# Transition from single-domain to vortex state in soft magnetic cylindrical nanodots


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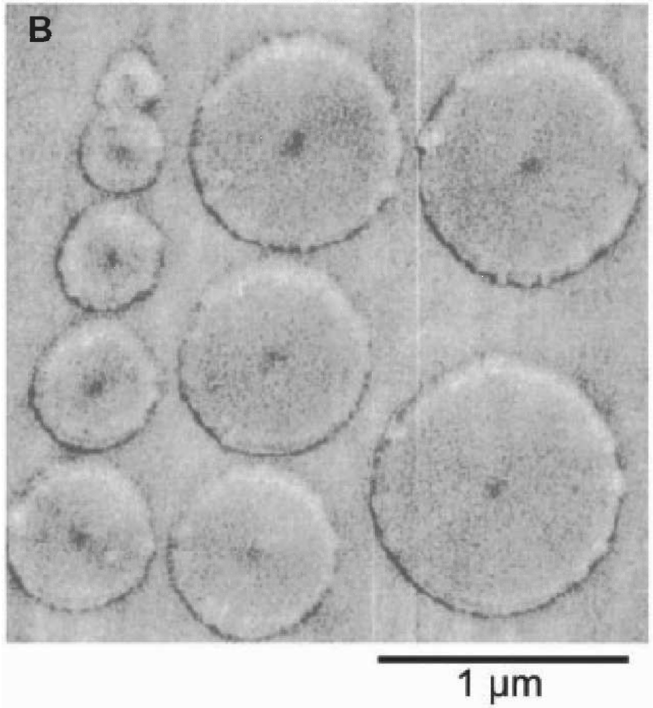
# Outline

- Introduction
- Analytical and numerical models
- Static properties
  - Magnetization distribution
  - Energy
  - Hysteresis
  - Surface and volume charges
  - Phase diagram
- Summary

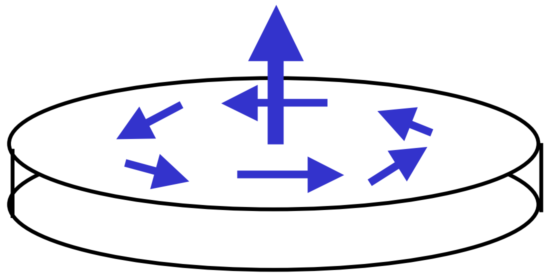
# Introduction




Shinjo et al., Magnetic Vortex Core Observation in Circular Dots of Permalloy, Science 289 (2000) 930

**Permalloy ($Ni_{80}Fe_{20}$) nanodots**

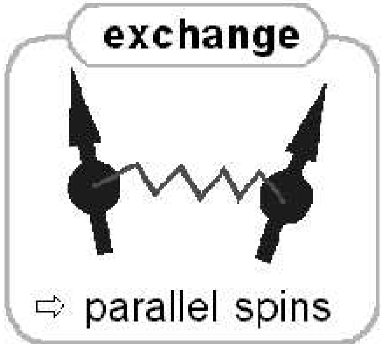
- **Saturation magnetization:**
  $M_s$ = $8 \cdot 10^5$ A/m = $8 \cdot 10^2$ G
  $J_s \approx 1$ T
- **Exchange constant:**
  $A$ = $13 \cdot 10^{-12}$ J/m = $1.3 \cdot 10^{-6}$ erg/cm
- **Anisotropy has been neglected**
- **Radius of 100 nm, thickness of 20 nm**

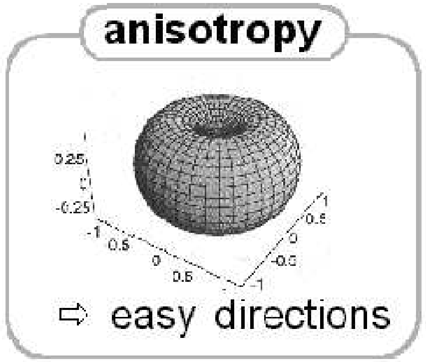


vortex state

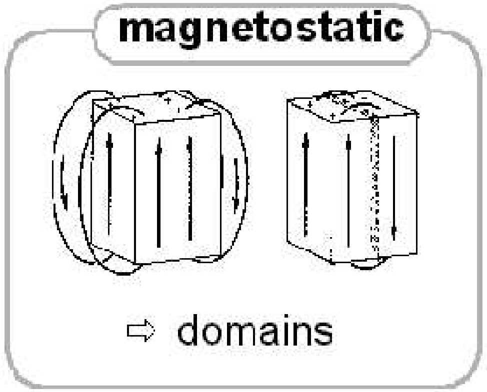
# Micromagnetics

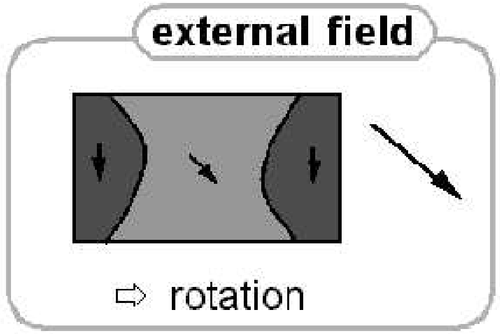
- Effective field $H_{eff}$ :
  - exchange
  - anisotropy
  - magnetostatic
  - external field
- Find energy minimums by integration of the Gilbert equation of motion
  or direct energy minimization




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



# Rigid vortex model

- **Usov ansatz**
  N.A. Usov, S. E. Peschany,
  Magnetization curling in a fine cylindrical particle,
  JMMM 118 (1993) L290-L294.

Magnetization outside the core (*r*>*a*)

$$M_x = -\sin\varphi$$

$$M_y = \cos\varphi$$

$$M_z = 0$$

Magnetization within the core (*r*<*a*)

$$M_x = -\frac{2ar}{a^2 + r^2}\sin\varphi$$

$$M_y = \frac{2ar}{a^2 + r^2}\cos\varphi$$

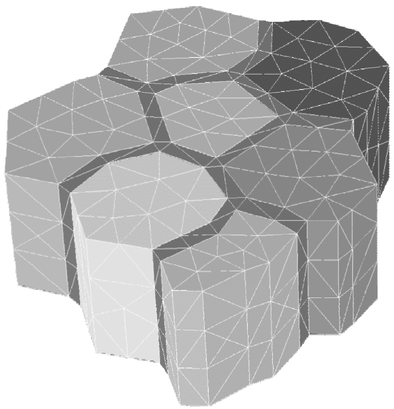
$$M_z = \sqrt{1 - \left(M_x^2 + M_y^2\right)}$$

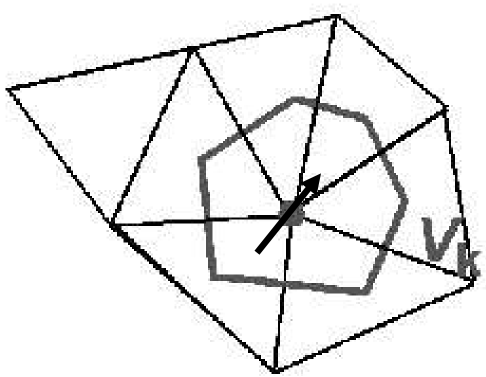
- Derived using a variational principle
- Vortex core size determined by magnetostatic and exchange energy

Properties:

- Surface charges in vortex core (top and bottom)
- Surface charges on the circumference for shifted vortices
- No volume charges

# Finite Element Approach






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

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

- energy as a function of $J_1$, $J_2$ … $J_N$

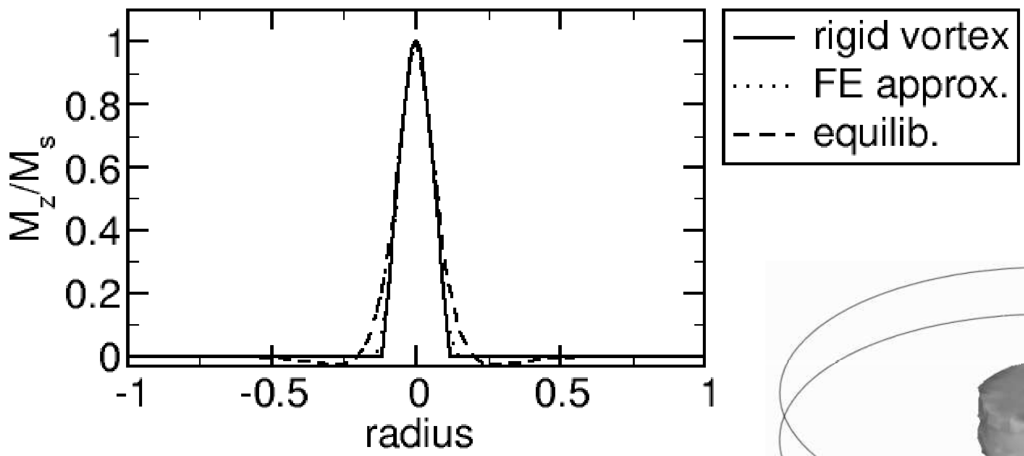
$$E(\vec{J}_1, \vec{J}_2 .... \vec{J}_N)$$

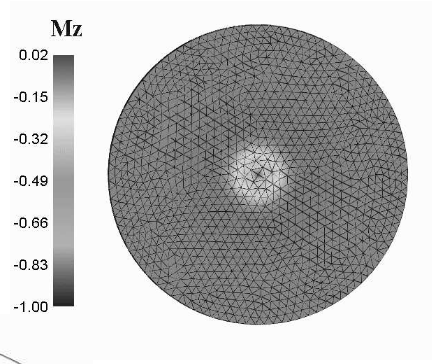
- effective field

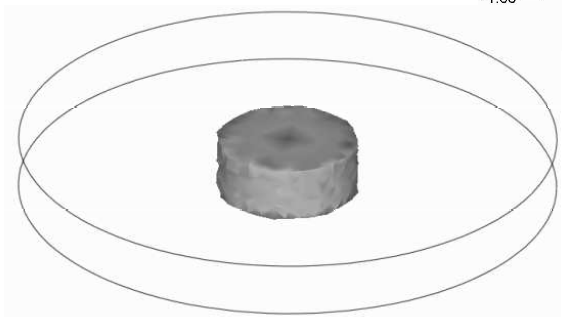
$$\vec{H}_k = -\frac{1}{V_k} \frac{\partial E(\vec{J}_1, \vec{J}_2 .... \vec{J}_N)}{\partial \vec{J}_k}$$

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

# Static properties



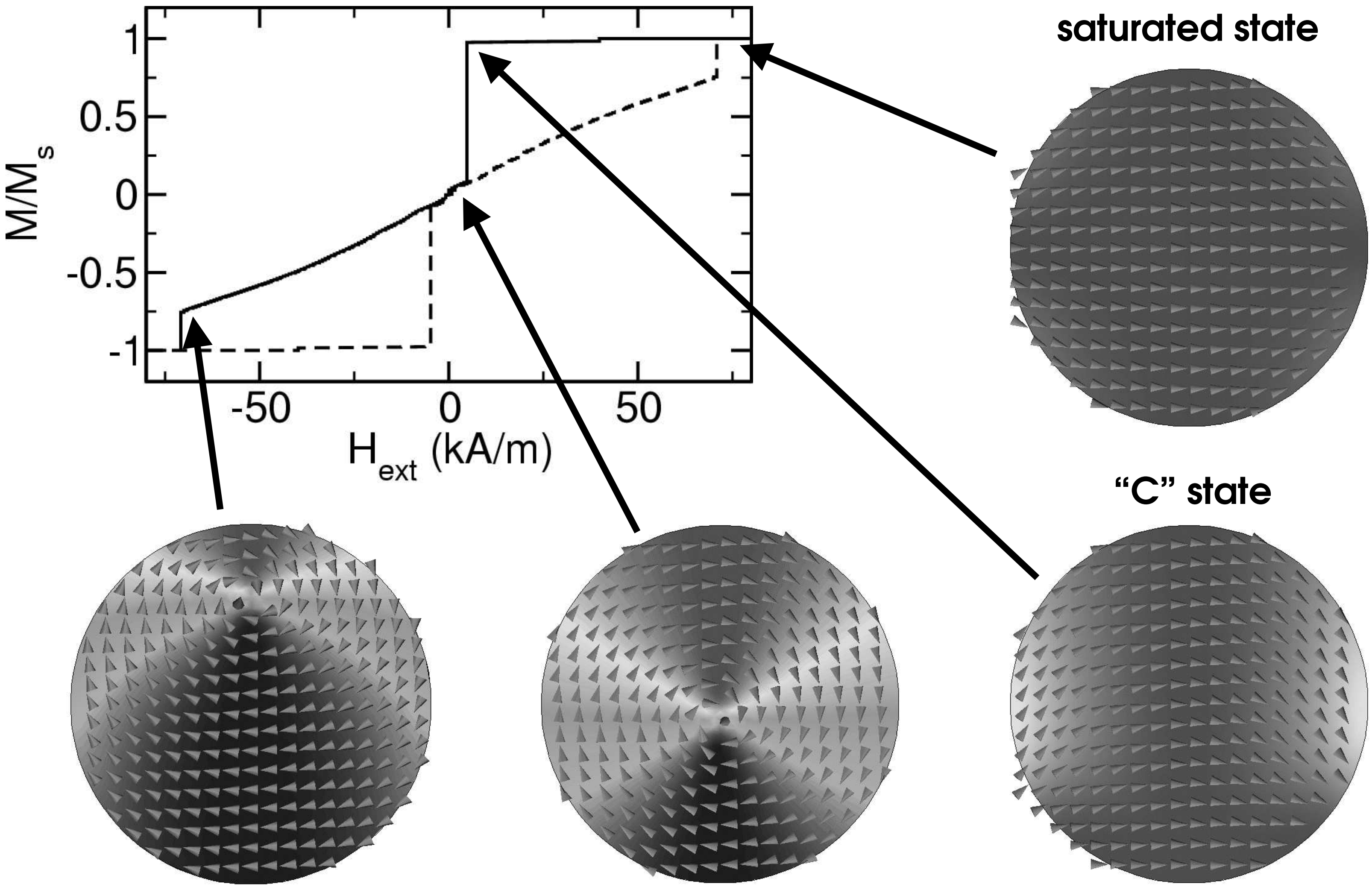



**Isovolume of vortex core**

| | Magnetostatic energy | Exchange energy | Total energy (J/m^3) |
|---|---|---|---|
| Rigid vortex model (Usov ansatz) | 4.321E+02 | 5.356E+03 | 5.788E+03 |
| FE simulation (equilib.) | 3.871E+02 | 5.150E+03 | 5.537E+03 |
| difference FE - analytical | -10.42% | -3.85% | -4.35% |

# Hysteresis loop

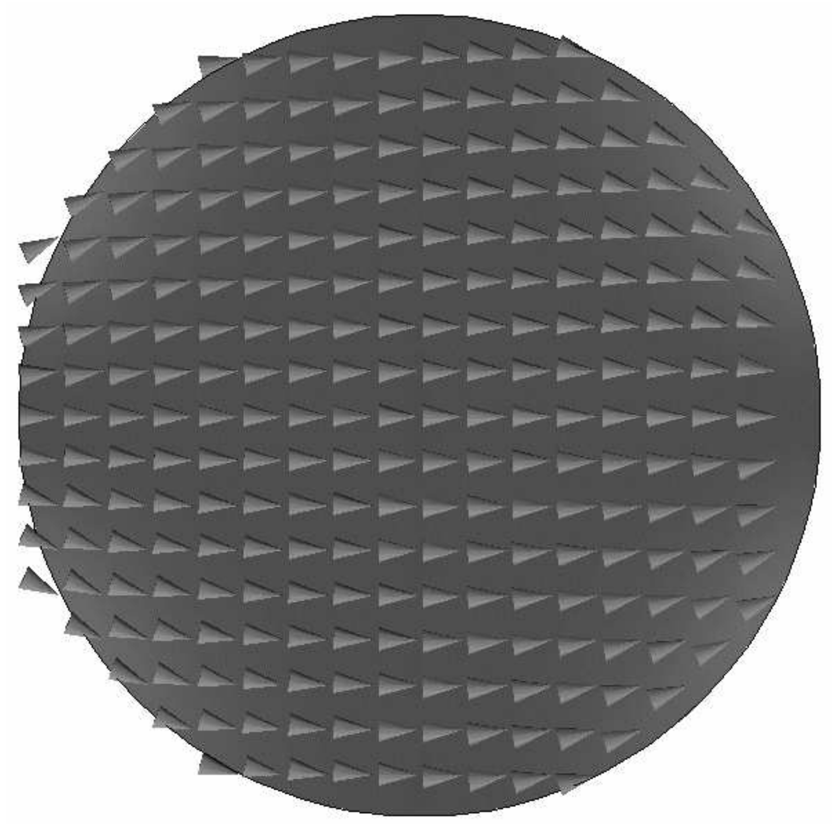



**annihilation field:**
**70 kA/m = 880 Oe = 88 mT**

**Equilibrium in zero field**

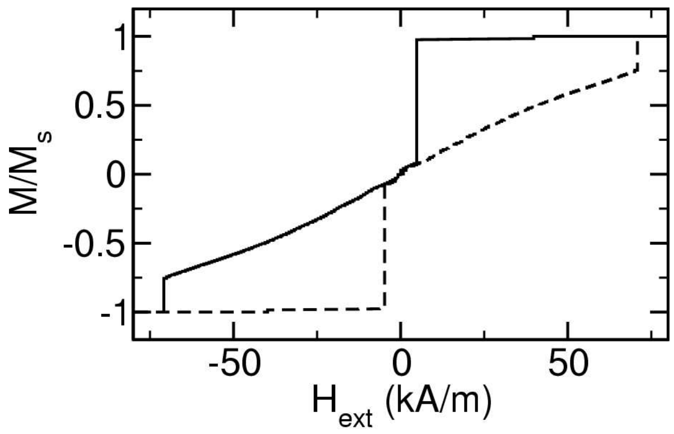
**nucleation field:**
**5 kA/m = 62 Oe = 6.2 mT**

# Hysteresis movie



- L/R=20/100 nm
- Nucleation field: 5 kA/m
- Annihilation field: 70 kA/m

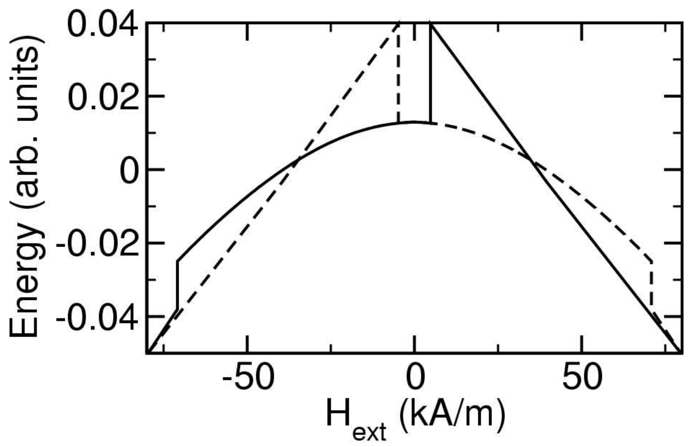
# Energy for shifted vortex

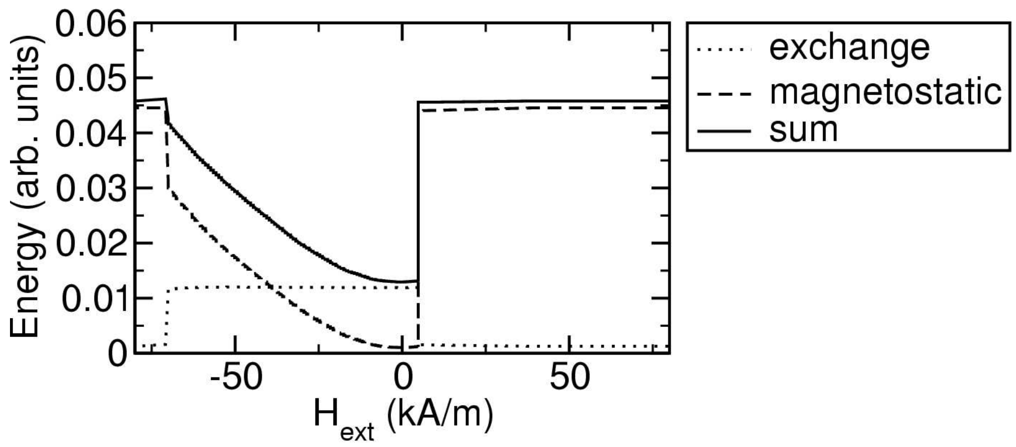



**Homogeneous magnetization becomes metastable for $H_{ext}$<35 kA/m**

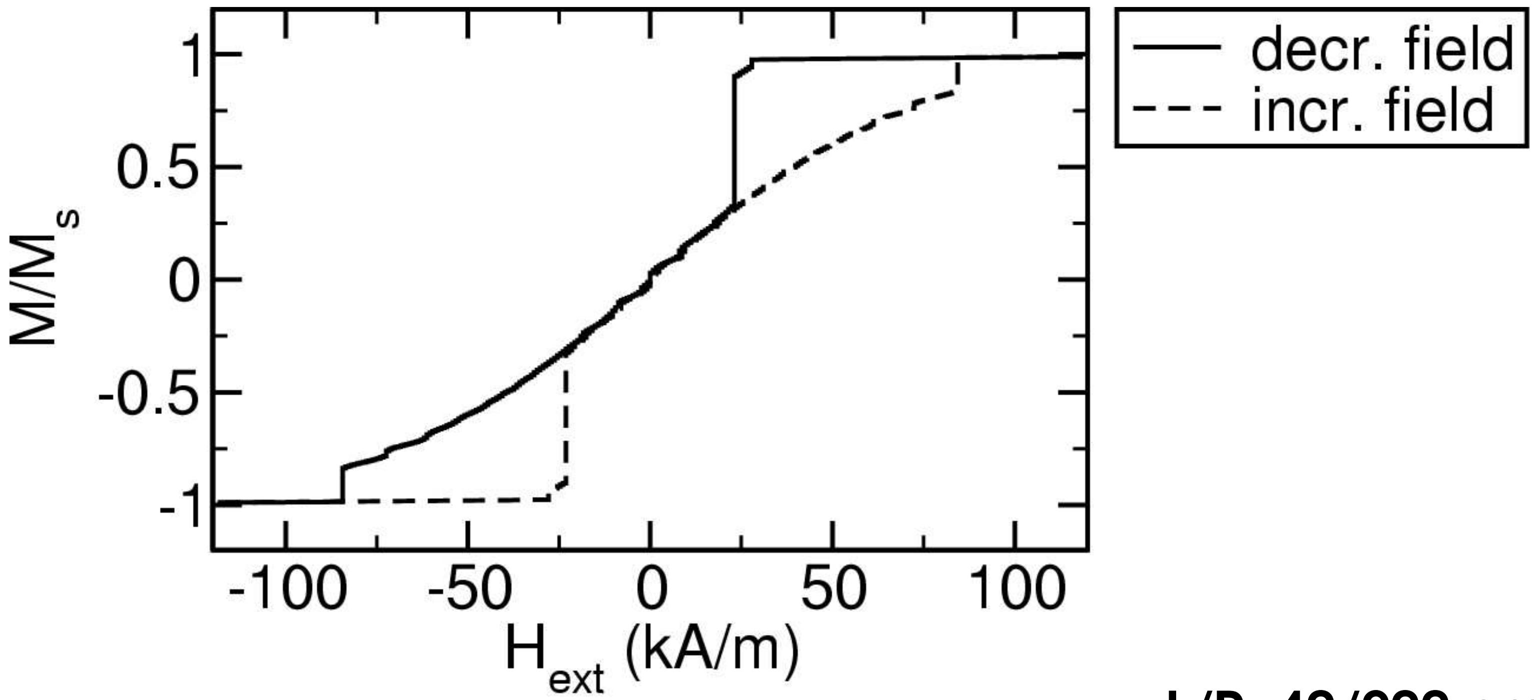
**nucleation field: 5 kA/m**

**annihilation field: 70 kA/m**



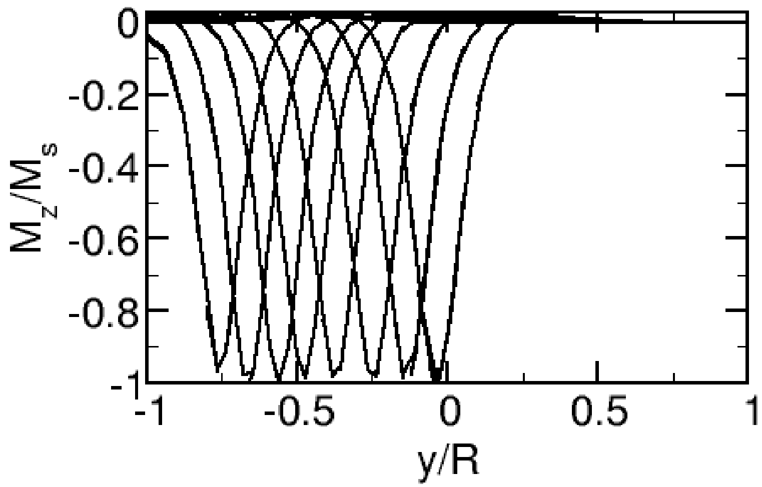



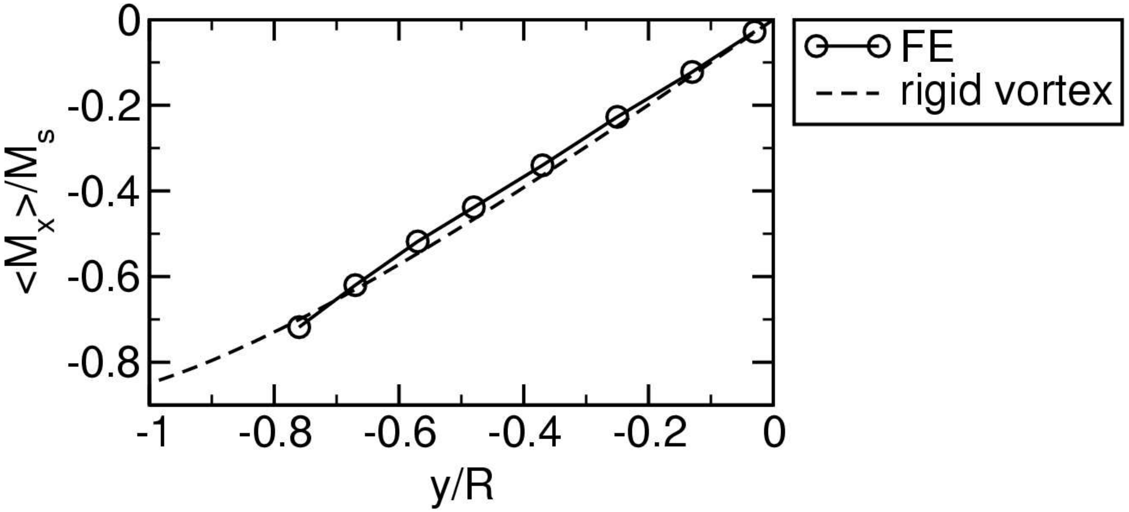
# Larger dot




- **L/R=40/200 nm**
- **Nucleation field: 28 kA/m**
- **Annihilation field: 84 kA/m**

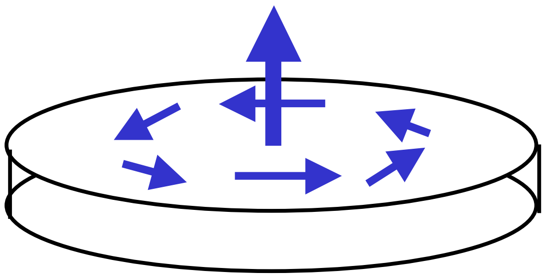
# Average magnetization



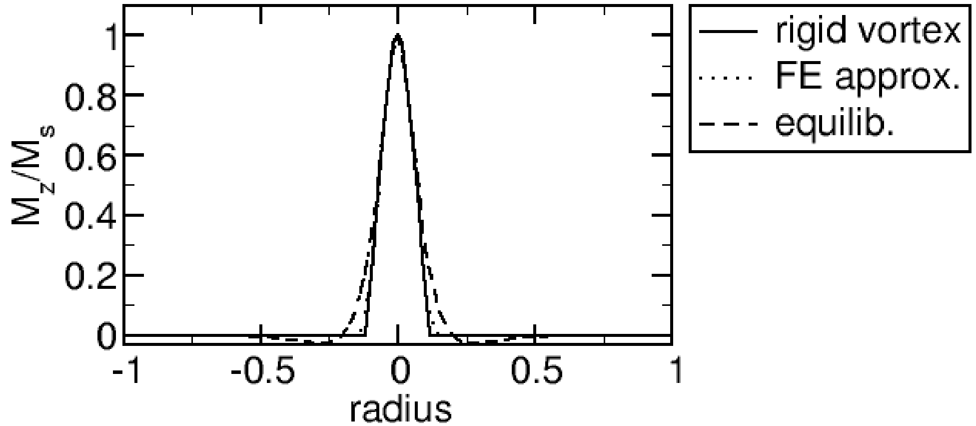



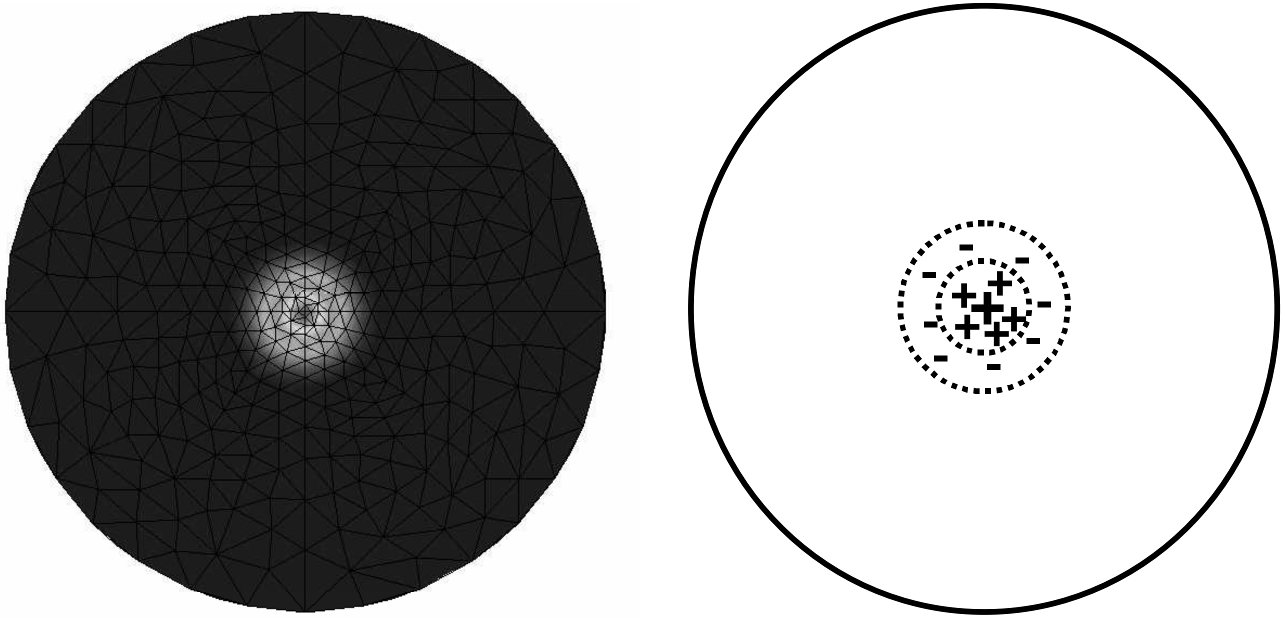

- **Shape of vortex core is hardly influenced**
- **Average magnetization in good agreement, but…**

# Surface charges



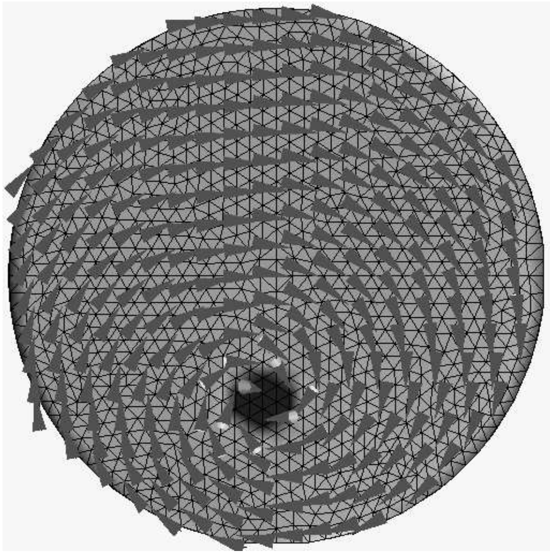
vortex state

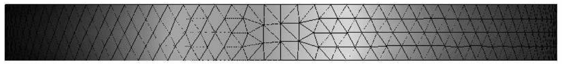


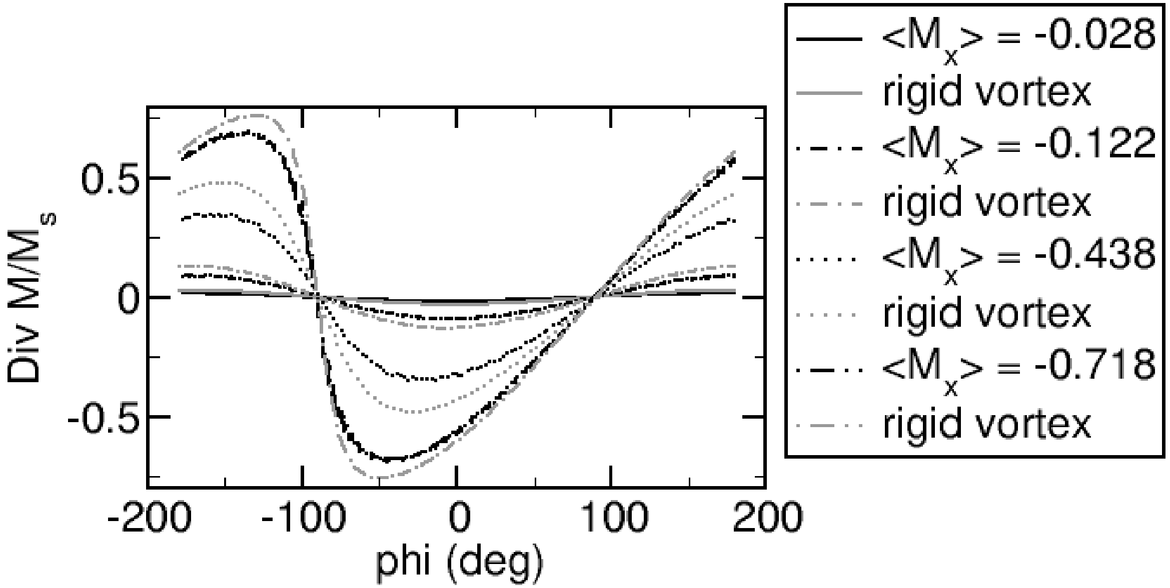
surface charge density

# Comparison with rigid vortex model

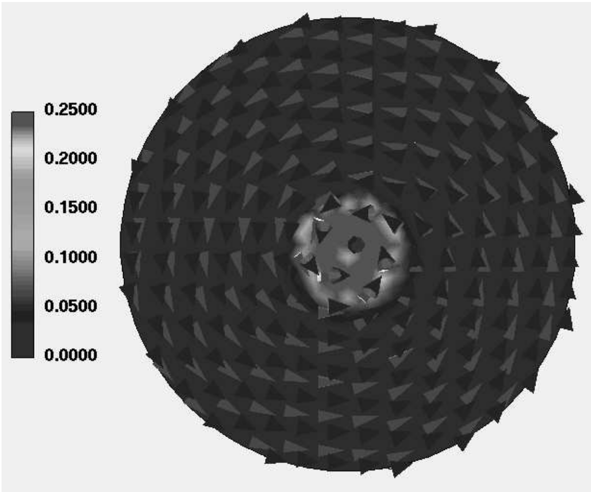




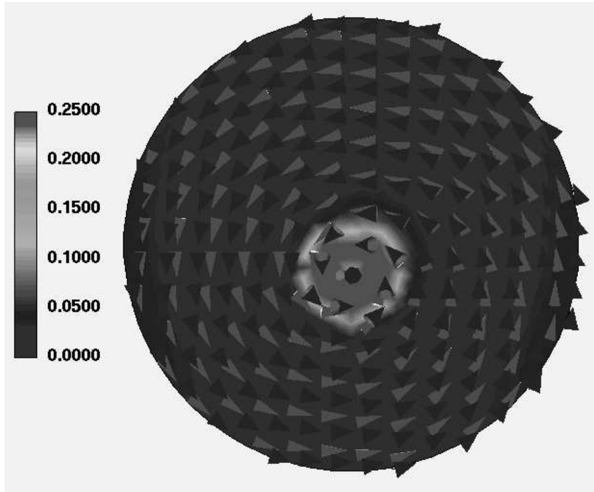
- Surface charge on circumference
- Rigid vortex model overestimates the charge density



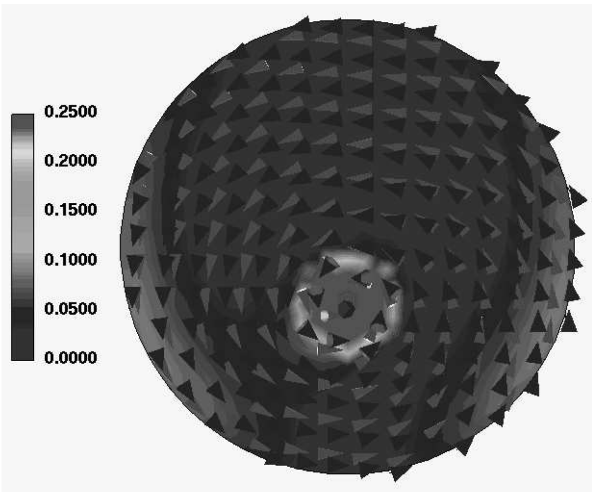
# Contour plots of $|M_{rv}-M_{FE}|$ /1



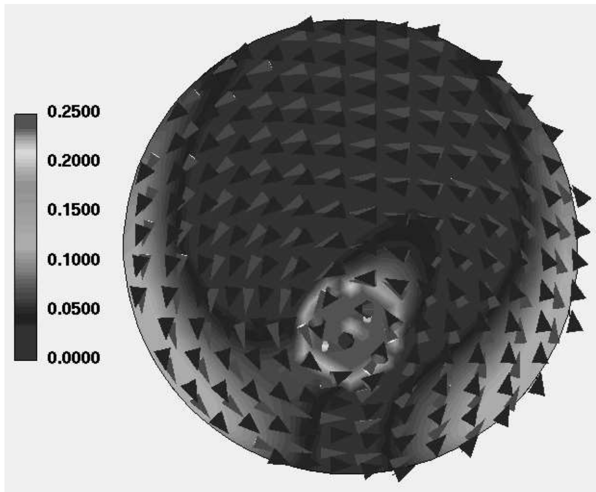

0.8 kA/m = 10 Oe, $\langle M_x \rangle$=-0.02, $b/R$ = -0.03




8.8 kA/m = 110 Oe, $\langle M_x \rangle$=-0.12, $b/R$ = -0.13

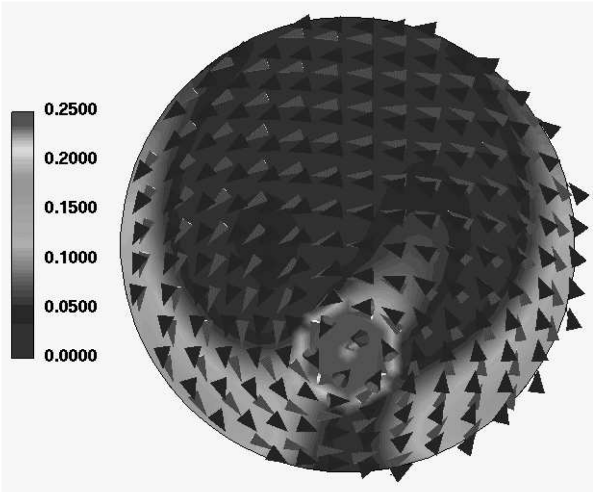



16.7 kA/m = 210 Oe, $\langle M_x \rangle$=-0.23, $b/R$ = -0.25

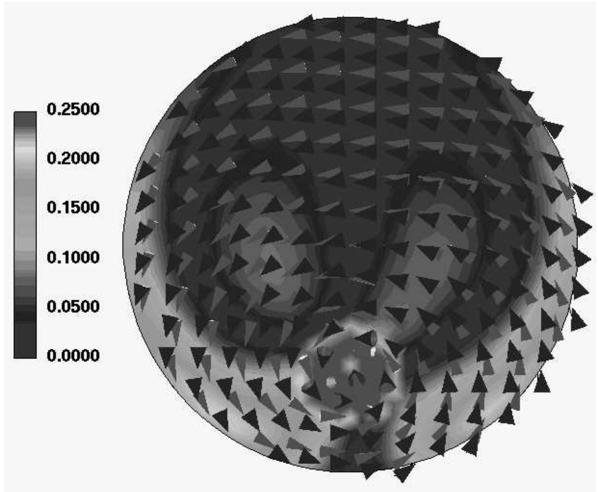



25.5 kA/m = 320 Oe, $\langle M_x \rangle$=-0.34, $b/R$ = -0.37

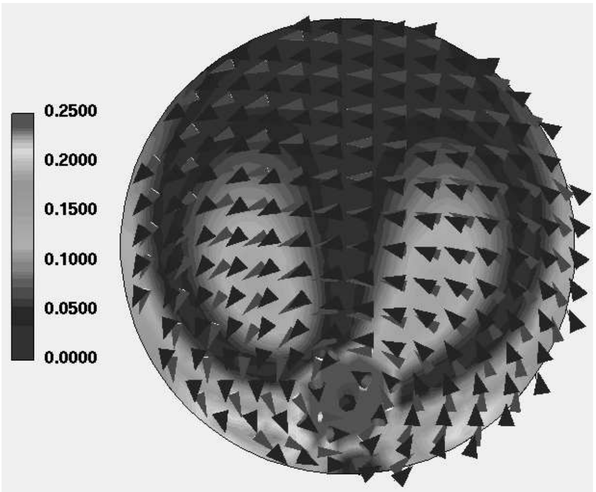
# Contour plots of $|M_{rv}-M_{FE}|/2$



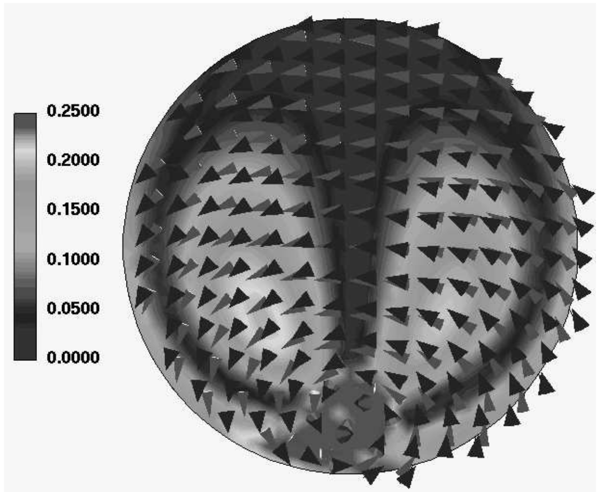

34.2 kA/m = 430 Oe, $\langle M_x \rangle$=-0.44, $b/R$ = -0.48




42.2 kA/m = 530 Oe, $\langle M_x \rangle$=-0.52, $b/R$ = -0.57

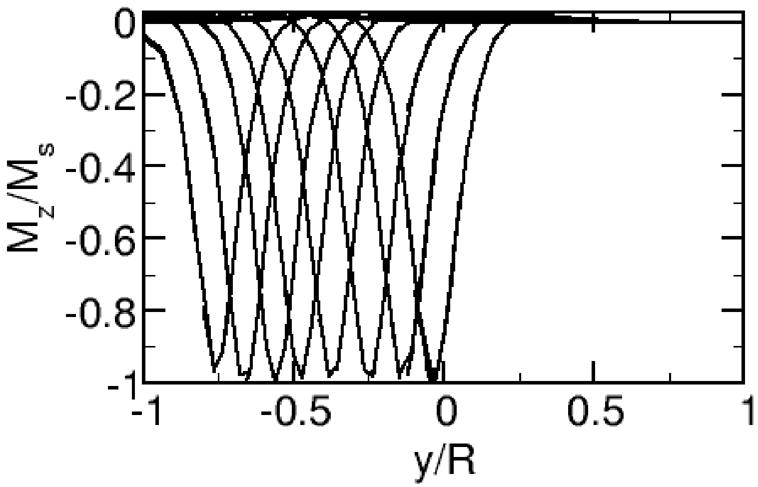


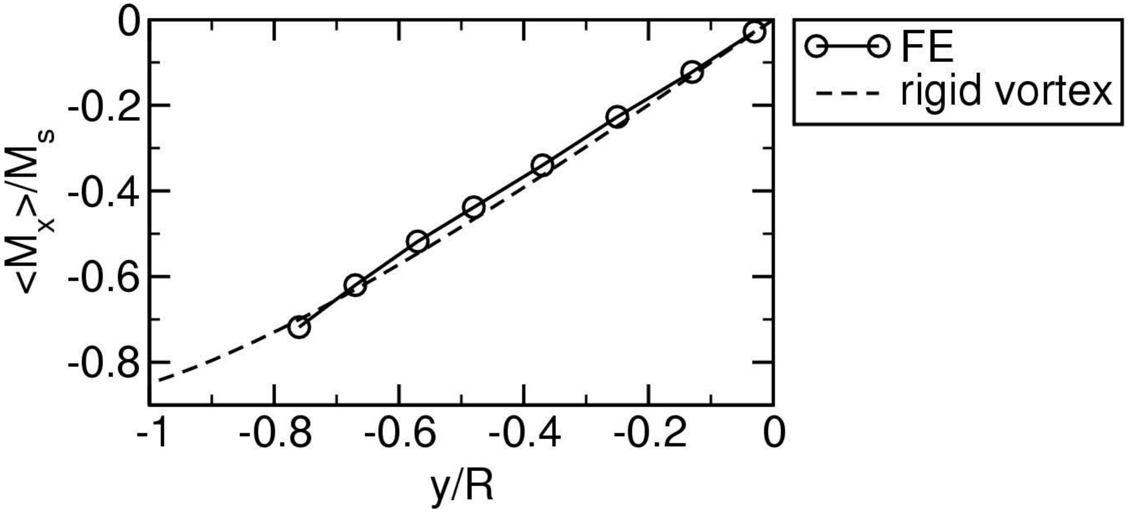

54.1 kA/m = 680 Oe, $\langle M_x \rangle$=-0.62, $b/R$ = -0.67




66 kA/m = 830 Oe, $\langle M_x \rangle$=-0.72, $b/R$ = -0.76

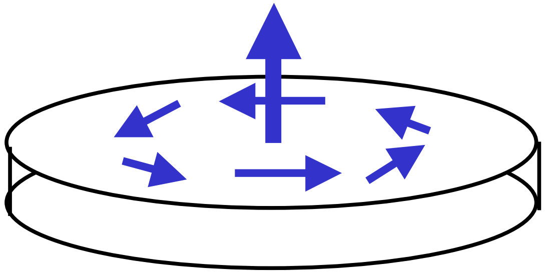
# Average magnetization



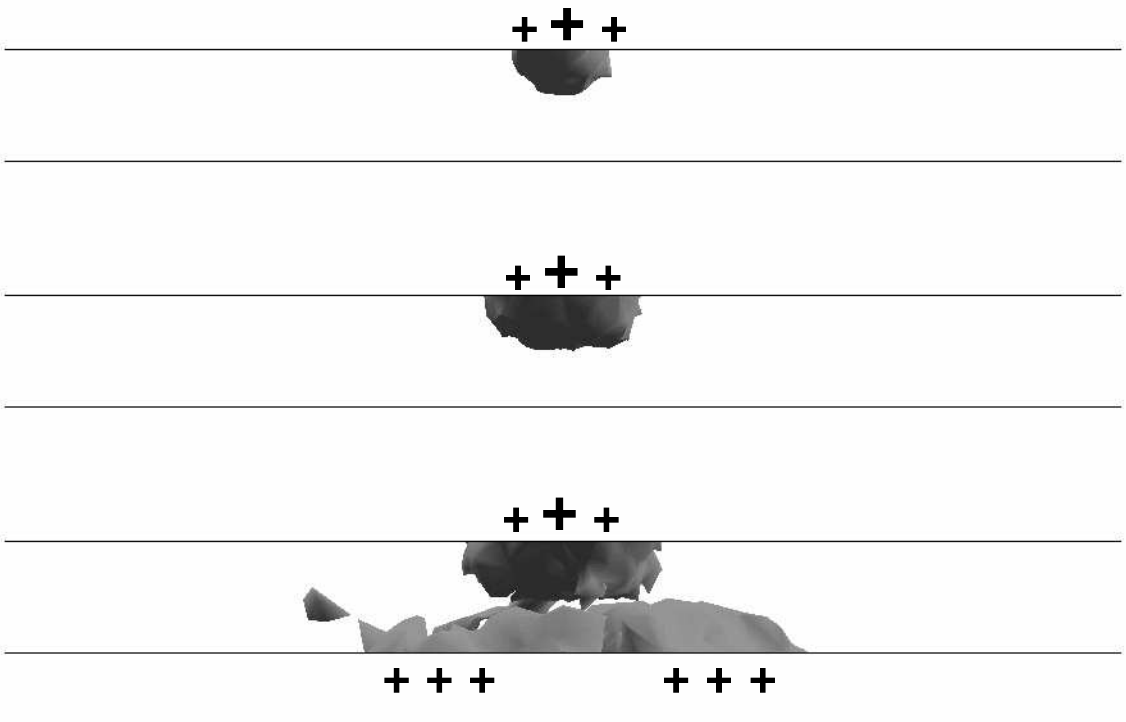




- **Shape of vortex core is hardly influenced**
- **Average magnetization in good agreement, but…**

# Volume charges in zero field /1



3D isosurface plots

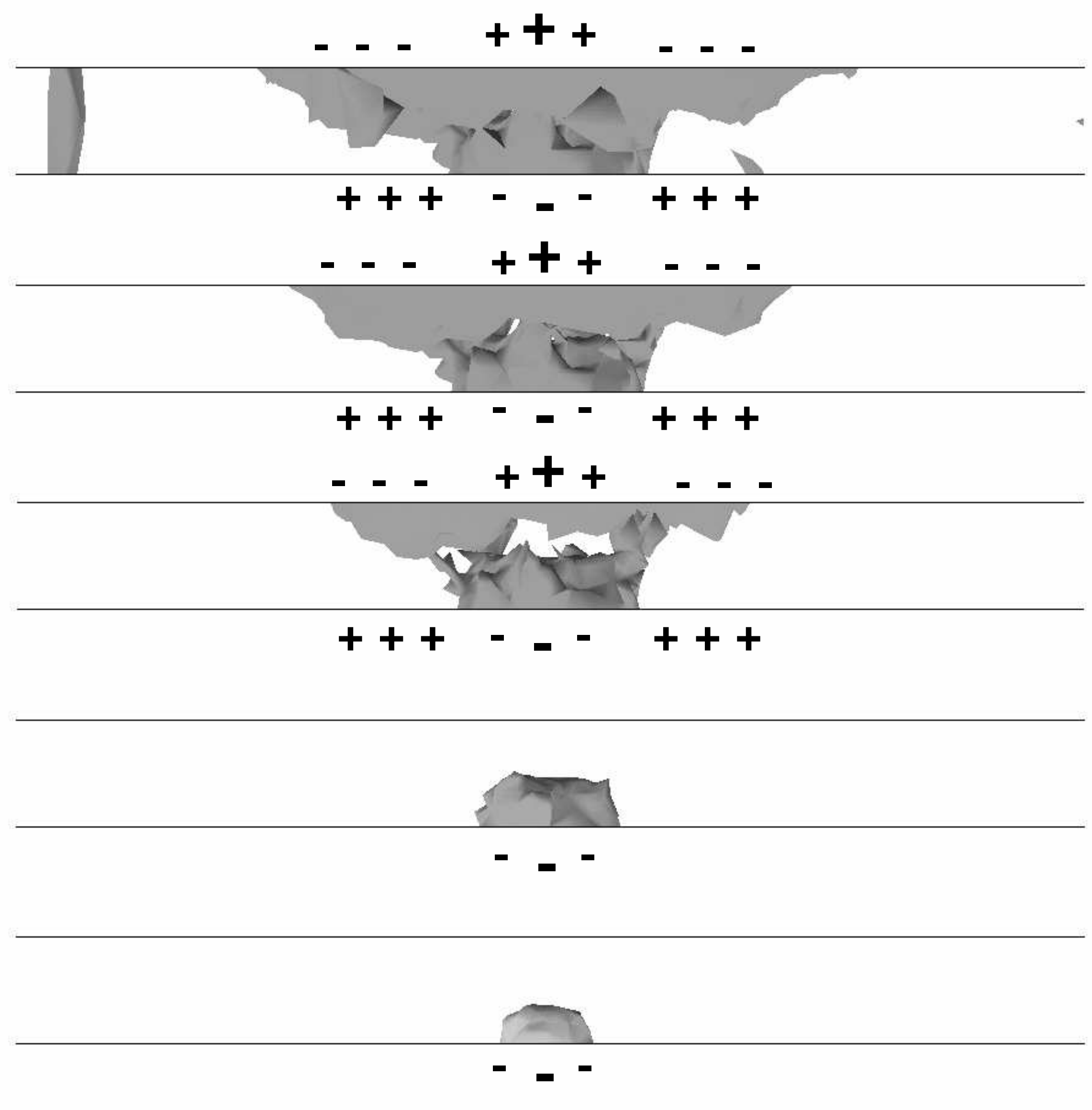


div $M/M_s$ = +1.0

div $M/M_s$ = +0.3

div $M/M_s$ = +0.09

# Volume charges in zero field /2




div $M/M_s$ = -0.03

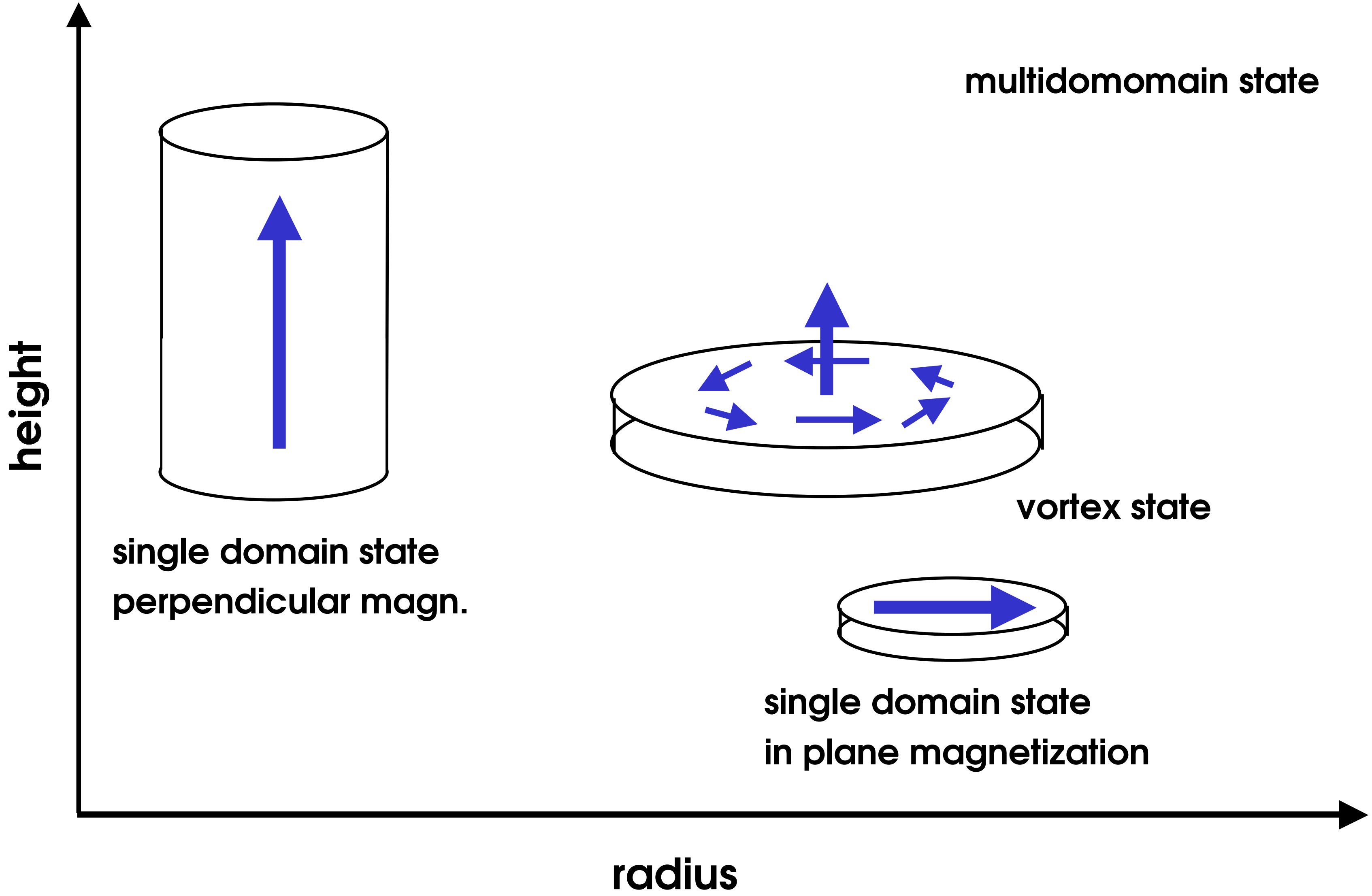
div $M/M_s$ = -0.05

div $M/M_s$ = -0.09

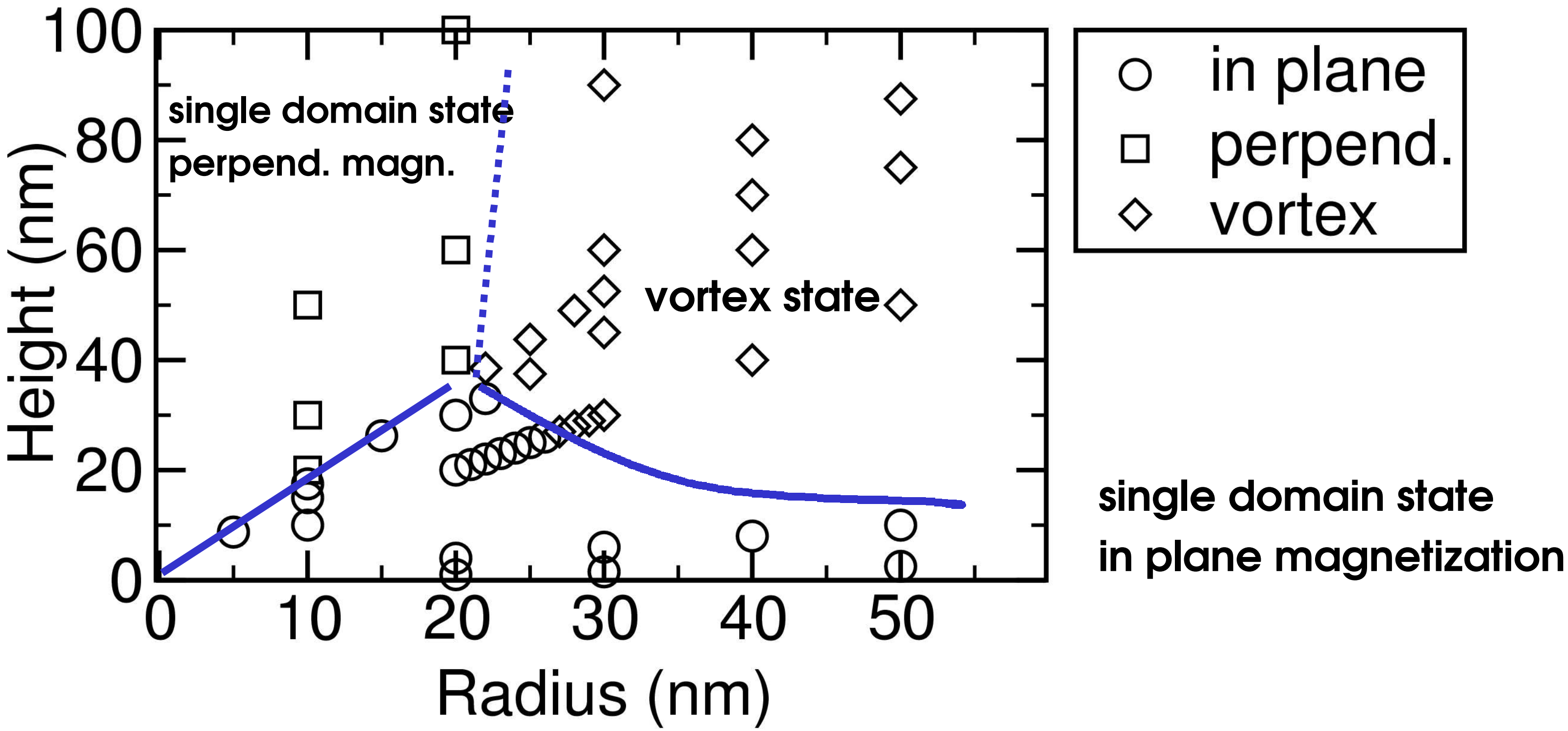
div $M/M_s$ = -0.3

div $M/M_s$ = -1.0

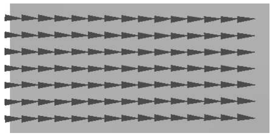
# Simple equilibrium states



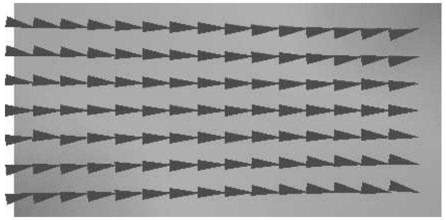
# Phase diagram



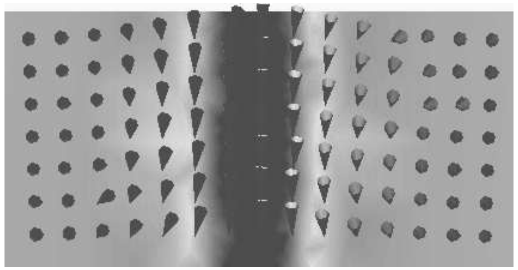
# Magnetization distributions



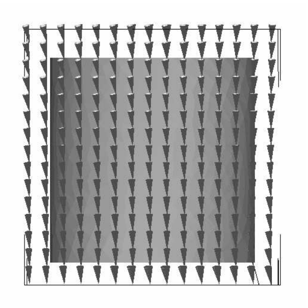
L/R=1
R=10 nm



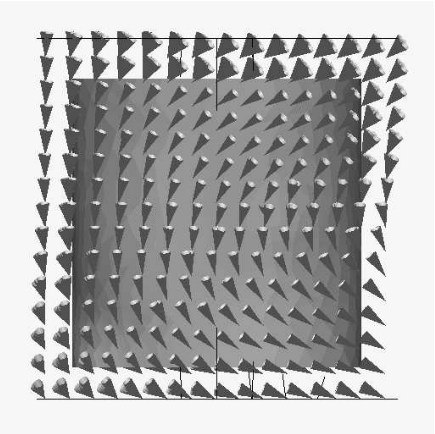
L/R=1
R=25 nm



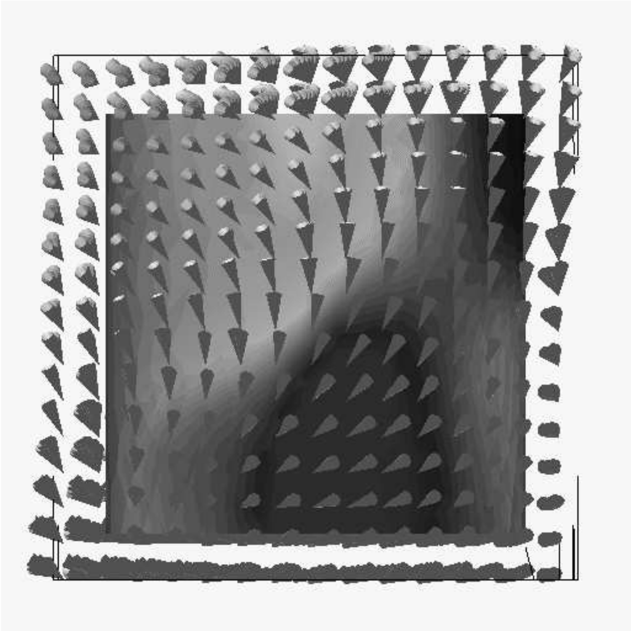
L/R=1
R=28 nm



L/R=2
R=10 nm



L/R=2
R=25 nm



L/R=2
R=40 nm

# Summary

- Investigation of static properties of permalloy nanodots using a 3D FE method
- Detailed comparison with the rigid vortex model and Usov ansatz
  - vortex is truly rigid
  - deviations in magnetization distribution
  - core edge: larger vortex core radii
  - shifted vortices:
    deviations in surface charge distribution
- Surface and volume charges (magnetostatics) determine static behavior
- sharp transition from in plane to vortex state