Magnetic systems studied with linear and circular polarized FEL radiation

SPIE Conference 8778: Advances in X-ray Free-Electron Lasers II: Instrumentation

Session II: Scientific Applications and Their Instrumentation Requirements

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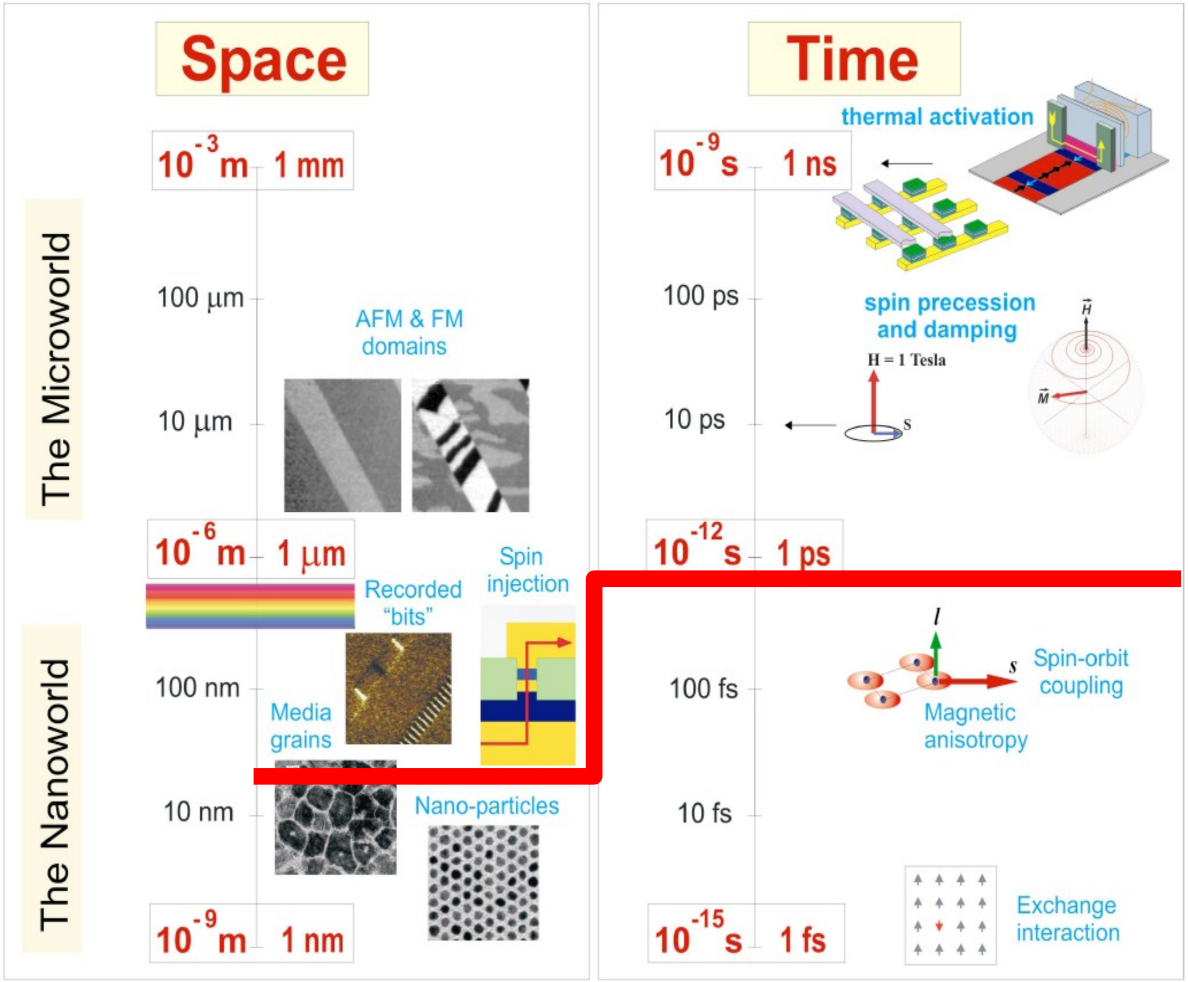
HELMHOLTZ ASSOCIATION

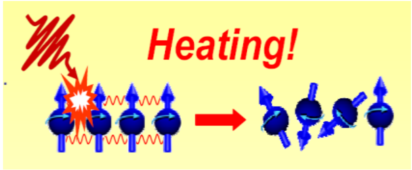
DESY

Outline

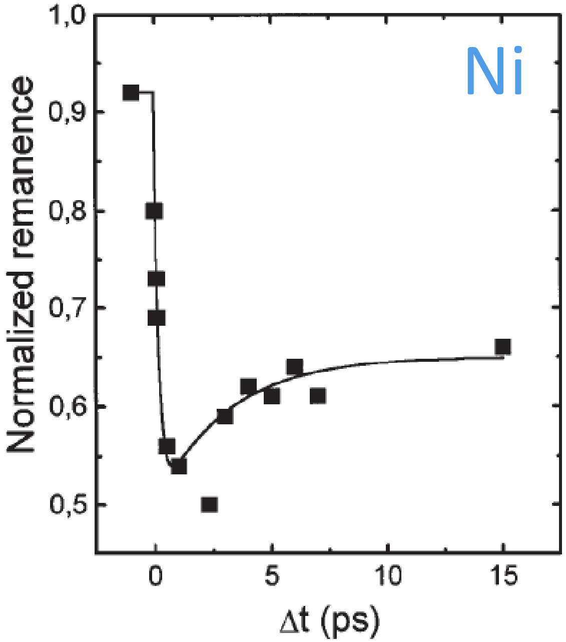
- Addressing ultra-fast dynamics in magnetic materials
- Probing magnetic multi-domain systems at FLASH
- Resonant magnetic imaging at FERMI@Elettra
- XMCD quenching with high fluence FEL shots
- Summary and Outlook

Addressing ultra-fast dynamics in magnetic materials





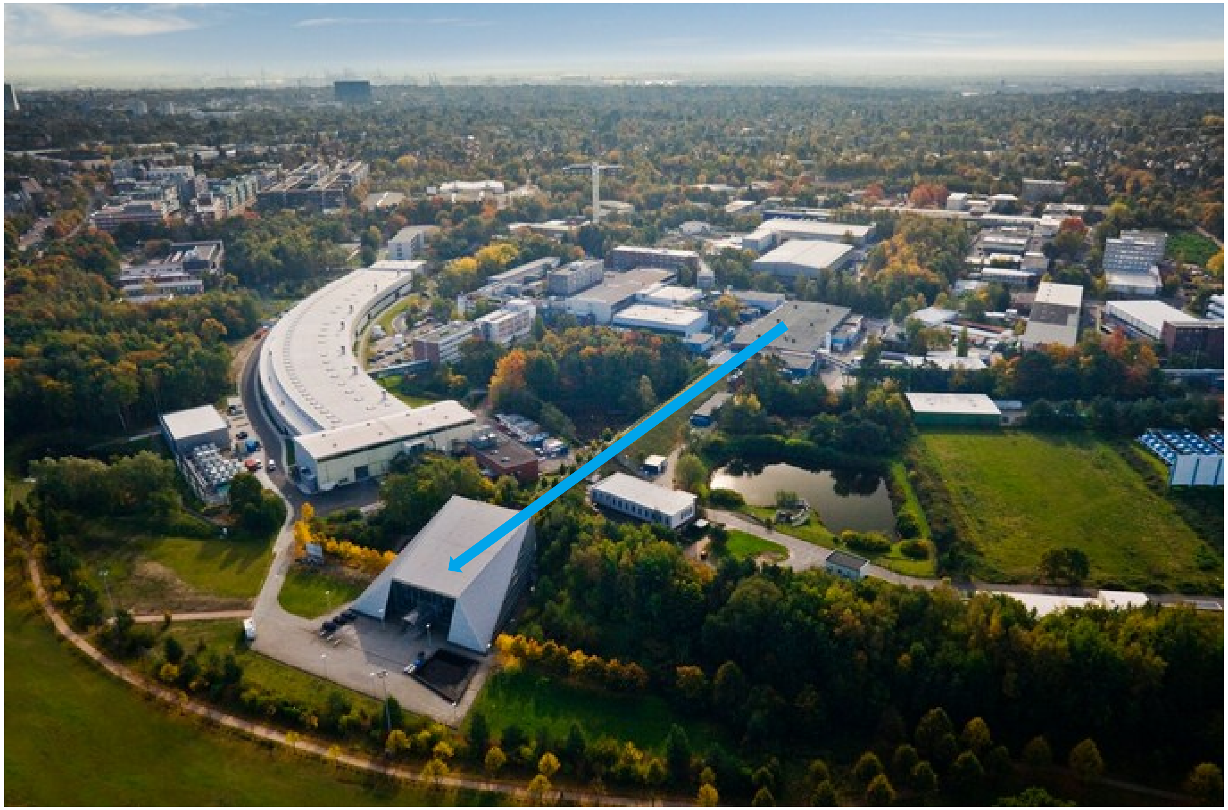
Thin Ni film in single-domain state



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

FELs allow to study magnetic materials on a sub-ps time and nanometer length scale at the same time.

Resonant magnetic scattering with linear polarized XUV pulses from FLASH

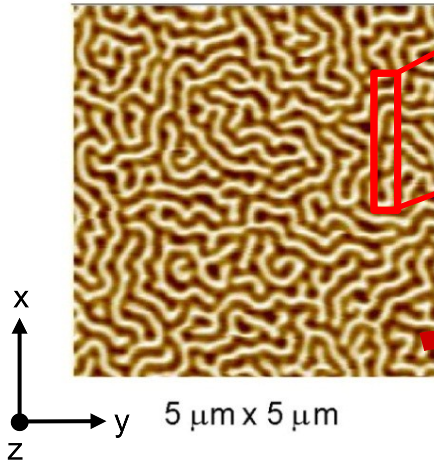


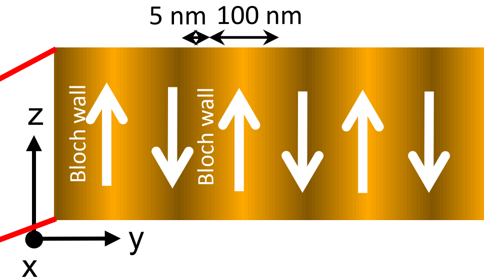
Probing magnetic systems with linear polarized pulses at FLASH

Sample system

Pt(5)/**[Co(0.8)/Pt(1.4)]**$_{16}$/Pt(6) on Si_3N_4(50) (nm)

Co/Pt multilayer which exhibits a worm domain like structure with magnetic out-of-plane anisotropy
(maze domain phase)

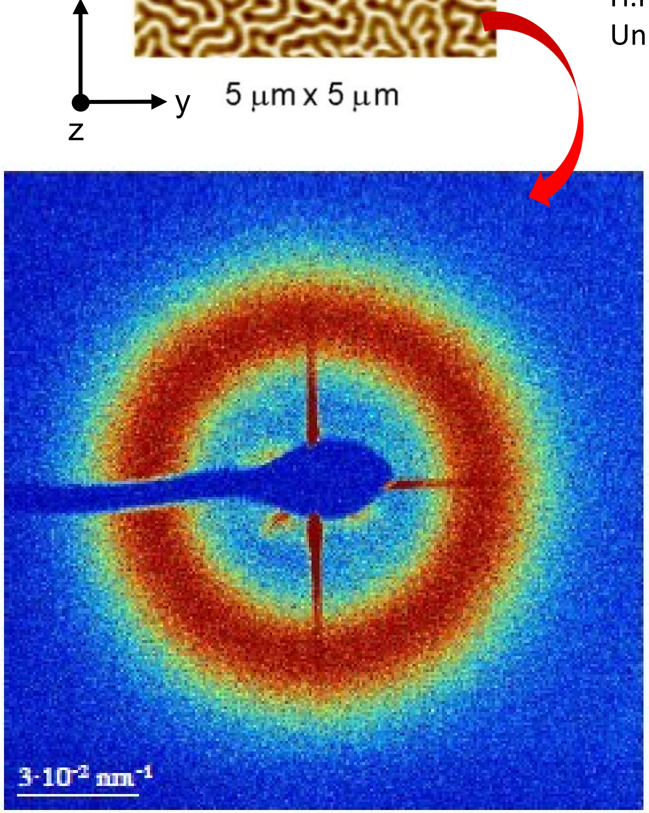




Samples made by the group of H.P. Oepen at the University of Hamburg

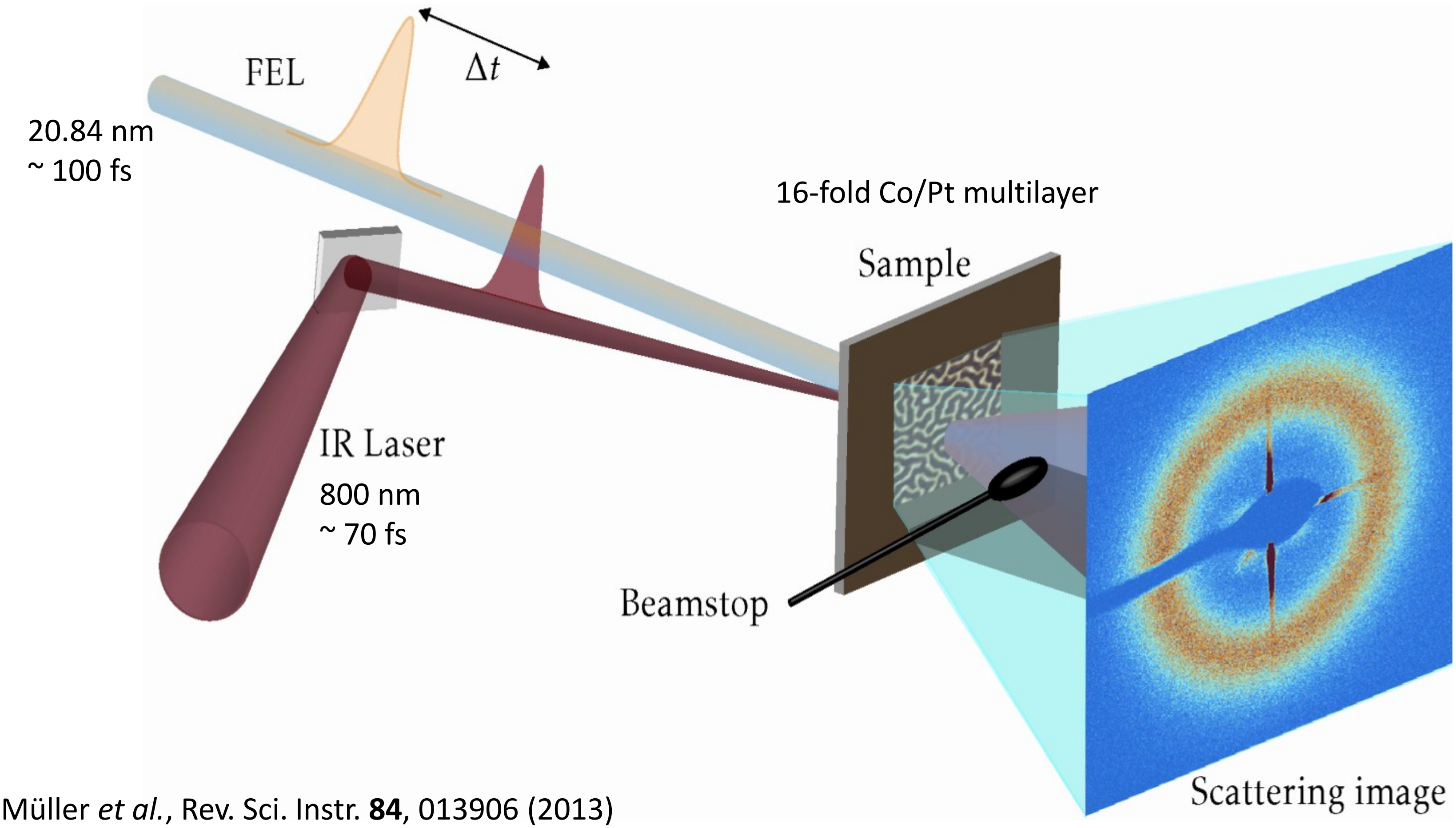
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Magnetic scattering in SAXS geometry



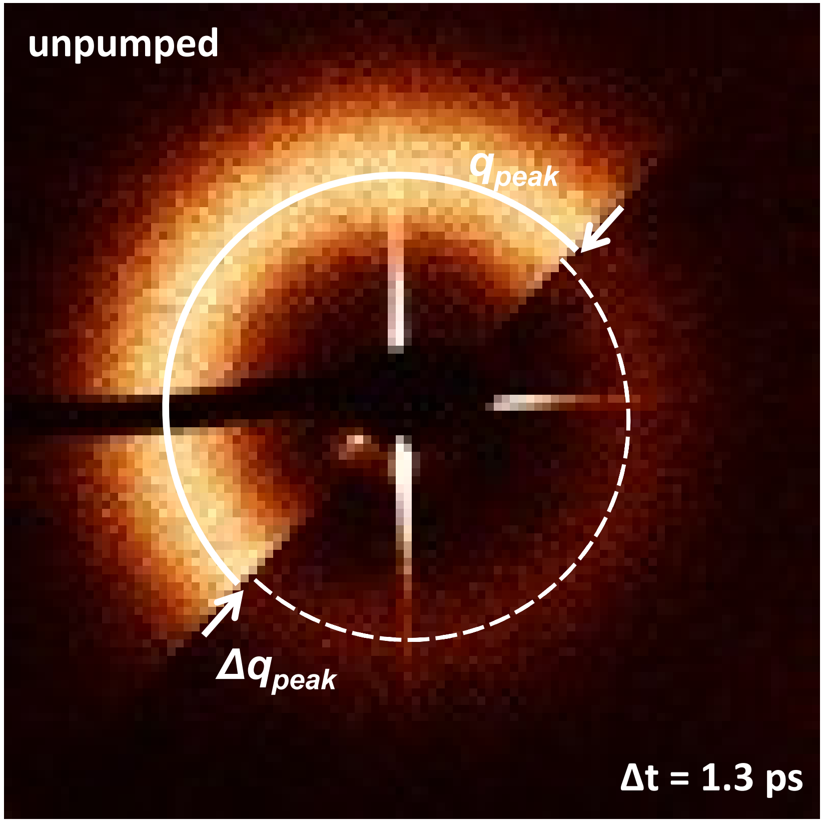
Photon energy tuned to Co M_3-resonance at 59.6 eV (20.8 nm)

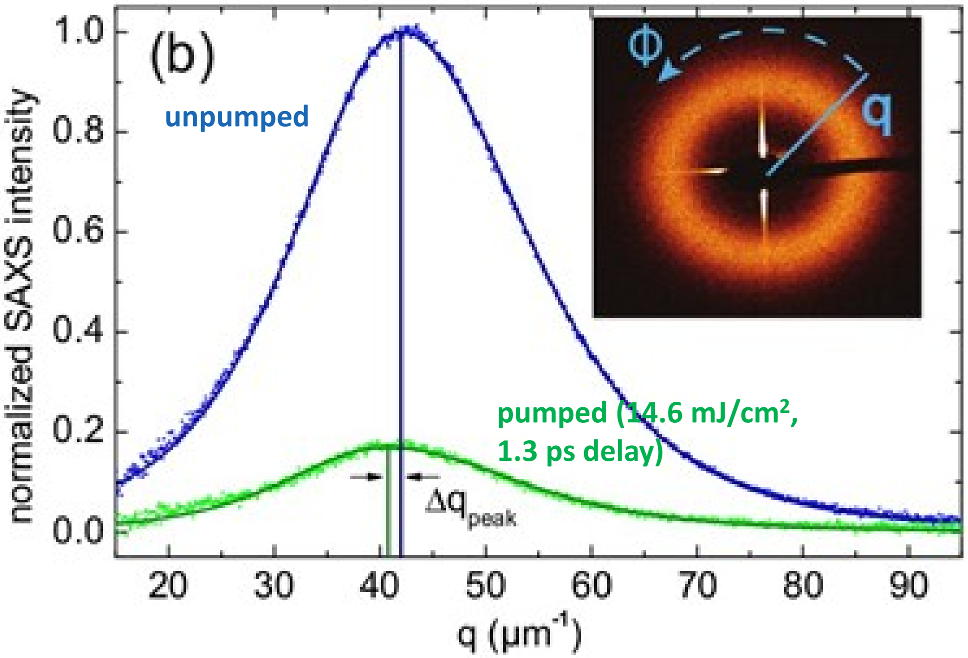
Pump–probe setup at FEL sources



L. Müller *et al.*, Rev. Sci. Instr. **84**, 013906 (2013)

Ultrafast demagnetization with linear polarized light at FLASH

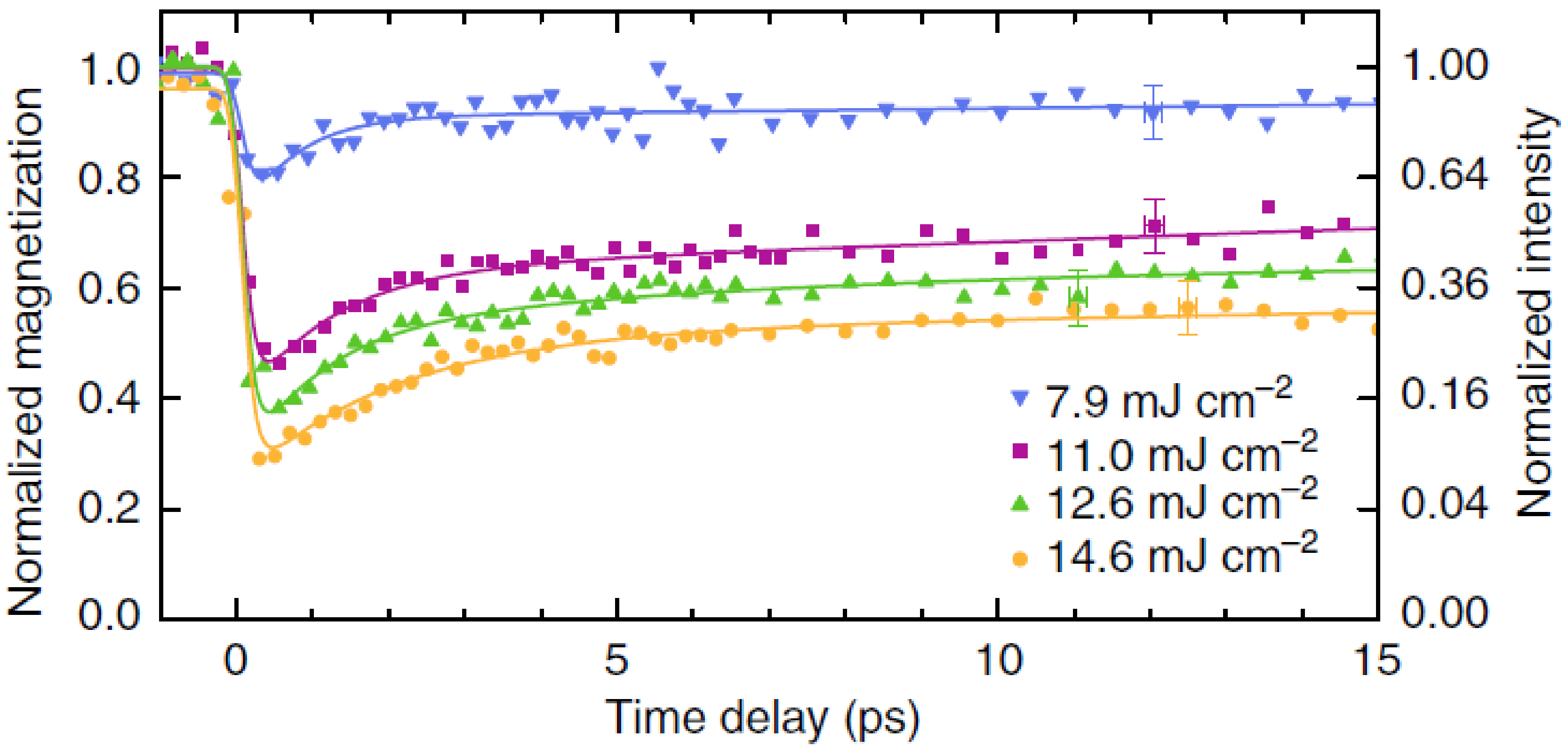




B. Pfau *et al. Nat. Commun.* **3**:1100 (2012)

→ IR pump – XUV probe experiment yields temporal AND spatial response of the magnetic system

Ultrafast demagnetization from SAXS data

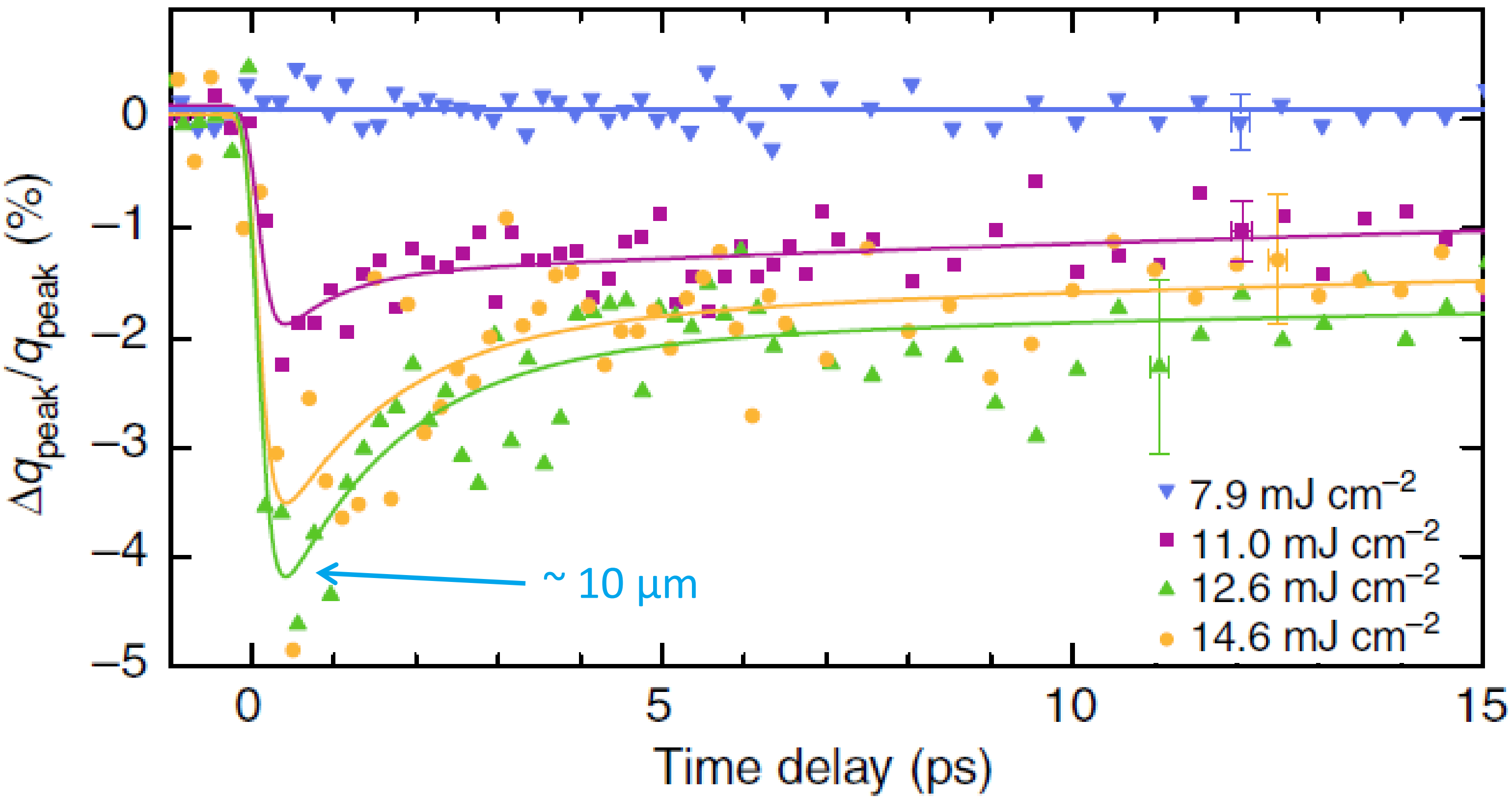


$\Delta t_{demagn} \leq 240$ fs

→ This is the first ultrafast demagnetization measurement at an FEL source.

Ultrafast spatial response of S(q)

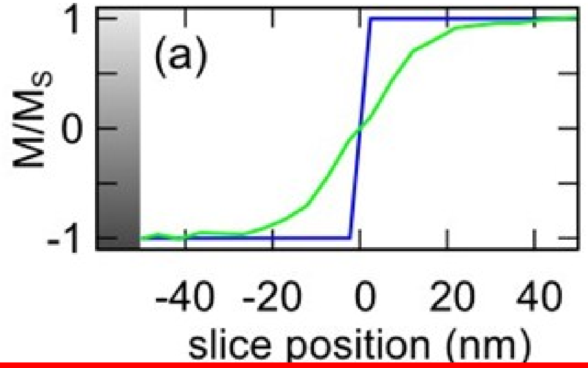
$\Delta t_{demagn} \leq 240$ fs

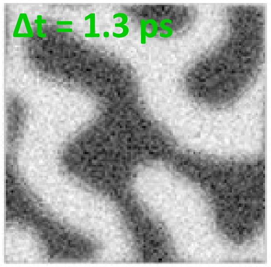


An ultrafast demagnetization constant of 0.5 ps implies domain-wall speeds up to 10^7 m/s

What causes the ultrafast spatial change in S(q)?

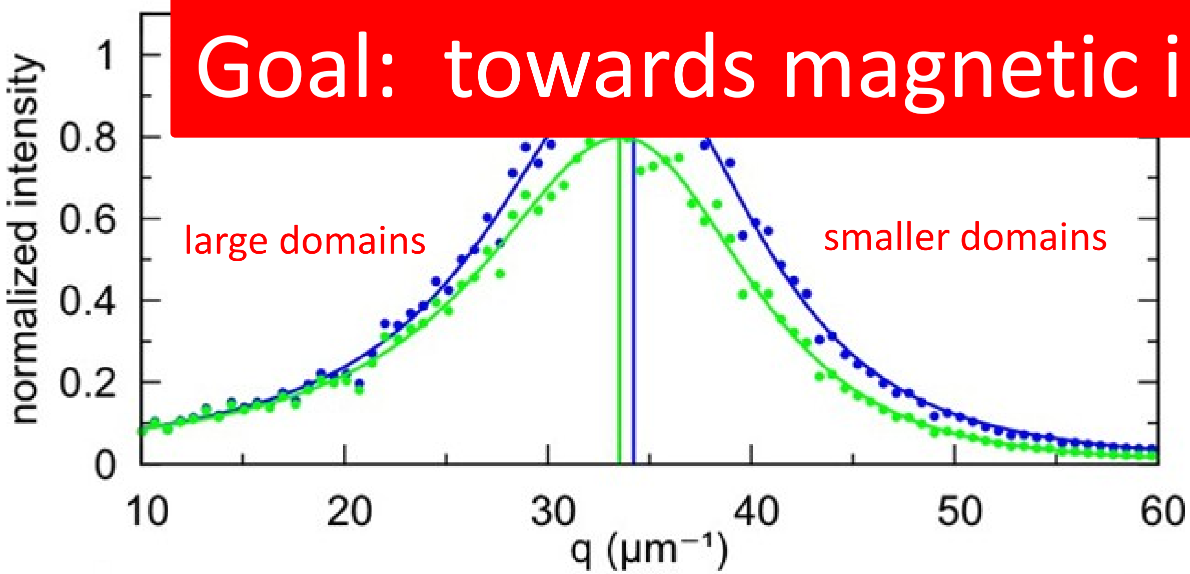
Spin polarized electrons blur magnetic domain structure





Why does a blurring of domain walls shift the peak?

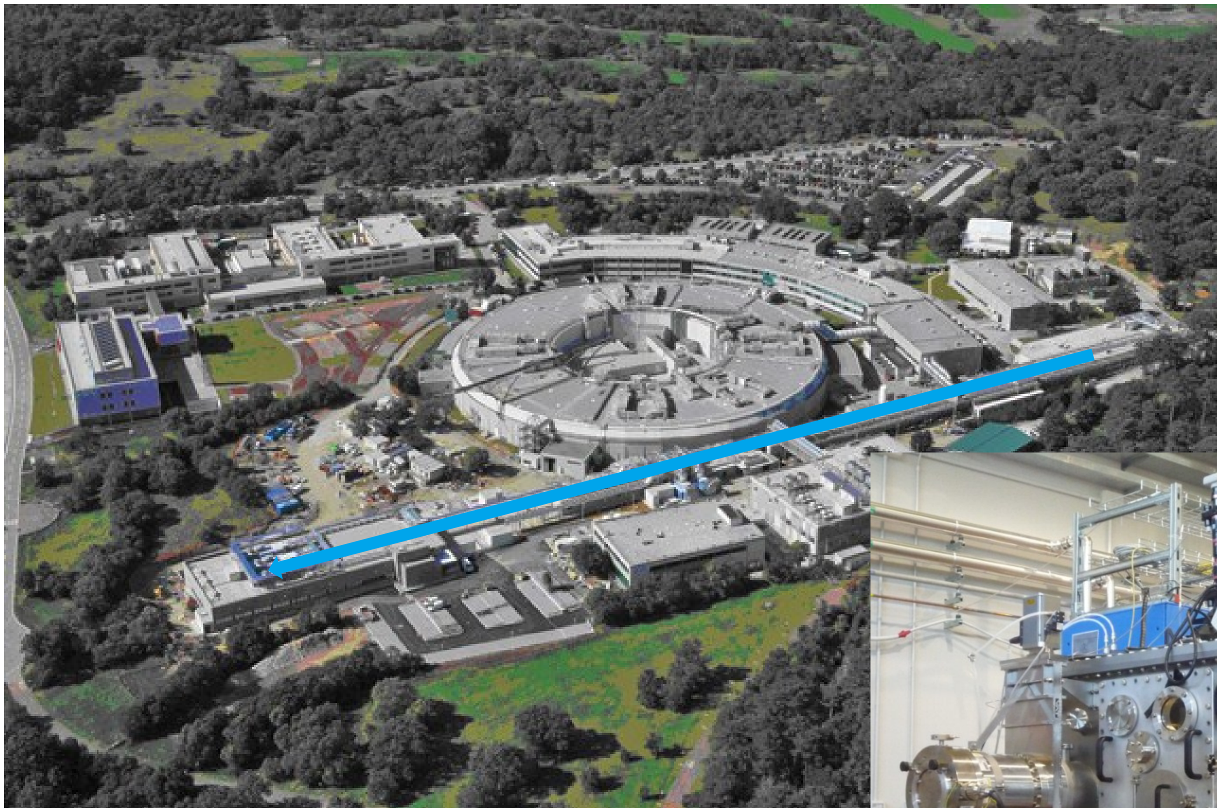
Goal: towards magnetic imaging



...n size distribution: smaller domains are affected stronger. As a result high *q* scattering intensity drops faster

Superdiffusive transport of optically excited spin-polarized electrons explains the peak shift on an ultrafast time scale.

FERMI@Elettra: Resonant magnetic FTH imaging at the DiProI beamline



DiProI

F. Capotondi
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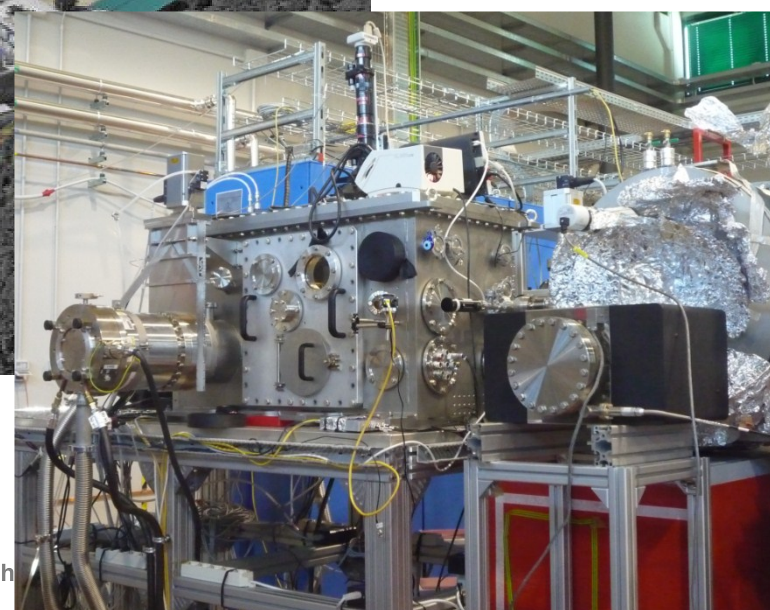
M. Kiskinova

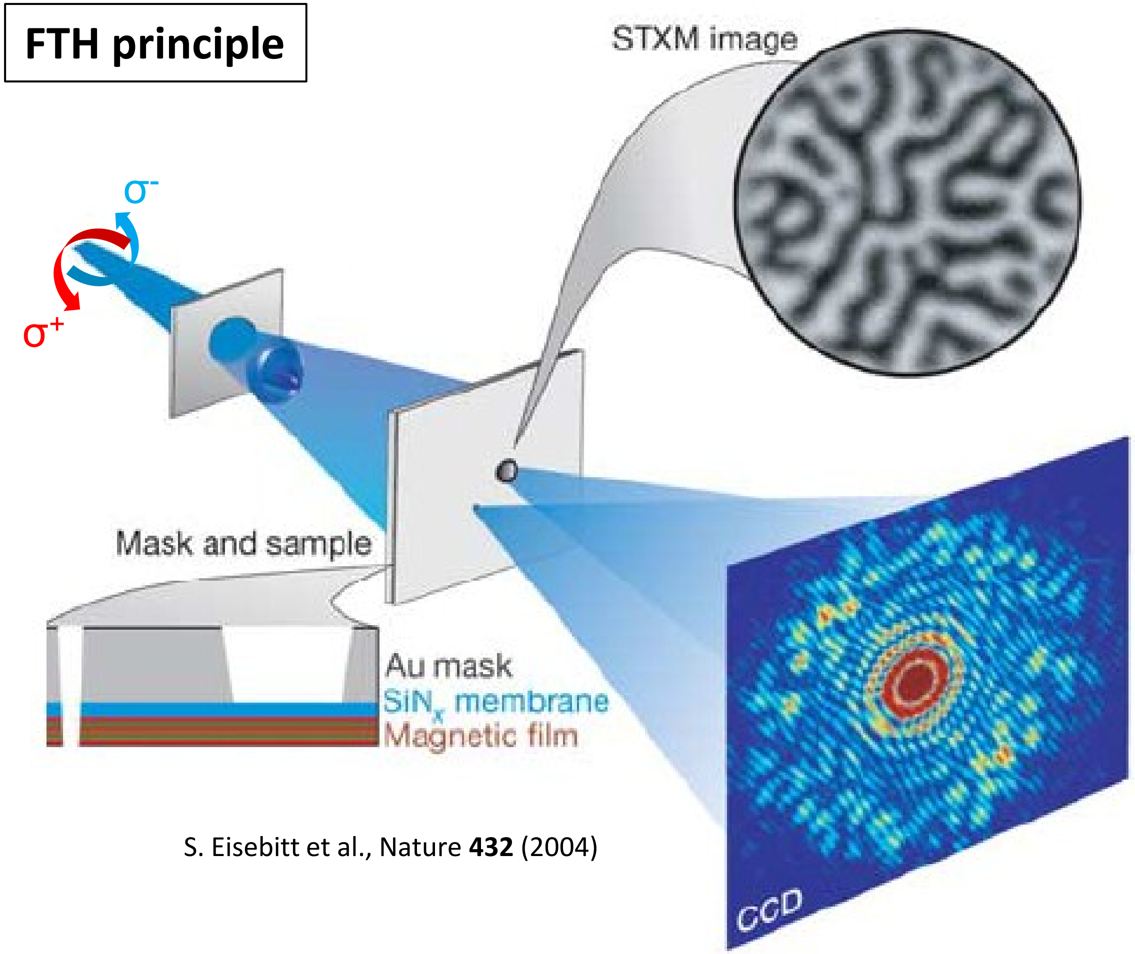


Magnetic imaging via Fourier transform holography (FTH) (I)

Magnetic FTH needs circular polarized photons

- thin film polarizer, afterburner or **Apple undulator**

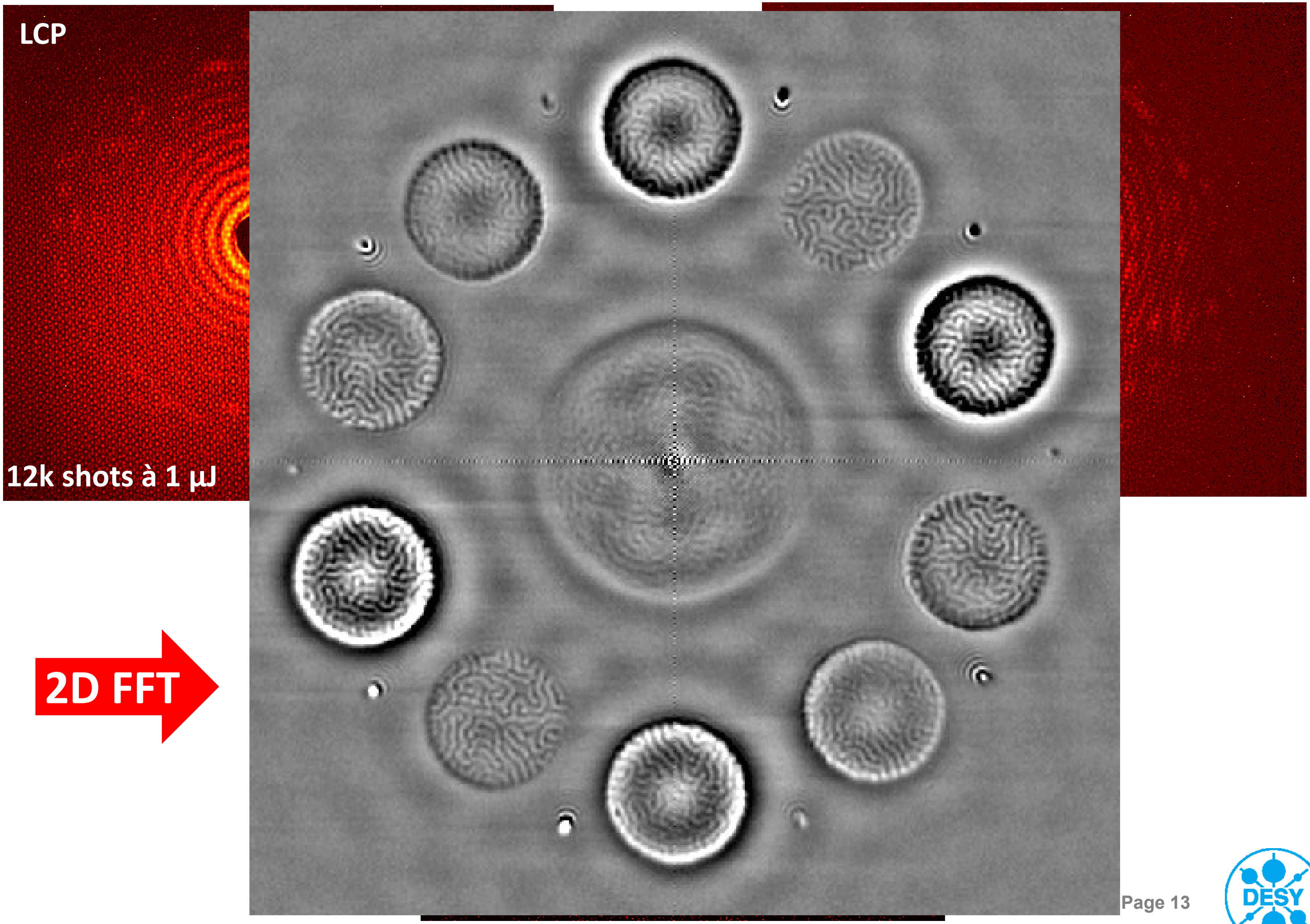
FTH principle



S. Eisebitt et al., Nature **432** (2004)

- Magnetic speckles
- Noise-resistant
- Contrast vs. resolution
- Signal: charge + magnetic

Magnetic imaging via Fourier transform holography (FTH) (II)

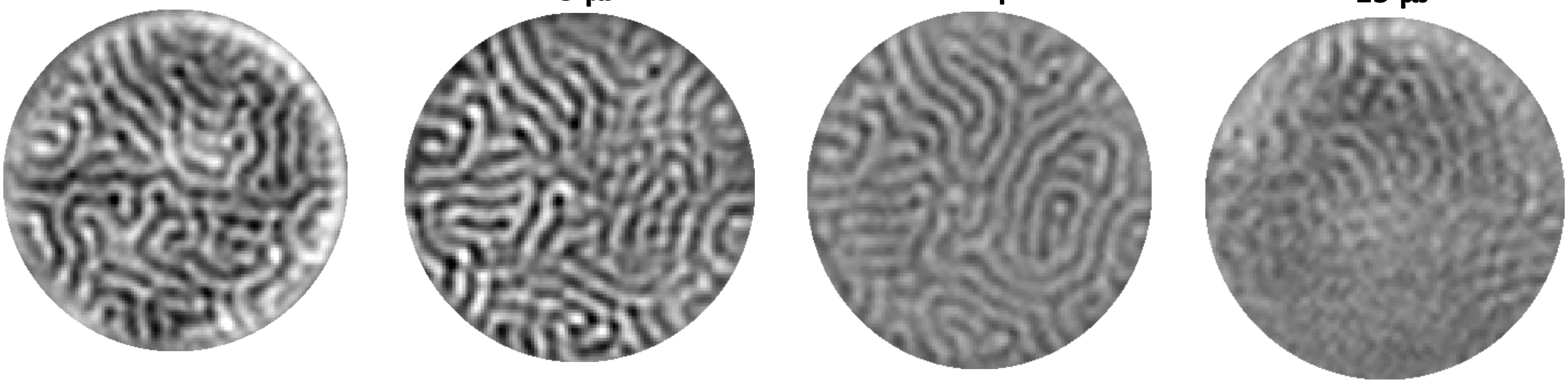


Stroboscopic FEL multi-shot IR-pump—XUV-probe imaging

Use FERMIs **seed laser** as a pump source

- → ~ 1 μJ FEL (0.91 mJ/cm^2)
- → time delay between pump and probe: Δt = 1 ps
- → multi-shot exposure (10x600 pulses / hologram)

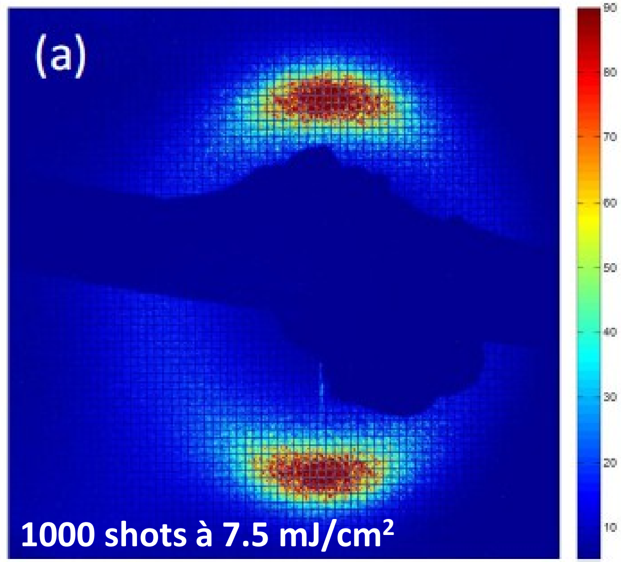
no IR pump | **5 μJ** | **10 μJ** | **15 μJ**

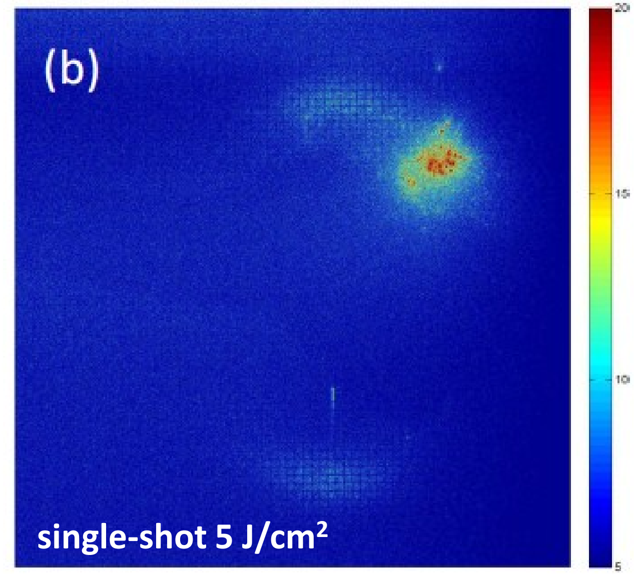


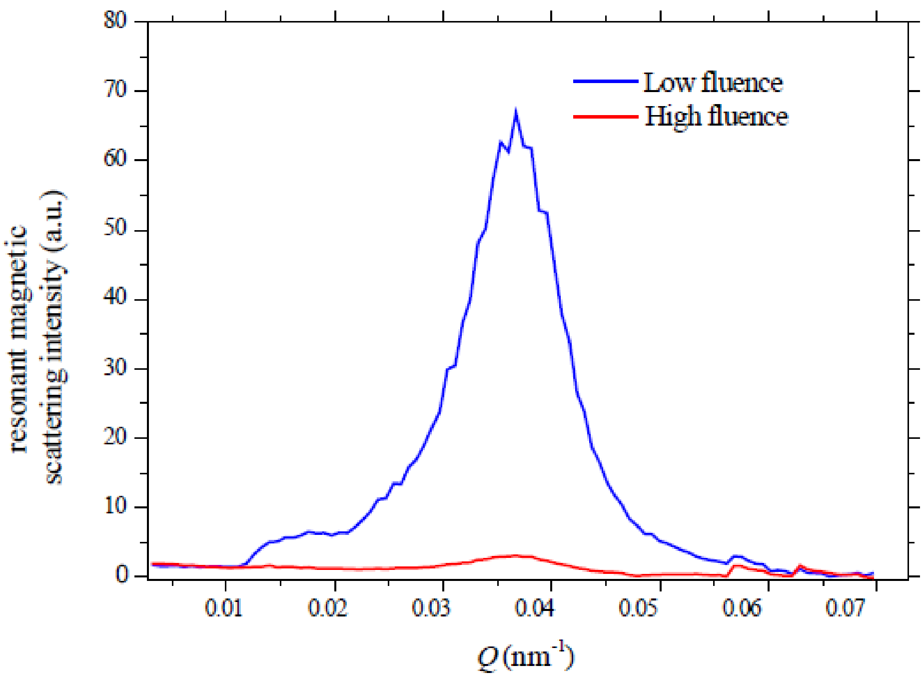
XMCD quenching with high fluence FEL shots (I)

5x5 µm²

- 16-fold Co/Pt multilayer
- stripe-domain phase
- Co M_3-edge at 59.6 eV (20.8 nm)
- linear polarization





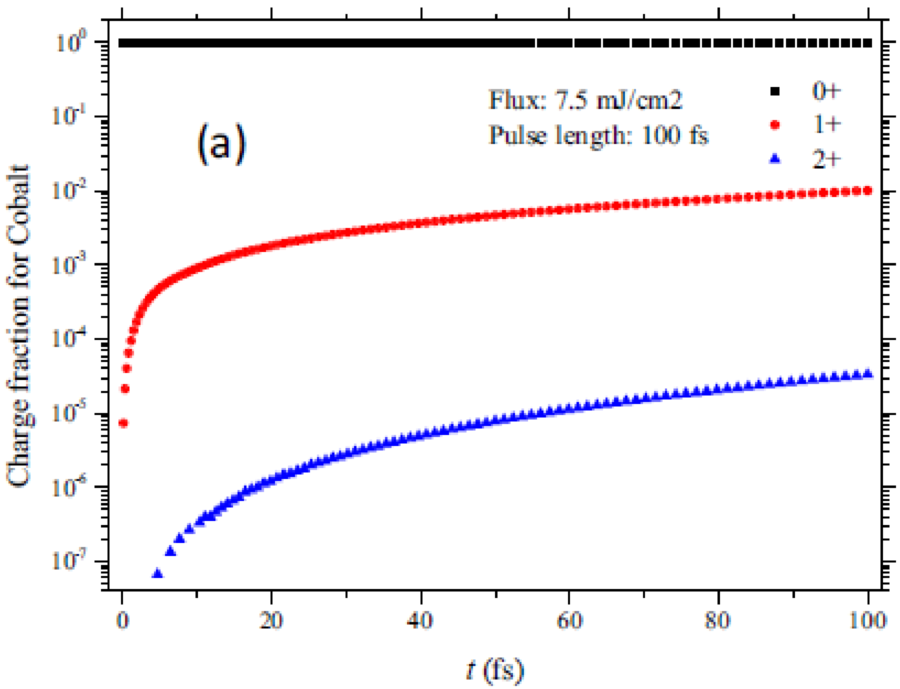


High fluence pulses are breaking down the X-ray magnetic scattering signal

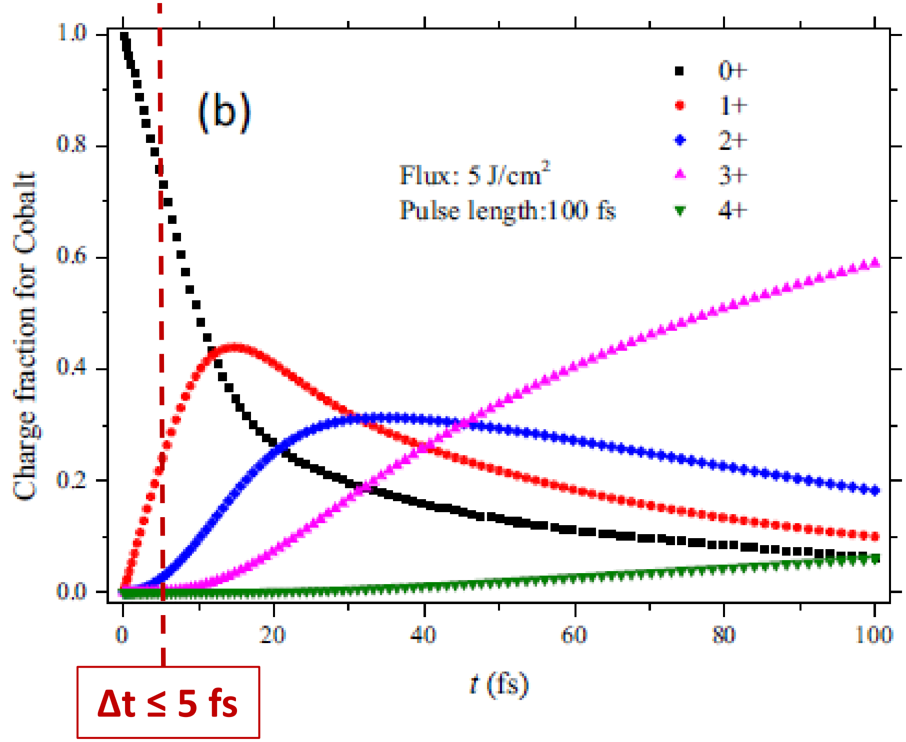
Why?

XMCD quenching with high fluence FEL shots (II)

<u>Low fluence case</u> (= as-prepared state)



<u>High fluence case</u> (strongly pertubed state)



→ Single-shot magnetic scattering and imaging at Co M_3-edge with high fluence FEL shots is hindered due to an ionization caused shift of the absorption edge

→ Extremely short pulses (≤ 5 fs) would improve the situation

L. Mueller *et al.*, Breakdown of the X-ray resonant magnetic scattering signal during intense pulses of XUV FEL radiation, PRL, under review

Summary

- Probing ultrafast demagnetization processes with laterally structured magnetic multilayers is possible on a sub-ps time and on a nanometer length scale as demonstrated at FLASH.
- Ultrafast spatial response was observed for the first time at FLASH. Spatial changes of the magnetic system were also recently imaged via FTH at FERMI.
- Stroboscopic magnetic imaging at Co *M*-edge is limited by both, photoionization induced XMCD quenching and high substrate absorption.

Outlook

- Further pump—probe imaging experiments at the *L*-edge at LCLS and FERMI.
- Applying magnetic CDI/phase retrieval + Gabor transforms at FEL sources.
- Employing FEL two-color split-pulse techniques at FERMI.

Thank you very much for your attention!

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FERMI @elettra

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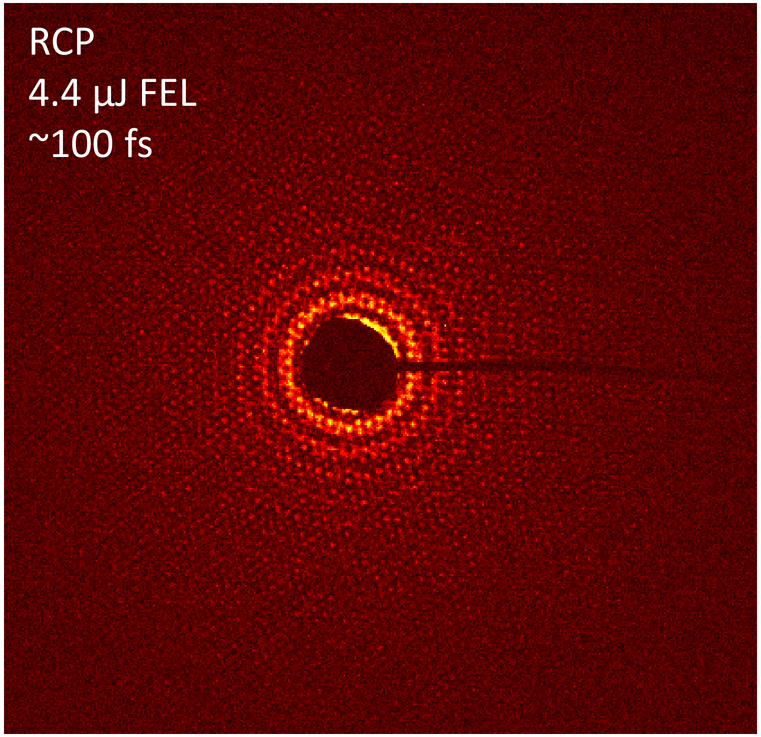
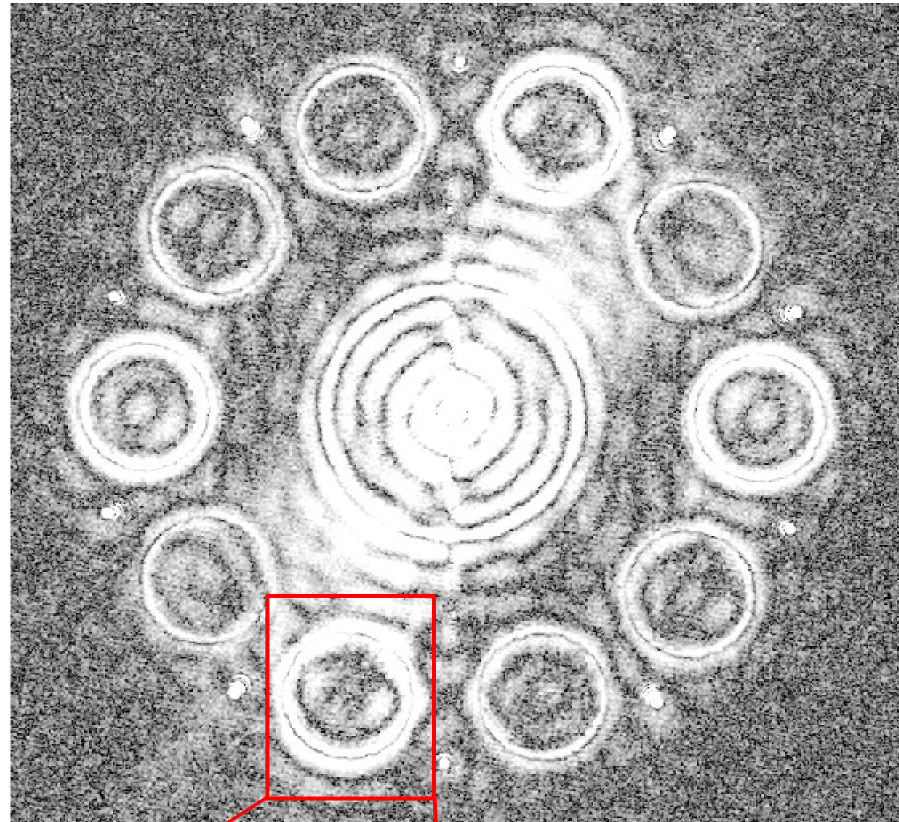
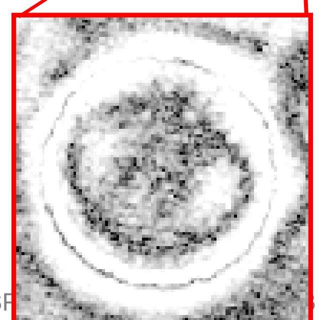
SFB 925: Light induced dynamics and control of strongly correlated quantum systems

Supplemental material

Single-shot FTH imaging at Co *M*-resonance?







Single-shot magnetic imaging limited due

- to high substrate absorption
- to XMCD quenching

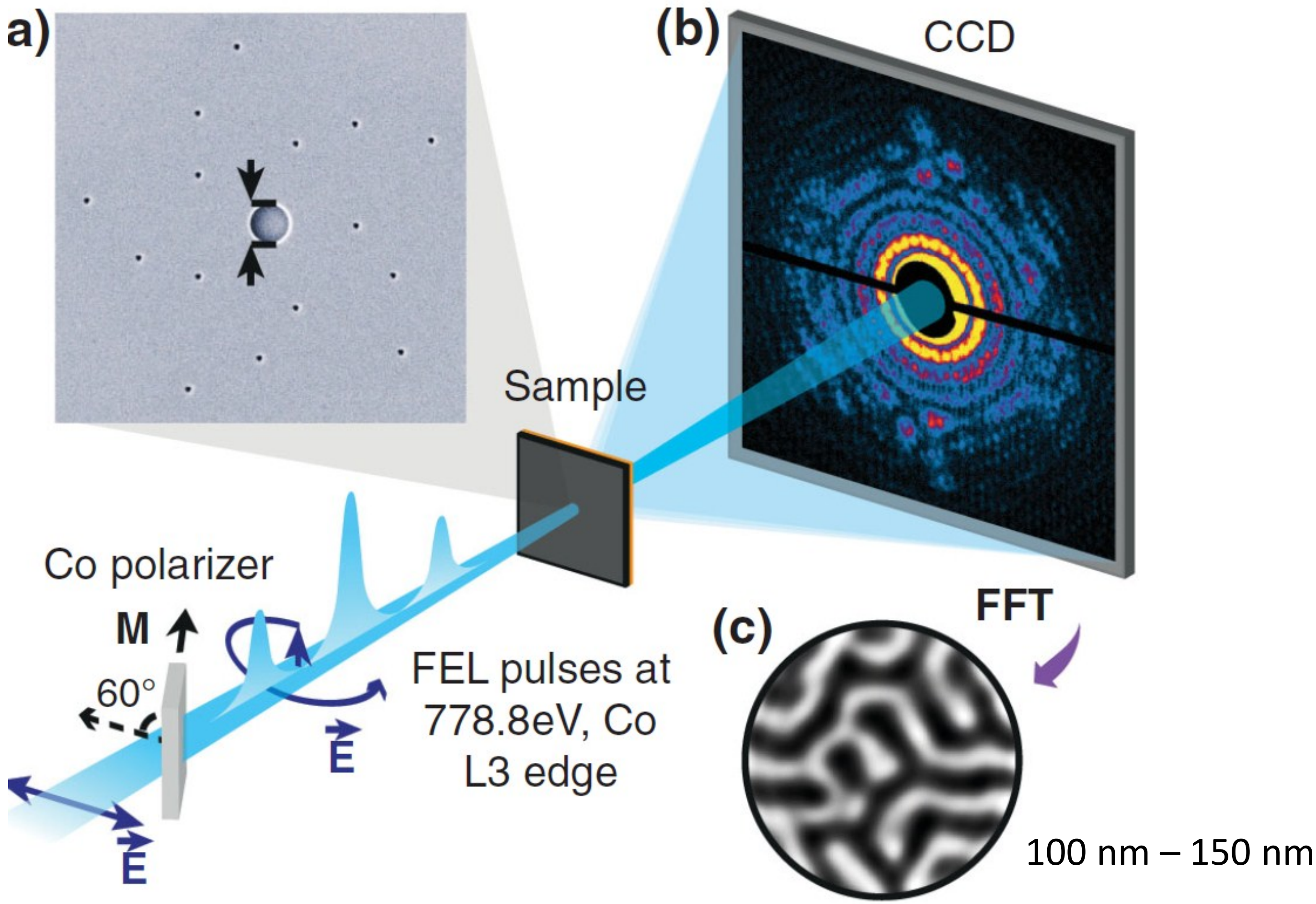
Magnetic contrast very weak but slightly visible

How high resolution single-shot magnetic imaging can work out: measuring at the Co *L* resonance

Single-shot FTH magnetic X-ray imaging at LCLS

Measuring @ Co L_3-edge leads to lower substrate absorption and thus enables high contrast single-shot imaging

- 58% CP FEL pulses
- Δt_{pulse} ~ 100 fs
- < 2 mJ/cm²



T. Wang et al., PRL **108**, 267403 (2012)

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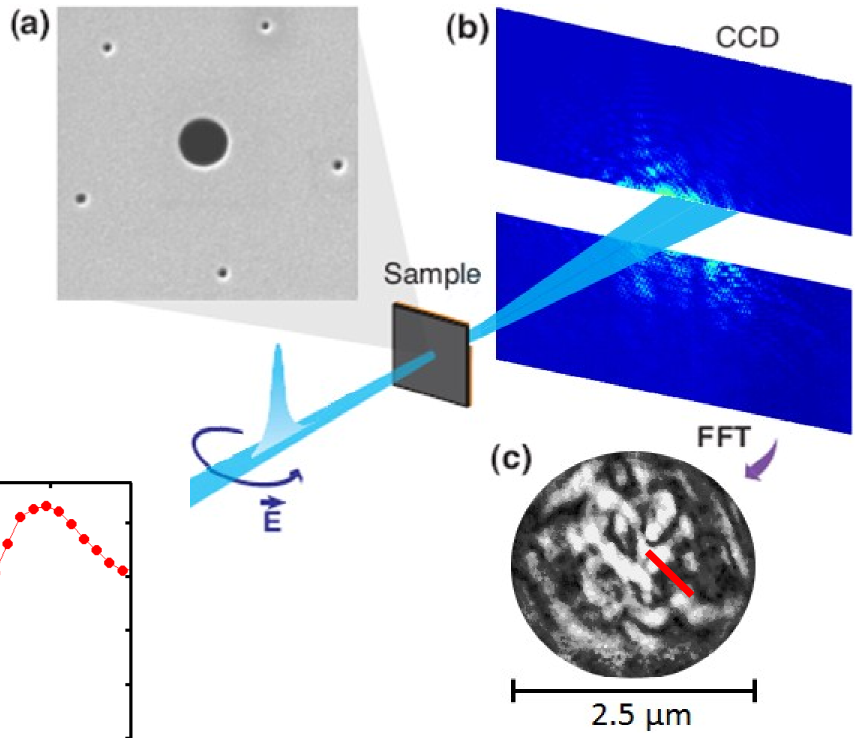
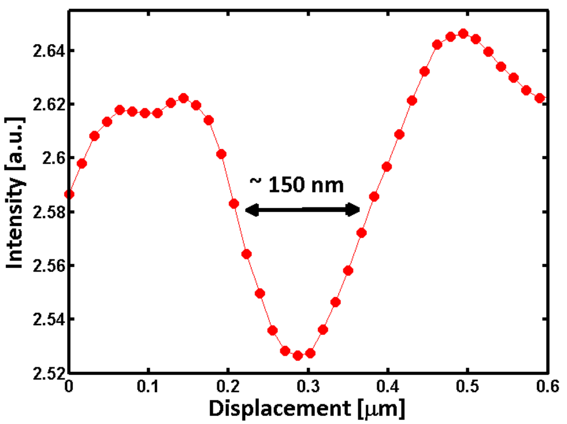
Magnetic imaging: Fourier transform holography

Apple II undulator
deliver linear and circular
polarized pulses, hence
enabling magnetic FTH
imaging without using
a soft X-ray polarizer



F. Capotondi *et al.*, Rev. Sci. Instr., submitted

- seede FEL
- FEL-1 [20 nm – 100 nm] at Co M_3 resonance (20.8 nm)
- Δt_{pulse} ~ 80-100 fs
- spot size ~ 50x50 µm^2
- fluence ~ 30 mJ/cm^2
- stripe-domain phase



→ High pulse intensities destroy ferromagnetic order
→ Photoionization of weakly bound 3d and 4s electrons increases the binding energy of 3p electrons
→ Substrate absorption at 20.8 nm

} shorter pulses!