Methoden moderner Röntgenphysik II: Streuung und Abbildung

Lecture 13	Vorlesung zum Haupt- oder Masterstudiengang Physik, SoSe 2017 G. Grübel, A. Philippi-Kobs, O. Seeck, T. Schneider, L. Frenzel, M. Martins, W. Wurth		
Location	Lecture hall AP, Physics, Jungiusstraße		
Date	Tuesday	12:30 - 14:00	(starting 4.4.)
	Thursday	8:30 - 10:00	(until 13.7.)

DESY

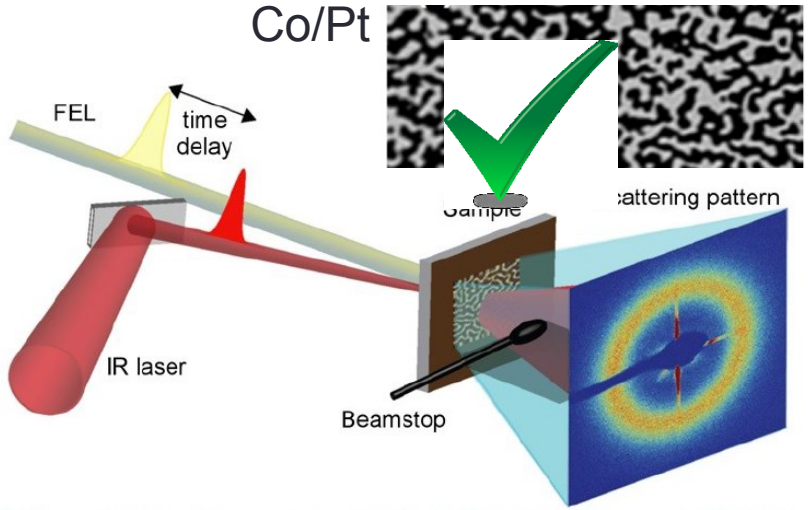
Part II

Magnetism – Magnetic Thin Films

by André Philippi-Kobs (AP)

[23.5.] Magnetic small angle scattering of magnetic domain pat

- Introduction of magnetism in thin films
- Resonant scattering & X-ray magnetic circular dichroism



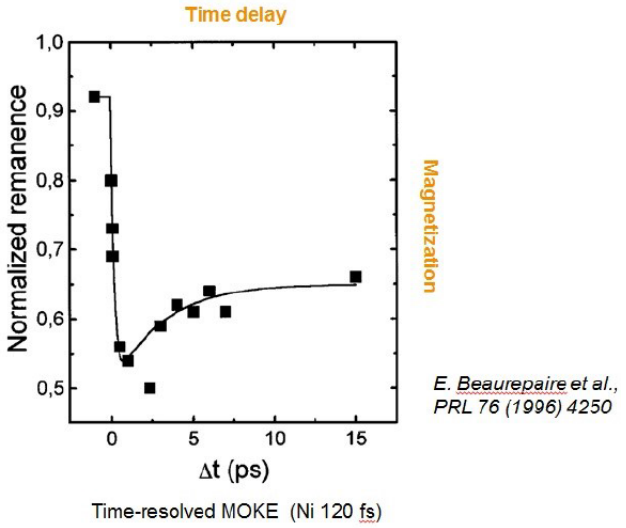
B. Pfau et al., Nature Communications, Vol. 3, 11; DOI:doi:10.1038/ncomms2108 (2012)
L.Müller et al., Rev. Sci. Instrum. 84, 013906 (2013)

[30.5.] Imaging of magnetic domains

- Fourier transform holography (FTH)
- Scanning transmission X-ray microscopy (STXM)
- Coherent diffraction imaging (CDI), Ptychography

[1.6.] Femtomagnetism

- Introduction of ultrafast magnetization dynamics
- Pump-probe experiments of nano-scale magnetic domain patterns



E. Beaurepaire et al., PRL 76 (1996) 4250

[13.6.] Related aspects

- Determination of coherence via magnetic domain patterns
- Magnetic XRD of antiferromagnets and chiral systems
- Further electronic inhomogeneities probed by X-rays (charge density wave; Abrikosov vortices in superconductors)

DESY

Resonant magnetic small angle X-ray scattering (mSAXS) of magnetic domain patterns

1.) Ferromagnetism in a nutshell

- forms of magnetic phenomena
- contributions to free energy
- focus on systems with perpendicular magnetic anisotropy (Co/Pt multilayers)
- magnetic domains and domain walls

2.) Interaction of **polarized** photons with matter

- Recap: Charge and **Spin** X-ray Scattering by a single electron
- Recap classical concept of Absorption & Resonant Scattering (forced oscillator)
- Absorption and Resonant Scattering (QM concept, Fermi's Golden rule)
- Interactions of photons with ferromagnetic materials ➔ XMCD effect

(- XMLinearD and X-ray Natural Dichroism)

3.) Resonant magnetic SAXS of magnetic domain patterns

Interaction of **polarized** photons with matter

- From Absorption to Resonant Scattering (exp. approach):

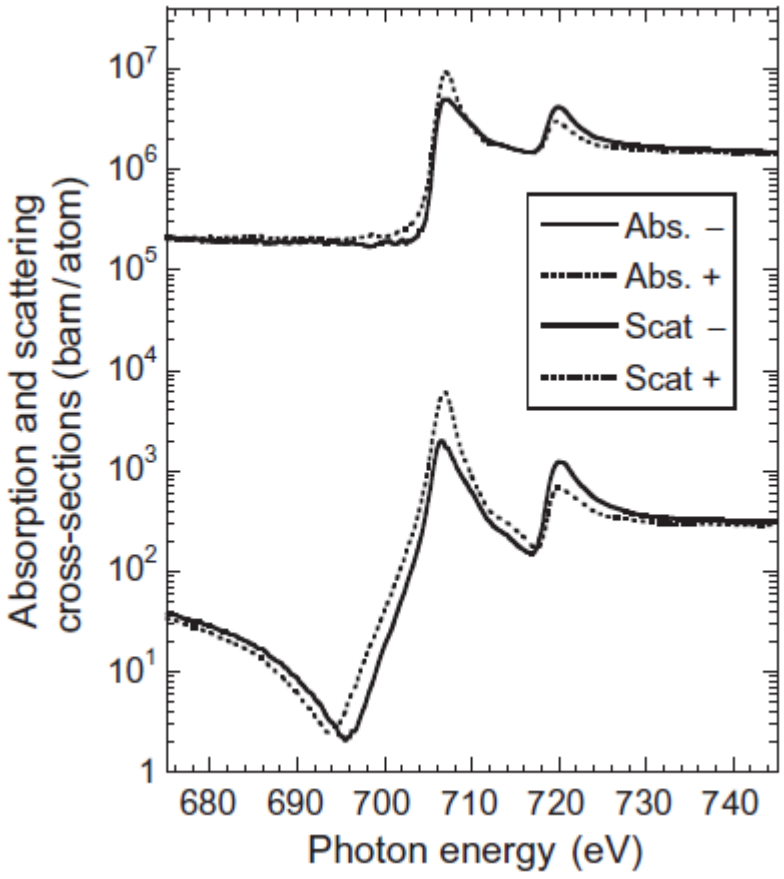
$$f'' = -(k/4\pi)\,\sigma_a(E)$$

Measure absorption cross-section for both helicities

↓ Kramers-Kronig relation

↓ f'

$$\sigma_{\text{scattering}} = f^2 = [Z + f'(\omega, \boldsymbol{\varepsilon})]^2 + [f''(\omega, \boldsymbol{\varepsilon})]^2$$



Interaction of **polarized** photons with matter

- Resonant scattering (qm concept): 2. Term of Fermi's Golden rule in dipole approx.

$$T_{if} = \frac{2\pi}{\hbar}\left|\langle f|\mathcal{H}_{\rm int}|i\rangle + \sum_n \frac{\langle f|\mathcal{H}_{\rm int}|n\rangle\langle n|\mathcal{H}_{\rm int}|i\rangle}{\varepsilon_i - \varepsilon_n}\right|^2 \delta(\varepsilon_i - \varepsilon_f)\rho(\varepsilon_f) \qquad \sigma = \frac{T_{if}}{\Phi_0}$$

↓ Dipol approximation etc. (as done for absorption term)

$$\frac{\hbar^2\omega^4}{c^2}\,\alpha_{\rm f}^2\left|\sum_n \frac{\langle a|\boldsymbol{r}\cdot\boldsymbol{\epsilon}_2^*|n\rangle\langle n|\boldsymbol{r}\cdot\boldsymbol{\epsilon}_1|a\rangle}{(\hbar\omega - E_R^n) + {\rm i}(\Delta_n/2)}\right|^2$$

Δ_n: line width

↓ J. P. Hannon et al., Phys. Rev. Lett **61**, 1245 (1988)

$$\begin{aligned}\langle a|\boldsymbol{r}\cdot\boldsymbol{\epsilon}_2^*|n\rangle\langle n|\boldsymbol{r}\cdot\boldsymbol{\epsilon}_1|a\rangle = \frac{\mathcal{R}^2}{2}\Big[&(\boldsymbol{\epsilon}_2^*\cdot\boldsymbol{\epsilon}_1)\left\{|C_{+1}|^2 + |C_{-1}|^2\right\}\\ &+ {\rm i}(\boldsymbol{\epsilon}_2^*\times\boldsymbol{\epsilon}_1)\cdot\hat{\boldsymbol{m}}\left\{|C_{-1}|^2 - |C_{+1}|^2\right\}\\ &+ (\boldsymbol{\epsilon}_2^*\cdot\hat{\boldsymbol{m}})(\boldsymbol{\epsilon}_1\cdot\hat{\boldsymbol{m}})\left\{2|C_0|^2 - |C_{-1}|^2 - |C_{+1}|^2\right\}\Big]\end{aligned}$$

Interaction of **polarized** photons with matter

- Resonant scattering: 2. Term of Fermi's Golden rule in dipole approximation

$$T_{if} = \frac{2\pi}{\hbar}\left|\langle f|\mathcal{H}_{\rm int}|i\rangle + \sum_n \frac{\langle f|\mathcal{H}_{\rm int}|n\rangle\langle n|\mathcal{H}_{\rm int}|i\rangle}{\varepsilon_i - \varepsilon_n}\right|^2 \delta(\varepsilon_i - \varepsilon_f)\rho(\varepsilon_f)$$

with $\sigma = \frac{T_{if}}{\Phi_0}$ and $\sigma_{\rm scattering} = f^2$

➔ The *elastic resonant magnetic scattering factor* in units [number of electrons] is given by

$$f(\omega,\boldsymbol{\varepsilon}_1) = \frac{\hbar\omega^2\alpha_f\mathcal{R}^2}{2cr_0}\left[\underbrace{(\boldsymbol{\epsilon}_2^*\cdot\boldsymbol{\epsilon}_1)\,G_0}_{\text{charge}} + \underbrace{\mathrm{i}(\boldsymbol{\epsilon}_2^*\times\boldsymbol{\epsilon}_1)\cdot\hat{\boldsymbol{m}}\,G_1}_{\text{XMCD}} + \underbrace{(\boldsymbol{\epsilon}_2^*\cdot\hat{\boldsymbol{m}})(\boldsymbol{\epsilon}_1\cdot\hat{\boldsymbol{m}})\,G_2}_{\text{XMLD}}\right]$$

$$G_1 = \sum_n \frac{|\langle a|C_{-1}^{(1)}|n\rangle|^2 - |\langle a|C_{+1}^{(1)}|n\rangle|^2}{(\hbar\omega - E_R^n) + \mathrm{i}(\Delta_n/2)}$$

For circularly polarized light

$$\mathrm{i}\left[(\boldsymbol{\epsilon}^{\pm})^*\times\boldsymbol{\epsilon}^{\pm}\right] = \mp\,\mathbf{e}_z$$

Charge: Natural linear dicroism
XMLD: X-ray magnetic linear dicroism

$$G_0 = \sum_n \frac{|\langle a|C_{+1}^{(1)}|n\rangle|^2 + |\langle a|C_{-1}^{(1)}|n\rangle|^2}{(\hbar\omega - E_R^n) + \mathrm{i}(\Delta_n/2)}$$

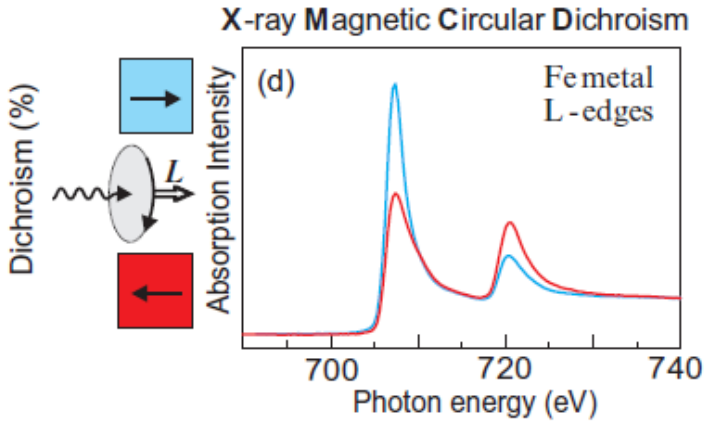
$$G_2 = \sum_n \frac{2|\langle a|C_0^{(1)}|n\rangle|^2 - |\langle a|C_{-1}^{(1)}|n\rangle|^2 - |\langle a|C_{+1}^{(1)}|n\rangle|^2}{(\hbar\omega - E_R^n) + \mathrm{i}(\Delta_n/2)}$$

Interaction of **polarized** photons with matter

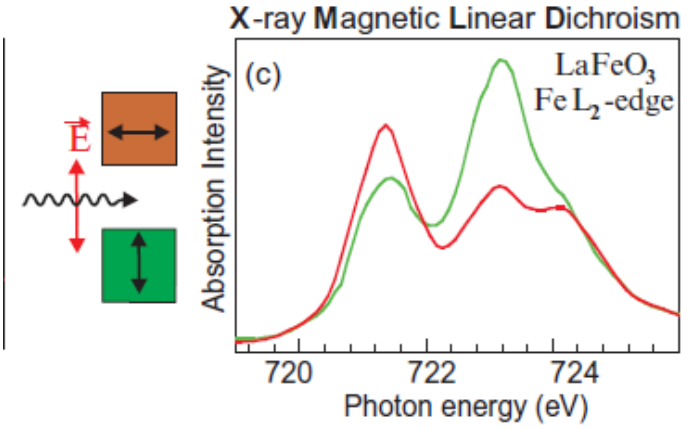
> XMCD and XMLD effect

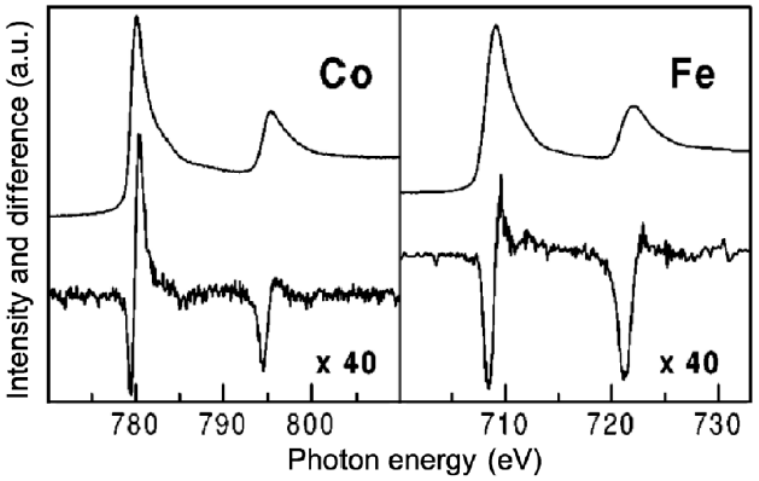
X-ray "magnetic" dichroism is due to spin alignment and the spin–orbit coupling.

– X-ray magnetic circular dichroism – XMCD – arises from *directional* spin alignment. The effect is parity even and time odd.

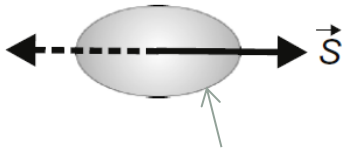


– X-ray magnetic linear dichroism – XMLD – arises from a charge anisotropy induced by *axial* spin alignment. The effect is parity even and time even.





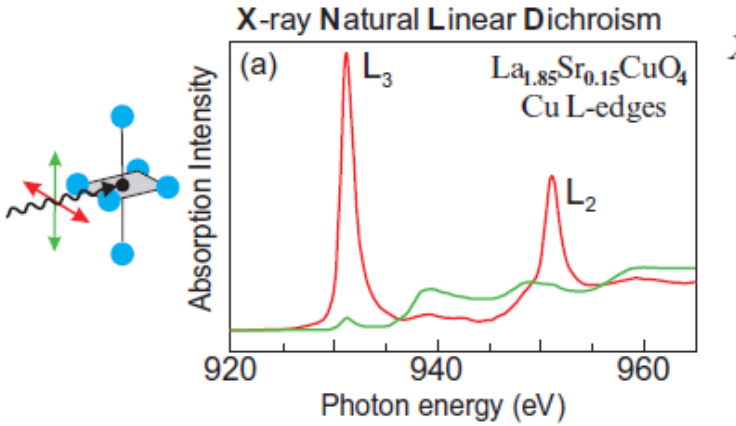
Aligned magnetic state

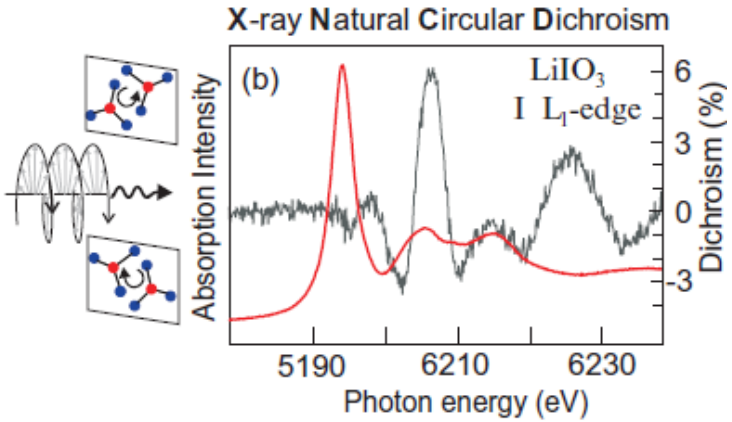


anisotropic charge distribution Due to SOC

Interaction of **polarized** photons with matter

- XNLD and XNCD effect

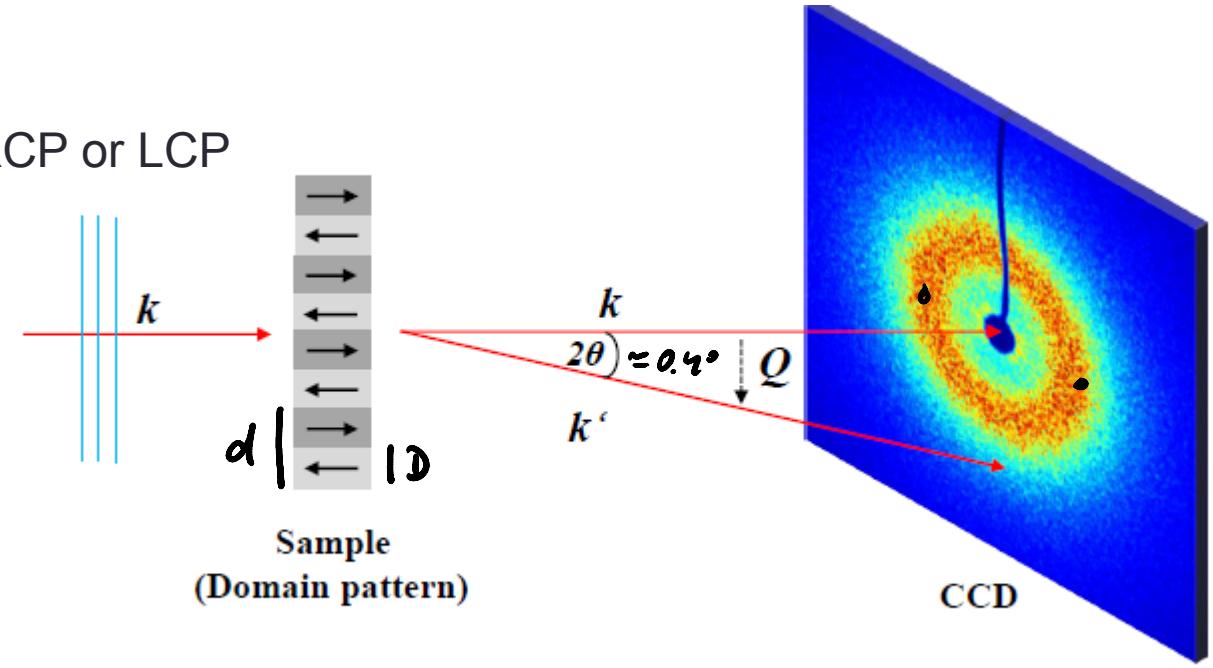




X-ray "natural" dichroism refers to the absence of spin alignment.

- X-ray natural linear dichroism – XNLD – is due to an anisotropic charge distribution. The effect is parity even and time even.
- X-ray natural circular dichroism – XNCD – may be present for anisotropic charge distributions that lack a center of inversion. The effect is parity odd and time even.

mSAXS of magnetic domain patterns

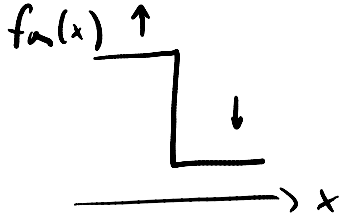


„magnetic grating/lattice“ = stripe domain pattern with equal domain size *D* (periodicity of *d* = 2*D*)

➔Scattering factor $f_m = M_z F^m$ varies in x-direction due to XMCD effect & alternating M_z

$$f_m(x) = f_m^0(x) \otimes \sum_{n=-\infty}^{\infty} \delta(x - n\,d)$$

unit cell ⊗ lattice



mSAXS of magnetic domain patterns

Scattering amplitude (Fourier transform of scattering factor):

$$A(Q) = \mathcal{FT}(f(n)) = \underbrace{\tilde{f}_n^0(Q)}_{\text{unit cell}} \underbrace{\sum_{n=-\infty}^{\infty} e^{-iQnd}}_{\text{lattice sum}}$$

with scattering vector (momentum transfer): $Q = k - k' = \frac{4\pi}{\lambda} \sin\Theta$

Scattering intensity:

$$I(Q) = |A(Q)|^2 = \begin{cases} |\tilde{f}_n^0(Q)|^2 \cdot N_d^2 & \text{for } e^{iQnd} = 1 \quad ① \\ \sim 0 & \text{else} \end{cases}$$

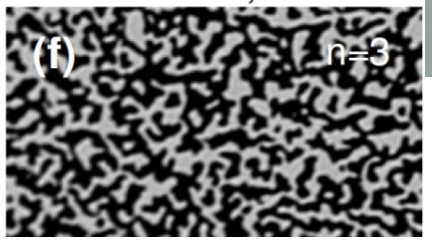
(N_d: 1/2 number of domains)

① for $Q \cdot d = 2\pi \Rightarrow Q = \frac{2\pi}{d}$

$$\Theta = \arcsin\left(\frac{\lambda}{2d}\right) = 0.2°$$

$d = 200\,\mu m$

$\lambda_{Laser} \approx 1.5\,\mu m$



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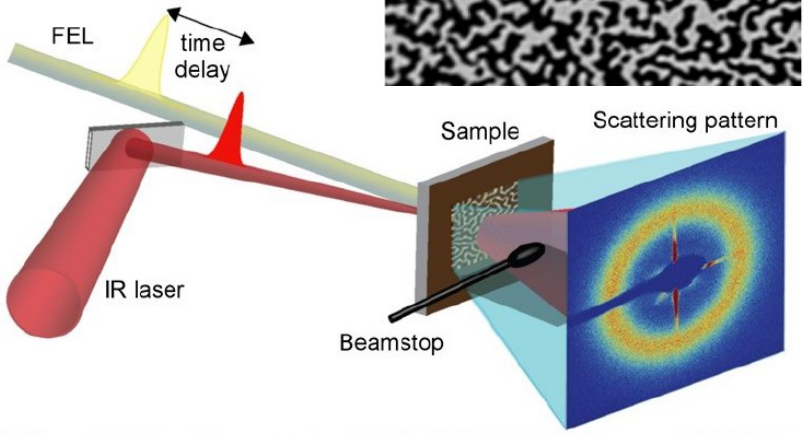

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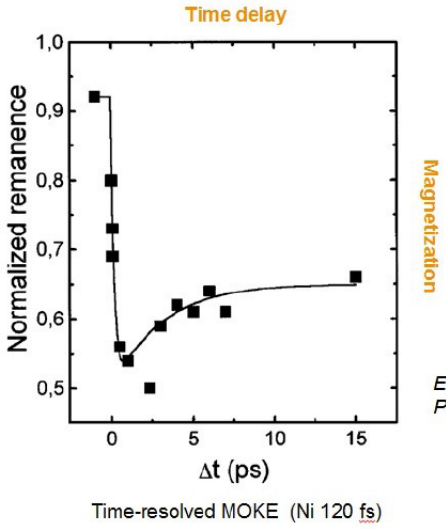
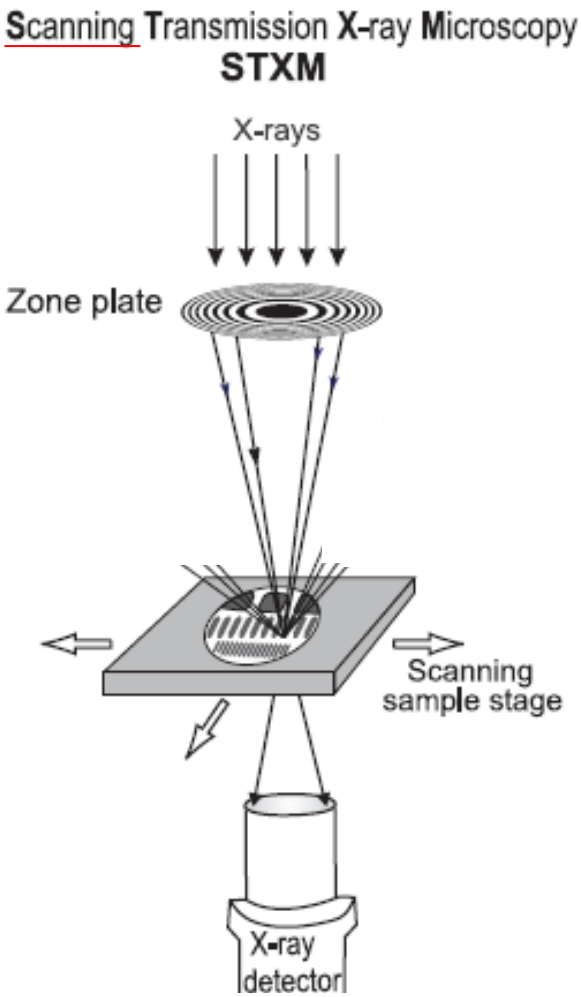


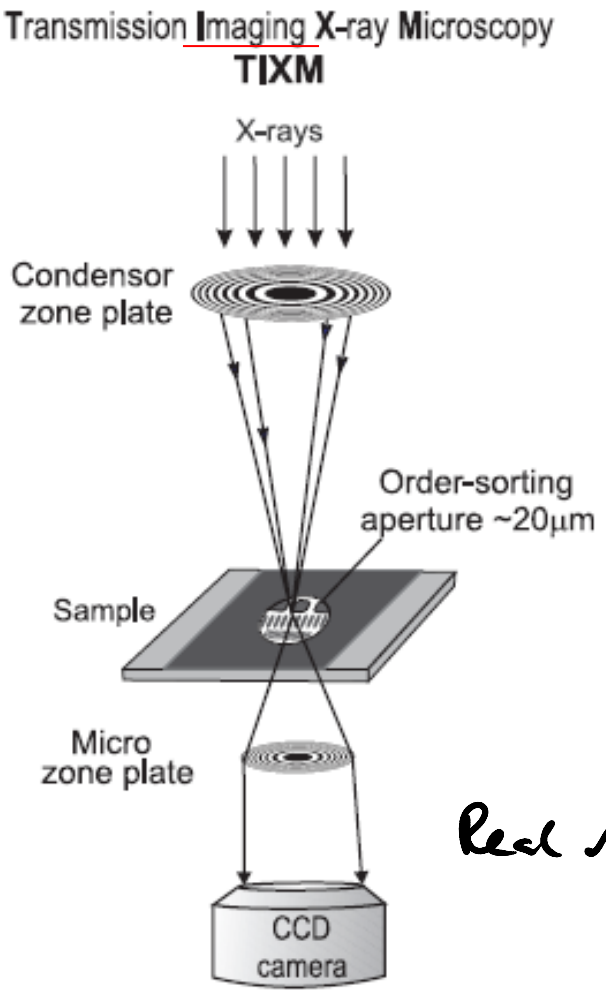
E. Beaurepaire et al., PRL 76 (1996) 4250

Time-resolved MOKE (Ni 120 fs)

Imaging of magnetic domain patterns with X-rays

- X-ray lenses based methods



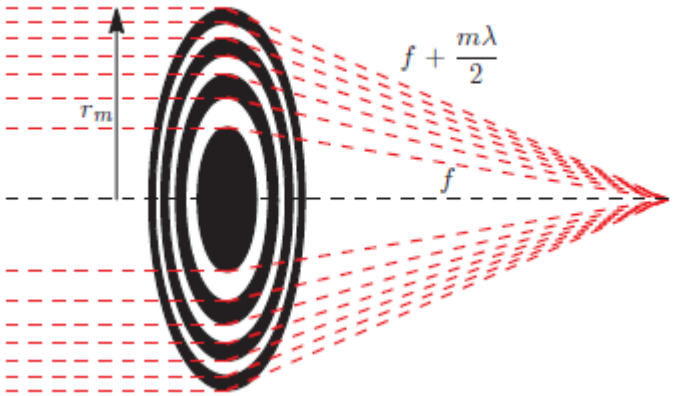


Real space image!

Imaging of magnetic domain patterns with X-rays

- X-ray lenses based method

Fresnel Zone plates:



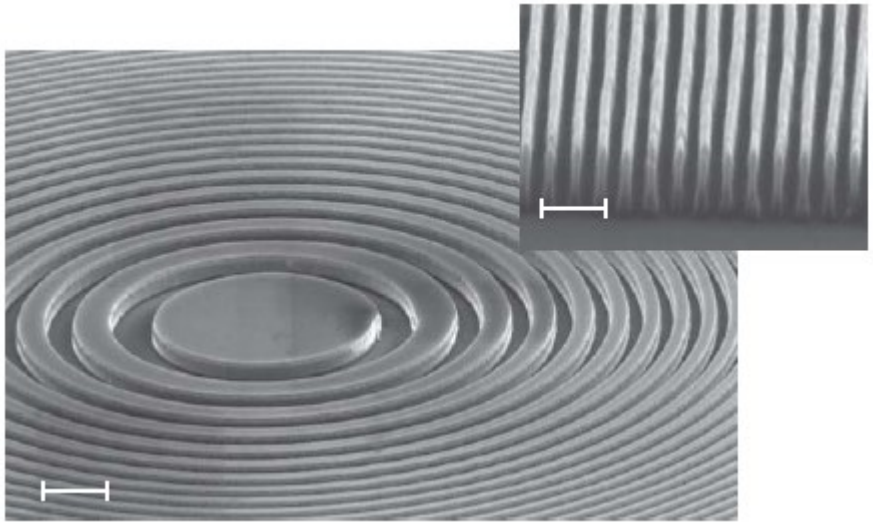
Condition for constructive interference at focus f:

$$r_m = \sqrt{m\lambda f + \frac{m^2\lambda^2}{4}} \approx \sqrt{m\lambda f}$$

Resolution determined by width of outermost zone Δr_m:

$$\Delta x = 1.22\, \Delta r_m$$

$\Delta r_m \geq 10$ nm nowadays



disadvantages:
- High absorption
- Hard to fabricate

Imaging of magnetic domain patterns with X-rays

- X-ray lenses based method

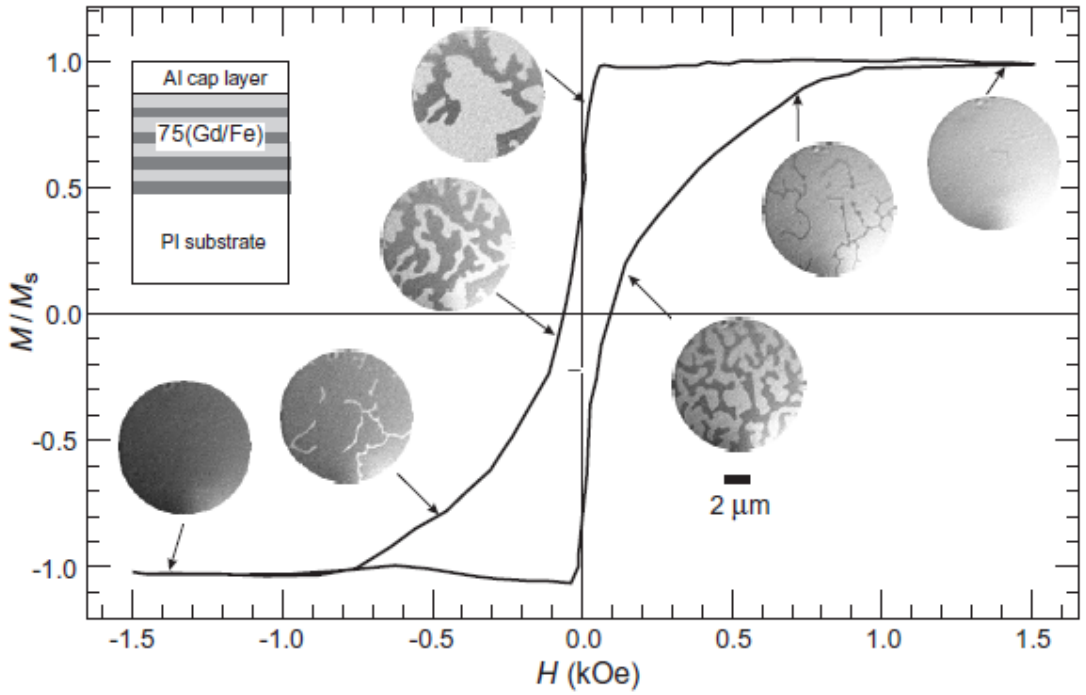


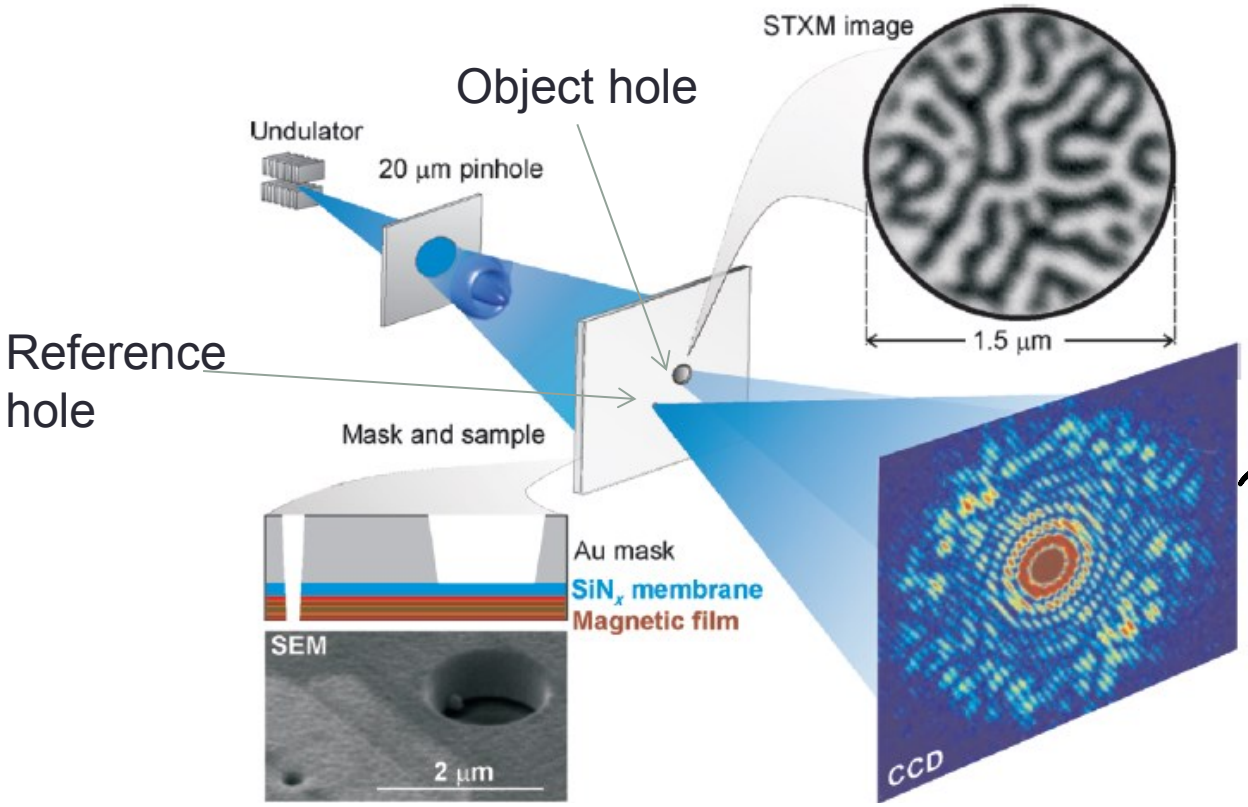
Fig. 10.22. TIXM images recorded at the FeL_3-edge as a function of applied field for a 75 × [Fe(4.1 Å)/Gd(4.5 Å)] multilayer deposited on polyimide and capped for protection with an Al layer [463, 482]

- Element-sensitivity
- Integration of gray values for each field value
  ➔ hysteresis

Imaging of magnetic domain patterns with X-rays

- Lensless Imaging – Fourier transform Holography

	Schlüsselelement-Herstellung		Bild-Rekonstruktion	
TXM	Zonenplatte	XXXXX	-direkt-	X
FTH	Optikmaske	XX	Einfache Fourier-Transformation	XX



transverse coherence length > distance between Object & reference hole

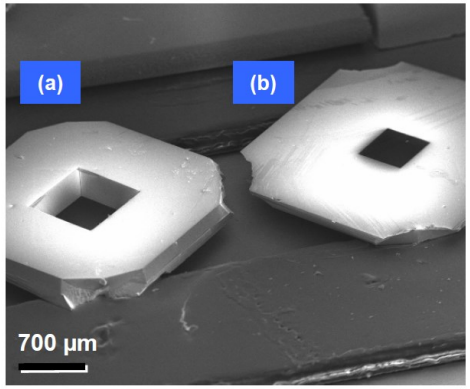
Hologram

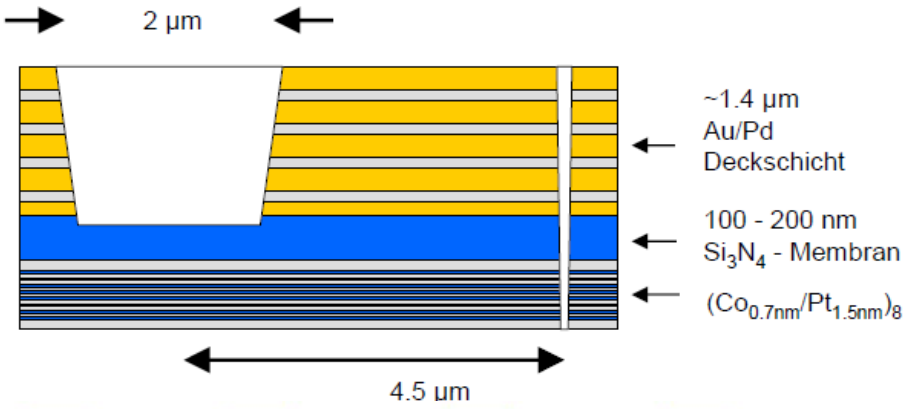
DESY

Imaging of magnetic domain patterns with X-rays

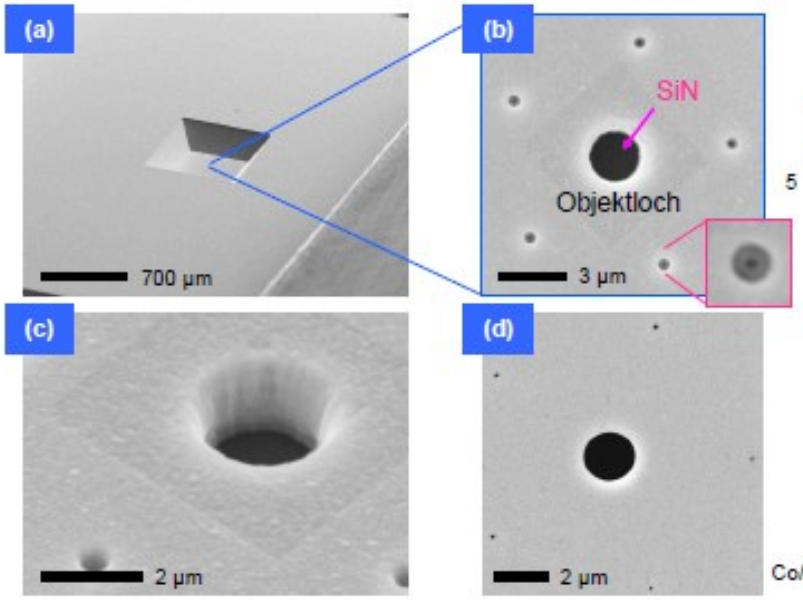
> Lensless Imaging – Fourier transform Holography

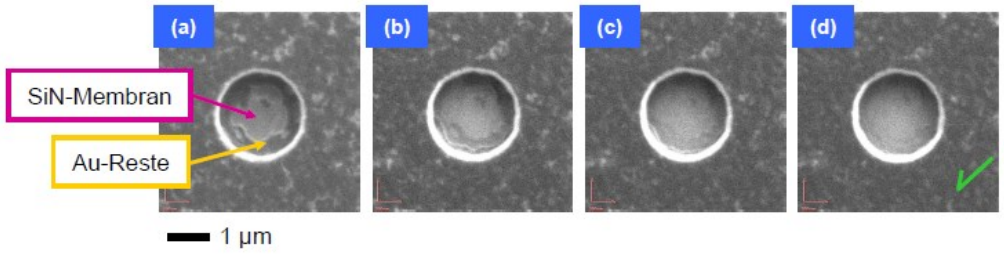
Mask and sample:

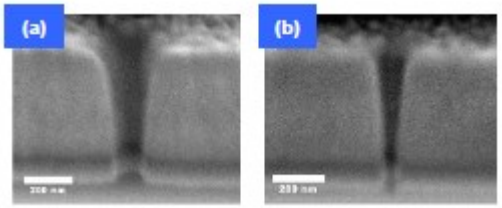




Preparation
by focused ion beam
technique







Imaging of magnetic domain patterns with X-rays

> Lensless Imaging – Fourier transform Holography (FTH)

Principle:

- Intensity on detector: $I(\vec{Q}) = \left| \sum_j \tilde{f}_j(\vec{Q}) e^{i\vec{Q}\cdot\vec{r}_j} \right|^2$ with $\tilde{f}_j(\vec{Q}) = FT(f_j(\vec{r}))$

- Scattering factor for circularly polarized light and **M**||**L**$_{ph}$:

$$f = \vec{\varepsilon}\cdot\vec{\varepsilon}' F^c - i(\vec{\varepsilon}\times\vec{\varepsilon}')\cdot\vec{m} F^m$$

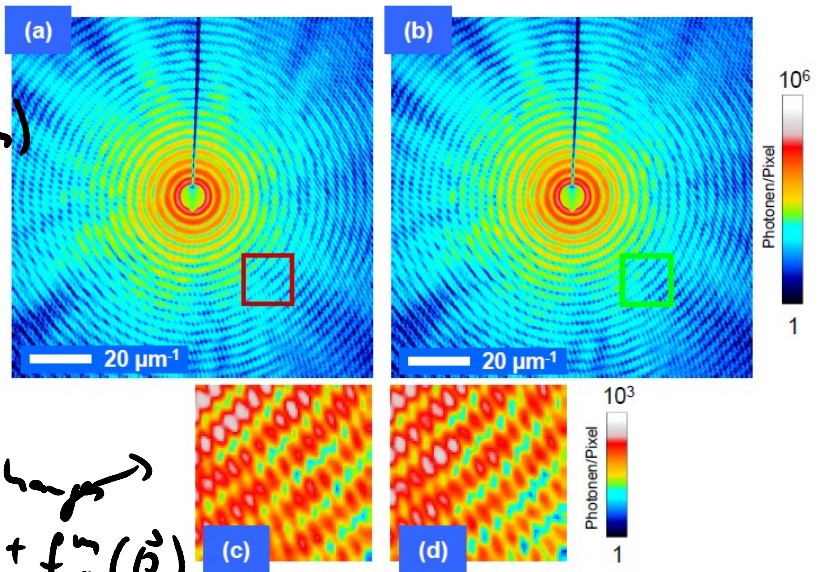
$$f = f^c(\vec{Q}) \pm f_0^m(\vec{Q}) \quad (+ \text{RCP}, - \text{LCP for } \vec{m} \parallel \vec{L}_{ph})$$

$$f^c(\vec{Q}) = f_0^c(Q) + f_R^c(\vec{Q})$$

- "Hologram" (= *I*(**Q**)) with RCP and LCP

$$I(\vec{Q}) = \left| \tilde{f}_0^c(\vec{Q}) + \tilde{f}_R^c(\vec{Q}) \pm \tilde{f}_0^m(Q) \right|^2$$

RCP LCP



static change due to $\pm f_0^m(\vec{Q})$

Imaging of magnetic domain patterns with X-rays

> Lensless Imaging – Fourier transform Holography (FTH)

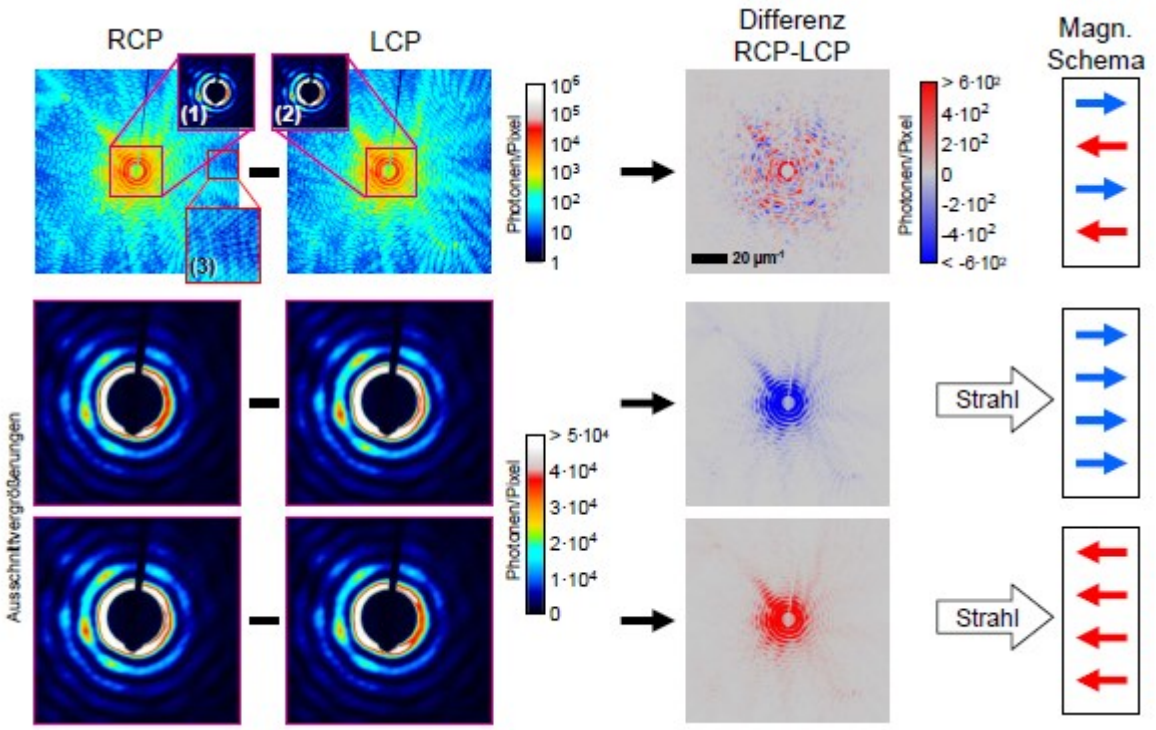
Principle:

- Difference hologram: $\Delta I(\vec{Q})$

$$= I^{+}(\vec{Q}) - I^{-}(\vec{Q})$$

$$= \tilde{f}_0^{-*} \cdot \tilde{f}_0^{c} + \tilde{f}_0^{-} \cdot \tilde{f}_0^{c*}$$

$$+ \tilde{f}_0^{-*} \tilde{f}_R^{c} + \tilde{f}_0^{-} \cdot \tilde{f}_R^{c*}$$



Imaging of magnetic domain patterns with X-rays

> Lensless Imaging – Fourier transform Holography (FTH)

Principle: Note: $FT^{-1}(\tilde{f}(\vec{q})) = FT^{-1}FT(f(\vec{r})) = f(\vec{r})$

- Reconstruction = Fourier transformation:

$FT^{-1}(\Delta I(\vec{q}))$ (inverse)

$= \underbrace{FT^{-1}(\tilde{f}_0^{*} \cdot \tilde{f}_0^{C}) + FT^{-1}(\tilde{f}_0 \cdot \tilde{f}_0^{C*})}_{\text{Autocorrelation}}$

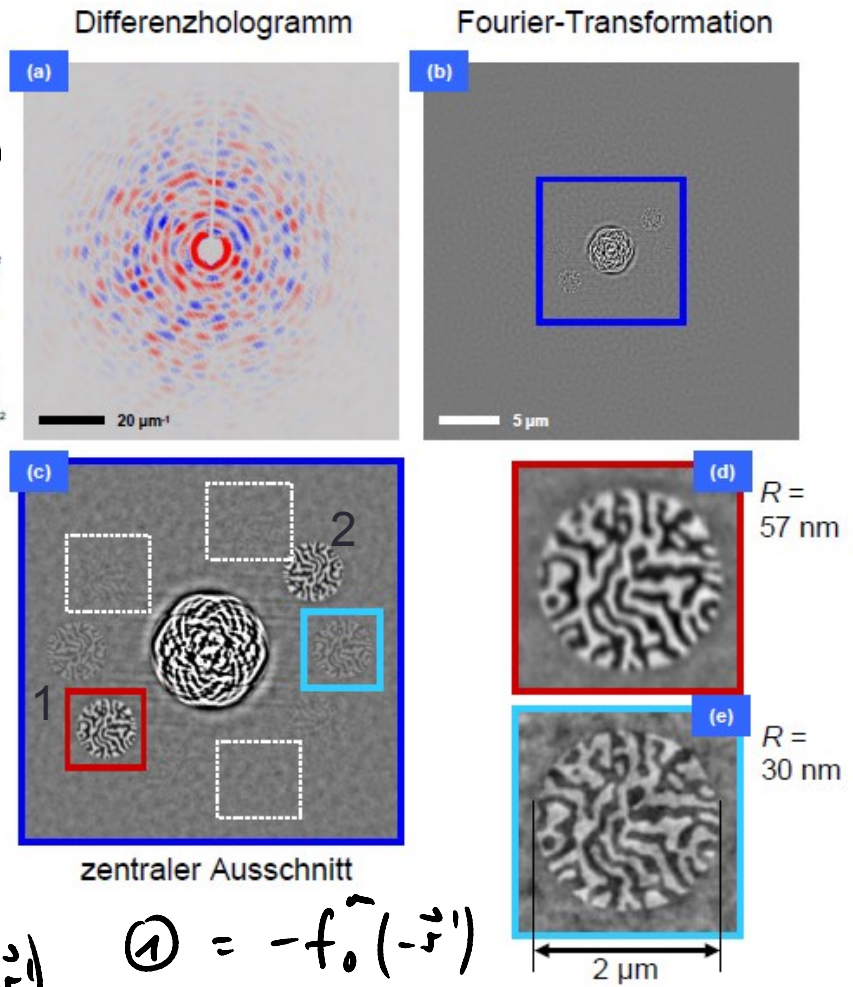
$+ \underbrace{\overset{①}{FT^{-1}}(\tilde{f}_0^{*} \cdot \tilde{f}_R^{C}) + \overset{②}{FT^{-1}}(\tilde{f}_0 \cdot \tilde{f}_R^{C*})}_{\text{Reconstruction}}$

$② = FT^{-1}(\tilde{f}_0) \otimes FT^{-1}(f_R^{C*})$

$= f_0(\vec{r}) \otimes f_R^{C*}(\vec{r})$ ← δ-fkt

$= \int f_0(\vec{r}) \, \delta(\vec{r} - \vec{r}') \, d\vec{r} = f_0(\vec{r}')$

$① = -f_0(-\vec{r}')$

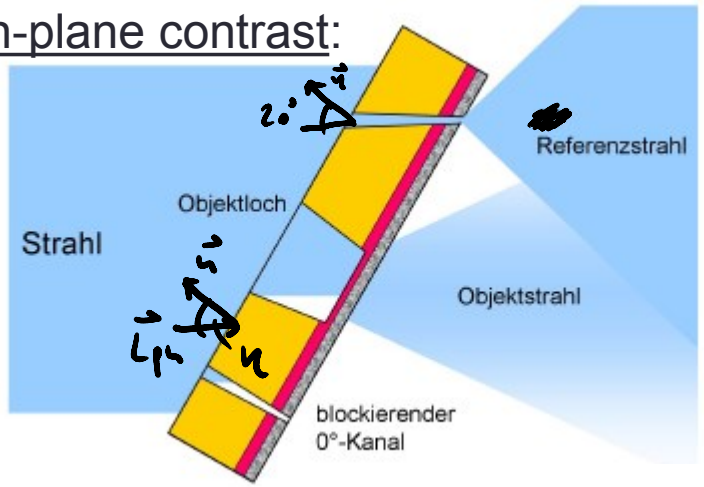


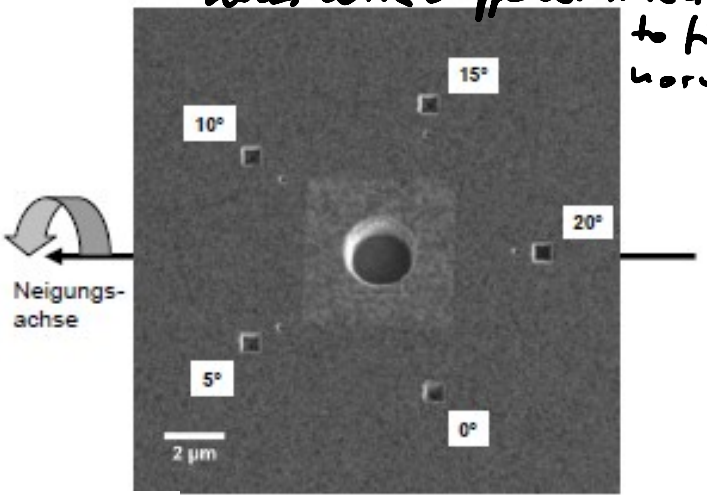
DESY

Imaging of magnetic domain patterns with X-rays

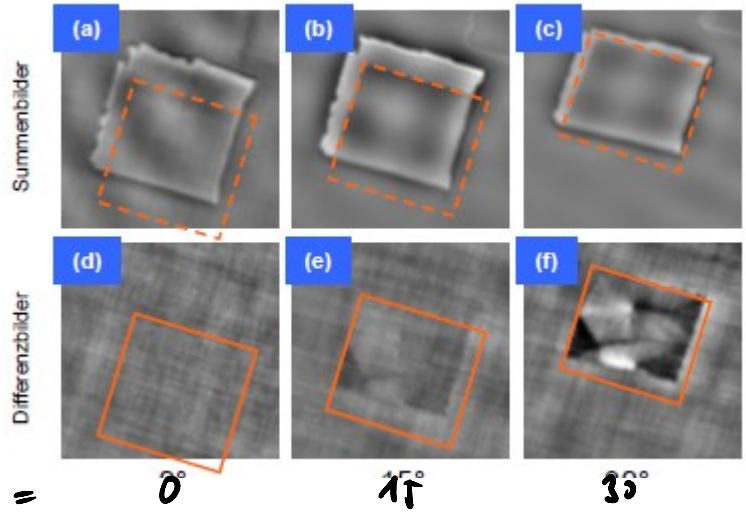
- Lensless Imaging – Fourier transform Holography (FTH)

In-plane contrast:





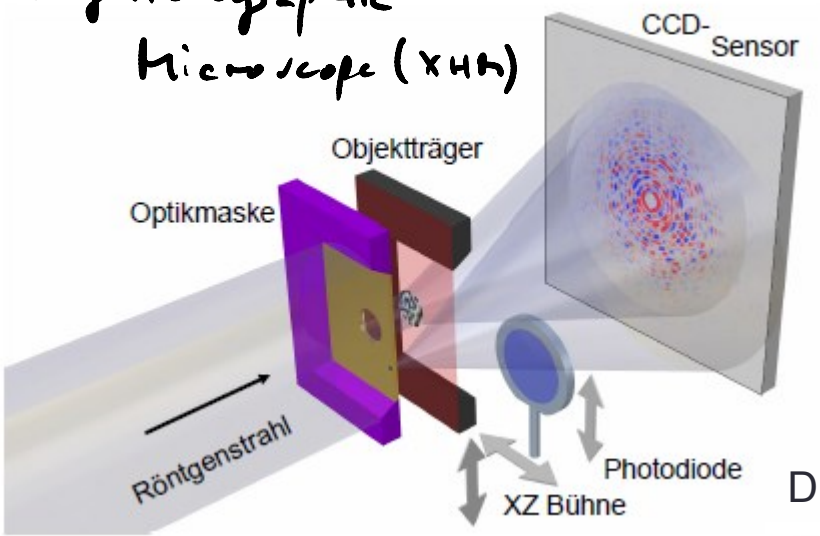
In-plane magnetized
20 nm thick Co film

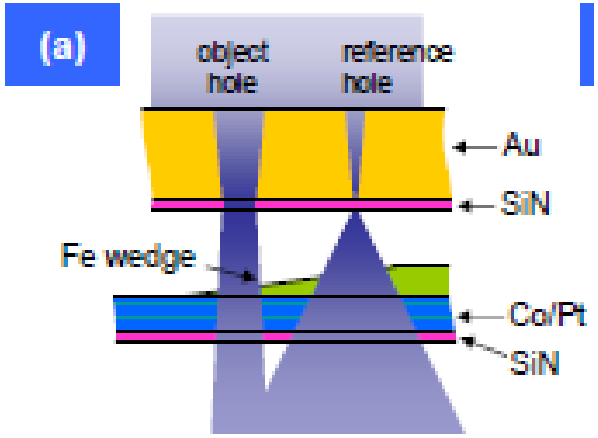


Imaging of magnetic domain patterns with X-rays

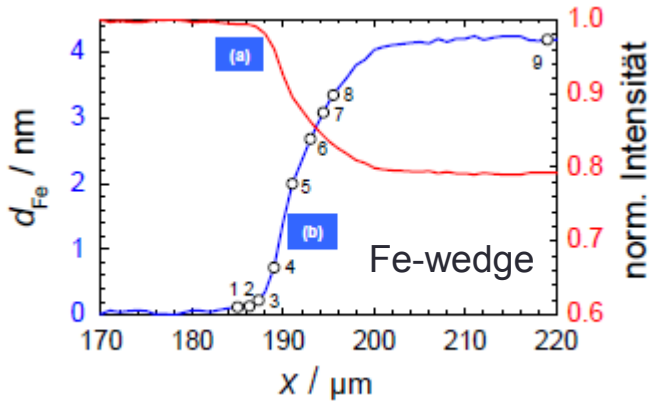
- Lensless Imaging – Fourier transform Holography (FTH)

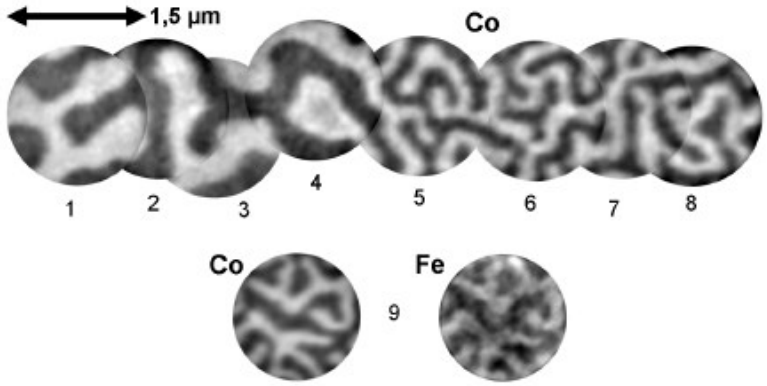
X-ray Holographic Microscope (XHM)





D. Stickler et al., Appl. Phys. Lett. **96**, 042501 (2010)





Element-selectivity

Imaging of magnetic domain patterns with X-rays

> Lensless Imaging – Coherent Diffraction Imaging (CDI)

	Schlüsselelement-Herstellung		Bild-Rekonstruktion	
TXM	Zonenplatte	XXXXX	-direkt-	X
FTH	Optikmaske	XX	Einfache Fourier-Transformation	XX
CDI	-direkt-	X	Phasen-Rückgewinnung	XXXXX