Methoden moderner Röntgenphysik II: Streuung und Abbildung

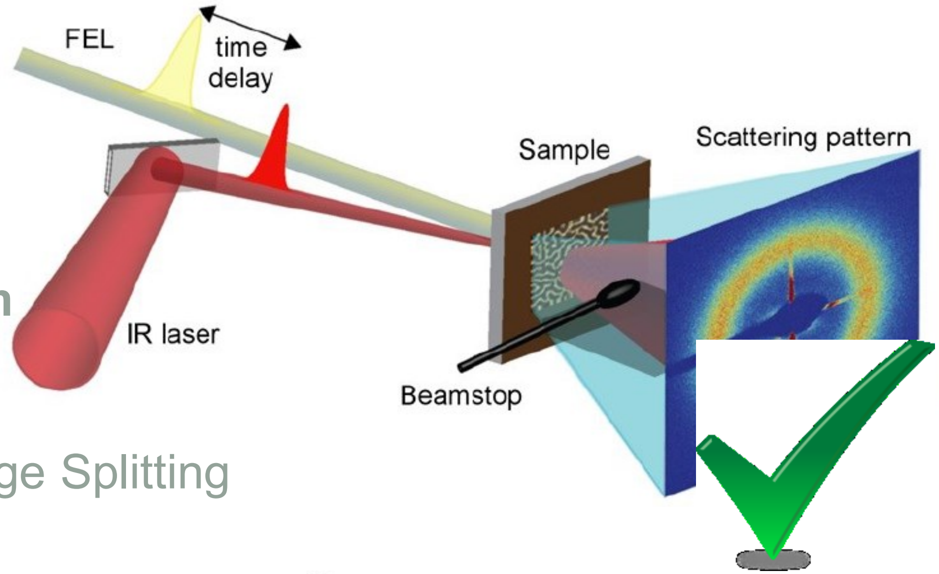
Lecture 19	Vorlesung zum Haupt- oder Masterstudiengang Physik, SoSe 2018		
	G. Grübel, A. Philippi-Kobs, F. Lehmkühler, L. Frenzel, M. Martins, W. Wurth		
Location	Lecture hall AP, Physics, Jungiusstraße		
Date	Tuesday	13:00 - 14:30	(starting 3.4.)
	Thursday	8:30 - 10:00	(until 12.7.)

Outline

Part II/2:

Studies on Magnetic Nanostructures

by André Philippi-Kobs (AP)

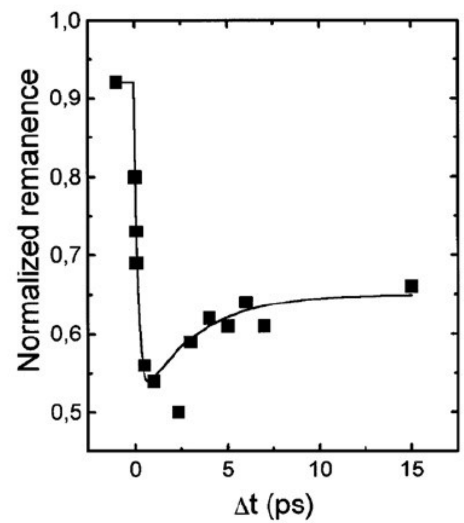


[19.6.] **X-ray Magnetic Circular Dichroism (XMCD) & Resonant Magnetic Small Angle X-ray Scattering (mSAXS)**

- Role of Spin-Orbit Coupling and Exchange Splitting
- Sum Rules
- XMLD and Natural Dicroisms
- mSAXS of Magnetic Domain Patterns

[21.6.] Femtomagnetism

- Introduction to Ultrafast Magnetization Dynamics Induced by Femtosecond Infrared Pulses
- Pump-Probe Experiments of Nano-Scale Magnetic Domain Patterns
- All-Optical Switching
- Manipulating Magnetism by XUV and THz Pulses



Time-resolved MOKE (Ni 120 fs)

Femtomagnetism

1.) Ultrafast demagnetization (IR pump, **λ = 800 nm**)

- Discovery and typical parameters
- Three-temperature model
- Ultrafast demagnetization of nano-scale domain patterns
    - TR Fourier transform holography

2.) All-optical switching (IR pump, **λ = 800 nm**)

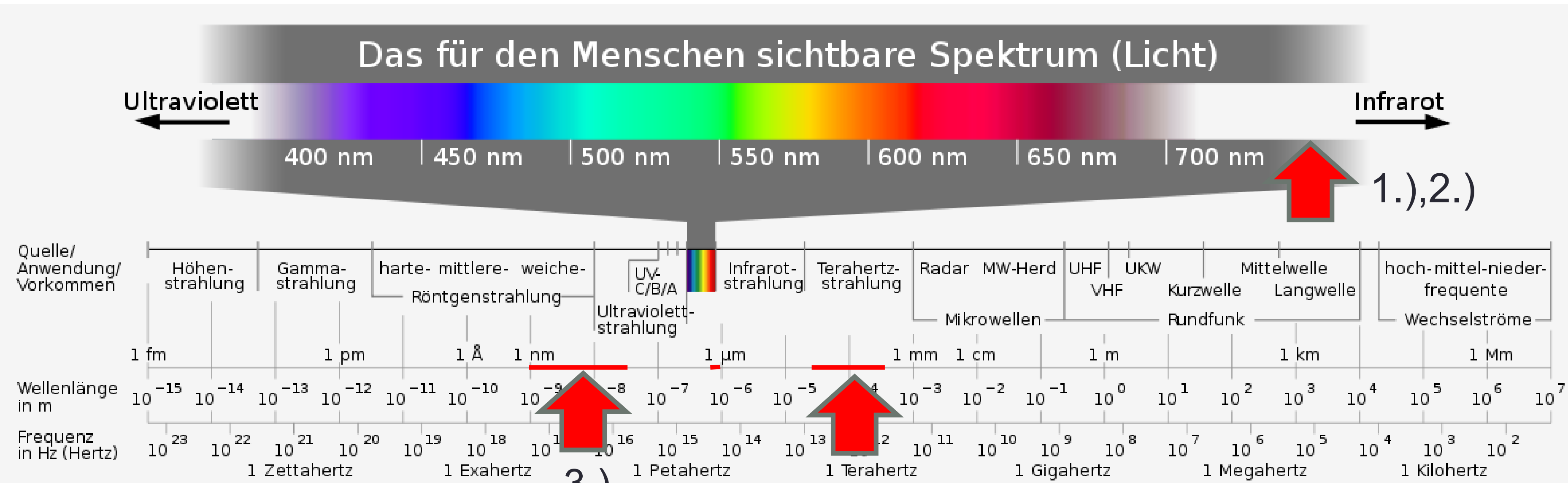
- Ferrimagnetic systems
- Is there AOS in ferromagnetic systems?

3.) High X-ray fluences (XUV pump, **λ = 20.8 nm**)

4.) THz dynamics (THz pump, **λ = 100 µm**)

Femtomagnetism

> Electromagnetic spectrum



3.)

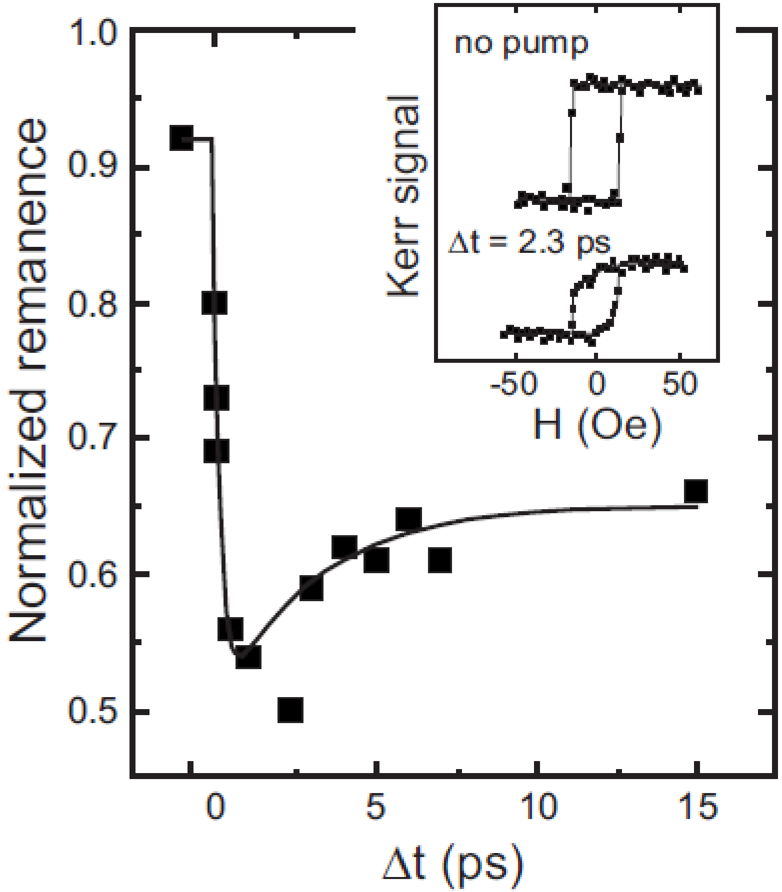
4.) THz gap

L-edges (soft X-rays)
M-edges (extreme UV, i.e., XUV)

Femtomagnetism

> Ultrafast demagnetization (IR pump, λ = 800 nm)

- Discovery and typical parameters



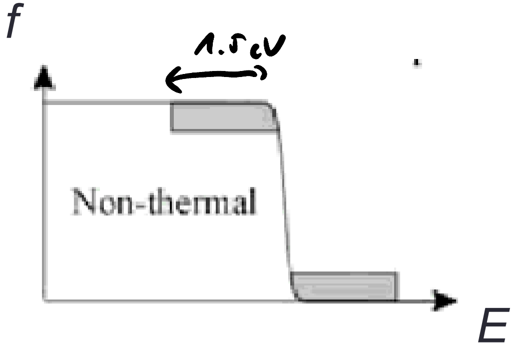
- Pulse duration 70 fs
- In-plane magnetized Ni film
- Characteristic time of demagnetization of 260 fs
- Recovery time of magnetization >100 ps
- Fluence of 7 mJ/cm² ($2.8*10^{16}$ Photonen/cm², $4*10^{29}$ Photonen/(cm²s))

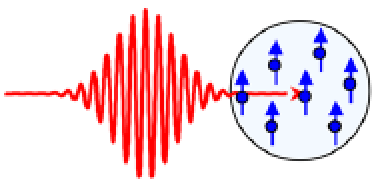
E. Beaurepaire *et al.*, Phys. Rev. Lett. **76**, 4250 (1996).

Femtomagnetism

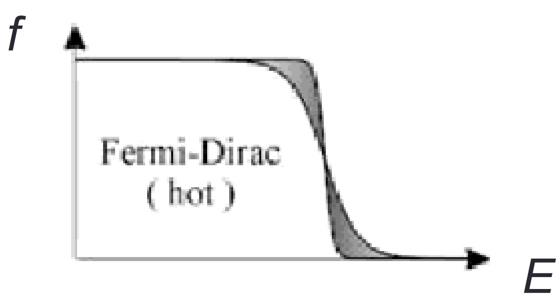
> Ultrafast demagnetization

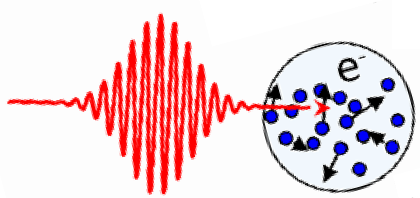
1.) Creation of highly excited electrons during the pulse duration (< 20 fs)





2.) Thermalization of electron system (<200 fs) due to electron-electron-scattering

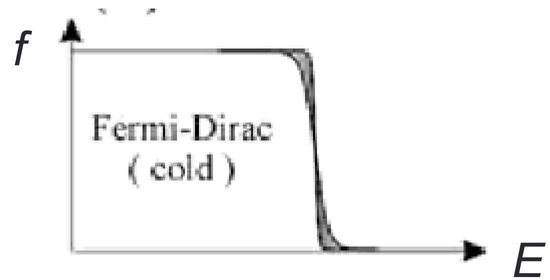


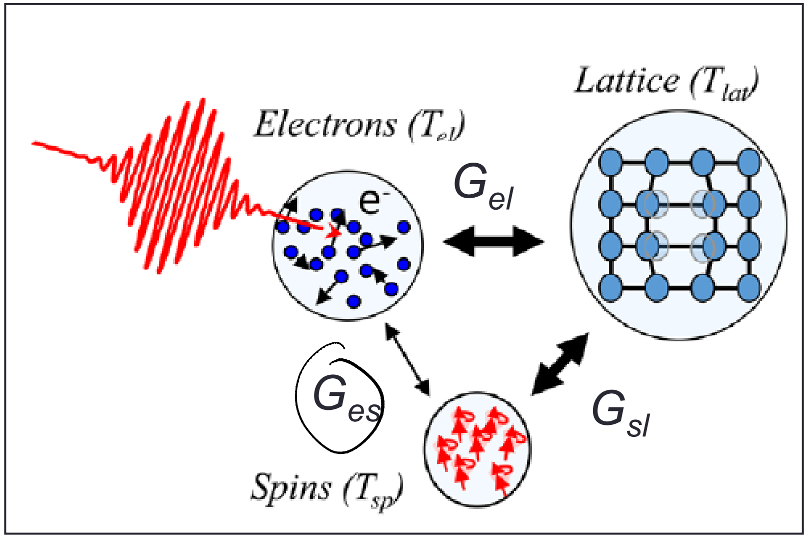


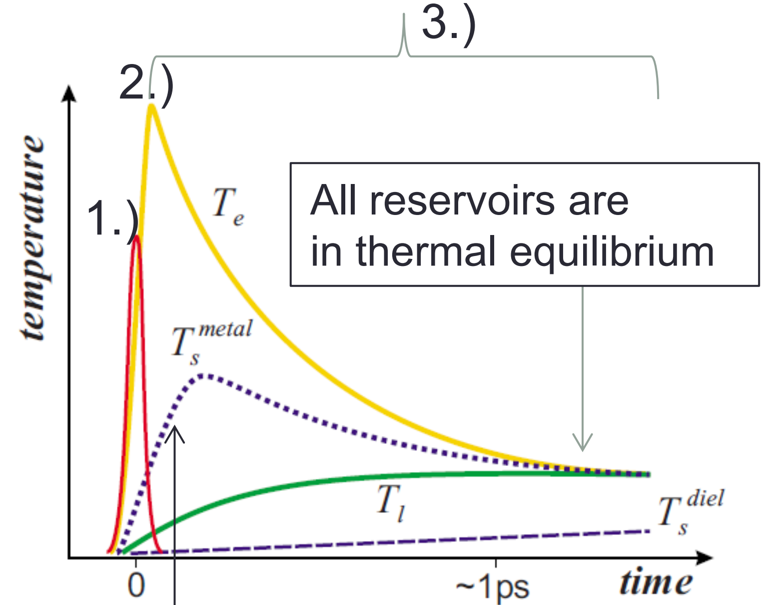
Femtomagnetism

> Ultrafast demagnetization

3.) Thermalization of electron, phonon, and spin reservoirs (<1 ps) due to electron-phonon-, electron-spin-, and phonon-spin-scattering







Ultrafast demagnetization

➔ Differential equations (Rate equations)

$$C_e d(T_e)/dt = -G_{el}(T_e - T_l) - G_{es}(T_e - T_s) + P(t),$$

$$C_s d(T_s)/dt = -G_{es}(T_s - T_e) - G_{sl}(T_s - T_l),$$

$$C_l d(T_l)/dt = -G_{el}(T_l - T_e) - G_{sl}(T_l - T_s),$$

Energy density of pulse

C_i: specific heat, T_i: temperature of electrons, phonons, spins
G_i: strength of interaction between electrons, phonons, spins

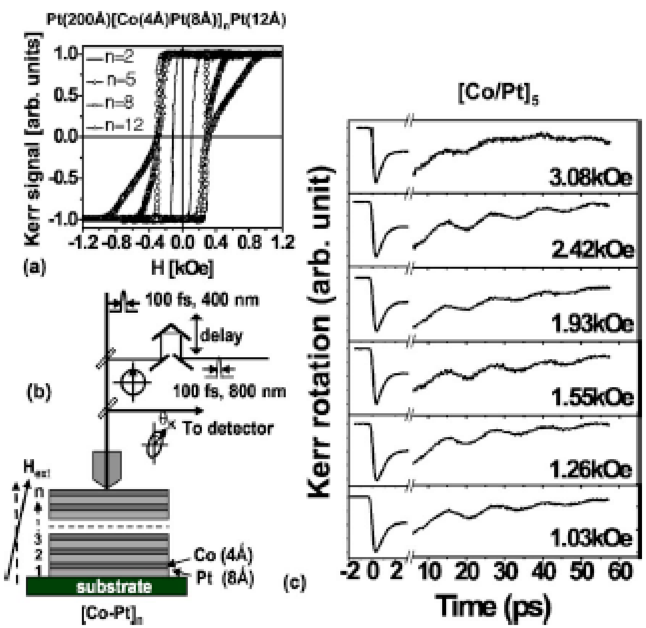
Femtomagnetism

> Ultrafast demagnetization

4.) Cooling of sample due to interaction with environment (~100 ps – 100 ms)

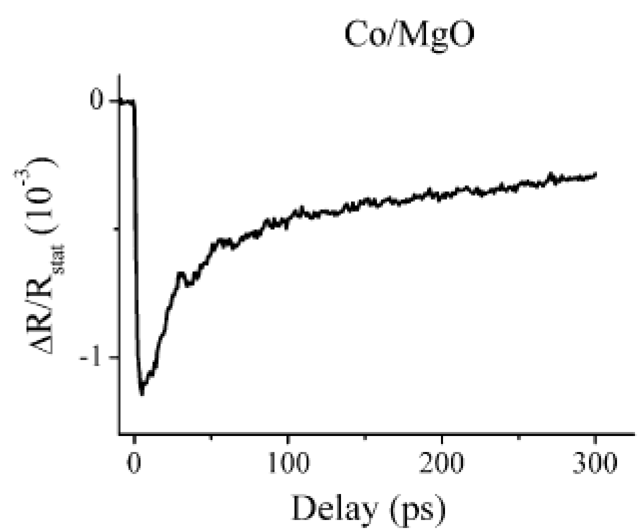
JOURNAL OF APPLIED PHYSICS 101, 09D102 (2007)

Ultrafast magnetization dynamics in high perpendicular anisotropy [Co/Pt]$_n$ multilayers



Chemical Physics 318 (2005) 137–146

Ultrafast magnetization dynamics in ferromagnetic cobalt: The role of the anisotropy



Femtomagnetism

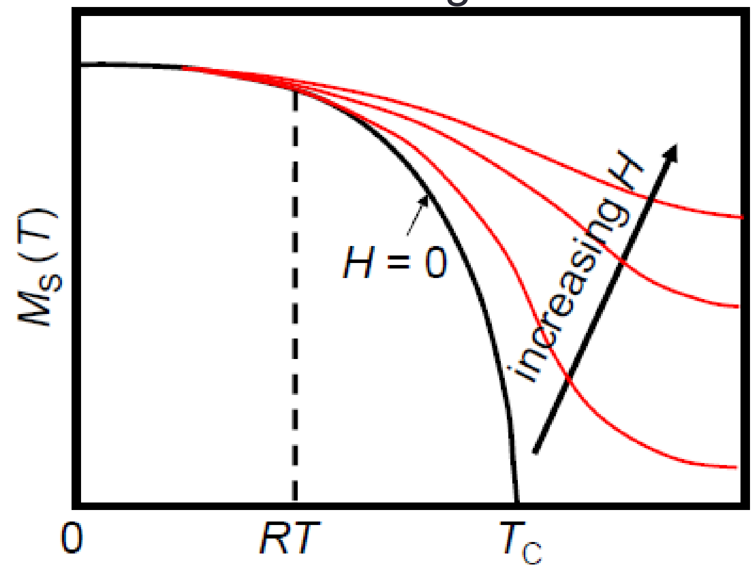
> Ultrafast demagnetization

- T-dependence of saturation magnetization (low T)

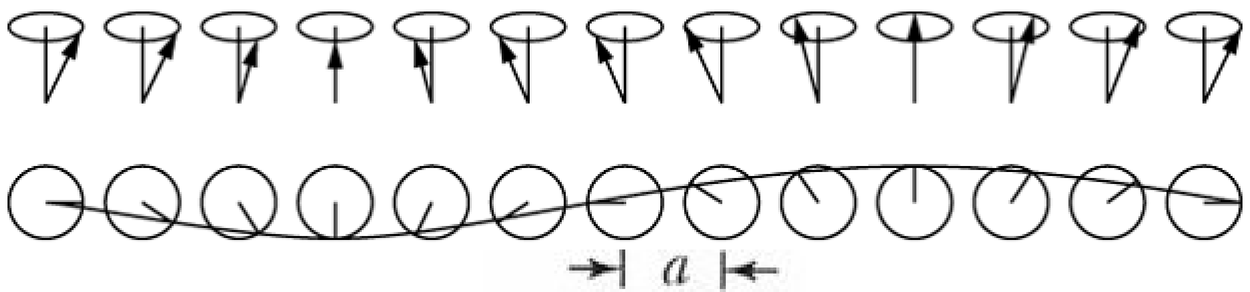
$$M_S(T) = M_S(0)(1 - BT^{3/2})$$

$$B = 3.3 \cdot 10^{-6}\ \mathrm{K}^{-3/2} \text{ for bulk Co}$$

"thermal" demagnetization

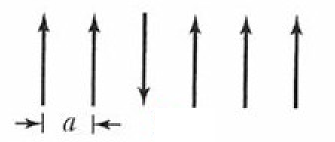


- Collective spin excitations = "magnons" or spin wave (low T)



Magnon reduces saturation magnetization by $\hbar$

- Single spin excitations (high T)



Single spin exc. reduces saturation magnetization by $\hbar$

Femtomagnetism

> Ultrafast demagnetization

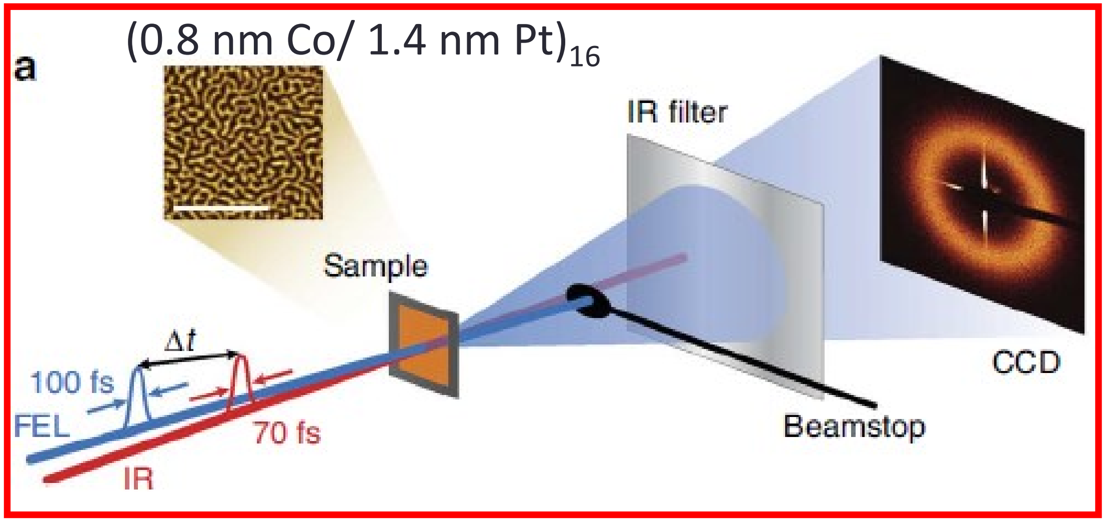
… of magnetic domain pattern

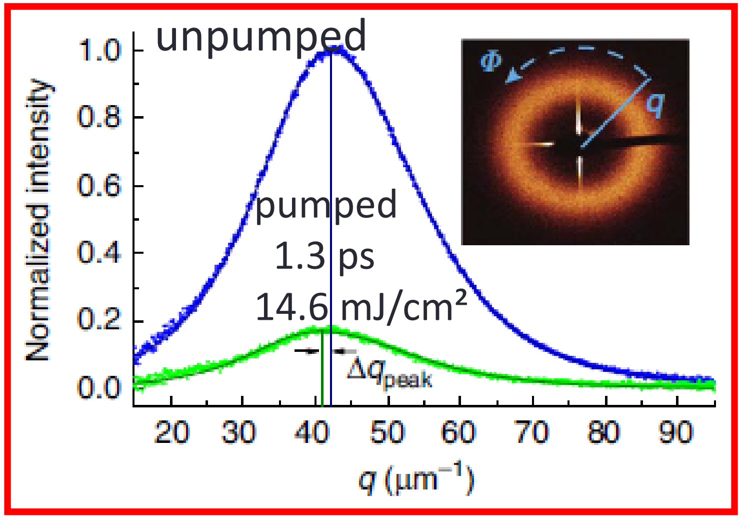
ARTICLE
Received 18 Apr 2012 | Accepted 3 Sep 2012 | Published 2 Oct 2012
DOI: 10.1038/ncomms2108

Ultrafast optical demagnetization manipulates nanoscale spin structure in domain walls

B. Pfau[1], S. Schaffert[1], L. Müller[2], C. Gutt[2], A. Al-Shemmary[2], F. Büttner[1,3,4,5], R. Delaunay[6], S. Düsterer[2], S. Flewett[1,4], R. Frömter[7], J. Geilhufe[8], E. Guehrs[1], C.M. Günther[1], R. Hawaldar[6], M. Hille[7], N. Jaouen[9], A. Kobs[7], K. Li[6], J. Mohanty[1], H. Redlin[2], W.F. Schlotter[10], D. Stickler[7], R. Treusch[2], B. Vodungbo[6,11], M. Kläui[3,4,5], H.P. Oepen[7], J. Lüning[6], G. Grübel[2] & S. Eisebitt[1,8]

IR-pump−XUV-probe experiment

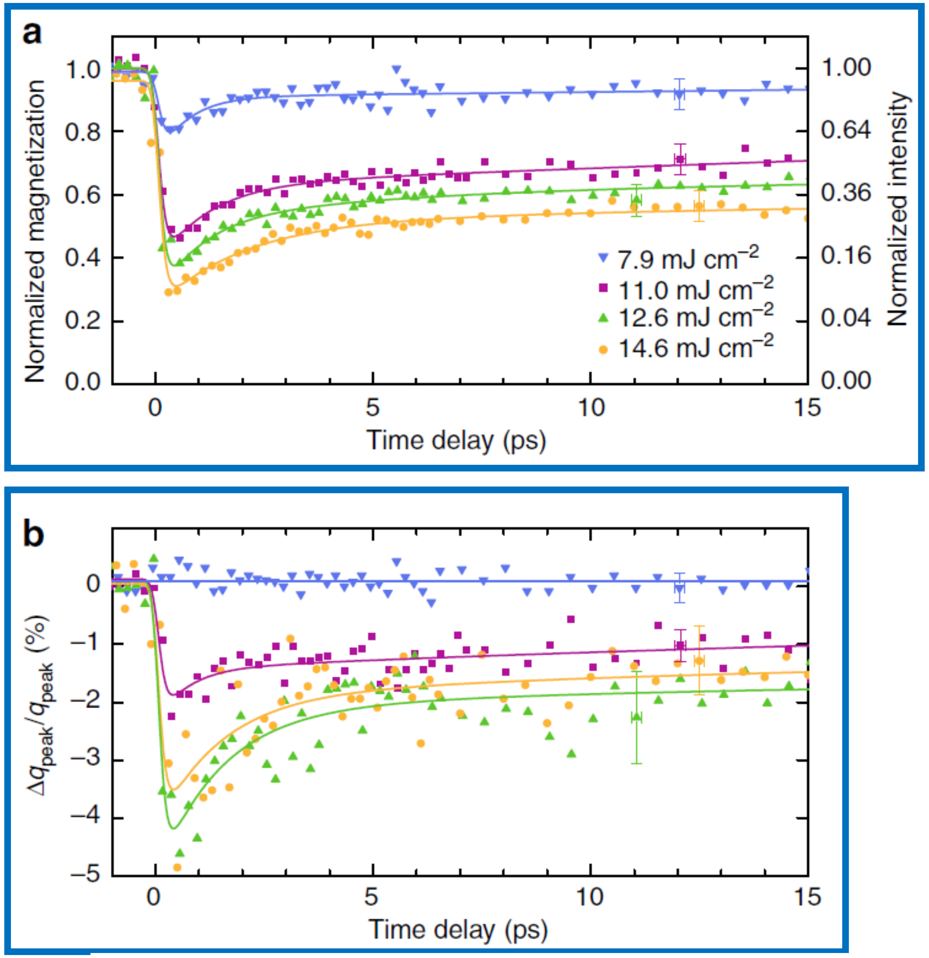




Femtomagnetism

> Ultrafast demagnetization

… of magnetic domain pattern



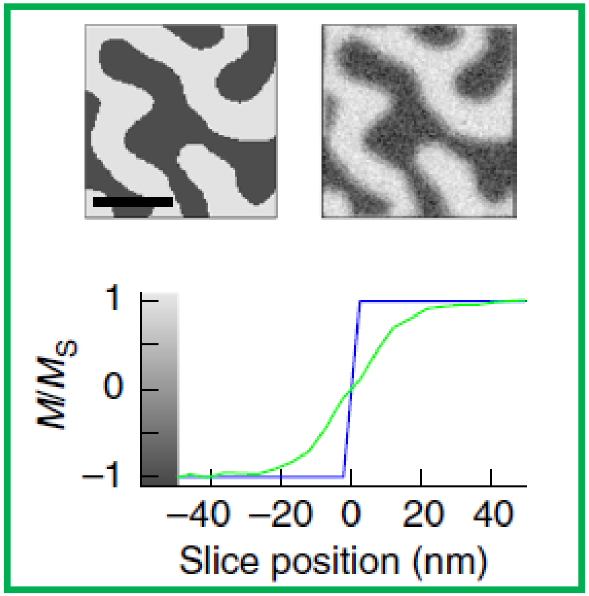
Ultrafast demagnetization (see above)

Decrease in radius of scattering ring

Femtomagnetism

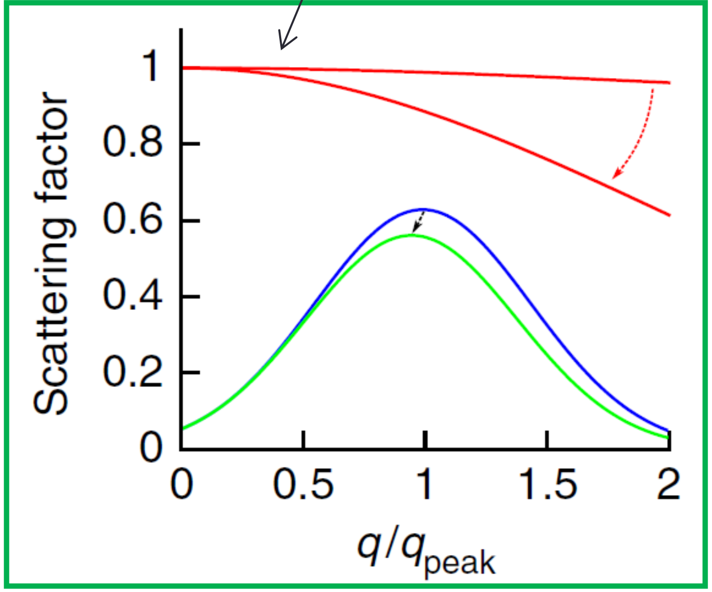
> Ultrafast demagnetization … of magnetic domain pattern

- Explanation of q_{peak} shift



Fourier transformation

Scattering form factor of domain wall



Super-diffusive currents broaden domain walls by 20 nm (FWHM)

Change of scattering form factor of domain walls and hence q_{peak}

B. Pfau *et al.*, Nat. Commun. **3** (2012).

Femtomagnetism

> Ultrafast demagnetization … of magnetic domain pattern

- Explanation of q_{peak} shift via superdiffusive currents (spin-dependent electron scattering)

Fermi's Golden rule: Scattering rate of electrons from state **k** to **k**'

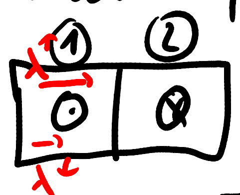
$$\Gamma_{\mathbf{k},\mathbf{k}'} = \frac{2\pi}{\hbar} |<\Phi_f(\mathbf{k}')|V|\Phi_i(\mathbf{k})>|^2 D_f(E'),$$

time between scattering events $\tau = 1/\Gamma$

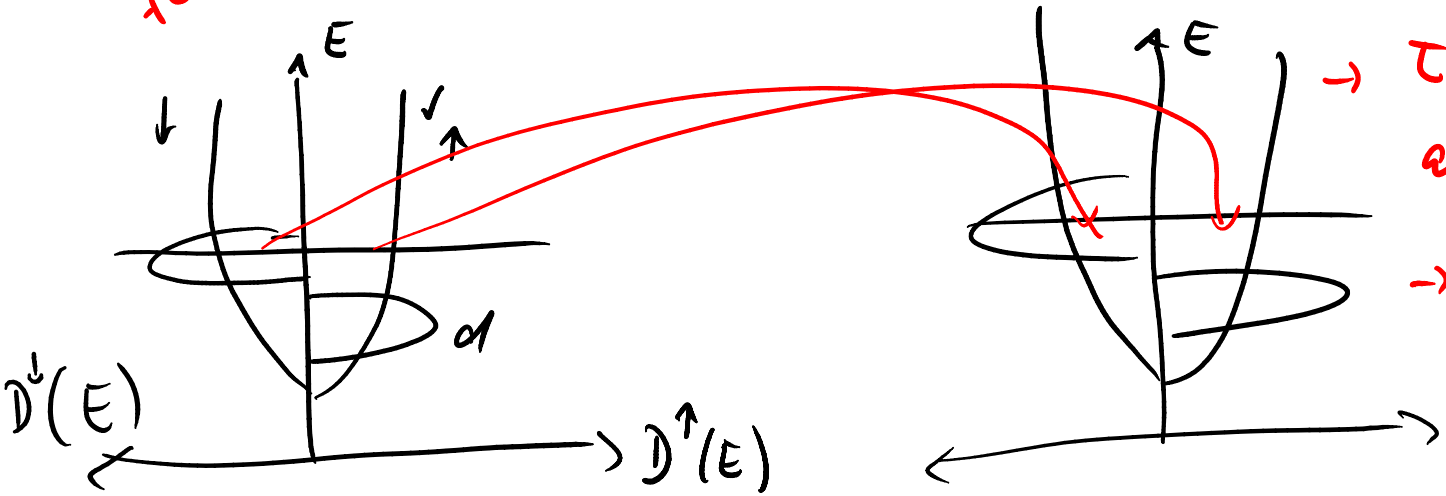
Mean free path:

$$\lambda = v_F \tau$$

good assumption: spin is conserved during scattering



1 → 1 (or 2 → 2)



→ $\tau_\downarrow << \tau_\uparrow$

as $D_f^\uparrow(E_F) << D_f^\downarrow(E_F)$

→ $\lambda^\uparrow >> \lambda^\downarrow$

Femtomagnetism

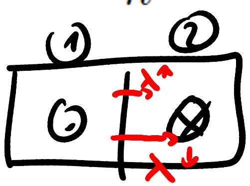
> Ultrafast demagnetization … of magnetic domain pattern

- Explanation of q_{peak} shift via superdiffusive currents (spin-dependent electron scattering)

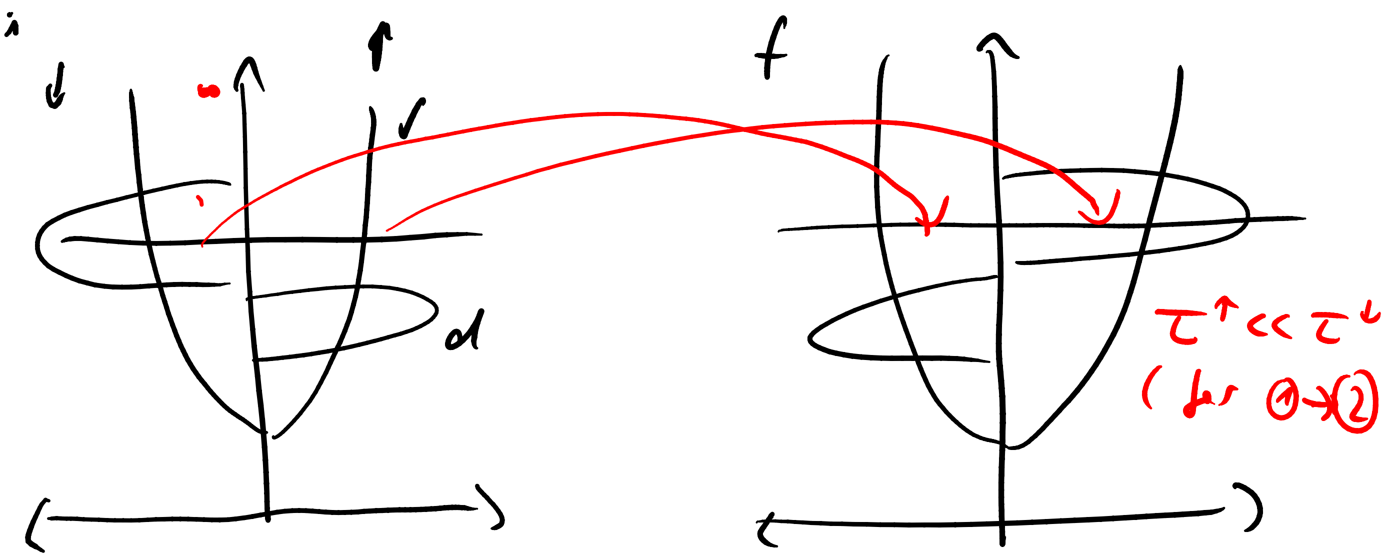
Fermi's Golden rule: Scattering rate of electrons from state **k** to **k'**

$$\Gamma_{\mathbf{k},\mathbf{k}'} = \frac{2\pi}{\hbar} | < \Phi_f(\mathbf{k}') | V | \Phi_i(\mathbf{k}) > |^2 D_f(E')$$

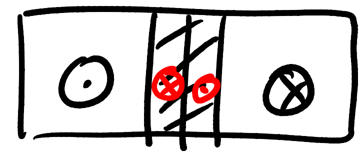
(1) → (2)



across Domain wall



scattered spins



→ accumulation of minority spins around domain wall

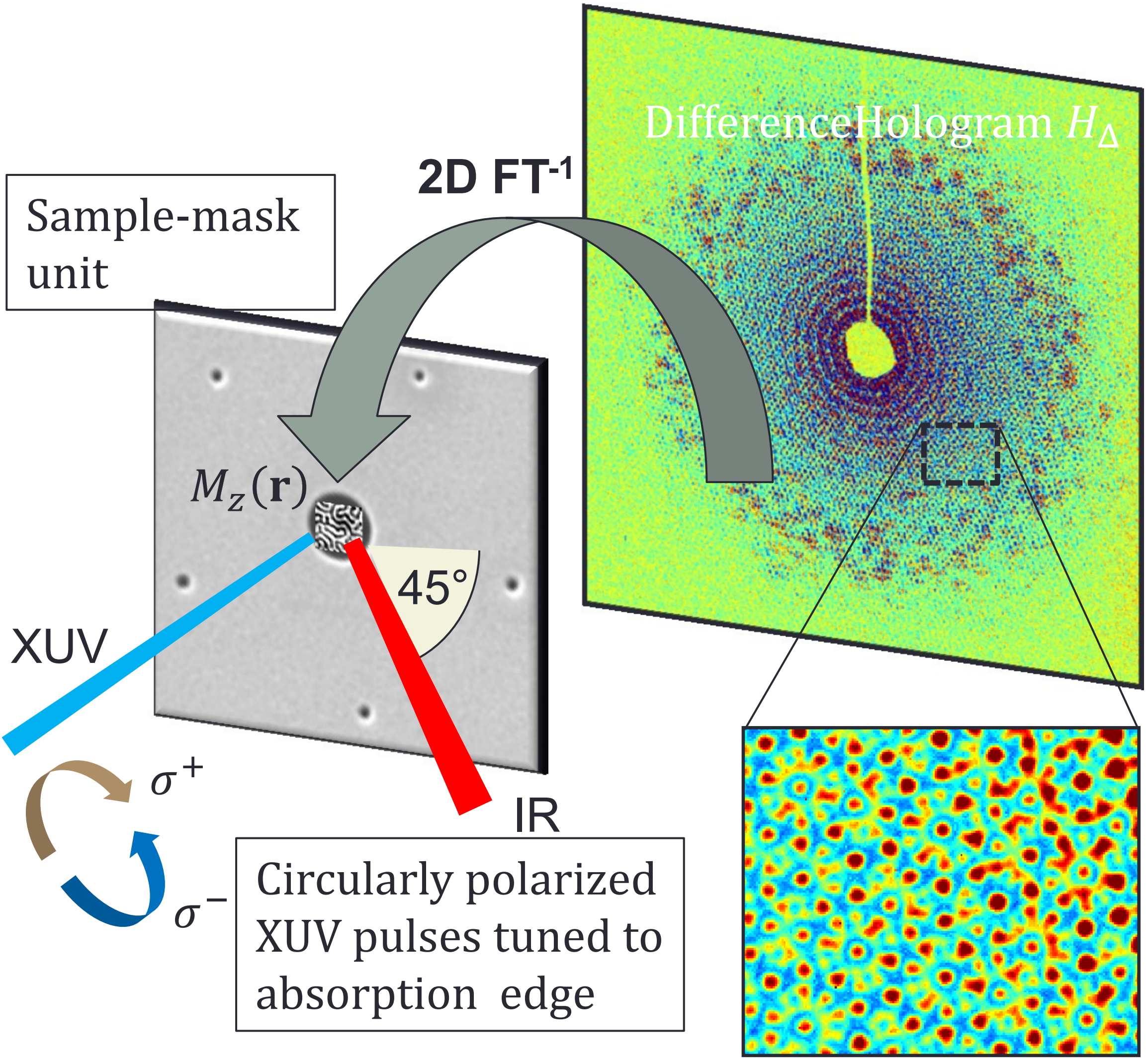
≙ reduction of M_s

≙ broadening of domain wall!

DESY

Femtomagnetism

> Ultrafast demagnetization … of magnetic domain pattern -

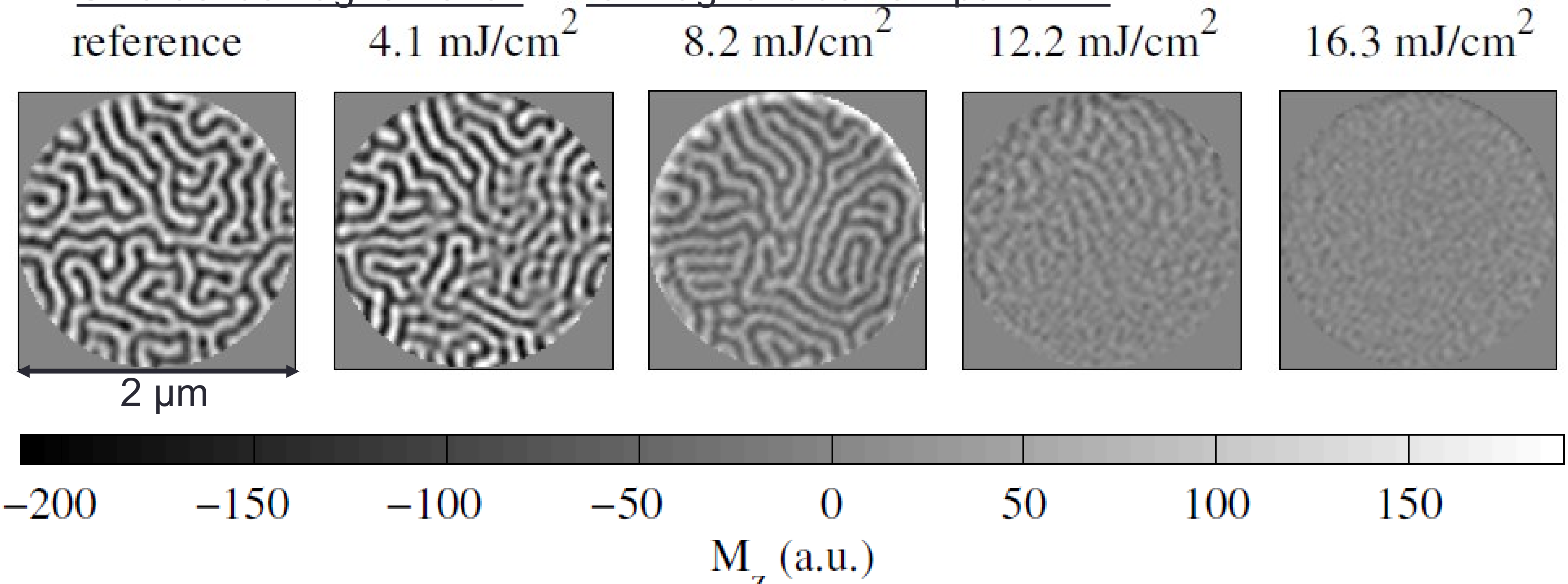


Experimental parameters at FERMI

- 600 shots per helicity
- 4.1 mJ/cm² ≤ fluence ≤ 16.3 mJ/cm²
- Repetition rate 10 Hz
- λ = 20.8 nm (M-edge of Co)
- Fixed time delay of 1 ps
- Pump laser (λ = 780 nm) at 45° with respect to sample surface
- Sample: $(Co(0.4\ nm)/Pd(0.2\ nm))_{30}$

Femtomagnetism

> Ultrafast demagnetization … of magnetic domain pattern -



- Blurring due to domain rearrangements initiated by quasi-static heating (thermal demagnetization)
- Global contrast scale ∝ saturation magnetization ➔ ultrafast demagnetization on the nanoscale
- Small contrast at high fluences due to high demagnetization and/or domain rearrangements
- Resolution of 40 nm limited by exp. geometry is too low to resolve domain wall broadening

Femtomagnetism

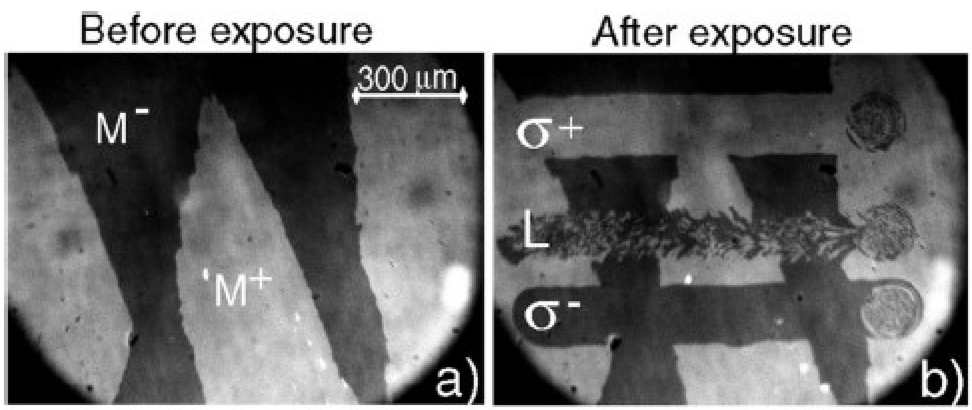
PRL 99, 047601 (2007) PHYSICAL REVIEW LETTERS week ending 27 JULY 2007

All-Optical Magnetic Recording with Circularly Polarized Light

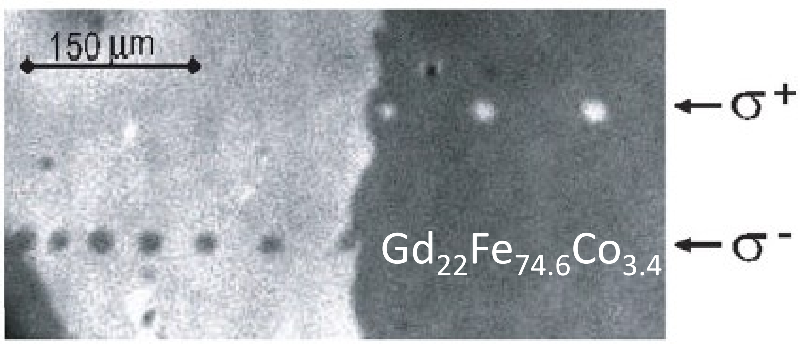
C. D. Stanciu,[1,*] F. Hansteen,[1] A. V. Kimel,[1] A. Kirilyuk,[1] A. Tsukamoto,[2] A. Itoh,[2] and Th. Rasing[1]
[1]*Institute for Molecules and Materials, Radboud University Nijmegen, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands*
[2]*College of Science and Technology, Nihon University, 7-24-1 Funabashi, Chiba, Japan*
(Received 2 March 2007; published 25 July 2007)

> <u>All-optical switching</u>

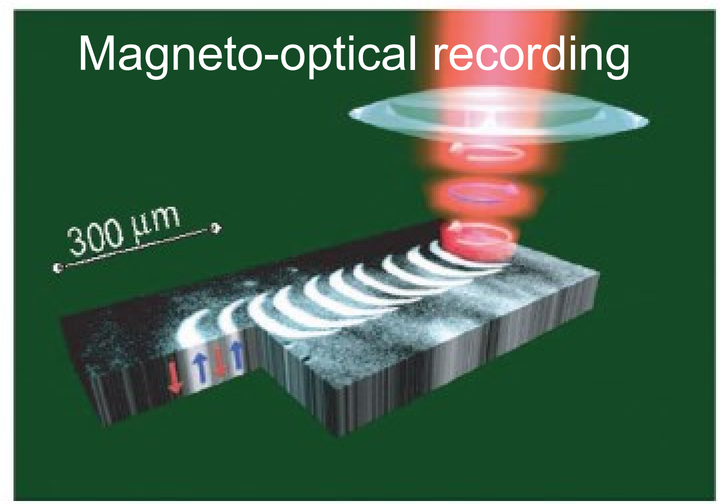
- Discovery for ferrimagnetic materials



Multi-shot



Single-shot



Femtomagnetism

> All-optical switching

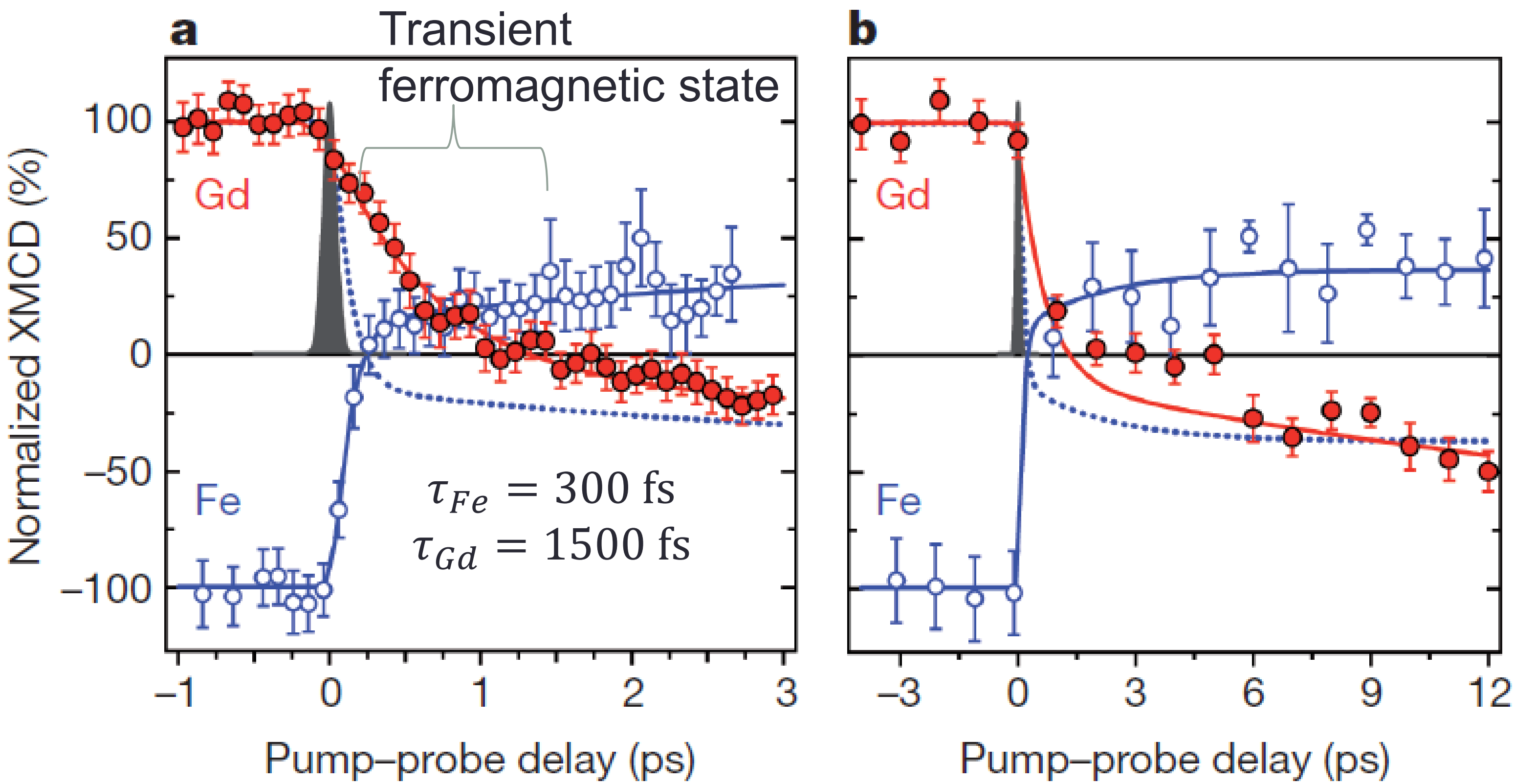
- Time-resolved and element-selective studies

doi:10.1038/nature09901

Transient ferromagnetic-like state mediating ultrafast reversal of antiferromagnetically coupled spins

2011

I. Radu[1,2], K. Vahaplar[1], C. Stamm[2], T. Kachel[2], N. Pontius[2], H. A. Dürr[2,3], T. A. Ostler[4], J. Barker[4], R. F. L. Evans[4], R. W. Chantrell[4], A. Tsukamoto[5,6], A. Itoh[5], A. Kirilyuk[1], Th. Rasing[1] & A. V. Kimel[1]



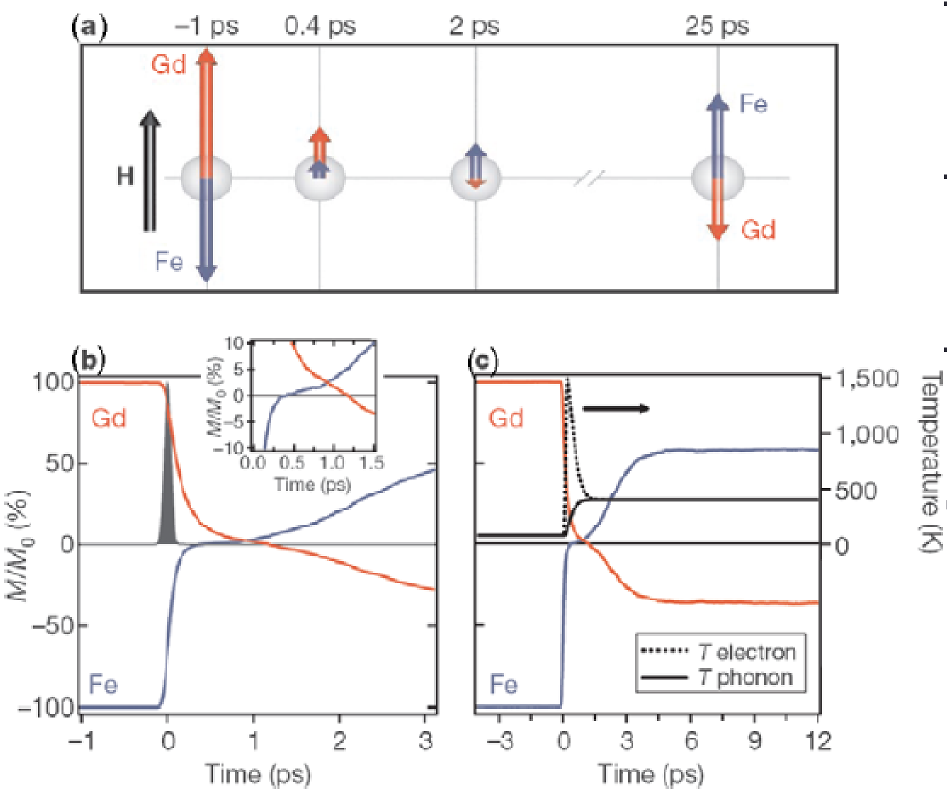
Femtomagnetism

Rep. Prog. Phys. 76 (2013) 026501 (35pp) doi:10.1088/0034-4885/76/2/026501

Laser-induced magnetization dynamics and reversal in ferrimagnetic alloys

> All-optical switching

- Time-resolved and element-selective studies (theoretical model)



Helicity-independent AOS switching:

- 0-0.3 ps: complete demagnetization of Fe
- 0.4-1.5 ps: transfer of magnetic moment from Gd to Fe to enhance entropy yields to switching of magnetization of Fe
- 1.5-2 ps: antiferromagnetic coupling between Gd and Fe yields to reversing magnetization of Gd
- > 2 ps: Recovery of magnetic moments due to cooling

➔ All-optical switching of ferrimagnets!

Helicity-dependent AOS switching due to

- MCD effect (%-effect at off-resonance) + transfer of angular momentum?
- Inverse Faraday effect?

$\vec{H}_{IFE} \propto (\vec{E} \times \vec{E}^*)$

Femtomagnetism

> All-optical switching

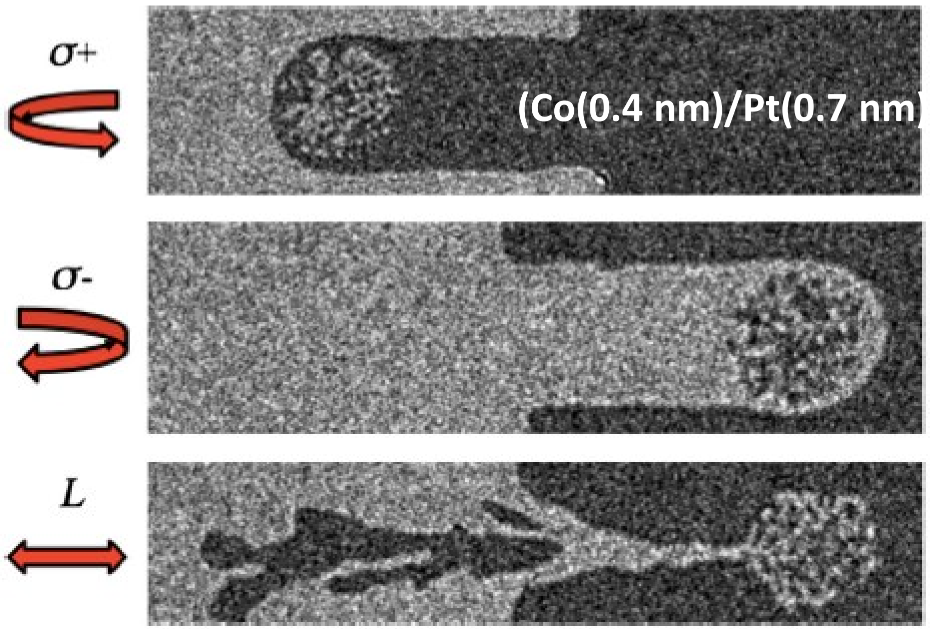
- Is there all-optical switching for ferromagnetic materials?

SCIENCE sciencemag.org 12 SEPTEMBER 2014 • VOL 345 ISSUE 6202

MAGNETISM

All-optical control of ferromagnetic thin films and nanostructures

C.-H. Lambert et al., Science **345**, 1337 (2014).



Multi-shot

Many open questions, like e.g.:

- Does deterministic single-pulse HD-AOS work in ferromagnets?
- If yes, for which parameters?
- Underlying mechanisms?
  - Inverse Faraday effect
  - MCD

What we are doing?

We had a beamtime at FLASH in December 2017 to tackle these questions!

Femtomagnetism

PRL 110, 234801 (2013) PHYSICAL REVIEW LETTERS week ending 7 JUNE 2013

Breakdown of the X-Ray Resonant Magnetic Scattering Signal during Intense Pulses of Extreme Ultraviolet Free-Electron-Laser Radiation

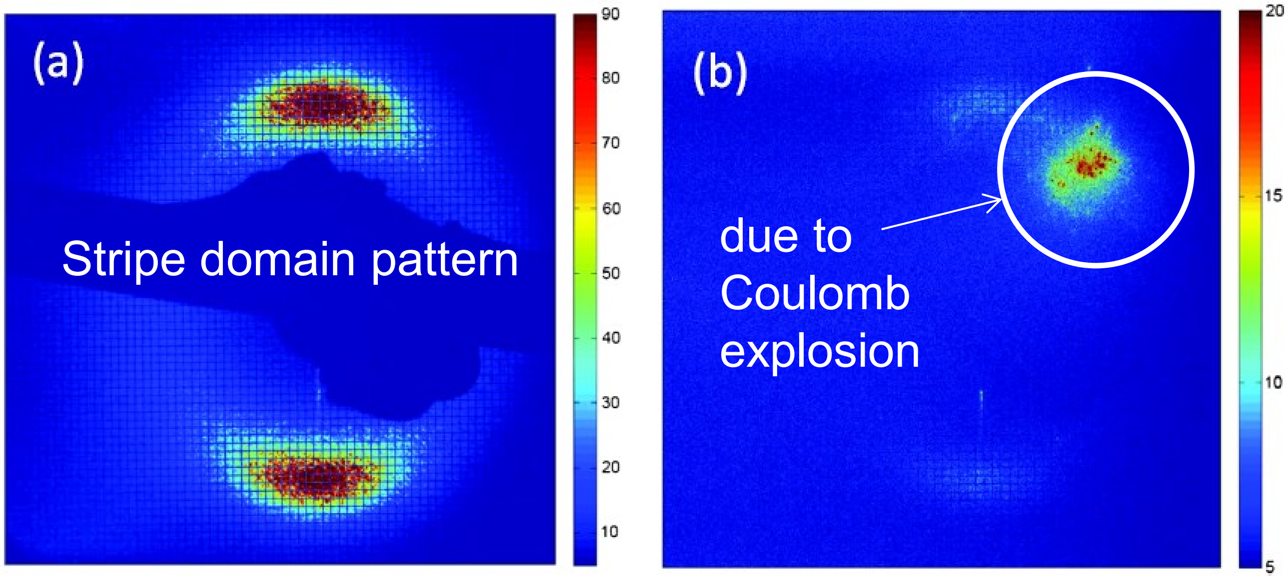
L. Müller,[1,*] C. Gutt,[1,2] B. Pfau,[3] S. Schaffert,[3] J. Geilhufe,[4] F. Büttner,[3] J. Mohanty,[3] S. Flewett,[3] R. Treusch,[1] S. Düsterer,[1] H. Redlin,[1] A. Al-Shemmary,[1] M. Hille,[5] A. Kobs,[5] R. Frömter,[5] H. P. Oepen,[5] B. Ziaja,[1,2,6,7] N. Medvedev,[1,6] S.-K. Son,[1,6] R. Thiele,[1,6] R. Santra,[1,2,6,8] B. Vodungbo,[9] J. Lüning,[9] S. Eisebitt,[3,4] and G. Grübel[1,2]

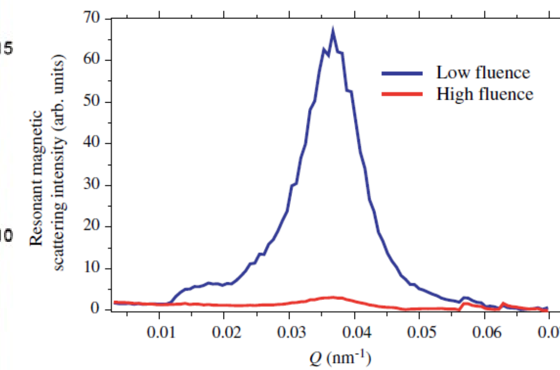
> High X-ray fluences

What is happening at high X-ray fluences (λ = 20.8 nm, i.e., M-edge of Co)?

Experiment at FLASH (**Fr**ee-electron **Las**er in **H**amburg),pulse duration of ~100 fs

1000 shots à 7.5 mJ/cm² 1 shot à 5 J/cm²





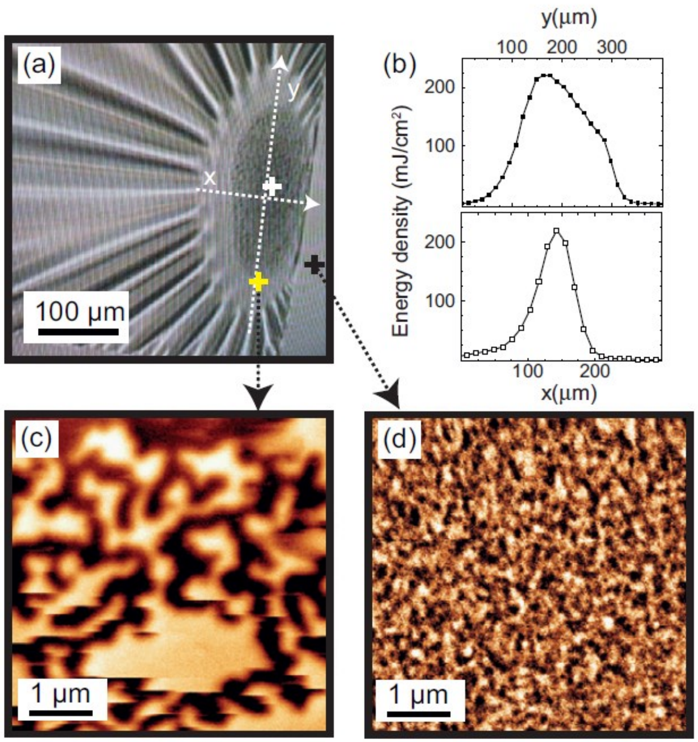
➔ Intra-pulse "quenching"/ breakdown of the resonant mSAXS signal
➔ Violation of principle "diffract before destruct"
➔ X-ray pulse <u>does not</u> only act as a non-invasive probe

Femtomagnetism

> High X-ray fluences

- Beam damage

Fluence of 200 mJ/cm²



epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS
January 2015
EPL, 109 (2015) 17001
www.epljournal.org
doi: 10.1209/0295-5075/109/17001

Femtosecond-laser–induced modifications in Co/Pt multilayers studied with tabletop resonant magnetic scattering

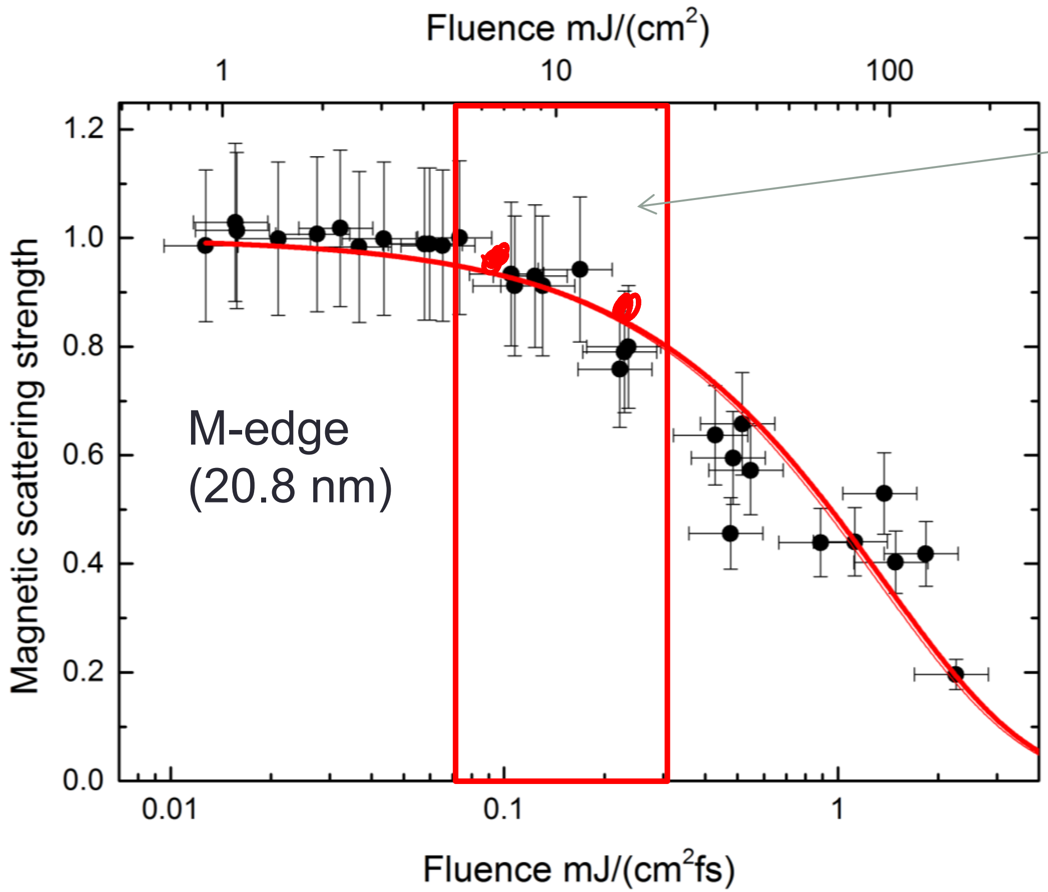
C. Weier[1], R. Adam[1], D. Rudolf[1], R. Frömter[2], P. Grychtol[3], G. Winkler[2], A. Kobs[2], H. P. Oepen[2], H. C. Kapteyn[3], M. M. Murnane[3] and C. M. Schneider[1]

➔ Single shot experiments
➔ Many membranes needed

Femtomagnetism

> <u>High X-ray fluences</u>

- Fluence dependence of quenching (measured at FEL FERMI in Trieste, Italy)



- Typically used in „classical“ pump-probe experiments!

➔ Variation of scattering strength by ~20%

➔ Effect superimposed on data!

Femtomagnetism

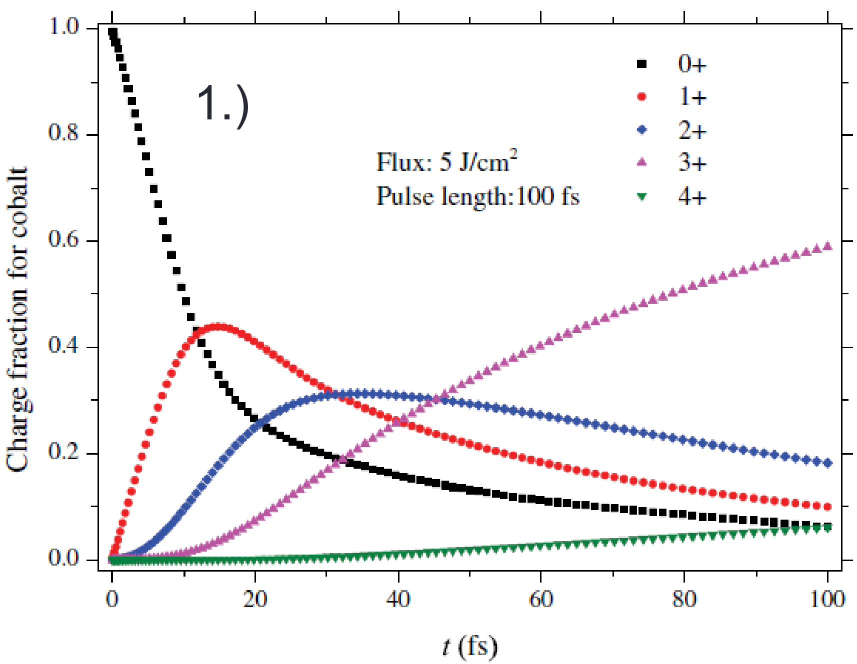
PRL 115, 107402 (2015) PHYSICAL REVIEW LETTERS week ending 4 SEPTEMBER 2015

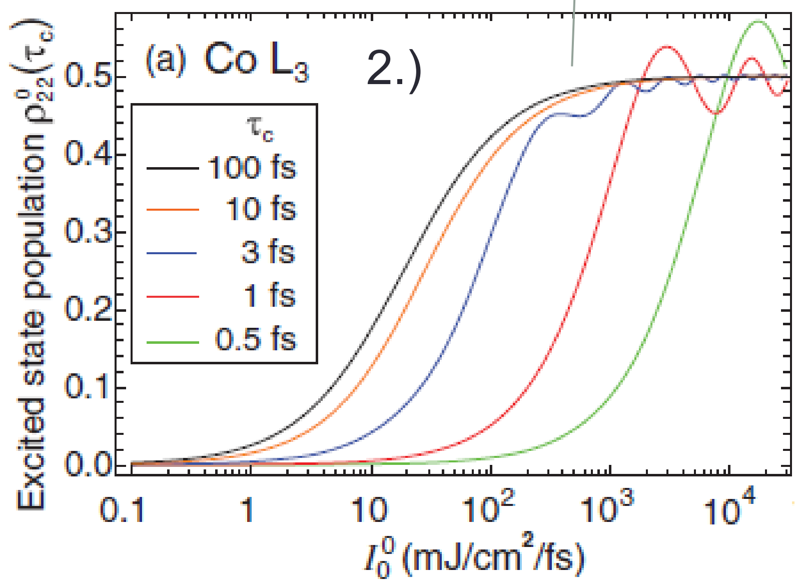
Creation of X-Ray Transparency of Matter by Stimulated Elastic Forward Scattering

J. Stöhr[1,*] and A. Scherz[2,†]

> High X-ray fluences

Possible reasons for quenching (ongoing research)
1.) Creation of highly ionized state and changing band-structure
2.) Stimulated elastic forward scattering
3.) Ultrafast demagnetization





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Femtomagnetism

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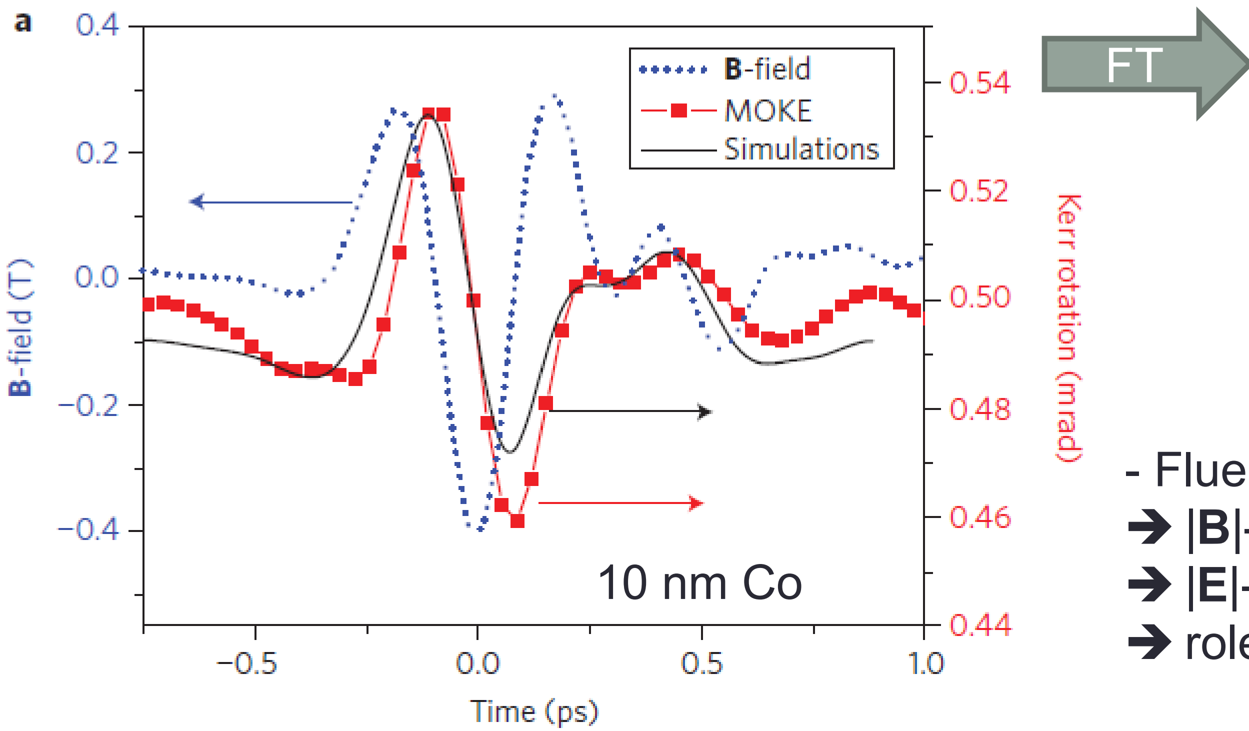
> THz dynamics

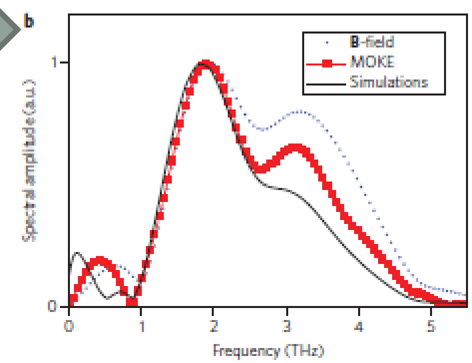
Idea and typical parameters

Off-resonant magnetization dynamics phase-locked to an intense phase-stable terahertz transient

C. Vicario[1], C. Ruchert[1], F. Ardana-Lamas[1,2], P. M. Derlet[3], B. Tudu[4], J. Luning[4] and C. P. Hauri[1,2]*

Coherent control of magnetization (magnetization can follow **B**-field of THz-pulse)



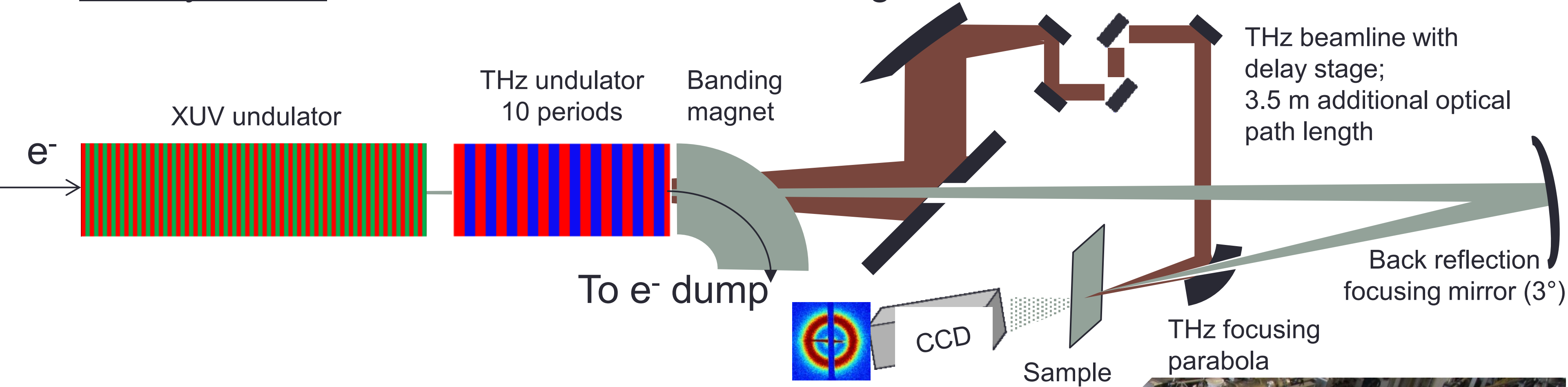


- Fluence of 10 mJ/cm²
➔ |**B**|-field of 200 mT
➔ |**E**|-field of 60 MV/m
➔ role of **E**-field?

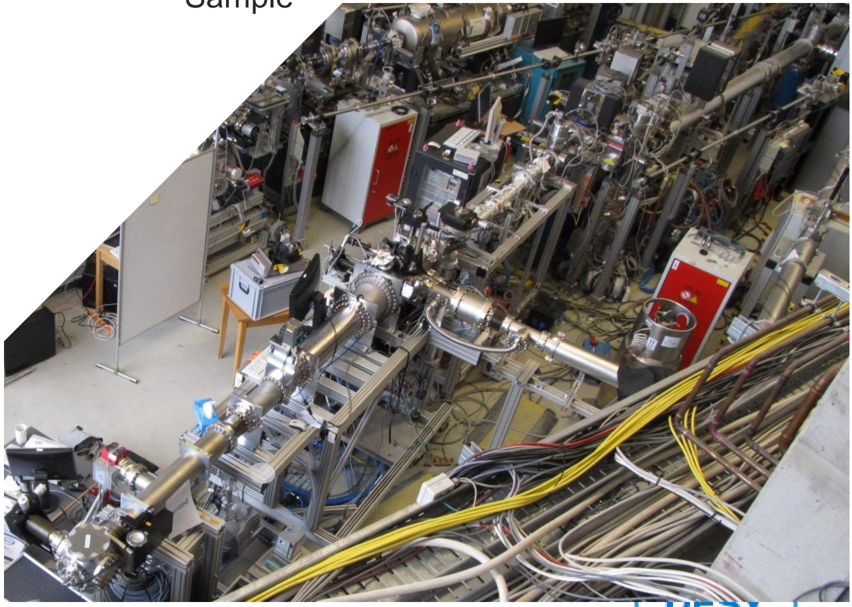
Femtomagnetism

> THz dynamics

What are we doing?

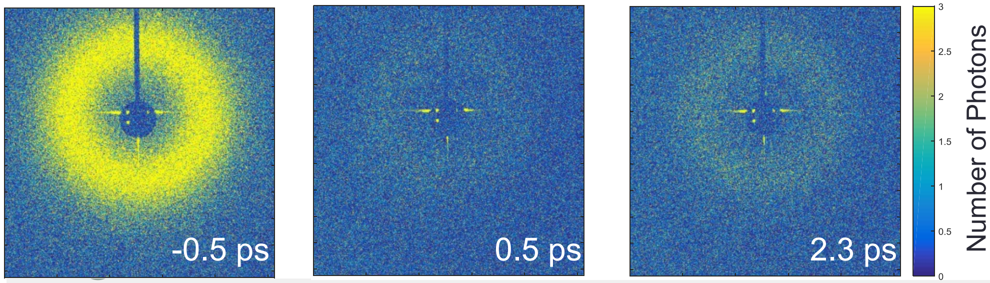


- THz radiation produced from same electron bunch as XUV by a separate electromagnetic undulator with 10 periods
  - ➢ Produces *10 full cycles of THz radiation*
- Intrinsic synchronization of XUV and THz pulse; jitter
  as low as 5 fs (rms)
  - ➢ Measurements under phase stable conditions
- THz frequencies from 1.5 – 30 THz



Femtomagnetism

> THz dynamics   What are we doing



- THz radiation (30 μm and longer) from FLASH demagnetizes a nanoscale magnetic domain systems.
- The demagnetization is accompanied by a shift in the $S(q)$ peak position of ~ 8%.
- In contrast to IR demagnetization, the dynamics of both seems to be different