A "quick" look at magnetism using time-resolved soft x-ray microscopy

Hendrik Ohldag (SSRL)
Yves Acremann (PULSE)

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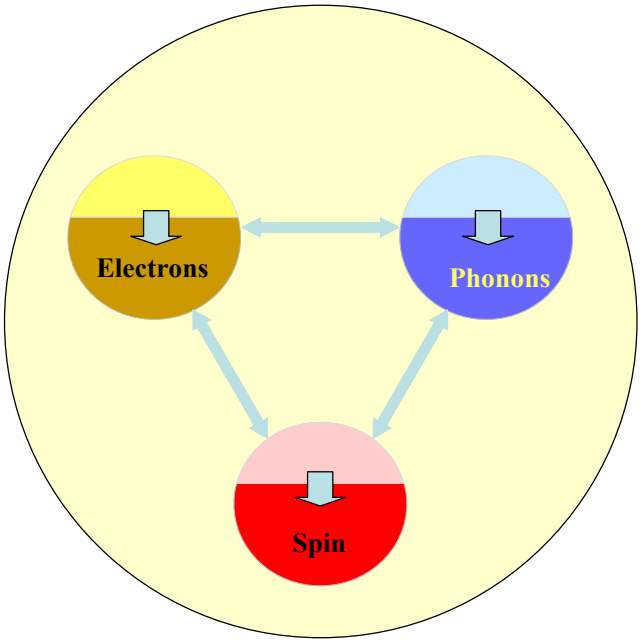
Stanford Synchrotron Radiation Laboratory
A national user facility for academia, industry, and national laboratories

Why picosecond x-ray microscopy and how does it work?

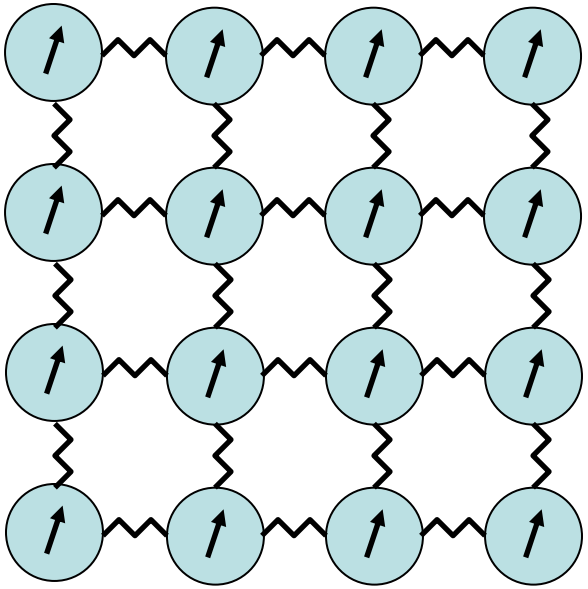
Different Views on Magnetism

The fundamental interactions



Femtosecond spectroscopy

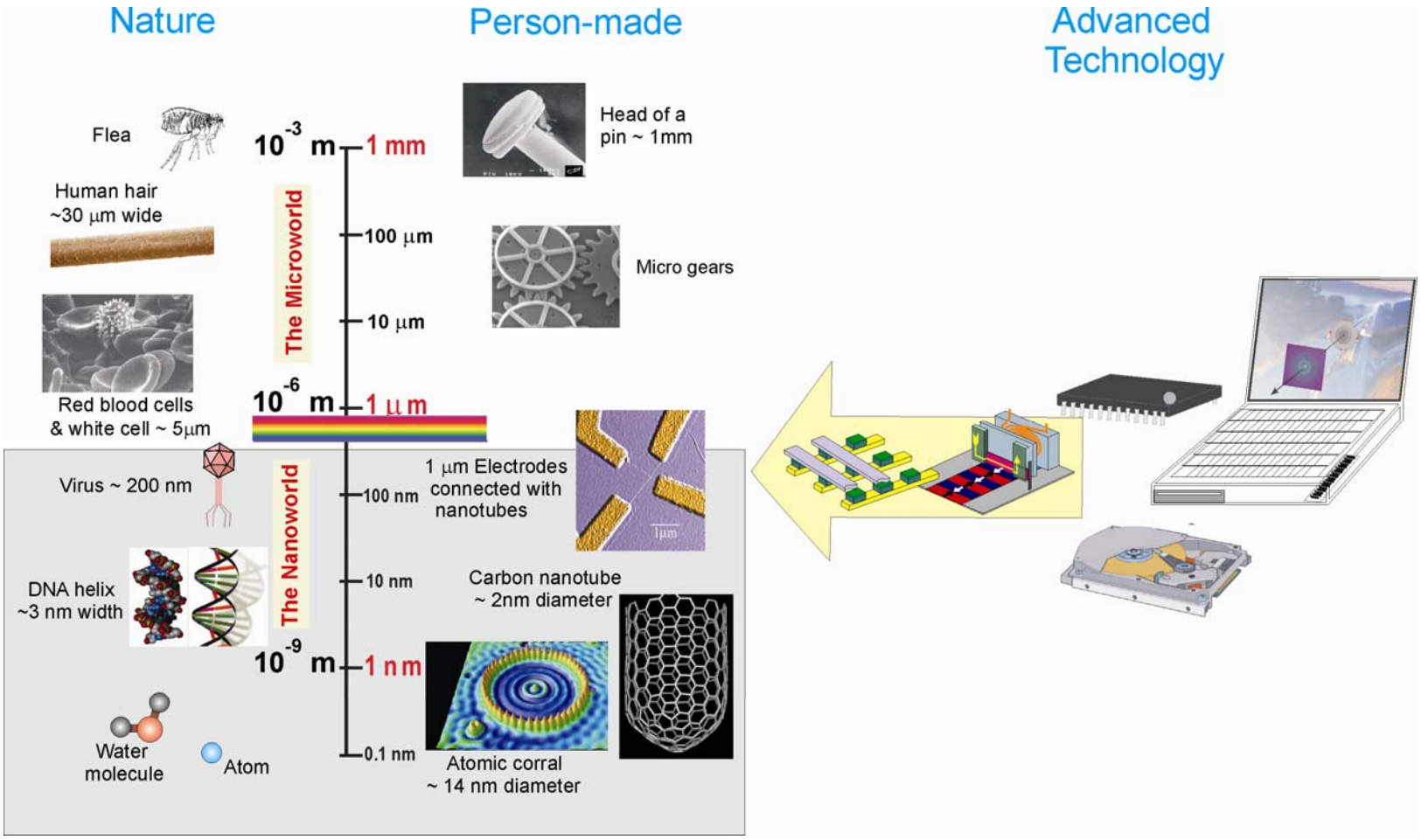
The micromagnetic picture



Picosecond microscopy / holography
Time scale: years to picoseconds

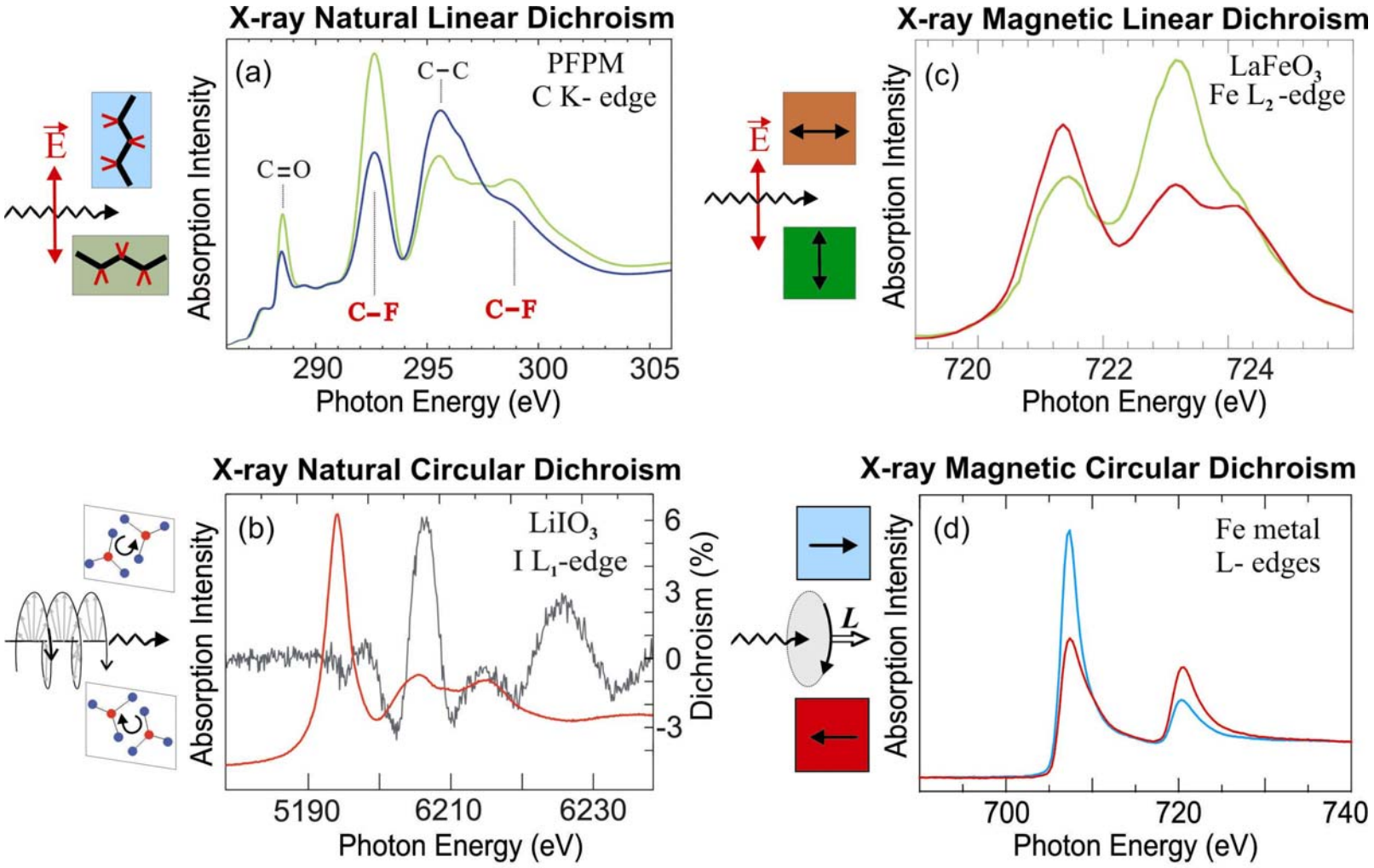
Femtosecond and picosecond experiments address different problems in magnetism. Fundamental (inter- and intraatomic) processes happen in femtoseconds, but observables related to long range order (like a domain pattern on the nm scale) will change on a picosecond time scale.

The Small – The Fast – The Complex



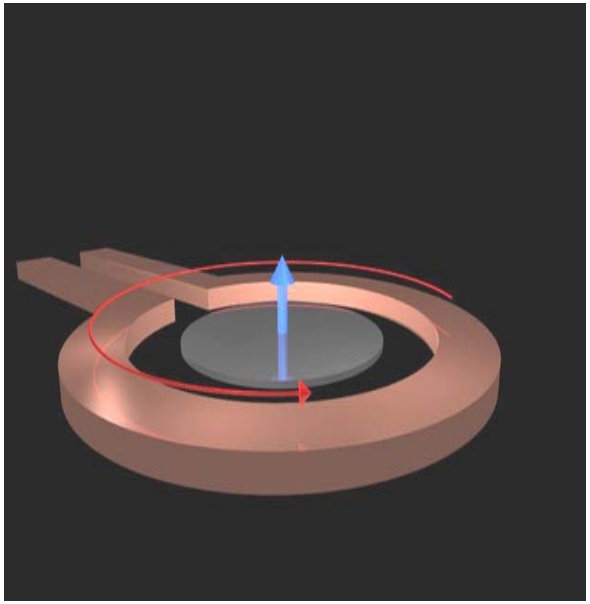
The future requires techniques that:
look below the surface, distinguish components and resolve dynamic motions to understand new classes of materials and devices. X-rays provide a unique combination of nm spatial, ps time, elemental, and chemical, resolution with either bulk or surface sensitivity.

X Ray Dichroism

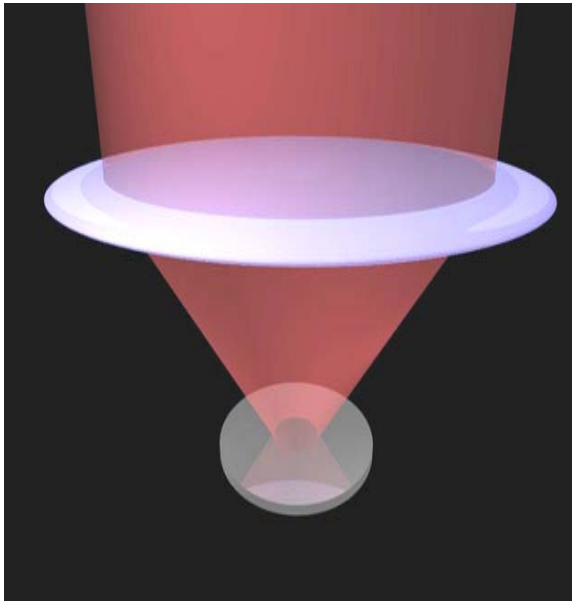


Polarized X-rays provide element specific information about **long range order** (magnetic, crystallographic, charge, …) in a sample. Different order phenomena can be investigated at the same time, e.g. Multiferroics, HTSC, CMR materials etc… → Look at correlations, **XPCS** etc.

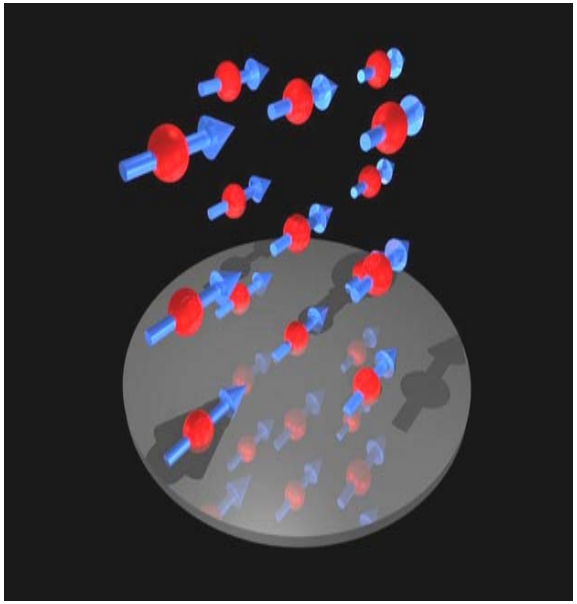
How to Manipulate a Ferromagnet



By applying a magnetic field



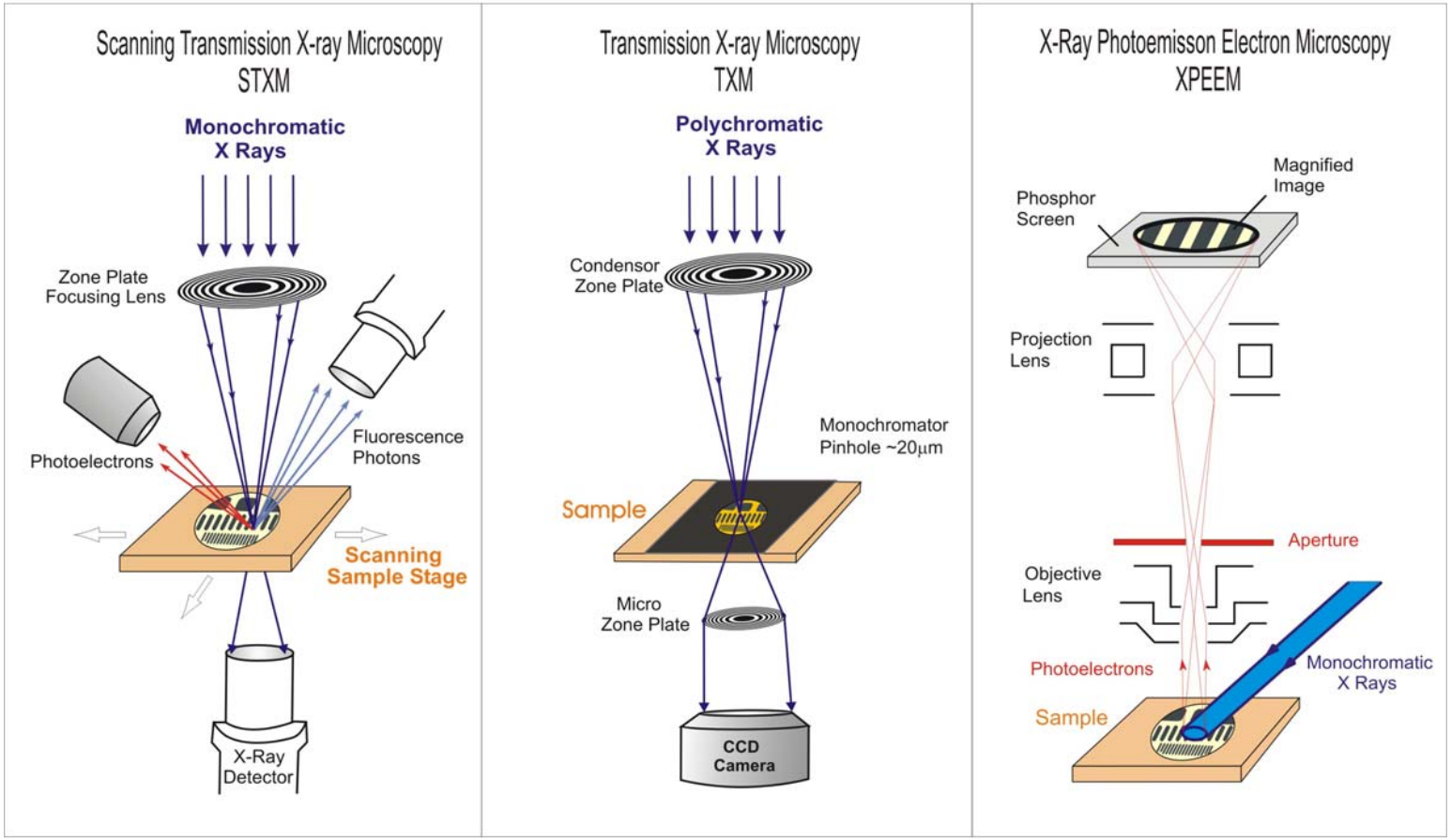
By heating (using a laser pulse)



By spin polarized electrons!

Different switching methods lead to characteristic switching patterns, that can be identified on a picosecond time scale. Picosecond magnetic field pulses and spin currents can be generated using existing Mhz laser sources or electronics.

How to look at a FM?



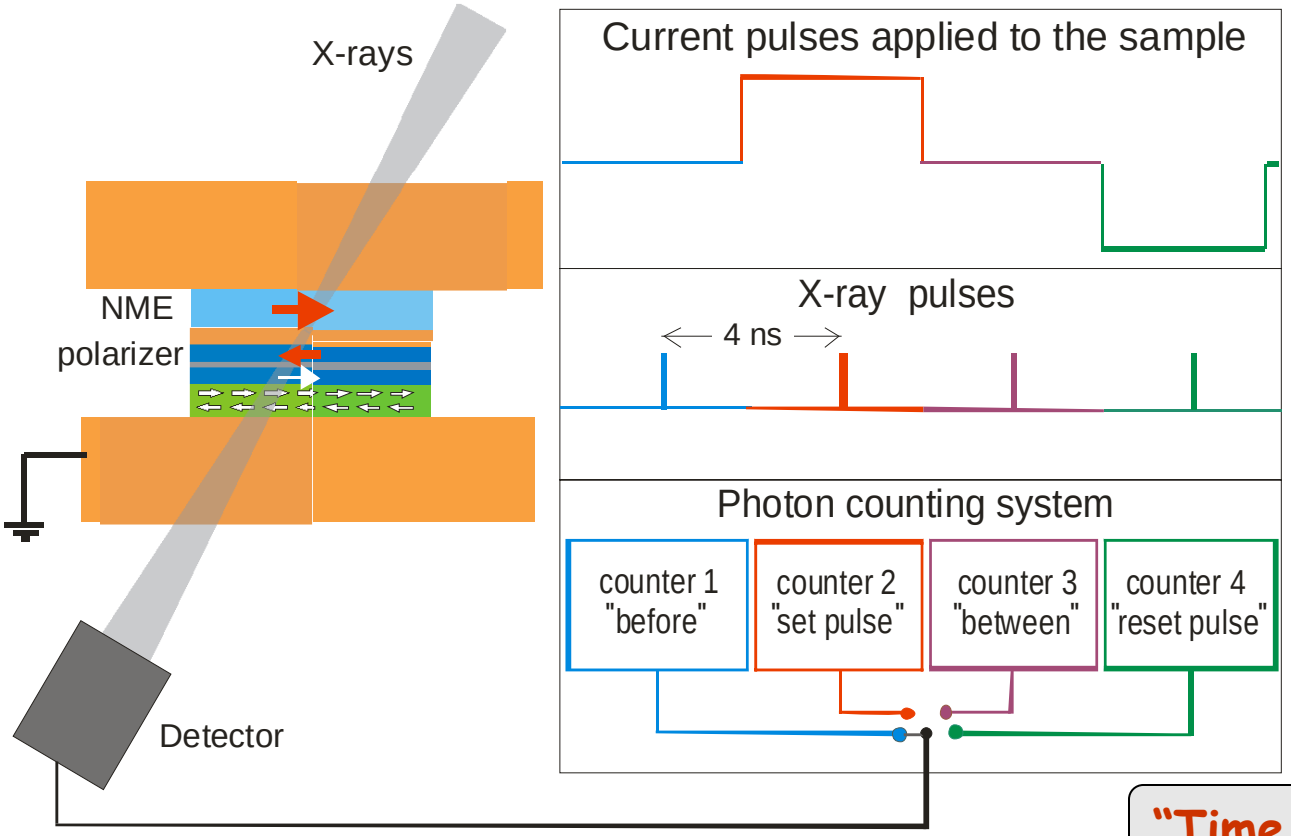
X Ray absorption can be detected in transmission, fluorescence or electron yield

→X-ray and electron microscopy is possible with high spatial resolution.

→X-ray microscopy using FEL type sources is very challenging,

The SSRL "Time machine"

STXM



"Time Machine"

Challenge: Achieve stability so that small signals from small structures can be detected.

Solution: Time machine → slow drifts (kHz and slower) do not affect the signal, different points in time can be measured "simultaneously".

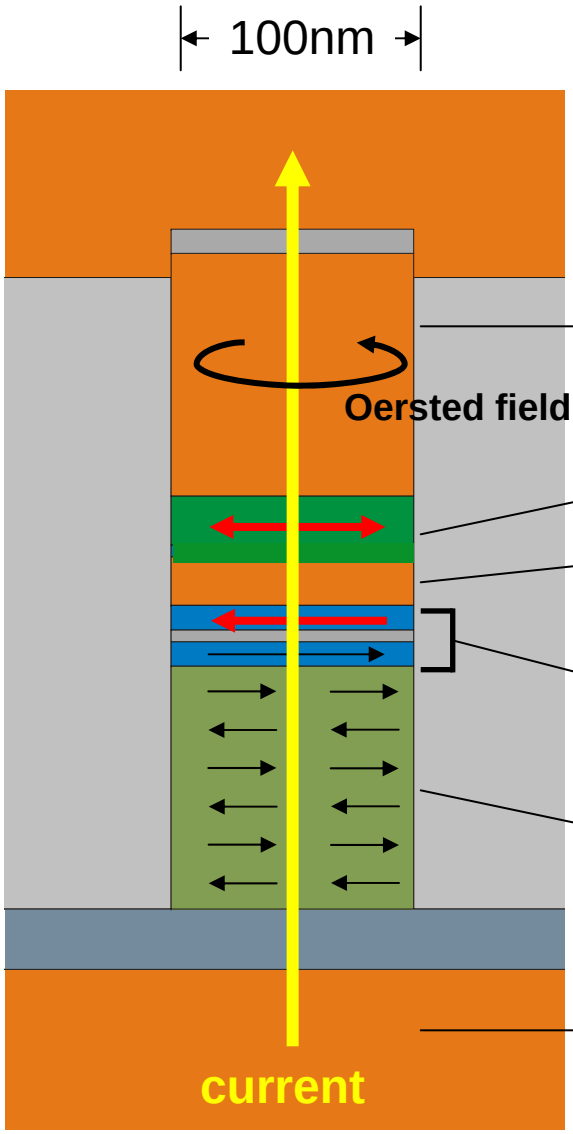
"Additional benefit": Time resolution and pump probe capability.

Example:

Switching nanomagnets through Spin Injection and Oersted Fields

Samples

prepared by Jordan Katine, *Hitachi Global Storage*



Au 100 Å
Cu 1600 Å

$Co_{.86}Fe_{.14}$ 20 Å to be switched

Cu 35 Å

$Co_{.86}Fe_{.14}$ 20 Å polarizes spins

Ru 8 Å

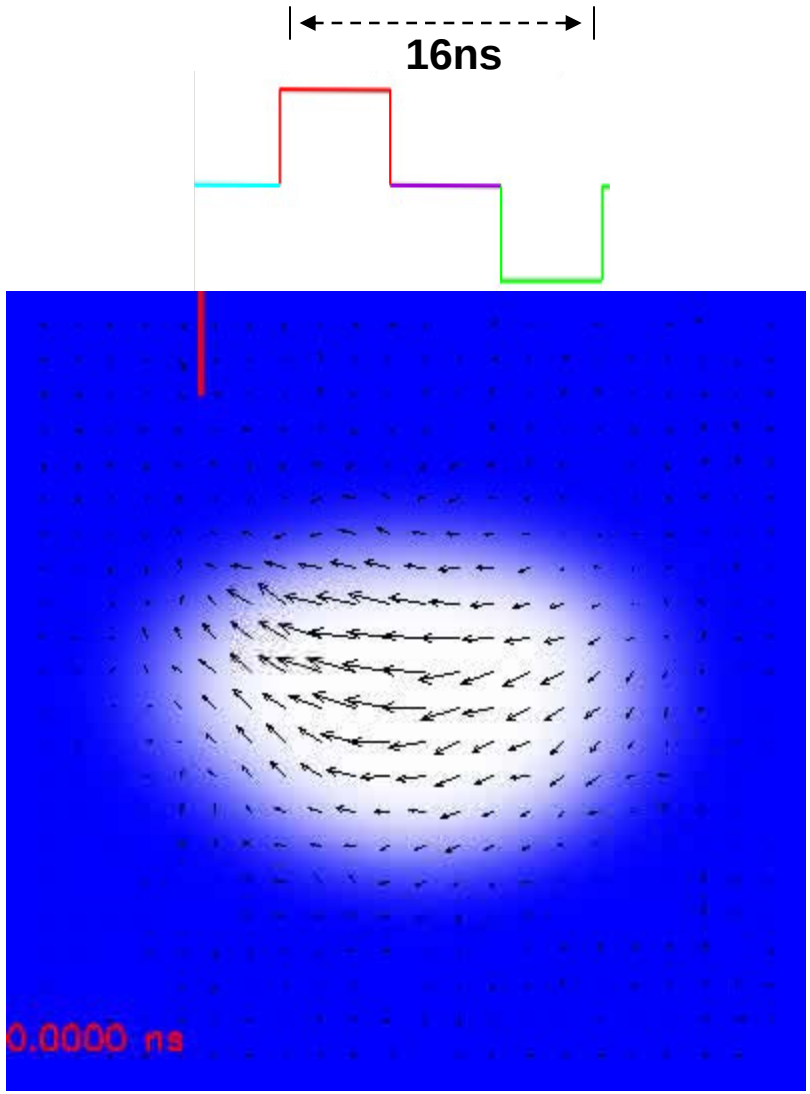
$Co_{.86}Fe_{.14}$ 18 Å

PtMn 175 Å
Ta 25 Å

Cu 200 Å
Ta 50 Å

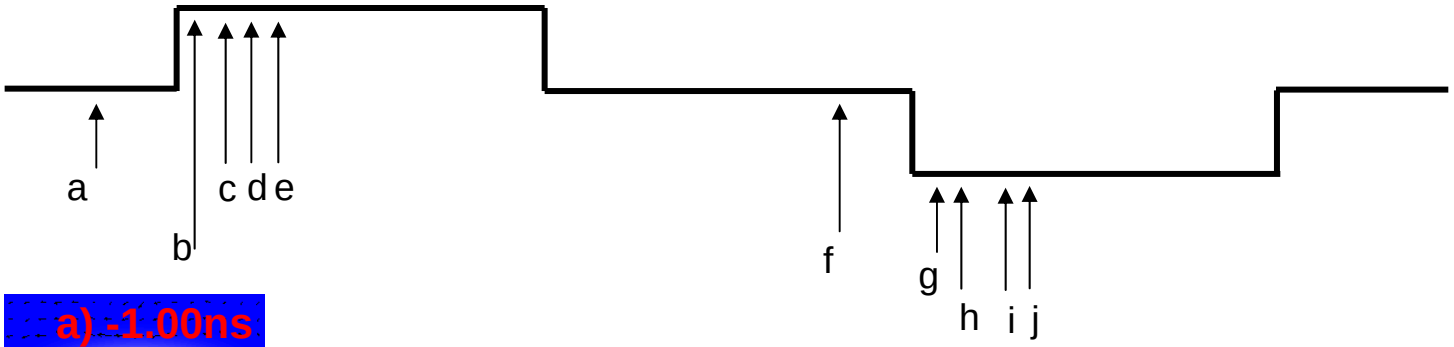
Reversal Movie for 100x200nm sample

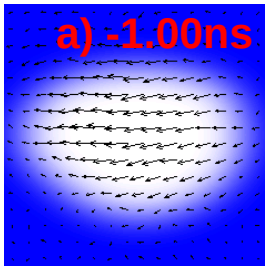
100x200nm
2nm free layer



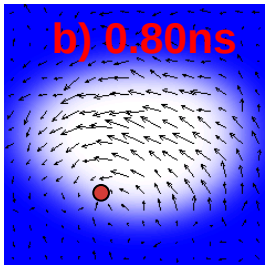
Images taken every 200ps

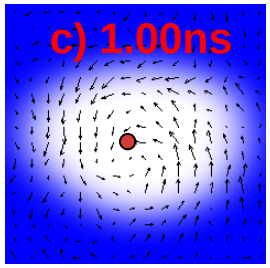
Switching through Vortex Motion

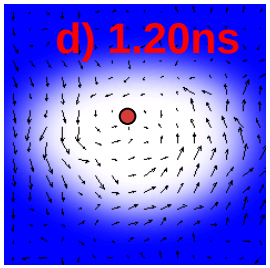


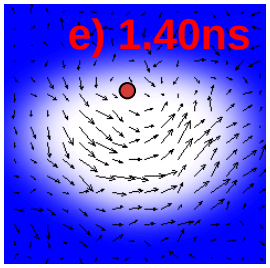


● ● - denotes the vortex core



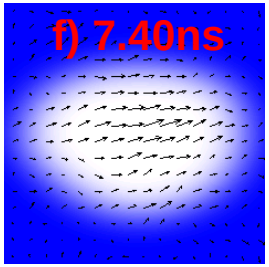


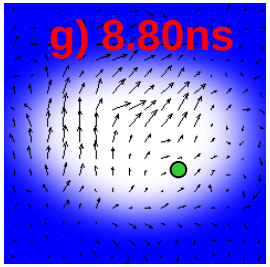


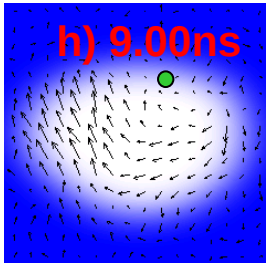


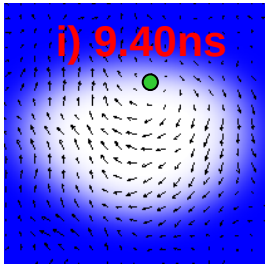
The Oersted field creates the vortex

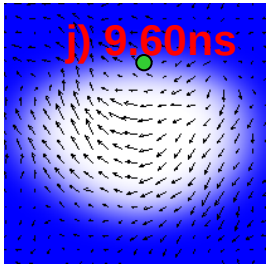
Spin injection moves the vortex







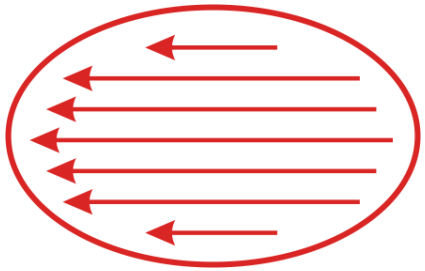




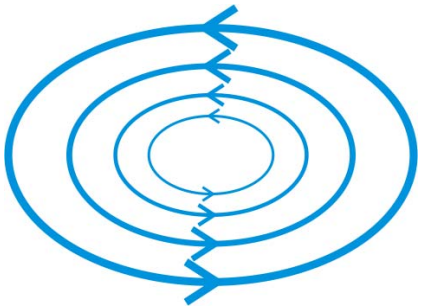
Simulated Vortex-driven switching

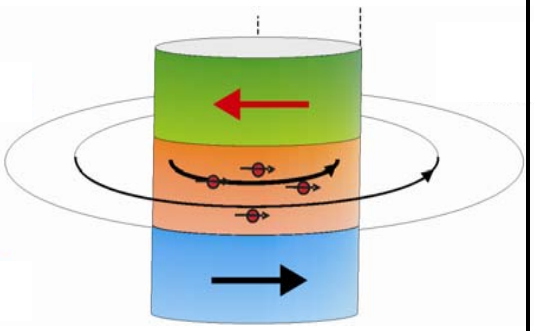
Interplay of spin and charge current

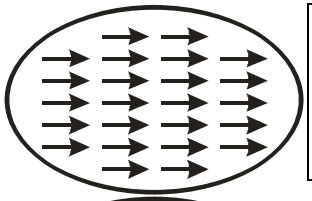
Spin Current



Oersted Field

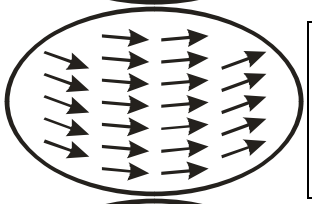




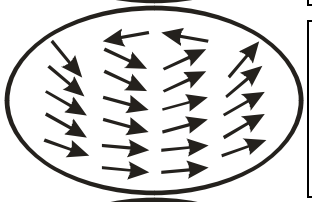


Initially, spin-torque = 0

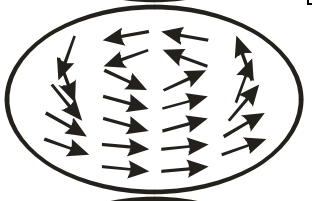
$$\vec{M} \times (\vec{M} \times \vec{S}) = 0$$

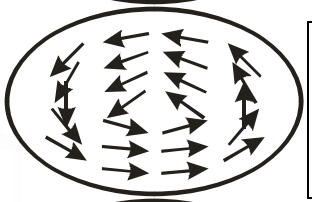


Charge current induces C-state, spin-torque ≠ 0

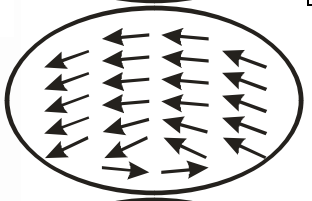


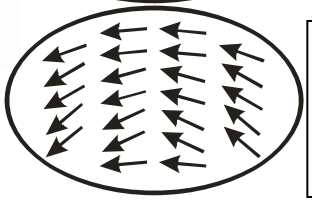
Spin-torque amplifies the angles in the C-state, forming a vortex





Vortex driven across sample

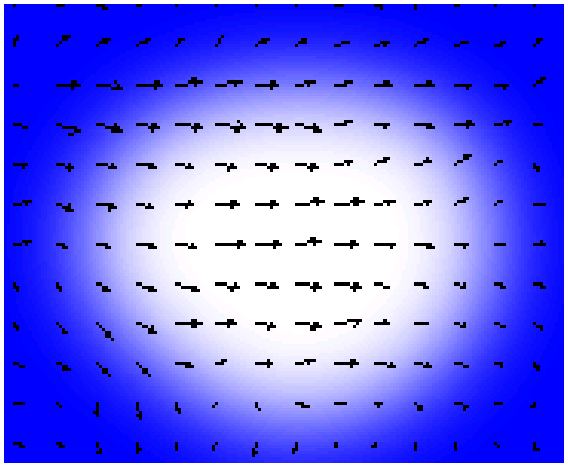




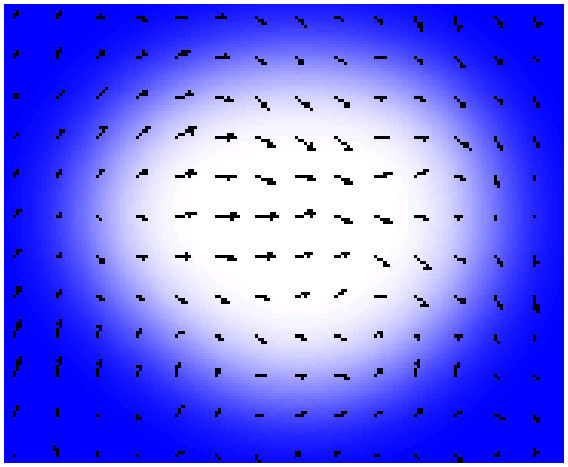
Vortex exits leaving a switched magnetization

Making the sample smaller …

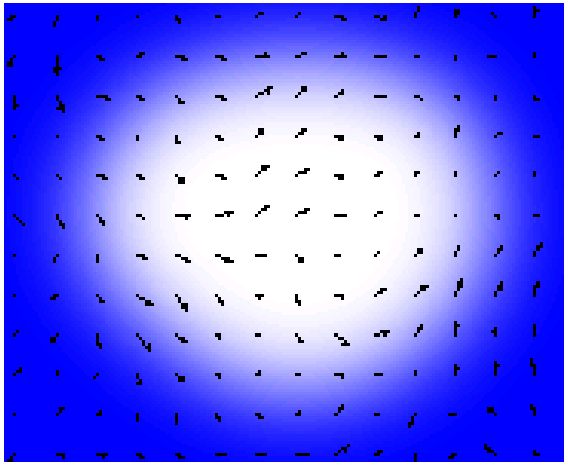
11ns



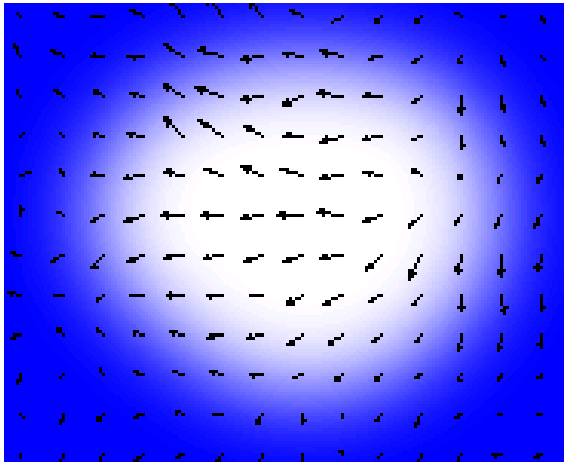
12ns



13ns



14ns



100x150nm, 2nm thick free layer, the magnetization seems to "vanish" during the switching process. What happens here ???

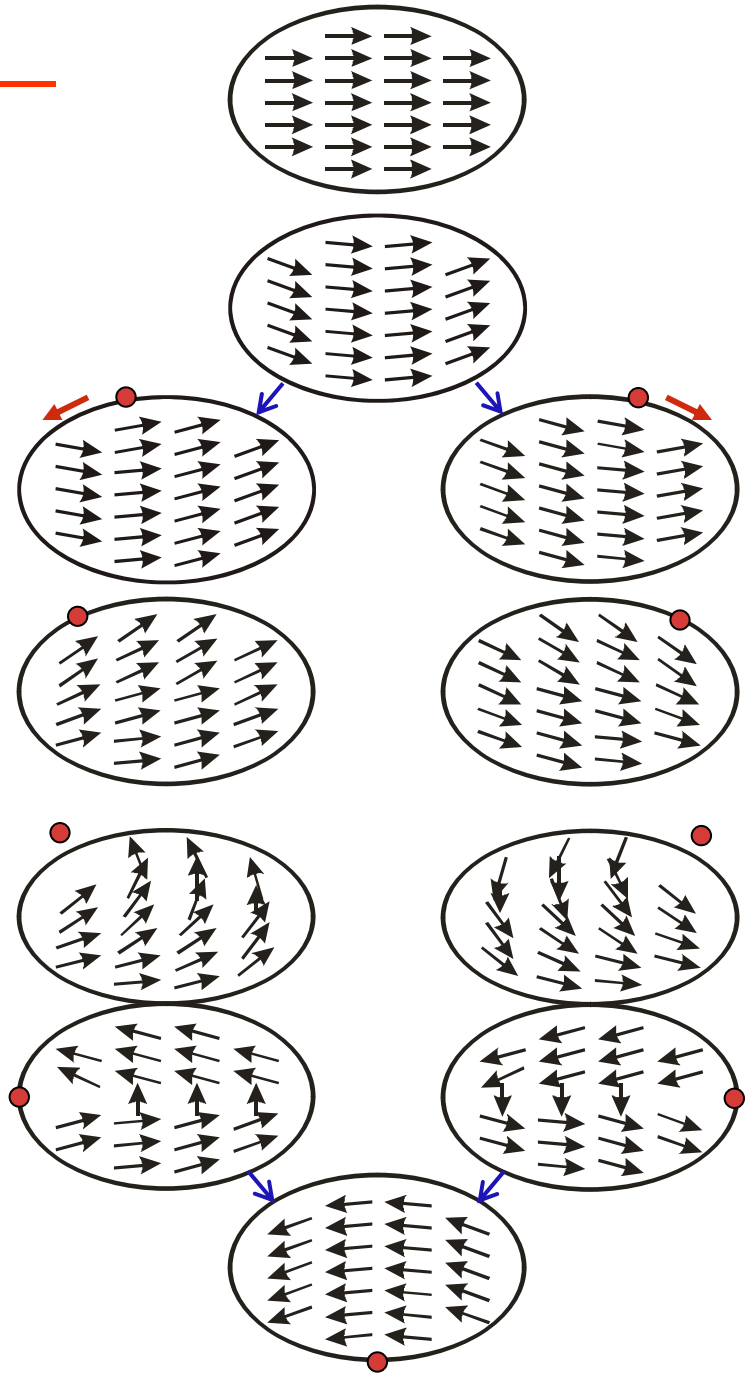
Simulated C-State Flip-Over

Highly sensitive to initial conditions

Can flip over *either direction* based on slight changes in:

- charge current
- spin current
- starting angles

→ XMCD Contrast disappears during reversal



● - denotes the vortex core

… and it all depends sensitively on the starting condition.

A microscopic starting point…
(relatively easy to analyze)

… turns into complex dynamics

Using a fairly simple model the final outcome can be predicted based on the initial dynamics in the first few picoseconds. Challenge is to "see" what happens in the first few picoseconds. We "see" the avalanche moving.

Summary:

There are plenty of challenges and unsolved issues at the forefront of magnetism science out there, that can be addressed with picosecond time resolution using state of the art x-ray microscopy (nm spatial resolution).

For example

- The magnetic switching of nanostructures depends strongly on the boundary and starting conditions.

- The dynamic evolution of the switching pattern can be very complex, however the long term dynamic behavior is determined by how the system reacts in the first few picoseconds after the excitation.

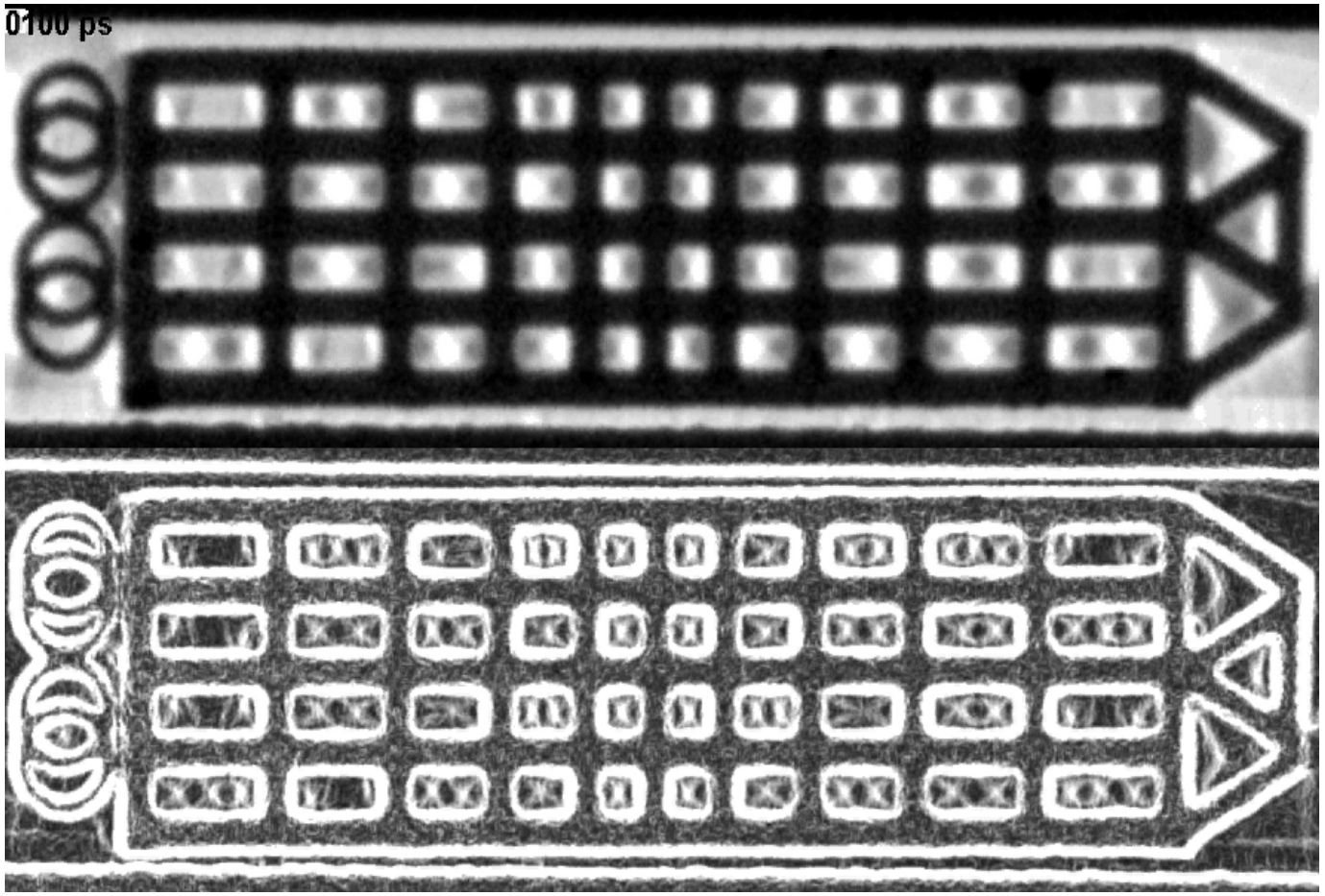
Required for such a microscopic approach is a high average brightness source, since such a source enables us to use current state of the art microscopes.

- STXM microscopy will profit from increased time resolution.

- Full field microscopy will profit from increased time resolution and permanent access to picosecond X-rays, instead of relying on 2-bunch mode

→ The APS has a strong X-ray Microscopy group to support such a program.

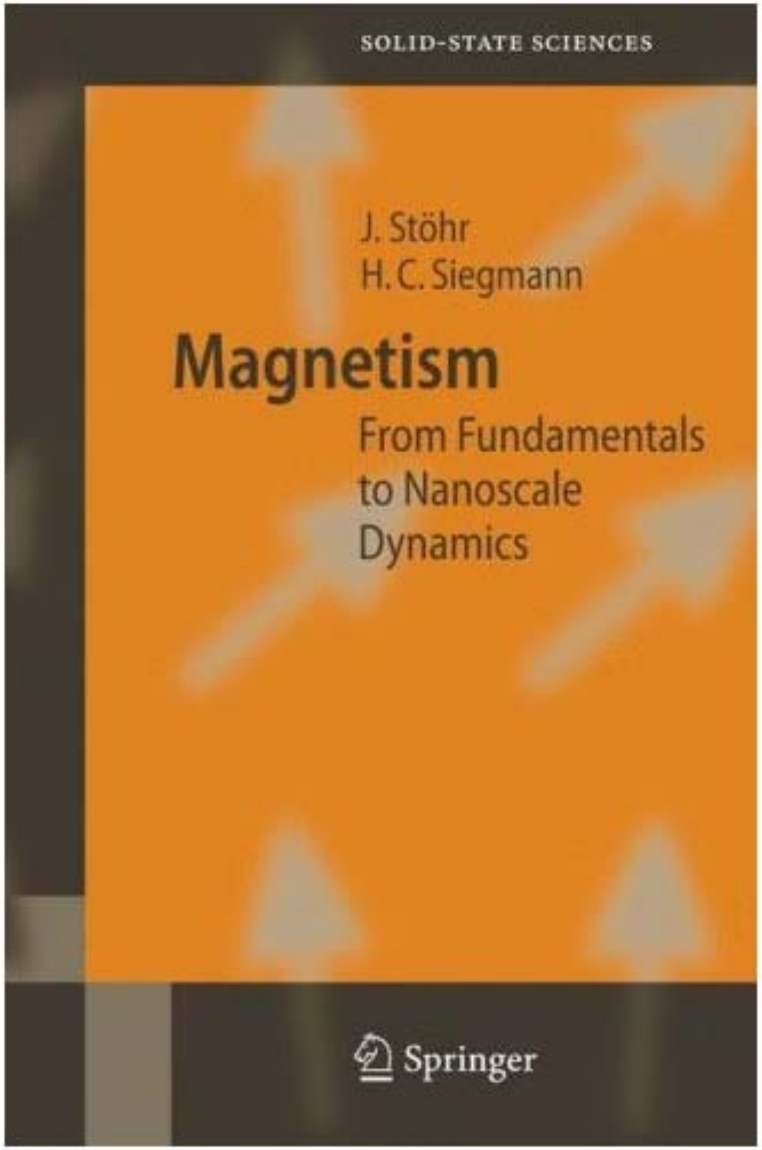
Full Field Microscopy



Full field PEEM microscopy, using 125 MHz laser source to generate magnetic field pulse with an Austonswitch. These types of experiments push both limits, spatial and temporal resolution and take days in 2B mode.

Only very moderate energy resolution is needed here (~1000)

Acknowledgements



SLAC:

J.P. Strachan

V. Chembrolu

A. Tulapurkar

S.D. Andrews

H.C. Siegmann

J. Stöhr

ALS:

T. Tyliszczak

Hitachi:

J.A. Katine

M.J. Carey

Cornell University:

V. Pribiag

R. Buhrman

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H. Stoll

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