# Methoden moderner Röntgenphysik II: Streuung und Abbildung

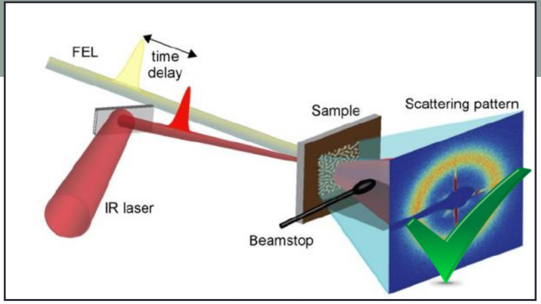
| | | | |
|---|---|---|---|
| Lecture 26 | Vorlesung zum Haupt- oder Masterstudiengang Physik, SoSe 2021 | | |
| | G. Grübel, O. Seeck, V. Markmann, F. Lehmkühler, A. Philippi-Kobs, M. Martins | | |
| Location | online | | |
| Date | Tuesdays | 12:30 - 14:00 | (starting 6.4.) |
| | Thursdays | 8:30 - 10:00 | (until 6.7.) |

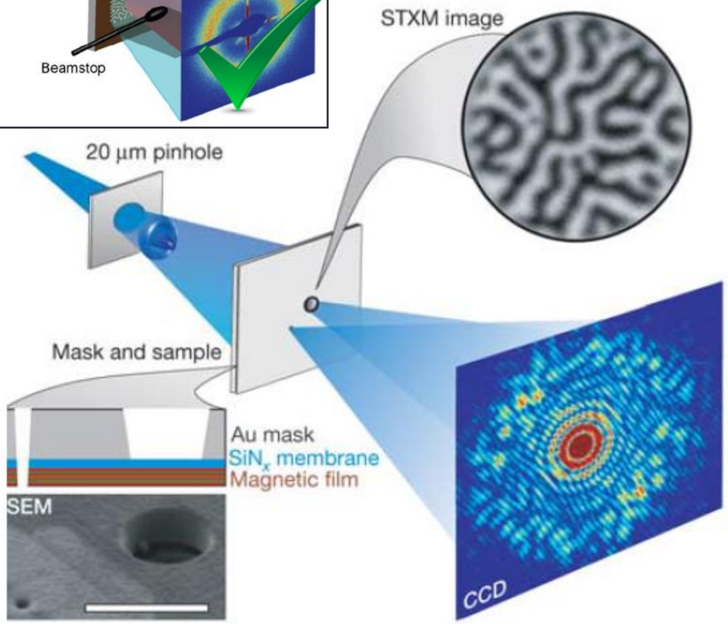
# Outline

**Part II/3:**

## Studies on Magnetic Nanostructures

by André Philippi-Kobs (AP)



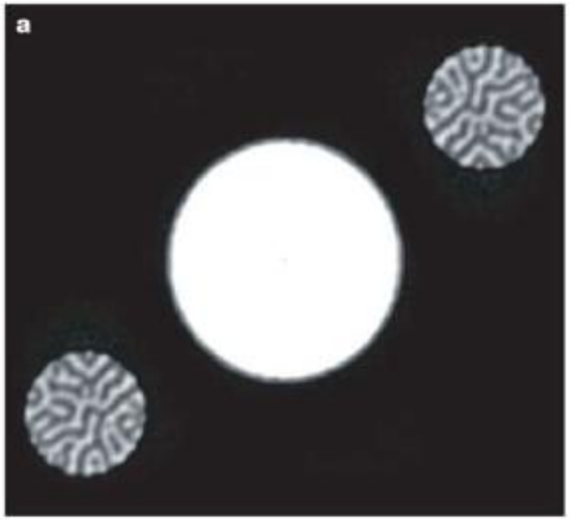

[6.7.] Imaging of Magnetic Domains

- **Fourier Transform Holography (FTH)**
- Scanning Transmission X-ray Microscopy (STXM)
- Coherent Diffraction Imaging (CDI)

**Lensless imaging of magnetic nanostructures by X-ray spectro-holography**

**S. Eisebitt[1], J. Lüning[2], W. F. Schlotter[2,3], M. Lörgen[1], O. Hellwig[1,4], W. Eberhardt[1] & J. Stöhr[2]**

NATURE | VOL 432 | 16 DECEMBER 2004 |

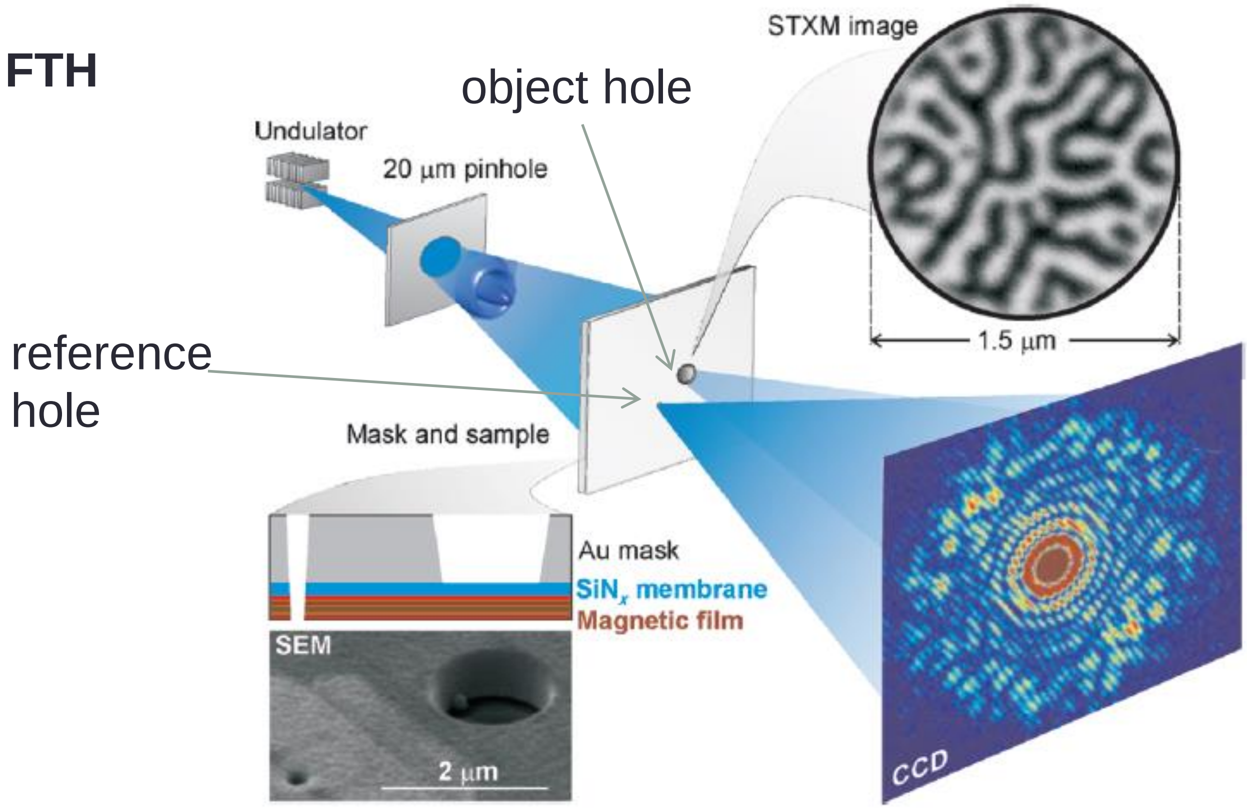



FTH

# Imaging of magnetic domain patterns with X-rays

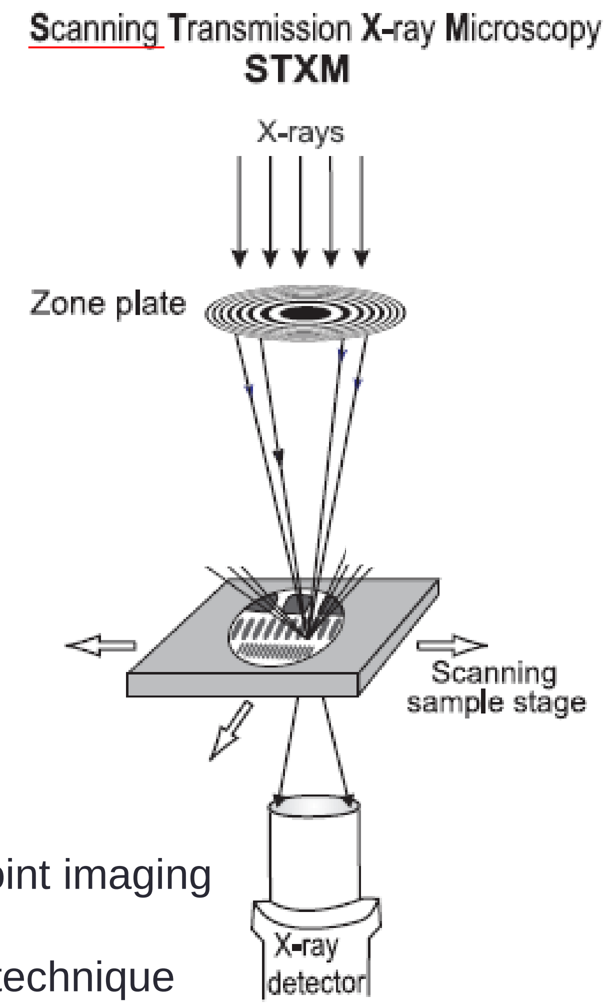
> Brief excursion on Lensless Imaging – Fourier transform Holography

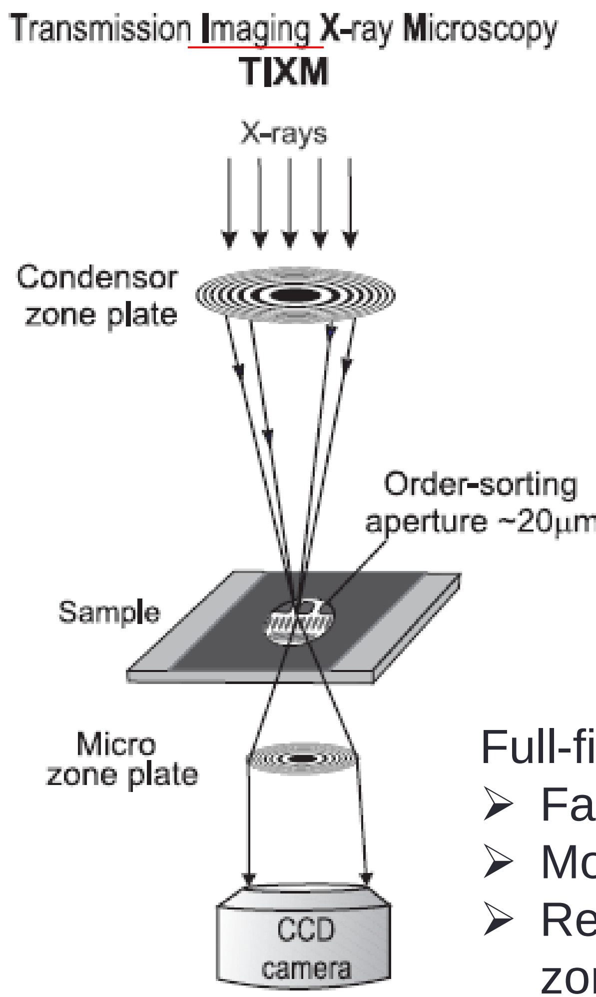
| | Schlüsselelement-Herstellung | | Bild-Rekonstruktion | |
|---|---|---|---|---|
| TXM | Zonenplatte | XXXXX | -direkt- | X |
| FTH | Optikmaske | XX | Einfache Fourier-Transformation | XX |
| CDI | -direkt- | X | Phasen-Rückgewinnung | XXXXX |



# Imaging of magnetic domain patterns with X-rays

> X-ray lenses based methods




Point-by-point imaging
- Slow
- Simple technique
- Resolution limit = focal-spot size

Full-field microscopy
- Fast (detector limited)
- More difficult
- Resolution limit by zone plate

# Imaging of magnetic domain patterns with X-rays

## > X-ray lense-based method

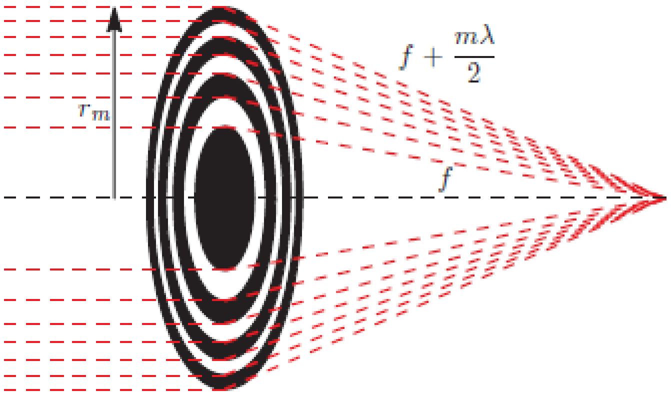
See, e.g., X-Ray Data Booklet, Sec 4.4
http://www.x-ray-optics.de

Fresnel Zone plates:
Condition for constructive interference at focal distance *f*

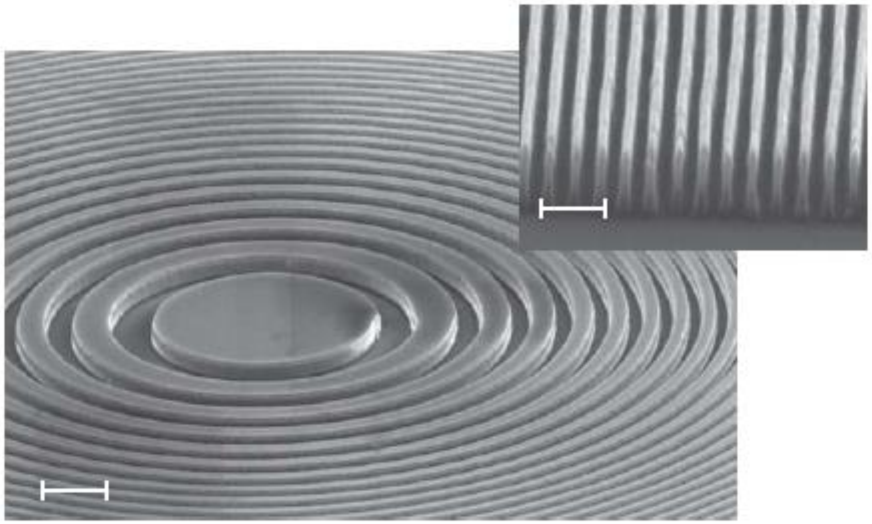
$$r_n = \sqrt{m\lambda f + \frac{m^2\lambda^2}{4}} \approx \sqrt{m\lambda f}$$

All zones have the same area

$$A_m = \pi(r_{m+1}^2 - r_m^2) = \pi\lambda f$$




Resolution determinded by width of outermost zone
$\Delta x = 1.22\Delta r_m \approx 10\mathrm{nm}$ nowadays
(7.8 nm FWHM shown in 2017 [Sci. Rep. 7, 43624]).



disadvantages:
- High absorption (5-30% efficiency)
- Hard to fabricate



DESY

# Imaging of magnetic domain patterns with X-rays

> X-ray lense-based method

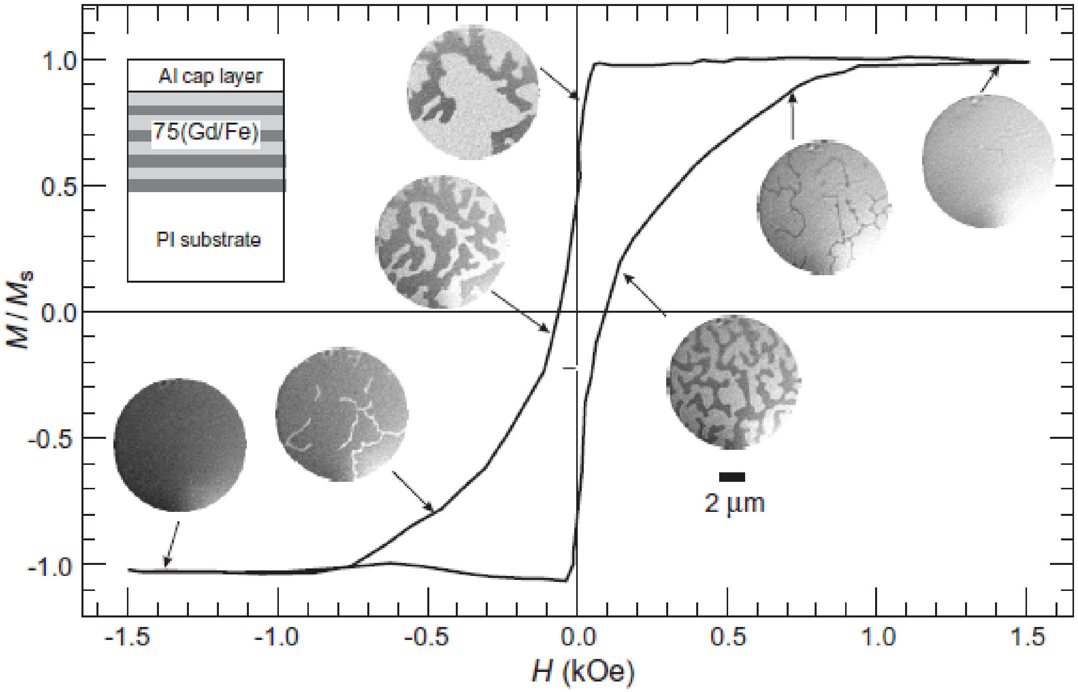



**Fig. 10.22.** TIXM images recorded at the FeL3-edge as a function of applied field for a 75 × [Fe(4.1 Å)/Gd(4.5 Å)] multilayer deposited on polyimide and capped for protection with an Al layer [463, 482]

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

Stöhr and Siegmann, Magnetism

# Imaging of magnetic domain patterns with X-rays

> Brief excursion on Lensless Imaging – Fourier transform Holography

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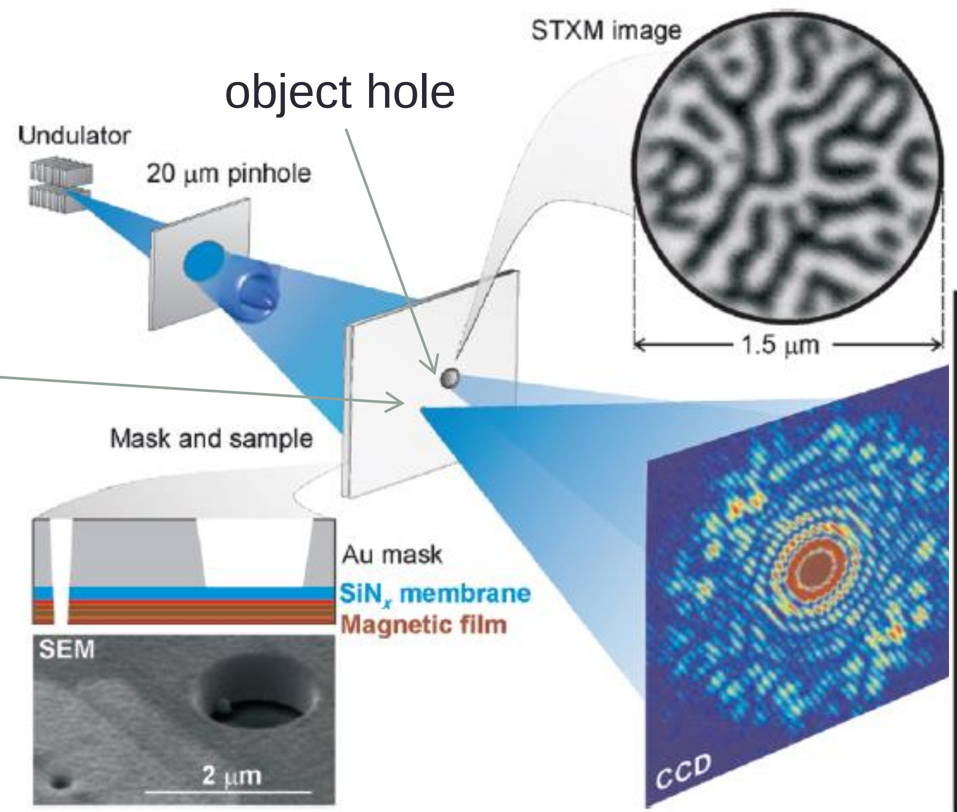
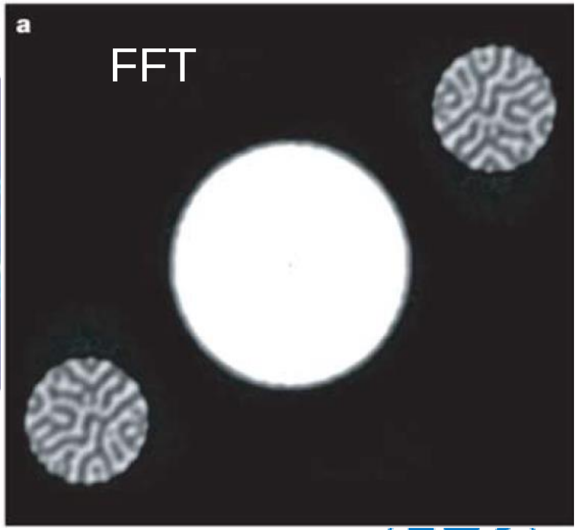
Requirement: transversal coherence length > largest length scale in sample = mask diameter

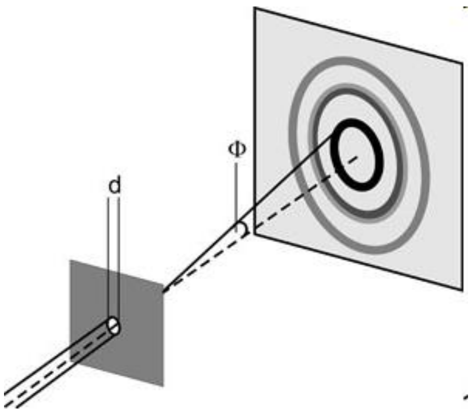
object hole

reference hole



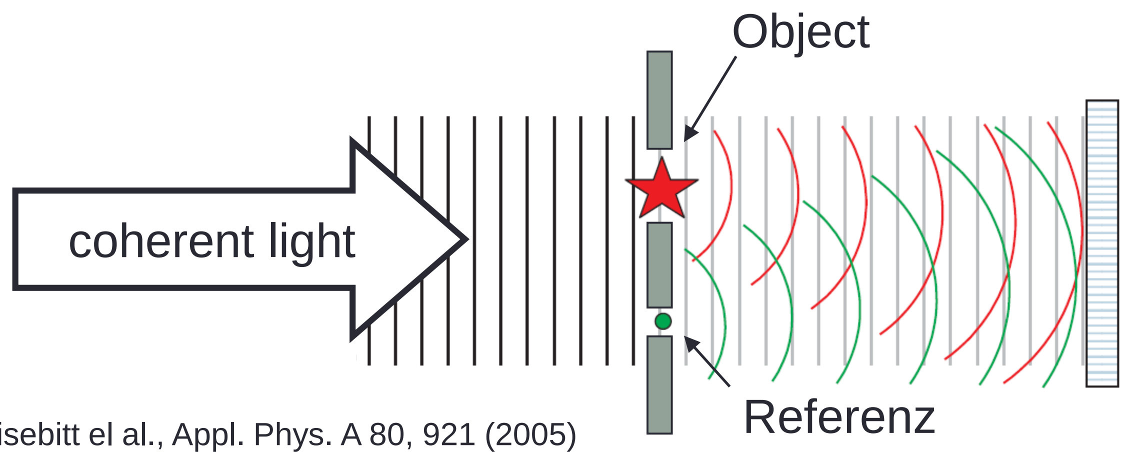



# Image the nanoscale – Fourier-transform holography




Usually, in a scattering experiment the phase is lost – only the intensity is recorded

Solution: 'Detect' phase via interference of object wave with a reference wave



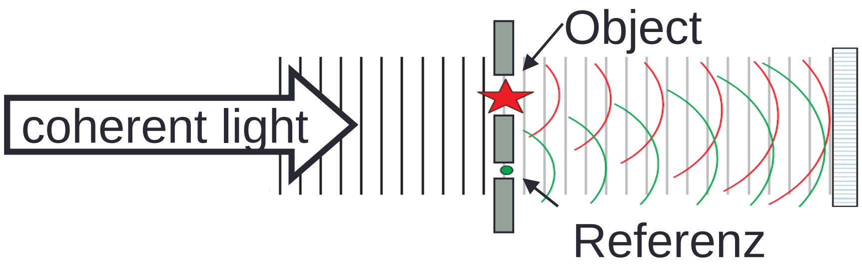

$$I = |A(\mathrm{obj}) + A(\mathrm{ref})|^2$$

S. Eisebitt el al., Appl. Phys. A 80, 921 (2005)

Object and reference wave interfere if object and reference are illuminated coherently and the (polarization) state of the light is not changed by the scattering…

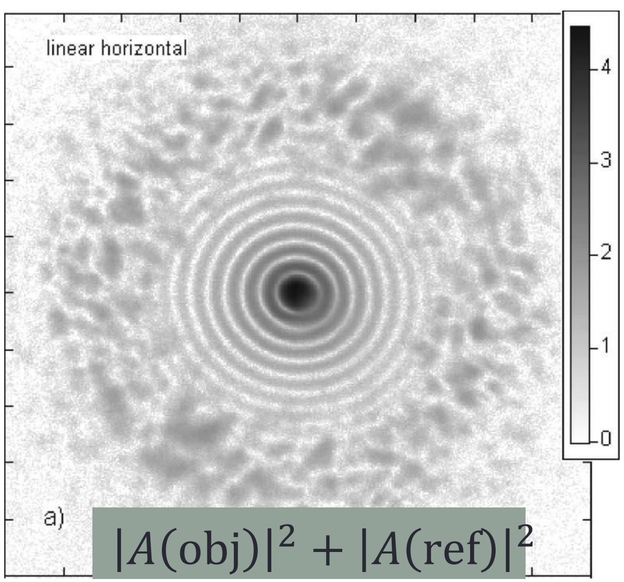
# Image the magnetic nanoscale – magnetic FTH

… unfortunately, magnetic scattering does exactly that with linear light



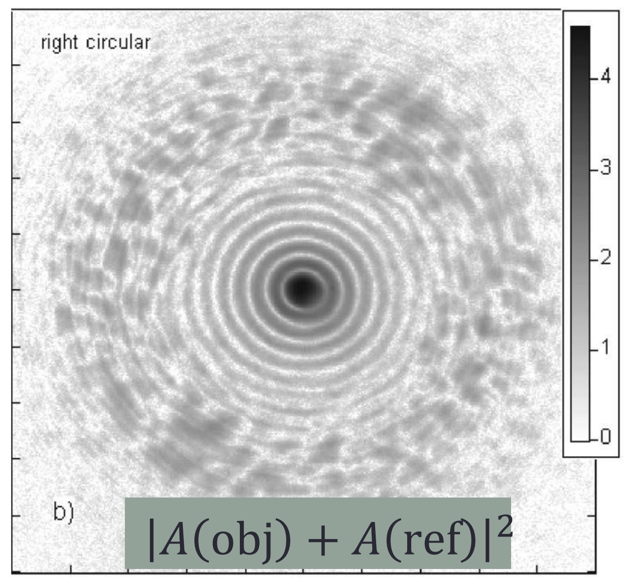

detector $I_{\text{lin}} = |A(\text{obj})|^2 + |A(\text{ref})|^2$

S. Eisebitt el al., Appl. Phys. A 80, 921 (2005)



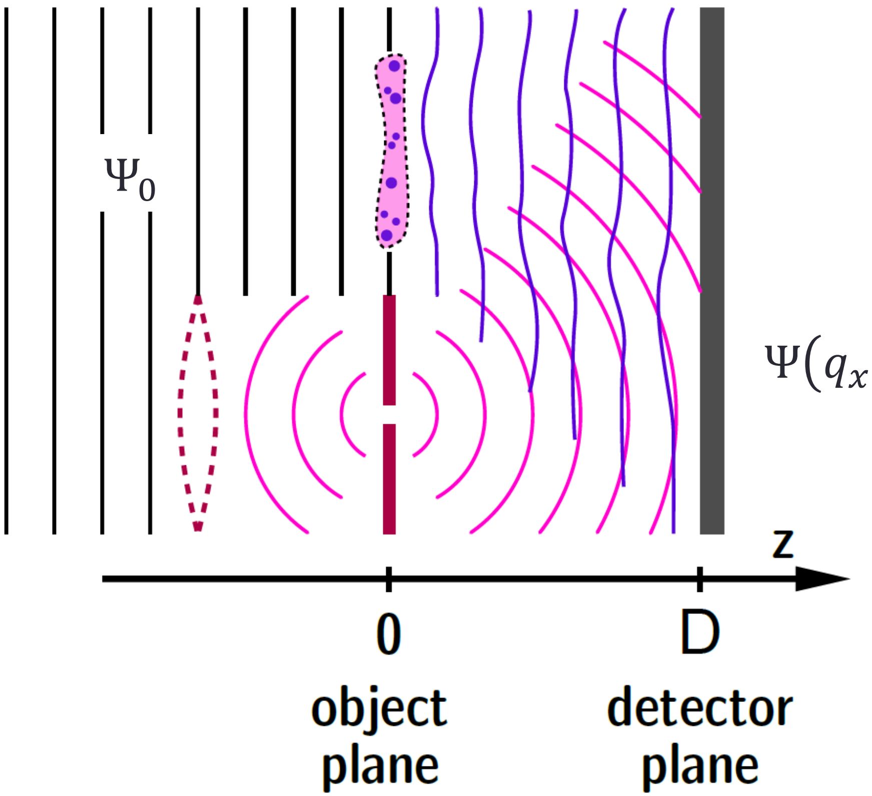

Linear light

S. Eisebitt et al., PRB, **68** 104419 (2003).




Circular light

# FTH image formation




- Sample transmits incoming wavefield
  $\Psi(x,y) = t(x,y)\Psi_0$
- In the far field $\left(F \ll 1, F = \frac{\ell^2}{D\lambda}\right)$ one masures a Fraunhofer pattern described by

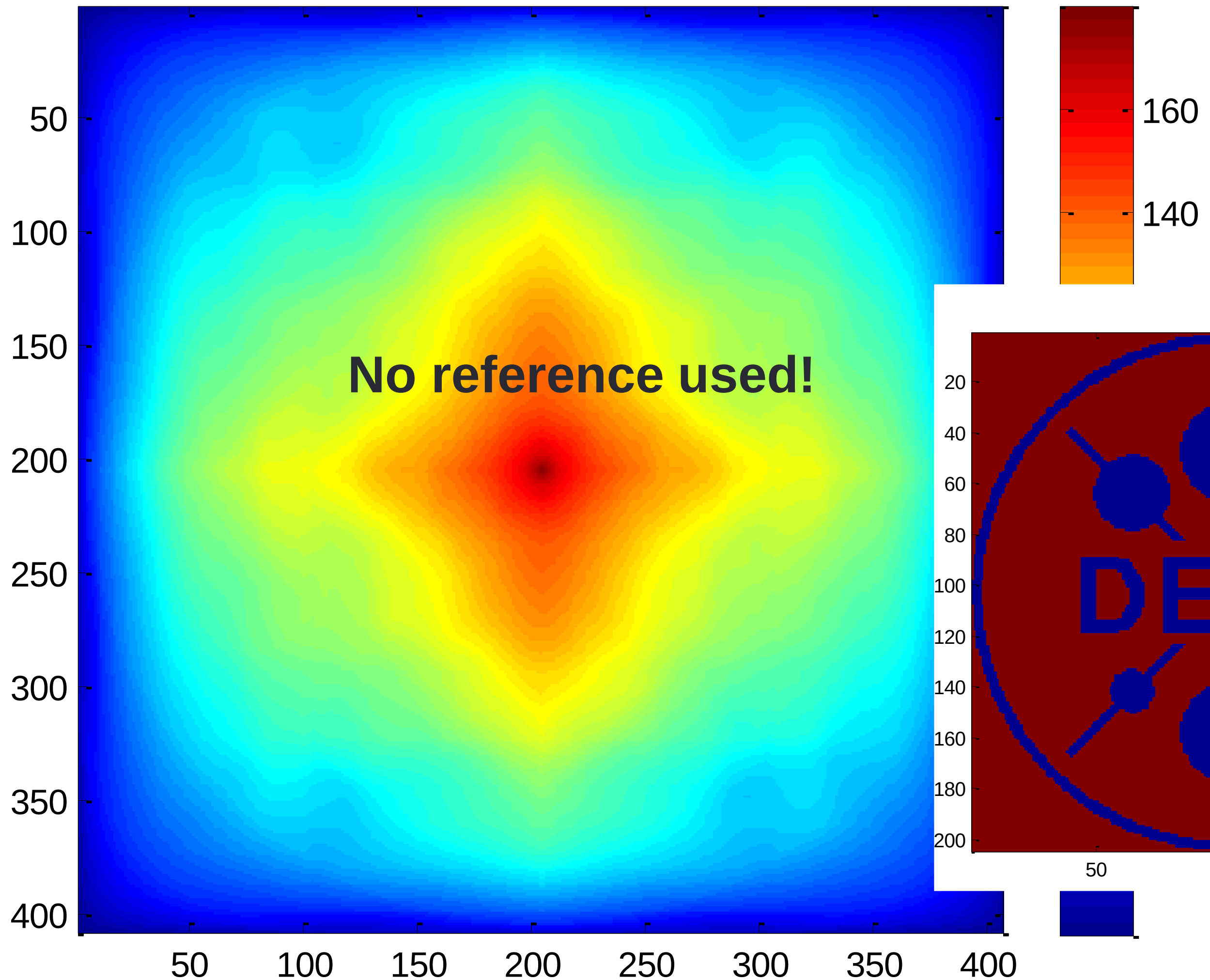
$$\Psi(q_x,q_y) = \iint_{-\infty}^{\infty} \Psi(x,y) \exp\left(-i\left(q_x x + q_y y\right)\right)\, \mathrm{d}x\mathrm{d}y$$

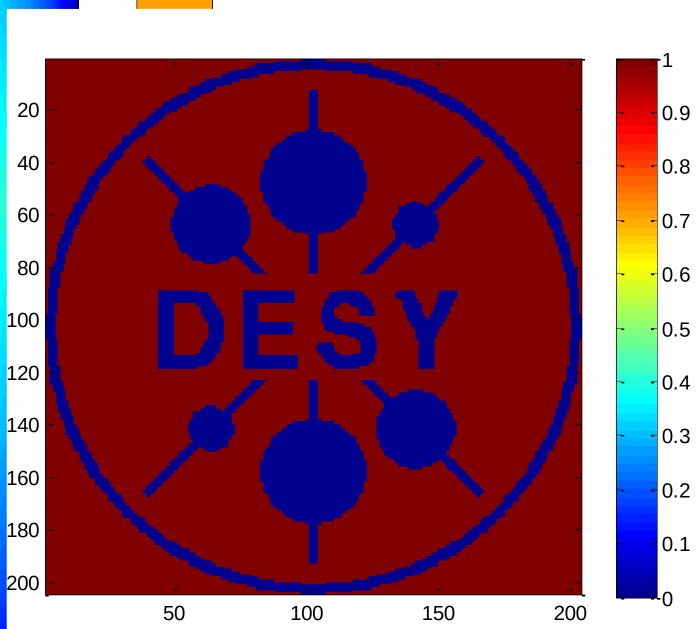
  This is the Fourier transform of the transmitted wavefield which again is directly related to the sample structure.
- Unfortunately we measure the absolute square of the wavefield and the phase is lost. Hence we get

$$\begin{aligned} p(r') &= F^{-1}\{F^*(\Psi(r))F(\Psi(r))\} \\ &= \Psi^*(-r) * \Psi(r) \\ &= \iint_{-\infty}^{\infty} \Psi^*(-r)\Psi(r+r')\mathrm{d}r \end{aligned}$$

$p(r')$ is the spatial autocorrelation function or the Patterson map

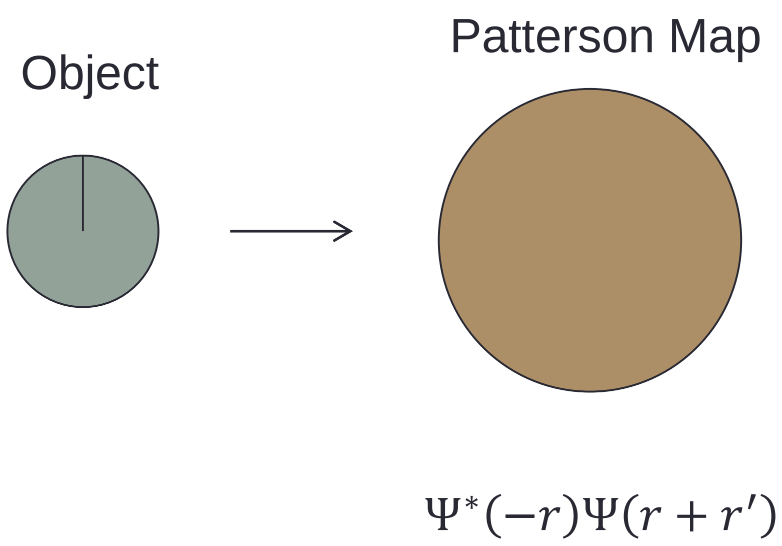
# What does the Patterson map tell us?

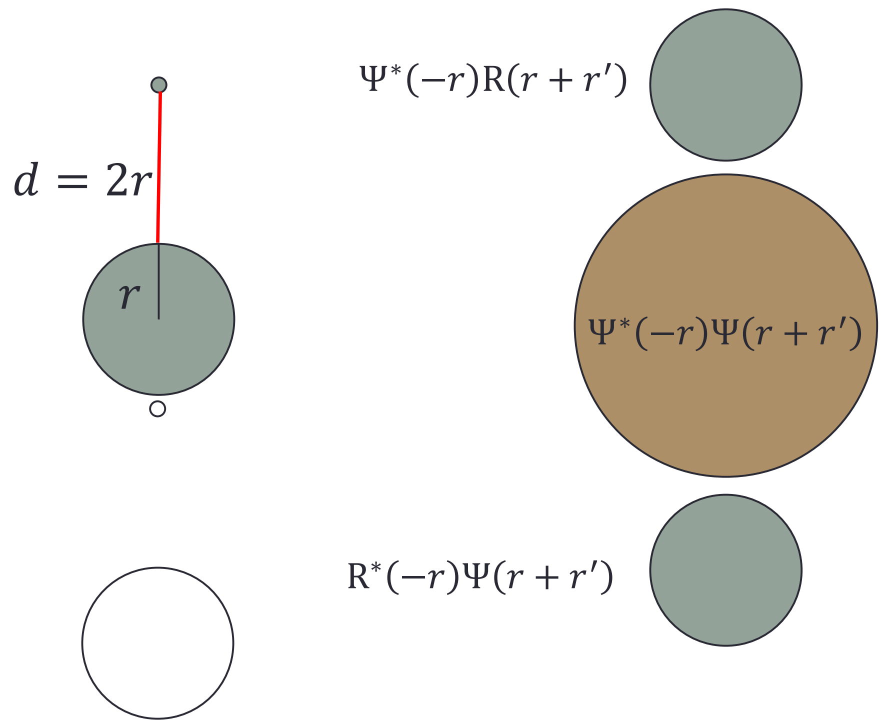


# The trick of the reference

- No reference
- With reference




Needs iterative phase retrieval (CDI)
Not necessarily ‘easy’

Real space image comes from FFT
Resolution limited by reference size

# Imaging of magnetic domain patterns with X-rays

## > Lensless Imaging – Coherent Diffraction Imaging (CDI)

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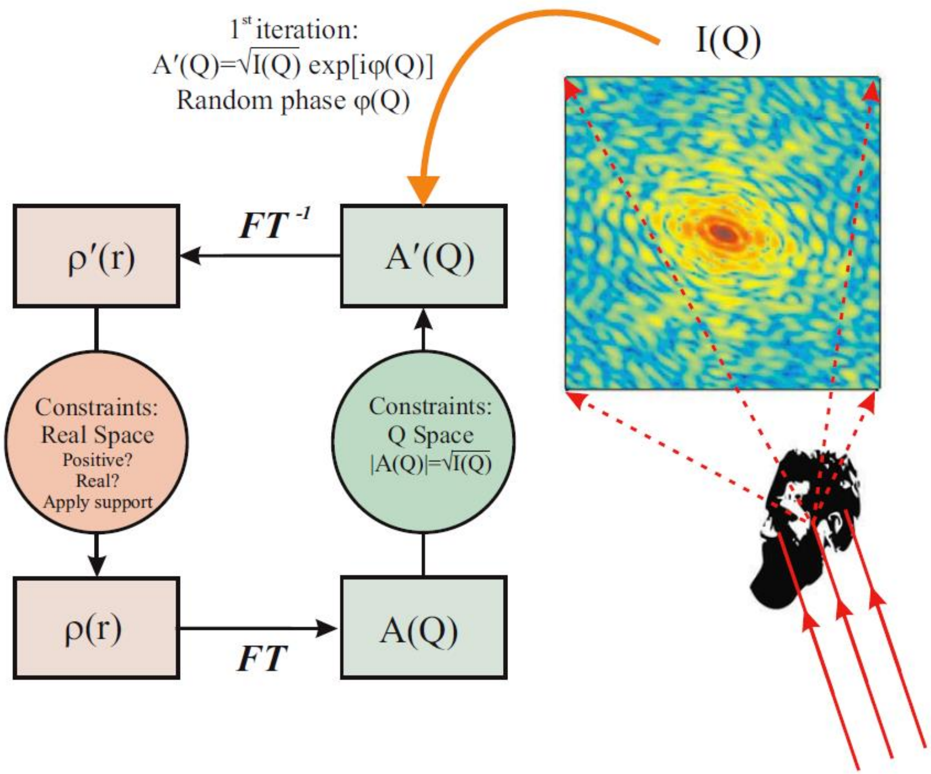
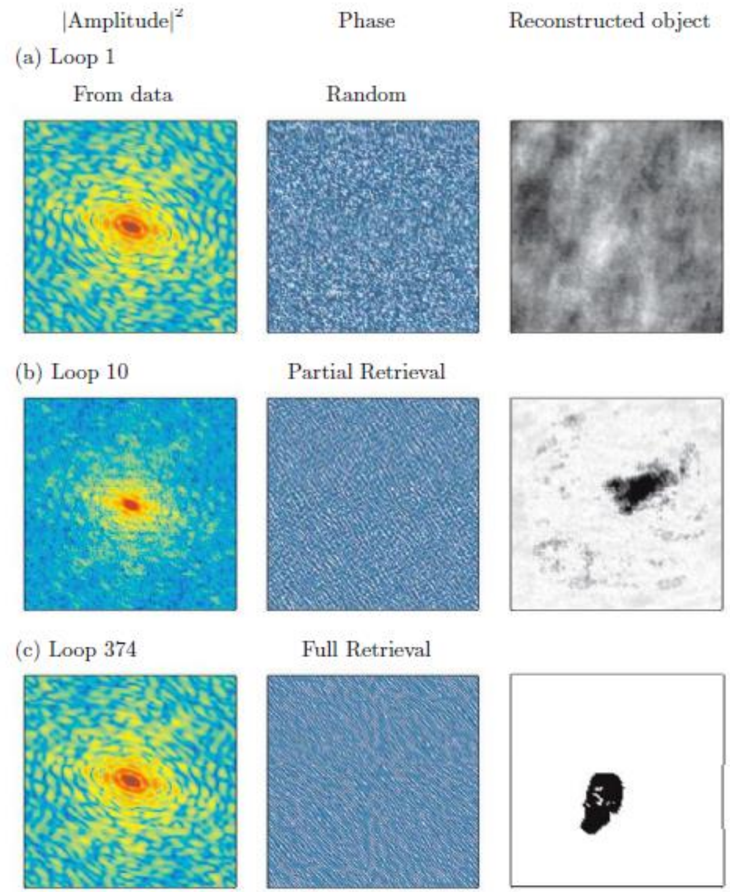


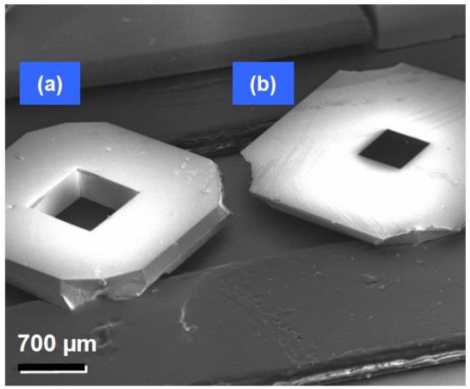



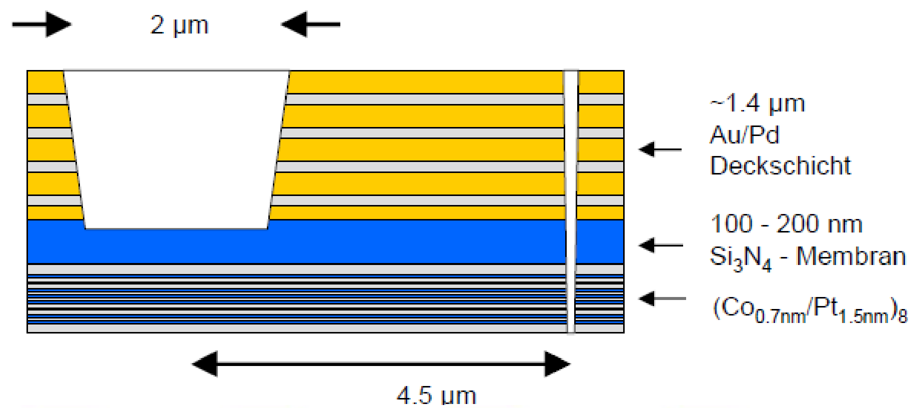
# Imaging of magnetic domain patterns with X-rays

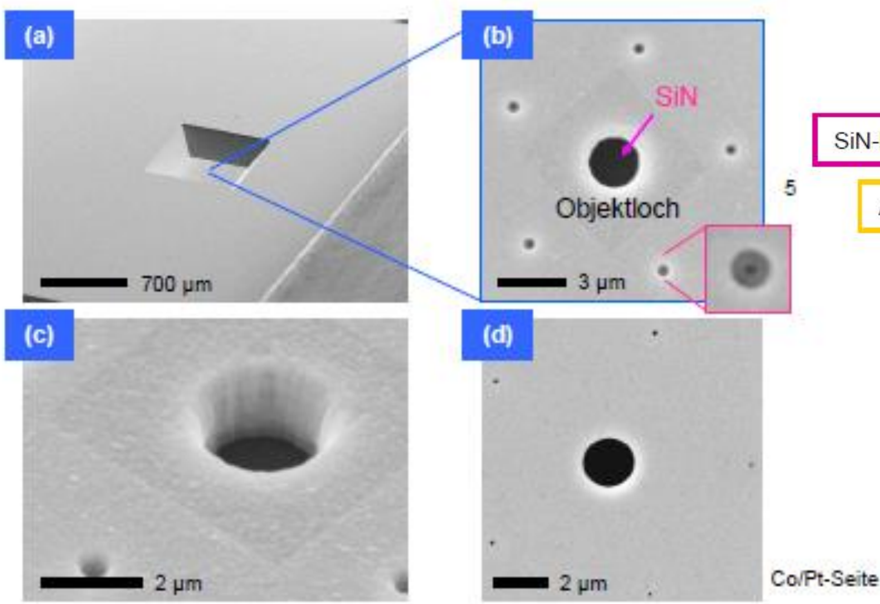
> Lensless Imaging – Fourier transform Holography

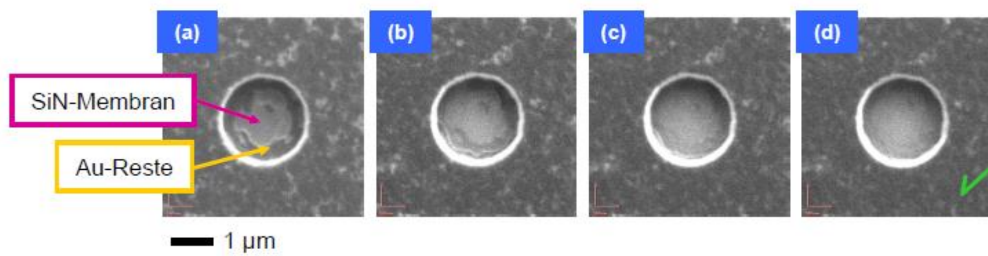
Mask and sample:

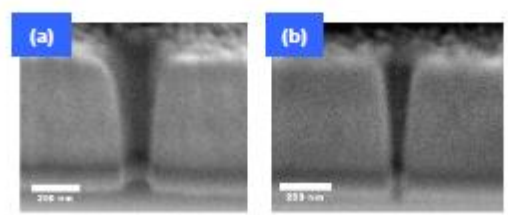
Preparation
by focused ion beam
technique



# Imaging of magnetic domain patterns with X-rays

> Lensless Imaging – Fourier transform Holography (FTH)

$$\tilde{f}_j(\vec{Q}) = FT(f_j(\vec{r}))$$

Principle:

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

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

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

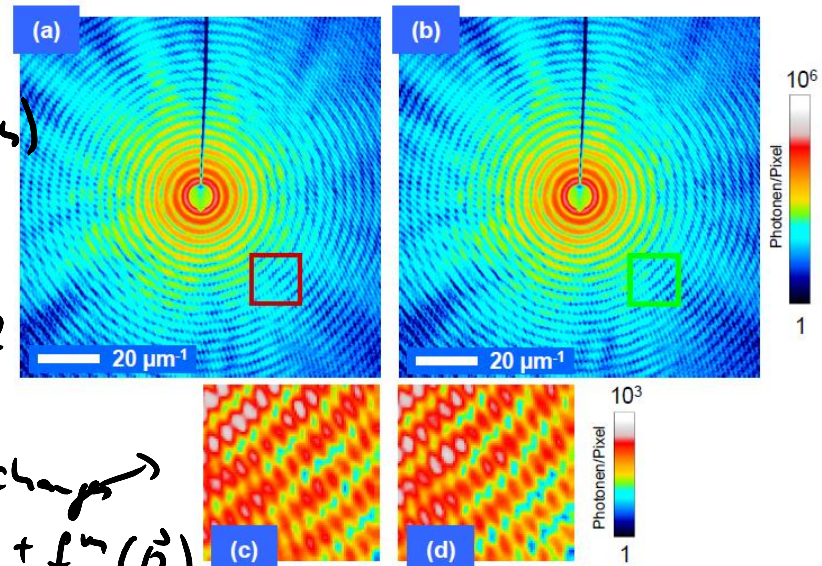
$$f = f^c(\vec{Q}) \pm f_0^m(\vec{Q}) \quad (+\text{RCP}, -\text{LCP for } \vec{m} \parallel \vec{L}_{ph})$$

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

- “Hologram” (= $I$(**Q**)) with RCP and LCP

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

subtle changes due to $\pm f_0^m(\vec{Q})$



# Imaging of magnetic domain patterns with X-rays

> Lensless Imaging – Fourier transform Holography (FTH)

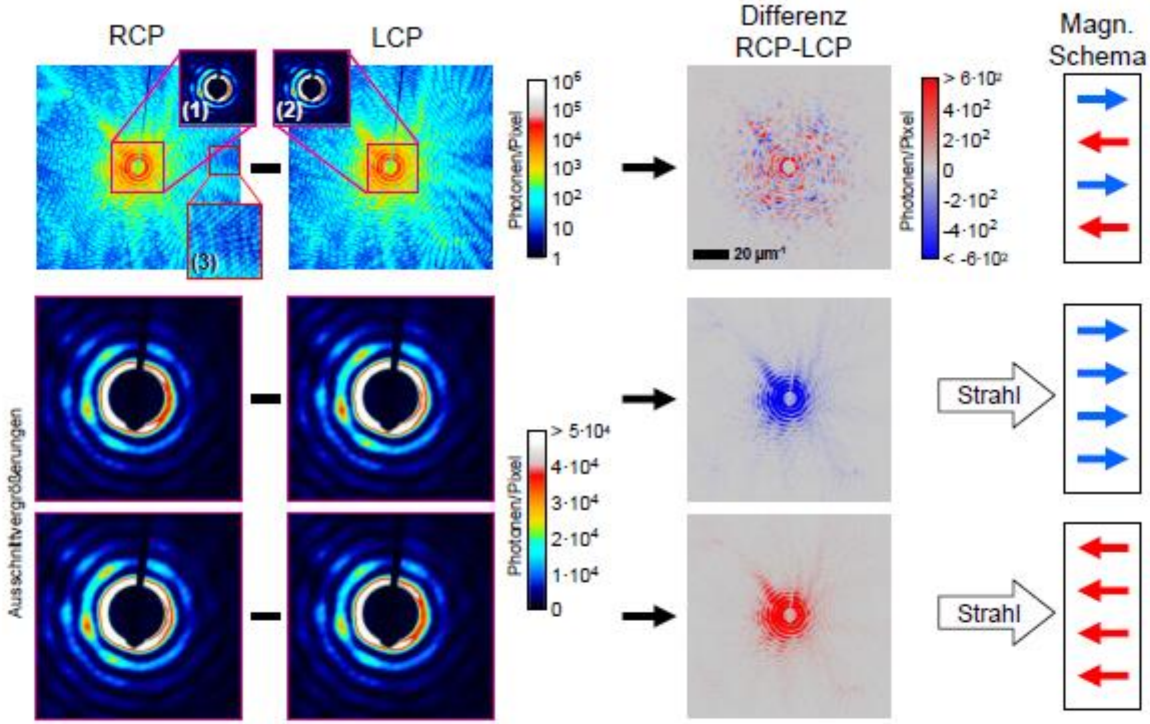
Principle:

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

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

$$= \tilde{f}_0^{-*} \cdot \tilde{f}_0^{c} + \tilde{f}_0^{-} \cdot f_0^{c*}$$

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



# Imaging of magnetic domain patterns with X-rays

> Lensless Imaging – Fourier transform Holography (FTH)

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

- Reconstruction = Fourier transformation: $= f(\vec{r})$ (inverse)

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

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

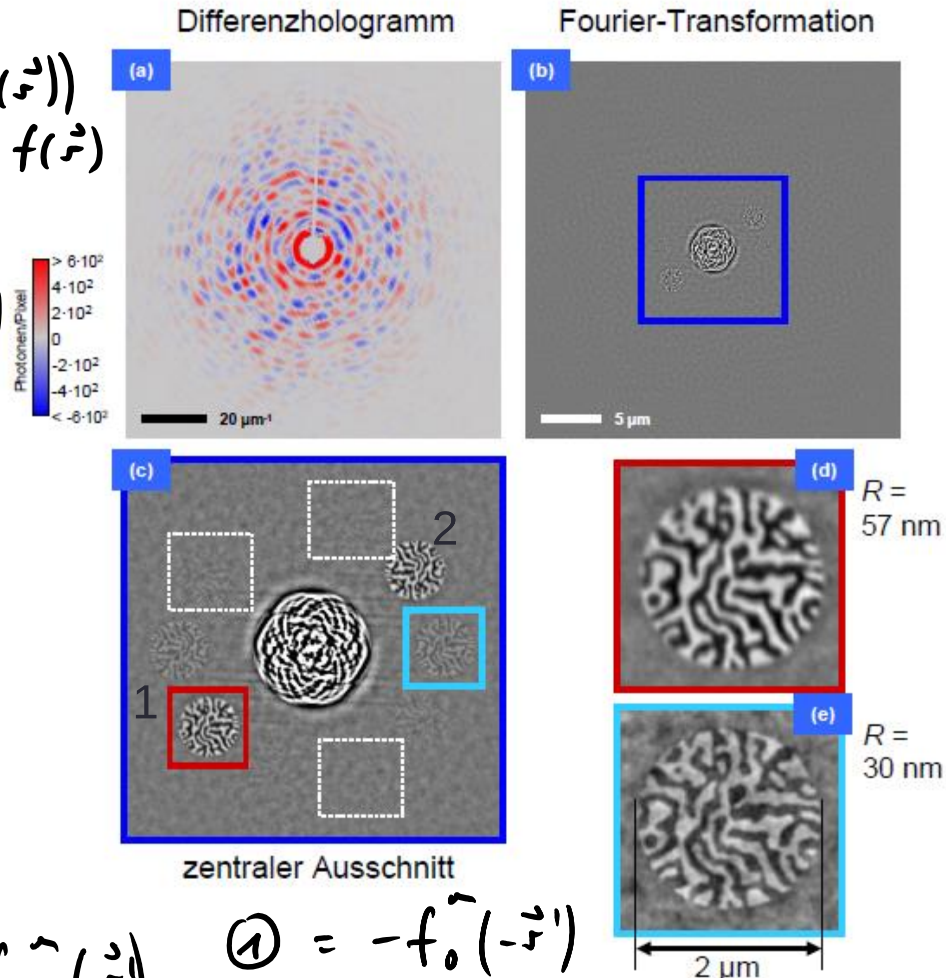
$$\underbrace{+ \overset{①}{FT^{-1}(\tilde{f}_0^{\sim *} \cdot \tilde{f}_R^{c})} + \overset{②}{FT^{-1}(\tilde{f}_0^{\sim} \cdot \tilde{f}_R^{c*})}}_{\text{Reconstructions}}$$

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

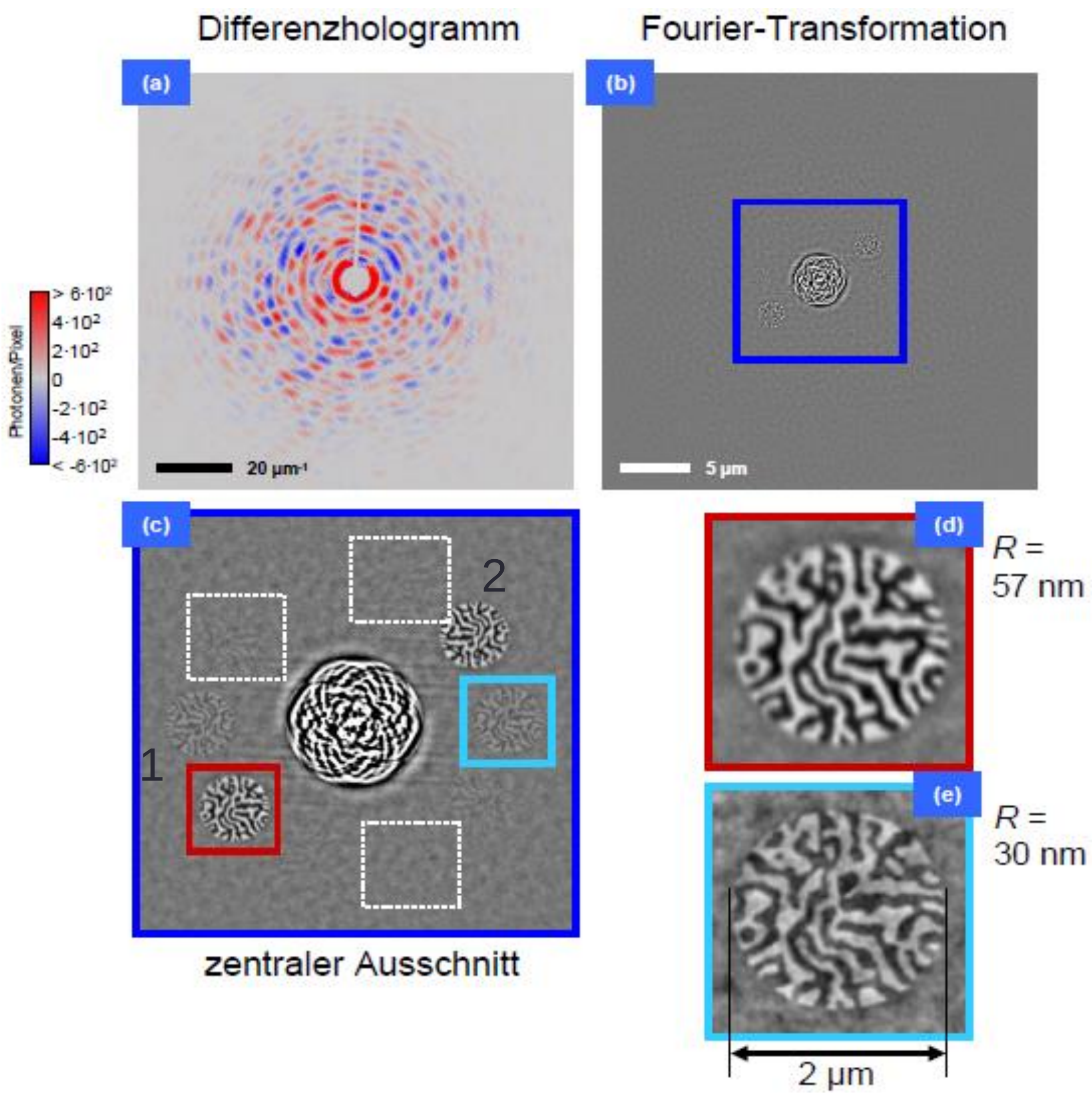
$$= f_0^{\sim}(\vec{r}) \otimes f_R^{c*}(\vec{r}) \leftarrow \delta\text{-Fkt}$$

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

$$① = -f_0^{\sim}(-\vec{r}')$$



# Imaging of magnetic domain patterns with X-rays

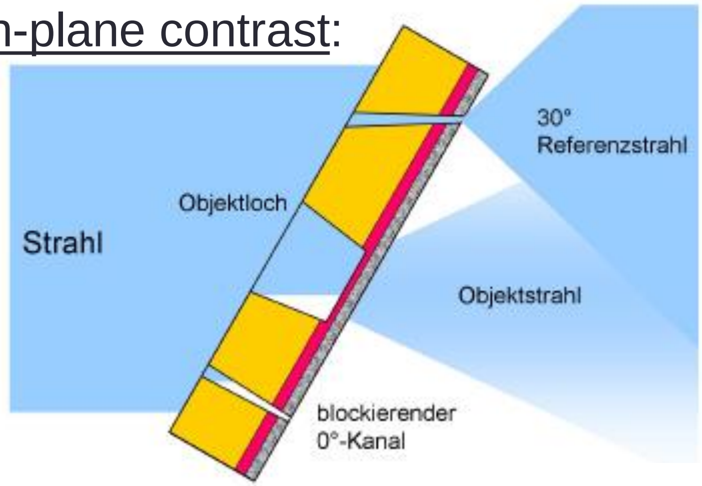



The FT of the Hologram shows the Patterson map of the Holographic mask with the magnetic structure. In the center there is the object-hole autocorrelation. The 10 reference-hole-object-hole cross correlations (2 for each reference hole) are arranged outside of that area. Large references yield high contrast but low resolution whereas small reference holes yield high resolution at low contrast.

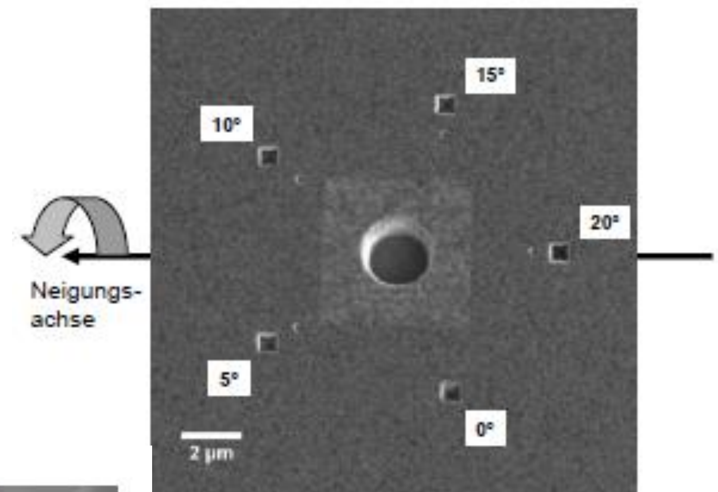
# Imaging of magnetic domain patterns with X-rays

> Lensless Imaging – Fourier transform Holography (FTH)

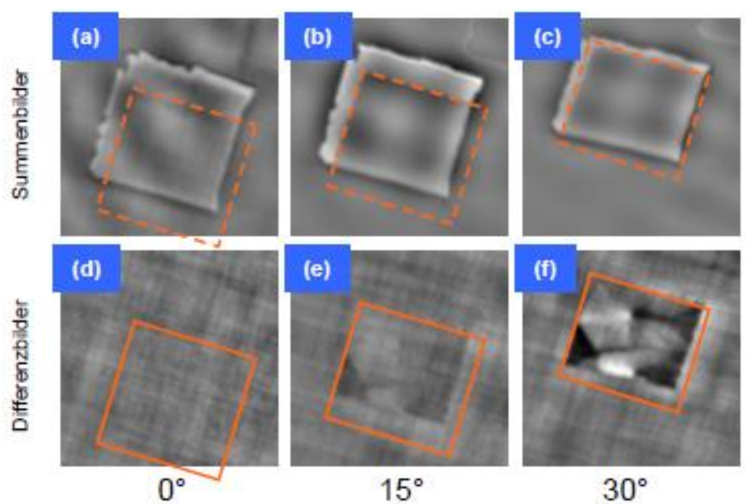
In-plane contrast:




References holes with different inclinations

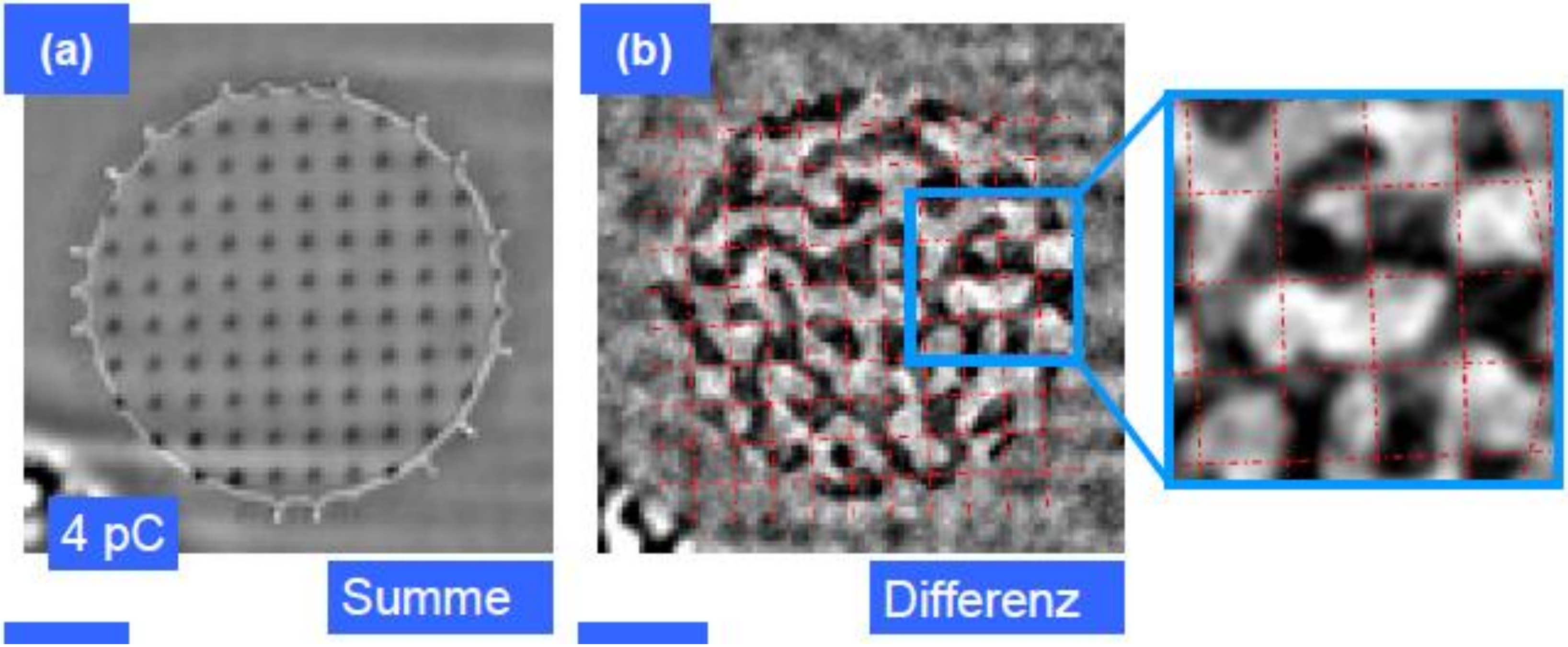


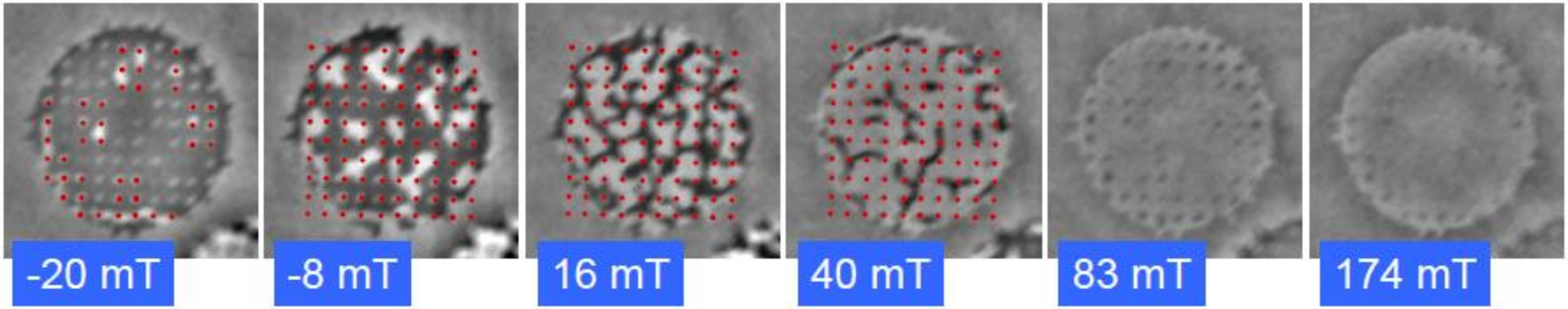

In-plane magnetized 20 nm thick Co film




$$\Delta I_{XMCD} \propto \vec{M} \cdot \vec{L}_{\gamma}$$

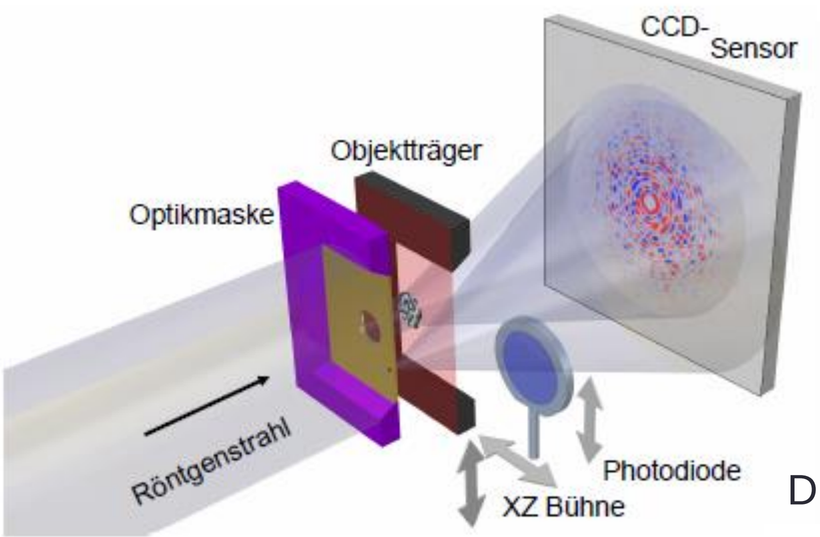
# > Lensless Imaging – Fourier transform Holography (FTH)

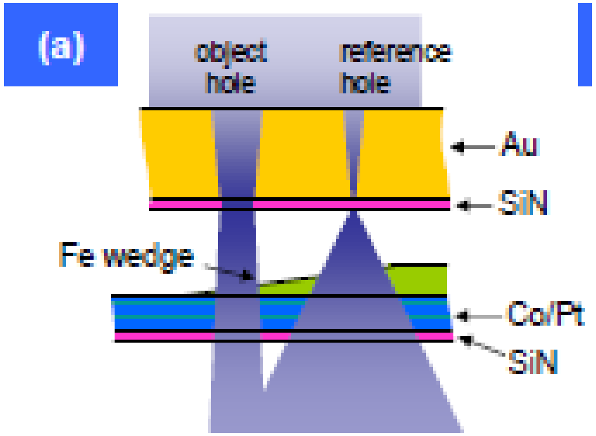


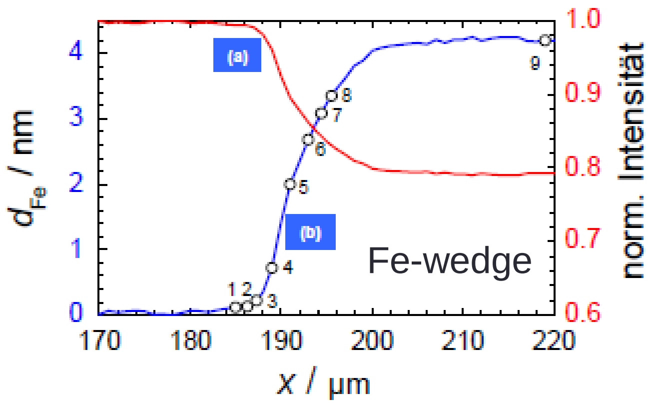
# Imaging of magnetic domain patterns with X-rays

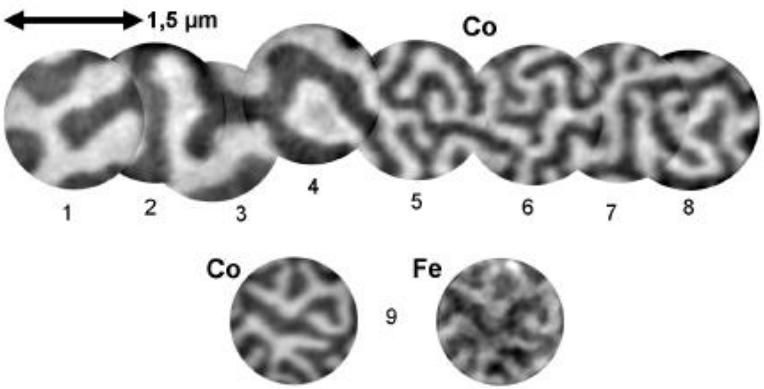
> Lensless Imaging – Fourier transform Holography (FTH)




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




Element-selectivity