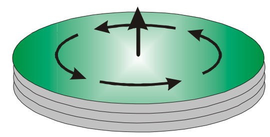
Magnetization Dynamics: Relevance to Synchrotron Experiments

C.H. Back

Universität Regensburg



- Eigenmodes in confined magnetic structures (TR-XPEEM)
- Spin Dynamics of the AF/FM phase transition in FeRh
- Conclusion

Acknowledgements:

Matthias Buess	Universität Regensburg, now SLS
Ingo Neudecker	Universität Regensburg
Korbinian Perzlmaier	
Thomas Haug	
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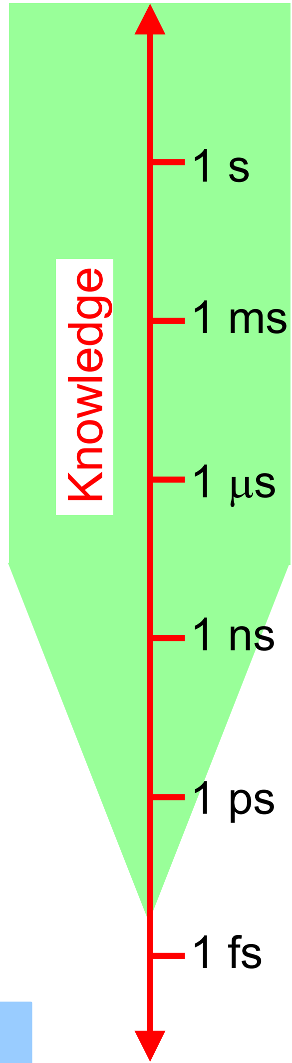
Uwe Krey	
J. Raabe	SIM Beamline Swiss Light Source
F. Nolting	
C. Quitmann	
Jan-Ulrich Thiele	Hitachi Global Storage Technologies
San Jose Research Center	
Stefan Maat	
Eric E. Fullerton	
Torsten Kachel	BESSY
Christian Stamm	

Time Scales for Magnetization Processes



Stability

Thermally activated magnetization processes (viscous regime, domain nucleation, domain growth)

Precessional Regime

(Precessional Switching)

Landau-Lifshitz-Gilbert equation:

$$\dot{\mathbf{M}} = -\gamma\, \mathbf{M} \times \mathbf{H}_{\mathrm{eff}} + \frac{\alpha}{M} (\mathbf{M} \times \dot{\mathbf{M}})$$

Ultrafast demagnetization processes (optical excitation)

What do we want to know ?

High frequency response of films and small elements (MRAM, Write-Head, Read-Head)

(methods: Ferromagnetic Resonance, Brillouin Light Scattering, Time Resolved Kerr Microscopy, X-PEEM, Electronic Detection)

Thermal noise and thermally excited spin waves

(methods: Brillouin Light Scattering, High Frequency Noise Measurements)

Simple and fast switching stragegy (MRAM, Magnetic Media)

(methods: Inductive Methods, High Frequency GMR/TMR Sensing, Time Resolved Magneto-Optic Methods, X-PEEM)

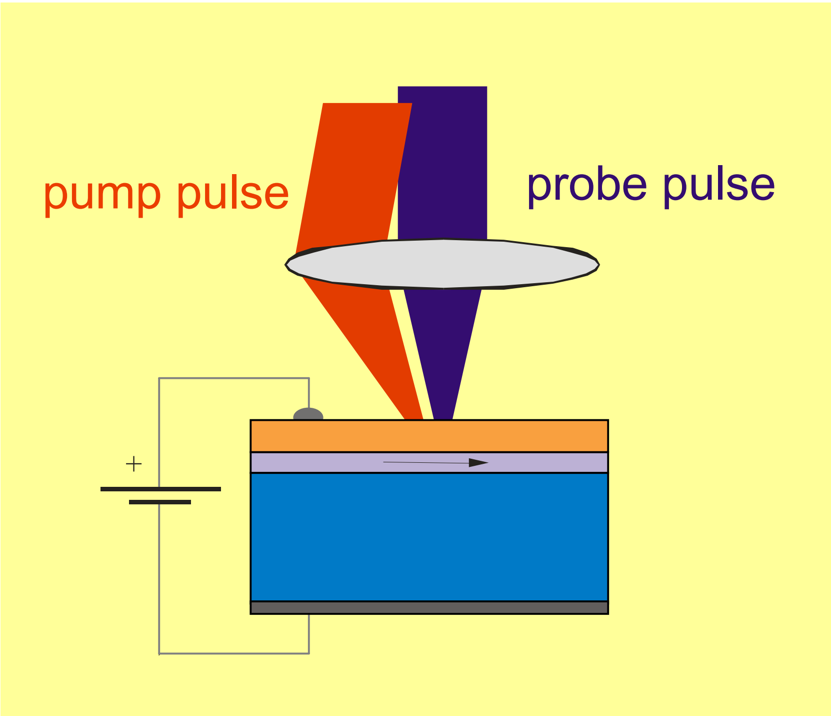
Basic underlying physics: Excitations in confined magnetic structures

Non linear dynamics

Precessional switching

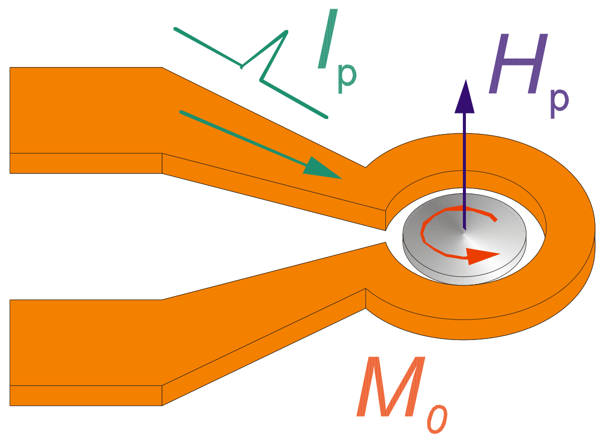
Triggering Magnetization Dynamics

Triggering the magnetization dynamics by fs optical pulses



Change of the internal field (saturation magnetization, anisotropy field) or ultra fast field generation

Magnetic field generation using an optical switch and a microcoil



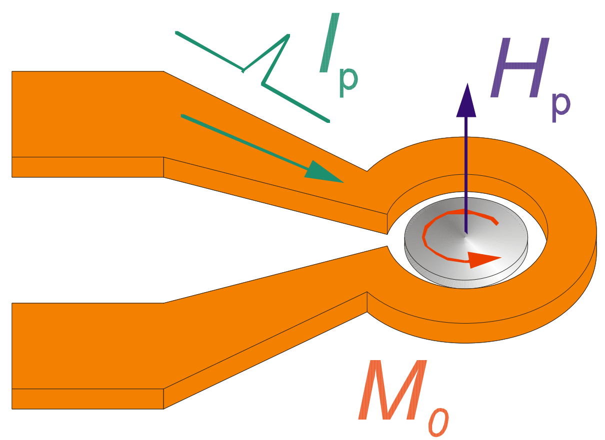
In-plane and out of plane field pulses

- Eigenmodes in confined magnetic structures (TR-XPEEM)
- Spin Dynamics of the AF/FM phase transition in FeRh
- Conclusion

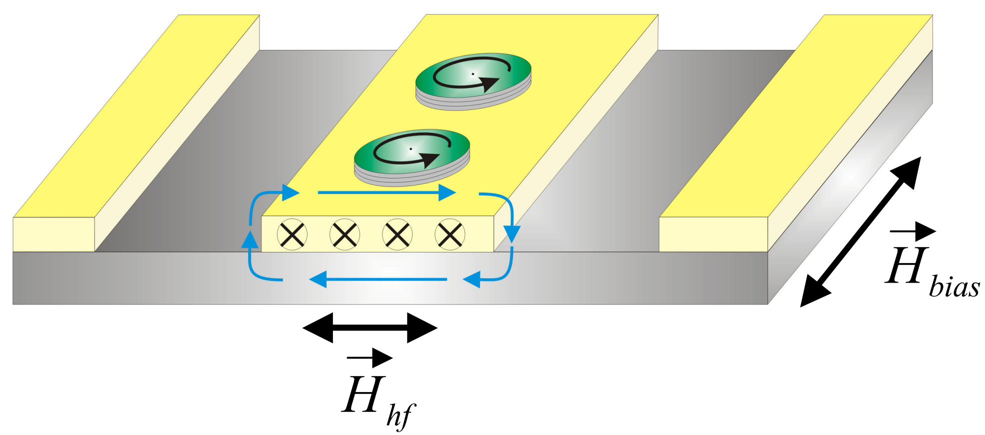
Pulsed Precessional Motion: Excitation of the Magnetic Ground State

(via a magnetic field pulse)

(a) Current pulse through a strip line into a single turn coil

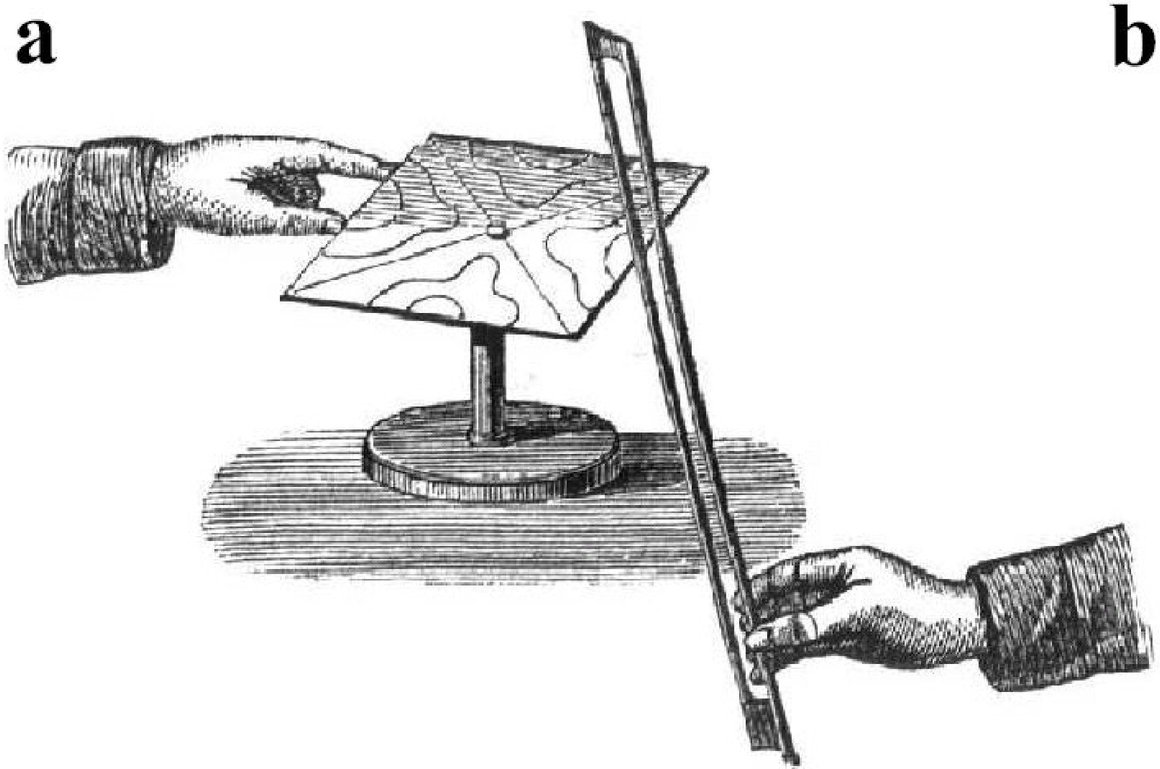


(b) Excitation via a coplanar waveguide

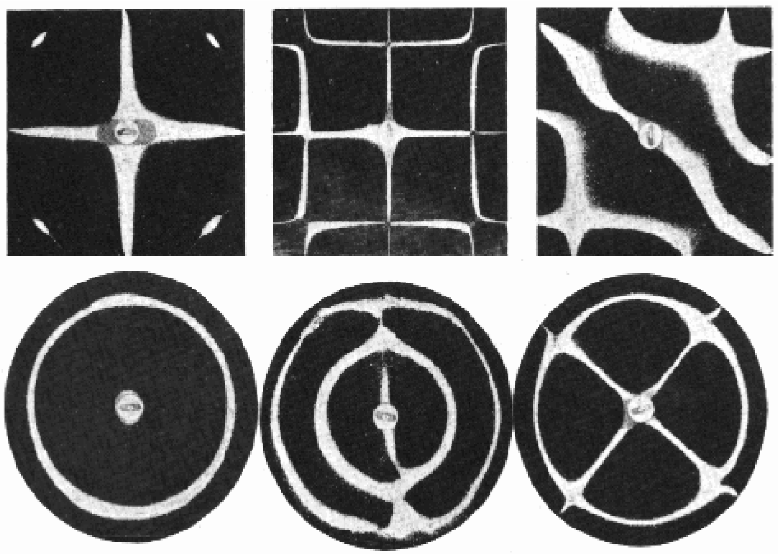


Chladni (1756-1827)

a



b



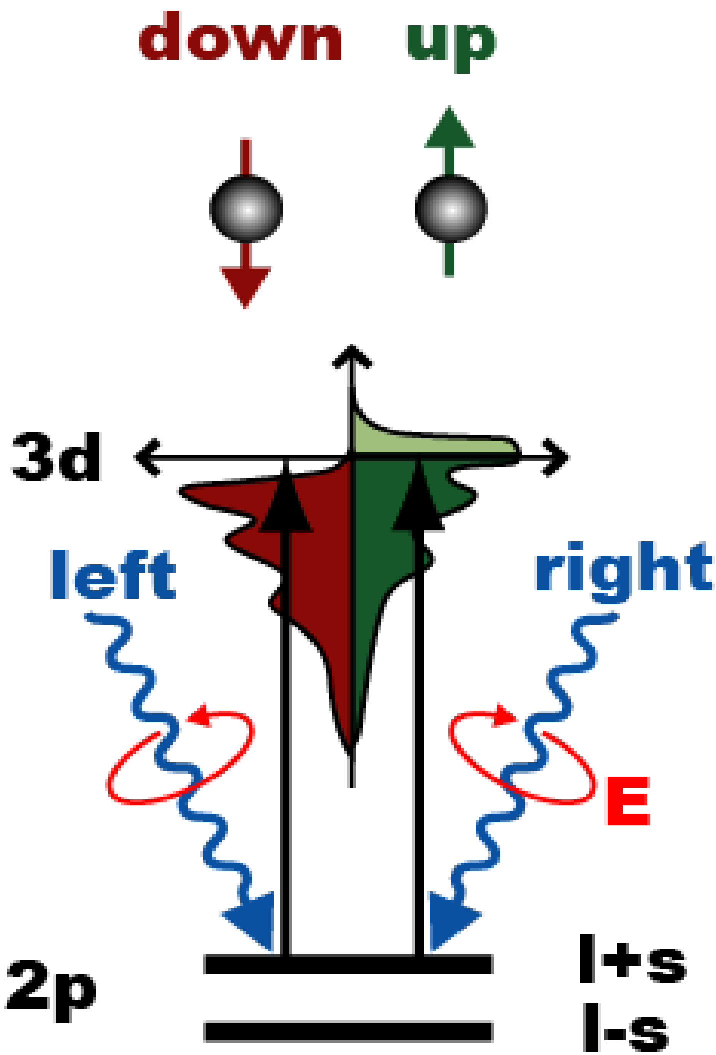
Mechanical analogon:

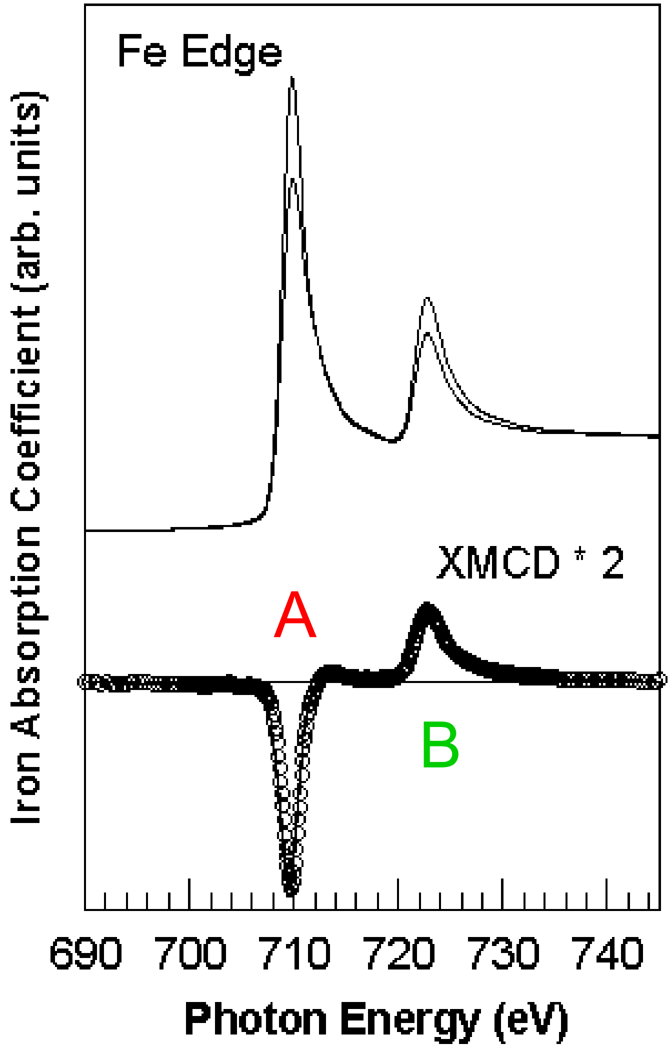
Chladni‘s sound figures

The Dynamo-X team @ the SIM beamline SLS

- SIM beamline
  C. Quitmann, F. Nolting, U. Flechsig, D. Zimoch,
  J. Krempasky, T. Schmidt
- Laser, synchronization & gating
  S. Johnson, G. Ingold, C. Buehler
- Sample preparation
  D. Weiss (U-Regensburg)
- Simulations and Kerr measurements
  R. Höllinger, M. Buess, C.H. Back (U-Regensburg)
- Diagnostics
  K. Holldack (BESSY), B. Kalantari, T. Korhonen
- Experiments
  J. Raabe (SIM beamline, U-Regensburg)

X-Ray Magnetic Circular Dichroism (XMCD)





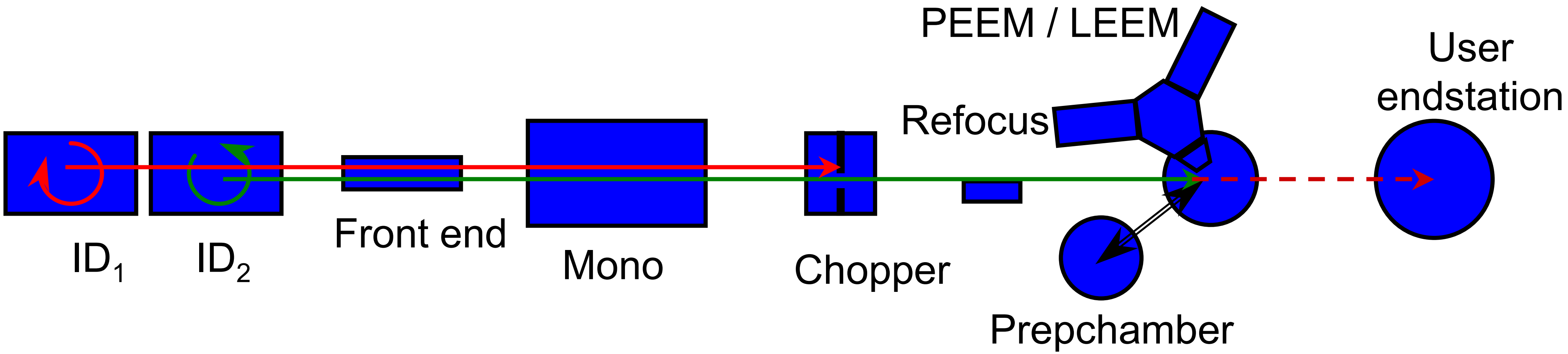
Dichroism sum rules

S ~ A - 2B

L ~ A + B

G. Schütz et al. Phys. Rev. Lett. **58**, 737 (1987)

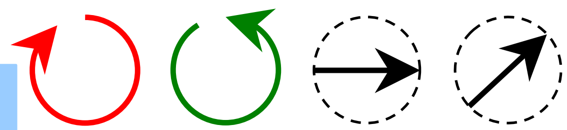
SIM Beamline Layout



Undulator

T. Schmidt

- 2 Elliptical undulators
- 95eV < hν < 2000 eV
- $>10^{19}$ photons/s/mrad^2/mm^2/400mA
- Flexible polarization:



Optics

U. Flechsig

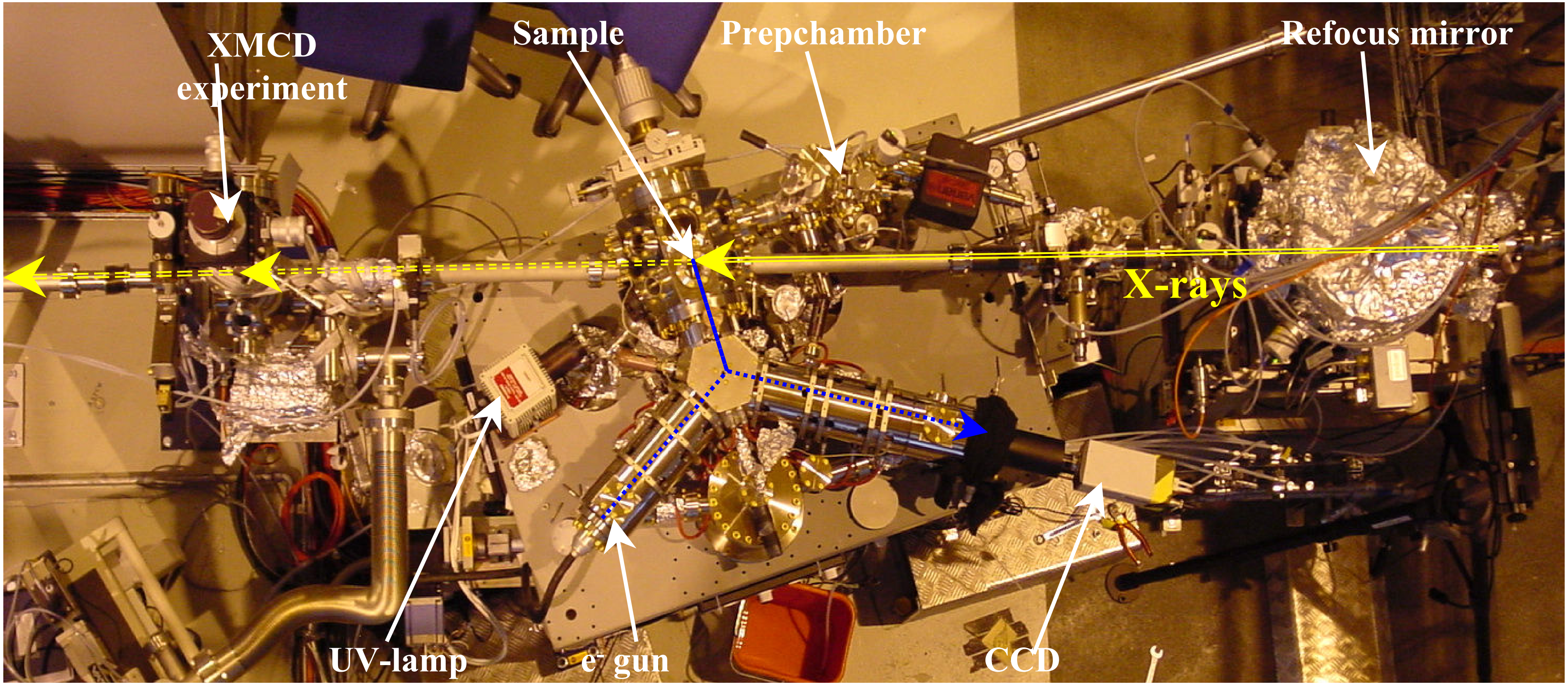
- Plane grating monochromator
- E/DE ~ 10^3
- Switch helicity
- Focus 30x100mm^2

Endstation

C. Quitmann & F. Nolting

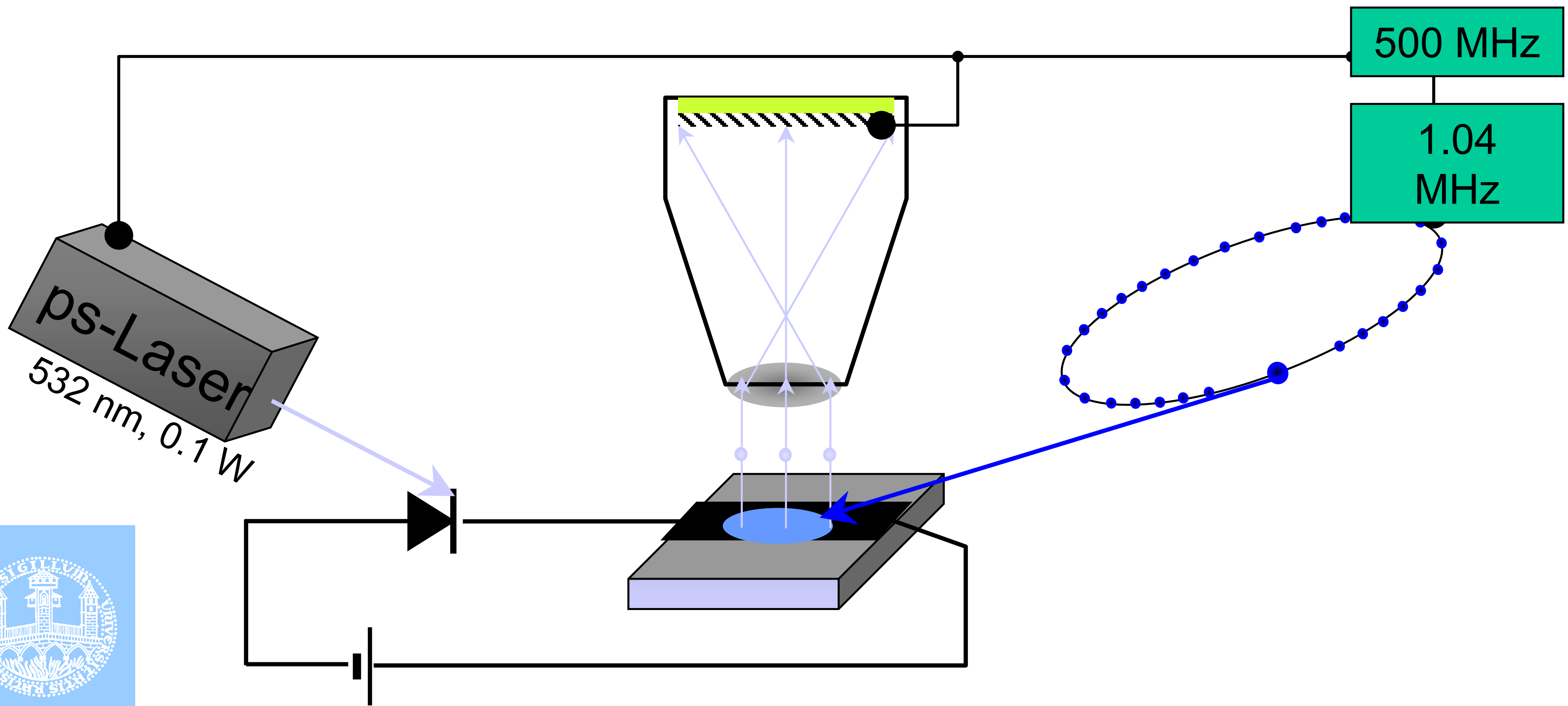
- SLS endstation:
  - **PEEM / LEEM**
    Energy filter
    Sample rotation, cooling
    ELMITEC
  - Additional Prepchamber
  - User endstation

PEEM @ SIM Beamline

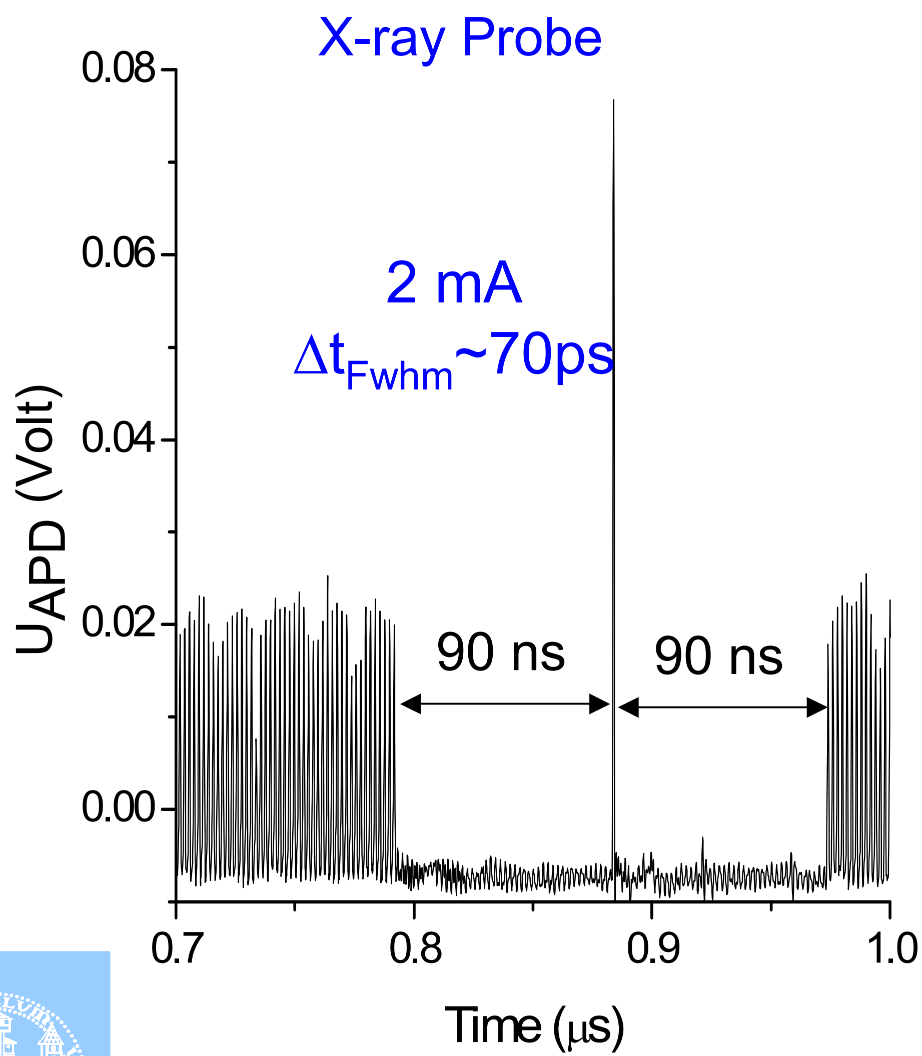


Dynamo-*X* at the SIM beamline at SLS: Principle

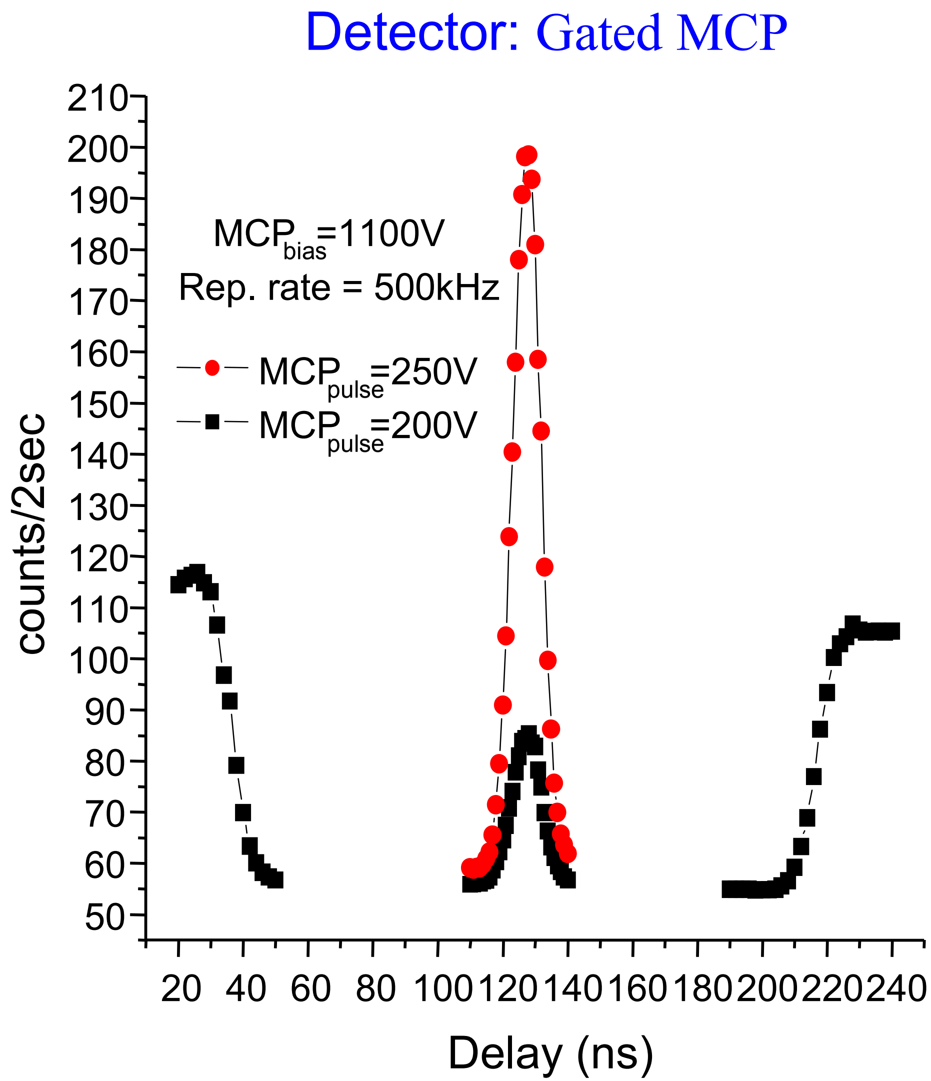
Pump	Detection	Probe
stripline / coil	gated PEEM	X-ray stroboscope
Pulse: H ~ 60 Oe, 100 ps	Δx ~100nm, ~ 1 ML	~1keV, Δt= 70ps



Dynamo-*X:* X-ray probe & gating



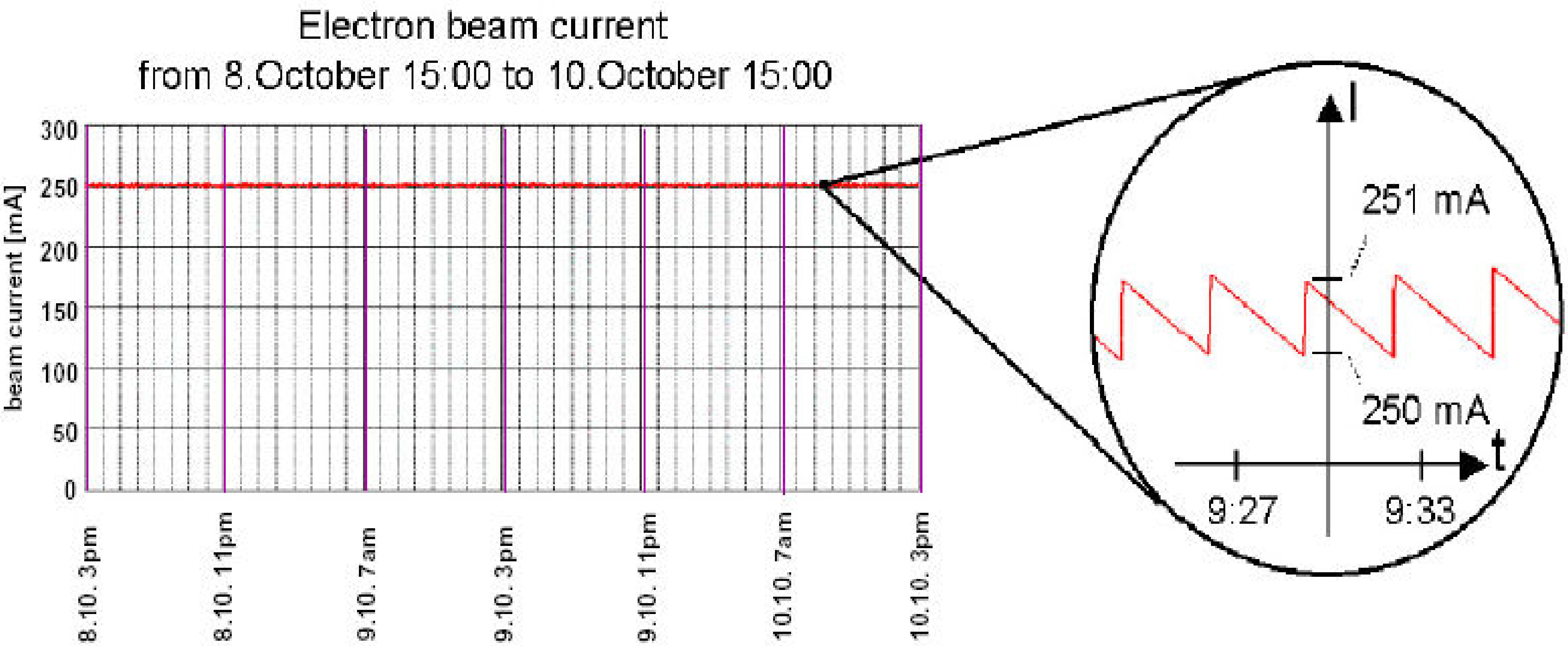
APD monitors filling pattern
Collaboration: K. Holldack BESSY



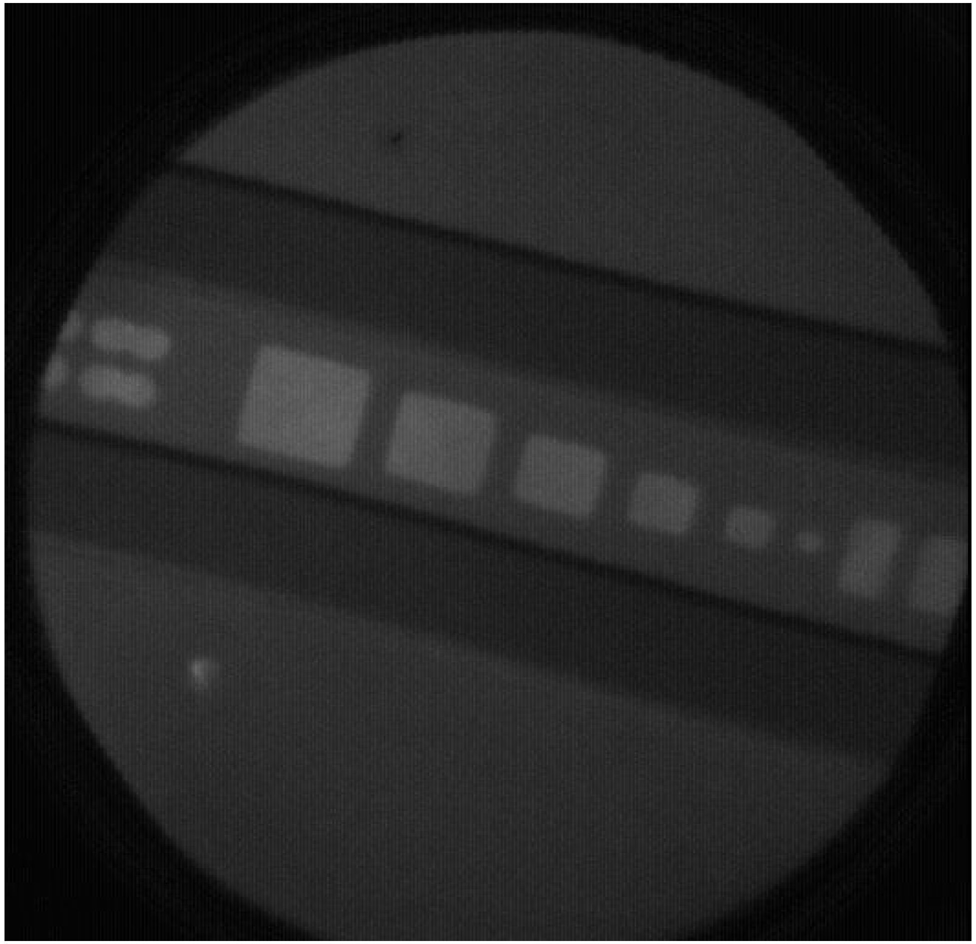
Pulsed MCP Supply: C. Buehler PSI

Institut für Experimentelle und Angewandte Physik der Universität Regensburg

Top-up mode


Electron beam current
from 8.October 15:00 to 10.October 15:00
beam current [mA]
300
250
200
150
100
50
0
8.10. 3pm
8.10. 11pm
9.10. 7am
9.10. 3pm
9.10. 11pm
10.10. 7am
10.10. 3pm
I
251 mA
250 mA
t
9:27
9:33

Magnetic Contrast



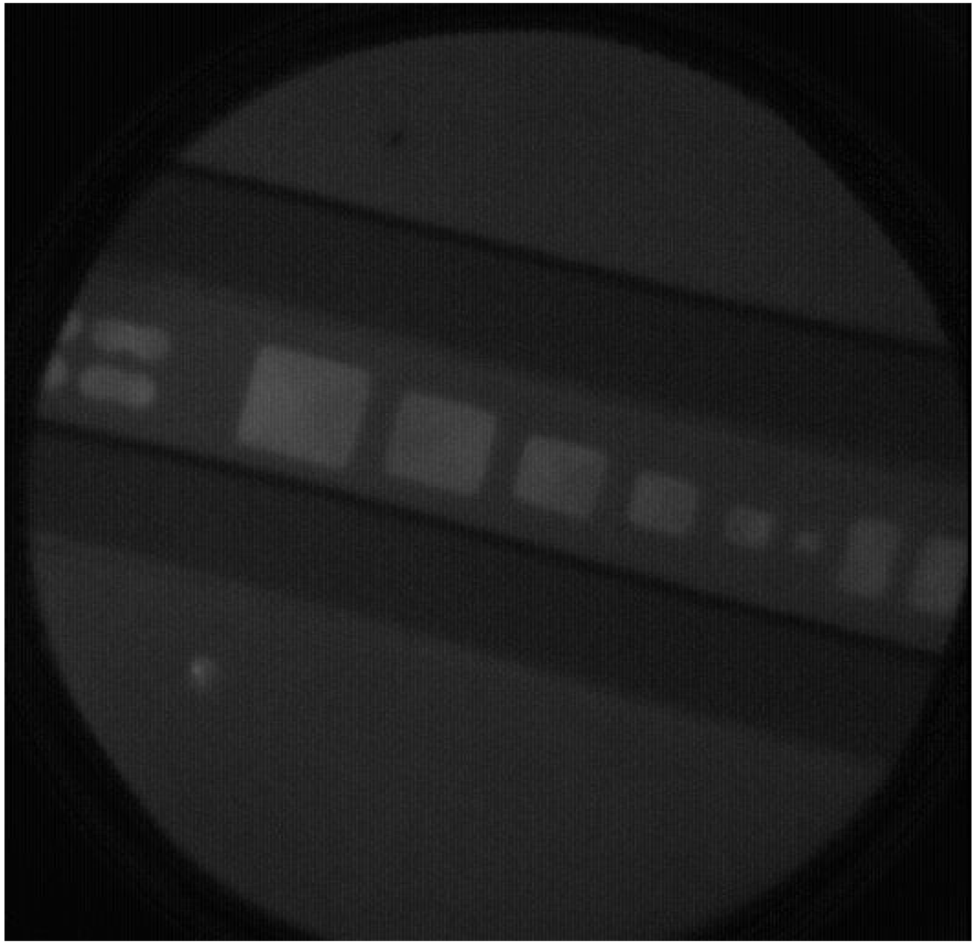


Image1: P = C+

Image2: P = C-

Magnetic Contrast

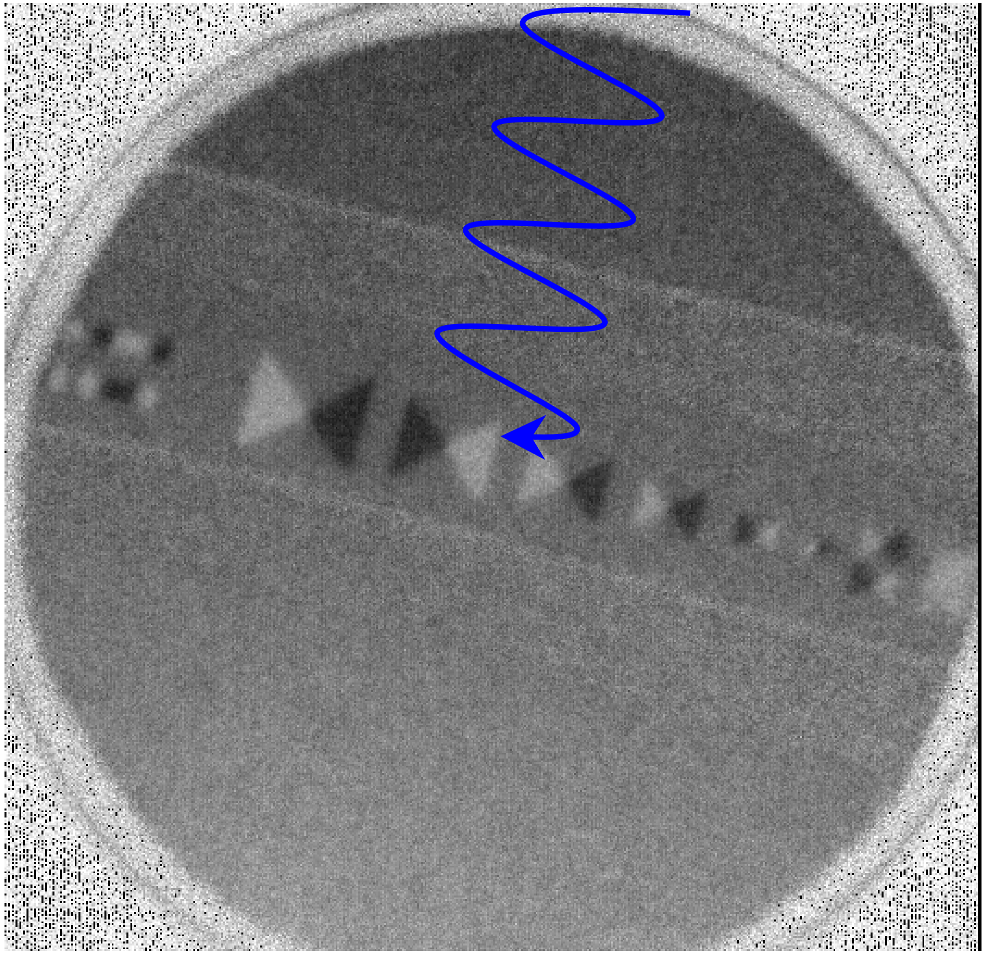
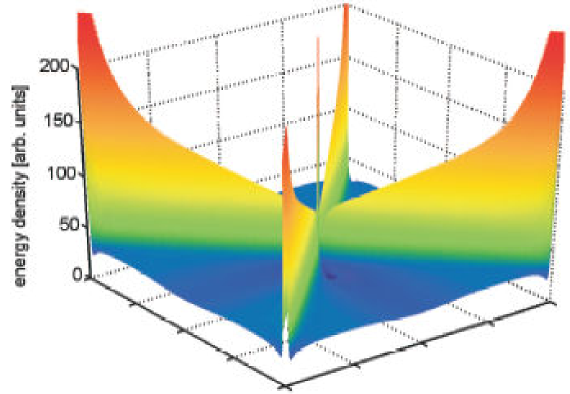


Image1 / Image2: C+ / C-

XMCD Contrast: $I \sim \vec{M}(r) * \vec{P}$

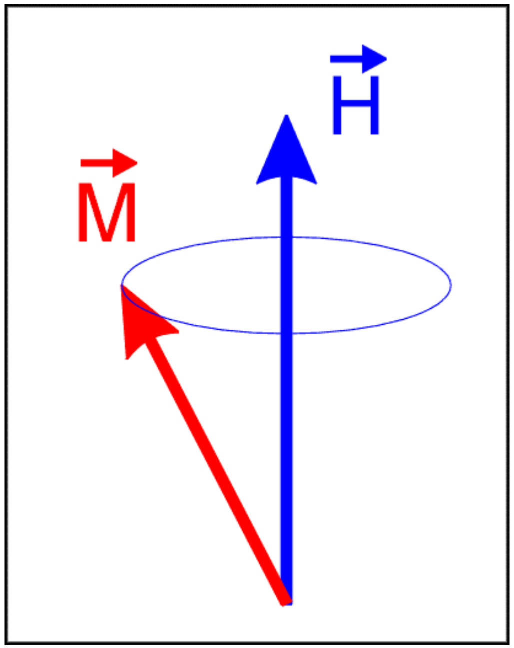
Landau- Lifshitz- Gilbert- equation:

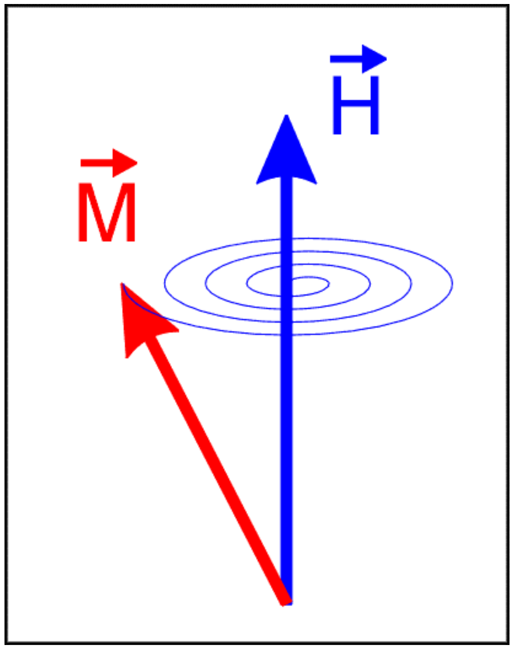


$$\frac{d\vec{M}}{dt} = -\gamma_0(\vec{M}\times\vec{H}_{eff}) - \alpha\frac{\gamma_0}{M}\left[\vec{M}\times(\vec{M}\times\vec{H}_{eff})\right]$$

$$\vec{H}_{eff} = -\frac{\partial E}{\partial \vec{M}}$$

sets the time scale



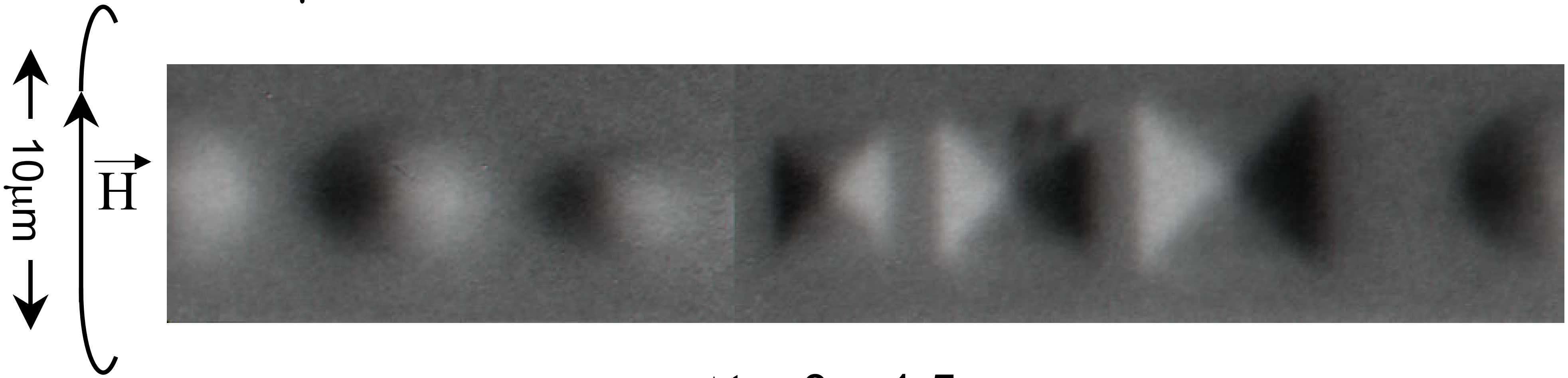


Results: Dynamics in Permalloy microstructures

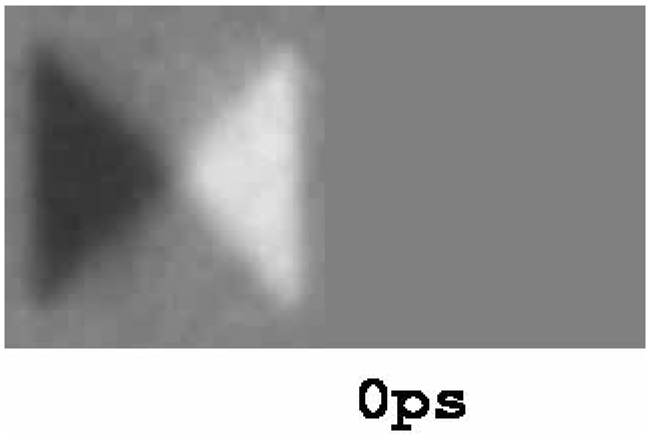
•Sample
Permalloy, t=10nm
Disks & squares
∅~2 – 6 μm

•Excitation
~60 Oe in plane
~200 ps rise time

• Image:
Fe-L3 XMCD
Δt = 33 ps / frame



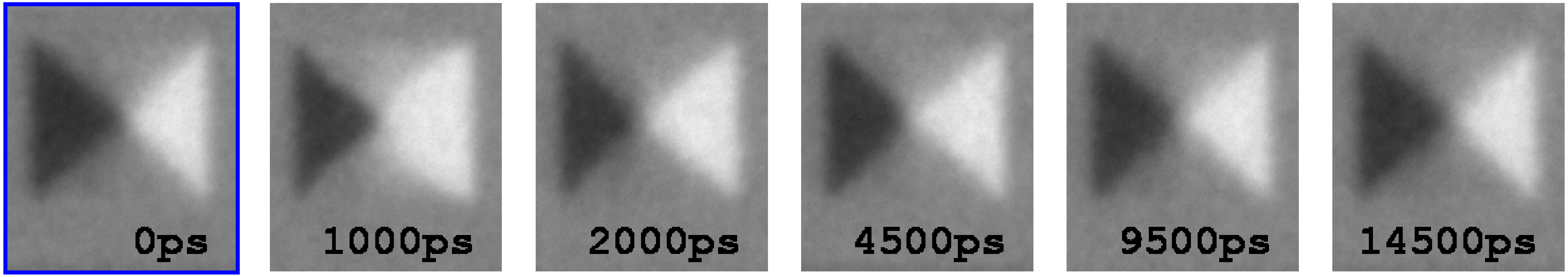
Δt = 0 – 1.5ns



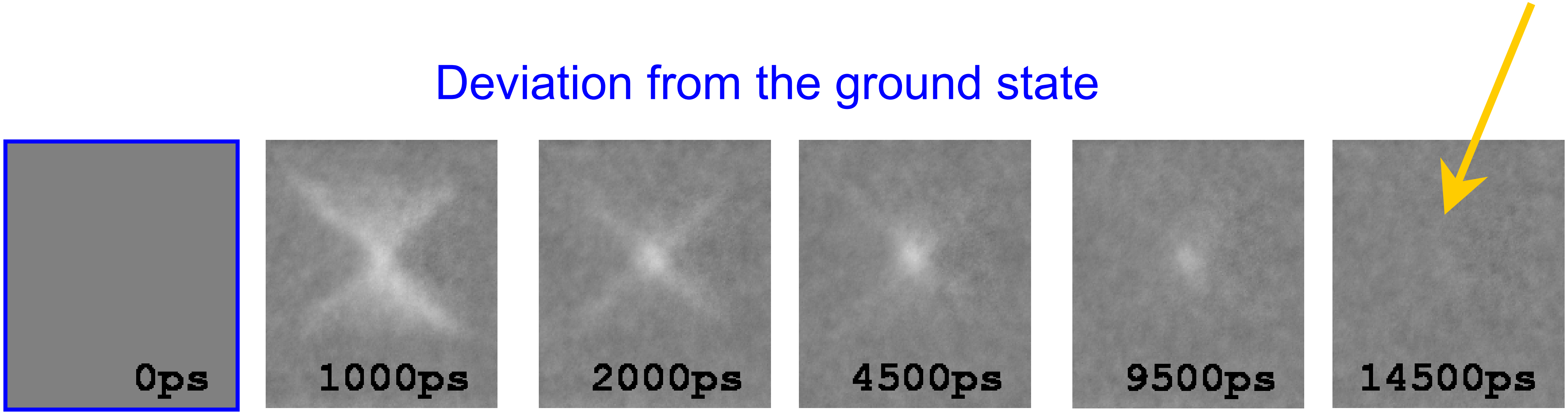
Pump – Probe Problems

- Relaxation ⇒ Ground state ?
- Pump: 16 ns (laser: 62.5MHz = 500MHz / 8)
  Probe: 1μs

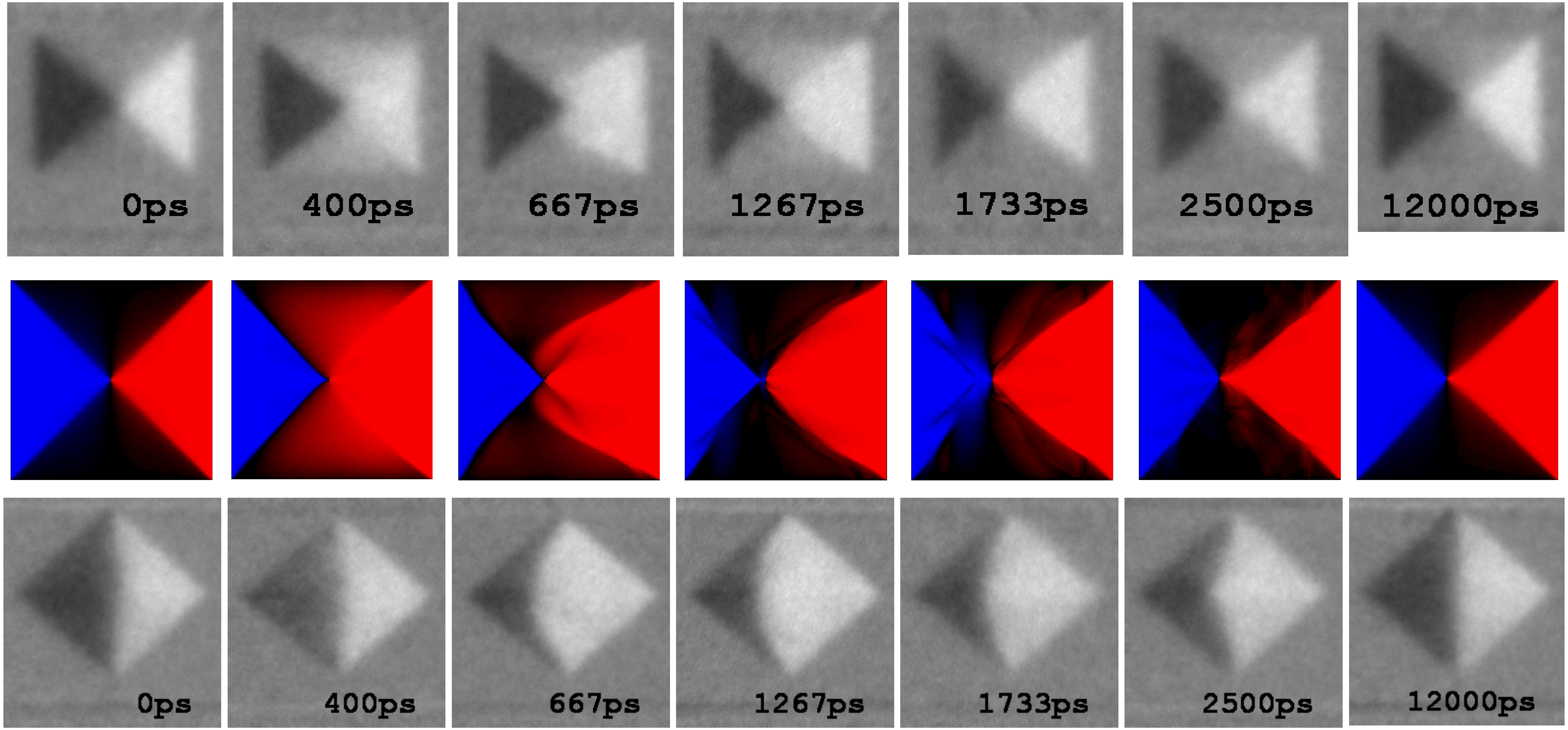
Dichroic image series



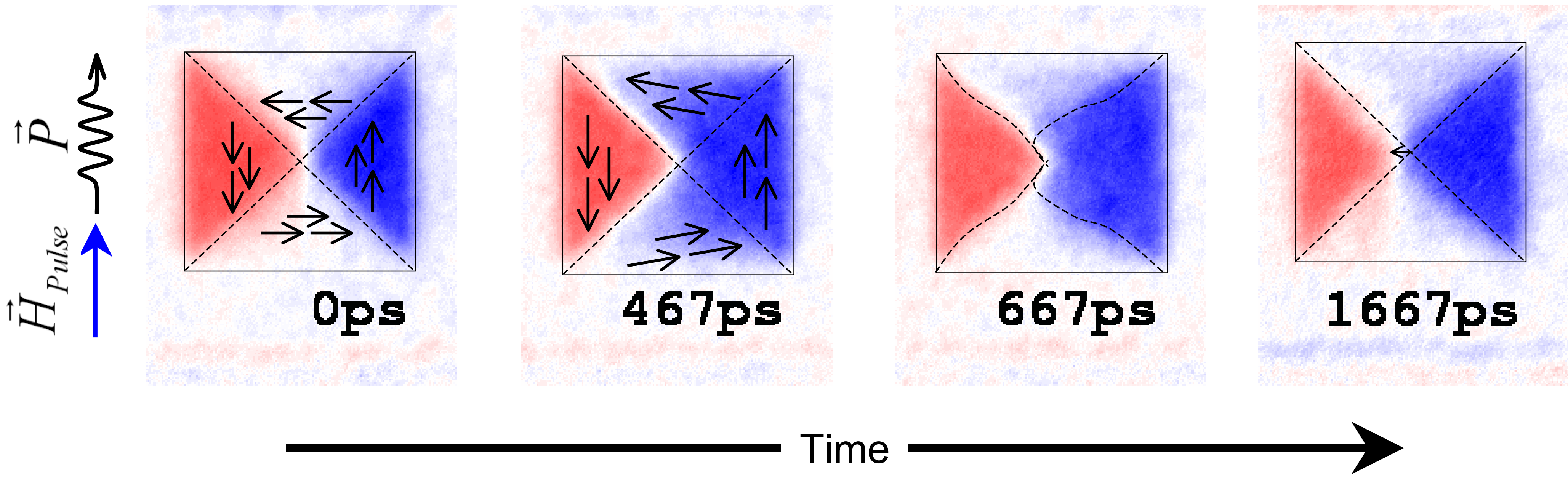
Deviation from the ground state



Squares in the Landau structure



- Coherent rotation within the domains (1.9 GHz and 2.5 GHz)
- Domain wall shift ⊥ H_p, Vortex moves ⊥ H_p (~700 m/s, maximum displacement 750 nm after 1050 ps)
- Vortex moves slower than domain walls
- Domain walls buldge (in contrast to quasi static experiments)



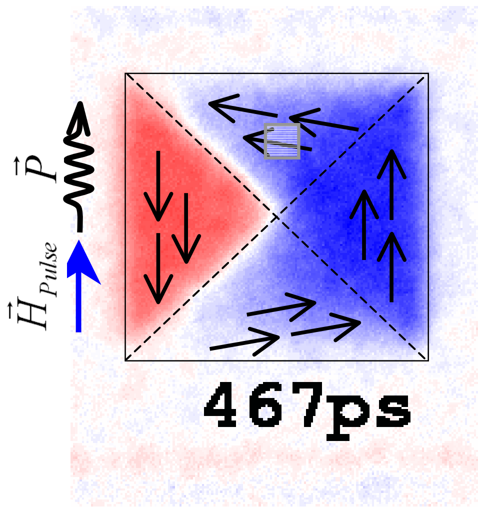
Domain precession:
467ps ~ ½T_{prec}
~ 2 GHz

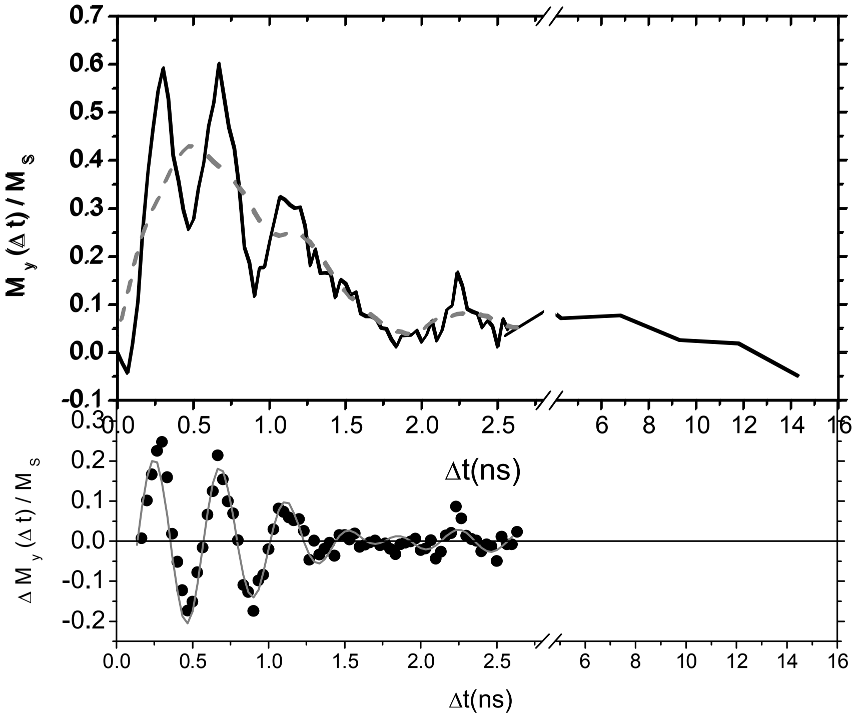
Wall oscillation:
~700 m/s

Vortex motion:
slow

J. Raabe et al., PRL **94,** 217204 (2005)

Precessional Motion within the domains: M ⊥ H





- Single damped oscillator is not sufficient!

$$M_y(\Delta t) = M_S\left[A_1 \sin(\omega_1 \Delta t) + A_2 \sin(\omega_2 \Delta t + \pi)\right] e^{-\Delta t/\tau}$$

- Fit (Phase shift = π):
  - $\omega_1/2\pi = 2.0$ GHz
  - $\omega_2/2\pi = 2.5$ GHz
  - $\tau = 0.63$ ns

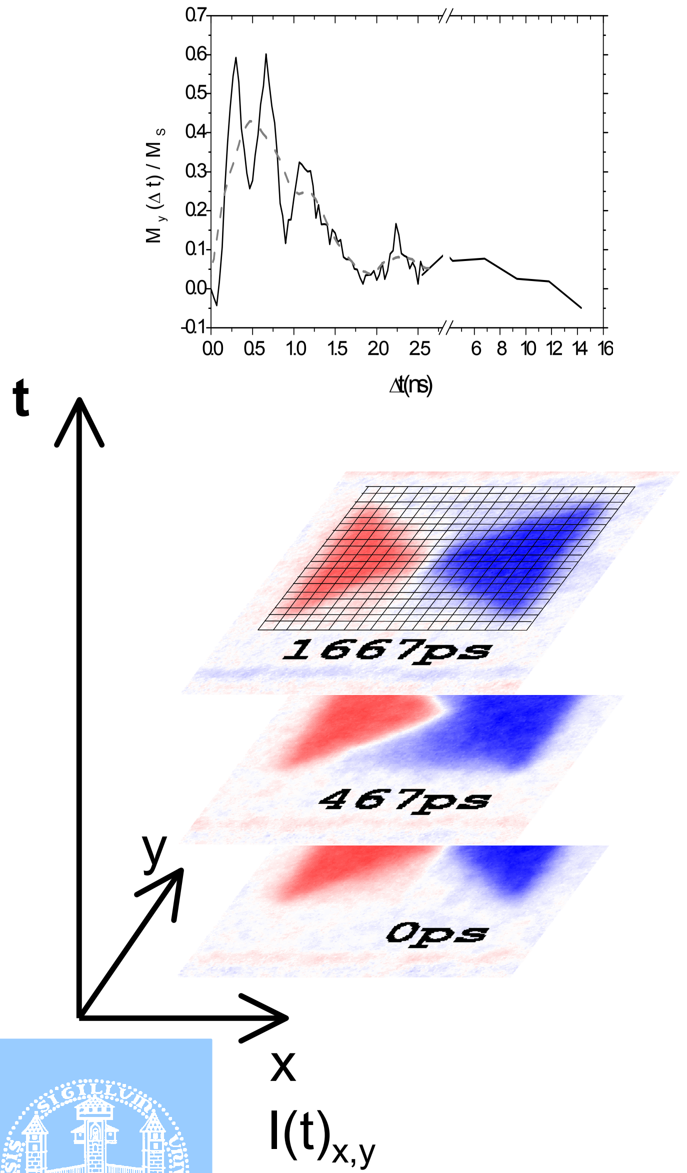
Two frequencies!

Theory disk:

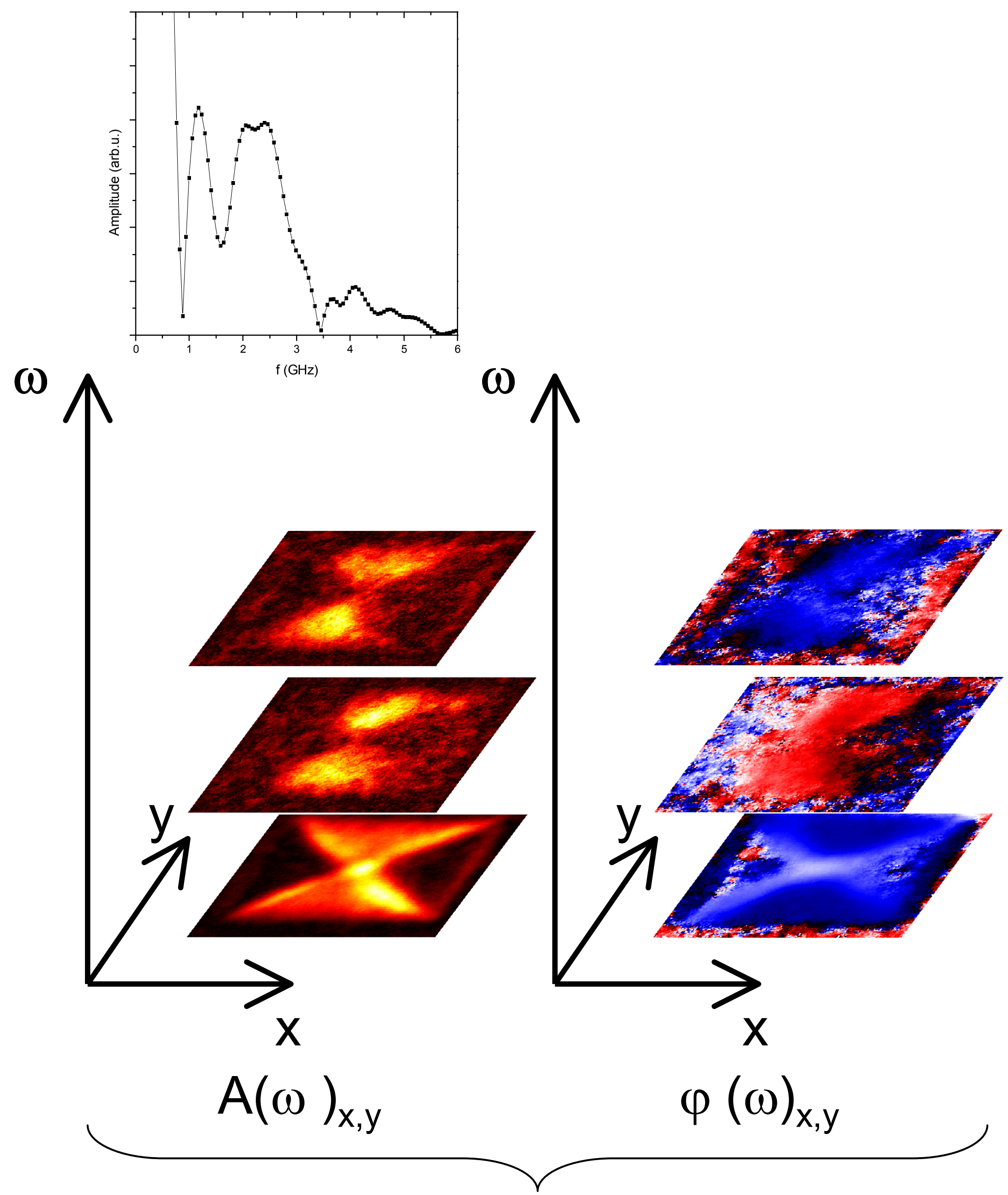
Magnon scattering @ vortex core ⇒ splitting of normal modes?

B. A. Ivanov and C. E. Zaspel
Appl. Phys. Lett. **81**, 1261 (2002) &
Phys. Rev. Lett. **94**, 027205 (2005).

Fourier analysis of the magneto-static modes



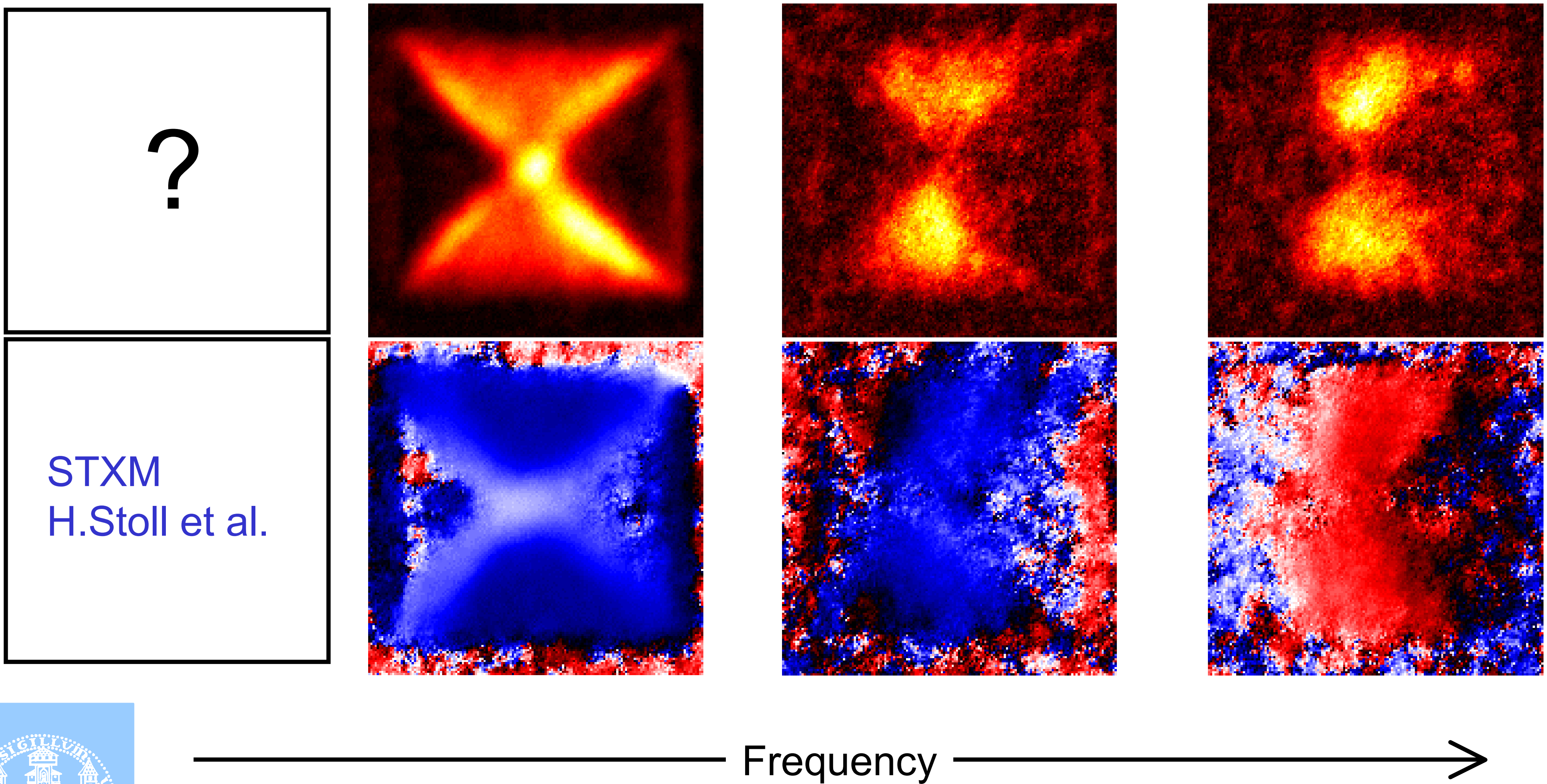
Time domain



Frequency domain

Modes

Vortex motion 1/10 ns	Wall mode 0.23 GHz	Domain mode1 2.0 GHz	Domain mode2 2.4 GHz



J. Raabe et. al., Phys. Rev. Lett **94**, 217204 (2005)

Summary

- spatial resolution is improved !
- element specificity !
- need to work on time resolution !
- Ideally we would like soft X-ray pulses with < 100 fs length.

  Alternatively: Point detectors (STXM) with added temporal resolution (streak cameras, solid state detectors with electronic box car).

Eigenmodes in confined magnetic structures (TR-XPEEM)

Vortex core dynamics in disks (TR-STXM)

Spin Dynamics of the AF/FM phase transition in FeRh

Conclusion

Ultrafast generation of ferromagnetic order

Optical pump-probe setup at the University of Regensburg

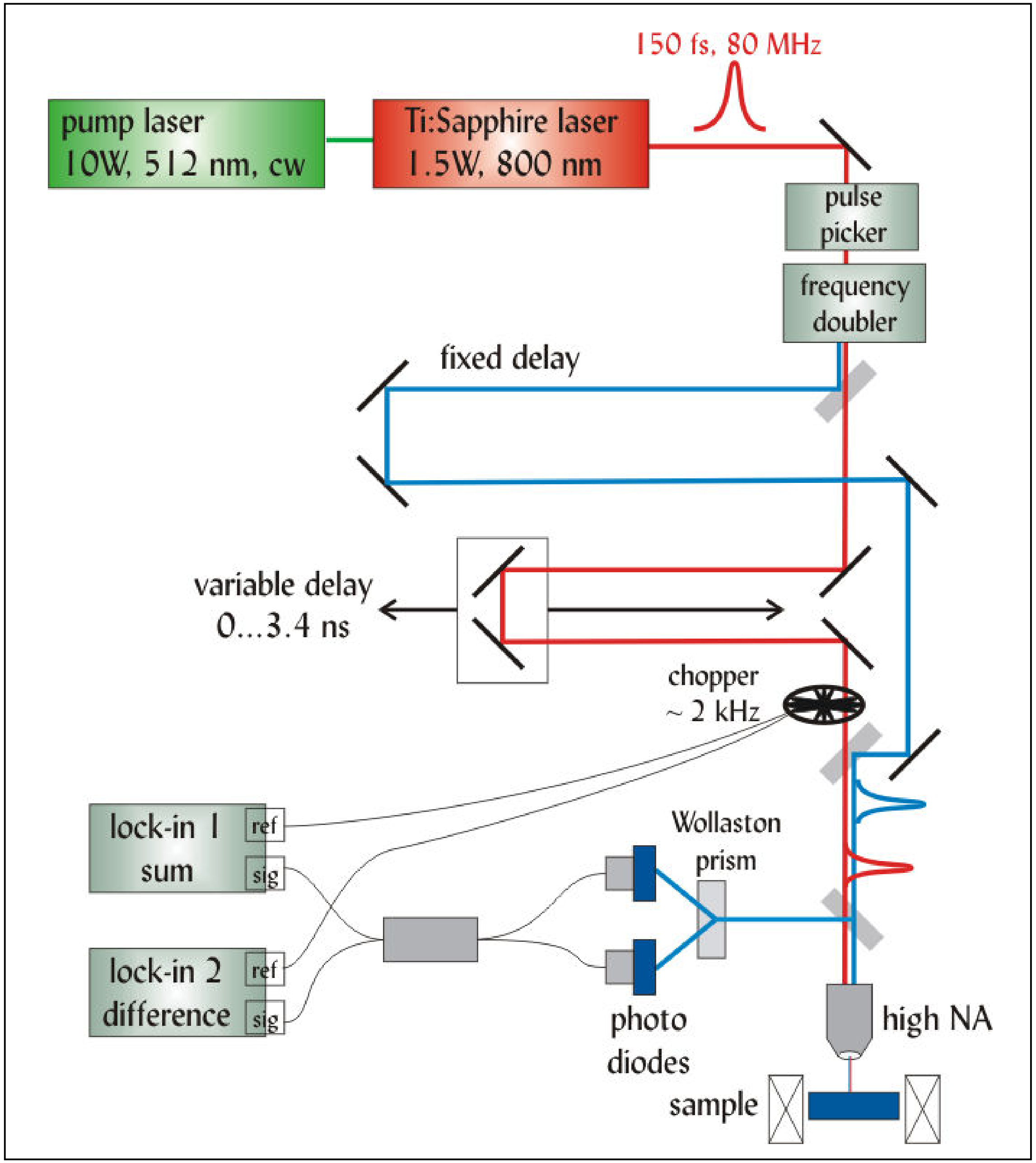
pump: $\varnothing = 2\ \mu m$, $\lambda = 800$ nm,

150 fs, 1-10 mJ/cm^2

probe: $\varnothing = 1\ \mu m$, $\lambda = 400$ nm,

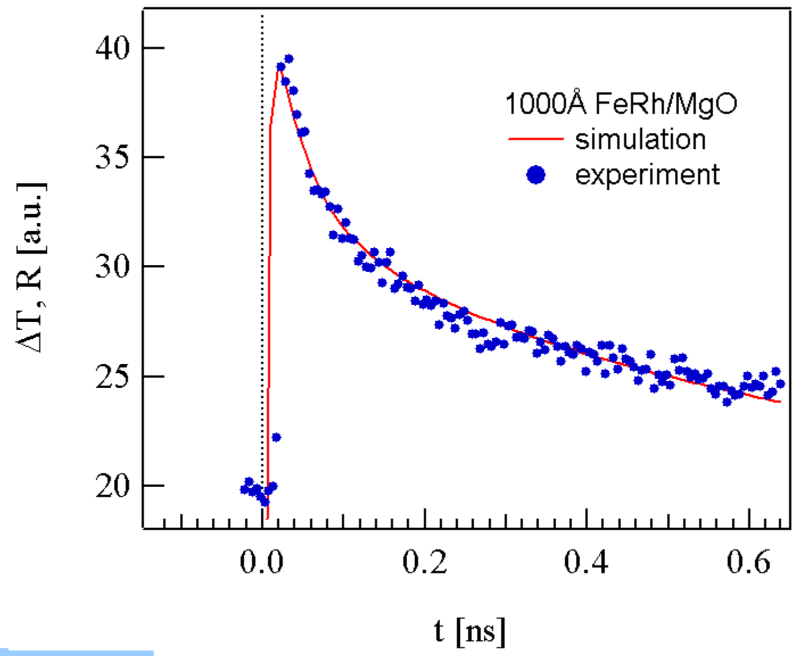
150 fs, 0.5mJ/cm^2

heat with pump pulse, then measure reflectivity and Kerr rotation as a function of delay time

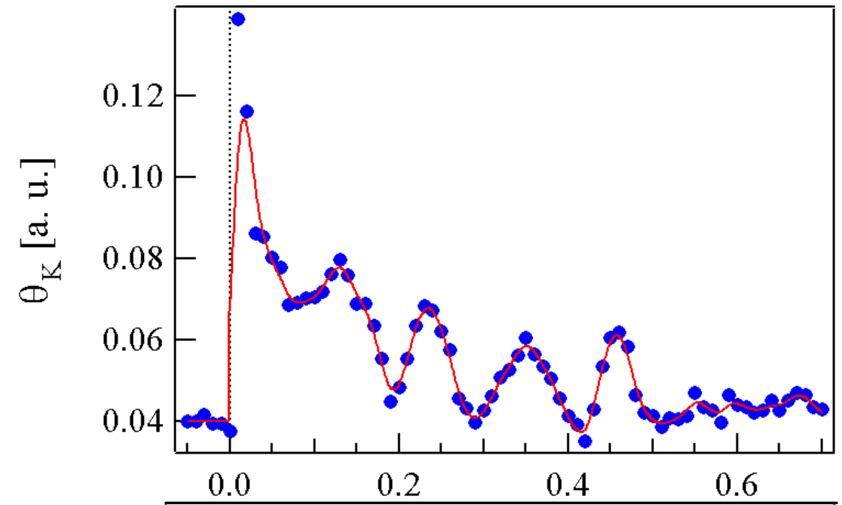


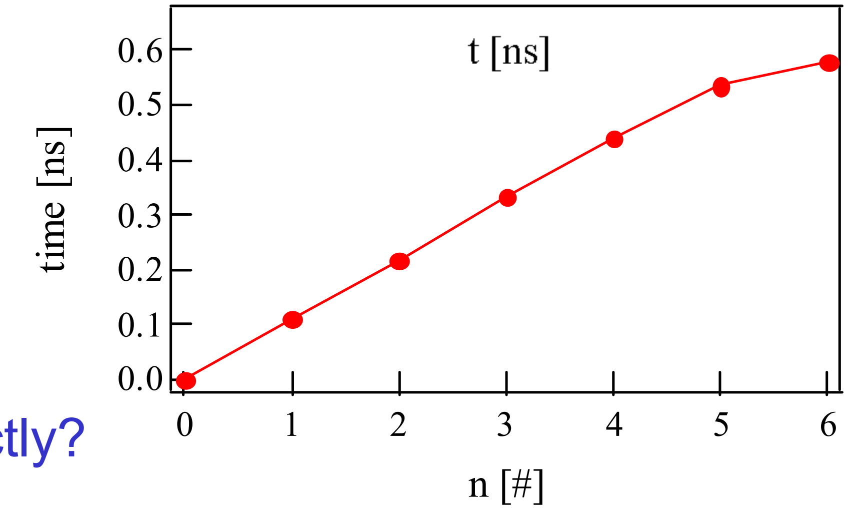
FeRh - experimental results, “long” time scales

reflectivity data matches results of Temprofile simulations
(run R(t) calculations for various z, average calculations weighted relative to absorption depth)



Measuring the Kerr rotation in an external applied field (500 Oe) precession with a period of about 110 ps is observed





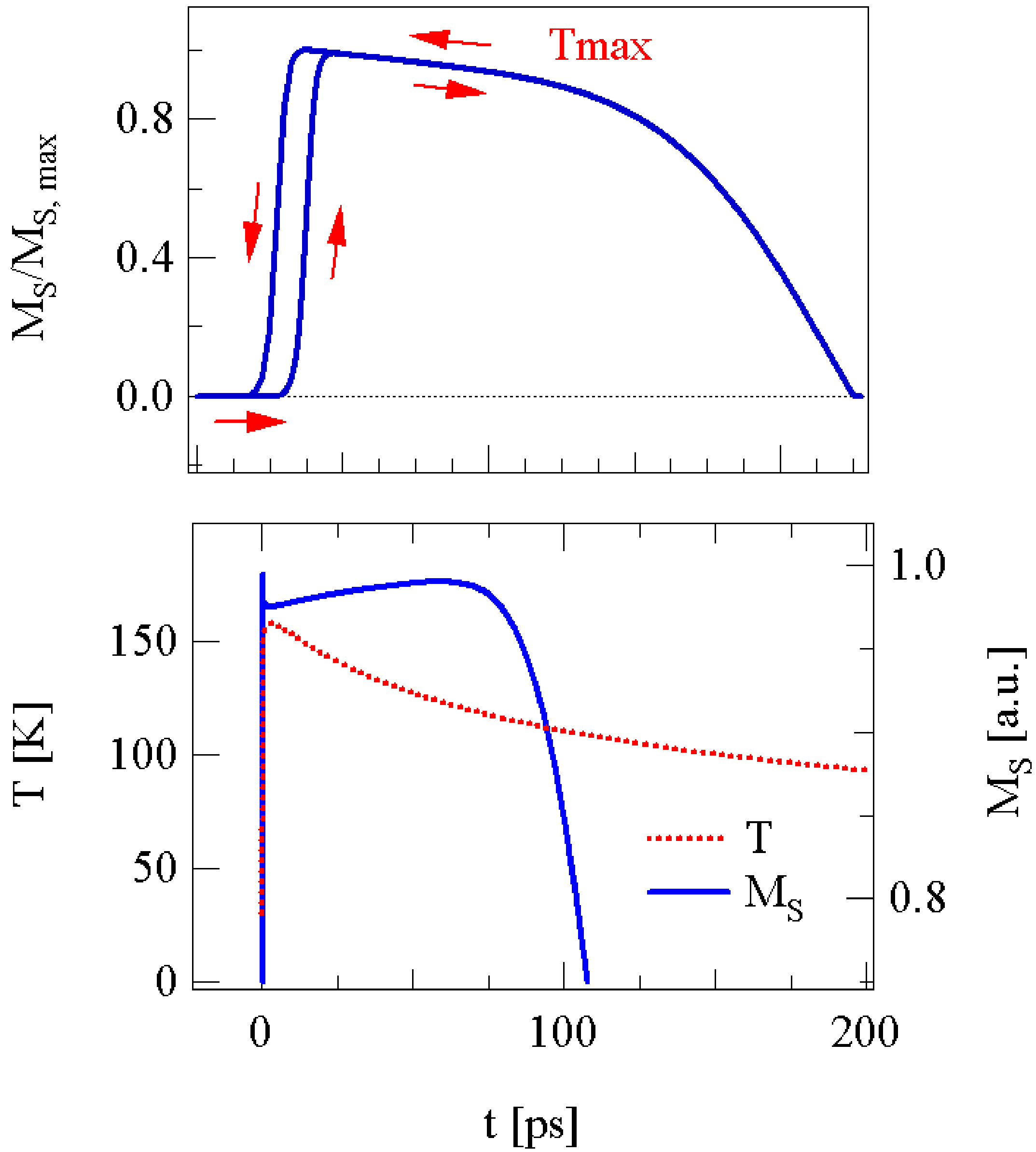
- AF-FM transition can be very fast
- how can that be, and how fast exactly?

Naïve modelling

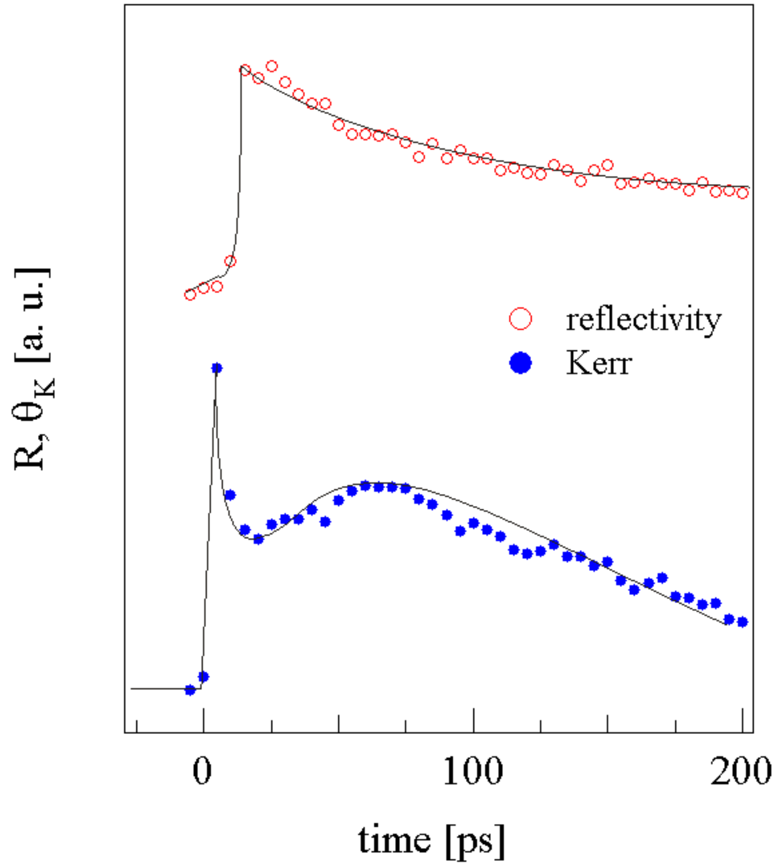
calculate thermal profiles using magneto-optical software
Temprofile 5.0 by M. Mansuripur

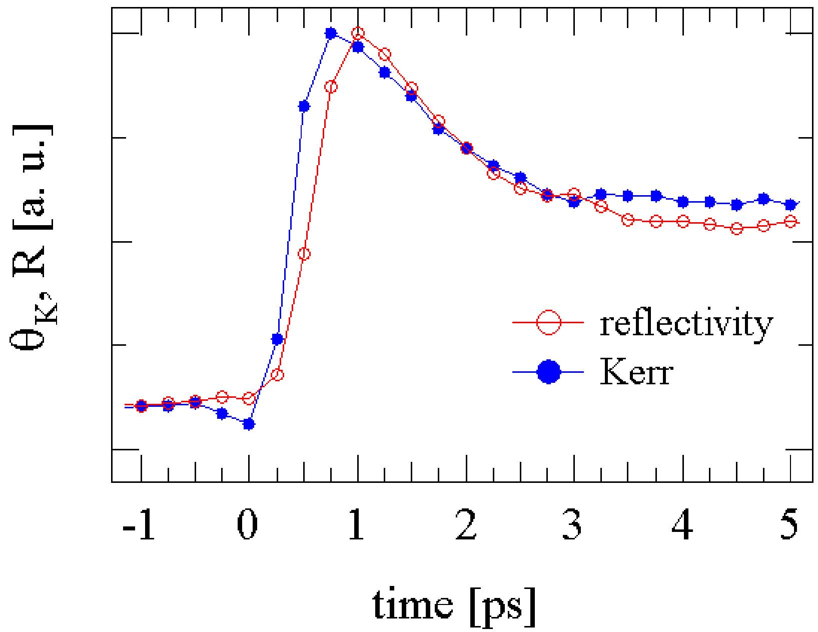
- optical absorption in multilayer
- instantaneous electron-phonon-spin coupling
- 3-D thermal diffusion

convolve with experimental data for M(T) to get expected magnetic response



FeRh - experimental results, “short” time scales





- Kerr response on 100 ps time scale qualitatively resembles expected behavior,
- quantitative differences – due to geometry, configuration ???
- rise time ~ 500 fs: AF-FM transition can be fast!
- interesting physics ?!

Summary

- FeRh is a unique material with a AM/FM phase transition at room temperature accompanied by lattice expansion

- The AM/FM transition can be driven within 1 ps (in an external field)

- Chicken or Egg ?
  Ultrafast experiments indicate that FM order seems to establish BEFORE the lattice expands