

STATIC AND DYNAMIC MAGNETIC IMAGING USING X-RAY BASED TECHNIQUES

Victor Ukleev

Spin and Topology in Quantum Materials

Helmholtz-Zentrum Berlin für Materialien und Energie, Germany

Advanced Microscopy techniques for characterizing the
magnetic properties of materials

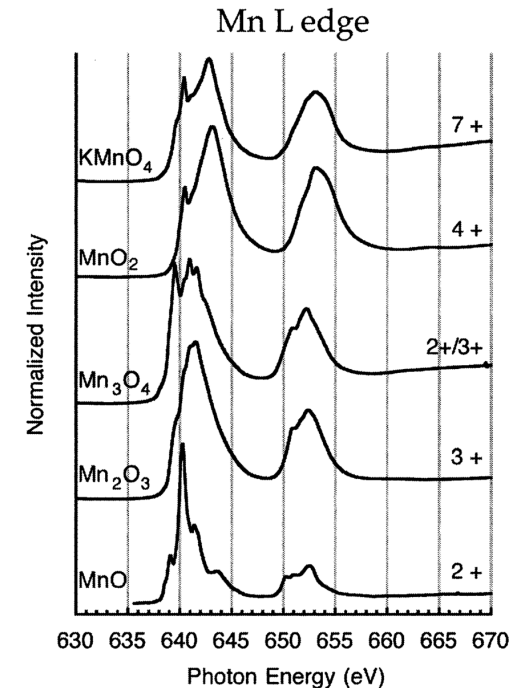
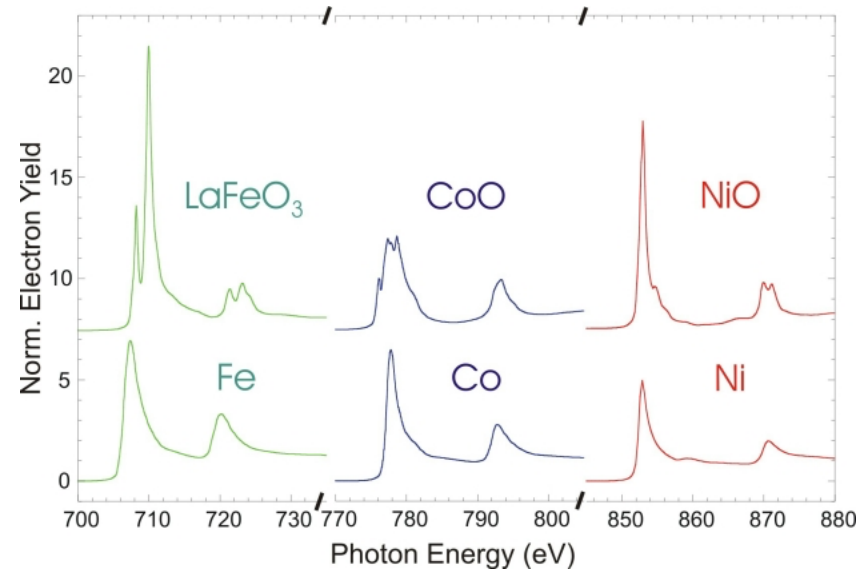
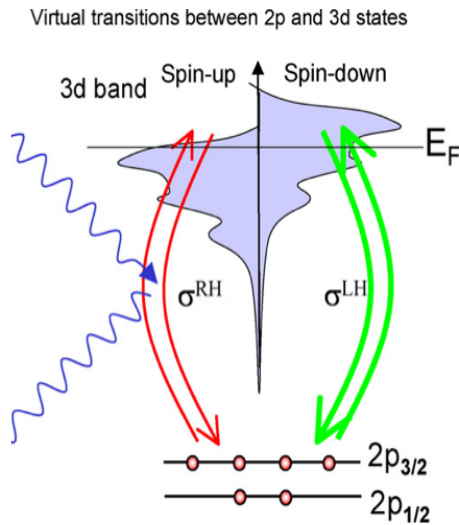
EPFL
Switzerland
16.11.2022

- Introduction:
 - x-ray absorption and x-ray magnetic dichroism
 - resonant x-ray absorption and scattering
 - polarized x-ray sources and beamline optics
 - Classic x-ray magnetic imaging techniques
 - Photoemission electron microscopy (PEEM)
 - Transmission x-ray microscopy
-
- State-of-the-art techniques
 - Coherent x-ray diffraction imaging and holography
 - Three-dimensional x-ray imaging
 - Time-resolved magnetic x-ray imaging with synchrotrons and free-electron lasers
 - Summary

Polarization-dependent x-ray absorption

INTRODUCTION

- *L*-edges of transition metals: probes valence states and magnetism
- Peak corresponds to transition from core level to valence band
- Soft x-rays: ~ 100 eV ... ~ 2 keV
- Due to the symmetry of the transition operator we obtain the dipole selection rules: $\Delta s=0$ $\Delta l=\pm 1 \rightarrow$ orbital and spin moment selectivity



Sensitivity to magnetism

Theoretical prediction -> 1975

PHYSICAL REVIEW B VOLUME 12, NUMBER 11 1 DECEMBER 1975

Calculation of the M_{23} magneto-optical absorption spectrum of ferromagnetic nickel

J. L. Erskine*
Department of Physics, University of Illinois, Urbana, Illinois 61801

E. A. Stern†
Department of Physics, University of Washington, Seattle, Washington 98195
 (Received 28 April 1975)

Experimental observation -> 1987

VOLUME 58, NUMBER 7 PHYSICAL REVIEW LETTERS 16 FEBRUARY 1987

Absorption of Circularly Polarized X Rays in Iron

G. Schütz, W. Wagner, W. Wilhelm, and P. Kienle^(a)
Physik Department, Technische Universität München, D-8046 Garching, West Germany

R. Zeller
Institut für Festkörperforschung der Kernforschungsanlage Jülich, D-5175 Jülich, West Germany

and

R. Frahm and G. Materlik
Hamburger Synchrotronstrahlungslabor am Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg 52, West Germany
 (Received 22 September 1986)

Polarization-dependent absorption of circularly polarized x-rays by magnetic materials (magnetic atoms)

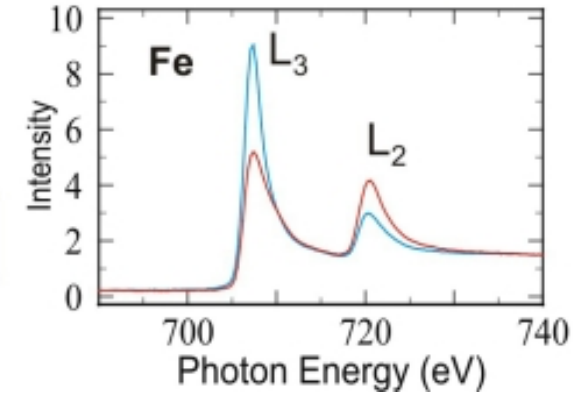
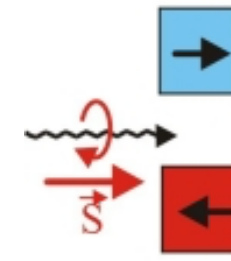
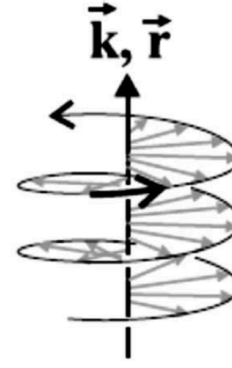
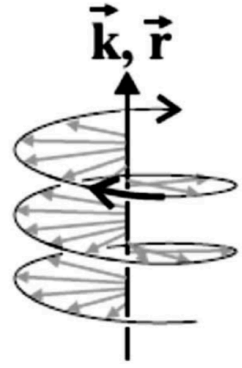
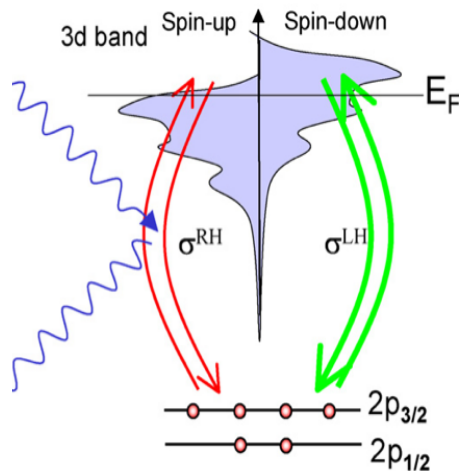
- Element-specific magnetic contrast
- Spin and orbital moment selectivity
- Very high sensitivity

• X-ray techniques can be transferred into it's magnetic counterpart, by tuning the x-ray energy to a corresponding XMCD sensitive edge: microscopy, spectroscopy, diffraction, reflectometry, small-angle scattering, etc.

X-ray magnetic circular dichroism (XMCD)

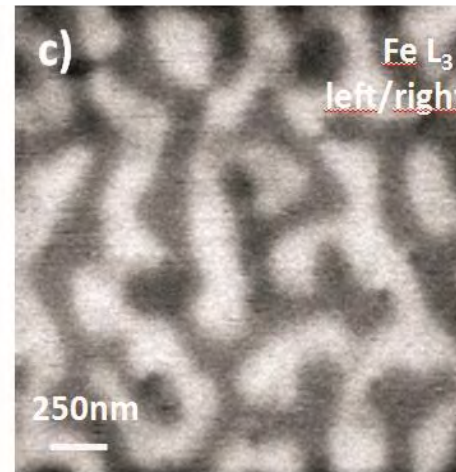
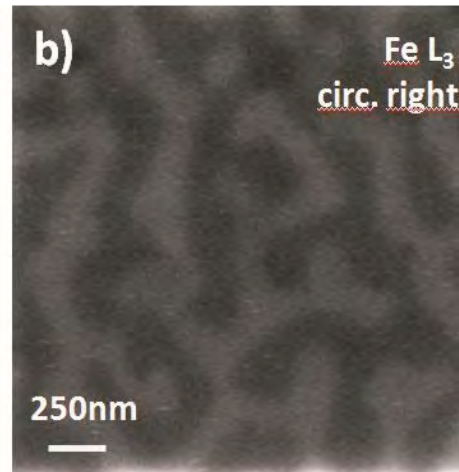
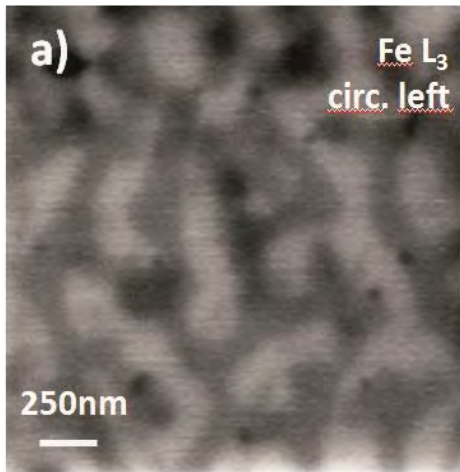
Circular dichroism - a tool to study ferro(ferri)magnets

Virtual transitions between 2p and 3d states



$$I(z) = I_0 e^{-\mu_x z}$$

where μ is material-specific coefficient dependent on photon energy



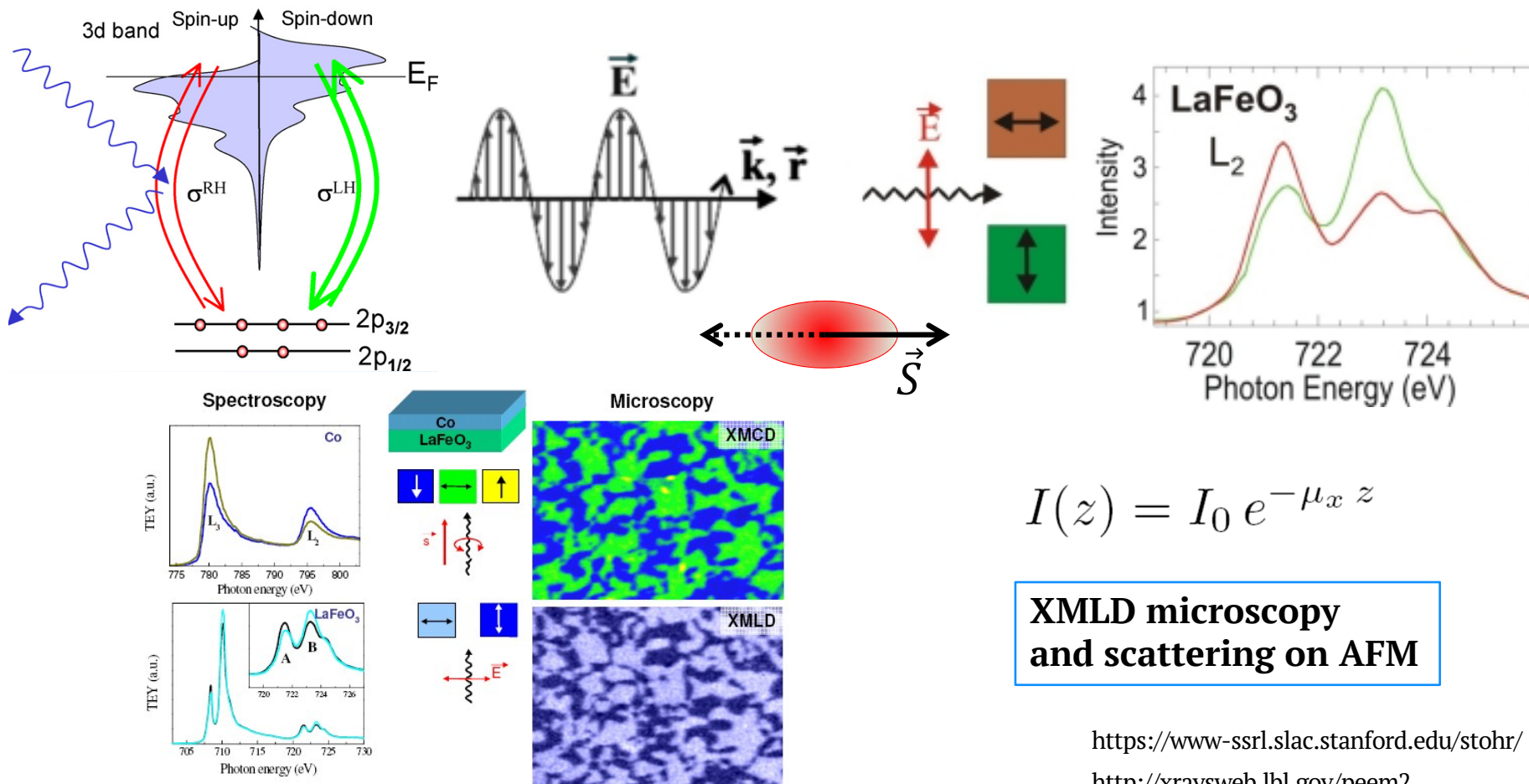
**XMCD microscopy
and scattering**

X-ray magnetic linear dichroism (XMLD)

INTRODUCTION

Linear dichroism - a tool to study antiferromagnets

- XMLD is sensitive to the antiferromagnetic order: spin orbit coupling breaks spherical symmetry of the charge density
- XMLD is quadratic to magnetization
- Similarly to XMCD allows to employ magnetic and element-selective imaging



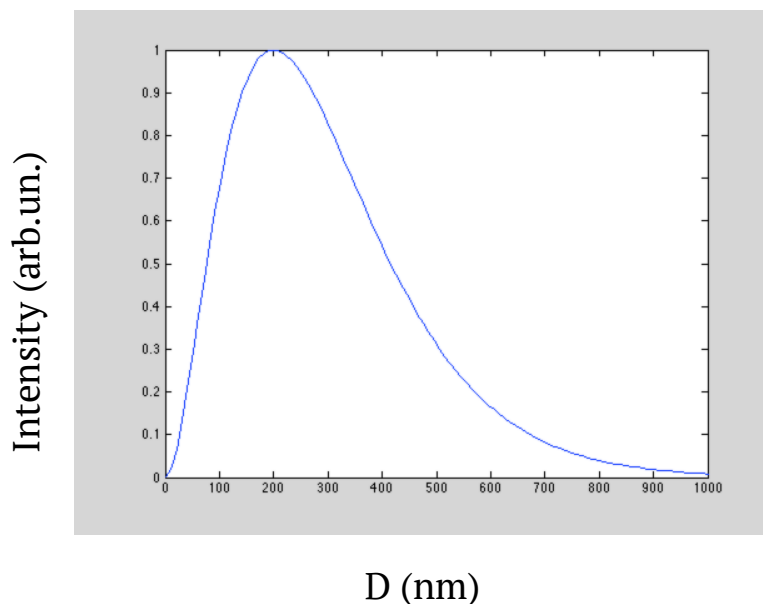
X-ray resonant magnetic scattering (XRMS)

- Same transition is used to observe resonant scattering and diffraction: $L_{2,3}$ edges of TM correspond to soft x-rays in the energy range of 480 – 950 eV, $\lambda \sim 15\text{-}20 \text{ \AA}$
- Resonant x-rays allow both reciprocal (scattering) and real-space (imaging)

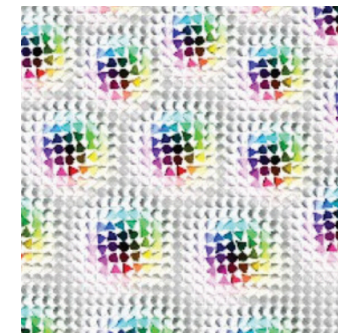
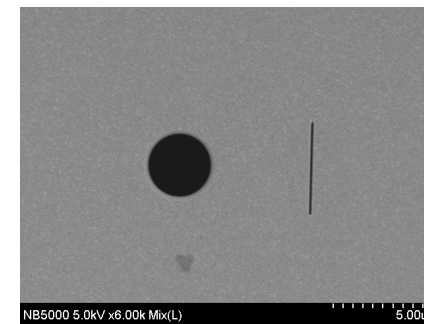
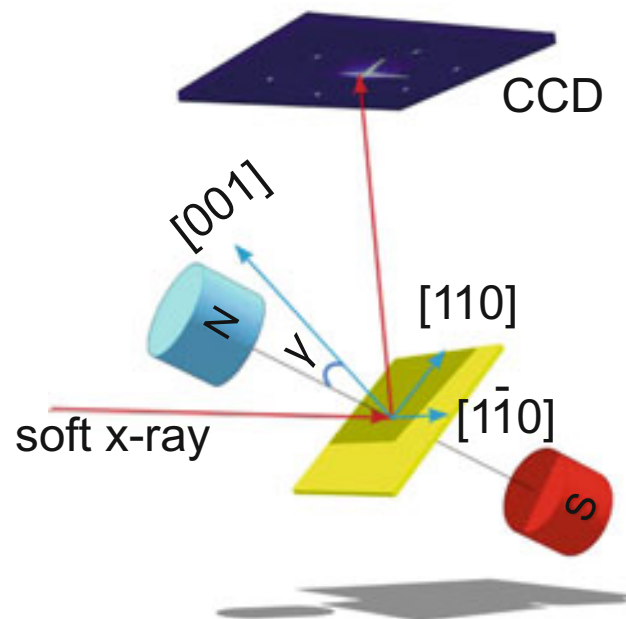
Thickness: transmission vs magnetic scattering intensity

$$I_{mag} \sim M^2 = (\mu A z)^2$$

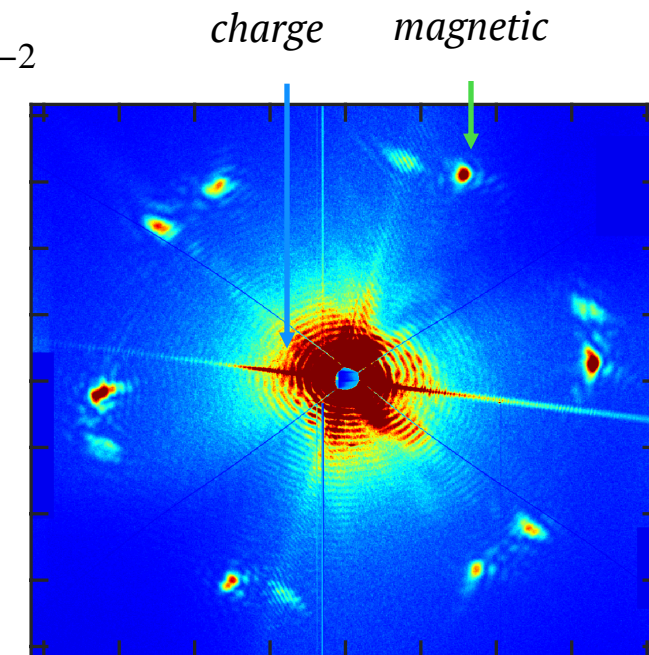
$$I_{trans} = I_0 \exp(-l_{att} z)$$



$$f^n = \underbrace{(e_n \cdot e'_n) f_c^n}_{\text{charge}} + \underbrace{i(e_n \times e'_n) \cdot M^n f_{m1}^n}_{\text{magnetic}} + \underbrace{(e_n \cdot M^n)(e'_n \cdot M^n) f_{m2}^n}_{\text{magnetic}}$$



$$\frac{\sigma_m}{\sigma_c} \sim 10^{-2}$$



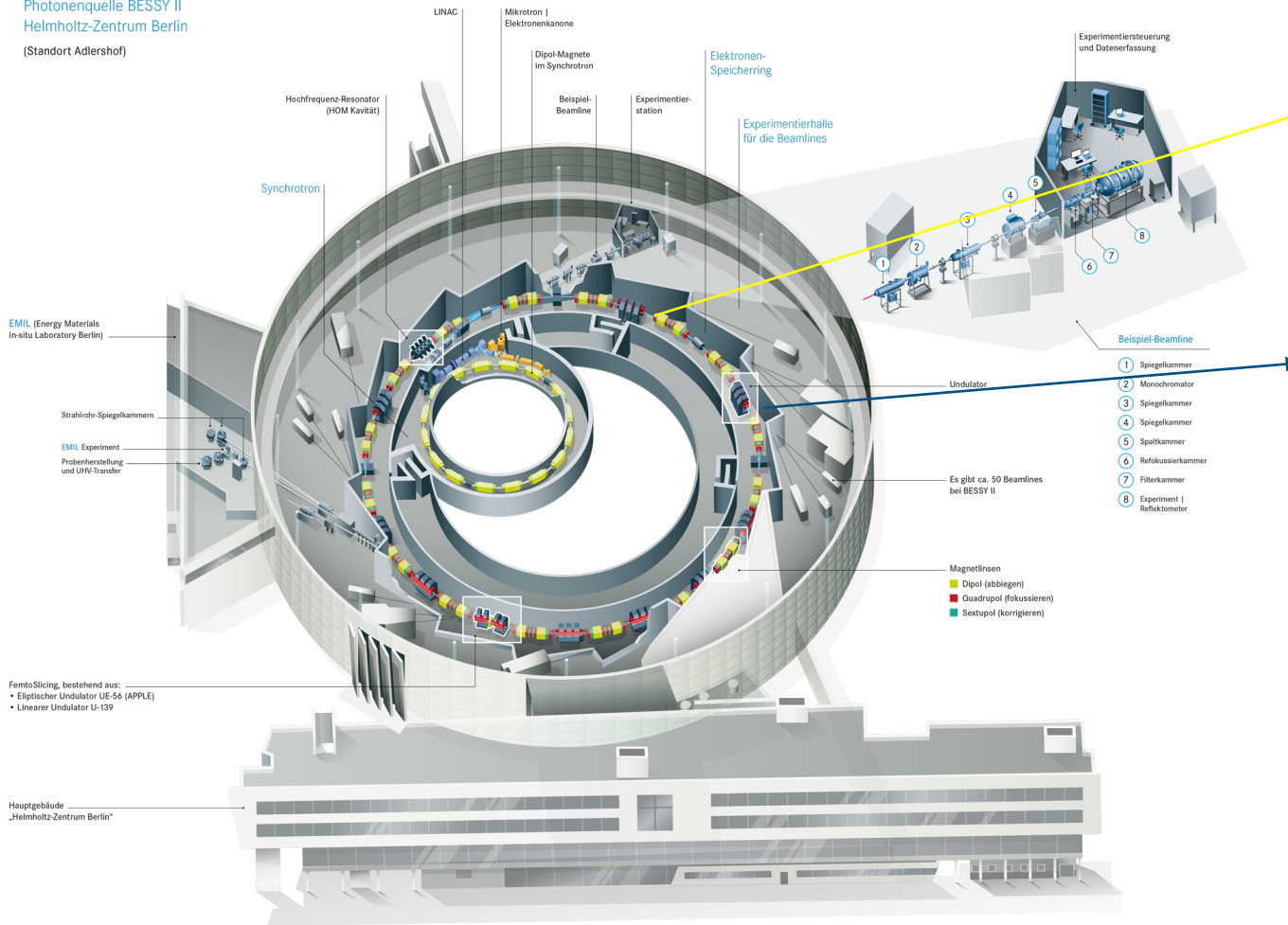
V.U., unpublished

INTRODUCTION

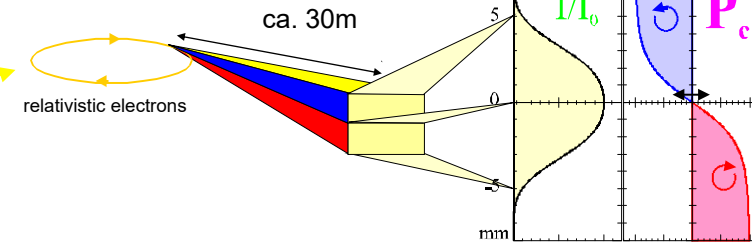
Polarized synchrotron x-rays

Polarised synchrotron radiation by bending magnets and insertion devices (IDs)

Photonenquelle BESSY II
Helmholtz-Zentrum Berlin
(Standort Adlershof)



bending magnet



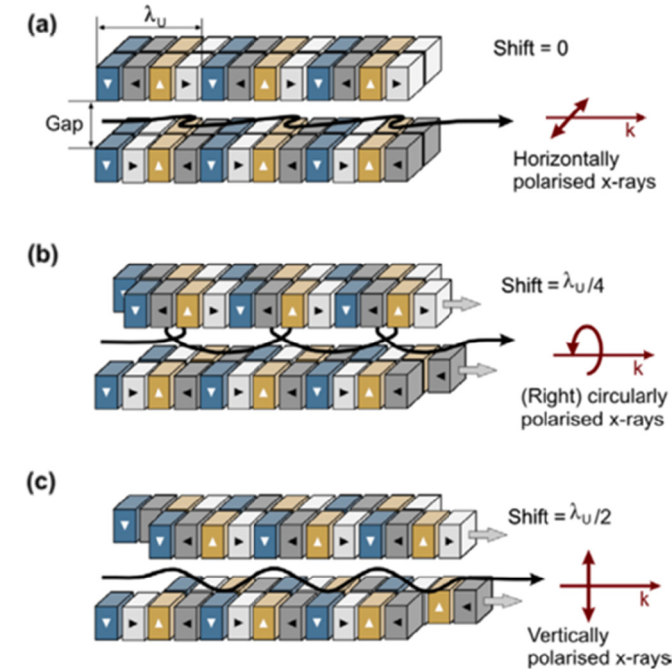
Circular +

Linear horizontal

Circular -

Controlled by the beamline optics

undulator

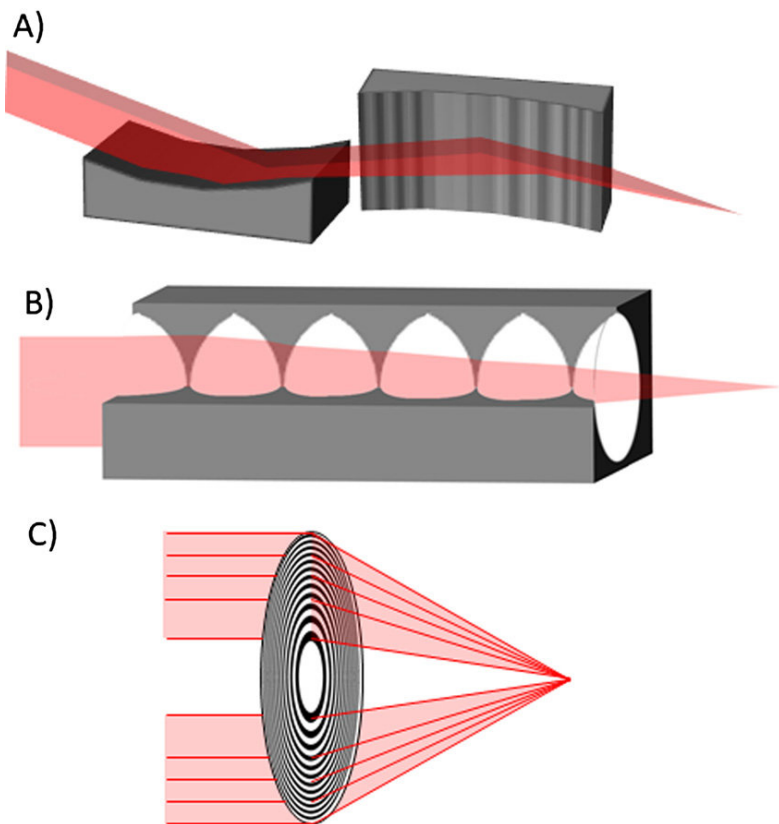


Circular, elliptic
any linear angle, in principle
controlled by the undulator

~1000 higher brilliance

X-ray optics

INTRODUCTION



(A) Kirkpatrick–Baez (KB) mirror system

Diffraction, spectroscopy, etc.

(B) compound refractive lenses (CRL)

High energy x-rays

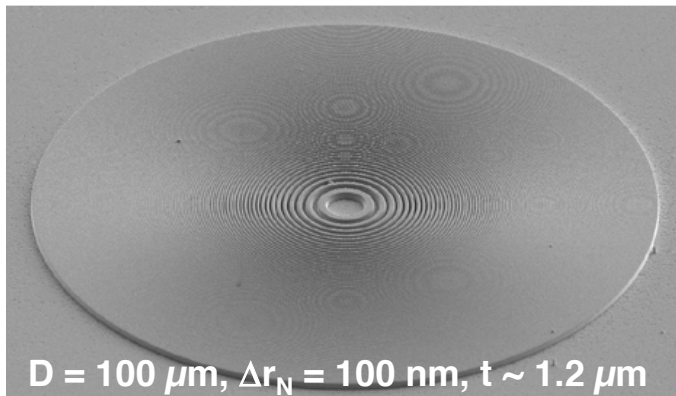
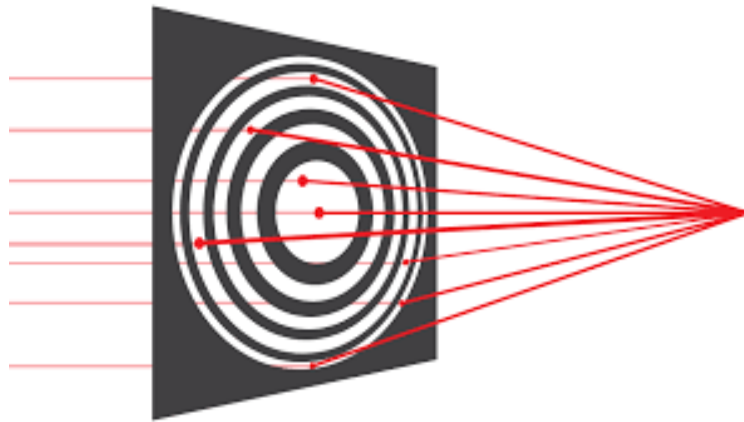
(C) Fresnel zone-plates (FZP)

Microscopy, nano-spectroscopy

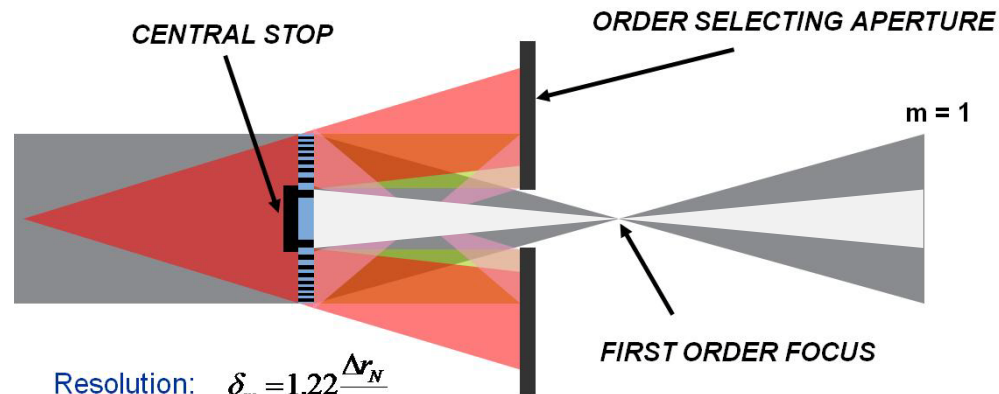
X-ray Optics	CRLs	Fresnel ZP	KB Mirrors
ZP-equivalent Numerical Aperture (based on outermost zone; smaller is better)	30 nm	30 nm	16 nm
Achievable Focus Resolution (Typical Value Best Possible)	Very High (1 μm <30 nm)	Very High (200 nm 10 nm)	Very High (1 μm 20 nm)
Handling/Ease of Alignment (Compact)	✓	✓	✗
Achromatic	✗	✗	✓
Working Distance Range Selection	5 mm – 10's m	1 mm – 30 mm	10 cm – 10's m
Efficiency	~50%	~10%	~75%
In-line with Beam	✓	✓	✗
Price (including beamline costs & motion control systems)	Depends	High	Mid to High (long beamline & stability needs)

X-ray optics

INTRODUCTION



Alternate 'zones' modify phase/amplitude of incident wavefront:
for material of thickness (t), wavelength (λ), refractive index ($1-\delta-i\beta$), the phase shift $\Delta\phi$, is: $\Delta\phi = 2\pi\delta t/\lambda$



Resolution: $\delta_m = 1.22 \frac{\Delta r_N}{m}$

Focal length: $f_m = \frac{D \Delta r_N}{m \lambda}$

Working distance is 0.5 - 1.5 mm depending on the ZP and the x-ray wavelength

λ (nm)	Material	δ	β	Thick [†] (nm)	Transmission
13.5	Ru	0.113	0.017	59.7	0.38
13.5	Mo	0.076	0.0064	88.8	0.59
0.155 (8 keV)	Si	7.67e-6	1.77e-7	10000	0.86
0.155 (8 keV)	Au	4.77e-5	4.96e-6	1600	0.52

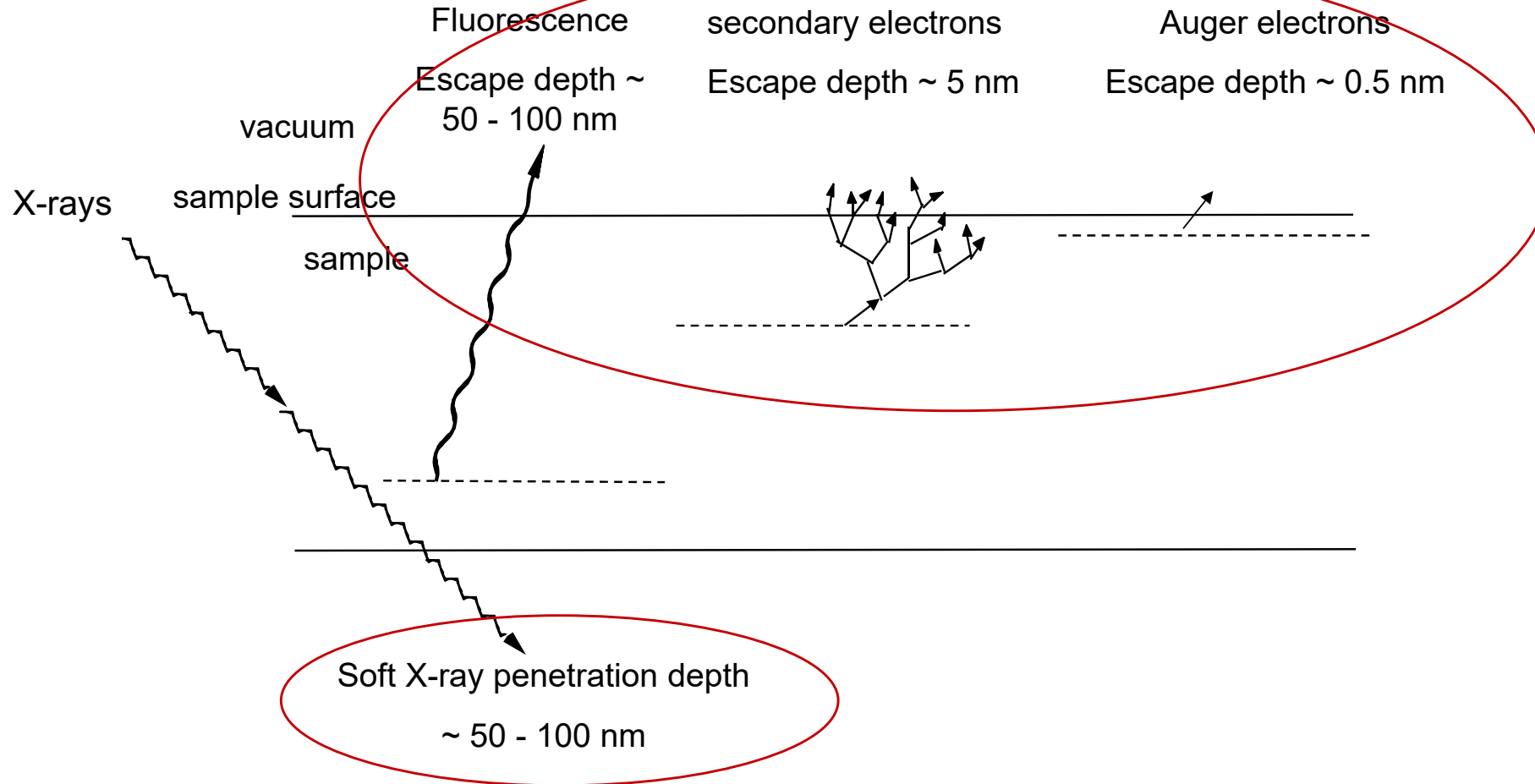
<http://zoneplate.lbl.gov/theory>

Barrett, R., X-ray Optics for Synchrotron Radiation Beamlines (ESRF)

X-ray detection

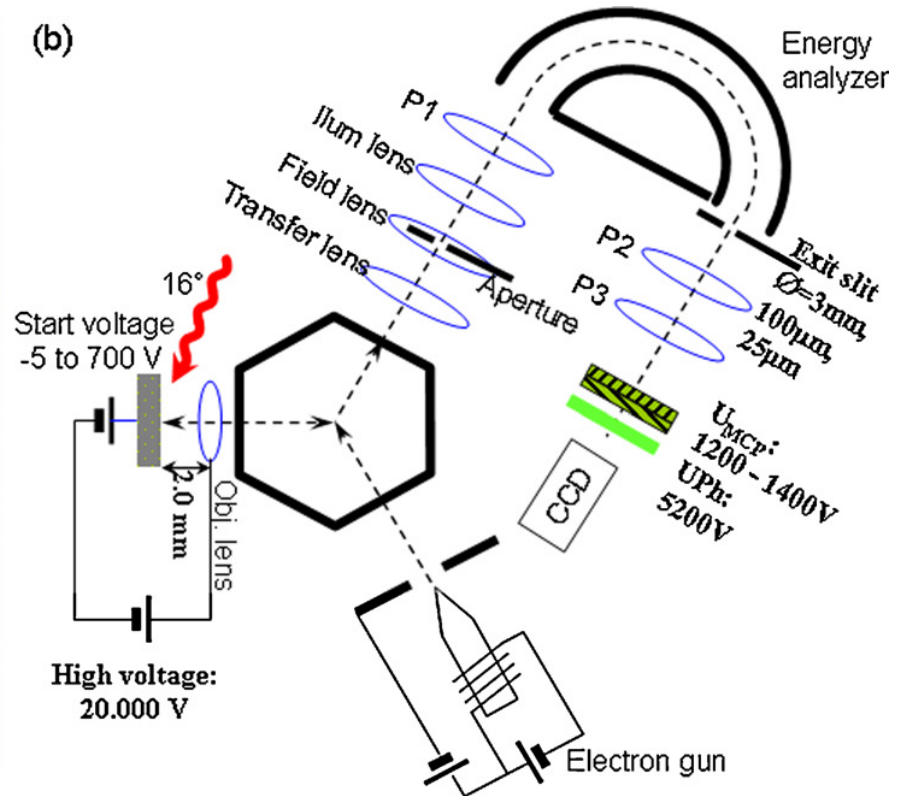
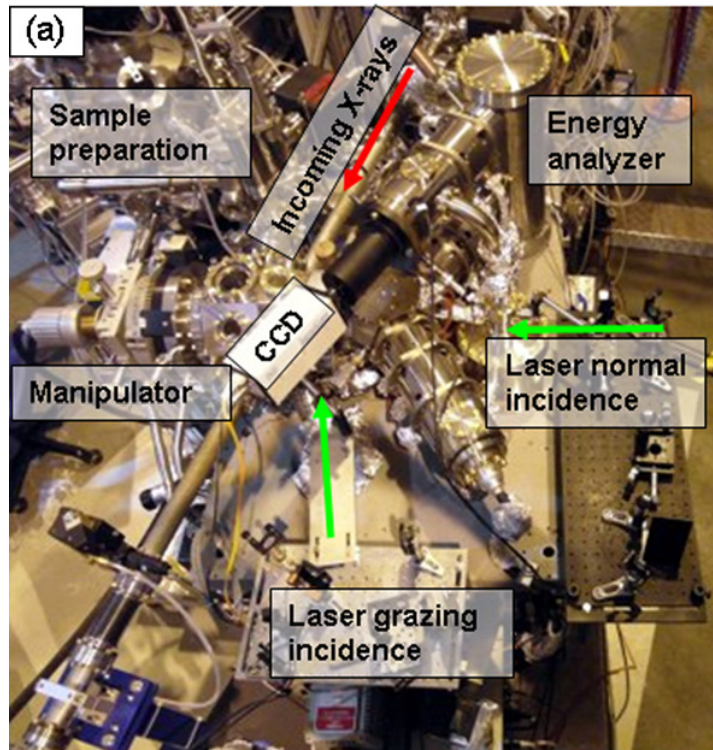
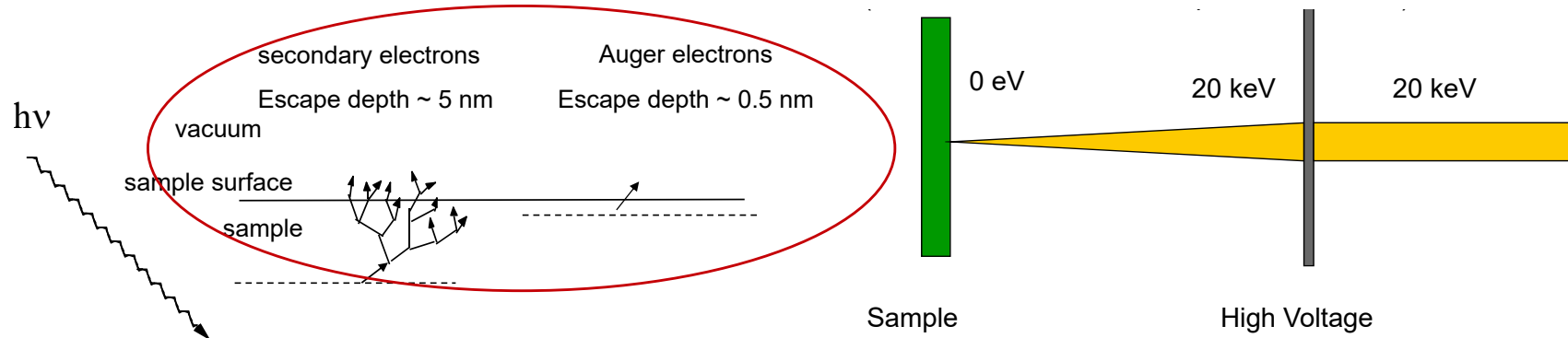
INTRODUCTION

Photoemission electron microscopy (PEEM)

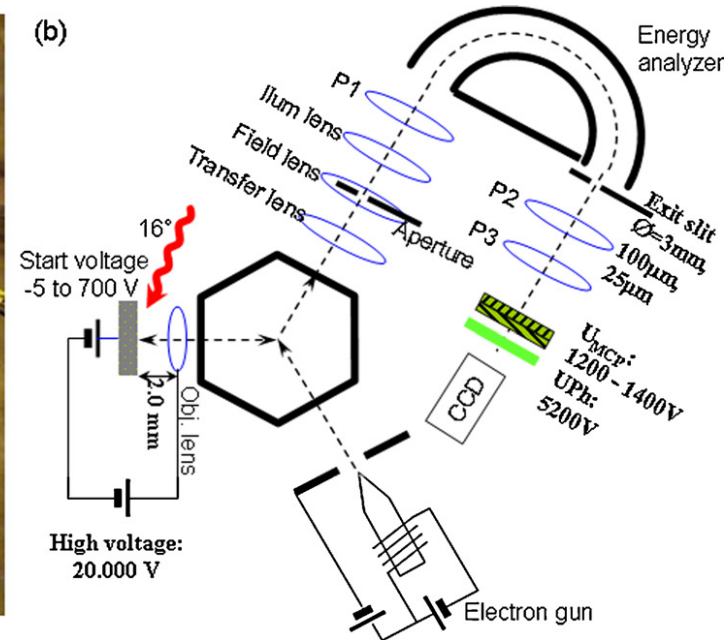
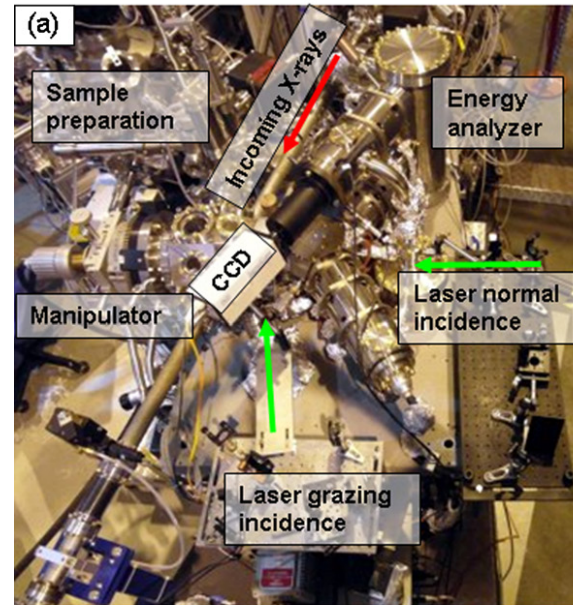


Transmission x-ray microscopy (TXM), scanning TXM, holography, coherent diffraction imaging, ptychography, etc.

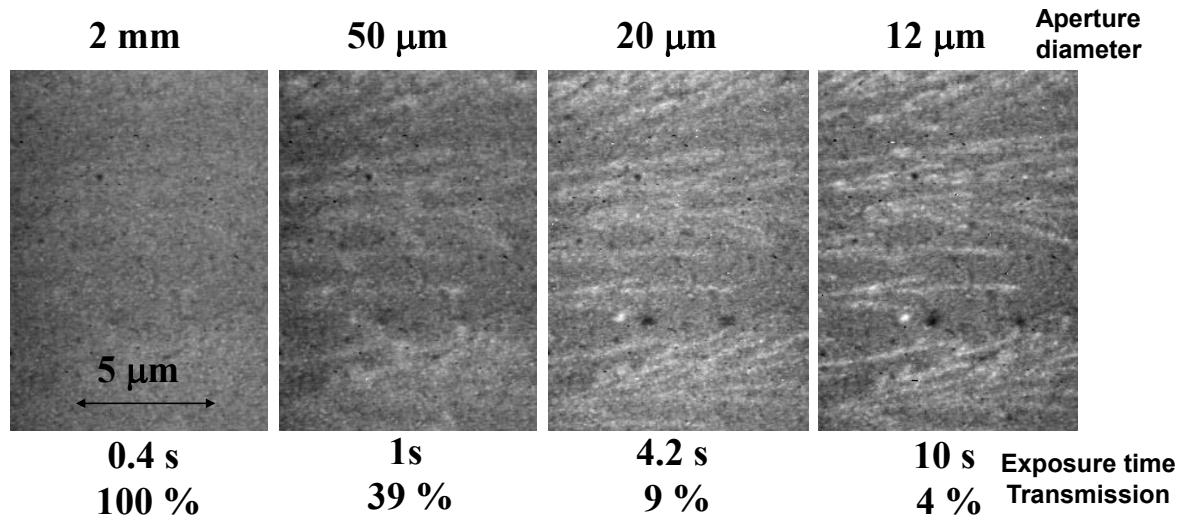
X-ray photoemission electron microscopy (PEEM)



X-ray photoemission electron microscopy (PEEM)



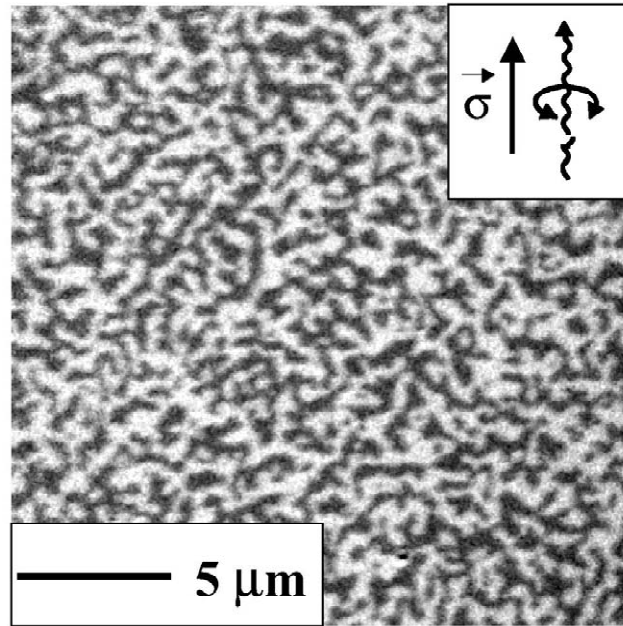
Aperture size and resolution



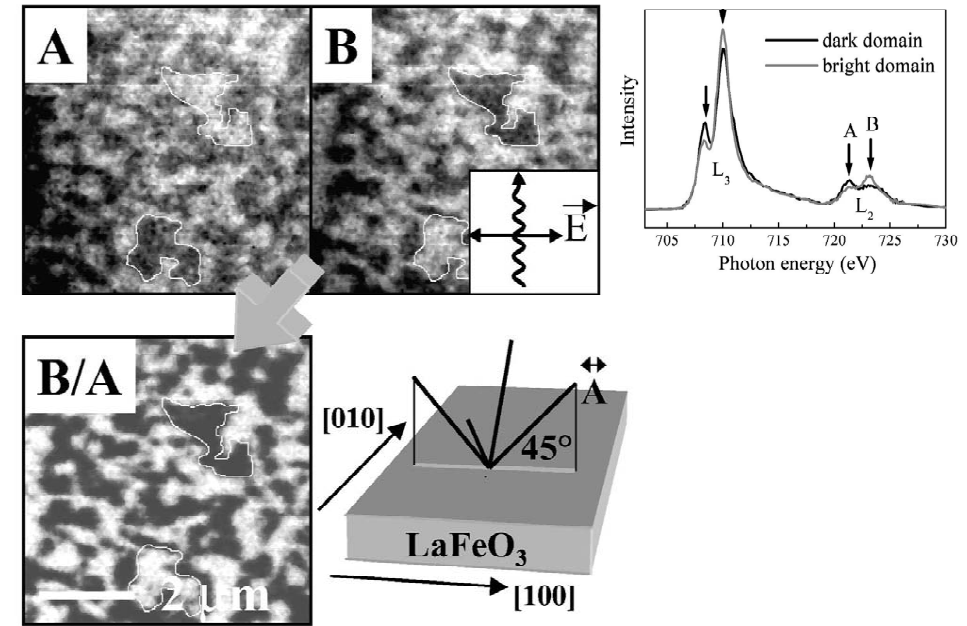
Aberration correction allows to push the resolution down to a few nm

X-ray photoemission electron microscopy (PEEM)

Magnetic domains

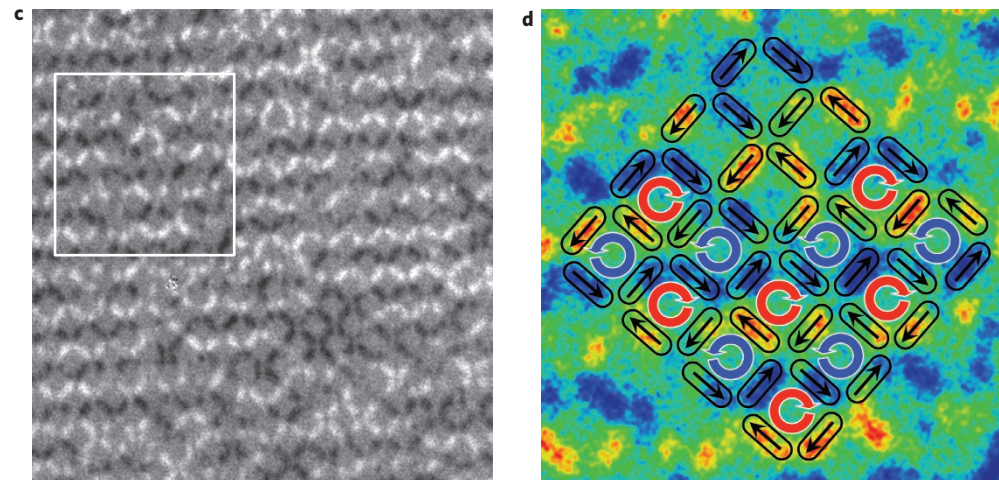
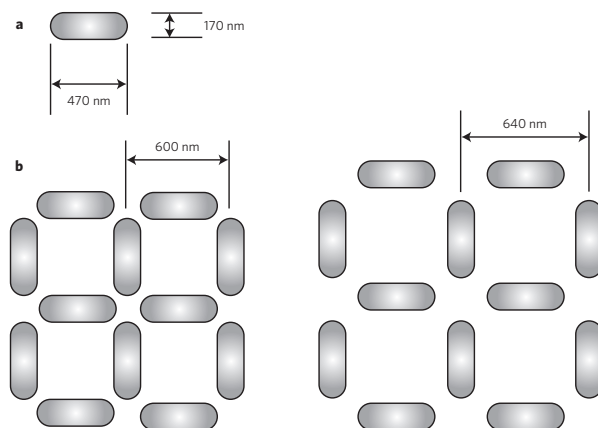


FM (0.7 nm Co) AFM (LaFeO₃)

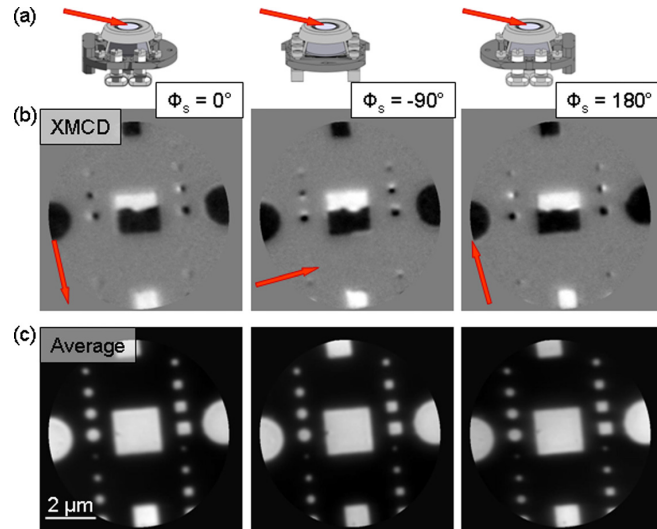


A. Scholl / Current Opinion in Solid State and Materials Science 7 (2003) 59–66

Artificial spin ice

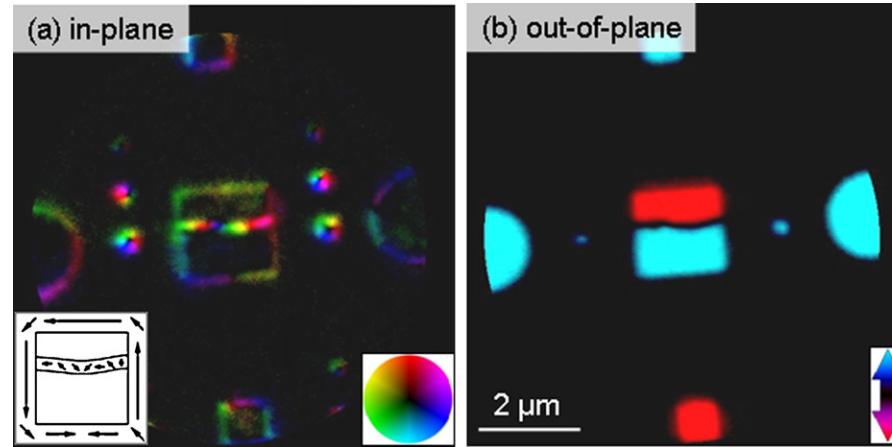


Vector mapping of magnetization



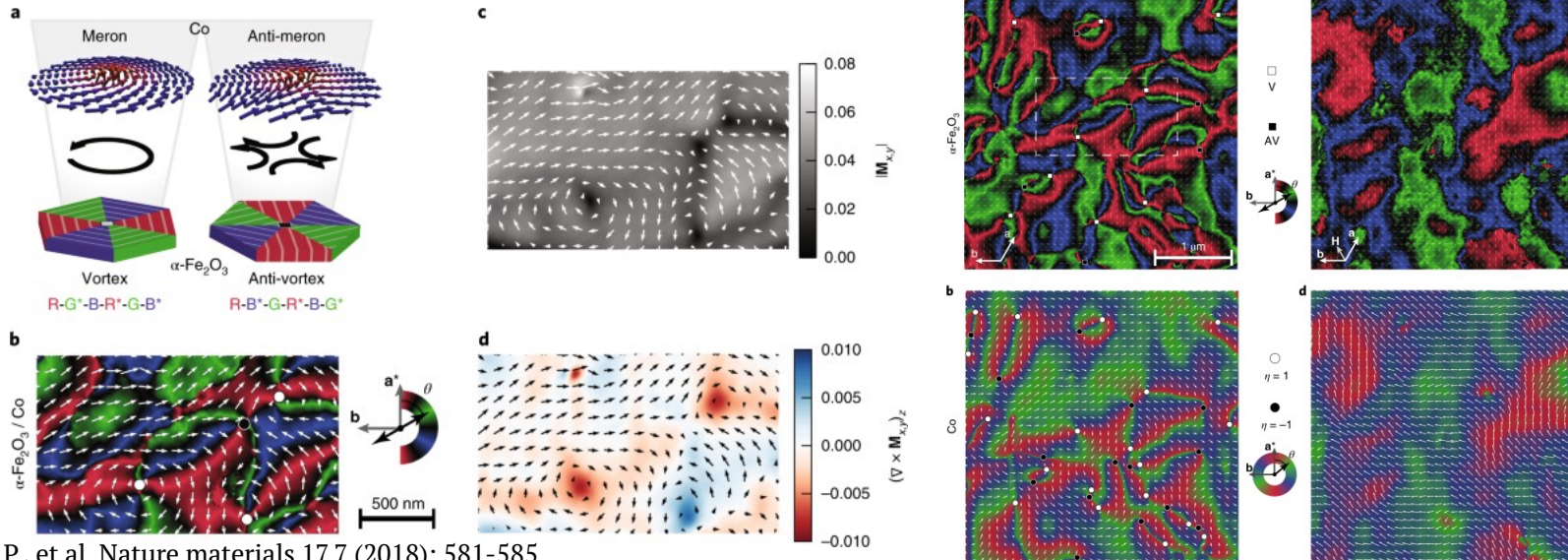
$$I_{\text{XMCD}} = (I_{\sigma+} - I_{\sigma-}) / (I_{\sigma+} + I_{\sigma-}) = \mathbf{M} \cdot \mathbf{K} = \langle \mathbf{M} \rangle \cos(\alpha)$$

Patterned FiM GdFeCo nanostructure



L. Le Guyader et al., Journal of Electron Spectroscopy and Related Phenomena 185 (2012)

Topological AFM vortices in $\alpha\text{-Fe}_2\text{O}_3/\text{Co}$

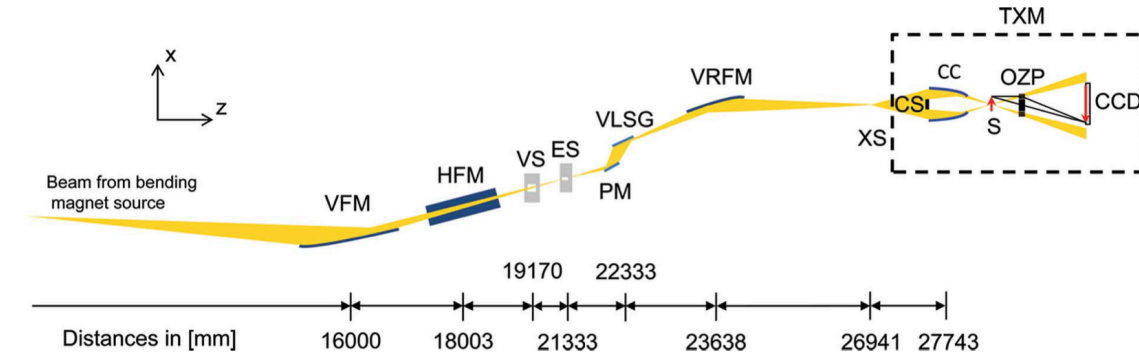


Chmiel, F. P., et al. Nature materials 17.7 (2018): 581-585.

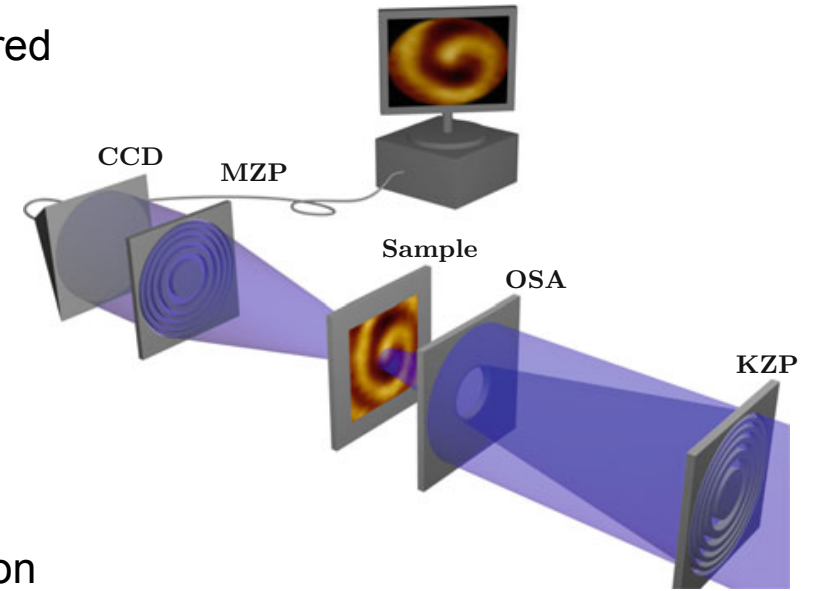
Transmission x-ray microscopy

TECHNIQUES

Beamline layout (MISTRAL, ALBA, Spain)

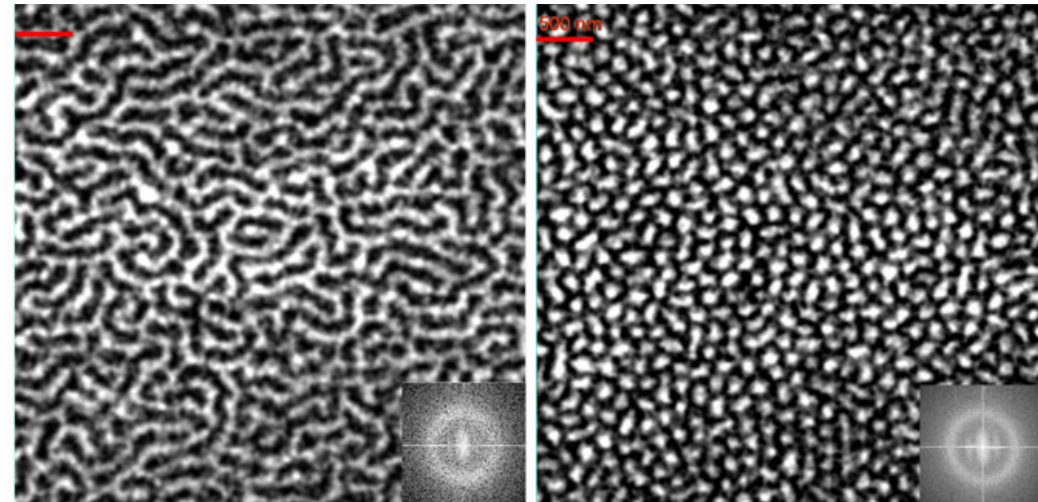
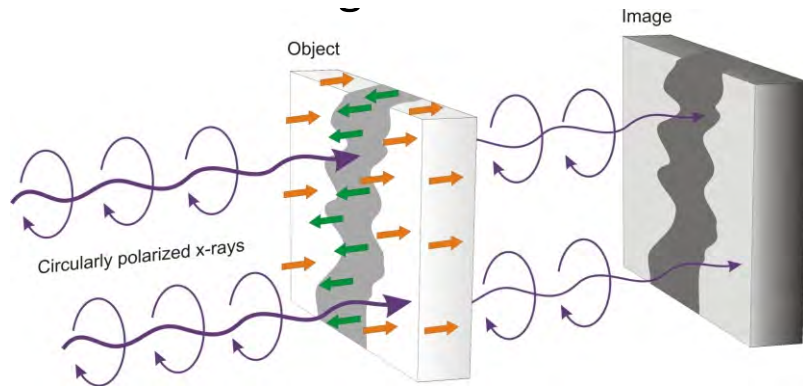


Full-field image measured by a 2D detector



~10 nm spatial resolution

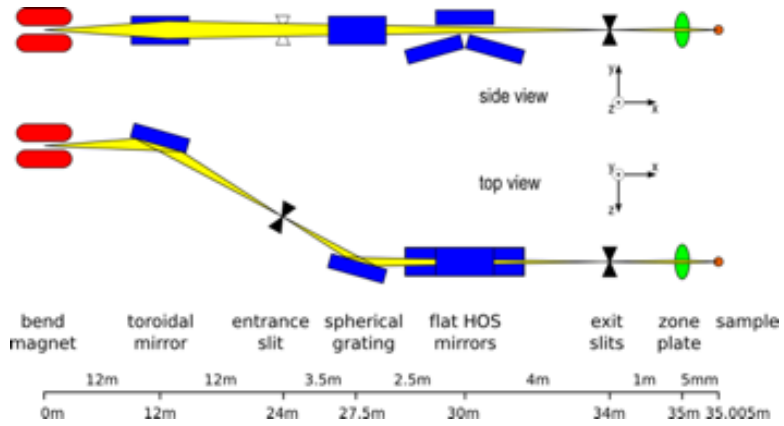
XMCD contrast in transmission



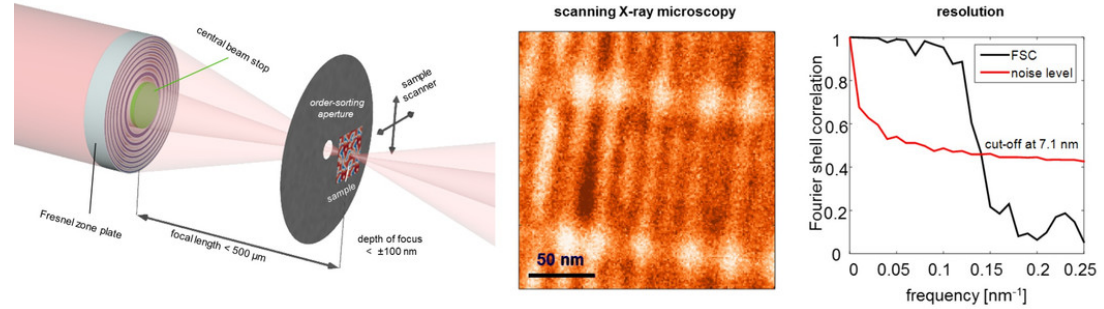
TECHNIQUES

Scanning transmission x-ray microscopy

Beamline layout (PoLux, Swiss Light Source, PSI)



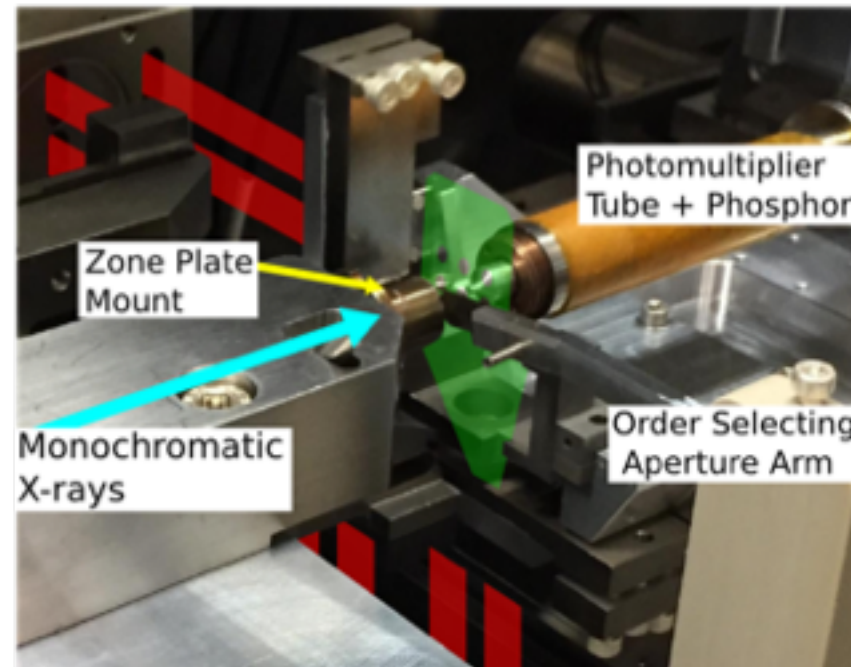
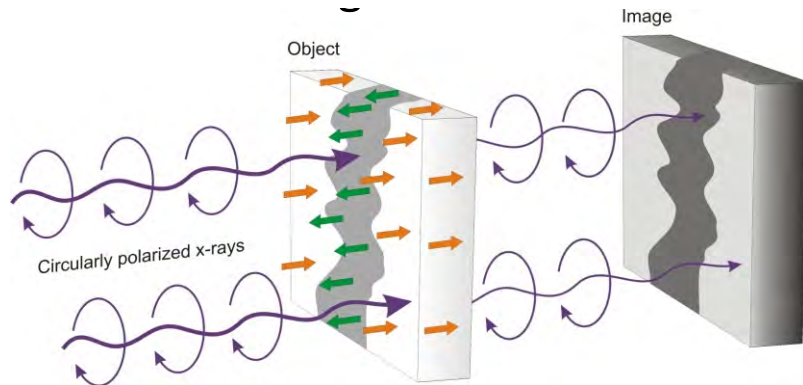
STXM scheme



Roesner, B, et al., Optica 7, 11, 1602 (2020)

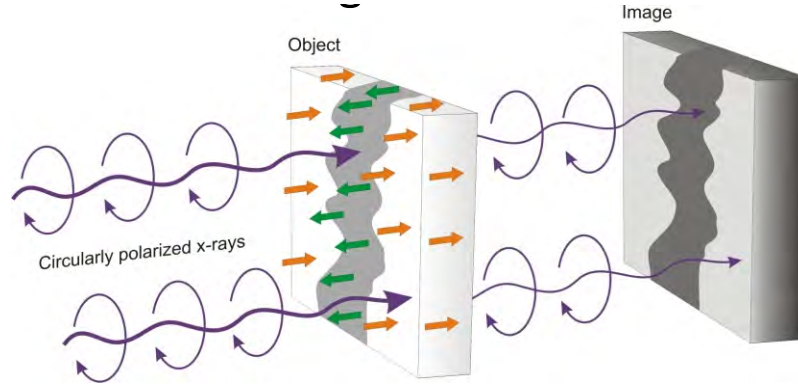
7 nm is the highest resolution achieved

XMCD contrast in transmission



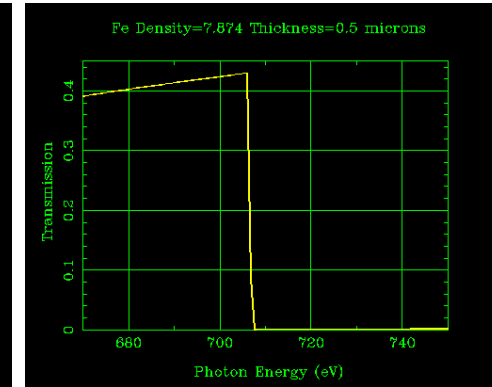
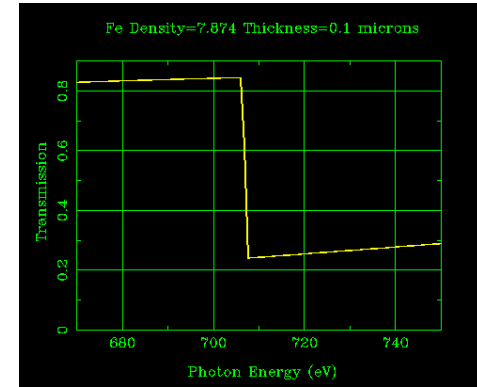
Scanning transmission x-ray microscopy

XMCD contrast in transmission



Need thin samples!

https://henke.lbl.gov/optical_constants/

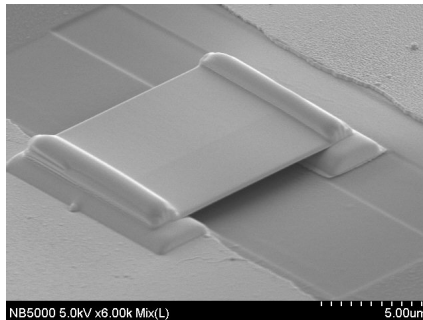


Transparent Si_3N_4 membranes



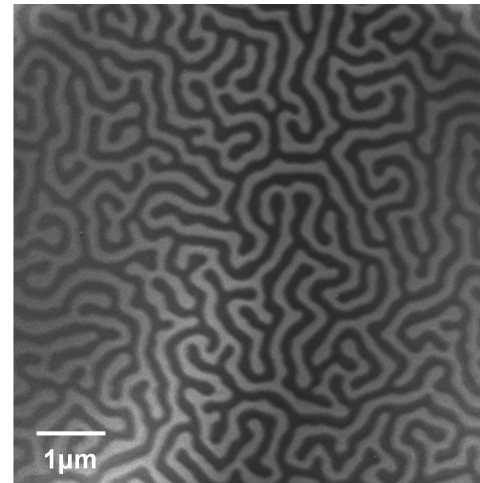
FeGd multilayer grown on Si_3N_4

Film deposition



Single crystal plate

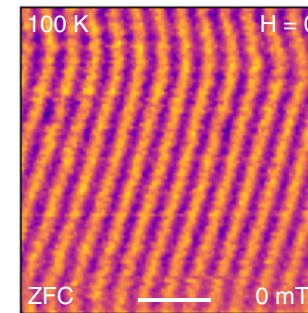
IEEE Trans. on Magn. 2015, 51, 2



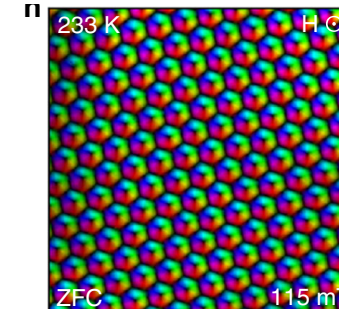
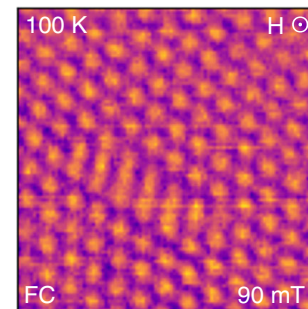
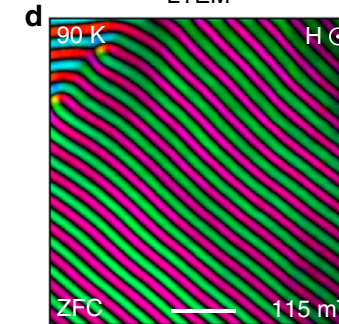
Cryogenic imaging →

Birch, M., et al., Nat Comm. 11(1), 1 (2020).

STXM



LTEM



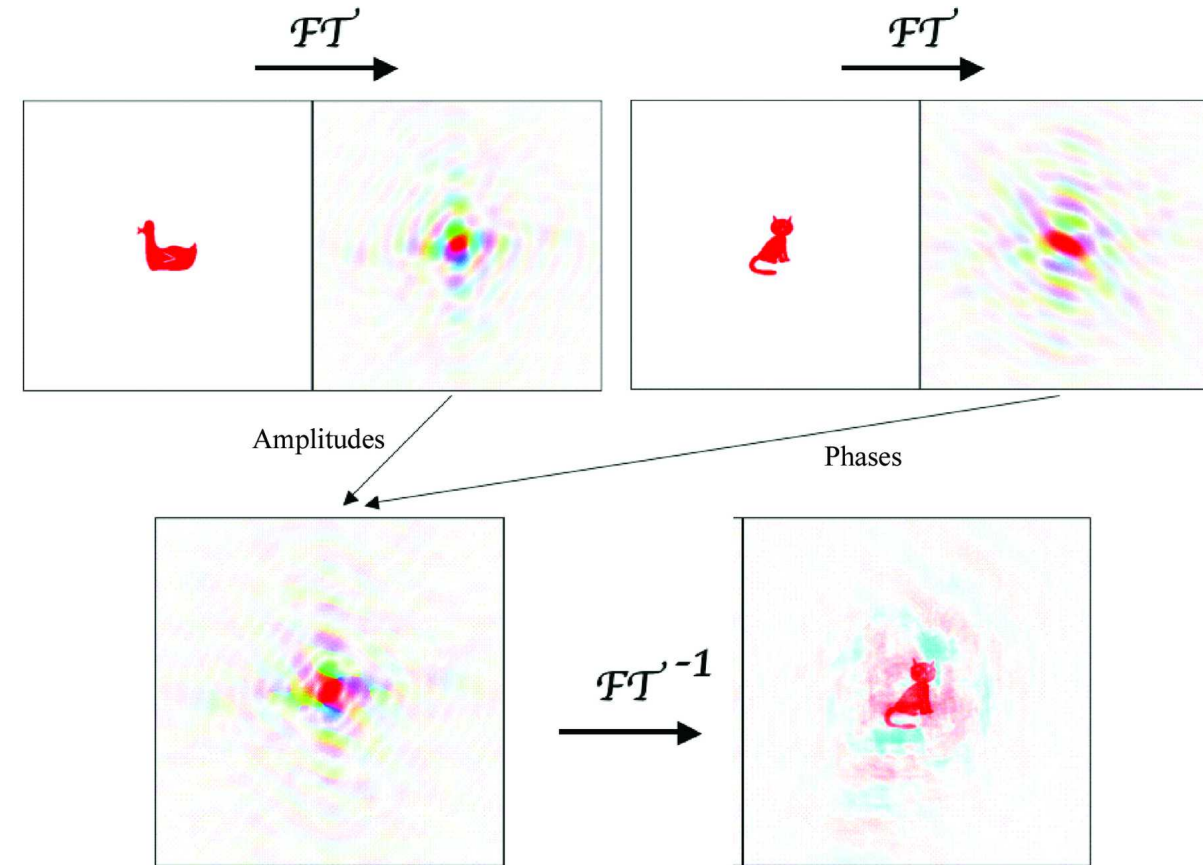
Phase problem

TECHNIQUES

- X-ray scattering factor: $f^n = f^c - i f_1^m$ is **complex**
- Scattering is a Fourier transform of the real-space density
 $I = |F(f^n)|^2$ is **real**

$$f^n = \underbrace{(e_n \cdot e'_n) f_c^n}_{\text{charge}} + \underbrace{i(e_n \times e'_n) \cdot M^n f_{m1}^n}_{\text{magnetic}} + \underbrace{(e_n \cdot M^n)(e'_n \cdot M^n) f_{m2}^n}_{\text{magnetic}}$$

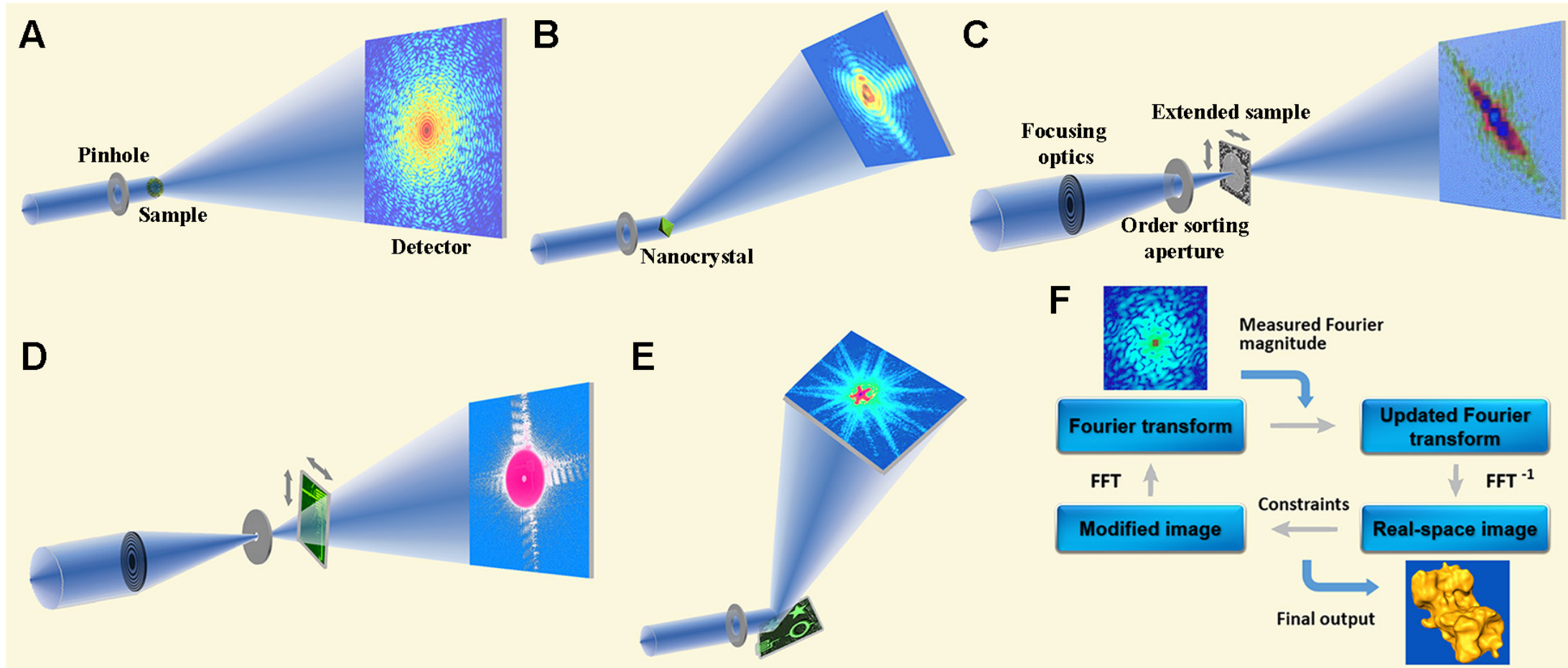
- Coherence-based methods allow to solve the phase problem and reconstruct the real-space image
- Coherent diffraction imaging, holography, ptychography, interferometry, etc.



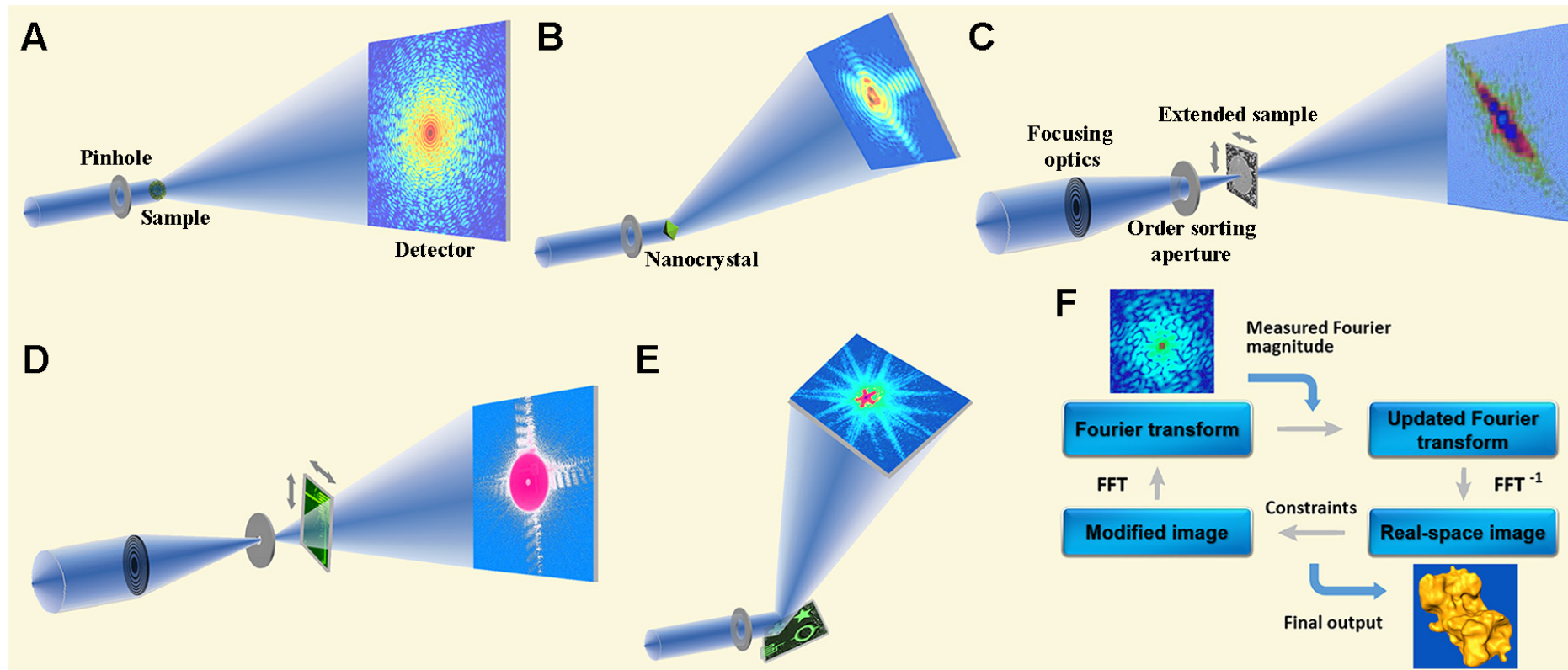
Coherent x-ray scattering / imaging

TECHNIQUES

- X-ray scattering factor: $f^{res} = f^c - i f_1^m$ is **complex**
- Measured intensity $I = |F(f^{res})|^2$ is **real**



- Coherence-based methods allow to solve the phase problem and reconstruct the real-space image
- Coherent diffraction imaging, holography, ptychography, etc.

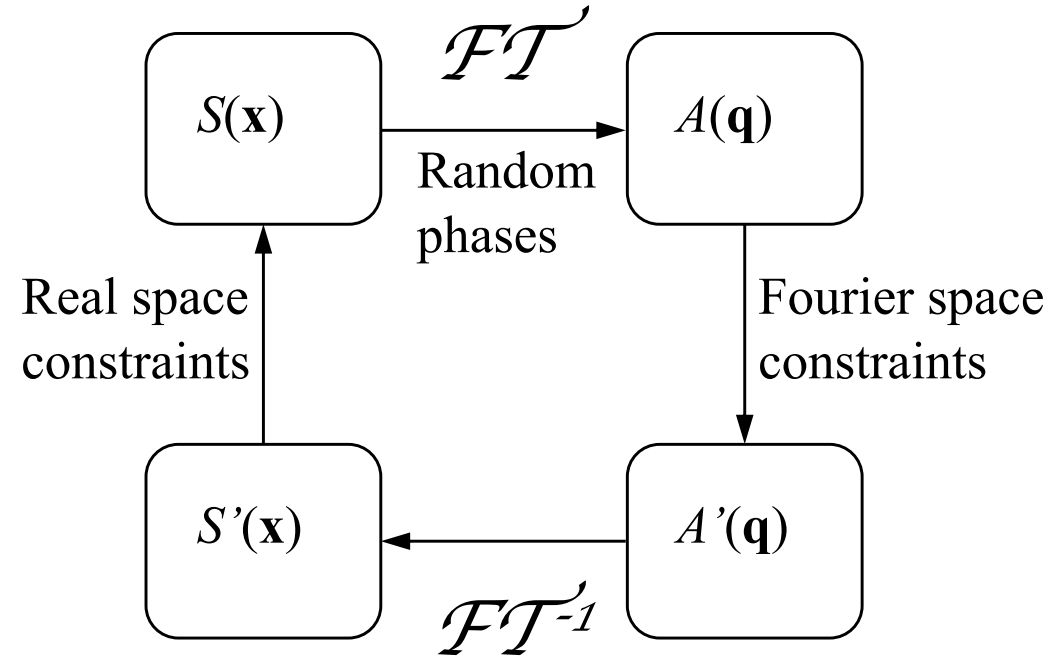
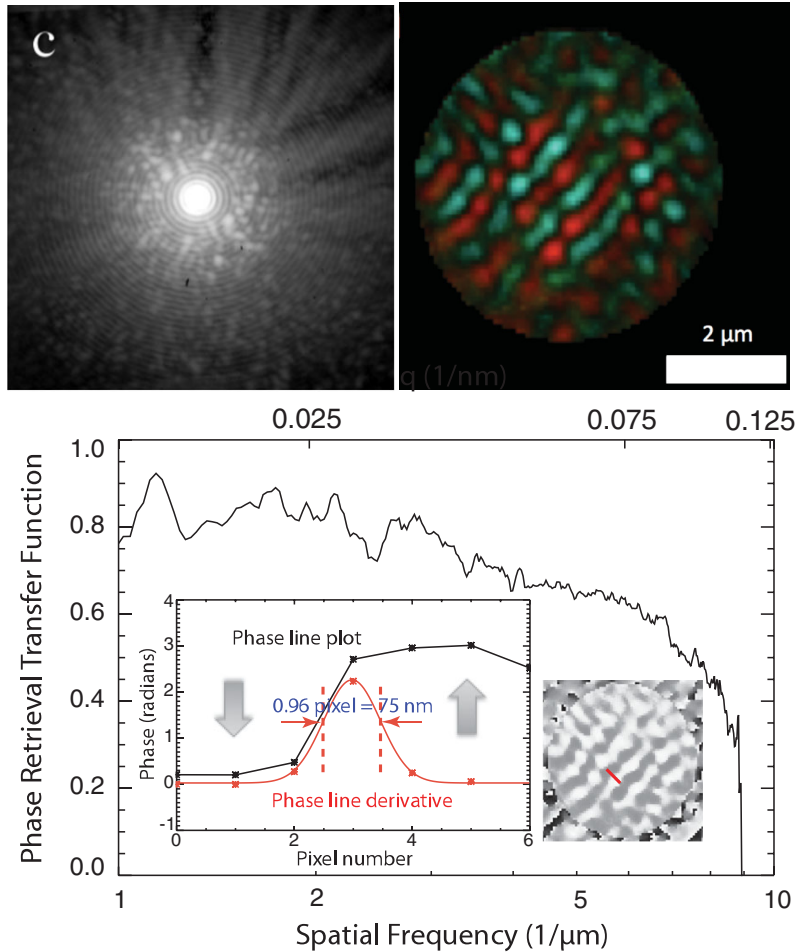


More detailed lectures on coherence-based technique are available at LINXS CoWork channel:

- 1) Introduction to CDI by Prof. Pablo Villanueva-Perez, <https://www.youtube.com/watch?v=RnBnwaYpgk8>
- 2) CDI principles and algorithms by Dr. Tomas Ekeberg, <https://www.youtube.com/watch?v=N3bbGsEApzE>
- 3) Bragg CDI by Dmitry Dzhigaev, <https://www.youtube.com/watch?v=jiY9e4pl2t0>
- 4) Ptychography by Virginie Chamard, <https://www.youtube.com/watch?v=LEfmq1afQo8>
- 5) Algorithms in Bragg CDI by Prof. Ian Robinson, <https://www.youtube.com/watch?v=MabspCO3yUs>

Coherent x-ray scattering / imaging

- Measured intensity $I = |F(f^{res})|^2$
- Iterative phase retrieval can be used if the sample size is smaller than the coherent size of the beam (oversampling ratio $\sigma > 2$)

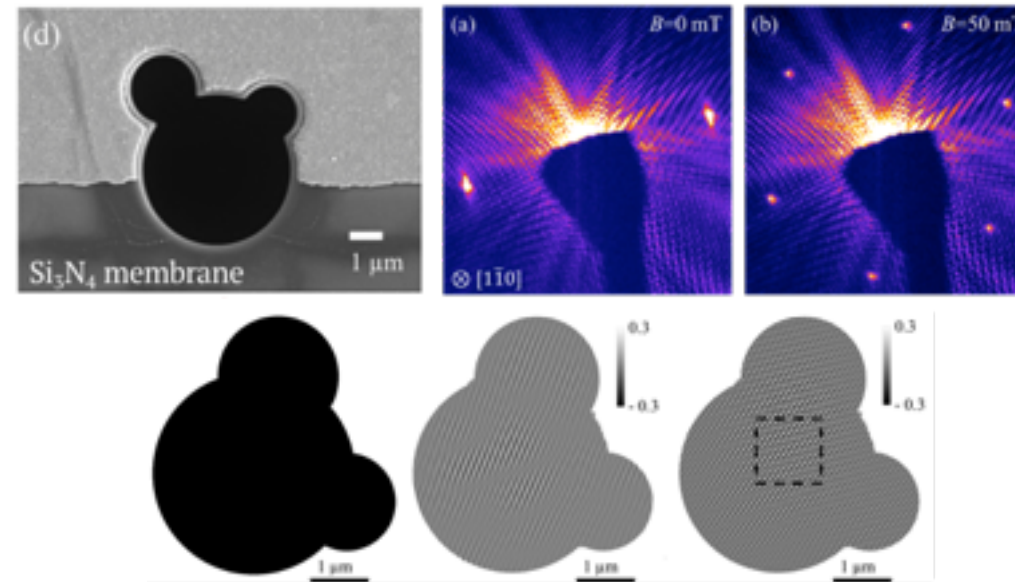
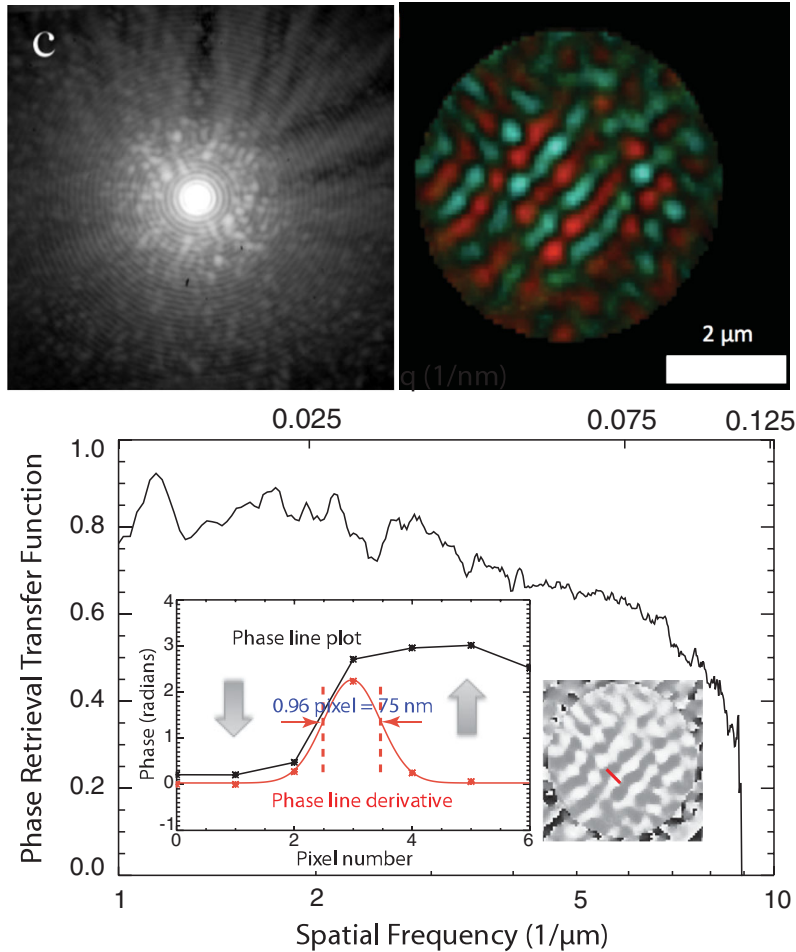


$$\text{PRTF}(\mathbf{u}) = \frac{|\mathcal{F}_{\mathbf{u}}\{\bar{\gamma}_M\}|}{\sqrt{I(\mathbf{u})}} = \frac{|\langle \Gamma_M(\mathbf{u}) \exp(i\phi_0) \rangle|}{\sqrt{I(\mathbf{u})}}$$

Real-space resolution estimated from PRTF $d < 50$ nm
(~ 30 - 40 nm) without focusing optics

Coherent x-ray scattering / imaging

- Measured intensity $I = |F(f^{res})|^2$
- Iterative phase retrieval can be used if the sample size is smaller than the coherent size of the beam (oversampling ratio $\sigma > 2$)



Estimate of the resolution is given by the frequency at which the PRTF reaches a value of 0.5.

Ukleev, V., et al., Quant. Beam. Sci. 2 (2018)

$$\text{PRTF}(\mathbf{u}) = \frac{|\mathcal{F}_{\mathbf{u}}\{\bar{\gamma}_M\}|}{\sqrt{I(\mathbf{u})}} = \frac{|\langle \Gamma_M(\mathbf{u}) \exp(i\phi_0) \rangle|}{\sqrt{I(\mathbf{u})}}$$

Real-space resolution estimated from PRTF $d < 50$ nm
(~ 30-40 nm) without focusing optics

Fourier transform holography

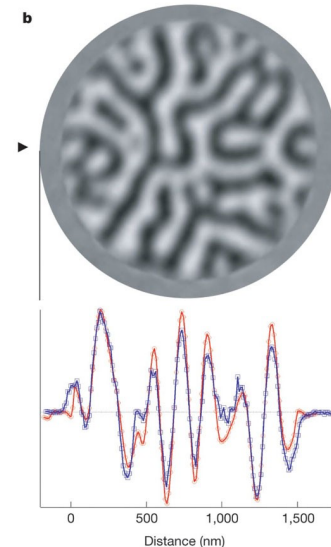
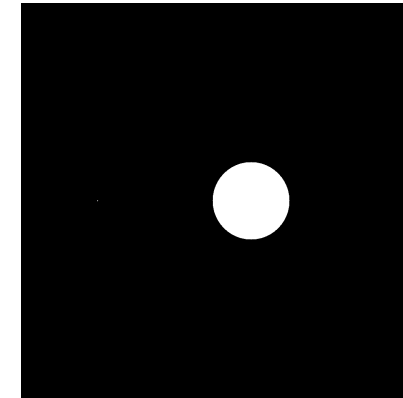
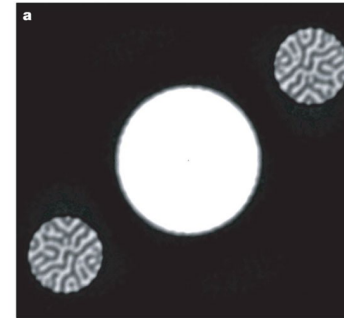
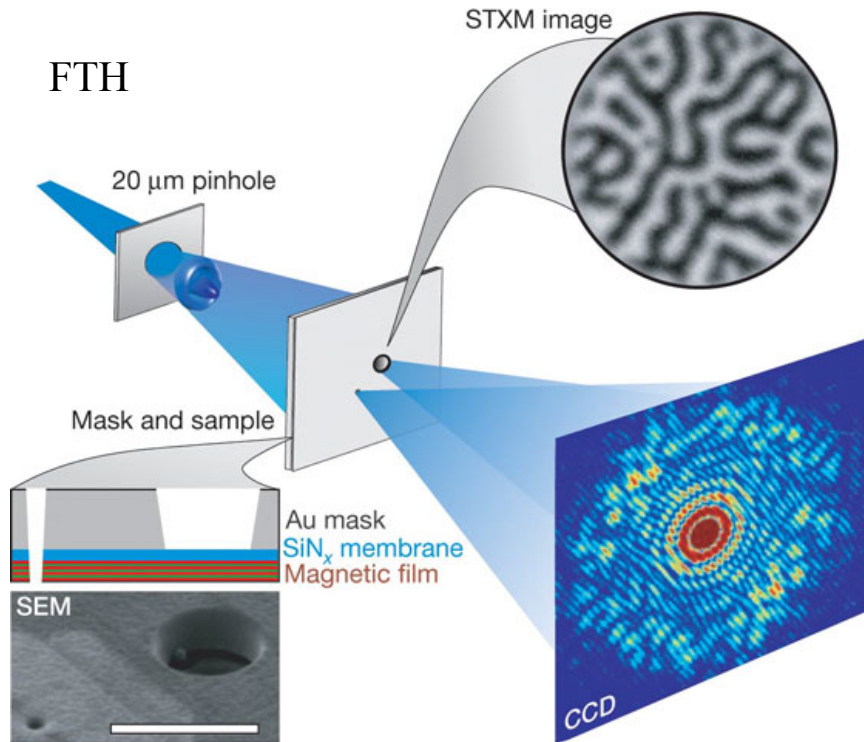
- Phase problem can be solved with the amplitude modulation by a reference wave:

$$\mathcal{F}^{-1} \{ |F(u, v)|^2 \} = f \otimes f = o \otimes o + r \otimes r + o \otimes r + r \otimes o,$$

Real-space reconstruction via single Fourier transform

Charge and magnetic contrast separation:

$$I = |f_c|^2 + |f_m|^2 + if_c f_m \quad I = |f_c|^2 + |f_m|^2 - if_c f_m \quad I = 2if_c f_m$$



Note: x-ray holography ≠ electron holography

Fourier transform holography (FTH) with a reference hole is limited by the intensity/resolution ratio

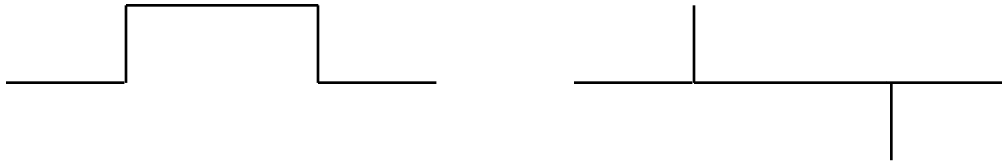
- Phase problem can be solved with the amplitude modulation by a reference wave:

The phase is encoded in the interference pattern (object and reference)

$$\mathcal{F}^{-1} \{ |F(u, v)|^2 \} = f \otimes f = o \otimes o + r \otimes r + o \otimes r + r \otimes o,$$

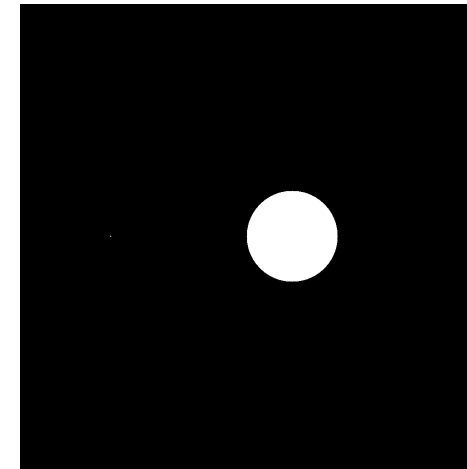
Derivative of the step function is two delta functions

$$\begin{aligned} \mathcal{L}^{(n)} \{ f \otimes f \} = & \frac{1}{2} (-1)^n [A^* r(x + x_0, y + y_0) + r \otimes g] + \frac{1}{2} [A r^*(x_0 - x, y_0 - y) + g \otimes r] \\ & + \mathcal{L}^{(n)} \{ o \otimes o \} + (-1)^n o \otimes g + g \otimes o + (-1)^n A^* o(x + x_0, y + y_0) + A o^*(x_0 - x, y_0 - y) \end{aligned}$$

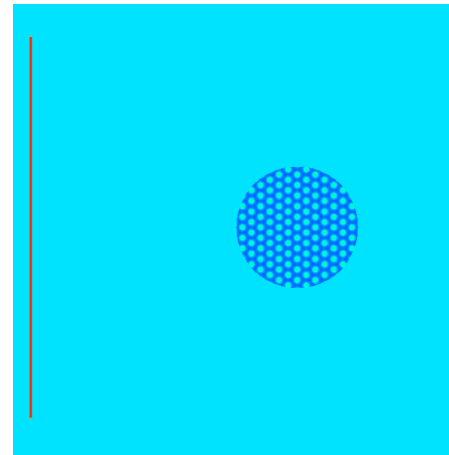
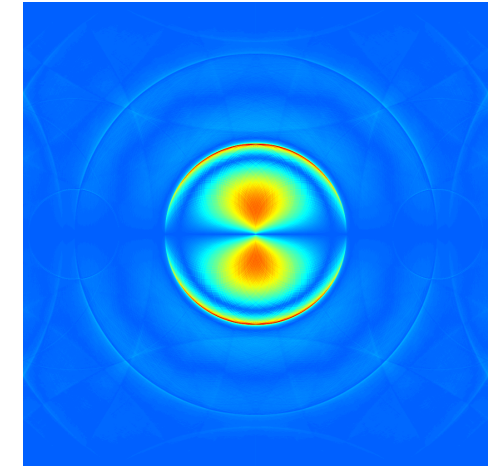


Reference slit can improve the contrast compared to reference hole without losing the resolution

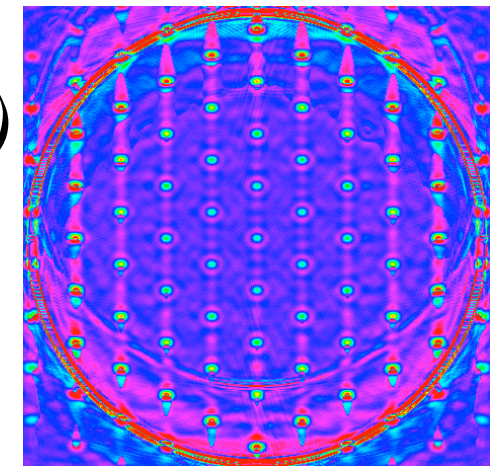
Guizar-Sicairos, M. and Fienup, J.R., 2007. Holography with extended reference by autocorrelation linear differential operation. Optics express, 15(26), pp.17592-17612.



$$\mathcal{F}^{-1}(I)$$



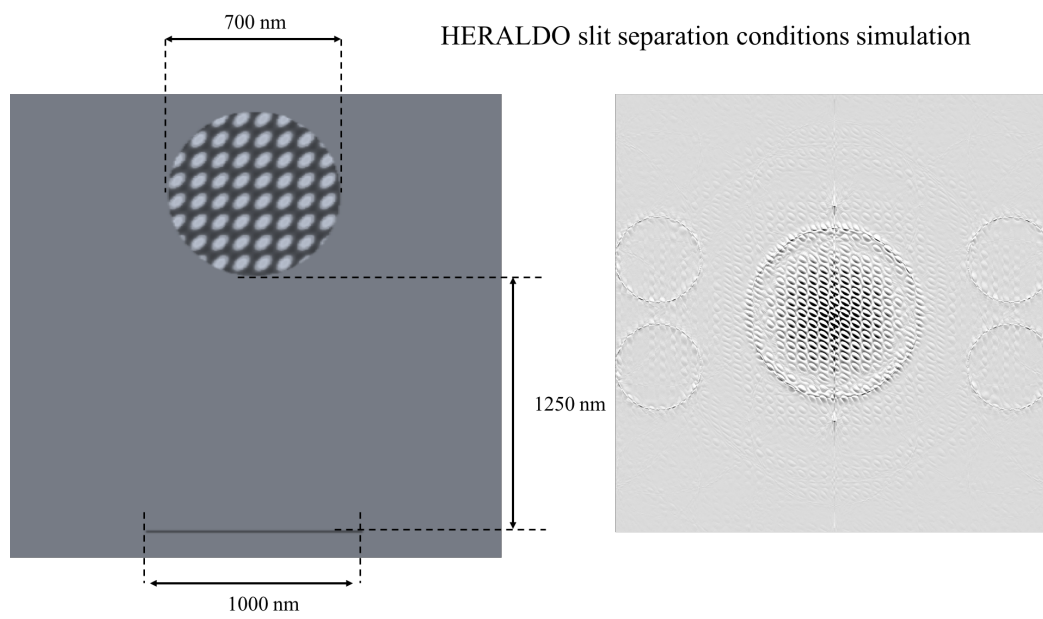
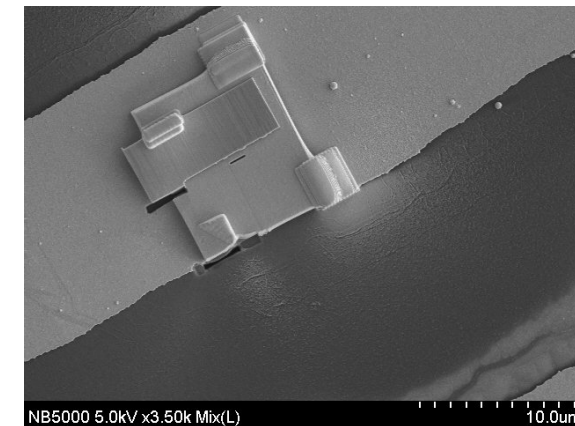
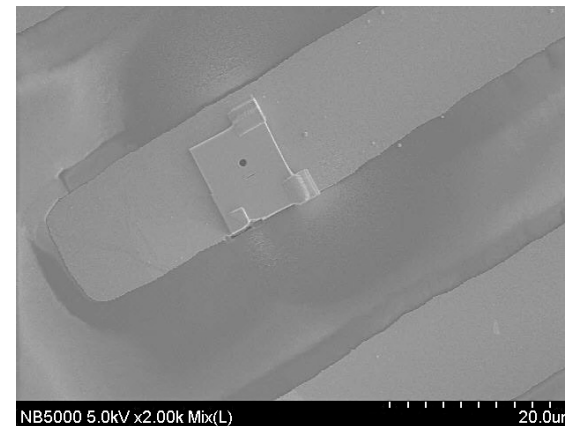
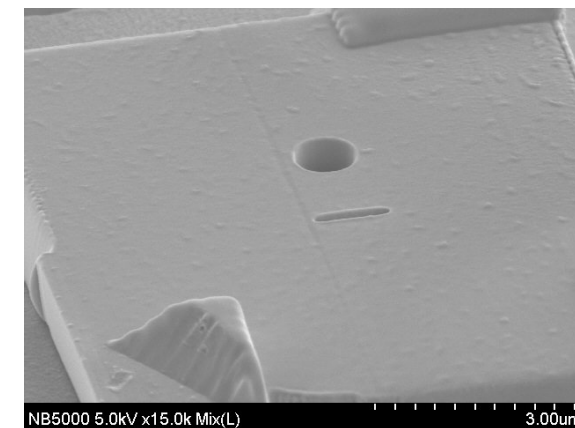
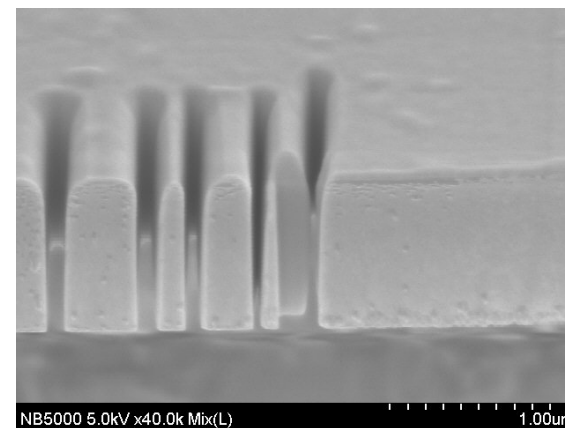
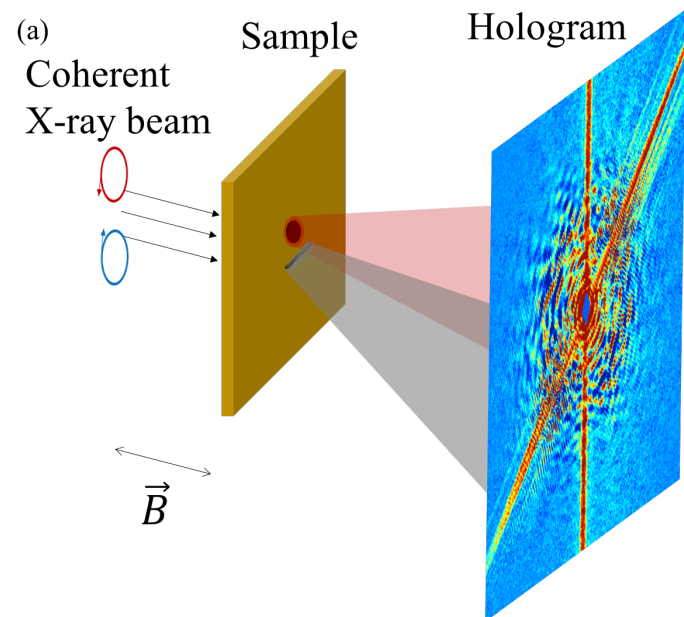
$$\frac{\partial}{\partial \vec{s}} \mathcal{F}^{-1}(I)$$



Fourier transform holography (FTH) with a reference hole is limited by the intensity resolution ratio

Holography with extended reference (HERALDO)

HERALDO example: skyrmion host $\text{Co}_8\text{Zn}_8\text{Mn}_4$



Aperture size: $d=700$ nm

Slit size:

$w=0.04$ μm, $l=1$ μm

Holography with extended reference (HERALDO)

- Phase problem can be solved with the amplitude modulation by a reference wave:

$$\mathcal{F}^{-1} \{ |F(u, v)|^2 \} = f \otimes f = o \otimes o + r \otimes r + o \otimes r + r \otimes o,$$

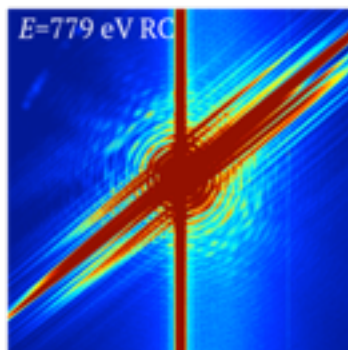
Real-space reconstruction via Fourier transform an linear differential operator (HERALDO)

No compromise between the contrast and resolution

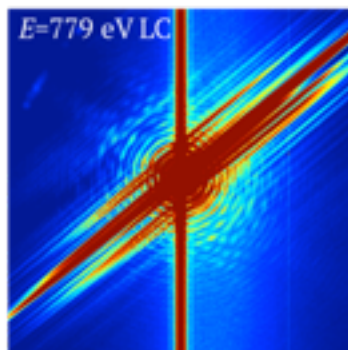
HERALDO example: $\text{Co}_8\text{Zn}_8\text{Mn}_4$

$$I = |f_c|^2 + |f_m|^2 + i f_c f_m \quad I = |f_c|^2 + |f_m|^2 - i f_c f_m$$

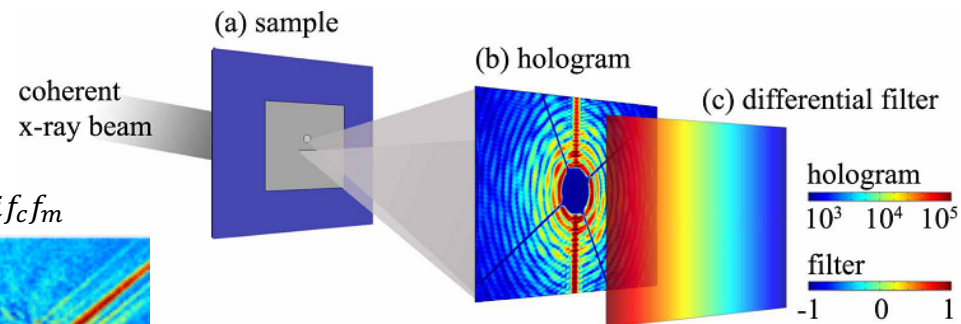
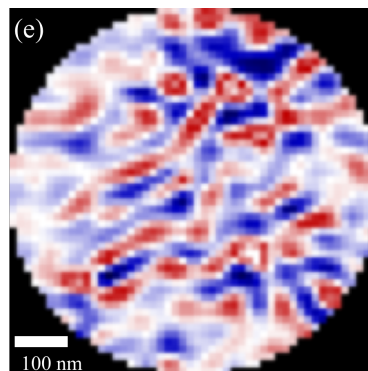
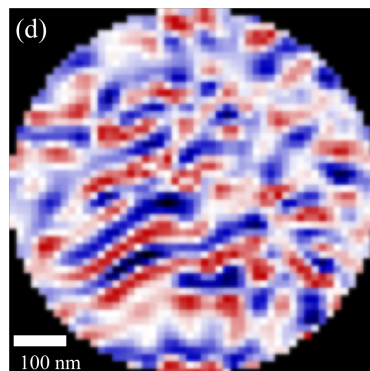
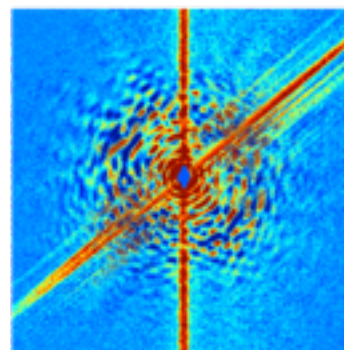
$$I = 2i f_c f_m$$



Co L_3 edge

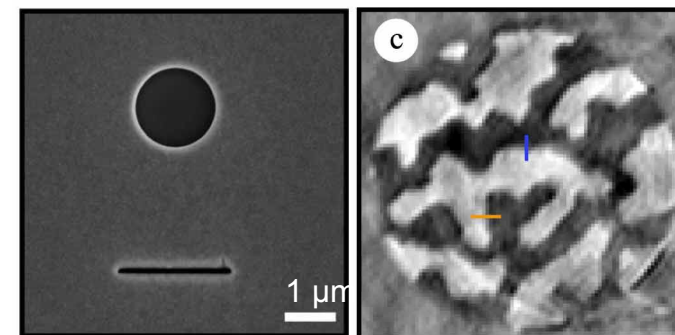


Mn L_3 edge

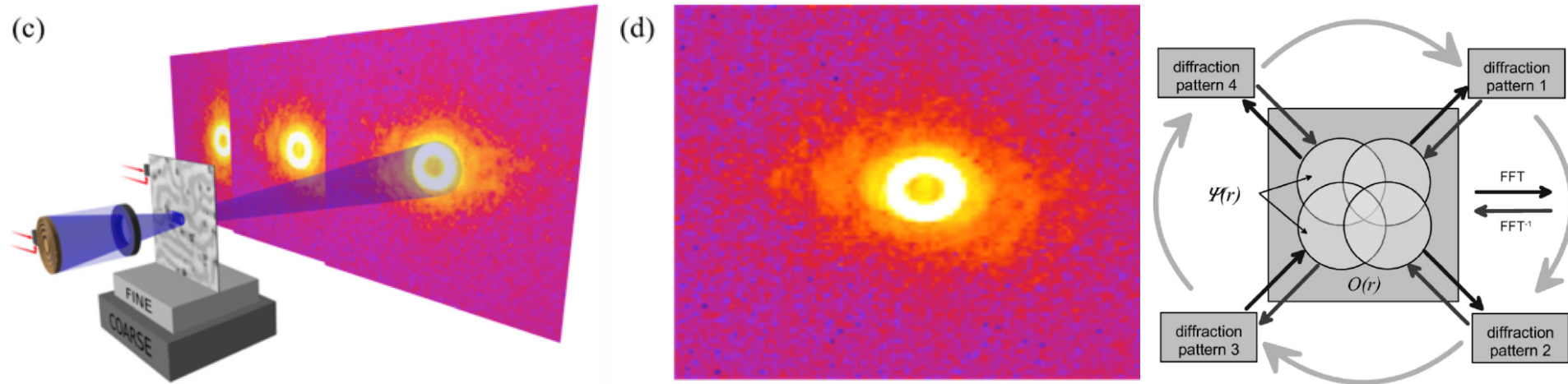


$$\frac{d}{d\vec{X}} \{ t \otimes t \} = C + \frac{d}{d\vec{X}} \{ o \otimes r \} + \frac{d}{d\vec{X}} \{ r \otimes o \} = C + (-o) \otimes \frac{d}{d\vec{X}} \{ r \} + \frac{d}{d\vec{X}} \{ r \} \otimes o$$

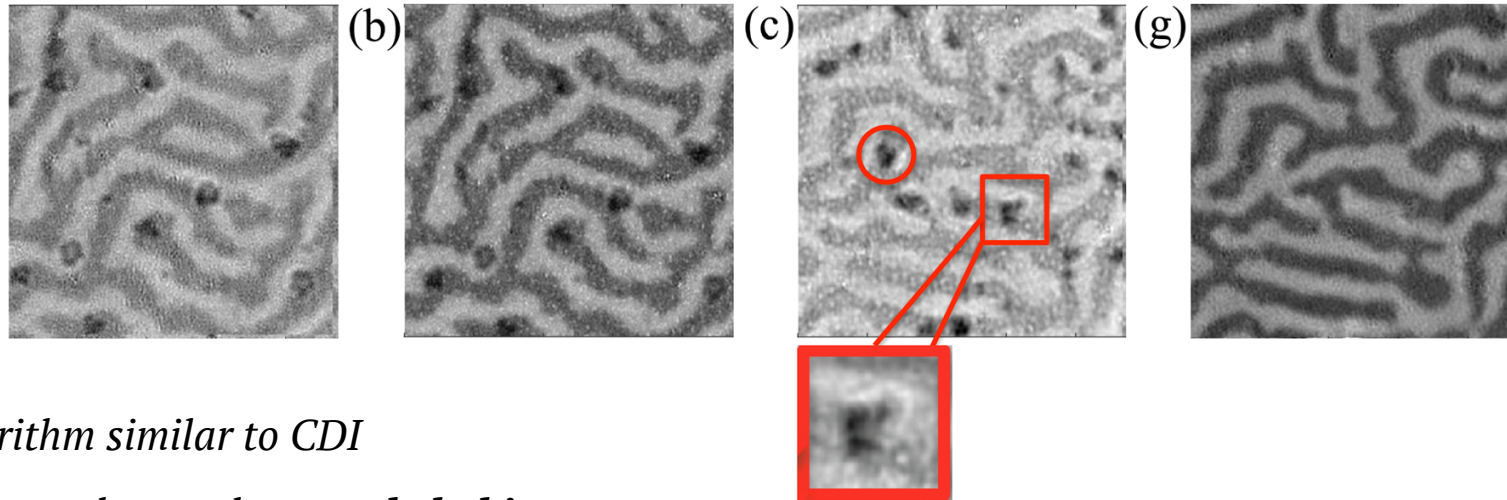
$$\rightarrow \frac{d}{d\vec{X}} \{ t \otimes t \} = C - o_{(X+a)} + o_{(X+b)} + cc$$



Taking coherent scattering patterns from overlapping regions using FZP



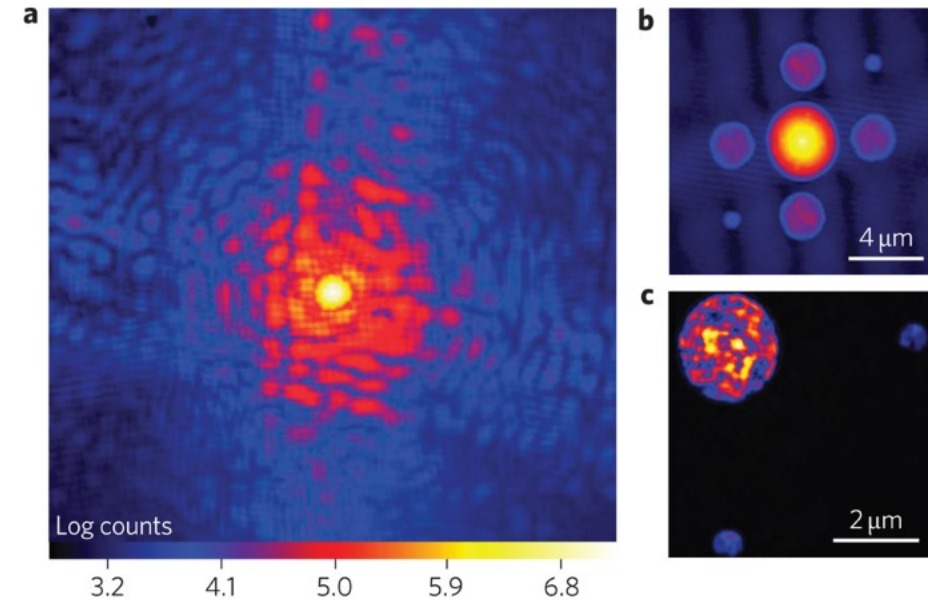
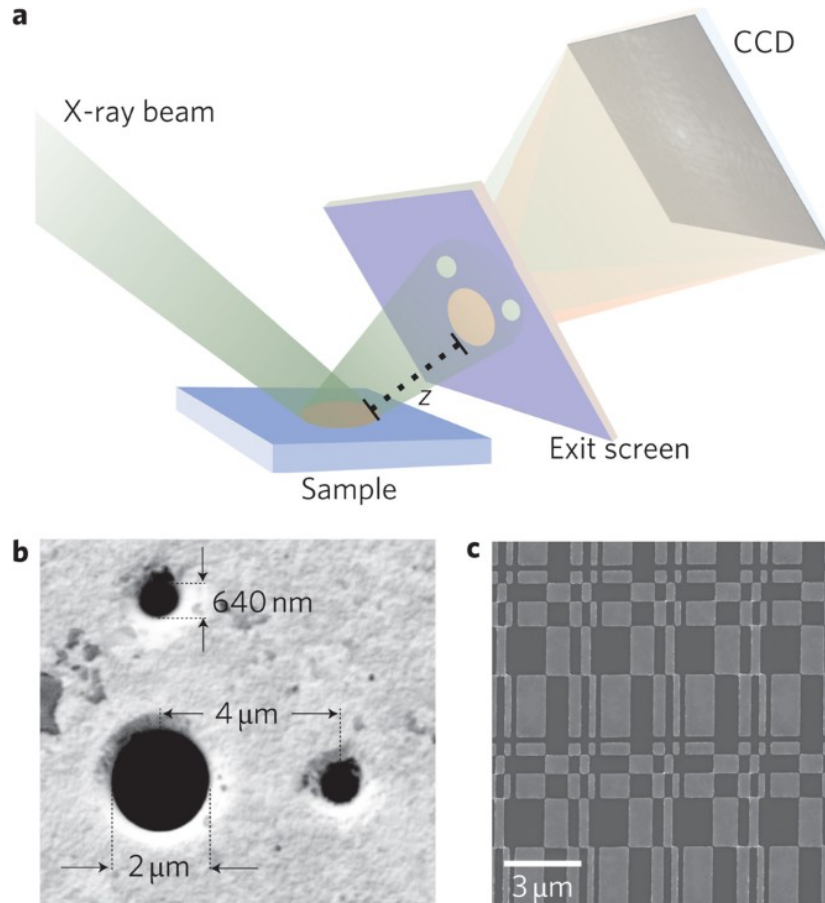
15 nm real-space resolution imaging of magnetic domains in SmCo_5



- *Reconstruction algorithm similar to CDI*
- *Ptychography can be used to study **extended objects***

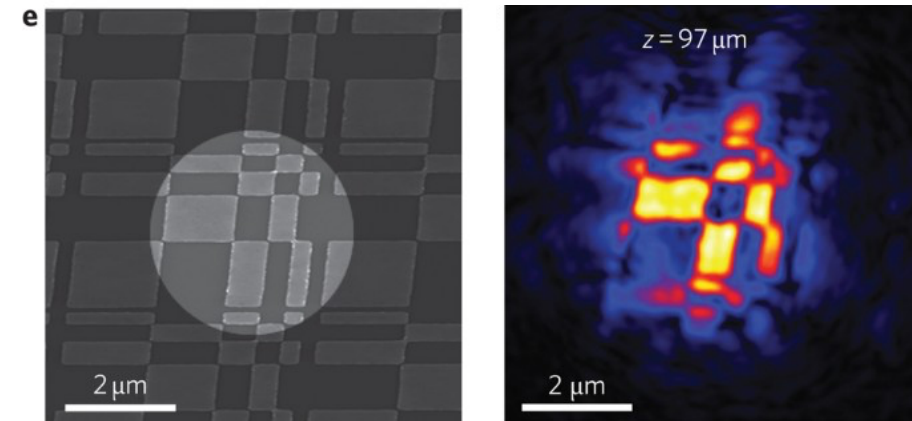
X-ray holography in reflection

Holographic mask is placed after reflected beam



SEM

reconstruction

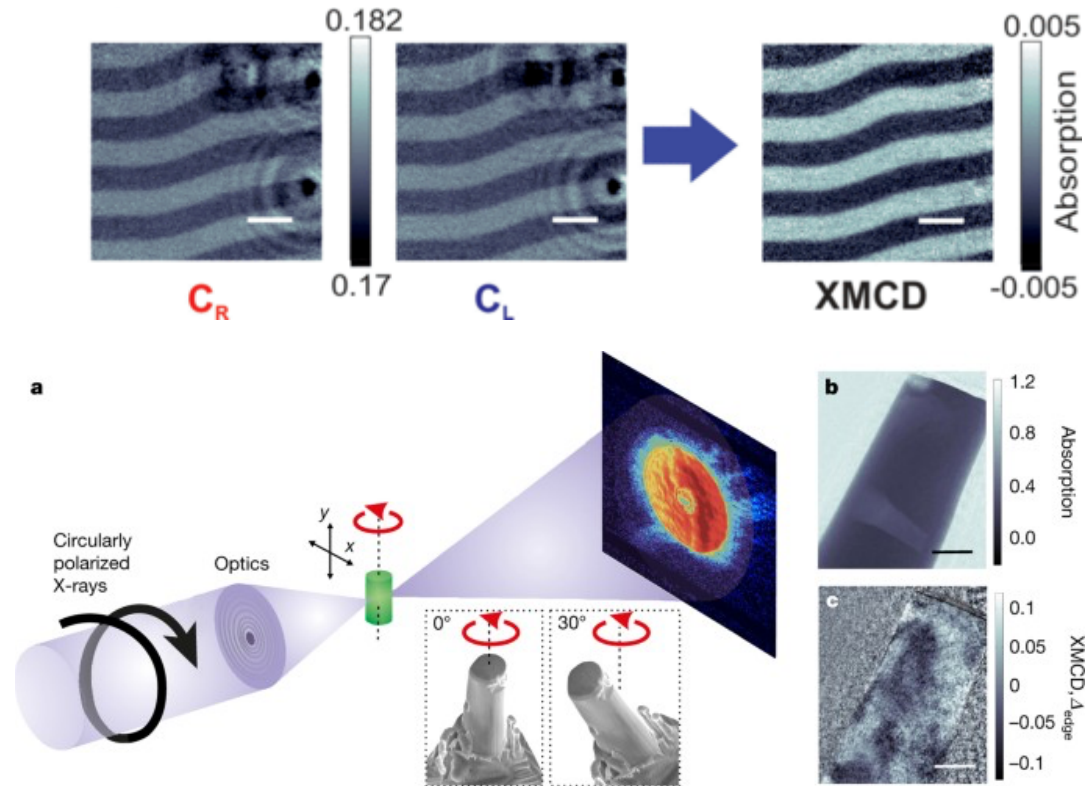
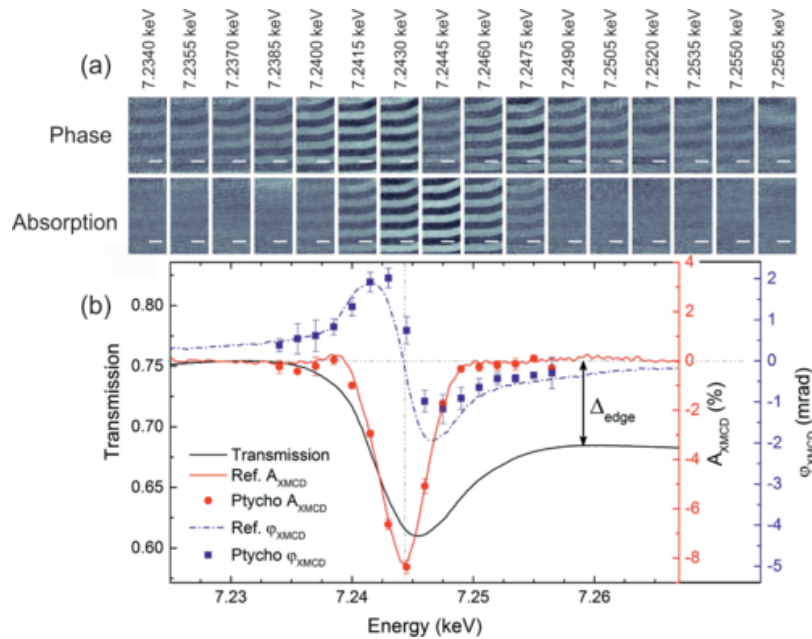


- *So far only demonstrated only for charge patterns...*
- *Ptychography is also possible*
- *~60 nm resolution*

TECHNIQUES

X-ray imaging in three dimensions

Hard x-ray resonant tomography (Gd L_3 edge)

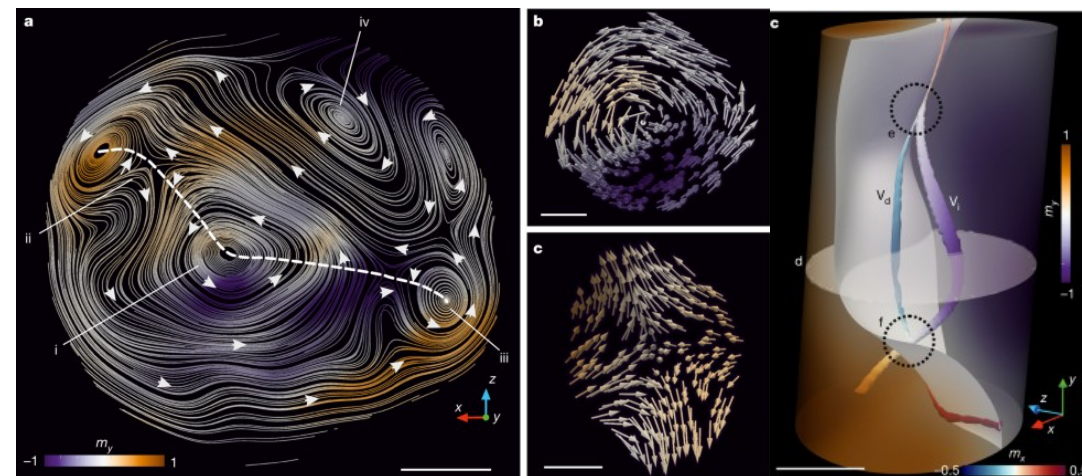


Magnetic contrast variation across the edge

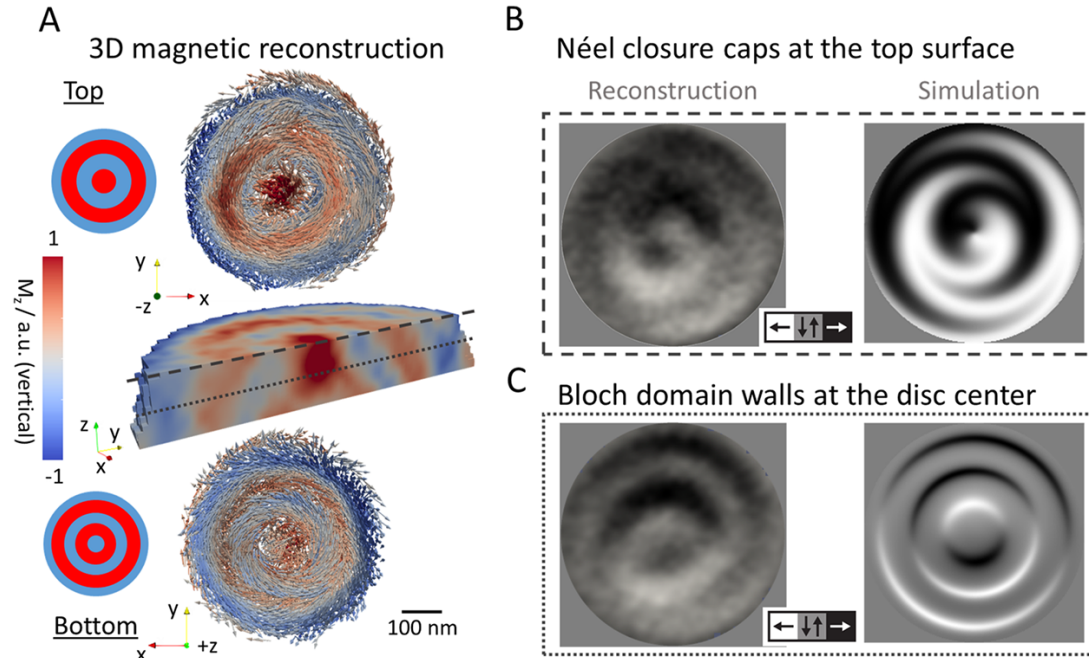
- *High energy allows transmission of a few tens μm*
- *Ptychographic scans are measured for multiple projections to reconstruct 3D magnetization vector distribution*

Donnelly, C., et al., Phys. Rev. B 94, 064421 (2016)

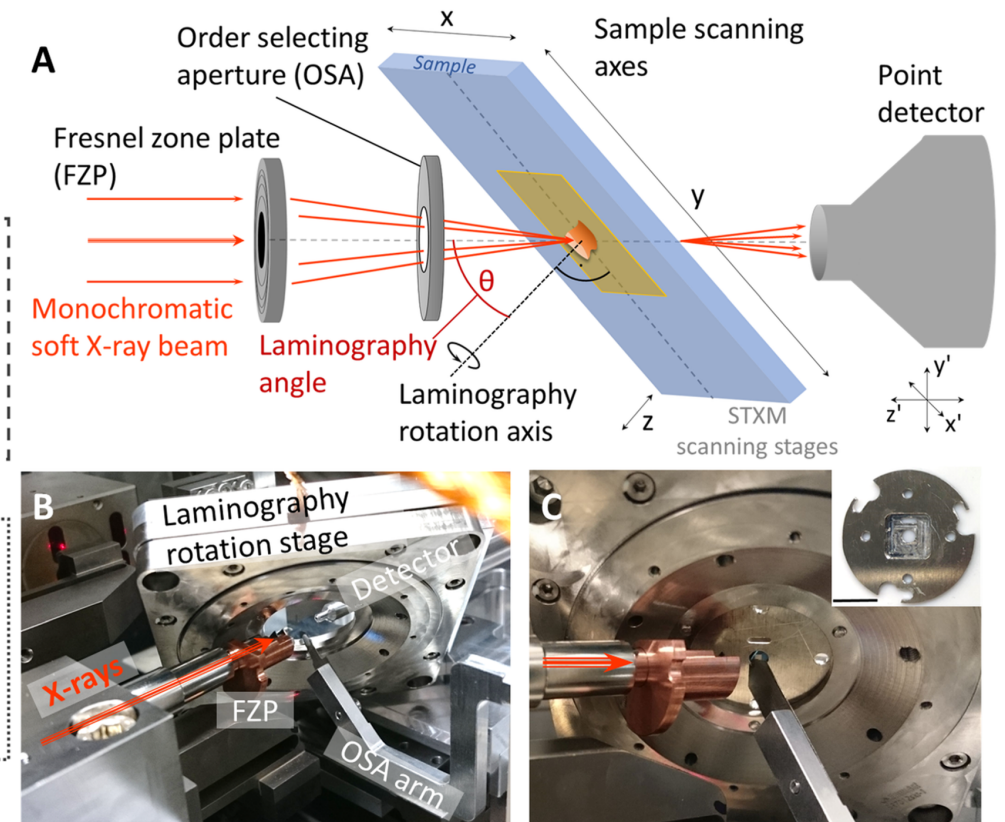
Donnelly, C., et al., Nature 547, 328–331(2017)



Soft x-ray resonant laminography (TM L_3 edge or RE M -edge)



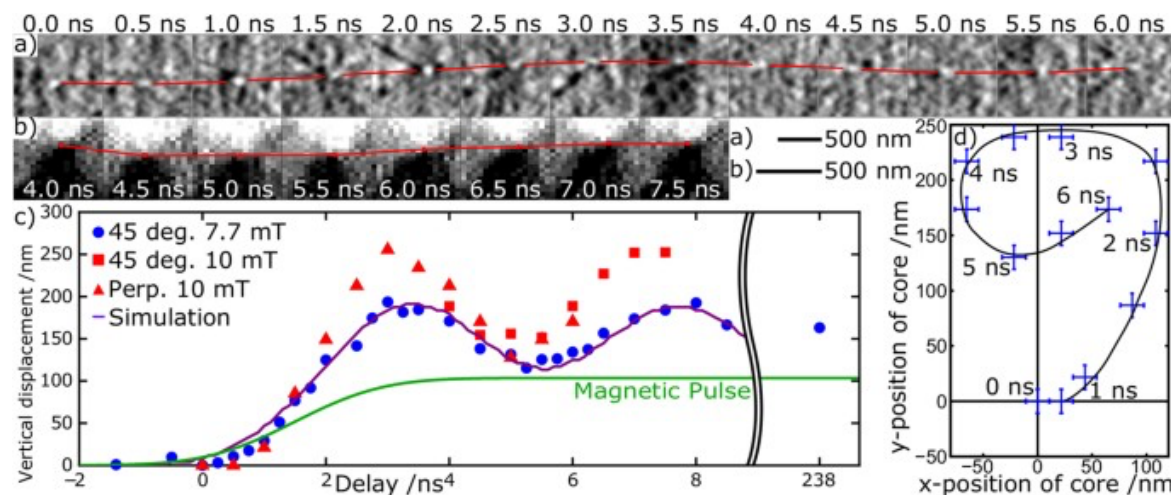
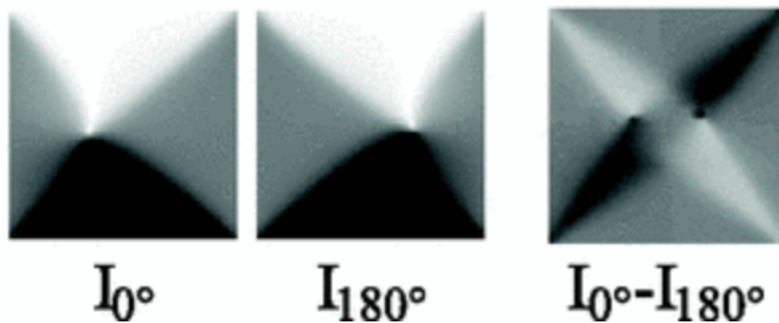
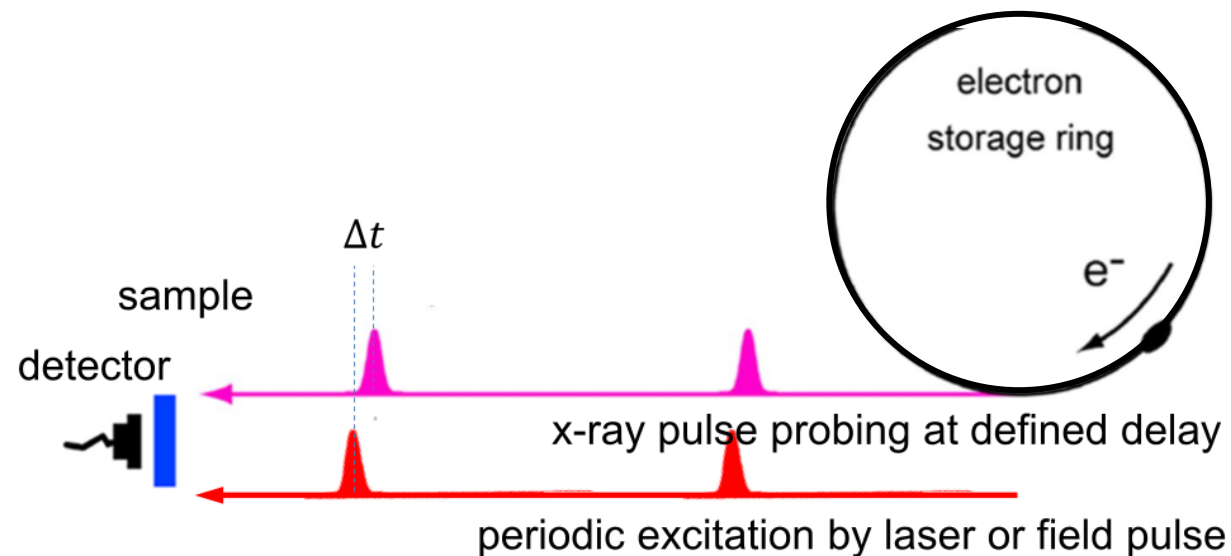
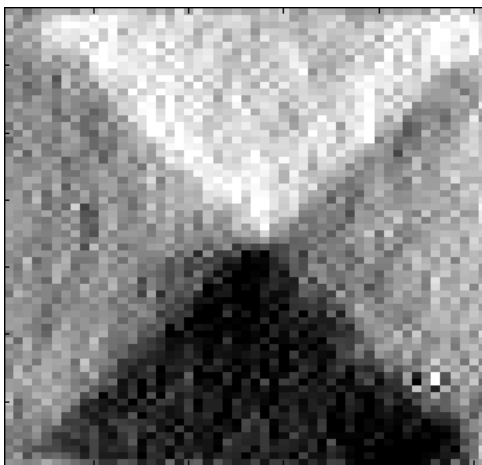
Reconstruction of the magnetic structure of a permalloy nanodisc



- *Naturally thin or nanofabricated samples*
- *Multiple projections to reconstruct 3D magnetization vector distribution measured with single rotation axis*
- *Challenging to introduce complex sample environment*

Stroboscopic pump-probe imaging: synchronized x-ray and excitation pulses (magnetic field, laser pulses, etc.)

Sub-100 ps imaging of *periodic* phenomena
PEEM, STXM, holography, 3D methods, etc.



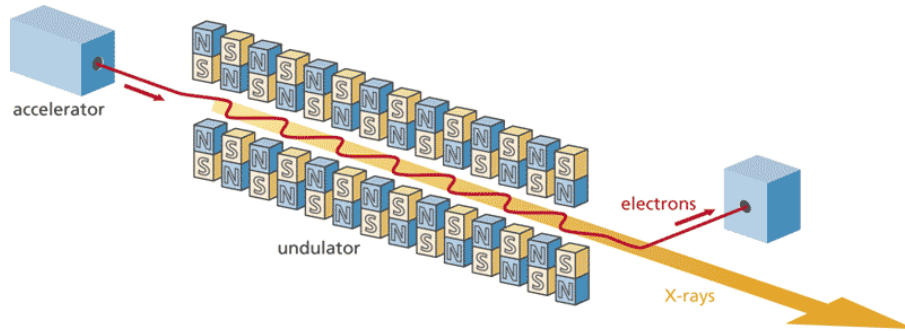
TECHNIQUES

Time-resolved imaging

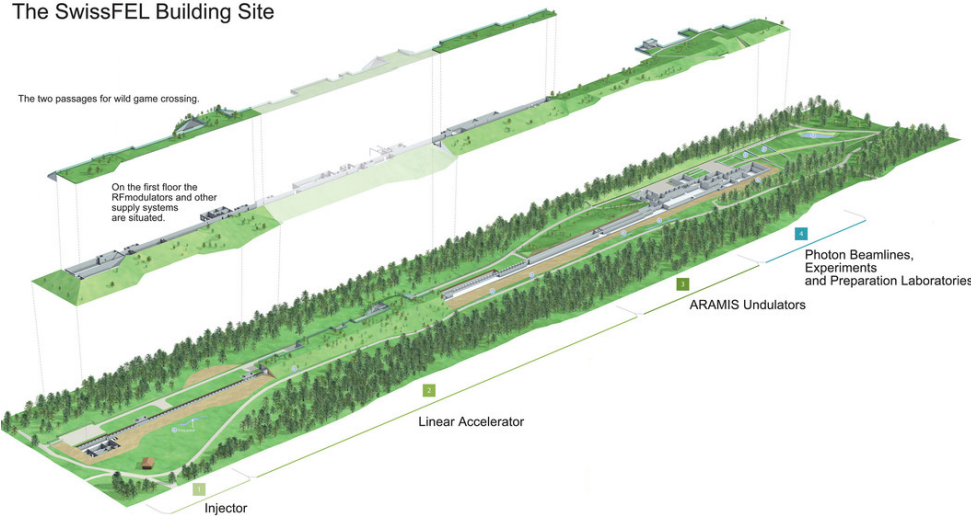
Time resolution is limited by the pulse duration

Need high-flux x-ray source with fs pulses to study spin dynamics at atomic scales:

x-ray free-electron laser



The SwissFEL Building Site



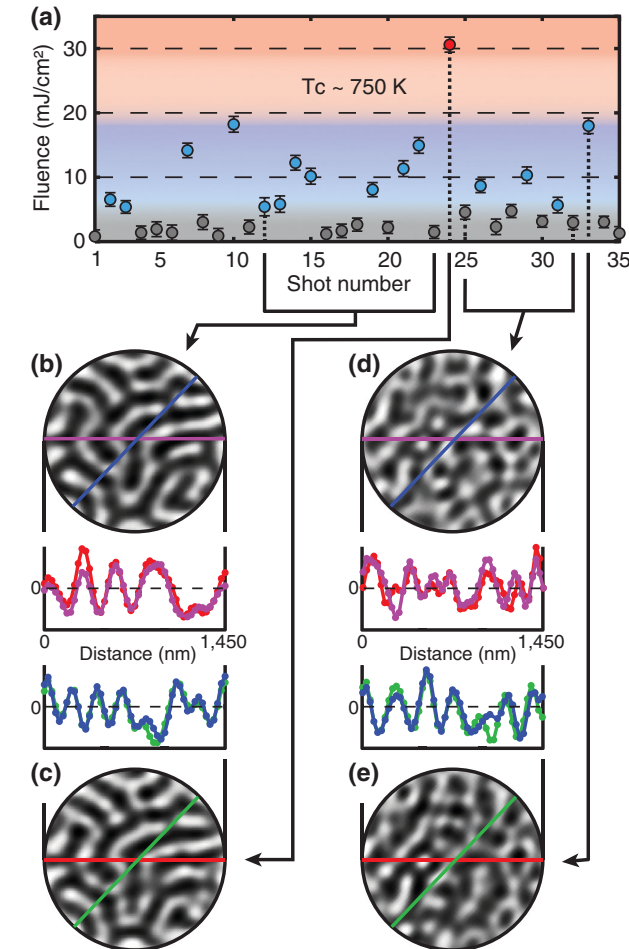
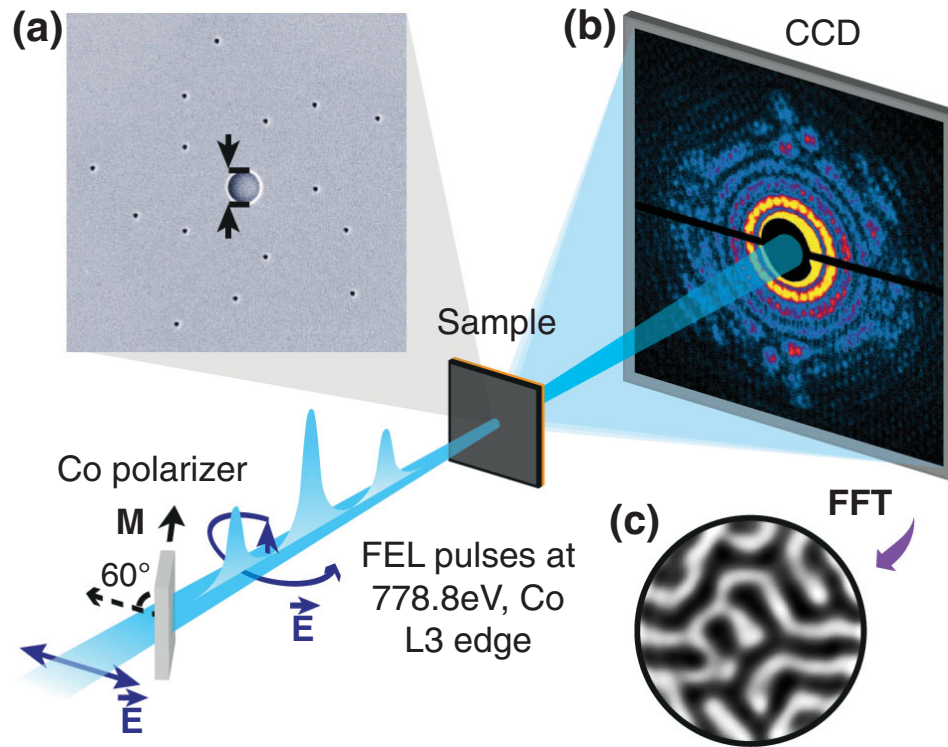
Please, watch this (5min) movie about SwissFEL
<https://www.youtube.com/watch?v=P2CG69hRYR8>

Time resolution is limited by the pulse duration

Need high-flux x-ray source with fs pulses to study spin dynamics at atomic scales:

x-ray free-electron laser

XFEL experiment@LCLS: single-shot imaging



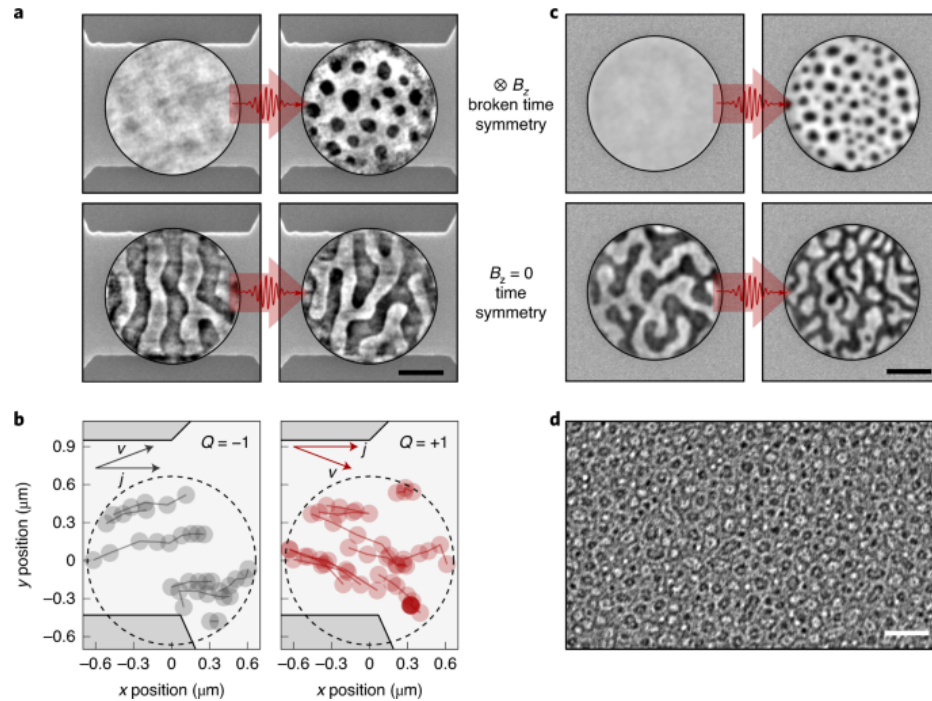
Damage of the spin structure by the pulses longer than 80 ps! -> non-linear interaction of x-rays with electronic order

Time resolution is limited by the pulse duration

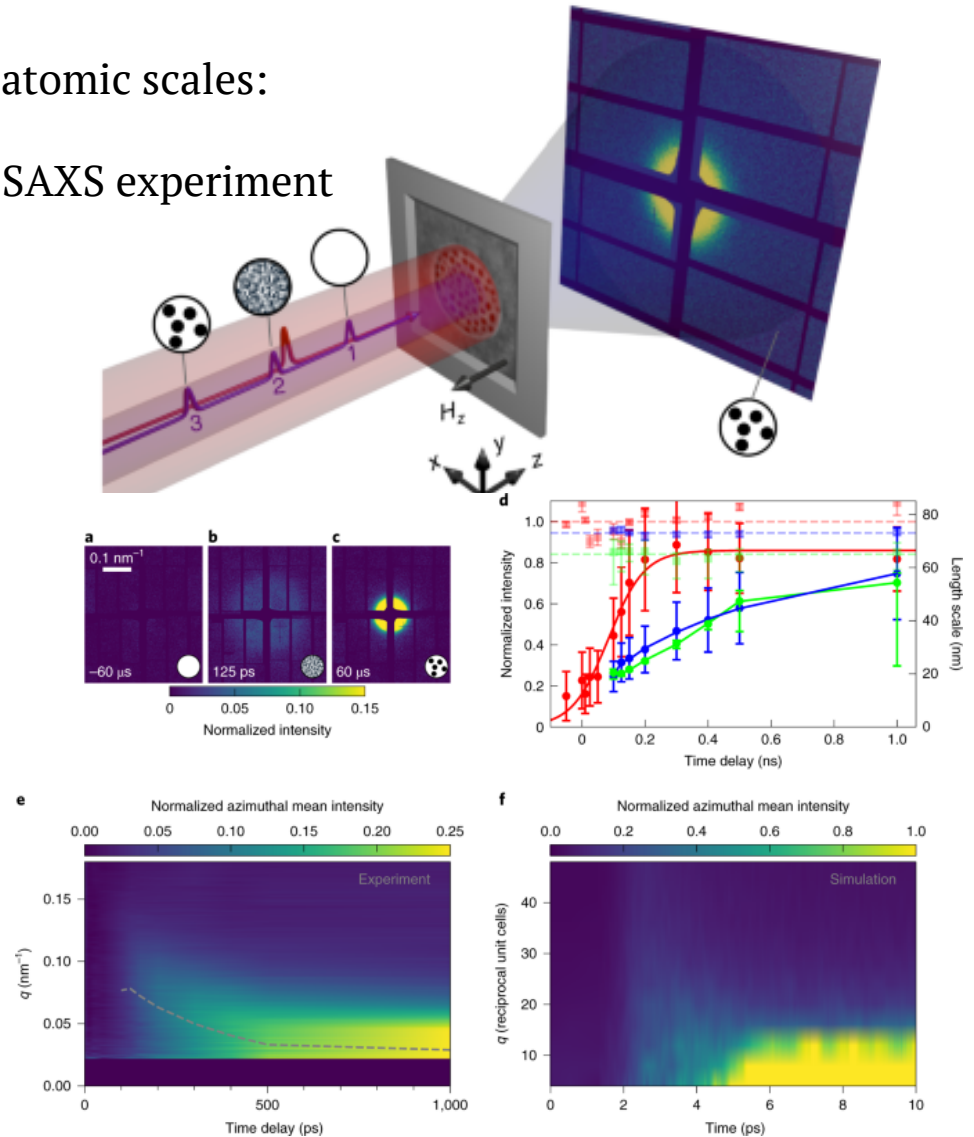
Need high-flux x-ray source with fs pulses to study spin dynamics at atomic scales:

x-ray free-electron laser

Synchrotron-based FTH imaging:



XFEL SAXS experiment



Nucleation of magnetic skyrmions by optical laser pulses:
time scale >10 ps

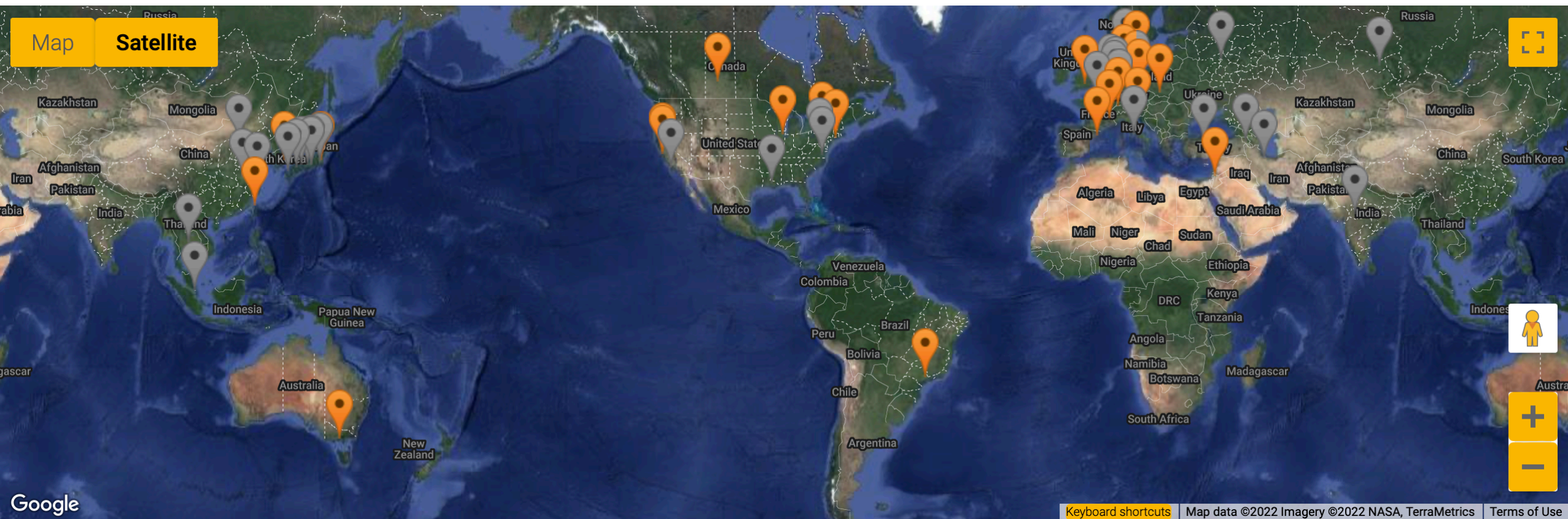
Comparison to other magnetic imaging techniques

Method	Probe	Spatial resolution	Temporal resolution	Magnetization direction	Sample type	Instrument type
Kerr microscopy	Optical photons	Fair (>300 nm)	Very good (fs)	Any	Surface (Kerr) Thin film (Faraday)	Lab.
Lorentz TEM (+DPC, holography, etc.)	Electrons	Very good (<10 nm)	Good (ps)	In-plane	Thin film	Lab.
MFM	Cantilever	Good (10-100 nm)	Bad (min)	Out-of-plane	Surface	Lab.
Neutron imaging	Neutrons	Bad (μm)	Bad (min)	Any	Bulk	Neutron source
PEEM	X-rays + Electrons	Good (10-100 nm)	Good (ps)	Out-of-plane (NI) In-plane (GI)	Surface	Synchrotron
STXM (+ holography, ptychography, etc.)	X-rays	Good (10-100 nm)	Good (ps)	Out-of-plane	Thin film 'thinned bulk' <1 μm	Synchrotron

Where?

SUMMARY

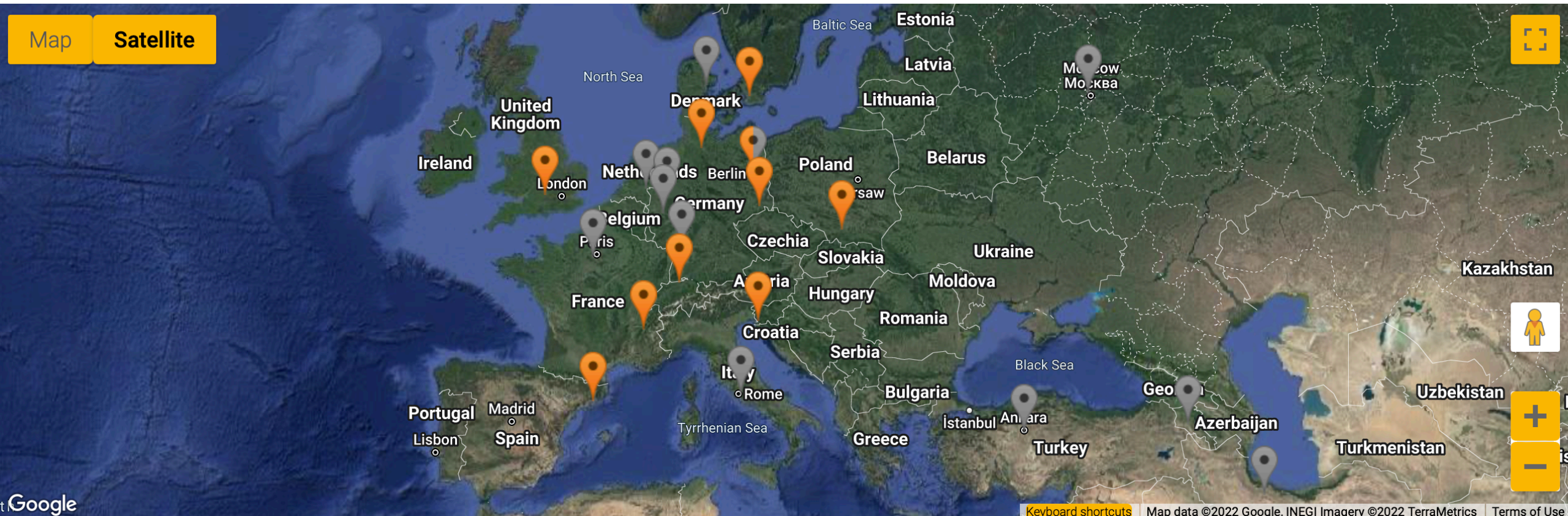
Lightsources of the World



Where?

SUMMARY

...and of Europe



<https://www.wayforlight.eu/>

When?

SUMMARY

Facility	Deadline
CHESS (USA)	2022/12/20
Pohang XFEL (Korea Rep.)	2022/12/31
Canadian Light Source (Canada)	2022/12/31
European XFEL (Germany)	2022/12/29
MAX IV (Sweden)	2023/02/28
ESRF (France)	2023/03/01
PETRA-III (Germany)	2023/03/01
BESSY-II (Germany)	2023/03/01
APS (USA)	2023/04/17
SwissFEL (Switzerland)	2023/06/30
ALS (USA)	2023/07/31
SLS (Switzerland)	to be announced (SLS 2.0 upgrade is upcoming)

Committee decision ~2-3 months after the proposal submission deadline

Beamtime ~4-12 months after the proposal submission deadline

<https://lightsources.org/for-users/proposal-deadlines/>

Beamlines (example)

Method	Beamline	Facility	Energy range	Magnetic field	Temperature range
PEEM	SIM SPEEM@UE49-PGM I06 CIRCE HERMES	SLS PSI, Switzerland BESSY II, Germany Diamond, UK ALBA, Spain SOLEIL, France	90-2000 eV 100-1800 eV 100-1300 eV 100-2000 eV 70-2500 eV	~100 mT ~100 mT available available available	120-800 K 45-600 K 100-1900 K 100-1500 K 150-2000 K
TXM	MISTRAL SPEEM@UE41-PGM	ALBA, Spain BESSY II, Germany	270-1200 eV 180-2800 eV	2 mT no	105-300 K 100-300 K
STXM	POLLUX HERMES MAXYMUS	SLS PSI, Switzerland SOLEIL, France BESSY II, Germany	250-1600 eV 70-2500 eV 200-1900 eV	200 mT 20 mT 250 mT	280-400 K 150-600 K 30-350 K
Holography / coherent diffraction imaging in transmission	ALICE-2 COMET@SEXTANTS MaReS@BOREAS	BESSY II, Germany SOLEIL, France ALBA, Spain	depends on beamline 50-1700 eV 50-4000 eV	700 mT 1000 mT 2000 mT	10-350 K 30-800 K 20-400 K

- Real-space imaging of magnetization down to (sub)10 nm is possible using resonant x-rays
- Element selectivity is naturally provided
- Complex sample environment (high vacuum, cryogenic temperatures, magnetic fields, optics, etc.)
- Naturally thin or nanofabricated samples or surfaces
- Coherent imaging has great potential to push the resolution to ~1 nm limit
- Three-dimensional imaging is possible
- Time-resolved imaging (sub-100 ps routinely, fs time scale at FELs) is possible

- Fundamentals of magnetic dichroism, sum rules, etc.

Stöhr, J. "X-ray magnetic circular dichroism spectroscopy of transition metal thin films." *Journal of Electron Spectroscopy and Related Phenomena* 75 (1995): 253-272.
van der Laan, G., and Figuera, A. I. "X-ray magnetic circular dichroism—A versatile tool to study magnetism." *Coordination Chemistry Reviews* 277 (2014): 95-129.

- Resonant x-ray scattering

Fink, J., et al. "Resonant elastic soft x-ray scattering." *Reports on Progress in Physics* 76.5 (2013): 056502.
Paolasini, L., and de Bergevin F. "Magnetic and resonant X-ray scattering investigations of strongly correlated electron systems." *Comptes Rendus Physique* 9.5-6 (2008): 550-569.

- X-ray magnetic imaging

Fischer, P. "Magnetic imaging with polarized soft x-rays." *Journal of Physics D: Applied Physics* 50.31 (2017): 313002.
Reeve, R. M., et al. "Magnetic imaging and microscopy." *Handbook of Magnetism and Magnetic Materials* (2020): 1-52.

- Coherence

Nugent, K. A. "Coherent methods in the X-ray sciences." *Advances in Physics* 59.1 (2010): 1-99.
Munro, P. "Coherent x-ray imaging across length scales." *Contemporary Physics* 58.2 (2017): 140-159.
LINXS Webinar CoWork series on YouTube <https://www.youtube.com/playlist?list=PLoa4trwK2Db7kaHauxrN9KhPYgS44Oo8Y>

- Dynamics

Raftrey, D., and Fischer, P. "Advanced magnetic X-ray spectro-microscopies to characterize mesoscopic magnetic materials." *Journal of Magnetism and Magnetic Materials* 545 (2022): 168734.
Huang, N., et al. "Features and futures of X-ray free-electron lasers." *The Innovation* 2.2 (2021): 100097.

HZB PHOTON SCHOOL

ON-LINE LECTURES, 27th – 31st March, 2023

ON-SITE TRAININGS, 3rd – 6th April 2023*

HZB Wilhelm-Conrad-Röntgen-Campus, Berlin-Adlershof

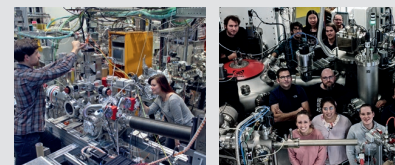
CLOSING DATE
FOR APPLICATION:
5th
DECEMBER
2022



A Practical Introduction to Photon Science

The program of this school is aimed primarily at master students and other early stage researchers in physics, chemistry, materials science, engineering, and life or environmental sciences. Students will be introduced to advanced synchrotron- and laboratory-based photon science methods that probe the physical, chemical, and electronic structures of materials as well as the function and dynamics of complex material systems. The basic and specialized lectures are given by experienced teachers, who are HZB scientists or BESSY II super-users from our partner universities and research centers.

*contingent on BESSY II is operating at a level that allows HZB employees access



TRAININGS IN:

- Synchrotron-based methods from BESSY II beamlines
- Laboratory-based methods
- Data collection, treatment, interpretation, and presentation
- How to write successful beamtime proposals



hz-b.de/photonschool

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