Spin dynamics at finite temperatures

U. Nowak

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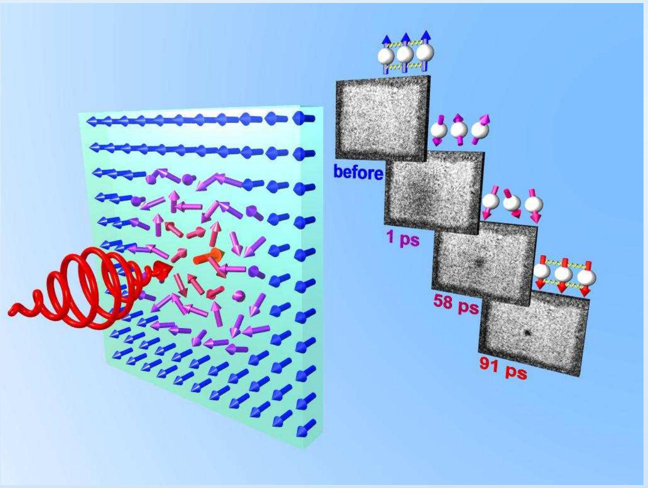
Topics:

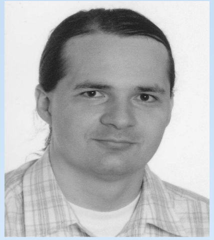
- Motivation
- Theoretical framework for thermal spin dynamics
- Laser induced spin dynamics and opto-magnetic writing
- Domain wall motion and spin Seebeck effect
- Summary



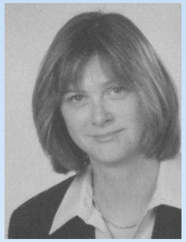
(http://www.ultramagnetron.org)

People involved

In Konstanz:



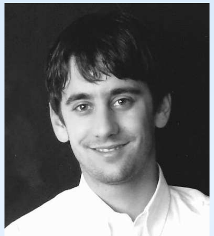
S. Gerlach



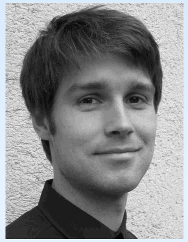
D. Hinzke

N. Kazantseva

F. Schlickeiser



O. Storz



S. Wienholdt

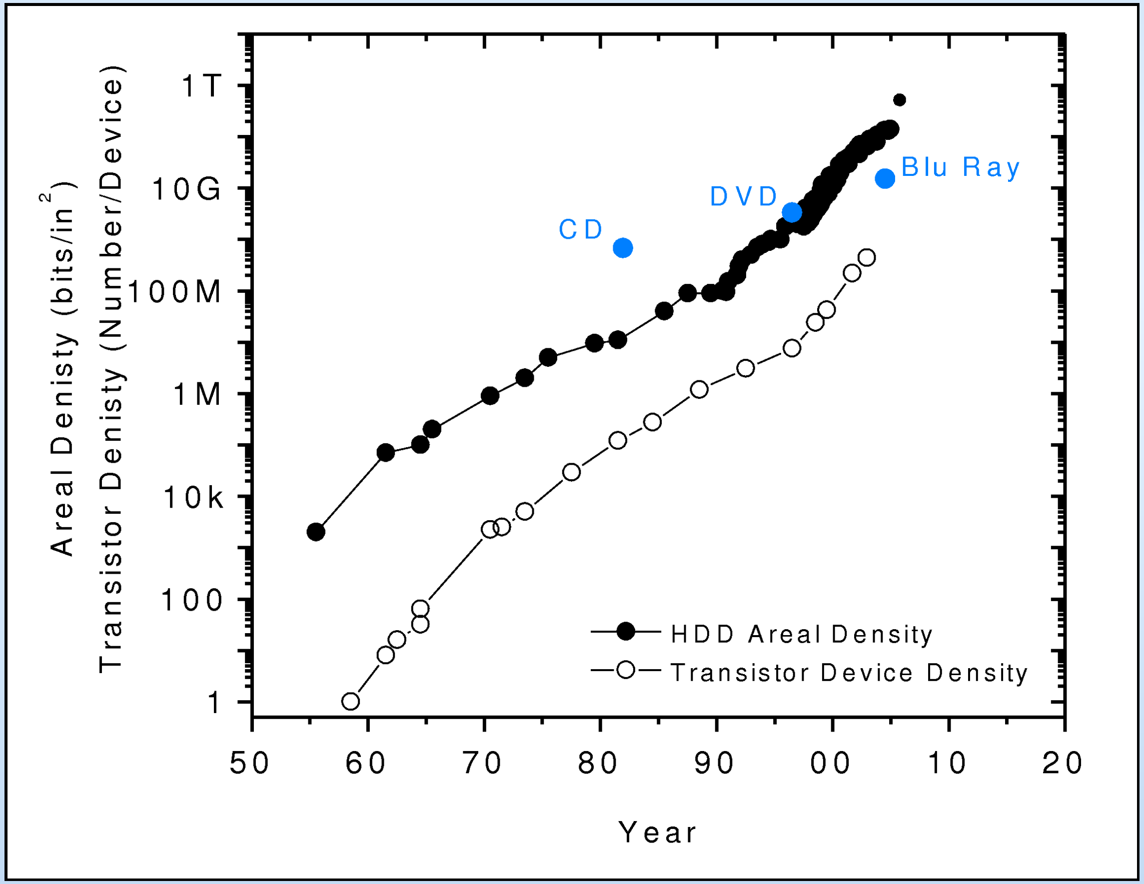
U. Ritzmann

Collaborations:

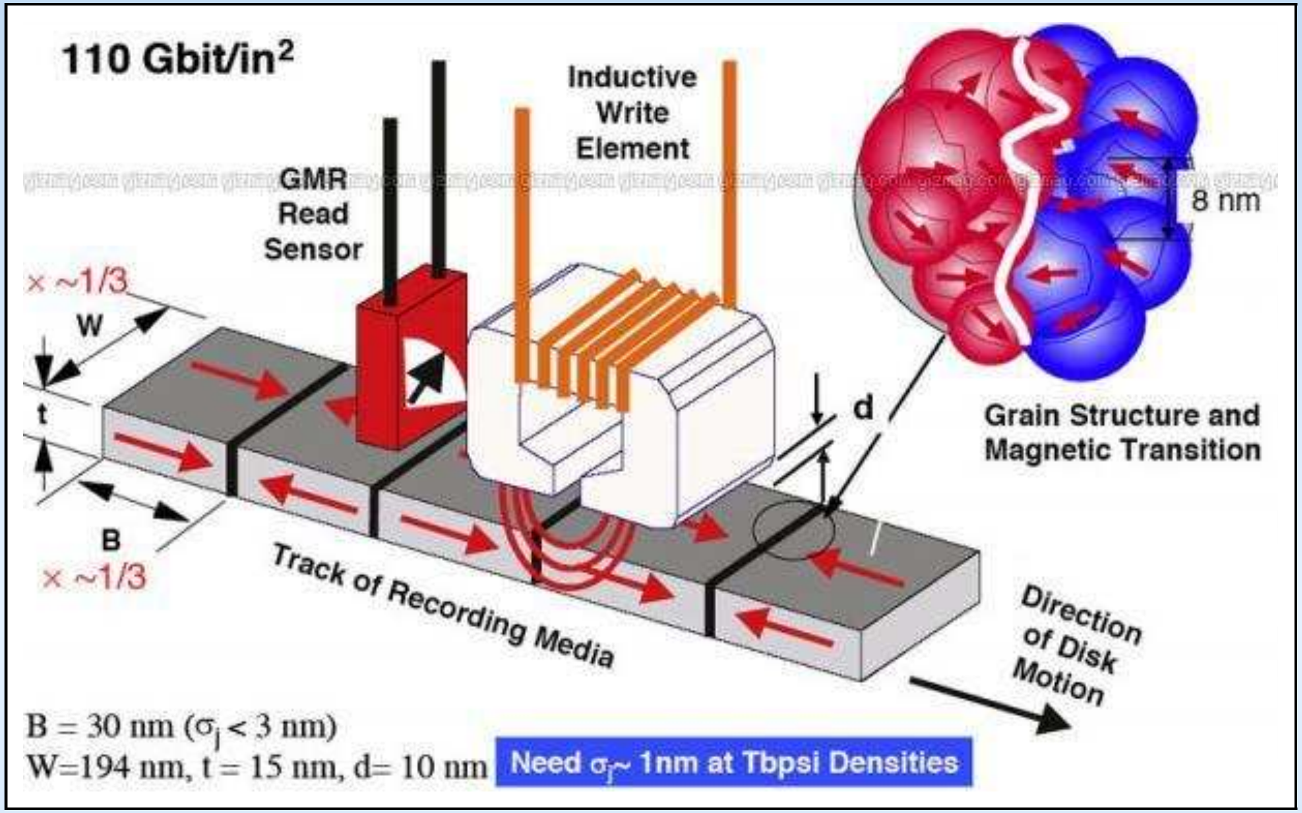
- *T. Ostler, J. Barker, R. Evans, R. W. Chantrell*, University of York, UK
- *U. Atxitia, O. Chubykalo-Fesenko*, CSIC, Madrid, Spain
- *K. Vahaplar, A. Kalashnikova, A. Kimel, A. Kirilyuk, Th. Rasing*, Radboud University Nijmegen, Netherlands

Information storage

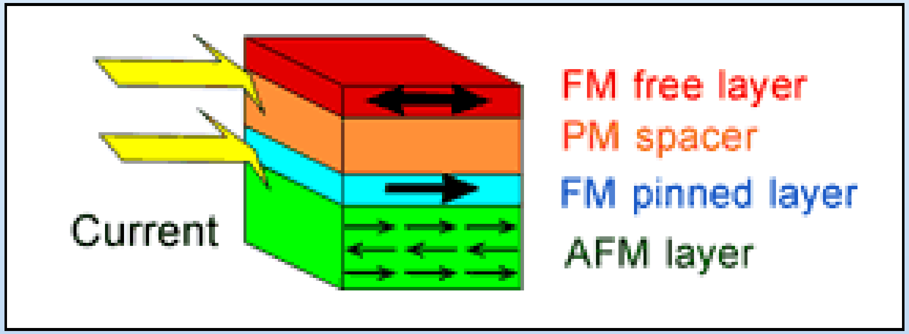
- information storage is a key technology in the modern world
- important criteria for hi-tech storage devices are storage density, speed, stability, and price
- leading storage device is hard disc: 2005 storage density is 245 GBit/in^2 demonstration in Seagate labs



Hard discs: a nano-technology

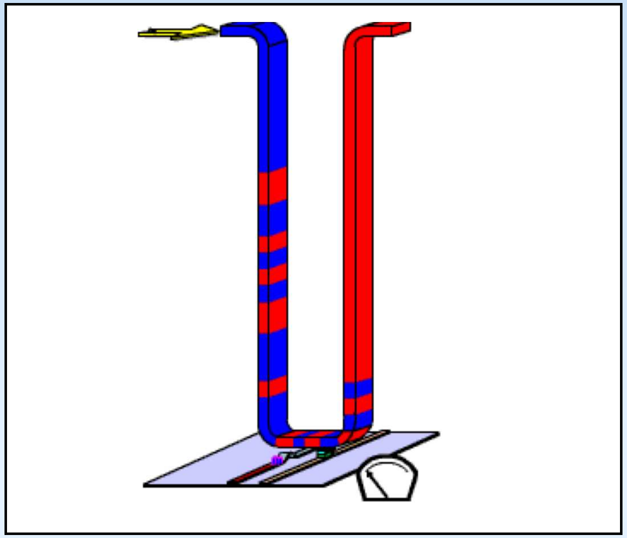


- bit dimension: $\ll 30 \times 200$nm
- read/write head flies < 10nm high
- data rate > 1Gbit/sec
- time scale of writing procedure < 1ns



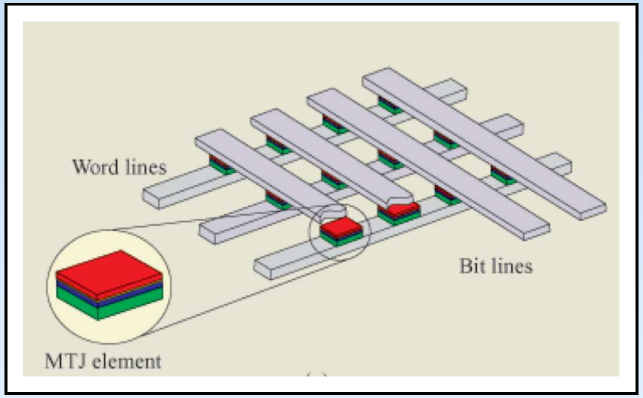
Ideas for future storage devices

Racetrack memory



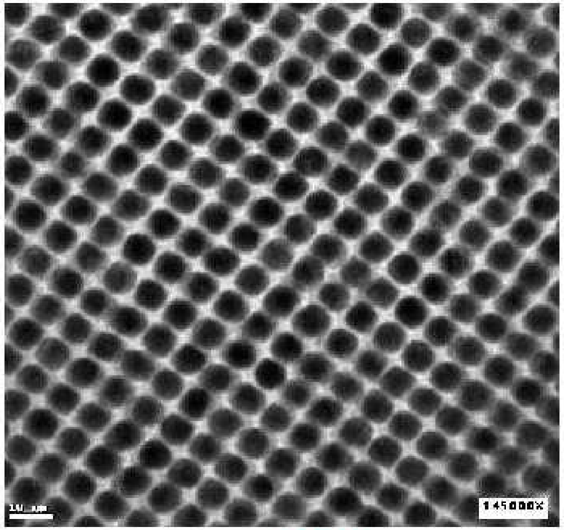
- information stored in domain walls
- domain wall pattern is moved with a current (spin torque effect)

(TA-) MRAM



- information stored in array of magnetic tunnel junctions
- some concepts envolve spin torque switching and thermal acivation

Bit patterned media



•6.3+/-0.3 nm FePt particles

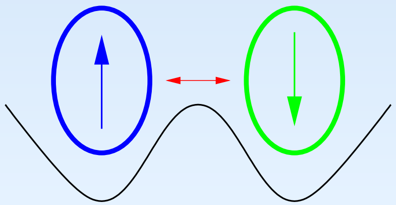
$\sigma_{Diameter} \cong 0.05$

S. Sun, Ch. Murray, D. Weller, L. Folks, A. Moser, Science 287, 1989 (2000).

- improved hard disc
- information stored in single magnetic nanoparticles

Magnetic data storage: ultimate limits

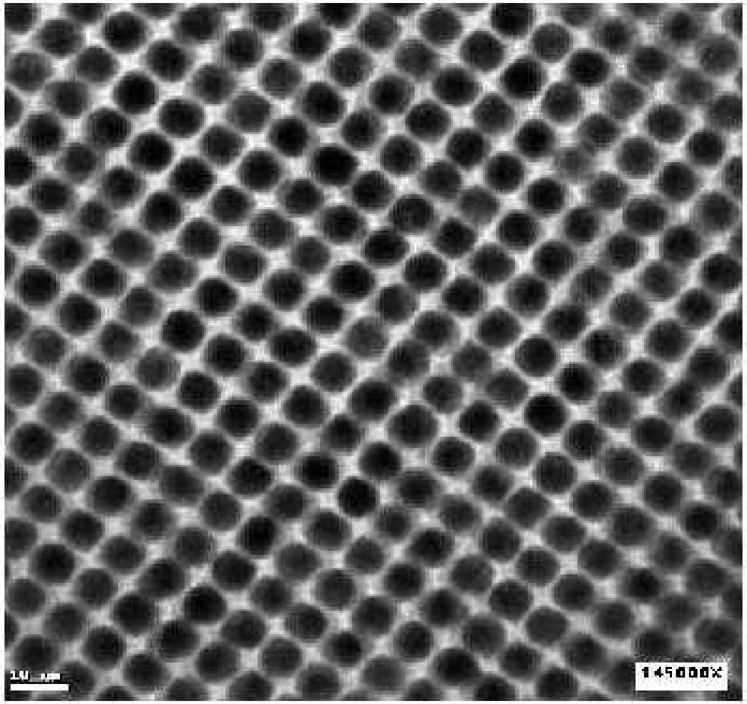
- idea: self-organised magnetic array of nanoparticles as storage media
- problems:
  - super-paramagnetic limit:



$$\Delta E \approx K_1 V$$

small volume $V \longrightarrow$ need materials with high anisotropy constant K_1

  - large $K_1 \longrightarrow$ coercivity is also large (e. g. ≈ 18T for FePt)



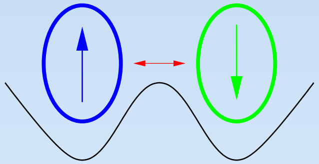
•6.3+/-0.3 nm FePt particles

$\sigma_{Diameter} \cong 0.05$

S. Sun, Ch. Murray, D. Weller, L. Folks, A. Moser, Science 287, 1989 (2000).

Heat assisted magnetic recording

- super-paramagnetic limit:



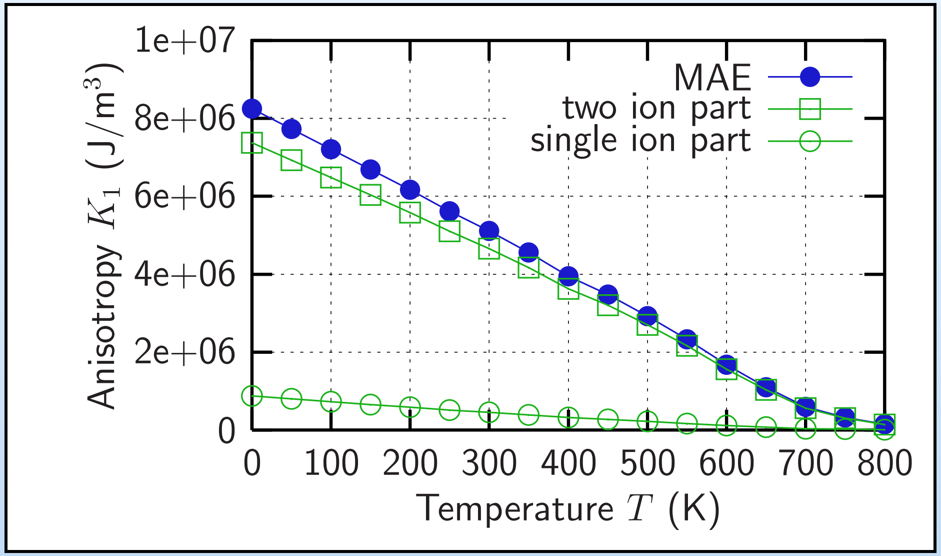
$$\Delta E \approx K_1 V \ll k_\mathrm{B} T$$

for nanoparticles in the nanometre regime:

⇨ materials with high anisotropy constant K_1

⇨ coercivity is also large (e. g. ≈ 18T for FePt)

- HAMR:



(*Mryasov et al., Europhys. Lett.* **69**, *805 (2005)*)

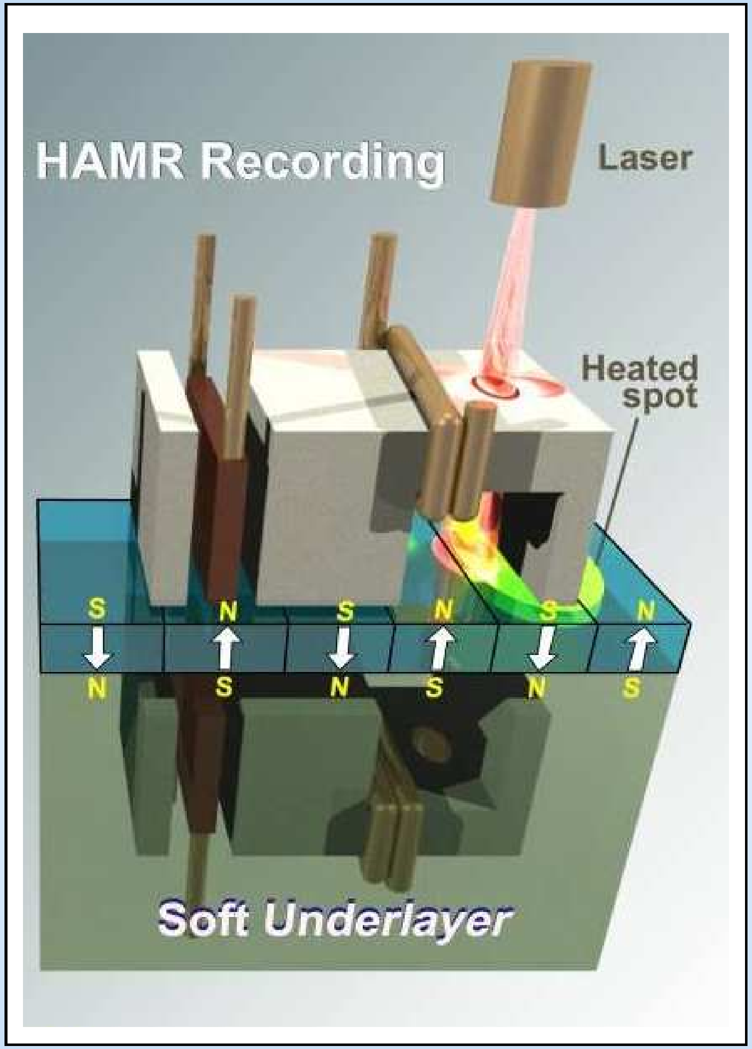


image by Mark Lutwyche, Seagate

Pump probe experiments and HAMR

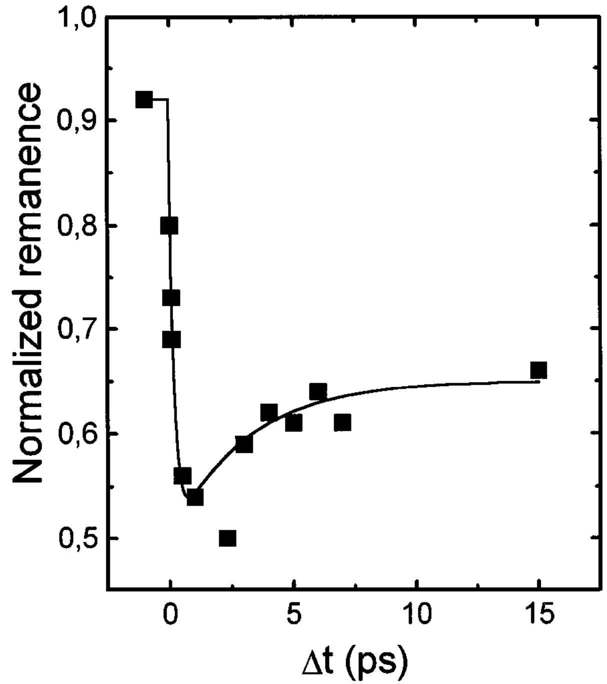


FIG. 2. Transient remanent longitudinal MOKE signal of a Ni(20 nm)/MgF_2(100 nm) film for 7 mJ cm^{-2} pump fluence. The signal is normalized to the signal measured in the absence of pump beam. The line is a guide to the eye.

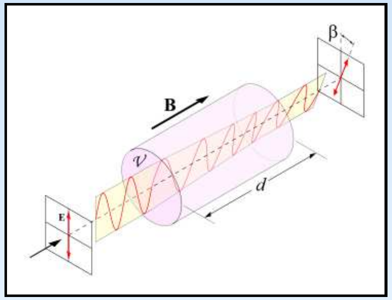
- magnetisation can break down and recover on ps time scale

(*Beaurepaire, Merle, Daunois, Bigot, Phys. Rev. Lett.* **76**, *4250 (1996)*)

⇨ search for new heat-assisted magnetic recording schemes

Opto-magnetic writing

- writing information without applying an external magnetic field
- uses circularly polarised light
- field pulse due to inverse Faraday effect: $\mathbf{B} \sim \mathbf{E} \times \mathbf{E}^*$



(http://en.wikipedia.org/wiki/Faraday_effect)

- time scale: some picoseconds
- writing procedure with combined field and temperature pulse

(*Kimel et al. Phys. Rev. Lett.* **99**, *047601 (2007), Nature* **435**, *655 (2005)*)

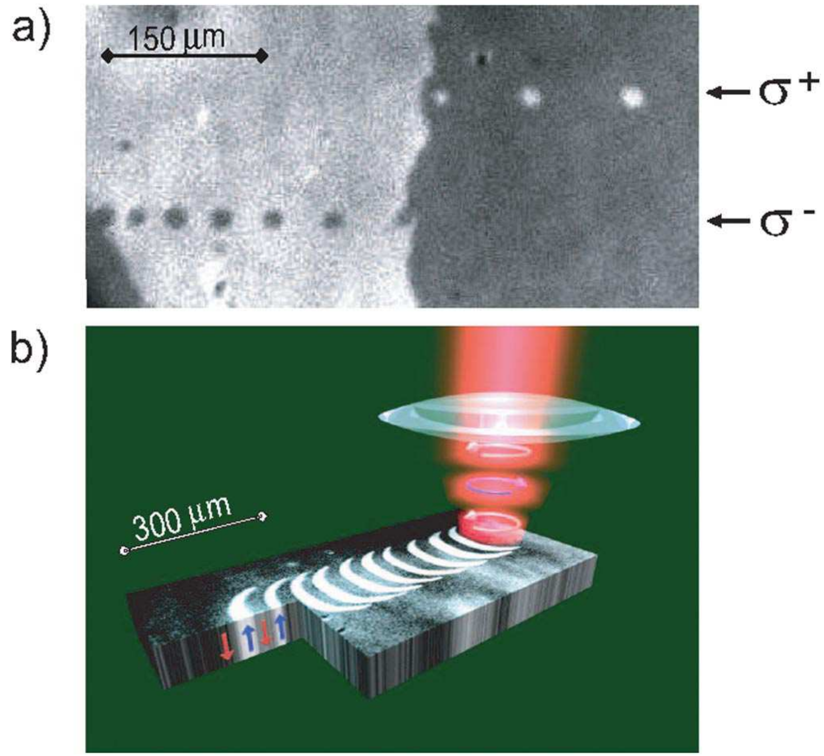


FIG. 4 (color). All-optical magnetic recording by femtosecond laser pulses. (a) The effect of single 40-fs circular polarized laser pulses on the magnetic domains in $Gd_{22}Fe_{74.6}Co_{3.4}$. The domain pattern was obtained by sweeping at high-speed ($\sim$50 mm/s) circularly polarized beams across the surface so that every single laser pulse landed at a different spot. The laser fluence was about 2.9 mJ/cm^2. The small size variation of the written domains is caused by the pulse-to-pulse fluctuation of the laser intensity.

Modeling of light-induced reversal mechanisms

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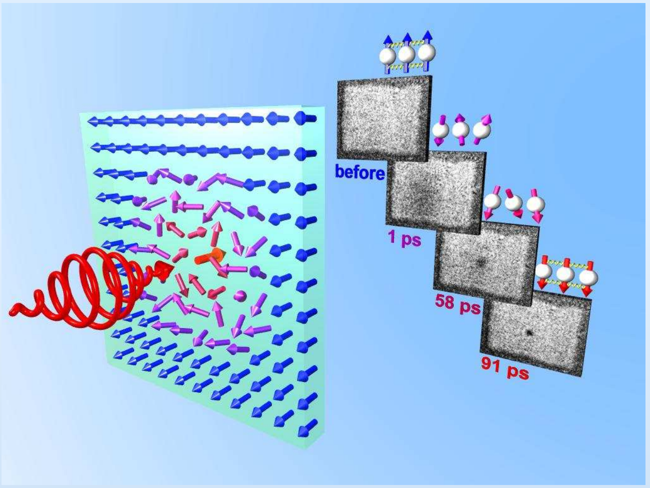


(http://www.ultramagnetron.org)

Goals and concepts

- **goals:** understanding of spin structures and dynamics, involving
  - time scales from femtoseconds to years
  - length scales from electronic to sample size
  - temperatures from zero up to the Curie temperature
- **concepts:** multi-scale modelling

electronic structure:

- e.g. SDFT theory
- periodic structures, layers or small clusters
- ☺ many material properties from first principles
- ☹ mainly ground state calculations

⇔

atomic spin model:

- e.g. stochastic Landau - Lifshitz equation, Monte Carlo methods
- up to 10^7 spins
- ☺ finite temperatures, dynamic properties
- ☹ some phenomenological modelling needed

⇔

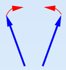
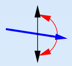
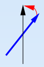
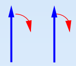
continuum theory:

- Landau-Lifshitz-Bloch equation of motion
- up to some μm^3
- ☺ non-equilibrium thermodynamics for realistic sample size
- ☹ more phenomenological modelling needed

Atomic spin model

- model of localised spins $\underline{S}_i = \underline{\mu}_i / \mu_s$ on a given lattice

$$\mathcal{H} = -J \sum_{\langle ij \rangle} \underline{S}_i \cdot \underline{S}_j - d_z \sum_i (S_i^z)^2 - \mu_s \underline{B} \cdot \sum_i \underline{S}_i - w \sum_{i<j} \frac{3(\underline{S}_i \cdot \underline{e}_{ij})(\underline{e}_{ij} \cdot \underline{S}_j) - \underline{S}_i \cdot \underline{S}_j}{r_{ij}^3}$$

exchange  anisotropy  external field  magneto-static 

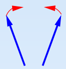
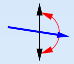
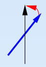
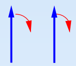
- parameters (Heisenberg exchange, anisotropy constants, atomic magnetic moment):
  - phenomenological: fit experimental values
  - derived from first principles (*Mryasov et al., Europhys. Lett.* **69**, *805 (2005)*)

    (*Szunyogh et al., Phys. Rev. B* **79**, *020403(R) (2009)*)
- dipolar interaction with $w = \mu_0 \mu_s^2 / 4\pi$ leads to:
  - shape anisotropy
  - non-trivial domain configurations
  - large numerical effort

Atomic spin model

- model of localised spins $\underline{S}_i = \underline{\mu}_i / \mu_s$ on a given lattice

$$\mathcal{H} = -J \sum_{\langle ij \rangle} \underline{S}_i \cdot \underline{S}_j - d_z \sum_i (S_i^z)^2 - \mu_s \underline{B} \cdot \sum_i \underline{S}_i - w \sum_{i<j} \frac{3(\underline{S}_i \cdot \underline{e}_{ij})(\underline{e}_{ij} \cdot \underline{S}_j) - \underline{S}_i \cdot \underline{S}_j}{r_{ij}^3}$$

exchange  anisotropy  external field  magneto-static 

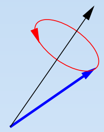
- aims:
  - ground states $\longrightarrow$ energy minimisation
  - zero temperature dynamics $\longrightarrow$ Landau-Lifshitz-Gilbert equation of motion
  - equilibrium thermodynamics $\longrightarrow$ Monte Carlo, mean-field, spin wave theory, random phase approximation, Langevin dynamics

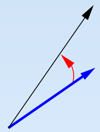
☞ **non-equilibrium thermodynamics** $\longrightarrow$
  - Langevin dynamics *(Brown, Phys. Rev.* **130**, *1677 (1963))*
  - time-quantified Monte Carlo *(Nowak et al. Phys. Rev. Lett.* **84**, *163 (2000))*

Stochastic Landau-Lifshitz-Gilbert equation

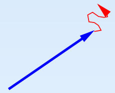
- **Landau-Lifshitz-Gilbert equation** with thermal noise:

$$\dot{\underline{S}}_i = -\frac{\gamma}{(1+\alpha^2)\mu_s}\,\underline{S}_i \times \underline{H}_i(t) - \frac{\alpha\gamma}{(1+\alpha^2)\mu_s}\,\underline{S}_i \times \left(\underline{S}_i \times \underline{H}_i(t)\right)$$

precession  $t_{\text{prec}} \approx 1/\gamma B$

relaxation  $t_{\text{relax}} \approx t_{\text{prec}}/\alpha$

with $\underline{H}_i(t) = -\frac{\partial \mathcal{H}}{\partial \underline{S}_i} + \underline{\zeta}_i(t)$

fluctuations 

and $\langle \underline{\zeta}_i(t) \rangle = 0, \quad \langle \zeta_{i\eta}(0)\zeta_{j\theta}(t) \rangle = \delta_{ij}\delta_{\eta\theta}\delta(t) 2\alpha k_{\text{B}} T \mu_s/\gamma.$

α: describes coupling to the heat bath ($\longrightarrow$ damping constant)

- minimal time scales:
  - for the demagnetisation

$$\tau_{\text{dis}} \approx \frac{\mu_s}{2\alpha\gamma k_B T} \approx 300\text{fs}$$

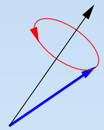
  - for the reordering process

$$\tau_{\text{re}} \approx \frac{\mu_s}{\alpha\gamma J} \approx 1\text{ps}$$

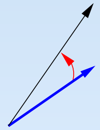
Stochastic Landau-Lifshitz-Gilbert equation

- **Landau-Lifshitz-Gilbert equation** with thermal noise:

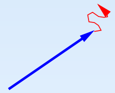
$$\underline{\dot{S}_i} = -\frac{\gamma}{(1+\alpha^2)\mu_s}\,\underline{S_i} \times \underline{H_i}(t) \qquad \text{precession} \qquad t_{\text{prec}} \approx 1/\gamma B$$



$$-\frac{\alpha\gamma}{(1+\alpha^2)\mu_s}\,\underline{S_i} \times \left(\underline{S_i} \times \underline{H_i}(t)\right) \qquad \text{relaxation} \qquad t_{\text{relax}} \approx t_{\text{prec}}/\alpha$$



with $\underline{H_i}(t) = -\frac{\partial \mathcal{H}}{\partial \underline{S_i}} + \underline{\zeta_i}(t)$ — fluctuations



and $\langle \underline{\zeta}_i(t) \rangle = 0, \quad \langle \zeta_{i\eta}(0)\zeta_{j\theta}(t) \rangle = \delta_{ij}\delta_{\eta\theta}\delta(t) 2\alpha k_{\mathrm{B}} T \mu_s/\gamma.$

α: describes coupling to the heat bath ($\longrightarrow$ damping constant)

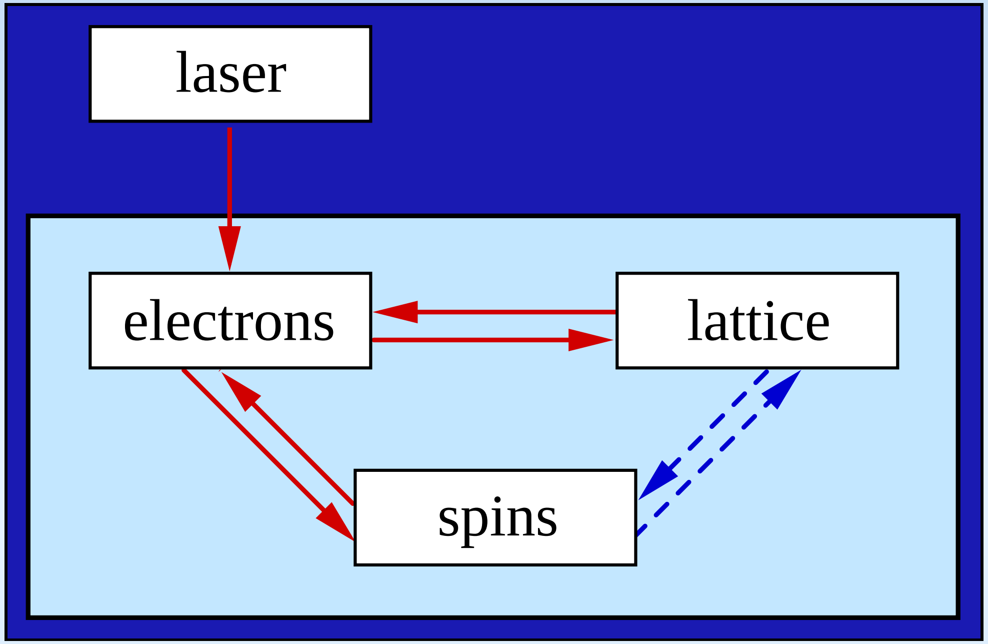
- Langevin dynamics simulation:

  numerical integration of the LLG equation

  (see e. g. *Nowak, Ann. Rev. of Comp. Phys.* **9**, *105 (2001))*

  - Heun-method $\Rightarrow$ Stratonovich integral
  - simulation of 10^7 spins possible with FFT methods $(\approx 40\text{nm})^3$

Simulating the magnetic response to the heat pulse



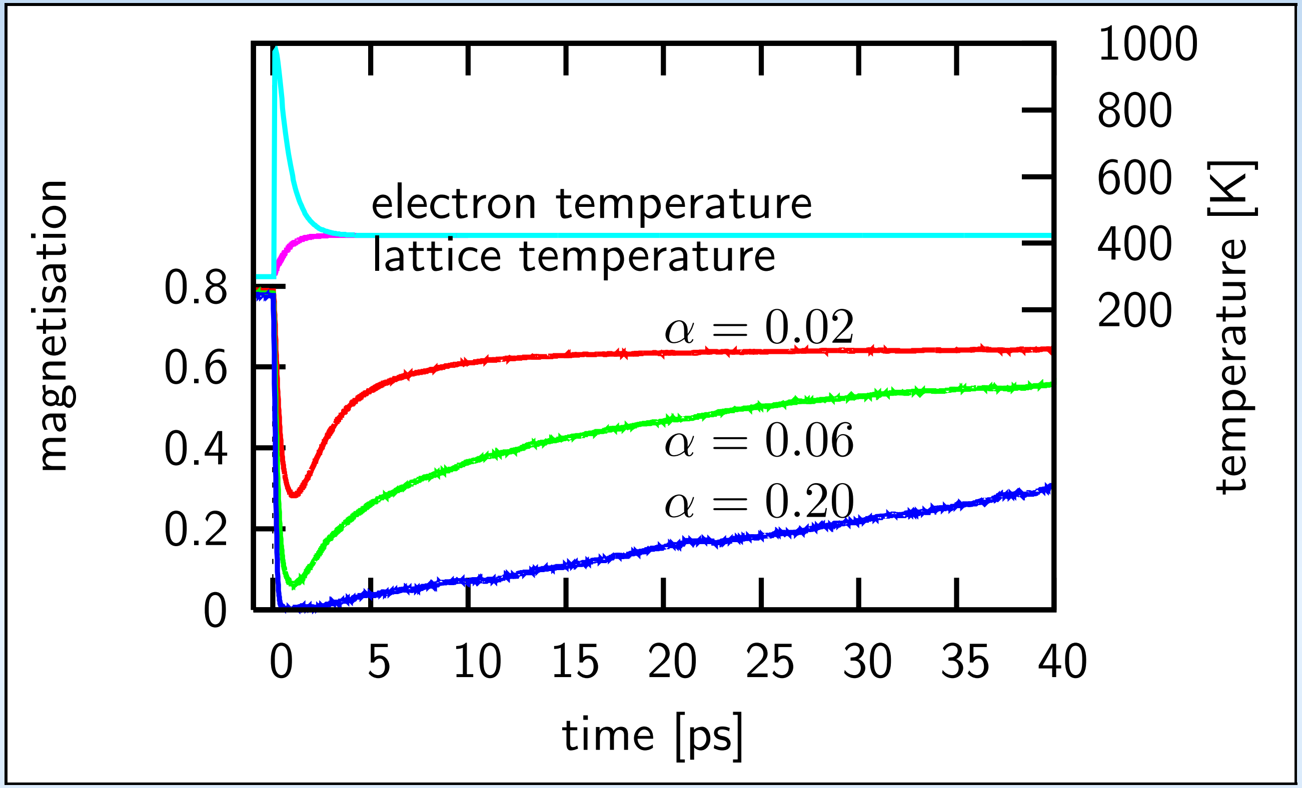
- two temperature model: (*Kaganov, Lifshitz, Tanatarov, Sov. Phys. JETP* **4**, *173 (1957)*)

$$\text{electrons:} \quad C_e \frac{\mathrm{d}T_e}{\mathrm{d}t} = -G_{el}(T_e - T_l) + P(t)$$

$$\text{lattice:} \quad C_l \frac{\mathrm{d}T_l}{\mathrm{d}t} = G_{el}(T_e - T_l)$$

- perform thermodynamic spin model simulations with $T_e(t)$ as temperature of the heat bath

Magnetisation dynamics for different α



(Kazantseva et al., Europhys. Lett. **90**, *247201 (2003))*

- electron (and lattice) temperature from two-temperature model, material parameters for Ni, realistic assumptions for laser power and duration

(Rieh, Dürr, Eberhardt, Phys. Rev. Lett. **81**, *27004 (2008))*

- Langevin dynamics simulations for model with 80^3 spins and periodic boundary conditions

Magnetic states after 19ps

- $\alpha = 0.02$: faster recovery due to non-zero initial magnetisation
- $\alpha = 0.2$: slow recovery due to zero initial magnetisation

Micromagnetic continuum theory

- description on a length scale $\gg$ lattice constant a:

  magnetisation assumed as smooth vector field $\underline{S}(\underline{r})$ with constant length

$$E = \frac{J}{2a}\int_V (\nabla \underline{S})^2 \, \mathrm{d}V - \frac{d_z}{a^3}\int_V S_z^2 \, \mathrm{d}V - M_\mathrm{s}\int_V \underline{S}\cdot\underline{B}\, \mathrm{d}V - \frac{\mu_0}{2}\int_V \underline{S}\cdot\underline{H}_\mathrm{s}\, \mathrm{d}V$$

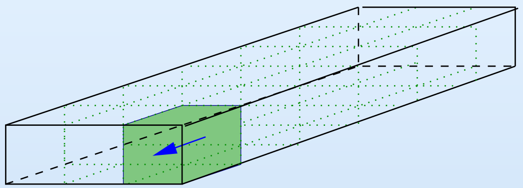
exchange — anisotropy — external field — magneto-static

- Landau-Lifshitz-Gilbert equation is standard equation of motion

- for a micromagnetic theory at elevated temperatures:

  ☹ LLG equation with Langevin dynamics will fail:

  thermally excited spin wave spectrum is limited by cell size



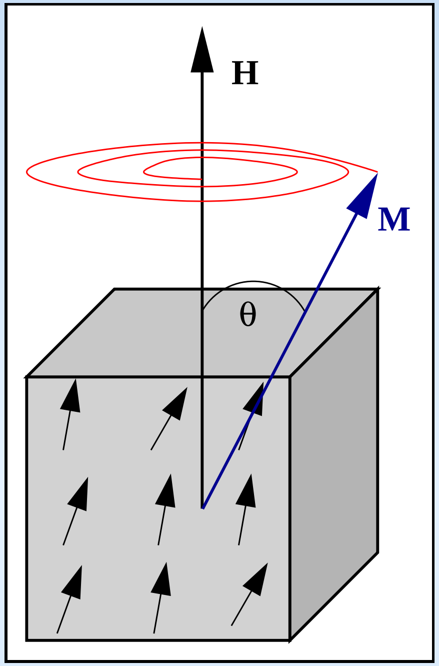
  ☺ alternative approach must include thermodynamics of the cell (macro-spin) itself

  ⇨ Landau-Lifshitz-Bloch equation *(Garanin, Phys. Rev. B* ***55,*** *3050 (1997))*

(Garanin and Chubykalo-Fesenko, Phys. Rev. B ***70****, 212409 (2004))*

Magnetisation relaxation close to Curie temperature

Consider relaxation of magnetisation which is initially tilted by an angle θ with respect to an external field



- at zero temperature:

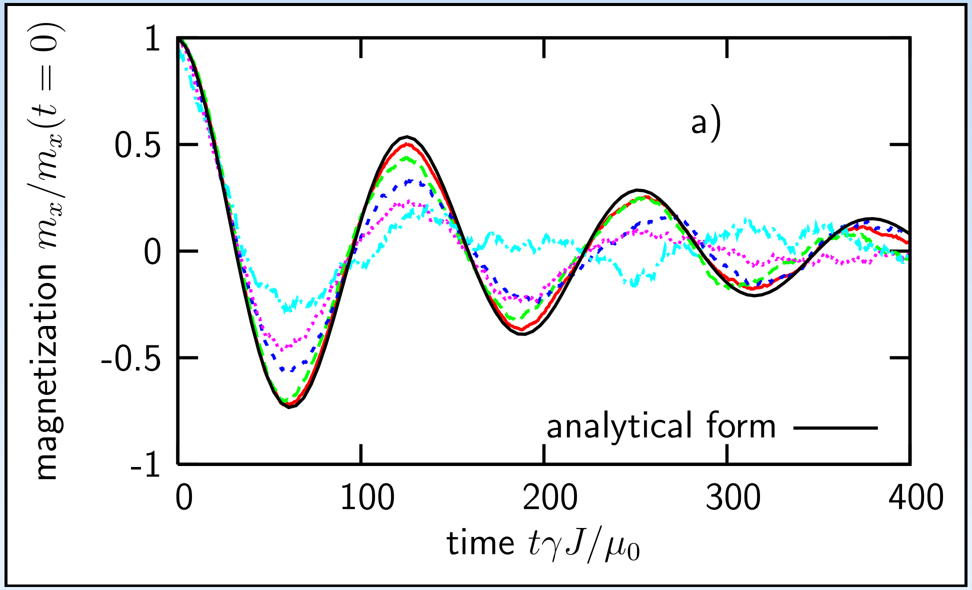
$$m_x(t) = m_0 e^{-t/\tau_\perp} \cos(t/\tau_p)$$

  with transverse relaxation time $\tau_\perp = 1/\alpha\gamma H$

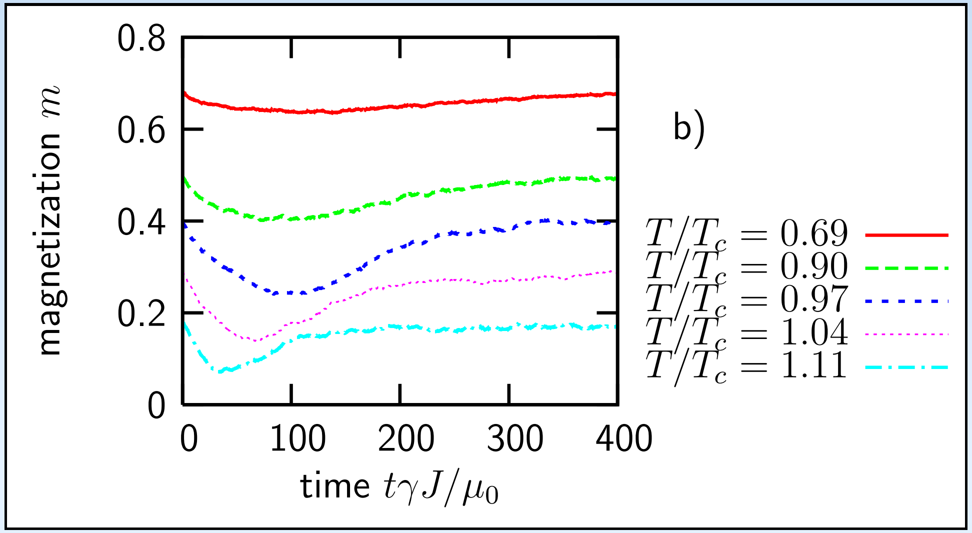
- for finite temperature:
  - simulation of spin model (48^3 spins) with LLG equation
  - simulation of single macro-spin with LLB equation

Simulation of spin model with LLG equation

$\theta = 30^\circ$

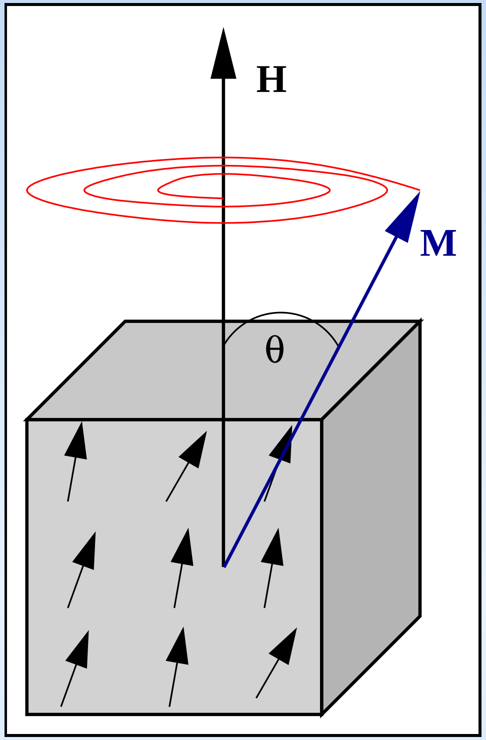


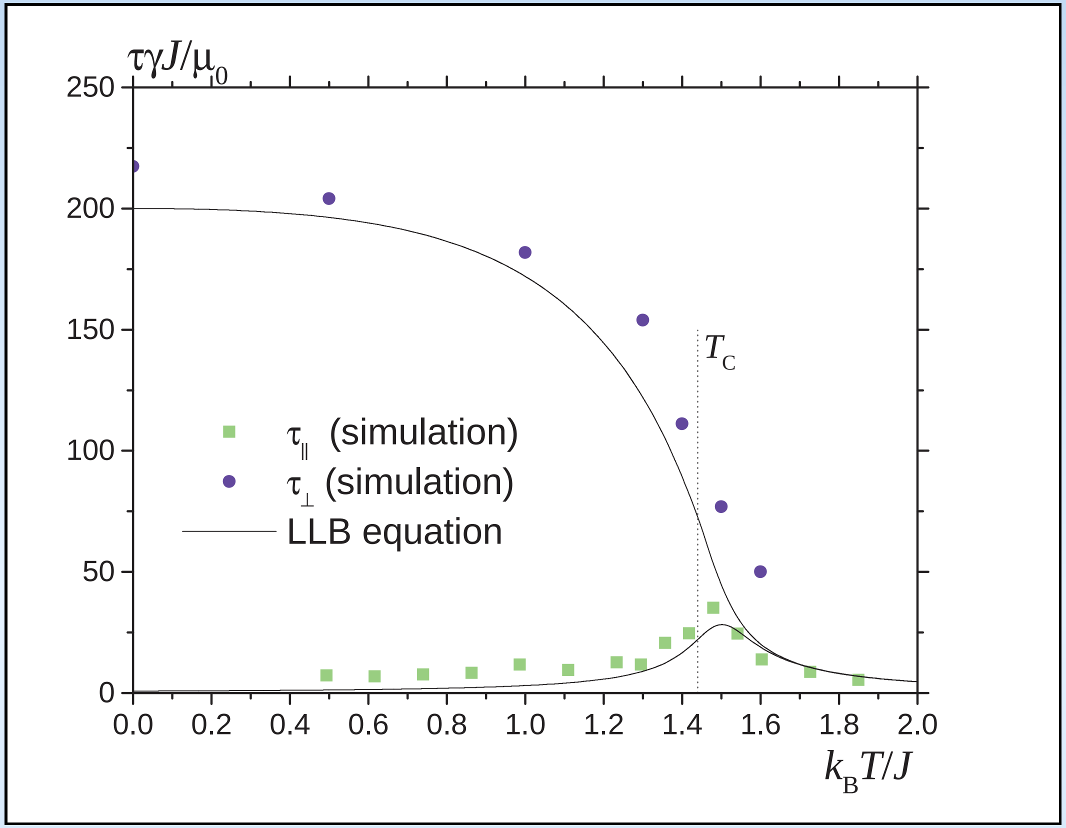
$\theta = 135^\circ$



- $\theta = 30^\circ$: transverse relaxation faster approaching $T_c \rightarrow \tau_\perp$ decreases
- $\theta = 135^\circ$: magnetisation shows dip during reversal

Longitudinal and transverse relaxation time

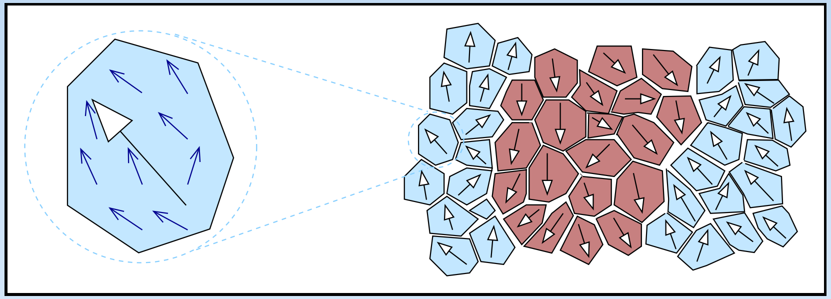




- longitudinal relaxation time shows critical slowing down
- transverse relaxation time breaks down close to Curie temperature
- magnitude of magnetisation not constant in time (and space)

☺ all these effects well described by LLB equation

Landau-Lifshitz-Bloch equation of motion



- atomistic simulations only possible up to $(20\mathrm{nm})^3$ system size; for larger samples macro-spin models are neccessary
- new, alternative approach is **Landau-Lifshitz Bloch equation** for the macroscopic thermodynamic magnetisation $\underline{m} = \langle \underline{S} \rangle$:

*(Garanin, PRB 55, 3050 (1997)), Garanin and Chubykalo-Fesenko, PRB **70**, 212409 (2004))*

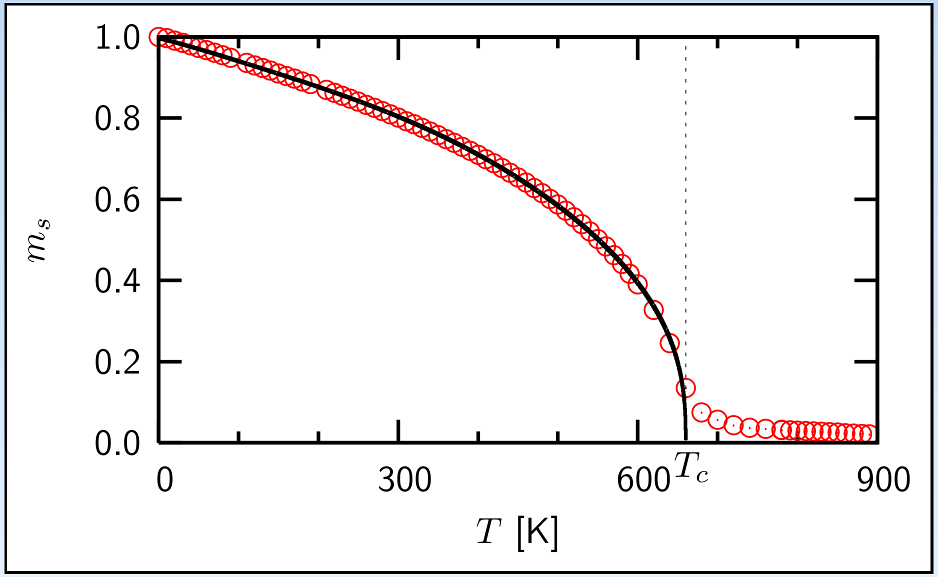
$$\dot{\mathbf{m}}_i = -\gamma \mathbf{m}_i \times \mathbf{H}^i_{\text{eff}} + \frac{\gamma \alpha_{||}}{m_i^2} \Big(\mathbf{m}_i \cdot (\mathbf{H}^i_{\text{eff}} + \zeta^i_{||}) \Big) \mathbf{m}_i - \frac{\gamma \alpha_\perp}{m_i^2} \mathbf{m}_i \times \Big(\mathbf{m}_i \times (\mathbf{H}^i_{\text{eff}} + \zeta^i_\perp) \Big)$$

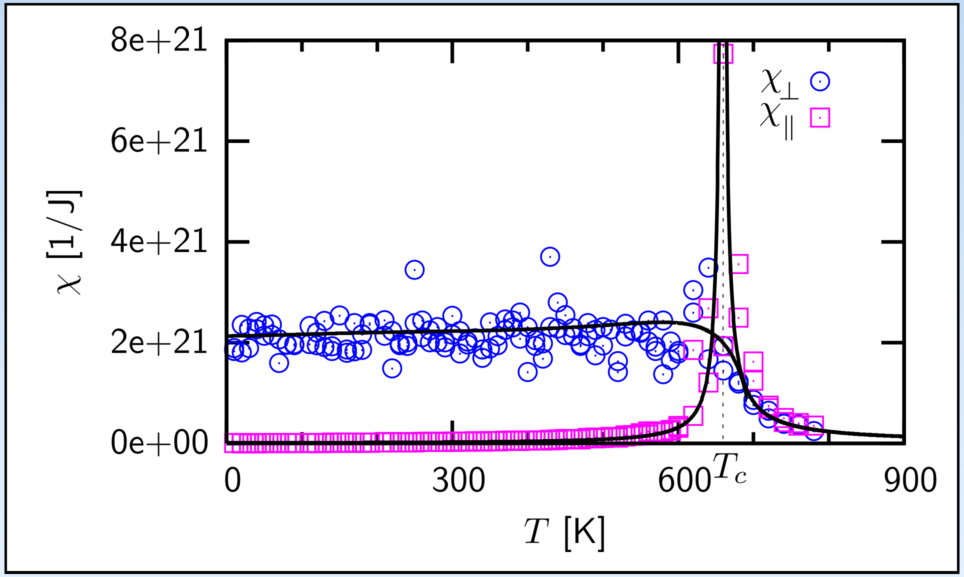
$\alpha_{\|} = \frac{2\lambda T}{3T_c}$ and $\alpha_\perp = \lambda(1 - \frac{T}{3T_c})$ for $T < T_c$ and $\alpha_\perp = \alpha_{\|}$ for $T \geq T_c$

$$\mathbf{H}^i_{\text{eff}} = \mathbf{H} - \frac{m^i_x \mathbf{e}_x + m^i_y \mathbf{e}_y}{\tilde{\chi}_\perp} - \frac{2A(T)}{m_e^2 M_s^0 \Delta^2} \sum_j (\mathbf{m}_j - \mathbf{m}_i) - \begin{cases} -\frac{1}{2\tilde{\chi}_{\|}}(1 - \frac{m_i^2}{m_e^2})\mathbf{m}_i & T \leq T_c \\ \frac{1}{\tilde{\chi}_{\|}}(1 - \frac{3T_c m_i^2}{5(T - T_c)})\mathbf{m}_i & T \geq T_c \end{cases}$$

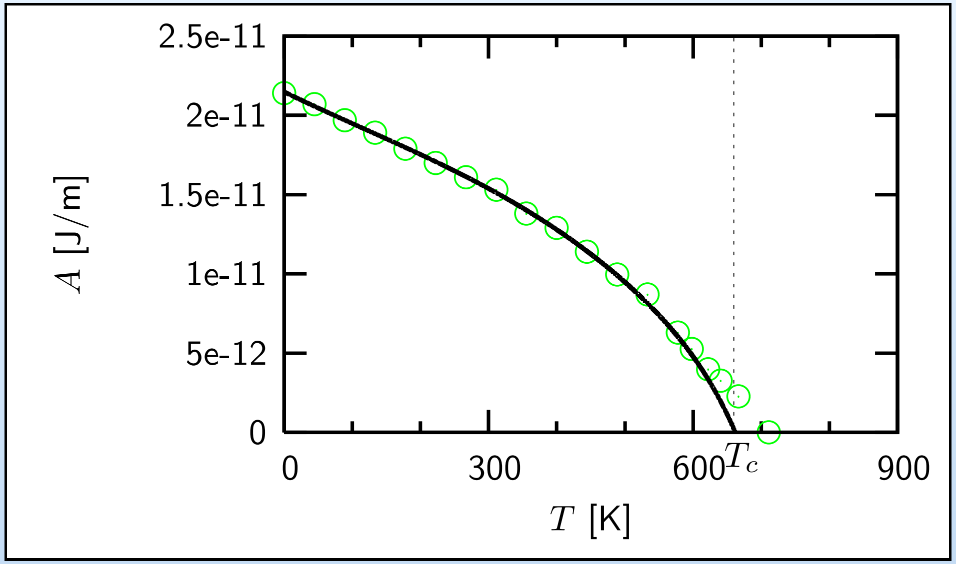
- one needs $m_e(T)$, $A(T)$, $\tilde{\chi}_\perp(T)$, $\tilde{\chi}_{\|}(T)$

Equilibrium properties for LLB approach





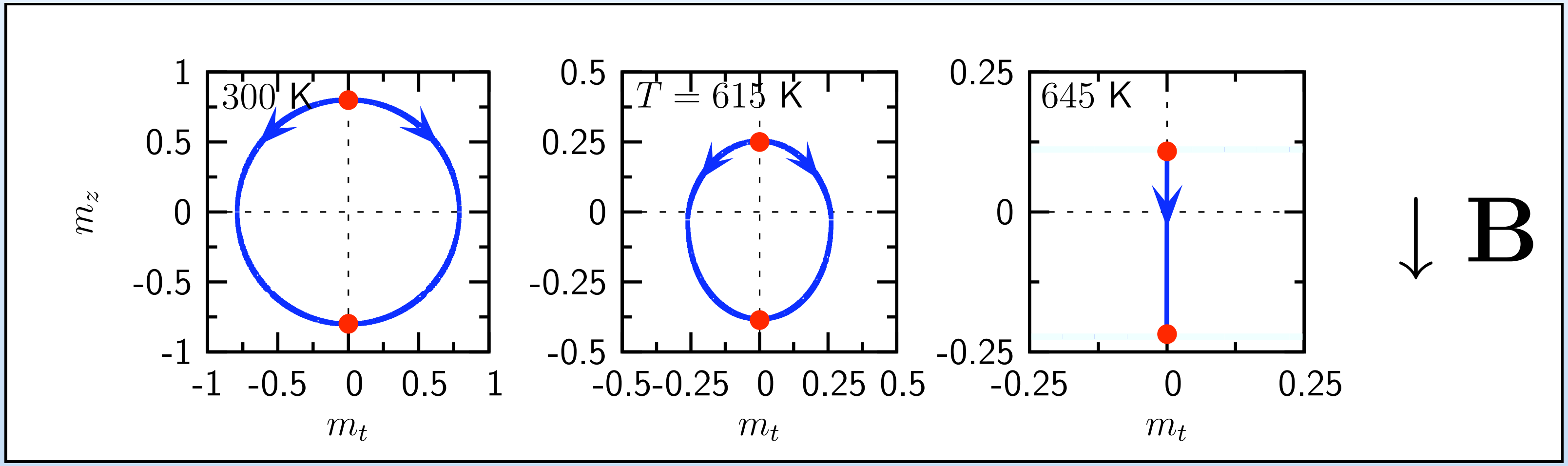
- zero field magnetisation $m_s(T)$
- susceptibilities $\chi_\parallel(T)$ and $\chi_\perp(T)$
- exchange stiffness $A(T)$
- here from Langevin dynamics simulations of the FePt model
- alternatively from other methods (MFA, MC, RPA) or from experiment



Single LLB macro-spin: reversal paths

- different reversal paths possible, depending on temperature:

circular	elliptical	linear
circular	elliptical	linear



(Kazantseva et al., Europhys. Lett. **86***, 27006 (2009))*

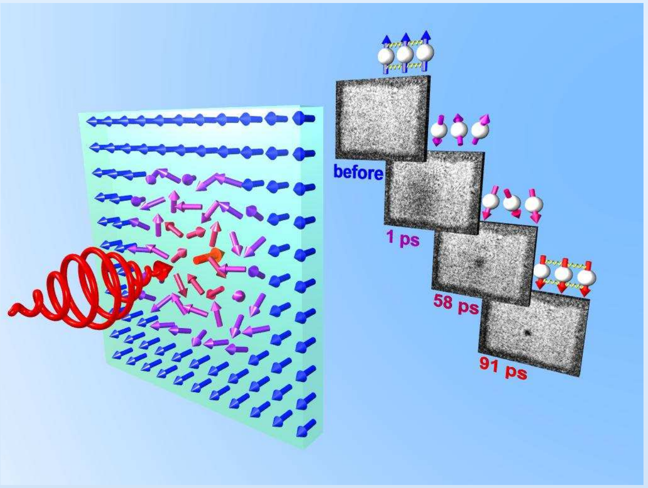
Modeling of light-induced reversal mechanisms

U. Nowak

Universität Konstanz, Germany

Topics:

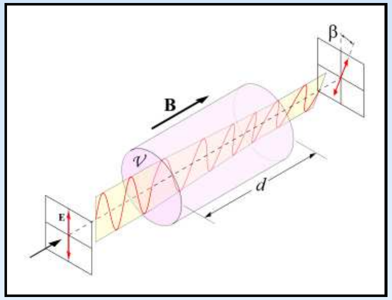
- Motivation
- Theoretical framework for thermal spin dynamics
- **Laser induced spin dynamics and opto-magnetic writing**
- Domain wall motion and spin Seebeck effect
- Summary



(http://www.ultramagnetron.org)

Opto-magnetic writing

- writing information without applying an external magnetic field
- uses circularly polarised light
- field pulse due to inverse Faraday effect:
  $\mathbf{B} \sim \mathbf{E} \times \mathbf{E}^*$



(http://en.wikipedia.org/wiki/Faraday_effect)

- time scale: some picoseconds
- writing procedure with combined field and temperature pulse

(*Kimel et al. Phys. Rev. Lett.* **99**, *047601 (2007), Nature* **435**, *655 (2005)*)

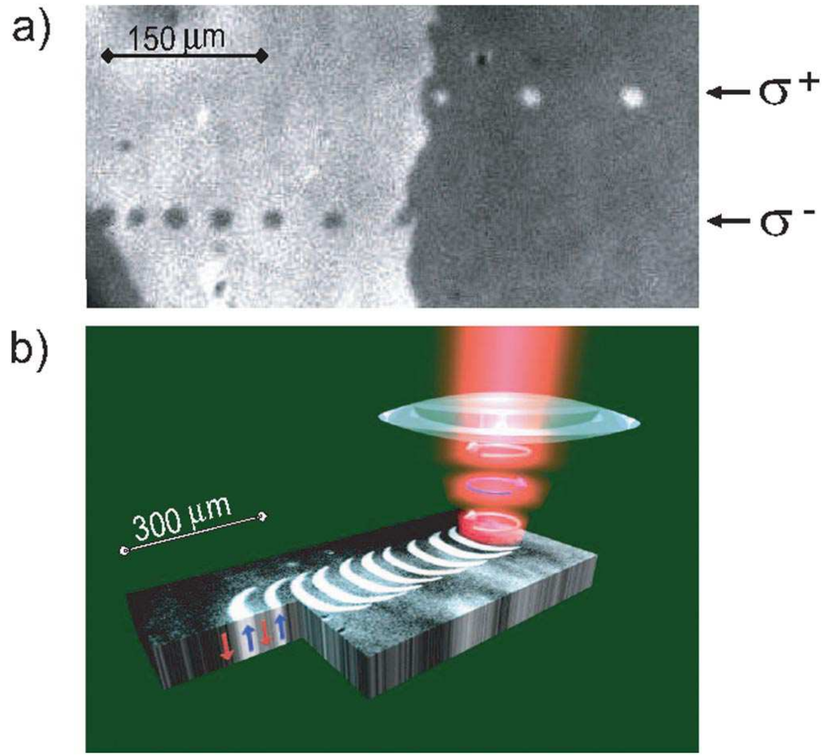
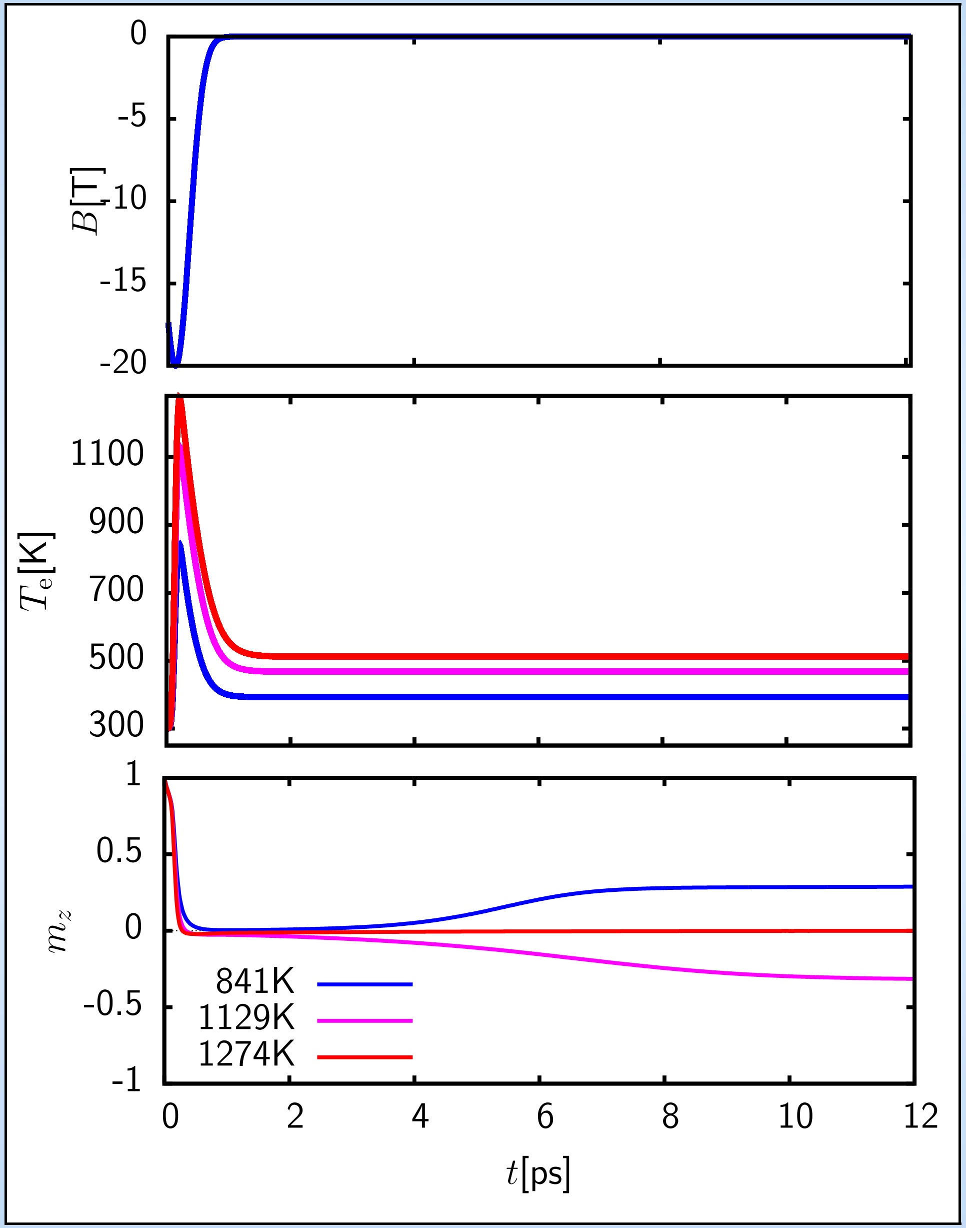


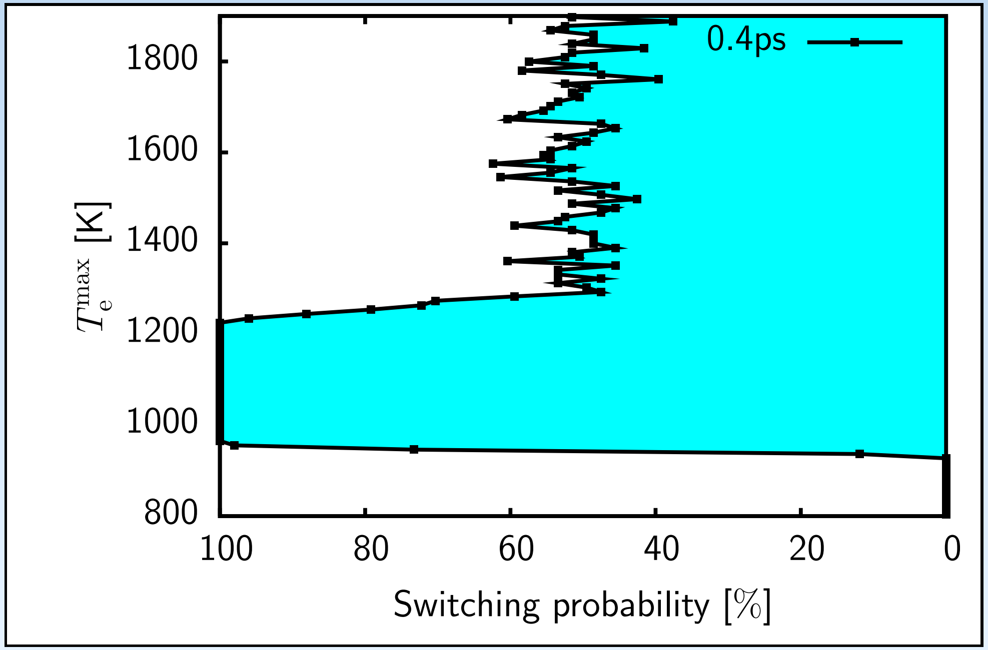
FIG. 4 (color). All-optical magnetic recording by femtosecond laser pulses. (a) The effect of single 40-fs circular polarized laser pulses on the magnetic domains in $Gd_{22}Fe_{74.6}Co_{3.4}$. The domain pattern was obtained by sweeping at high-speed ($\sim$50 mm/s) circularly polarized beams across the surface so that every single laser pulse landed at a different spot. The laser fluence was about 2.9 mJ/cm^2. The small size variation of the written domains is caused by the pulse-to-pulse fluctuation of the laser intensity.

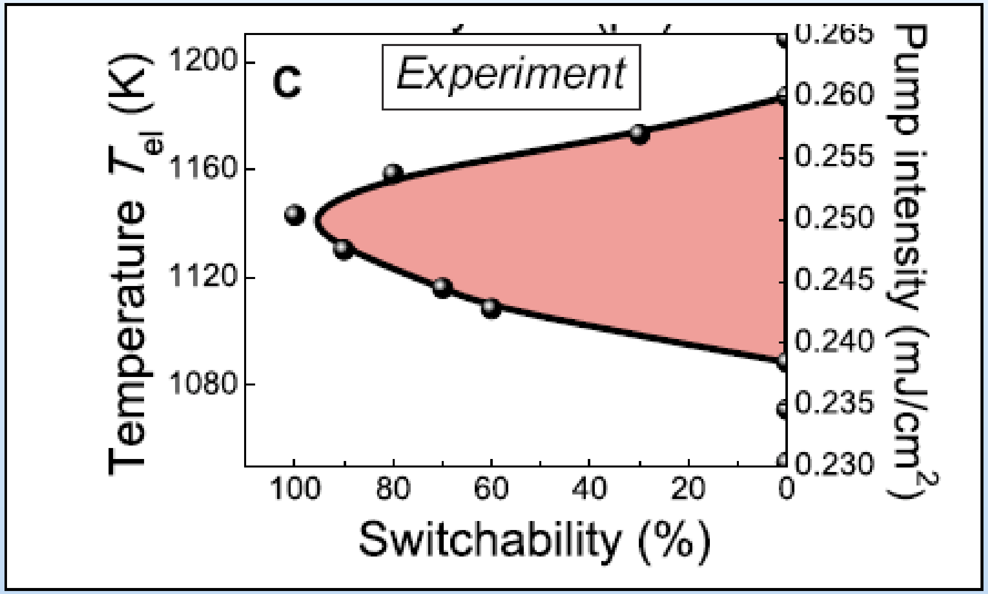
Single LLB macro-spin: Opto-magnetic reversal



- magnetic field $\mathbf{B}$ in z direction
  - $\mathbf{B} \sim \mathbf{E} \times \mathbf{E}^*$ (inverse Faraday effect)
  - B_{max} = 20 T
  - field pulse duration time Δt = 0.4ps
- electron temperature T_{e}
  - calculated from two-temperature model
- simulation parameters for GdFeCo:
  - $T_c = 500$K, Anisotropy $K = 6.05 \times 10^5$Jm^{-3}
  - cell size $\Delta = 30$ nm
  - magnetization averaged over 100 simulation runs

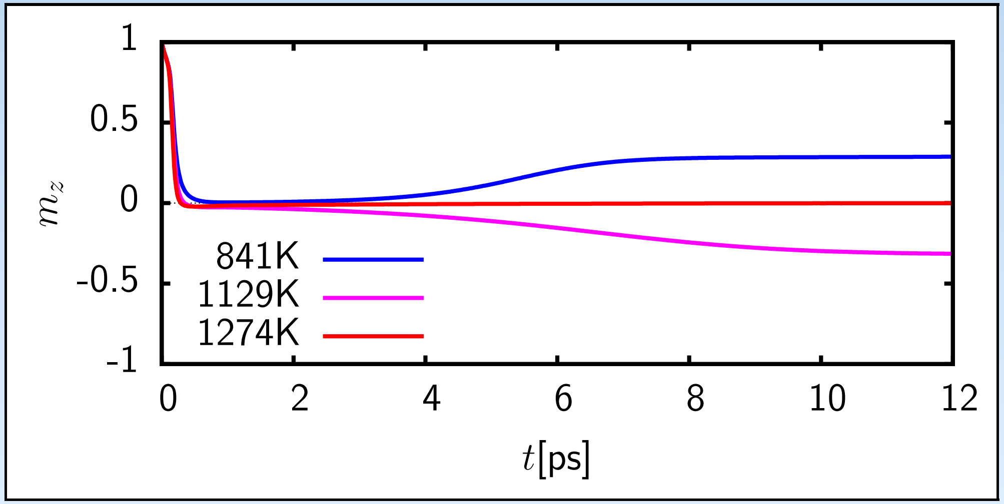
Opto-magnetic reversal window

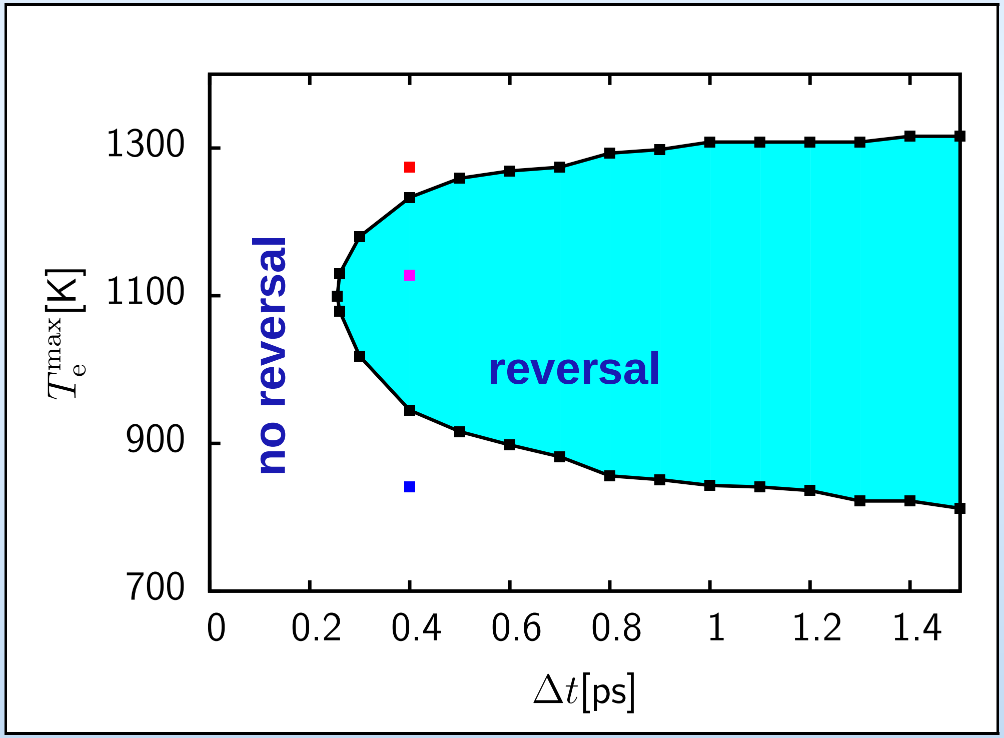




- ”reversal window” found numerically as well as experimentally *(Vahaplar et al., Phys. Rev. Lett* **103**, *117201 (2009)*
- opening of ”reversal window” depends on the field pulse duration as well as the maximum electron temperature
- for high temperature pulses:
  - numerically: sample demagnetised
    - ► P_{SW} = 50 %
  - experimentally: sample reverts to initial state (independent of helicity)
    - ► P_{SW} = 0 %

Opto-magnetic reversal window





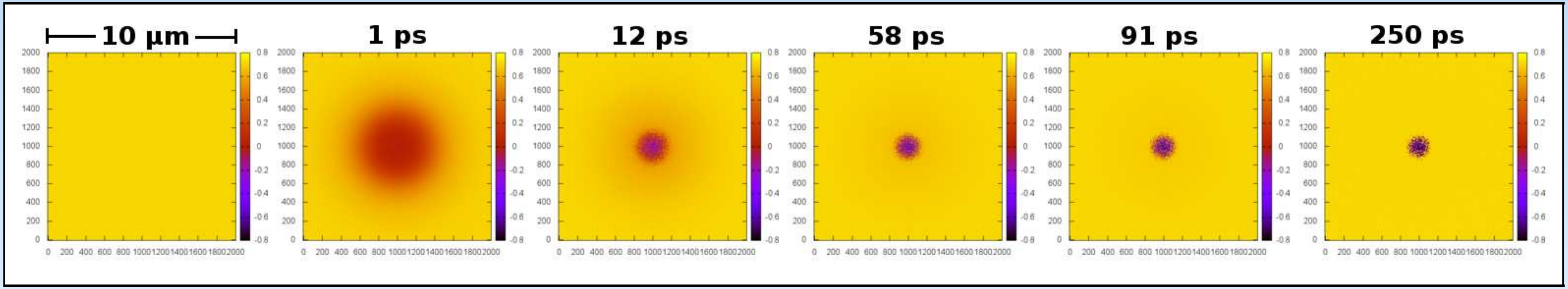
◀ T_e^{max} **too low!**

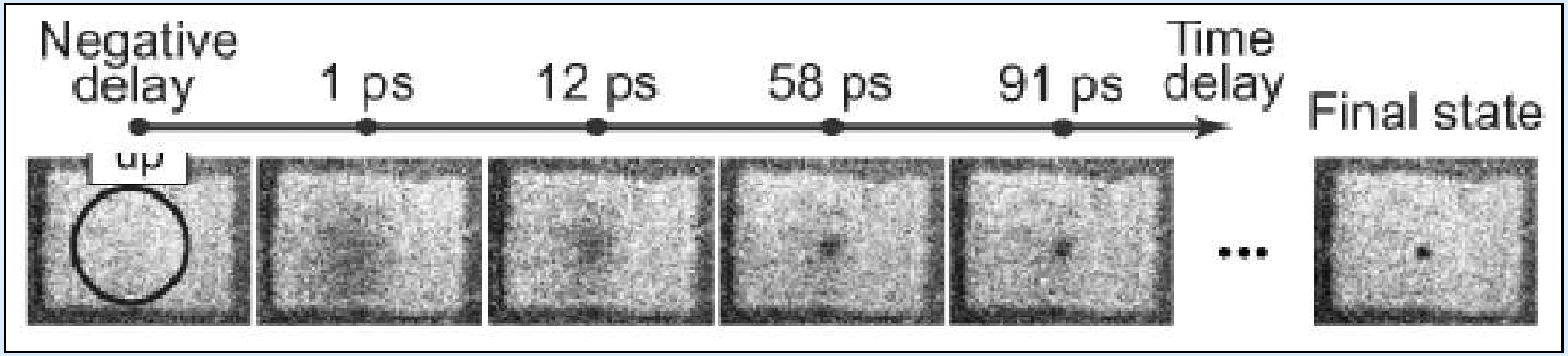
◀ T_e^{max} **too high!**

◀ T_e^{max} ✓

- ”reversal window” depending on peak electron temperature and length of field pulse
- window depends also on:
  - electron-phonon coupling
  - electron and phonon specific heats
  - material parameters of the spin model: damping constant, susceptibility and anisotropy
  - temperature

Opto-magnetic reversal in extended systems





(*Vahaplar et al. Phys. Rev. Lett.* **103**, *117201 (2007)*)

- simulation of an extended films of size $10 \times 10\ \mu\mathrm{m}^2$ possible including dipole-dipole interaction
- laser power assumed to have a gaussian shape

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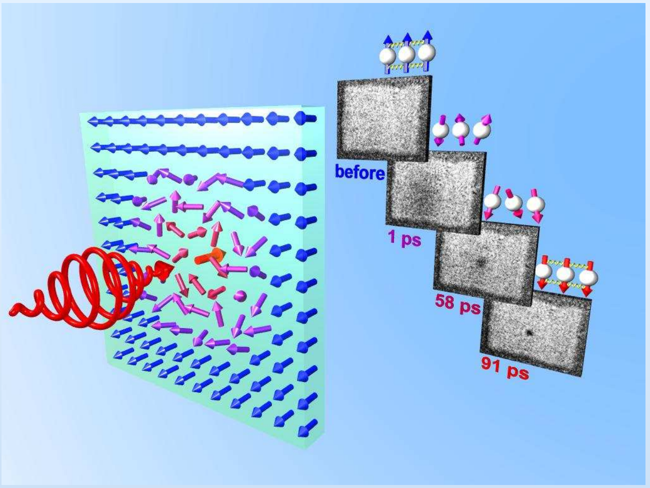


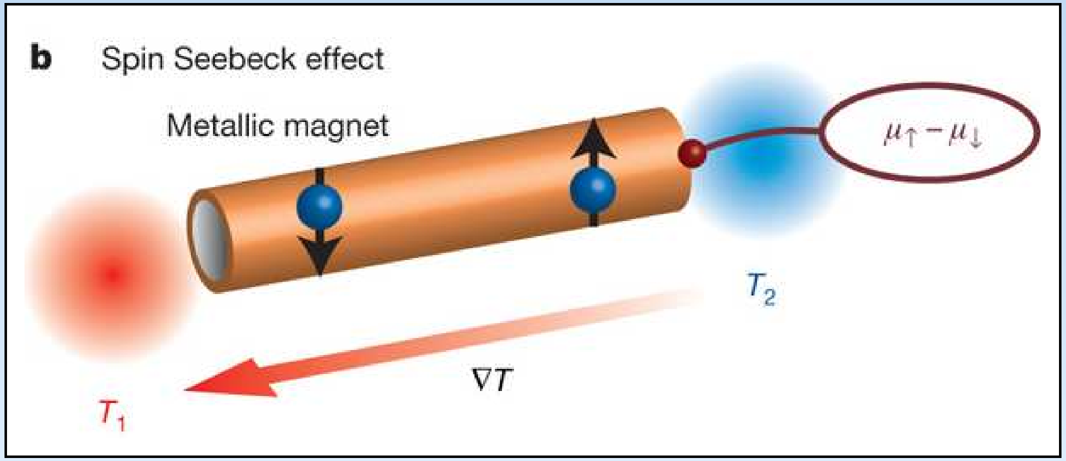
(http://www.ultramagnetron.org)

Spin Seebeck effect

Spin Seebeck effect:

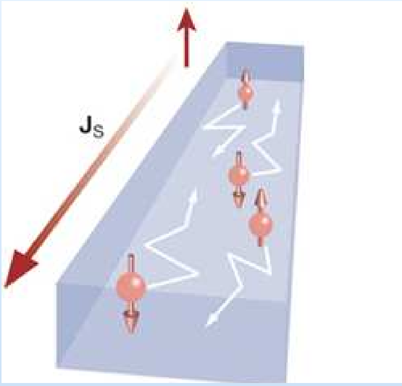
generation a spin voltage through a temperature gradient in a ferromagnet

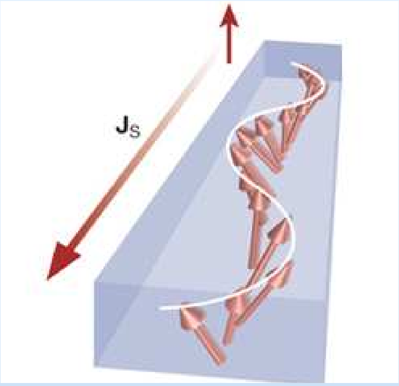
(K. Uchida et al., Nature **455***, 778 (2008))*



Spin current:

flow of angular momentum ⇨ two possible types of carriers *(Y. Kajiwara et al., Nature* **464***, 262 (2010))*

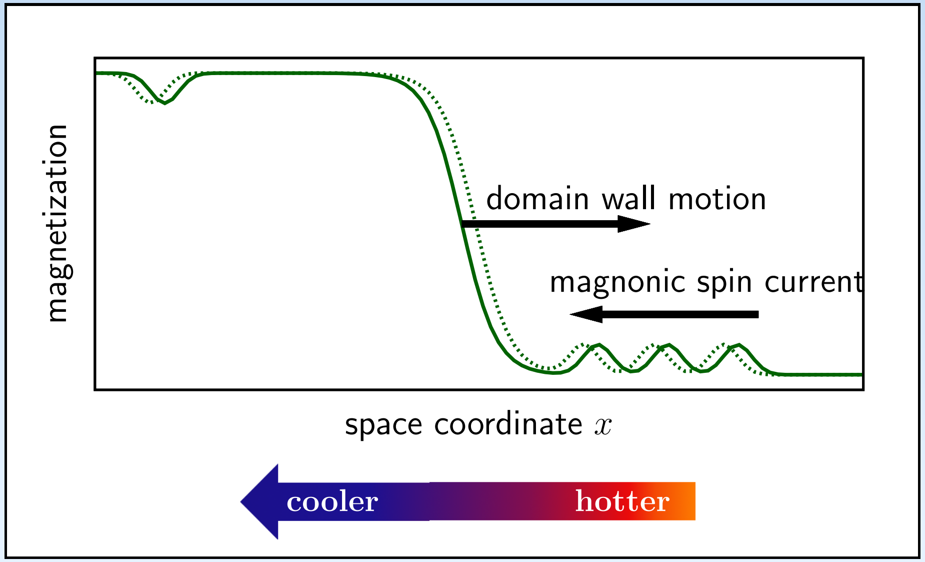




- spin current via polarized electrons
- chargeless spin current via magnons

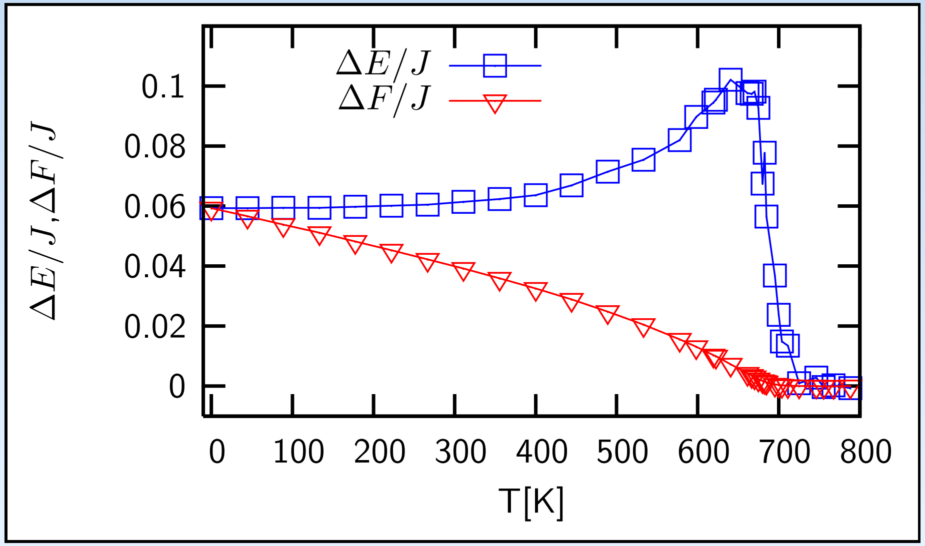
Domain wall in a temperature gradient

Microscopic view:



- magnons from the hotter region enter the colder region changing their sign in the wall
- by conservation of angular momentum the domain wall is pushed towards the hotter region

Thermodynamic view:



(D. Hinzke et al., PRB ***77****, 094407 (2008))*

- free energy $F = E - TS$ of a domain wall is a monotonious decaying function of temperature
- in a temperature gradient the free energy of the domain wall is minimized by moving towards the hotter region

Domain wall motion in a temperature gradients

Microscopic view:

stochastic LLG equation

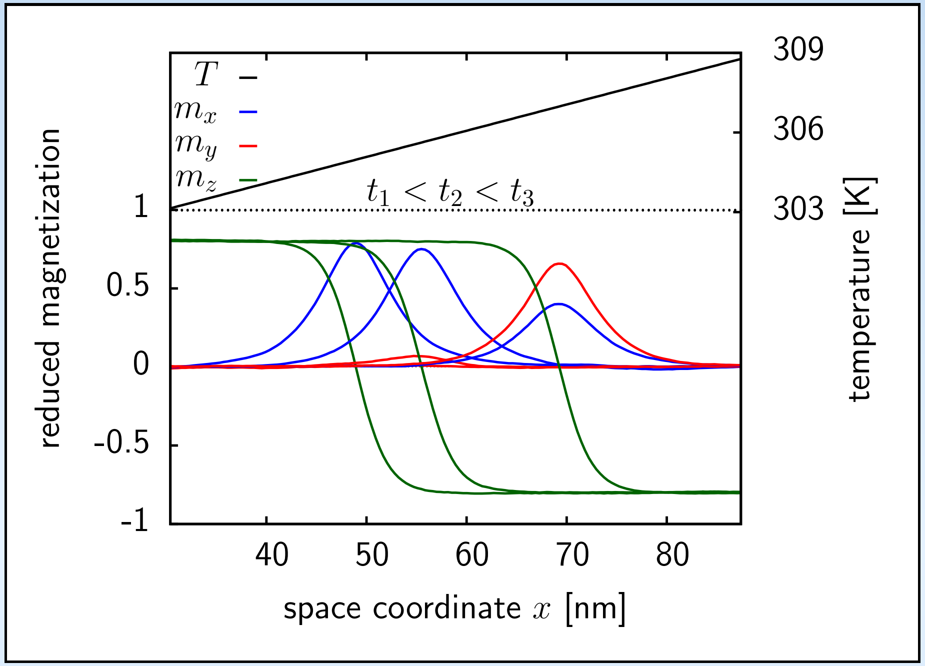
- spin model simulation of the LLG equation
- magnon current created by hot boundary
- domain wall is attracted by hot boundary

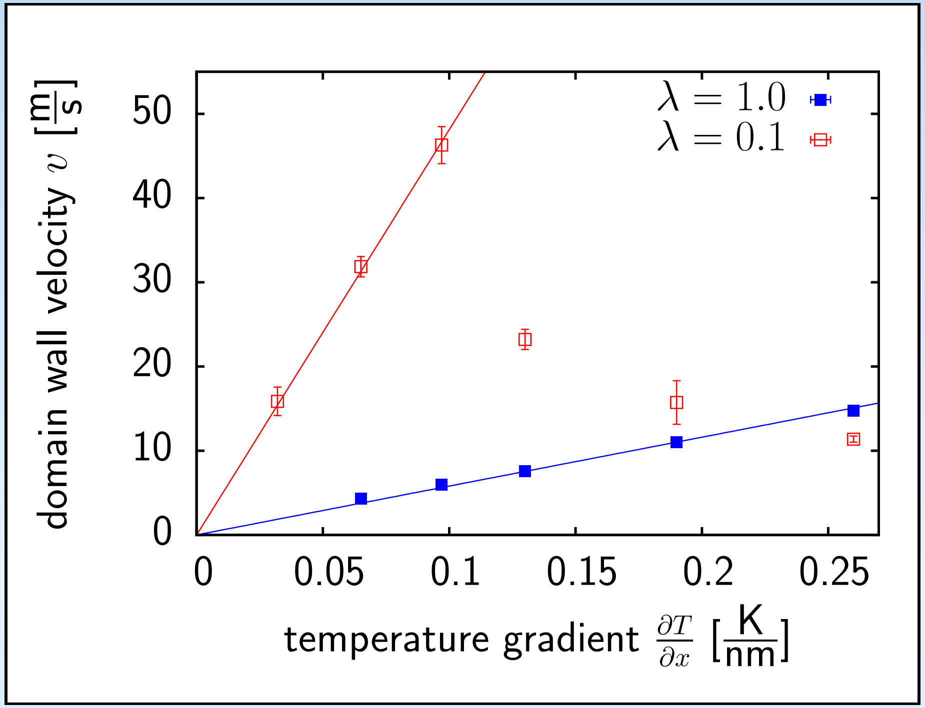
Thermodynamic view:

LLB equation

- micromagnetic simulation of the LLB equation
- domain wall moves into the hotter region
- domain wall motion is accompanied by precession (above Walker breakdown)

Domain wall motion in a temperature gradient





- simulation of the Landau-Lifshitz-Gilbert equation of motion
- domain wall moves towards hotter region
- shape and orientation of the domain wall changes

- simulation of the Landau-Lifshitz-Bloch equation of motion
- $v \approx 50$ m/s for $\frac{\partial T}{\partial x} \approx 0.1$ K/nm $\longrightarrow$ should be measurable
- Walker breakdown

Final remarks

Summary:

- multiscale modelling:
  - spinmodel for FePt from frist principles — *Europhys. Lett.* **69**, *805 (2005)*
  - from first principles to macro-spins — *Phys. Rev. B,* **77**, *184428 (2008)*
  - exchange stiffness at finite temperatures — *Phys. Rev. B,* **82**, *134440 (2010)*
- high temperature spin dynamics:
  - rapid heating dynamics with LLB equation — *Appl. Phys. Lett.* **91**, *232507 (2007)*
  - LLG equation describes ps spin dynamics — *Europhys. Lett.* **81**, *27004 (2008)*
  - linear vs. elliptical reversal: analytical results — *Europhys. Lett.* **86**, *27006 (2009)*
  - ultra-fast spin dynamics: the effect of colored noise — *Phys. Rev. Lett.* **102**, *057203 (2009)*
  - opto-magnetic writing — *Phys. Rev. Lett.* **103**, *117201 (2009)*
- domain wall motion by spin currents:
  - current induced domain wall motion — *Phys. Rev. B* **91**, *232507 (2010)*
  - non-adiabatic spin torque — *Phys. Rev. Lett.* **105**, *056601 (2010)*
  - domain wall motion in temperature gradients — *in preparation*

Acknowledgment:

- EU: FP7 Research Project UltraMagnetron
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- DFG: SFB 767