

Spin dynamics in nanostructures

A. Sukhov, C.L. Jia, J. Berakdar

Martin-Luther-Universität Halle-Wittenberg



P. Horley¹, V.K. Dugaev²

¹Centro de Investigación en Materiales Avanzados, Chihuahua, Mexico

²Rzeszow University of Technology, Poland



Overview

Introduction

ultrafast magnetization dynamics

magnetic domain walls dynamics

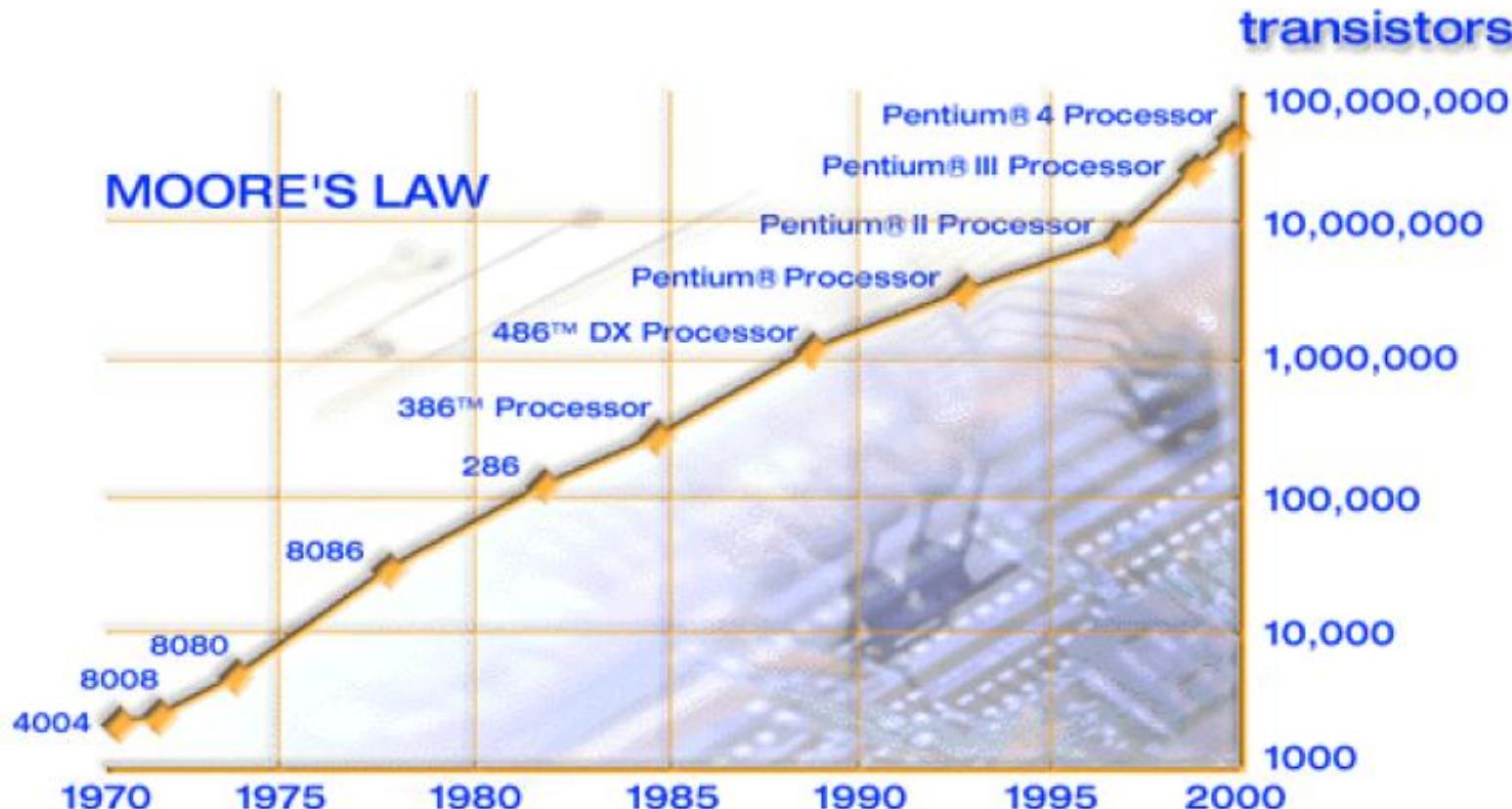
multiferroic dynamics



motivations

Moore's law

Moore's Law: Number of transistors on a chip doubles each 18 months



Quelle: Intel



Moore's Law for Storage Devices

- Capacity increase
 - Hard disks: 100% per annum during the last three years (*Doubling every 18 months since 1994*)
 - Tapes: Doubling every 18 months
- Transfer rate: slower growth. Does not follow Moore's law
 - disks: single disks, from 2 to 8 MB/s (1990-2000)
 - tapes: from 3 MB/s to 12 MB/s (1990-2000)



motivations

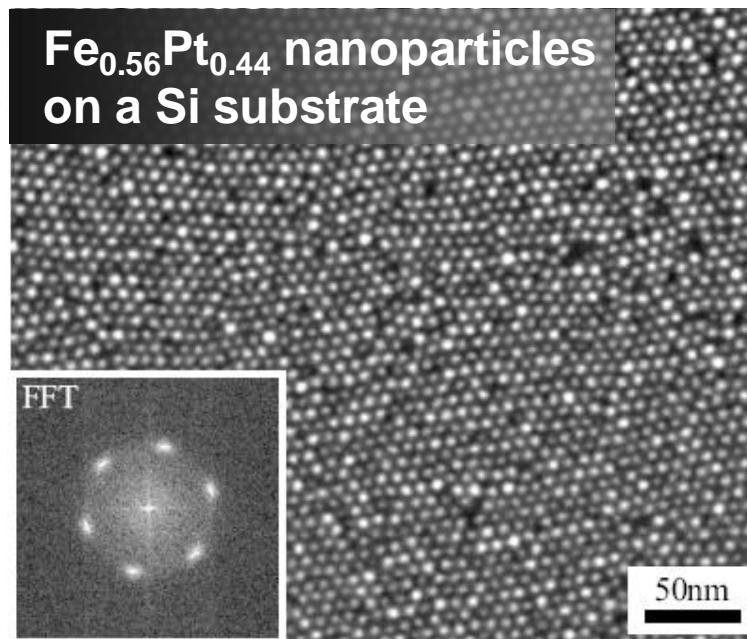
Moore's law

So how do we speed up?

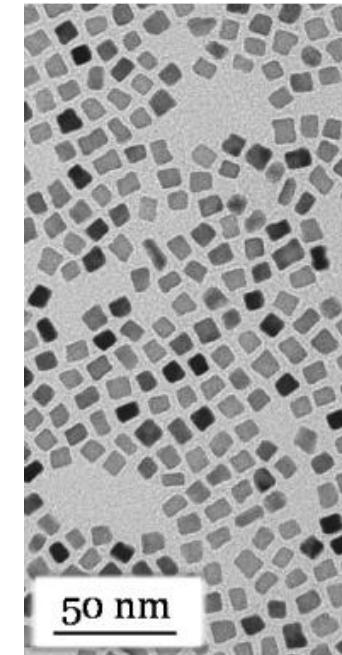


experiments

nanomagnets



Antoniak *et al.*
Mod. Phys. Lett. B, **21**, 1111 (2007)



Margeat *et al.*
Phys. Rev. B, **75**, 134410 (2007)

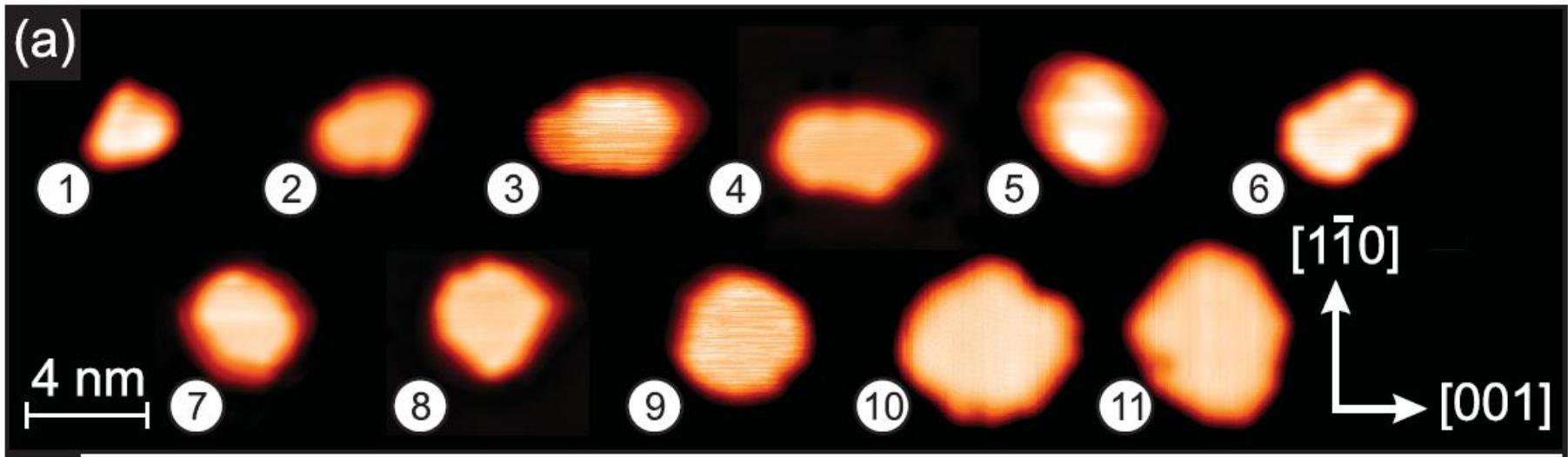
single domain
nanomagnet
(Fe₅₀Pt₅₀)

T^{prec} = 5 ps max. anisotropy field ~7 T magnetic moment ~22000 μ_B



experiments

nanomagnets



in-plane magnetized Fe/W(110) nanoislands.

S. Krause *et al.*, PRL 103, 127202 (2009).



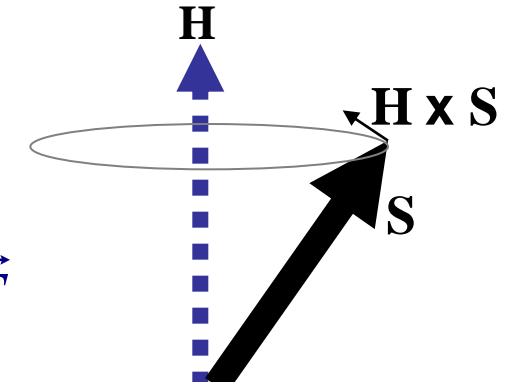
spin dynamics

torque and precession

angular momentum change

$$\frac{d\vec{L}}{dt} = \vec{T}_{\text{torque}}$$

$$\vec{S} = -\gamma \vec{L} \quad \Rightarrow \quad \frac{d\vec{S}}{dt} = -\gamma \vec{T}$$



$$\vec{T} = \vec{S} \times \vec{H} \quad \Rightarrow \quad \frac{d\vec{S}}{dt} = -\gamma (\vec{S} \times \vec{H})$$

(Landau & Lifshitz, 1935)

$$|\vec{S}| = \text{const.}, \quad \omega_L = \frac{\gamma H}{2\pi}$$

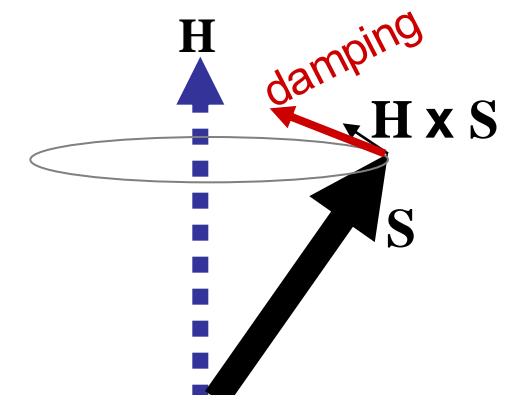
Larmor frequency

$$\gamma = 2.21 \times 10^5 \text{ m A}^{-1} \text{s}^{-1}$$



spin dynamics

torque and precession



$$\frac{d\vec{S}}{dt} = -\gamma \vec{S} \times \vec{H} + \alpha \hat{\vec{S}} \times \dot{\vec{S}}$$

free precession damping

(Landau-Lifshitz-Gilbert equation)



finite T Landau-Lifshitz-Gilbert equation

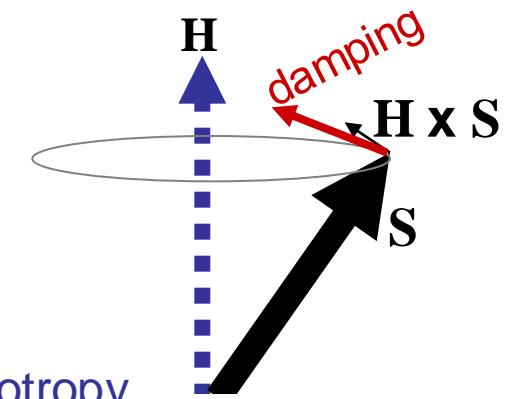
effective field:

energy functional

$$\mathcal{H} = \mathcal{H}_A + \mathcal{H}_F$$

$$\mathcal{H}_A = -D f_A(\mathbf{S}) \quad \text{magnetic anisotropy}$$

$$\mathcal{H}_F = -\mathbf{S} \cdot \mathbf{b}_0(t) \quad \text{Zeeman energy } (\mathbf{b}_0 = \text{external field})$$



effective field + thermal noise

$$\mathbf{H}^{eff}(\tau) = -\delta\mathcal{H}/\delta\mathbf{S} + \zeta(\tau)$$

$$\langle \zeta_\eta(\tau') \rangle = 0; \langle \zeta_\eta(\tau') \zeta_\theta(\tau'') \rangle = \delta_{\eta\theta} \delta(\tau'' - \tau') \epsilon; \epsilon = \alpha \frac{k_B T}{D}$$

Sukhov, Berakdar J. Phys.:Cond.Mat. **20**, 125226 (2008); Phys. Rev. B **78**, 054417 (2008)



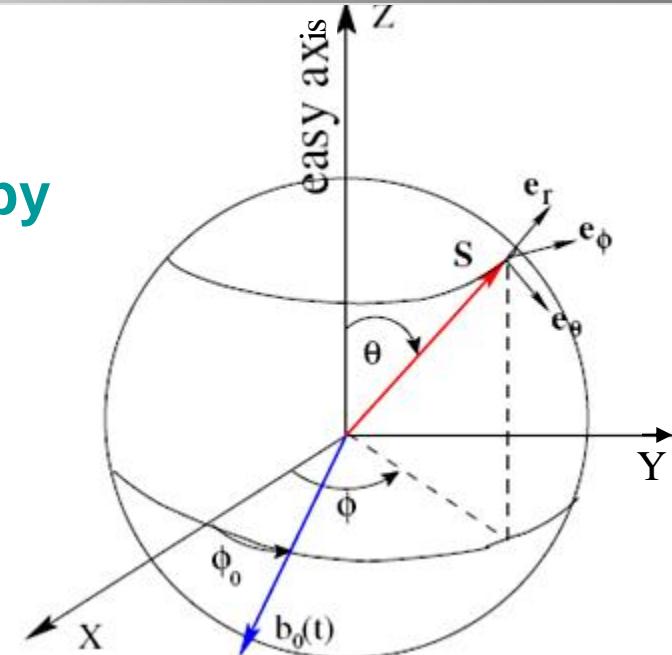
field-free solution

macro-spin dynamics

external field=0, T=0, uniaxial anisotropy

→ time evolution is analytical

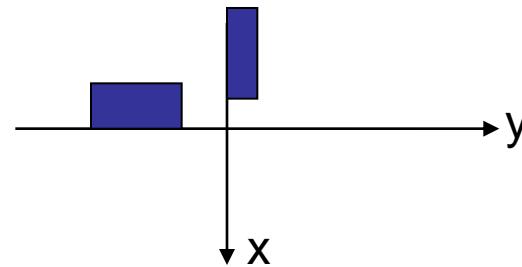
$$\phi_f(t) = \phi_f(\bar{t}_0) + \frac{t - \bar{t}_0}{1 + \alpha^2} + \frac{1}{\alpha} \ln \left| \frac{\cos \theta_f(\bar{t}_0) (1 + \sqrt{1 + \tan^2 \theta_f(\bar{t}_0)} \cdot e^{-\frac{2\alpha(t-\bar{t}_0)}{1+\alpha^2}})}{1 + \cos \theta_f(\bar{t}_0)} \right|,$$
$$\tan \theta_f(t) = \tan \theta_f(\bar{t}_0) \cdot e^{-\frac{\alpha}{1+\alpha^2}(t-\bar{t}_0)}.$$



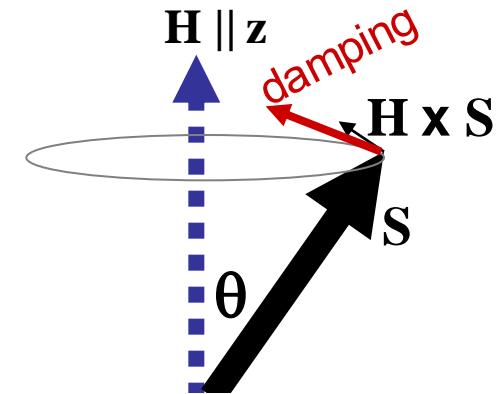


pulsed fields

stroboscopic evolution



$\varepsilon = \text{pulse duration}, \quad b_0/\varepsilon = \text{pulse strength}$



$\text{pulse duration} < T^{\text{prec}}$ \rightarrow stroboscopic evolution:

control fields are those that lead to

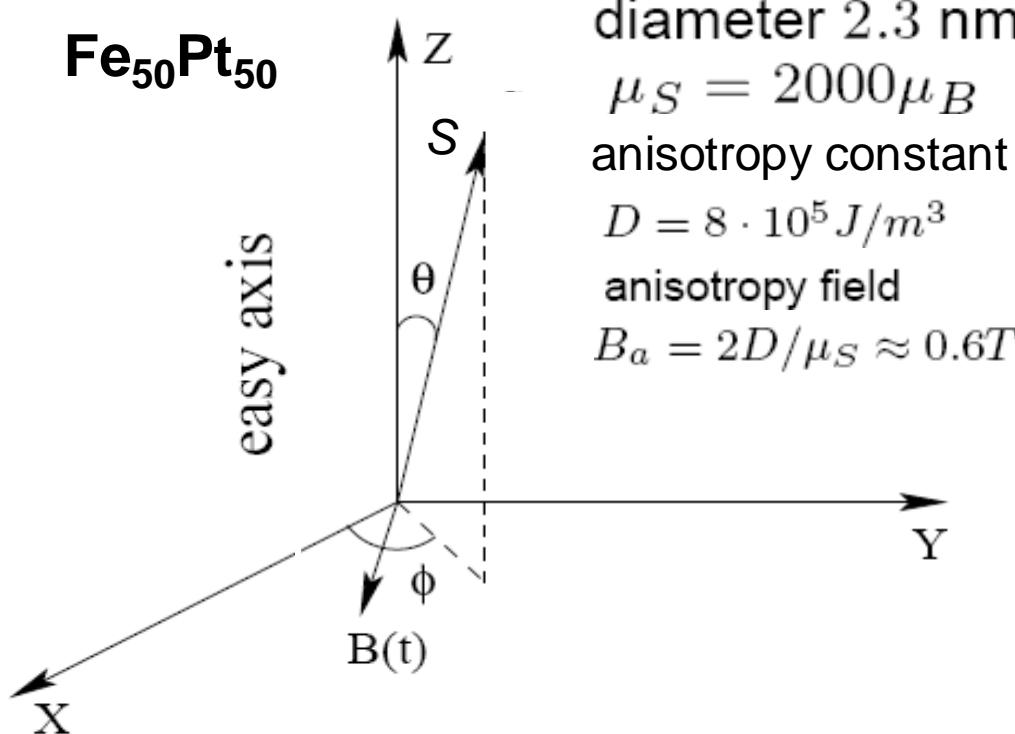
$$\theta(t^+) > \theta(t^-) \quad \forall t^+, t^-. \quad t^- := t_0 - \varepsilon_2, \quad t^+ := t_0 + \varepsilon_2$$

Sukhov, Berakdar, Phys. Rev. Lett. **102**, 057204 (2009)



spin dynamics

nanomagnet

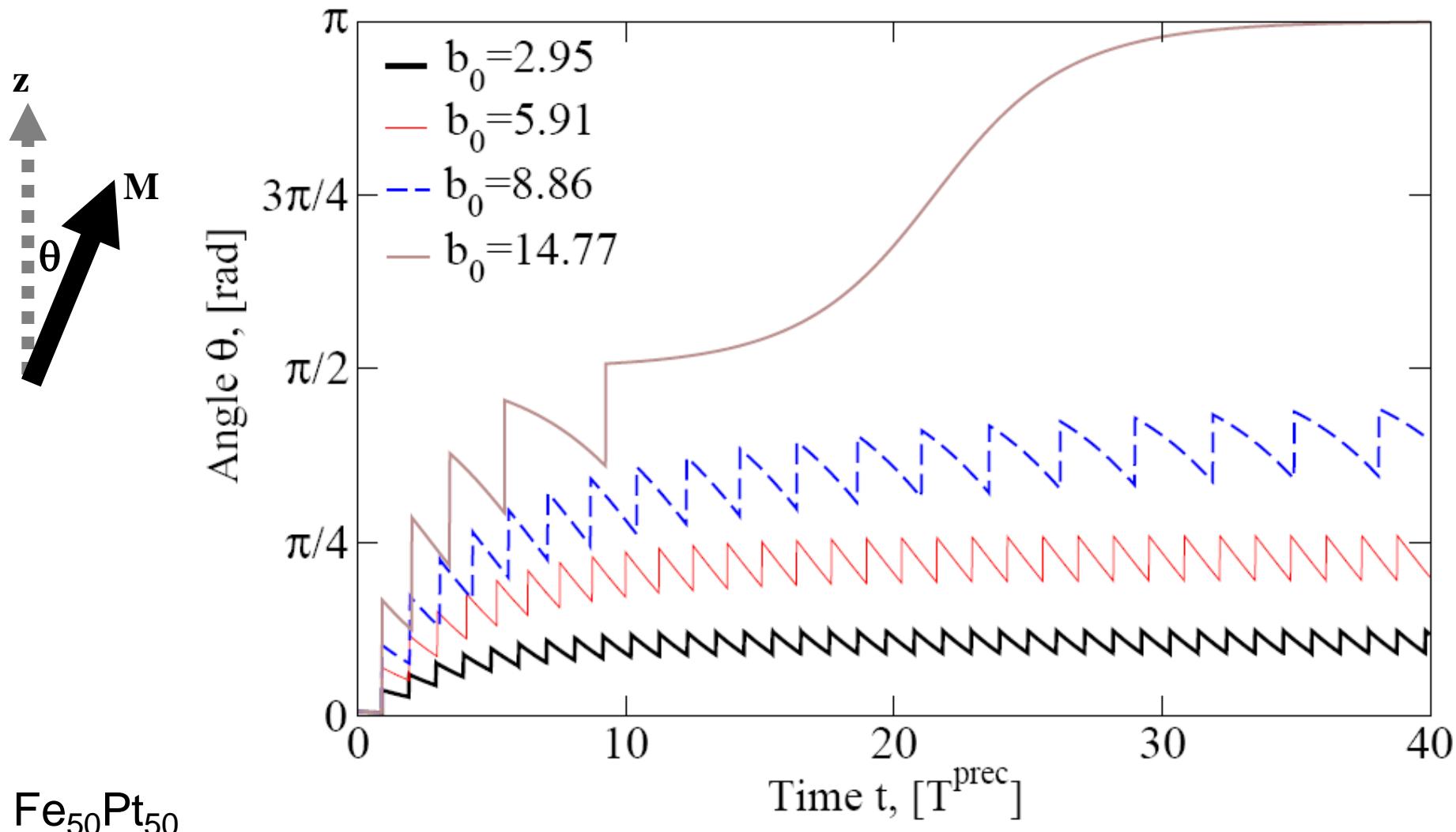


exp.: Antoniak *et. al.*, EPL **70**, 250 (2005)



switching & freezing

stroboscopic evolution



$\text{Fe}_{50}\text{Pt}_{50}$

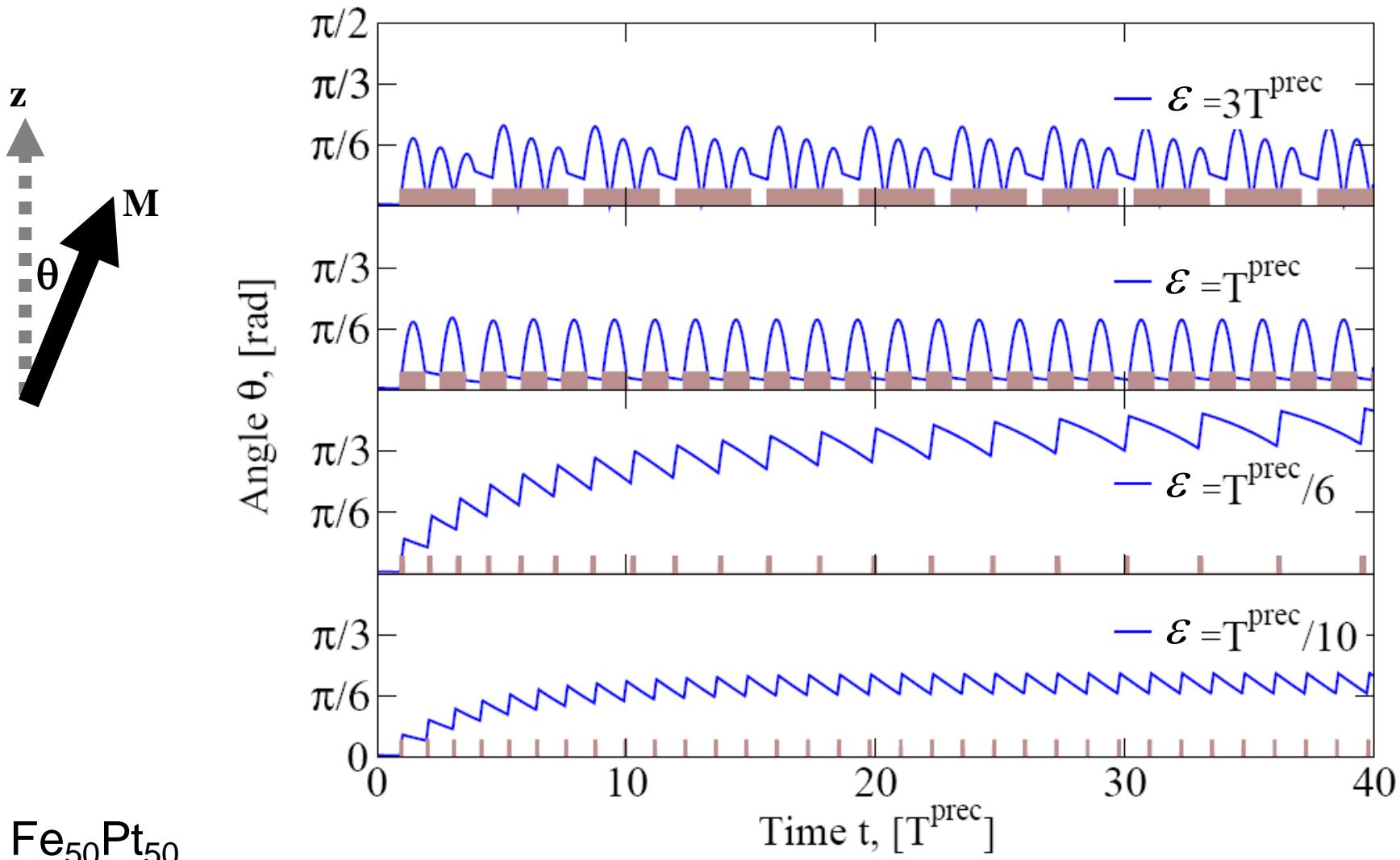
Antoniak *et al.* Phys. Rev. Lett. **97**, 117201 (2006) (exp.)

$\alpha = 0.05$.



ultrafast control

local control fields



Fe₅₀Pt₅₀

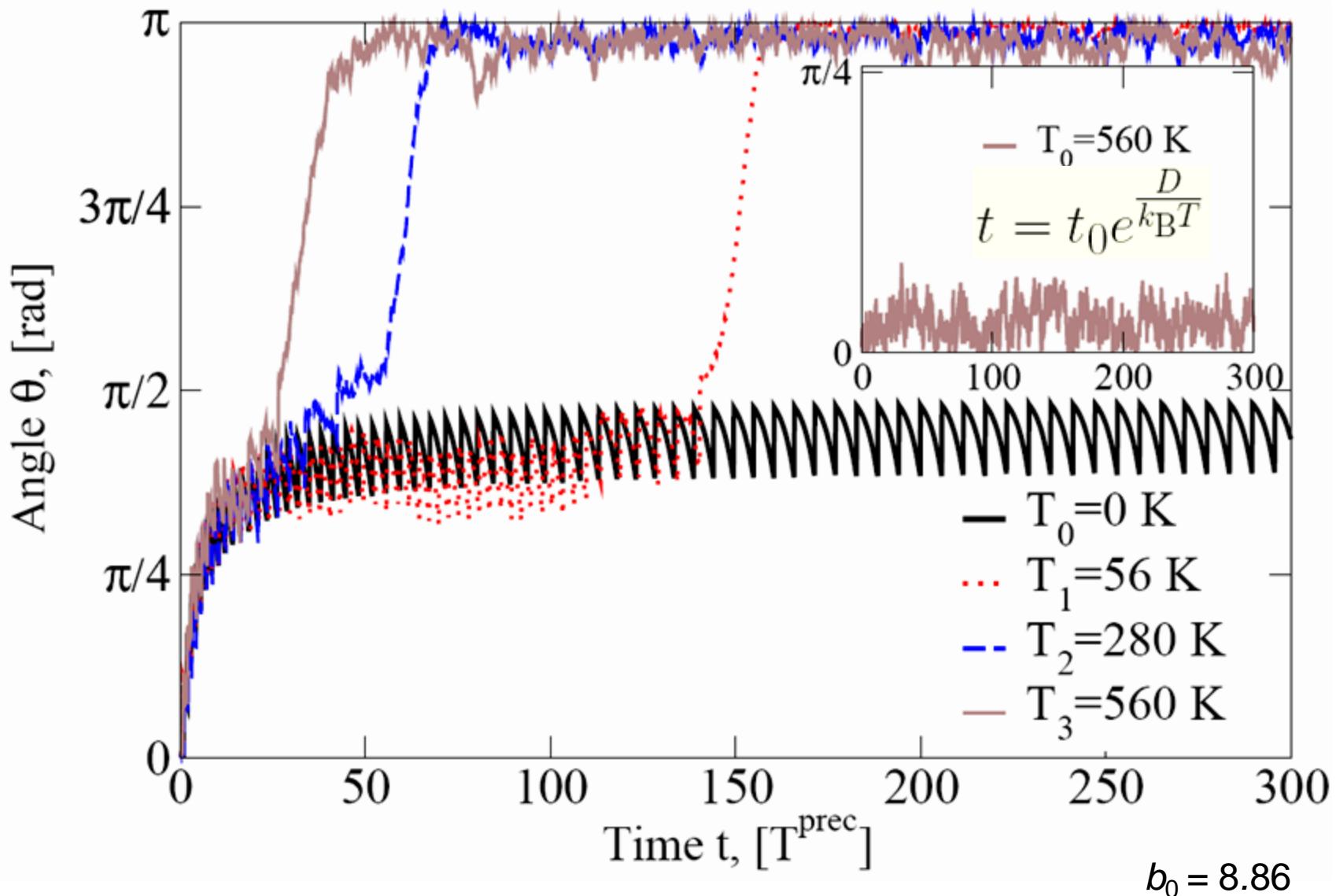
Antoniak *et al.* Phys. Rev. Lett. **97**, 117201 (2006) (exp.)

$b_0 = 0.3, \alpha = 0.05$.



field-assisted thermal switching

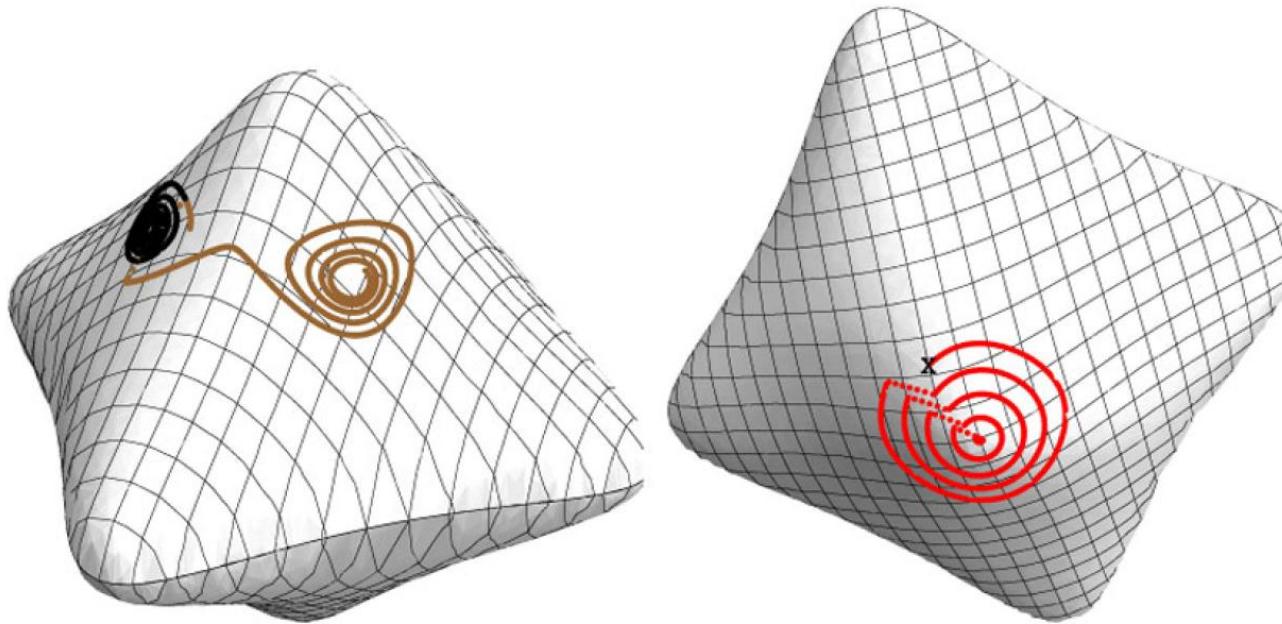
magnetic sensors





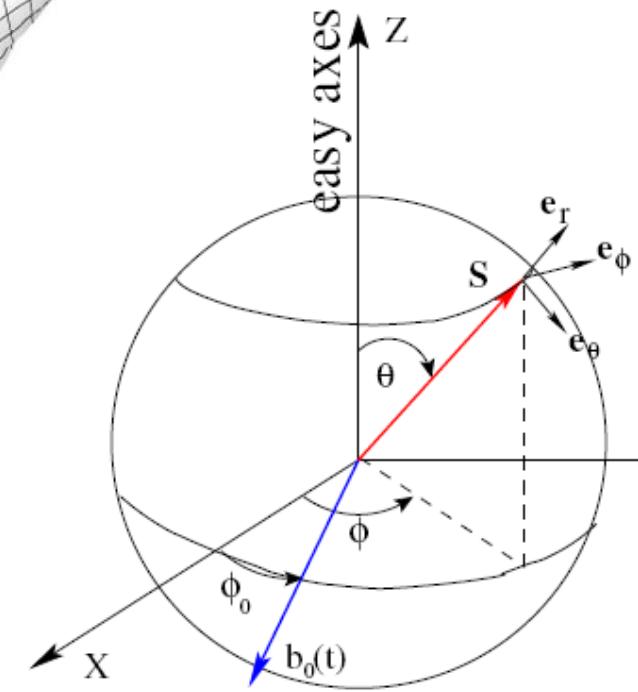
cubic anisotropy

nanomagnets



$\text{Fe}_{70}\text{Pt}_{30}$

experiments by
Antoniak *et al.* *Europhys. Lett.* **70**, 250 (2005)



J. Phys.:Cond.Mat. **20**, 125226 (2008); Phys. Rev. B **78**, 054417 (2008)



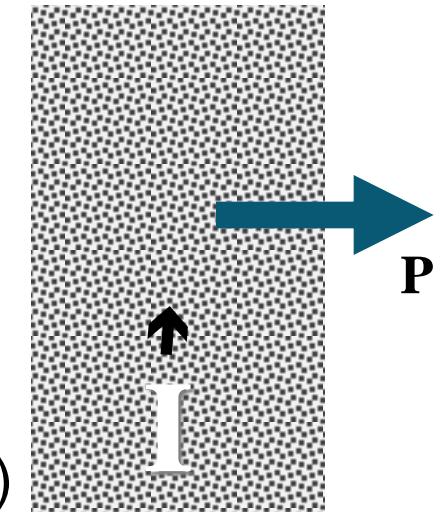
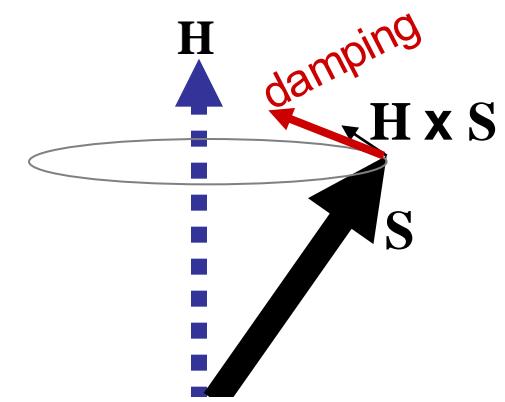
current-induced dynamics

$$\frac{d\vec{L}}{dt} = \vec{T}$$

$$\vec{S} = -\gamma \vec{L} \quad \Rightarrow \quad \frac{d\vec{S}}{dt} = -\gamma \vec{T}$$

$$\frac{d\vec{S}}{dt} = \text{free precession} + \text{damping} + \text{spin current torque}$$

$$= -\gamma \vec{S} \times \vec{H} + \alpha \hat{\vec{S}} \times \dot{\vec{S}} + \gamma \hat{\vec{S}} \times (\hat{\vec{S}} \times \vec{J})$$





summary

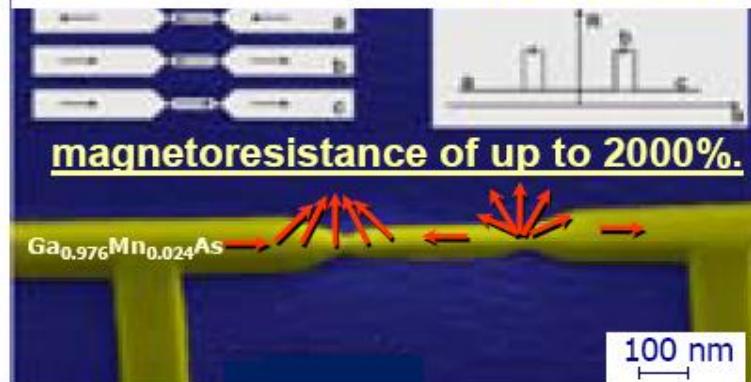
fast pulsed fields (or currents) are needed

- analytical solution for stroboscopic evolution at T=0
- local control scheme for spin switching and freezing
- field-assisted fast thermal switching

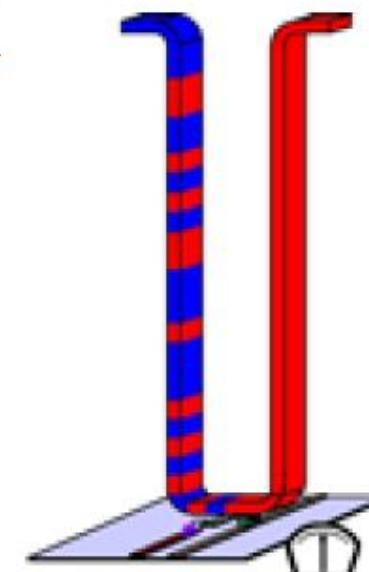


Domain wall dynamics

Rüster et al., Phys. Rev. Lett. 91, 216602 (2003).



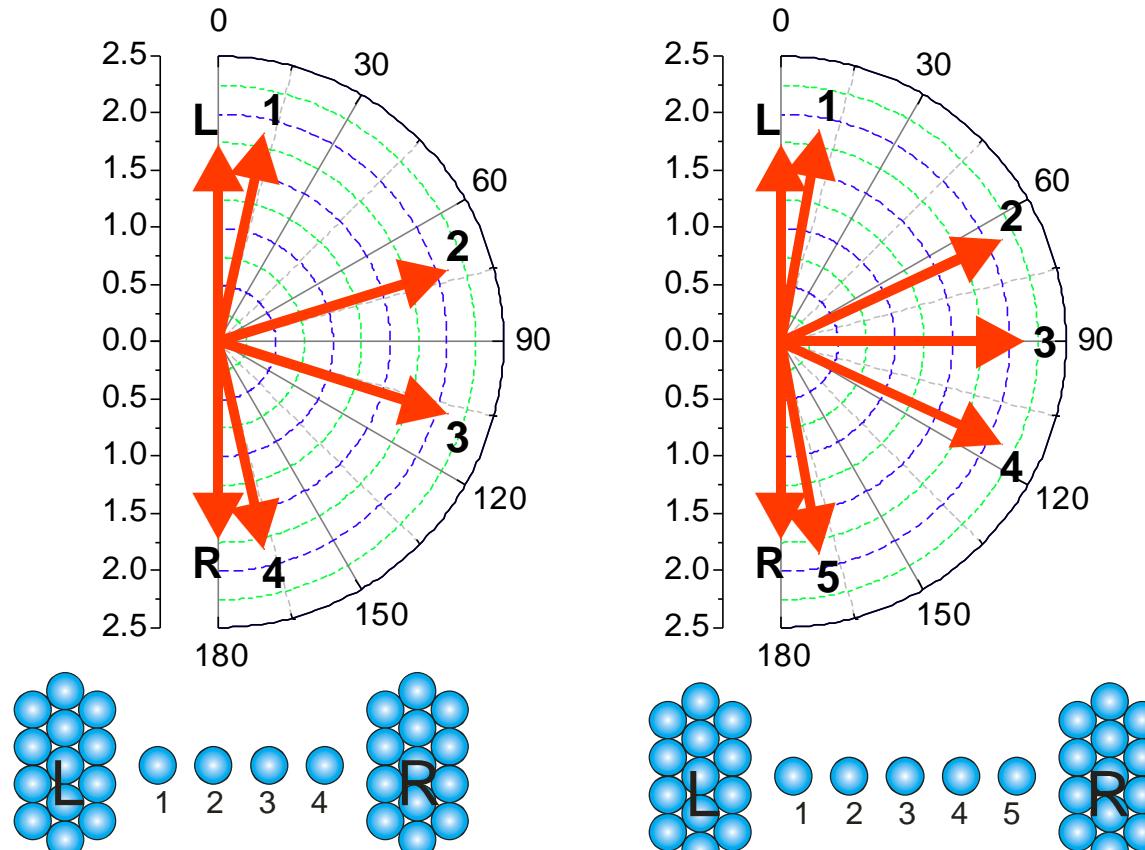
leads switch magnetization
at $\sim 15\text{--}20 \text{ mT}$
island switch $\sim 60\text{--}90 \text{ mT}$



Racetrack memory
Copyright@IBM-Corp.



Domain wall dynamics

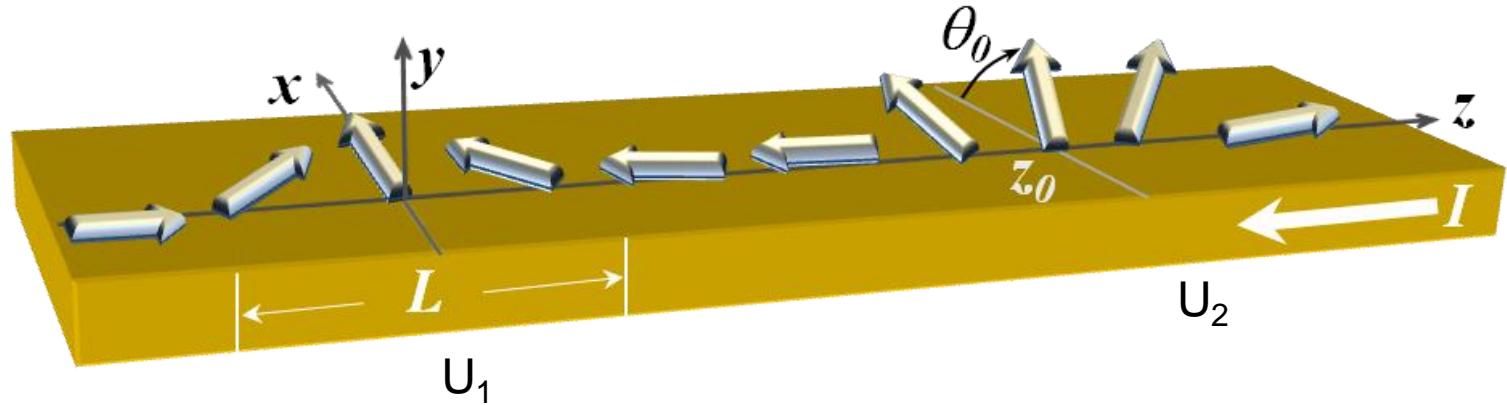


Magnetic structure Co wire

Czerner *et al.*, PRB 77, 104411 (2008)



current induced domain wall interaction



$$\bar{H} = \int dz a_\alpha^\dagger(z) \left[-\frac{\partial_z^2}{2m} \delta_{\alpha\beta} - J \boldsymbol{\sigma}_{\alpha\beta} \cdot \mathbf{M}(z) \right] a_\beta(z)$$

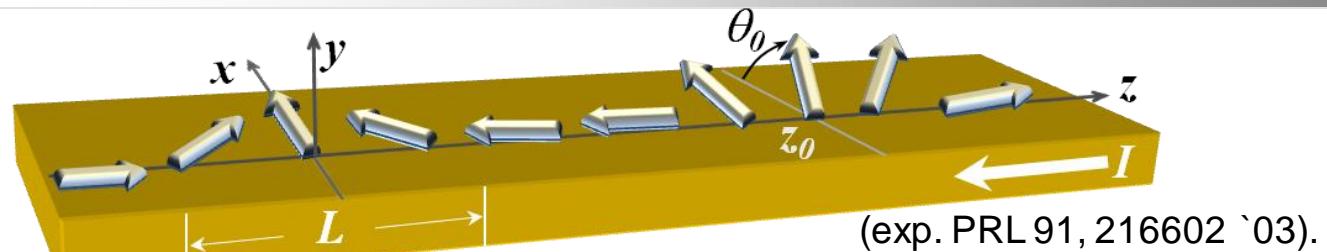
$$\delta\psi_\varepsilon(z) = \int_{-\infty}^{\infty} dz' G_\varepsilon(z, z') U_1(z') \psi^0(z').$$

$$\Delta E_\sigma = \int_{-\infty}^{\infty} dz \delta\psi_{\varepsilon\sigma}^\dagger(z) U_2(z) \delta\psi_{\varepsilon\sigma}(z).$$

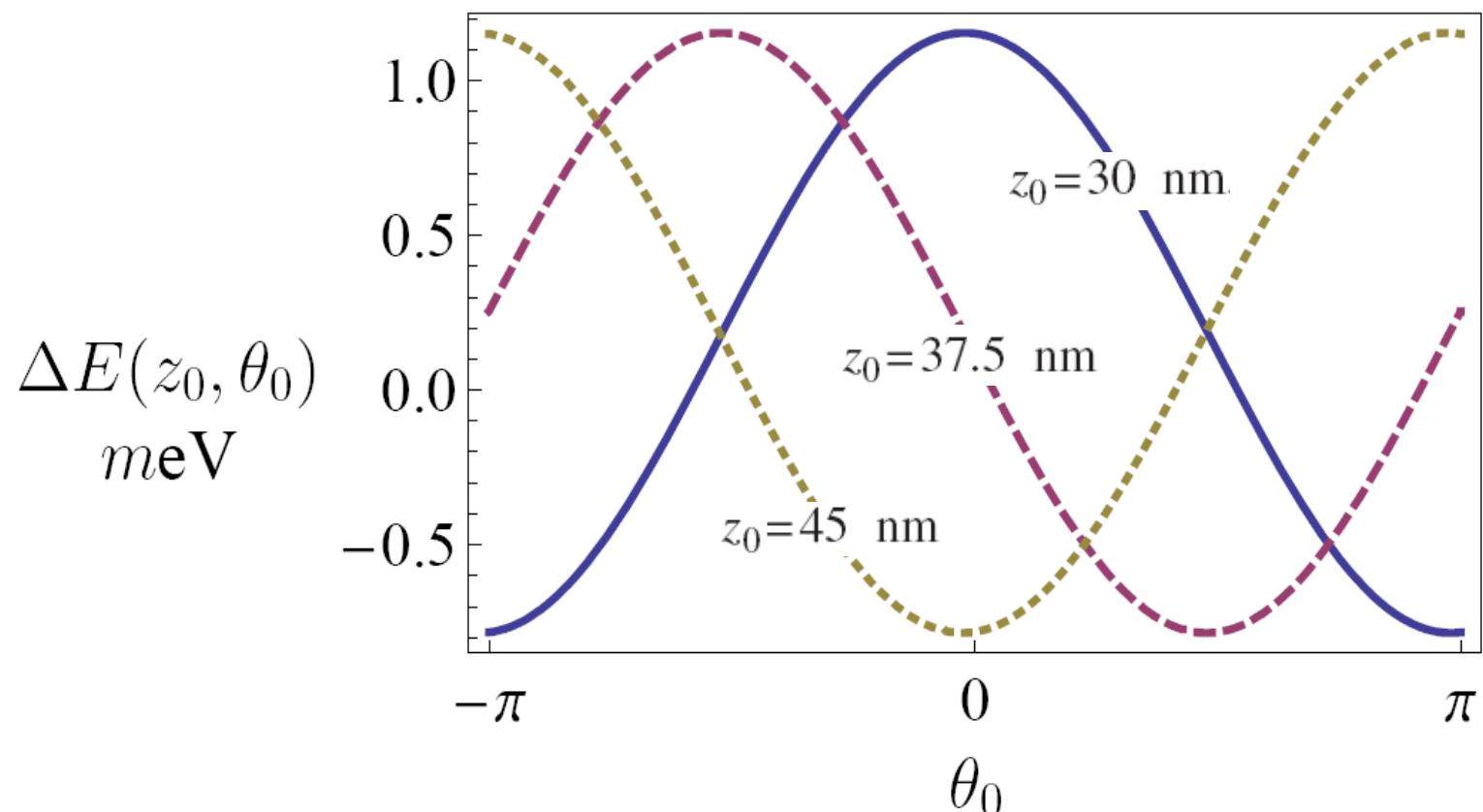
Sedlmayr, Berakdar Eur. Phys. Lett. 88, 57003 (2008)



current induced domain wall interaction



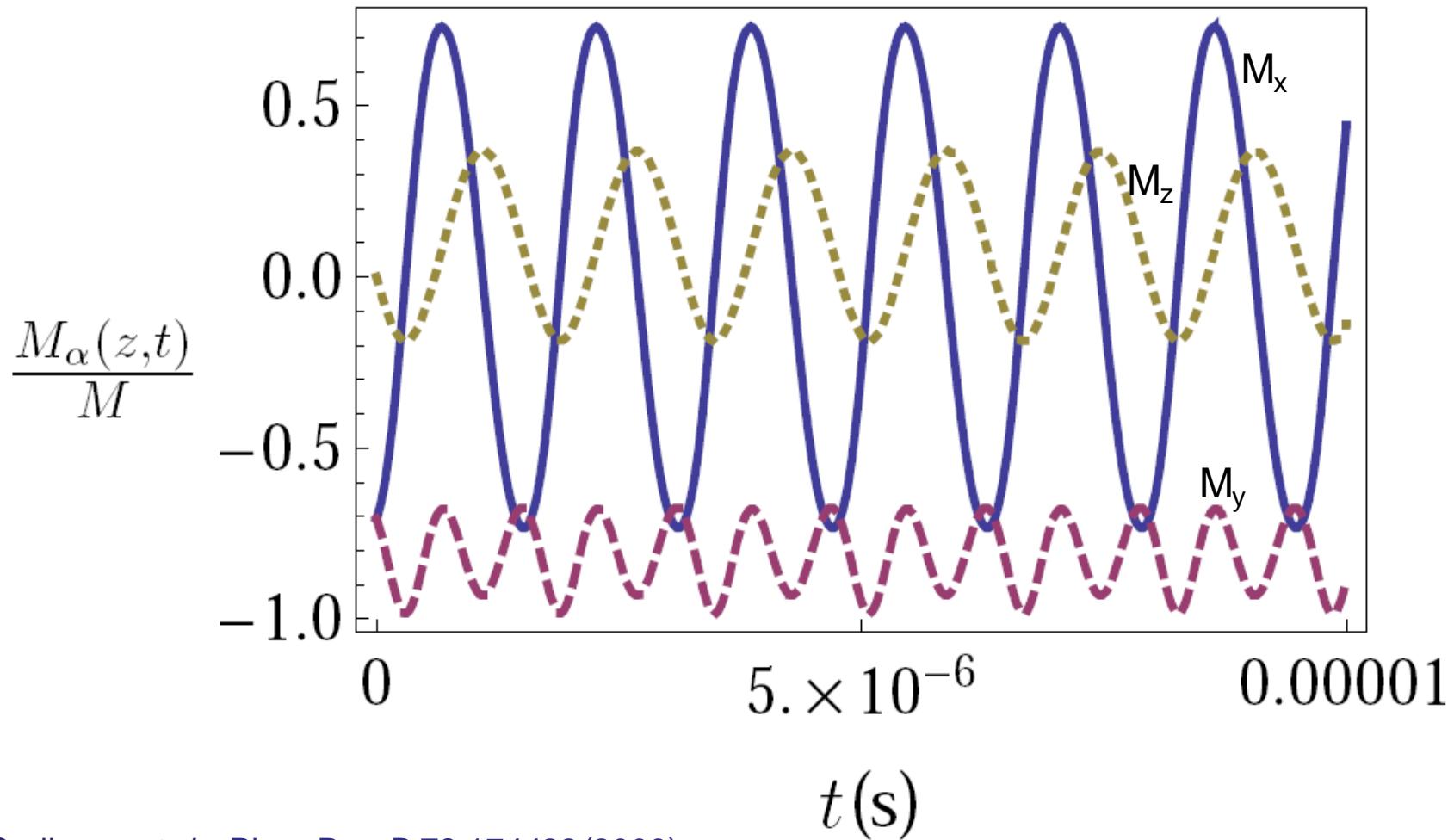
$$L = \lambda_F, JM = 15 \text{ meV}, \varepsilon_F = 83.7 \text{ meV}, \lambda_F = 6 \text{ nm}$$





current induced domain wall interaction

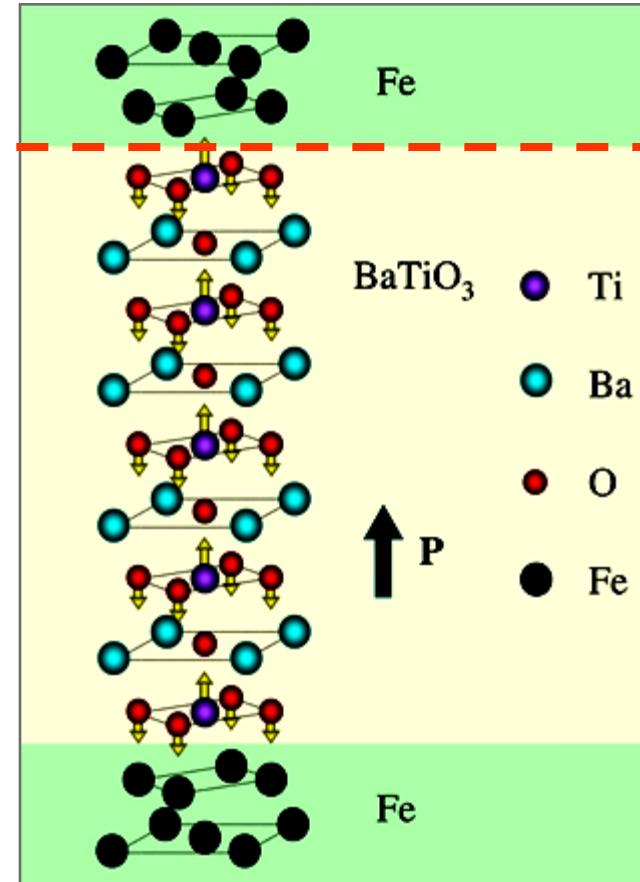
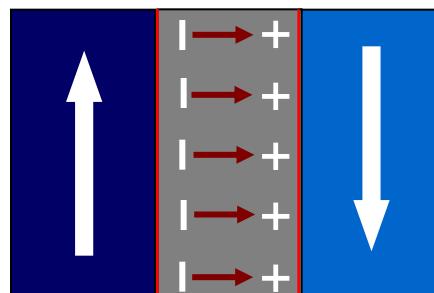
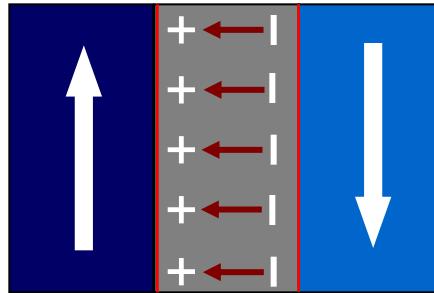
$$\Delta \mathbf{T}(z, z_0, \theta_0) \propto \mathbf{M}(z, z_0, \theta_0) \times \Delta \mathbf{S}(z, z_0, \theta_0)$$



Sedlmayr *et al.*, Phys. Rev. B **79**, 174422 (2009)



Dynamics of multiferroic structure



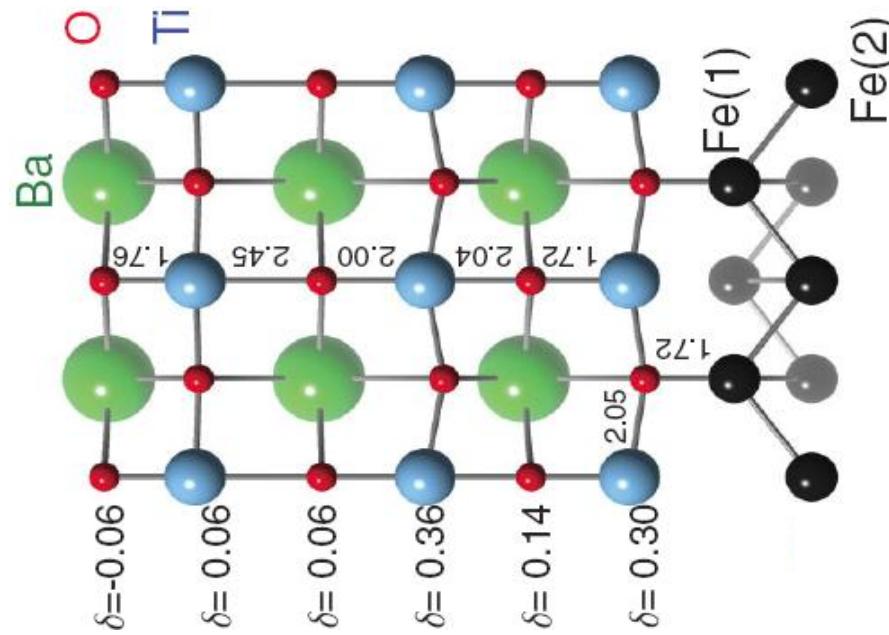
Duan *et al.*, Phys. Rev. Lett. 97, 047201 (2006)
Sahoo *et al.*, Phys. Rev. B 76, 092108 (2007).



Dynamics of multiferroic structure

BaTiO₃/Fe(001)

Meyerheim *et al.*, Phys. Rev. Lett. **106**, 087203 (2011)



Ferro- elektrisch (BTO)

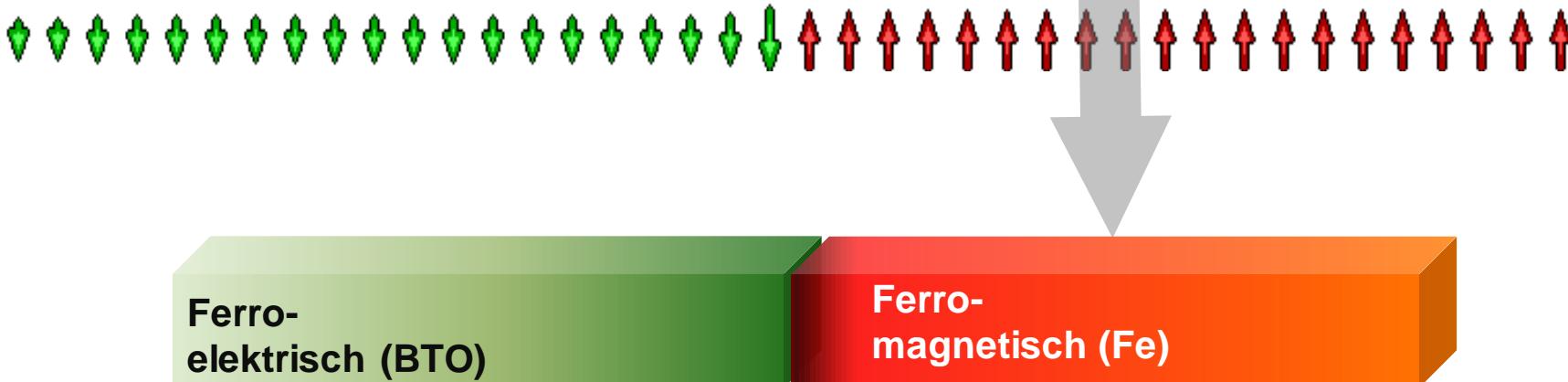
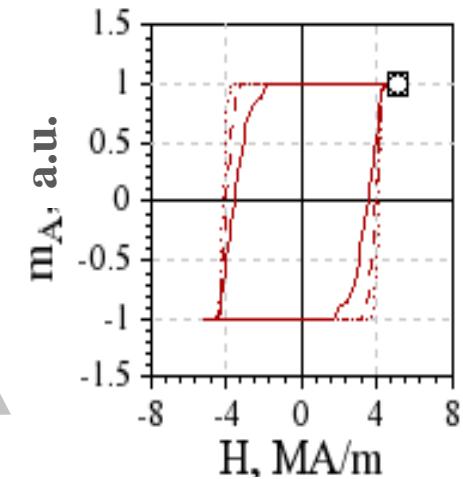
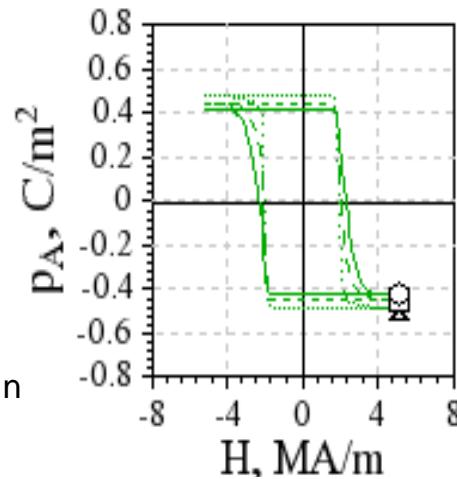
Ferro-magnetisch (Fe)

$$F_\Sigma = F_{\text{FE}} + F_{\text{FM}} + E_c, \quad E_c = \lambda P_S \mu_S \mathbf{p}_0 \cdot \mathbf{S}_0,$$



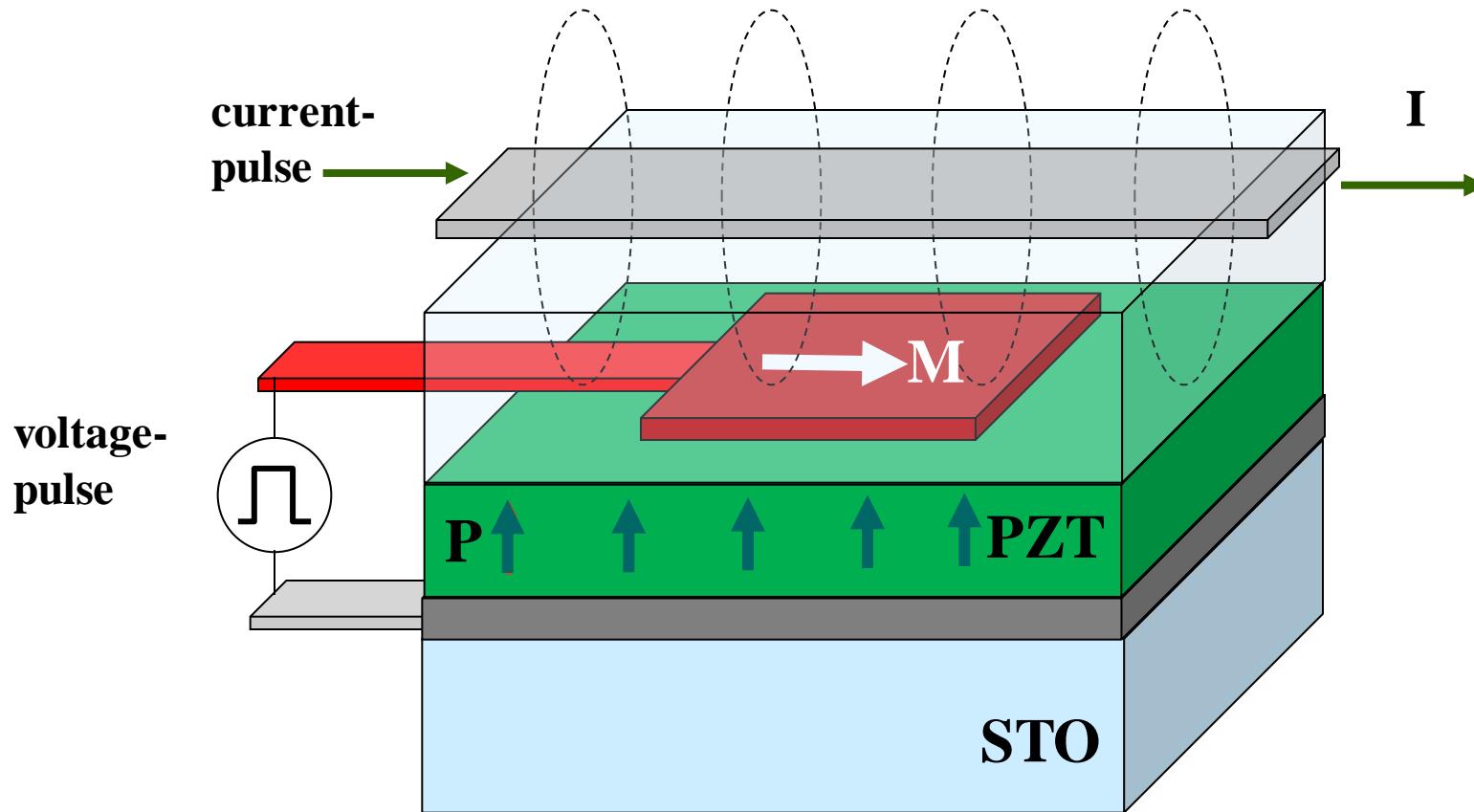
Dynamics of multiferroic structure

Average over
o Total chain
□ Half of the chain
△ Quarter of the chain





Dynamics of multiferroic structure





summary

domain walls in nanowires

current-induced DWs dynamics at low-dimensions

is affected by DW interaction which offers opportunities

as additional control parameter

multiferroics

switching by electric fields via magneto-electric coupling

is more realistic in layered structures