Ultrafast Magnetization Dynamics with Polarized Electrons

H.C. Siegmann

Stanford Synchrotron Radiation Laboratory
Stanford Linear Accelerator

Collaborators:

Joachim Stöhr, C. Stamm, I. Tudosa, Y. Acremann (Stanford)

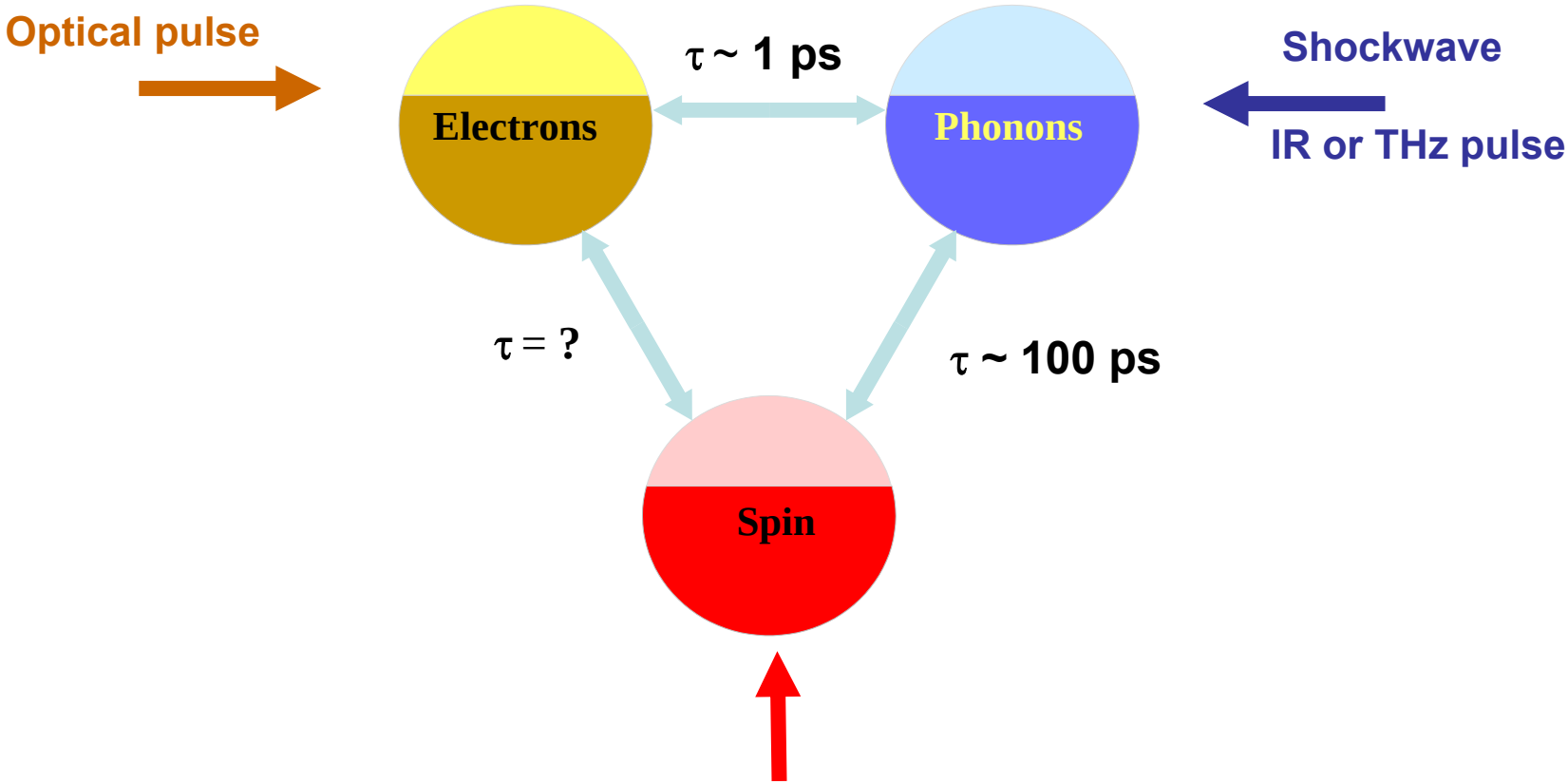
A. Vaterlaus (ETH Zürich) **magnetic imaging**

A. Kashuba (Landau Inst. Moscow) ; A. Dobin (Seagate) **theory**

D. Weller, G. Ju, B.Lu (Seagate Technologies)
G. Woltersdorf, B. Heinrich (S.F.U. Vancouver) } **samples**

Why do we want to study magnetization dynamics?

- Moving the magnetization is a basic operation in magnetism. New *ultrafast* methods of switching the magnetization to be evaluated with respect to *speed*, *energy consumption*, and *reliability*:
- **Precessional switching** with magnetic field pulses
- **Switching by spin current injection**
- **All optical switching**



Most direct way:

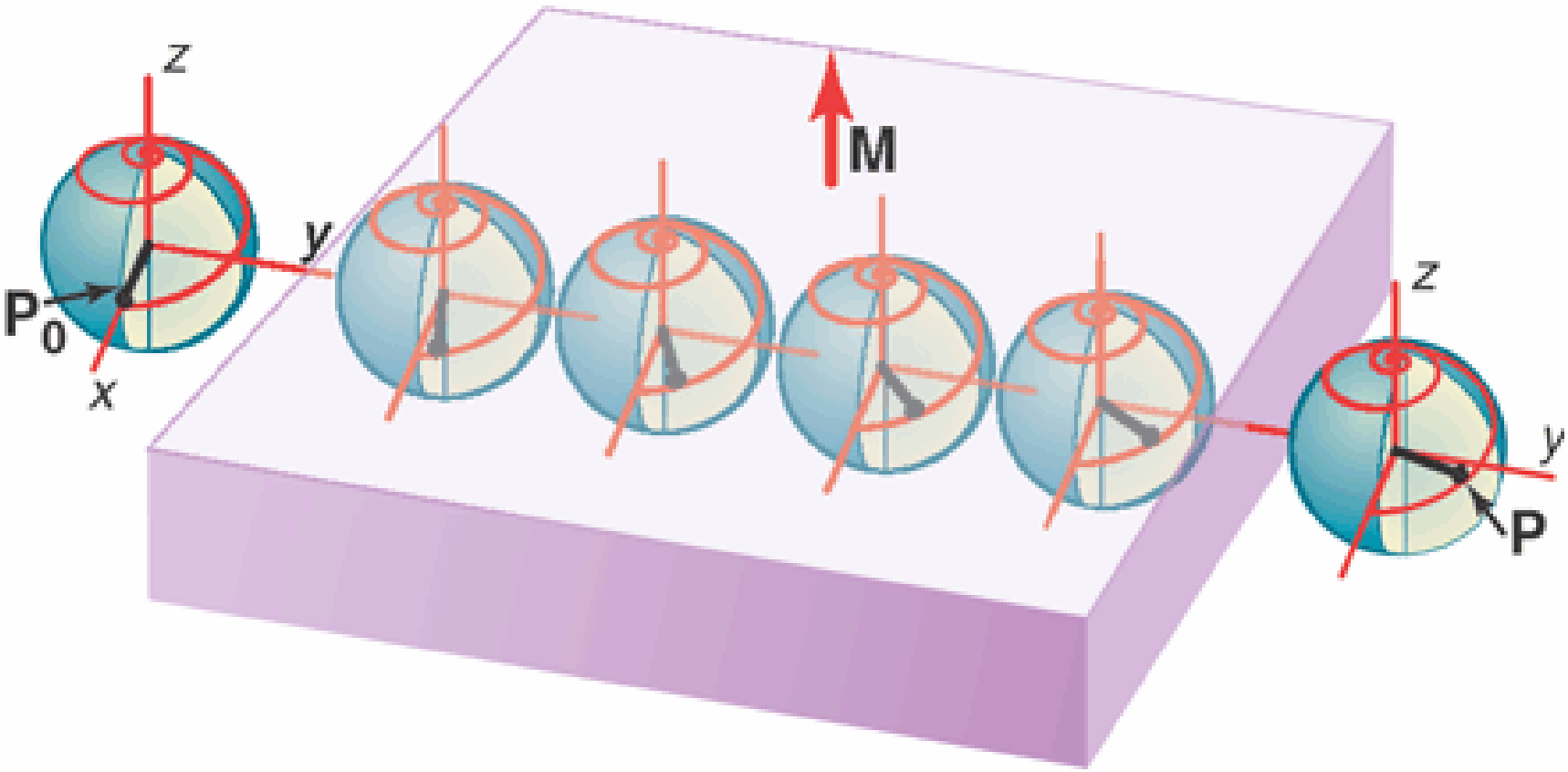
Commonly used:Oersted switching

Precessional or ballistic switching

Exchange switching (spin injection)

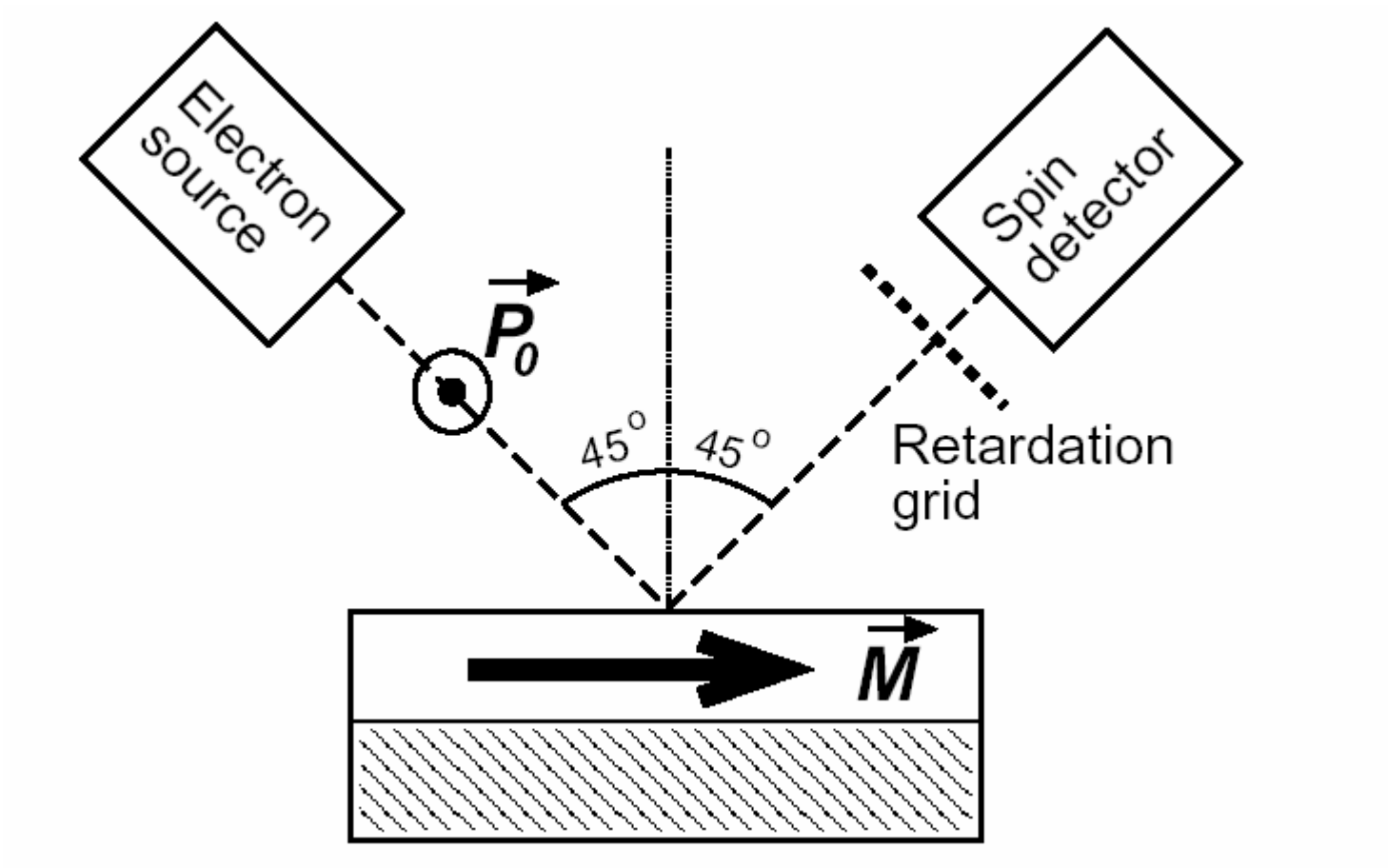
Motion of the Spin Polarization Vector in a Ferromagnet

W. Weber, S. Riesen, H.C. Siegmann, "The dynamic response of the magnetization to hot spins", in *Spin Dynamics in Confined Magnetic Structures II***,** B. Hillebrands and K. Ounadjela eds, Springer 2003



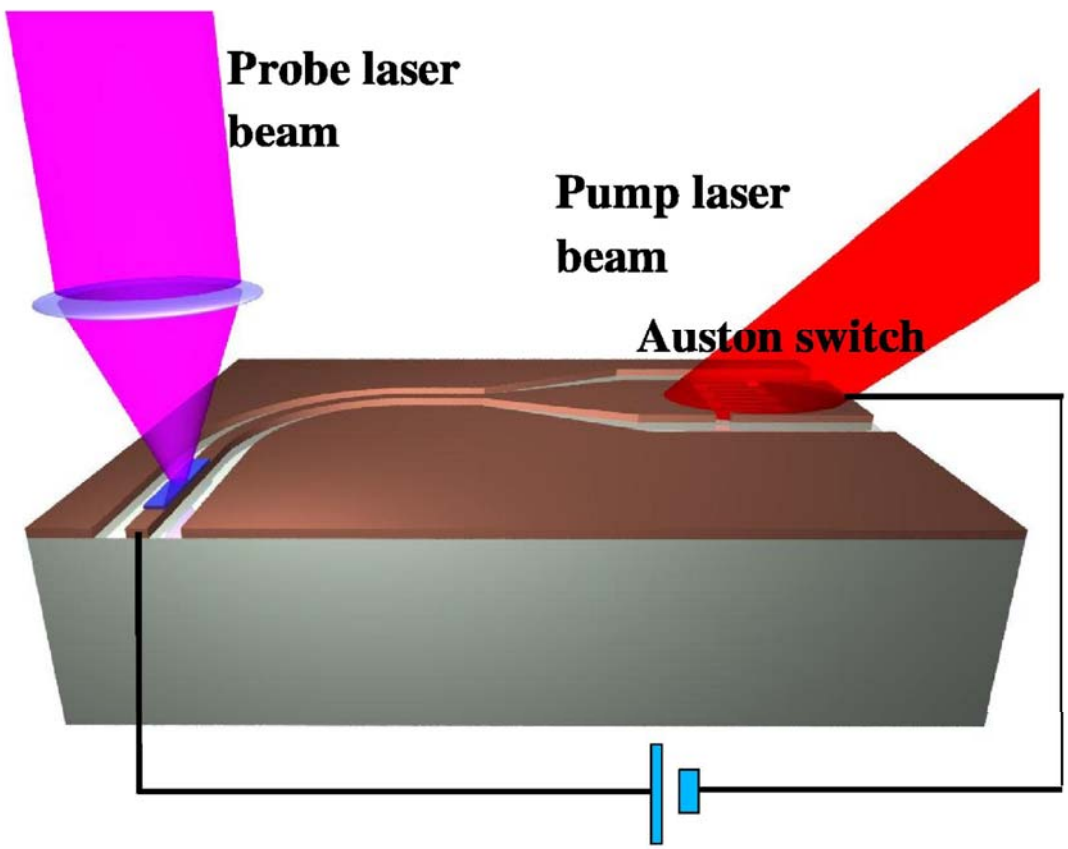
The change of the direction of the spin leads to a torque on M that is useful to excite magnetization dynamics and switching.

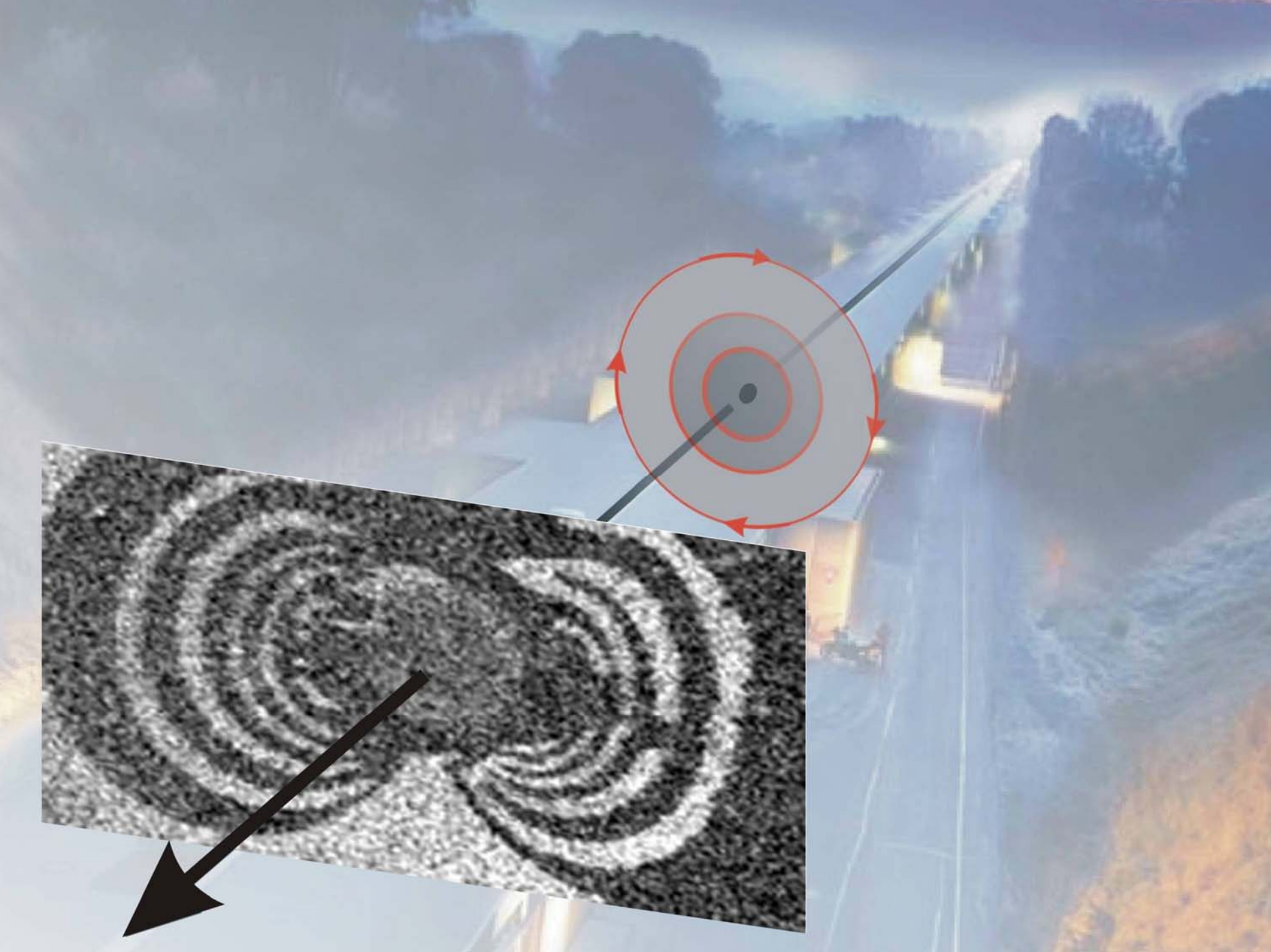
Reflection of Polarized Electrons



*The motion of **P** indicates spatial separation of the two spin states, and yields a quantitative measure of the torque on **M** in reflection.*

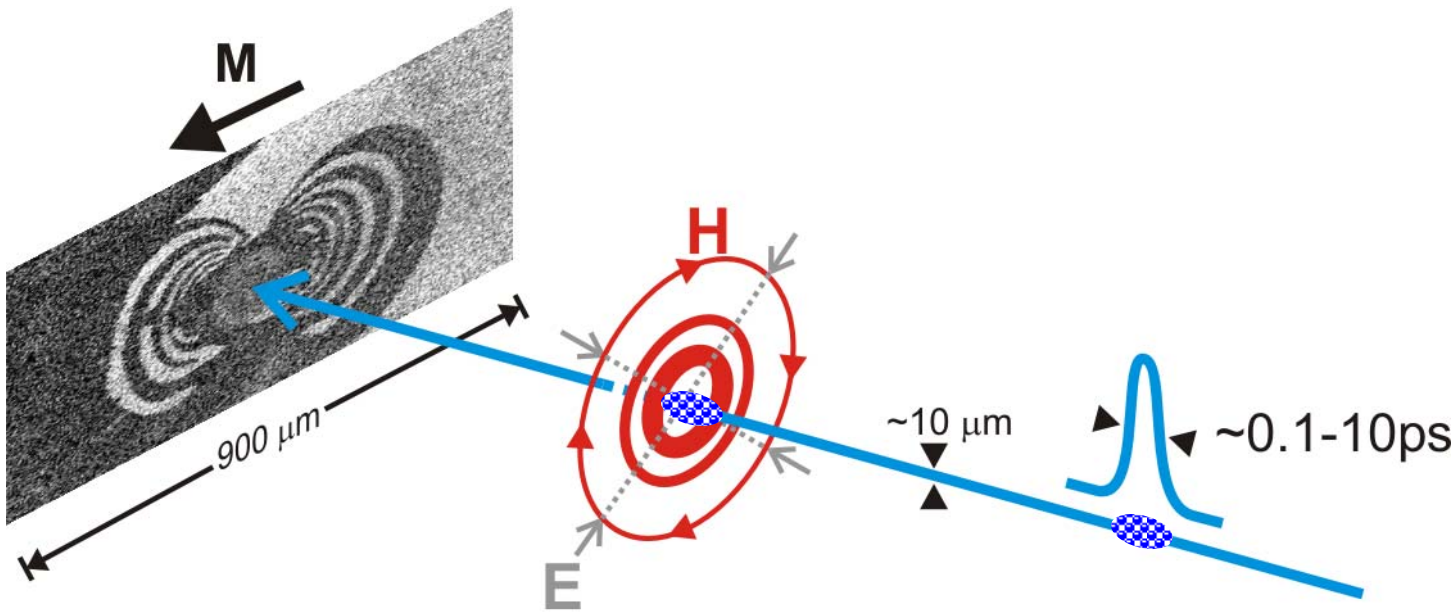
Time-resolved magneto-optic Kerr effect





Experiment

PhD Thesis: Ioan Tudosa

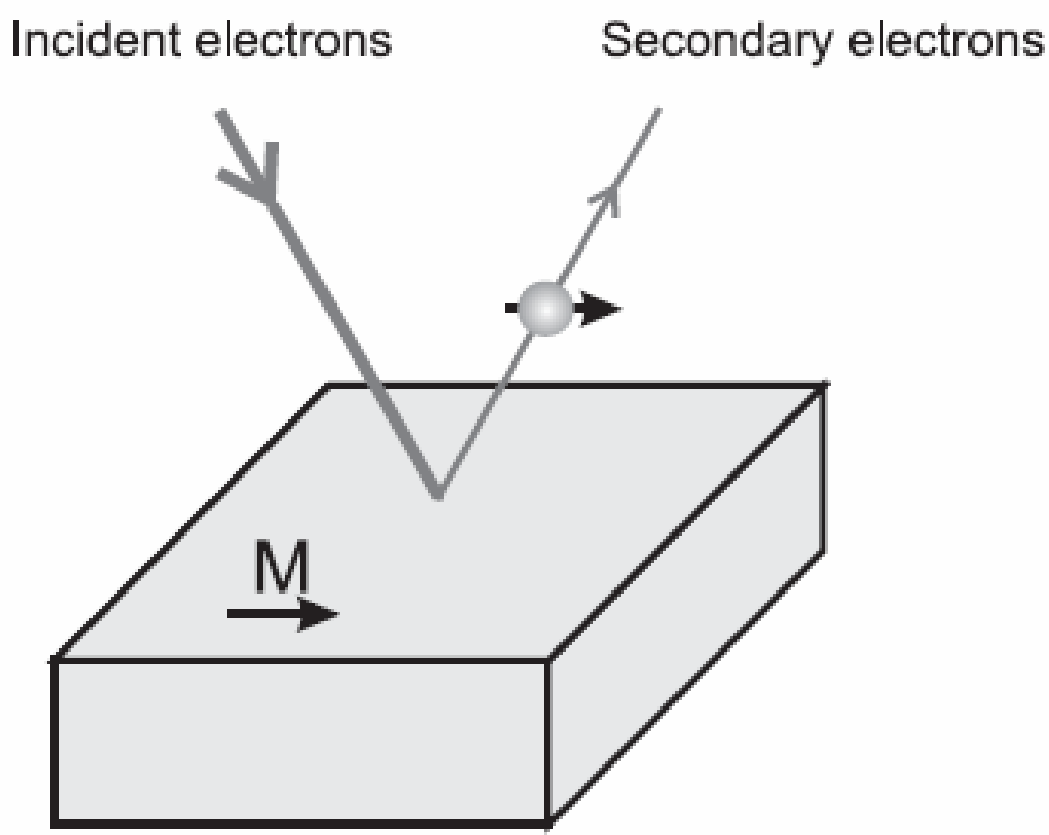


Magnetic sample

Electromagnetic field of the beam

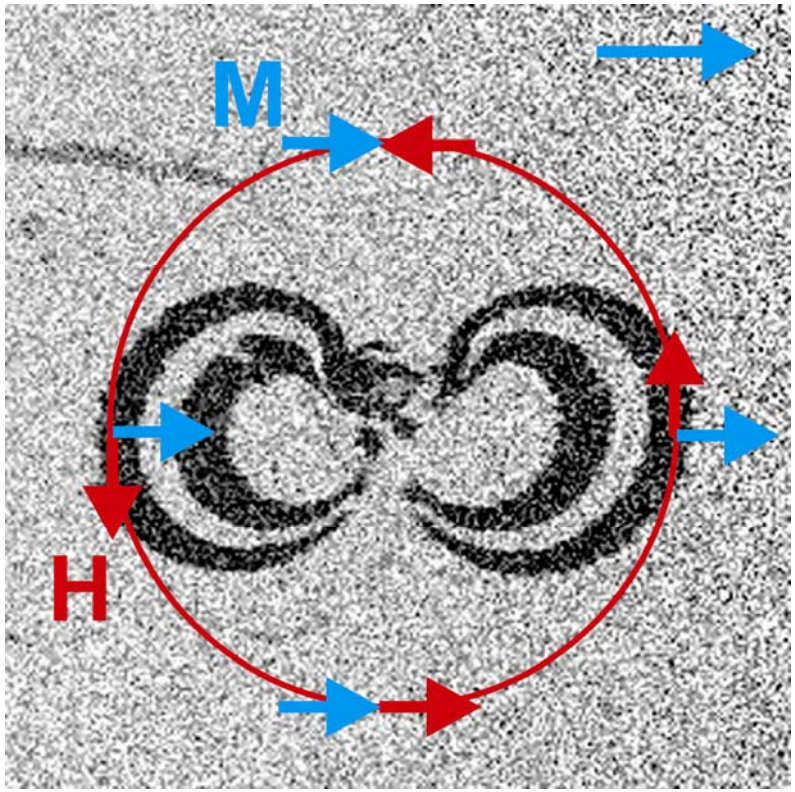
SLAC linac beam 28 GeV

Scanning electron microscopy with polarization analysis
(SEMPA)



Torques on in-plane magnetization by beam field

Initial magnetization of sample

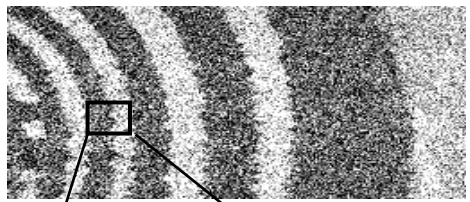


Max. torque

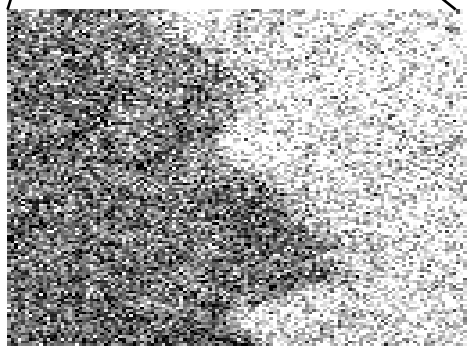
Min. torque

another sample:
soft thin film

261 x 92 μm



13 x 9.2 μm



Fast switching occurs when **H** ⊥ **M**

Precessional clock

Frequency: $\omega = (e/m) B$

Time elapsed is ω/φ, where φ is the precession angle.

B is the demagnetization field generated by the motion of the magnetization during the field pulse:

$$B = - M \cos\gamma,$$

γ is the angle between M and the film normal .

As B is generated by the field pulse, the precessional stop watch is started by the field pulse.

Torque of a magnetic field H on the magnetization M:

T = M x H

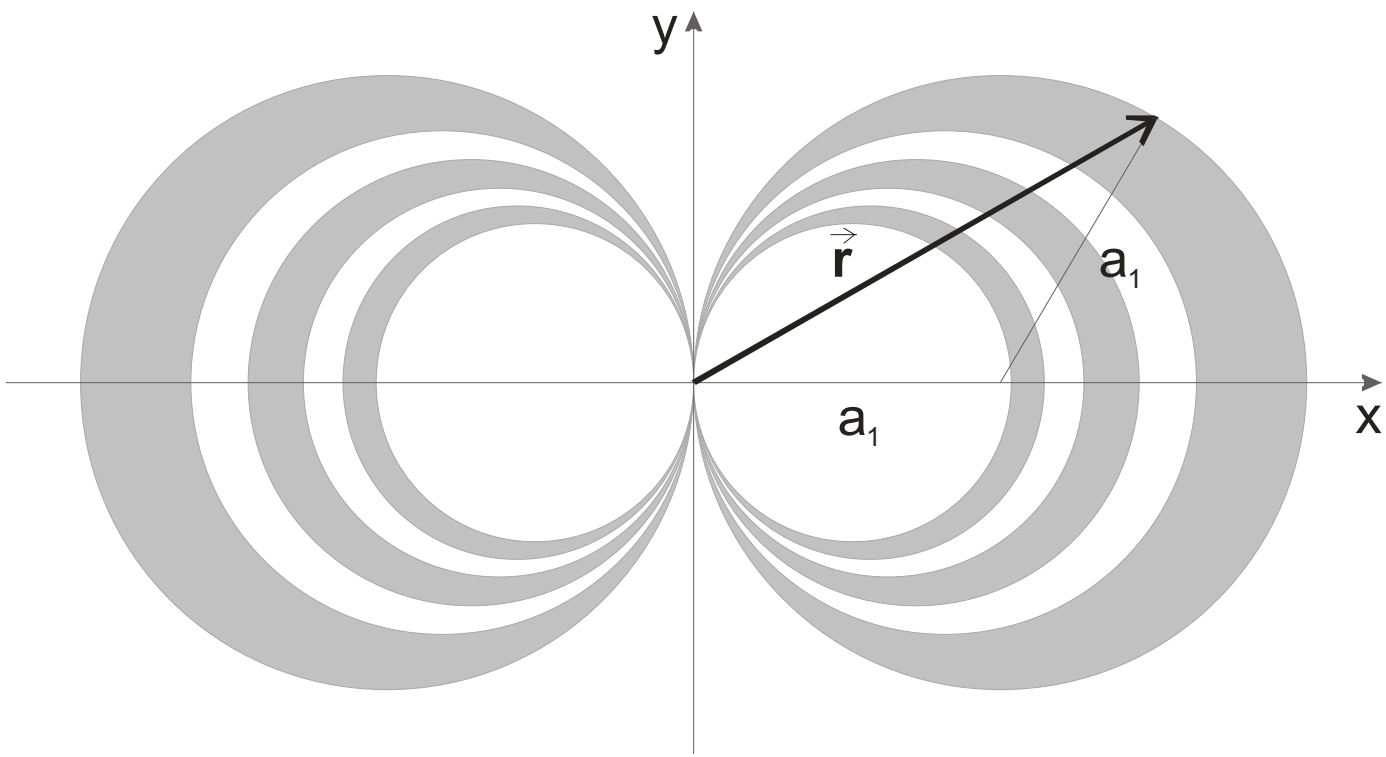
Lines of constant torque with M||x are circles:

$$\vec{H} = \frac{i}{2\pi r}\left[\frac{y}{r}, \frac{x}{r}\right]; \; H_y = const \quad \frac{x}{r^2}$$

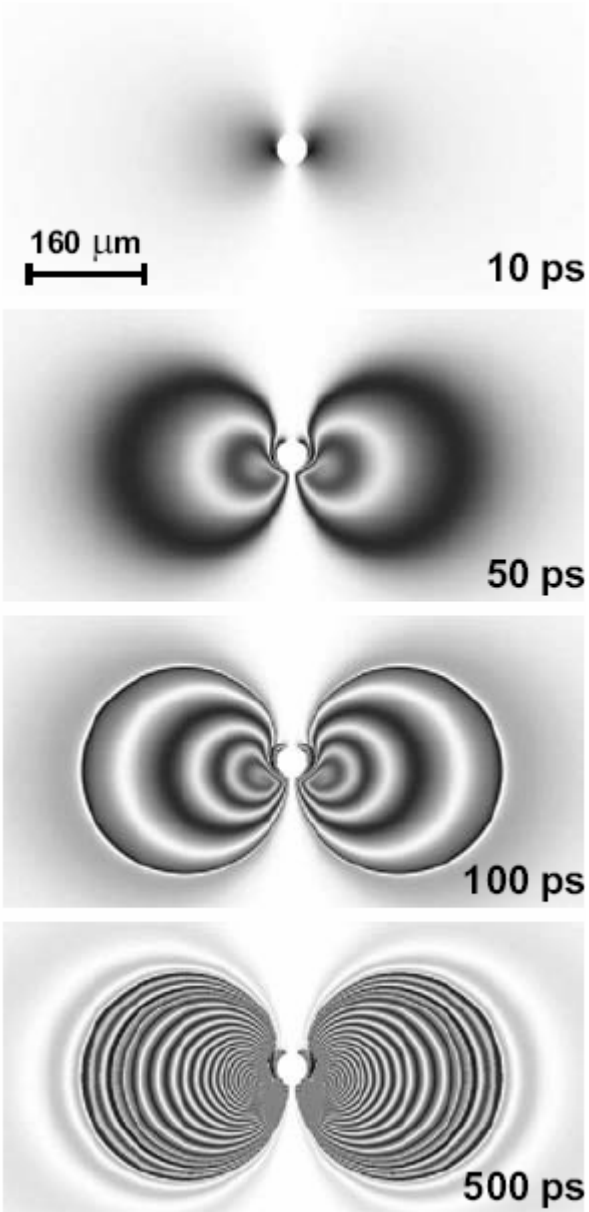
$$\frac{x}{x^2 + y^2} = const = \frac{1}{2a_\nu}$$

$$\left(\frac{x - a_\nu}{a_\nu}\right)^2 + \left(\frac{y}{a_\nu}\right)^2 = 1$$

Lines of constant torque with M || x



Constant torque = constant excitation energy of the spin system

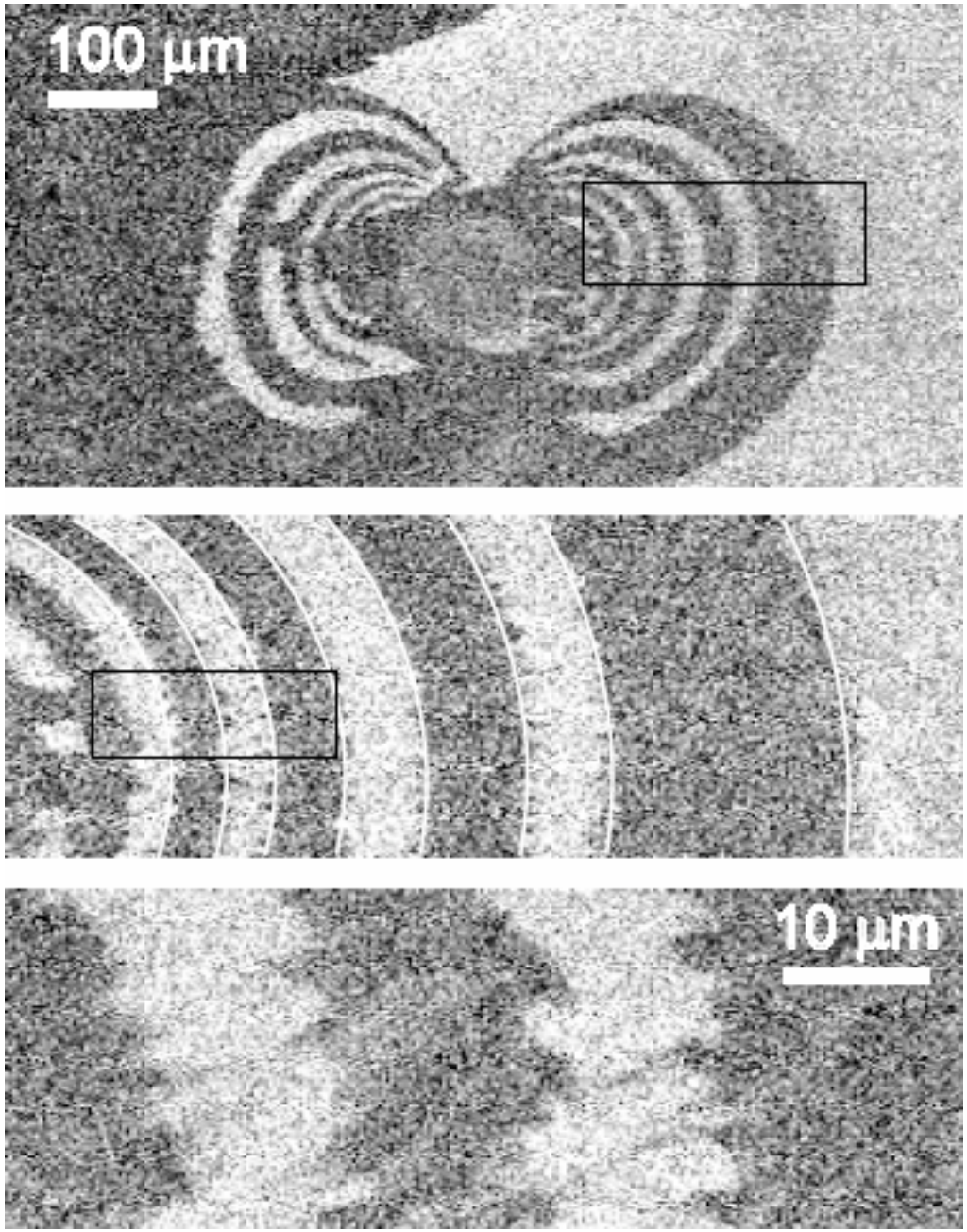


Calculated Evolution of the component M_x of the magnetization along the horizontal easy axis.

(White $M_x = +1$ and black $M_x = -1$)

The calculation was done with LLG using the damping parameter from ferromagnetic resonance

The calculation is is for a single crystalline film of 10 ML Fe on GaAs.



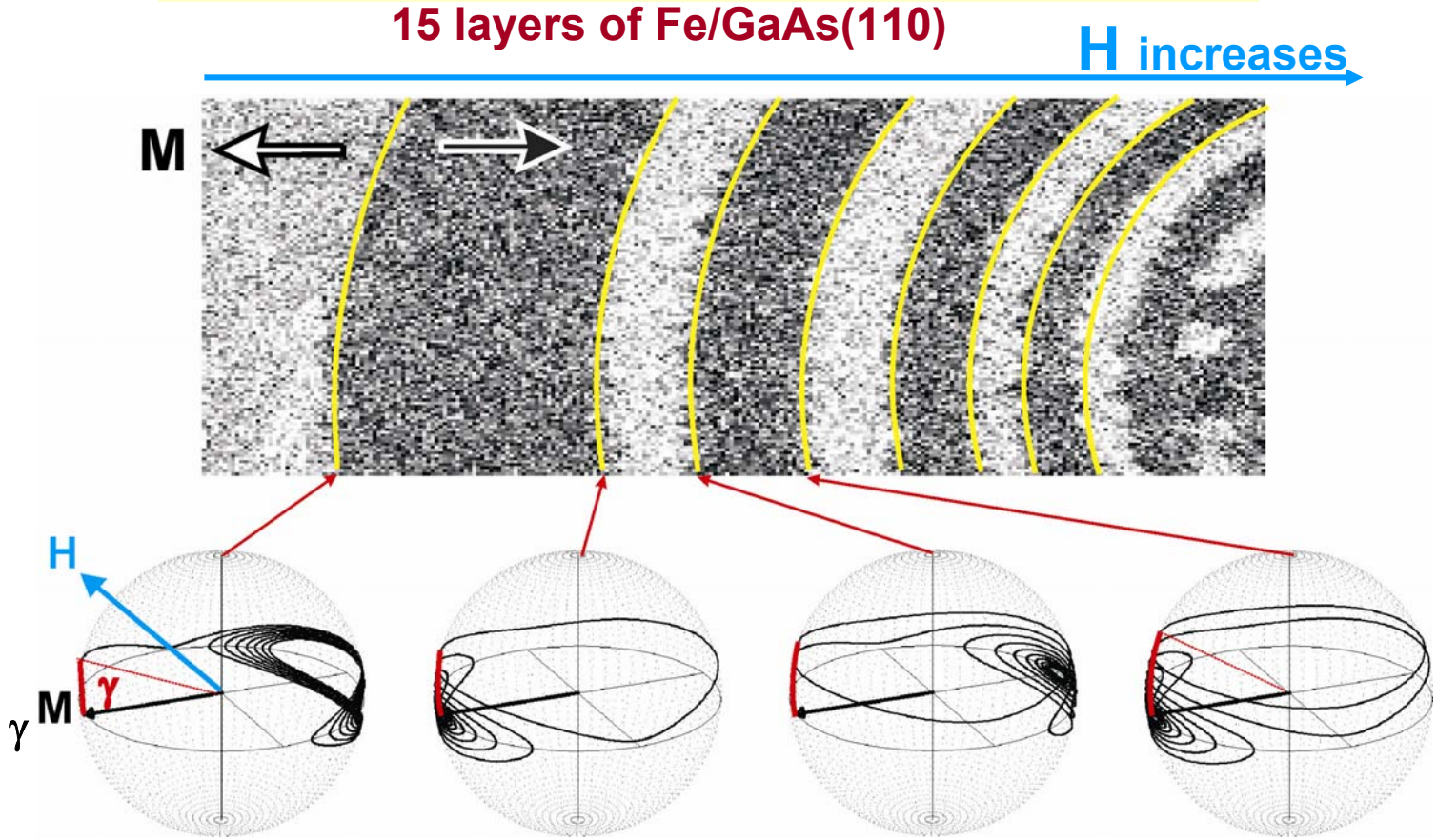
Magnetic pattern generated with a single electron bunch in a 15 ML Fe/GaAs(001 epitaxial bcc Fe film.

Prior to the field pulse, *M* is aligned horizontally to the right, shown in light gray. The regions were *M* has switched to the left are shown as dark gray.

Image taken with SEMPA

Origin of observed switching pattern

15 layers of Fe/GaAs(110)

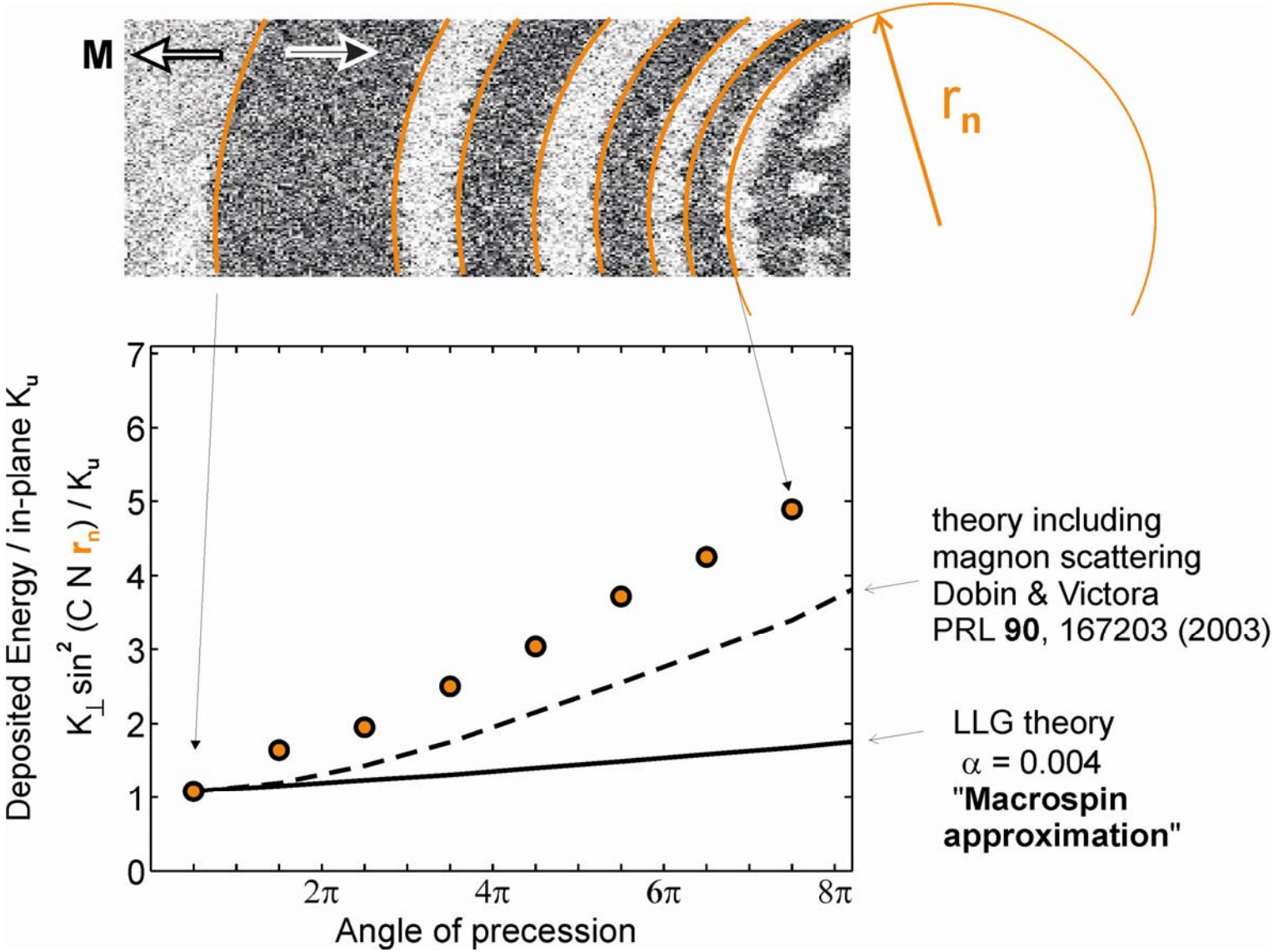


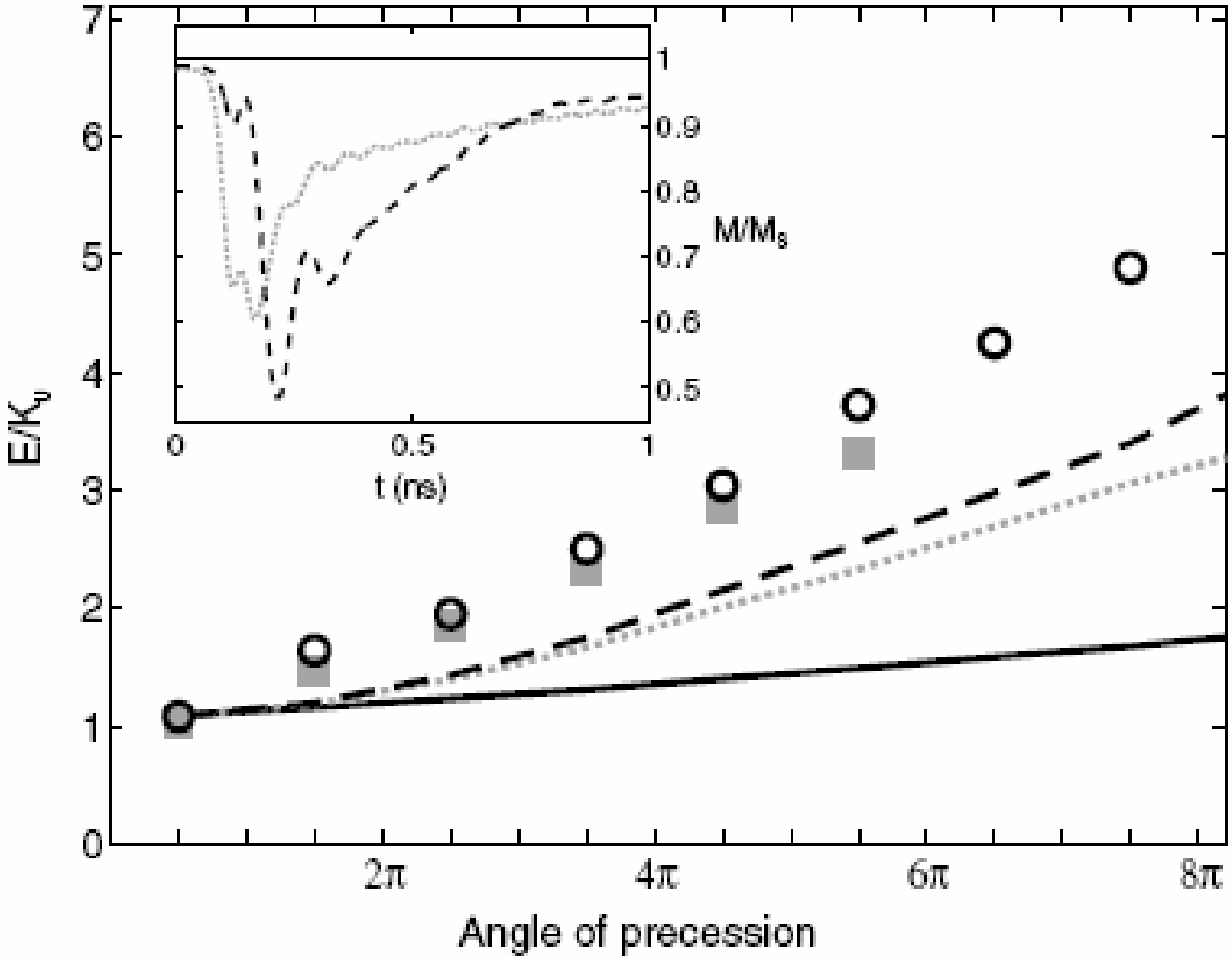
Line positions depend on:

- angle $\gamma = B\,\tau$
- in-plane anisotropy K_u
- out-of-plane anisotropy $K_\perp$
- LLG damping parameter α

} from FMR data

Breakdown of the Macrospin Approximation

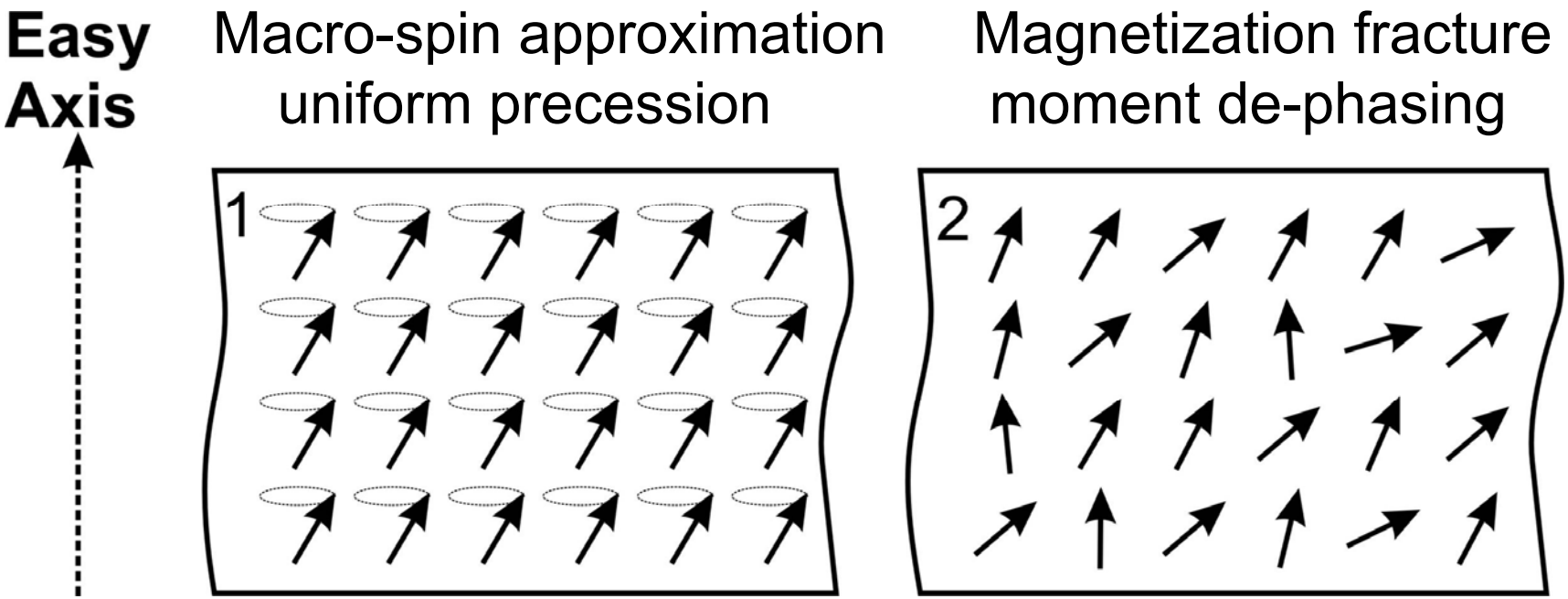




Universal Precessional Switching Diagram

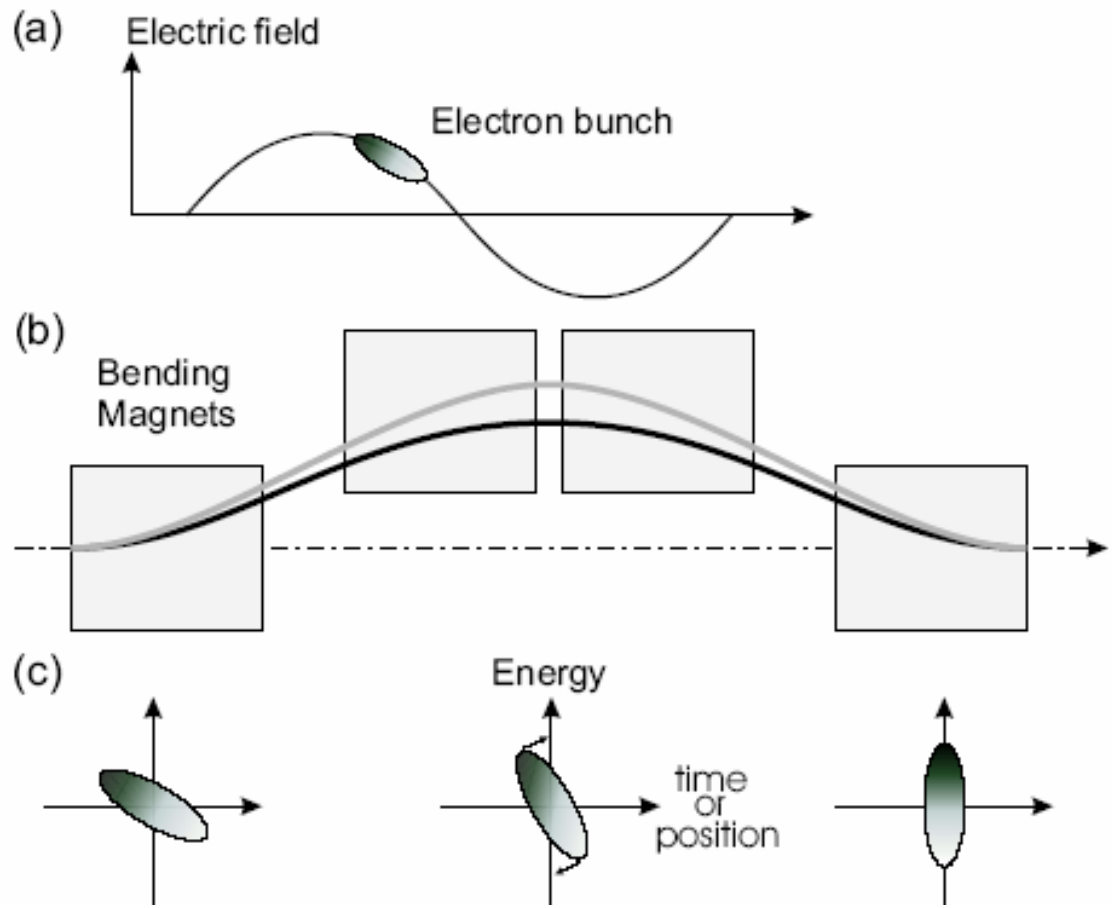
Energy deposited in the spin system in units of the uniaxial in-plane anisotropy constant *Ku* vs the precession angle. Data points are for 10 ML Fe (squares) and 15 ML Fe (circles). Full line as expected from FMR, broken lines including the Suhl instability.

Magnetization fracture under ultrafast field pulse excitation



Breakdown of the macro-spin approximation

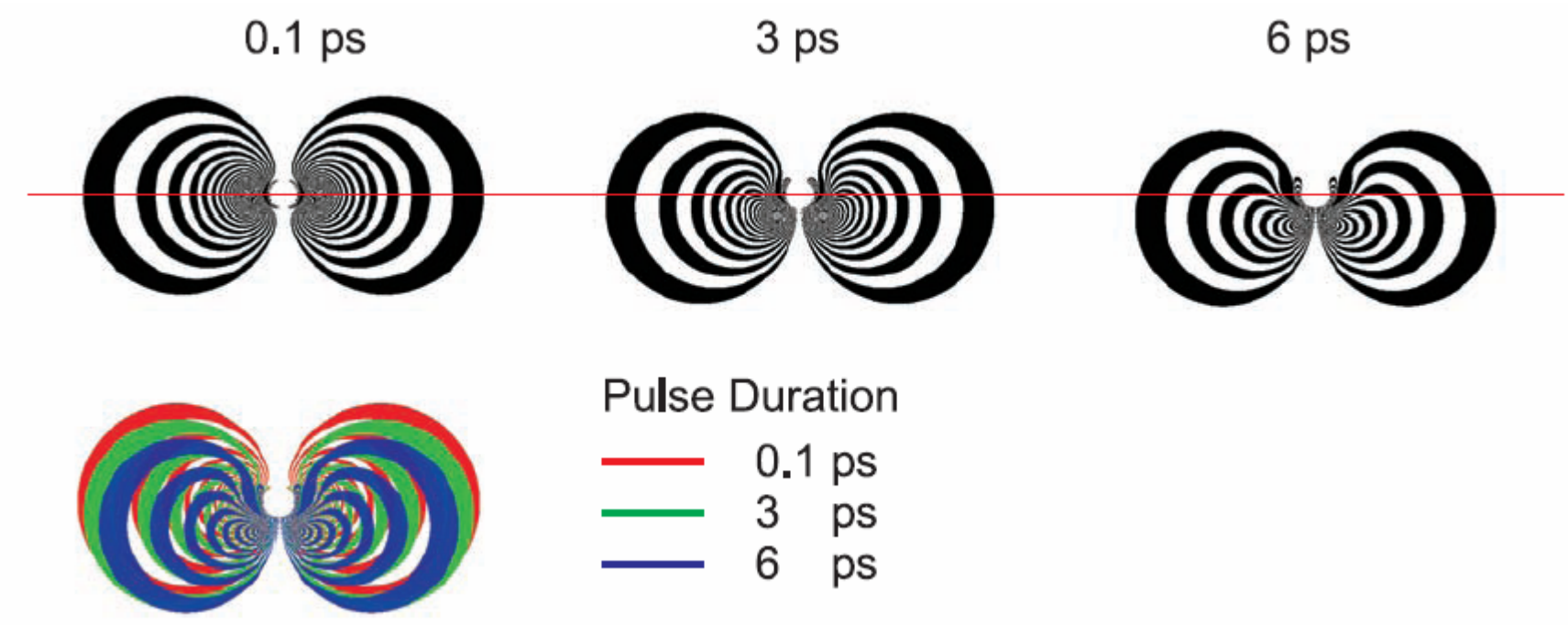
Tudosa *et al.,* Nature **428**, 831 (2004)

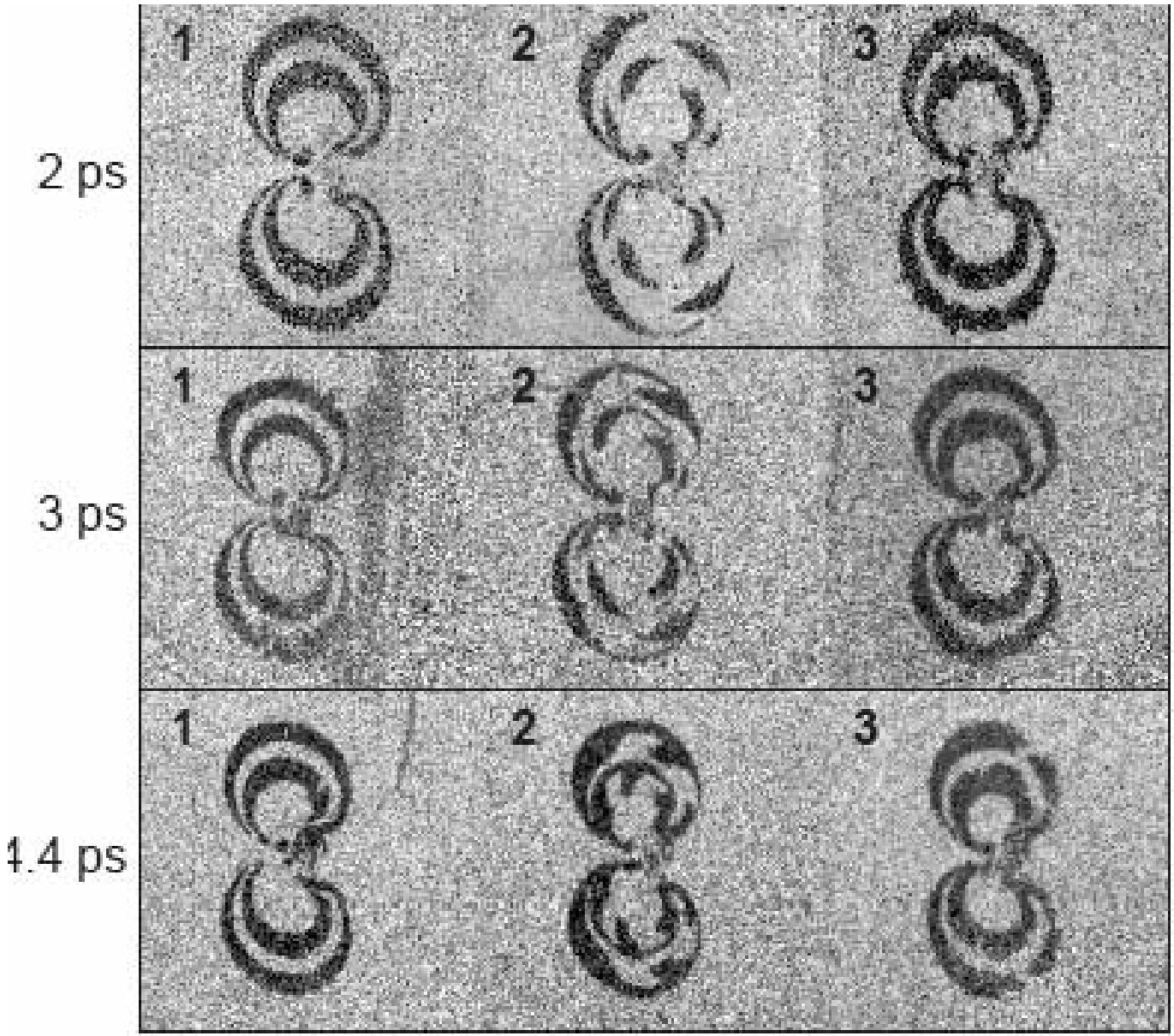


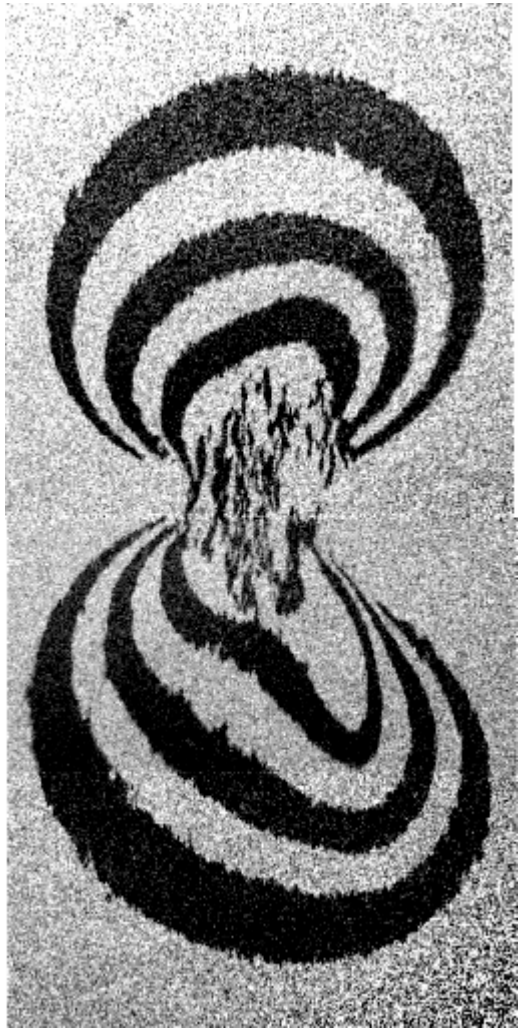
Electron Bunch Compression. (a) generation of energy-position "chirp"; (b) four-bending-magnet chicane rotates the bunch by 90° due to the shorter path of the electrons in the tail; (c) The emerging bunch is compressed in its length but its energy spread is increased. ***The bunch charge is conserved: Bτ = const.***

Pulse length and magnetic pattern keeping the charge/bunch constant

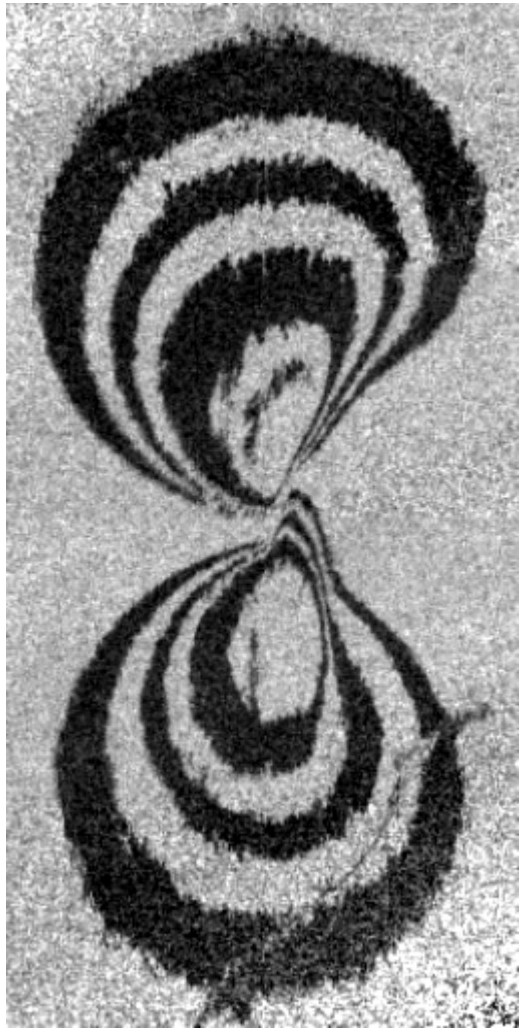
(red line indicates center where the electron bunch passed and direction of the magnetic anisotropy)



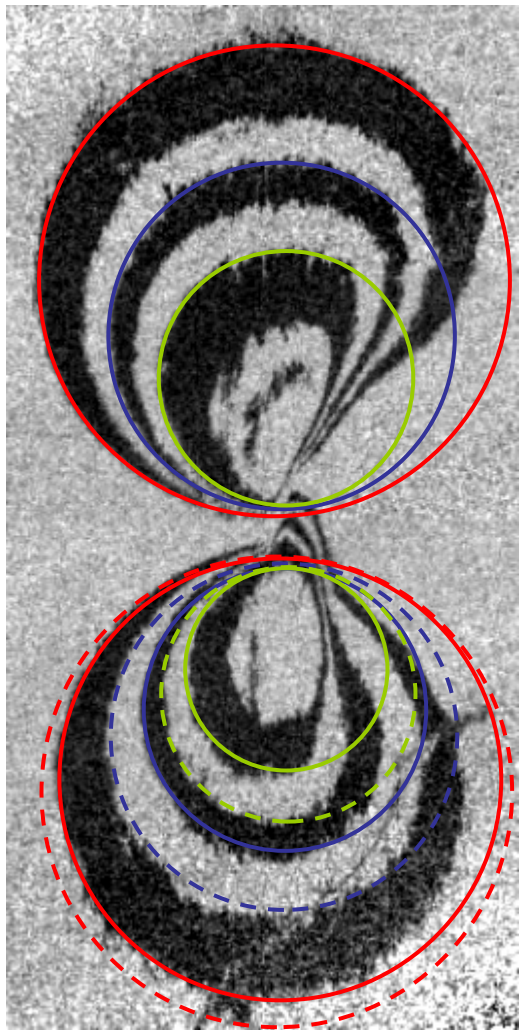

2 ps
3 ps
1.4 ps
1
2
3
1
2
3
1
2
3



Pattern with pulse of 2.3 ps



Pattern with pulse of .067 ps



Conclusions

- The breakdown of the macrospin approximation for fast field pulses may limit the speed in magnetic switching

- Breakdown is believed to arise from angular momentum transfer within the spin system – higher spin wave modes

- There is more dephasing than predicted by the Suhl instability

For more, see: http://www-ssrl.slac.stanford.edu/stohr

and

J. Stöhr and H. C. Siegmann
Magnetism: From Fundamentals to Nanoscale Dynamics
800+ page textbook (Springer, to be published in Spring 2006)