Magnetic Imaging: Studying Magnetic Textures with X-Rays

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TEM & X-Ray Interface Group
ALBA Synchrotron
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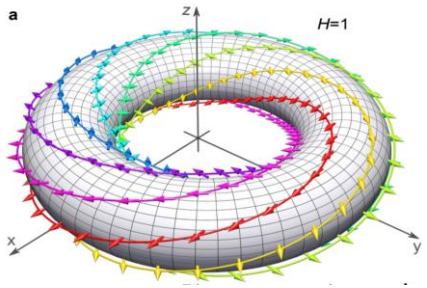
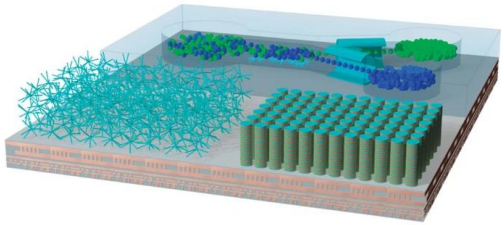
New trends in Spin textures

3D Magnetism

hopfions



Interconnected networks

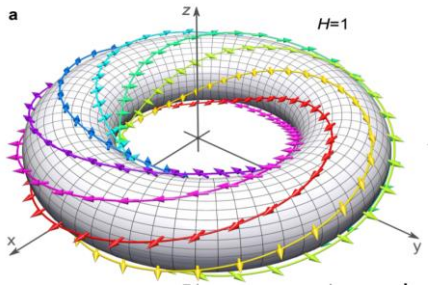


A. Fernandez-Pachecho et al. Nat. Commun. 8 (2017) 15756

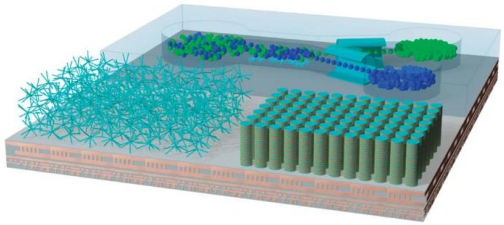
New trends in Spintronics

3D Magnetism

hopfions

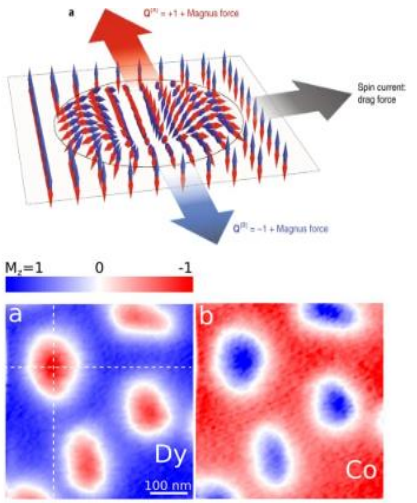


Interconnected networks



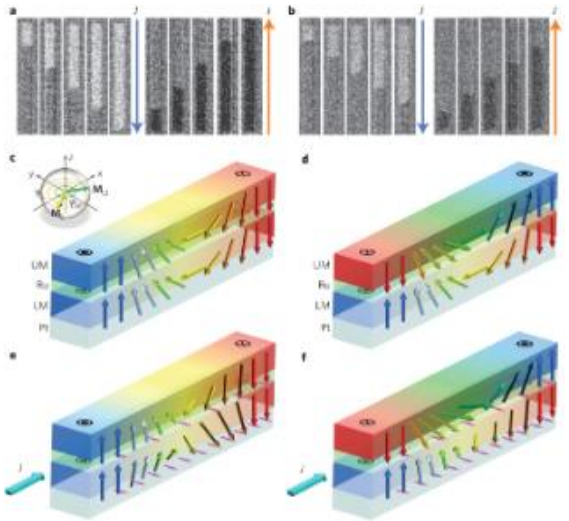
Antiferromagentic spintronics

Skyrmions



Luo et al., Comm. Phys. **6**, 218 (2023)

Fast domain wall motion



A. Fernandez-Pachecho et al. Nat. Commun. 8 (2017) 15756

New trends in Spintronics

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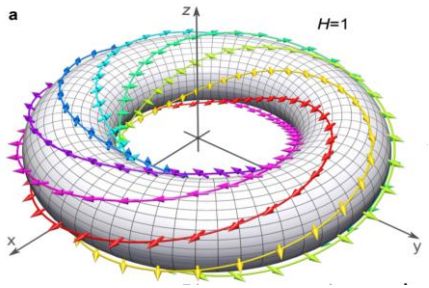

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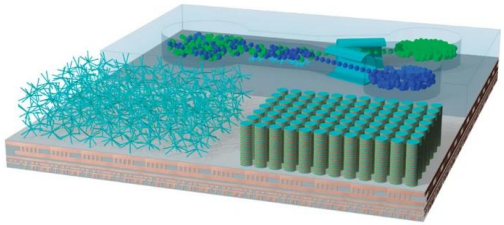

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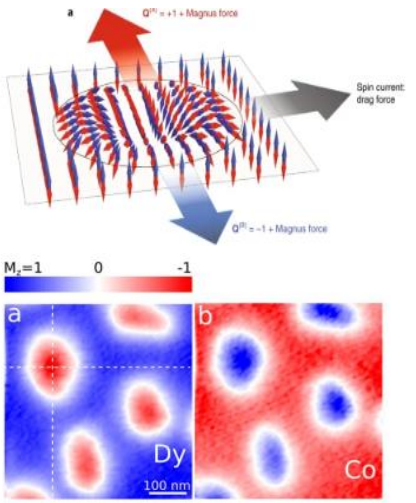
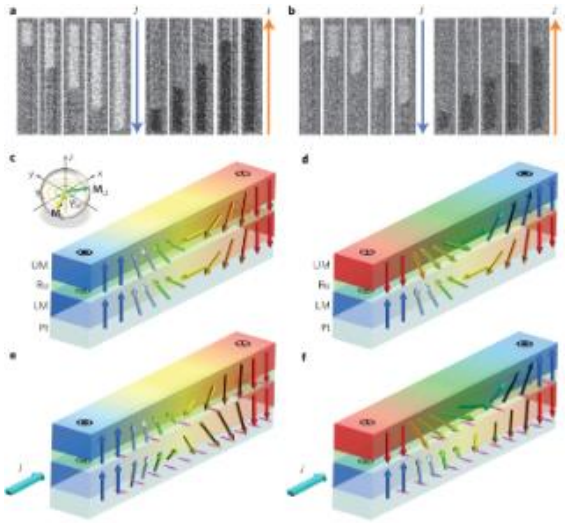
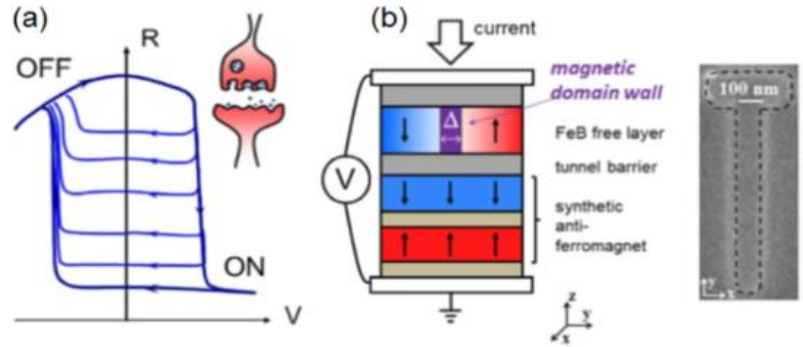


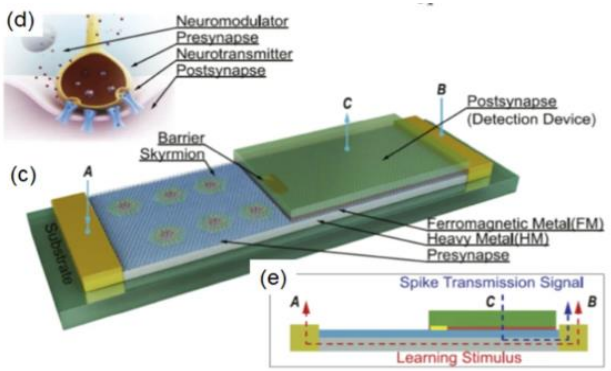
Luo et al., Comm. Phys. **6**, 218 (2023)

Fast domain wall motion



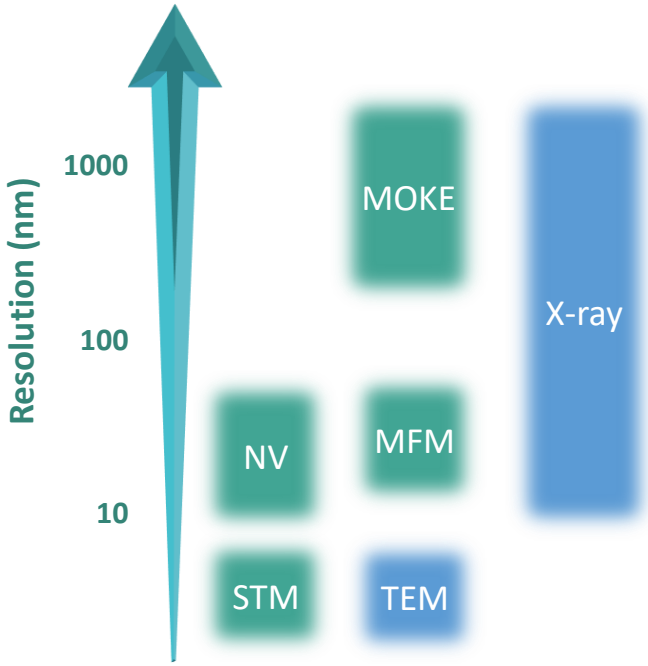
Neuromorphic computing





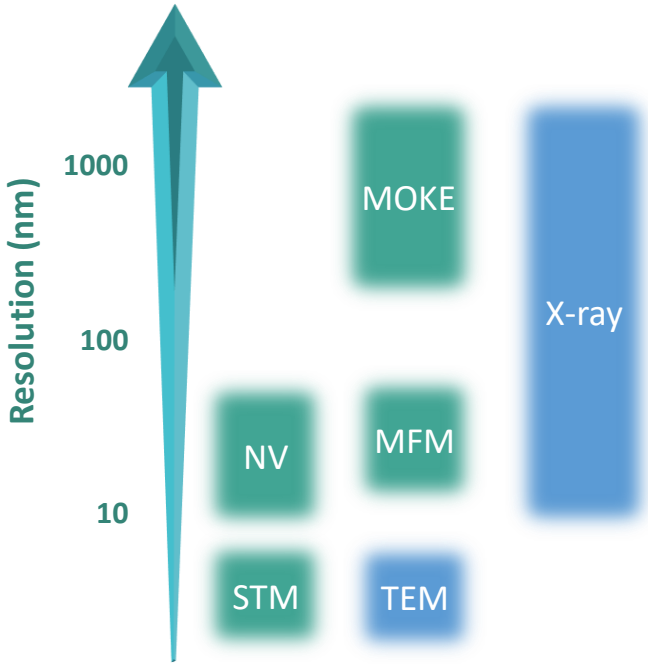
A. Fernandez-Pachecho et al. Nat. Commun. 8 (2017) 15756

How to choose?



- Spatial resolution
- Depth sensitivity
- Sample environment
- Accessibility
- Time resolution

How to choose?



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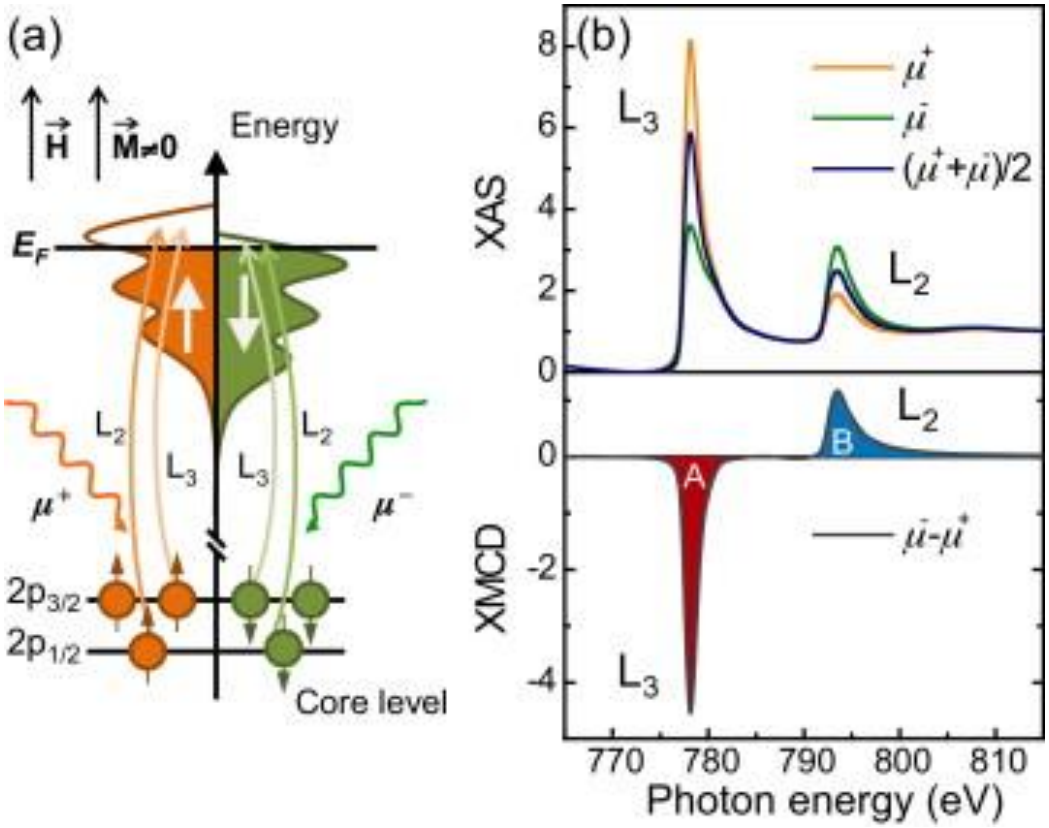
Synchrotron light source

How to see the magnetism: XMCD



- Element Sensitivity

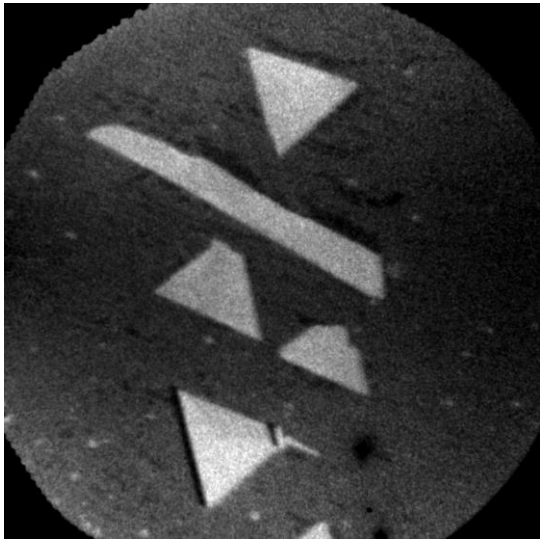
- Magnetic sensitivity

Coupled with microscopes, it provides the unique ability to resolve magnetic textures in complex three-dimensional nanostructures.

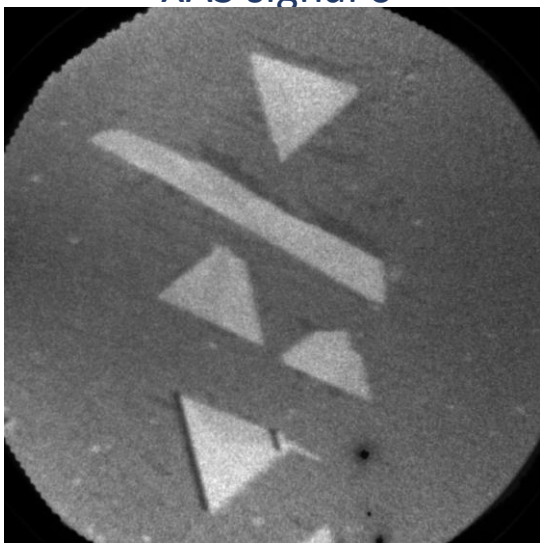
Peter Fischer and Hendrik Ohldag 2015 Rep. Prog. Phys. 78 094501

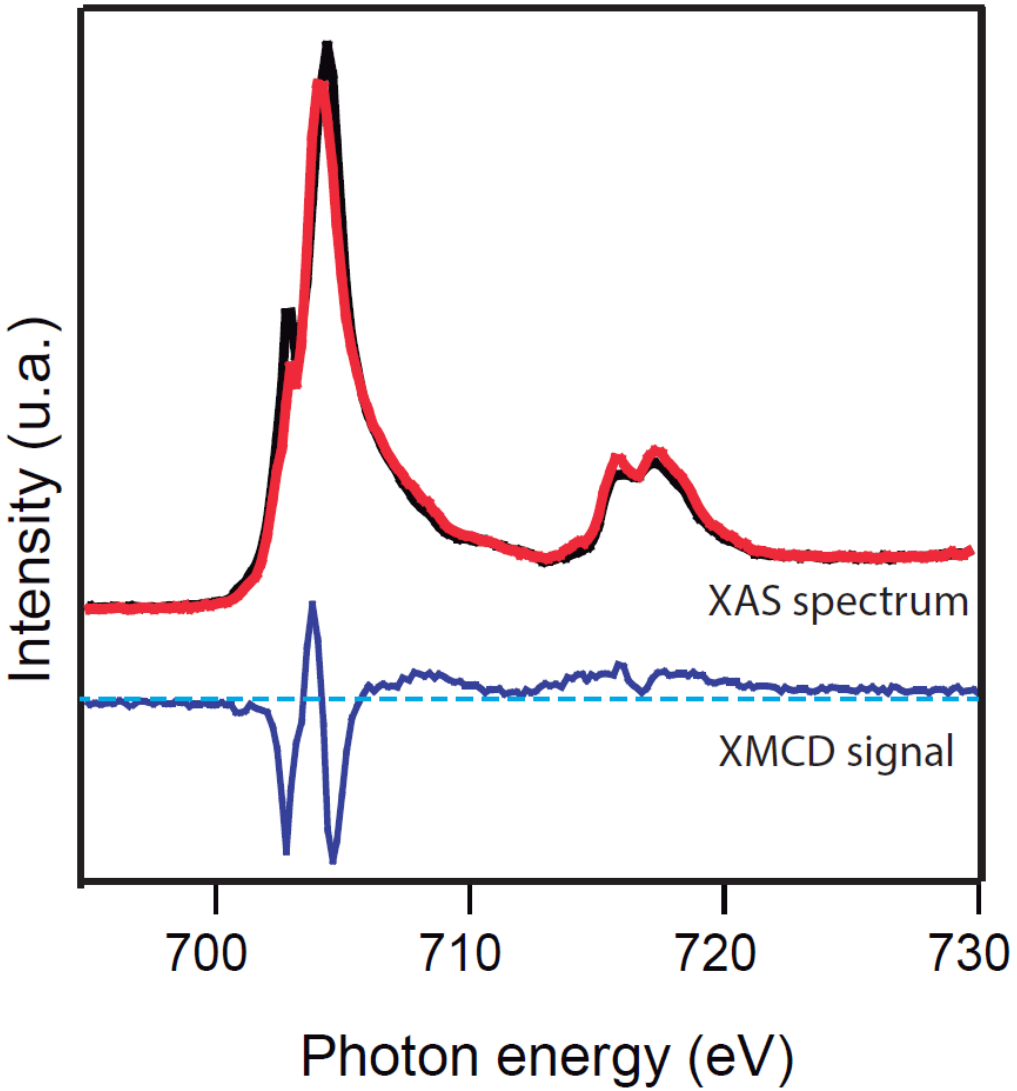
How to see the magnetism: XMCD

XAS signal σ+



XAS signal σ-





How to see the magnetism: XMCD

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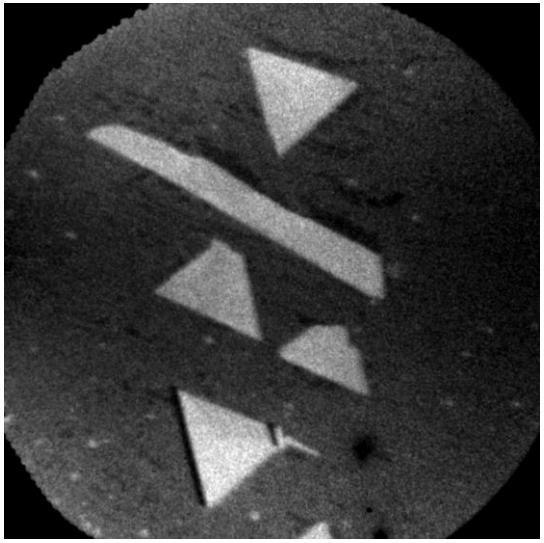

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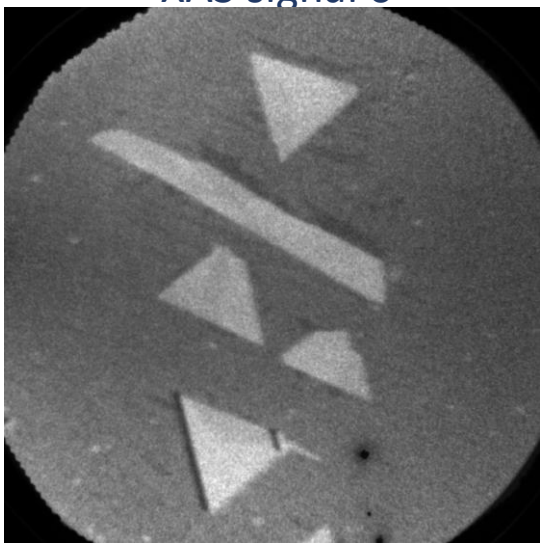
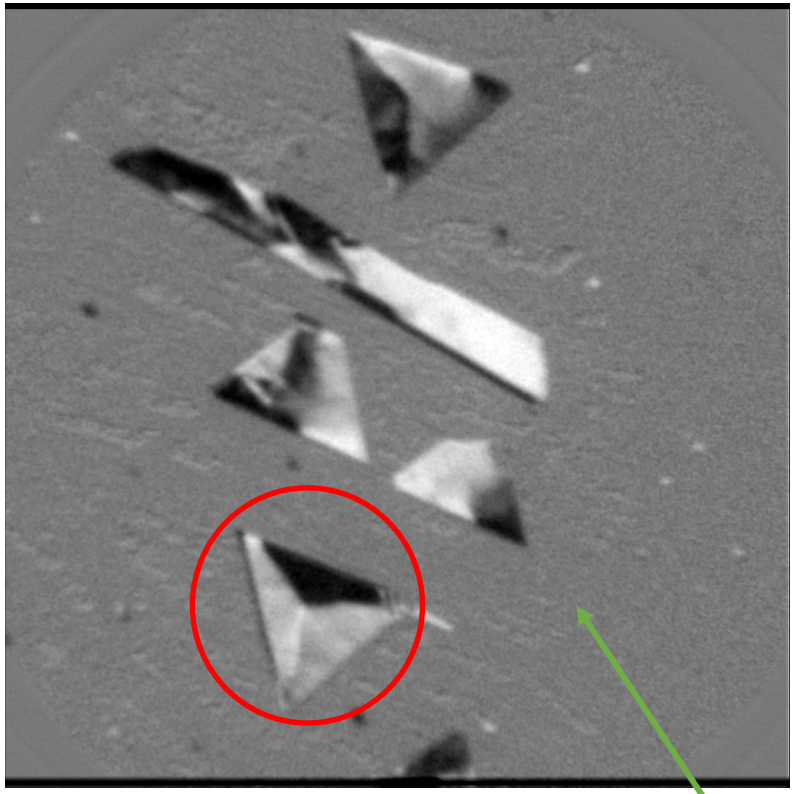


XMCD Image

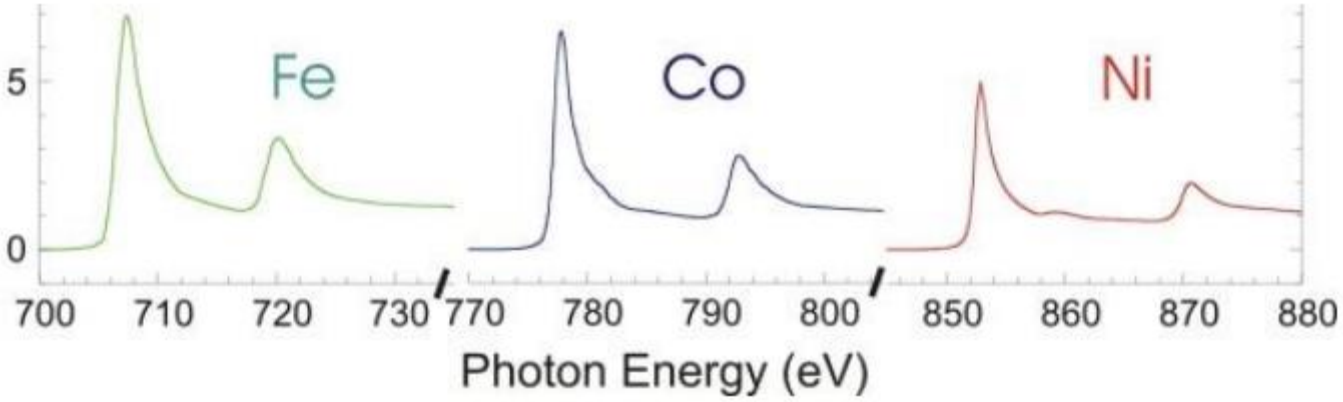


Magnetic contrast

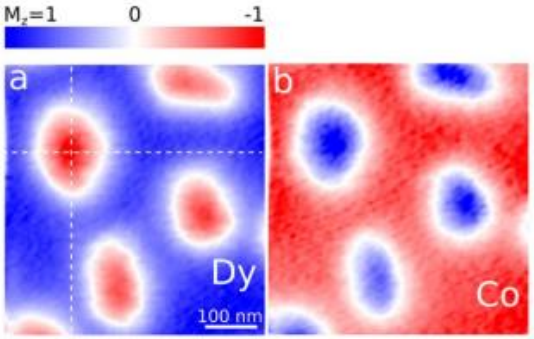
Non magnetic contrast

XMCD: Element specificity

Different elements can be targeted separately!

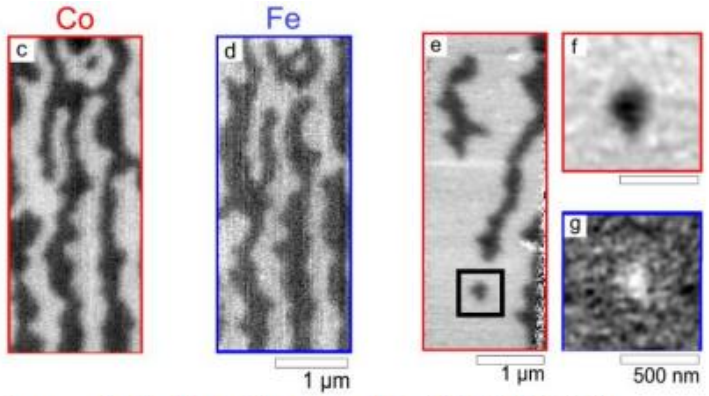


For ferrimagnets:
Ferrimagnetic skyrmions in DyCo3 films



Luo et al., Comm. Phys. **6**, 218 (2023)

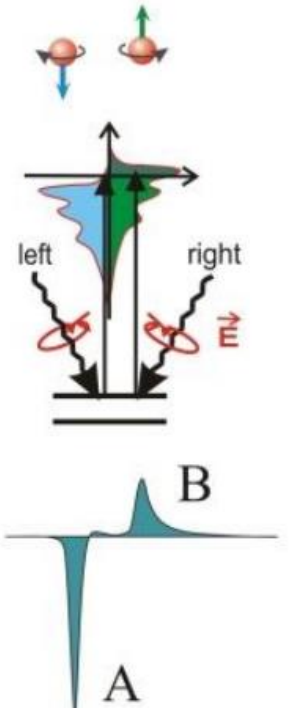
For synthetic antiferromagnet:
Synthetic antiferromagnet skyrmion



Juge et al., Nat. Comm. **13**, 4807 (2022)

XMCD: Spin and orbital

As well as measuring something proportional to m, it provides a quantitative measure of the magnetic moment!



L3 edge $p_{3/2}$: $l + s$

→ +ve Photon angular momentum

→ spin "up"

→ orbital "up"

L2 edge $p_{1/2}$: $l - s$

→ +ve Photon angular momentum

→ spin "down"

→ orbital "up"

By combining L_2 and L_3 can isolate spin and orbital moments

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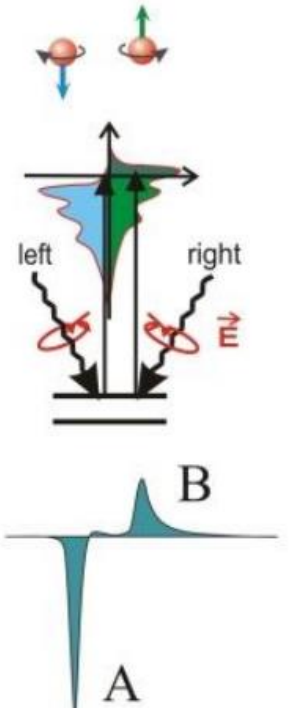
As well as measuring something proportional to m, it provides a quantitative measure of the magnetic moment!



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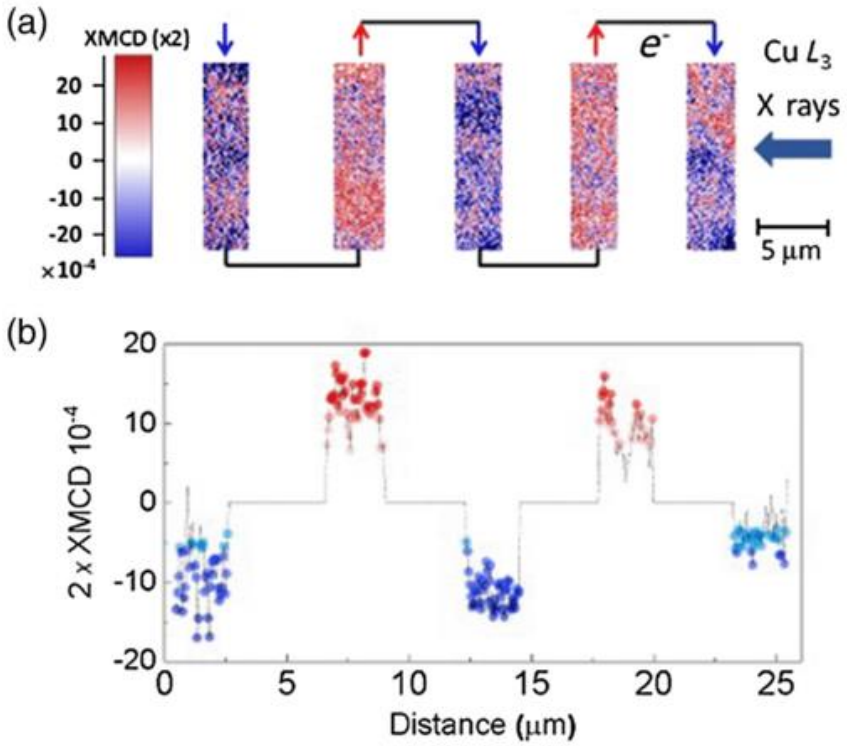
By combining L_2 and L_3 can isolate spin and orbital moments

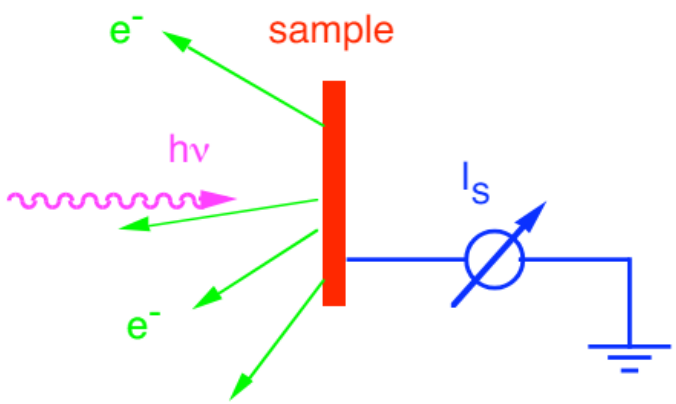
Image of the spin accumulation due to the Spin Hall Effect



S. Ruiz-Gomez et al, PRX 2022

Imaging the x-ray absorption

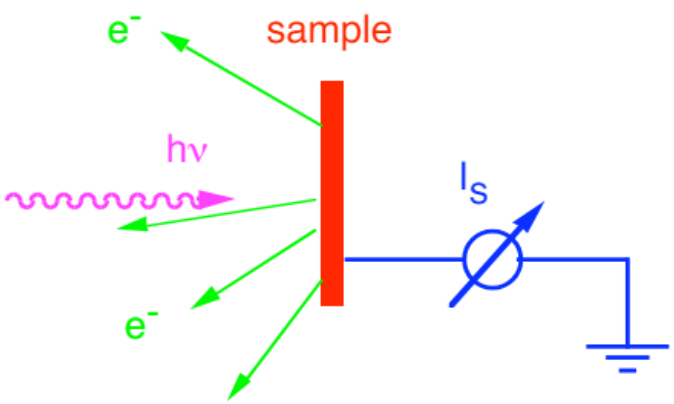
Total Electron Yield



- Proportional absorption
- Surface sensitivity (few nm)
- Thick or thin samples

Imaging the x-ray absorption

Total Electron Yield



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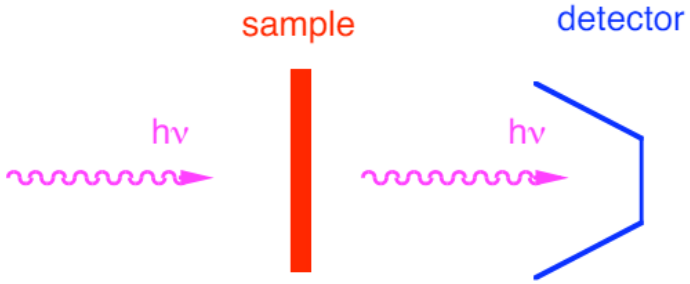
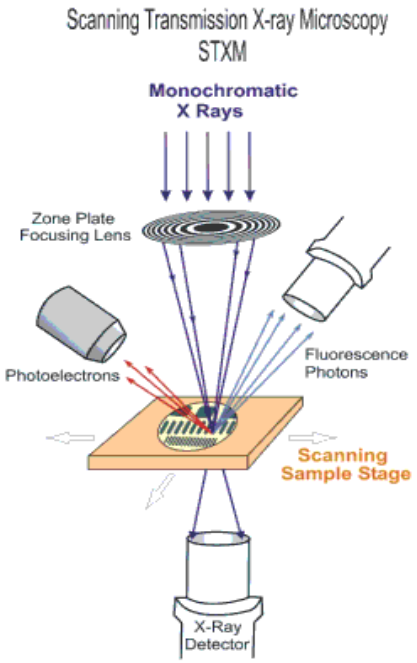
Transmission



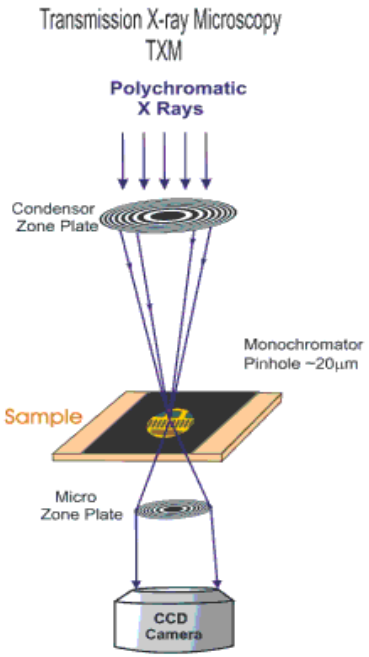
- Real absorption
- “Bulk sensitivity”
- Thin samples (soft x-rays)
- Thick samples (hard x-rays)

Imaging magnetism with the power of x-rays

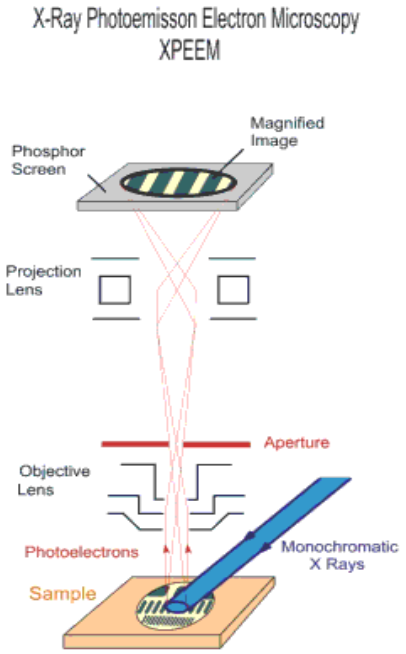
In real space



J. B. Kortright et al, AIP 507, 49 (2000).



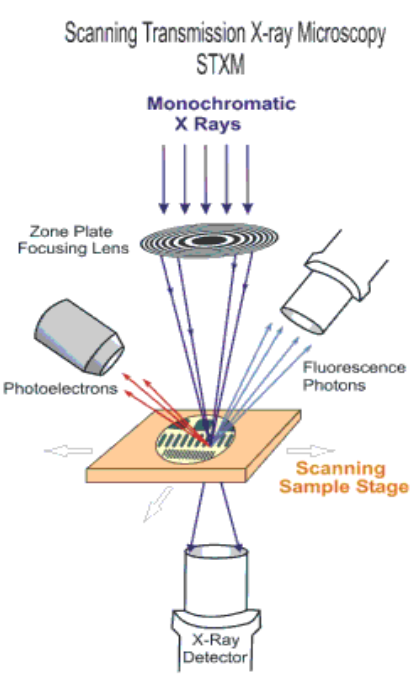
P. Fisher et al. Z. f. Phys. B101 313 (1996)



J. Stoehr et al. Science 259 658 (1993)

Imaging magnetism with the power of x-rays

In real space or in reciprocal space



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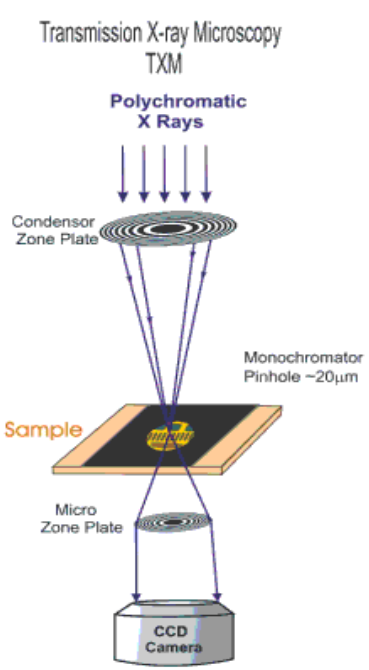

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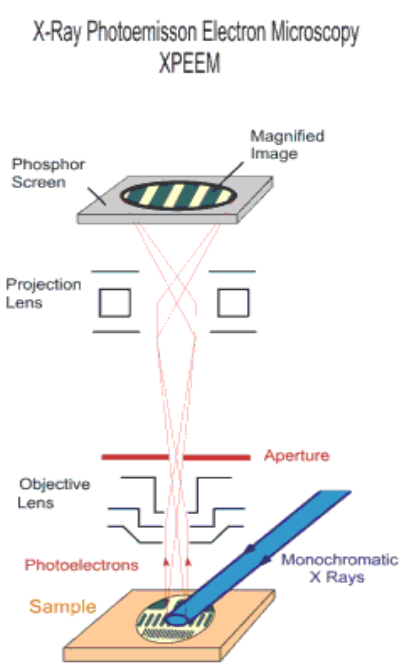
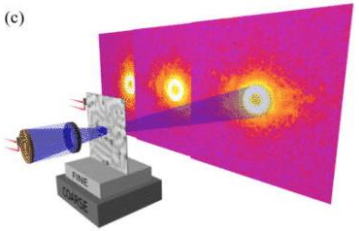


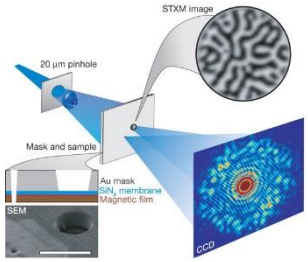
J. Stoehr et al. Science 259 658 (1993)

X-ray ptychography



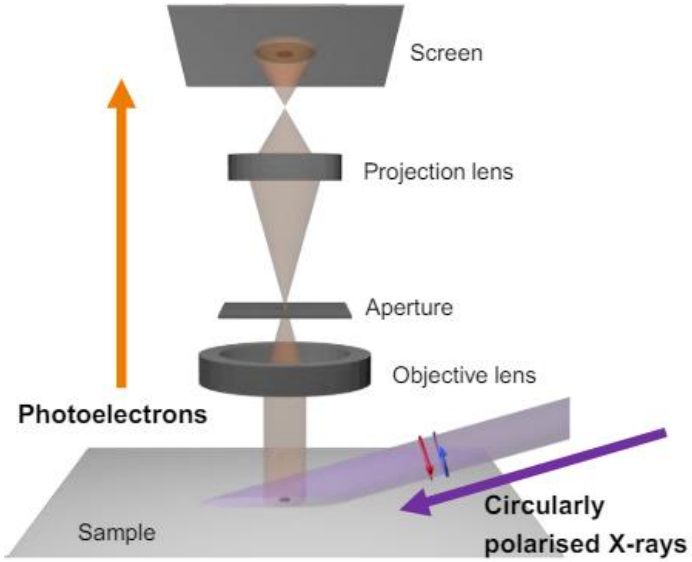
X. Shi, et al. APL 108 094103 (2016)

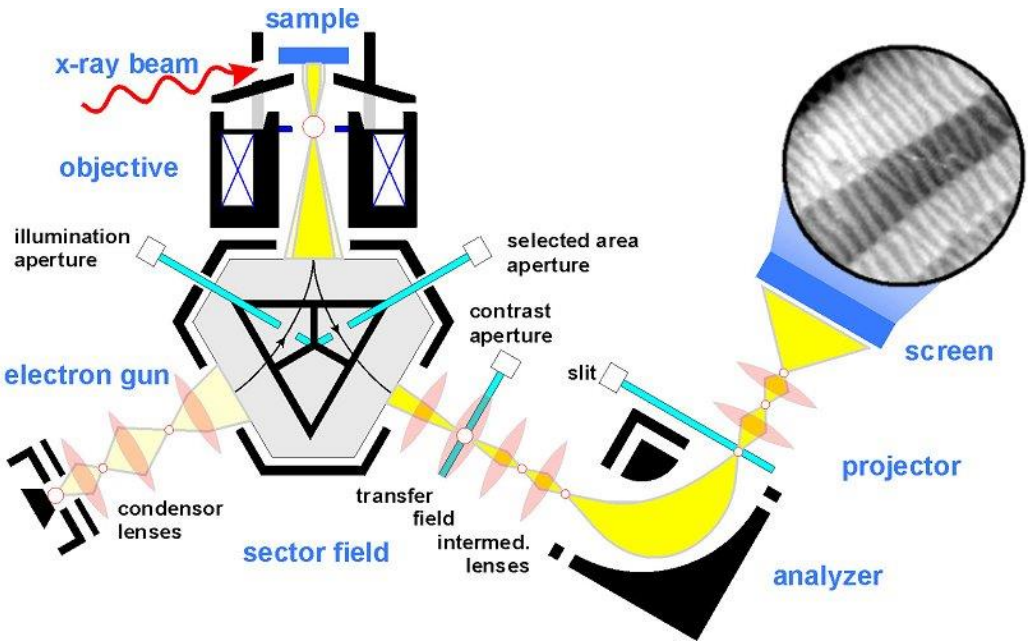
X-ray holography



S. Elsebitt et al. Nature 432 885 (2004)
F. Willems et al. Strucuct. Dyn. 4 0143301 (2017)

Photo Emission Electron Microscopy: PEEM





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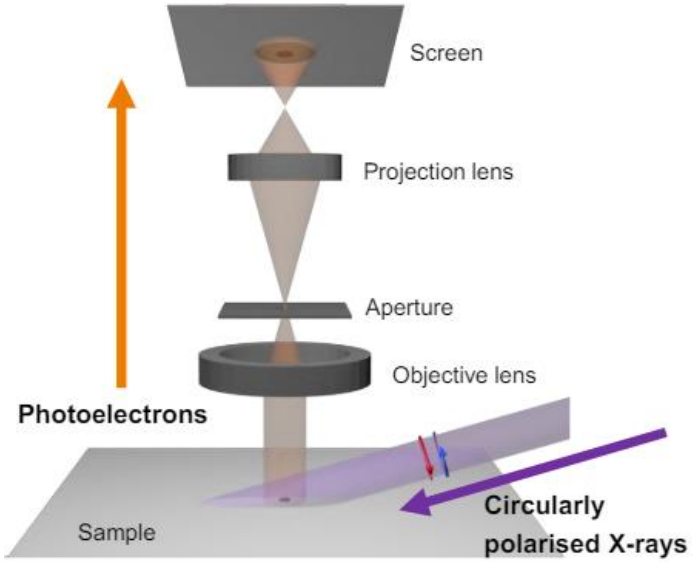
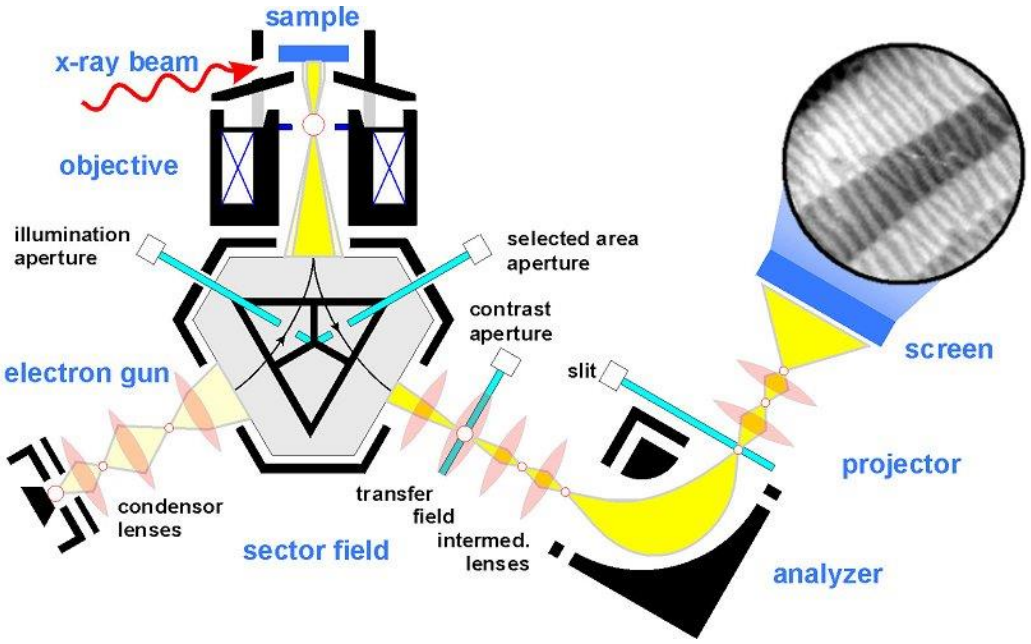
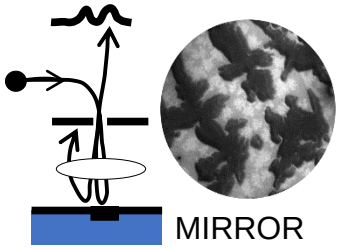
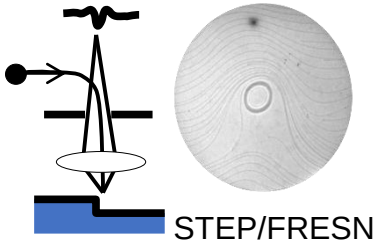
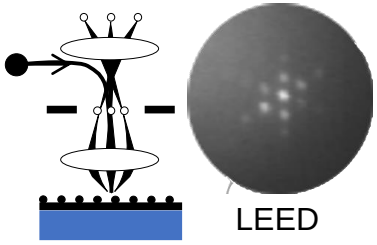




LEEM Mode

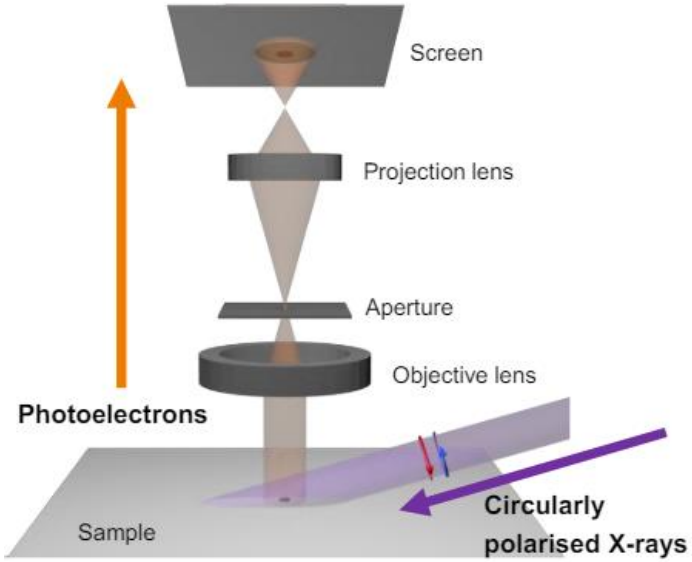

MIRROR

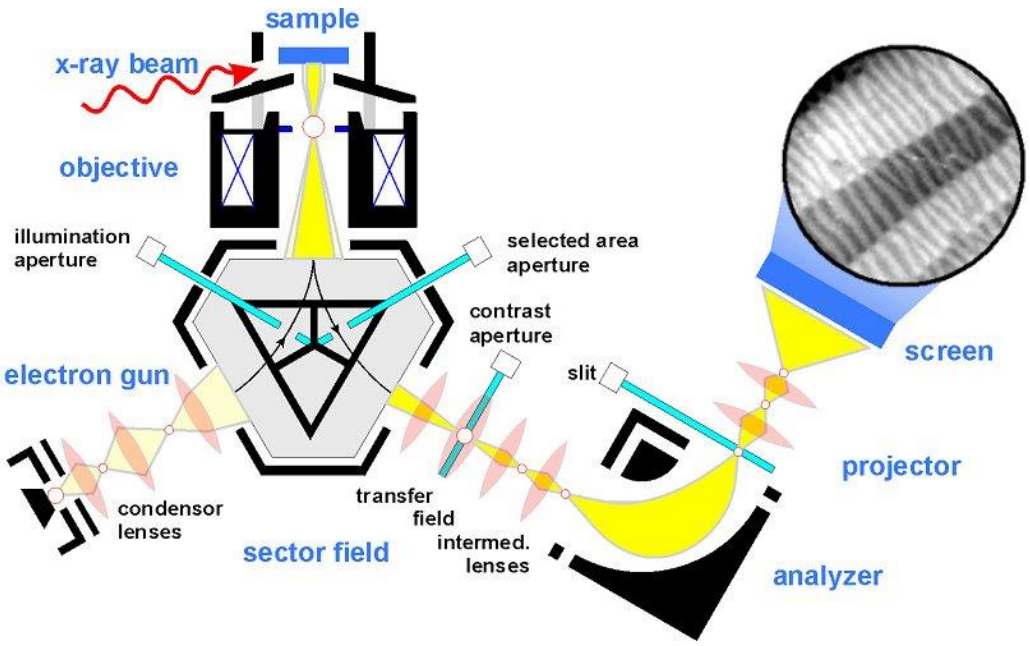

STEP/FRESNEL


LEED


DARK FIELD

Photo Emission Electron Microscopy: PEEM





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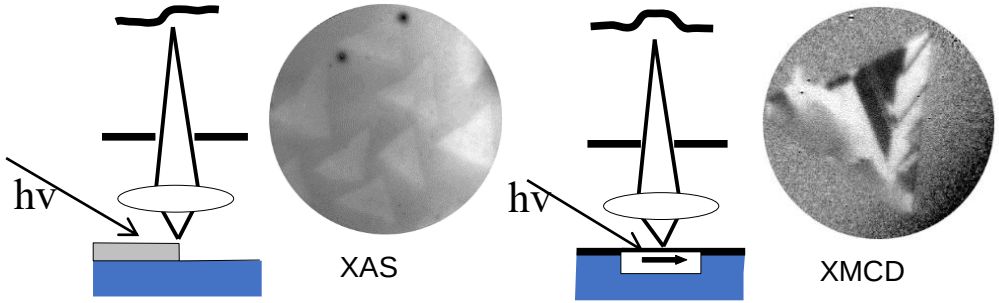

XMCD PEEM imaging

… Pixelwise substractionof images with opposite circular photon polarization
… XMCD “intensity” $\sim m*s$ with s the beam direction
… White/black/grey means parallel/antiparallel/perpendicular or not magnetic
… Resolution around 30 nm

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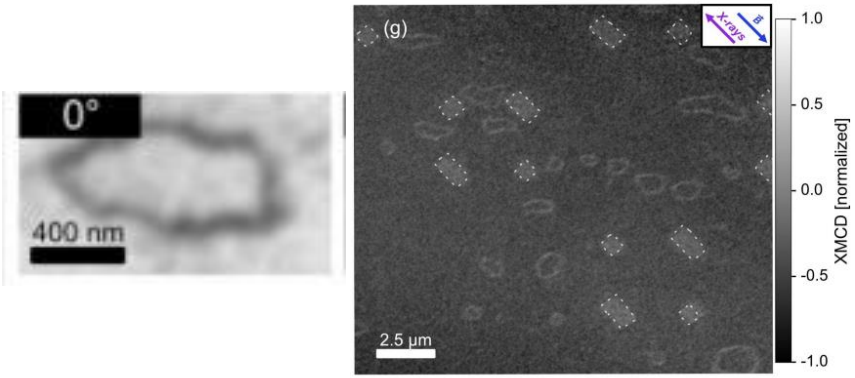
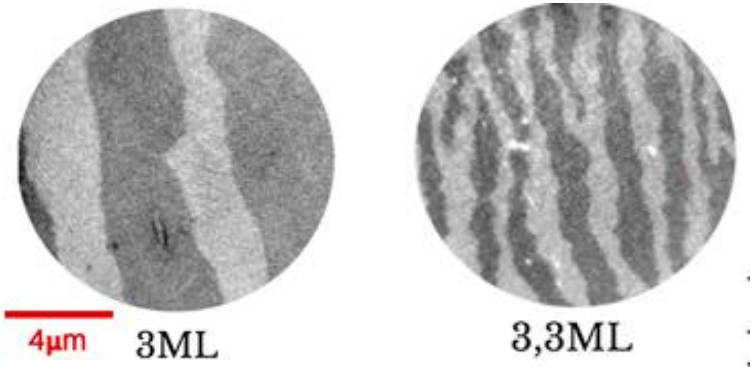
In- plane & out of plane contrast

360° domain wall rings in
Synthetic Anti-Ferromagnets



M. Cascales et al. J. Synchrotron Rad. (2024)

stripe domains and elliptical
skyrmion in PMA films



Lorenzo Camosi et al 2021 New J. Phys.

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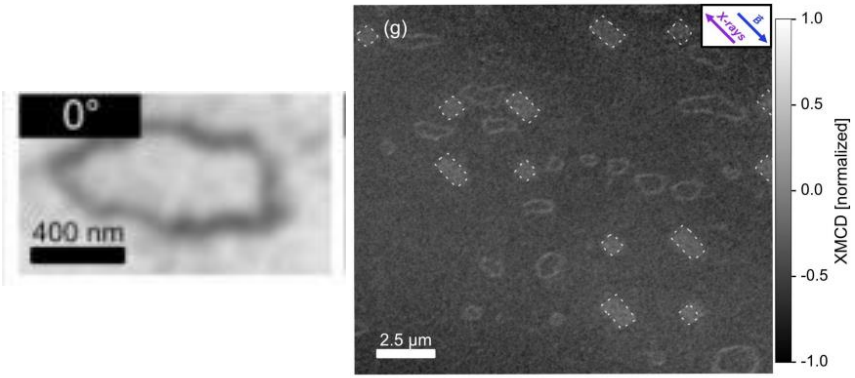
… XMCD “intensity” $\sim m*s$ with s the beam direction
… White/black/grey means parallel/antiparallel/perpendicular or not magnetic
… Resolution around 30 nm

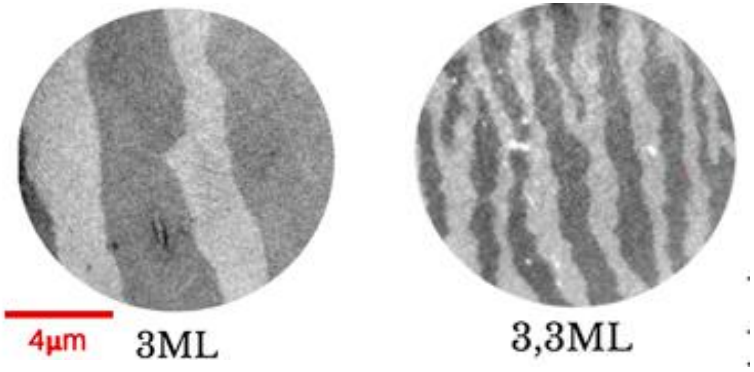
In- plane & out of plane contrast

360° domain wall rings in
Synthetic Anti-Ferromagnets



M. Cascales et al. J. Synchrotron Rad. (2024)

stripe domains and elliptical
skyrmion in PMA films



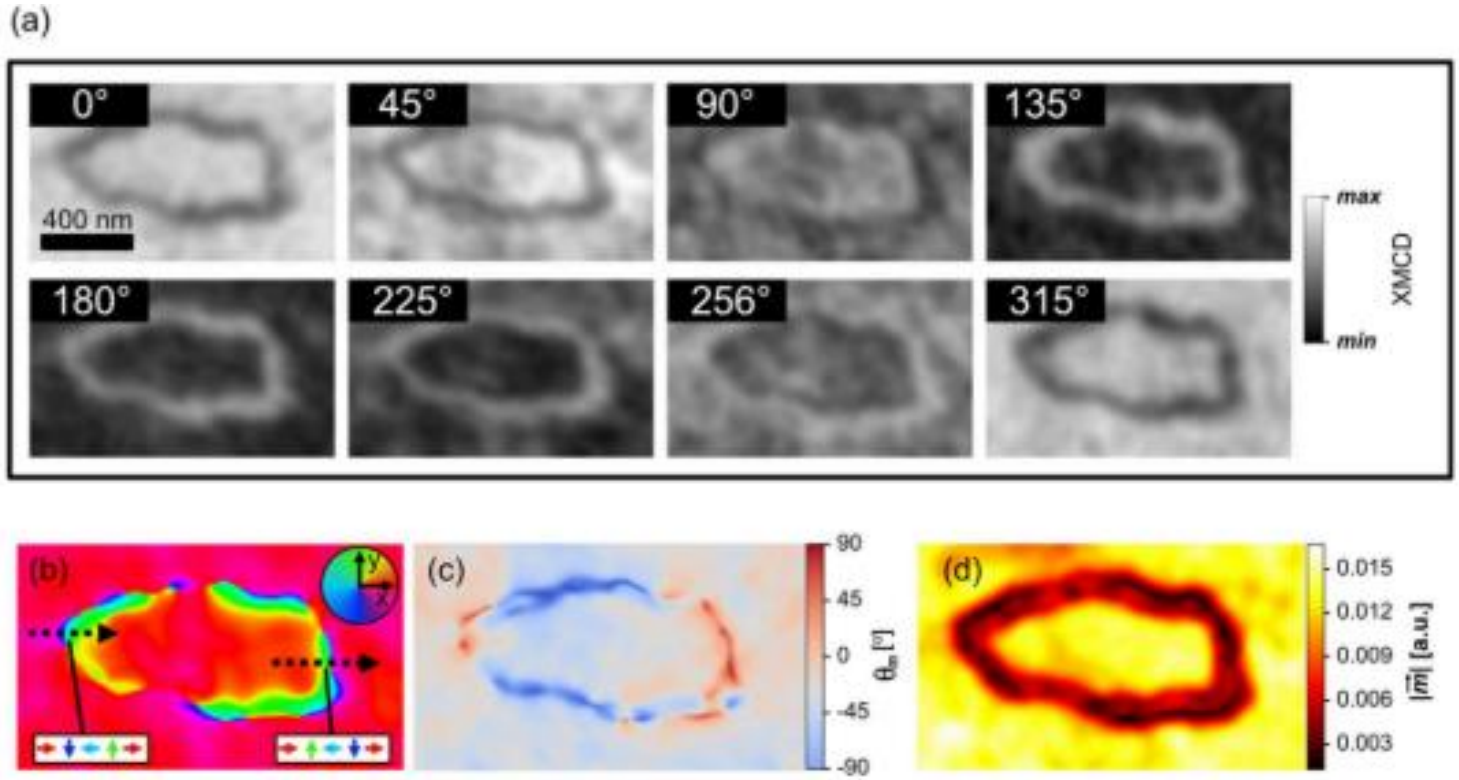
Lorenzo Camosi et al 2021 New J. Phys.

How to obtain the 3D magnetization vector?

XMCD PEEM imaging

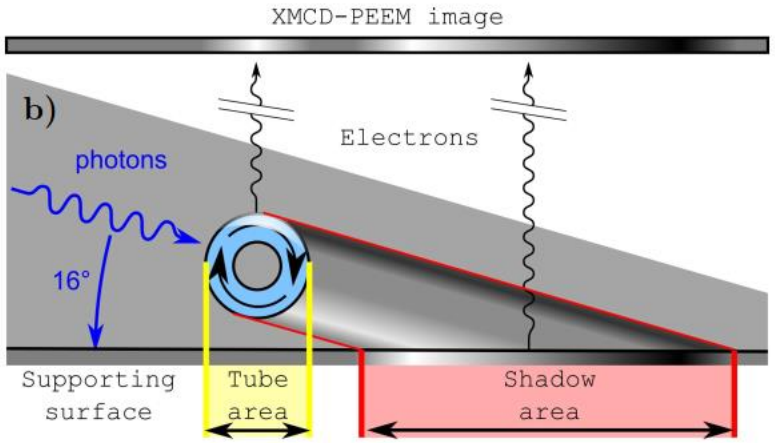
… Pixelwise substractionof images with opposite circular photon polarization
… XMCD “intensity” $\sim m*s$ with s the beam direction
… White/black/grey means parallel/antiparallel/perpendicular or not magnetic
… Resolution around 30 nm

3D reconstruction of the magnetization



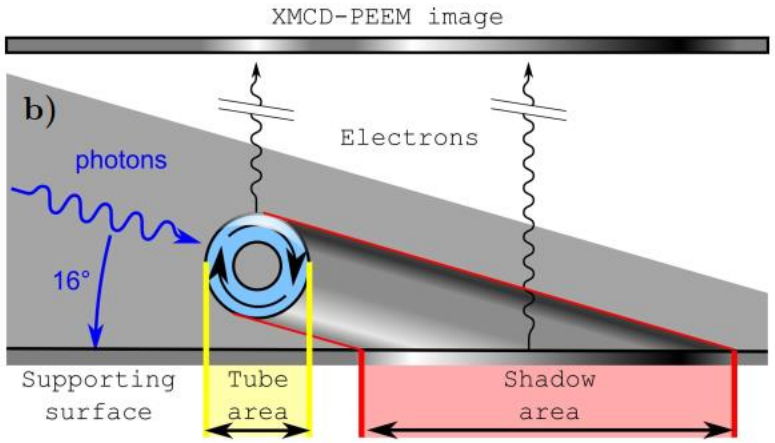
M. Cascales et al. J. Synchrotron Rad. (2024). 31, 336–342

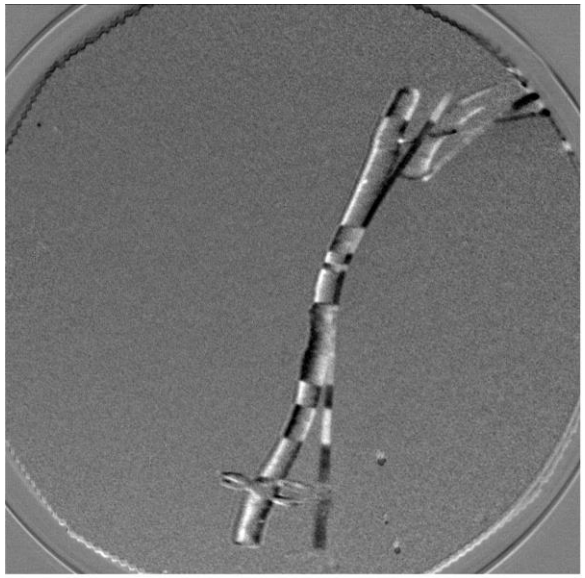
How to image 3D nanostructures? Shadow XMCD PEEM



M. Stano et AL. SciPost Physics, 5, 4, (2018)
J. Kimling et al. Phys. Rev. B , 84:174406 (2011)

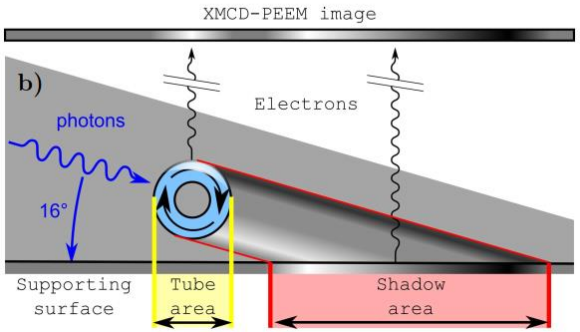
How to image 3D nanostructures? Shadow XMCD PEEM

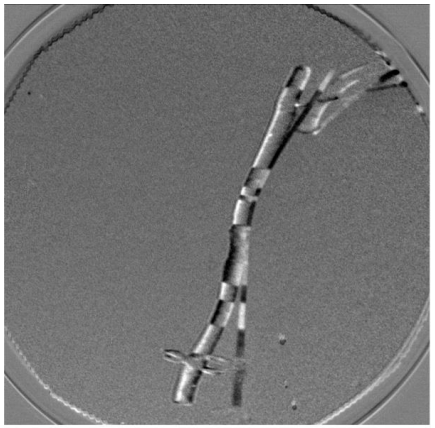


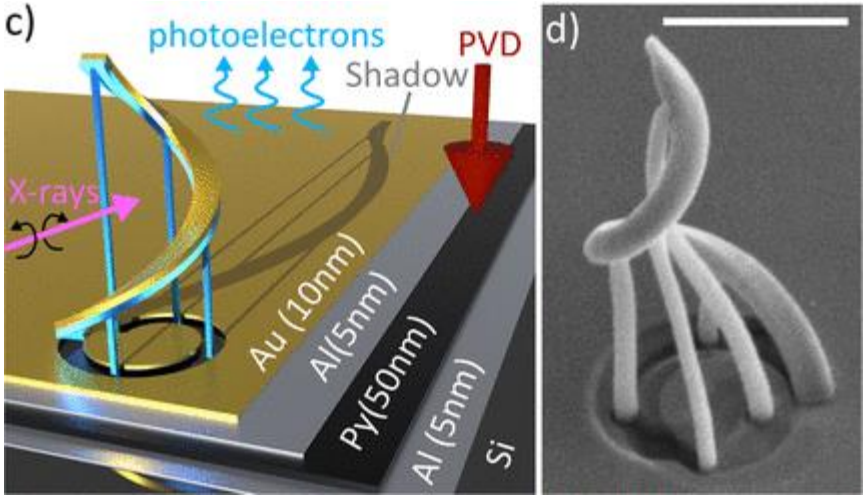


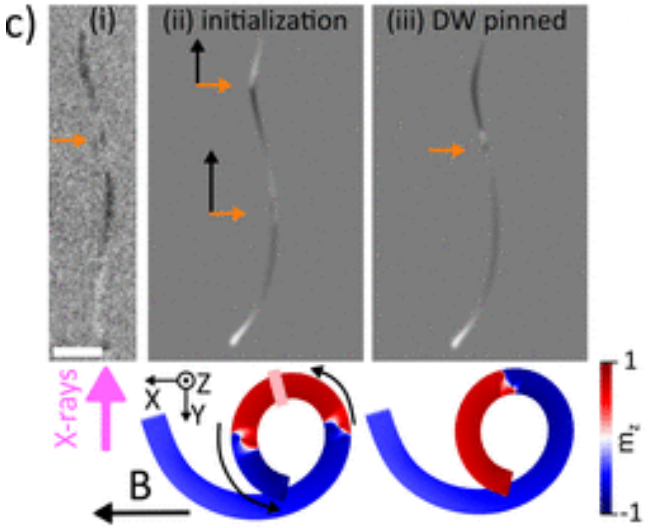
M. Stano et AL. SciPost Physics, 5, 4, (2018)
J. Kimling et al. Phys. Rev. B , 84:174406 (2011)

How to image 3D nanostructures? Shadow XMCD PEEM





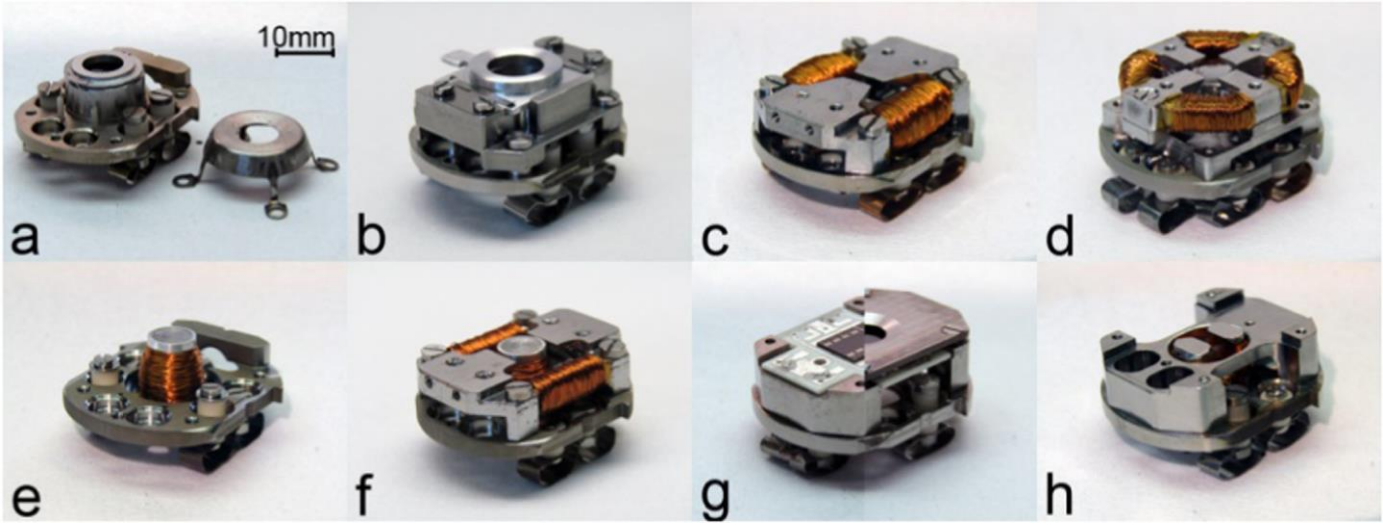




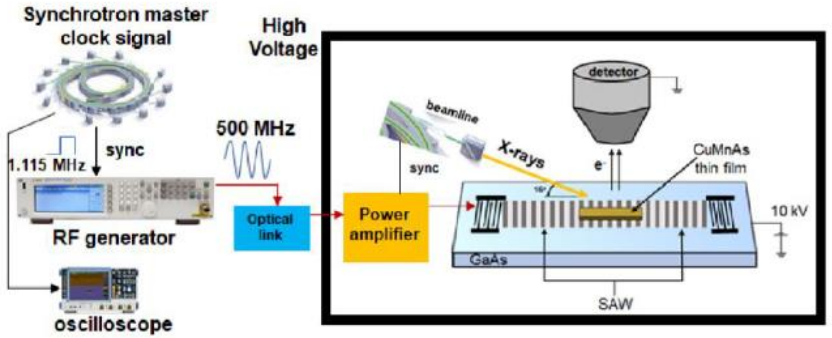
M. Stano et AL. SciPost Physics, 5, 4, (2018)
J. Kimling et al. Phys. Rev. B , 84:174406 (2011)

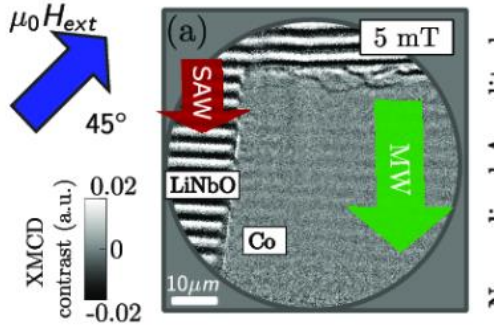
Sample environment

Temperature Multimodal Magnetic Fields Current and bias



In-situ GHz excitation





M. Waqas Khaliq et al., Physical Review Materials (2024)
M. Rovirola et al. PRR (2024)

Summary XMCD- PEEM

Strength

…Extreme surface sensitivity: down to subML, compensated SAF.

… Combination with several surface science techniques: LEEM, LEED, XPS & ARPES spectro-microscopy.

… Variable imaging temperature.

… Shadow-PEEM imaging of thicker objects (simultaneous).

… Any substrate: epitaxial growth, piezos, etc

… Flexible sample environment

Weakness

… Samples must be flat, conductive.

… Ultra-high vacuum.

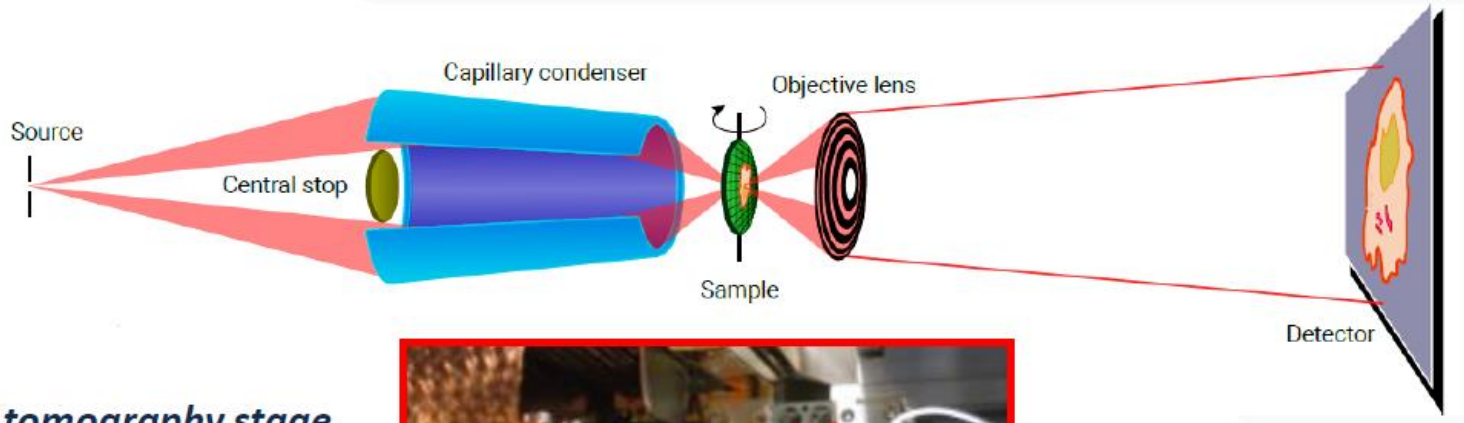
… Sample at high voltage (≥ 10 kV): risk of discharges.

…Complex setup for fast signals.

... In situ fields limited by imaging artifacts.

… Rotation for obtaining full vector magnetization is slow

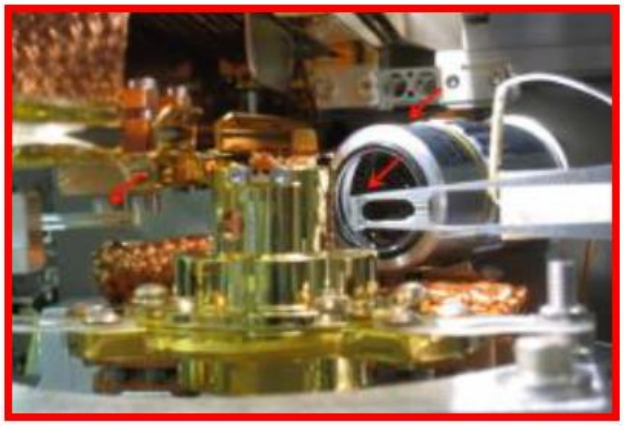
Transmission X-Ray Microscopy: TXM



Cryo tomography stage

T ≈ 100K

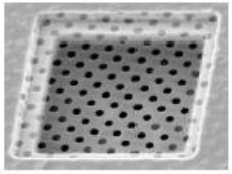
X,Y,Z, Θ

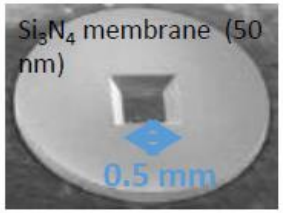


2D spectro-imaging:
< 30 nm resolution

3D cryo-tomography:
50 nm resolution

Cartridge





Transmission X-Ray Microscopy: TXM

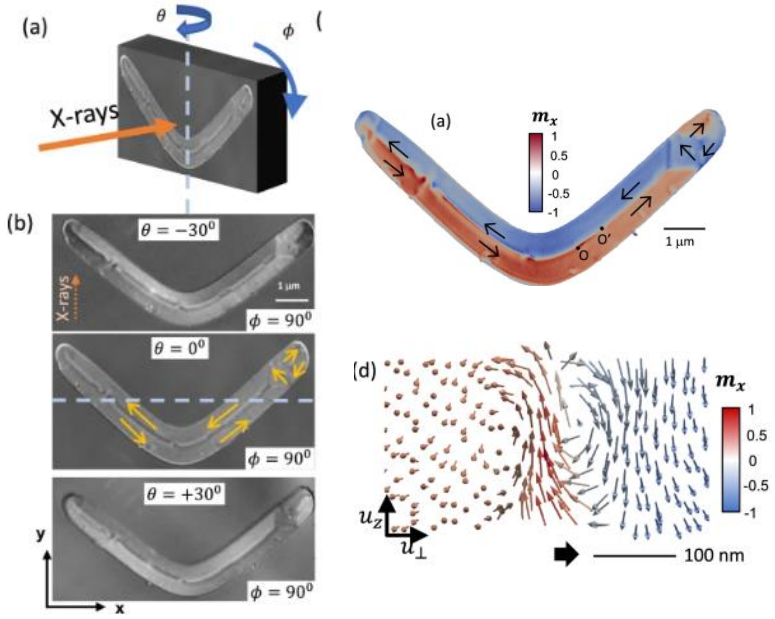
… Normal incidence: out of plane magnetization
… Tilting for in-plane magnetization
… Full thickness average
… White/black/grey means parallel/antiparallel/perpendicular or not magnetic

Transmission X-Ray Microscopy: TXM

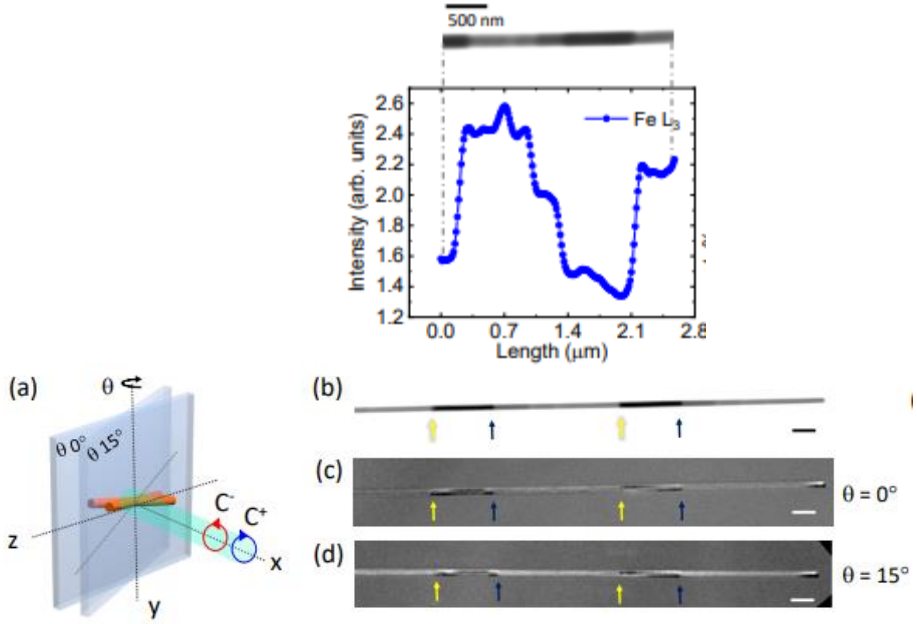
… Normal incidence: out of plane magnetization
… Tilting for in-plane magnetization
… Full thickness average
… White/black/grey means parallel/antiparallel/perpendicular or not magnetic

In plane contrast

Topological defects in a microstructures



Nanowires with chemical defects



J. Hermosaet al. Communications Physics, 6, 49 (2023)

Transmission X-Ray Microscopy: TXM

… Normal incidence: out of plane magnetization
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… Full thickness average
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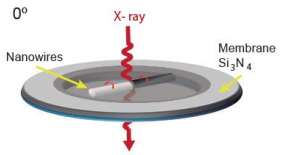
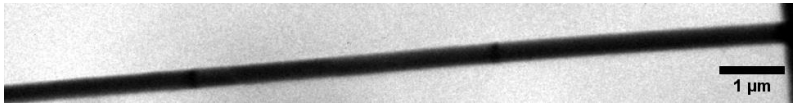
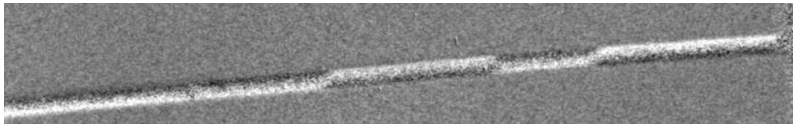
Nanostructures



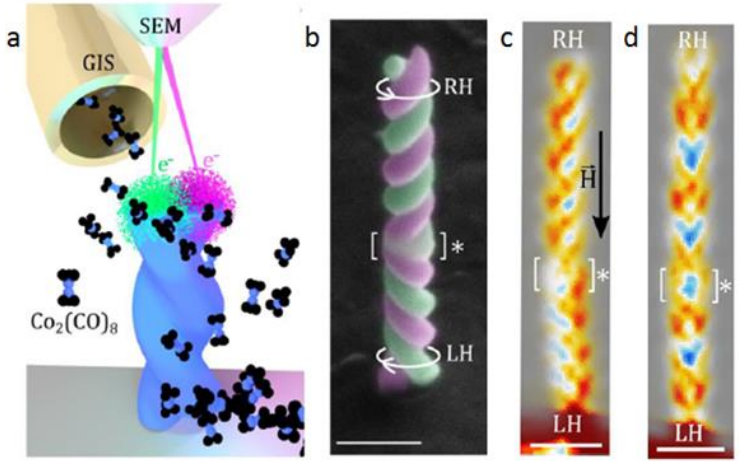
Transmission Image



XMCD

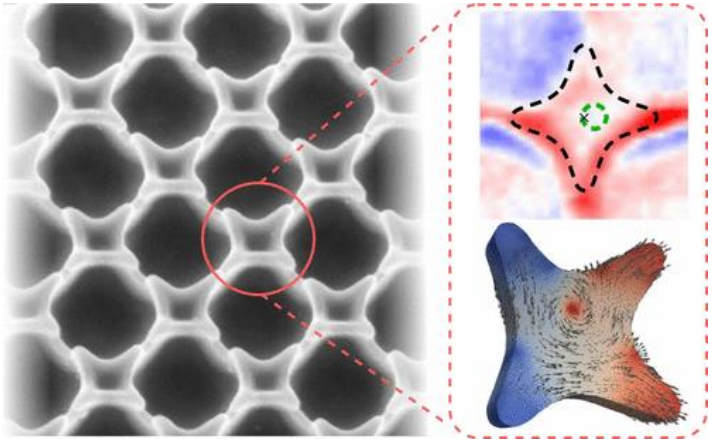


Magnetic Helix



ACS Nano 2020, 14, 7, 8084–8092

3D Magnetic Nanoarchitectures



Nano Lett. 2024, 24, 49, 15774–15780

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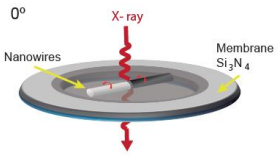
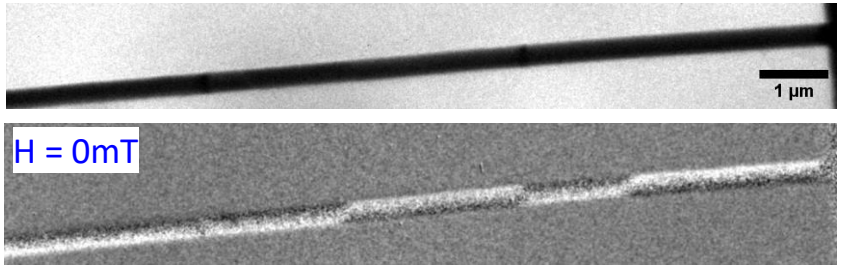


Transmission Image

XMCD



Transmission X-Ray Microscopy: TXM

… Normal incidence: out of plane magnetization
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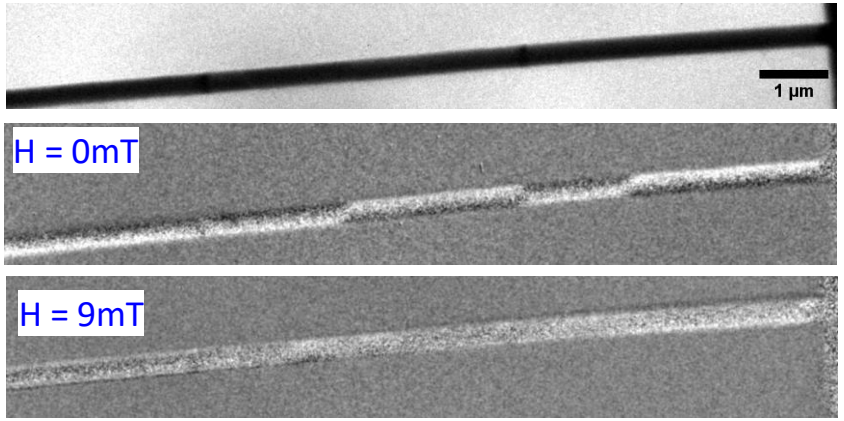
… Full thickness average
… White/black/grey means parallel/antiparallel/perpendicular or not magnetic

In-situ applied magnetic fields

Transmission Image

XMCD

XMCD



Transmission X-Ray Microscopy: TXM

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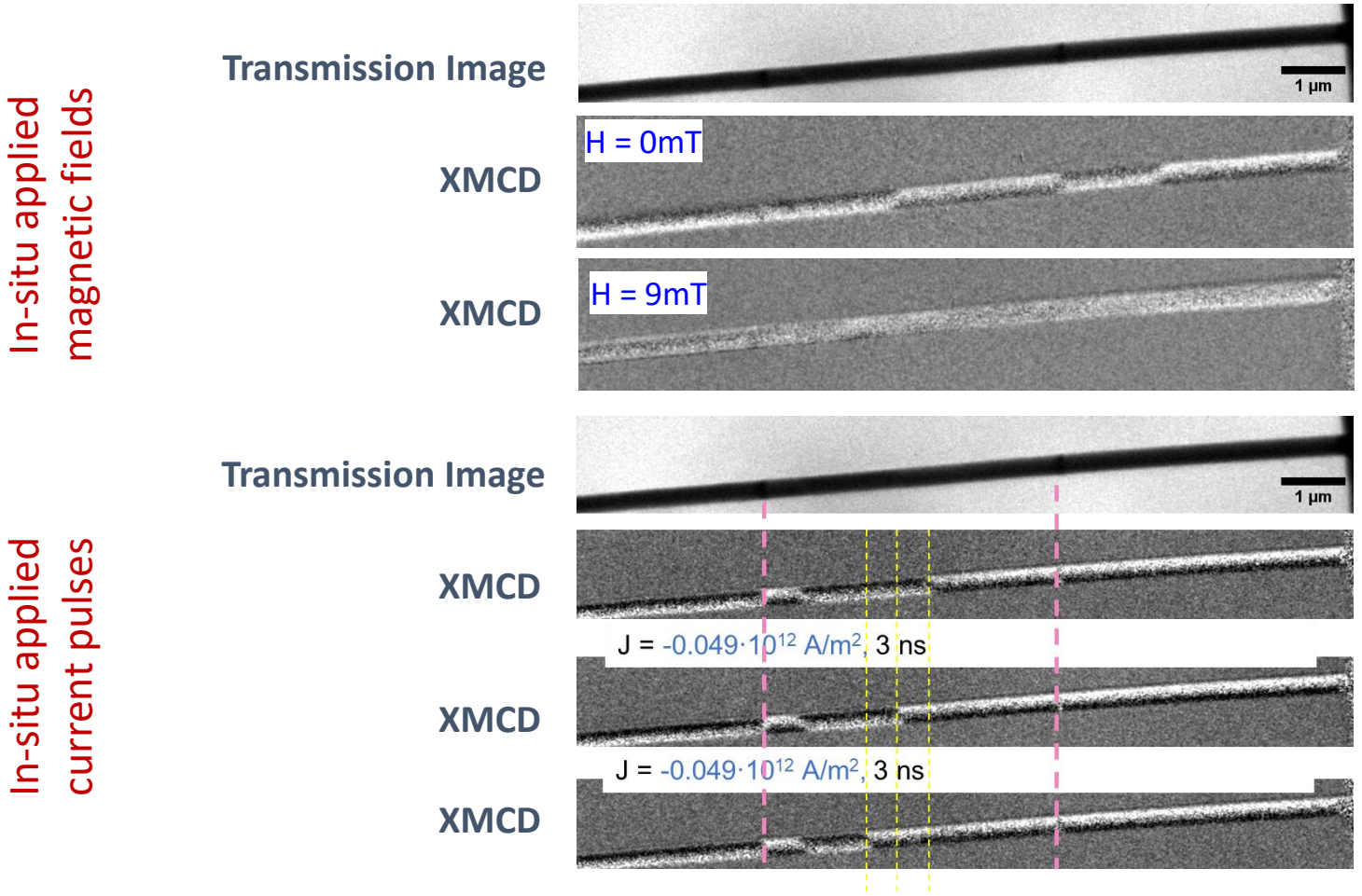
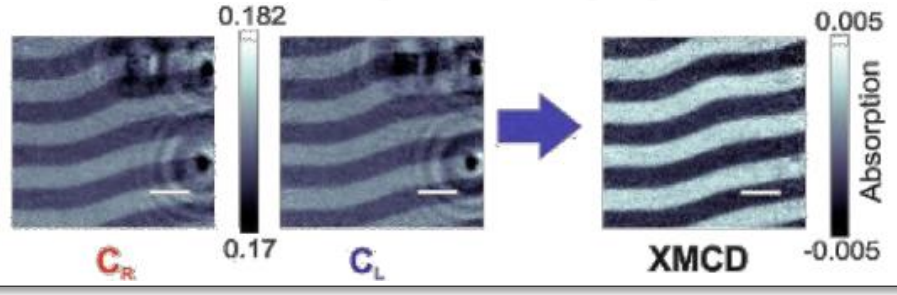
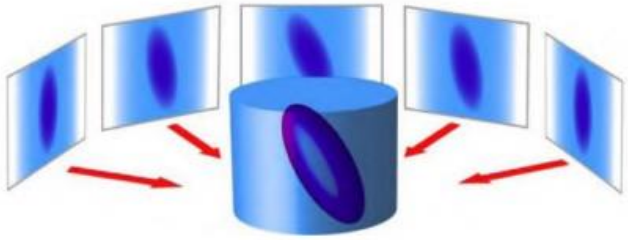


What about vectorial imaging?

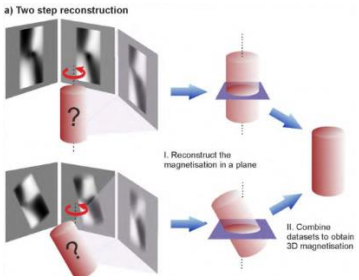
2D Magnetic Imaging



Projections

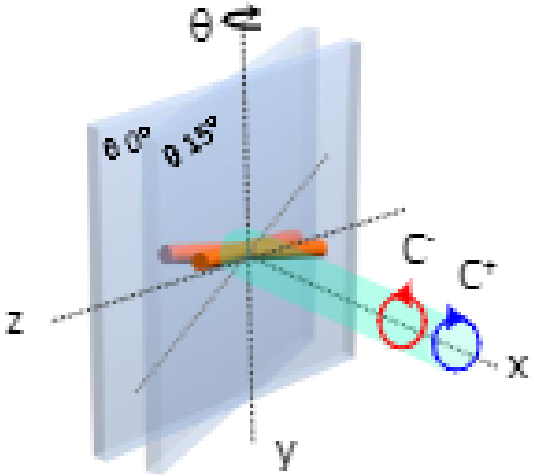


Reconstruction Algorithm



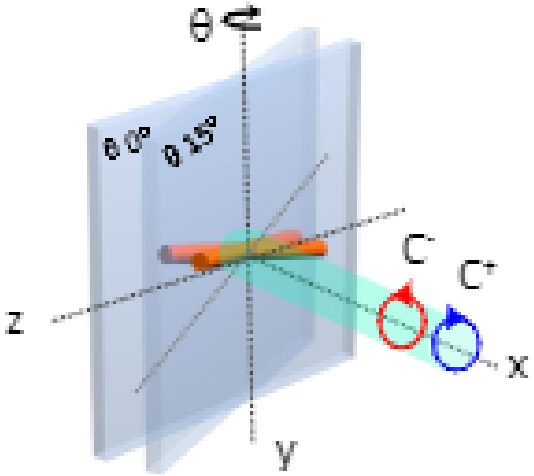
Hierro Rodriguez et al., Nat. Comm. 11 6382 (2020)

Vectorial imaging TXM/STXM



- Slow!
- Defocus of the sample
- Many projections
- Complex Analysis

Vectorial imaging TXM/STXM



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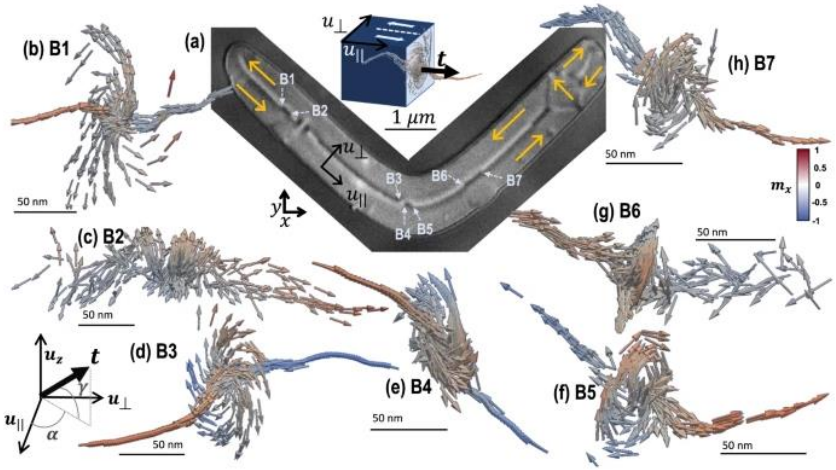
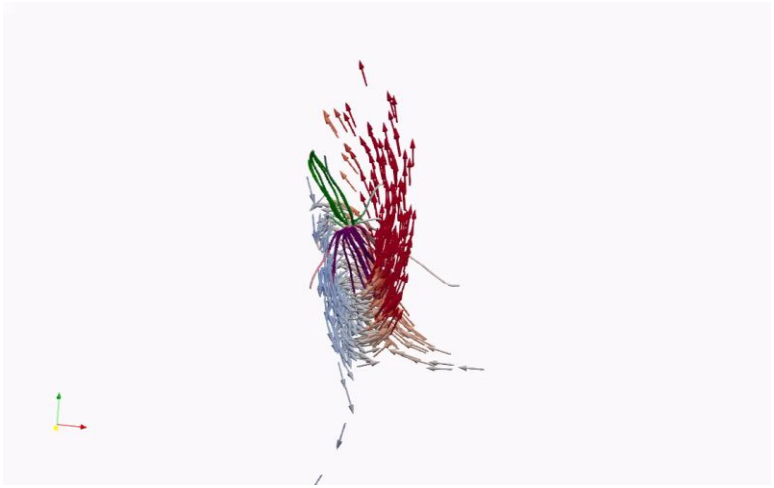




Hierro Rodriguez et al., Nat. Comm. 11 6382 (2020)

Summary TXM

Strength

… Buried layers.

…Flatness, conductivity or surface cleanliness not necessary.

…Photon-in photon-out: imaging not perturbed by external magnetic fields.

… 3D & free-standing objects.

…3D magnetization map of samples up to hundreds of nm thick.

… Easy to perform correlative experiments with TEM

Weakness

… At least nm thickness.

…Transparent substrate.

… (Mistral) Fixed temperature (100/300K).

… (Mistral) Very limited space.

… (Mistral) Electrical contacts require chamber venting

Summary STXM

Strength

… Flatness, conductivity or surface cleanliness not necessary.

… Photon-in photon-out: imaging not perturbed by external magnetic fields.

… 3D & free-standing objects.

… Buried layers.

… Highest energy resolution.

… Low demands in the optics setup.

… Fastest detectors: avalanche photodiodes.

… Versatile: detectors run simultaneously

Weakness

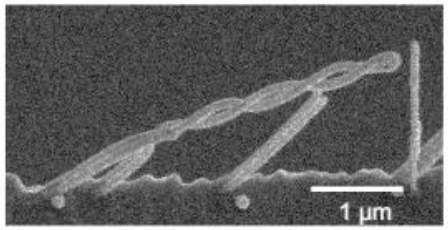
… At least nm thickness.

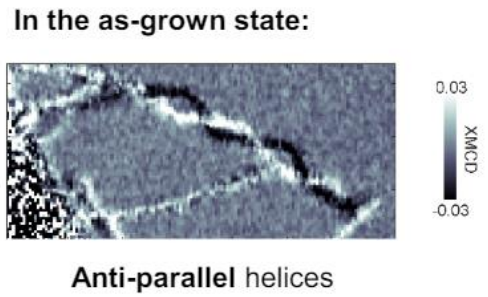
… Transparent substrate.

… High demand on mechanics.

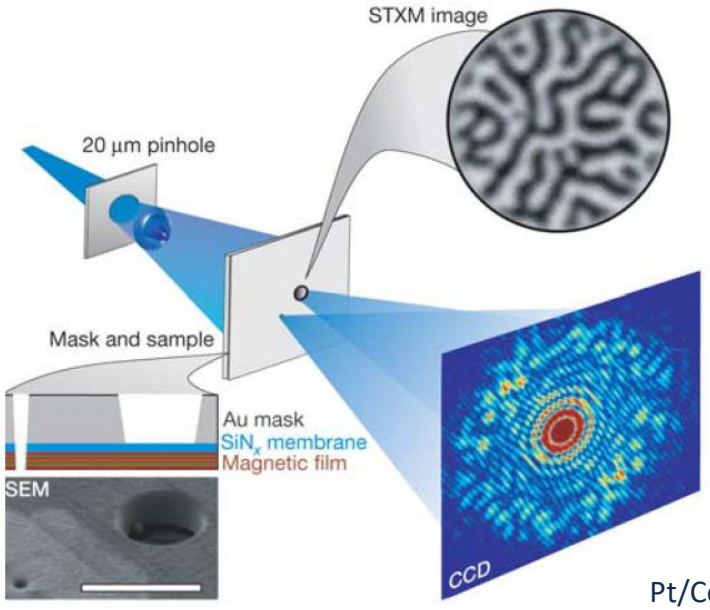
…Slow.

… Complex electronics, especially for TR





Lensless diffractive imaging

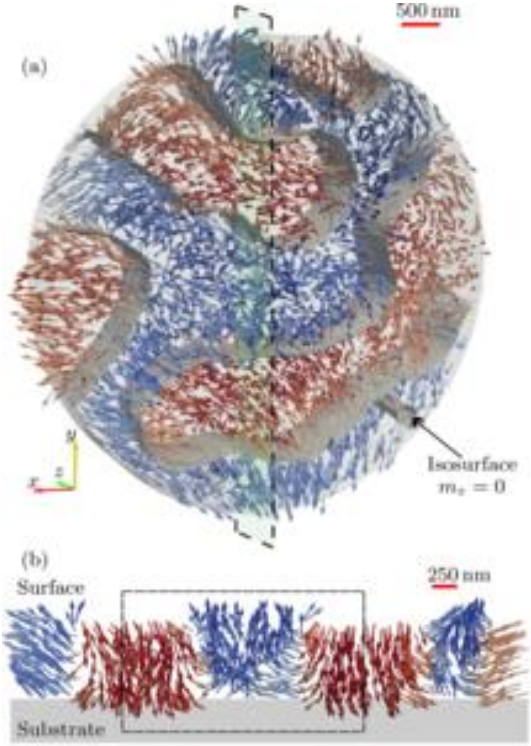


Stefan Eisebitt et al., Nature 432 (2004)

X-ray magnetic holography

- Full field
- Direct Fourier inversion of interference pattern sample aperture-reference aperture
- Resolution limited by reference size (20-30 nm)
- No depth of field limitation (but transmission, radiation damage)

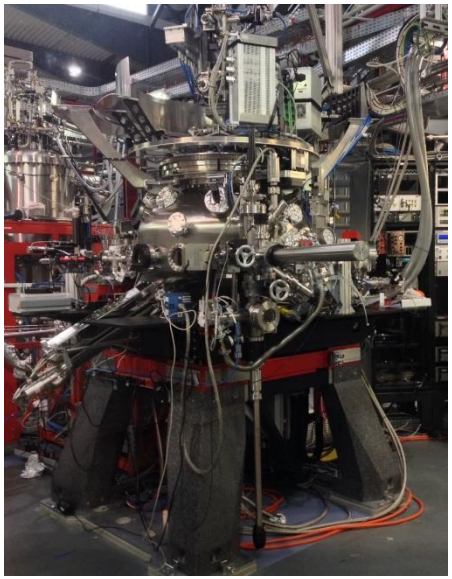
Pt/Co multilayer
50 nm resolution
10 min acquisition



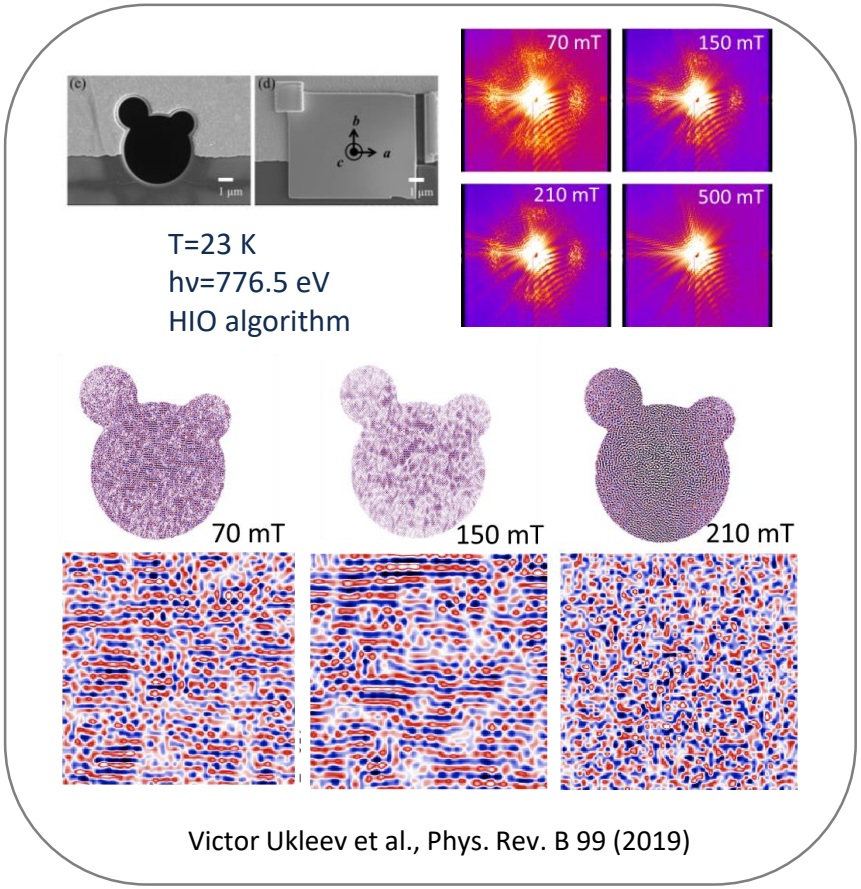
3D X-ray magnetic tomography holography

Lensless diffractive imaging

MARES experimental station @ BOREAS beamline

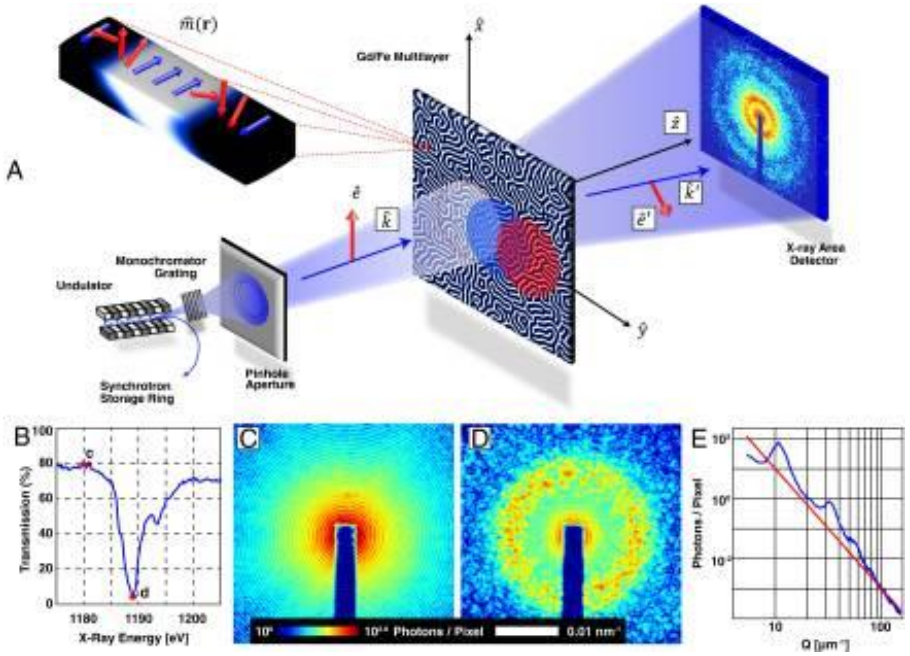


- 6-axis, 20-380 K cryomanipulator
- 2T HTS closed cycle magnet
- In situ surface preparation
- Adapter for sample platelets and transfer system



Victor Ukleev et al., Phys. Rev. B 99 (2019)

Lensless diffractive imaging: Ptychography



Dichroic coherent diffractive imaging
Ashish Tripathi et al., PNAS 108 (2011)

- Coherent diffractive imaging.
- phase and absorption contrast
- Scanning with overlapping field of view
- Sub-spot resolution
- Can be combined with excitations
- It can be combined with 3D imaging
- Resolution limited by
  - wavelength
  - experimental factors: detector solid angle, efficiency, dynamic range, coherence, wavefront stability, sample details,…

45 nm (hard x-rays) [vs 14 nm non magnetic]
Claire Donnelly et al, Phys. Rev. B 94, 06442 (2016)

12 nm (soft x-rays) [vs 5 nm non magnetic]
Xiaowen Shi et al, Appl. Phys. Lett. 108, 094103 (2016)

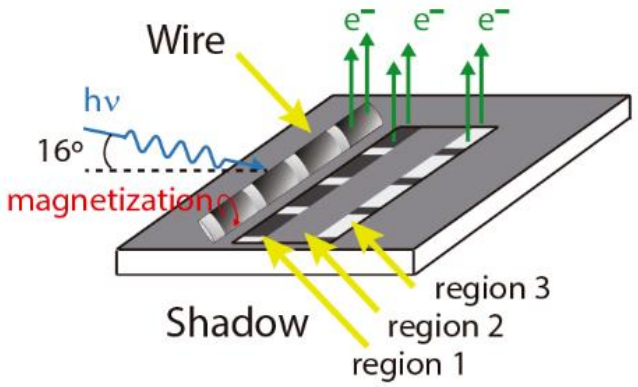
Take-home message

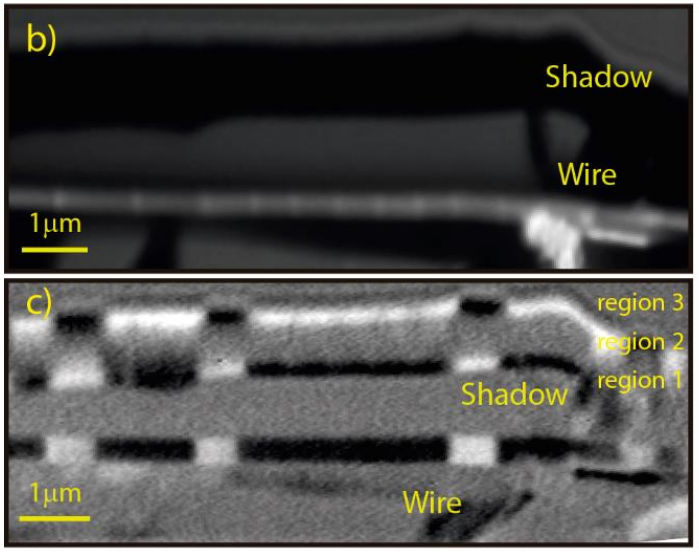
- It is important to choose the proper technique taking into account resolution, sensitivity, sample environment and time resolution
- XMCD - High spatial resolution imaging of magnetization
- Element-specific
- Can penetrate through the samples or measure only the surface
- Can combine with in operando measurements and time resolution
- Requires submission of beamtime proposal for user beamtime

This techniques are more powerful if we combine them

Correlative microscopy

Shadow XMCD-PEEM Microscopy

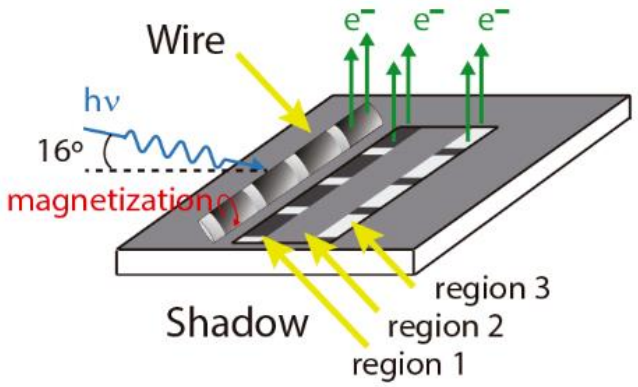


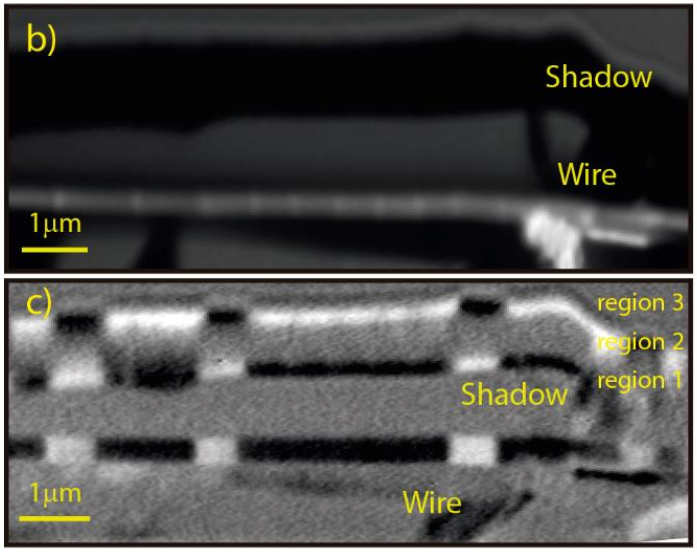


M. Foerster, et al. Ultramicroscopy., 96:082110, 2010.
S. Ruiz-Gomez, et al. Scientific Reports 8,16695 (2018).
S. Ruiz-Gomez, et al. Nanoscale, 12,17880 (2020).
L. Alvaro-Gomez, et al. PRB (2022).

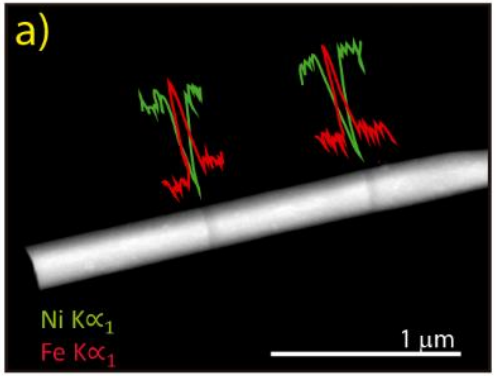
Correlative microscospy

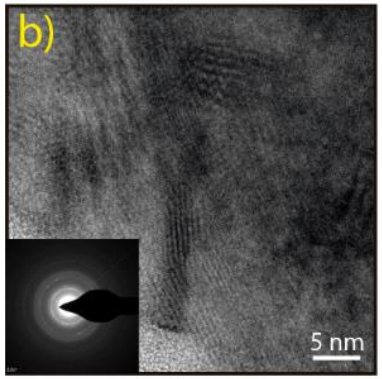
Shadow XMCD-PEEM Microscopy

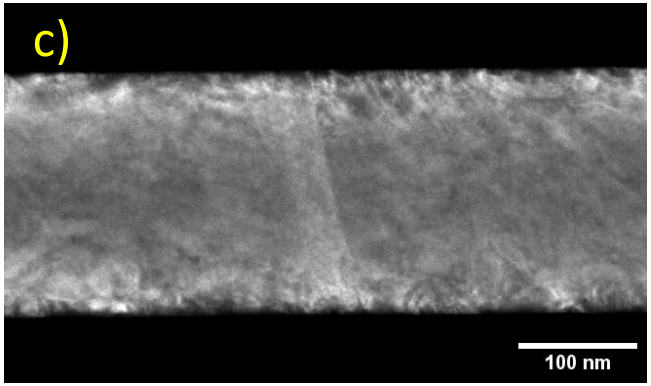




TEM







M. Foerster, et al. Ultramicroscopy., 96:082110, 2010.
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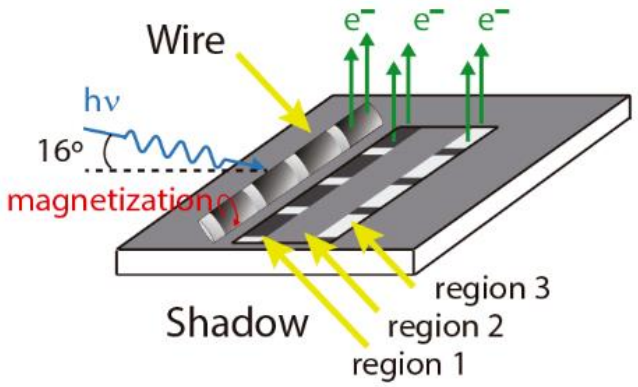
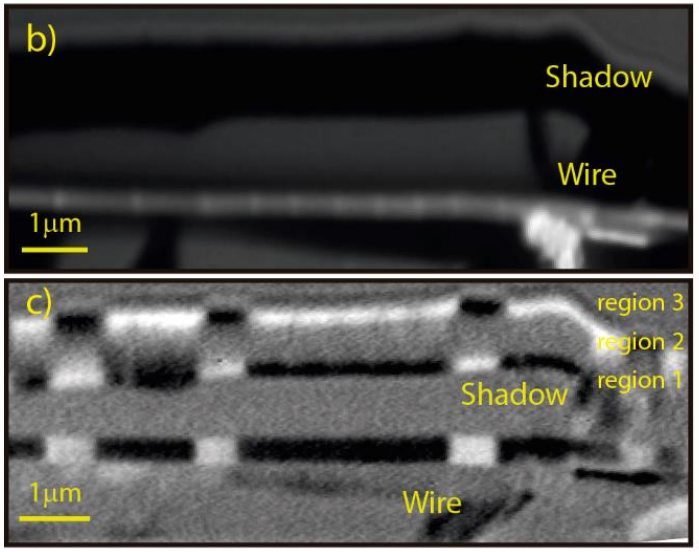
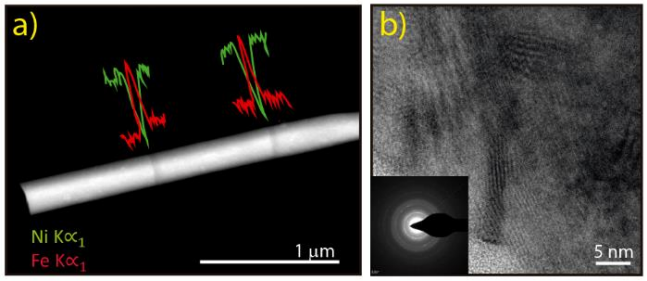
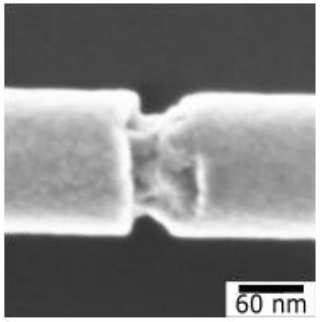
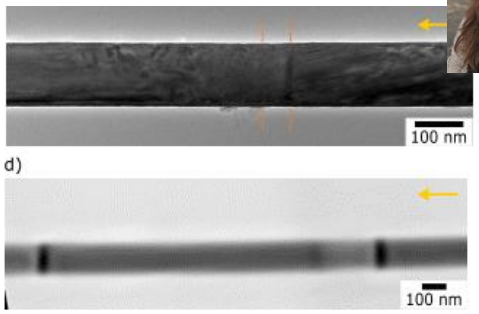




TEM







Laura Álvaro Gomez Thesis

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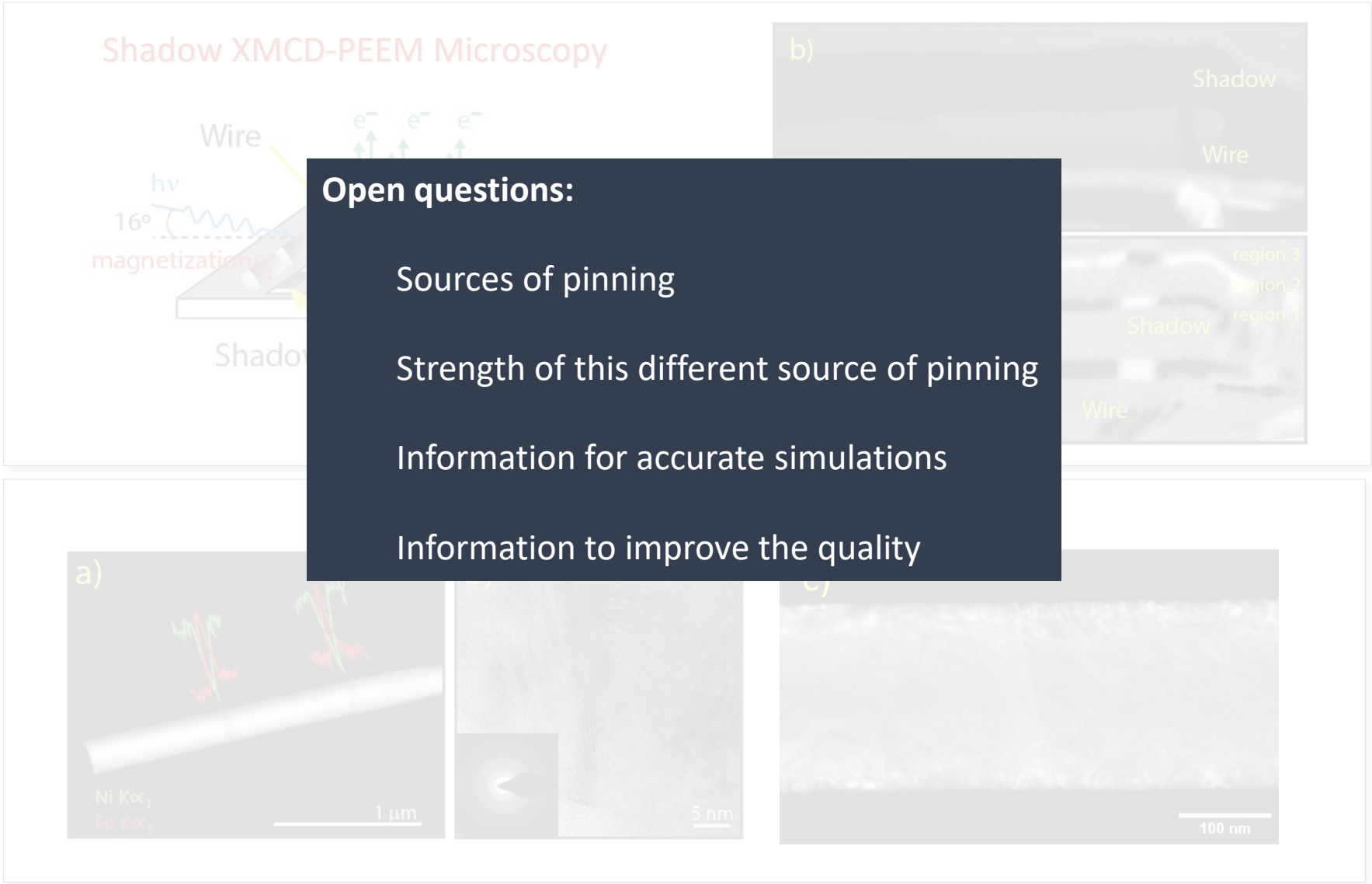
Correlative microscospy



Open questions:

- Sources of pinning
- Strength of this different source of pinning
- Information for accurate simulations
- Information to improve the quality

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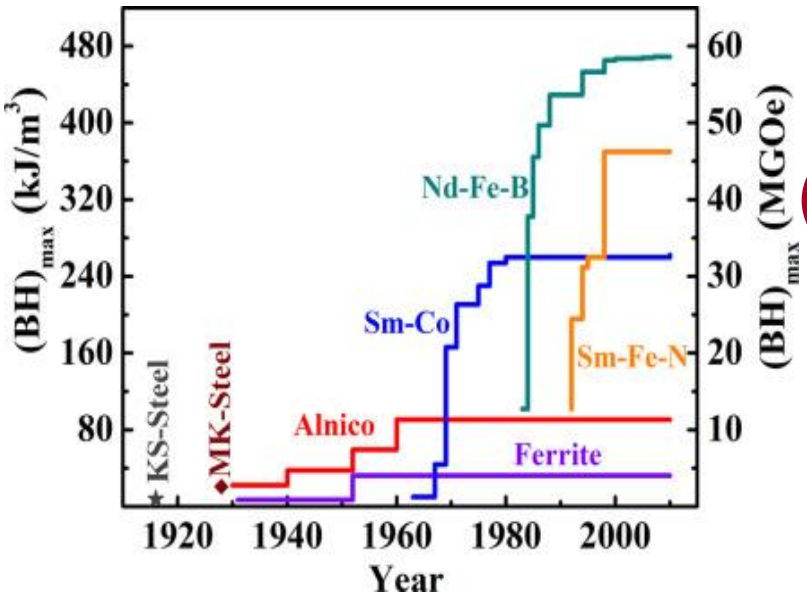
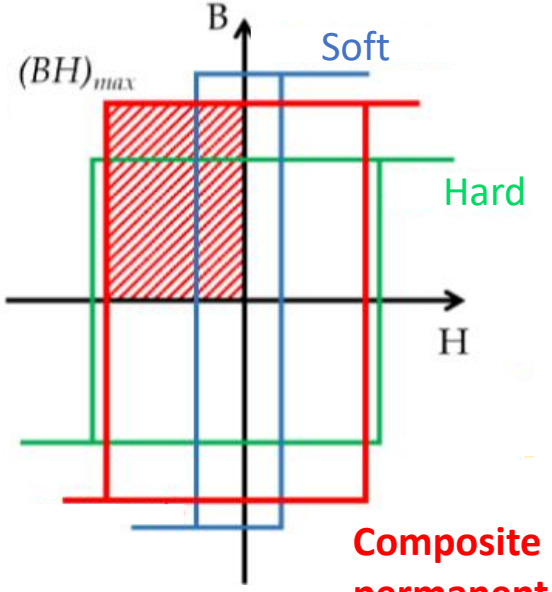
Permanent magnets and the problem of rare earths...



$BH_{máx}$

Alternatives :



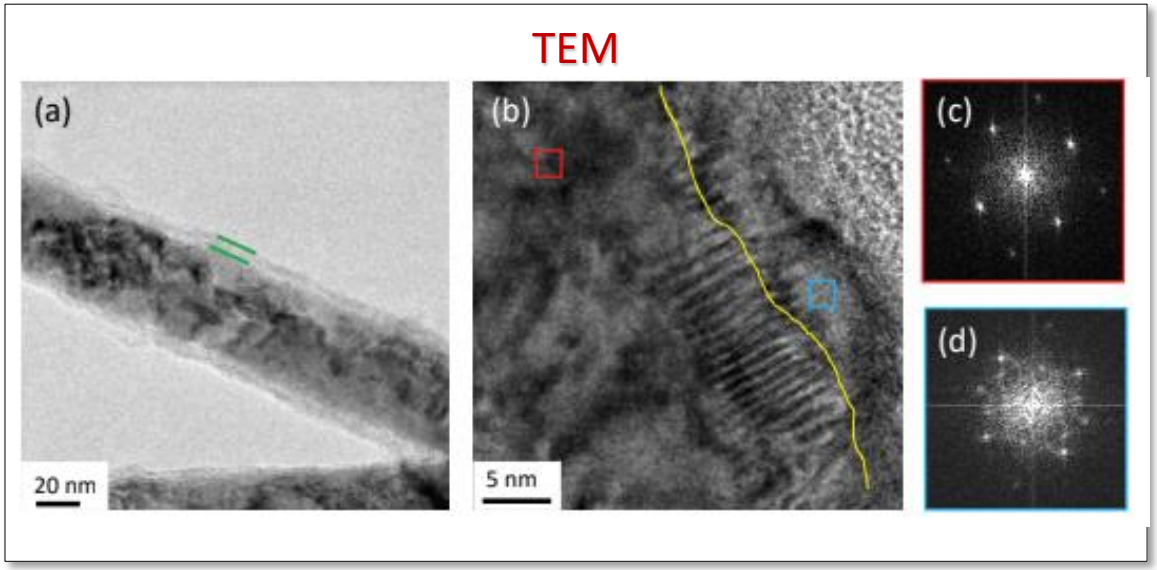
Composite permanent magnets

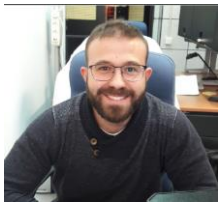
FeCo NWs

Strontium ferrite powder

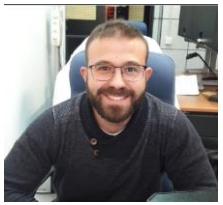
Bonded magnet

Correlative microscopy

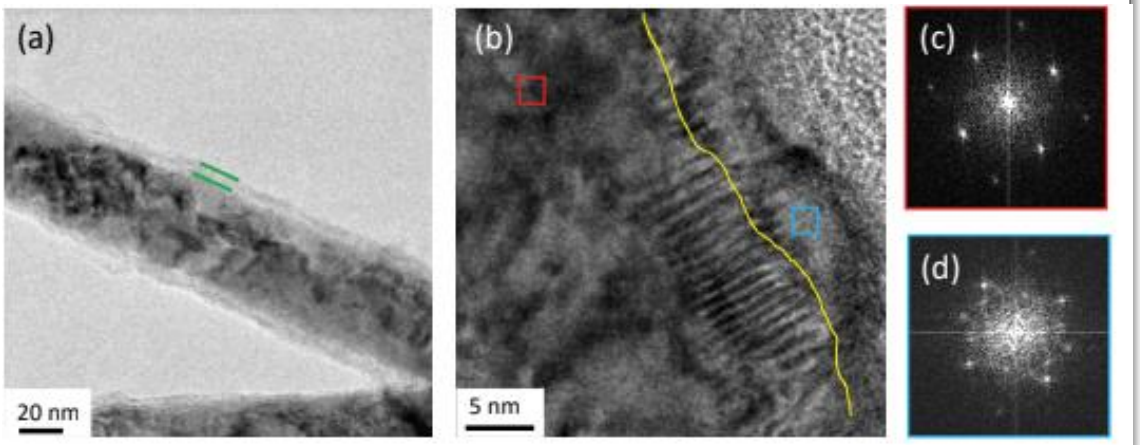




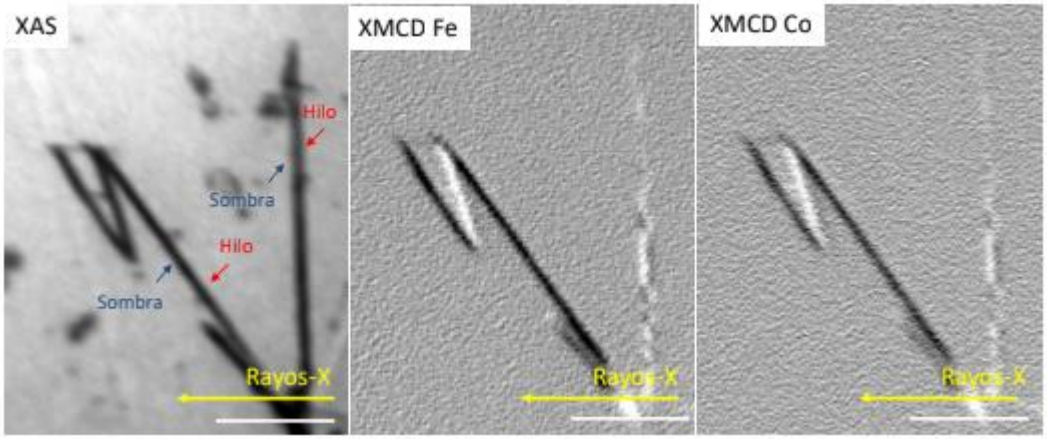
Correlative microscopy



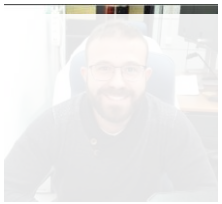
TEM



Shadow PEEM



Correlative microscospy



Open questions:

- Role of the oxidize shell
- Interaction between the nanowires and platelets
- Distribution of wires inside the magent
- Information for accurate simulations
- Information to improve the quality

20% increase in remanence

48% increase in energy product

Take-home message

- It is important to choose the proper technique taking into account resolution, sensitivity, sample environment and time resolution
- XMCD - High spatial resolution imaging of magnetization
- Element-specific
- Can penetrate through the samples or measure only the surface
- Can combine with in operando measurements and time resolution
- Requires submission of beamtime proposal for user beamtime

This techniques are more powerful if we combine them

The combination of different microscopies techniques (TEM, PEEM and TXM)...

....Full description of the 3D spin textures

... Evaluation of crystallinity and effect on the magnetic properties

... Understanding pinning mechanism for spin textures as domain walls

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