INSTITUT JEAN LAMOUR

www.ijl.univ-lorraine.fr

CNRS UNIVERSITÉ DE LORRAINE

Magnetic Microscopy

Stephane Mangin

THE EUROPEAN SCHOOL ON MAGNETISM

UNIVERSITÉ DE LORRAINE

http://spin.ijl.cnrs.fr

INSTITUT JEAN LAMOUR SPINTEAM

Special thanks !

Jeffrey McCord

Thomas Hauet

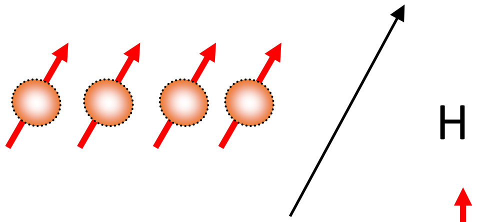
Daniel Lacour

Kiel University
Christian-Albrechts-Universität zu Kiel

INSTITUT JEAN LAMOUR SPIN TEAM

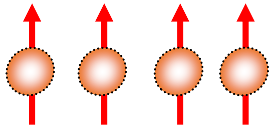
Interactions

Zeeman Energy



$$E_{zee} = - \mu_0 \overrightarrow{M} \cdot \overrightarrow{H}$$

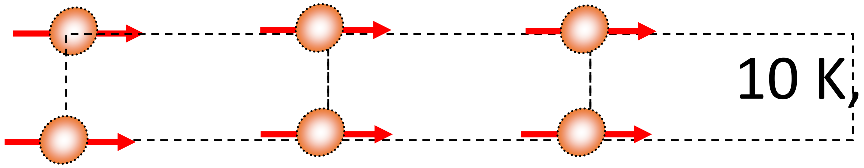
Exchange



1000 K, 100 T

$$E_{exc} = -J\vec{S}_1 \cdot \vec{S}_2$$

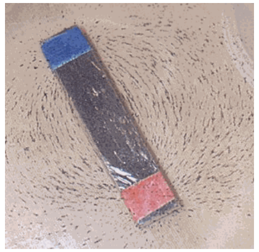
Magneto-crystalline anisotropy



10 K, 0.01 to 10 T

$$E_K = -K\,cos^2(\theta)$$

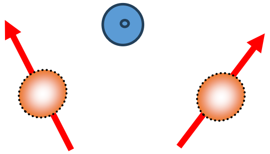
Dipolar



1 K, 10 mT

$$E_{dip} = - \mu_0 \overrightarrow{M} \cdot \overrightarrow{H}_{dip}$$

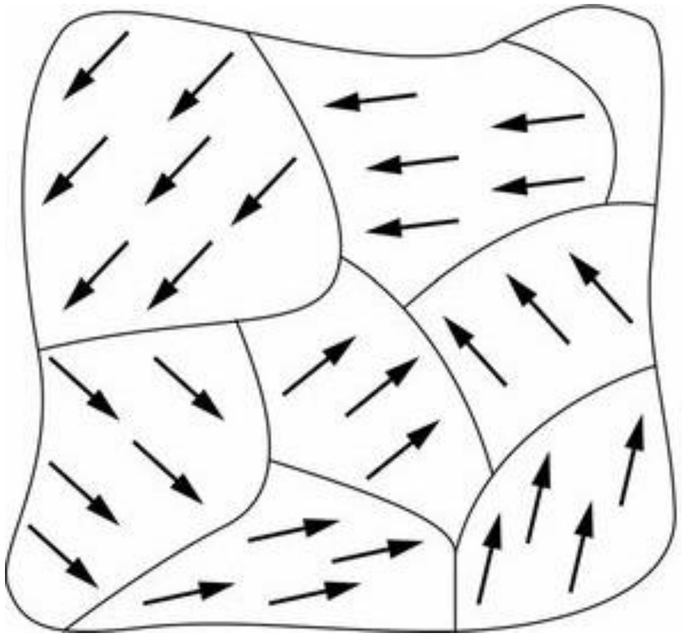
Dzyaloshinskii–Moriya interaction (DMI)

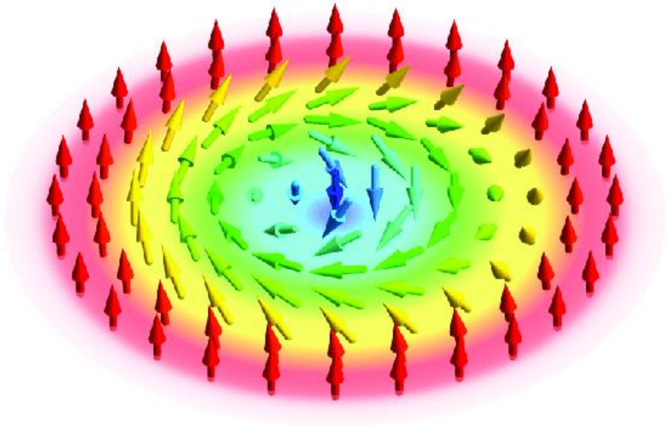


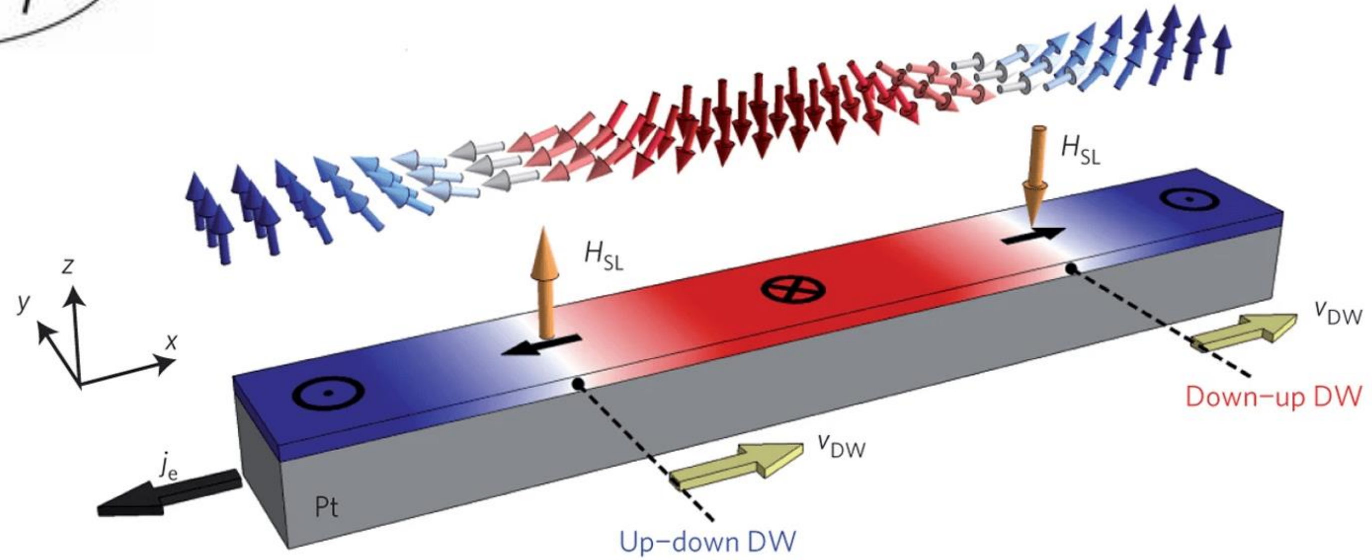
$$E_{DMI} = \overrightarrow{D}_{12} \cdot (\overrightarrow{S}_1 \times \overrightarrow{S}_2)$$

Configuration results from competition of the different interactions

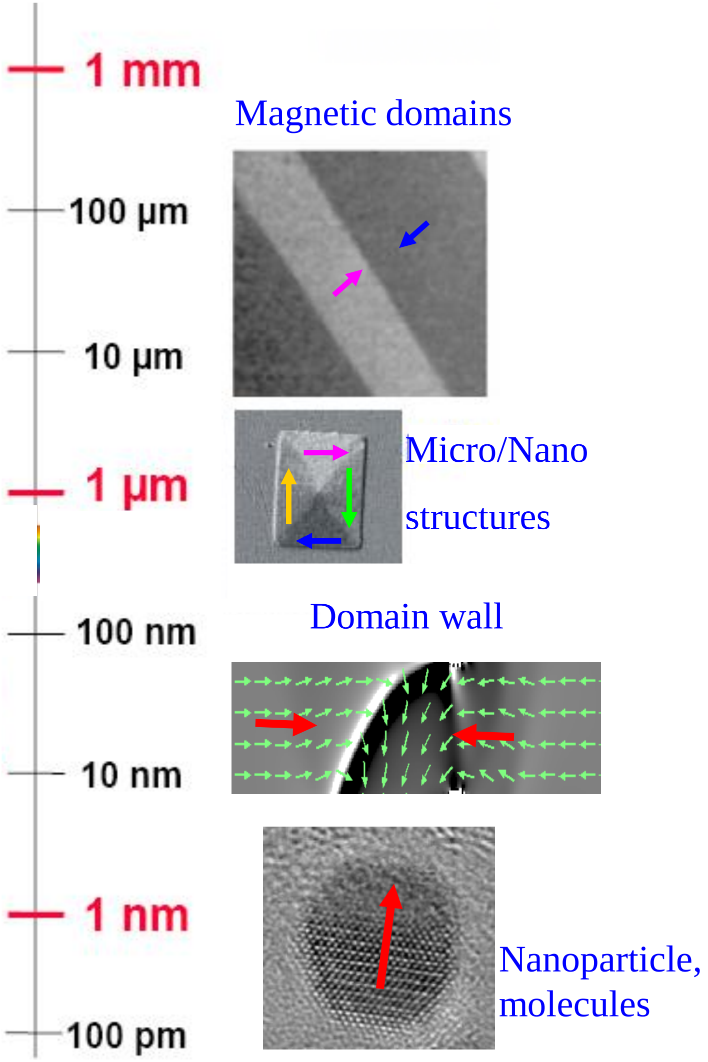
Magnetic configurations



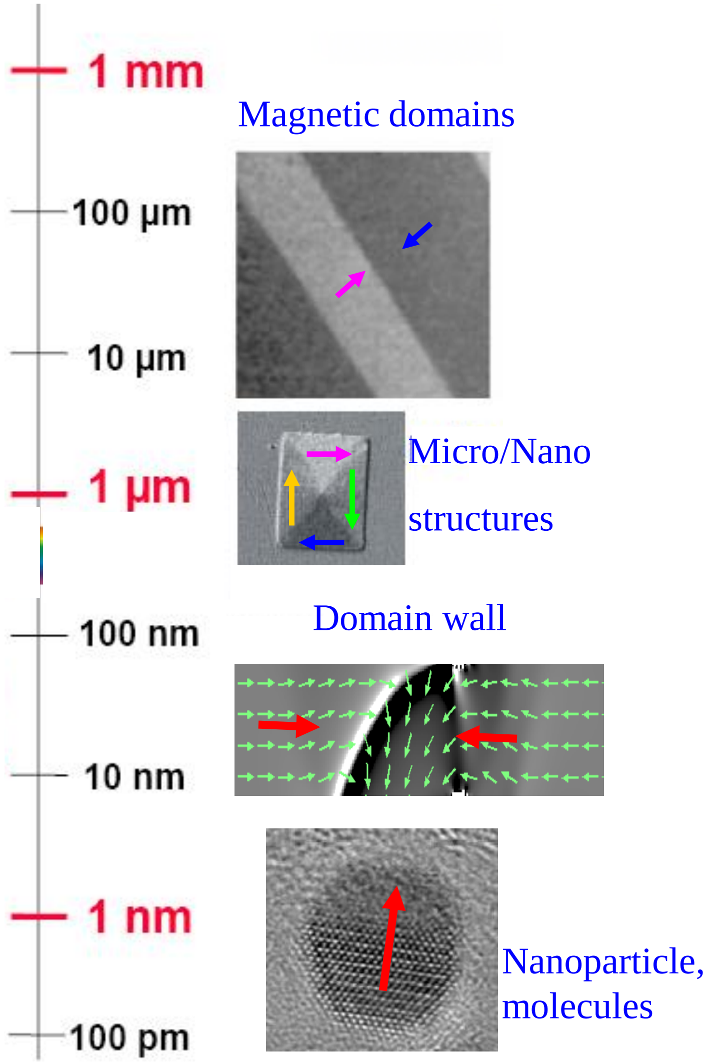




Spatial scale



Spatial scale



Magneto-optical microscopy (MO)

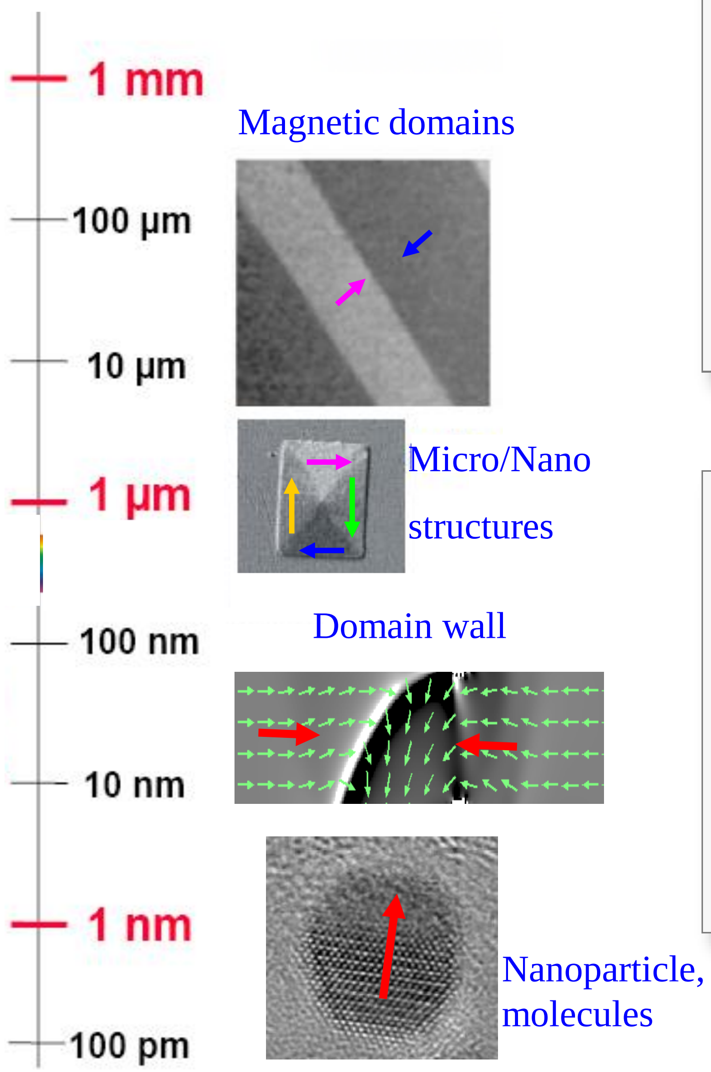
Scanning electron microscopy (SEMPA)

Transmission electron microscopy (TEM)

X-Ray microscopy

Magnetic force microscopy (MFM)

Spatial scale



What is measured?

- Magnetization, induction, stray field?
- Elemental resolution
- Direct or indirect?
- Quantitative or not?

Environmental conditions

- Temperature
- Field: magnetic field, electric
- Electric current, light etc.
- Strain
- Additional measuring techniques

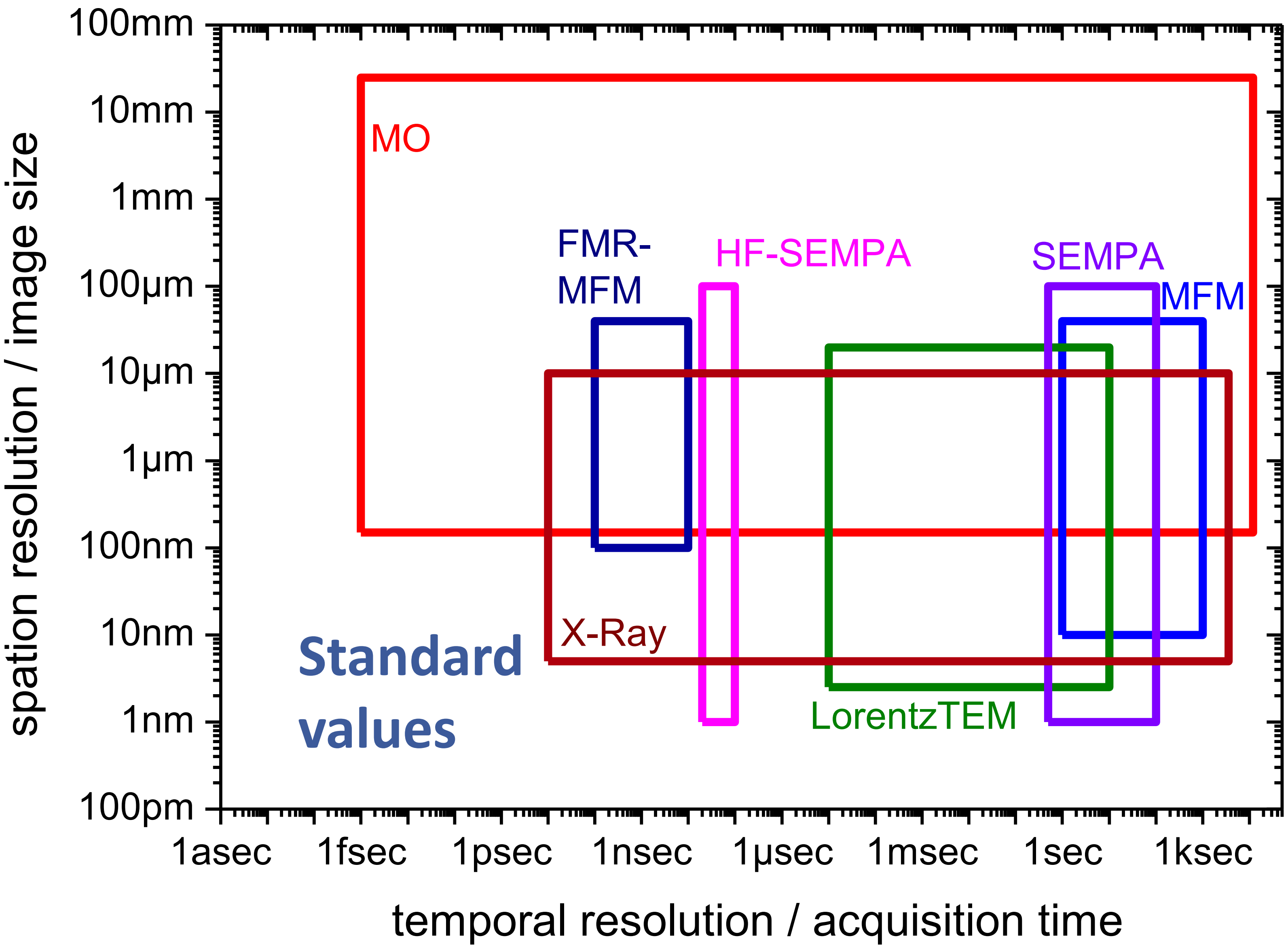
Which specifications?

- Magnetization: 1D, 2D, 3D
- Depth resolution: surface or volume?
- Lateral resolution
- Sensitivity
- Time/Spectral resolution

Versatility

- Sample preparation needed
- Time per one measurement
- In situ / ex situ
- Large-scale or in-lab?
- Expensive or cheap?

O. Fruchart, ESM 2017



Magneto-optical microscopy (MO)

Scanning electron microscopy (SEMPA)

Transmission electron microscopy (TEM)

X-Ray microscopy

Magnetic force microscopy (MFM)

	Bitter pattern	MFM	SEM-I Secondary	TEM Fresnel and Foucault	TEM DPC	TEM Holography	SEM-II Back-scattered	SEMPA	SPLEEM	MOKE (Kerr microscopy)	XPEEM	STXM[a]
Contrast mechanism	∇B_{ext}	∇B_{ext}	∇B_{ext}	B	B	B, Φ_B	B	M	M	M	M	M
Evaluation of the magnetization, M(r)	Indirect	Indirect	Q	Indirect	Q	Q	Q	Q	Q	Q	Q	Q
Spatial resolution (nm) $\frac{\text{Typical}}{\text{Limit}}$	$\frac{300}{80}$	$\frac{60}{20}$	$\frac{1000}{800}$	$\frac{50}{\sim 10}$	$\frac{10}{2}$	$\frac{20}{5}$	$\frac{2000}{1000}$	$\frac{150}{20}$	$\frac{40}{20}$	$\frac{800}{250}$	$\frac{300}{50}$	$\frac{30}{15}$
Depth of information (nm)	500–1000	20–500	10–50 nm	Thickness integrated <150 nm	Thickness integrated <100 nm	Thickness integrated <100 nm	10,000	1–2	<1	<20 (metals)	<5 nm	Thickness integrated <100 nm
Time for image acquisition	30 msec	5–20 mins	10–60 sec	50 msec–60 sec	5–60 secs	50 msec–10 sec	10–60 sec	1–100 min	~1sec	1 msec–5 sec	~1sec	~1sec
Limits on applied magnetic fields	None	<500 kA/m	Not advised	~100–500 kA/m	~100–500 kA/m	50 kA/m	Not advised	Not advised	Not advised	None	Not advised	None
Imaging conditions	None	In air	HV	HV	HV	HV	HV	UHV	UHV	In air	UHV	None
Max thickness	None	None	None	<150 nm	<100 nm	<100 nm	None	None	None	None		60–100 nm
Sample smoothness	R	R	NR	Preferred	Preferred	Preferred	NR	NR	R	R	NR	NR
Sample clean surface	NR	NR		Preferred	Preferred	Preferred	NR	R	R	NR	Preferred	NR

K. Krishnan, Fundamentals and applications of magnetic materials, OXFORD University Press (2016)

Type of measurements

Photons detection

- **Laser**
  - Kerr
  - Faraday
- **X rays**
  - MTXM
  - STXM
  - X-holography

Electrons detection

- **X rays**
  - X-PEEM
- **Electron in Electron out**
  - TEM Lorentz
  - SEMPA
  - SP-LEEM
  - e-holography

Scanning local probes

- MFM
- SNOM
- MRFM
- SP-STM
- NV microscopy
- SHPM

NV = NV center of diamond probe
MFM = magnetic force microscopy
MRFM = magnetoc resonance force microscopy
MTXM = magnetic transmission X-ray microscopy
SEMPA = scanning electron microscopy with polarization analysis
SNOM = scanning near field optical microscopy

SP-LEEM = spin polarized low energy electron microscopy

SHPM = scanning all probe microscopy

Outlines

Magneto-optical microscopy (MO)

Scanning electron microscopy (SEMPA)

Transmission electron microscopy (TEM)

X-Ray microscopy

Magnetic force microscopy (MFM)

Outlines

Magneto-optical microscopy (MO)

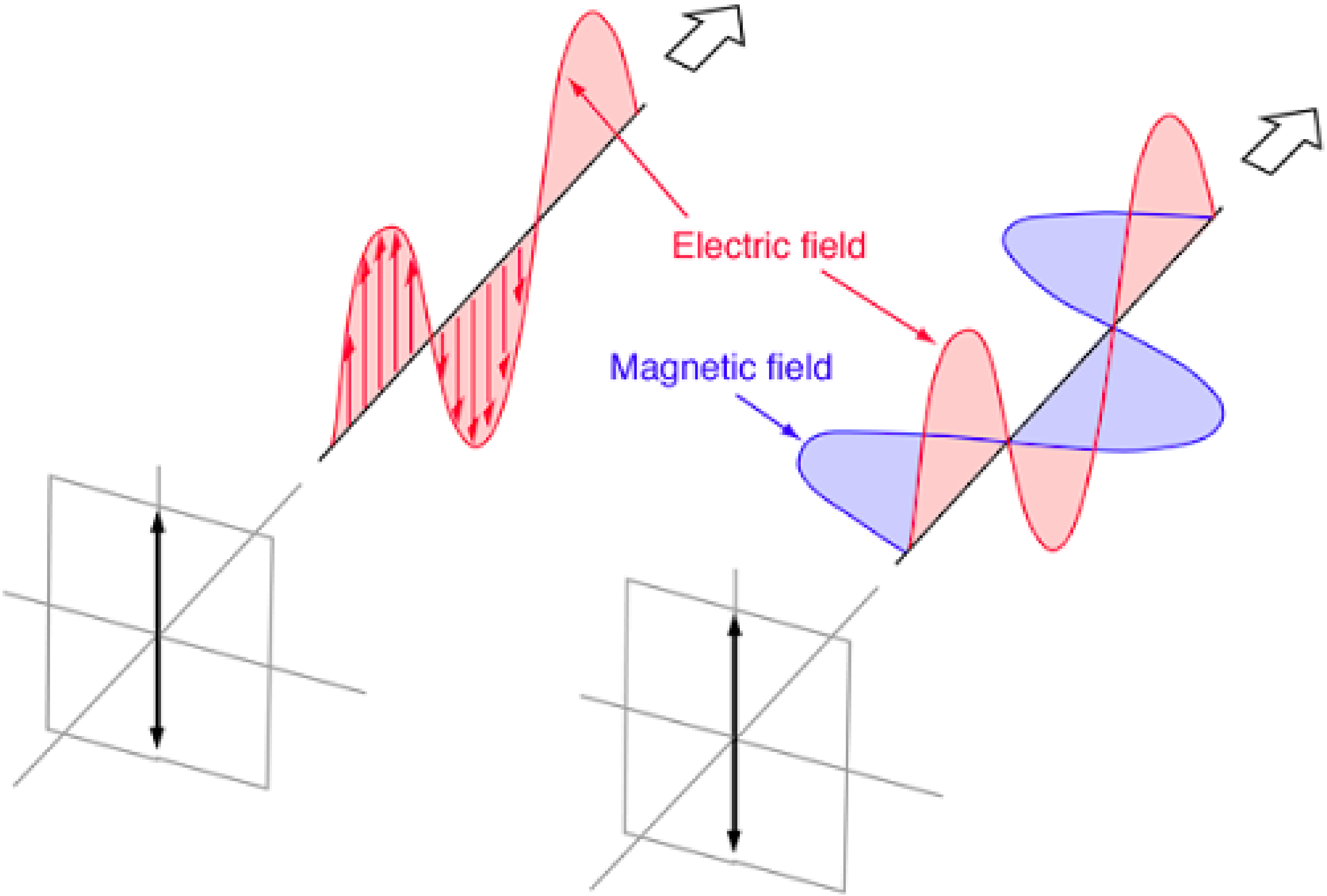
Scanning electron microscopy (SEMPA)

Transmission electron microscopy (TEM)

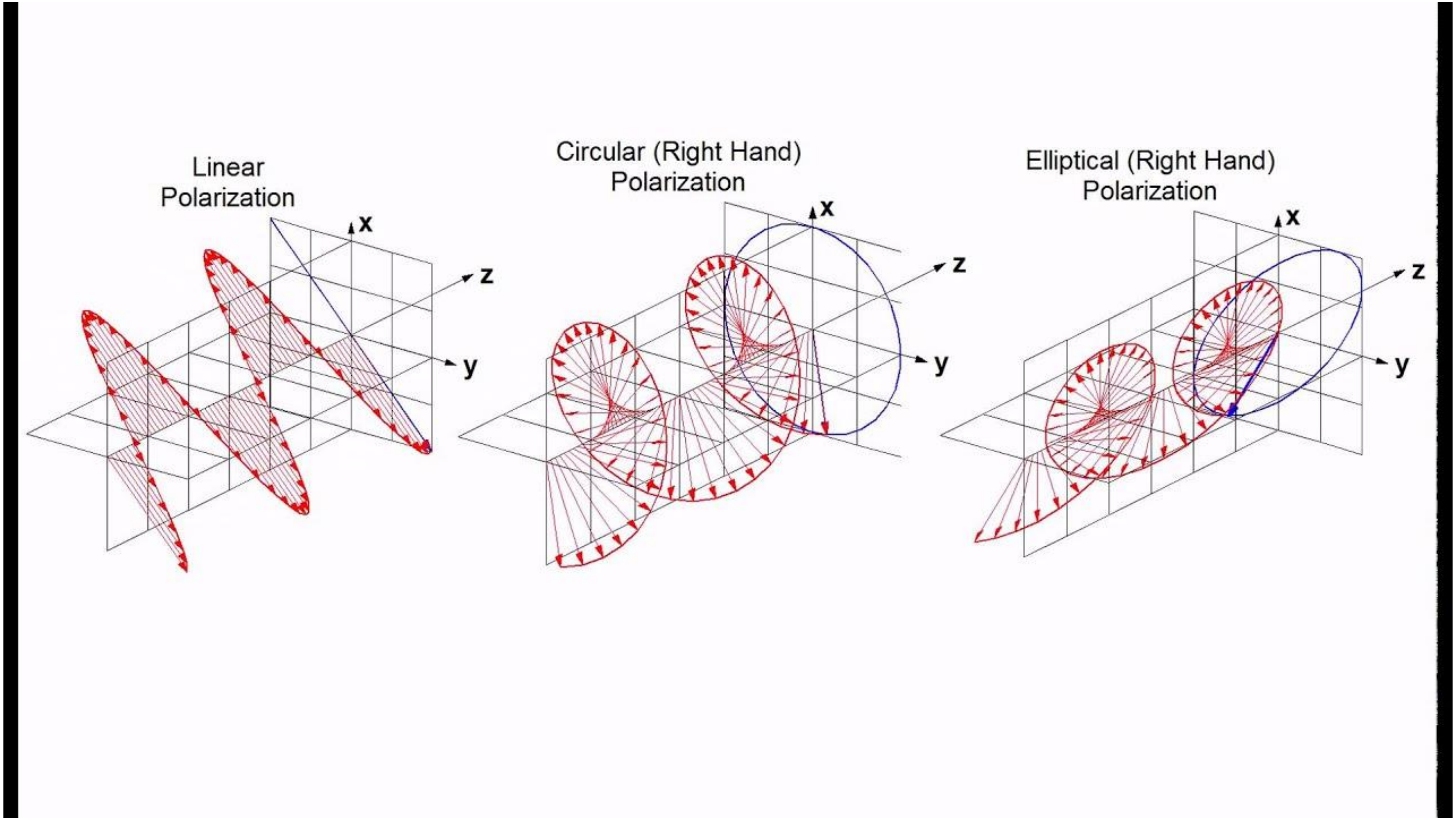
X-Ray microscopy

Magnetic force microscopy (MFM)

Linearly polarized light



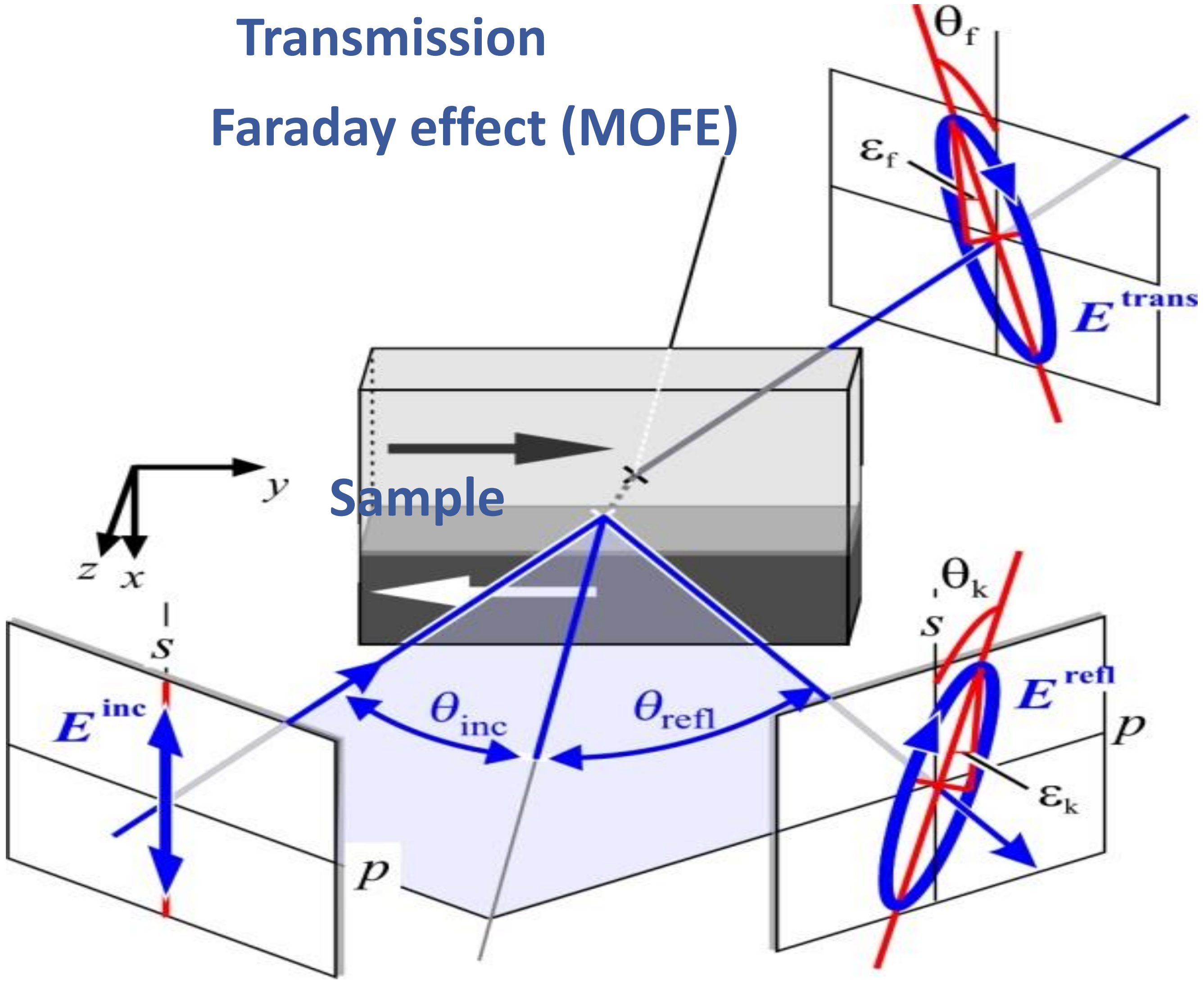
polarized light



Magneto-optic effect

Transmission

Faraday effect (MOFE)



Reflection

Kerr effect (MOKE)

M. Faraday (1846), J. Kerr (1877)

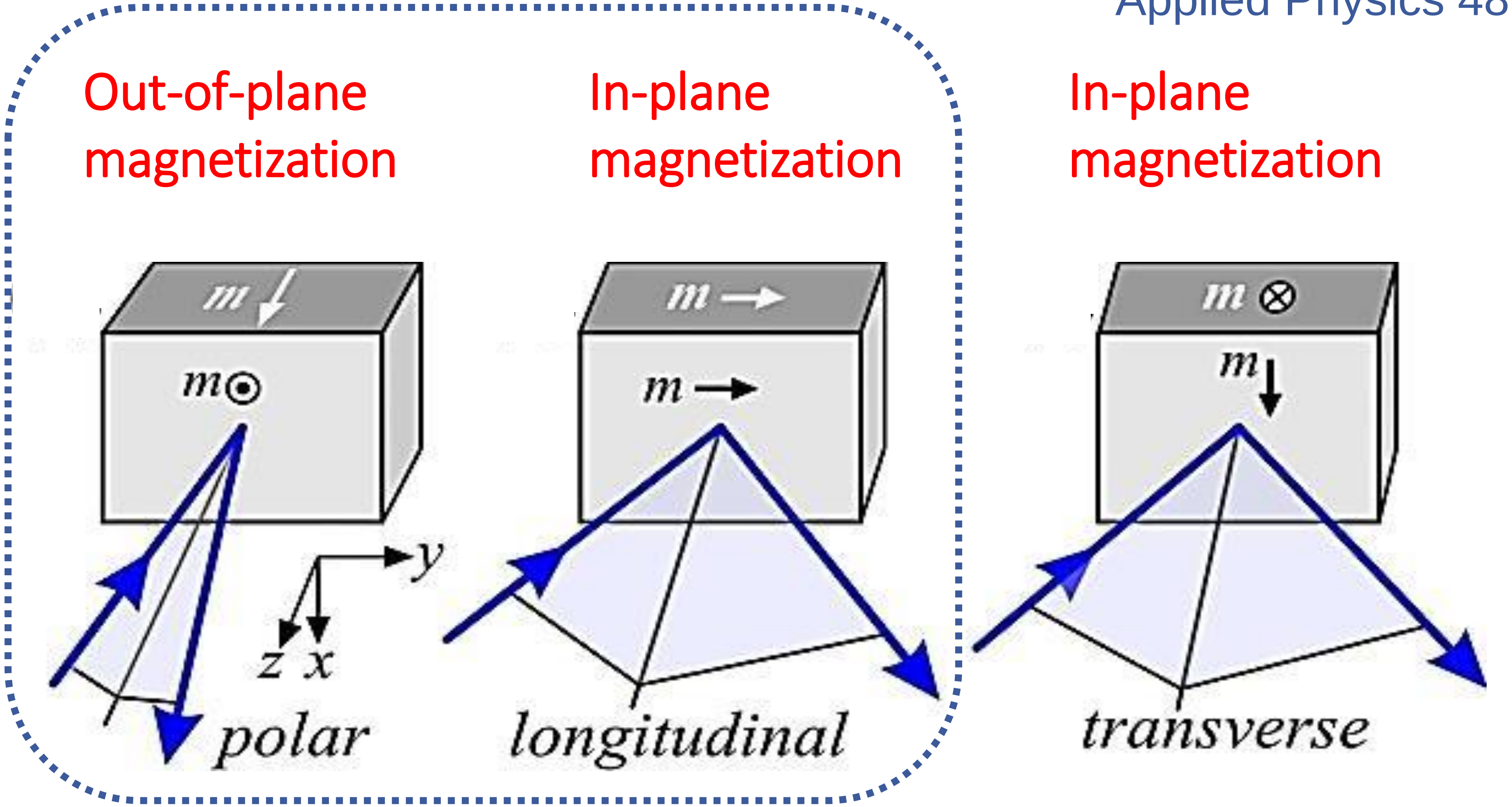
Longitudinal Faraday and Kerr effect under an angle of incidence ϑ_{inc} relative to the surface normal. The case of s-polarization is sketched. By the MO interaction with the magnetic medium the linearly polarized incoming light (E^{inc}) is transformed to an elliptically polarized light E^{trans} and E^{refl}. The resulting Faraday rotation ϑ_f and ellipticity e_f, respectively, Kerr rotation ϑ_k and ellipticity e_k are shown. ϑ_{refl} is the angle of reflection of light.

J.McCord, Journal of Physics D: Applied Physics 48, 333001 (2015)

Magneto-optic effect

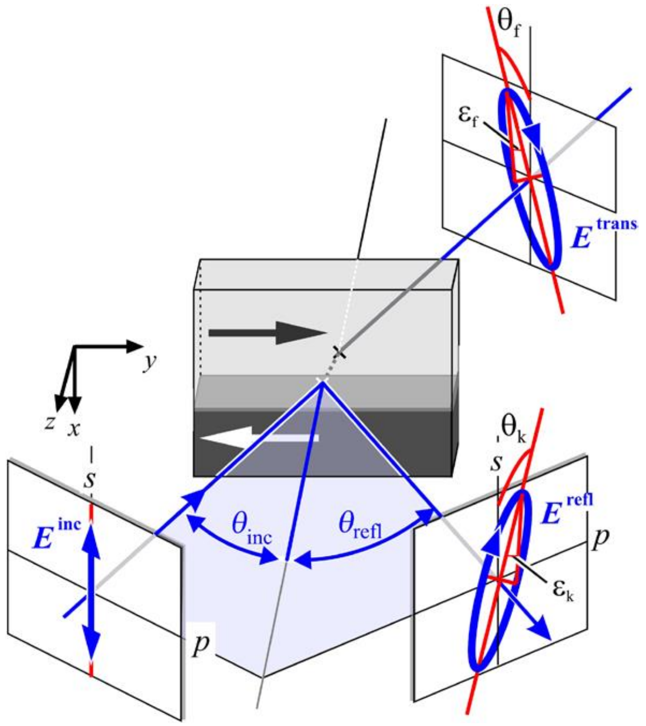
The effects might come together!

J.McCord, Journal of Physics D: Applied Physics 48, 333001 (2015)



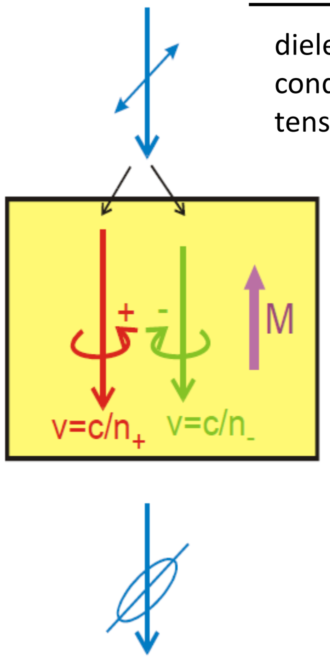
The three basic configurations of the (a) polar, (b) longitudinal, and (c) transverse magneto-optical Kerr effect. The unit vector of magnetization ***m*** is lying along the corresponding sensitivity axes (as indicated).

Magneto-optic effect



M. Faraday (1846), J. Kerr (1877)

Classical description :



dielectric conductivity tensor

$$\overleftrightarrow{\sigma} = \begin{bmatrix} \sigma_0 & -\sigma_1 m_z & 0 \\ \sigma_1 m_z & \sigma_0 & 0 \\ 0 & 0 & \sigma_0 \end{bmatrix}$$

diagonalization

$$\sigma_+ = \sigma_0 - i\sigma_1$$
$$\sigma_- = \sigma_0 + i\sigma_1$$
$$\sigma_z = \sigma_0$$

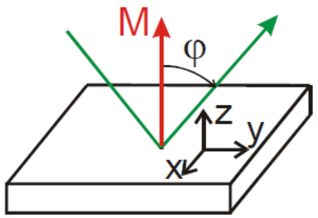
$$n_\pm(\omega) = \sqrt{1 + \frac{4\pi i}{\omega}\sigma_\pm(\omega)}$$

More generally : 3 useful configurations

$$\overleftrightarrow{\sigma}(\vec{M}) = \begin{bmatrix} \sigma_0 & -\sigma_1 m_z & \sigma_1 m_y \\ \sigma_1 m_z & \sigma_0 & -\sigma_1 m_x \\ -\sigma_1 m_y & \sigma_1 m_x & \sigma_0 \end{bmatrix}$$

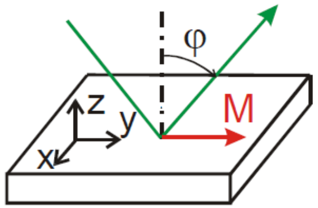
Polar Kerr effect (PMOKE)

M ⊥ sample surface



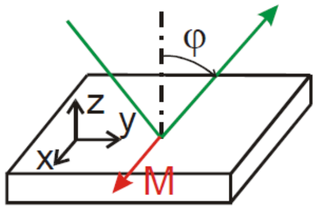
Longitudinal Kerr effect (LMOKE)

M || plane of incidence

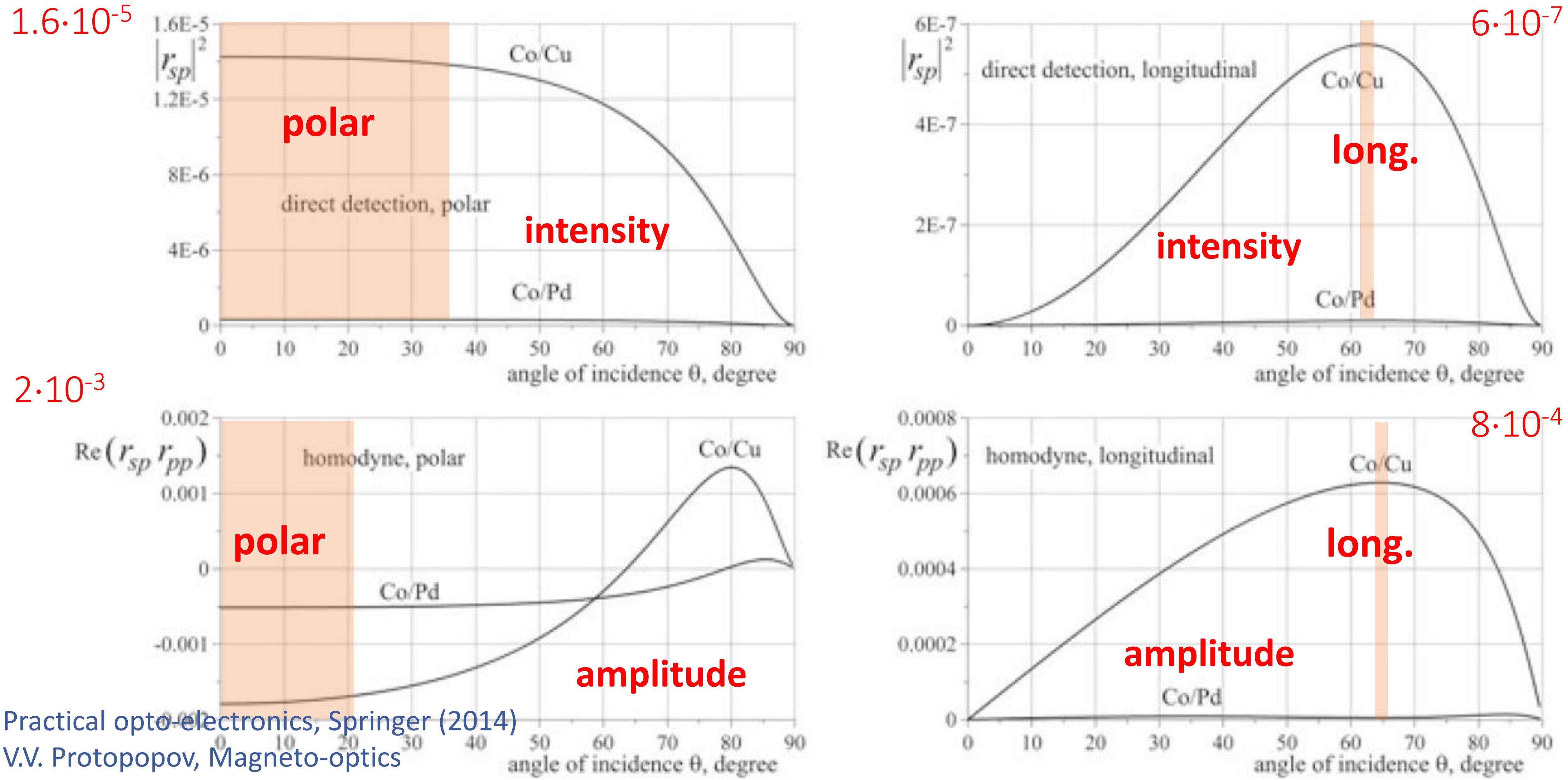


Transversal Kerr effect (TMOKE)

M ⊥ plane of incidence



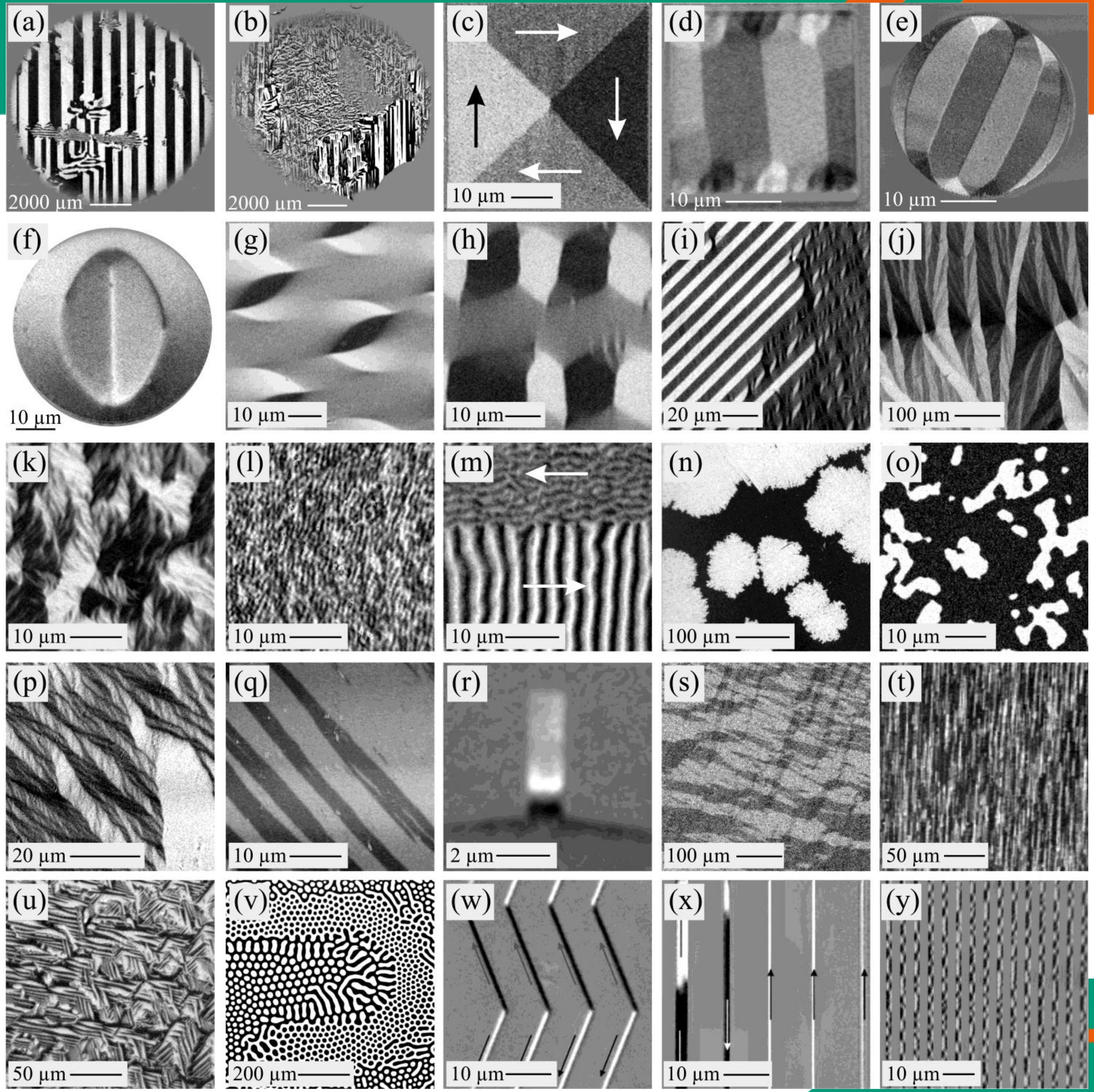
Magneto-optic effect



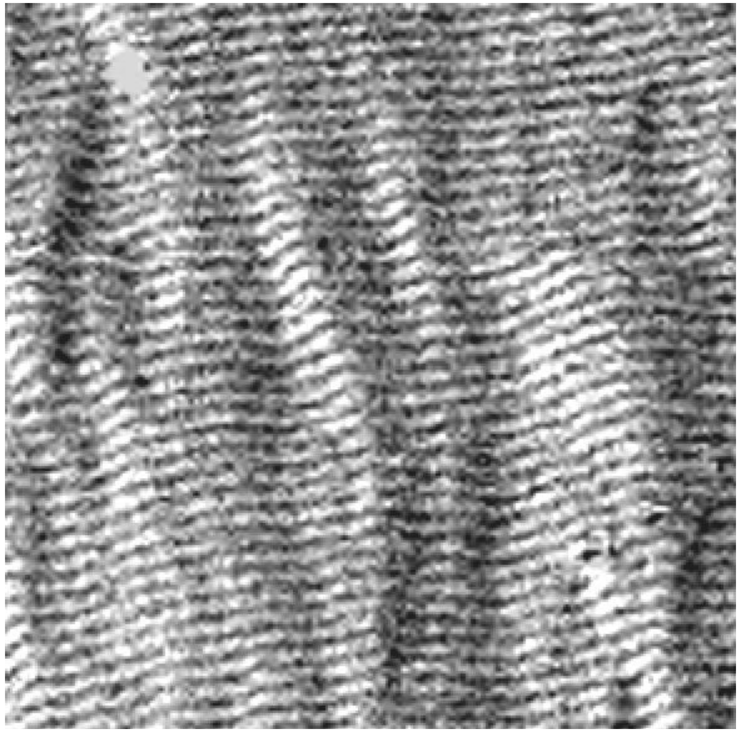
Practical opto-electronics, Springer (2014)
V.V. Protopopov, Magneto-optics

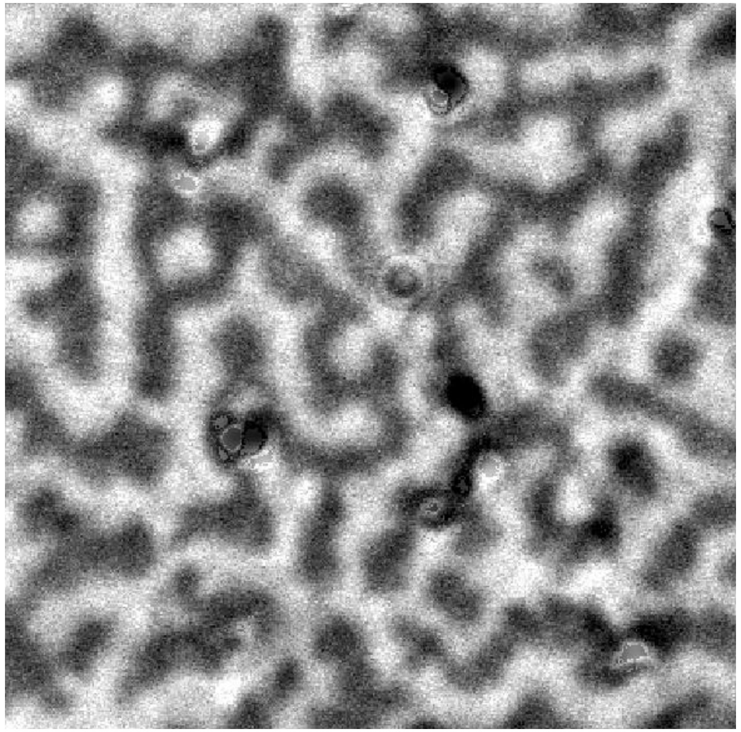
	MOKE (Kerr microscopy)
Contrast mechanism	**M**
Evaluation of the magnetization, **M(r)**	Q
Spatial resolution (nm) Typical / Limit	800 / 250
Depth of information (nm)	<20 (metals)
Time for image acquisition	1 msec–5 sec
Limits on applied magnetic fields	None
Imaging conditions	In air
Max thickness	None
Sample smoothness	R
Sample clean surface	NR

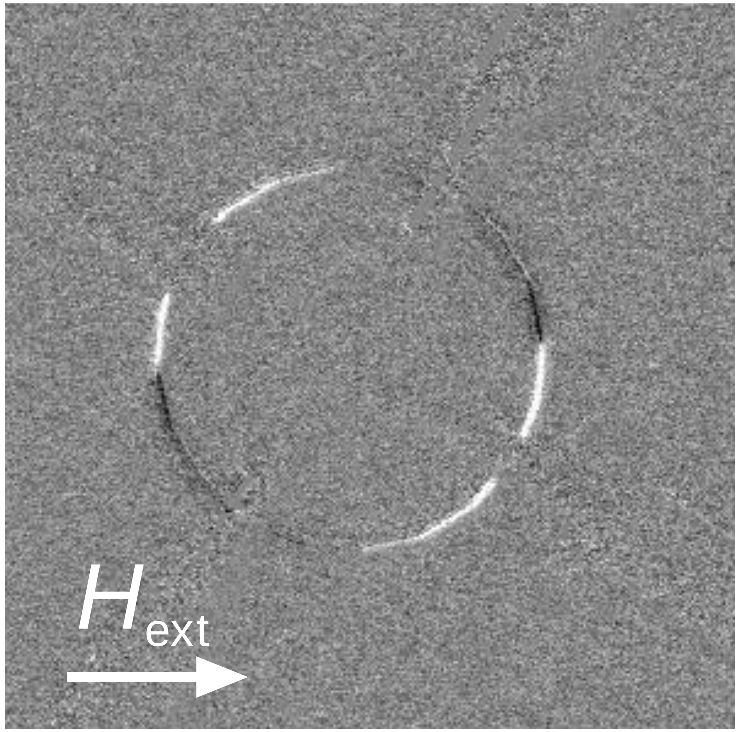
Topical Review
J. McCord,
J. Phys. D: Appl. Phys. 48, 333001 (2015)



Ultimate resolution







Stripe domains in $Ni_{81}Fe_{19}$

Domain width 250 nm

Interaction domains in $Nd_2Fe_{14}B$

Domain width 400 nm

(sample O. Gutfleisch, TU Darmstadt)

Magnetic domains in a angle sensor

Stripe width 300 nm

Localization accuracy 10 nm

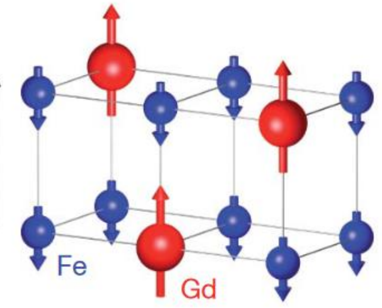
(sample R. Mattheis, IPHT Jena)

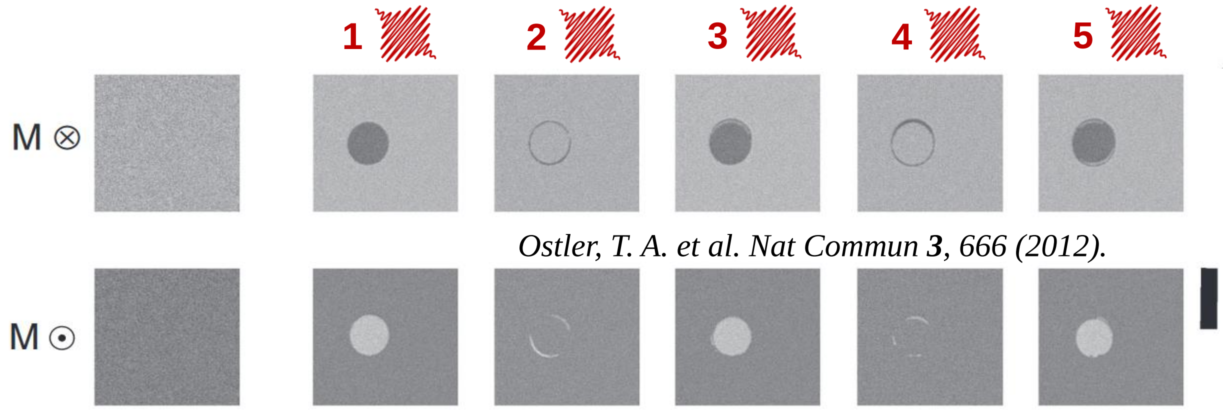
150 nm resolution

J. McCord, J. Phys. D: Appl. Phys. 48, 333001 (2015)

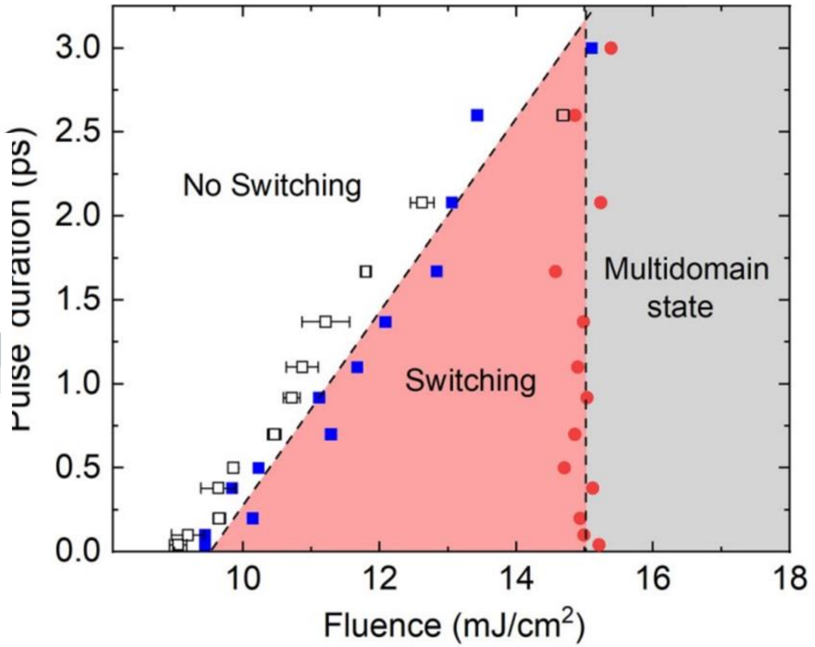
All Optical – Helicity Independent switching

Characteristics





Ostler, T. A. et al. Nat Commun ***3****, 666 (2012).*



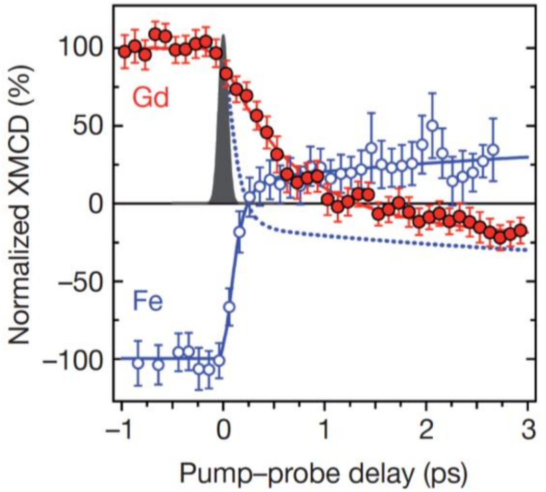
Single pulse & Fast

Characteristic State diagram

Specific materials

➡ Gd based Material

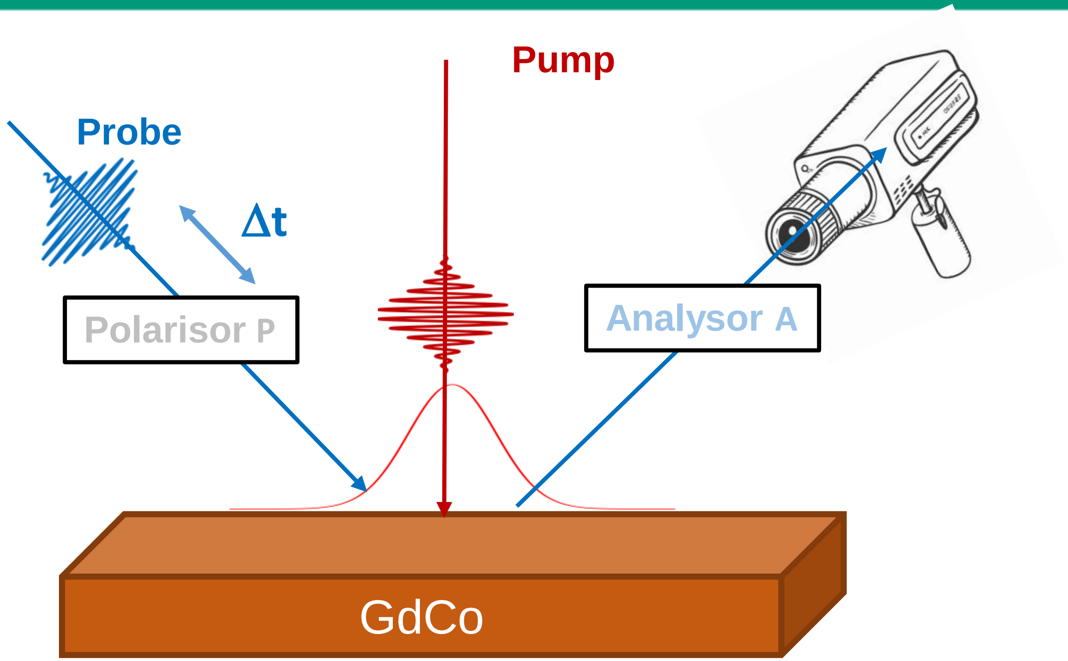
➡ MnRuGa



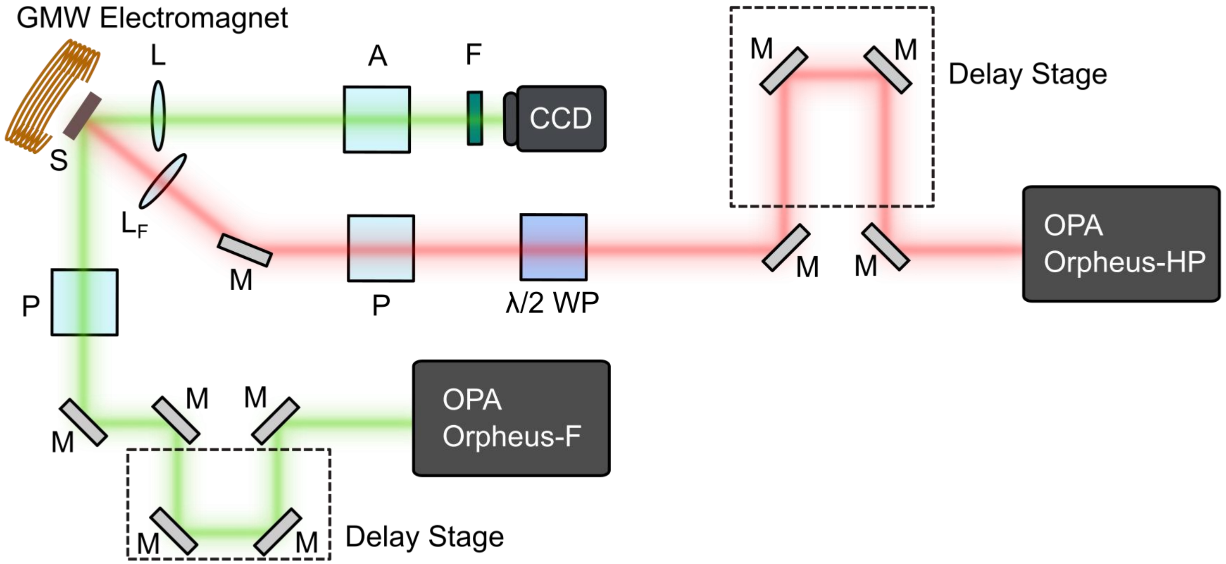
Wei, J. et al.
Phys Rev Applied 15, 054065 (2021).

Radu, I. et al. Nature ***472****, 205–208 (2011).*

Dynamic

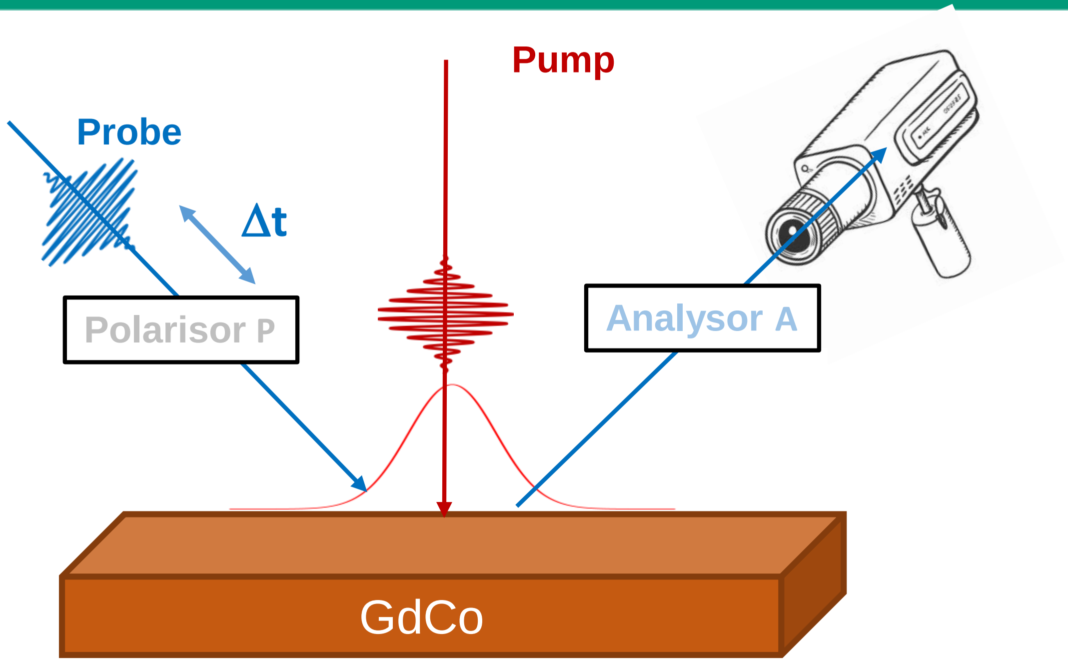


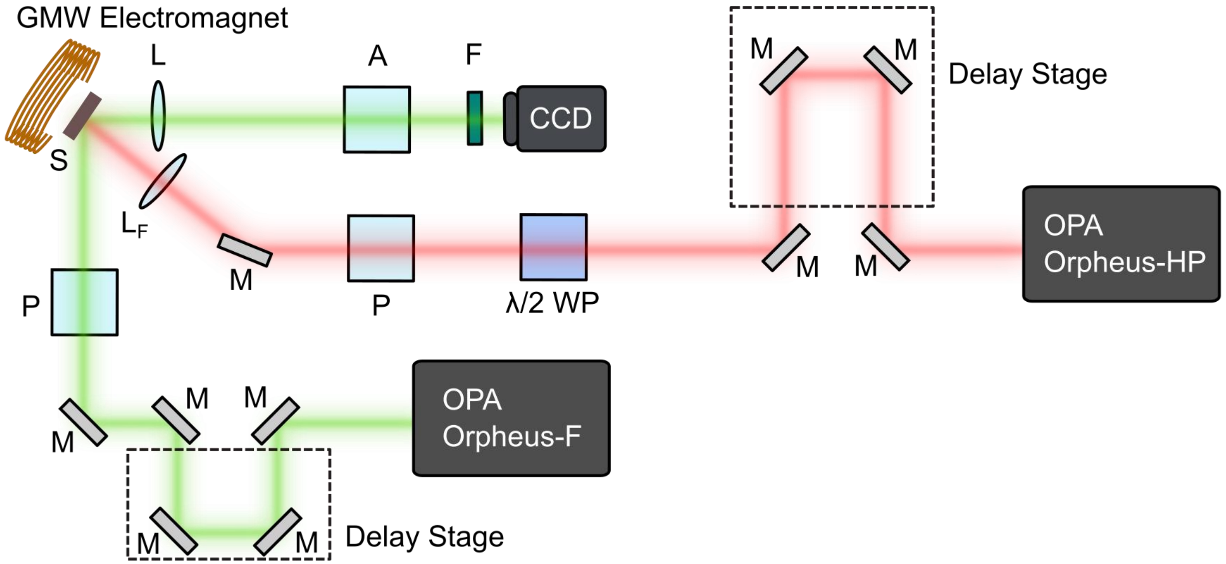
Pump
Probe
Δt
Polarisor P
Analysor A
GdCo

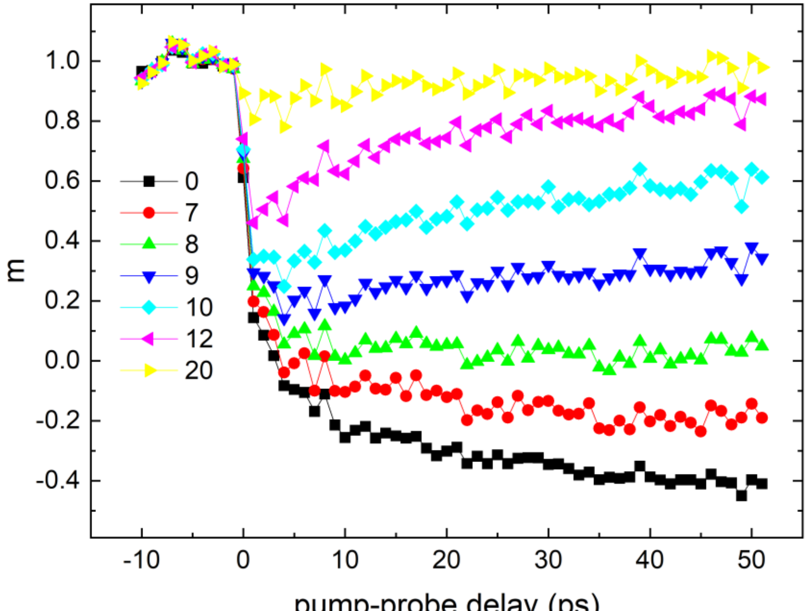


GMW Electromagnet
L
A
F
CCD
S
L_F
M
P
λ/2 WP
Delay Stage
OPA
Orpheus-HP
OPA
Orpheus-F

Dynamic


Pump
Probe
Δt
Polarisor P
Analysor A
GdCo


GMW Electromagnet
L
A
F
CCD
S
L_F
M
P
λ/2 WP
Delay Stage
OPA
Orpheus-HP
OPA
Orpheus-F


m
pump-probe delay (ps)
0
7
8
9
10
12
20

Magneto-optical imaging

- Flat and smooth surface required
- Imaging through substrate and covering layers (devices)
- Spatial resolution below 200 nm

- Magnetization can be observed directly
- Quantitative measurements possible
- Almost no influence on magnetization (but light induced heat)

- Straightforward sample manipulation (fields, temperature, stress)
- Surface sensitive (approx. 30 nm)

Outlines

Magneto-optical microscopy (MO)

Scanning electron microscopy (SEMPA)

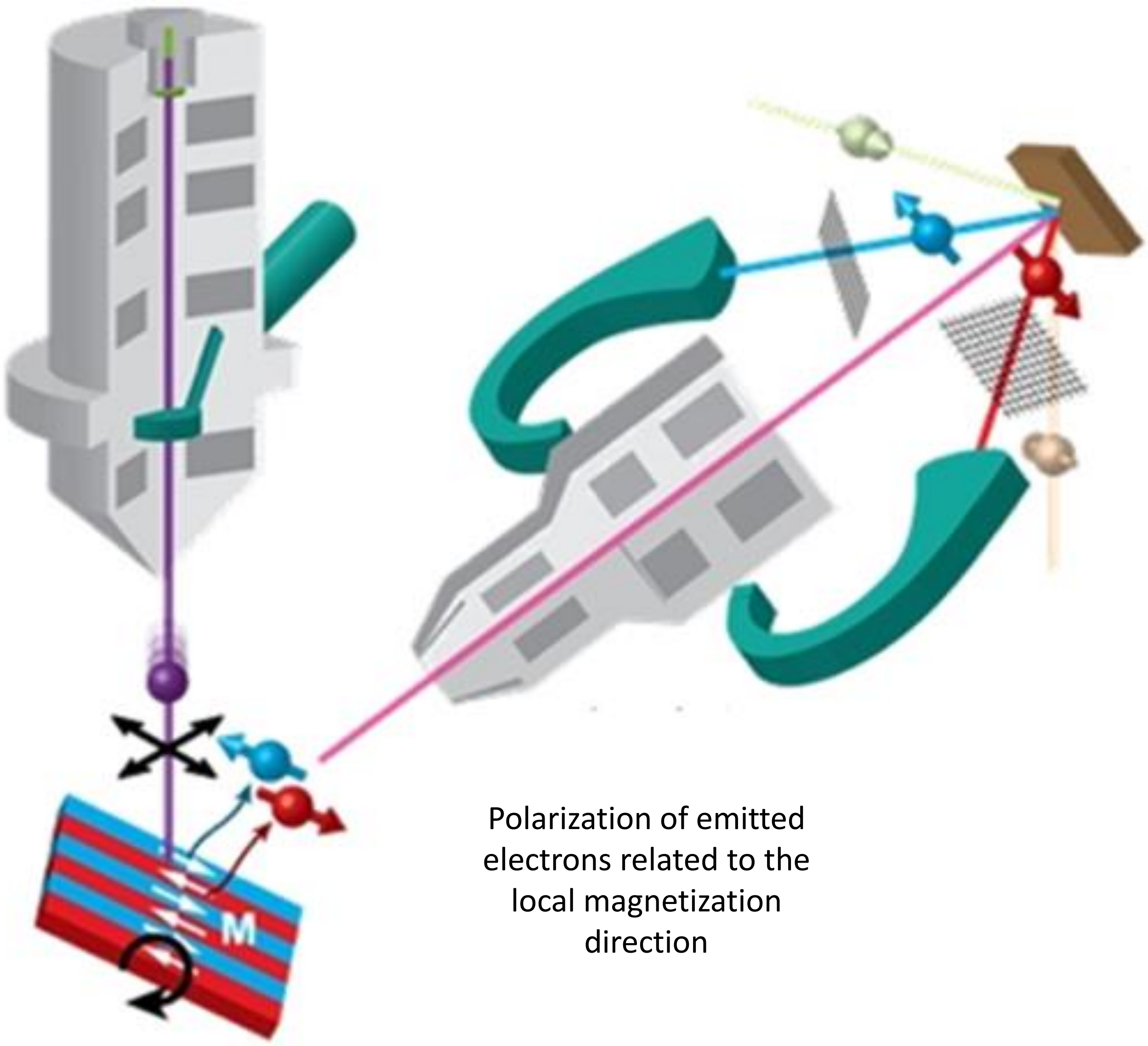
Transmission electron microscopy (TEM)

X-Ray microscopy

Magnetic force microscopy (MFM)

Scanning Electron Microscopy with Polarization Analysis

	SEMPA
Contrast mechanism	M
Evaluation of the magnetization, **M(r)**	Q
Spatial resolution (nm) Typical / Limit	150 / 20
Depth of information (nm)	1–2
Time for image acquisition	1–100 min
Limits on applied magnetic fields	Not advised
Imaging conditions	UHV
Max thickness	None
Sample smoothness	NR
Sample clean surface	R

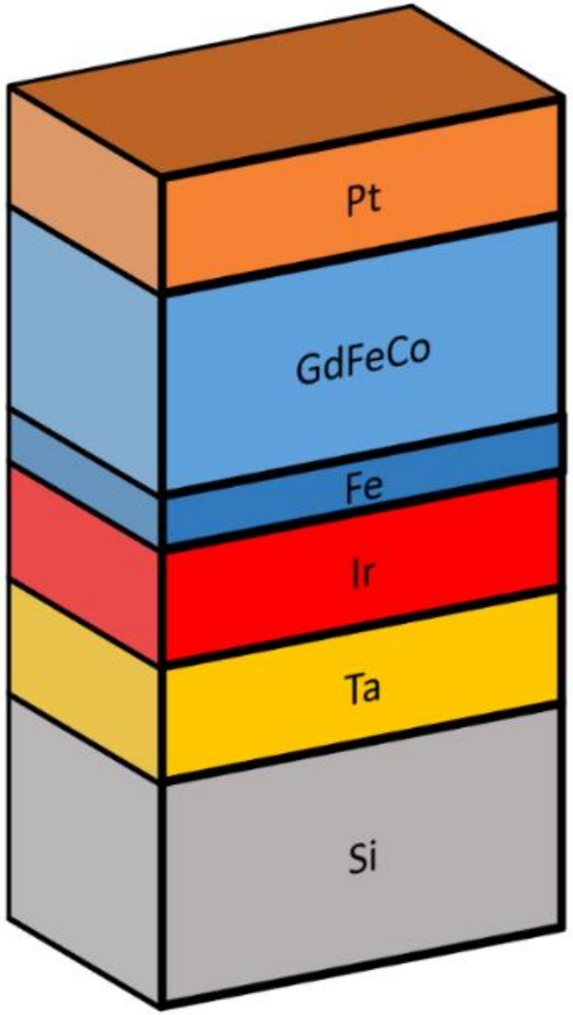


Scanning electron beam

Polarization of emitted electrons related to the local magnetization direction

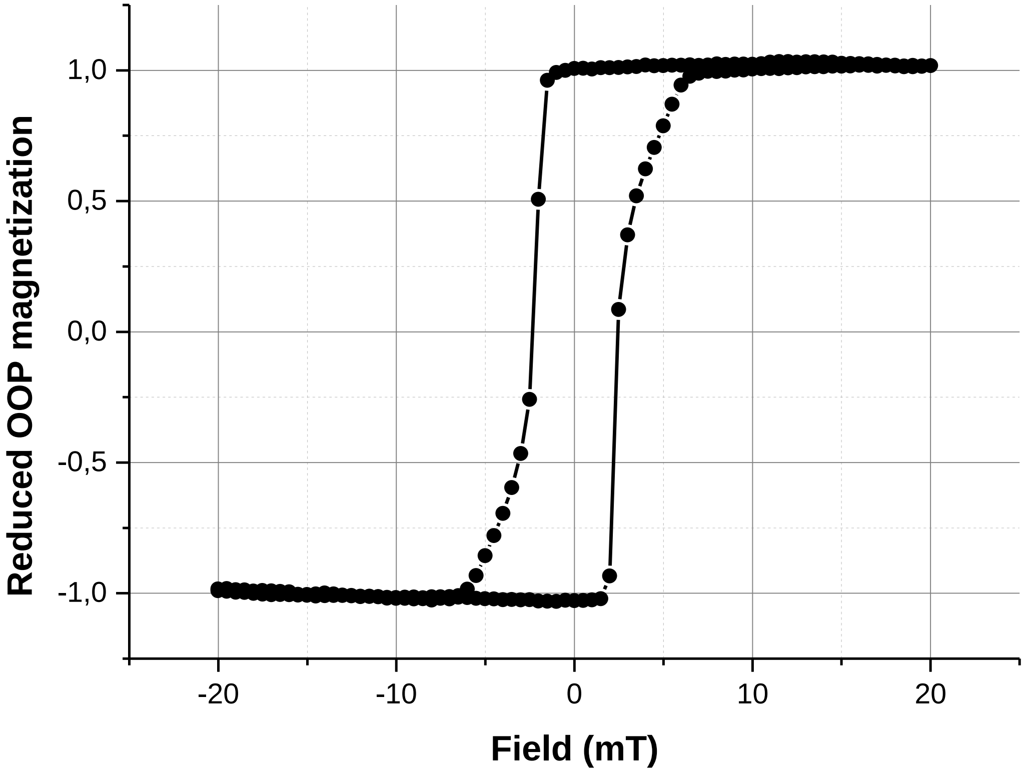
One exemple

- GdFeCo ferrimagnet
- DMI enhancement: Fe dusting layer for interfacial (Ir/Fe) and Pt capping layer
- Small Pt layer for surface sensitive imaging technique
- Si//Ta(5)/Ir(5)/Fe(0.3)/[$Gd_{26.1}Fe_{65.5}Co_{8.3}$](8)/Pt(1.5)



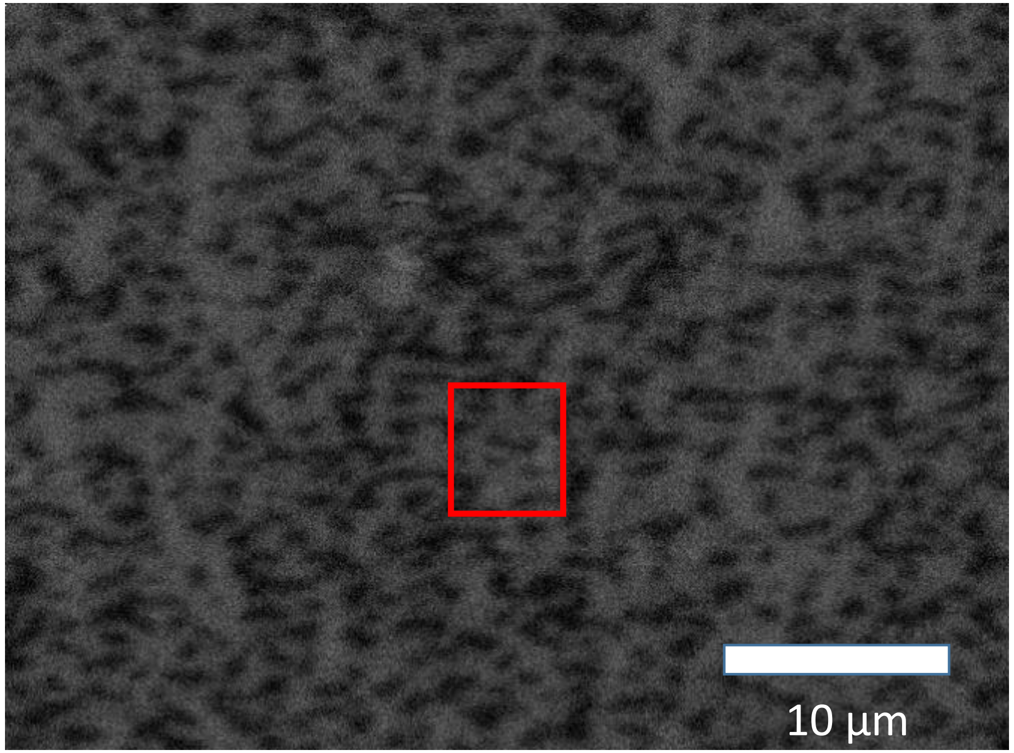
KLÄUI-LAB

- OOP anisotropy
- Nucleation using relaxation after IP saturation



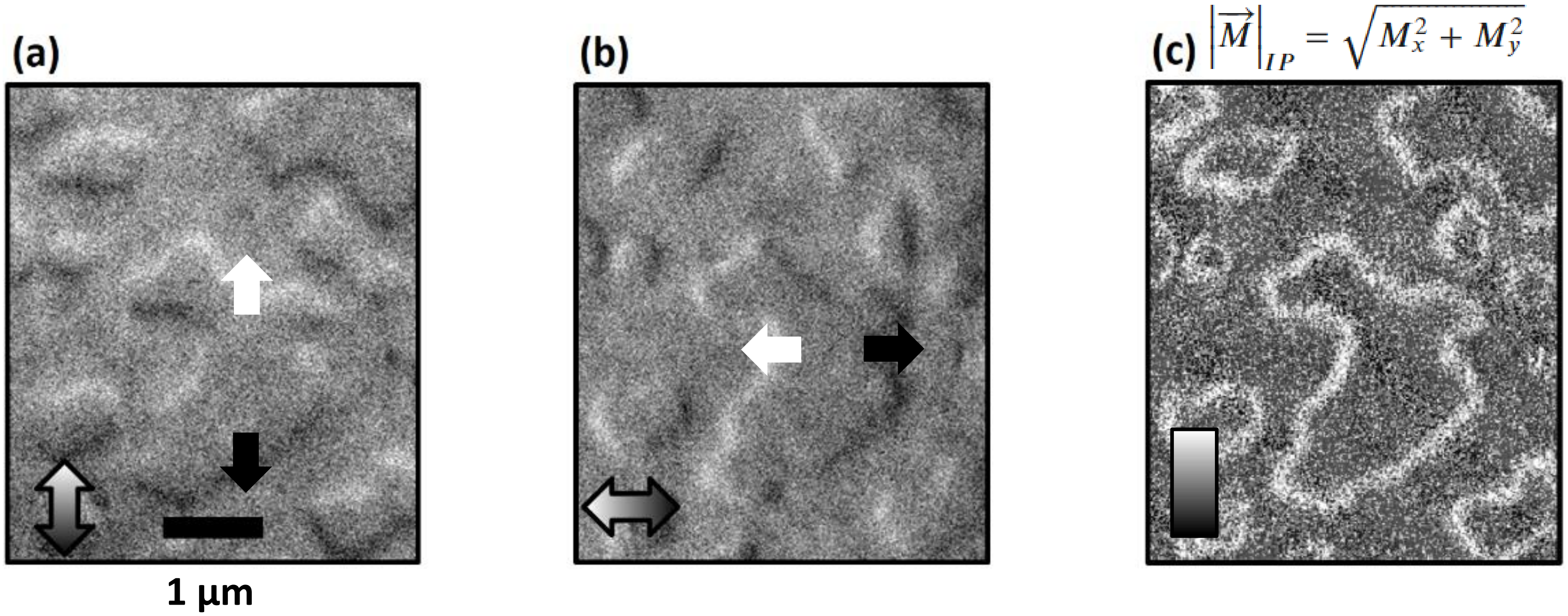
Spin textures observed at room

- OOP anisotropy
- Nucleation using relaxation after IP saturation
- µm-sized spin textures nucleated
- To determine the chirality, observation of the domain wall spin configuration is necessary



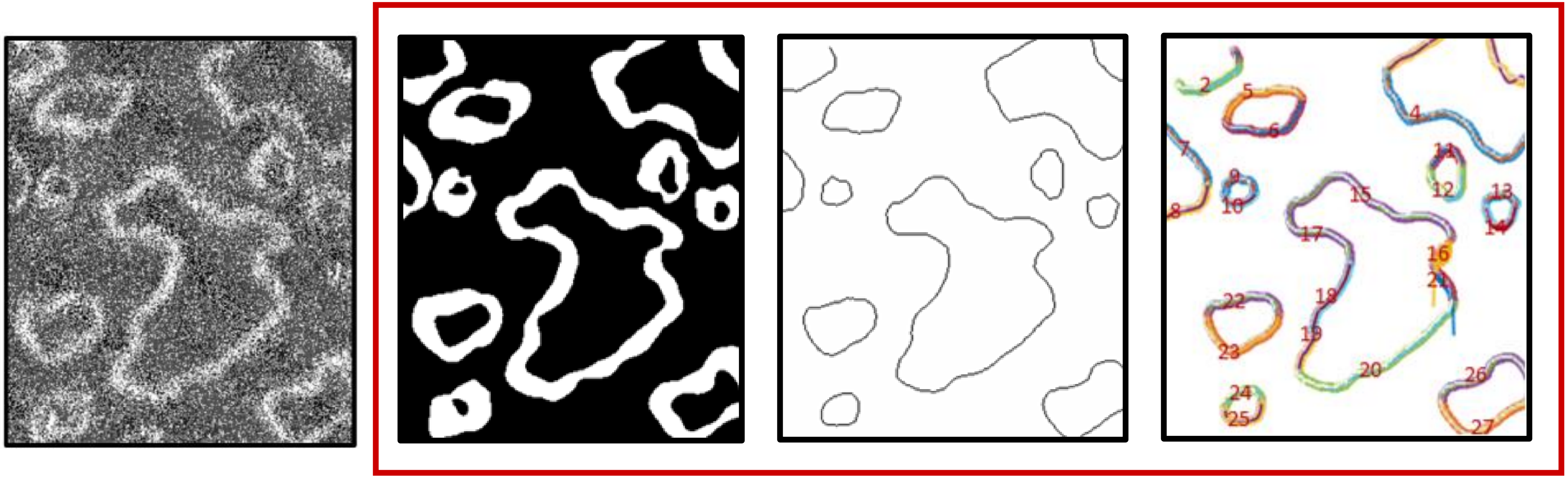
Kerr microscopy at RT, 0 mT

Determination of the domain wall width



- Observation of the $IP|_x$ and $IP|_y$ components of the magnetization
- Localization of the domain walls

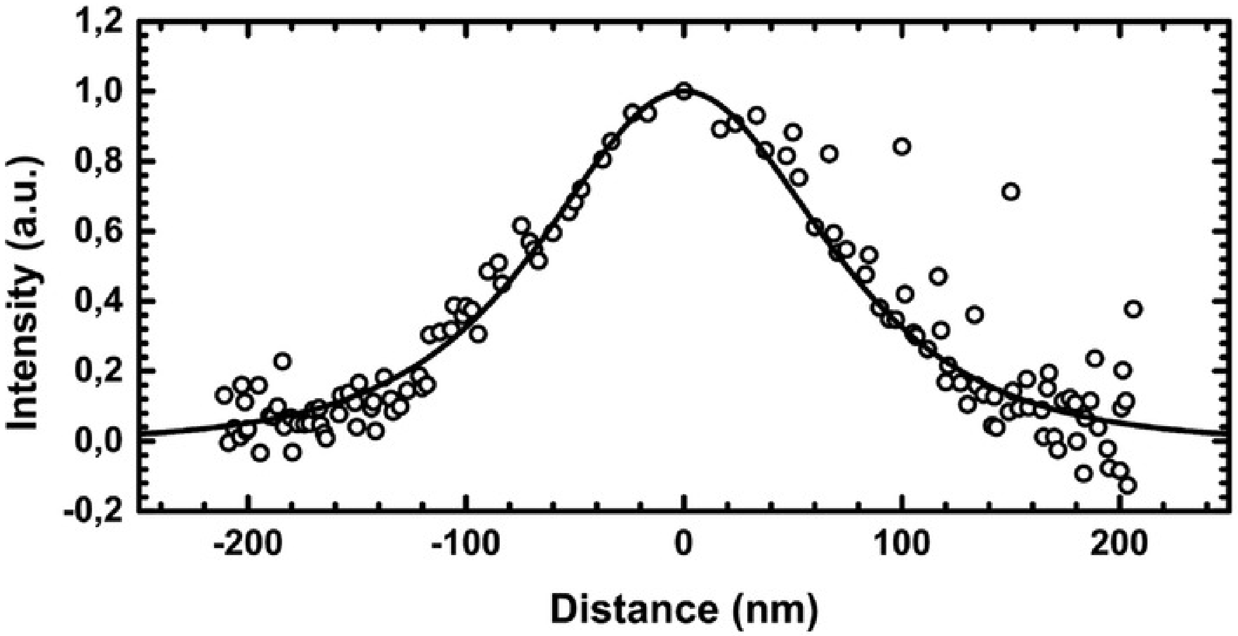
Determination of the domain wall width



Binarization, skeletonize, polynomial fitting

→ Determination of the local normal of the skeleton

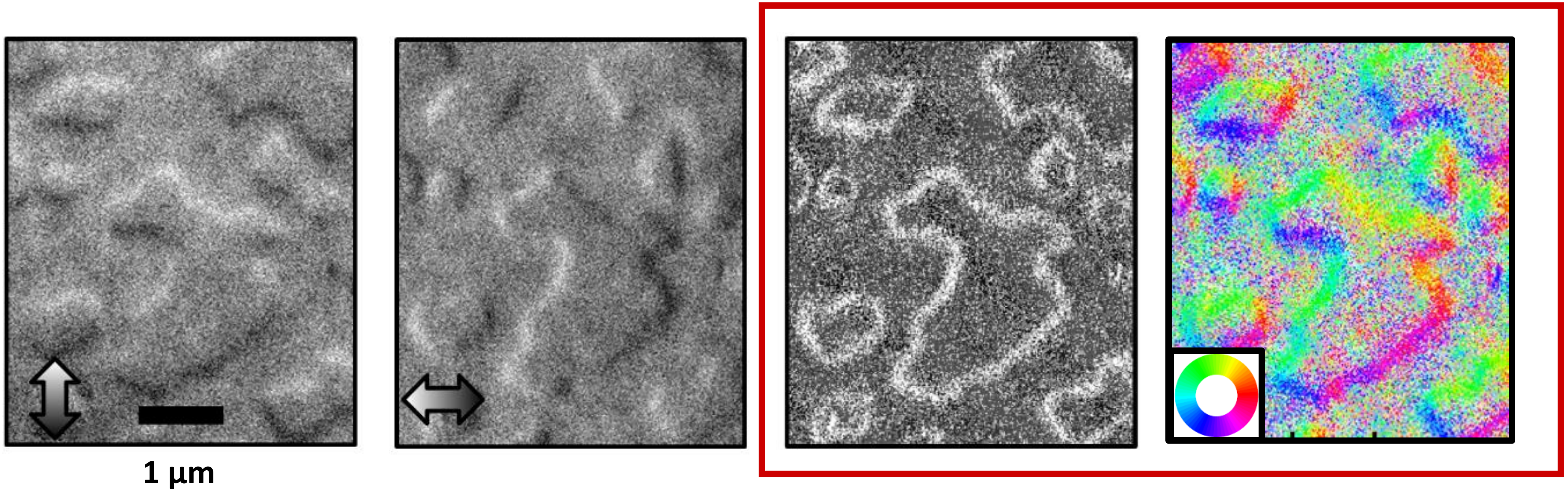
Determination of the domain wall width



Distribution of the domain wall profile: Intensity $\propto \cosh^{-1}(x/\Delta) \otimes e^{-(x^2/2\sigma^2)}$

$\rightarrow \delta_{real} = \pi\,\Delta = 175 \pm 5$ nm

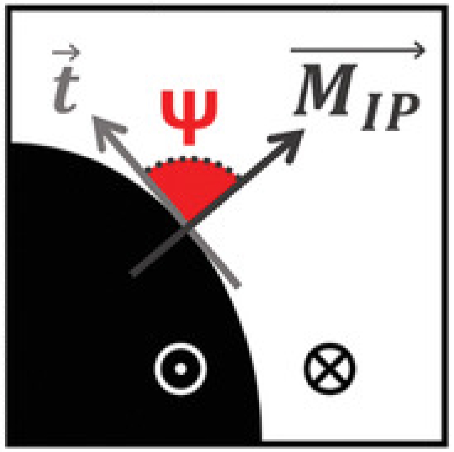
Determination of the chirality



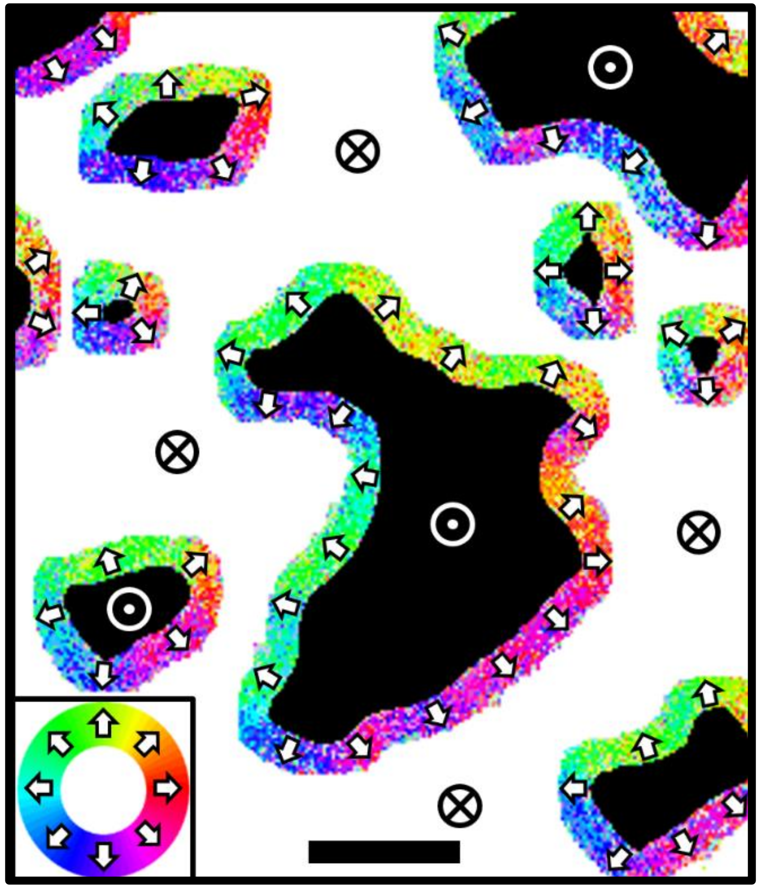
- ❖ We determined firstly the position of the DW
- ❖ We can also deduct the direction of the local magnetization

Determination of the chirality

- Qualitatively, Néel-type spin textures

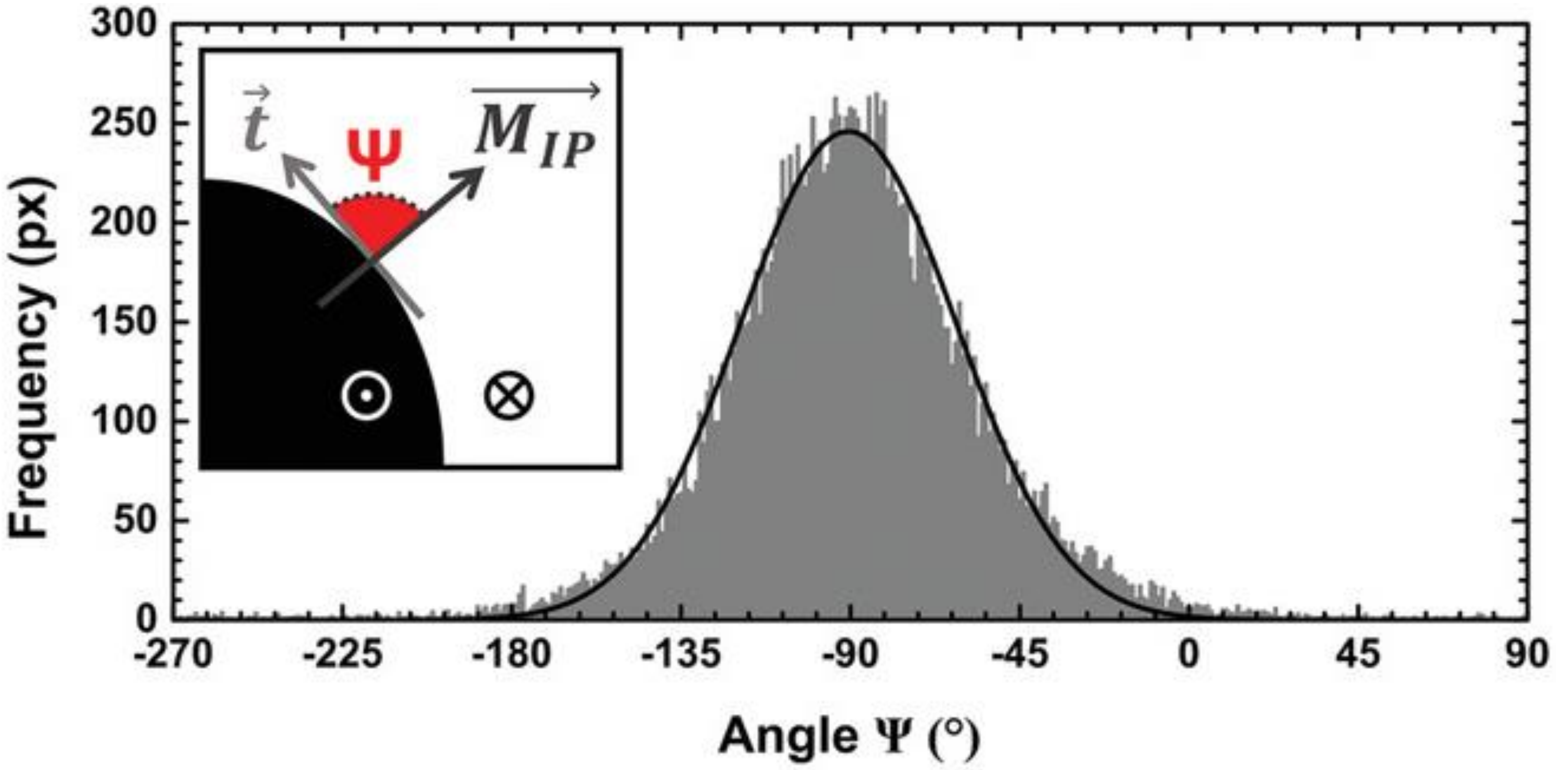


- Homochirality



1 μm

Determination of the chirality



→ Pure right-hand Néel-type chirality

Determination of the exchange stiffness A

$$\Delta = \Delta_0 - \frac{1}{\frac{2\pi(Q-1)}{d} + \frac{1}{\Delta_0 - \Delta_\infty}}$$

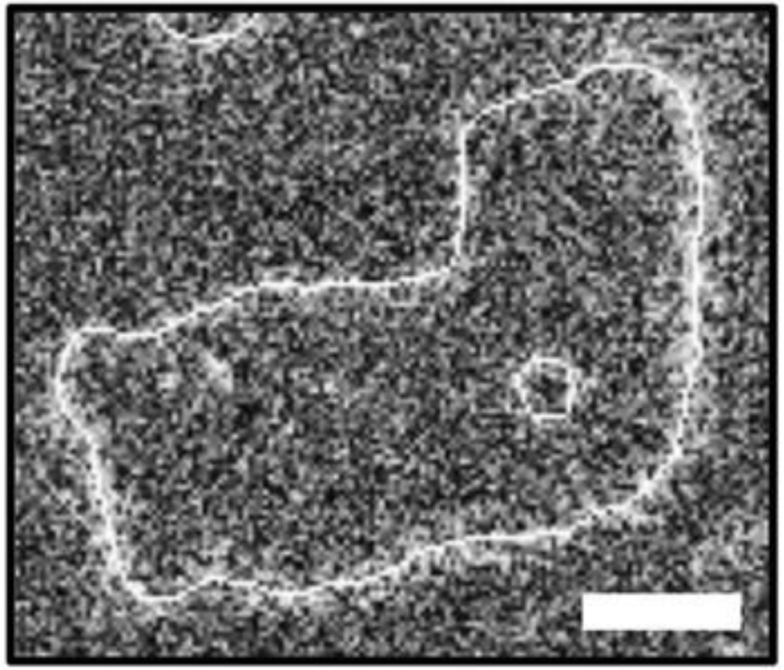
$$Q = \frac{2K_u}{\mu_0 M_s^2}, \quad \Delta_0 = \sqrt{\frac{A}{K_{eff}}}, \quad K_{eff} = K_u - \frac{\mu_0 M_s^2}{2}, \quad \Delta_\infty = \sqrt{\frac{A}{K_u + \frac{\mu_0 M_s^2}{2} sin^2(\Psi)}}$$

$$\Delta = f(A, K_u, M_s, d, \Psi)$$

- Δ, Ψ: measured using SEMPA imaging
- Thickness d known, measurement of the uniaxial anisotropy K_u and the saturation magnetization M_s using magnetometer.

→ The exchange stiffness is found numerically and equal to: $A = 8{,}0 \pm 0.5.\, pJ.\, m^{-1}$

Observation of a ferrimagnetic skyrmionium

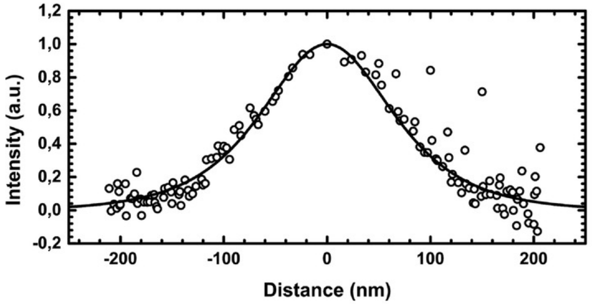


500 nm

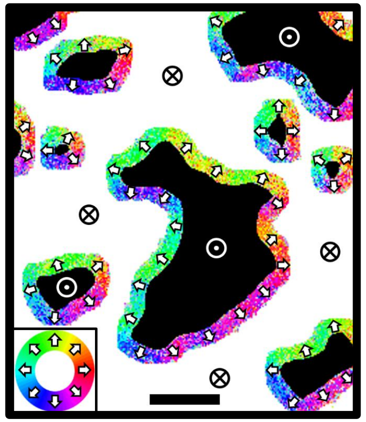
→ First observation of a ferrimagnetic skyrmionium in ferrimagnetic materials

Conclusion of our SEMPA study

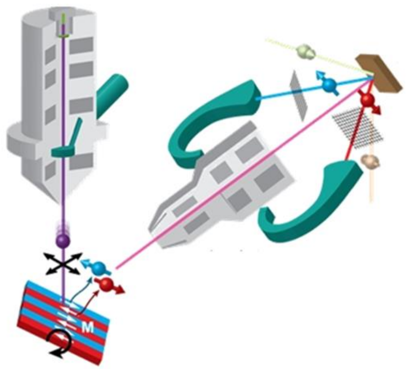
❖ Determination of the domain wall width



❖ Determination of the chiral character of the spin textures: pure right-hand Néel-type



❖ Extraction of the exchange stiffness could be possible with SEMPA



❖ Observation of a ferrimagnetic skyrmionium

B. Seng, et al Adv. Func. Mater 2102307 (2021).

Outlines

Magneto-optical microscopy (MO)

Scanning electron microscopy (SEMPA)

Transmission electron microscopy (TEM)

X-Ray microscopy

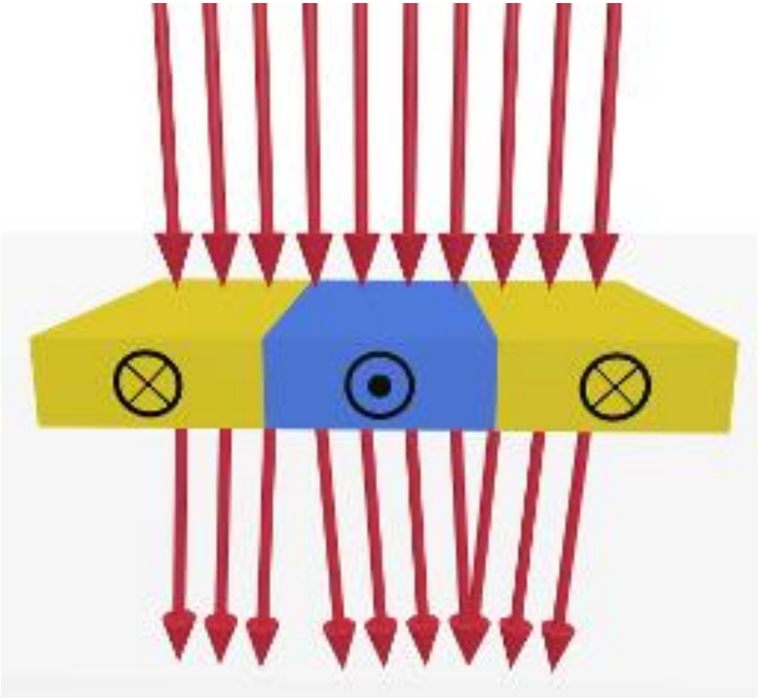
Magnetic force microscopy (MFM)

TEM Lorentz microscopy

	TEM Fresnel and Foucault	TEM DPC
Contrast mechanism	B	B
Evaluation of the magnetization, M(r)	Indirect	Q
Spatial resolution (nm) $\frac{\text{Typical}}{\text{Limit}}$	$\frac{50}{\sim 10}$	$\frac{10}{2}$
Depth of information (nm)	Thickness integrated <150 nm	Thickness integrated <100 nm
Time for image acquisition	50 msec–60 sec	5–60 secs
Limits on applied magnetic fields	~100–500 kA/m	~100–500 kA/m
Imaging conditions	HV	HV
Max thickness	<150 nm	<100 nm
Sample smoothness	Preferred	Preferred
Sample clean surface	Preferred	Preferred

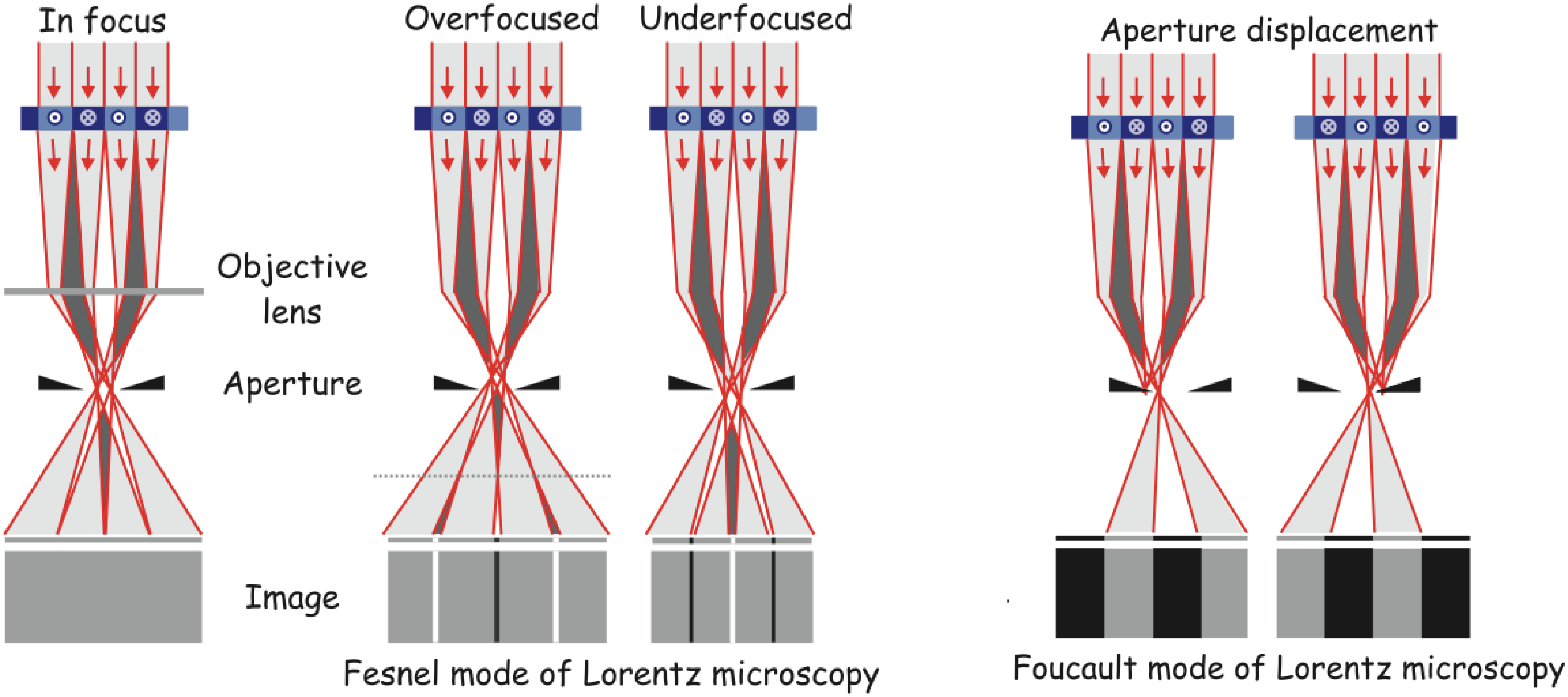
$$F = |e|(\mathbf{v} \times \mathbf{B})$$

Lorentz force



Lorentz deflection angle

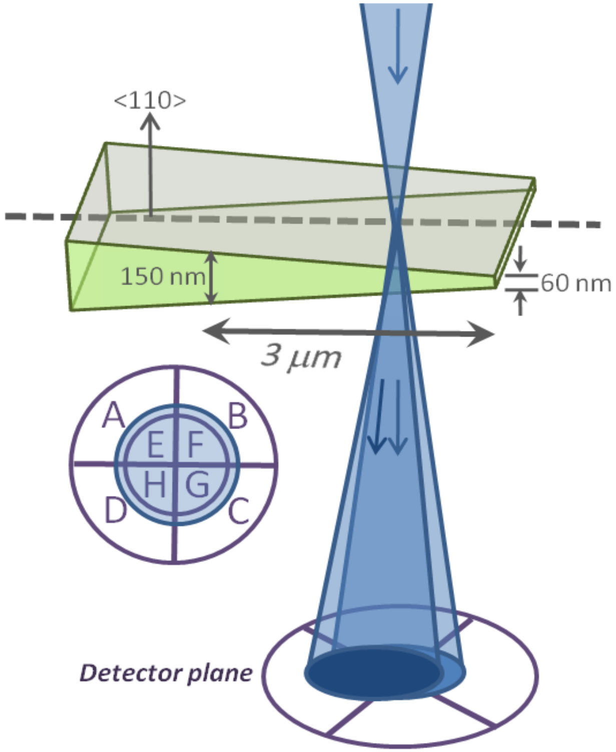
$$\beta_L = \frac{e\lambda(\mathbf{B} \times \mathbf{n})}{\mathrm{h}} t \approx 100\,\mu\mathrm{rad}$$

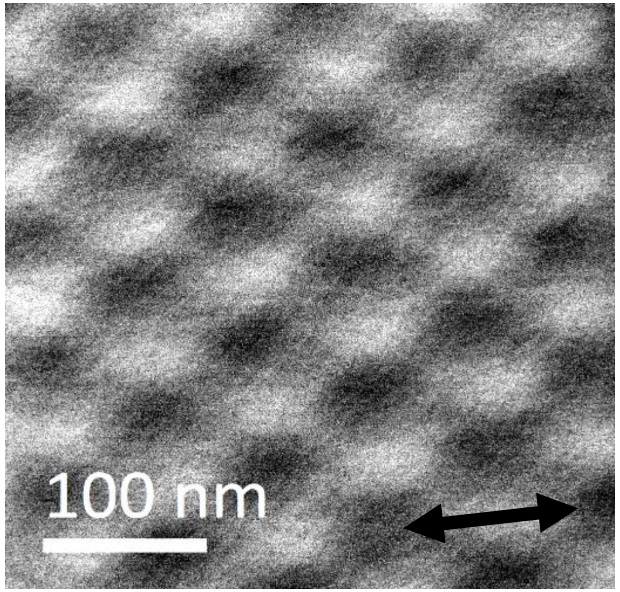


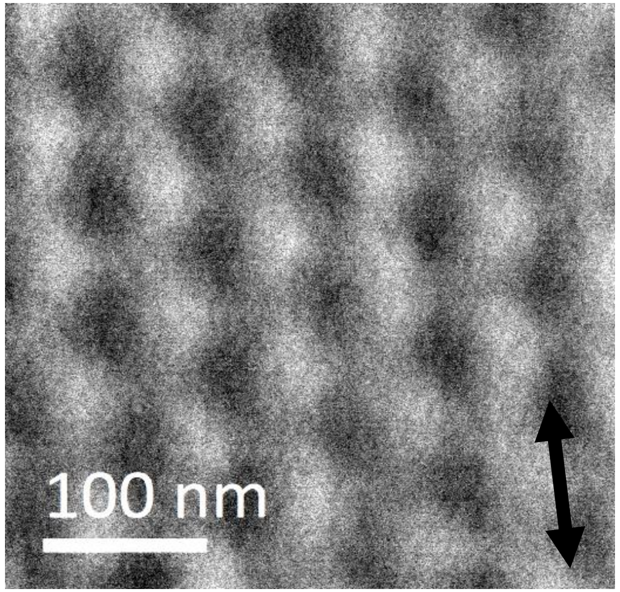
Highlight domain walls

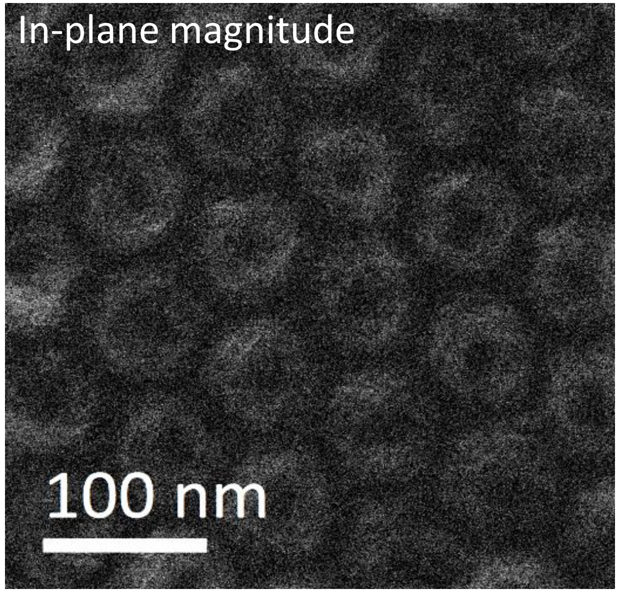
Highlight domains

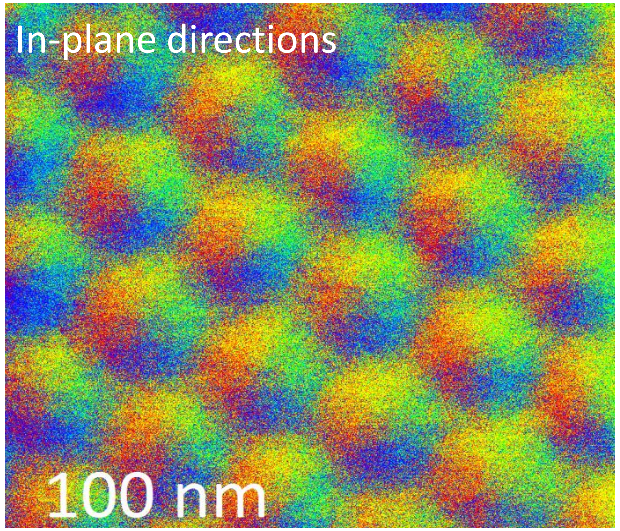
Skyrmion lattice

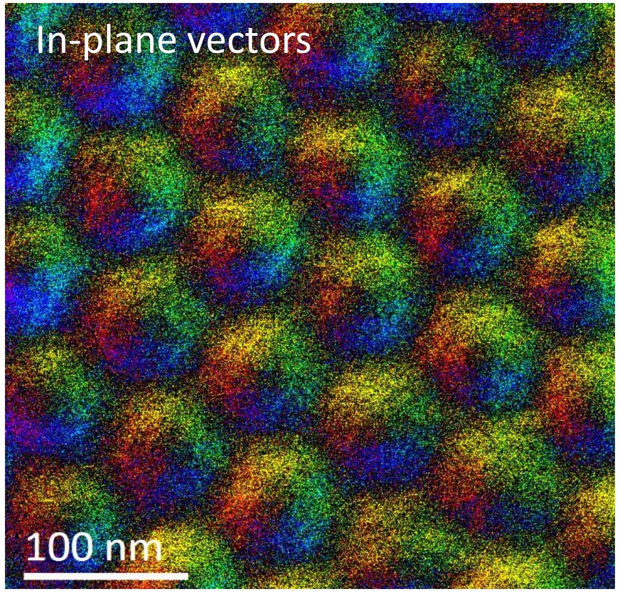




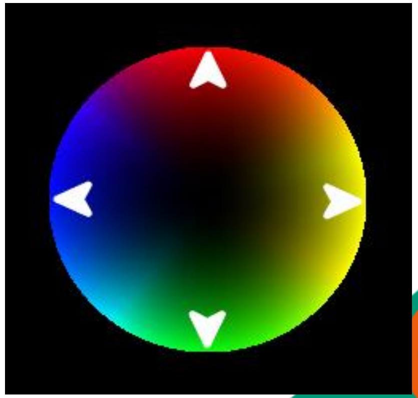




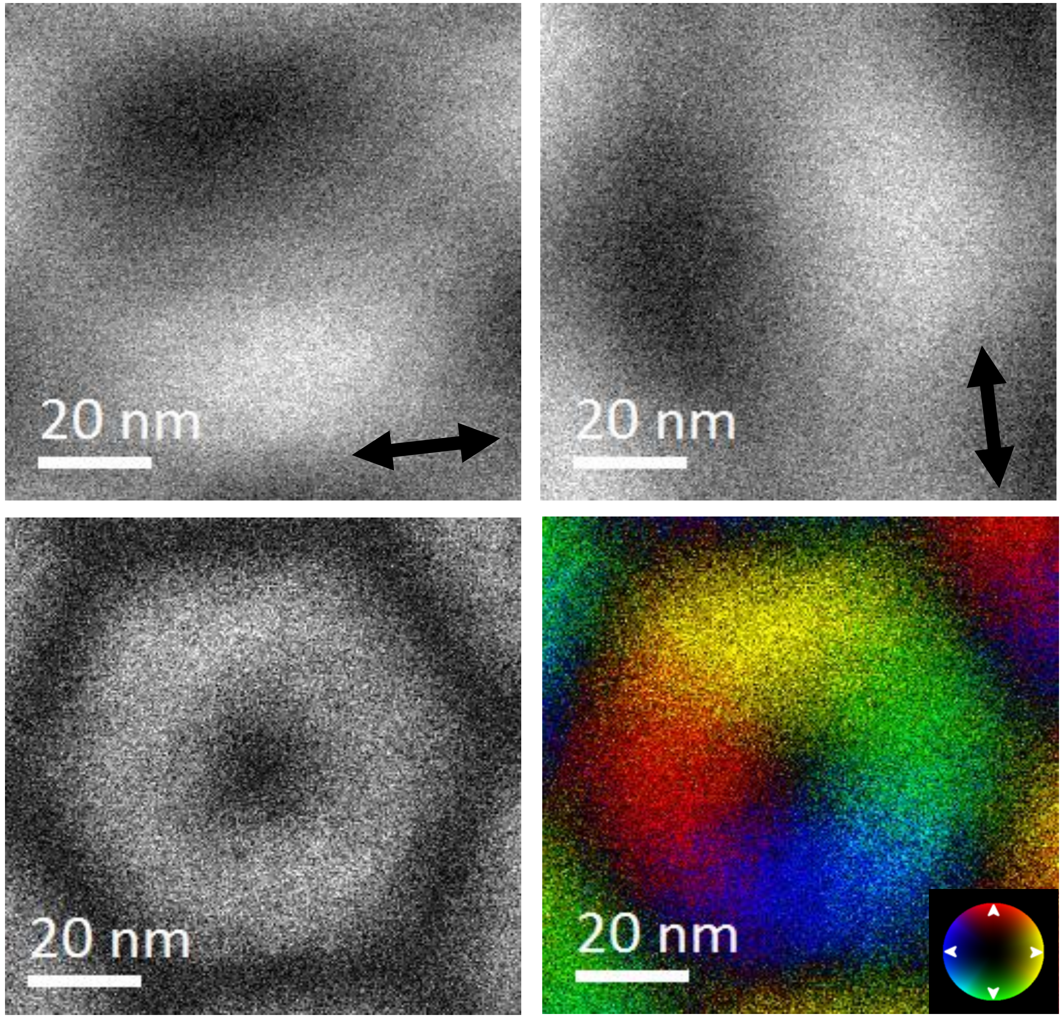




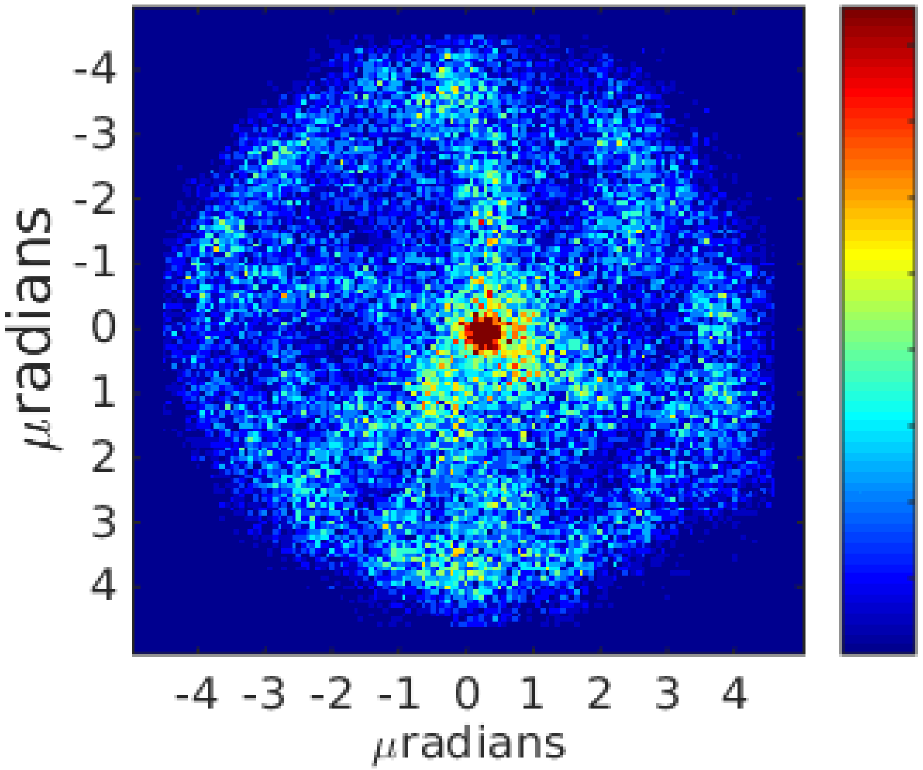
***H* = 796 Oe**



Material from S. McVitie, Univ. Glasgow, UK



3D histogram analysis



- Lorentz deflection angle +/- 4 μradians – equiv. to B_S~0.2 Tesla
- Six-fold symmetry

Material from S. McVitie, Univ. Glasgow, UK

Outlines

Magneto-optical microscopy (MO)

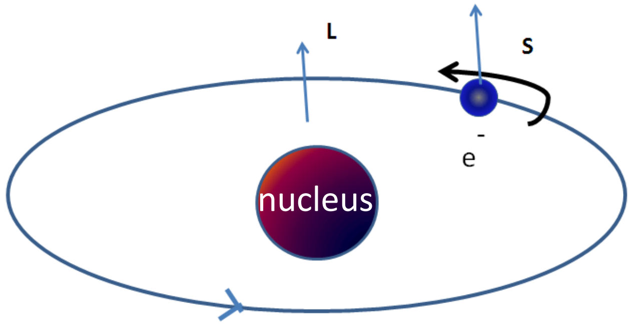
Scanning electron microscopy (SEMPA)

Transmission electron microscopy (TEM)

X-Ray microscopy

Magnetic force microscopy (MFM)

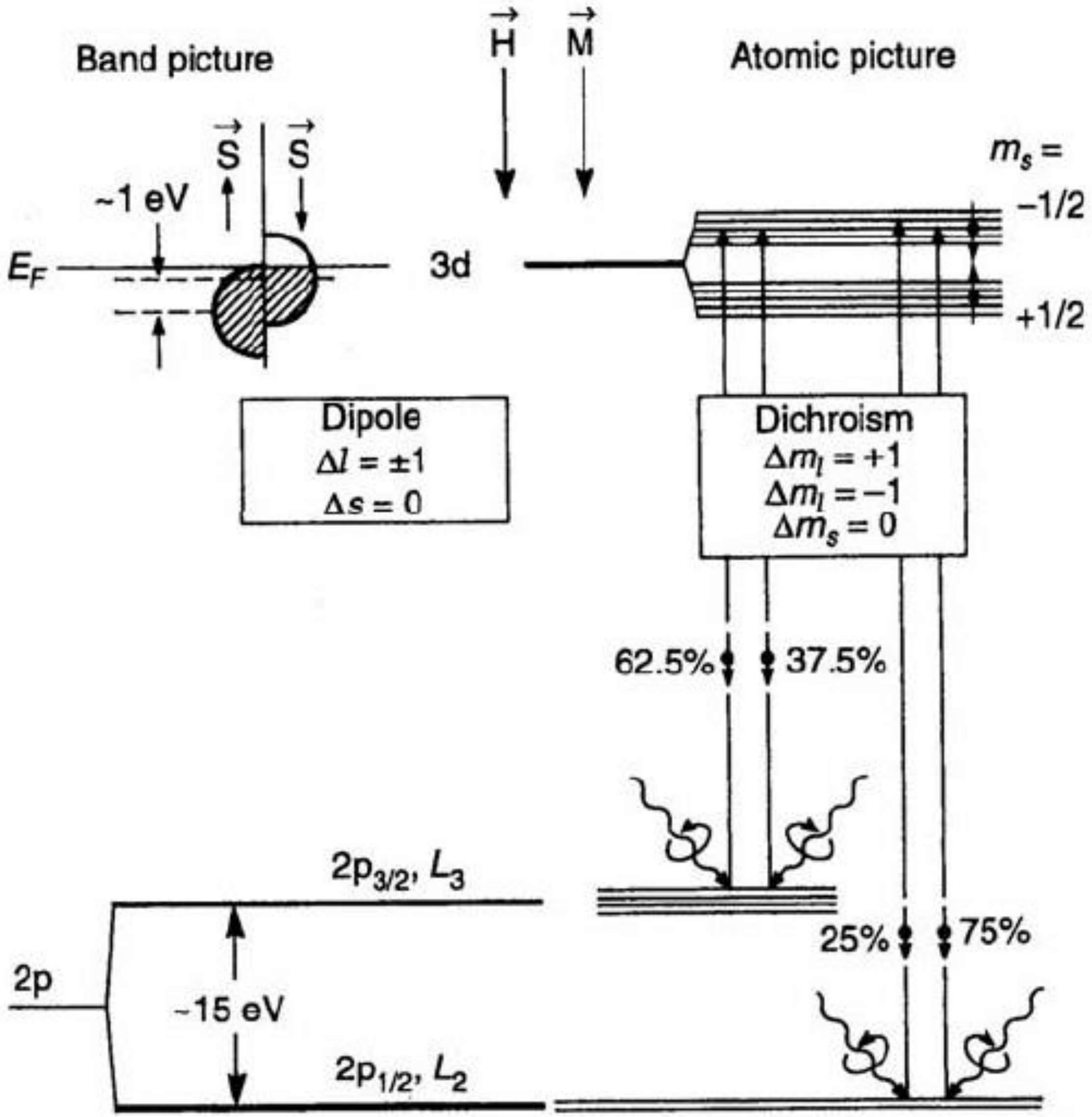
X-ray magnetic circular dichroism (XMCD)



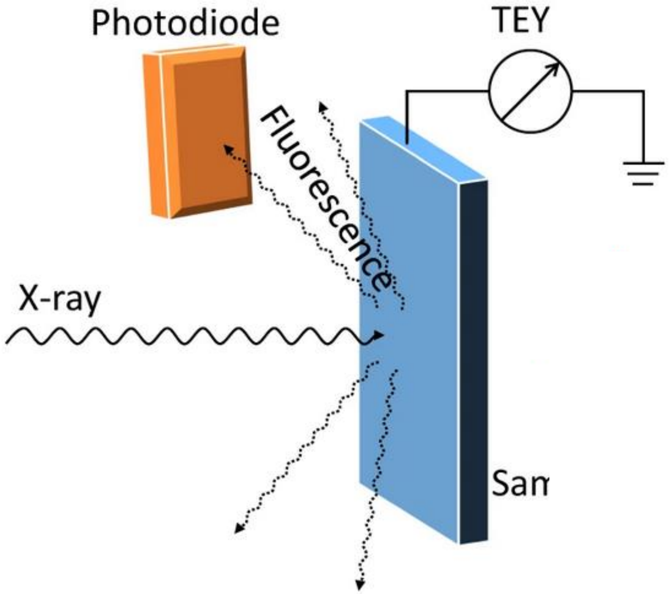
- XMCD disentangles spin and orbital magnetic moment

- XMCD disentangle the moment from specific atoms in an alloy or a multilayer

- XMCD requieres to work in synchrotron to get enough X-ray flux (700 - 900 eV for Fe,Co,Ni)

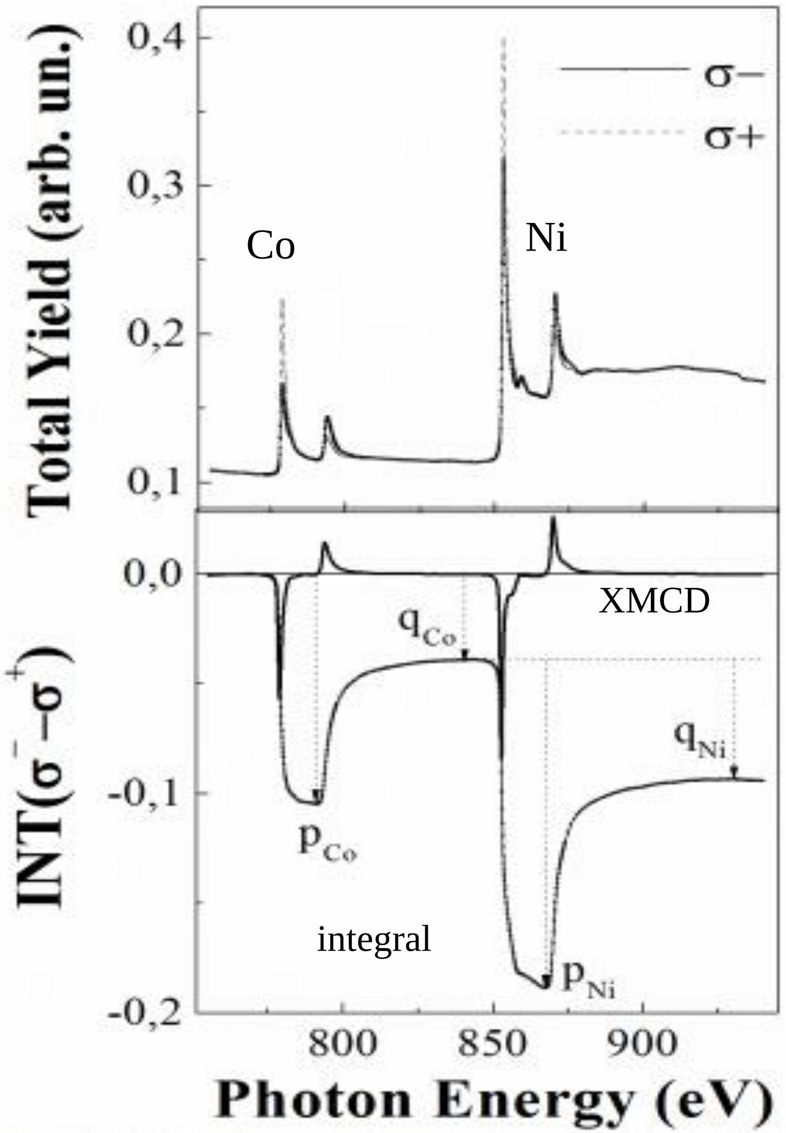


X-ray magnetic circular dichroism (XMCD)



$$m_{\mathrm{spin}}^{\mathrm{eff}} = 2\langle S_z^{\mathrm{eff}}\rangle \frac{\mu_B}{\hbar} = n_h \cdot \left(\frac{3p - 2q}{r}\right)\mu_B$$

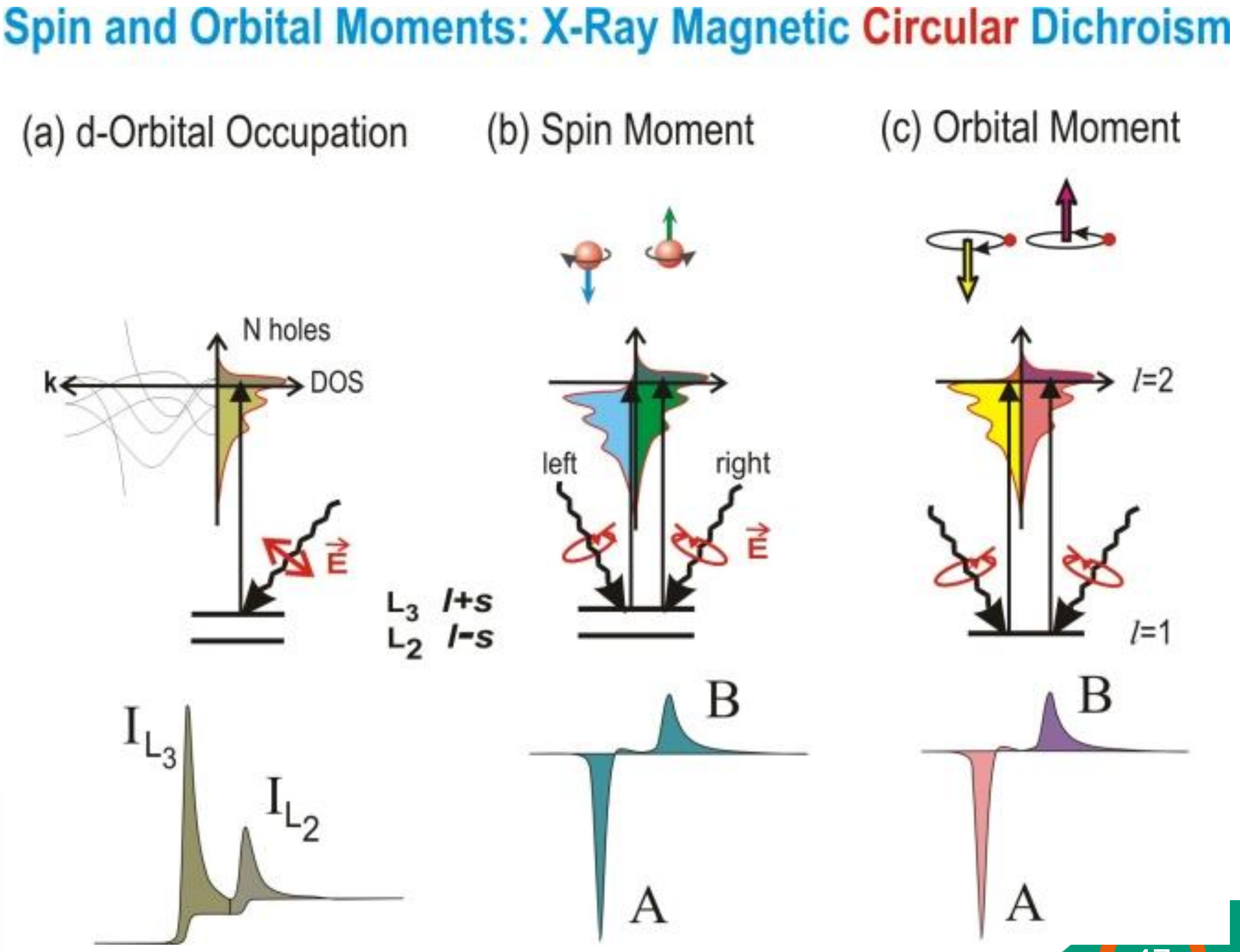
$$m_{\mathrm{orb}} = \langle L_z\rangle \frac{\mu_B}{\hbar} = n_h \cdot \left(\frac{2q}{3r}\right)\mu_B$$



« Surface » sensitive technic (< 50 nm)

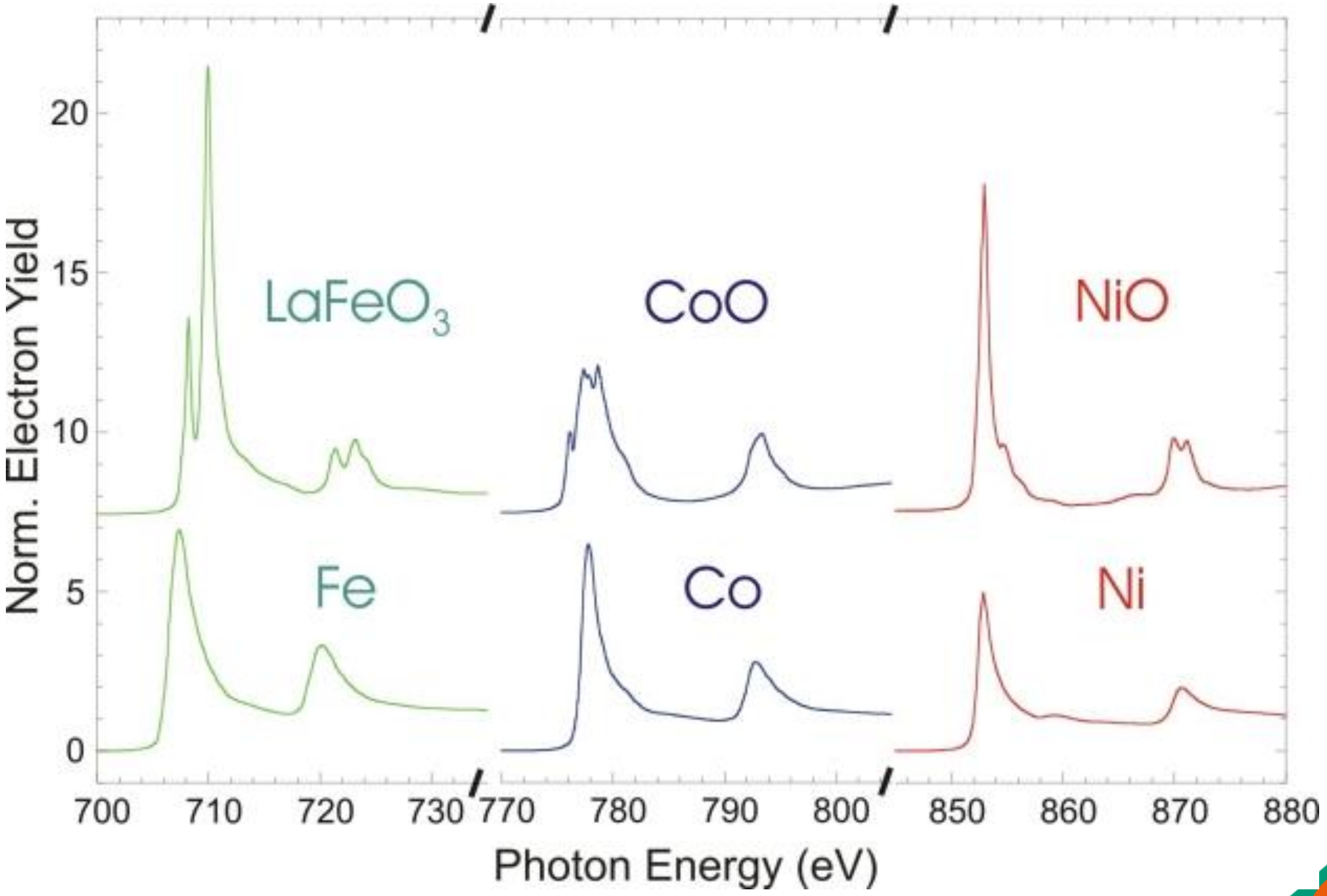
X-ray magnetic circular dichroism (XMCD)

Electronic transitions in conventional L-edge x-ray absorption (a), and x-ray magnetic circular x-ray dichroism (b,c), illustrated in a one-electron model. The transitions occur from the spin-orbit split 2p core shell to empty conduction band states. In conventional x-ray absorption the total transition intensity of the two peaks is proportional to the number of d holes (first sum rule). By use of circularly polarized x-rays the spin moment (b) and orbital moment (c) can be determined from linear combinations of the dichroic difference intensities A and B, according to other sum rules



https://www-ssrl.slac.stanford.edu/stohr/xmcd.htm

X-ray magnetic circular dichroism (XMCD)

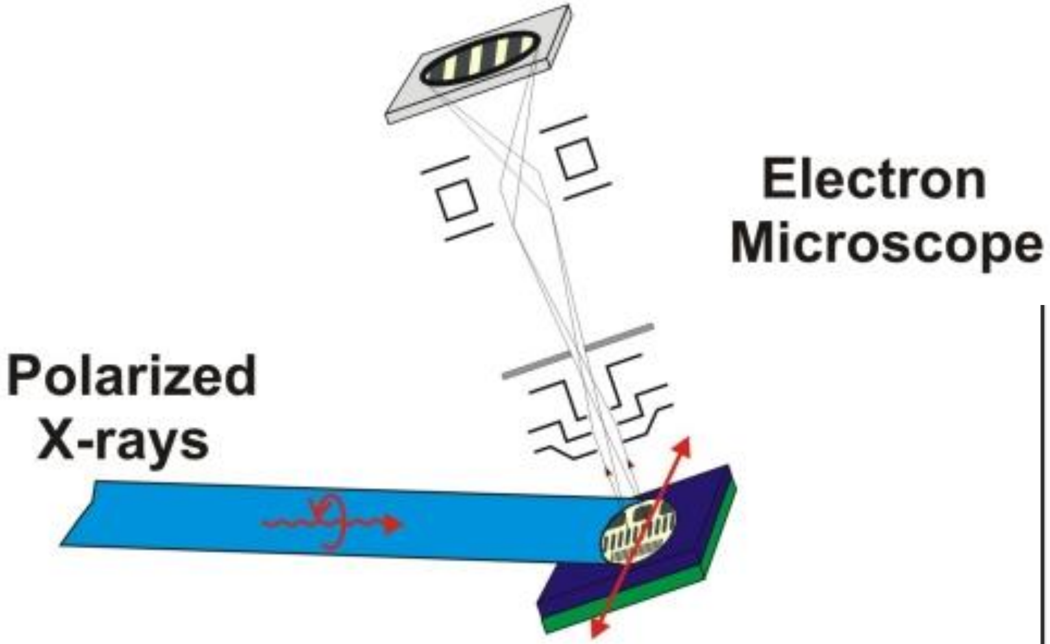


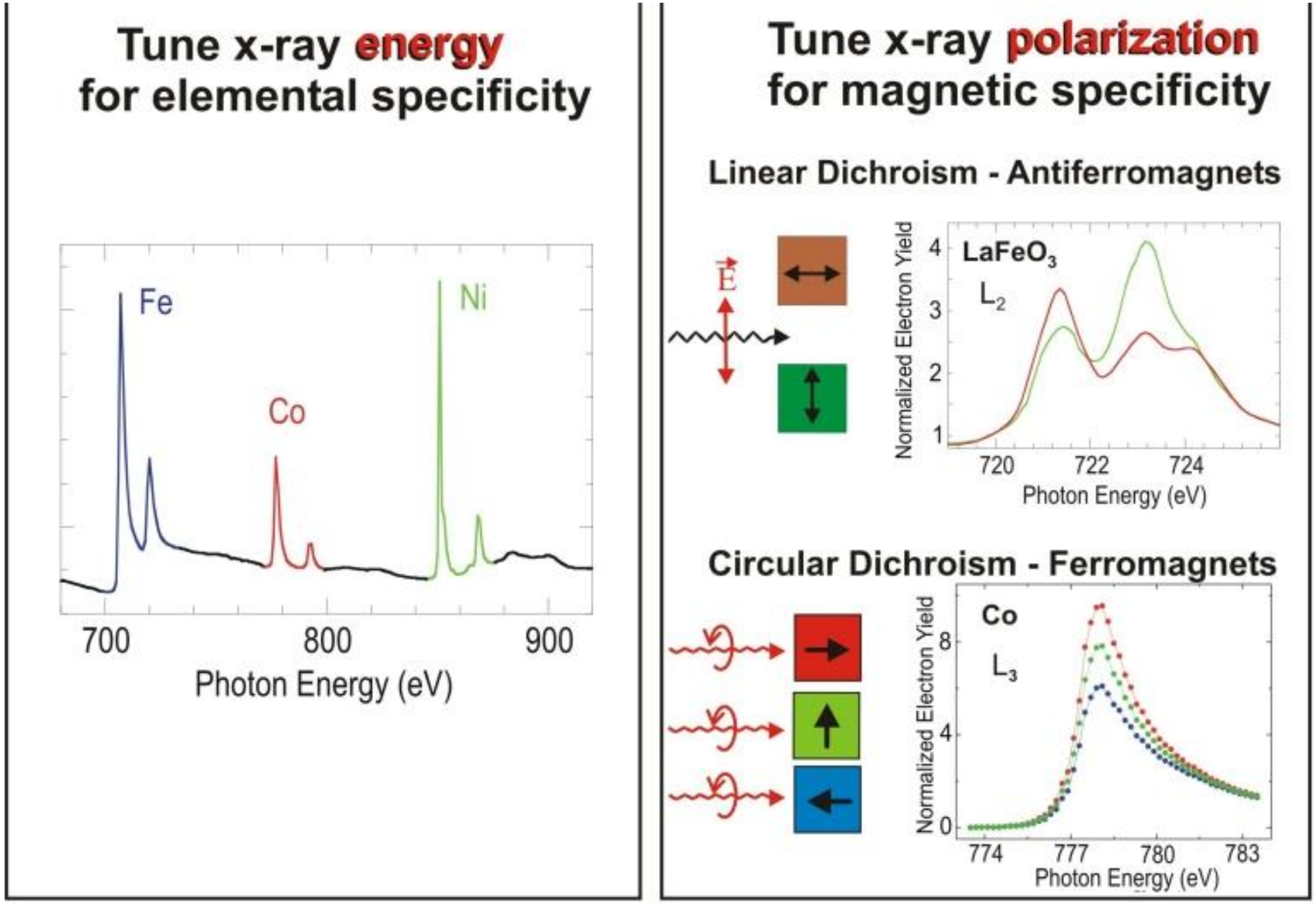
SLAC NATIONAL ACCELERATOR LABORATORY

https://www-ssrl.slac.stanford.edu/stohr/xmcd.htm

X-Ray Spectro-Microscopy

Photoemission electron microscopy (PEEM,

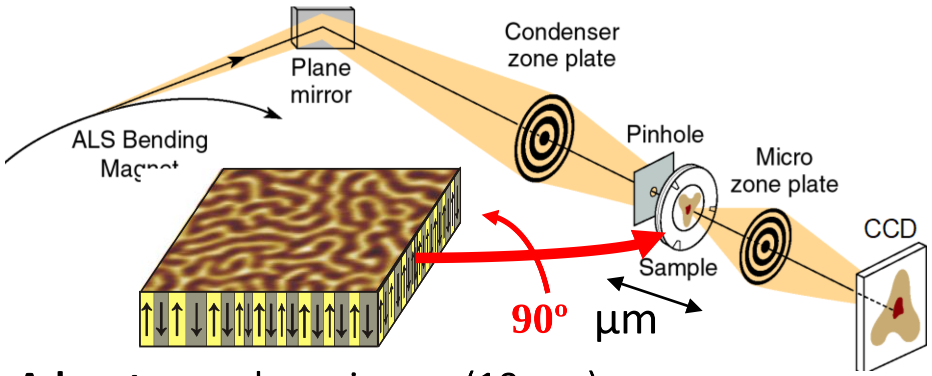




Magnetic imaging by means of PEEM. A layer in the sample is selected by tuning the x-ray energy to the desired element. X-ray polarization contrast at an absorption peak is used for imaging contrast. The local electron yield from a sample region, imaged by PEEM, depends on the relative orientation of the magnetic direction or axis and the polarization, as illustrated on the right.

Transmission X-ray microscopy (TXM)

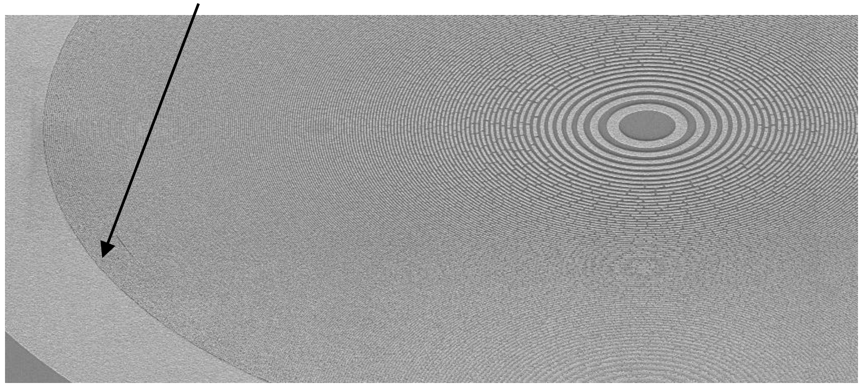
(ALS, SLS, BESSY II, ANKA)



Advantages : large image (10 µm)
with good, 50ps time resolution

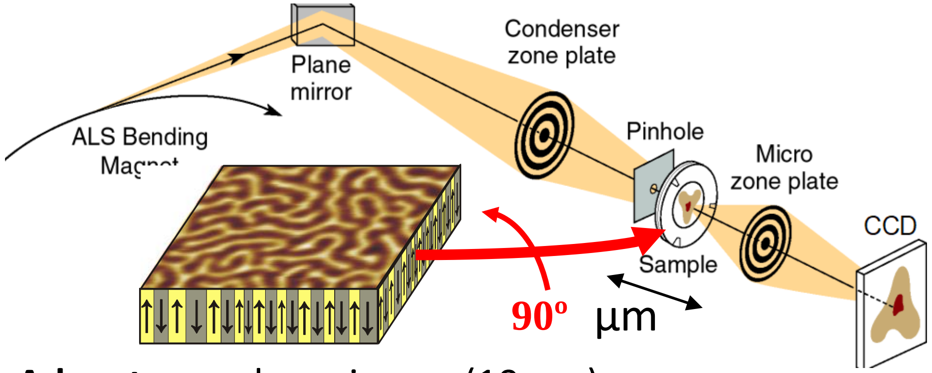
Disadvantages : mostly 300K, small field, lenses

Distance between 2 circles => resolution (here 15 nm)



Transmission X-ray microscopy (TXM)

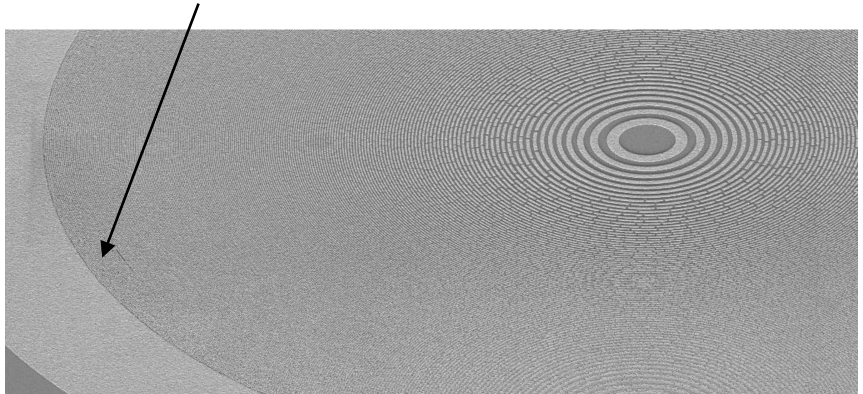
(ALS, SLS, SOLEIL, BESSY II, ANKA)



Advantages : large image (10 µm)
with good, 50ps time resolution

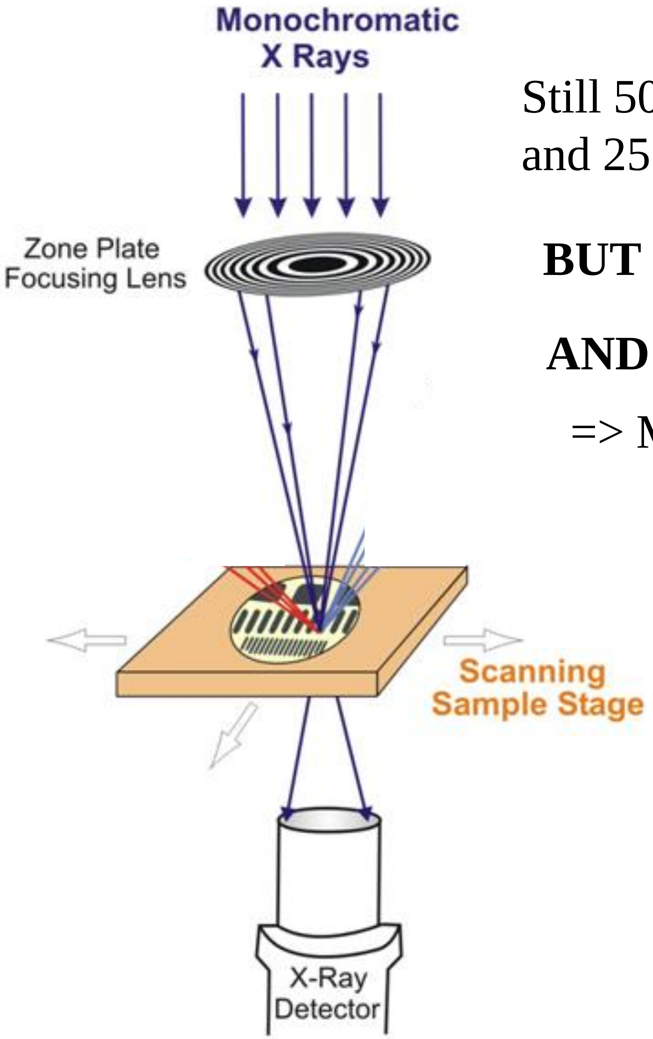
Disadvantages : mostly 300K, small field, lenses

Distance between 2 circles => resolution (here 15 nm)



Scanning TXM

(ALS, SSRL, SLS, Soleil)



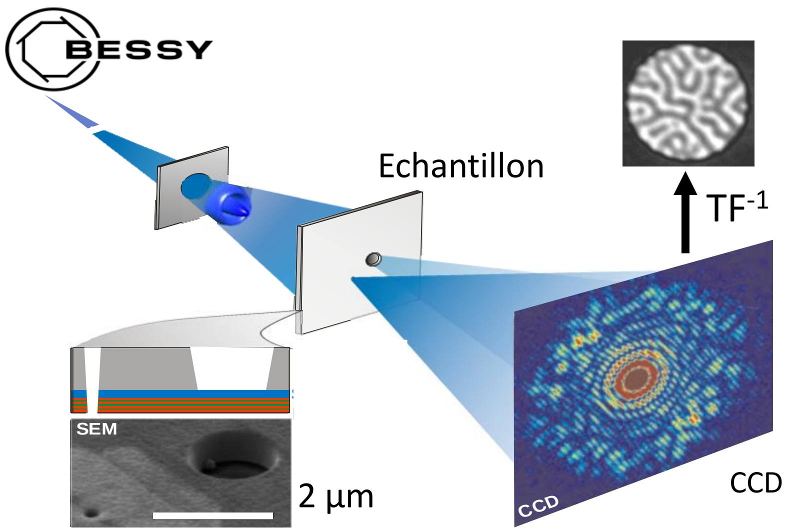
Still 50 ps time resolution and 25 nm resolution

BUT Only one lense

AND Scanning

=> More flux locally

X-ray Holography



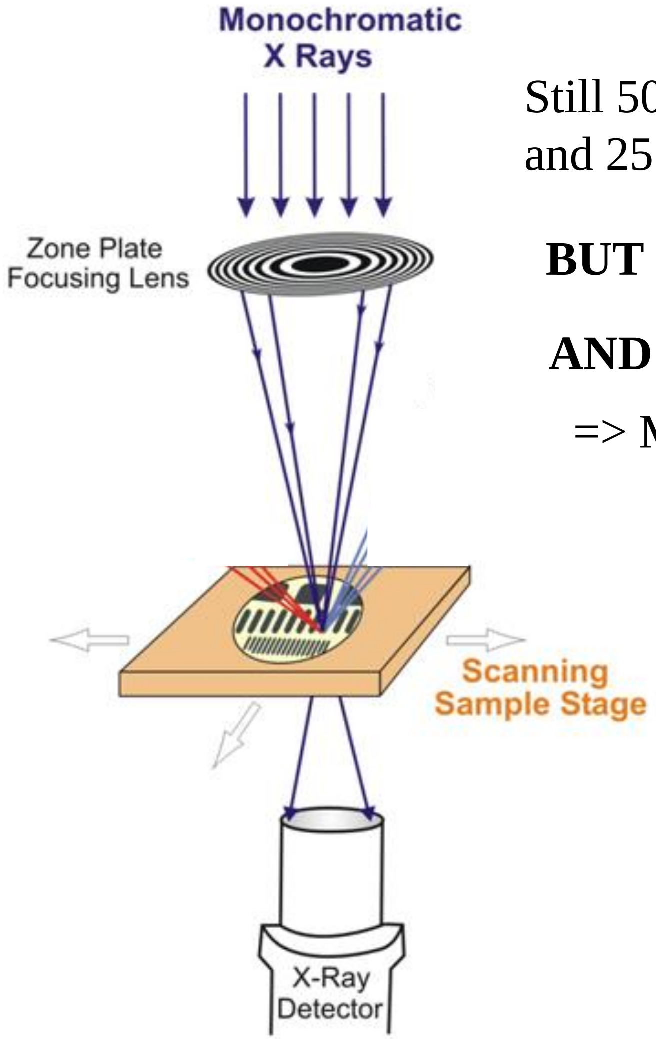
Advantage : 400K-10K, more space around the sample

Disadvantage : sample preparation,
limited image size (< 2 µm)
Loss in resolution (50nm)
Phase retrieval

Dynamics in MTXM, STXM,
Holography requieres stromboscopy

Scanning TXM

(ALS, SSRL, SLS, Soleil)



Still 50 ps time resolution and 25 nm resolution

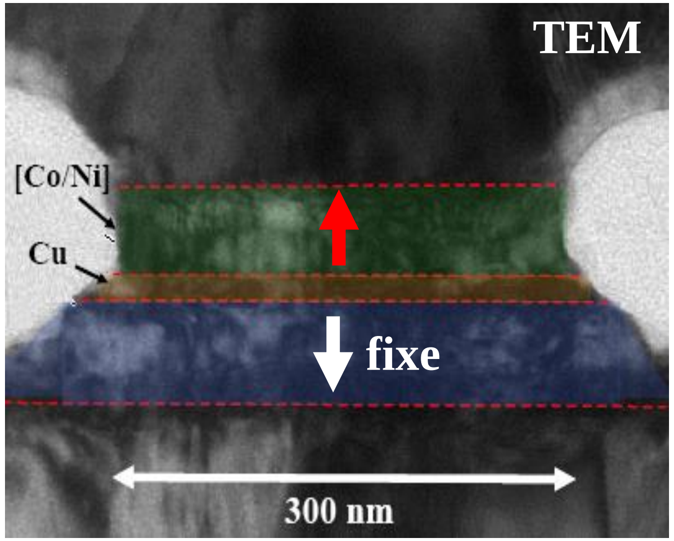
BUT Only one lense

AND Scanning

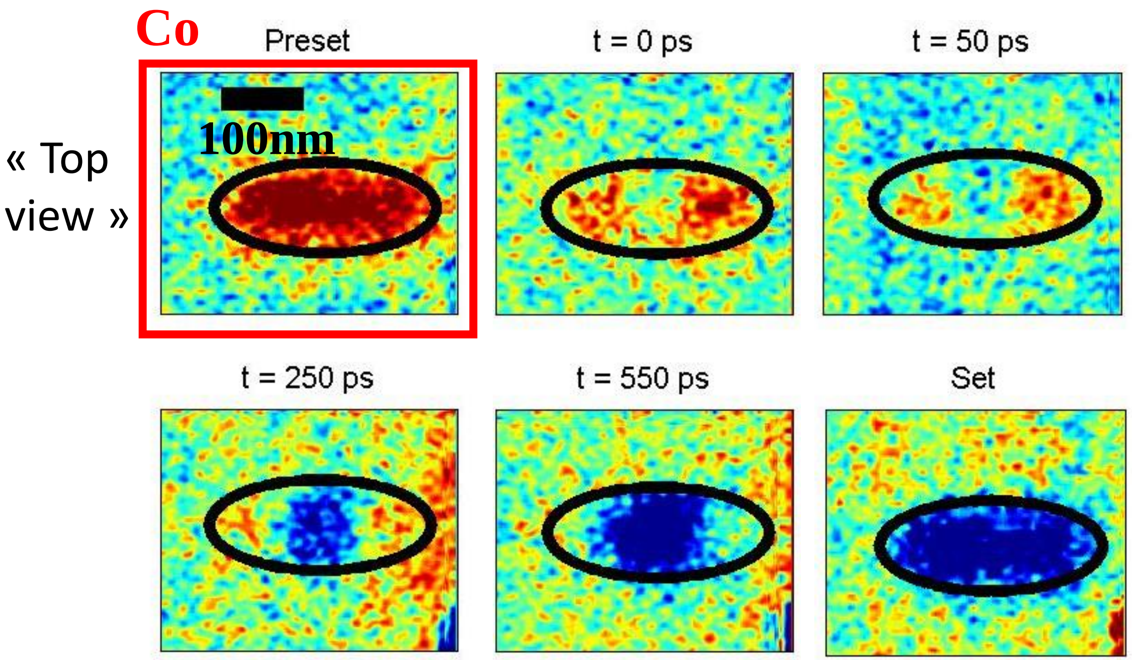
=> More flux locally

STT induced switching - STXM

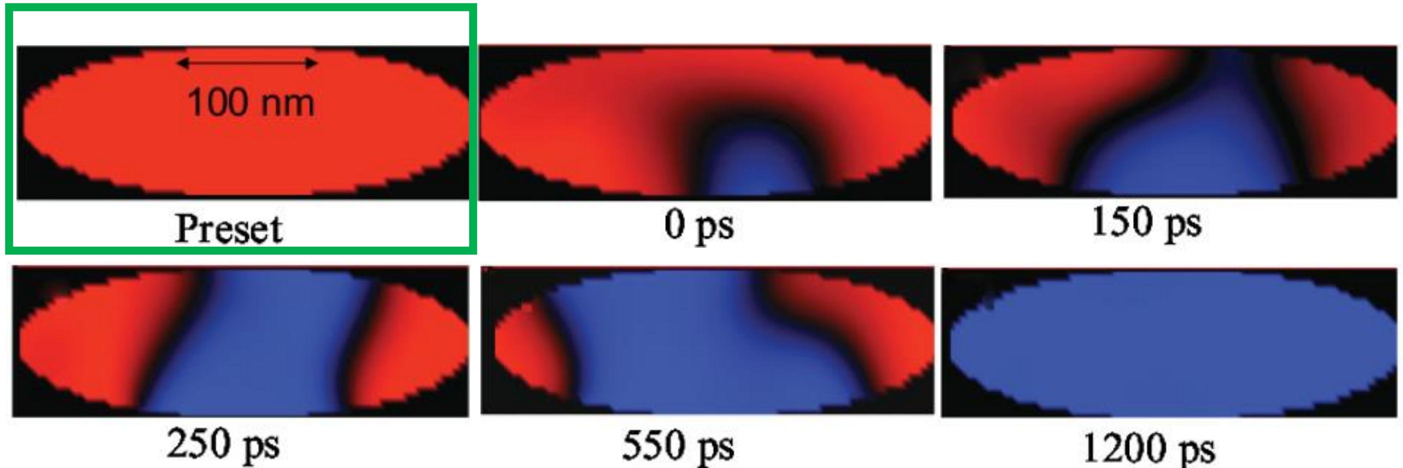
t=0ps



Excitation : Current pulsed at t=0ps



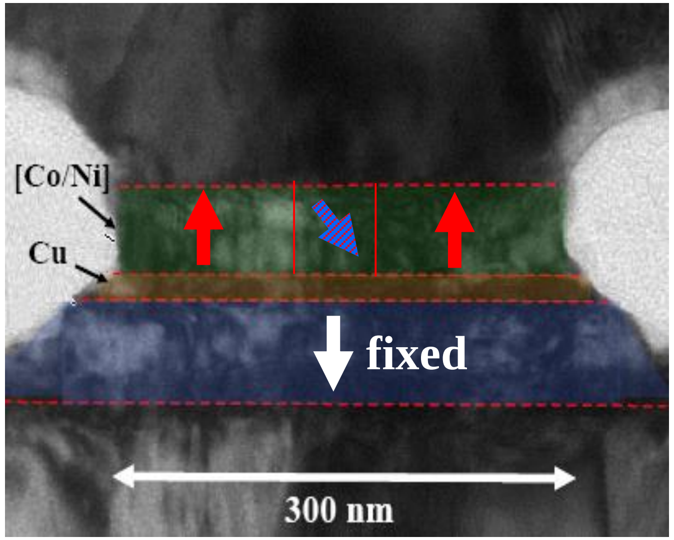
Micromagnetic simulation (Scheinfein code)



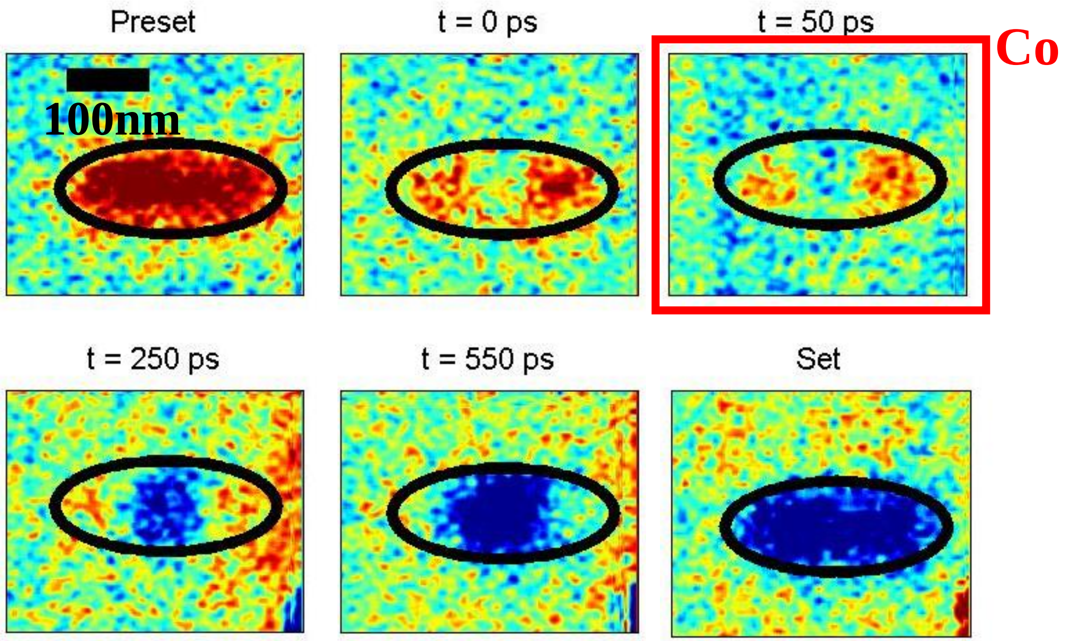
D.P. Bernstein et al., PRB(R) 83, 180410 (2011)

STT induced switching - STXM

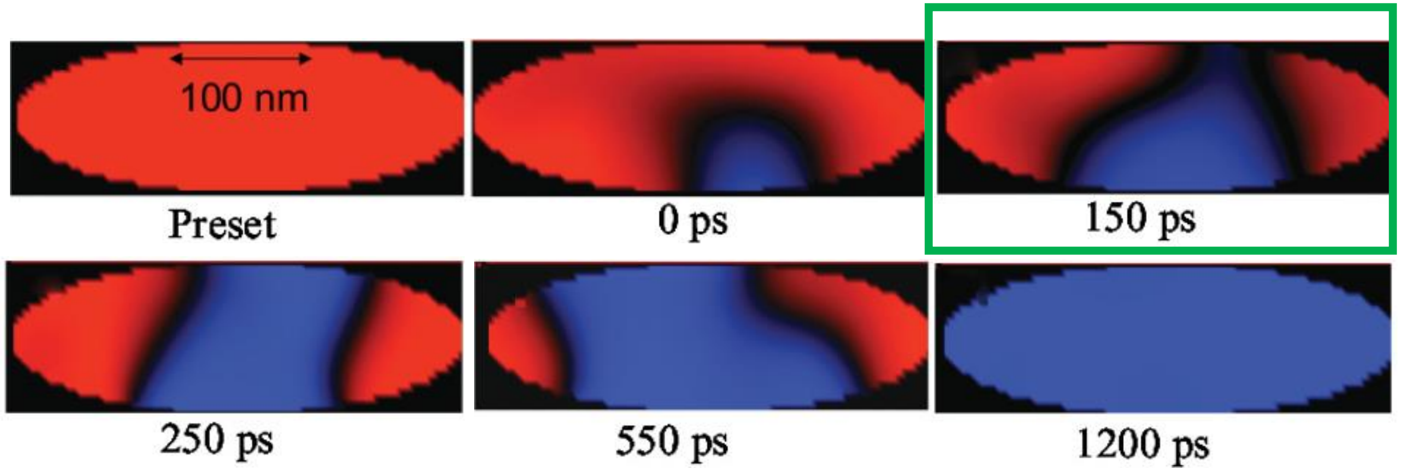
t=50ps



<u>Excitation :</u> Current pulsed at t=0ps



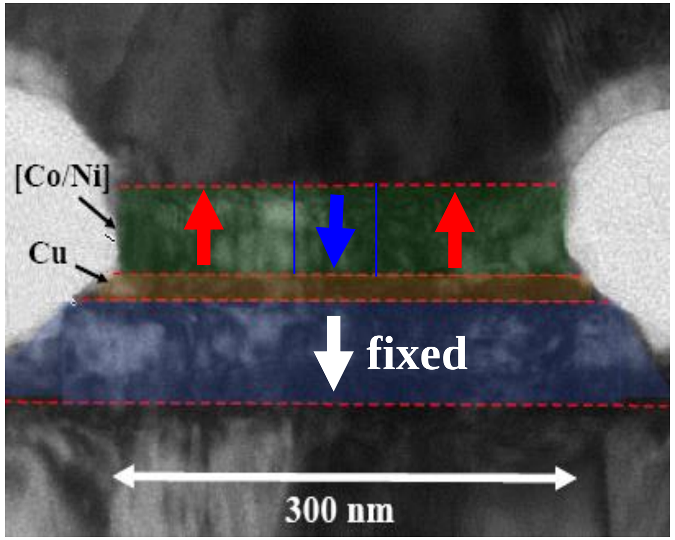
Micromagnetic simulation
(Scheinfein code)



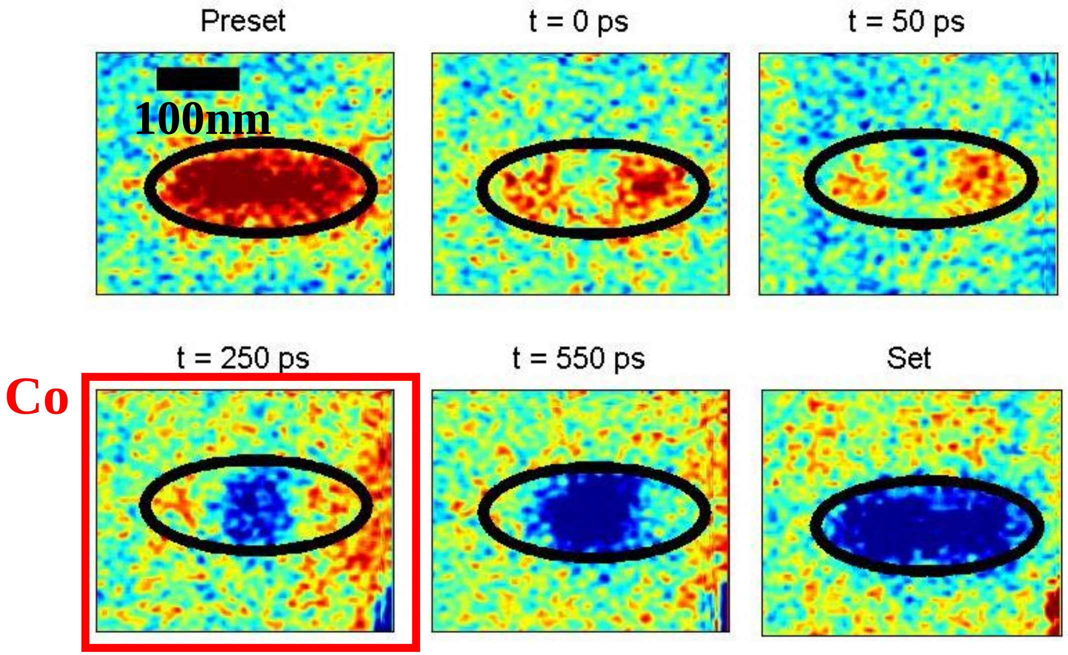
D.P. Bernstein et al., PRB(R) 83, 180410 (2011)

STT induced switching - STXM

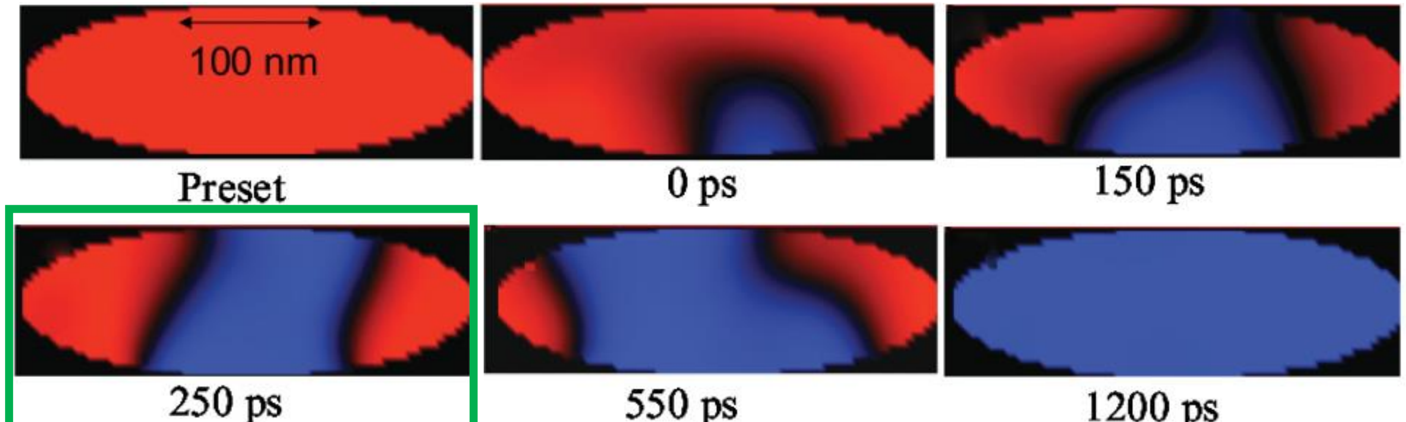
t=250ps



Excitation : Current pulsed at t=0ps



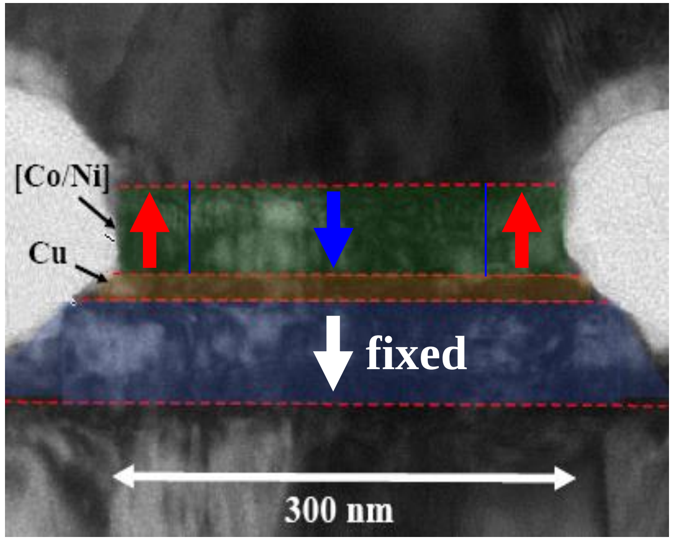
Micromagnetic simulation
(Scheinfein code)



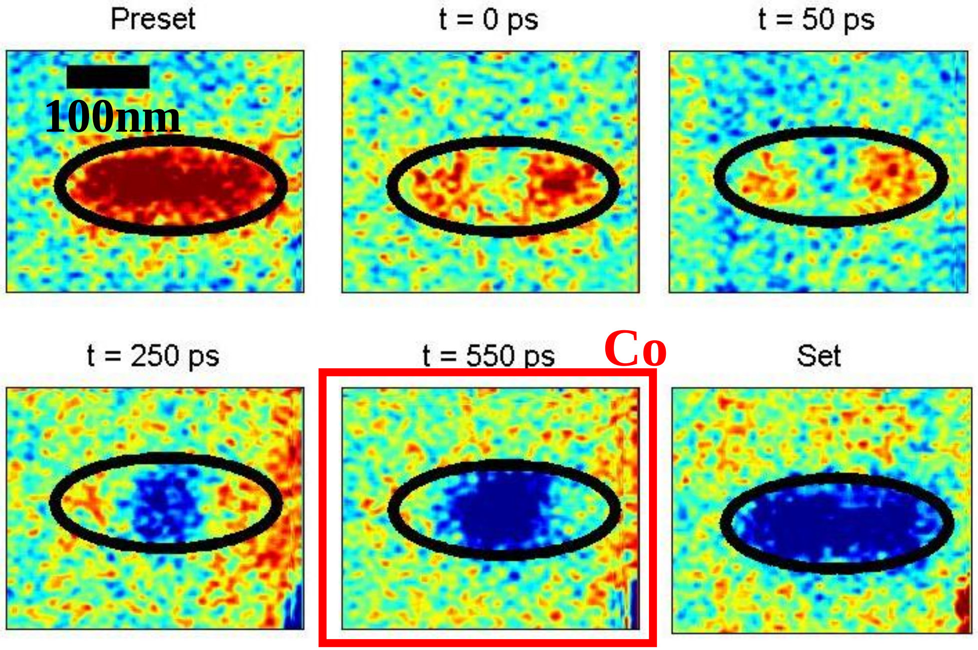
D.P. Bernstein et al., PRB(R) 83, 180410 (2011)

STT induced switching - STXM

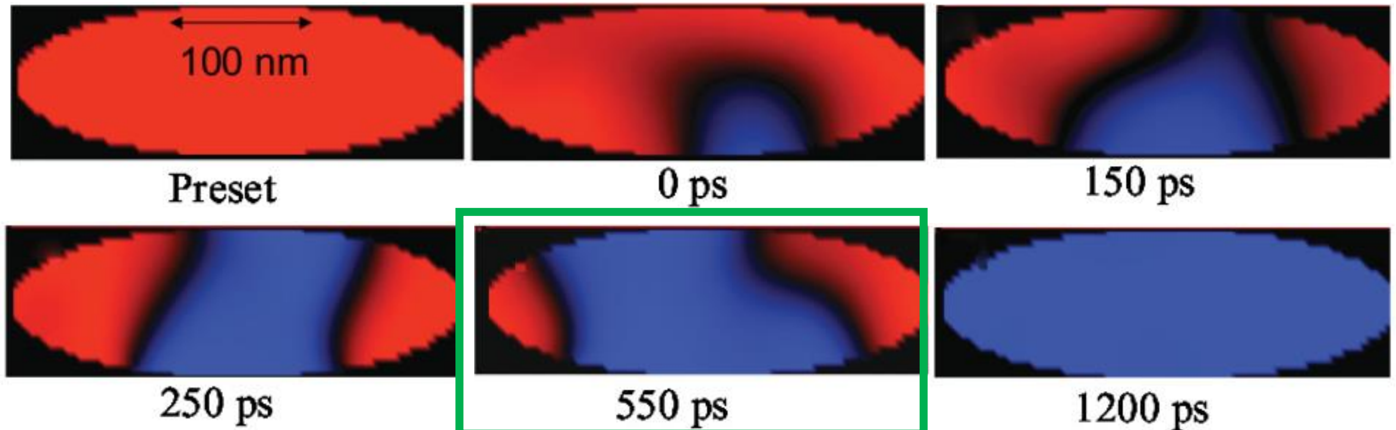
t=550ps



<u>Excitation :</u> Current pulsed at t=0ps



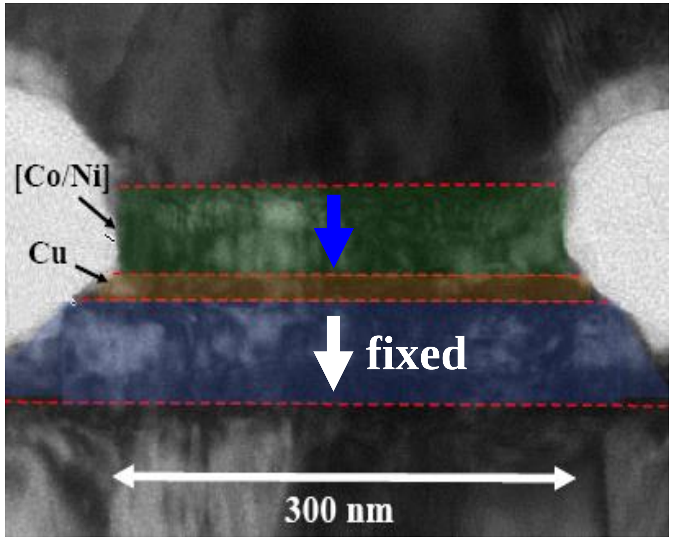
Micromagnetic simulation
(Scheinfein code)

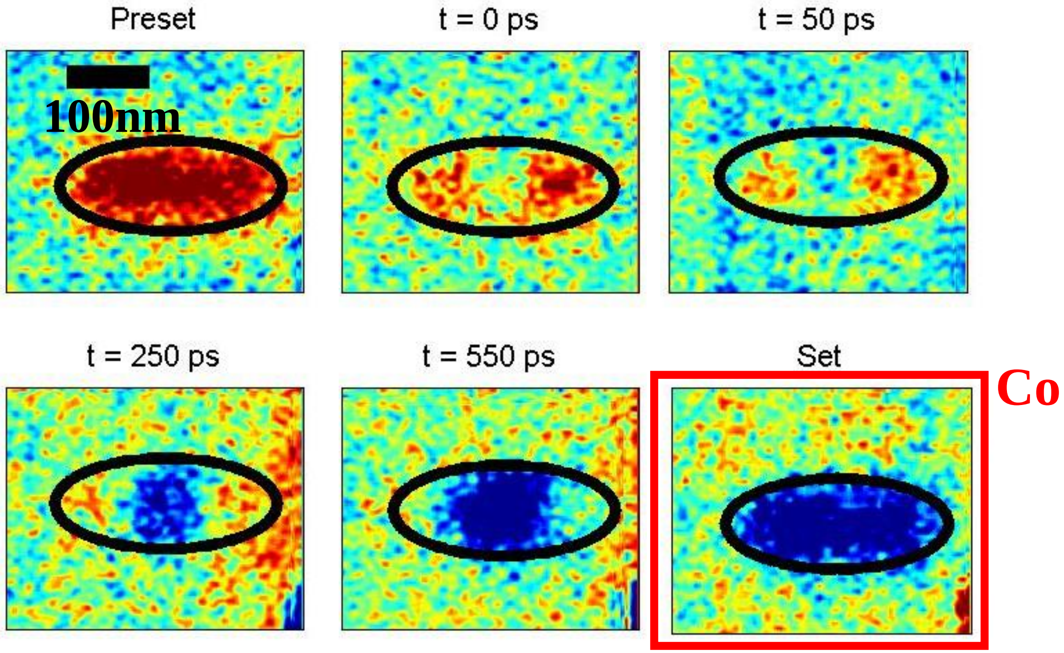


D.P. Bernstein et al., PRB(R) 83, 180410 (2011)

STT induced switching - STXM

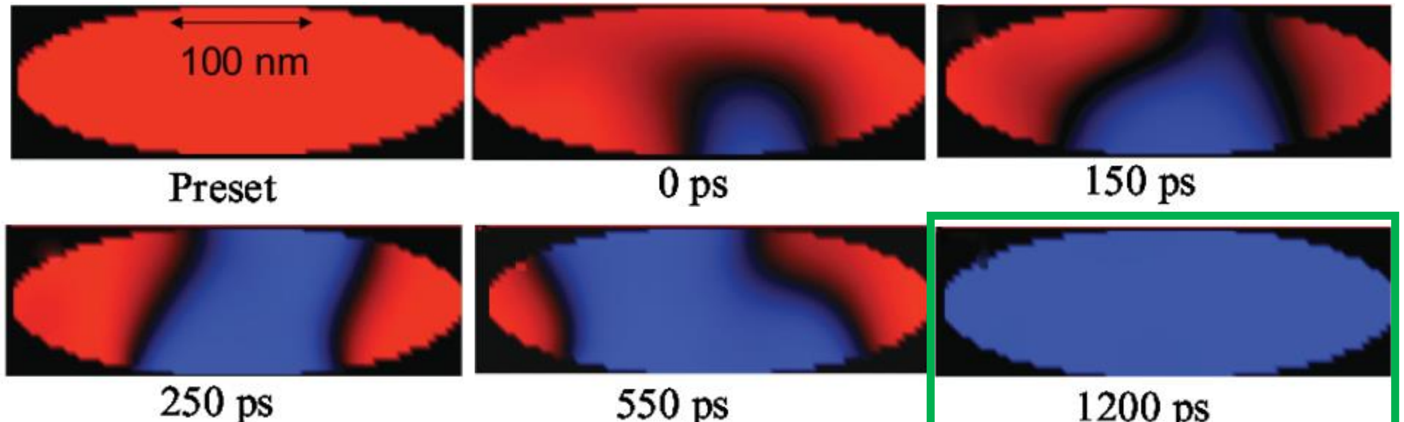
t=1000ps





<u>Excitation :</u> Current pulsed at t=0ps

Micromagnetic simulation
(Scheinfein code)



D.P. Bernstein et al., PRB(R) 83, 180410 (2011)

What is measured?

- Magnetization component
- Elemental resolution
- Direct
- Quantitative

Environmental conditions

- Temperature
- Field: magnetic field (not PEEM)
- Electric current, light etc.
- Strain
- Additional measuring techniques

Which specifications?

- Magnetization: 1D, 2D
- Depth resolution: surface/volume
- Lateral resolution 25 nm
- Sensitivity: <single layer
- Time/Spectral resolution

Versatility

- No sample preparation
- Time per measurement: s – min
- In situ
- Synchrotron radiation

Outlines

Magneto-optical microscopy (MO)

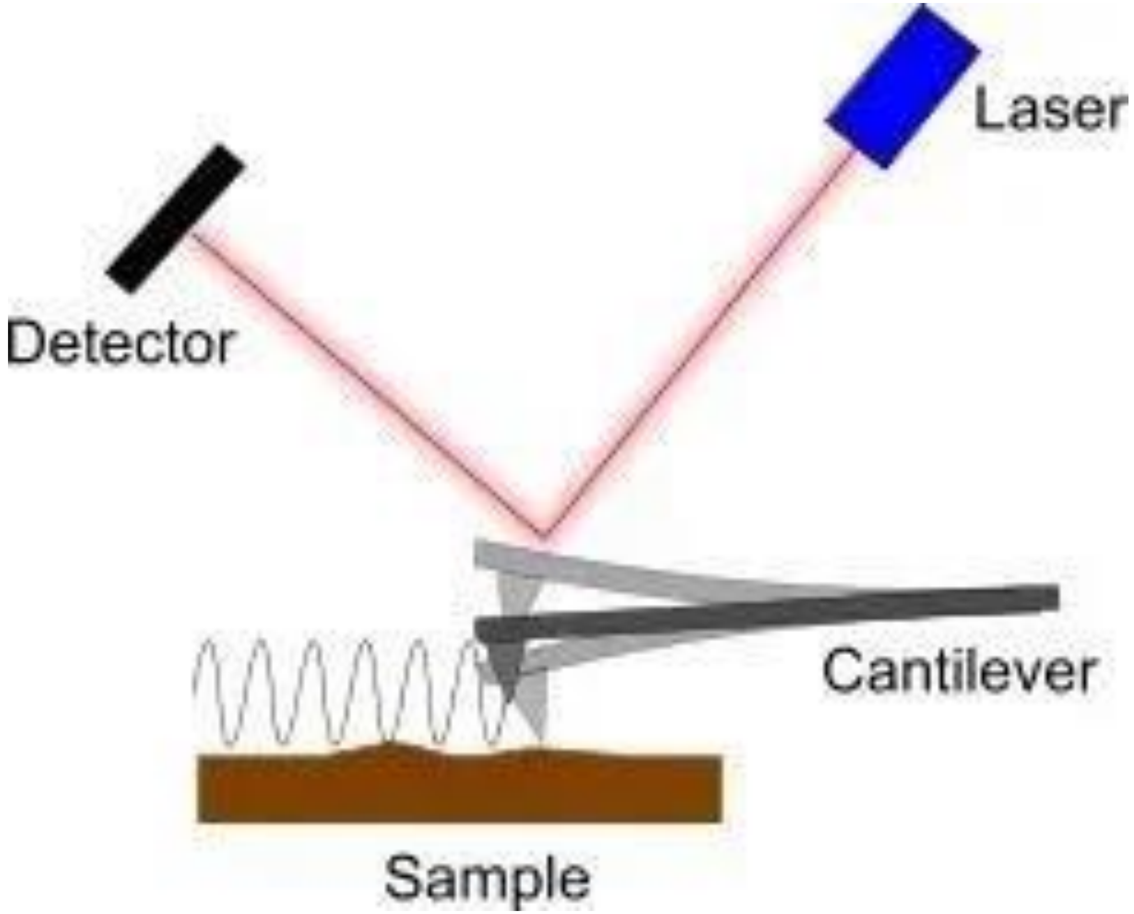
Scanning electron microscopy (SEMPA)

Transmission electron microscopy (TEM)

X-Ray microscopy

Magnetic force microscopy (MFM)

Scanning probe microscopy



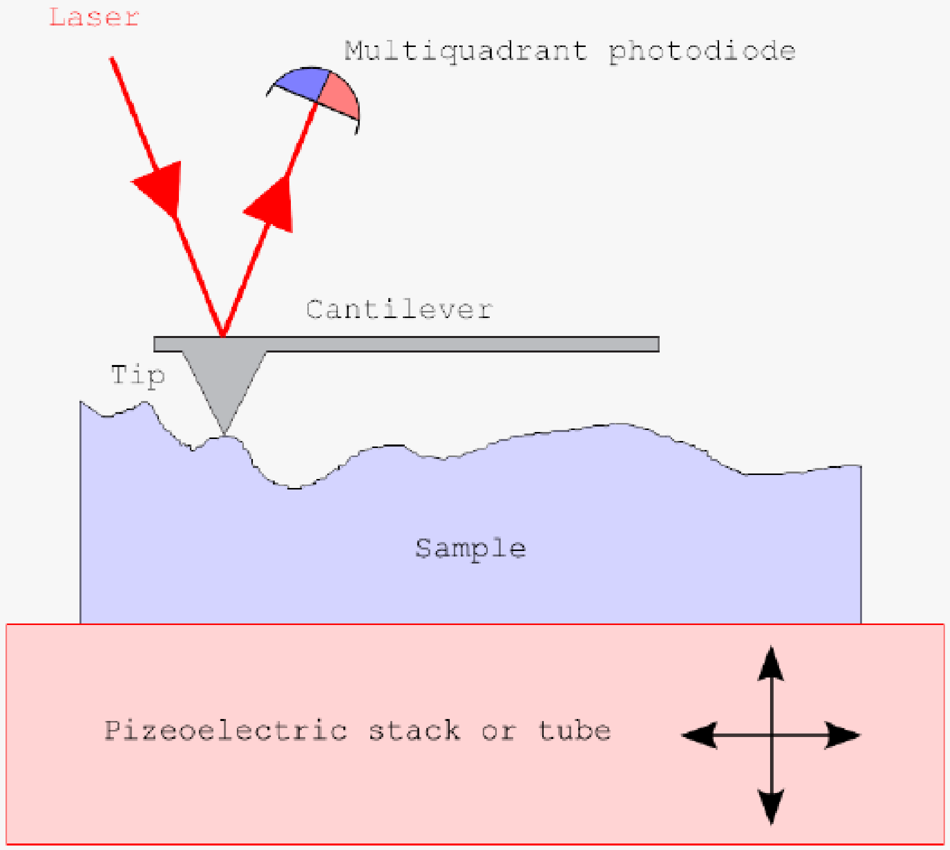
Interaction between the Tip and the sample

Different interaction = different techniqe

Making tip is an art !

Atomic Force Microscopy

The Atomic Force Microscope (AFM)



G. Binnig et al., Phys. Rev. Lett. 56, 930 (1986)

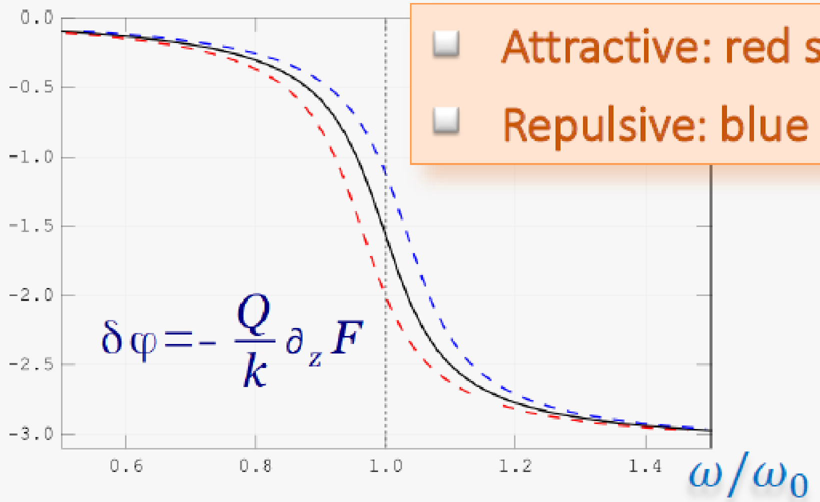
The cantilever as an oscillator

$$m\ddot{z} + \Gamma\dot{z} + kz = F(z)$$

with: $F(z) = F(z_0) + (z - z_0)\partial_z F$

Mere renormalization: $\omega_{0,\mathrm{eff}} = \omega_0\left(1 - \frac{1}{2k}\partial_z F\right)$

Probing forces with the phase shift



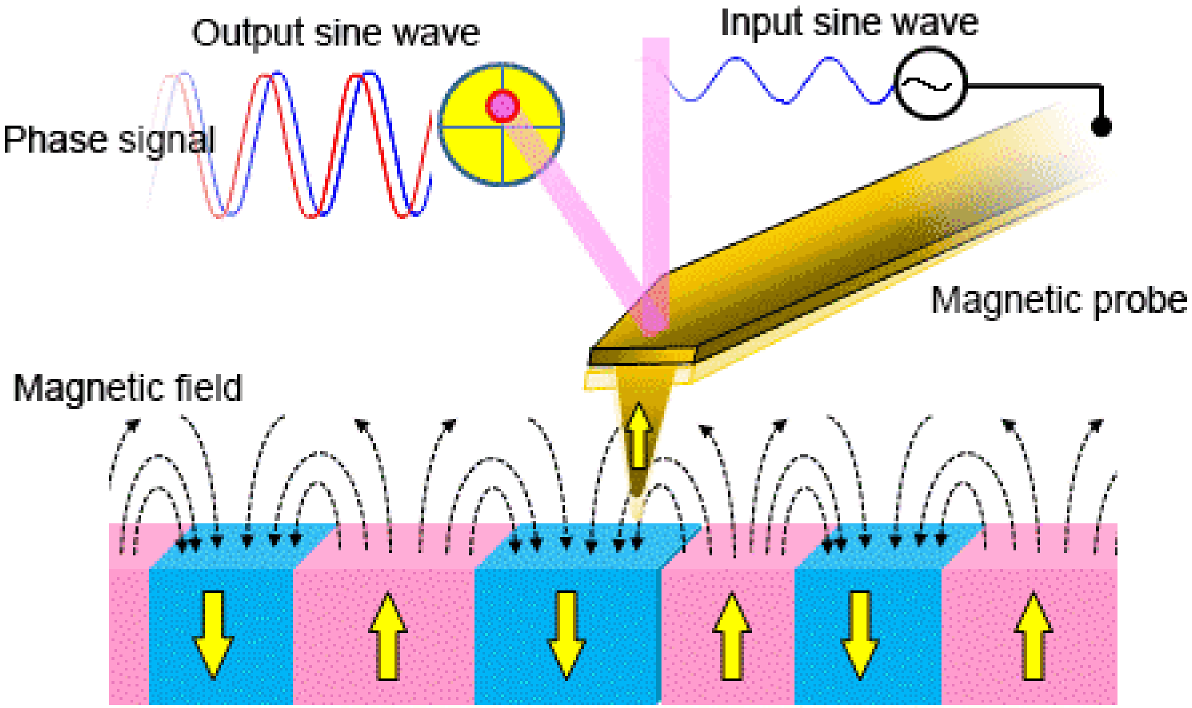
$$\delta\varphi = -\frac{Q}{k}\partial_z F$$

- Attractive: red shift
- Repulsive: blue shift

AFM characterizes topography

Magnetic Force Microscopy

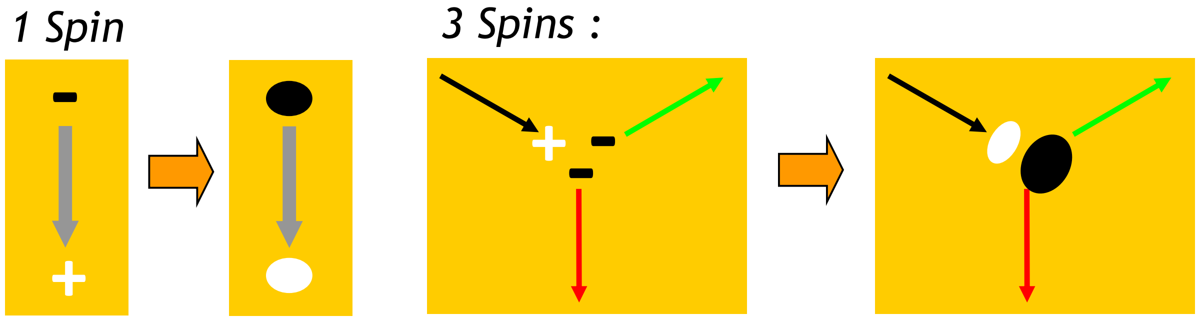
$$\vec{F} = \nabla(\vec{m} \bullet \vec{H}_D)$$

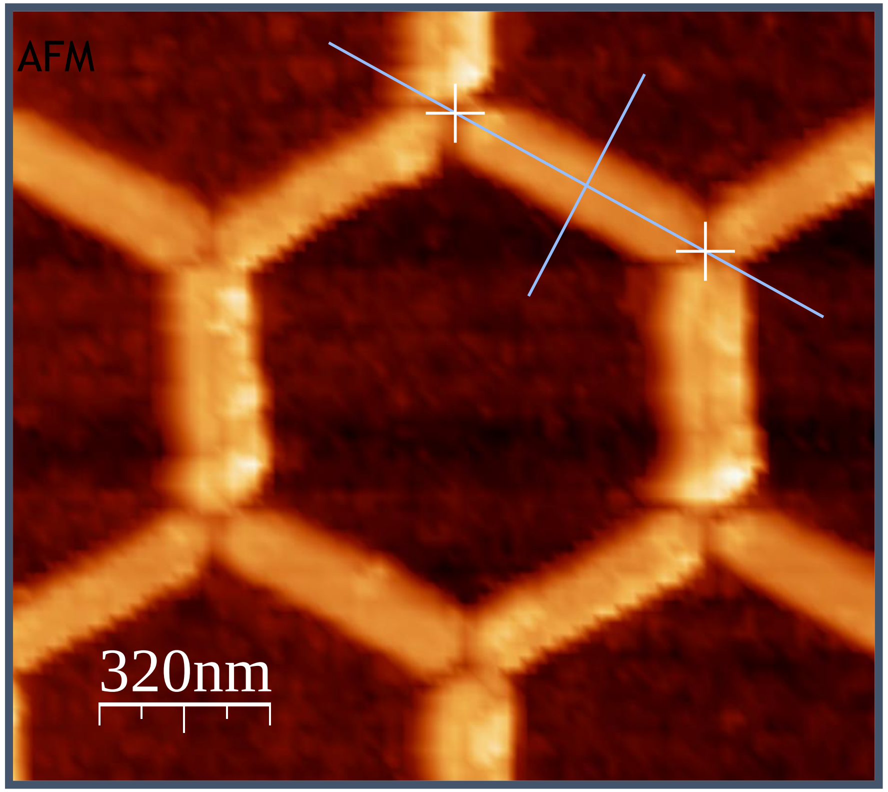


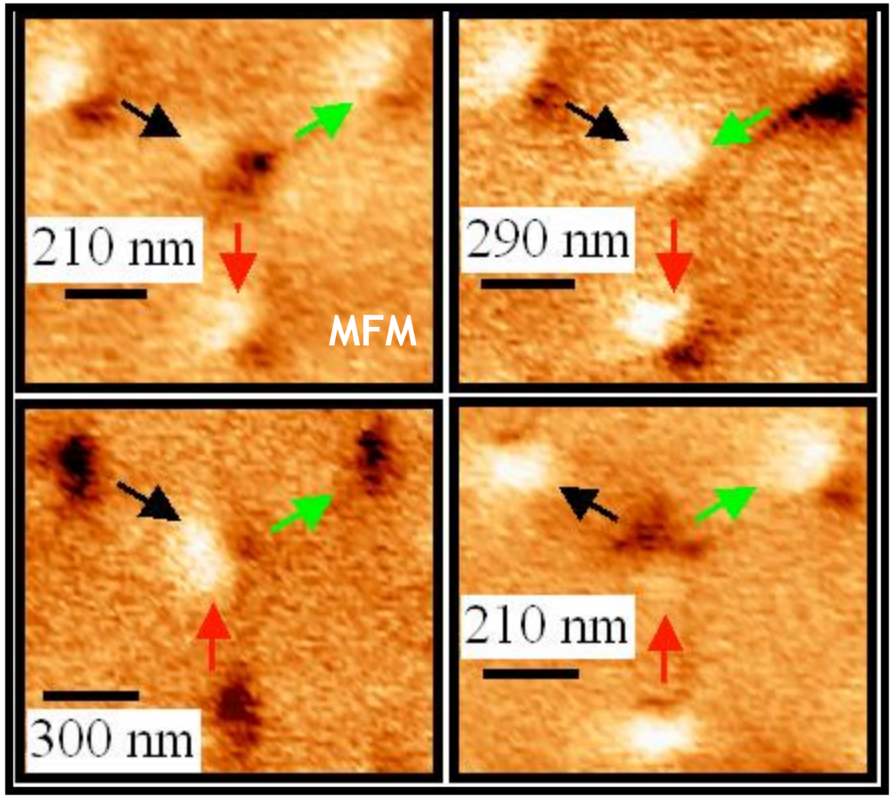
$$\rho = div\,(\vec{M}), \quad \sigma = \vec{M} \bullet \vec{n}$$

https://www.hitachi-hightech.com

$$\sigma = \vec{M} \bullet \vec{n}$$





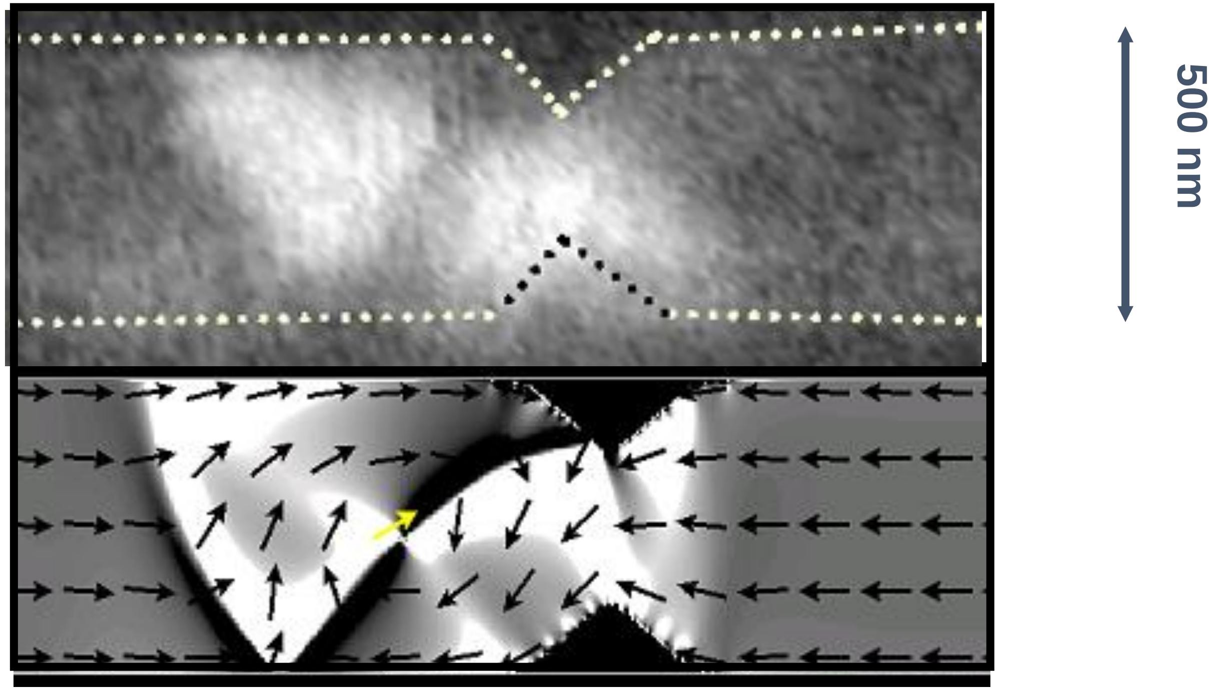


$$\rho = div\,(\vec{M})$$

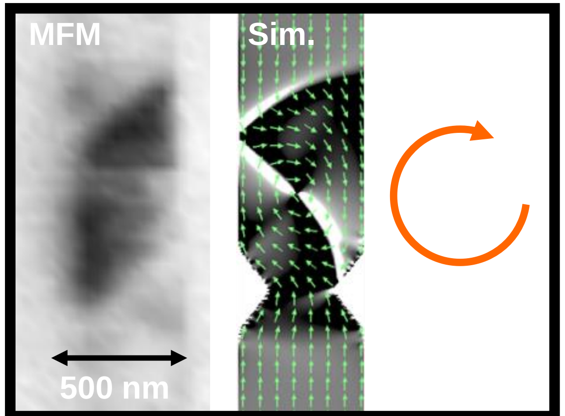
MFM

Simulation

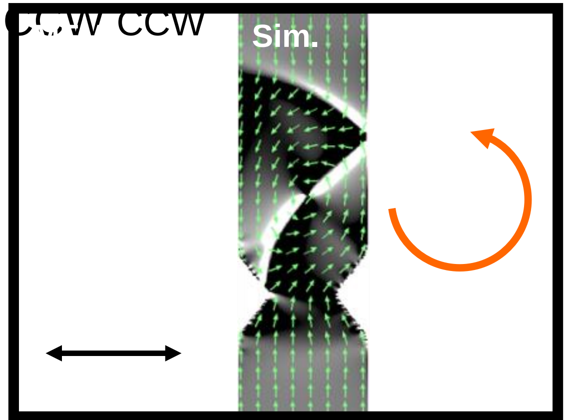
Domain wall Vortex



Domain wall Chirality CW



Domain wall Chirality CCW CCW



MFM - Caracteristic

Contrast mechanism	$\nabla \mathbf{B}_{ext}$
Evaluation of the magnetization, **M**(**r**)	Indire
Spatial resolution (nm) Typical / Limit	300 / 80
Depth of information (nm)	500–1000
Time for image acquisition	30 ms
Limits on applied magnetic fields	None
Imaging conditions	None
Max thickness	None
Sample smoothness	R
Sample clean surface	NR

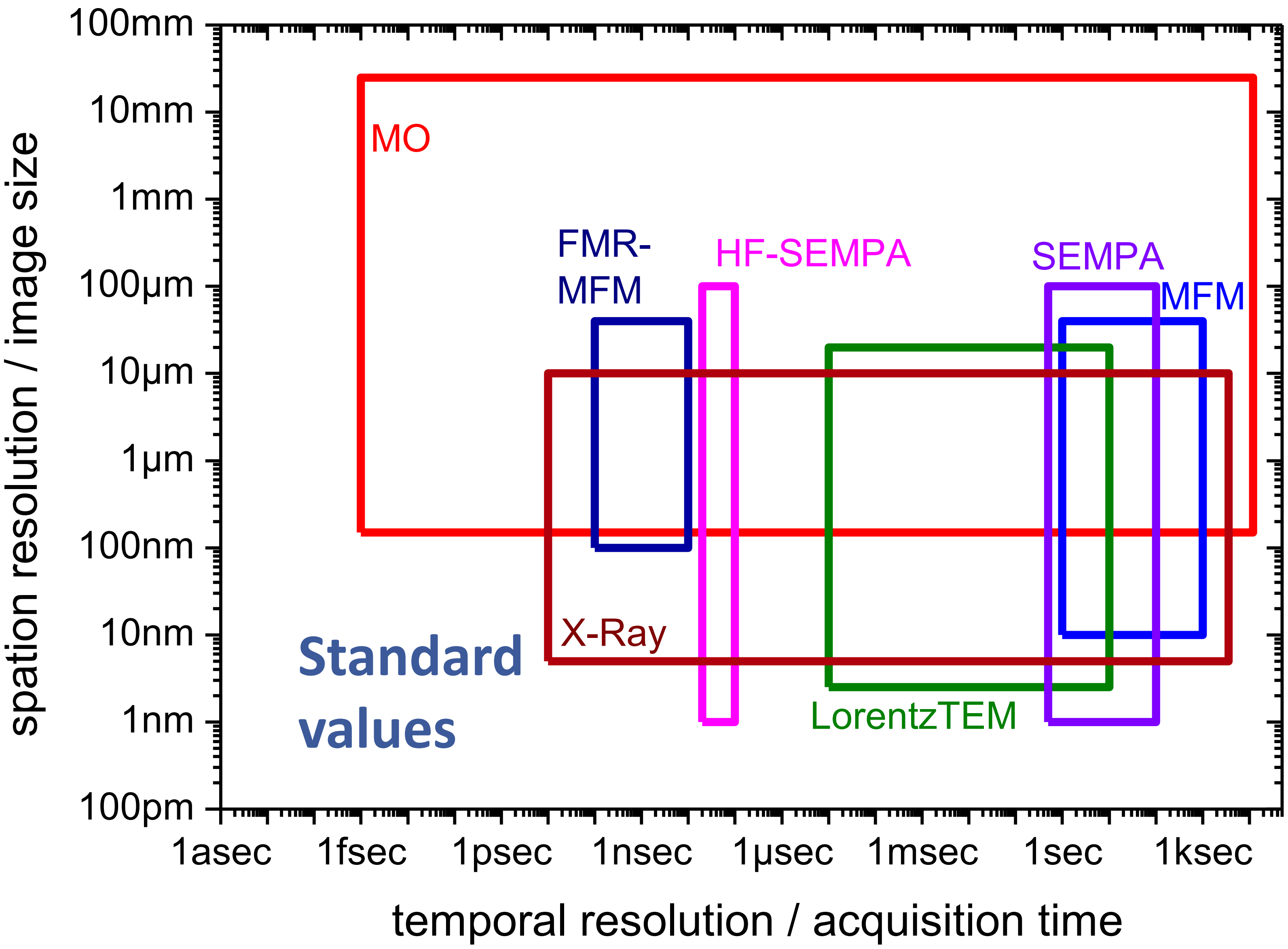
Maps the derivative of the magnetic stray field

$$\vec{F} = \nabla(\vec{m} \bullet \vec{H}_D)$$

Spatial resolution down to 10 nm (vacuum)
Non-destructive
Mostly sensitive to the z-component of stray field (depending on tip)

No sample preparation needed
Surface should be relatively flat

Tip quality is critical
Tip-sample interaction: induced change of magnetic state
Limitations to measure magnetically soft samples



Magneto-optical microscopy (MO)

Scanning electron microscopy (SEMPA)

Transmission electron microscopy (TEM)

X-Ray microscopy

Magnetic force microscopy (MFM)

Thank you !

THE EUROPEAN SCHOOL ON MAGNETISM