Leibniz-Gemeinschaft

Leibniz Institute for Solid State and Materials Research Dresden

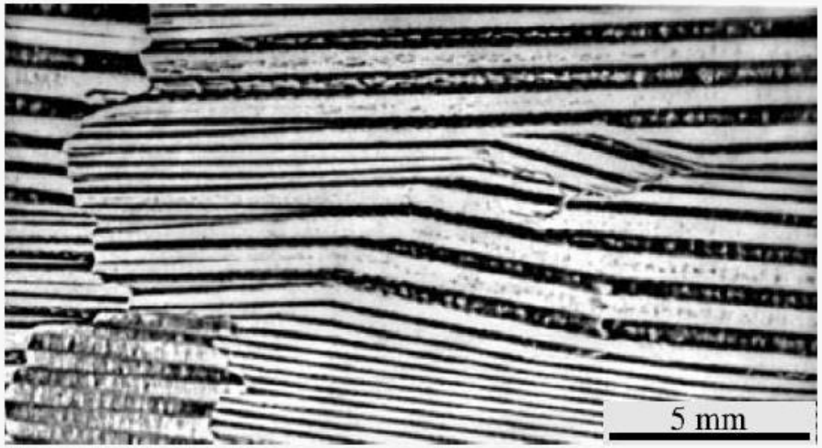
(T)EM for Magnetic Materials

Axel Lubk

What are relevant fields and magnetic structures?

Magnetic domains

- Numerous and complex shape of domains



History: Weiss domains

– Micromagnetic domains
– Domain walls
– Vortices, Bubbles, Skyrmions
– Memory devices
– …

Magnetic length scales

- Magnetic energy

$$E = A\left(\frac{\partial m_i}{\partial x_j}\right)^2 + K\sin^2\theta$$

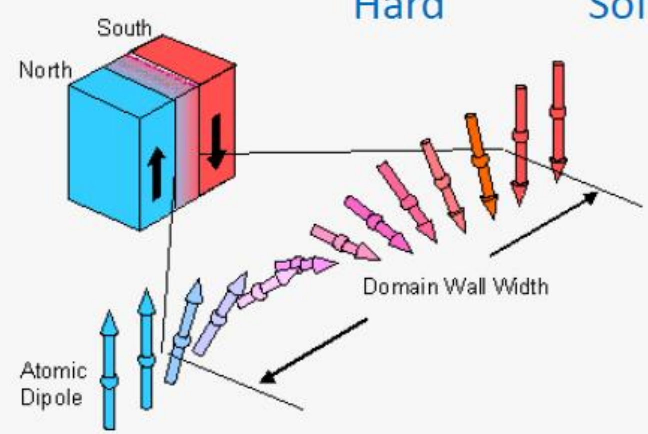
Exchange: J/m

Anisotropy: J/m^3

- Anisotropy exchange length

$$\Delta_u = \sqrt{A/K} \quad 1\ \text{nm} \rightarrow 100\ \text{nm}$$

Hard → Soft

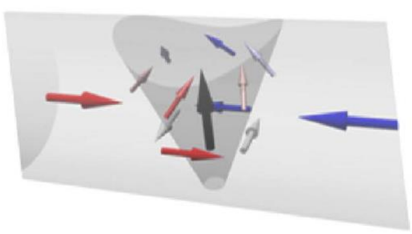


3D Nanomagnetism – A new paradigm in magnetism

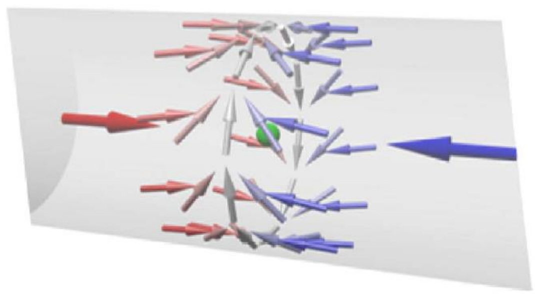
3D domain walls in NWs

topological 3D spin textures

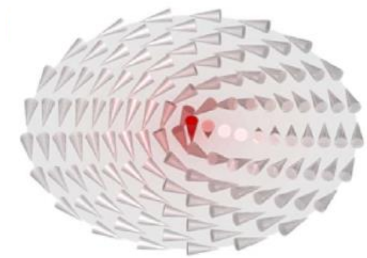
Transverse-Vortex



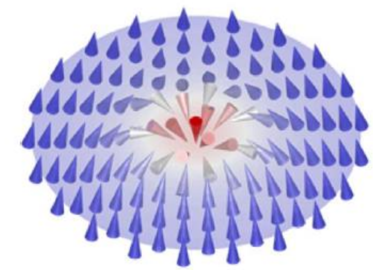
Bloch-Point



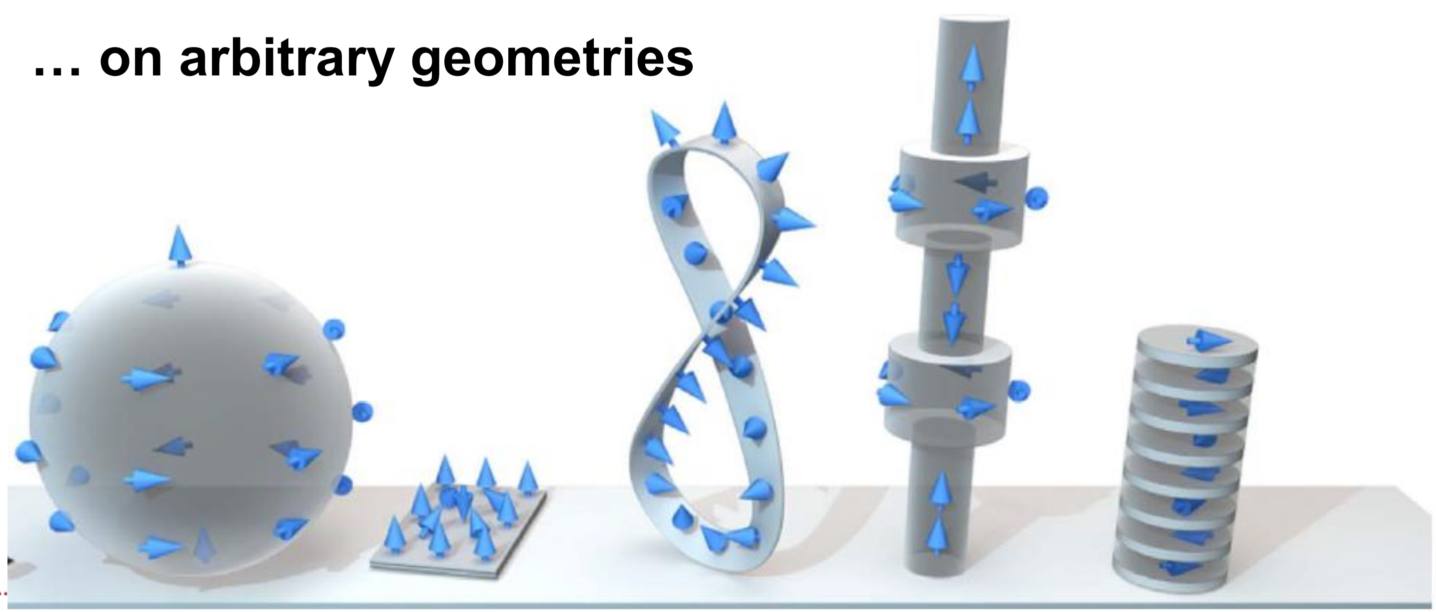
Magnetic vortex



Neél skyrmion



… on arbitrary geometries



Fernandez-Pacheco, A. et al. , *Nat Commun* **2017,** *8*, 15756.

High-Resolution Magnetic Imaging

Transmission **E**lectron **M**icroscopy

Scanning **T**unneling **M**icroscopy

Magnetic **F**orce **M**icroscopy

X-ray **M**agnetic **C**hiral **D**ichroism

Scanning **E**lectron **M**icroscopy with **P**olarization **A**nalysis

Spin-**P**olarized **L**ow-**E**nergy **E**lectron **M**icroscopy

Magneto-**O**ptic **K**err **E**ffect Microscopy

Recommended reading:

1. M. D. Graef, Magnetic imaging and its applications to materials, Academic press (2001).

1. **Electron microscopies for magnetic materials**
    a. TEM based magnetic imaging techniques
        i. Differential Phase Contrast
        ii. Lorentz TEM
    b. SEM based magnetic imaging techniques

2. Electron spectroscopies and time-resolved approaches for magnetic materials
    a. EELS and Energy-Loss-Chiral Dichroism
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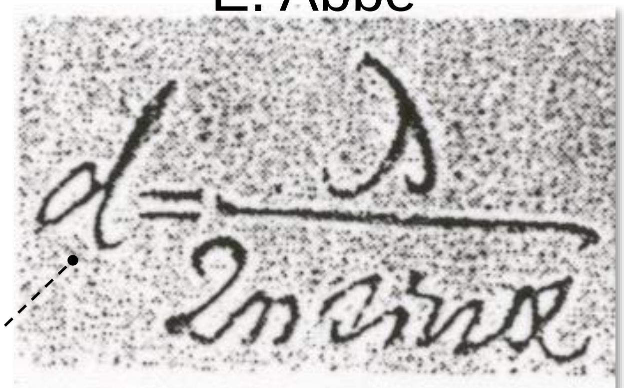
3. Summary

Why Electron Microscopy?

Light microscopy

R. Koch‘s microscope (1880)

E. Abbe



resolution

L. de Broglie

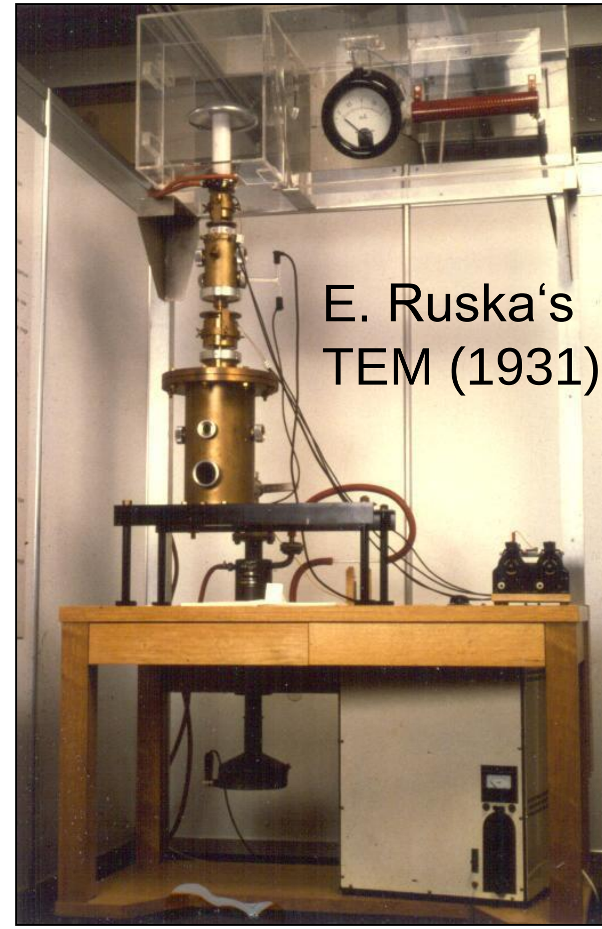
$$\lambda = \frac{h}{p} = \frac{h}{m\ v}$$

wave length

velocity

λ =2.5 pm @ 200 kV*

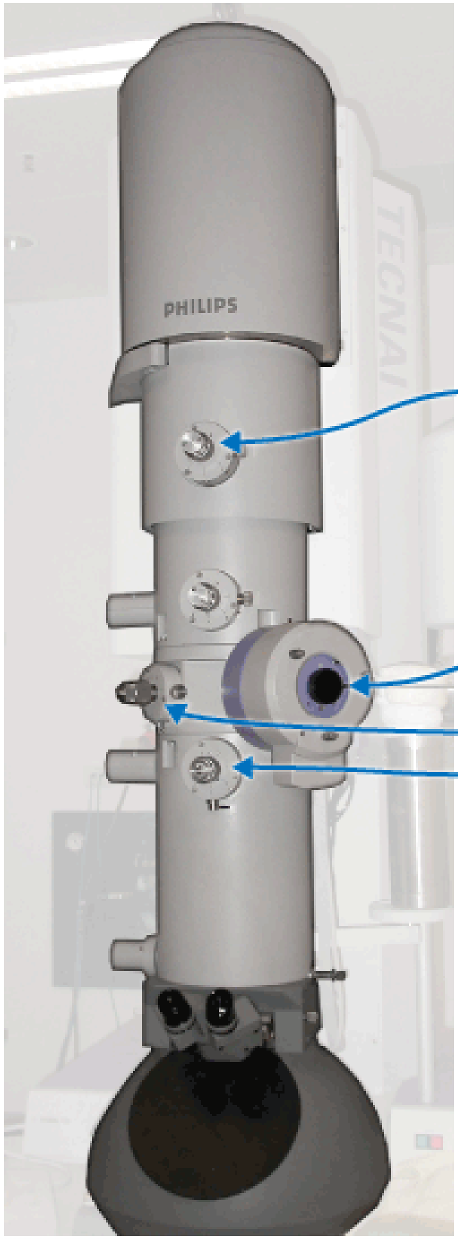
Electron microscopy

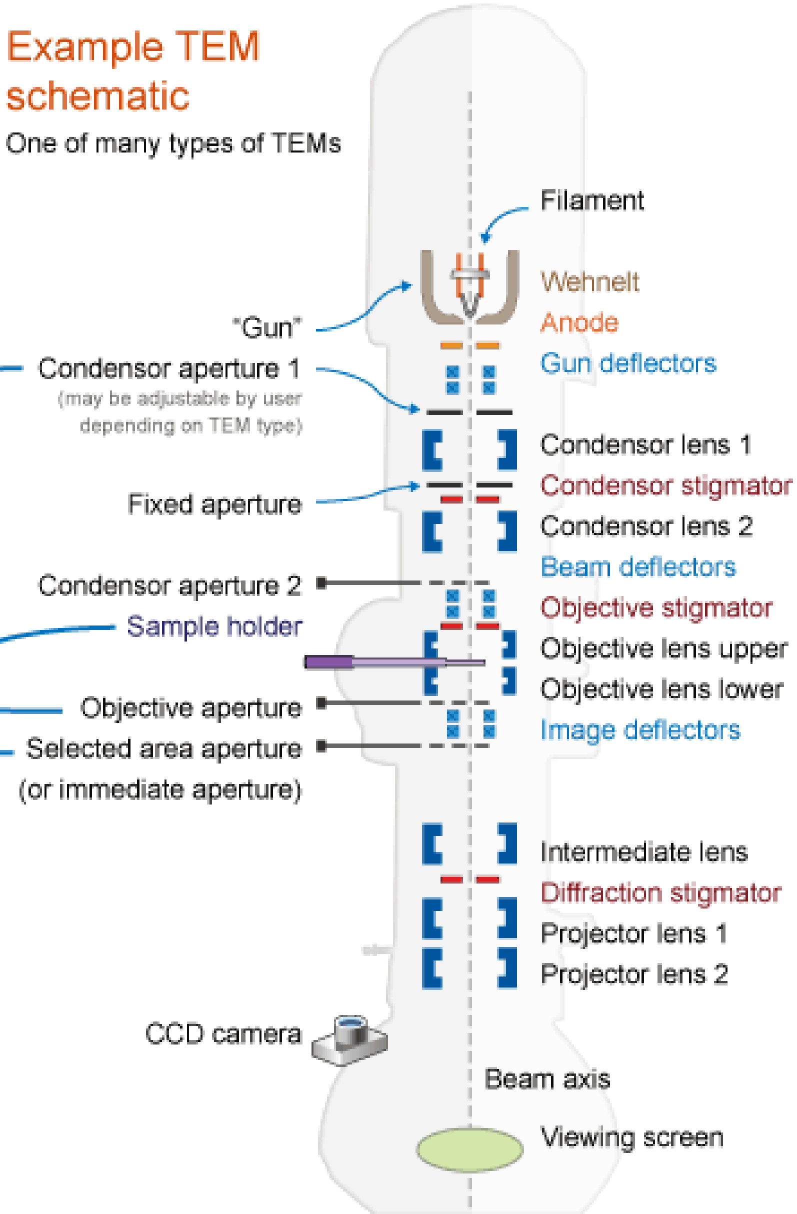


E. Ruska‘s TEM (1931)

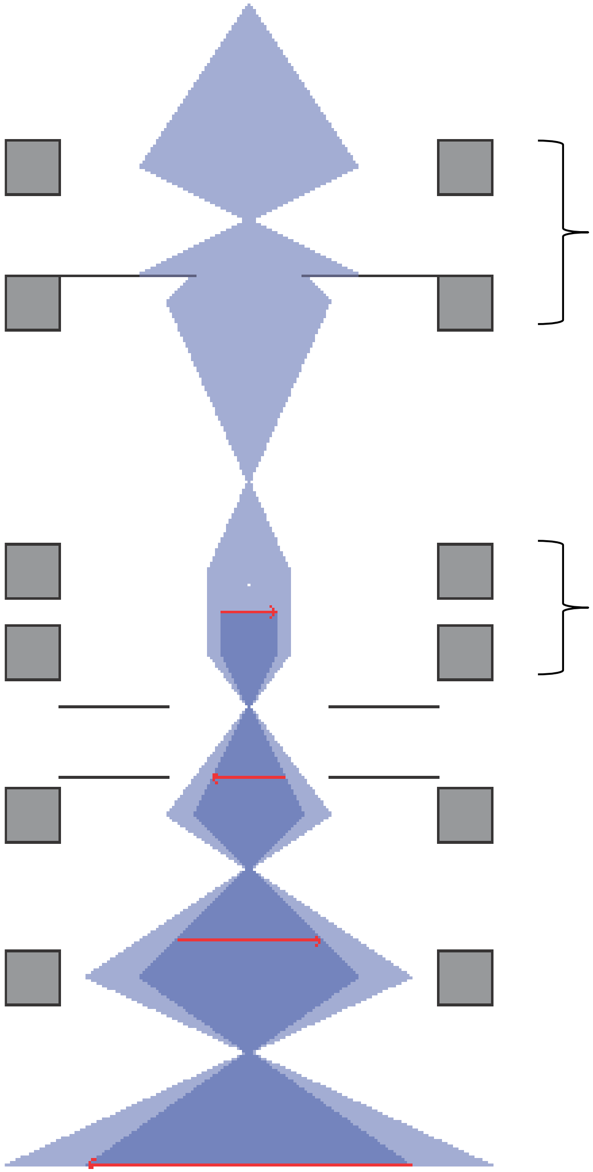
*** Why modern TEM‘s „only“ achieve 50 pm (and why do we not bother)?**

Transmission Electron Microscopy





TEM principle



Electron gun
- generation and acceleration of electrons

Condenser system
- beam shaping by set of magnetic lenses and apertures

Objective lens
- imaging lens of the TEM

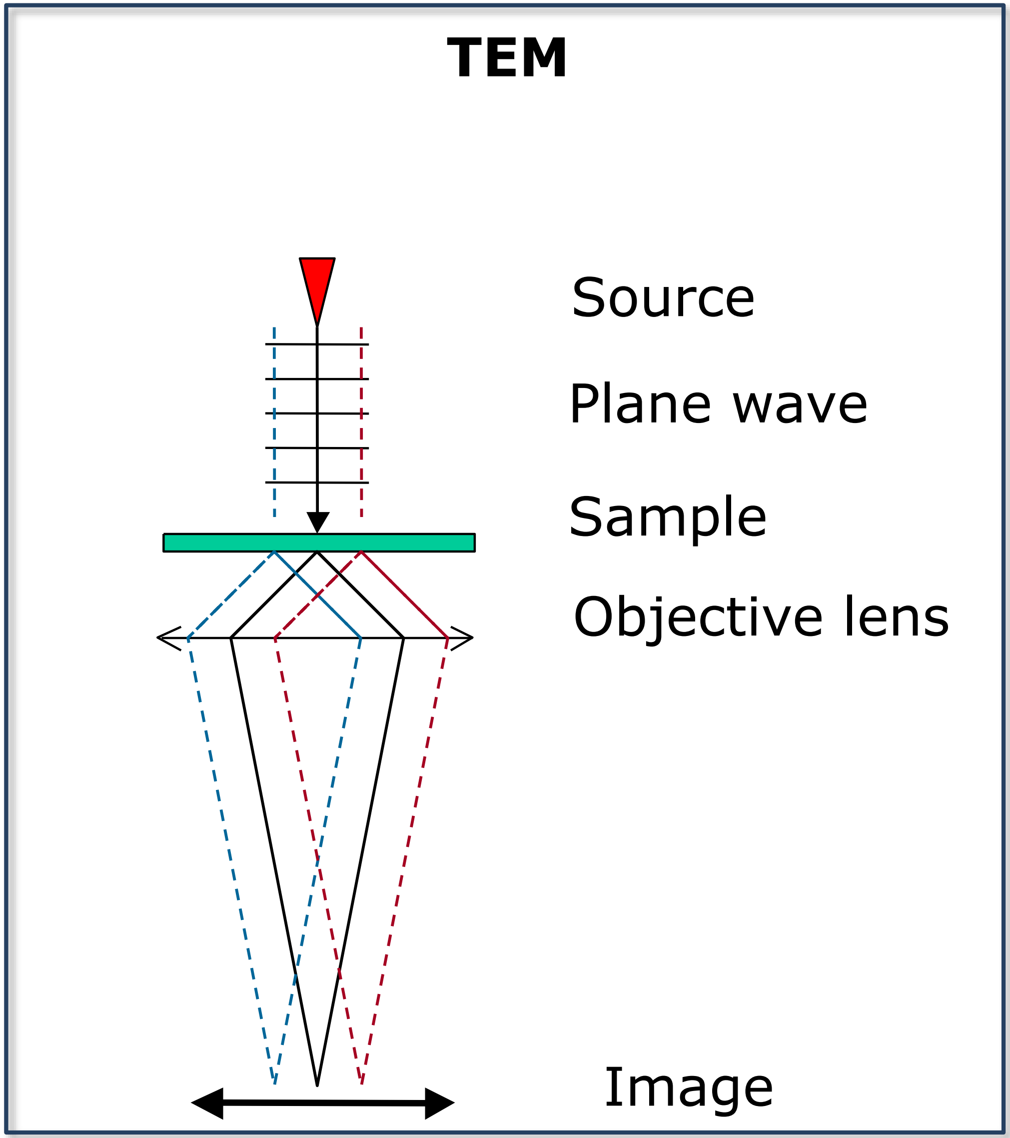
Intermediate lens
- switching between imaging and diffraction mode.

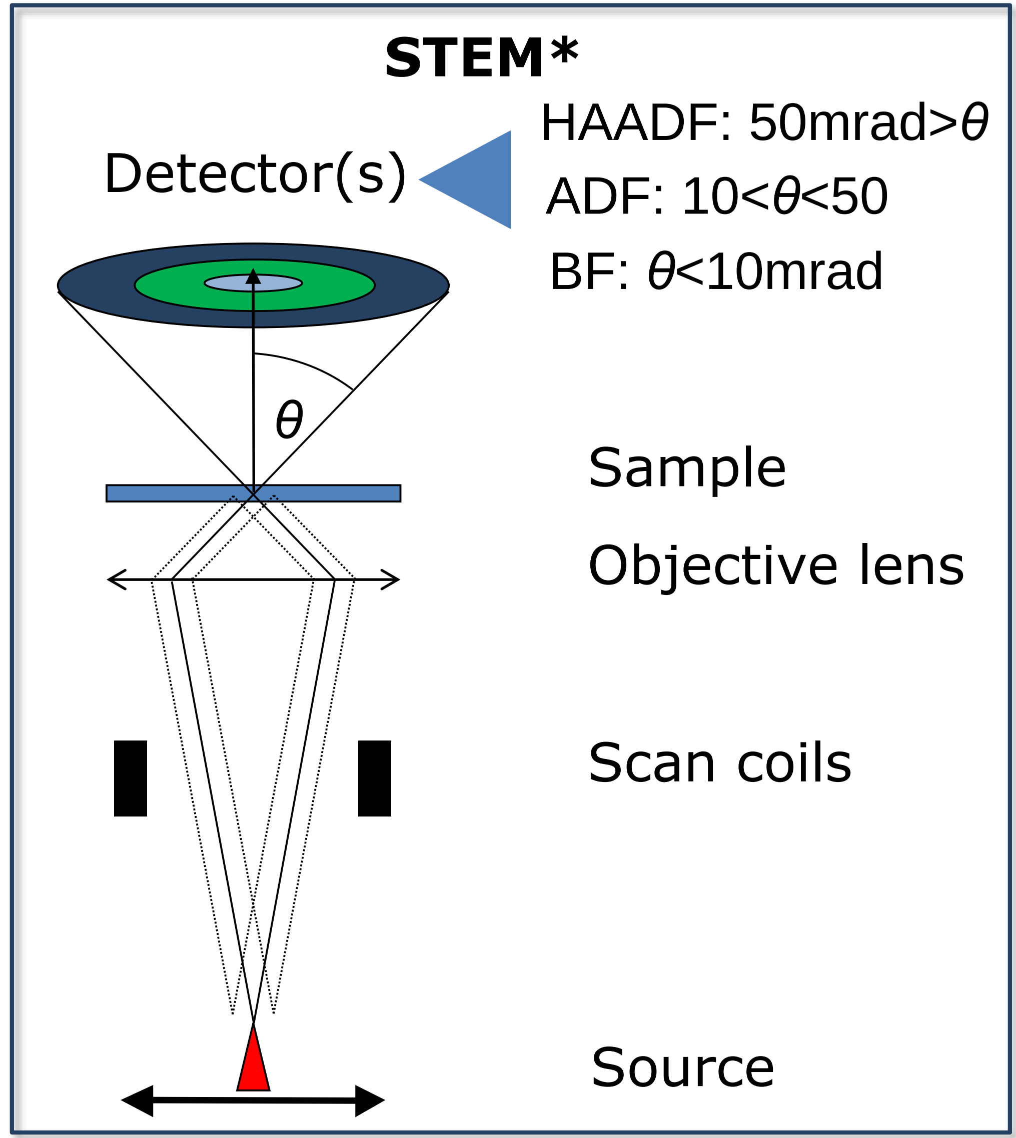
Projective lenses
- post magnification of second intermediate image.

Image observation
- detection of images or diffraction patterns.

TEM Principle

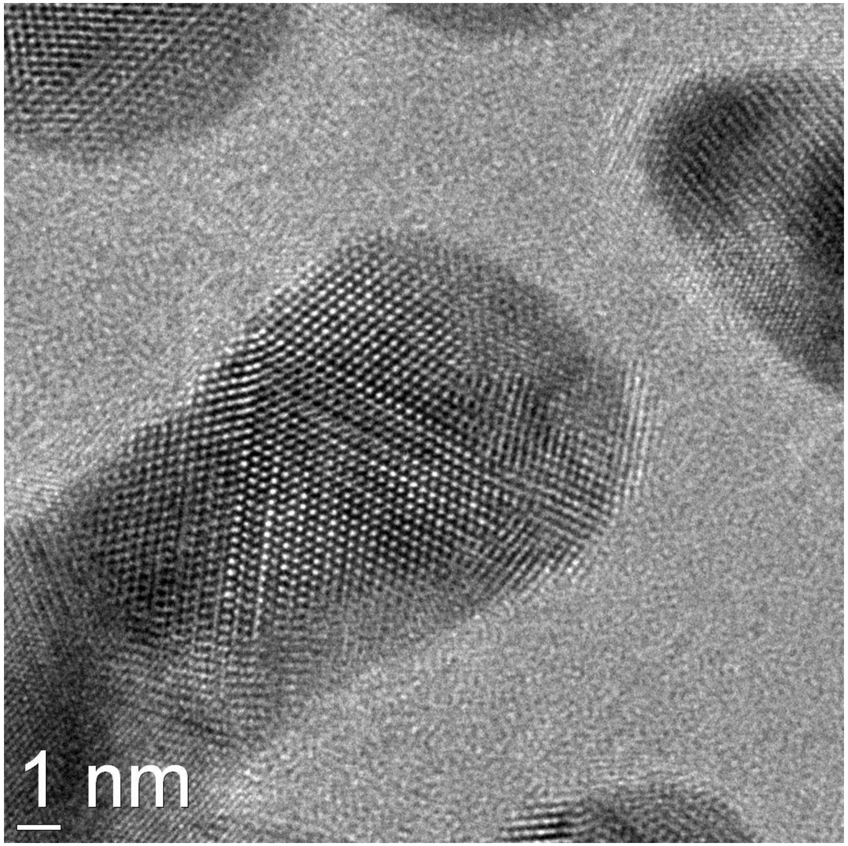
Minimal Model

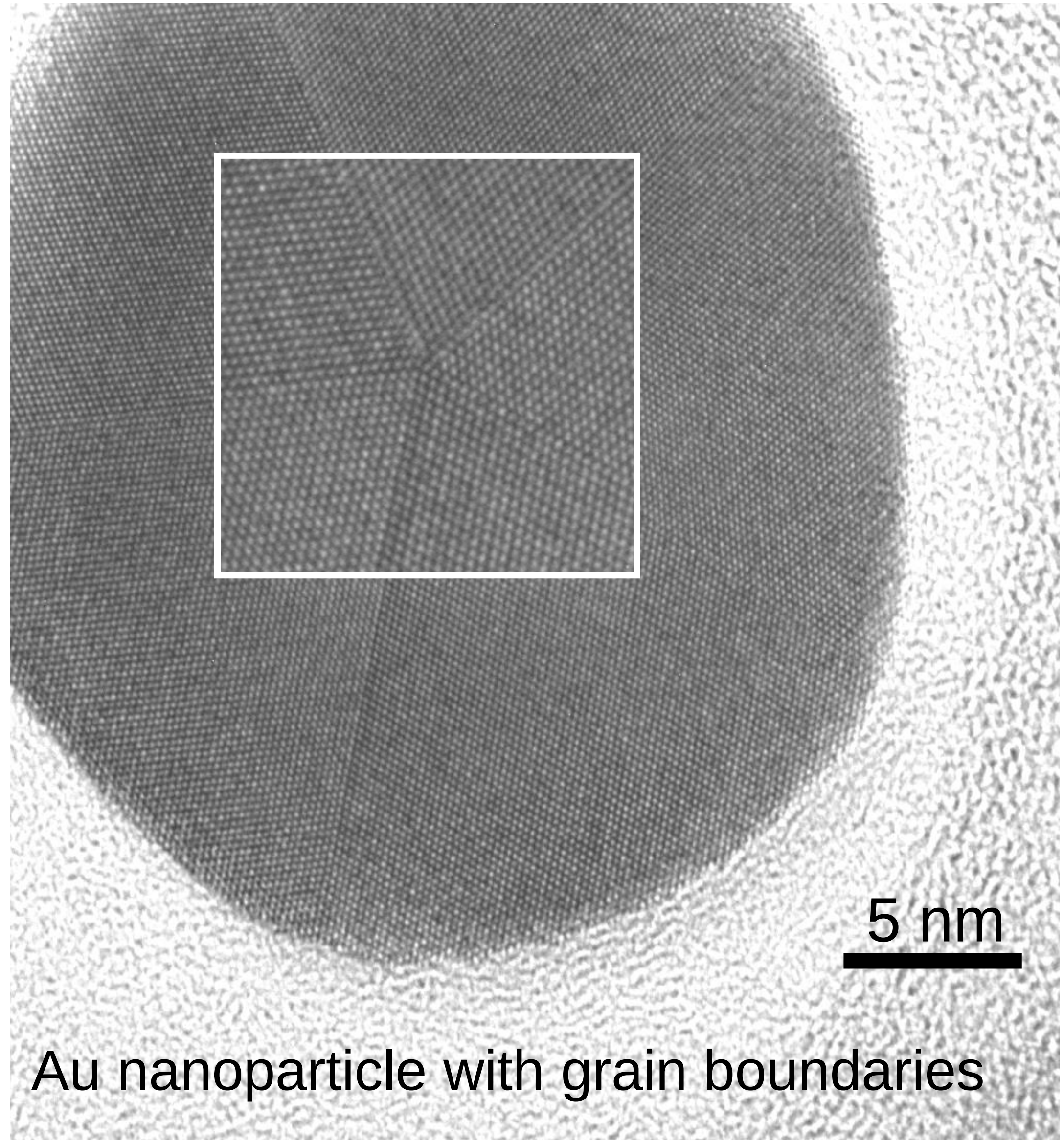




*** Does anybody sees the reciprocity between TEM and STEM?**

Magnification Series

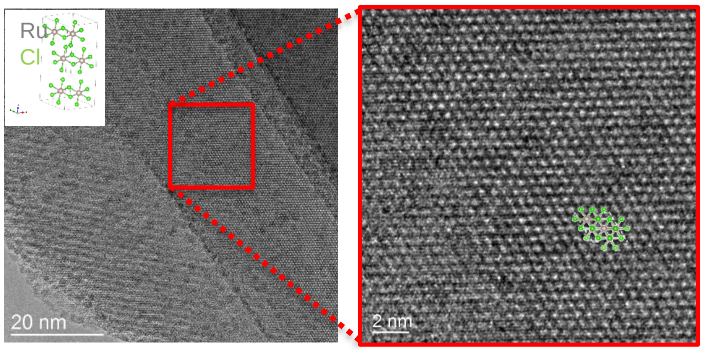




≈ turning the magnification wheel

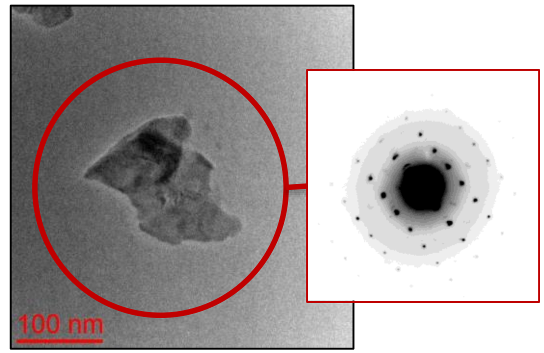
TEM techniques

Atomic resolution imaging



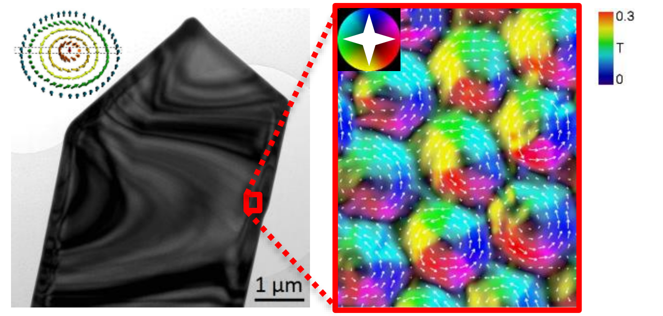
interface, defect studies

Electron Diffraction



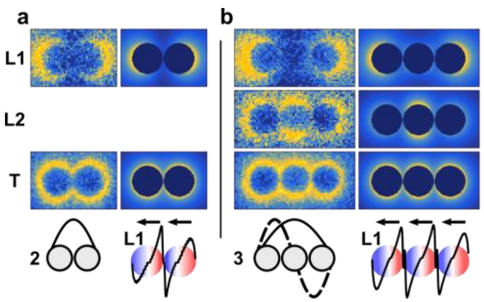
nanocrystal crystallography

Holography

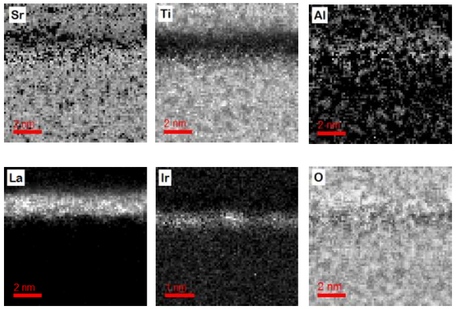


nanomagnetic fields

Electron Energy Loss Spectroscopy

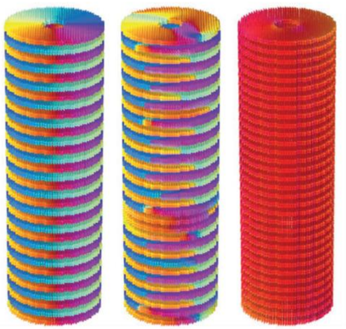


bulk / surface
plasmons, excitons



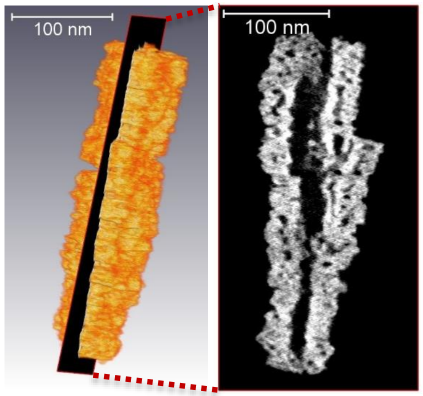
element, valency,
magnetic state

Tomography

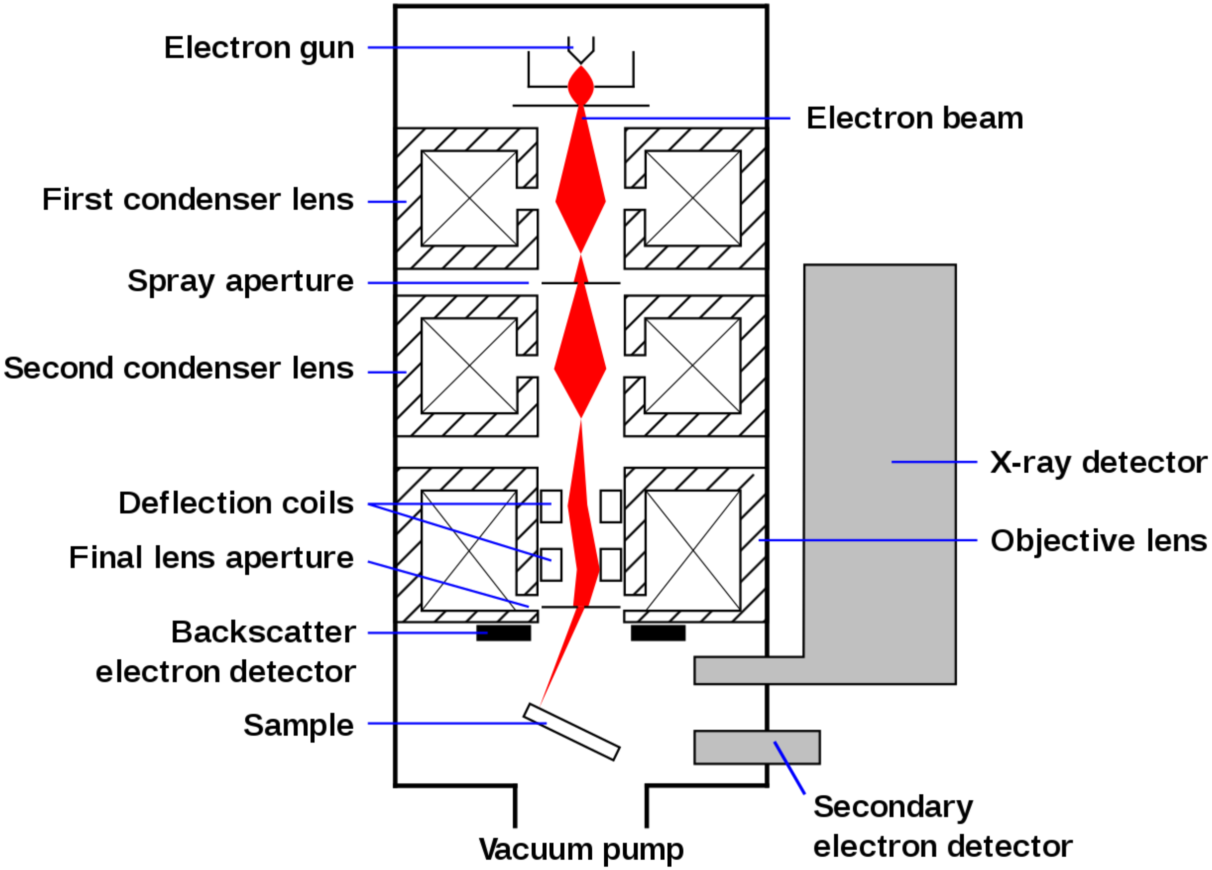


3D nanomagnetic
textures

3D morphology



Scanning Electron Microscopy



Comparison TEM - SEM

	SEM	TEM
accel. voltage	1-30 kV	60-300 kV
spatial resolution	50Å	1Å
information	topography, atomic number, chemical composition, crystallography, electric and magnetic fields	atomic number, chemical composition, crystallography, strain low-energy excitations, electric and magnetic fields
Magnetic imaging modes	SEM with Polarization Analysis	Lorentz TEM, Electron Holography, Differential Phase Contrast, Electron-Energy-Loss Magnetic Chiral Dichroism

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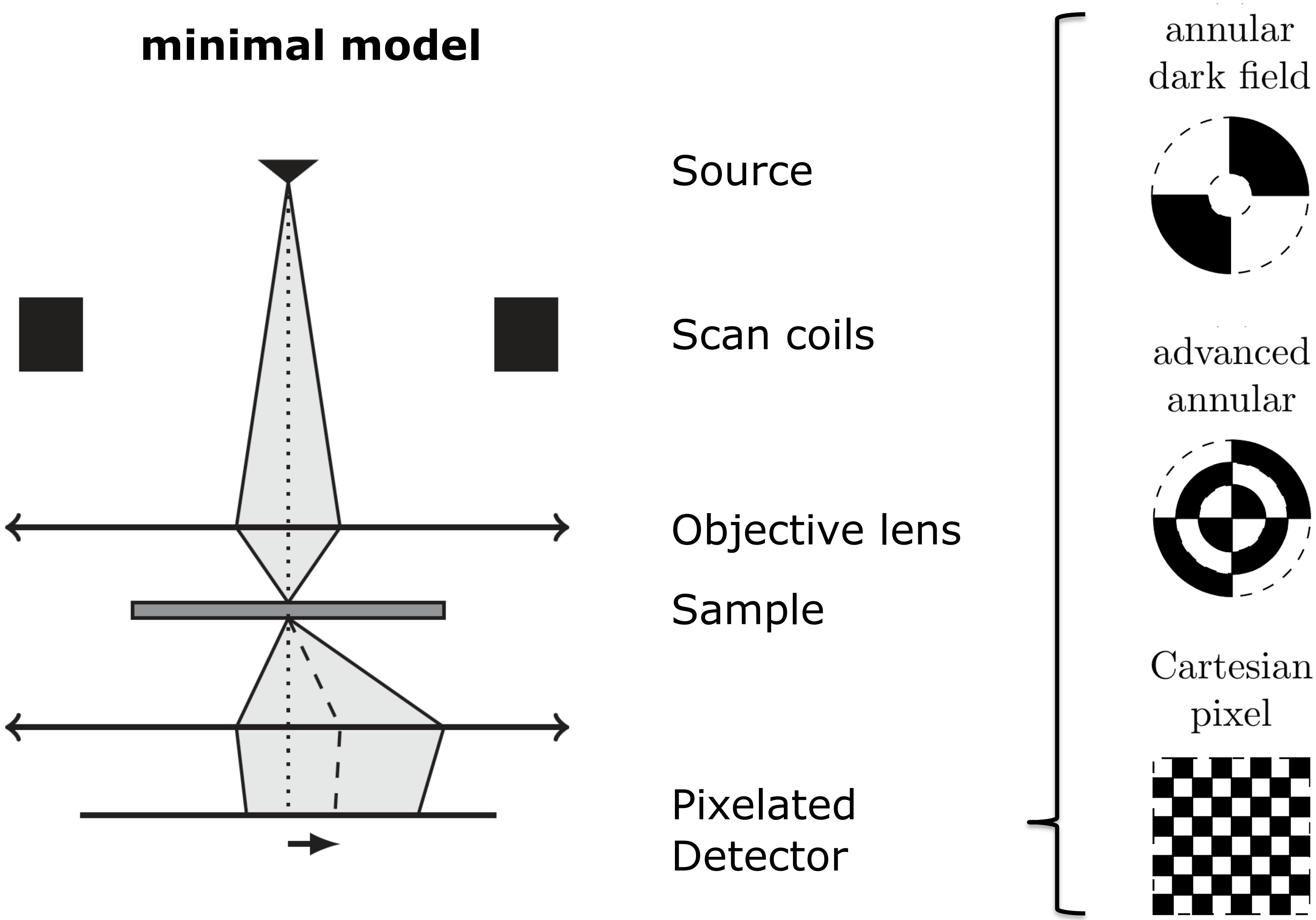
STEM-DPC

minimal model



Differential phase contrast - principle

Lorentz force

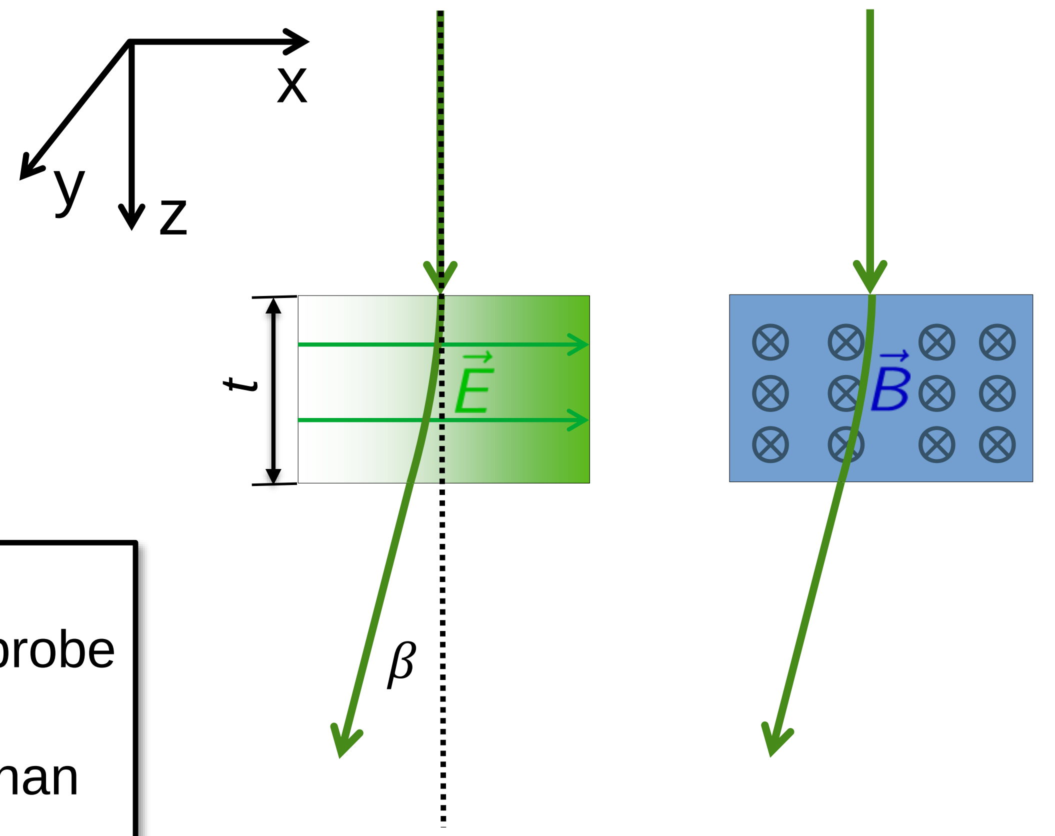
$$\boldsymbol{F} = -e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) = m\boldsymbol{a}$$

deflection of focussed probe*

$$\beta = \frac{\boldsymbol{v}_\perp}{v_0} = \frac{\boldsymbol{a}_\perp t}{v_0^2}$$

result remains valid for momentum expectation value of an extended probe

- if scattering angles are small
- and no field variations smaller than the beam diameter



electric part

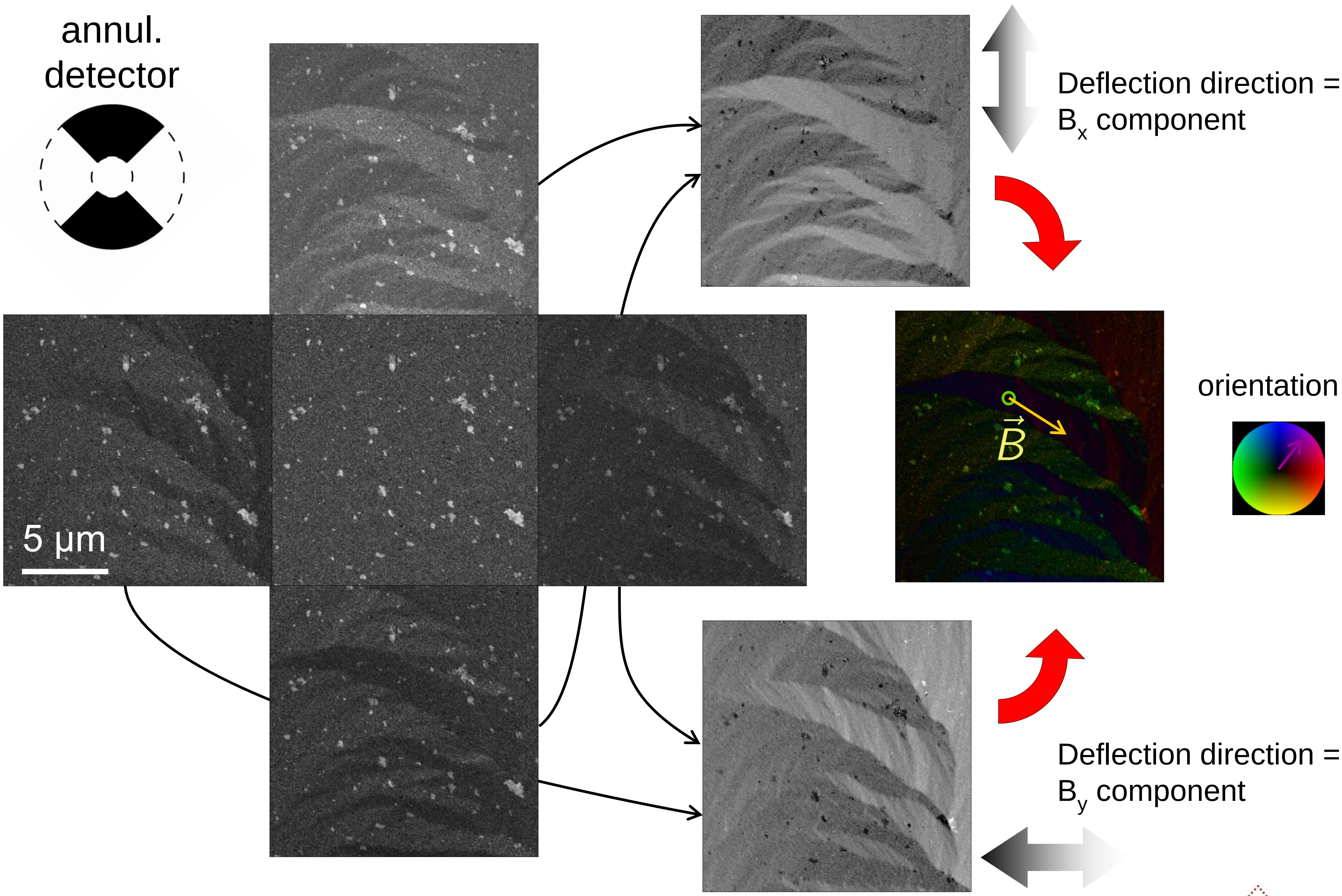
$$\beta = -\frac{et}{mv_0^2}\begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

pagnetic part

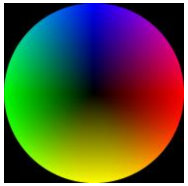
$$\beta = -\frac{et}{mv_0}\begin{pmatrix} -B_y \\ B_x \end{pmatrix}$$

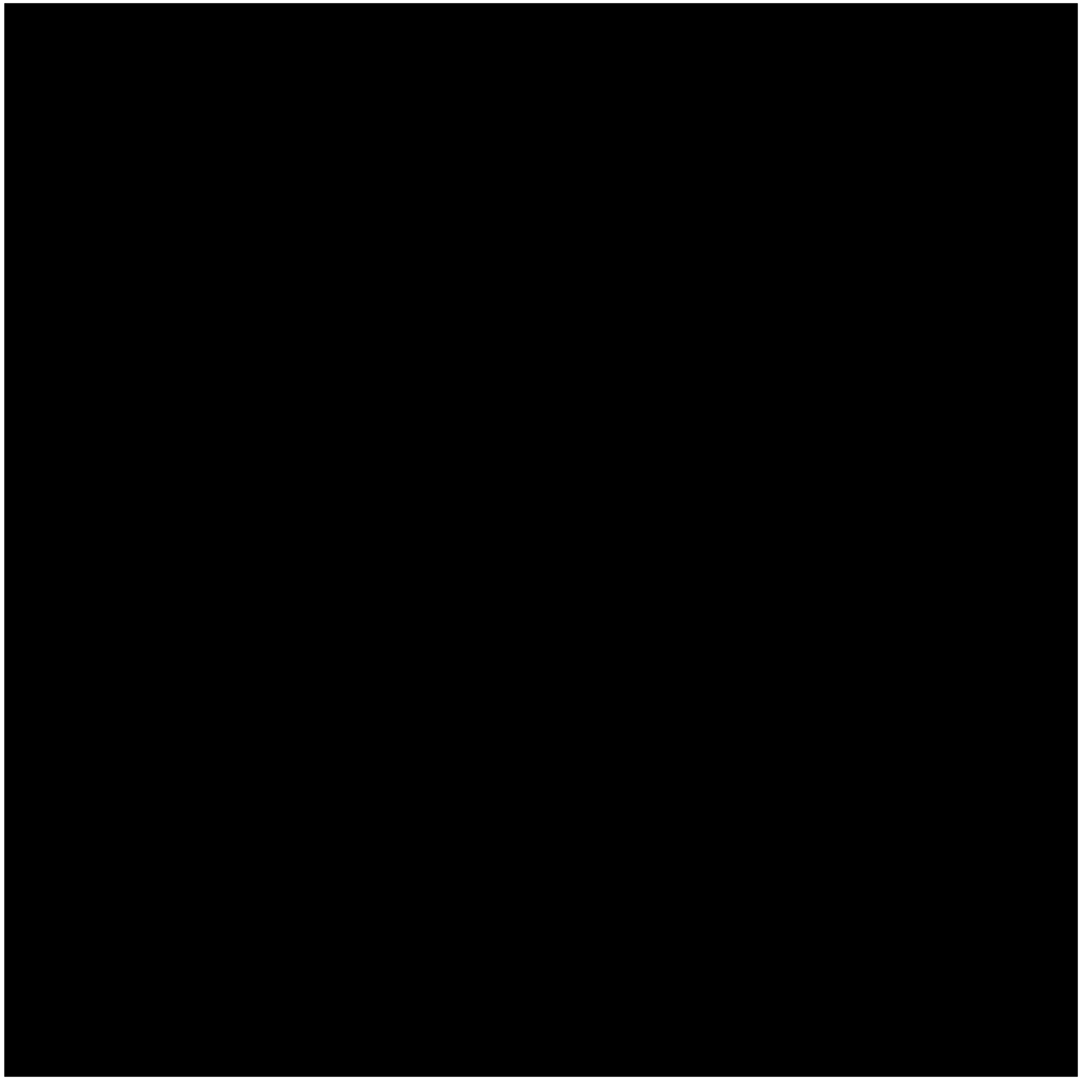
*** Please derive the formula by yourself**

Differential phase contrast – image reconstruction

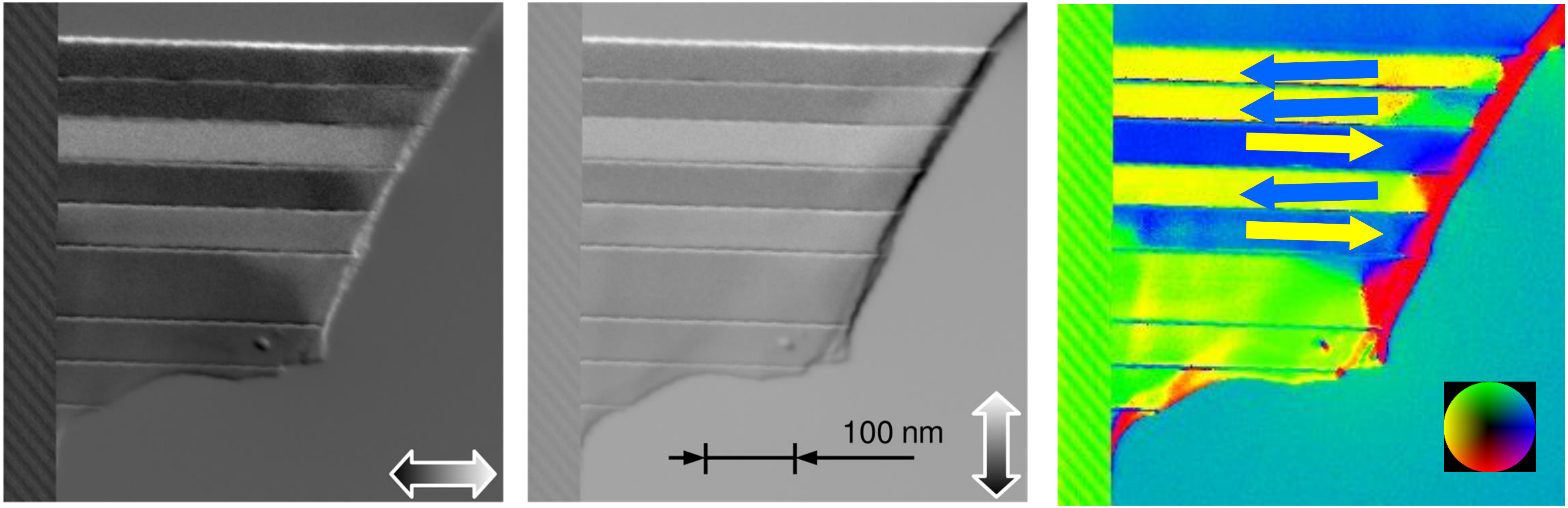


Differential phase contrast - Evolution of magnetization





[FeCoB/AlN] $_N$ magnetic multilayer



DPC: Pros & Cons

Pro:

- linear signal
- simple quantification
- sensitivity adjustable
  - trade off with resolution
- suppression of dynamical scattering

Con:

- (fast detector required)
- not so fast
- calibration of small scattering angles
- artifacts due to sub-beam diameter sample variations

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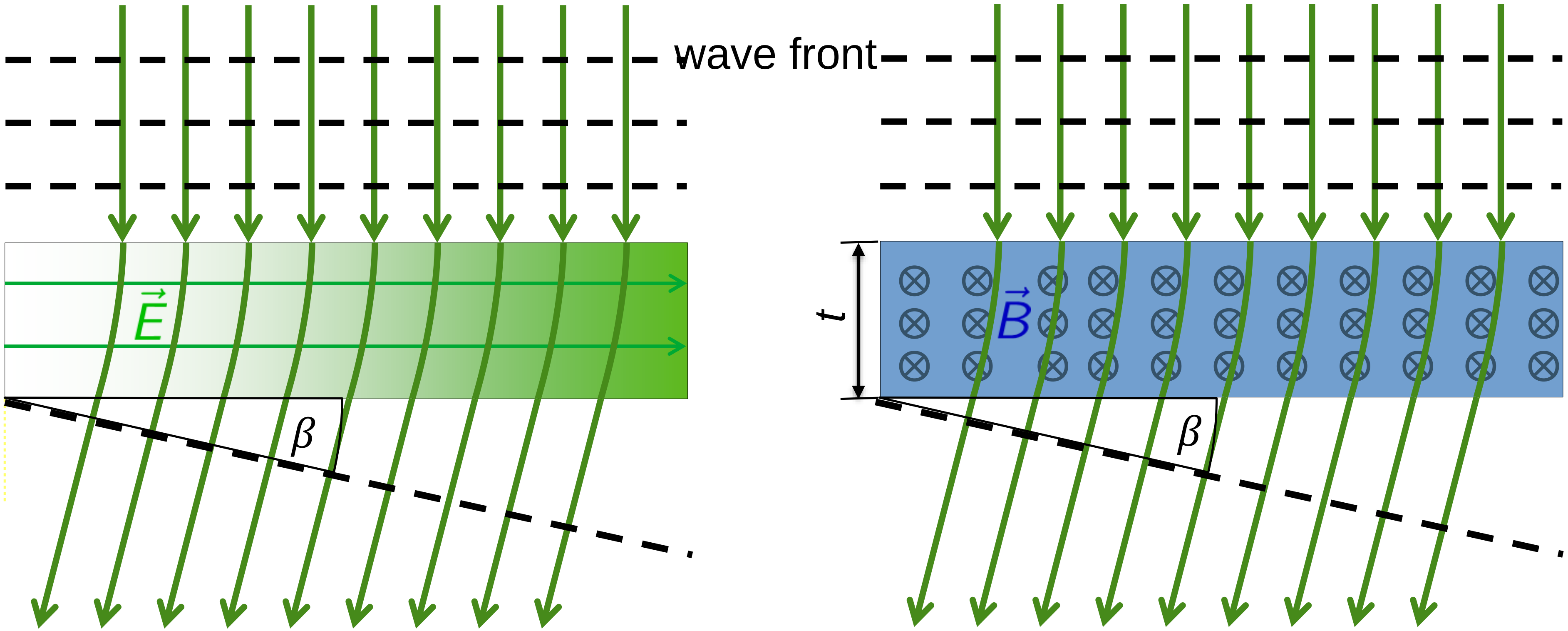
How do fields act on electrons waves?



deflection angle

$$\beta = -\frac{et}{mv_0^2}\begin{pmatrix}E_x\\E_y\end{pmatrix}$$

initial velocity

semiclassics

$$\beta = -\frac{et}{mv_0}\begin{pmatrix}-B_y\\B_x\end{pmatrix}$$

$$\beta = \frac{1}{k}\nabla\varphi$$

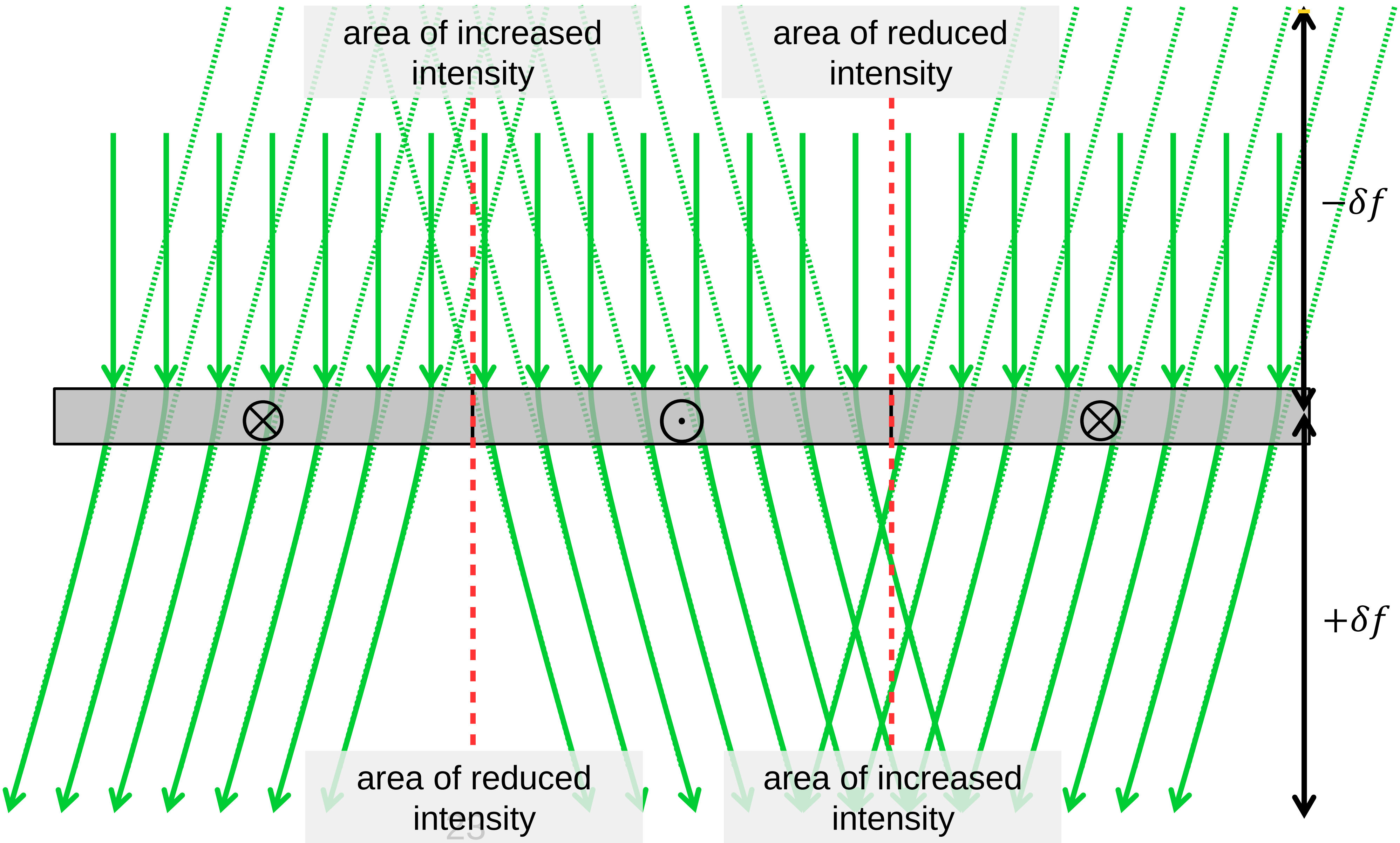
phase shift*

$$\varphi = \frac{et}{\hbar v_0}\Phi$$

$$\varphi = \frac{et}{\hbar}A_z$$

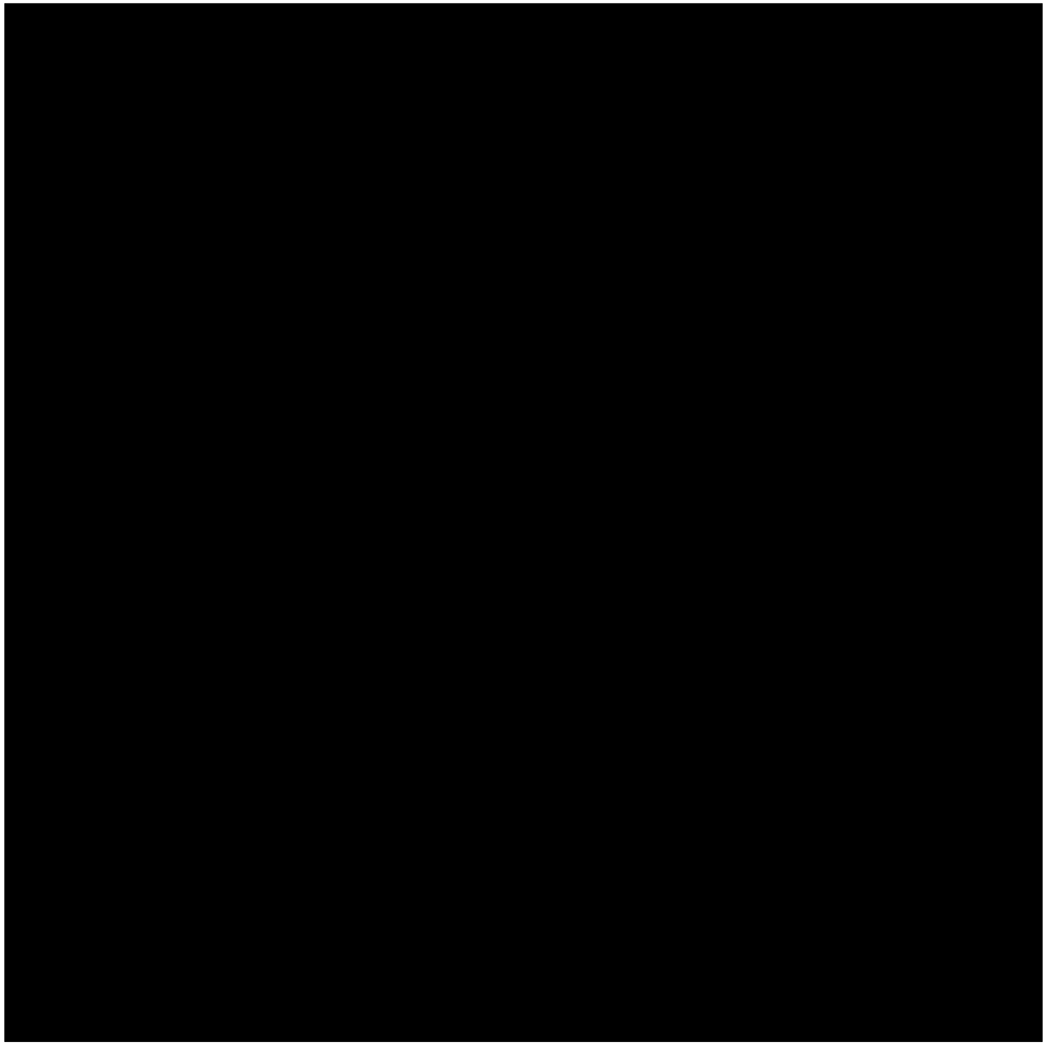
*** Electrons are waves! (more on that tomorrow)**

Converting phase shifts to contrasts: Fresnel imaging

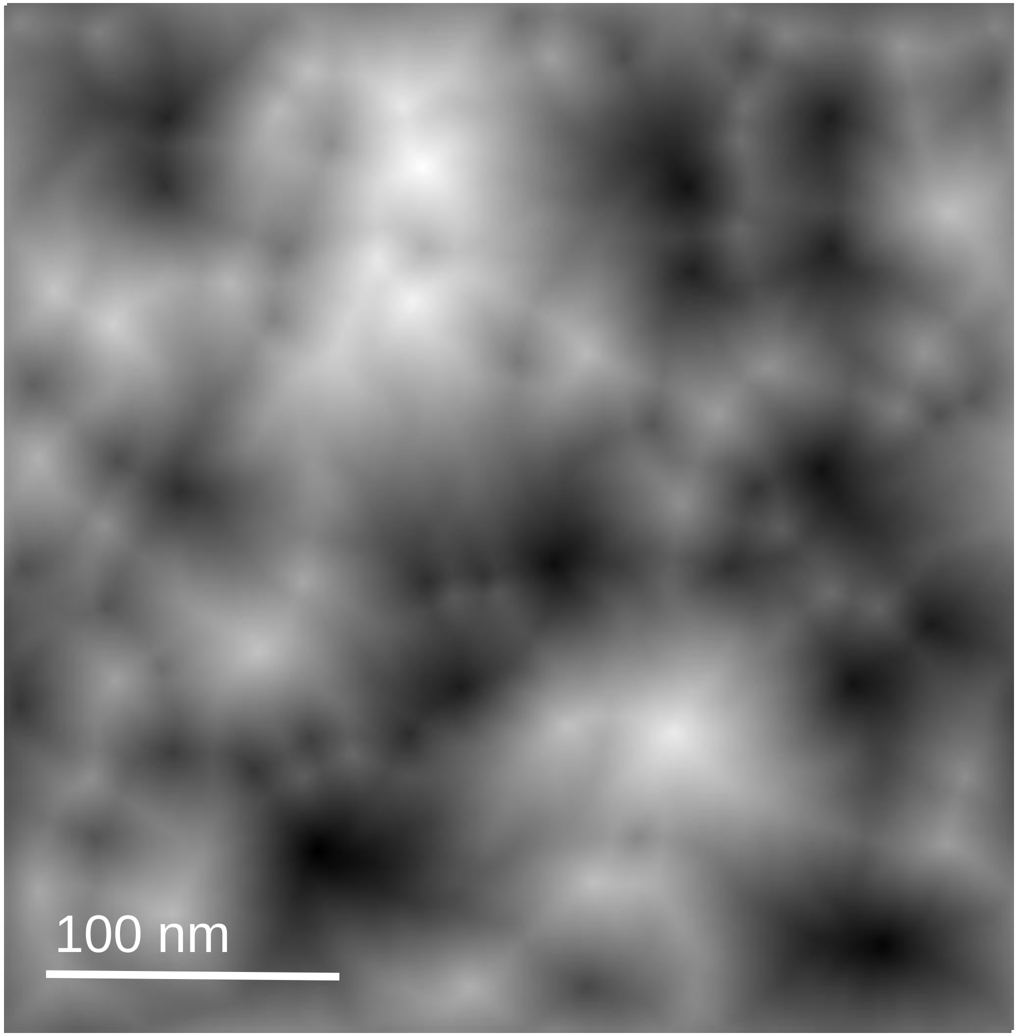


Converting phase shifts to contrasts: Fresnel imaging

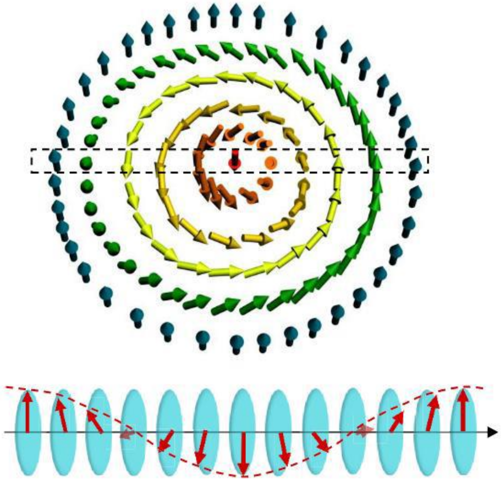
Fresnel image through-focus series



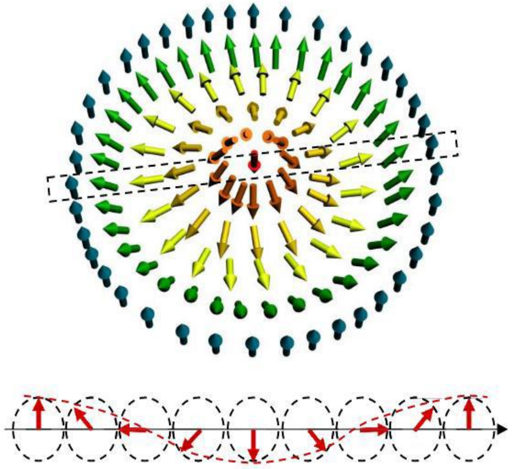
Phase grating φ



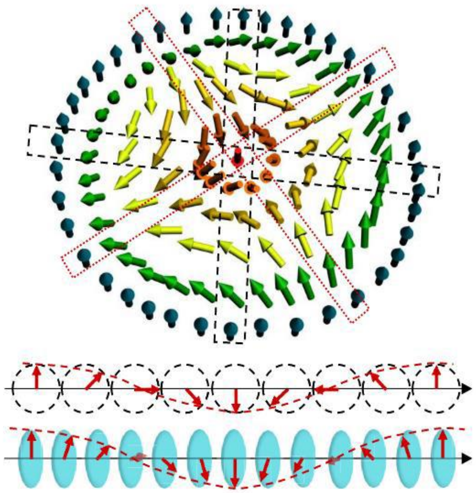
Magnetic Skyrmions



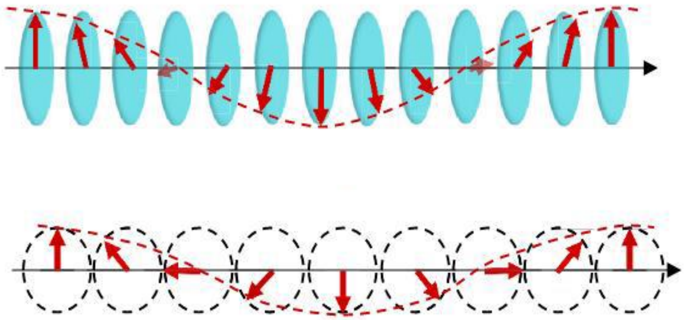
Bloch



Néel

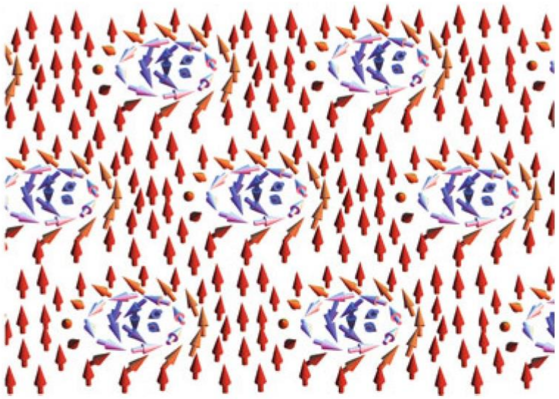


Anti



helical

cycloidal



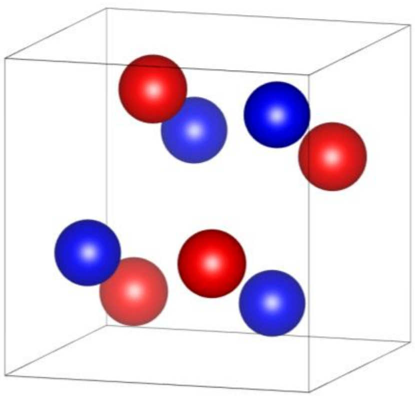
hexagonal lattice

[1] T. H. Skyrme, Proc. R. Soc. Lond. Ser. A 260, 127 (1961)[2] E. Ruff et *al*., Phys Rev B **96**, 165119 (2017)
[3] A. O. Leonov et *al*., New J. Phys. **18** (2016) 065003 [4] S. Seki, M. Mochizuki, SpringerBriefs in Physics (2016)
[5] A. K. Nayak et *al*., nature **548** (2017)

Converting phase shifts to contrasts: Fresnel imaging

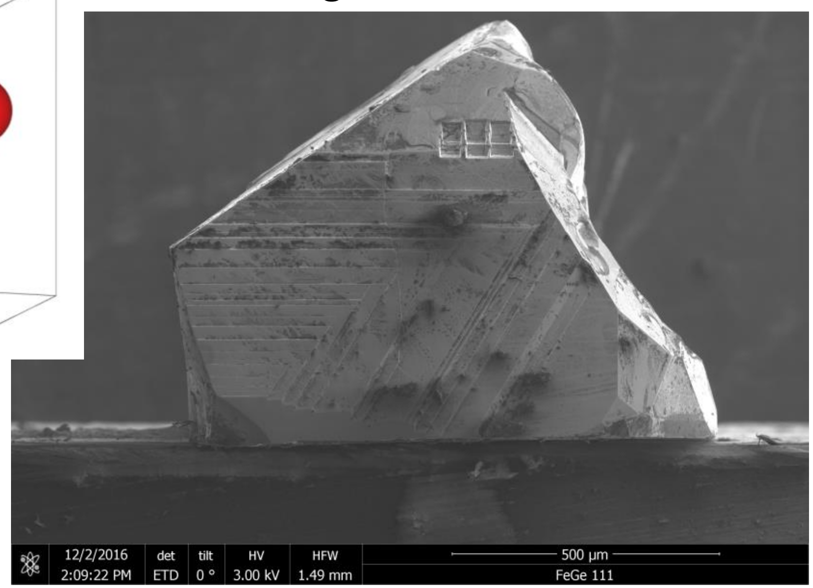
Skyrmions in isotropic helimagnet FeGe

Cubic $P2_13$ crystal structure

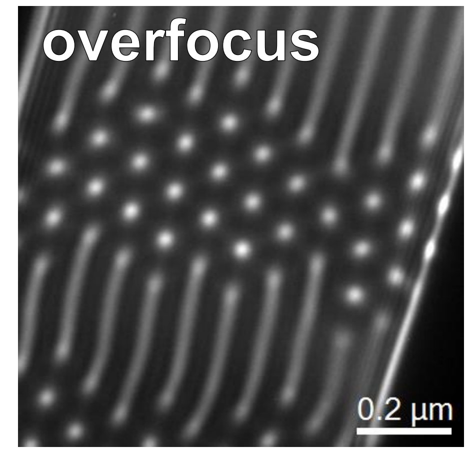


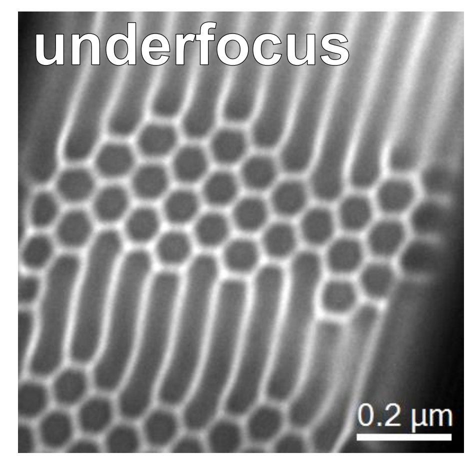
FeGe

SEM image

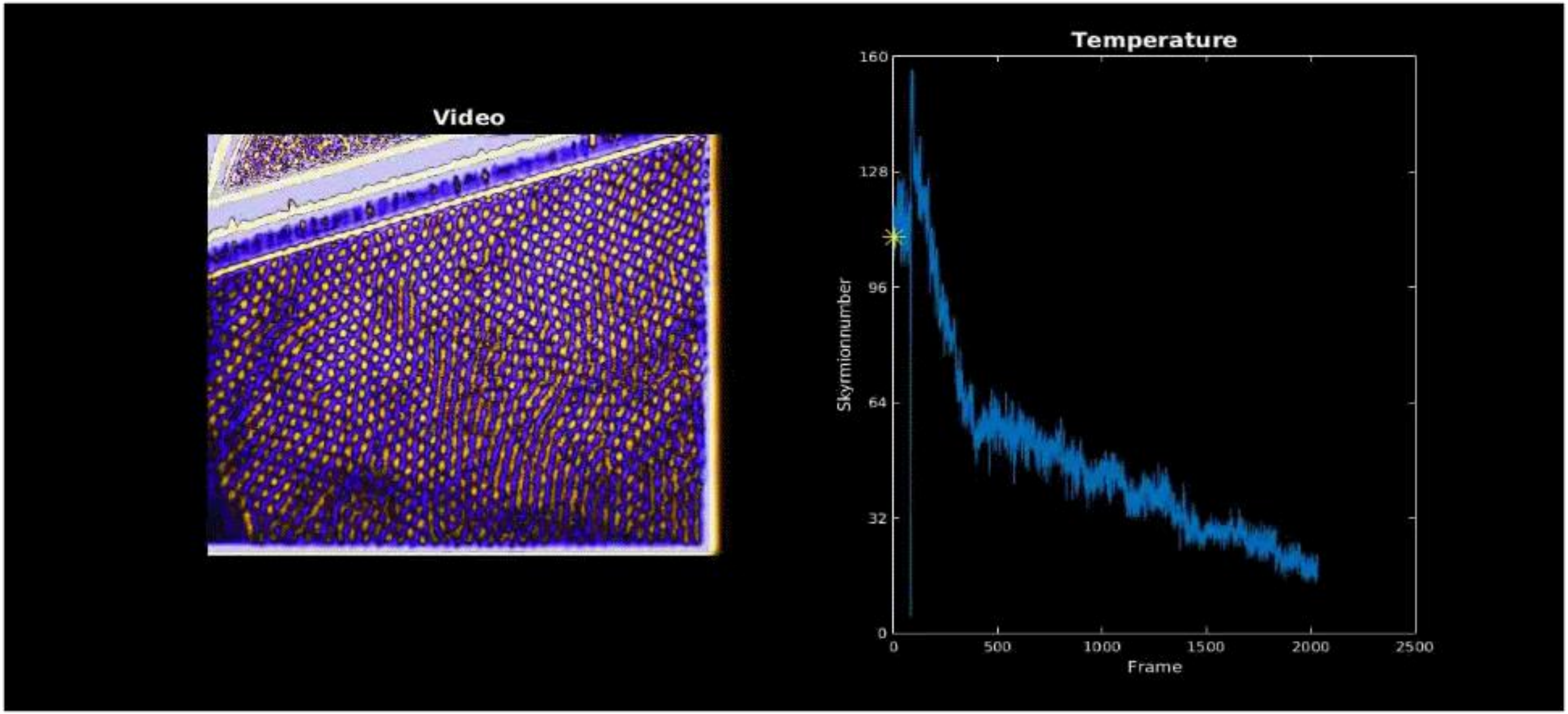


Sample from Marcus Schmidt (MPI-CPfS)

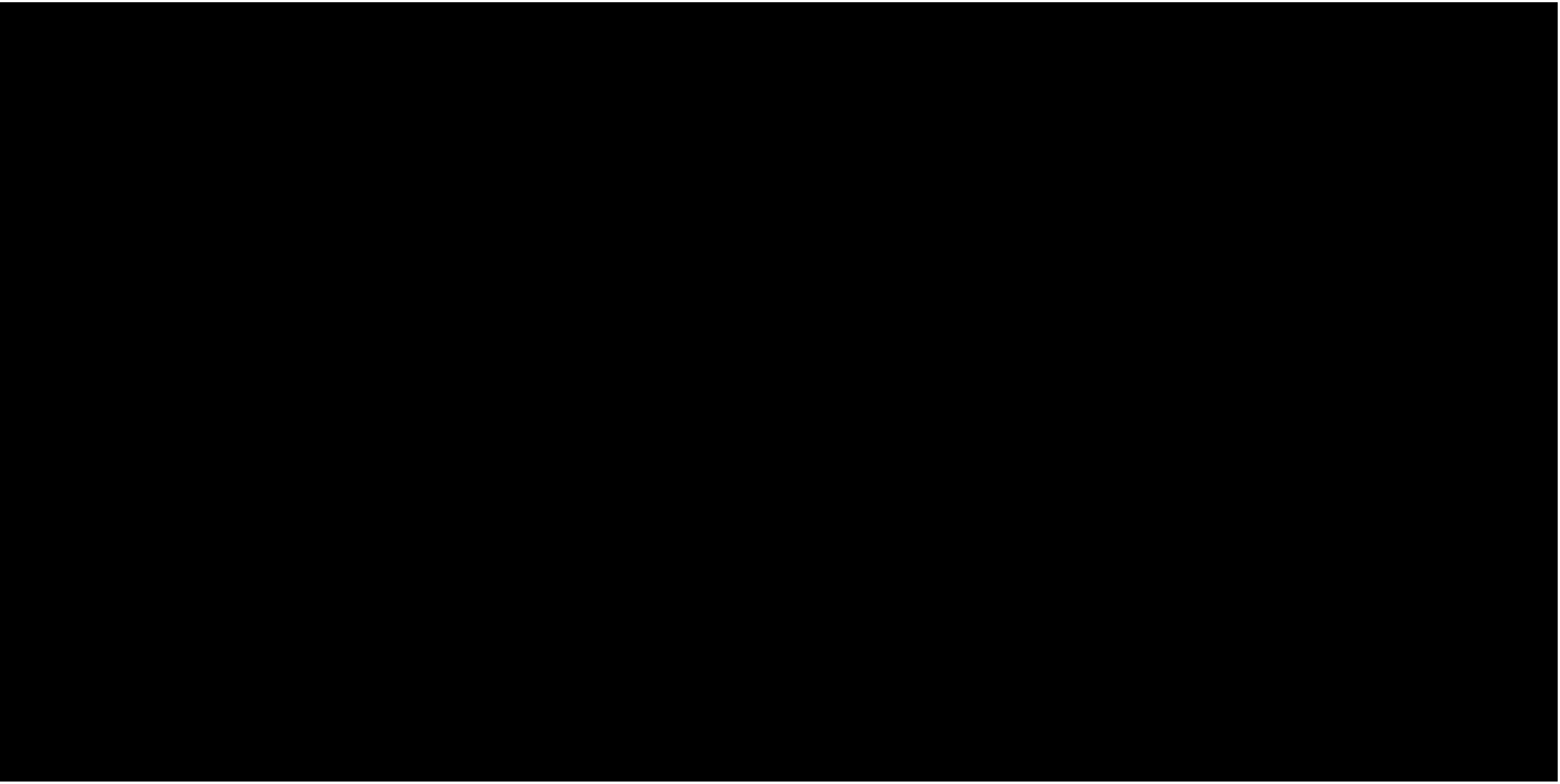




Converting phase shifts to contrasts: Fresnel imaging of Skyrmion dynamics



Converting phase shifts to contrasts: Fresnel imaging of Skyrmion dynamics



Fresnel imaging: Pros & Cons

Pro:

- simple
- fast
- sensitivity adjustable

Con:

- (partially) non-linear contrast
- defocus → unsharp images
- quantification difficult (but possible)
- sensitiv to dynamical scattering

Can be overcome by Holography! (tomorrow)

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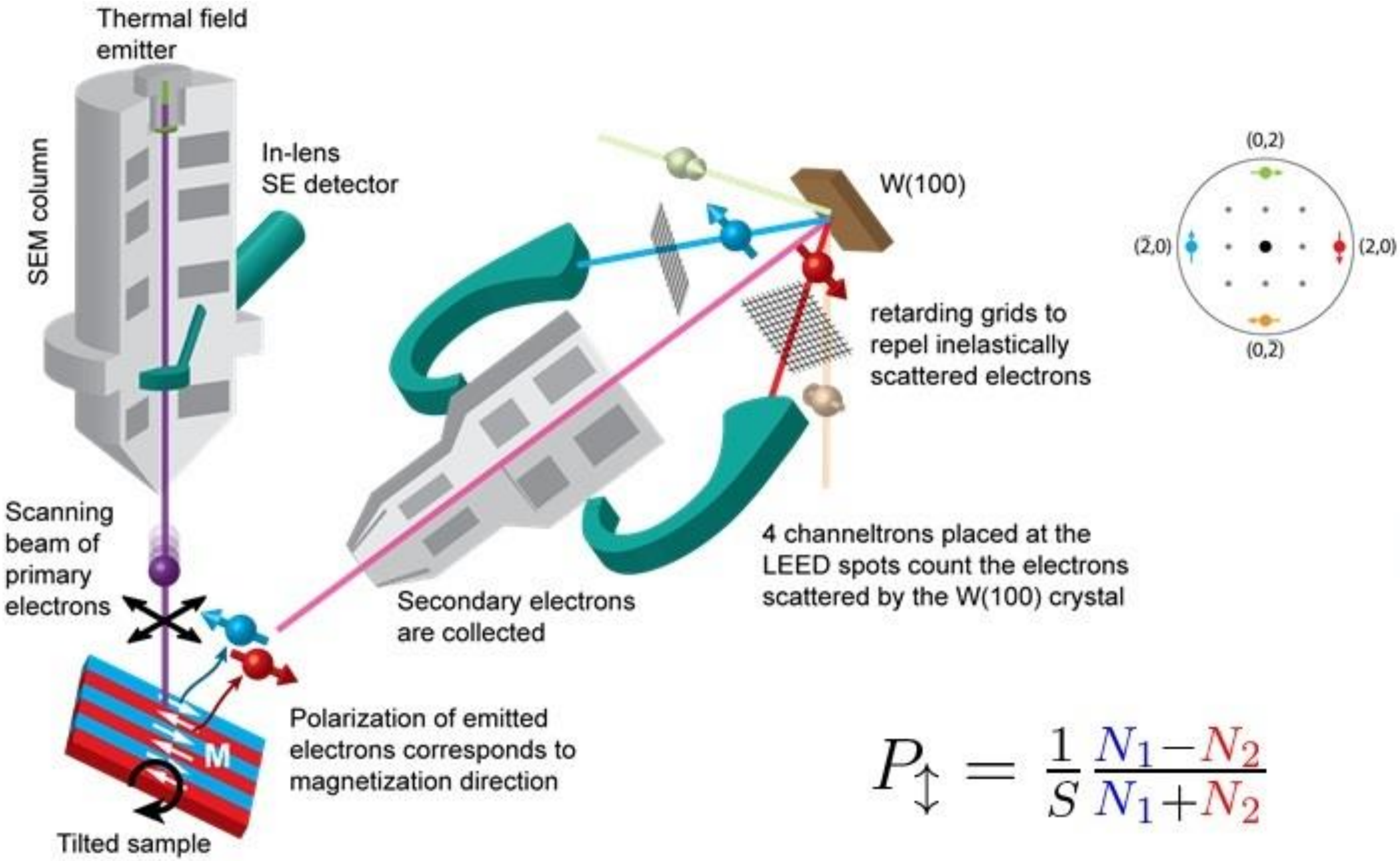
3. Summary

SEM with polarization analysis

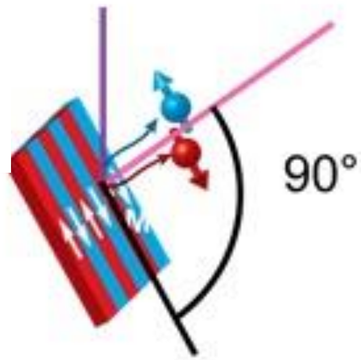


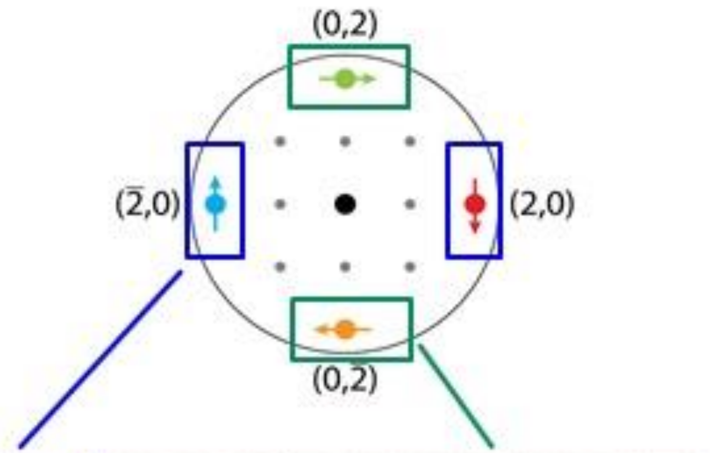
$$P_{\updownarrow} = \frac{1}{S}\frac{N_1 - N_2}{N_1 + N_2}$$

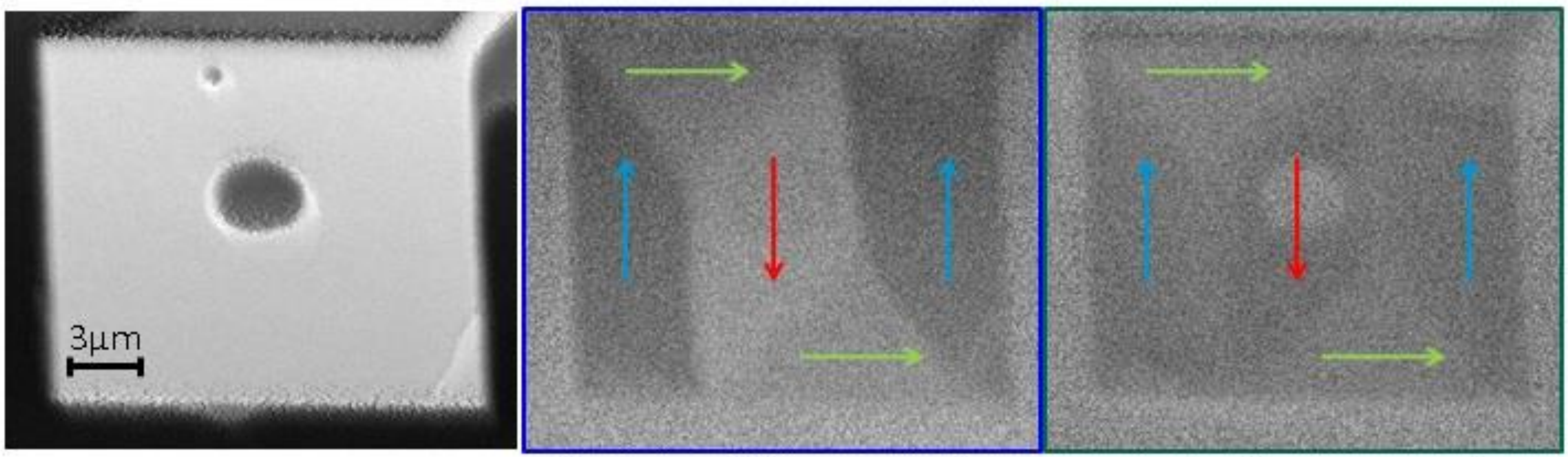
Koike et al in 1984

SEM with polarization analysis

Geometry for detection of in-plane polarization







SEM | horizontal detector pair | vertical detector pair

example of SEMPA imaging: 10µm Py Pad

SEM with polarization analysis

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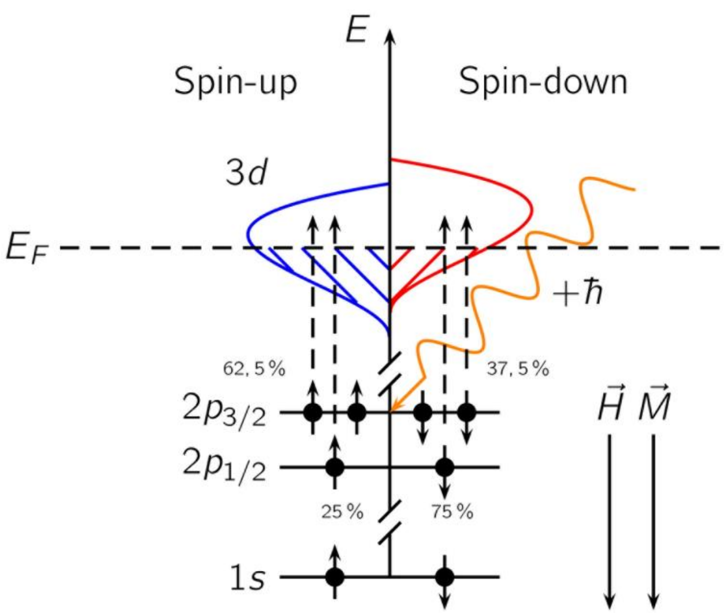
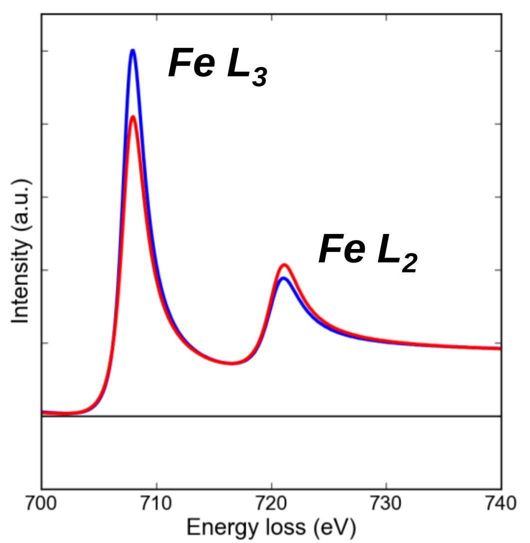
X-ray magnetic circular dichroism (XMCD)



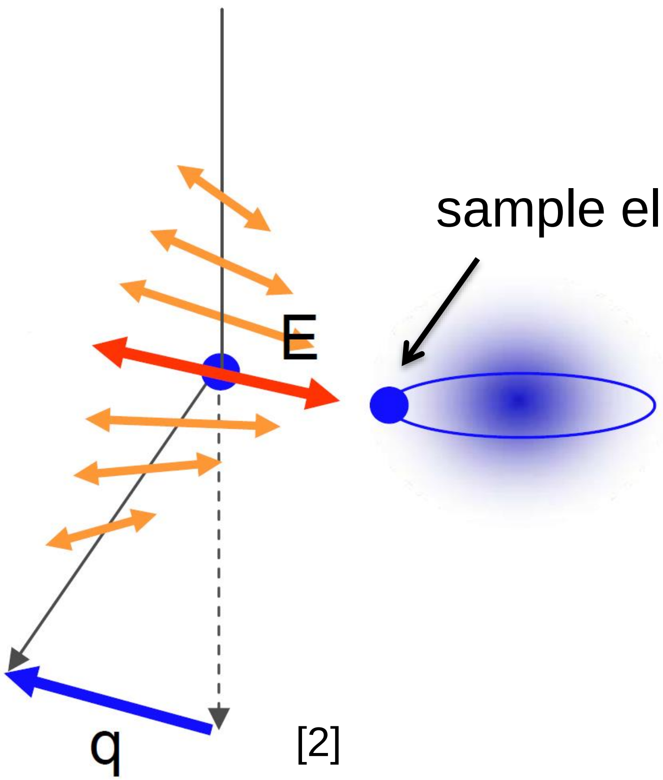


- ferromagnetic materials: imbalance of spin-up and spin-down electrons in 3d (4f…) shell
- measure difference through spin-dependent x-ray absorption process [1]
- angular momentum of light is transferred to photoelectron
- helicity of photon imposes constraints for the change of angular momentum in dipole transitions
- spin-orbit coupling in 2p states couples angular momentum to spin momentum
- absorption coefficient as function of energy is proportional to the final d states density.

[1] G. Schütz et al., Phys. Rev. Lett. 58 (1987)

XMCD and Electron energy-loss circular dichroism (EMCD)

Model of the ‘virtual photon’



• The FOURIER component of $\vec{E}$ giving rise to an electronic transition is parallel to momentum transfer ħ$\vec{q}$.

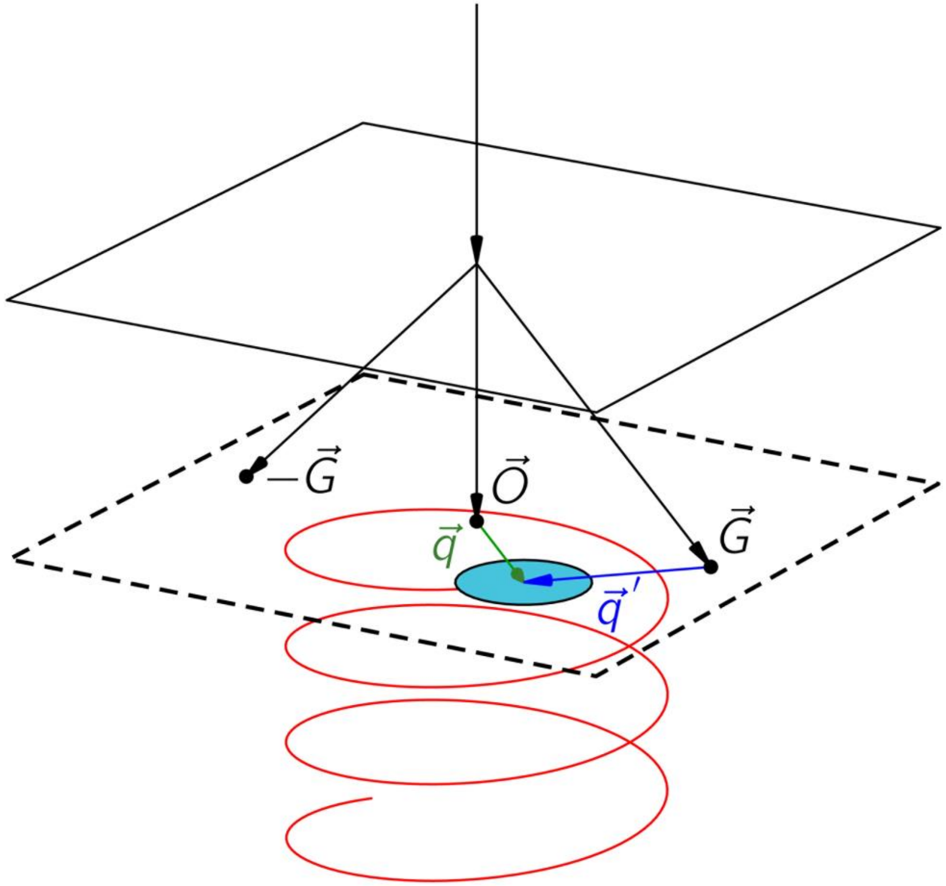
• Interpretation as an absorbed effective photon with polarisation $\vec{\varepsilon} \parallel \vec{q}$.

• EMCD = transfer of circularly polarised virtual photon.

• Electron (virtual photon) changes angular momentum by ±ħ.

[2] P. Schattschneider, Linear and Chiral Dichroism in the Electron Microscope. CRC Press (2012)

Classical EMCD



- Pertubation leading to an electric transition is an electric field $\vec{E} \propto \vec{q}\,\Re\left[e^{i(\omega t+\phi)}\right]$.

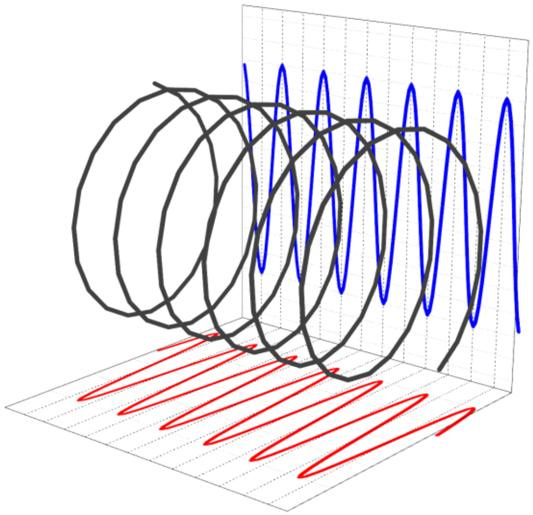
- Force two scattering vectors to exhibit a phase difference $\delta\phi = \phi' - \phi = \frac{\pi}{2}$.

- $\vec{E} + \vec{E}' = \ldots = \vec{q}\cos(\omega t + \phi) - \vec{q}\,'\sin(\omega t + \phi)$. (circular polarized virtual photon)

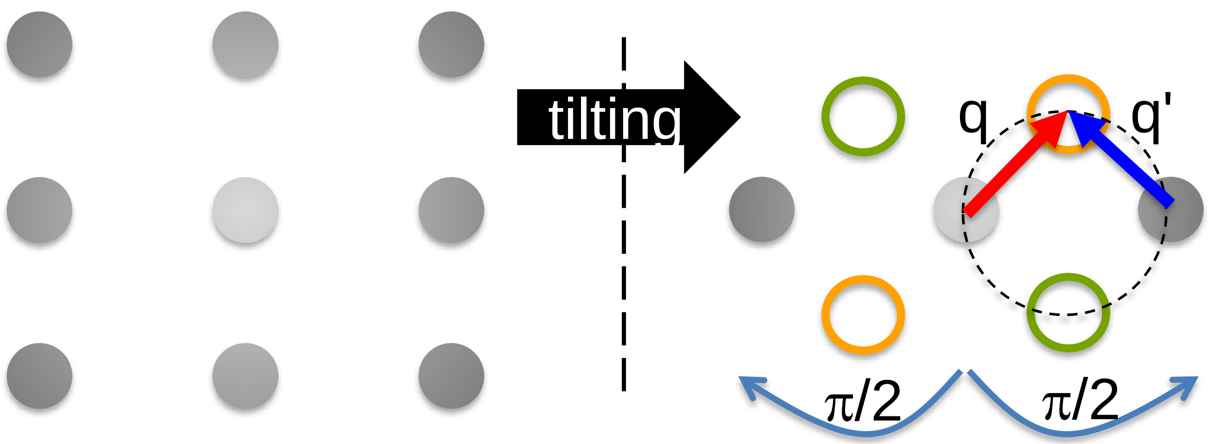
- Mirroring the position of the aperture gives opposite polarization.

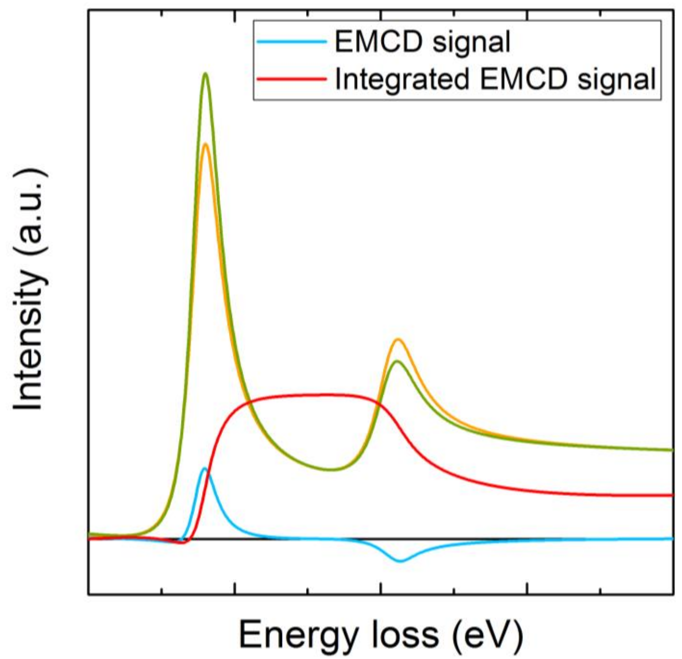
Classical EMCD

- Similarity between electron scattering and photon absorption leads to equivalence of EMCD and XMCD [3, 4].
- Scattering vector q replace the polarisation ε.
- Prerequisites:
  - (i) Superposition of two linear polarized waves (with a phase shift of $\pi/2$) to a circular polarized wave
  - (ii) Optimal for $q \perp q'$
  - (iii) Change of helicity



Diffraction pattern (zone axis) Three beam case



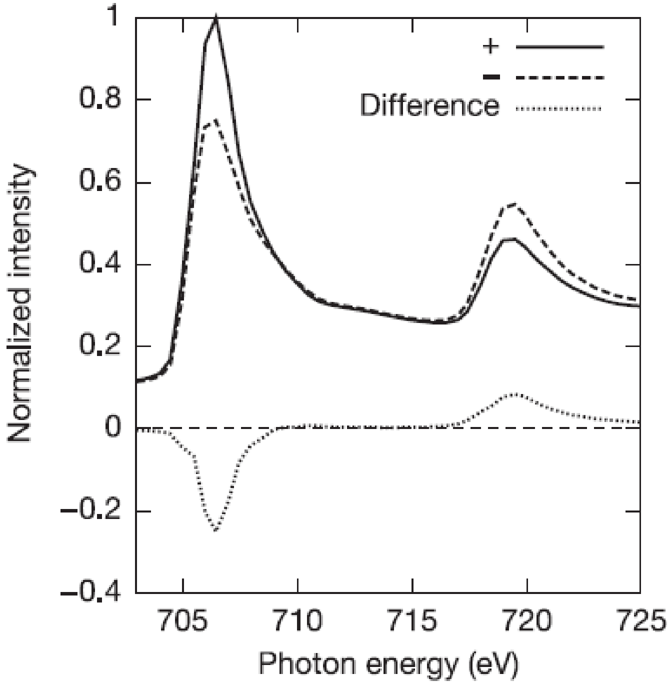


[3] C. Hébert and P. Schattschneider , Ultramicroscopy 96 (2003)
[4] P. Schattschneider et al., Nature 441 (2006)

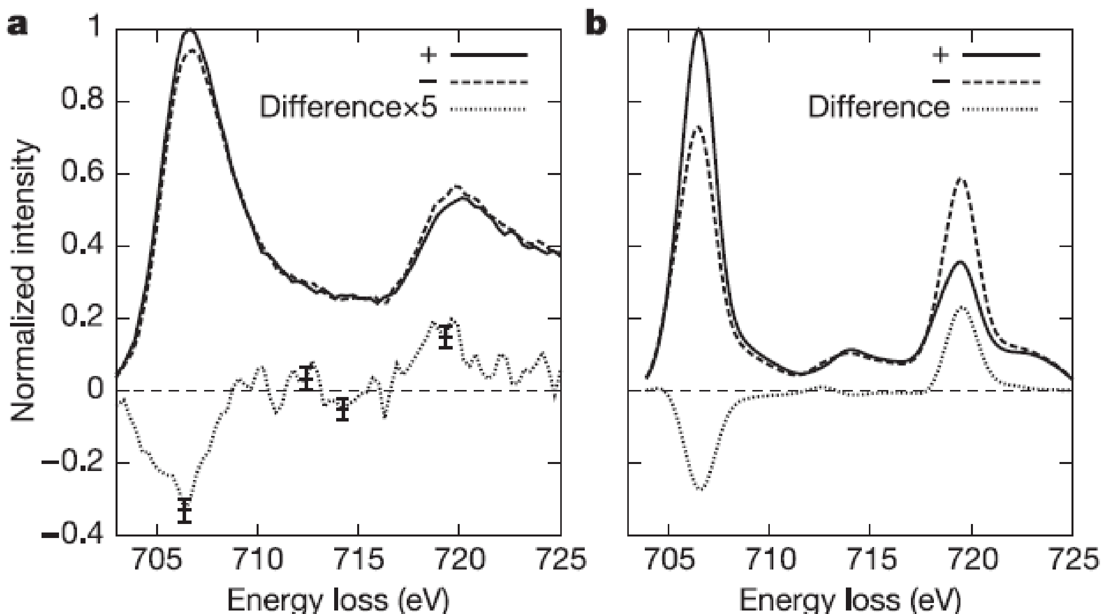
First experimental EMCD spectra

- (10 ± 2)-nm-thick Fe single crystal film.
- XMCD spectra from a focused 50 μm spot.
- EMCD spectra from illuminated area with 200 nm diameter.

Experimental XMCD spectra

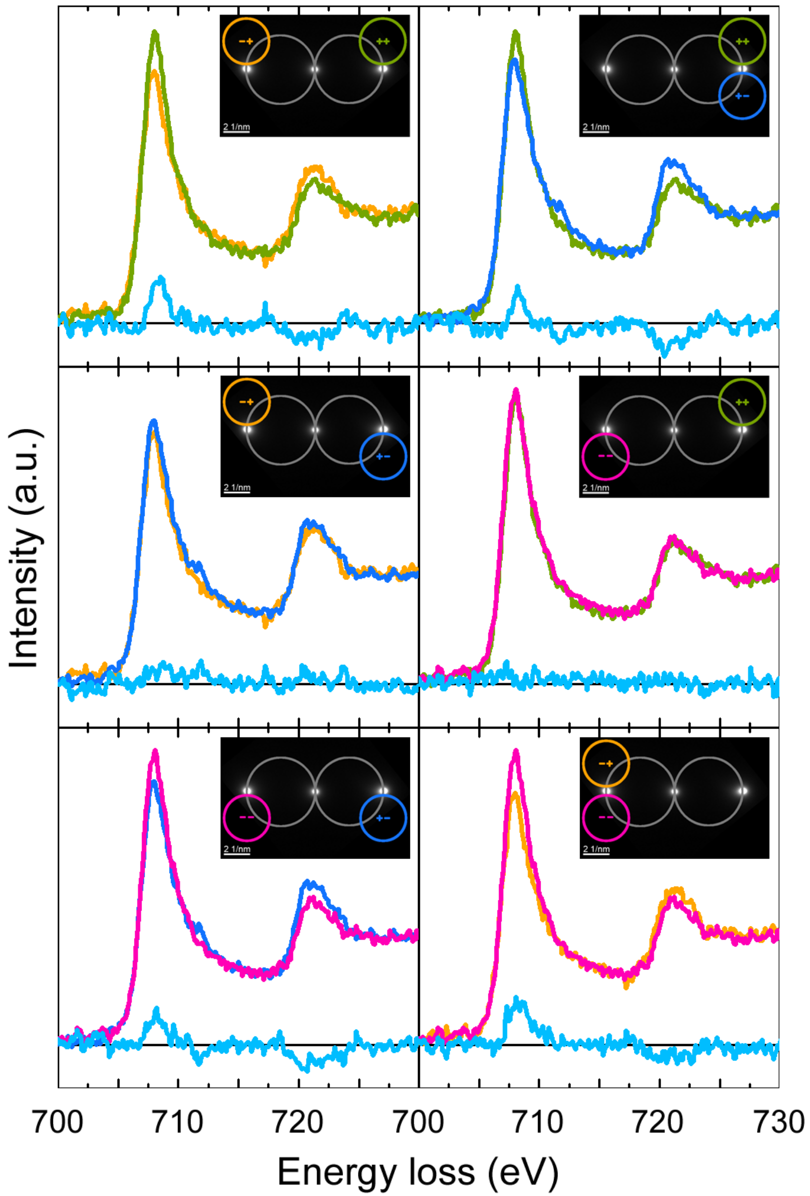


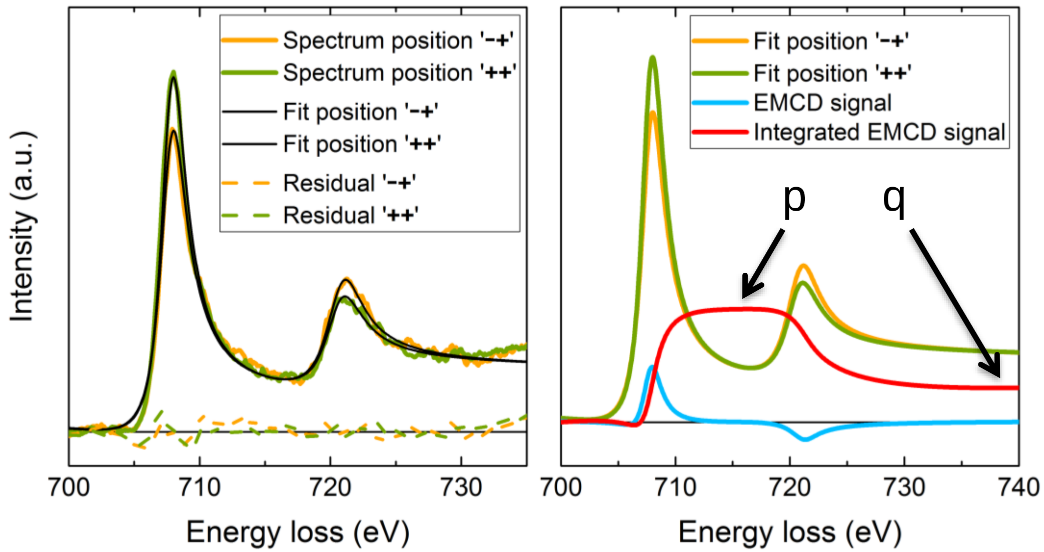
Experimental and simulated EMCD spectra



[3]

Quantifying magnetic properties of FePt nanoparticles





- Using sum rules [7]:

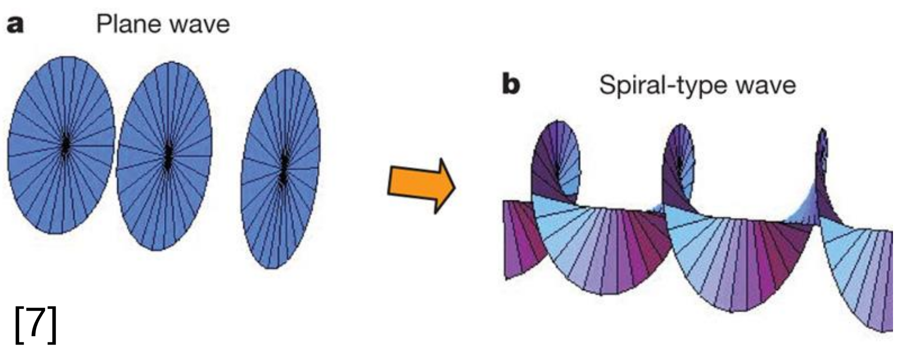
$$m_l/m_s = \frac{2q}{9p-6q} = 0.08 \pm 0.02$$

can be calculated, which agrees well with XMCD results [8, 9].

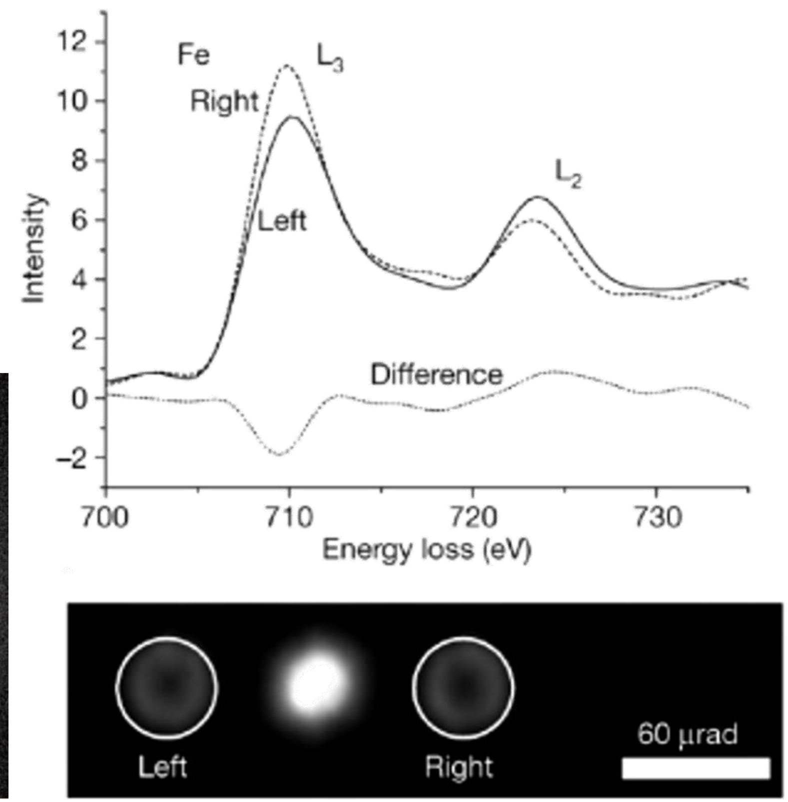
[7] J. Rusz et al., Physical Review B, 75 (2007)
[8] C. Antoniak et al., PRL 97 (2006)
[9] V. Dupuis et al., J. of Magn. and Magn. Mat. (2015)

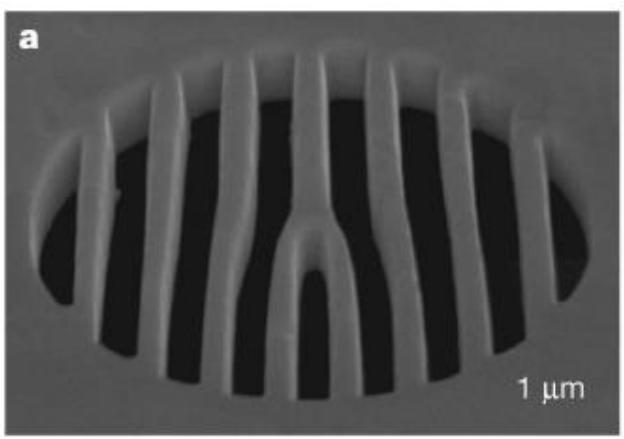
Towards atomic magnetic measurements

EMCD with vortex beams on magnetic nanostructures and nanoparticles (measuring out-of-plane magnetisation).

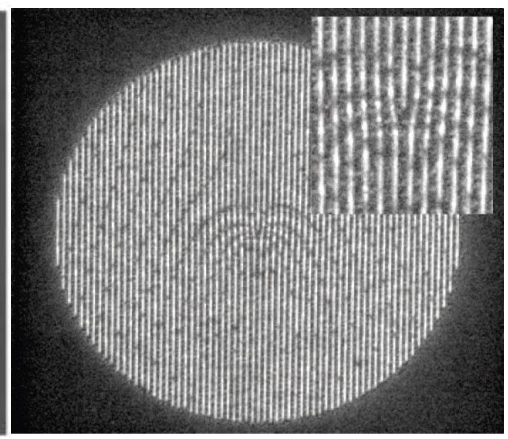


[7]





[8]



[9]

[8]

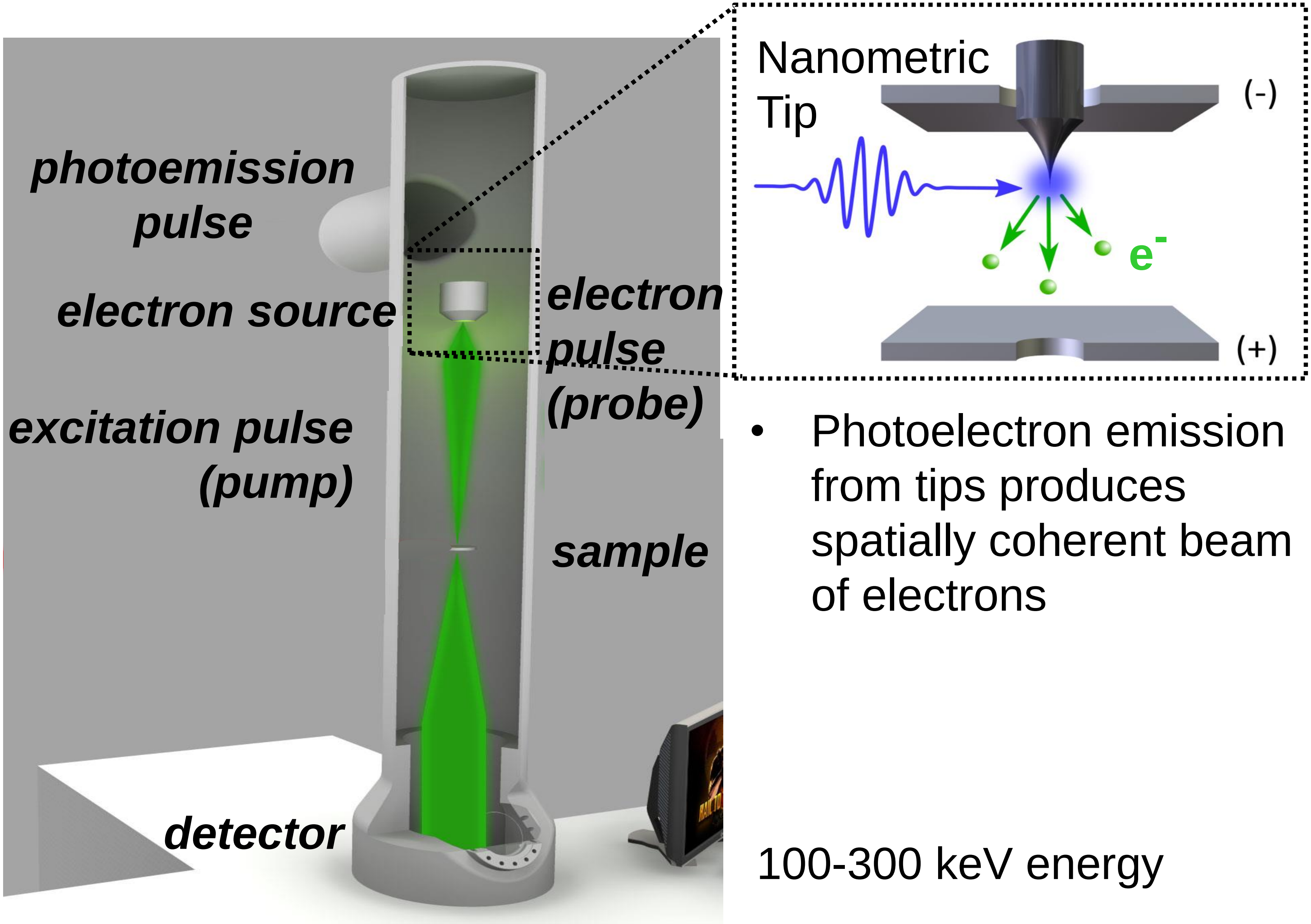
[7] M. Uchida and A. Tonomura, Nature 464 (2010)
[8] J. Verbeeck et al., Nature 467 (2010)
[9] B. McMorran et al.. Science 331 (2011)

1. Electron microscopies for magnetic materials
    a. TEM based magnetic imaging techniques
        i. Differential Phase Contrast
        ii. Lorentz TEM
    b. SEM based magnetic imaging techniques

2. Electron spectroscopies and time-resolved approaches for magnetic materials
    a. EELS and Energy-Loss-Chiral Dichroism
    b. Ultrafast TEM

3. Summary

Ultrafast Transmission Electron Microscopy

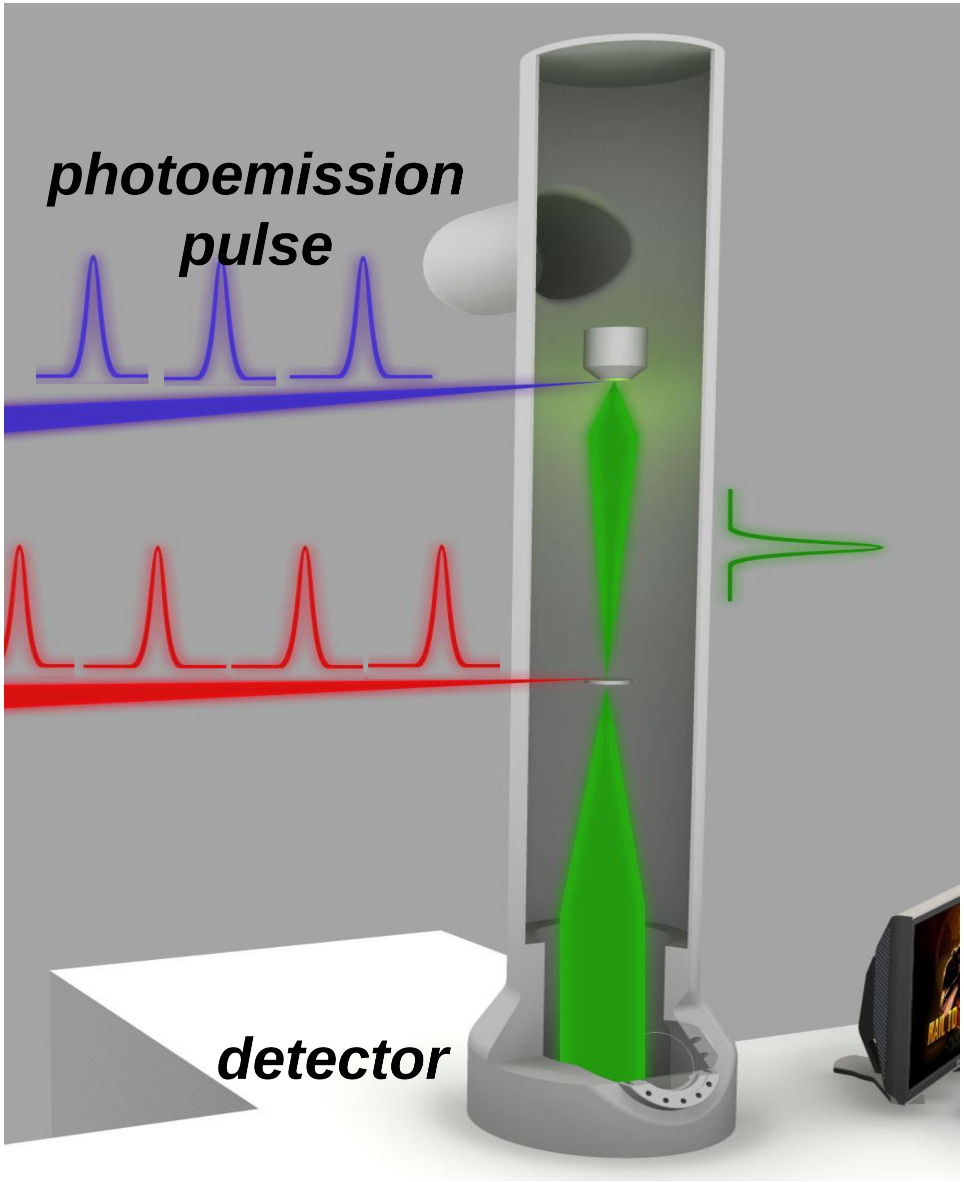


- Photoelectron emission from tips produces spatially coherent beam of electrons

100-300 keV energy

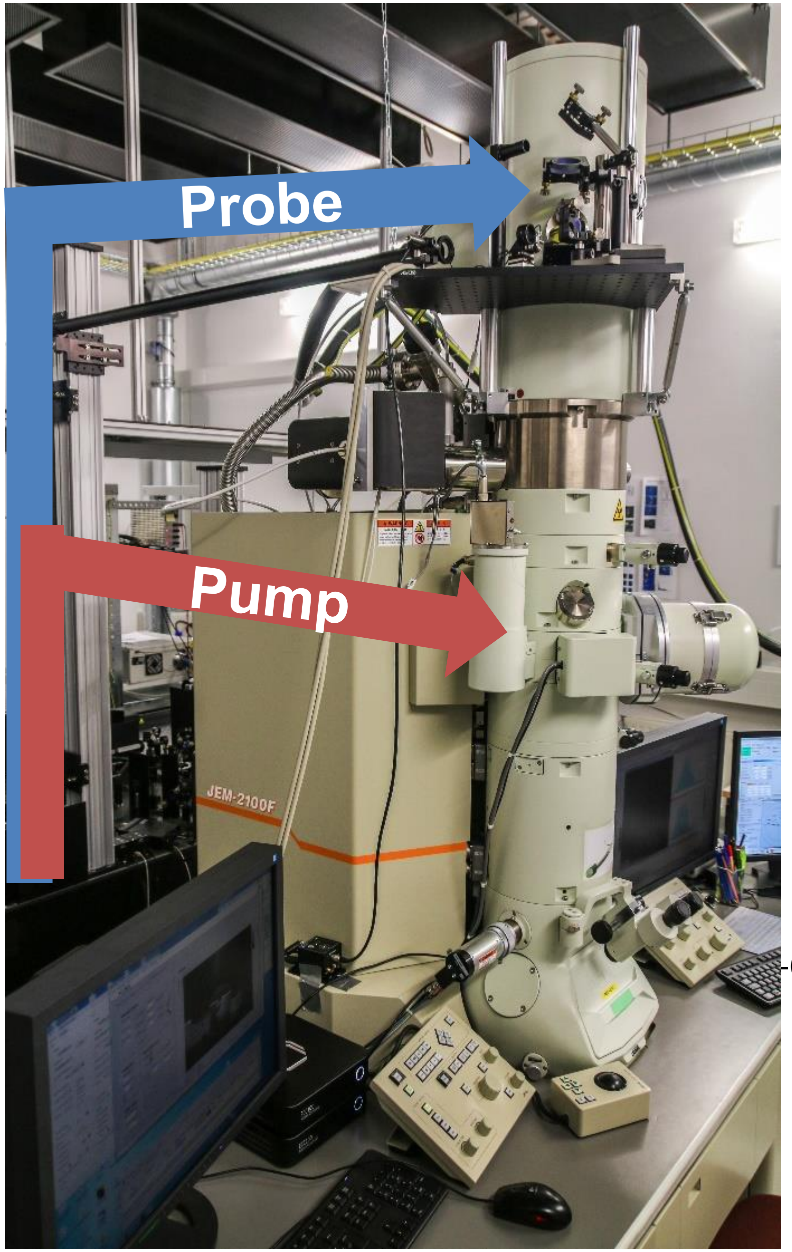
Early work: Osaka (1978), TU Berlin (80’s), Caltech (2005), LLNL (2006)

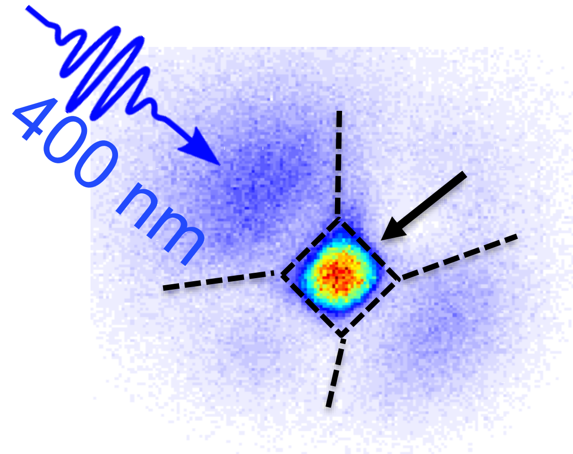
Ultrafast Transmission Electron Microscopy

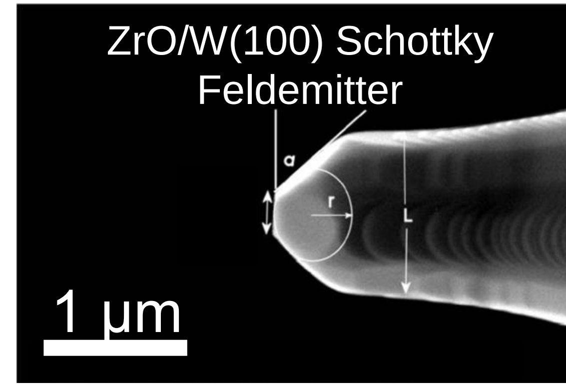


Stroboscopic approach:
sensitive to reversible dynamics

Ultrafast Transmission Electron Microscopy (UTEM)

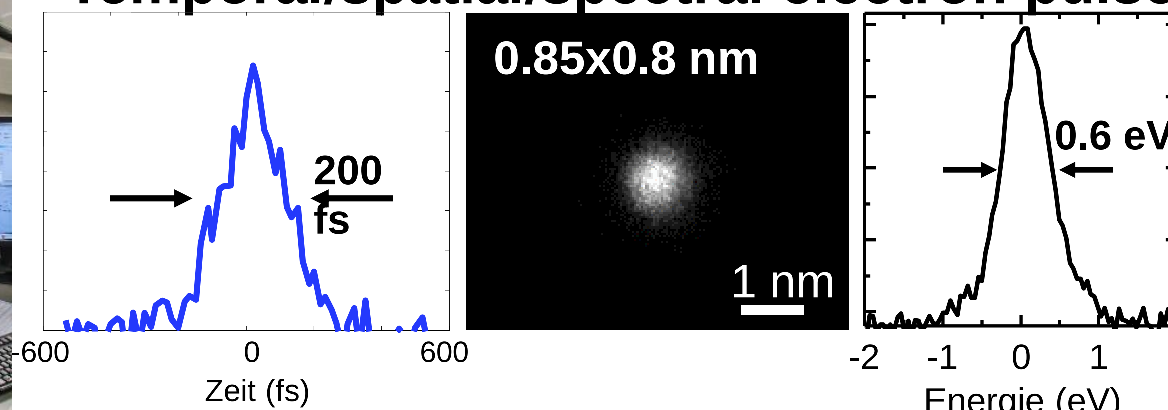






Liu et al., J. Vac. Sci Tech. (2010).

Temporal/spatial/spectral electron pulse

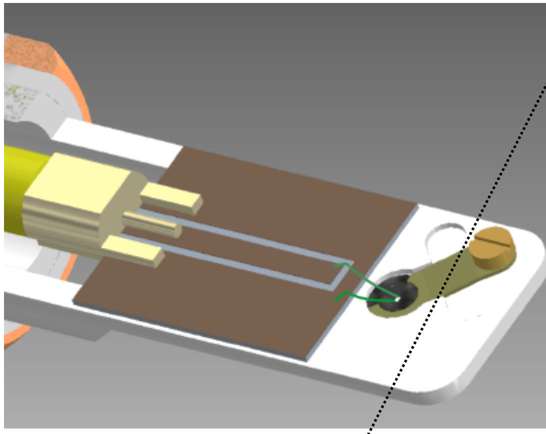


→ rms-Emittance: $\boldsymbol{\varepsilon = 2\, pm \cdot rad}$ (m. Apertur)

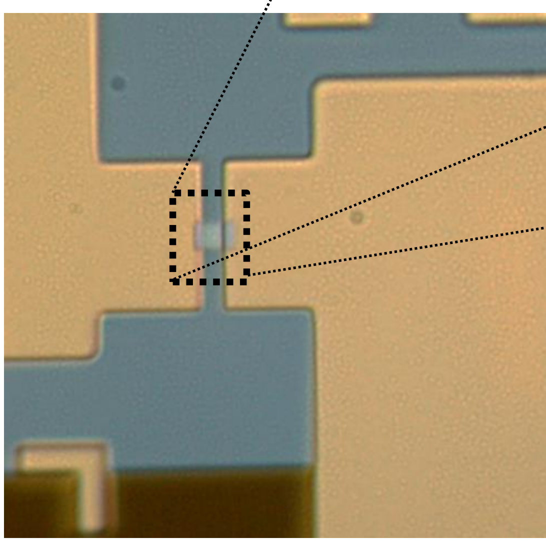
→ Peak Brillance: $1.75 \cdot 10^{13}$ A/m^2sr

A. Feist et al., Nature **521**, 200 (2015)
A. Feist *et al.*, Ultramicroscopy (2017)

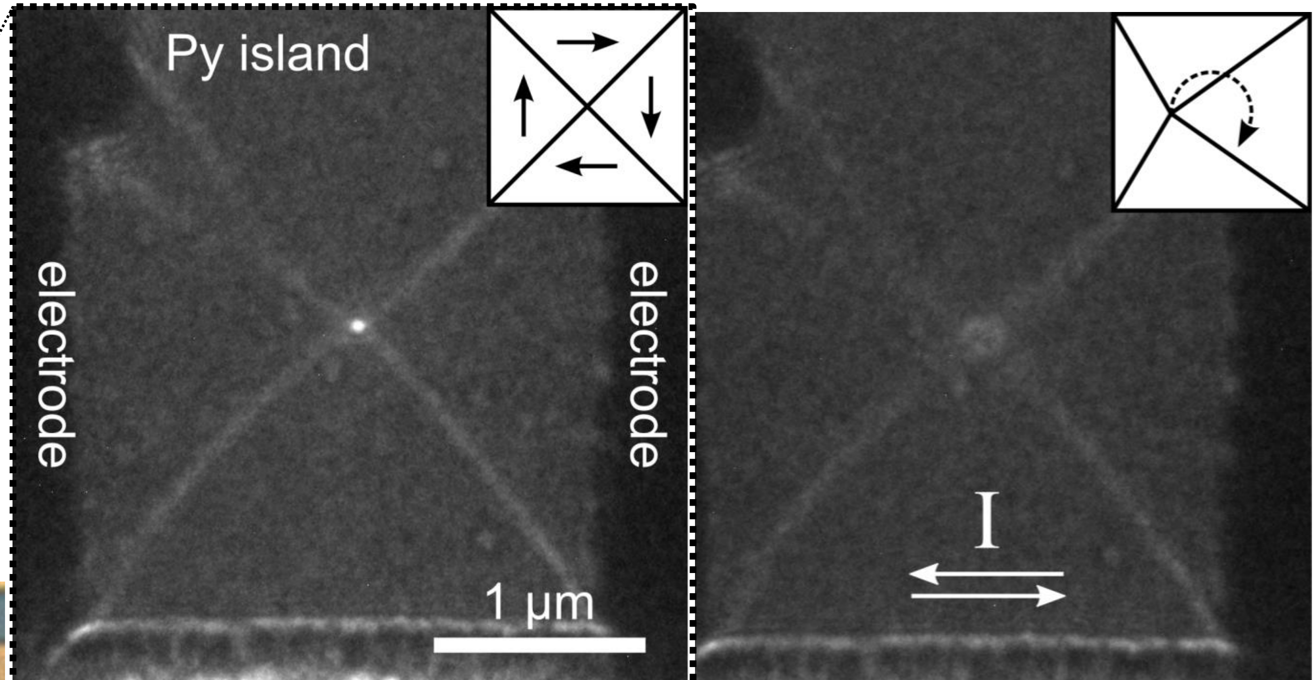
Current-driven magnetic vortex dynamics



Sample holder

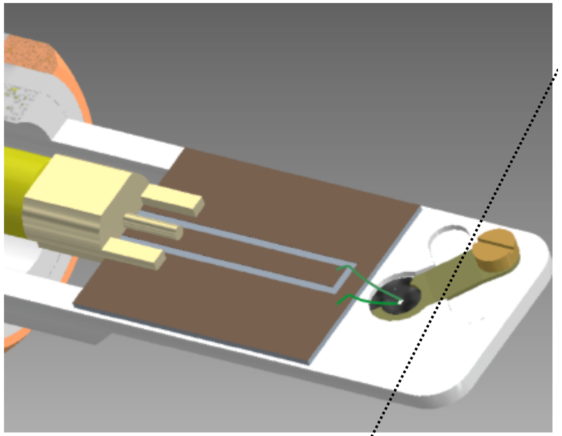


Top View

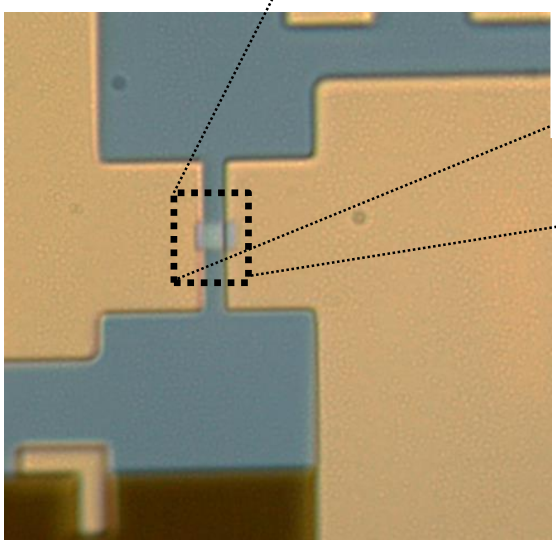


Time-averaged imaging:
S. D. Pollard et al., Nature Comm. 3, 1028 (2012).
See also Time-resolved SEMPA: R. Frömter *et al.*, APL (2016)

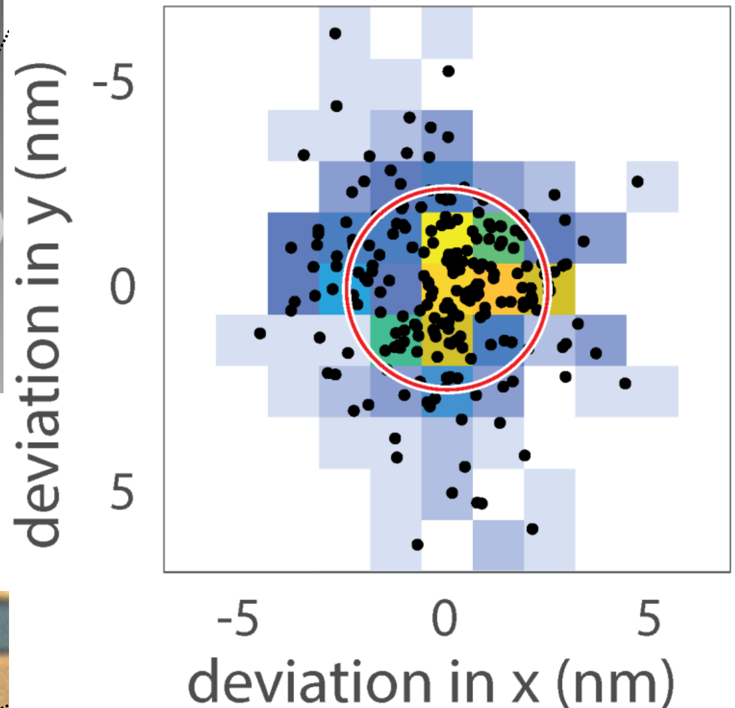
Current-driven magnetic vortex dynamics



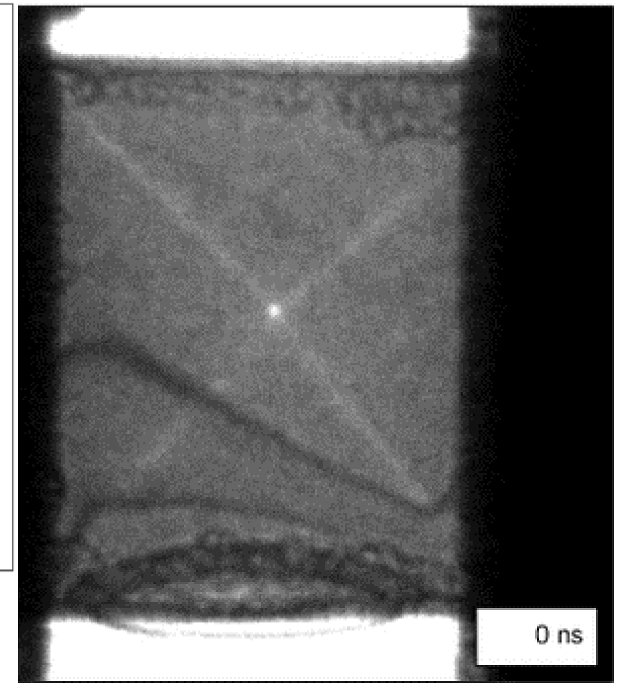
Sample holder



Top View



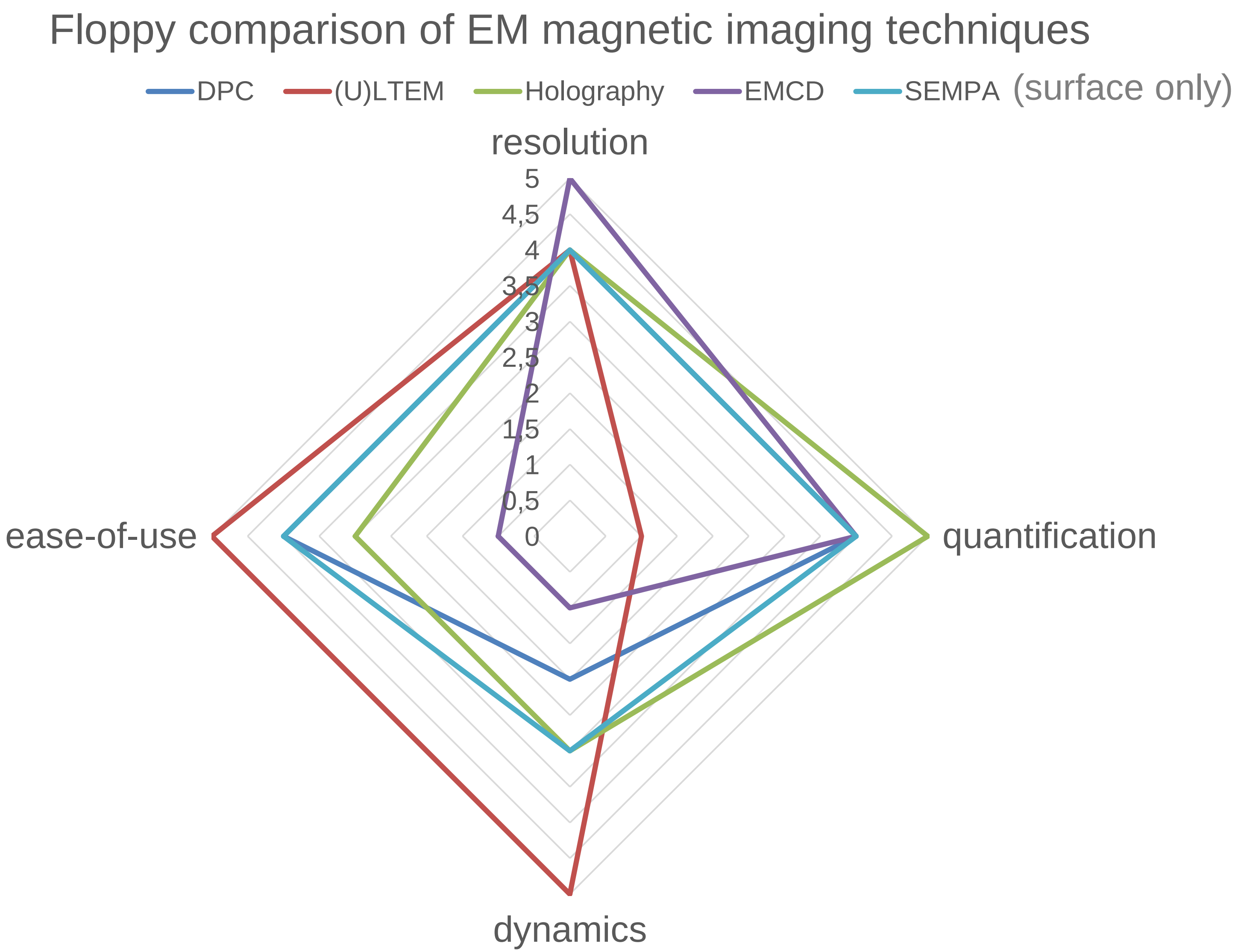
RMS dev.: 2 nm



4 ps pulses,
100 MHz resonance,

M. Möller et al., arXiv: **1907.04608** (2019)

Summary



Floppy comparison of EM magnetic imaging techniques
DPC
(U)LTEM
Holography
EMCD
SEMPA (surface only)
resolution
5
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
quantification
dynamics
ease-of-use