Magnetization dynamics for the layman: Experimental

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With the most generous help of Burkard Hillebrands
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Magnetization dynamics (classical description)

Landau-Lifshitz-Gilbert equation of magnetization motion

$$\frac{d\mathbf{M}}{dt} = -g_0\left[\mathbf{M}\times\mathbf{H}_{eff}\right] + \frac{a}{M_s}\left[\mathbf{M}\times\frac{d\mathbf{M}}{dt}\right]$$

g_0 : gyromagnetic ratio

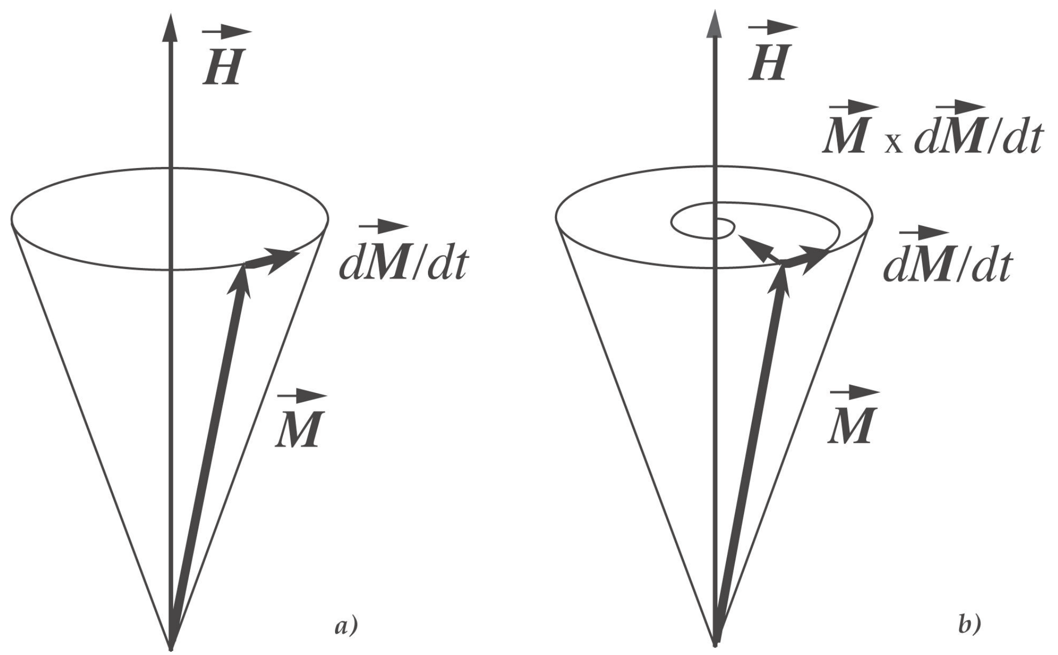
$\mathbf{H}_{eff}$: acting effective magnetic field (embedding the pulsed field)

a : Gilbert damping parameter

$$a = 0$$

$$\frac{d}{dt}\mathbf{M}^2(t) = 0$$

$$\frac{d}{dt}\left[\mathbf{M}(t)\cdot\mathbf{H}\right] = 0$$



$$a \neq 0$$

Magnetization dynamics (Cont'd)

Landau-Lifshitz equation with damping

$$\left(1+a^{2}\right)\frac{d\mathbf{M}}{dt}=-g_{0}\left[\mathbf{M}\times\mathbf{H}_{eff}\right]-\frac{a\,g_{0}}{M_{s}}\left\{\mathbf{M}\times\left[\mathbf{M}\times\mathbf{H}_{eff}\right]\right\}$$

Bloch-Bloembergen Equation

$$\frac{dM_{x,y}}{dt}=-g_{0}\left[\mathbf{M}\times\mathbf{H}_{eff}\right]_{x,y}-\frac{M_{x,y}}{T_{2}}$$

$$\frac{dM_{z}}{dt}=-g_{0}\left[\mathbf{M}\times\mathbf{H}_{eff}\right]_{z}-\frac{M_{z}}{T_{1}}$$

T_1 : Longitudinal relaxation time

T_2 : Transverse relaxation time

Magnetization dynamics (Cont'd)

Spin waves formalism : kinetic equations (valid for exchange dominated spin waves)

$$M = M_s - g_0 \hbar\, n'$$

$$M_z = M_s - g_0 \hbar (n_0 + n')$$

n_0 : Number of magnons with $k = 0$ (infinite wavelength)

n' : Number of all other magnons

Consider the following rate equations as an example (˜ "*TWO Magnons Model*"):

$$\frac{dn_0}{dt} = -(l_{0k} + l_{0s})n_0$$

$$\frac{dn'}{dt} = l_{0k} n_0 - l_{ks}\, n'$$

Where,

l_{0k} is the probability of destruction of a $k = 0$ magnon with the production of a $k \neq 0$ magnon,

l_{0s} and l_{ks} are the probability of disappearance of $k = 0$ and $k \neq 0$ magnons, respectively

Magnetization dynamics (Cont'd)

Combining :

$$M = M_s - g_0 \hbar n'$$
$$M_z = M_s - g_0 \hbar (n_0 + n')$$

and

$$\frac{dn_0}{dt} = -(l_{0k} + l_{0s})n_0$$
$$\frac{dn'}{dt} = l_{0k} n_0 - l_{ks} n'$$

One gets for the ***sole damping term*** :

$$\frac{dM}{dt} = -l_{0k}(M - M_z) + l_{ks}(M_s - M)$$
$$\frac{dM_z}{dt} = +l_{0s}(M - M_z) + l_{ks}(M_s - M)$$

Magnetization dynamics (Cont'd)

I. *Thus, depending on the formalism, one may define ONE, TWO or MORE parameters defining damping processes .....*

II. *This problem remains a yet unsolved issue of spin dynamics*

Small Excitations

I. *FMR in inhomogeneous films : a numerical experiment*

II. *Local dynamics*

III. *Spin waves quantization and localization*

IV. *Magnetic noise spectra*

FMR in inhomogeneous films

A ferrromagnetic resonance experiment measures both a resonance frequency and a line width.

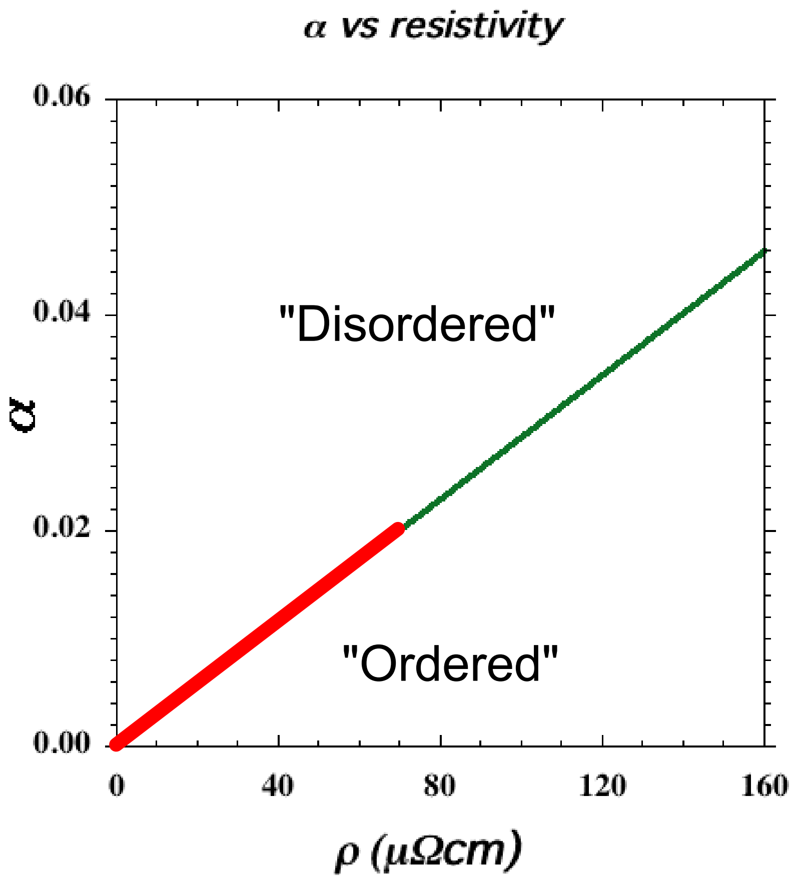
The latter reflects the effects of both damping AND inhomogeneity.

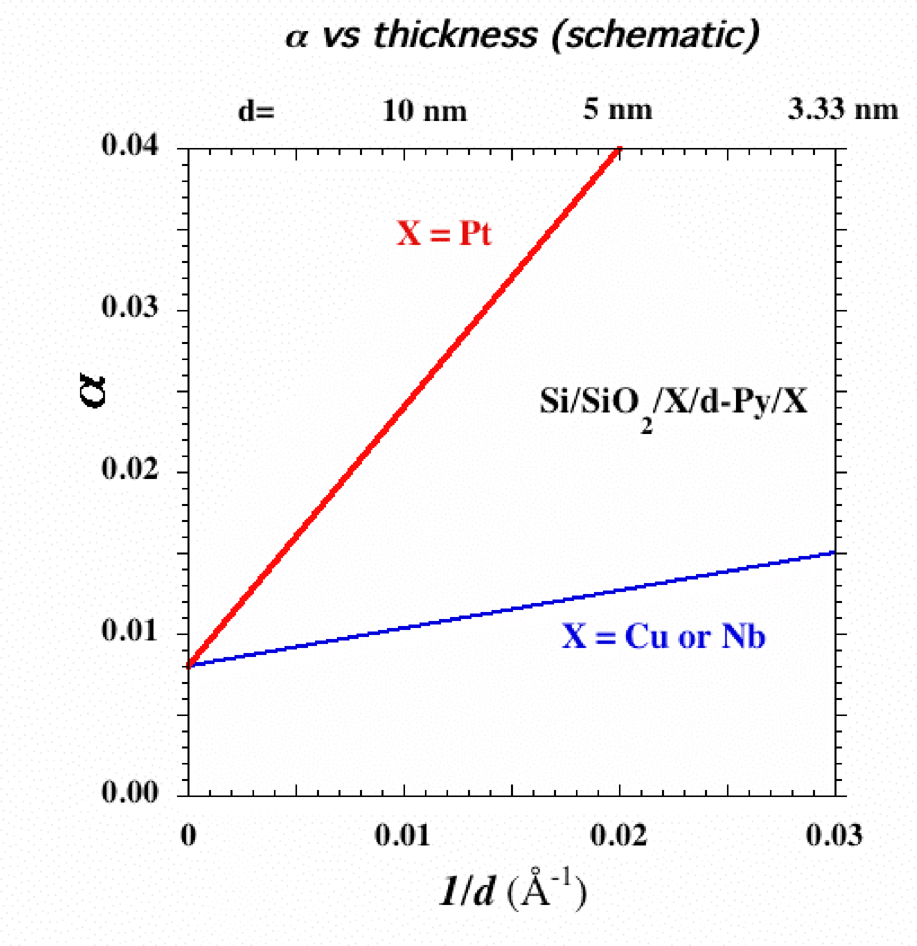
In the ***absence of inhomogeneities***, the damping parameter is, within the LLG formalism, related to the derivative of the absorbed power through:

$$a = \sqrt{3} g_0 DH_{pp} / 2w_r$$

For weak inhomogeneities treated as perturbations, the two-magnon model has been considered valid [?], whereas for large inhomogeneities the linewidth may be considered as a superposition of linewidths from independently resonating regions.

a ? *(schematic)*





- α directly correlated to electron scattering

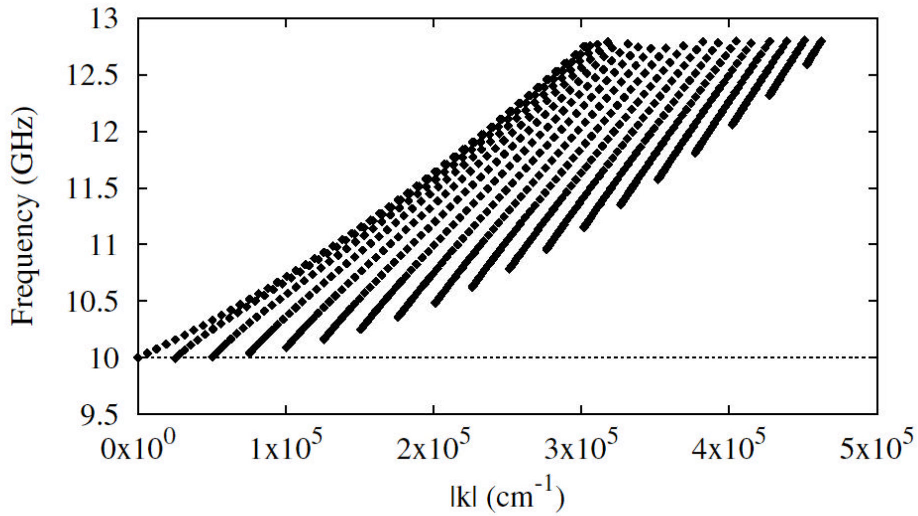
S. Ingvarsson et al. CondMat 0208207

See also: S. Mizukami et al. Jap. J. Appl. Phys. **40** (2001) 580

Multimode damping in inhomogeneous films

Dealing with inhomogeneities:

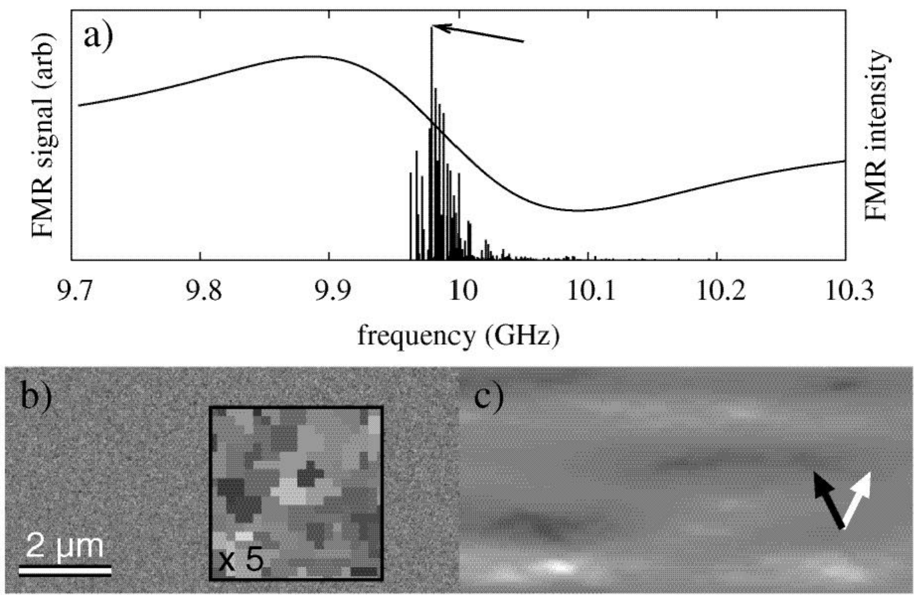
Calculation of eigenmodes in films taking defects into account

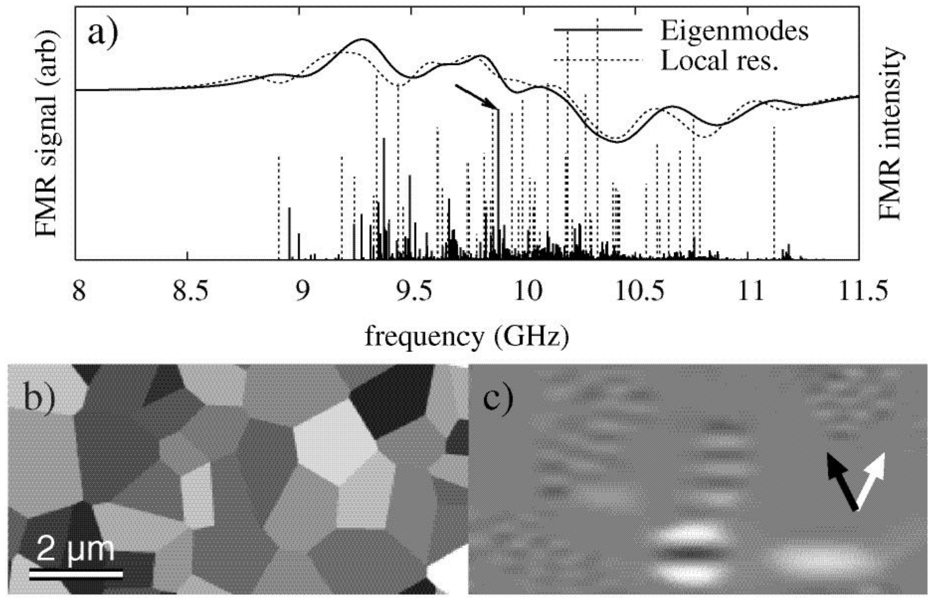


Precession frequencies of 3001 spin waves with resonant frequencies closest to the uniform resonance mode

R.D. McMichael, D.J. Twisselmann, A. Kunz, PRL **90**, 227601 (2003)

Multimode damping in inhomogeneous films



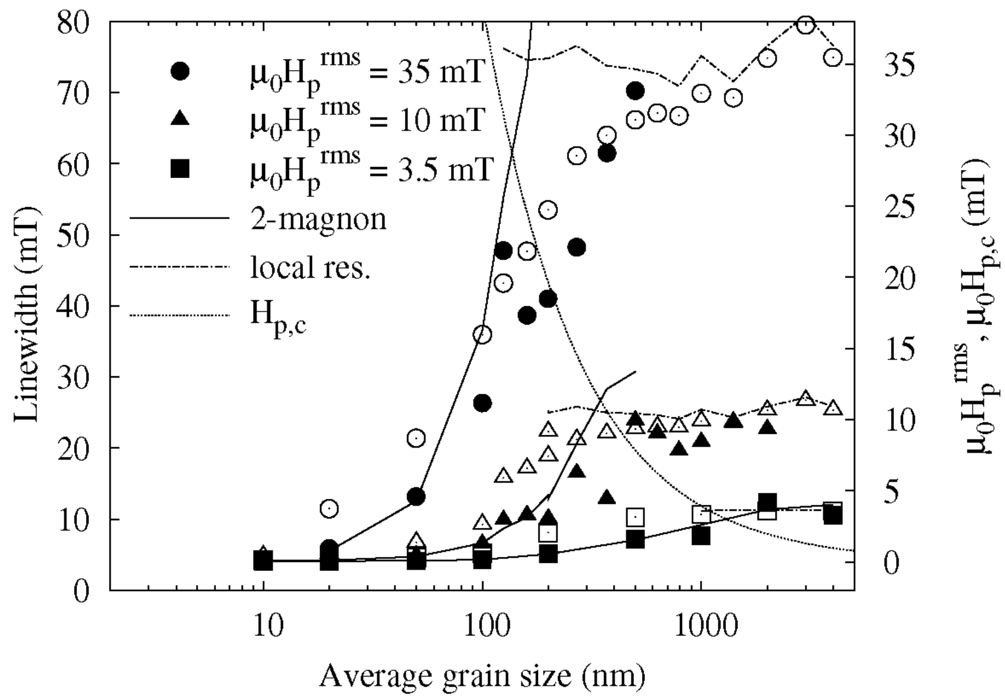


I. ***FMR signals are simulated by replacing each eigenmode spike with a Lorentzian peak with FWHM given by the LLG linewidth for α=0.01.***

II. ***This process makes use of a single damping coefficient***

R.D. McMichael, D.J. Twisselmann, A. Kunz,
PRL **90**, 227601 (2003)

Multimode damping in inhomogeneous films



I. ***Results exhibit a clear transition from a "TWO-Magnon" type behaviour to a "LOCAL Resonance" mode***

II. ***No comparison to experimental results, yet***

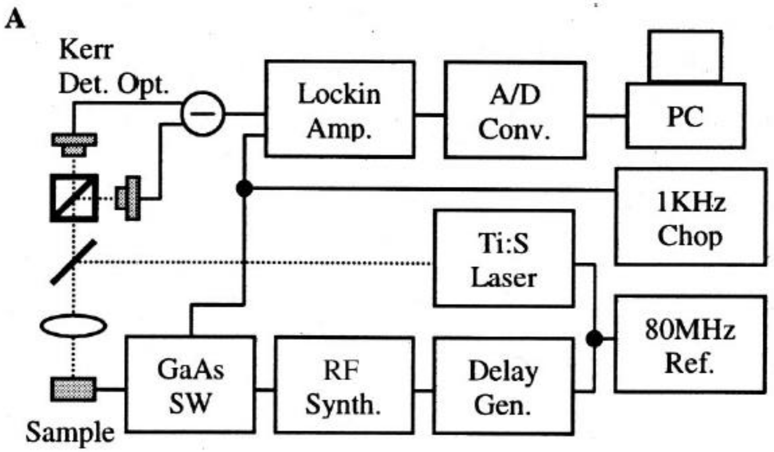
R.D. McMichael, D.J. Twisselmann, A. Kunz,
PRL **90**, 227601 (2003)

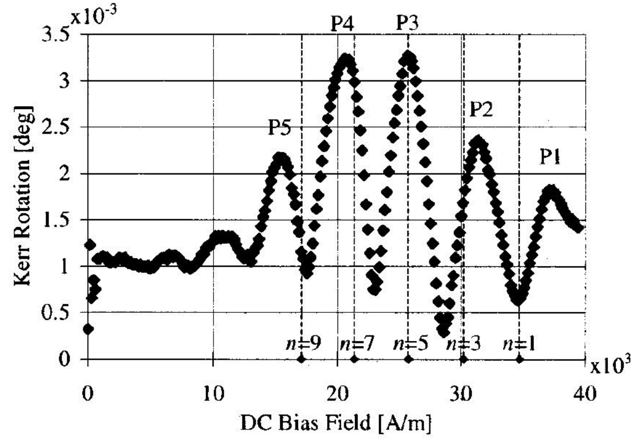
Local dynamics in square Py elements

Quantized magnetostatic modes under high frequency drive field

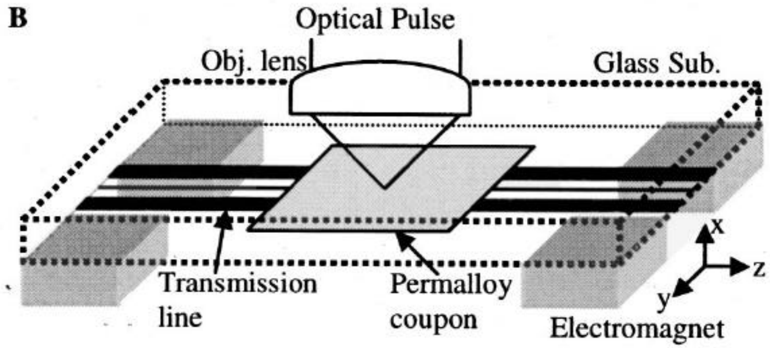
Spatially resolved FMR-Kerr-Microscopy:

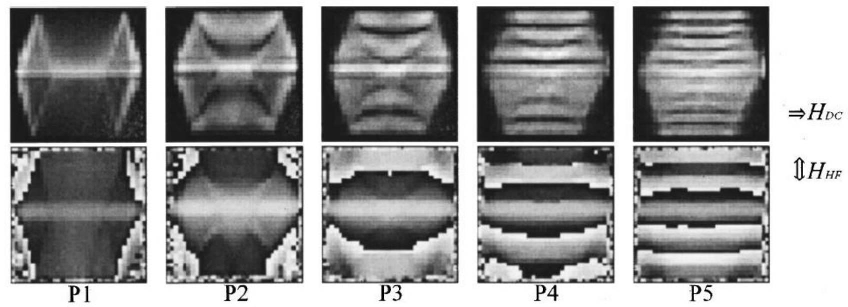
Synchronization of laser pulses with microwave source





Response at the center of a 50*50 µm2 Py square, 100 nm thick @ 7.04 GHz



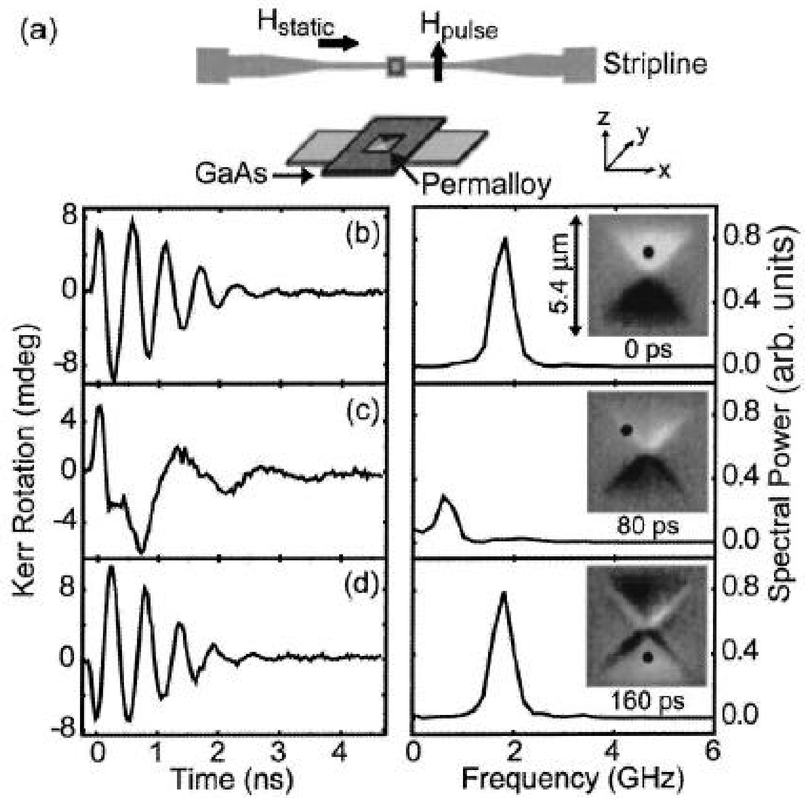


Amplitude (top) and phase (bottom) response *vs* position for P1-P5 @ 7.04 GHz

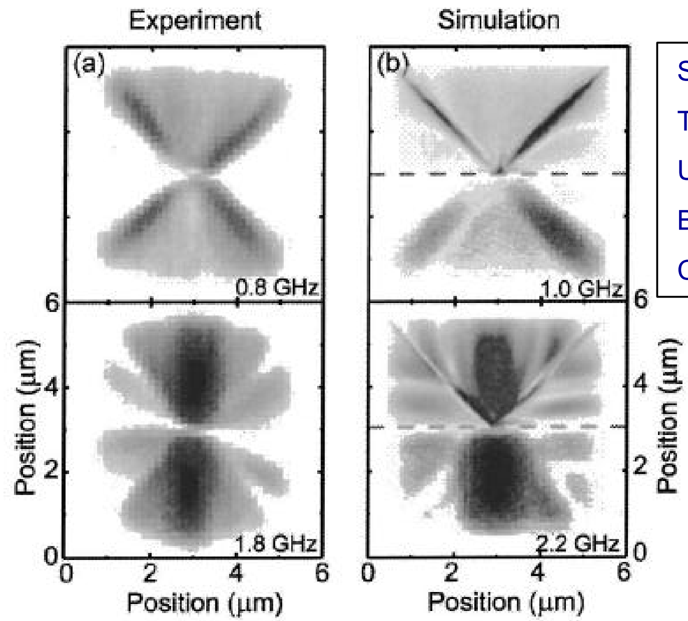
S. Tamaru, J.A. Bain et al., J. Appl. Phys. **91**, 8034 (2002)

theory: K. Guslienko, R. Chantrell, A.N. Slavin, PRB, in press

Spin dynamics in closure domains



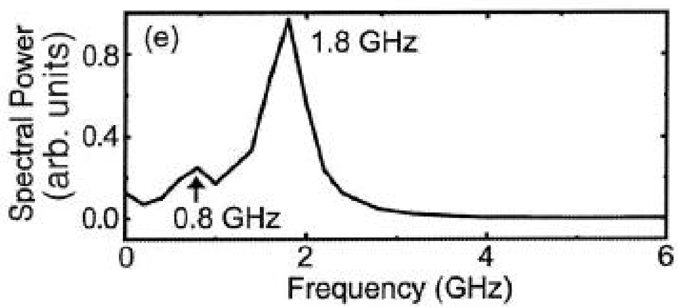
Polar Kerr response *vs* position and Fourier Transforms in 5 µm*5 µm Py platelets



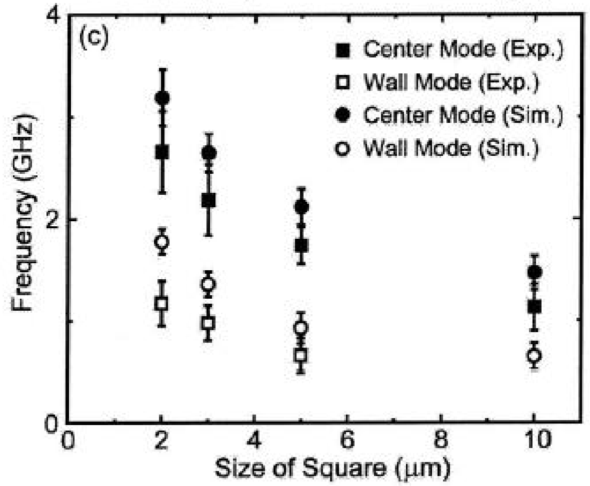
Simulations:

Top: Unconvolved

Bottom : Convolved



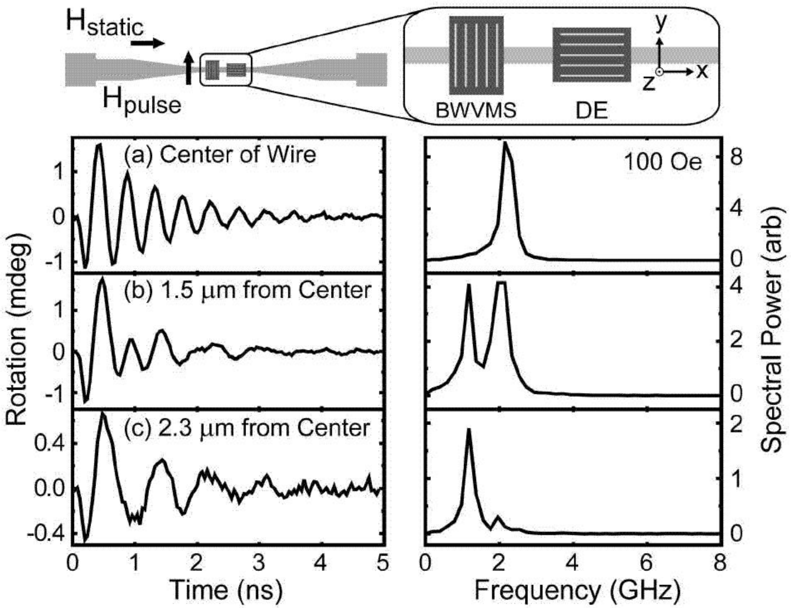
Average of the frequency power spectrum averaged over the whole sample



J.P. Park et al., Phys. Rev. B. **67**, 020403(R) (2003)

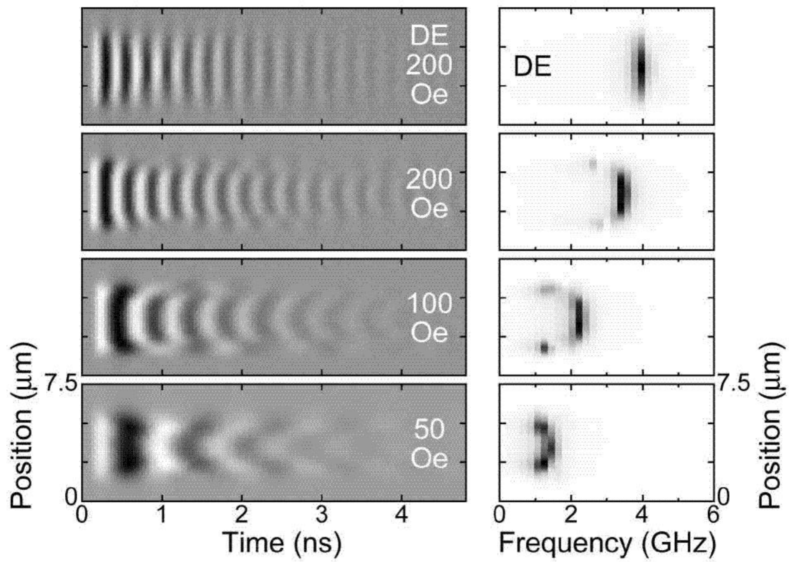
See also J. P. Park et al., PRL **89** (2002) 277201 (spin-wave modes in wires)

Spatially resolved spin-wave modes in magnetic wires



Polar Kerr rotation *vs* position in 5 µm width, 18 nm thick Py wires

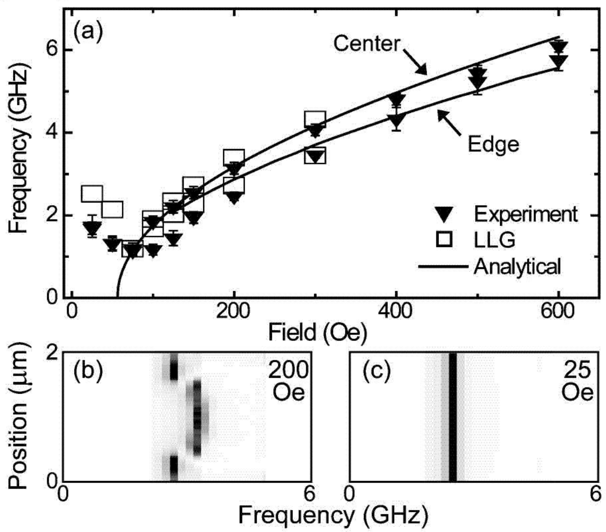
(BWVMS geometry)



Left: Time-domain images: 5 µm width Py wires

Right: Frequency domain

Note the absence of edge mode in the DE geometry



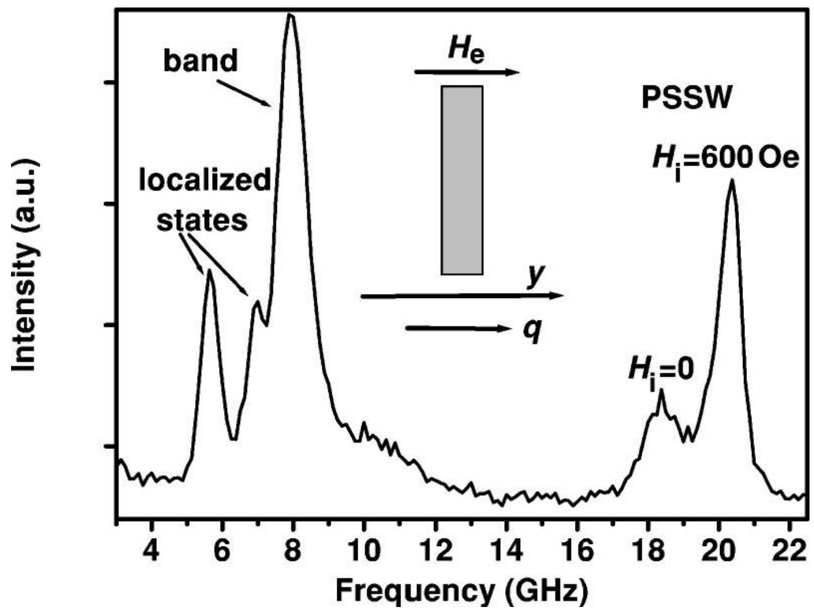
Comparison between experiments and LLG simulations

Note the tendency towards a uniform mode at low field

J.P. Park et al.,

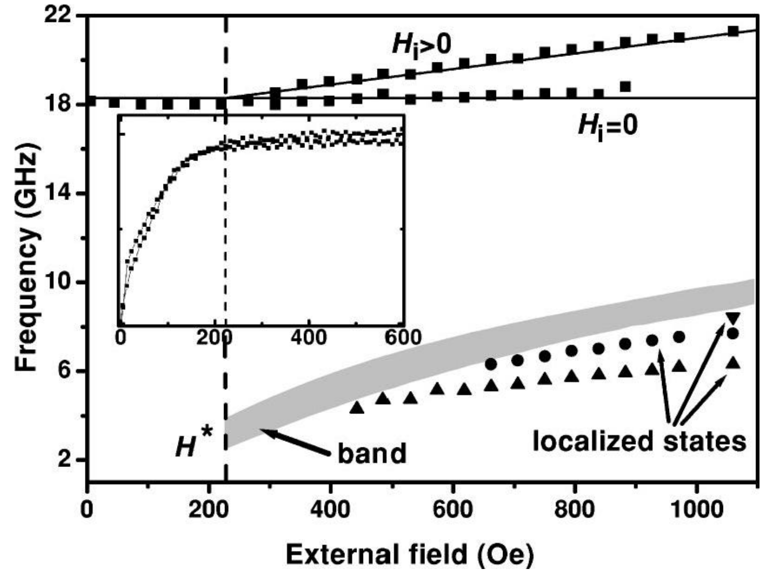
PRL **89**, 277201 (2002)

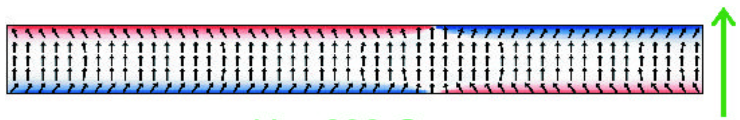
Localized thermal spin-waves in magnetic wires

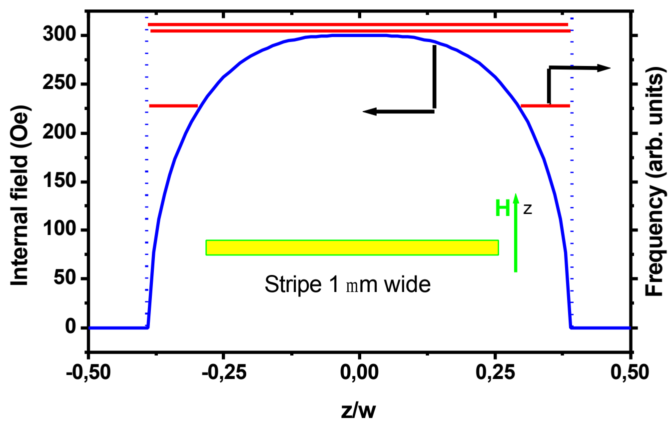


BLS spectrum, q=0.47 10^5 cm, H_e=800 Oe

PSSW: thickness mode



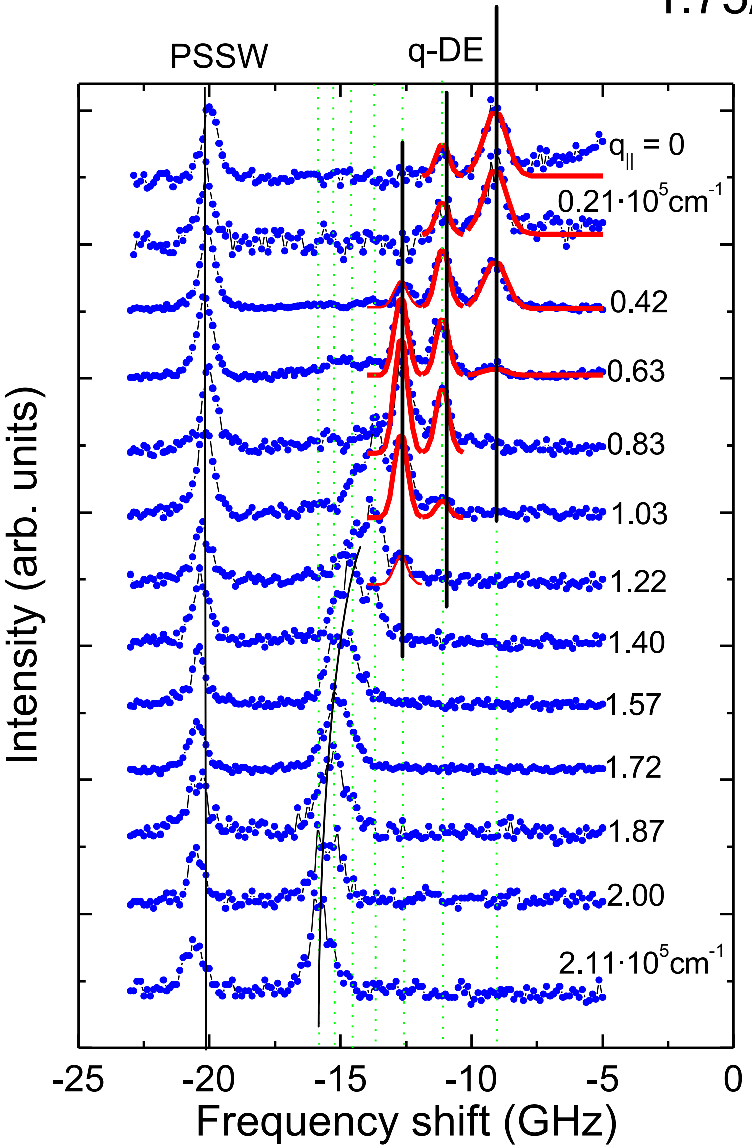


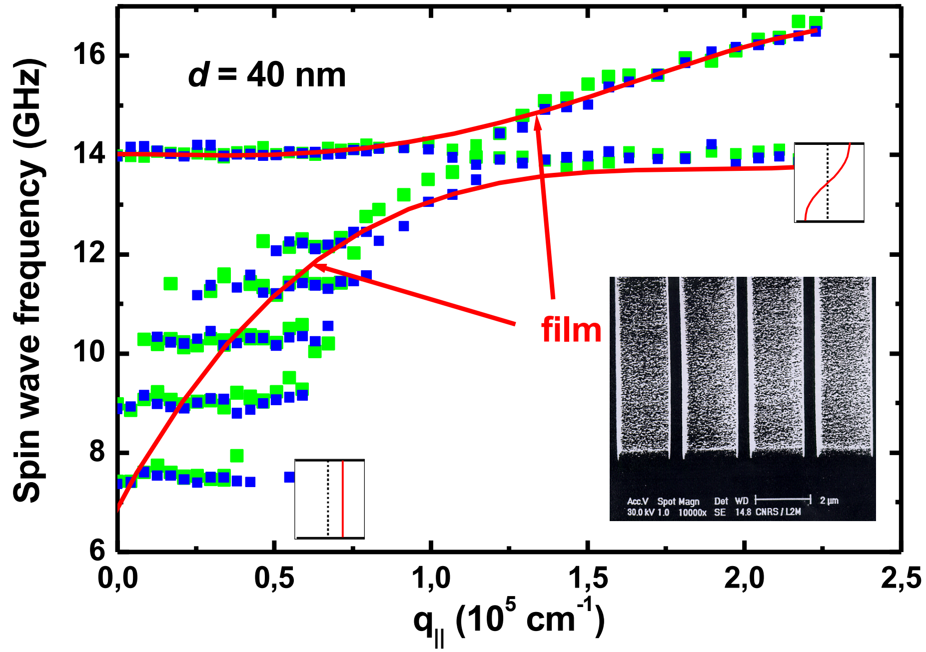


C. Bayer et al., Appl. Phys. Lett. **82,** 607 (2003)

Quantized spin waves in wires: BLS studies

35 mm NiFe wires
1.75/0.3 µm





localized dispersionless modes

S.O. Demokritov, B. Hillebrands, in: „Spin dynamics in confined magnetic structures“, Topics in Applied Physics **83** (2003), Springer

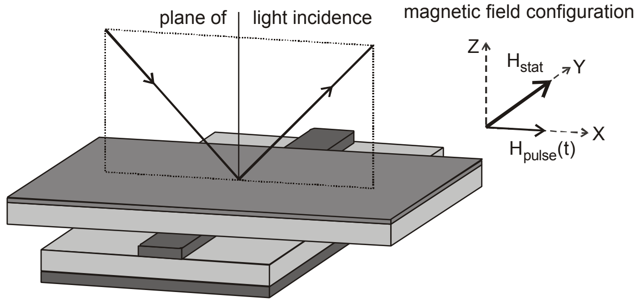
A common idea in all these studies :

?

A common idea in all these studies :

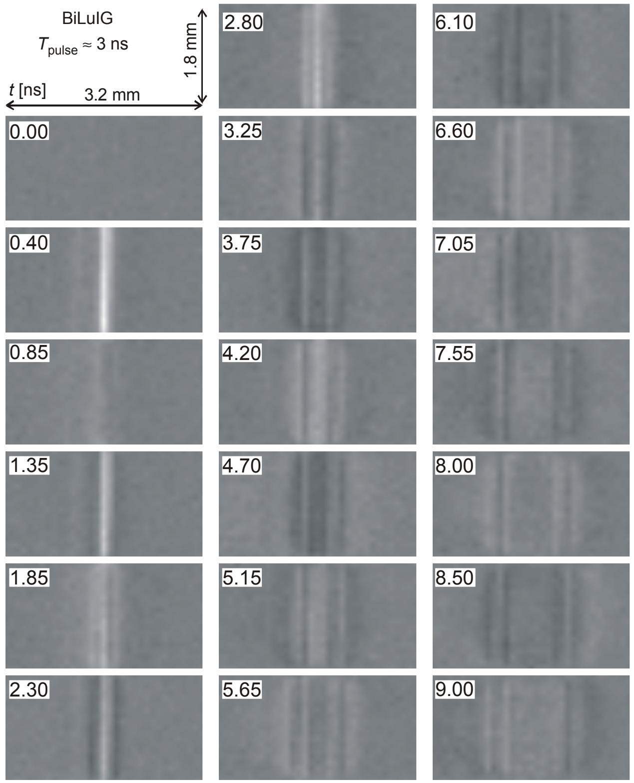
The internal field is not homogeneous

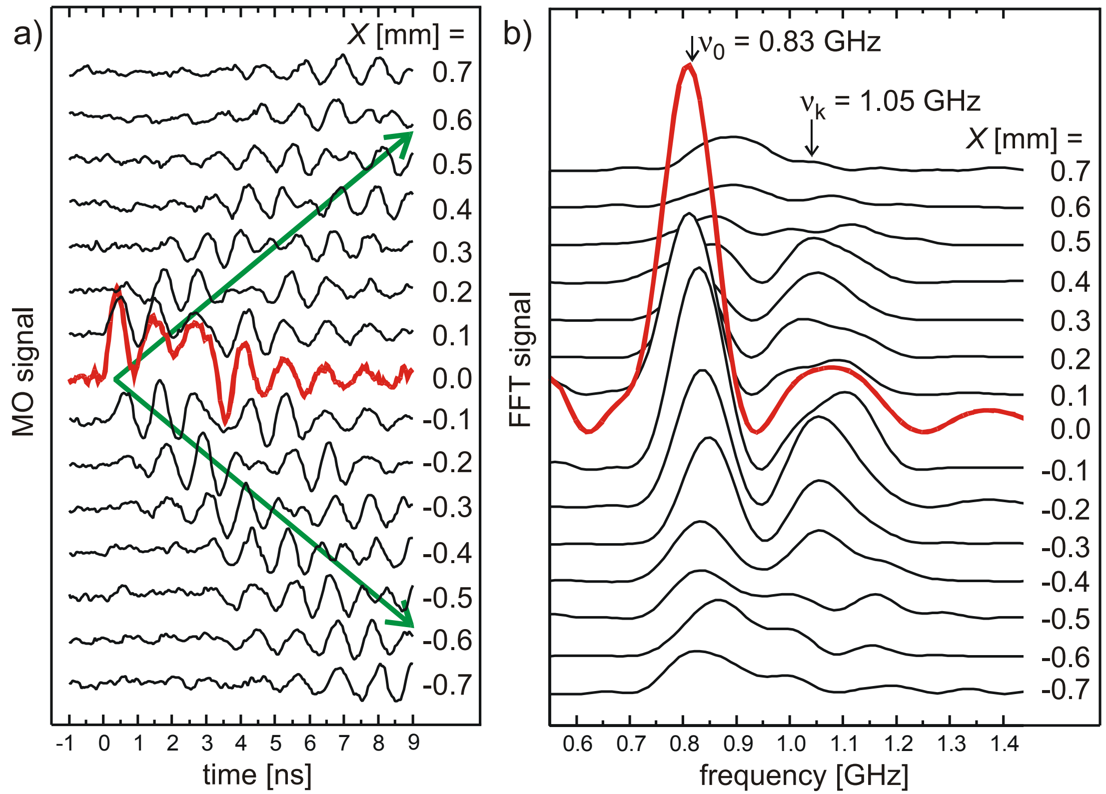
Spin wave propagation



H_{pulse} = 1 Oe, 3 ns
H_{stat} = 40 Oe

v_{group} = 6.6 cm/μs





x: distance to stripeline, x=0
group velocity

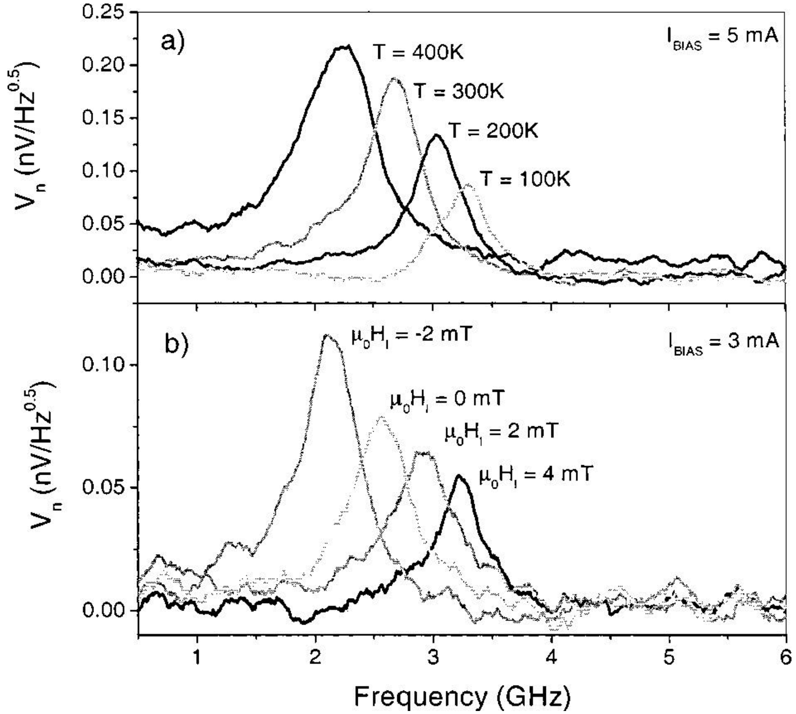
ν_0: uniform mode
ν_k: propagating spin wave

J. Fassbender, in: „Spin dynamics in confined magnetic structures II“, Topics in Applied Physics **87** (2003), Springer

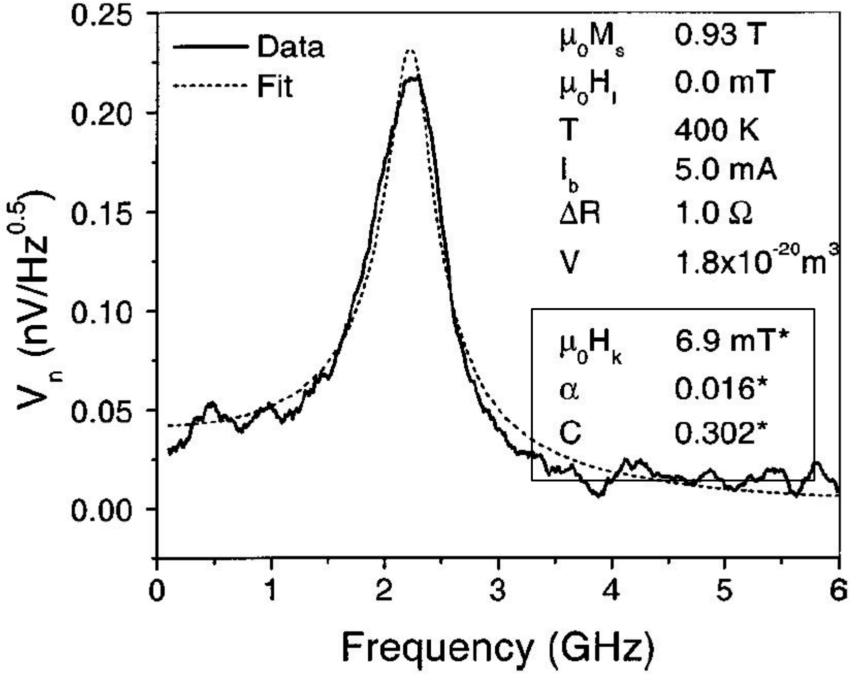
Magnetic noise spectrum in GMR device

$$V_n(f) = IDR\sqrt{\frac{k_B T}{2p\, f m_0 M_s^2 V}\; c_t''(f)}$$

NiFe/CoFe/Cu/CoFe/Ru/CoFe/IrMn-
spin valve device 1* 3 μm^2



[redacted]



Good fit by single-domain noise model with noise power proportional to imaginary part of dynamic susceptibility

N. Stutzke, S.L. Burkett, S.E. Russek,
Appl. Phys. Lett. **82**, 91 (2003);
J. Vac. Soc. Tech. A 21, 1167 (2003)

Large excitations, Switching

I. Conventional switching

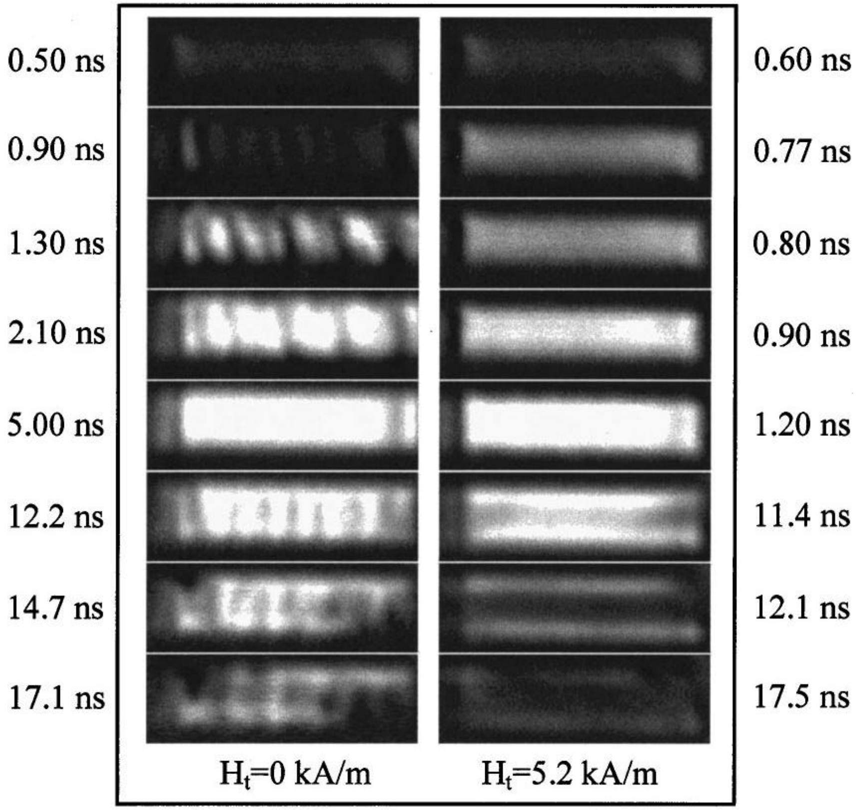
II. Precessional switching

III. rf assisted switching

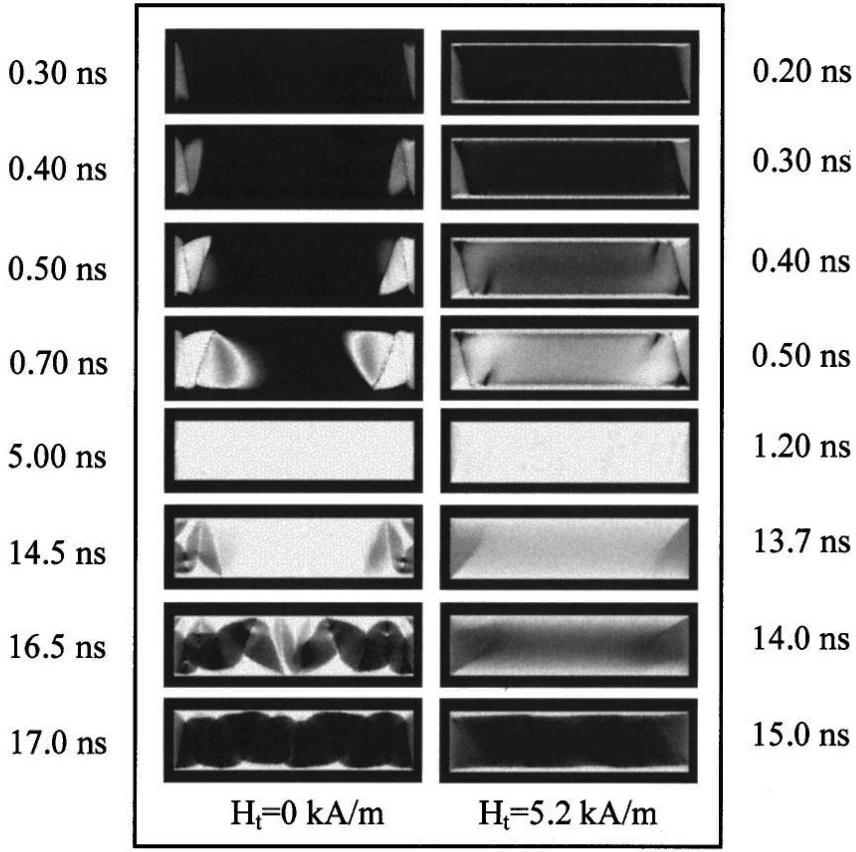
IV. wall motion in nano-wires

Early Experiments: Pulsed field along the easy axis

EXPERIMENTS



SIMULATIONS

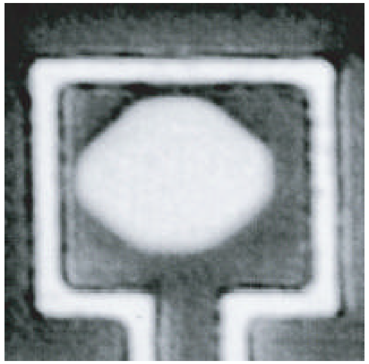


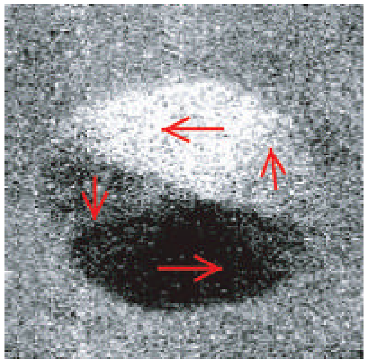
Switching mechanisms dominated by wall motion, domain expansion and nucleation, leading to an overall complexity

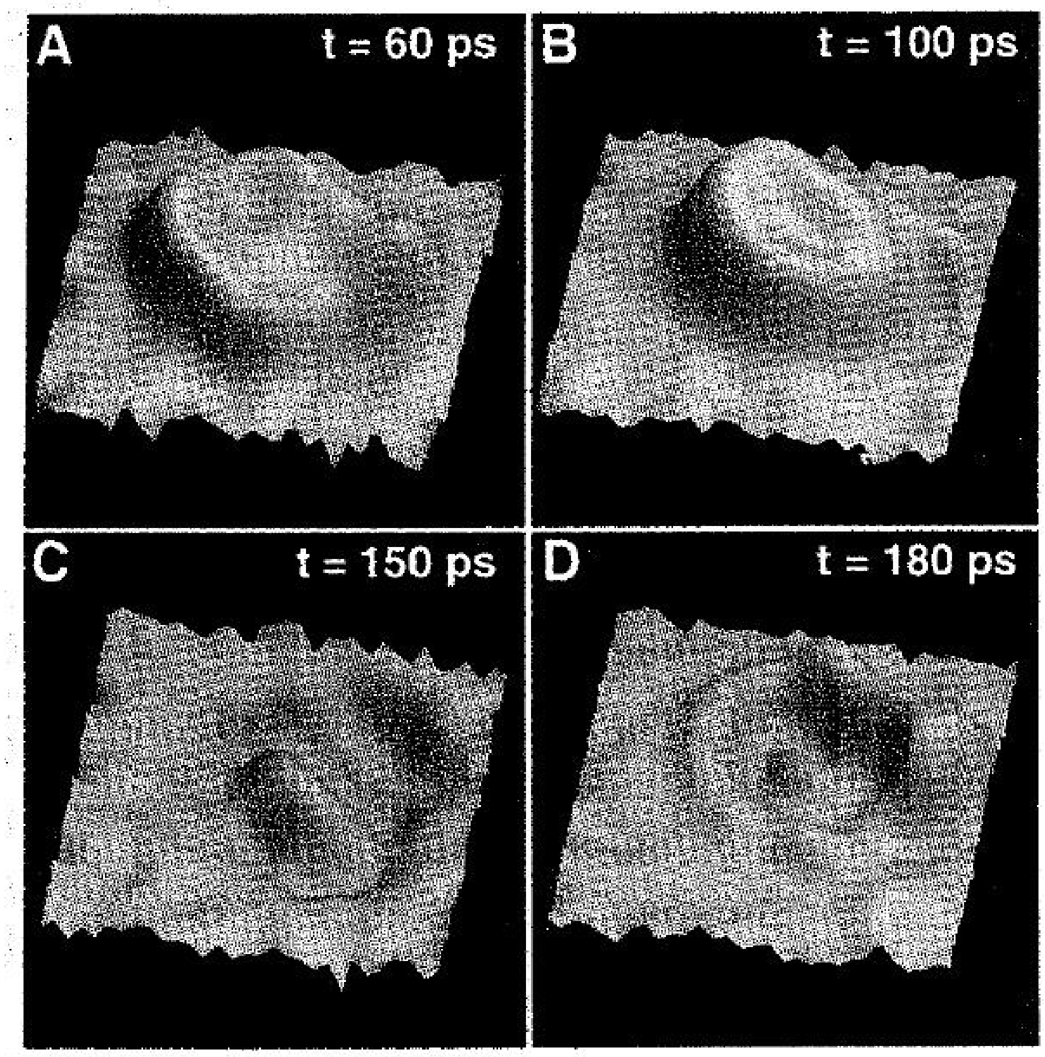
B. C. Choi et al., J. Appl. Phys. **89** (2001) 7171

Time resolved Kerr microscopy: a different kind of excitation

6 μm Co disk,
excited with current pulse
in microfabricated loop,
magneto-optic Kerr
microscopy

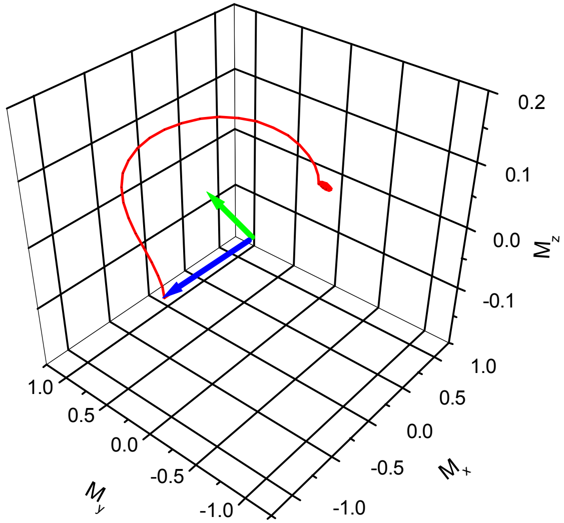






Y. Acremann et al., Science **290**, 495 (2000)

Precessional switching



Simultaneously demonstrated at MMM Seattle in fall 2001 by:

- Nijmegen group: pulse shaping by two fs laser pulses

  Th. Gerrits et al., Nature **418**, 509 (2002)

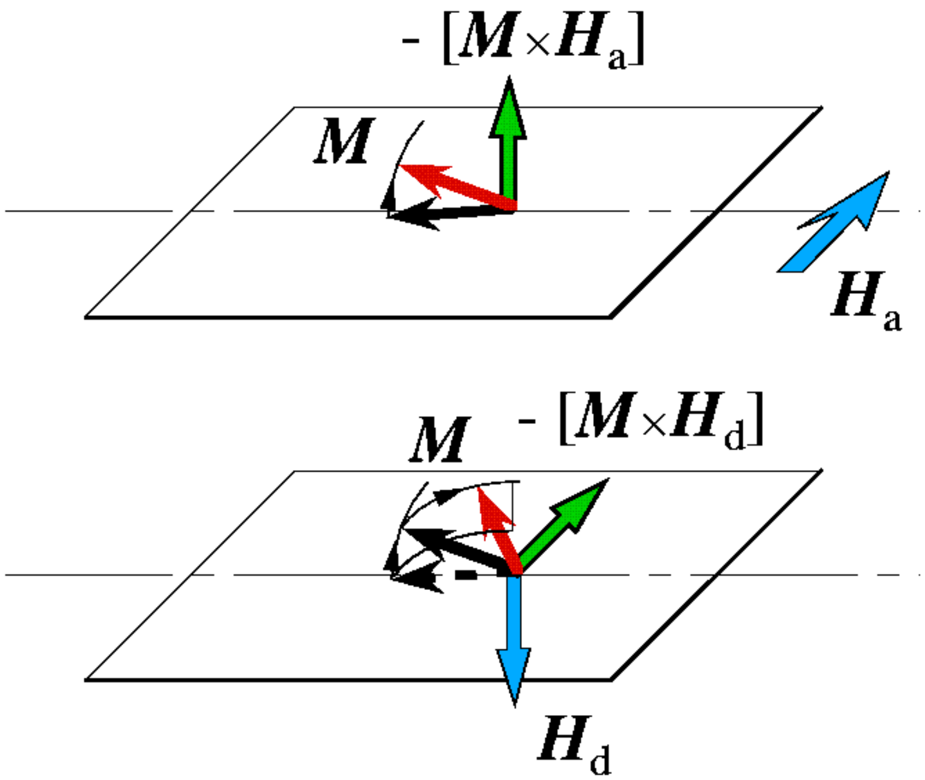
- NIST Boulder group: MR measurement

  S. Kaka and S.E. Russek, Appl. Phys. Lett. 80, 2958 (2002)

- Orsay group: MR measurement, multiple switching

  H.W. Schumacher et al., Phys. Rev. Lett. **90**, 017201 (2003)

Precessional switching : principle



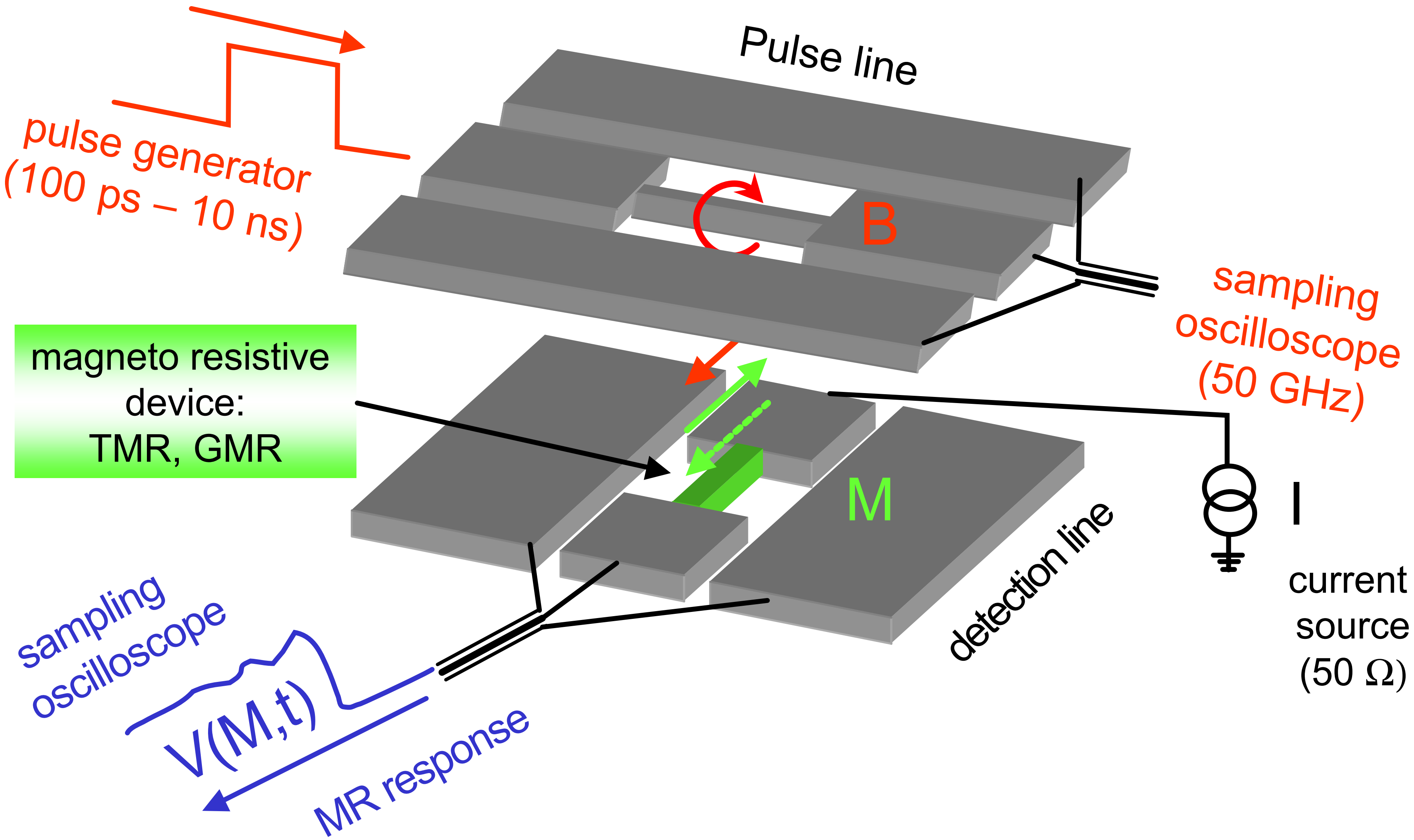
A **two-step** process particularly well suited to thin films:

1) The initial torque moves the magnetization out of plane

2) The torque due to the demagnetizing field allows for magnetization rotation along a trajectory that remains close to the plane of the film

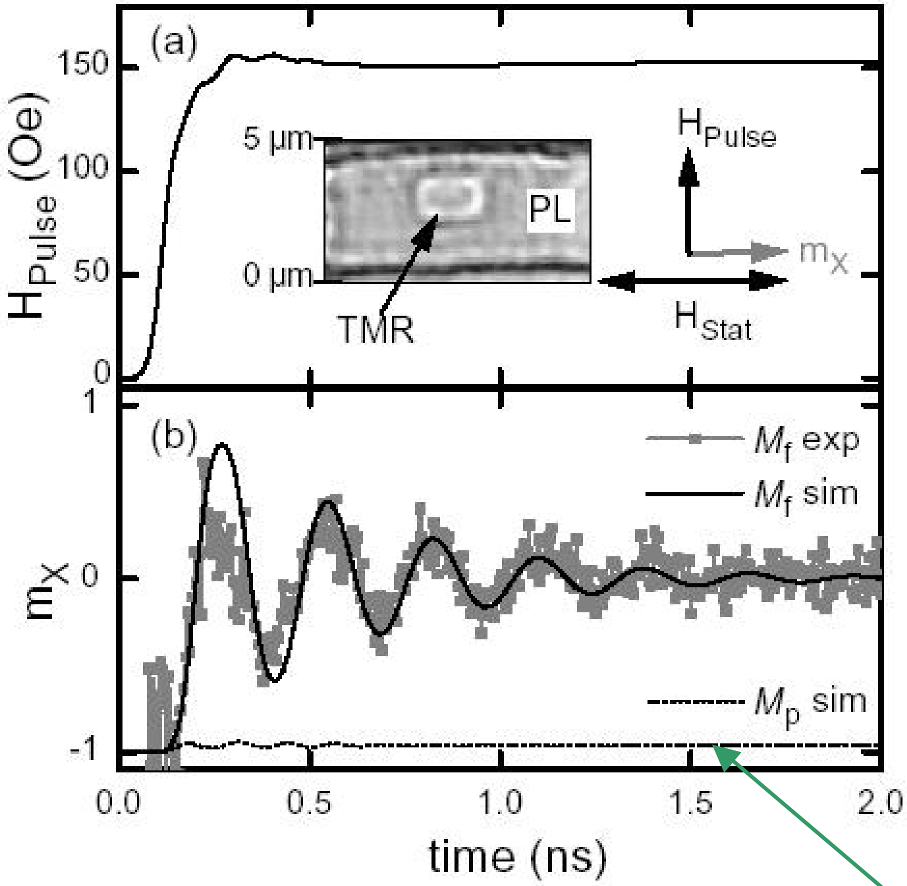
Experimental Method

H.W. Schumacher et al., APL 2002



Hard axis pulse response: large angle precession

Long hard axis pulse:



Magnetization response

- Pulse field above anisotropy field H_A
- T_{pulse} = 2.5 ns ps, H_{Pulse} = 150 Oe
- pinned layer aligned along easy axis
- static field: offset compensated
- large angle precession about H_{Pulse} (>90°)
- good LLG fit with α = 0.02-0.03

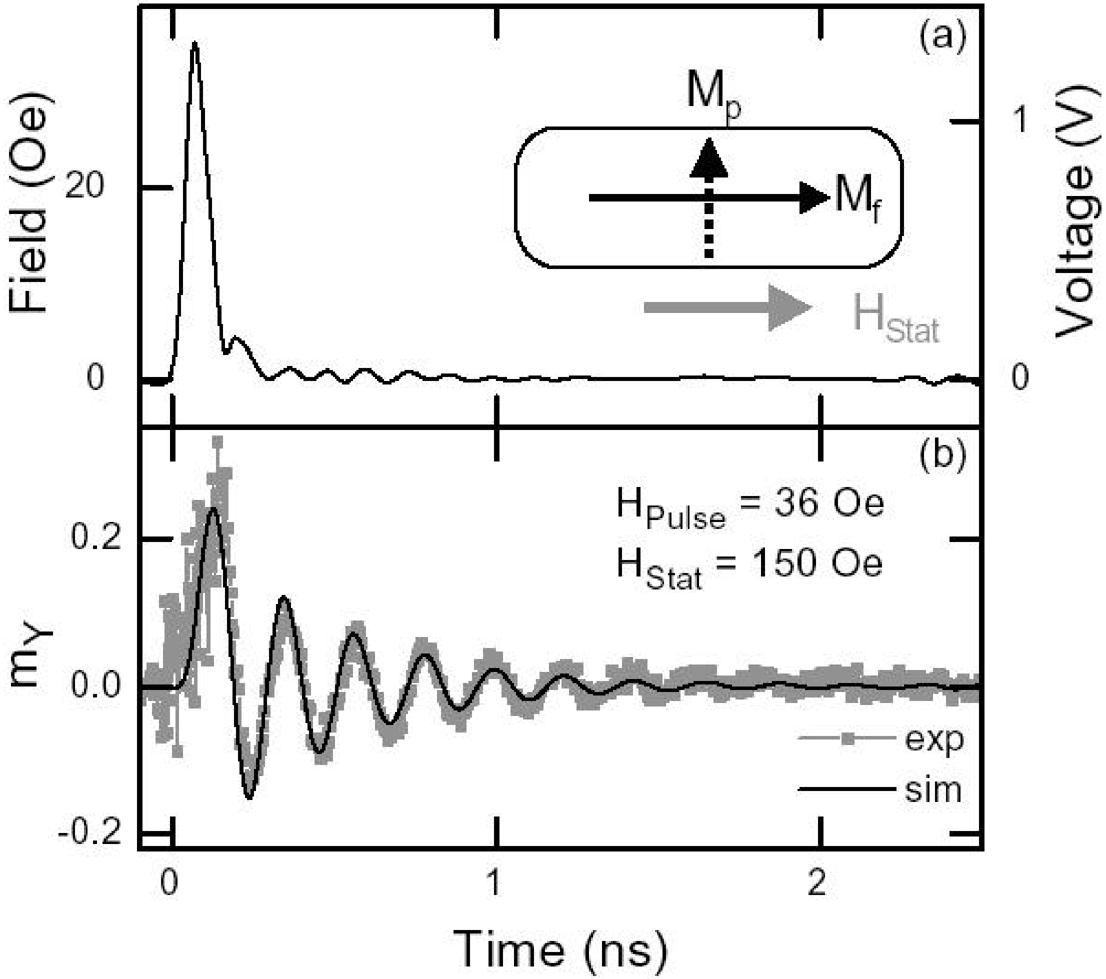
Calculated pinned layer response

TMR sample, 1.1x3.8 µm²

Hard axis pulse response: TMR elements

Short hard axis pulse:

TMR sample, 1.1x3.8 μm^2

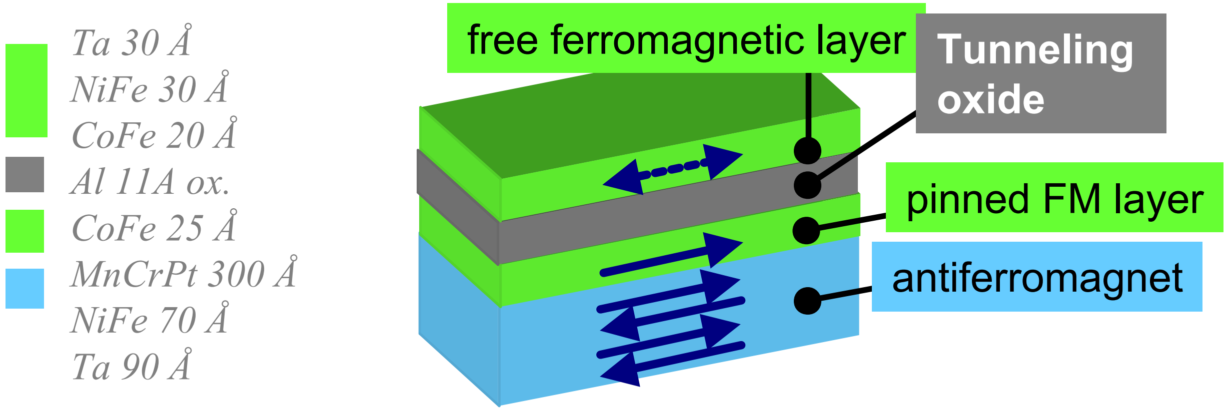


An even better agreement

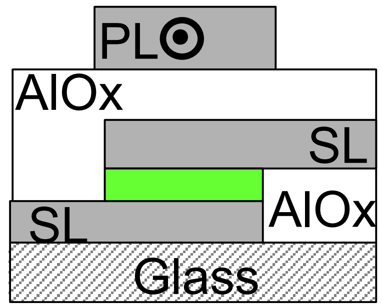
with a simple single spin model:

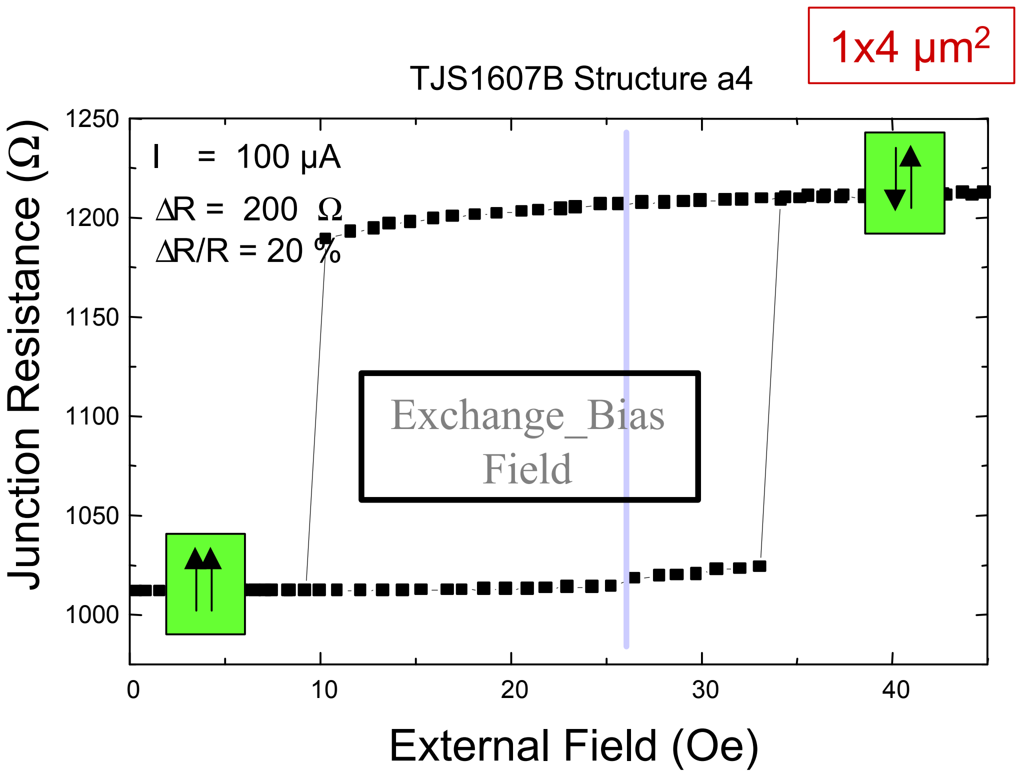
a **= 0.02**

Tunneling Magneto-Resistance (TMR) Samples



Pulse line on top:





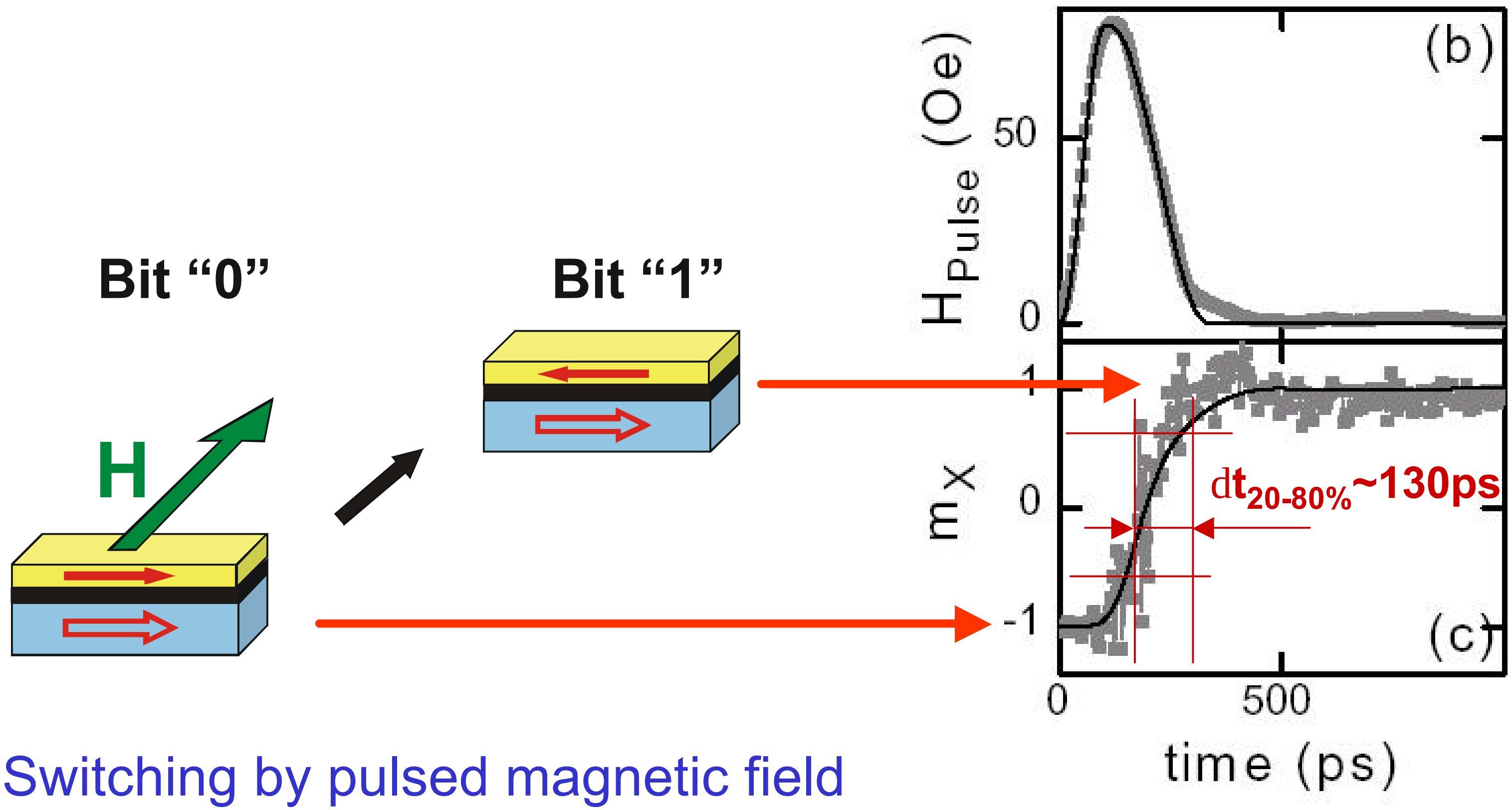
Sample dimensions:

Cells:	*1x2 μm²-2x4 μm²*
PL:	*0.25x5 μm²*
AlOx:	*0.25 μm*
H_C	~ 5 - 30 Oe
H_{Bias}	~ 0 - 20 Oe
R	~ 1-3 kΩ
MR	~ 20 %

H.W. Schumacher et al., JAP 2003

Precessional switching

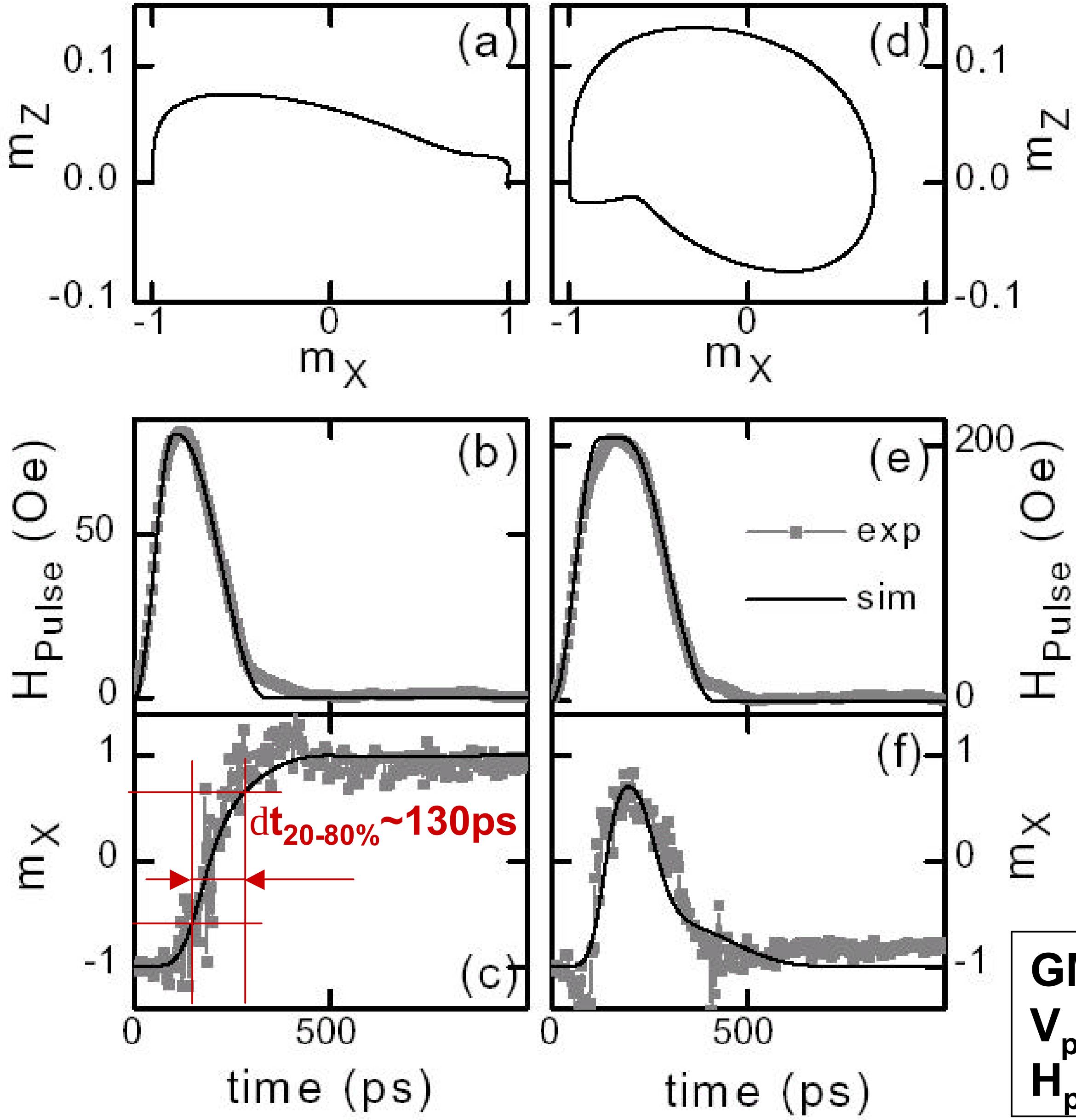
Experiment (CNRS Orsay):



Switching by pulsed magnetic field perpendicular to direction of magnetization

H.W. Schumacher et al., Phys. Rev. Lett. **90**, 017204 (2003)

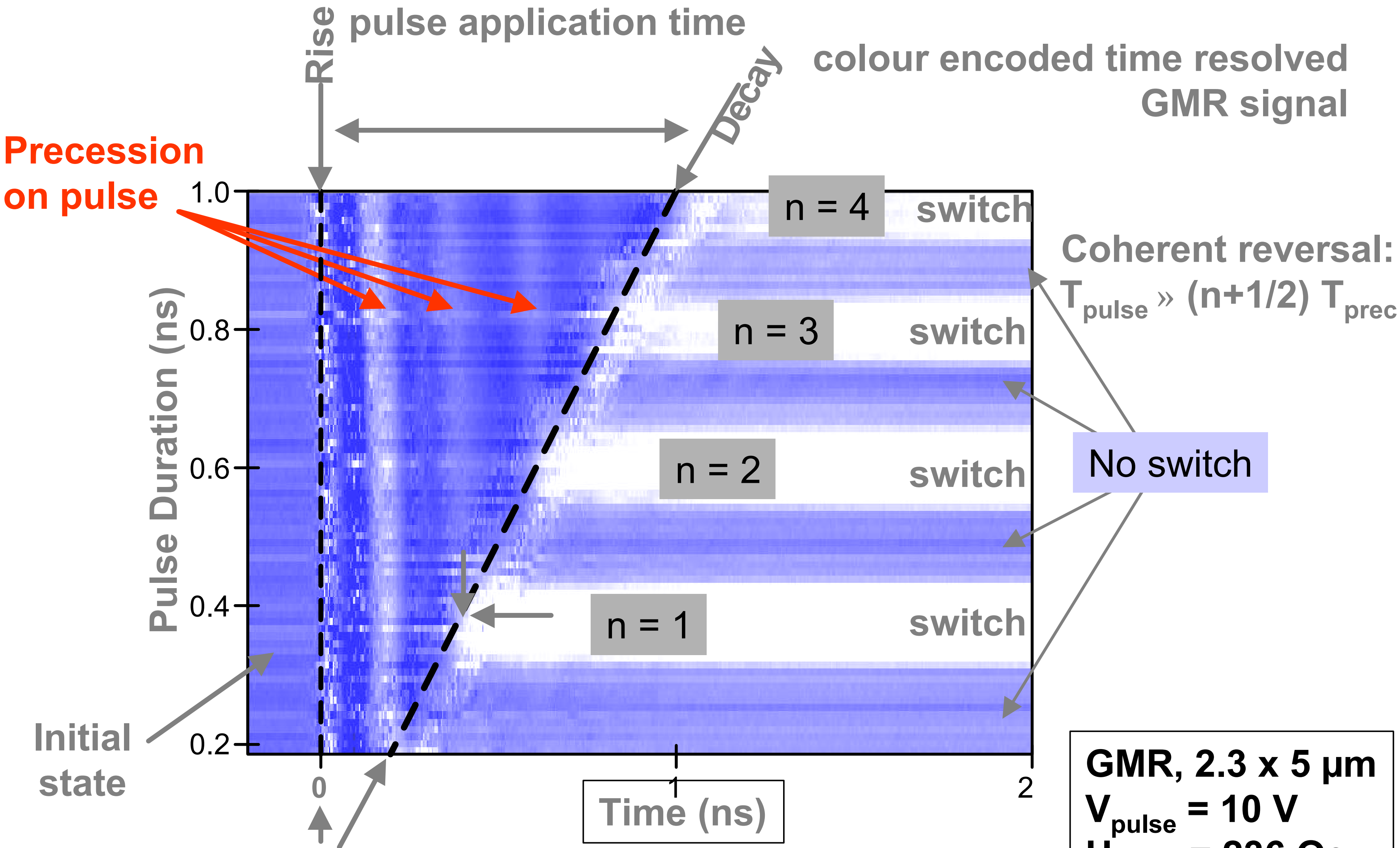
Quasi-Ballistic Switching



H.W. Schumacher et al., Phys. Rev. Lett. **90**, 017204 (2003)

GMR, 2.3 x 5 µm²
V_{pulse} = 10 V
H_{pulse} = 236 Oe

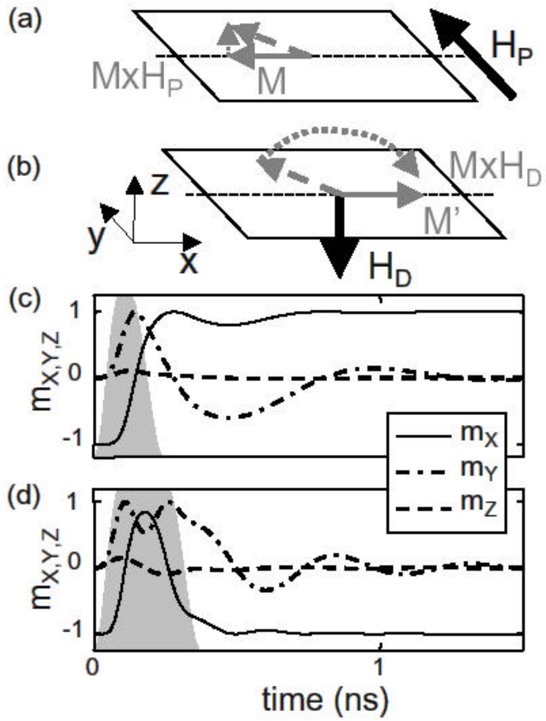
Phase Coherence (GMR Samples)

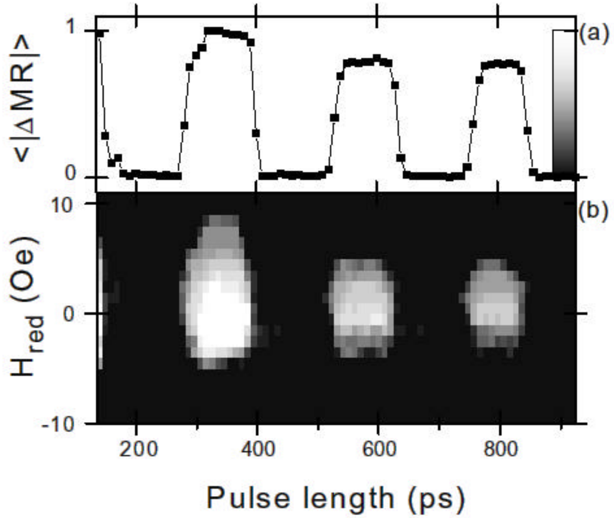


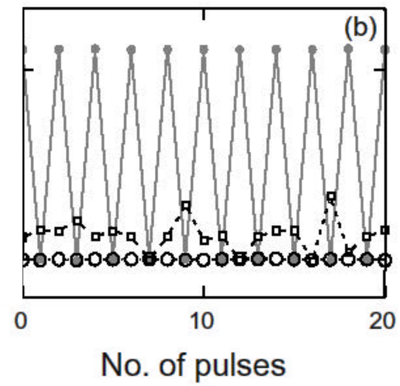
GMR, 2.3 x 5 µm
V_{pulse} = 10 V
H_{pulse} = 236 Oe

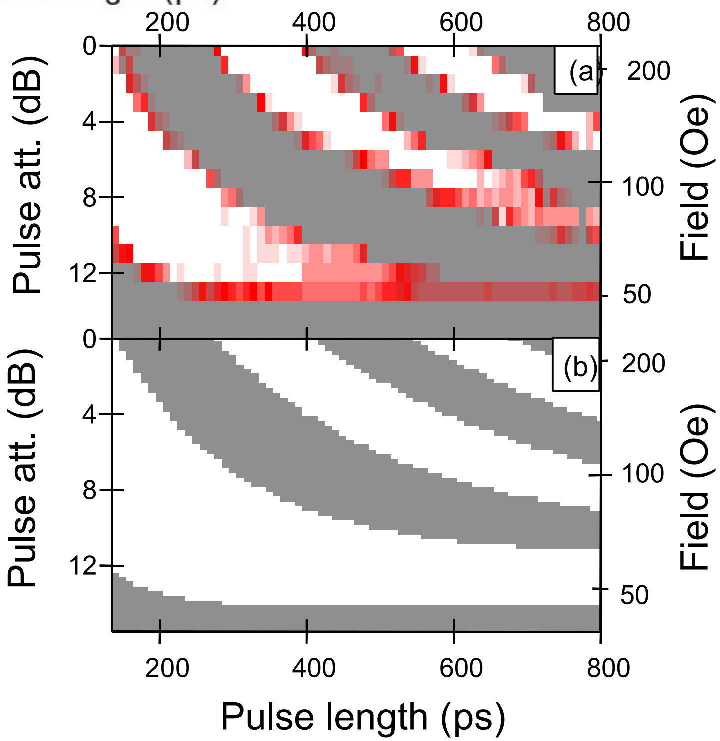
H.W. Schumacher et al., Phys. Rev. Lett. **90**, 017204 (2003)

Multiple switching



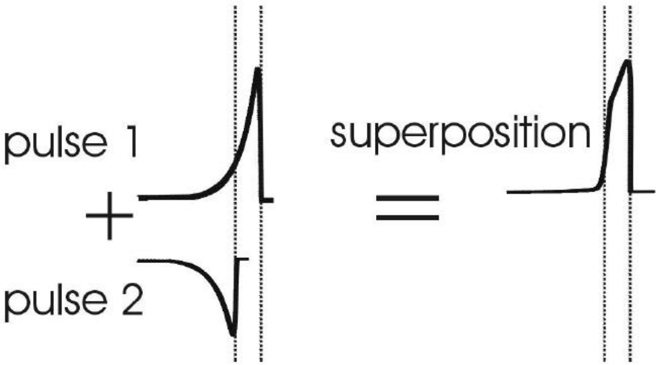


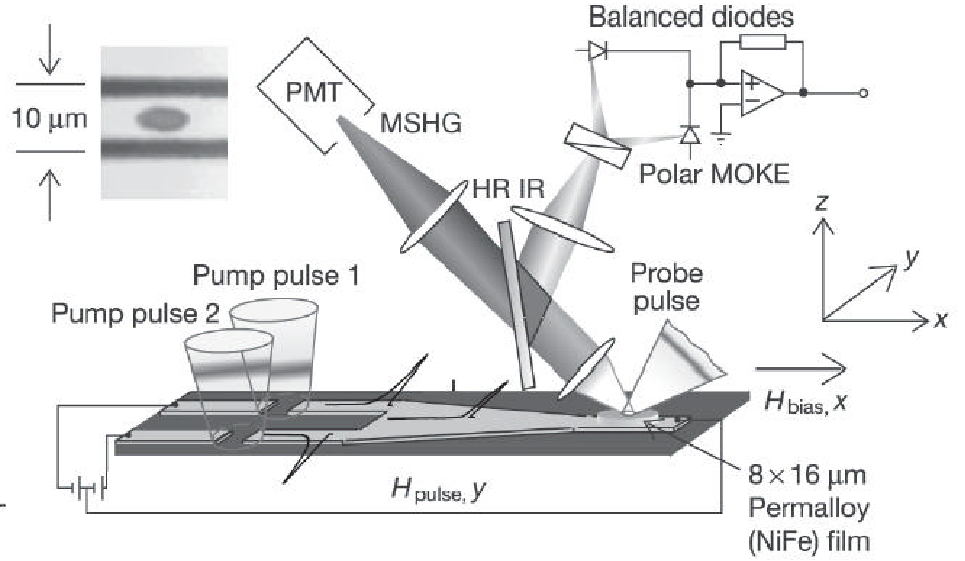


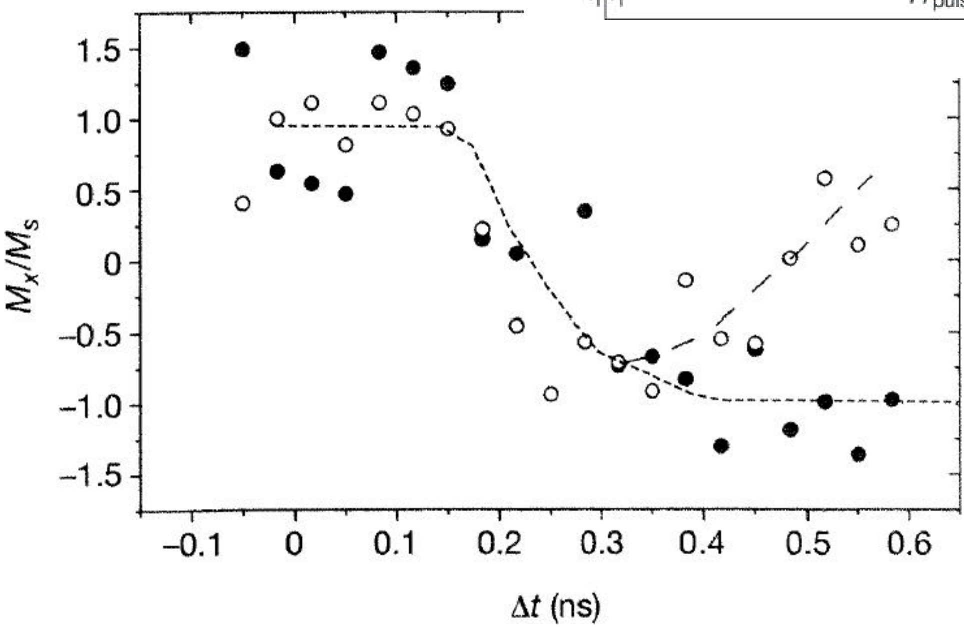


H.W. Schumacher et al., Phys. Rev. Lett. **90**, 017201 (2003)

Precessional switching by optical pulse shaping





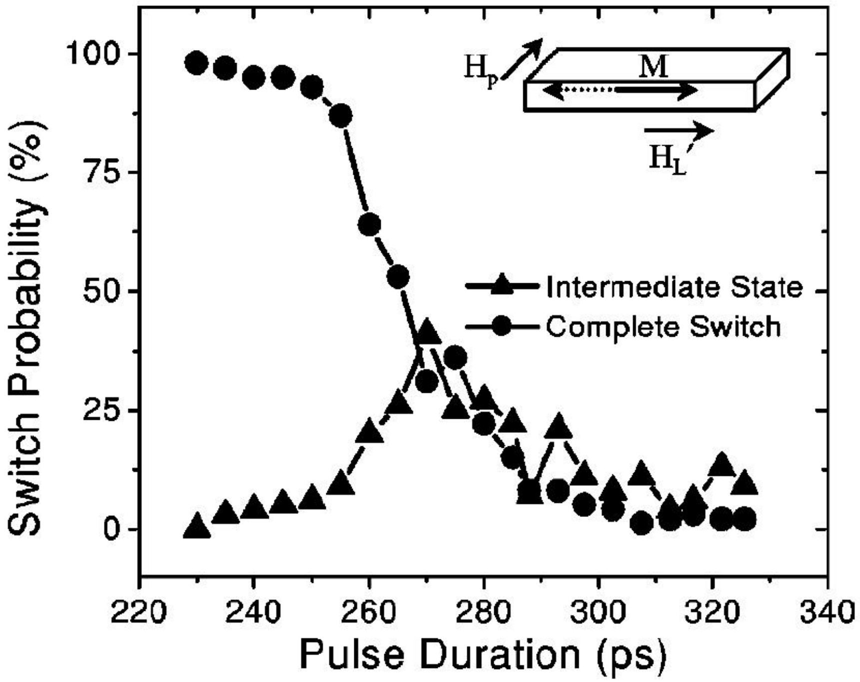


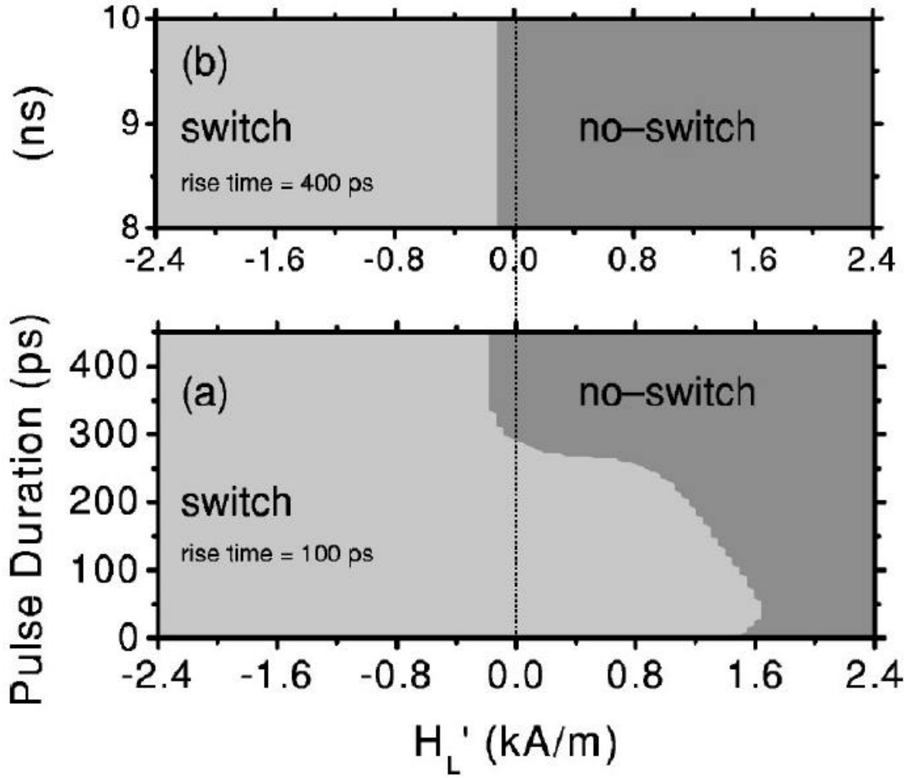
Th. Gerrits et al., Nature **418**, 509 (2002)

Precessional switching

0.45* 1.15 μm^2 spin valve

magnetoresistance measurement





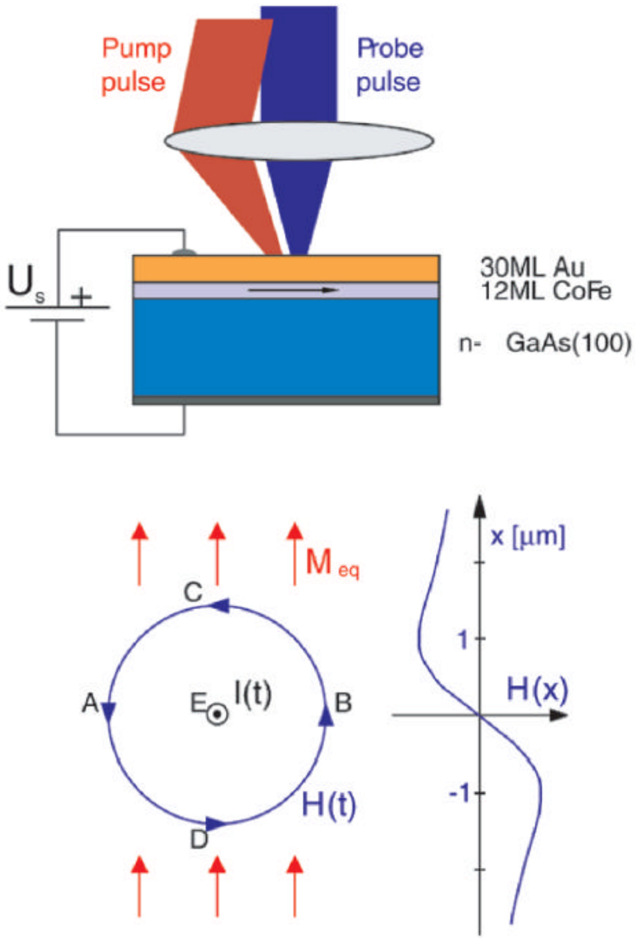
single domain simulation

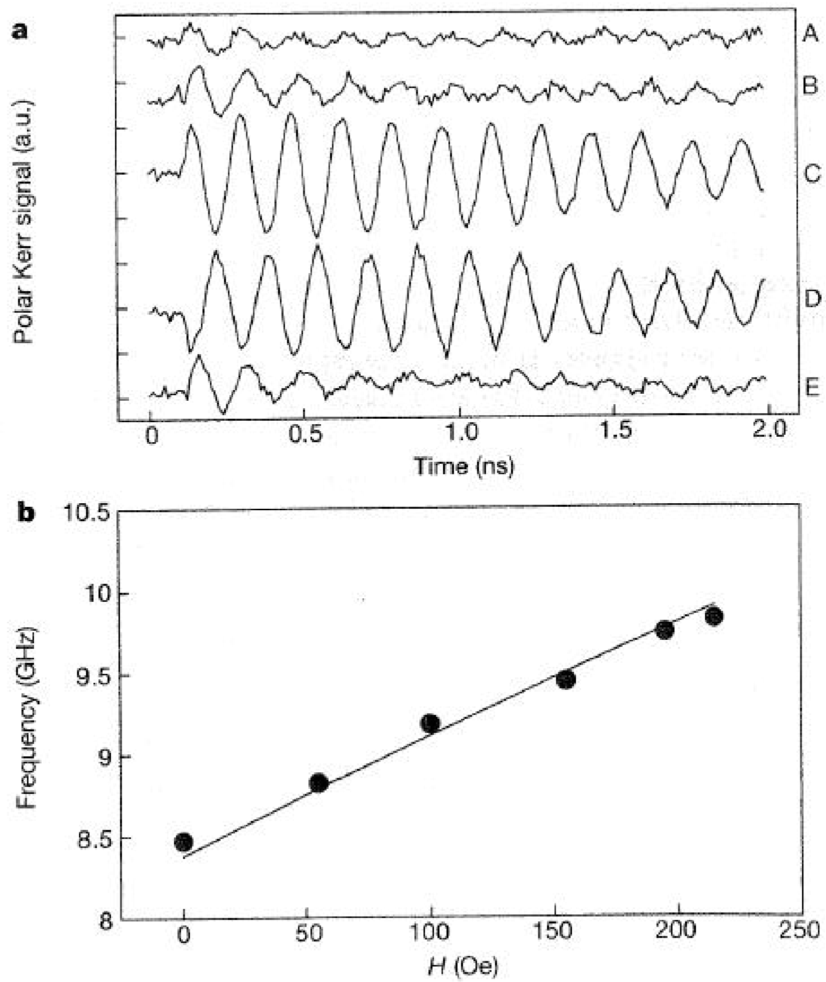
S. Kaka and S.E. Russek, Appl. Phys. Lett. **80**, 2958 (2002)

New techniques for excitation and switching

- generation of fast current pulses by Shottky barriers
  Y. Acremann et al., Nature **414**, 52 (2001)
- rf field assisted switching
  C. Thirion, W. Wernsdorfer, D. Mailly, Nature, in press
- microwave excitation and synchronization of laser pulses with microwave source
  S. Tamaru, J.A. Bain et al., J. Appl. Phys. **91**, 8034 (2002)

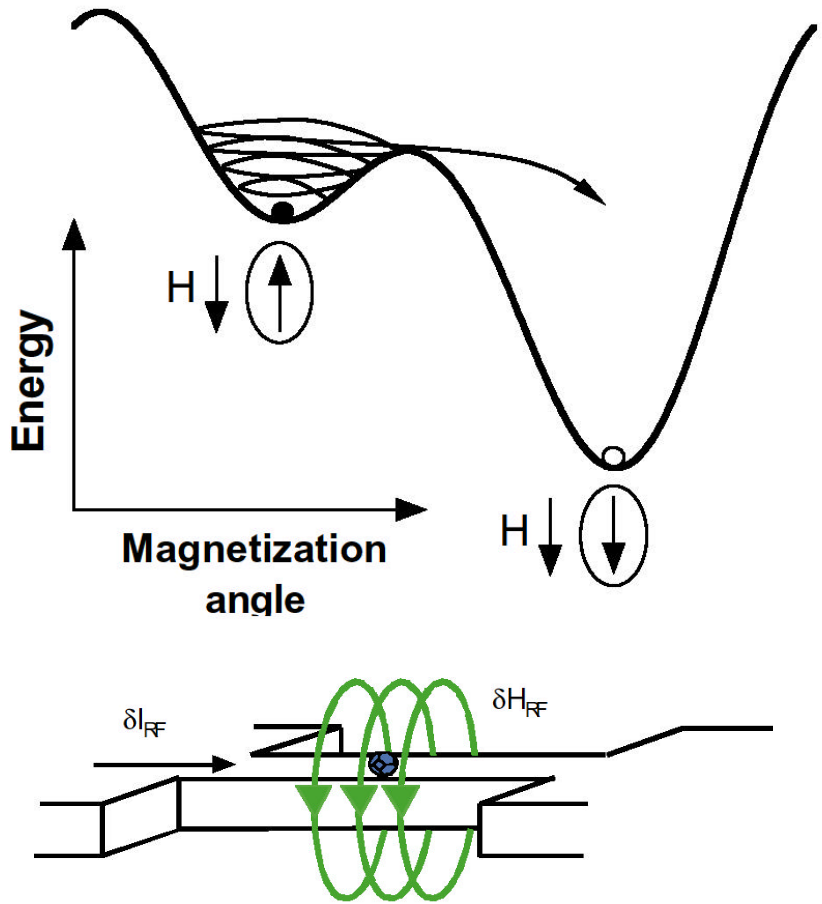
Ultrafast magnetic fields by a Schottky diode

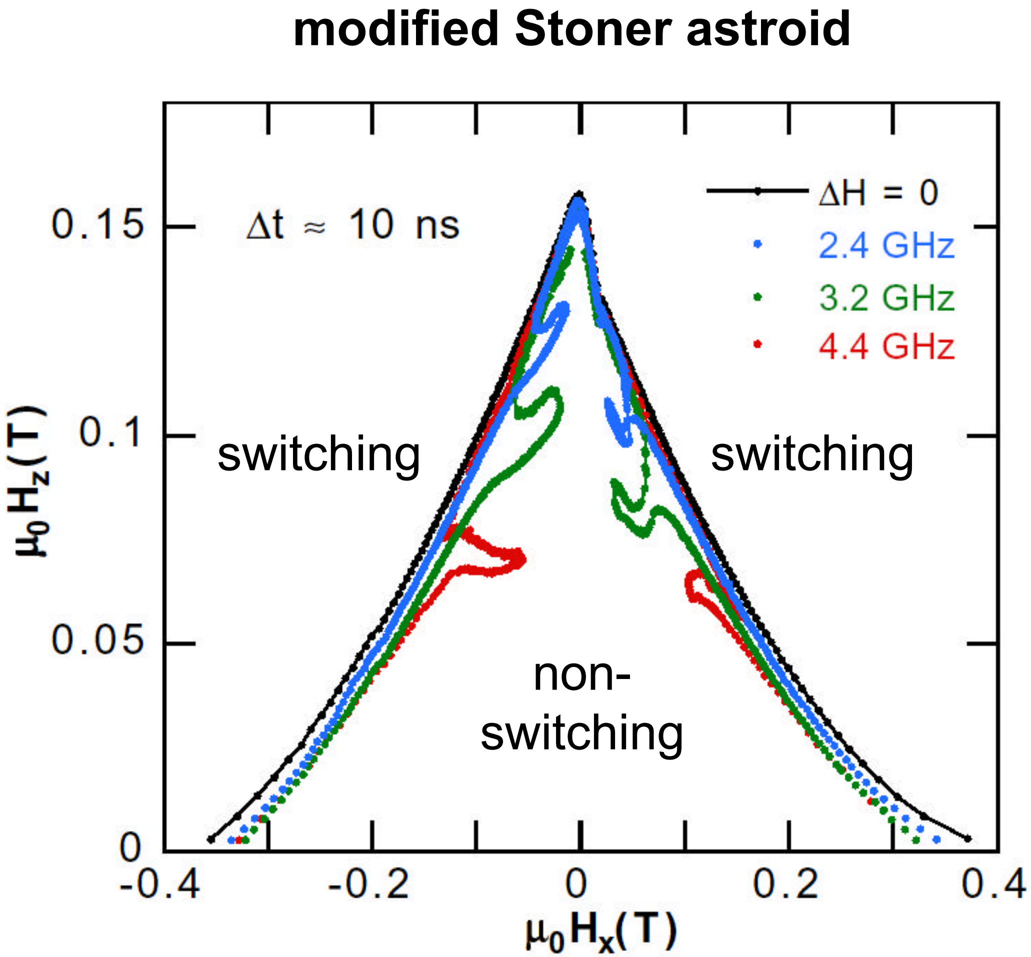




Y. Acremann et al., Nature **414**, 52 (2001)

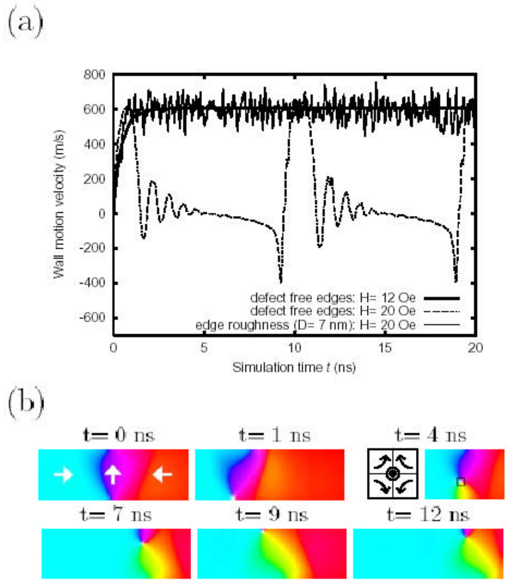
New switching techniques: rf field assist. switching

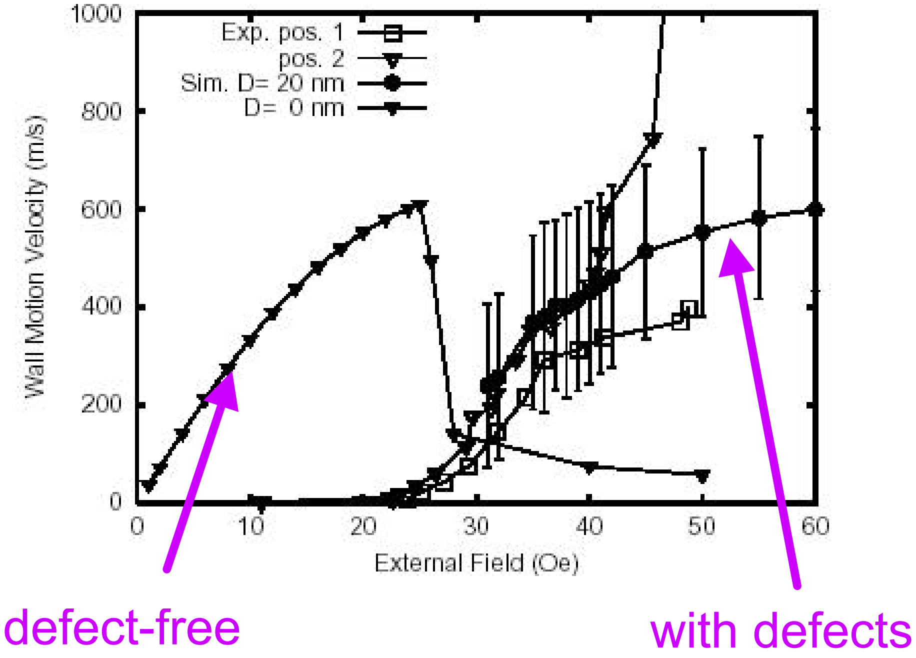




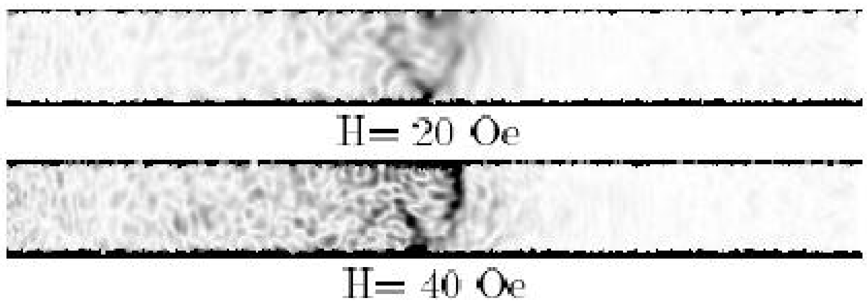
C. Thirion, W. Wernsdorfer, D. Mailly, Nature Materials 08/2003

Faster magnetic walls due to roughness in wires





(dm/dt)^2:



Counter-intuitive behaviour:

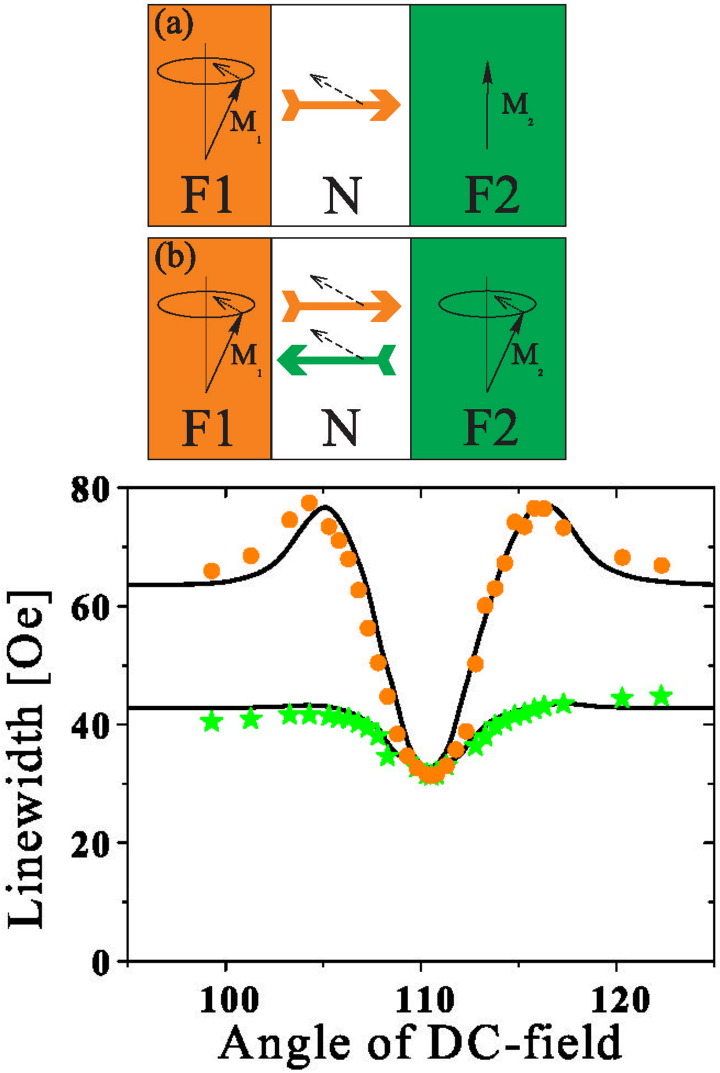
DW speed increases with increasing roughness

Roughness
- inhibits Walker velocity break-down found in sample without imperfections
- creates domain wall coercivity

Y. Nakatani, A. Thiaville, J. Miltat, Nature Materials, (August 2003)
Experiment: D. Atkinson et al., Nature Materials **2**, 85 (2003)

A hint towards more complexity: Spin pumping

GaAs(001) / 16Fe / 14Au / 40Fe / 20Au

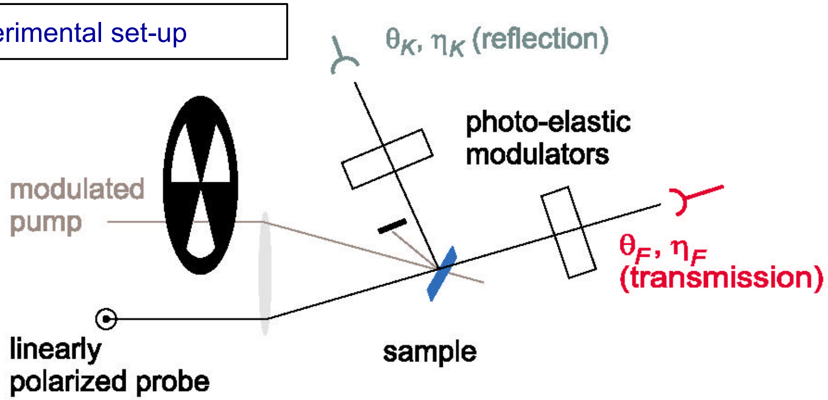


- FMR linewidth of thin layer (F1) increases in presense of thick layer (F2)
- spin current from precessing layer to non-precessing, off-resonant layer: additional Gilbert damping
- interface damping depends on precession angle
- spin pumping is directly related to the dynamic response of the interlayer exchange coupling

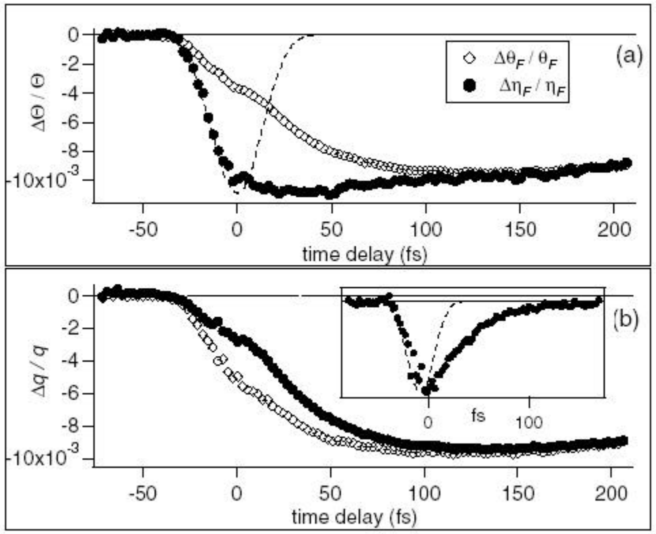
B. Heinrich, in: „Ultrathin magnetic structures III", B. Heinrich, J.A.C. Bland (eds), Springer; Phys. Rev. Lett. **90**, 187601 (2003)

Ultra-fast phenomena : thermalization of spin populations in ferromagnetic films

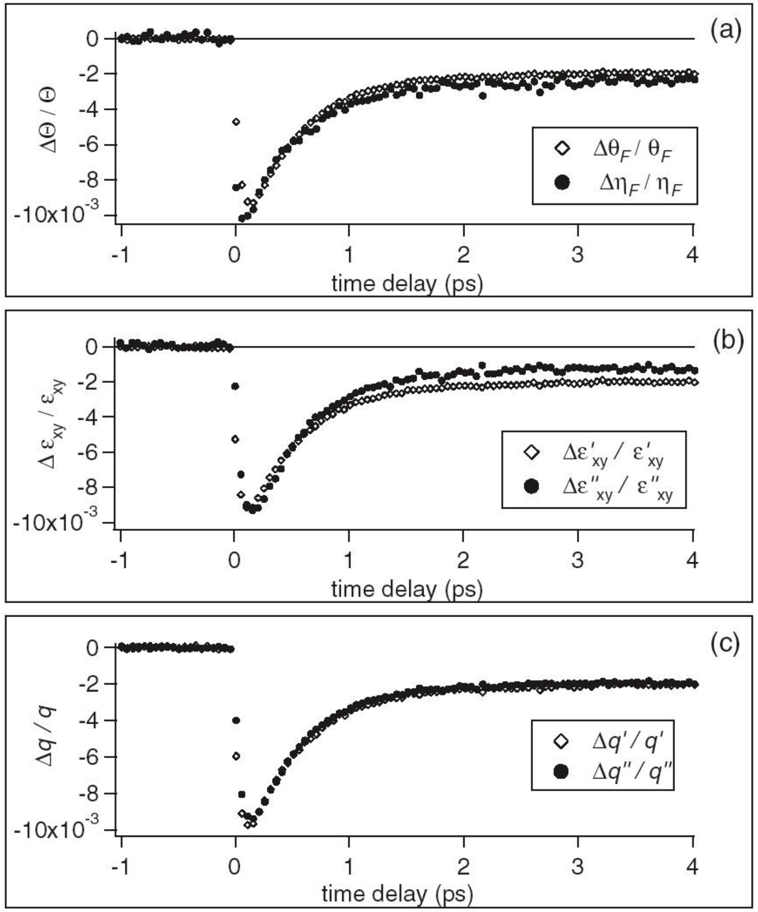
Experimental set-up



$$e=\tilde{e}_{xx}\begin{pmatrix}1 & i\tilde{Q} & 0\\ -i\tilde{Q} & 1 & 0\\ 0 & 0 & 1\end{pmatrix} \quad ; \quad \begin{aligned}\tilde{e}_{xx} &= e'_{xx}+ie''_{xx}\\ \tilde{Q} &= q'+iq''\end{aligned}$$



The ultrafast spin dynamics occurs during the thermalization of the electronic populations with a characteristic time of about 50 fs

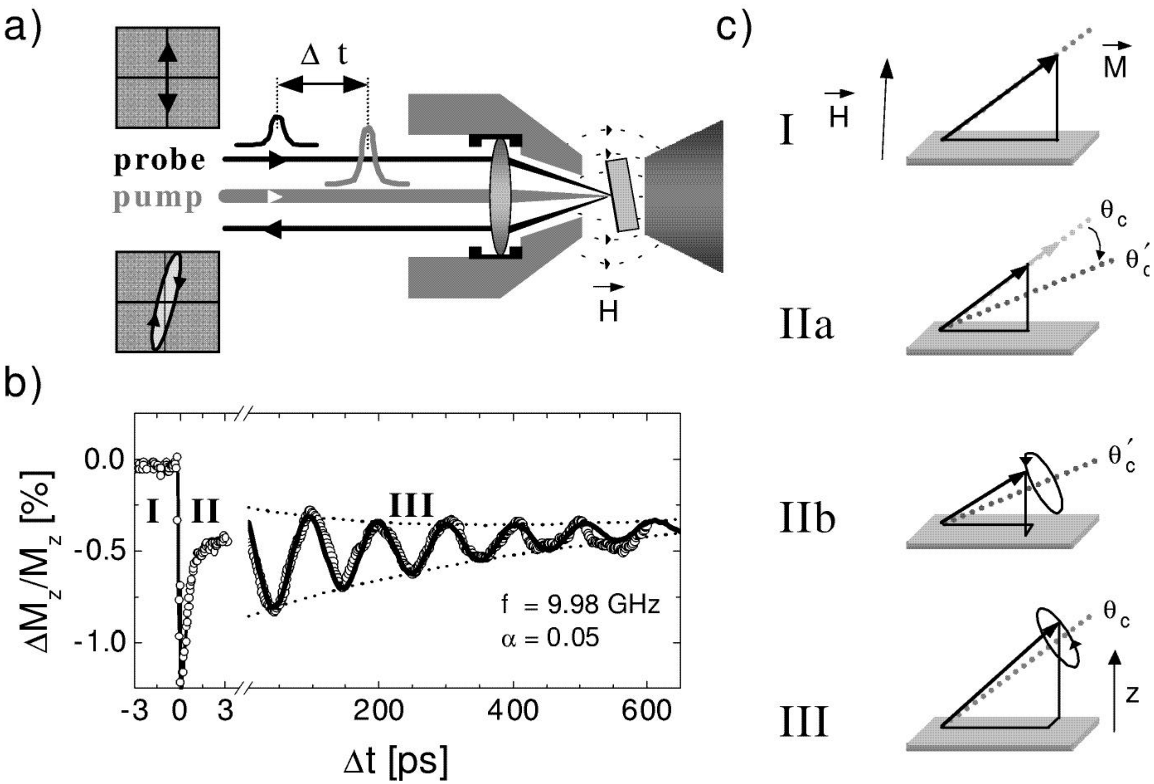


Temporal evolution of the optical parameters: note that Δq/q follows the same dynamics as the Faraday rotation, the ellipticity, the real and imaginary parts of ε for t> 150 fs

L. Guidoni et al., PRL **89** (2003) 017401

Ultra-fast phenomena :
Generation of coherent spin-waves

Experimental set-up



Existence of two time scales

Precession at "long" times arises from the out of equilibrium magnetization orientation post thermalization

M van Kampen et al., PRL **88** (2002) 227201

Take away message

I. ***O***bservations all linked to the **inhomogeneous character** of the (internal) **effective field**

II. ***D***efining the true magnetic dynamical properties of a thin film in its environment remains a challenging issue

III. ***E***xtremely fast development of experimental techniques (all optical, XMCD/XMLD microscopy, PEEM …)

IV. ***Y***et, the **10 ps, 1 nm** resolutions ultimate goal seems far away

V. ***F***ailing to have such tools, it will remain extremely hazardous either to stick to the LLG formalism or discard it on various grounds

VI. ***T***emperature effects have almost not yet been addressed in the spin dynamics of confined structures