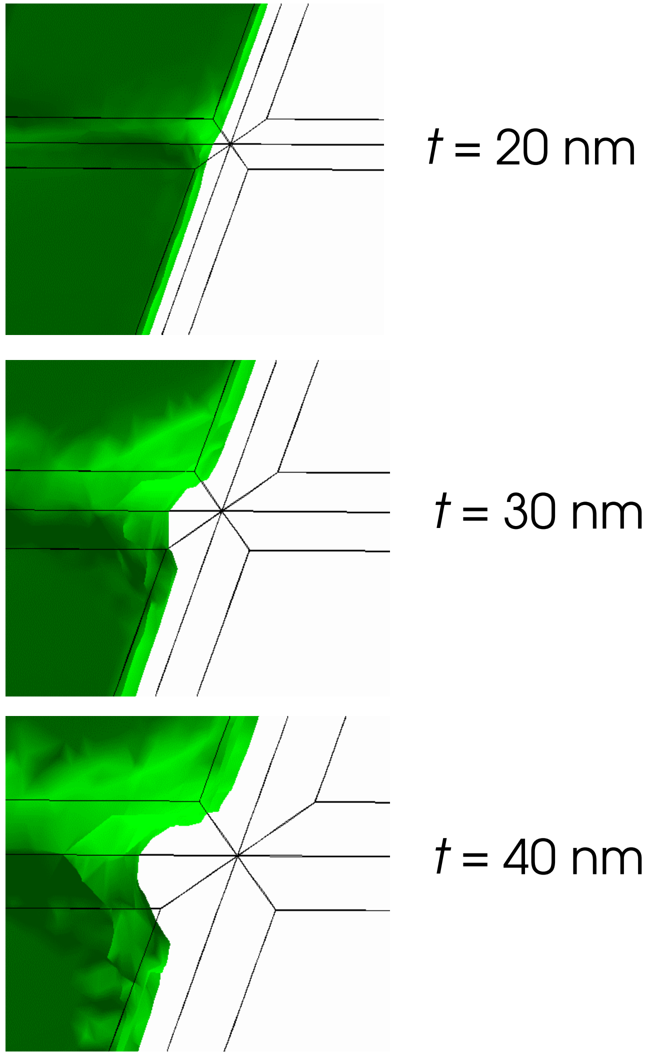




Attractive Pinning



Domain wall bending



- 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

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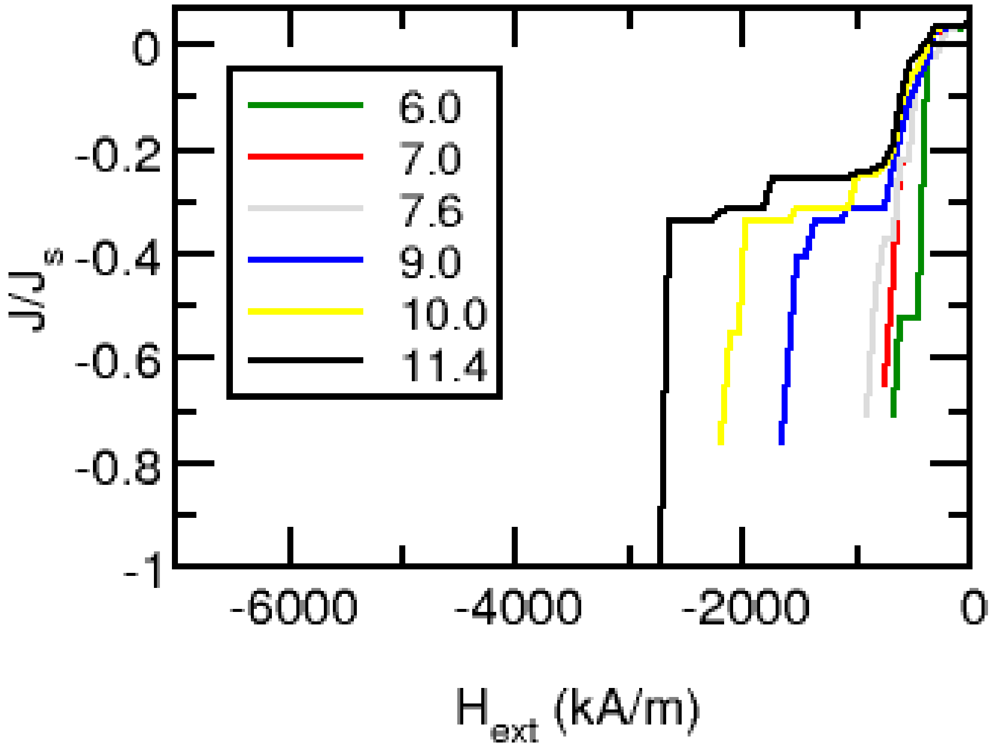
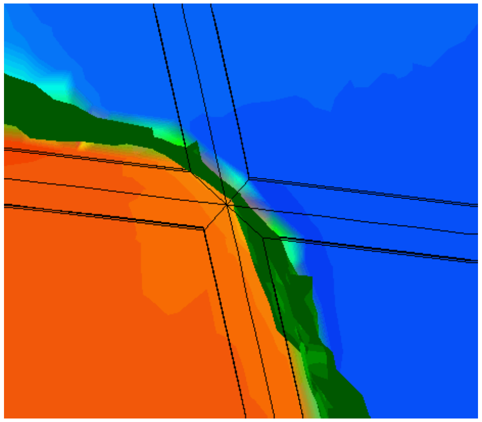
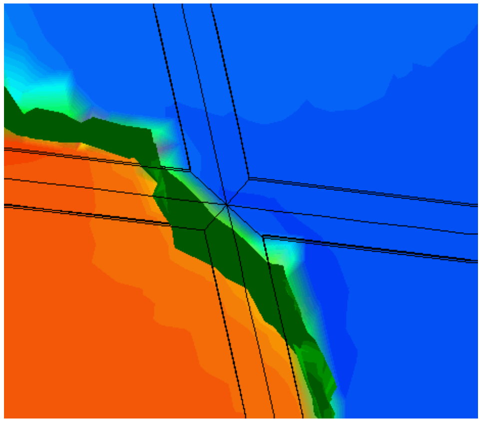
Repulsive Pinning

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

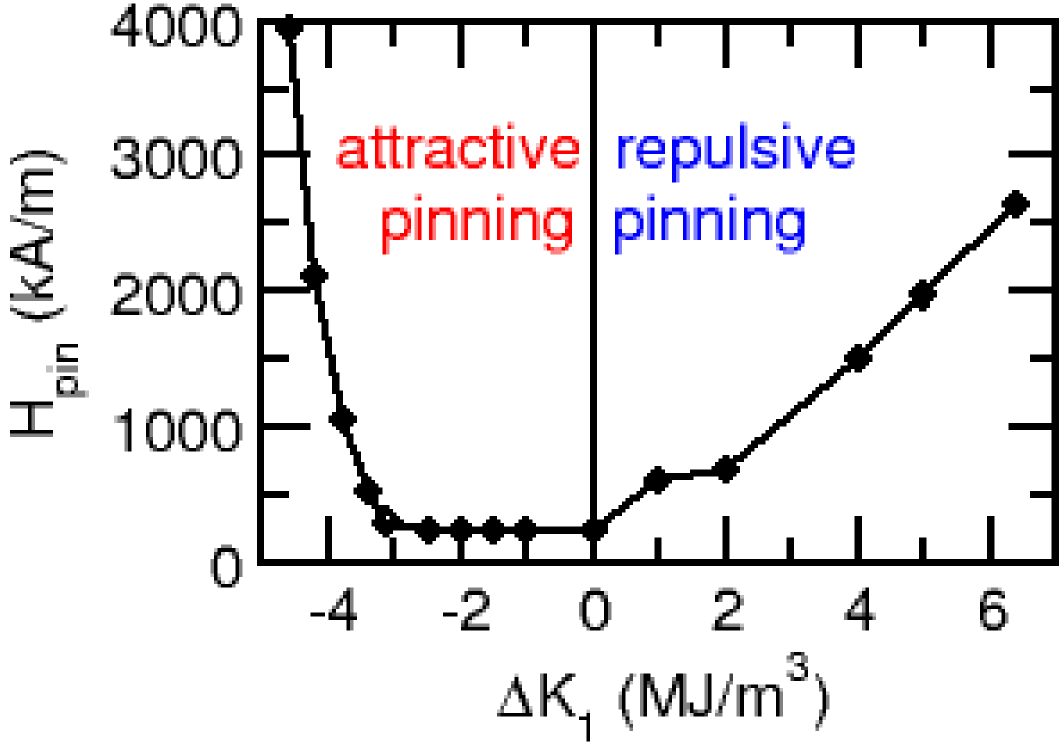


Domain wall depinning





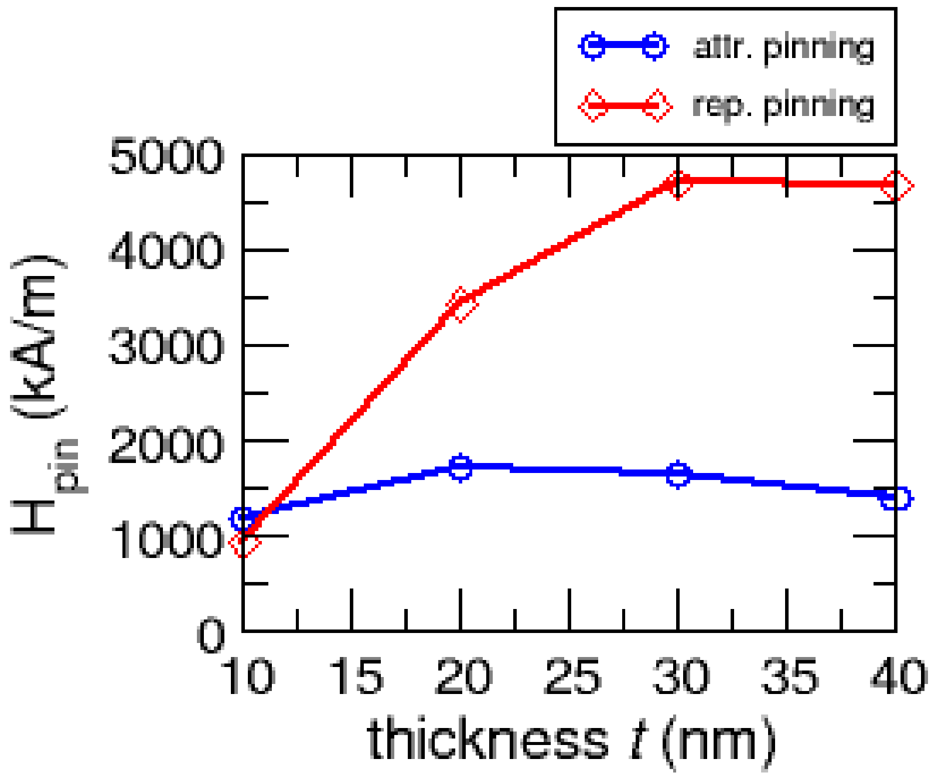
Pinning Fields



- 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

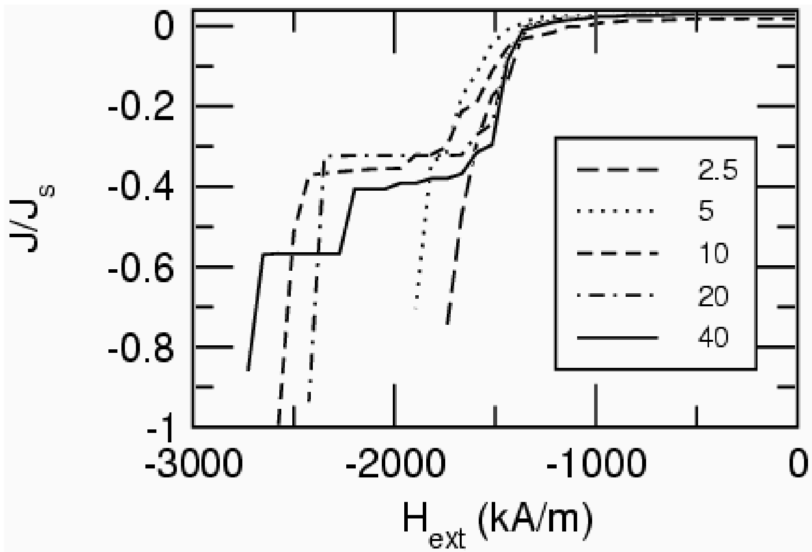


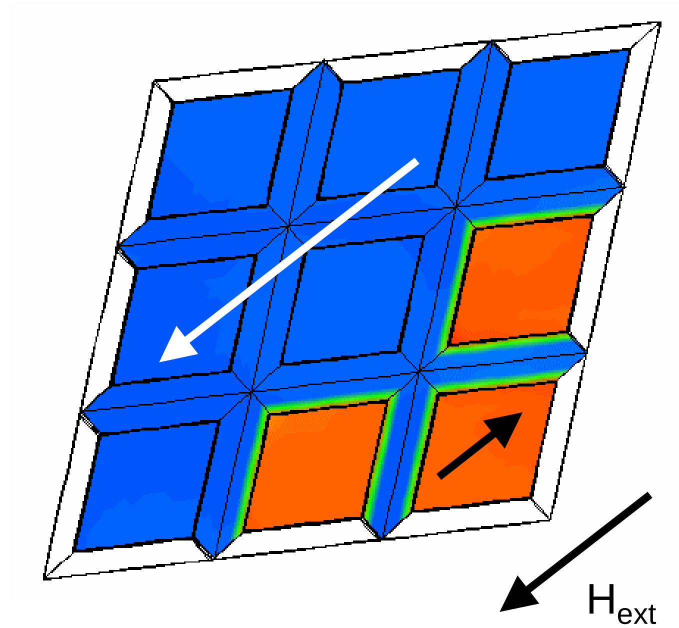
- Cells (Sm_2Co_{17}): K_1 = 5 MJ/ m^3
- Intercellular phase

  Attractive pinning: K_1=1.2 MJ/m^3

  Repulsive pinning: K_1=9.0 MJ/m^3

Thick Intercellular Phases





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

Summary

- Different pinning mechanisms depending on the composition

- Attractive Pinning:
  Pinning field decreases for increasing thickness of the intercellular phase
- Repulsive pinning:
  linear dependence of the pinning field on anisotropy
  maximum pinning field cannot be increased with increasing thickness of the intercell. phase

Acknowledgements

- **HITEMAG project**
  GRD1-1999-11125: Novel Permanent Magnets for High Temperature Applications