Sub-picosecond switching and the future of HAMR

J Barker, T Ostler, L Atkinson, RFL Evans, R.W. Chantrell
Physics Department, The University of York

D Hinzke, U Nowak
Universitaet Konstanz

Oksana Chubykalo-Fesenko, Unai Atxitia,
ICMM, Madrid

K Vahaplar, A Kalashnikova, Th Rasing, A Kirilyuk, A Kimel,

IMM, Radboud University Nijmegen, NL

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York

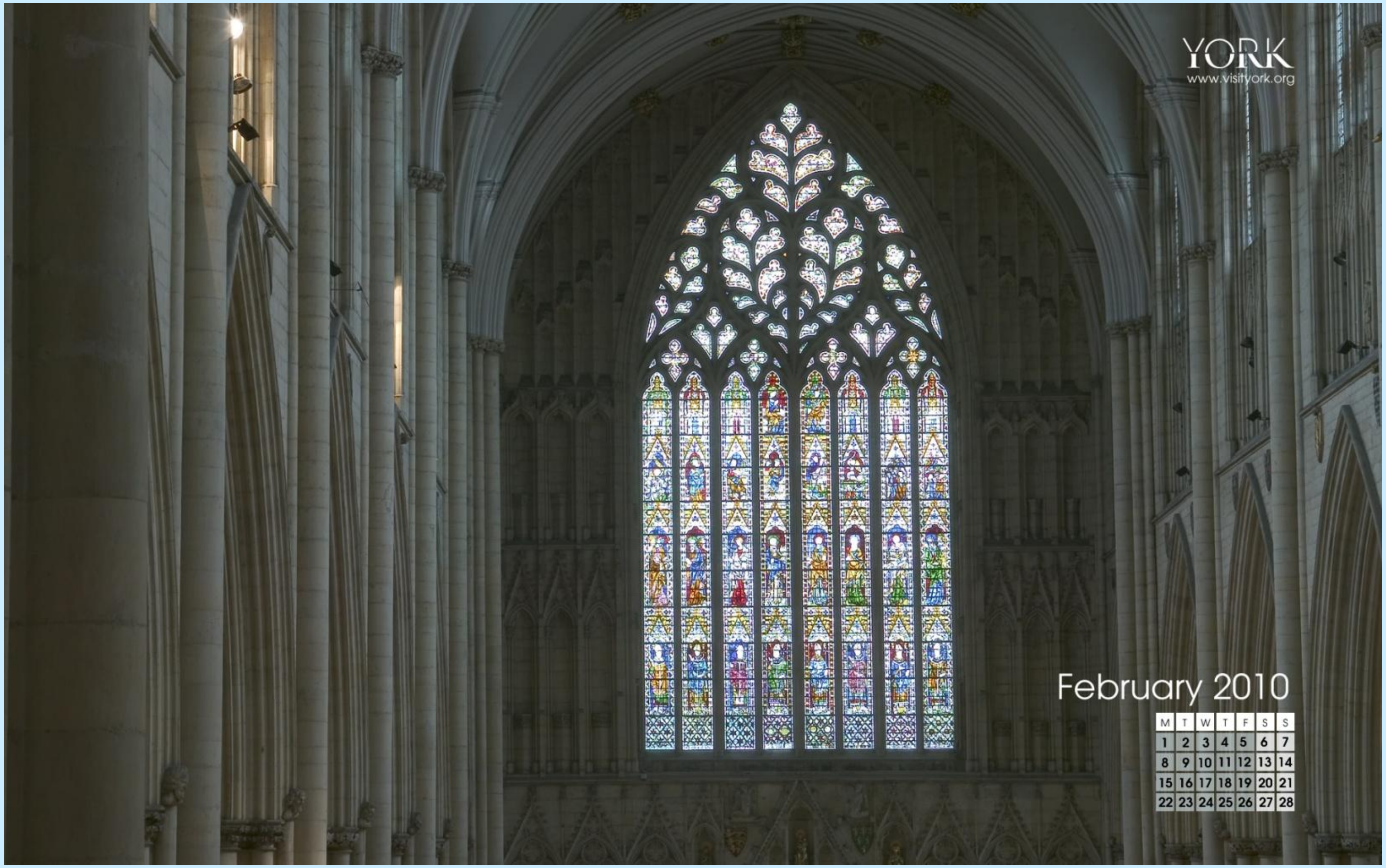
Very old city in north of England

Rich history from Viking, Roman and Medieval times

Middle ages – administrative capital of the north

University is much younger – 45 years

York Minster



Museum gardens

Whitby abbey (60 km from York)

Dissolution of the monasteries
Count Dracula arrived at Whitby!

Newton’s Apple tree!

Summary

- Introduction to pulsed laser processes
- New (linear) magnetisation reversal mechanism
- Linear reversal is calculated to give reversal times as fast as 300fs !
- Dynamics and the Landau-Lifshitz- Bloch (LLB) equation of motion
- LLB-micromagnetics and dynamic properties for large-scale simulations at elevated temperatures
- Opto-magnetic reversal – the ultimate speed record?

The need for atomistic/multiscale approaches to magnetisation dynamics

- Micromagnetics is based on a continuum formalism which calculates the magnetostatic field exactly but which is forced to introduce an approximation to the exchange valid only for long-wavelength magnetisation fluctuations.
- Thermal effects can be introduced, but the limitation of long-wavelength fluctuations means that micromagnetics cannot reproduce phase transitions.
- The atomistic approach developed here is based on the construction of a physically reasonable classical spin Hamiltonian based on ab-initio information.

Atomistic model

- Uses the Heisenberg form of exchange

$$E_i^{exch} = \sum_{j \neq i} J_{ij} \vec{S}_i . \vec{S}_j$$

- Spin magnitudes and J values can be obtained from ab-initio calculations.
- We also have to deal with the magnetostatic term.
- 3 lengthscales – electronic, atomic and micromagnetic – Multiscale modelling.

Model outline

Ab-initio information (spin, exchange, etc)

↓

Classical spin Hamiltonian → **Dynamic response solved using Langevin Dynamics (LLG + random thermal field term)**

↑

Magnetostatics

Dynamic behaviour

- Dynamic behaviour of the magnetisation is based on the Landau-Lifshitz-Gilbert equation

$$\dot{\vec{S}}_i = -\frac{\gamma}{1+\alpha^2}\vec{S}_i \times H_i(t) - \frac{\lambda\gamma}{1+\lambda^2}\vec{S}_i \times (\vec{S}_i \times \vec{H}_i(t))$$

- Where γ_0 is the gyromagnetic ratio and λ is a coupling constant
- Note that λ is NOT identical to the macroscopic damping parameter (later)

Langevin Dynamics

- Based on the Landau-Lifshitz-Gilbert equations with an additional stochastic field term h(t).
- From the Fluctuation-Dissipation theorem, the thermal field must must have the statistical properties

$$< h_j(t) >= 0 \qquad < h_i(0) h_j(t) >= \delta(t)\delta_{ij} 2\lambda k_b T / \gamma$$

- From which the random term at each timestep can be determined.
- h(t) is added to the local field at each timestep.

FePt Hamiltonian; link to ab-initio calculations

$$H = -\sum_{i,j} \frac{\tilde{J}_{ij}}{2} \vec{S}_i . \vec{S}_j - d^0 \sum_i (S_i^z)^2 - \sum_{ij} d_{ij}^2 S_i^z S_k^z - \tilde{\mu}\, \vec{B}. \sum_i \vec{S}_i$$

With new effective interactions $\tilde{J}_{ij} = J_{ij} + S_{FePt} \sum_k J_{ik} J_{jk}$

Single ion anisotropy $d^0 = d_{Fe} + d_{Pt} S_{FePt}^2 \sum_k J_{ik}^2$

2-ion anisotropy (new term) $d_{ij}^2 = 2 d_{Pt} S_{FePt}^2 \sum_k J_{ik} J_{jk}$

And moment $\tilde{\mu} = \mu_{Fe} + \mu_{Pt}$. $S_{FePt} = \sum_i J_{ik}$

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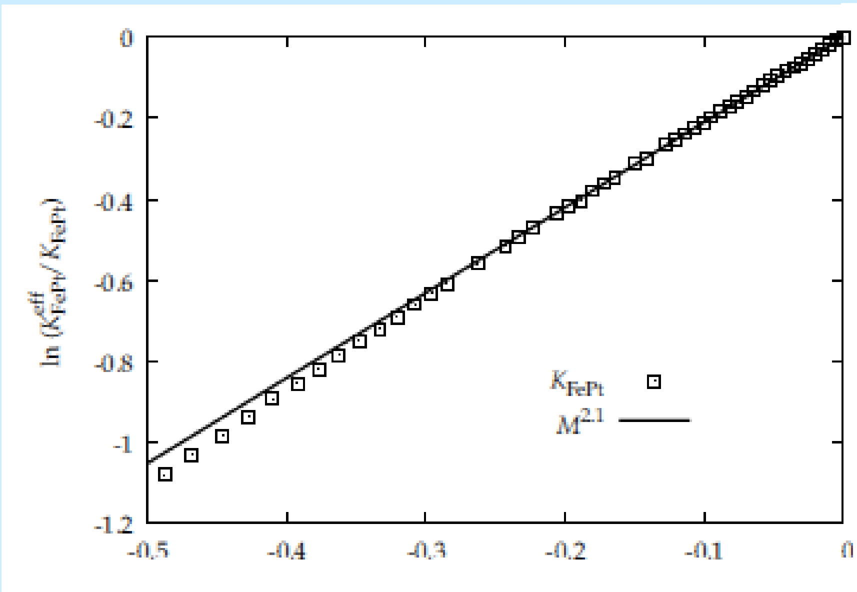
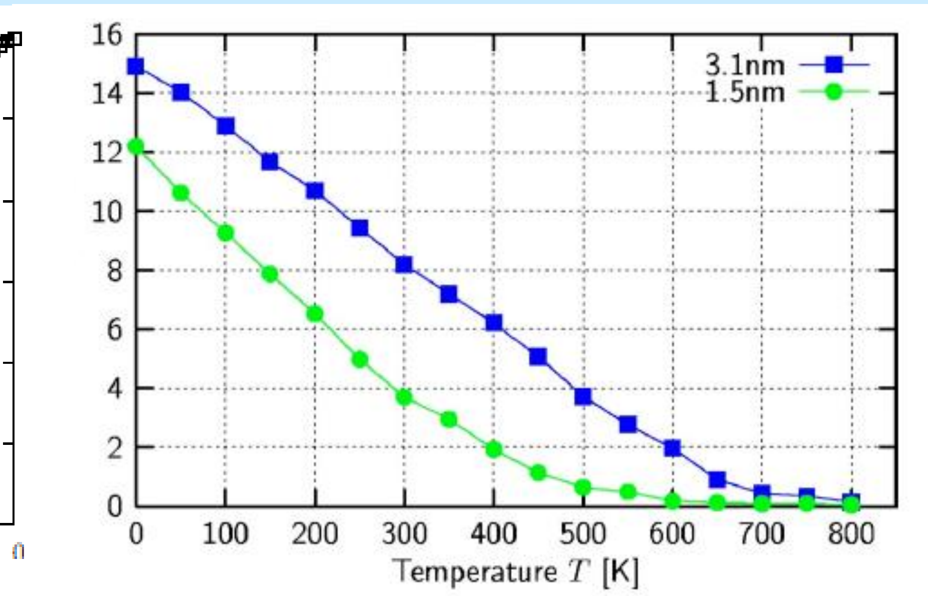
- All quantities can be determined from ab-initio calculations
- 2-ion term (resulting from the delocalised Pt degrees of freedom) is dominant

Important predictions of ab-initio/ atomistic model

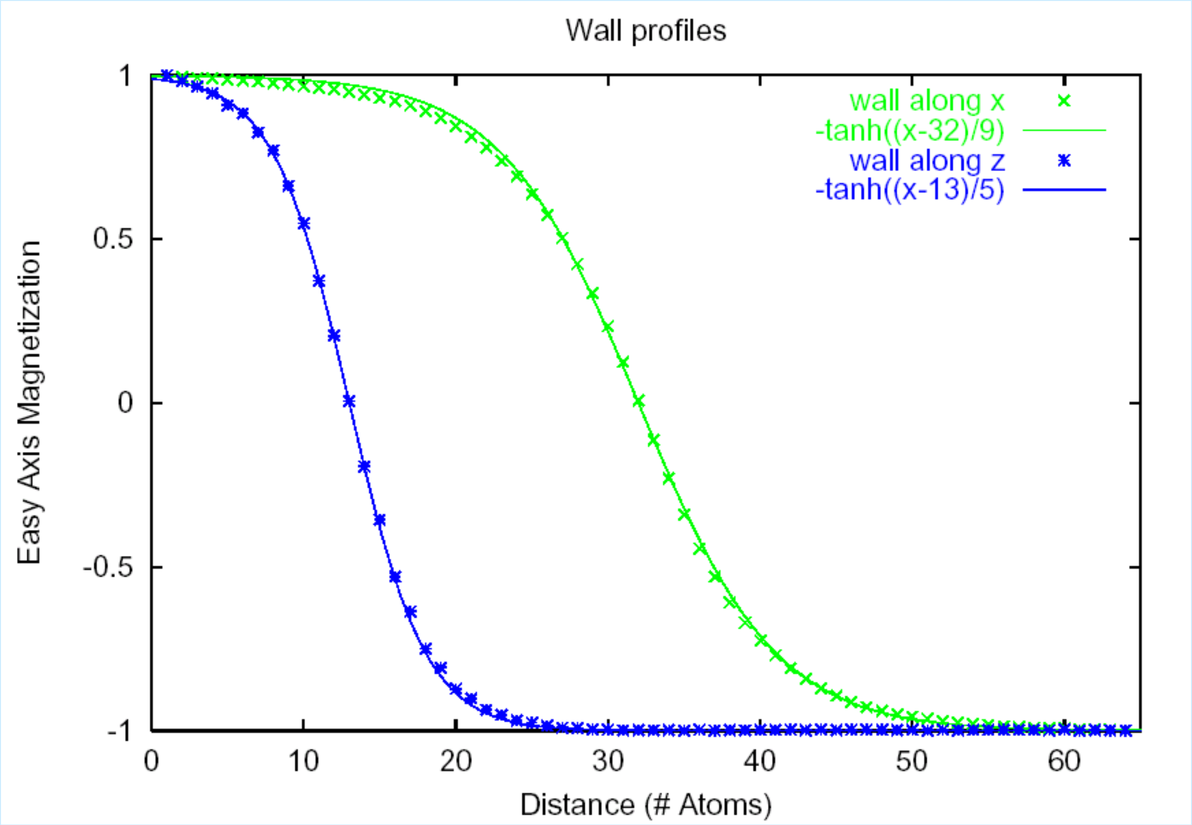




- Unusual scaling exponent
- Due to dominant 2-ion anisotropy
- Important factor for HAMR

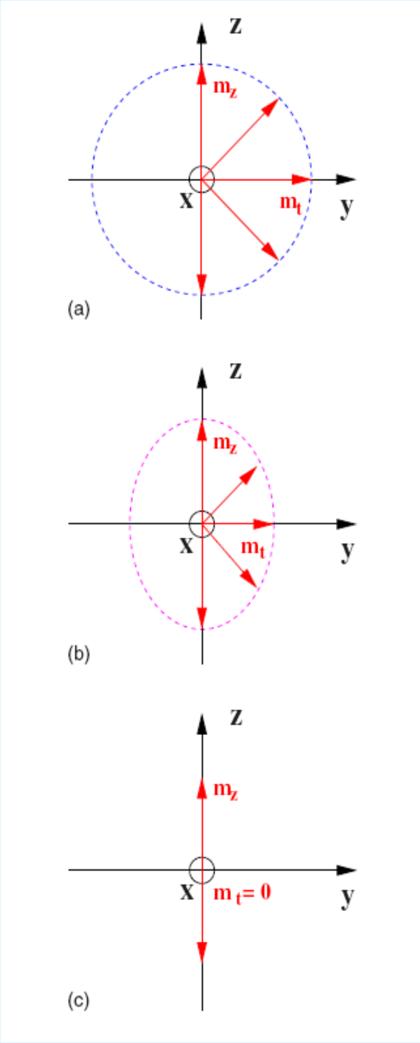
- Large finite size effect
- Due to loss of 2-ion anisotropy for surface atoms

Unusual properties of FePt 1: Domain Wall directionality

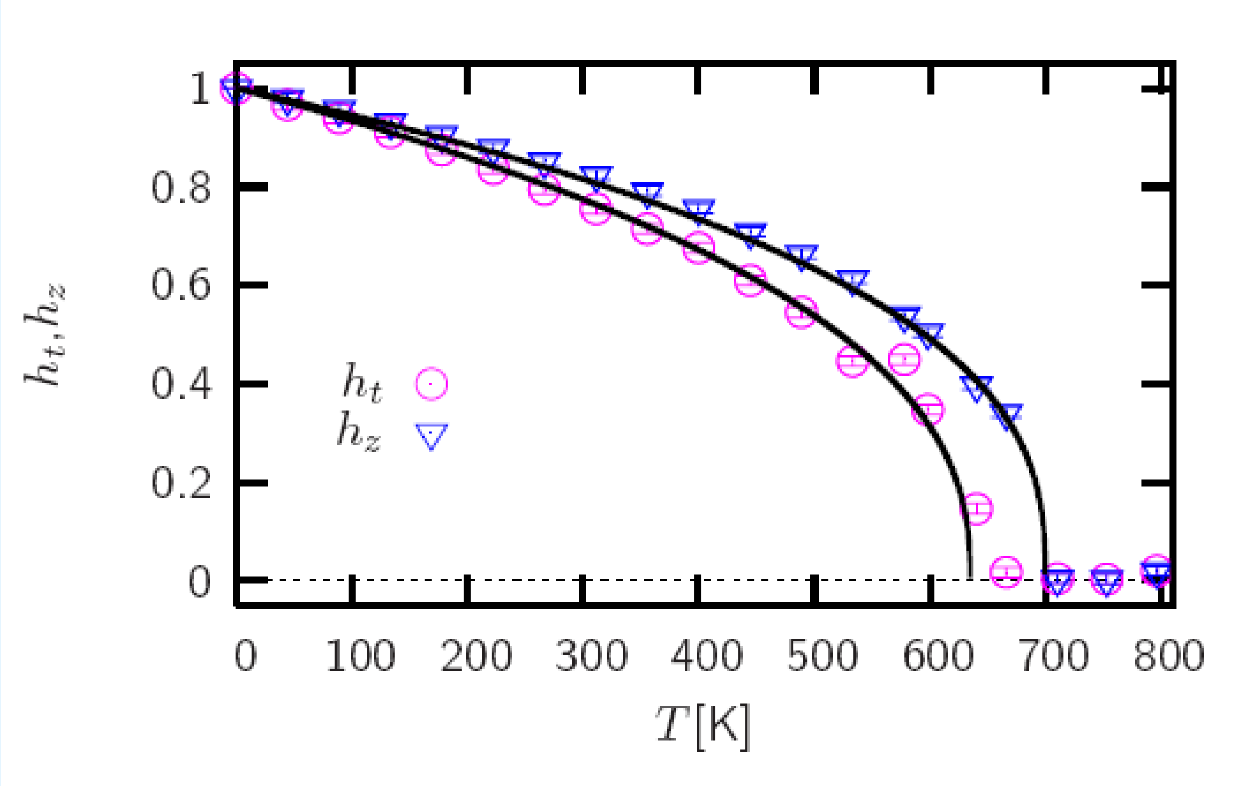


Atomic scale model calculations of the equilibrium domain wall structure

Unusual properties of FePt 2: Elliptical and linear Domain Walls



- Circular (normal Bloch wall); M_{tot} is orientationally invariant
- Elliptical; M_{tot} decreases in the anisotropy hard direction
- Linear; x and y components vanish

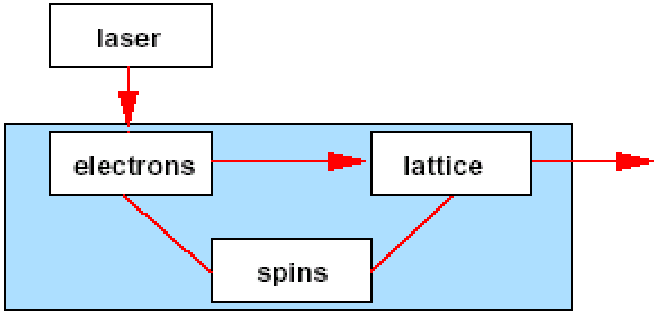


- Walls are elliptical at non-zero temperatures
- Linear walls occur close to T_c above a critical temperature which departs further from T_c with increasing K
- Analogue (see later) is linear magnetisation reversal – important new mechanism for ultrafast dynamics.

Laser Pump-probe experiments

- High energy laser beam (pump) causes rapid heating of a magnetic film
- Part of the beam is split off and used to measure the magnetisation of the film using the Magneto-Optic Kerr Effect (MOKE)
- Magnetisation changes on the sub-picosecond timescale can be demonstrated experimentally
- Very important physics
- Also, potentially important because of the possible use of Heat Assisted Magnetic Recording (HAMR)

2 temperature model



1. photon energy is transferred to electrons

2. energy is exchanged between electrons and phonons

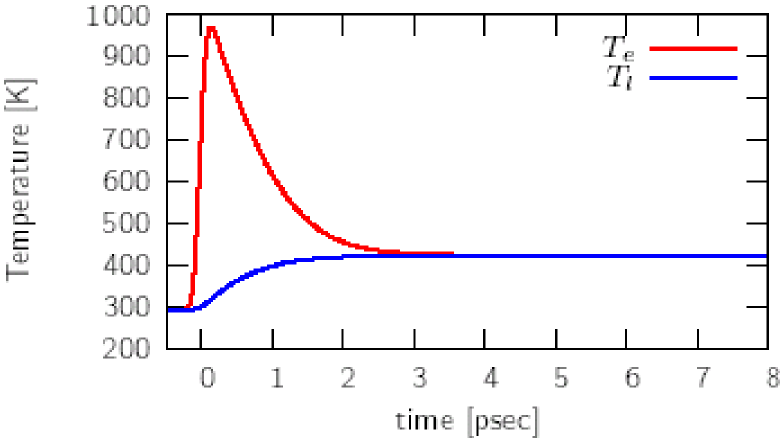
3. energy dissipates into environment

Two temperature model:

electrons: $C_e \frac{dT_e}{dt} = -G_{el}(T_e - T_l) + P(t)$

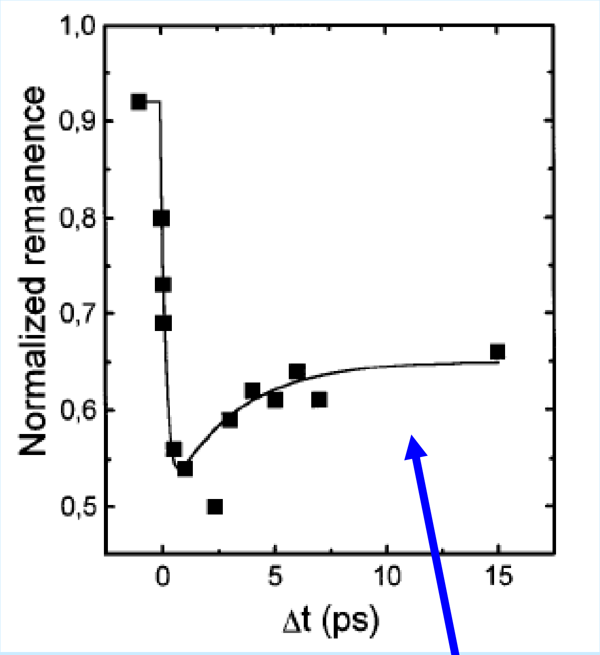
lattice: $C_l \frac{dT_l}{dt} = G_{el}(T_e - T_l)$

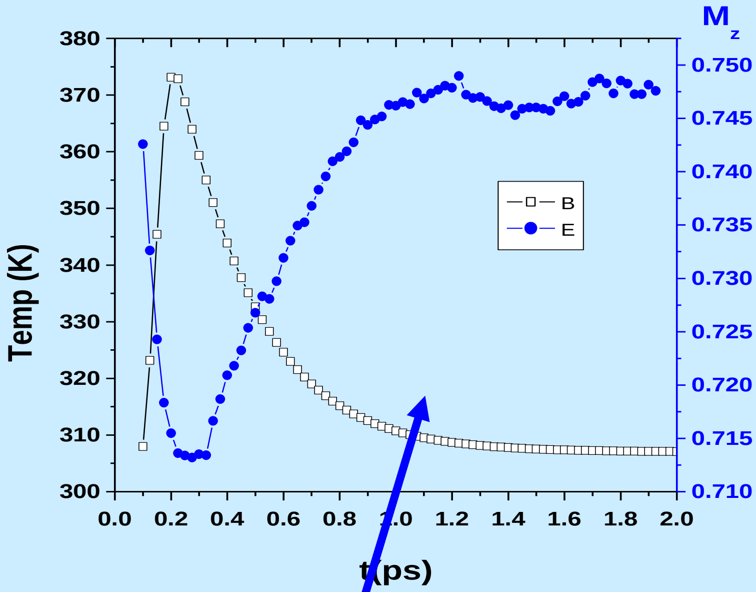
(M. I. Kaganov et al., Sov. Phys. JETP **4**, 173 (1957))



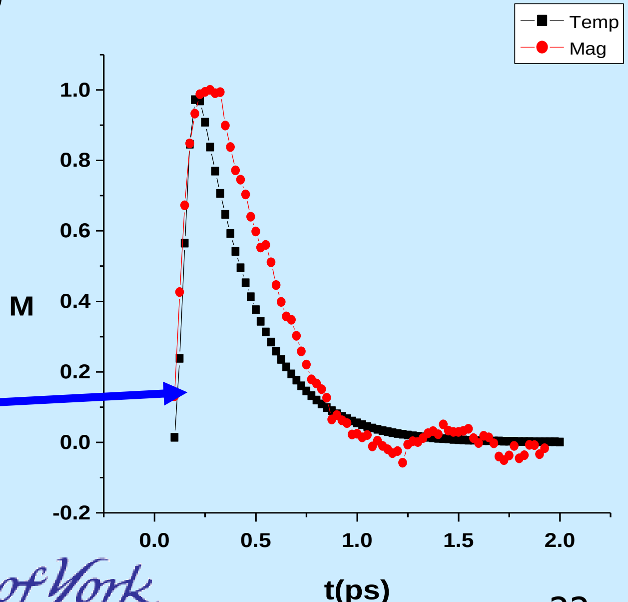
$\Rightarrow$ perform Langevin dynamics simulation with T_e as temperature of the heat bath

Ultrafast demagnetisation





- Experiments on Ni (Beaurepaire et al PRL 76 4250 (1996)
- Calculations for peak temperature of 375K
- Normalised M and T. During demagnetisation M essentially follows T



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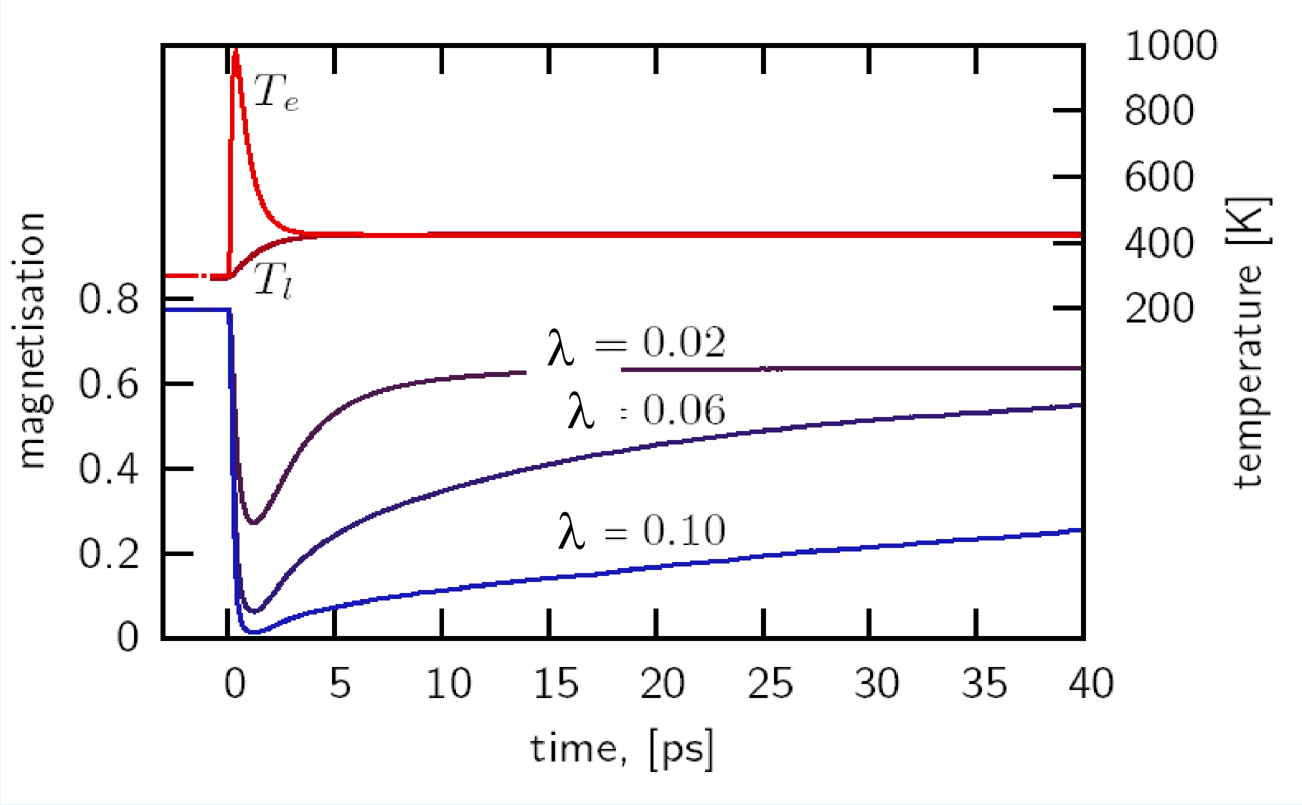
Pump-probe simulations – continuous thin film



- Rapid disappearance of the magnetisation
- Reduction depends on λ (coupling constant)

Dependence on λ

- λ governs the rate at which energy can be transferred into as well as out of the spin system.
- A characteristic time to disorder the magnetisation can be estimated as

$$\tau_{dis} \approx \frac{(1+\lambda^2)\mu_s}{2\lambda\gamma kT}$$

- During a laser pulse of duration, $t<\tau_{dis}$ the spin system will not achieve the maximum electron temperature

Experiments

PRL 102, 117201 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

Laser-Induced Magnetization Dynamics of Lanthanide-Doped Permalloy Thin Films

I. Radu,[1,2] G. Woltersdorf,[1] M. Kiessling,[1] A. Melnikov,[3] U. Bovensiepen,[3] J.-U. Thiele,[4] and C. H. Back[1]

[1]*Physics Department, Universität Regensburg, Universitätsstrasse 31, 93040 Regensburg, Germany*
[2]*BESSY GmbH, Albert-Einstein-Strasse 15, 12489 Berlin, Germany*
[3]*Physics Department, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany*
[4]*San Jose Research Center, Hitachi Global Storage Technologies, 3403 Yerba Buena Road, San Jose, California 95135, USA*

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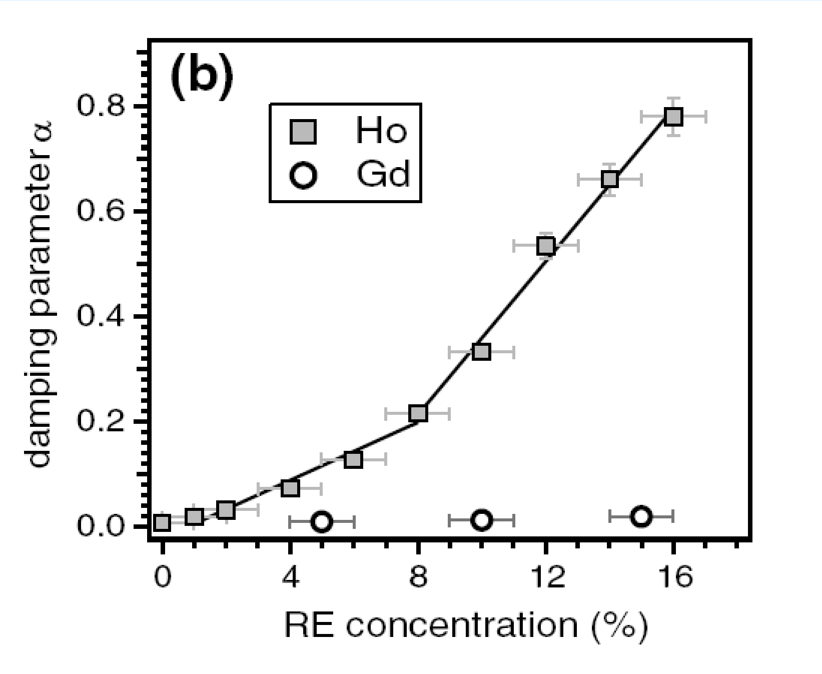
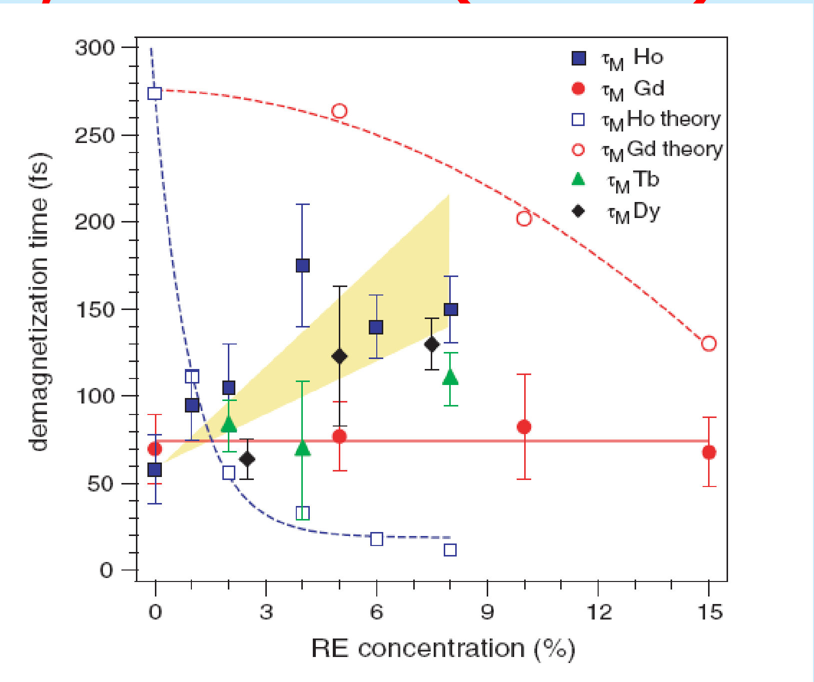
- Rare Earth doping increases the damping constant

Radu et al PRL 102, 117201 (2009)





- Experimental demagnetisation times increase with damping!
- Consistent with spin model if energy transfer predominantly via the FM spins
- No effect of Gd (isotropic).
- 'dominant fast relaxation process is slowed down by adding slow relaxing impurities.' (Radu et al)
- Complex energy transfer channels

Multiscale calculations and the LLB equation

- Large scale (micromagnetic) simulations essentially work with one spin/computational cell
- Single spin LLG equation cannot reproduce ultrafast reversal mechanisms at elevated temperature (conserves |M|)
- Pump- probe and HAMR simulations require an alternative approach
- Landau-Lifshitz-Bloch (LLB) equation?

LLB equation

Transverse (LLG) term

Longitudinal term introduces fluctuations of M

$$\dot{\mathbf{m}} = -\gamma[\mathbf{m}\times\mathbf{H}_{\text{eff}}] + \gamma\alpha_{\parallel}\frac{(\mathbf{m}\cdot\mathbf{H}_{\text{eff}})\mathbf{m}}{m^2} - \gamma\alpha_{\perp}\frac{[\mathbf{m}\times[\mathbf{m}\times\mathbf{H}_{\text{eff}}]]}{m^2}$$

- macro-spin polarization is $\mathbf{m} = \langle \mathbf{S} \rangle$
- longitudinal ($\alpha_{\parallel}$) and transverse ($\alpha_{\perp}$) damping parameters are given by $\alpha_{\parallel} = \alpha\frac{2T}{3T_c}$, $\quad \alpha_{\perp} = \alpha\left[1 - \frac{T}{3T_c}\right]$
- effective field:

$$\mathbf{H}_{\text{eff}} = \mathbf{H} - \frac{m_x\mathbf{e}_x + m_y\mathbf{e}_y}{\tilde{\chi}_{\perp}} + \begin{cases} \frac{1}{2\tilde{\chi}_{\parallel}}\left(1 - \frac{m^2}{m_e^2}\right)\mathbf{m}, & T \lesssim T_c \\ \frac{J_0}{\mu_s}\left(\epsilon - \frac{3}{5}m^2\right)\mathbf{m}, & T \gtrsim T_c \end{cases}.$$

here $\mathbf{H}$ is applied field and m_e is zero-field equilibrium spin polarization

the second term is an expression for the anisotropy field

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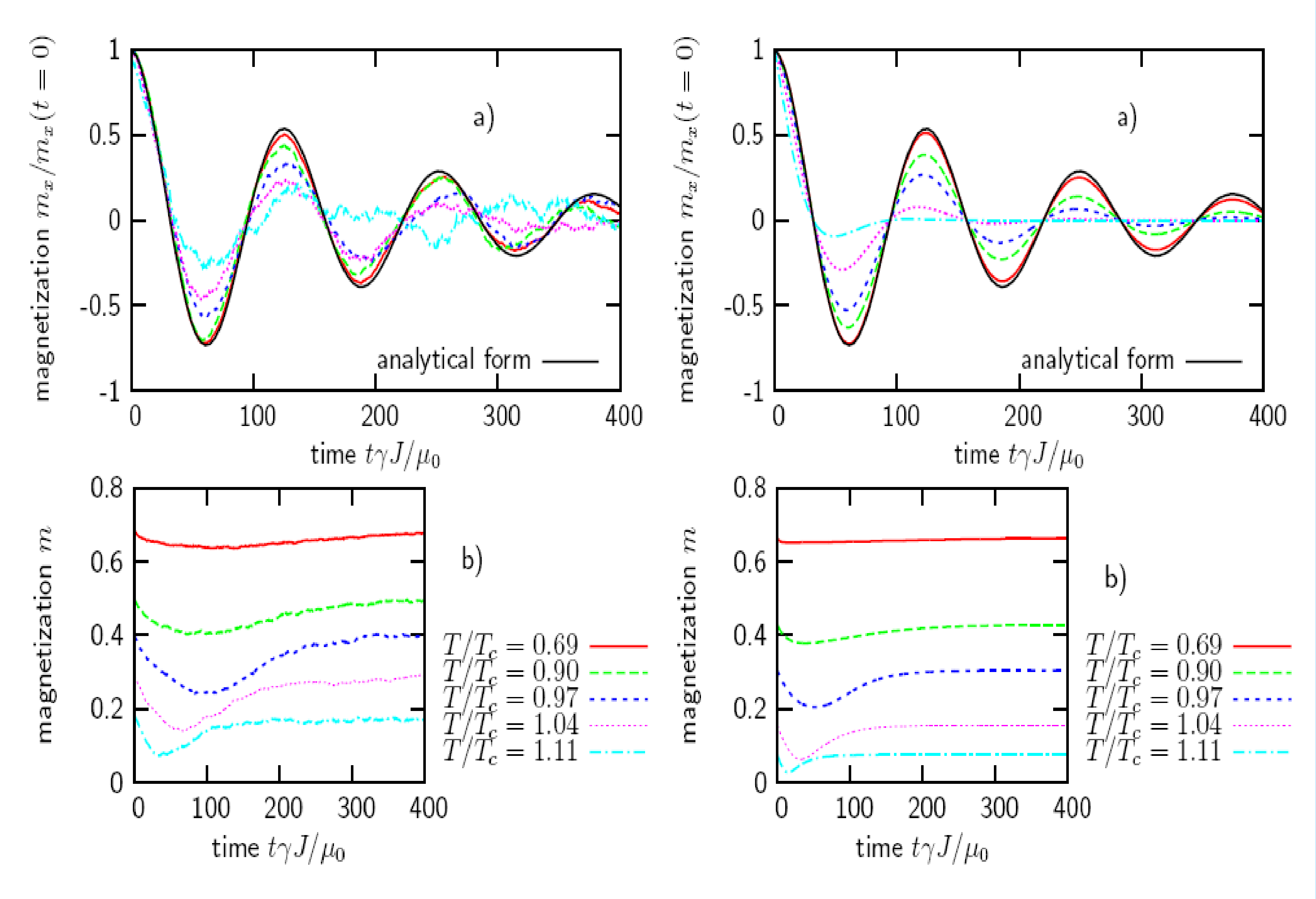

- Precessional dynamics for atomistic model (left) and (single spin) LLB equation (right)

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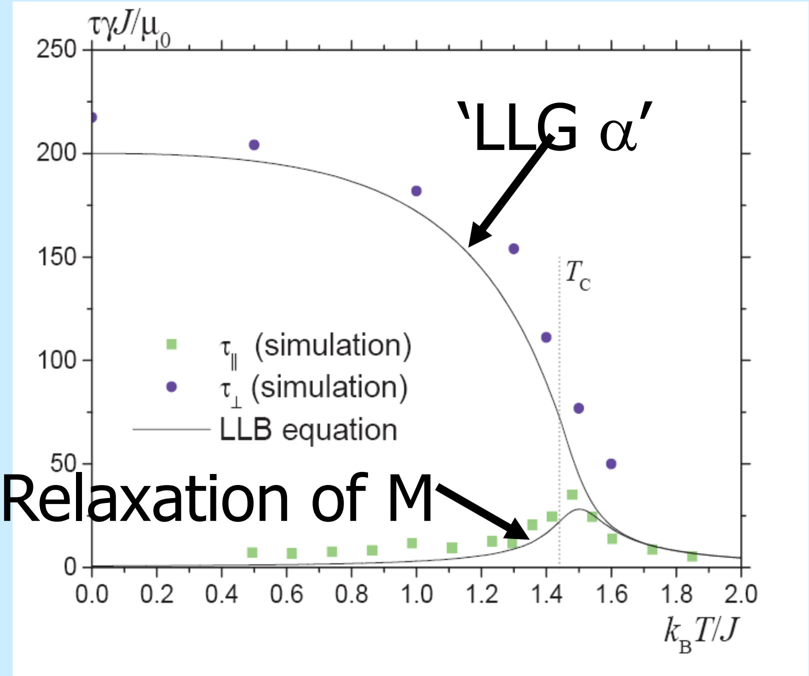
Relaxation times

- Critical slowing down at T_c
- Atomistic calculations remarkably well reproduced by the LLB equation
- Longitudinal relaxation is in the ps regime except very close to T_c



•Effective α increases with T (observed in FMR experiments)

•NB – single (temperature independent) value of λ. Increased damping arises from transfer of energy into spinwave modes.

•LLB equation seems a good candidate to replace LLG equation in micromagnetic models of ultrafast processes.

LLB parameters

- Important parameters are;
  - Longitudinal and transverse susceptibility
  - K(T), M(T)
- These can be determined from Mean Field theory.
- Also possible to determine the parameters numerically by comparison with the Atomistic model.
- In the following we use numerically determined parameters in the LLB equation and compare the dynamics behaviour with calculations from the atomistic model.

Opto-magnetic reversal

PRL 99, 047601 (2007) PHYSICAL REVIEW LETTERS week ending 27 JULY 2007

All-Optical Magnetic Recording with Circularly Polarized Light

C. D. Stanciu,[1,*] F. Hansteen,[1] A. V. Kimel,[1] A. Kirilyuk,[1] A. Tsukamoto,[2] A. Itoh,[2] and Th. Rasing[1]

[1]*Institute for Molecules and Materials, Radboud University Nijmegen, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands*

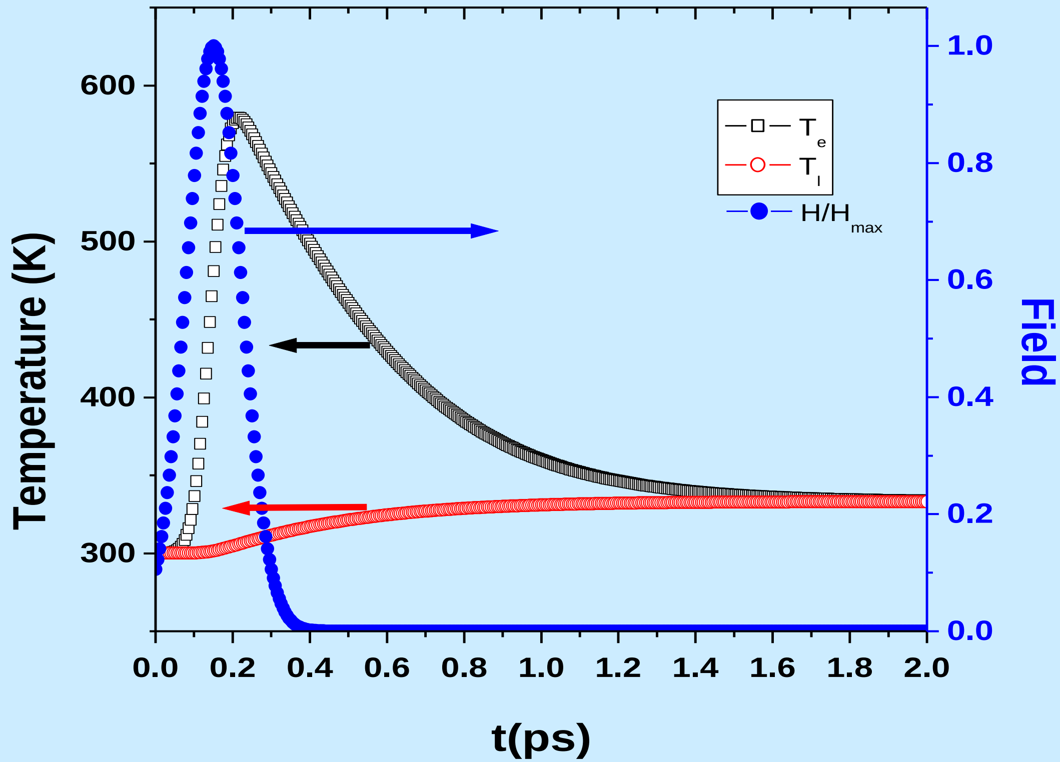
[2]*College of Science and Technology, Nihon University, 7-24-1 Funabashi, Chiba, Japan*

(Received 2 March 2007; published 25 July 2007)

We experimentally demonstrate that the magnetization can be reversed in a reproducible manner by a single 40 femtosecond circularly polarized laser pulse, without any applied magnetic field. This optically induced ultrafast magnetization reversal previously believed impossible is the combined result of femtosecond laser heating of the magnetic system to just below the Curie point and circularly polarized light simultaneously acting as a magnetic field. The direction of this opto-magnetic switching is determined only by the helicity of light. This finding reveals an ultrafast and efficient pathway for writing magnetic bits at record-breaking speeds.

- What is the reversal mechanism?
- Is it possible to represent it with a spin model?

Fields and temperatures



- Simple '2-temperature' model
- Problem – energy associated with the laser pulse (here expressed as an effective temperature) persists much longer than the magnetic field.
- Equlibrium temperature much lower than T_c

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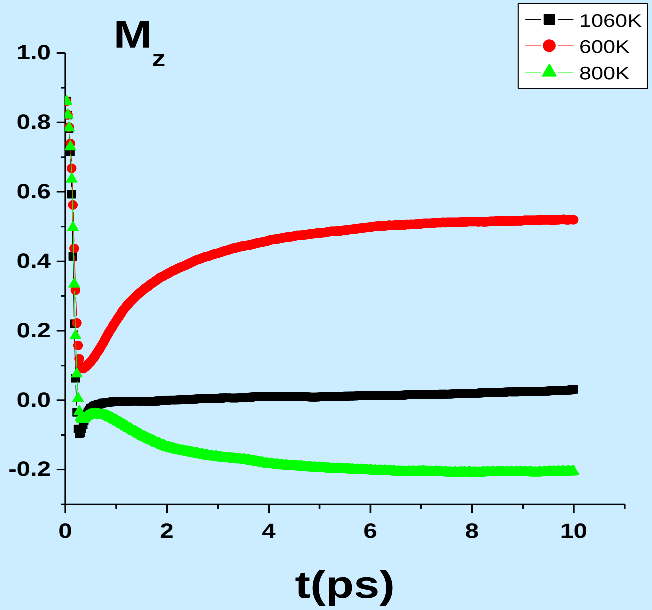
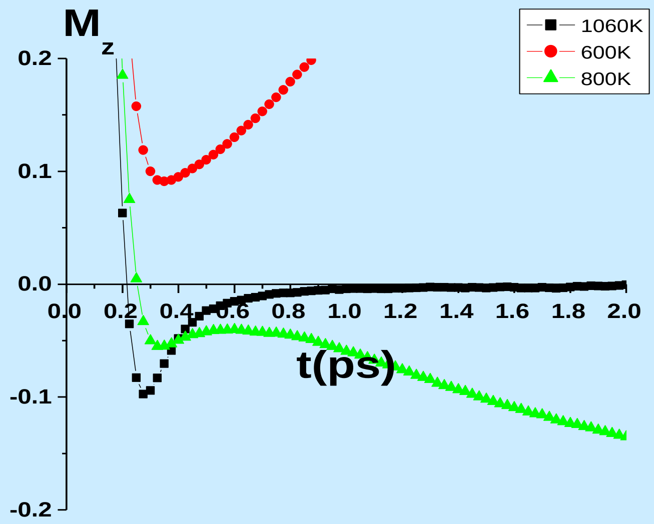
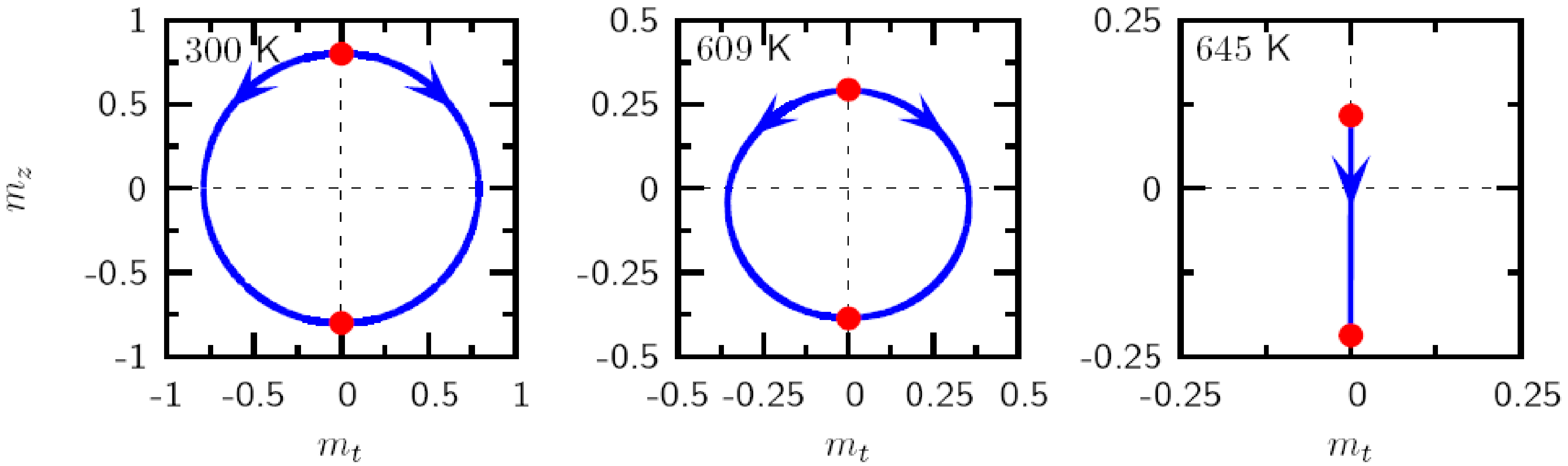
Magnetisation dynamics (atomistic model)





- ***Reversal is non-precessional*** – m_x and m_y remain zero. ***Linear reversal mechanism***
- Associated with increased magnetic susceptibility at high temperatures
- Too much laser power and the magnetisation is destroyed after reversal
- Narrow window for reversal

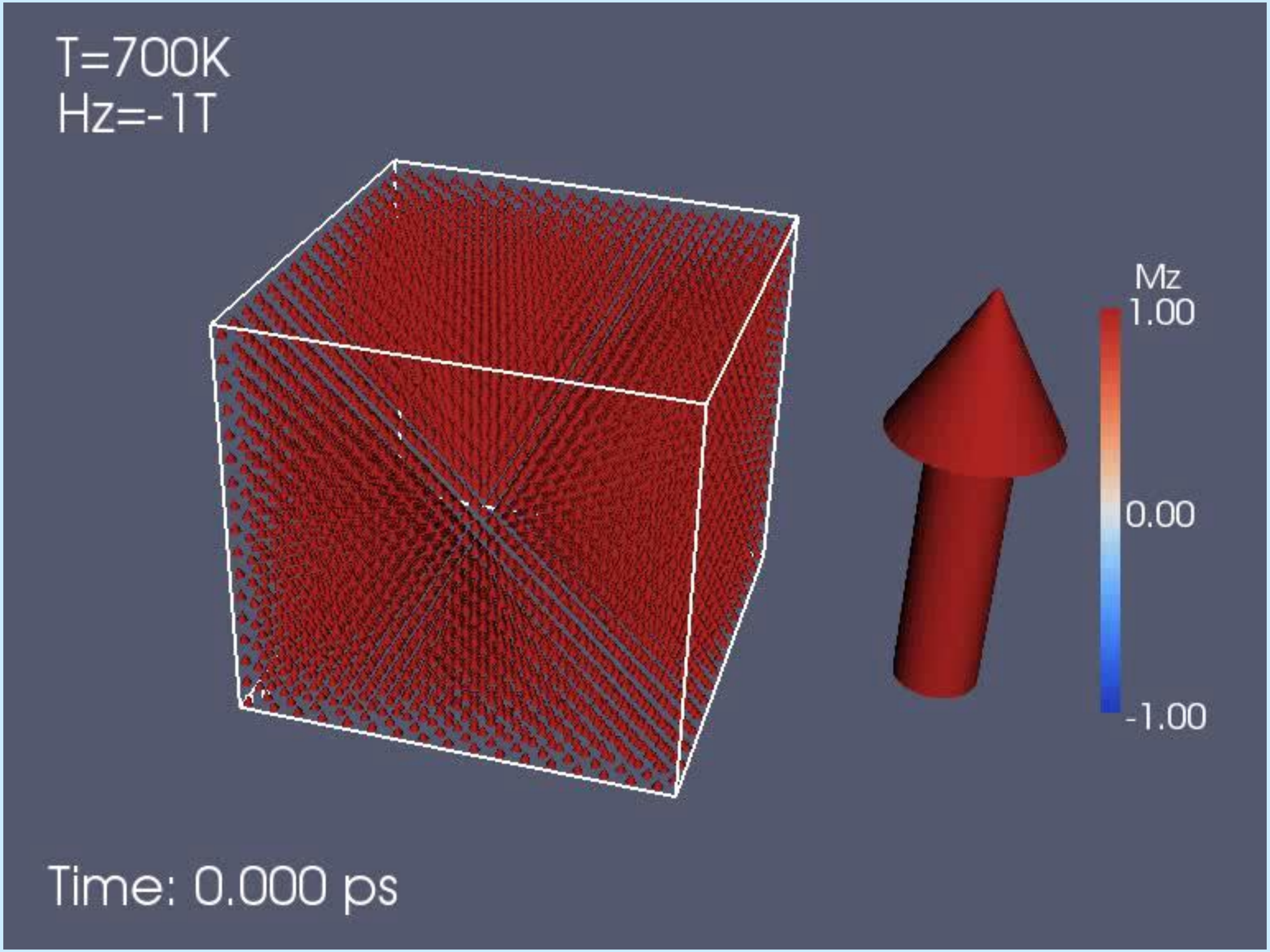
Linear reversal



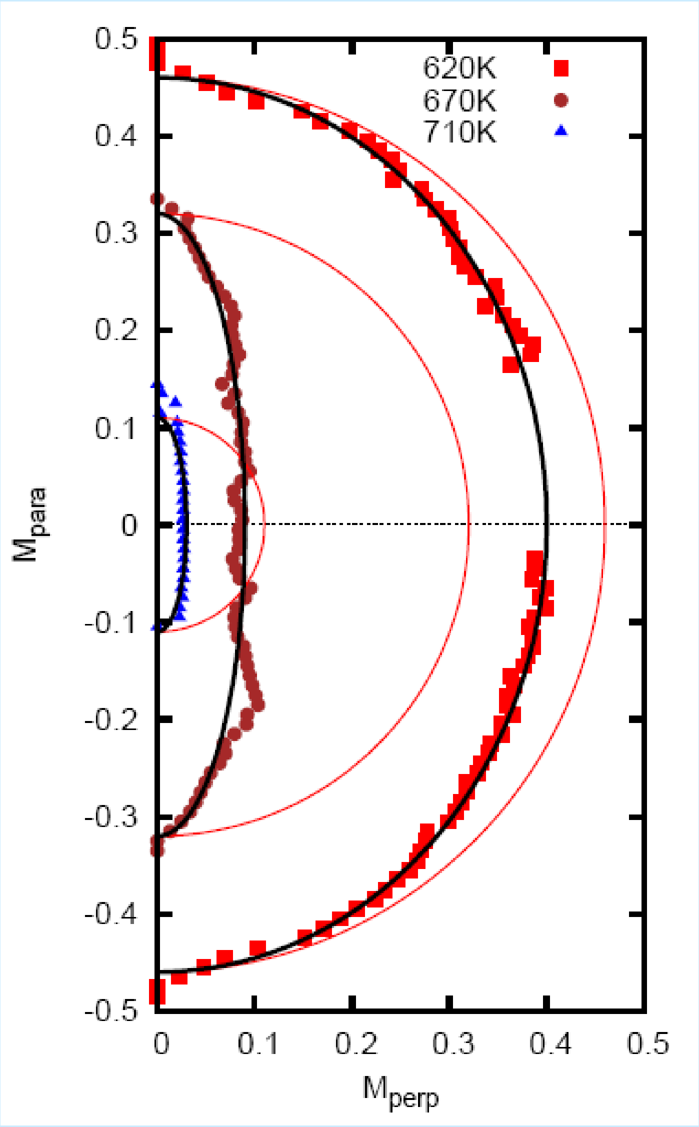
New reversal mechanism via a strongly non-uniform (demagnetised) state.

VERY fast (timescale of longitudinal relaxation)

Micromagnetics with LLG equation cannot reproduce behaviour

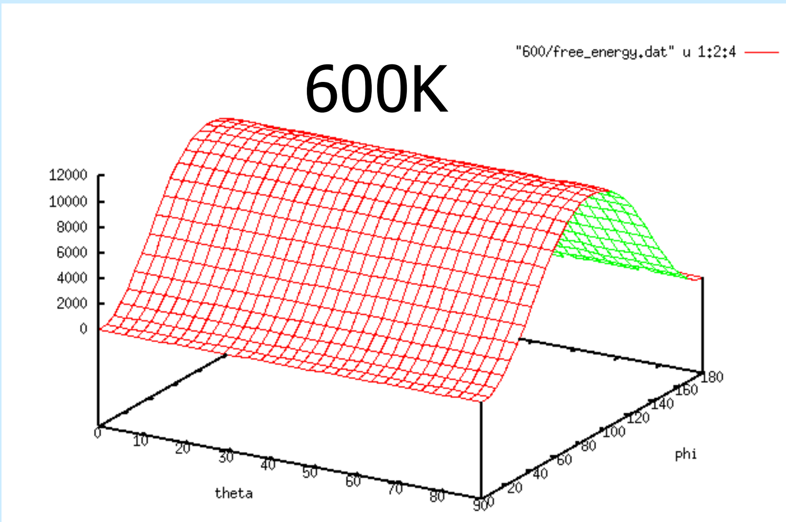

T=700K
Hz=-1T
Mz
1.00
0.00
-1.00
Time: 0.000 ps

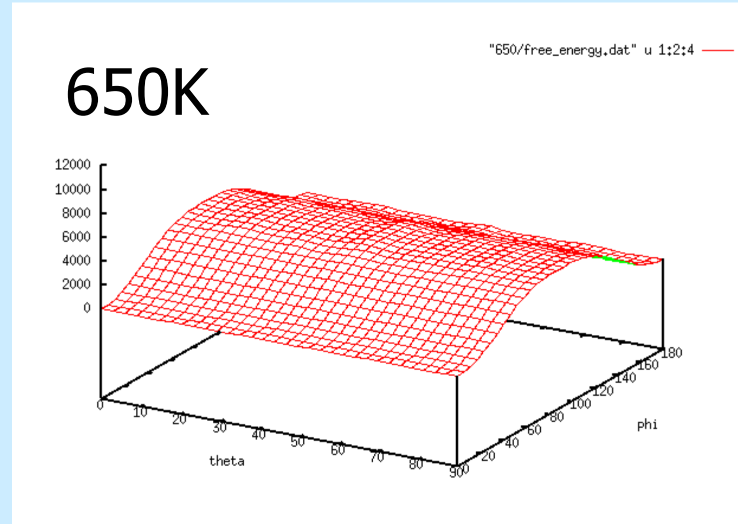
Transition from circular to linear reversal
(J Barker et. al, Appl. Phys Lett., 97, 192504 (2010))

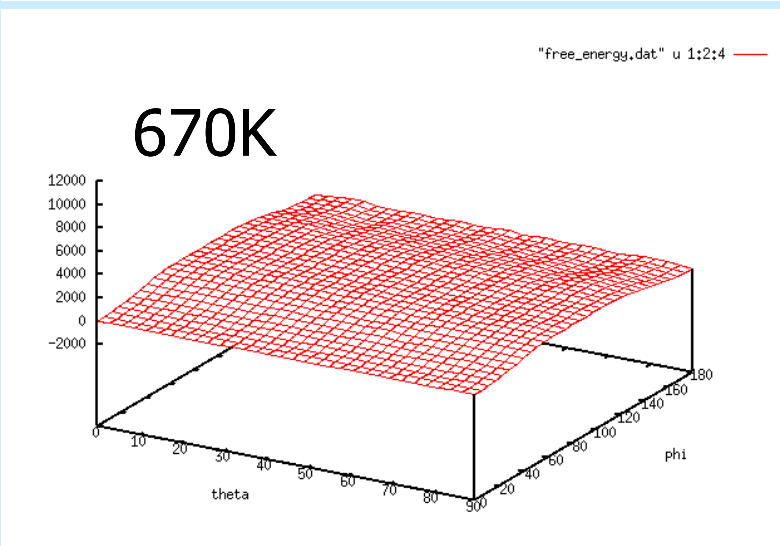


- At 620K KV/kT=85 – no reversal
- NB, timescale of calculation is 1 ns – KV/kT needs to be around 2 for reversal!
- Reversal occurs at 670K, where KV/kT=60.
- Effective energy barrier for linear reversal much lower than for coherent rotation.

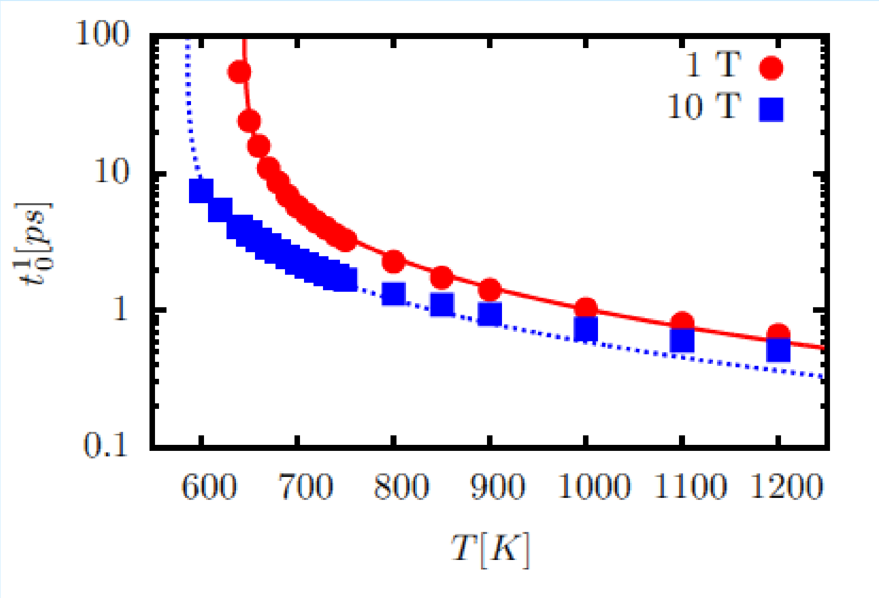
Energy barriers (constrained MC method, P. Asselin et. al. Phys. Rev. B, 82, 054415 (2010))

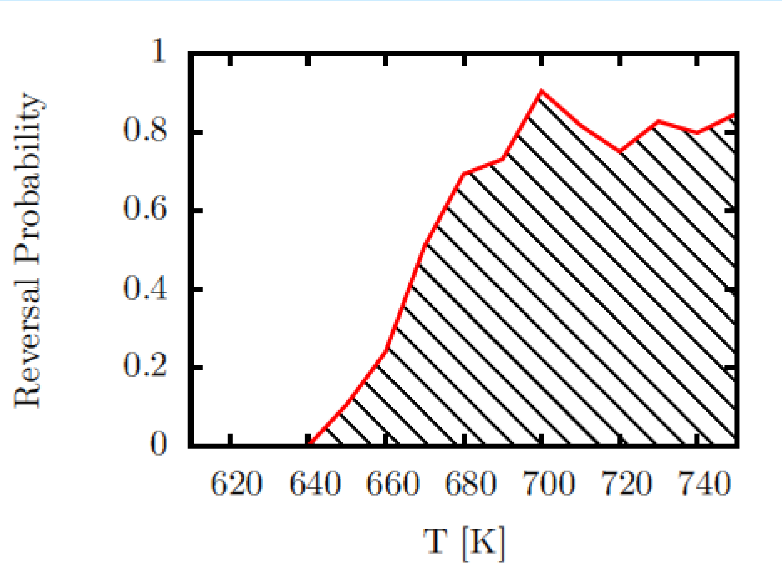






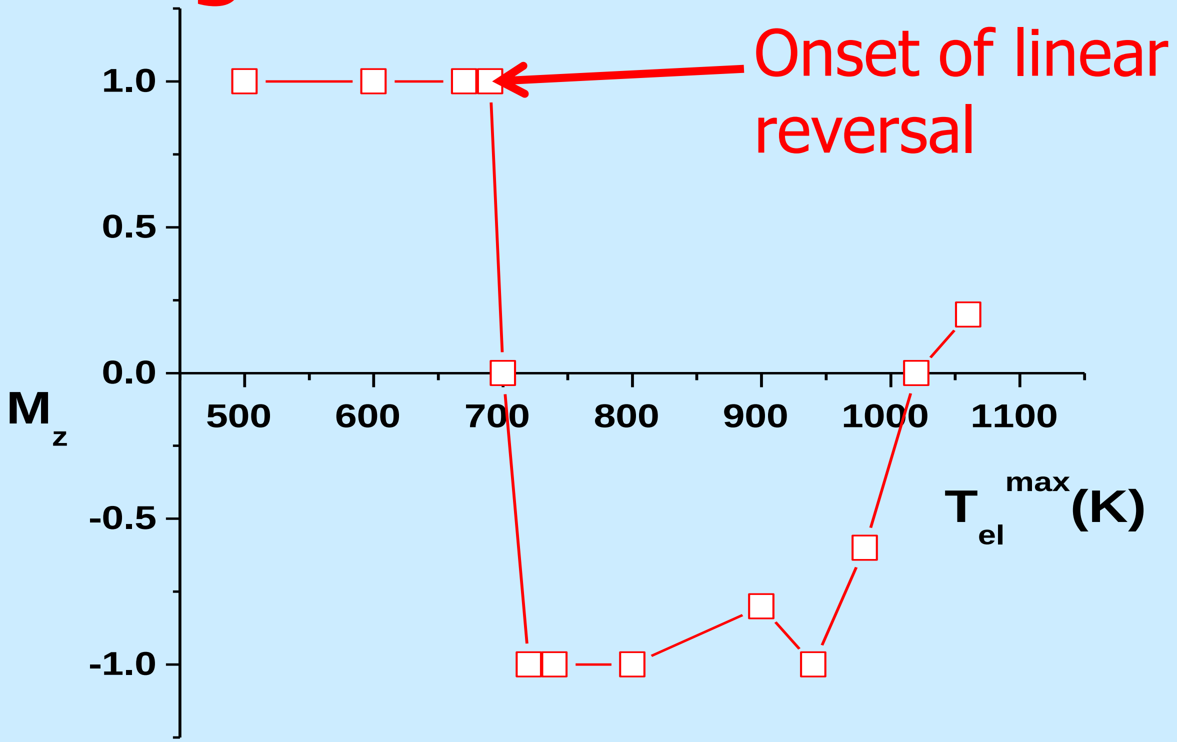
Rapid reduction in energy barrier in linear reversal regime





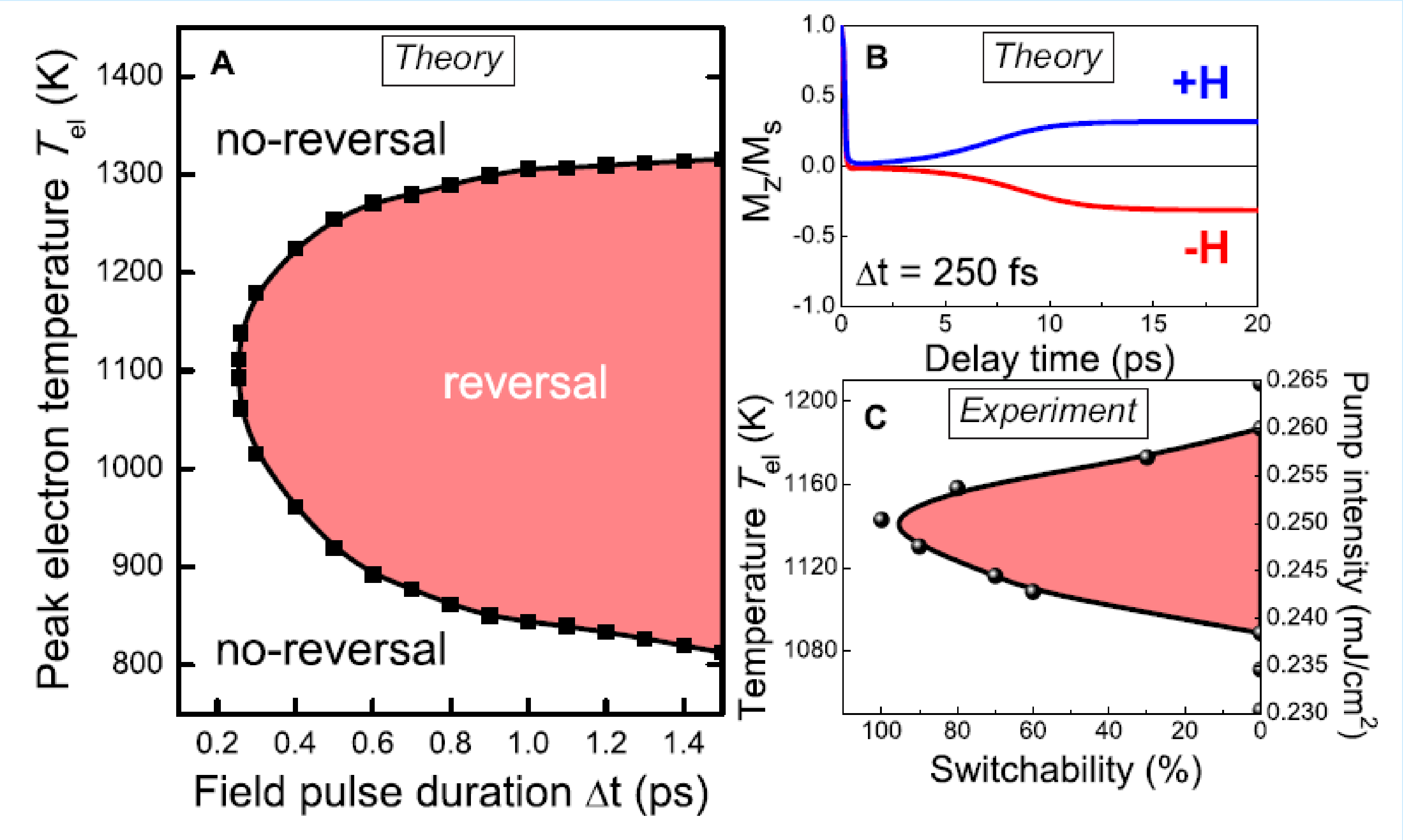
- Calculated relaxation times in good agreement with analytical theory (N. Kazantseva at. al., Europhys. Lett., 86, 27006 (2009)) – solid lines.

Optomagnetic‘Reversal window’



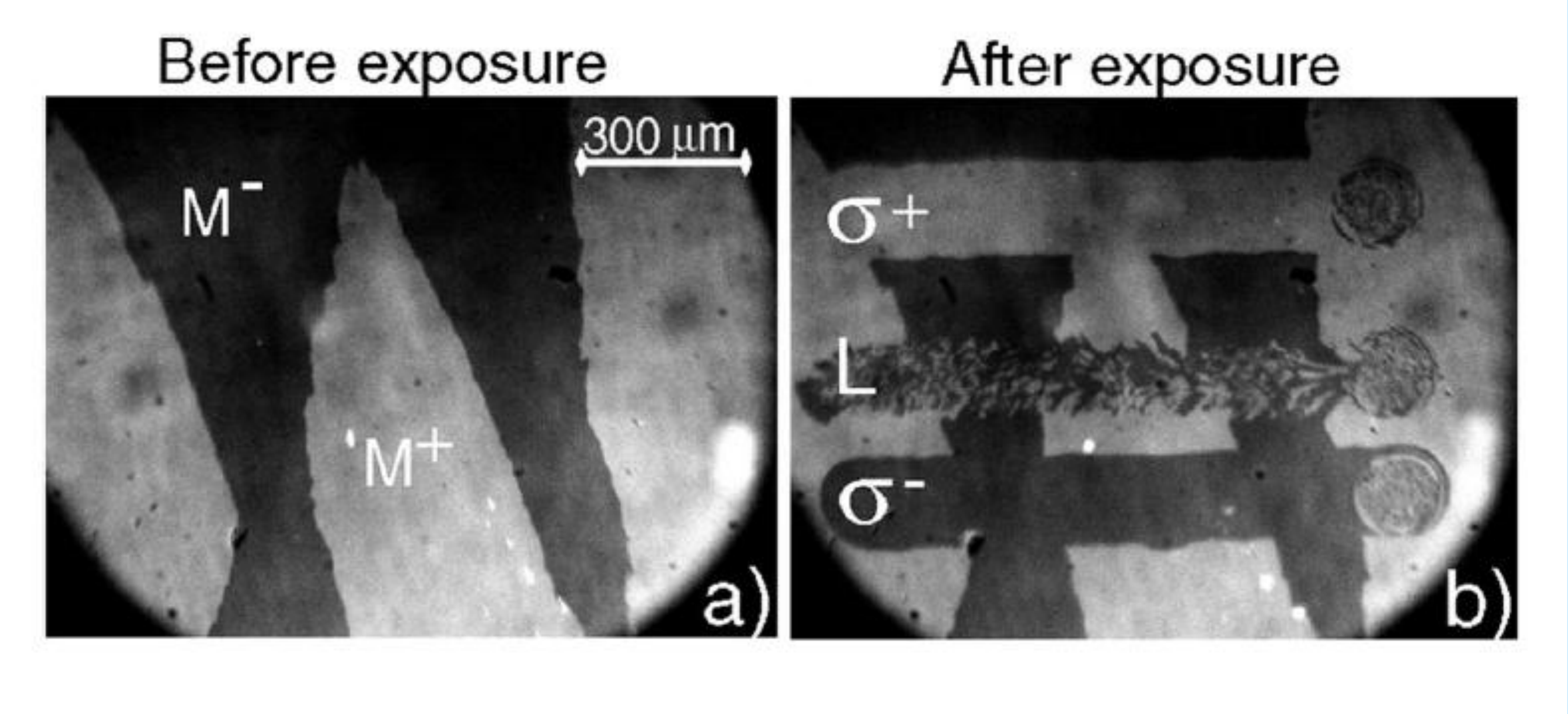
- Well defined temperature range for reversal
- Critical temperature for the onset of linear reversal
- BUT atomistic calculations are very CPU intensive
- LLB micromagnetic model used for large scale calculations

Reversal 'phase diagram'
Vahaplar et al Phys. Rev. Lett., 103, 117201 (2009)

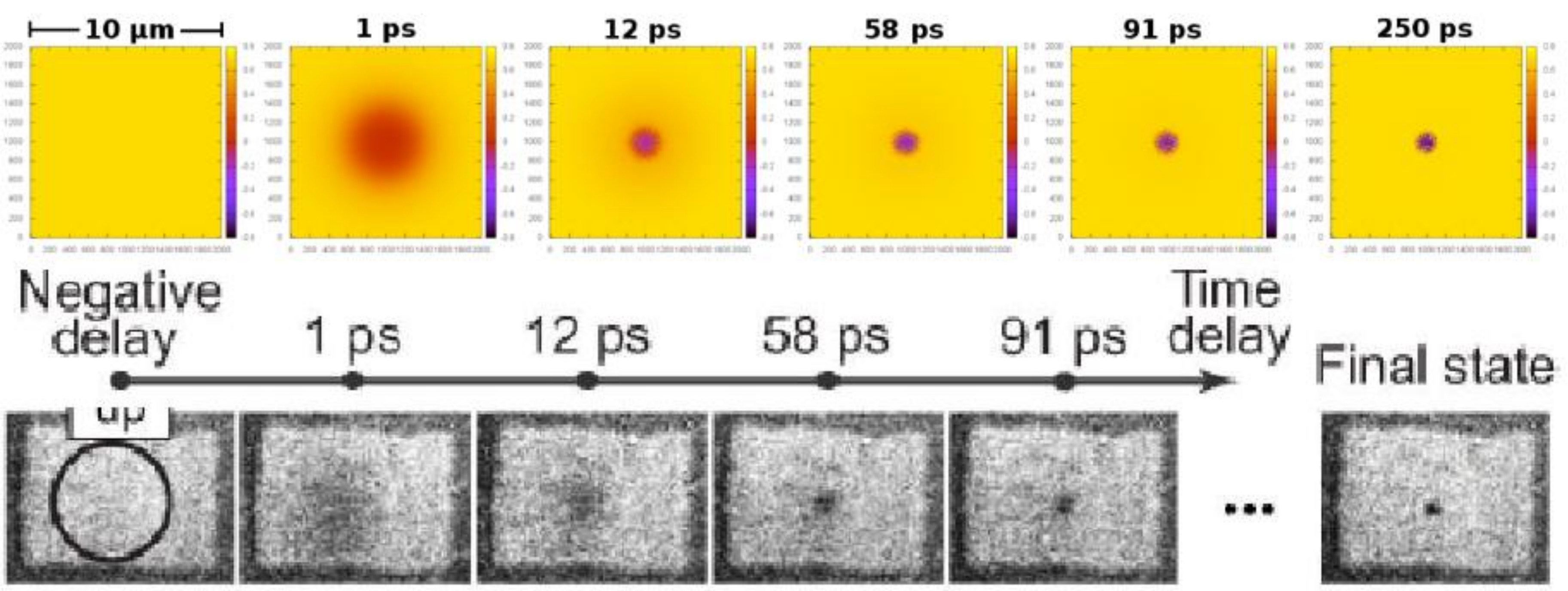


- Note the criticality of the experimental results
- Characteristic of linear reversal

Further evidence

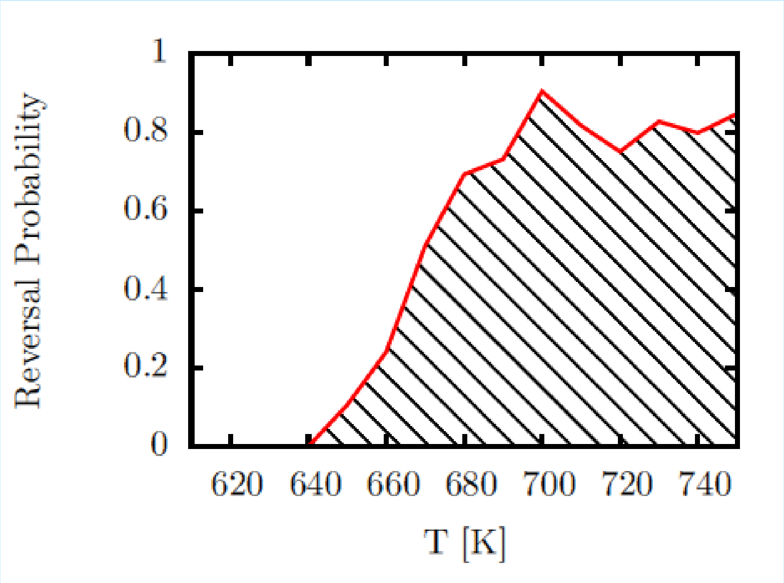


Large scale simulations (LLB micromagnetics)



- Top – LLB μ–Mag model predictions
- Bottom – experiments (Nijmegen group)

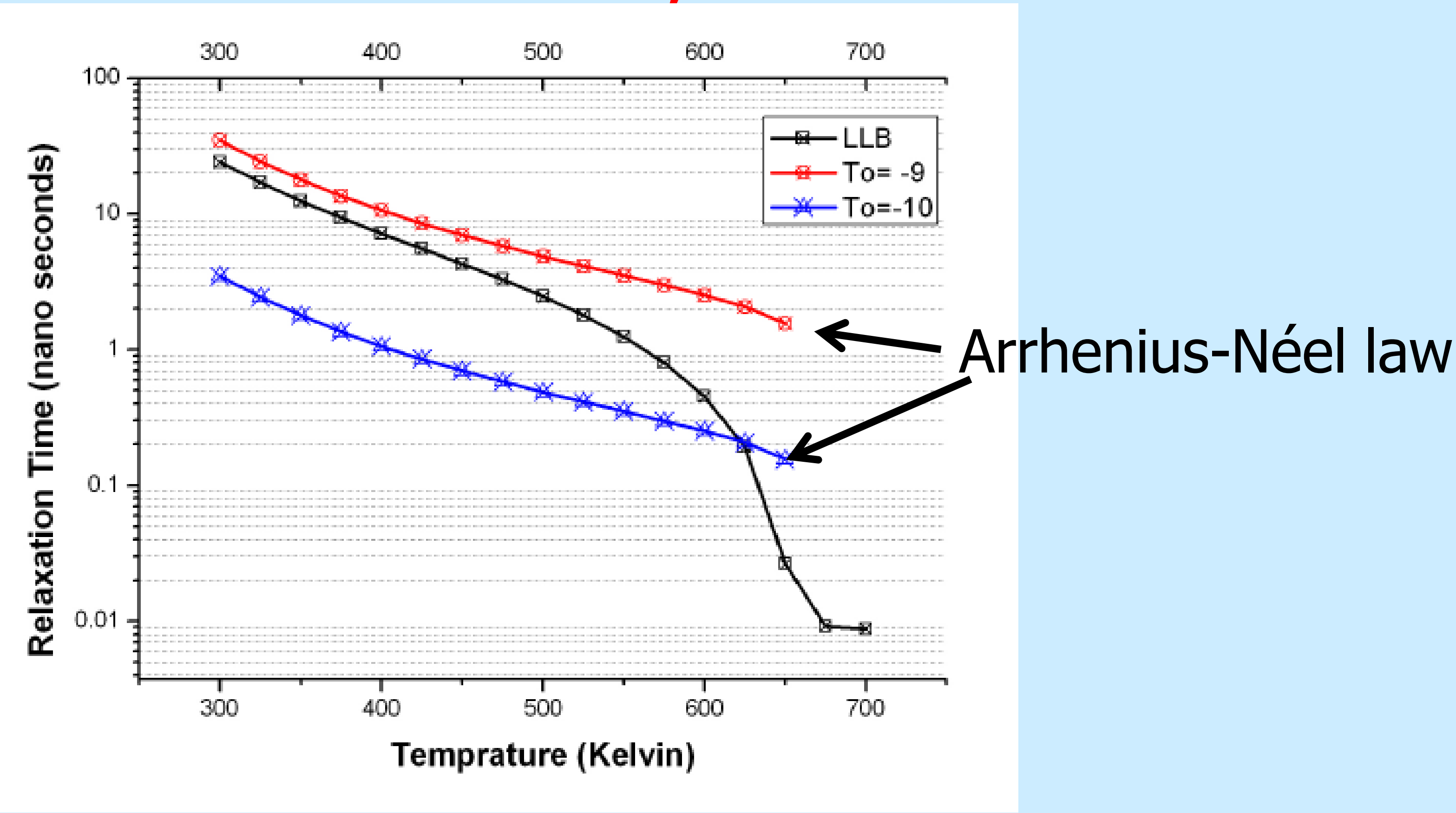
Linear reversal and HAMR



- Sharp transition at onset of linear reversal mechanism

- Transition to linear reversal gives sharp increase in probability of reversal into the field direction
- Good way to record
- Needs LLB-micromagnetic approach rather than LLG for recording models

Relaxation times; 6nm diam FePt



- Rapid decrease in linear reversal regime
- Note the failure of the Arrhenius-Néel law

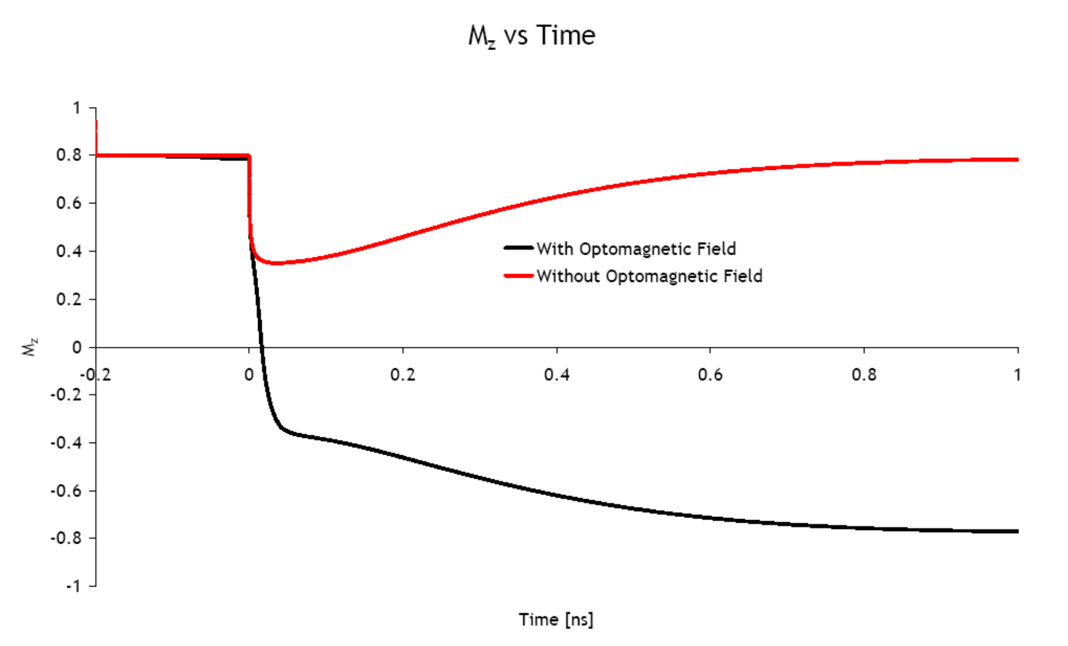
Implications for HAMR

- Rapid decrease of energy barrier due to linear reversal could be important
- Recording models should use LLB formalism
- Fast switching via linear reversal – possibility of extremely high data rates.
- All optical recording using the optomagnetic effect?

What if ....

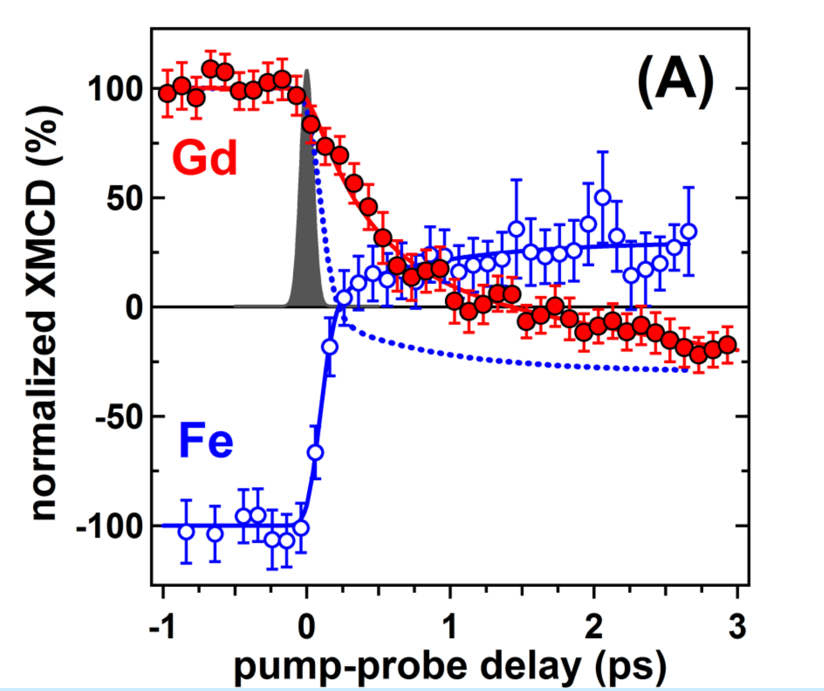
- It seems that the optomagnetic effect is biggest for intense pulses and very optically active materials
- What if
  - A smaller field were present in FePt
  - The direction of the laser were oriented at some angle to the perpendicular
  - We have done calculations assuming a field of 1T oriented at 45 deg.

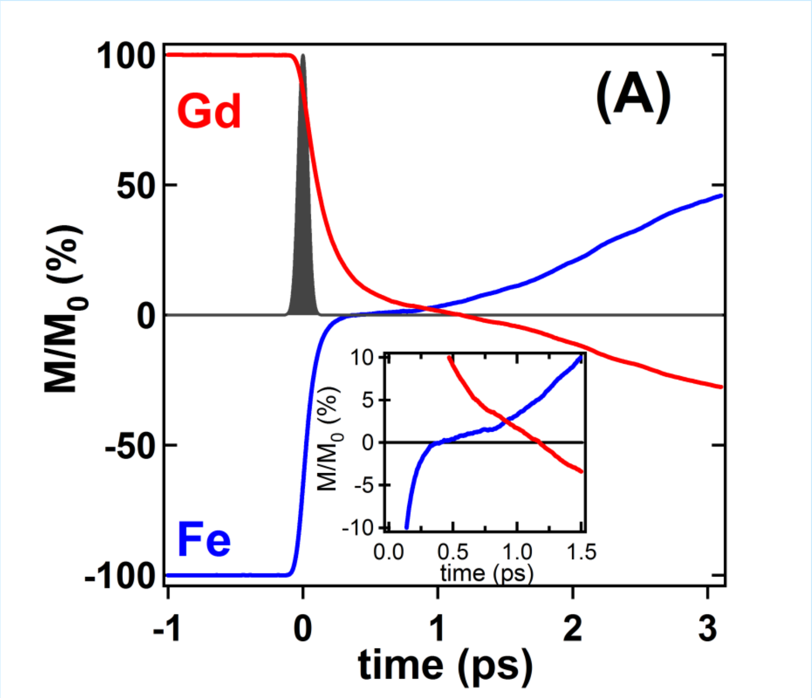
TOASTR
(Thermally and Optically Assisted Switching TRansitions)



- The maximum temperature was 600K
- successful reversal for conventional HAMR requires at least Tc (660K)
- Would require localised circularly polarised light – big challenge

Linear reversal in GdFeCo
(I. Radu et. al., Nature, 472, 205 (2011))





- Experiments (left) in good agreement with atomistic model calculations (right)

Differential sublattice demagnetisation

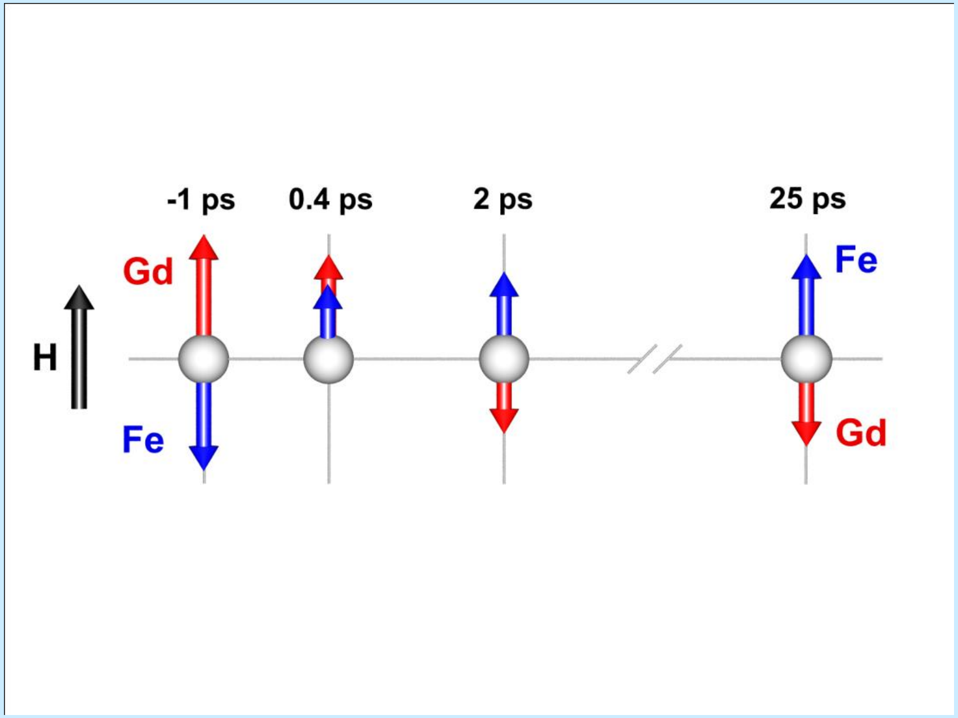
- TM and RE sublattices demagnetise at different rates *irrespective of the exchange interaction*.
- According to N. Kazantseva et. al., Europhys. Lett., 81, 27004 (2008), the demagnetisation time

$$\tau_D = \mu_s / \alpha$$

where μ_s is the atomic spin and α is the damping constant

- Consistent with experiments

BUT



- Sublattices do not act independently
- Remarkable transient FM state produced for about 400fs!
- Seems to drive magnetisation reversal………

Conclusions

- Atomistic model has been developed using Heisenberg exchange.
- The Landau-Lifshitz-Bloch (LLB) equation incorporates much of the physics of the atomistic calculations
- LLB-micromagnetics is shown to be successful in simulating ultrafast dynamics at elevated temperatures. Important for pump-probe simulations and models of HAMR. Also thermally assisted MRAM?
- New (linear) reversal demonstrated with sub-picosecond reversal times
- Demonstrates the probable thermodynamic origin of Opto-Magnetic reversal.
- Atomistic model also predicts transient FM state in the ultrafast reversal of GdFeCo

End of the story? Not quite!

- Calculations suggest a thermodynamic contribution to ultrafast dynamics (linear reversal).
- But
  - Energy transfer channels are not well represented
  - What is the origin of the field – Inverse Faraday Effect?
  - Electron/phonon coupling plays a role
  - Role of the R-E – is this important?
- These require detailed studies at the ab-initio level – the multiscale problem still remains!