INSTITUT JEAN LAMOUR
www.ijl.univ-lorraine.fr

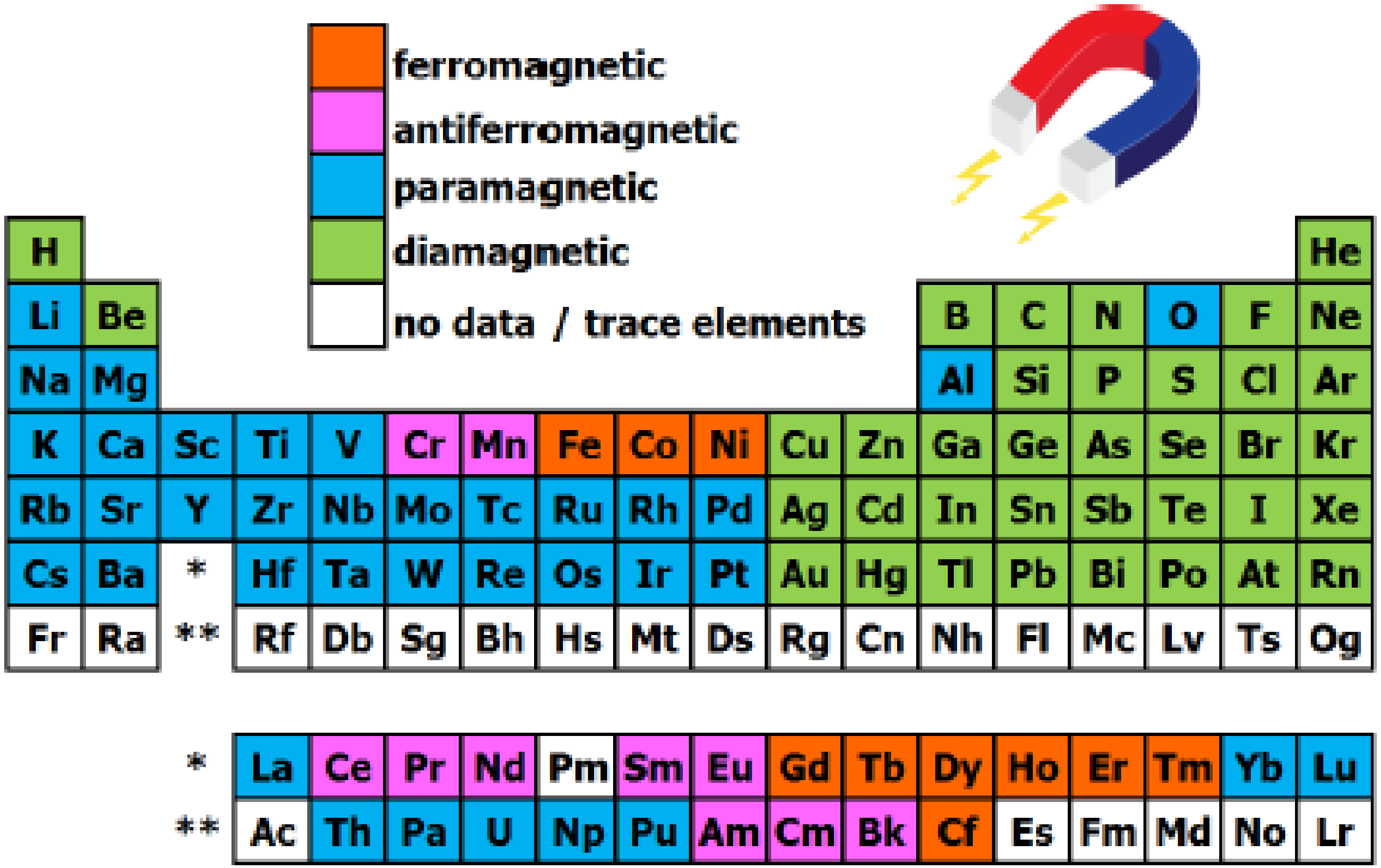
e-ESM, an online higher-education Magnetism event

Introduction to magnetometry techniques

Thomas Hauet

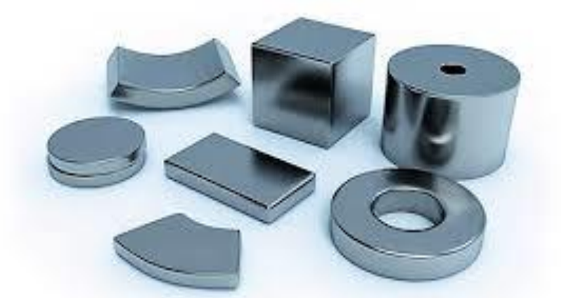
ESM2020, 01/10/2020

Most of the materials are magnetic




frog


Oscillator in Rolex watch


Magnets

Parameters, symbols and units

$$\vec{B} = \mu_0\left(\vec{H} + \vec{M}\right) = \underbrace{\mu_0(1+\chi)}_{\mu}\vec{H} \quad \text{avec} \quad \chi = \partial M / \partial H$$

Parameters : B (induction) in Tesla (= 10^4 Gauss= 10^4 Oe)
H (field) in A/m (H = 1 A/m => B = 1.256 10^{-6} T)
M (magnetization) in A/m (=10^{-3} emu/cm^3)
μ_0 (free space permeability) = 4π.10^{-7} H/m
χ (magnetic susceptibility)

Other material parameters : K (magnetic anisotropy energy) in J/m^3
J (magnetic exchange) in J/m
α (damping) with no unit
m_S , m_{orb}(spin , orbital atomic moment) in μB/atom

Your advisor needs to switch from CGS to SI : 1 emu/cm³ = 1 kA/m 1 erg/cm³ = 0.1 J/m³

Magnetometry

Measure of physical parameters **….** **as a function of external parameters**

- Magnetic moment
- Magnetic susceptibility
- Electrical resistance
- Specific heat
- Ferromagnetic resonance…

- DC or AC magnetic field
- Temperature
- Pressure
- Electric field
- Light…

Material/system

?

Physical parameters as a function of external parameters

Magnetometry : before to start

What type of sample ? Nanoparticles, molecules, liquids, bulk, thin film, devices, …

Which properties am I interested in ? Magnetic moment, susceptibility, spin or orbital moment, non-uniform configuration, damping, anisotropy, …

Which resolution do I need ?

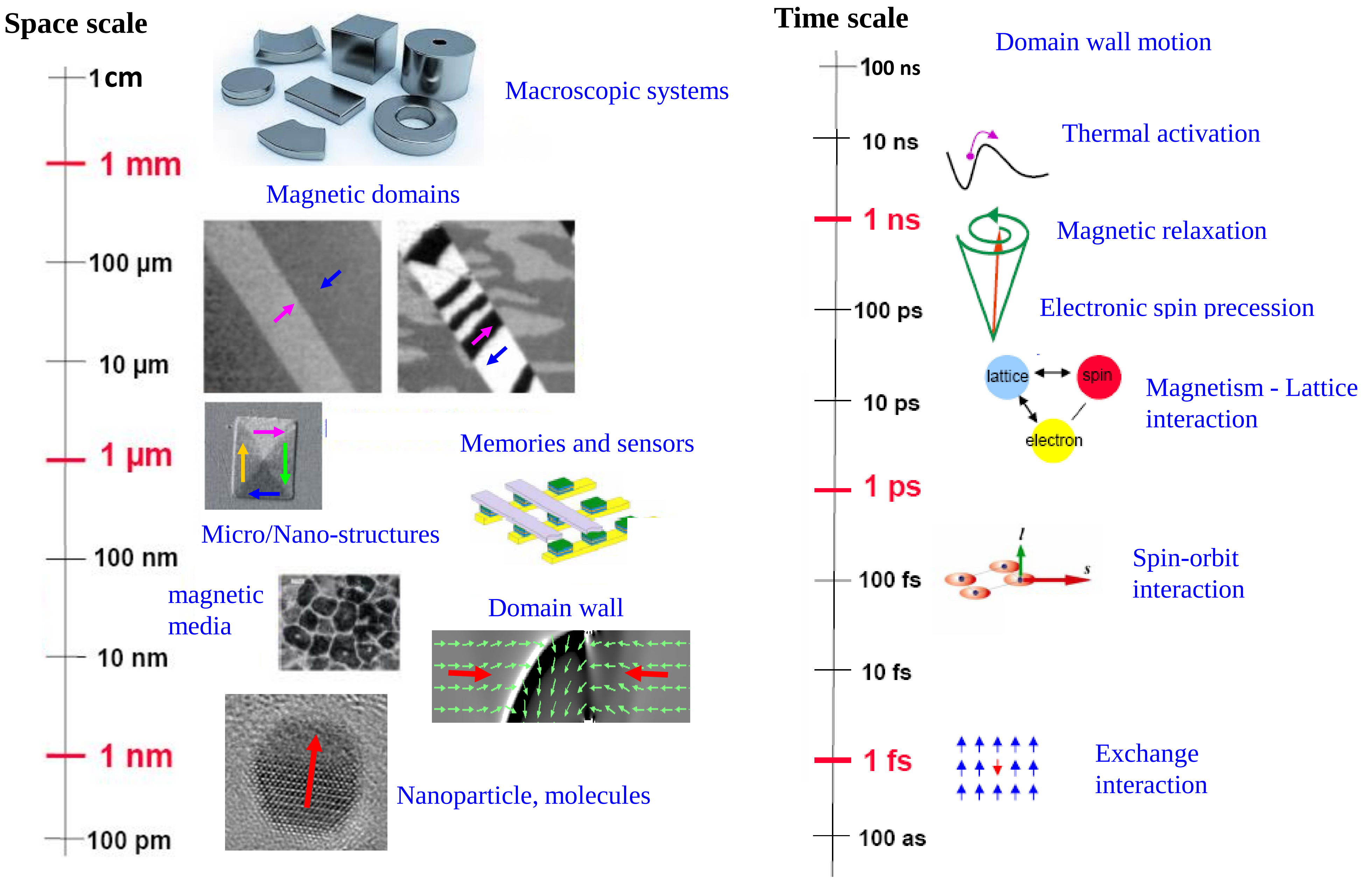
Which excitation do I want to study ? Magnetic field, temperature, electric field, ligth, pressure, …

Under which static condition ? Temperature, vacuum, oxidant atmosphere, pressure, magnetic field, …

Which time scale ? (excitation & measurement) Femtosecond, second, million years, …

Which space scale ? (sample size & measurement) Nanometer, meter, hundred meter, milliliters…

Space and time scales



Magnetometry : Outline

Vibrating sample magnetometry

Magneto-optical Kerr effect

Heat capacity measurement

Superconducting quantum interference device

Torque magnetometry

X-ray circular dichroism

ballistic electron magnetic microscopy

susceptometry

Ferromagnetic Resonance measurement

magnetic force microscopy

photoemission spectroscopy

magnetoresistivity

magnetic resonance force microscopy

N-V magnetometry

magnetic transmission X-ray microscopy

scanning electron microscopy with polarization analysis

scanning near field optical microscopy

spin polarized low energy electron microscopy

spin polarized scanning tunneling microscopy

scanning transmission X-ray microscopy

X-ray photoemission electron microscopy

Neutron diffraction

Outline : 1h30 talk

Vibrating sample magnetometry

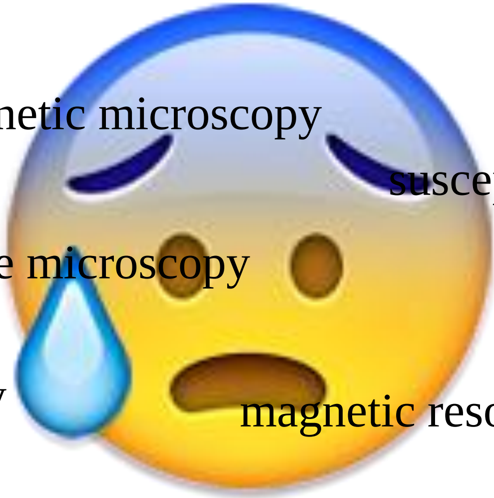
Magneto-optical Kerr effect

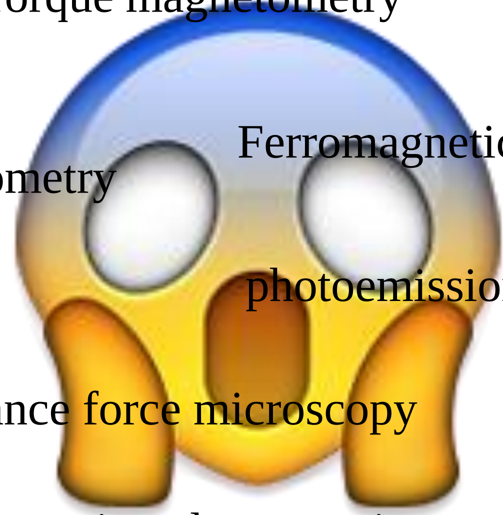
Heat capacity measurement

Superconducting quantum interference device

Torque magnetometry

X-ray circular dichroism





ballistic electron magnetic microscopy

Ferromagnetic Resonance measurement

susceptometry

magnetic force microscopy

photoemission spectroscopy

magnetoresistivity

magnetic resonance force microscopy

N-V magnetometry

magnetic transmission X-ray microscopy

scanning electron microscopy with polarization analysis

scanning near field optical microscopy

spin polarized low energy electron microscopy

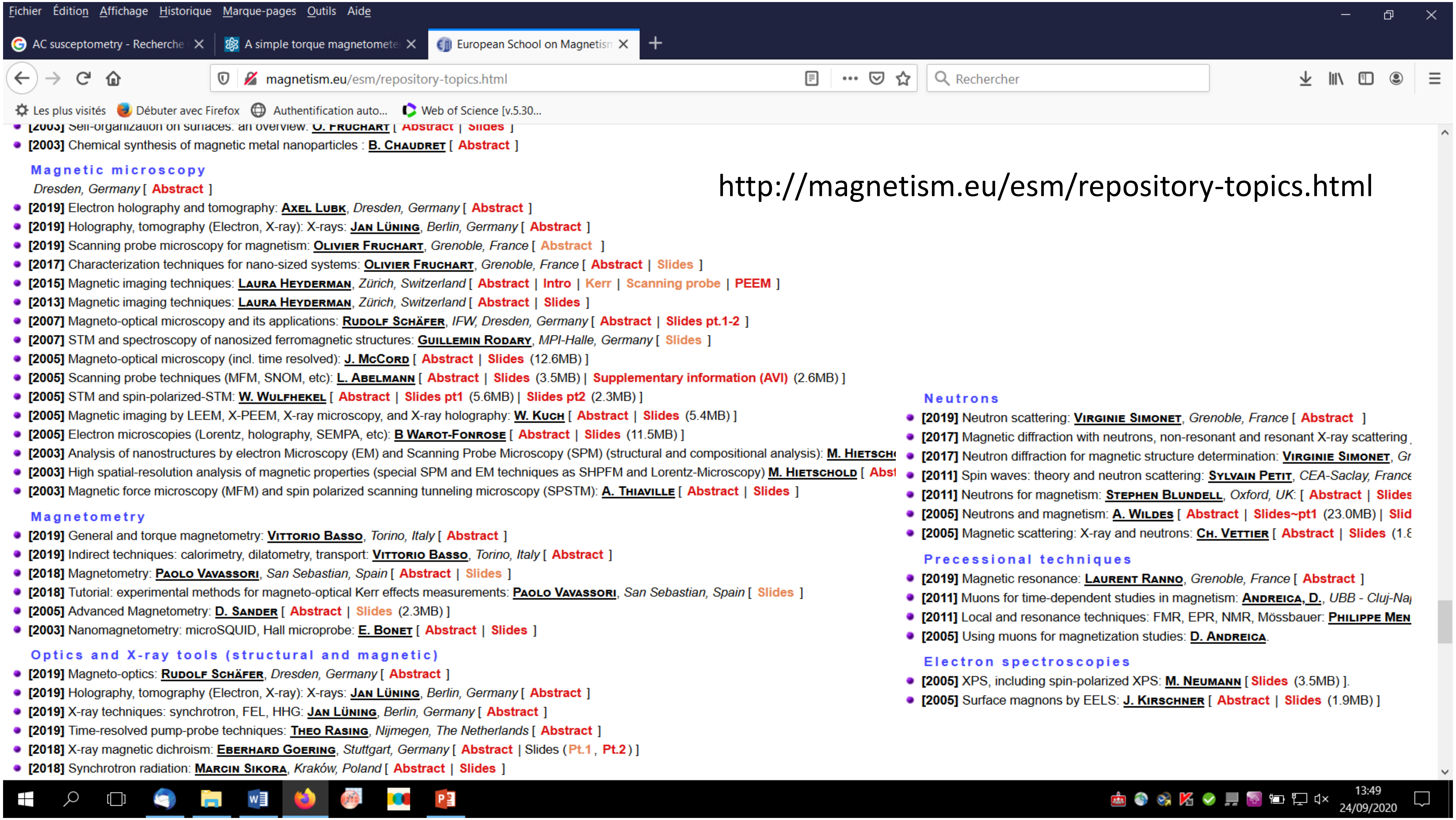
spin polarized scanning tunneling microscopy

scanning transmission X-ray microscopy

X-ray photoemission electron microscopy

Neutron diffraction

Many available data in ESM library



http://magnetism.eu/esm/repository-topics.html

Outline

I. Few preliminary details about the sample environment

→ Magnetic field, Temperature

II. Static macroscopic magnetometry techniques

→ VSM, SQUID, Torque, MOKE, XMCD

III. AC macroscopic magnetometry techniques

→ AC susceptometry

IV. Imaging techniques

→ Scanning probe microscopies, Photon-out

Help from European/French magnetometry networks

Special thanks to F. Mazaleyrat, Ph. Vanderbemden, L. Ranno, C.-S. Chang, B. Hillebrands, O. Fruchart

www.magnetometry.eu www.magnetometrie.cnrs.fr

Outline

I. Few preliminary details about the sample environment

→ **Magnetic field**, Temperature

II. Static macroscopic magnetometry techniques

→ VSM, SQUID, Torque, MOKE, XMCD, Photo-emission spectroscopy

III. AC macroscopic magnetometry techniques

→ AC susceptometry, FMR

IV. Imaging techniques

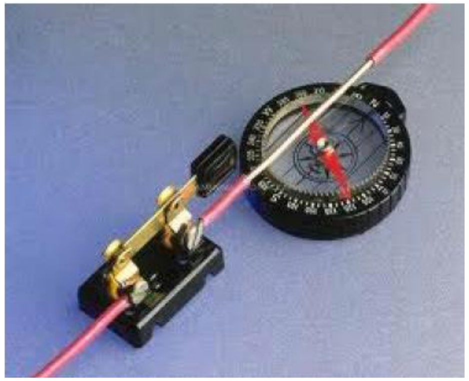
→ Scanning probe microscopies, Photon-out, Electron-out

Magnetic field amplitude scale

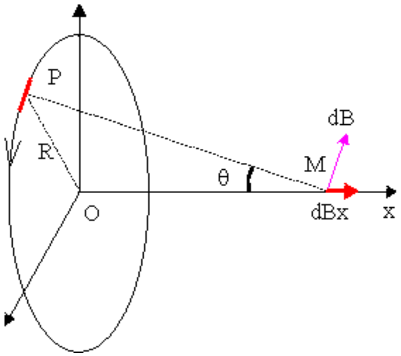
Human brain	10^{-15} T
Earth's magnetic field	$5x\ 10^{-5}$ T
Refrigerator magnet	0.05 T
Computer	0.1 T
MRI scanner	1 - 7 T
Laboratoire de Champs Magnétiques Intenses	**37 T**
Pulsed field magnet	100 T
White dwarf star	10 000 T
Pulsar	100 000 000 T

usual magnetometers (0.05 T – 7 T)

How to generate a magnetic field



1820 - Hans Christian Oersted



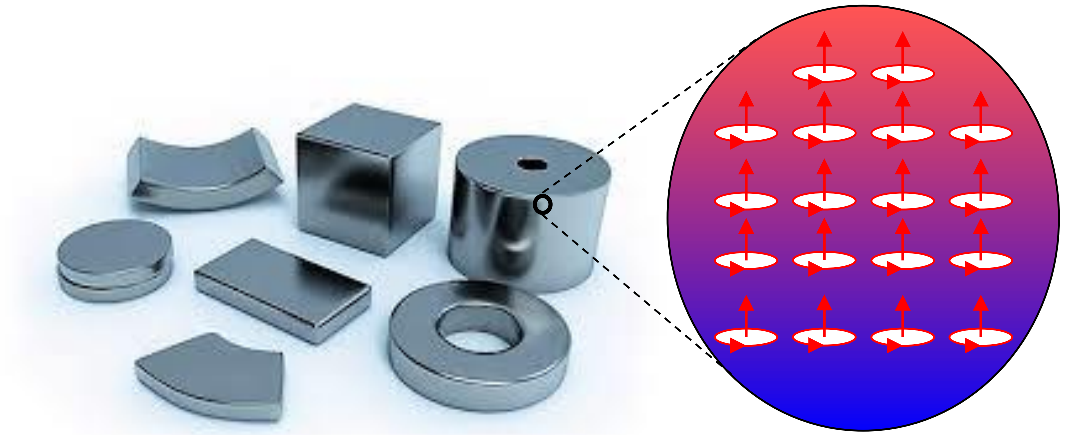
$$d\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \frac{I\, d\vec{l} \wedge (\vec{r} - \vec{r'})}{|\vec{r} - \vec{r'}|^3}.$$

Electromagnets :

- Requieres electric energy

  1 coil with R=25mm and 40 kA generates 1 Tesla

- Non-uniform or uniform fields
- Field can be tuned easily with current
- Can produce **DC, AC or pulsed fields** (µs, ns)

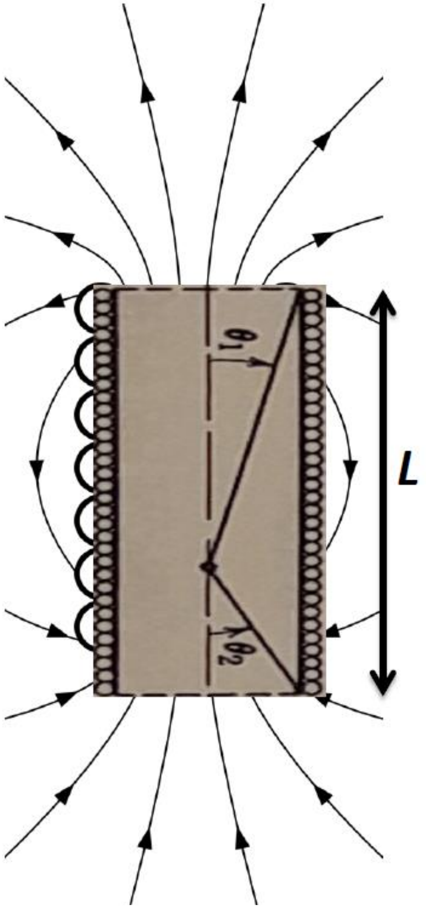


Permanent magnets :

- Assembly of dipoles $\vec{B} = \frac{\mu_0}{4\pi}\left[\frac{3(\vec{\mathcal{M}} \cdot \vec{r'}) \cdot \vec{r'}}{r'^5} - \frac{\vec{\mathcal{M}}}{r'^3}\right]$
- ***DC Magnetic flux with no energy***
- Non-uniform and uniform fields
- Big advantage for small sample space

Electromagnets : homogeneous field up to 3 Tesla

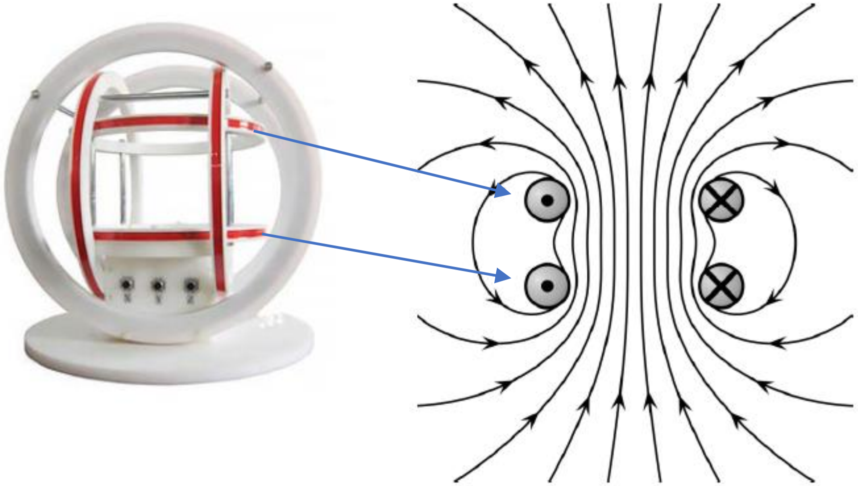
Coilset with N turns



Field along z-axis for N turns, current *I* and length *L*

$$B_z(z) = \frac{NI}{L}\left(\cos\theta_1 + \cos\theta_2\right)$$

Coilset in Helmoltz geometry

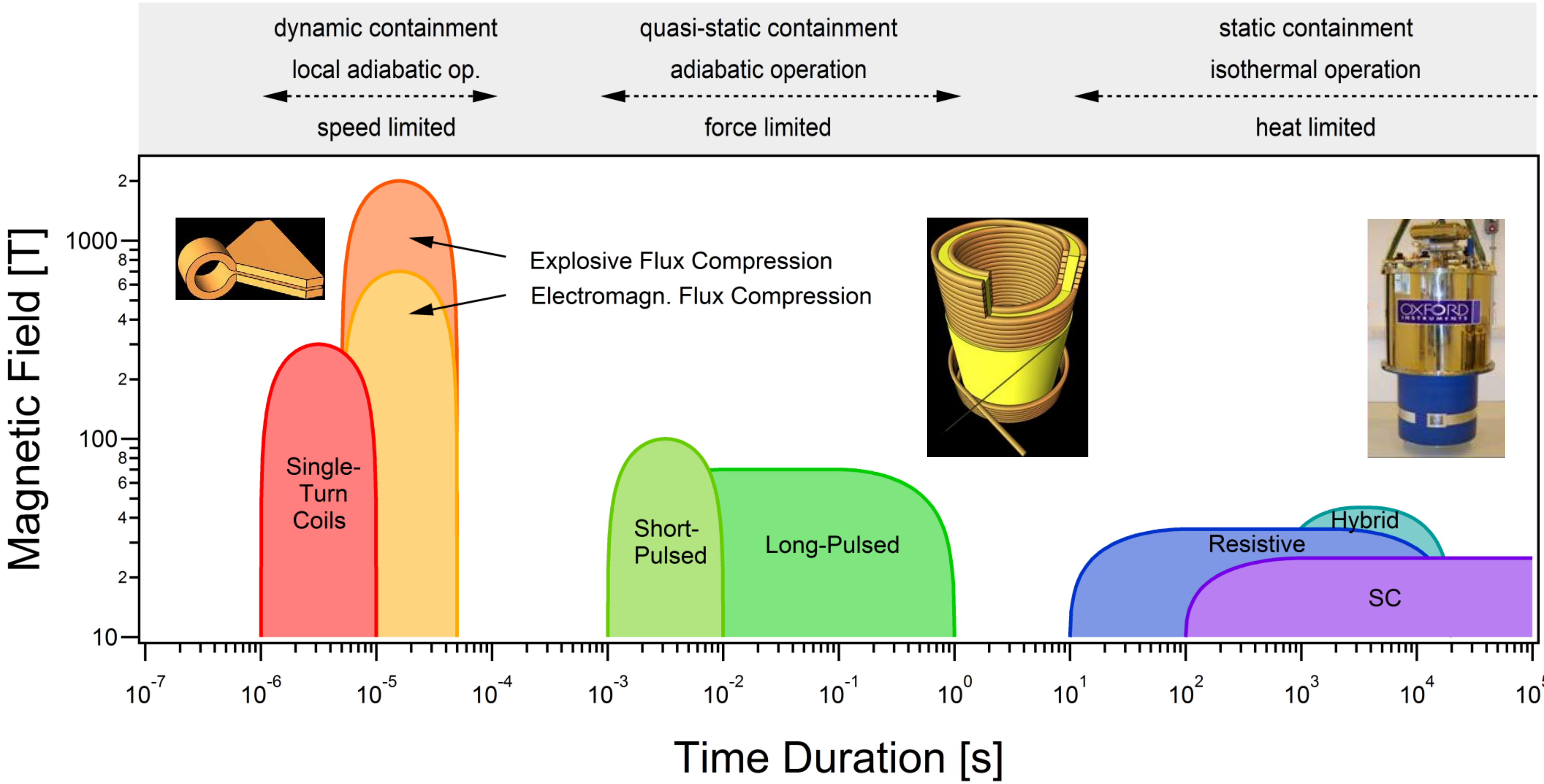


$$B_z(z) = \frac{\mu_0 I R^2}{d^3}\left[1 + \frac{3\left(b^2 - R^2\right)}{2d^4} z^2 + \frac{15(b^4 - 6b^2R^2 + 2R^4)}{16d^8} z^4 + \ldots\right]$$

Coil radius *R*, Coil distance *b*, Helmholtz condition: *b* = *R* → quadratic term vanishes

$$d = \sqrt{R^2 + \frac{1}{4}b^2}$$

Fields above 3 Tesla



Limitations :

1) Energy dissipation $P = \int \rho(x)\, \mathbf{J}^2(x) d^3x \propto \mathbf{B}^2$

2) Force de Lorentz $\mathbf{F} = \int \mathbf{J}(x) \times \mathbf{B}(\mathbf{x}) d^3x \propto \mathbf{B}^2$

Superconducting electromagnets

NbTi LTS	Nb_3Sn LTS	MgB_2 MTS	Bi-2212/Bi-2223 HTS	YBCO HTS
Tc = 9.8 K	Tc = 18.1 K	Tc=39K	Tc = 90-110K	Tc = 90-135K
Bmax	Bmax	Bmax	Bmax > 40 T @4.2K;	Bmax > 40 T @4.2K
(4.2K) 9.5T	(4.2K) 20T	(4k) 5T-10T ?	8 T @20K	12 T @20K
(2.2K) 11.5T	(2.2K) 23.5T		4 T @65K	8 T @65K

1960 (4 T)
NbZr, NbTi

7T

2000 (14 T)
Nb_3Sn split pair

2010 (23.5 T)
NbTi + Nb_3Sn

2018 (32 T)
NbTi+Nb_3Sn+HTS

2019 (32 T)
resistive+HTS

Outline

I. Few preliminary details about the sample environment

→ Magnetic field, **Temperature**

II. Static macroscopic magnetometry techniques

→ VSM, SQUID, Torque, MOKE, XMCD

III. AC macroscopic magnetometry techniques

→ AC susceptometry

IV. Imaging techniques

→ Scanning probe microscopies, Photon-out

Quick reminder on heat transfers

Radiation : **In average the coldest region gets more photons from the hotest region than it loses itself**

Stefan-Boltzmann's Law defines the relationship between the emission of black bodies with its temperature

Surface density of Radiative power= $\sigma \, \epsilon \, T^4$

σ : Stefan constant, ϵ : émissivity, T : temperature

Ways to limit radidative heat transfer :
- **reflective materials (metals with low roughness)**
- **thermal Screening by absorbant materials (N_2)**

Quick reminder on heat transfers

Radiation : In average, the coldest region gets more photons from the hotest region than it loses itself

Ways to limit radidative heat transfer :
- reflective materials (metals with low roughness)
- thermal Screening by absorbant materials (N2)

Conduction : Heat transfer, without moving material, between two media of different temperature (vibrations)

Fourier law's : heat flux density $= -\lambda \, \overrightarrow{grad} \, T$

(λ: Thermal conductivity)

Ways to limit heat transfer through conduction :
- **Materials with low thermal conductivity (thermal insulation)**
- **Removing materials between two region (vacuum)**

Quick reminder on heat transfers

Radiation : In average, the coldest region gets more photons from the hotest region than it loses

Ways to limit radidative heat transfer : - reflective materials (metals with low roughness)

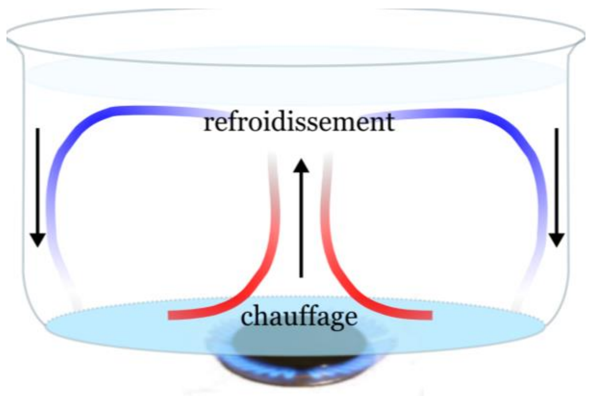
- thermal Screening by absorbant materials (N2)

Conduction : Heat transfer, without moving material, between two media of different temperature (vibrations)

Ways to limit heat transfer through conduction : - materials with low thermal conductivity (thermal insulation)

- absence of materials between two regions (vaccuum)

Convection : **Heat transfer by moving matter**

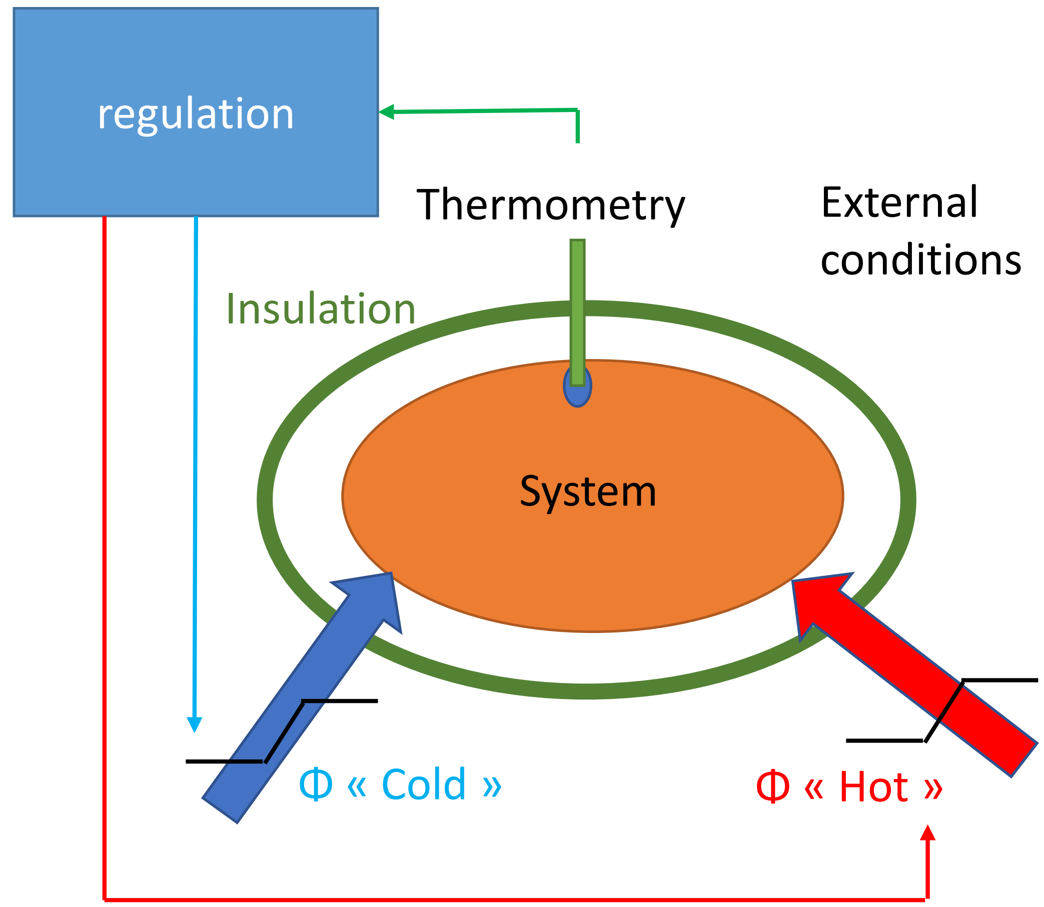


Ways to limit convective heat transfer : **- to limit matter motion**

- absence of matter between the two regions (vacuum)

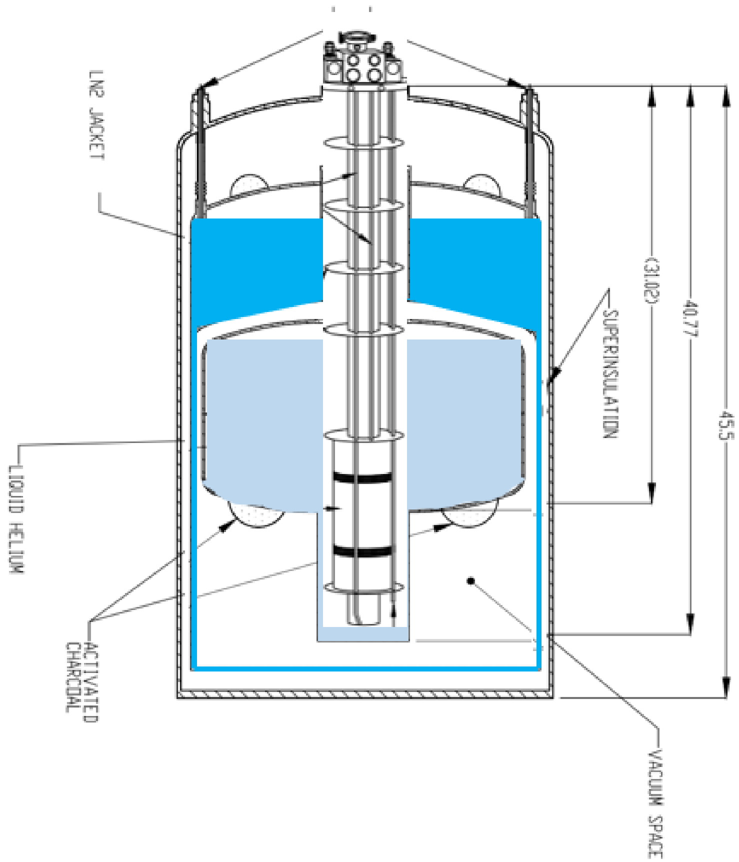
General design of a cryostat

1) Low temperature source
    - Cold flux
2) High temperature source
    - Hot flux
3) Control of the environment
    - Insulated system
4) Measure of tempearture
    - Well chosen thermometer

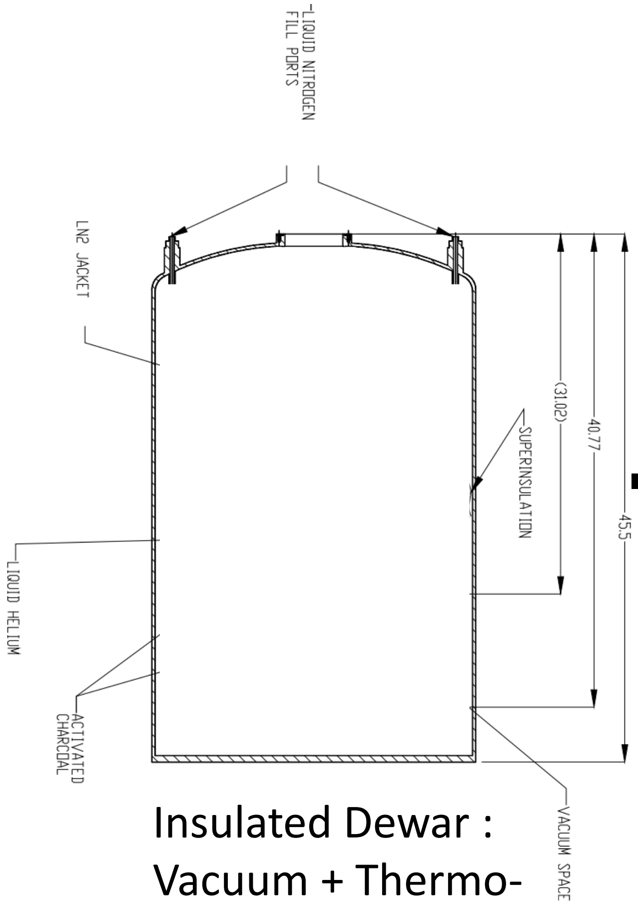


One example : QD PPMS cryostat

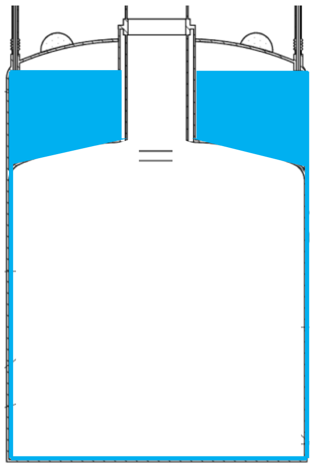
What’s inside ?



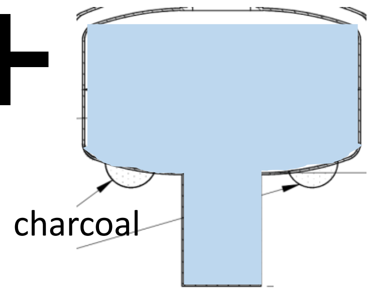
One example : QD PPMS cryostat



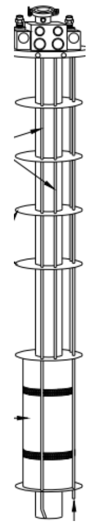
+



+



+



Insulated Dewar : Vacuum + Thermo-reflective walls

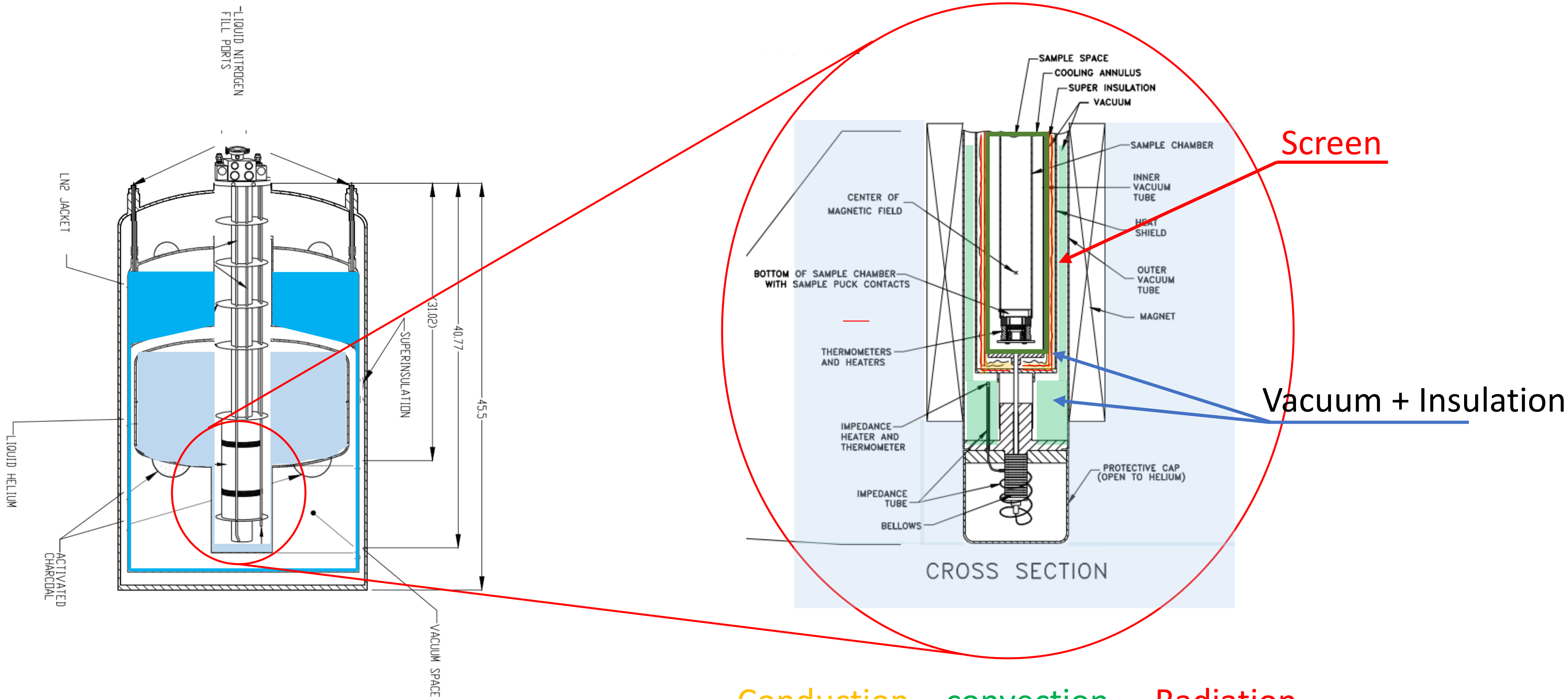
Cold screen LN2+ Vacuum + Thermo-reflective walls

LHe reservoir

PPMS Probe

~~Conduction~~ – ~~convection – Radiation~~

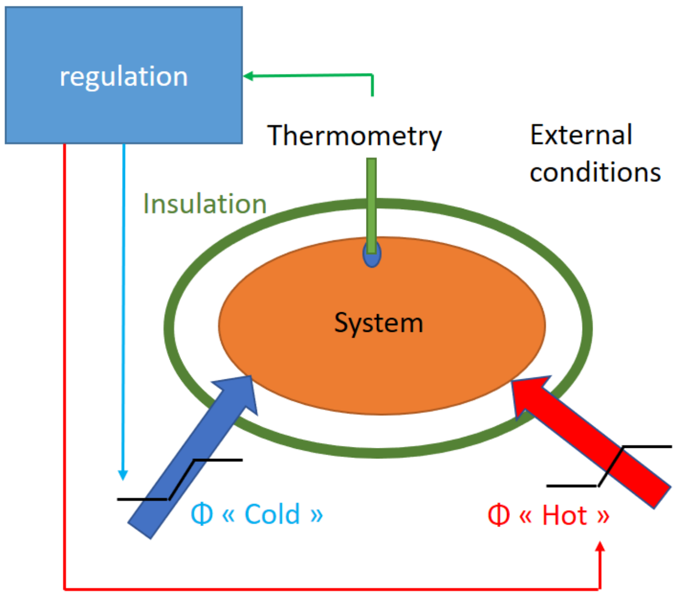
One example： QD PPMS cryostat

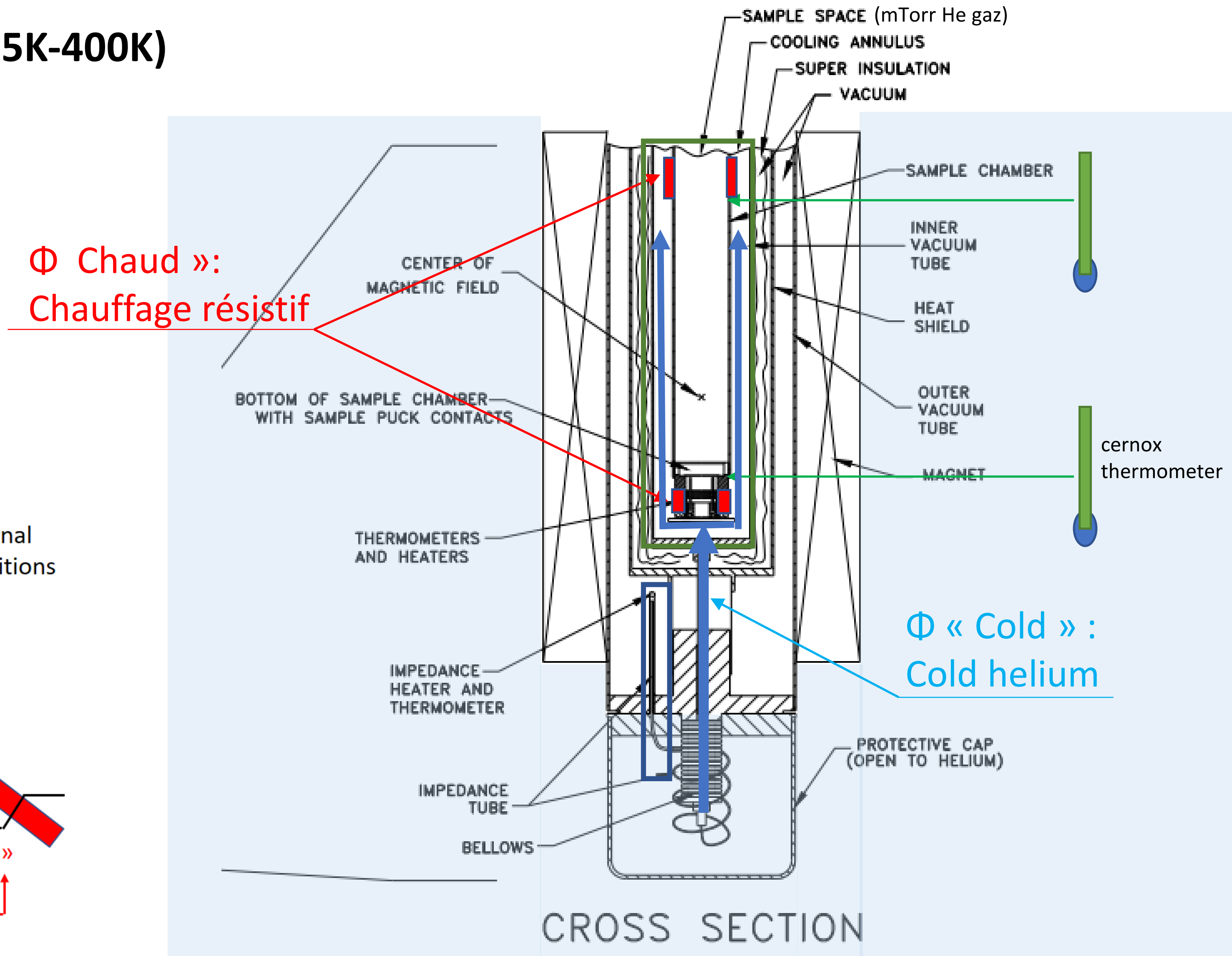


~~Conduction~~ – ~~convection~~ – ~~Radiation~~

One example : QD PPMS cryostat

Temperature control (5K-400K)





One example : QD PPMS cryostat

Temperature control (5K-400K)

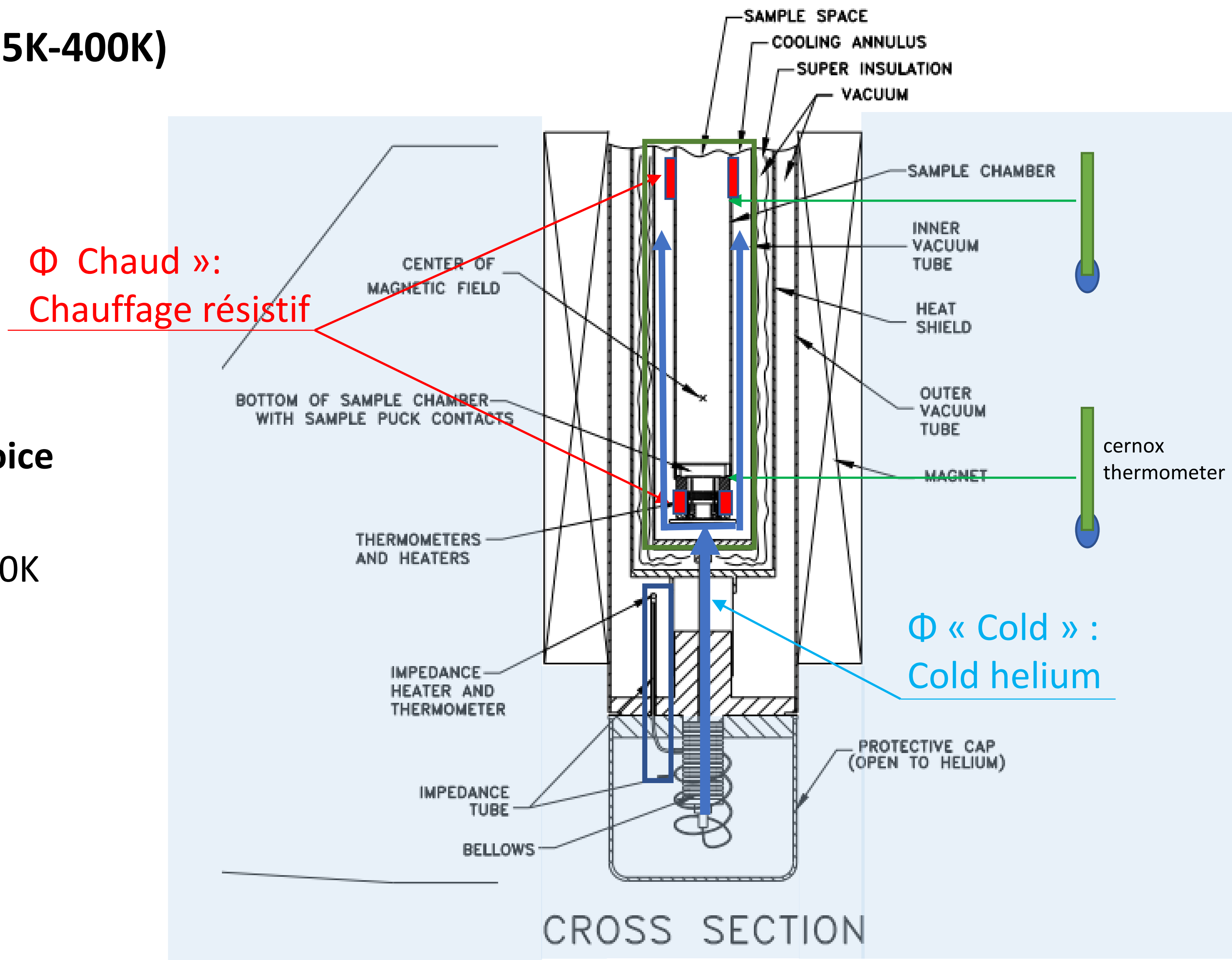
Thermometers choice

Cernox : 100mK -> 325 K
Platine resistance: 30K -> 800K

Typical magnetic field-dependent temperature errors[4] Δ T/T (%) at B (magnetic induction)

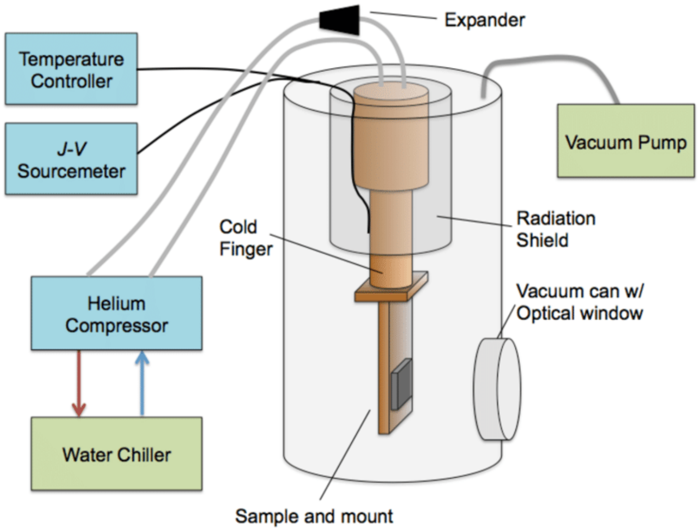
Package base parallel to field B					
T (K)	2.5 T	5 T	8 T	14 T	19 T
20	20	—	100	250	—
40	0.5	1.5	3	6	8.8
87	0.04	0.14	0.4	1	1.7
300	-0.01	0.001	0.02	0.07	0.13

[4] *Recommended for use when T = 30 K*

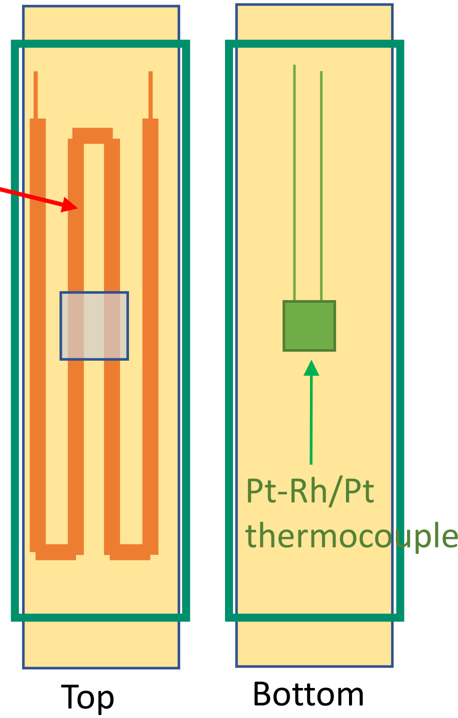


Other typical temperature control set ups

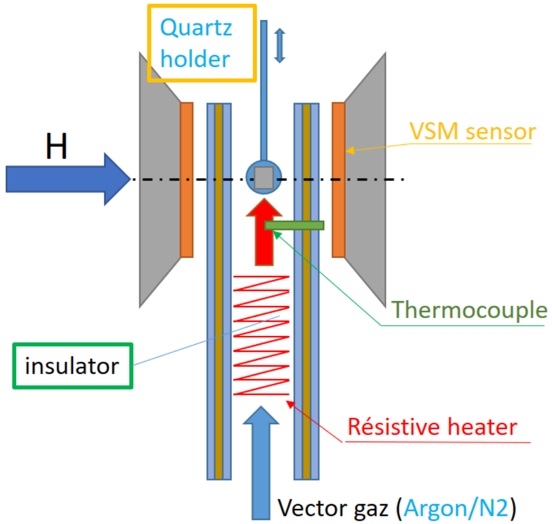
Cold finger crysotat



Resistive heater



Temperature control through gaz flow (conduction)



Outline

I. Few preliminary details about the sample environment

➡ Magnetic field, Temperature

II. Static macroscopic magnetometry techniques

➡ **VSM, SQUID**, Torque, MOKE, XMCD, Photo-emission spectroscopy

III. AC macroscopic magnetometry techniques

➡ AC susceptometry, FMR

IV. Imaging techniques

➡ Scanning probe microscopies, Photon-out, Electron-out

Macroscopic moment measurement

do not confuse the two m's : « M » and « m »

Magnetic moment [Am²]
or [emu] = [10^{-3} Am²]

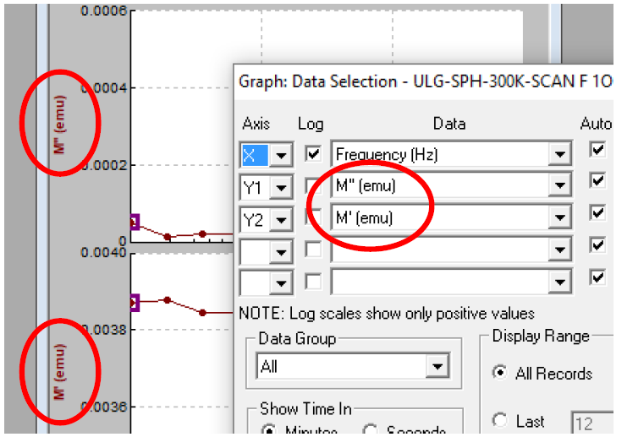
$$M = \frac{m}{V}$$

Parameter that is measured with VSM or SQUID

Magnetisation [A/m]

Volume [m³]

But in some tools you can find :

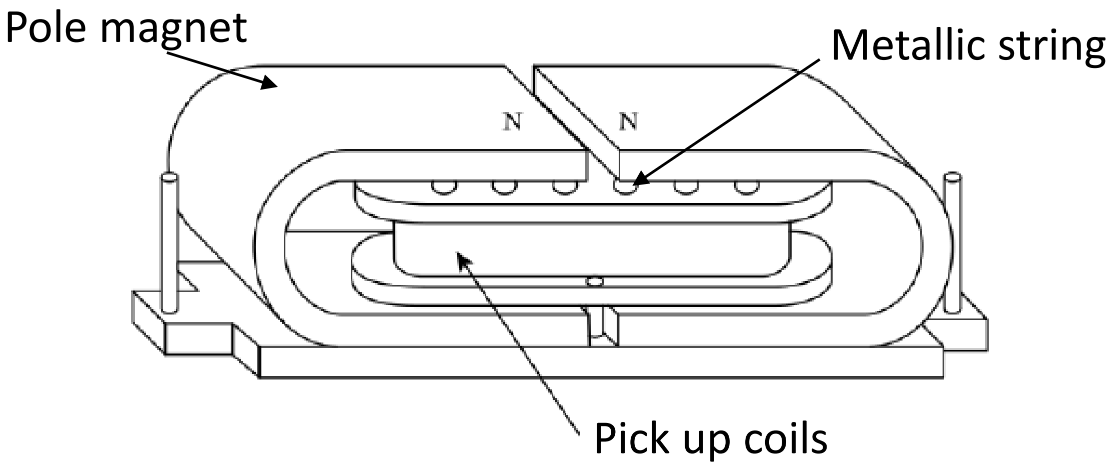


(argh!)

Induction to detect guitar string motion (1950's)

Figure 1 — The Frying Pan, *guitare hawaïenne* solid-body, *Rickenbaker 1931.*
[Pierrick Lotton, musique & technique, 2009]

Gibson Les Paul 1952



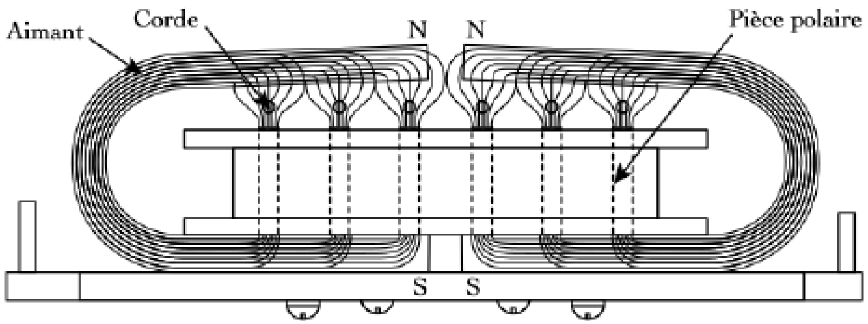


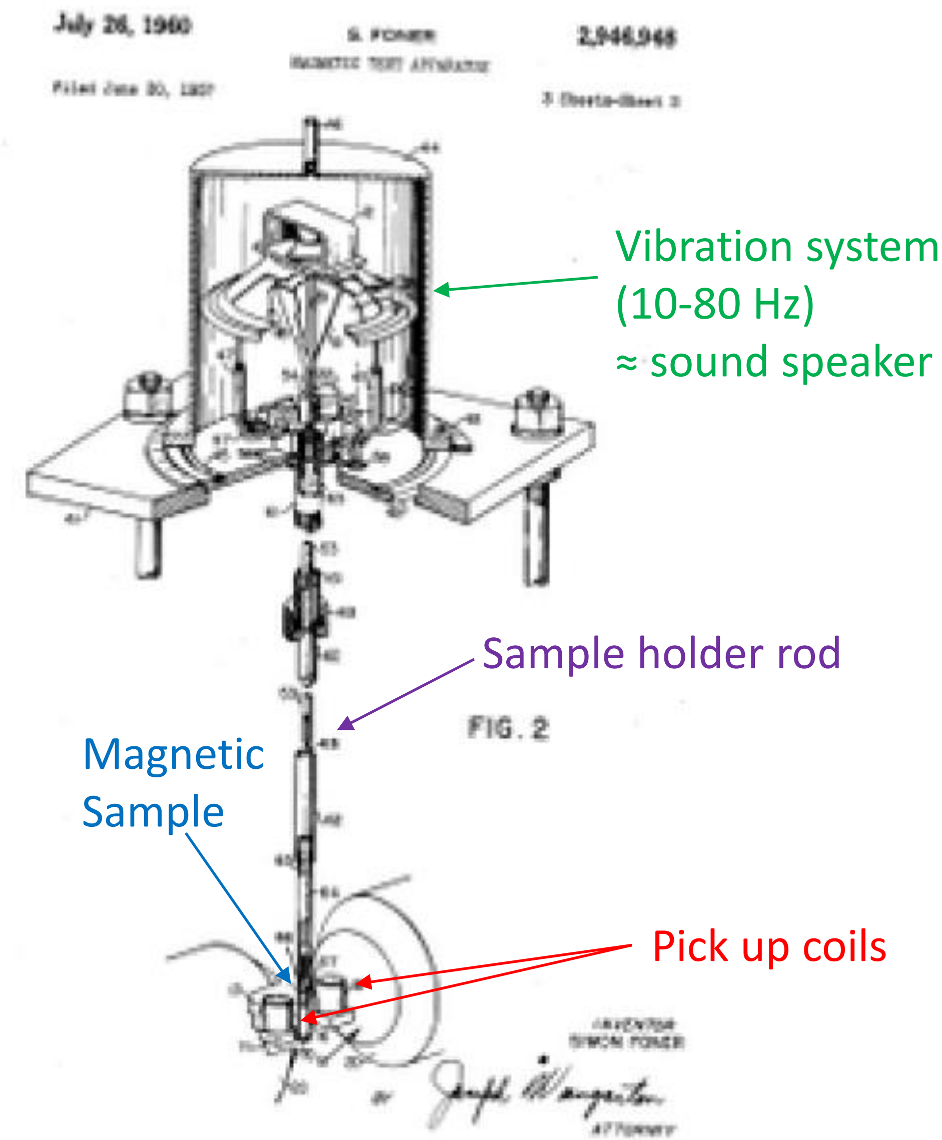
Figure 2 — Pickup *développé par G. Beauchamp pour Ric-kenbaker.*

String vibrations ➡ **AC magnetic field inside the pick up coils** ➡ **AC electrical current**

First vibrating sample magnetometer (1959)

Rev. of Scientific Instr. 1959
Brevet déposé en 1960

Simon FONER 1925 † 2007



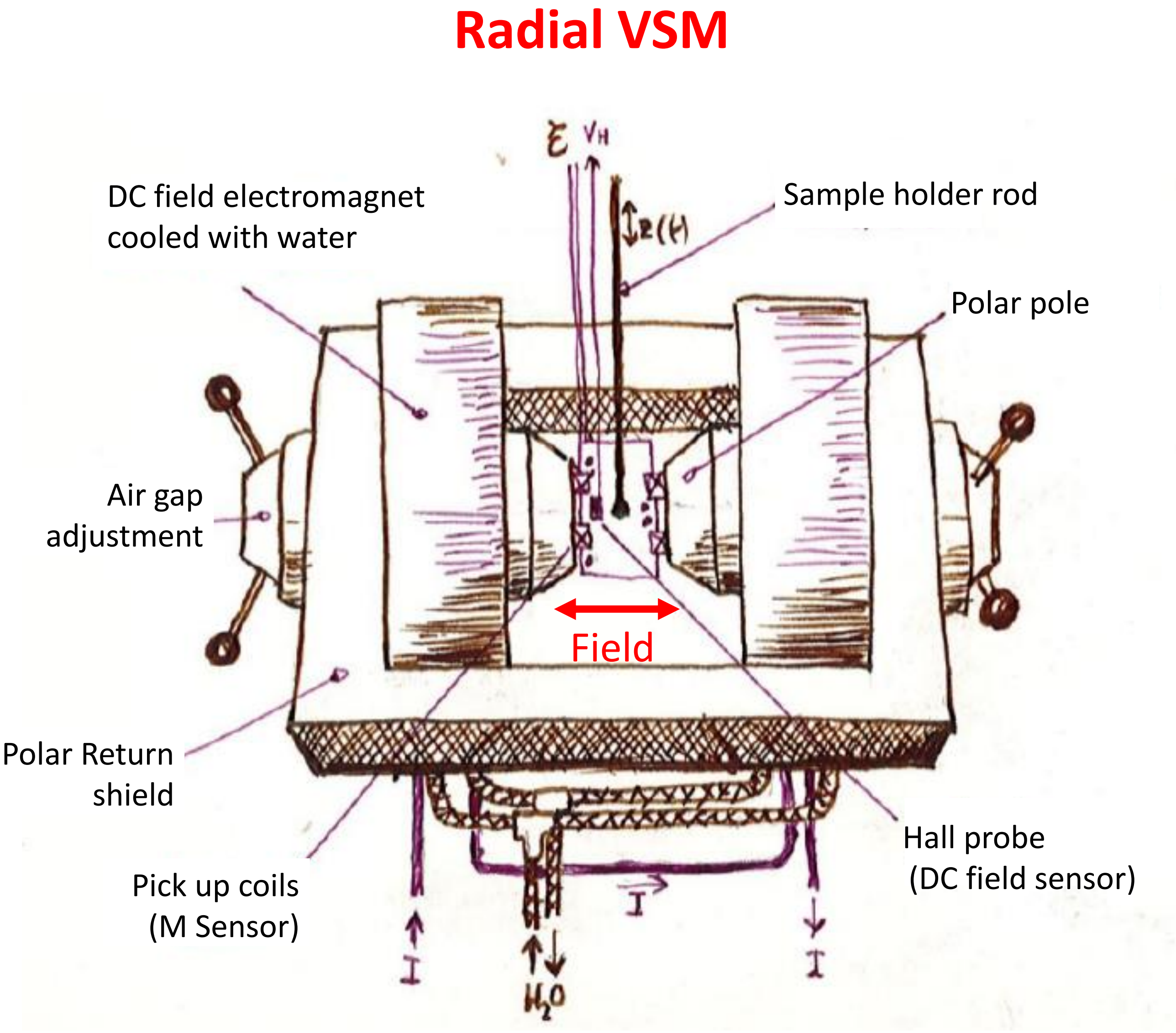
J. Appl. Phys. **79** (8), 15 April 1996

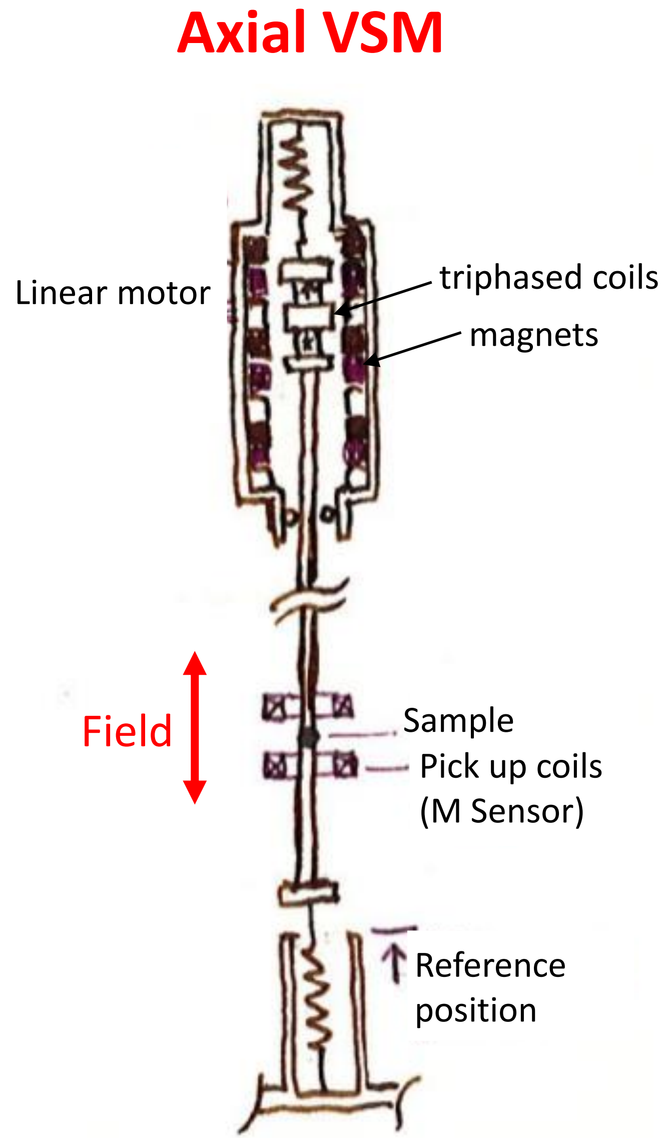
The vibrating sample magnetometer: Experiences of a volunteer

S. Foner
Francis Bitter National Magnet Laboratory and Department of Physics, MIT, Cambridge, Massachusetts 02139

That summer we were living in a small farm-hand's house about 1 km from the laboratory and just off the runway at Hanscom Field, a Strategic Air Command (SAC) base at that time. While shaving one evening I decided to try ac induction for magnetic measurements. With some Duco cement, a small \$2.00 (in 1955) replacement loudspeaker, a conical paper cup, and a paper straw (the latter components were light and conveniently available at night from the lunch room), the first working model VSM was assembled. Initial

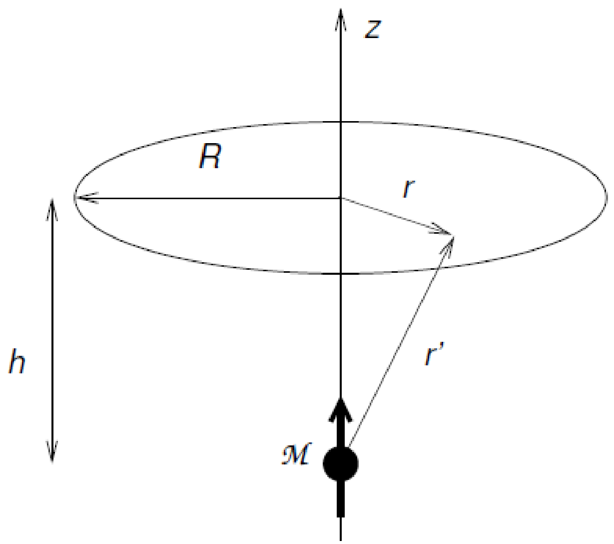
Two VSM geometries





Axial VSM equations

If the sample is considered as a single magnetic dipole :



$$\vec{B} = \frac{\mu_0}{4\pi}\left[\frac{3(\vec{\mathcal{M}}\cdot\vec{r'})\cdot\vec{r'}}{r'^5} - \frac{\vec{\mathcal{M}}}{r'^3}\right]$$

$$B_z = \frac{\mu_0}{4\pi}\left[\frac{3\mathcal{M}h^2}{(h^2+r^2)^{5/2}} - \frac{\mathcal{M}}{(h^2+r^2)^{3/2}}\right]$$

$$\phi = \int B_z dS = \int_0^R \frac{\mu_0}{4\pi}\left[\frac{3\mathcal{M}h^2}{(h^2+r^2)^{5/2}} - \frac{\mathcal{M}}{(h^2+r^2)^{3/2}}\right] 2\pi r dr$$

$$= \frac{\mu_0\mathcal{M}}{2}\left[-\frac{3h^2}{(h^2+R^2)^{3/2}} + \frac{1}{(h^2+R^2)^{1/2}}\right]$$

Taylor : $\phi = \frac{\mu_0\mathcal{M}}{2R}\left[-3 + \frac{9h^4}{2R^4} + 1 - \frac{h^2}{2R^2} + \frac{3h^4}{8R^4} + o(\frac{h^6}{R^6})\right]$

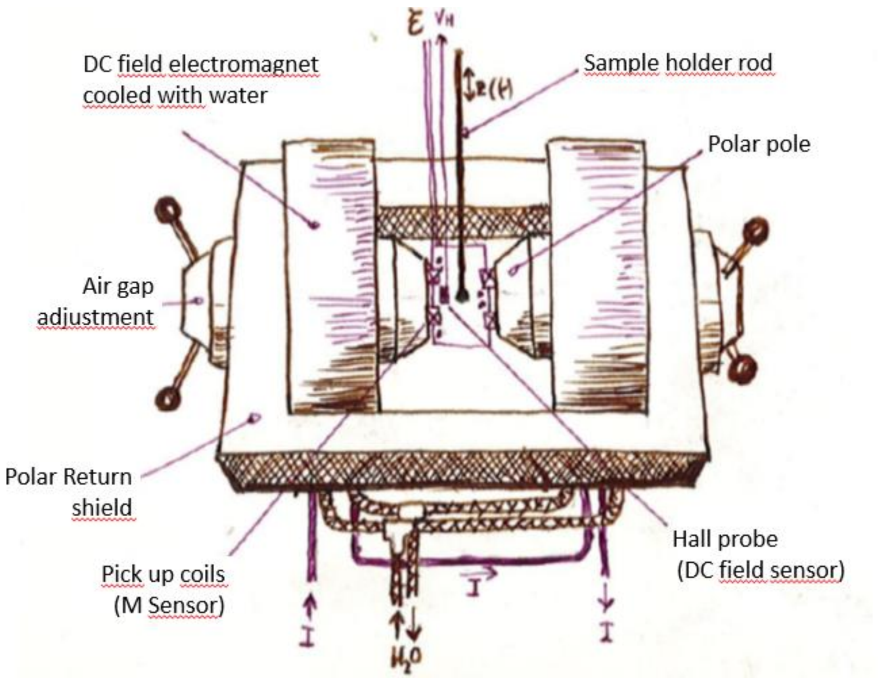
H<<R

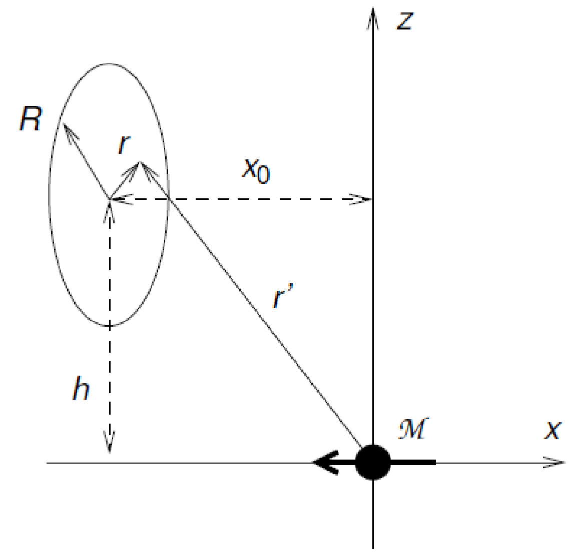
If the sample vibrates along z : $h(t) = h + a\sin(\omega t),\ a \ll h$

$$\frac{d\phi}{dt} = \frac{-\mu_0\mathcal{M}}{4R^3}\frac{d}{dt}\left(h^2 + 2ah\sin(\omega t) + a^2\sin^2(\omega t)\right)$$

Induced fem for n spires : $\mathcal{E} = -n\frac{d\phi}{dt} = \frac{n\mu_0\mathcal{M}ha\omega}{2R^3}$

Radial VSM equations

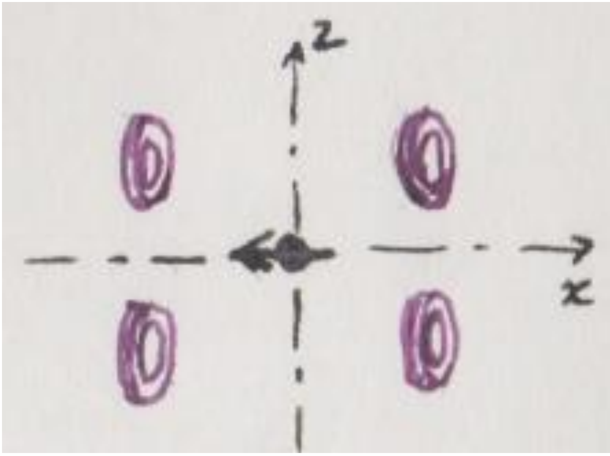




$$\mathcal{E} = \frac{3}{2} n \mu_0 \mathcal{M} a \iint \frac{r(r \sin\theta + h)}{r'^5} \left(5 \frac{x_0^2}{r'^2} - 1 \right) \mathrm{d}r \mathrm{d}\theta$$

$$r'^2 = x_0^2 + r^2 \cos^2\theta + (r \sin\theta + h)^2$$

$$h(t) = h + a \sin(\omega t)$$



Both VSMs carry good sensitivity (down to 10^{-9} A.m^2) because of the synchronous detection (Lock-In)

Two VSM geometries : usual tools

Radial VSM

MicroSense (USA),

Up to 2.7 Tesla
300K up to 1200K
Easy sample rotation

LakeShore (USA)

Axial VSM

Quantum Design (USA)

Up to 9-14 Tesla
2K up to 400K

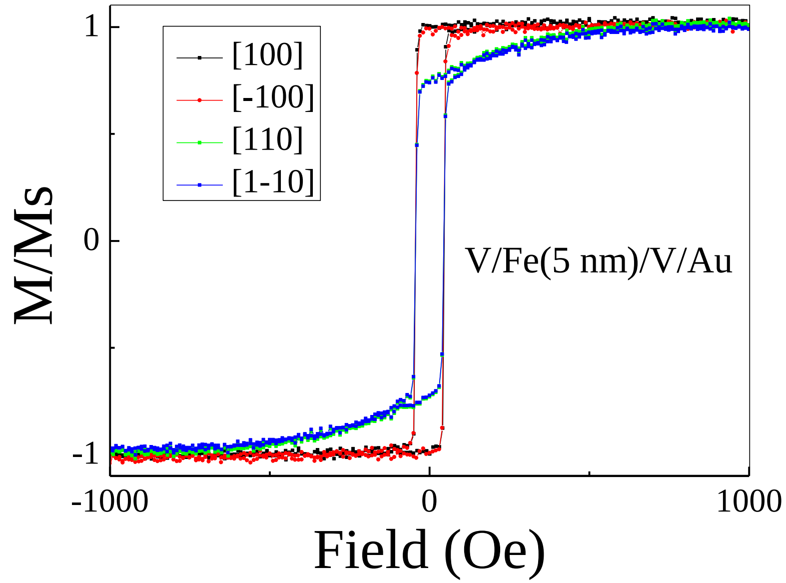
Cryogenic (UK)

Example 1 : anisotropies in crystals

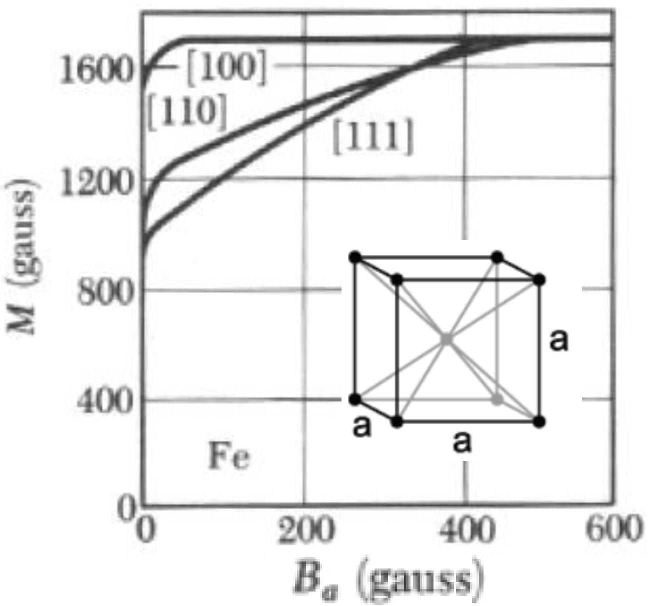
Fe bcc atomic lattice anisotropy leads to prefered directions for the atomic magnetic moments. This translate into an anisotropy of potential energy :

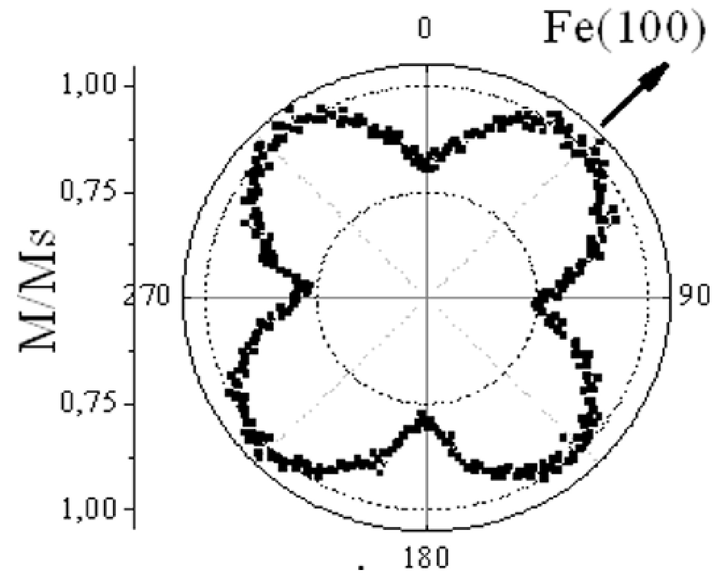
$$E_{mc} = K_1 \left(\alpha^2{}_1\alpha^2{}_2 + \alpha^2{}_2\alpha^2{}_3 + \alpha^2{}_3\alpha^2{}_1\right) + K_2 \left(\alpha^2{}_1\alpha^2{}_2\ \alpha^2{}_3\right);$$

where $\alpha_i = \cos\theta_i$; θ_i -angle between axis and M



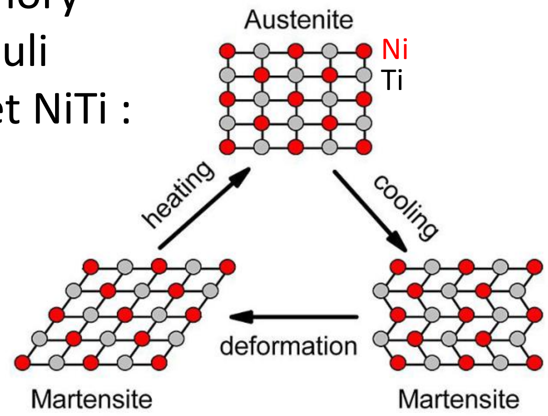
From the litterature :



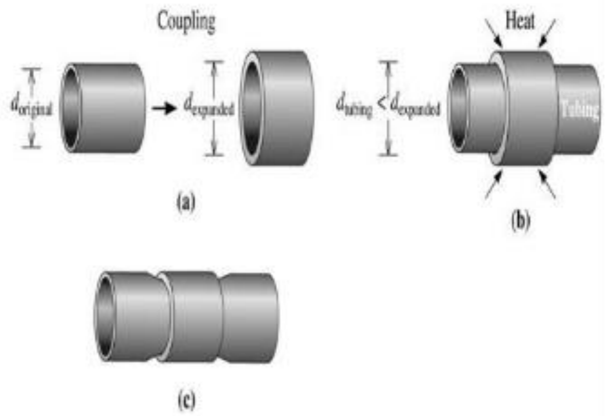


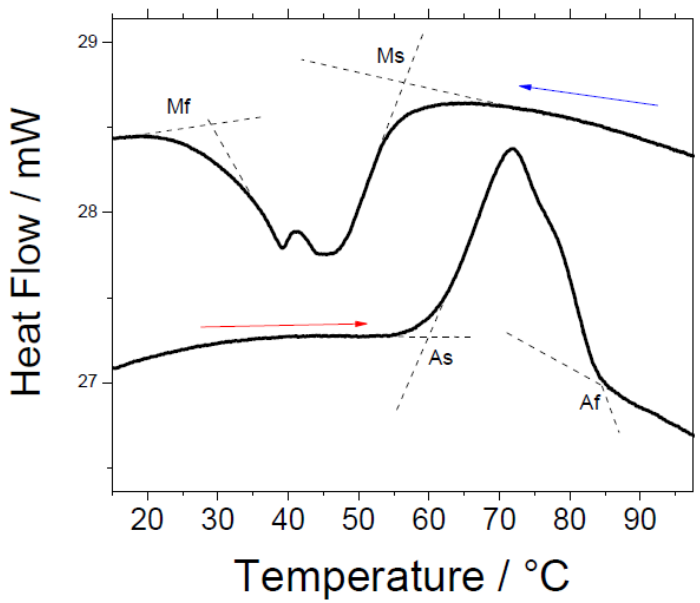
Example 2 : study of structural transitions

Shape memory effect in Pauli paramagnet NiTi :

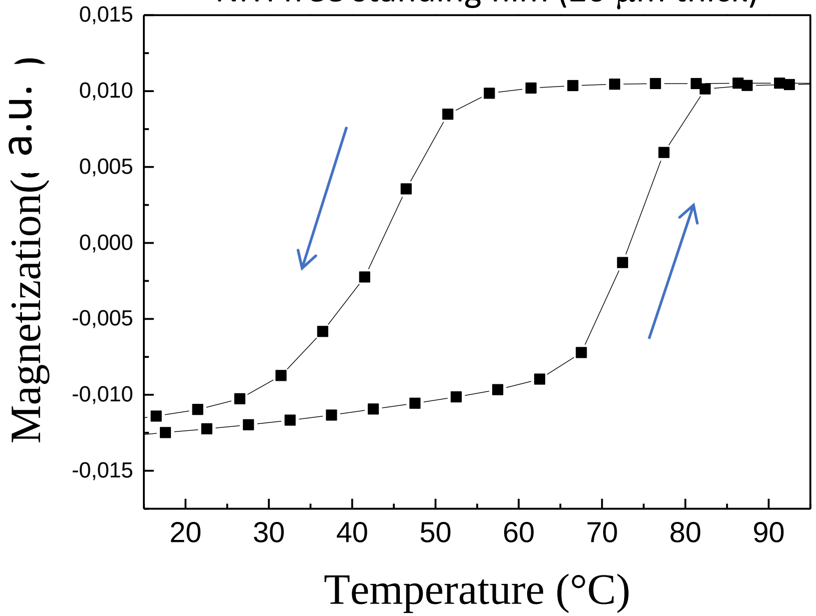


One example of industrial application :





NiTi free standing film (20 μm thick)

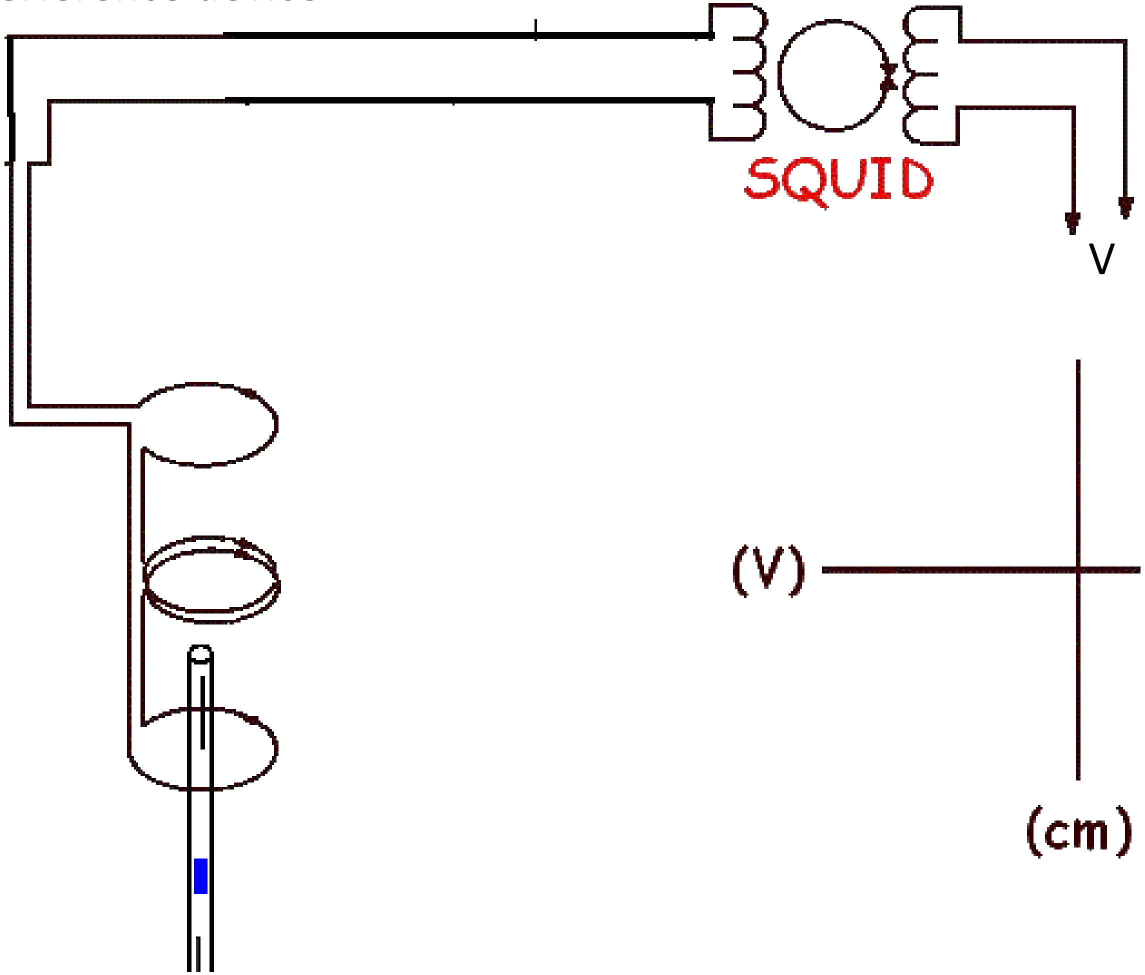


ACQUANDAS thin film solutions

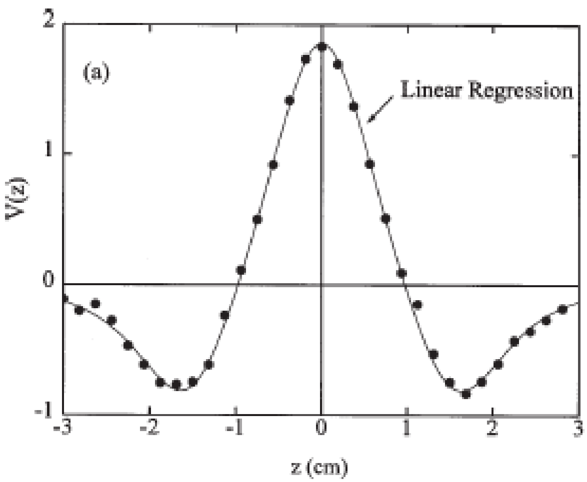
SQUID magnetometer

SQUID = Superconducting Quantum Interference device

http://squid-cmmp.blogspot.com/2011/07/blog-post.html



Measure good data for signal as low as 10^{-11} A.m^2



$$V(z) = \frac{-a^2 m(z)}{2}\left[\frac{1}{\{(z+d)^2+a^2\}^{\frac{3}{2}}} - \frac{1}{\{(z+b)^2+a^2\}^{\frac{3}{2}}} - \frac{1}{\{(z-b)^2+a^2\}^{\frac{3}{2}}} - \frac{1}{\{(z-d)^2+a^2\}^{\frac{3}{2}}}\right]$$

Magnetic flux through a superconducting coil

Perfect Superconducting coil

Electrons are coupled in Cooper pairs

Vector potential B=rot(A)

Superconducting current : $\vec{j} = \frac{ne}{m}(\hbar\vec{\nabla}\varphi - \frac{2e}{c}\vec{A})$

If there is no current : $\oint \vec{j}\vec{dl} = 0 = \hbar.2\pi.N + 2e \iint \vec{B}\vec{S}$

$$\Rightarrow \iint \vec{B}\vec{S} = N.\frac{h}{2e} = N\Phi_0$$

1 quantum $\Phi_0 = \frac{h}{2e} = 2.10^{-15}$ Tm^2 (=Wb Weber)

$\Rightarrow$

- **Magnetic flux in the coil is quantified**
- **when superconducting, magnetic field cannot vary inside the coil**

Magnetic flux through a superconducting coil

Perfect Superconducting coil

Electrons are coupled in Cooper pairs

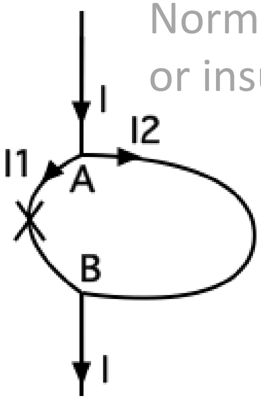
Superconducting current : $\vec{j} = \frac{ne}{m}(\hbar\vec{\nabla}\varphi - \frac{2e}{c}\vec{A})$

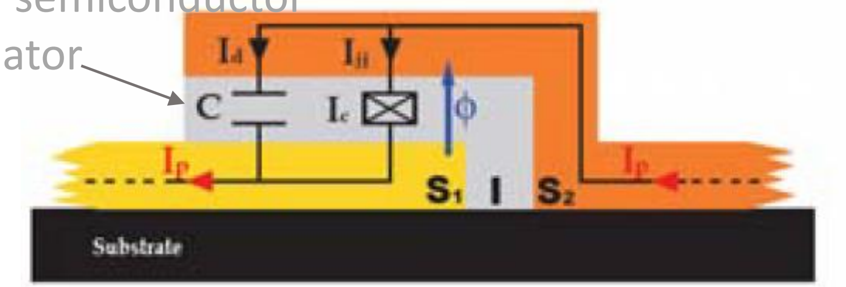
If there is no current : $\int \vec{j}\vec{dl} = 0 = \hbar.2\pi.N + 2e \iint \vec{B}\vec{S}$

$$\Rightarrow \iint \vec{B}\vec{S} = N.\frac{h}{2e} = N\Phi_0$$

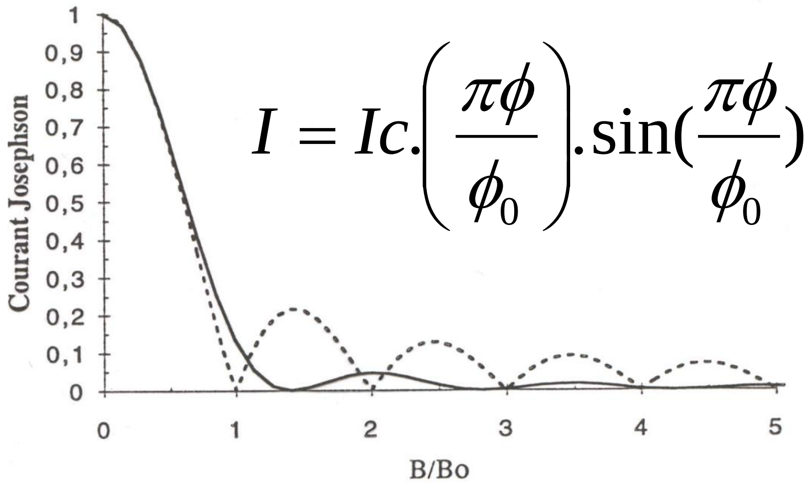
1 quantum $\Phi_0 = \frac{h}{2e} = 2.10^{-15}$ Tm^2 (=Wb Weber)

But magnetic field can penetrate through defect :



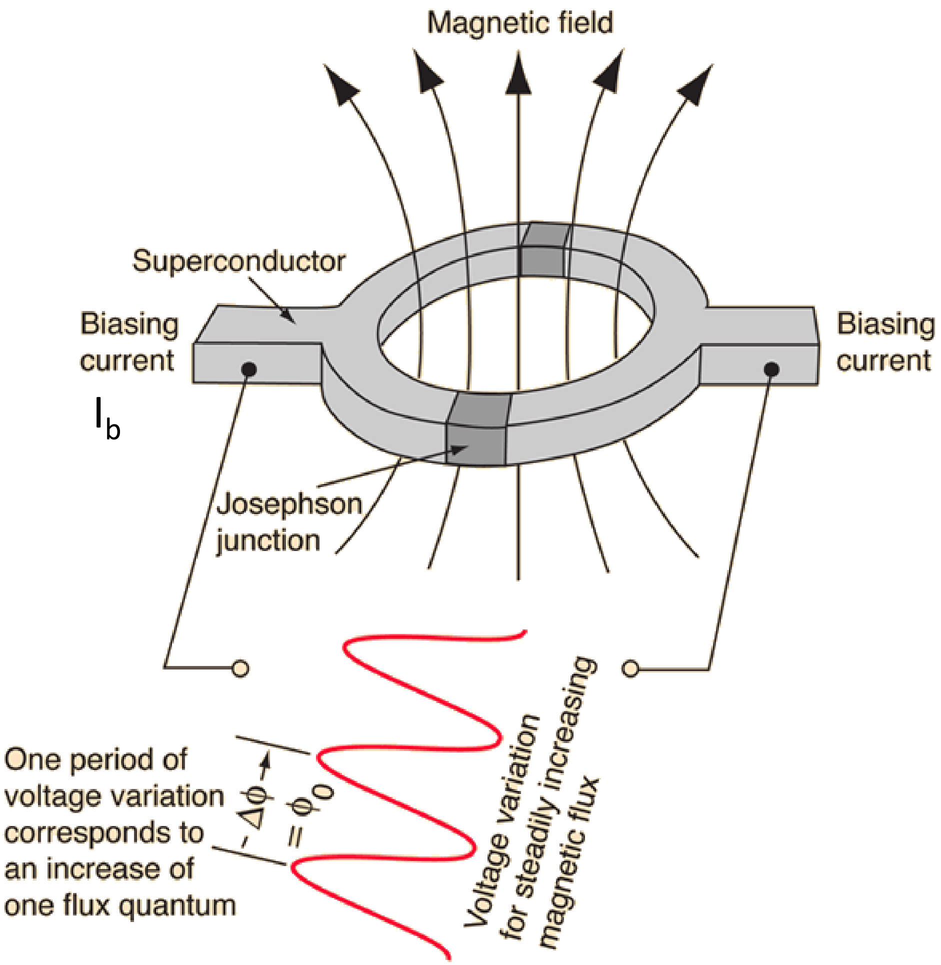


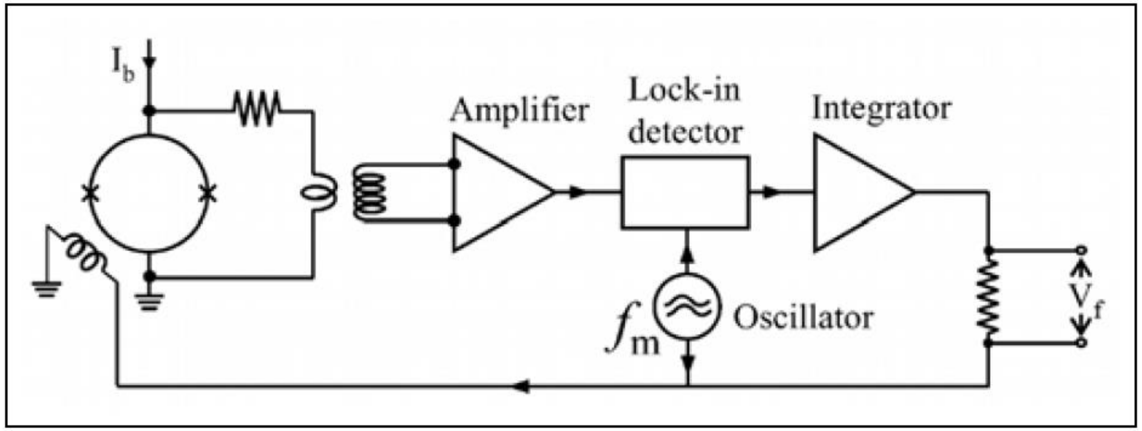
Josephson junction

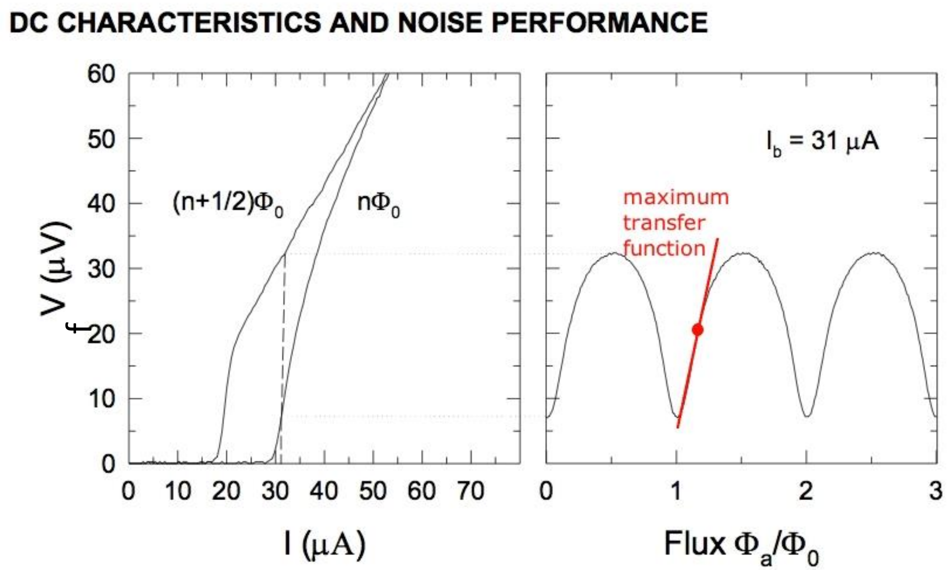


$$I = Ic.\left(\frac{\pi\phi}{\phi_0}\right).\sin\left(\frac{\pi\phi}{\phi_0}\right)$$

DC SQUID : 2 interfering Josephson junction







Measured Voltage-Current (*V-I*) and Voltage-Flux (*V-Φ*) characteristics of a typical M800 dc SQUID magnetometer operated 4.2 K.

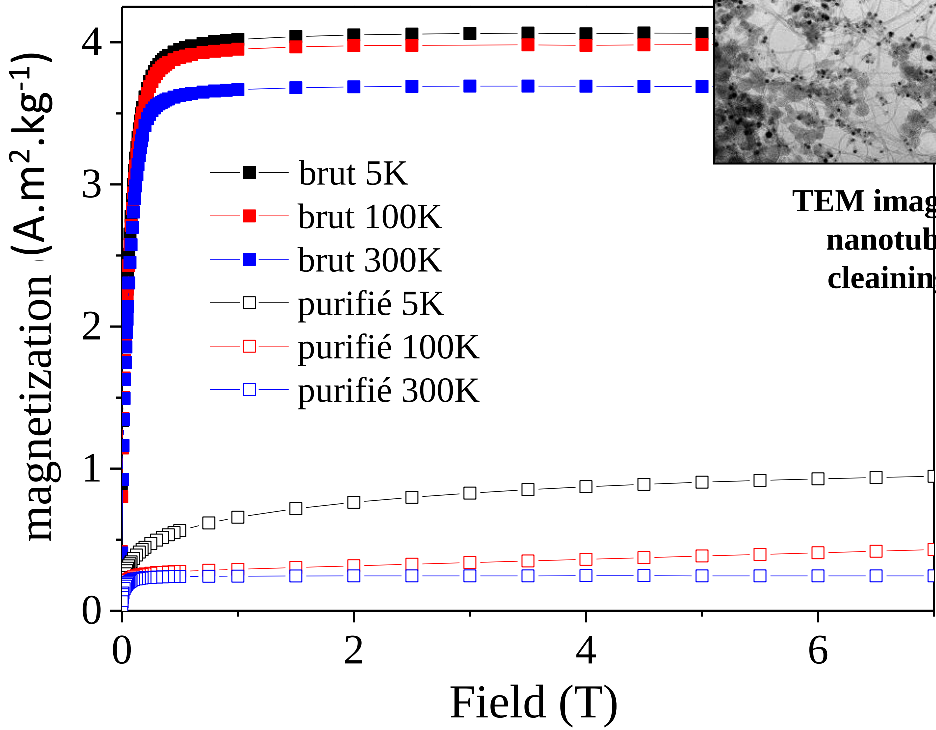
Résolution on magnetic flux of $10^{-6}\ \phi_0$

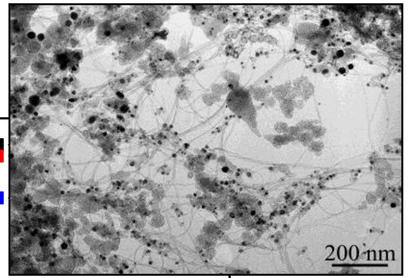
If SQUID radius= 1mm => $\Delta B \approx 10^{-15}$ T

R.L. Fagaly Review of Scientific Instruments **77**, 101101 (2006)

Example : detecting Ni nanoparticles

SQUID-VSM : Small signal measurement





TEM image of carbon nanotubes before cleaining process

Method for detection of Ni nanoparticles after they are used to grow carbon nanotubes

B.Vigolo et al. IJL Nancy
European Patent PCT/FR2011/052519 (2011)

VSM and SQUIDs limiting factors

Final Lock-in voltage =
Gain x Moment x Sample geometry factor x Coil geometry factor x Amplitude x Frequency

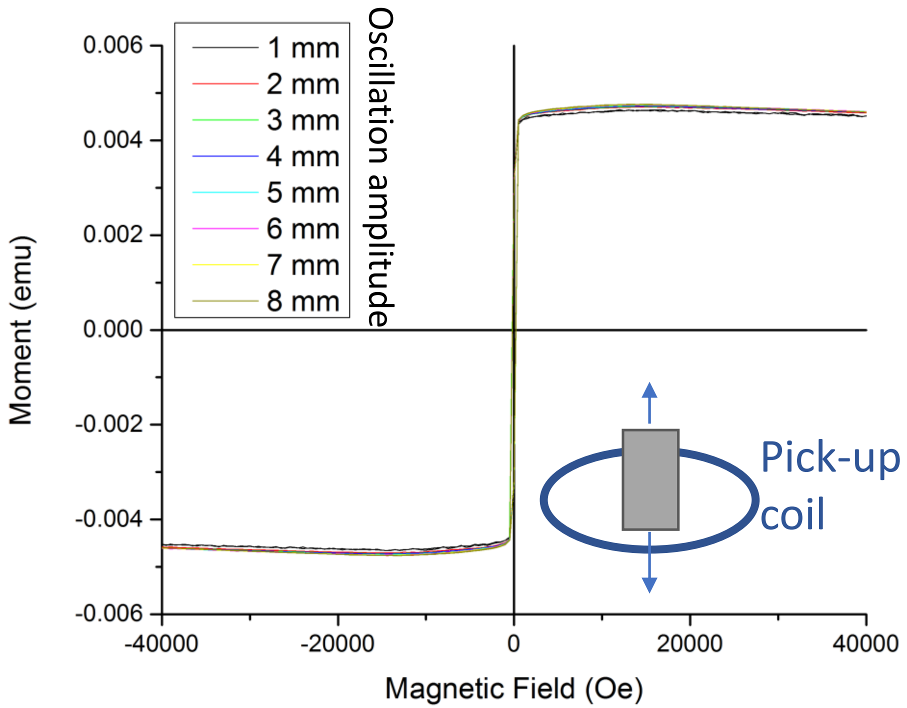
- The parameters in green are accounted for **through calibration with a standard** of known moment for a particular VSM coil set.

- This leaves sample moment coupled together with its geometry factor. This is very important to consider when interpreting the measured moment.

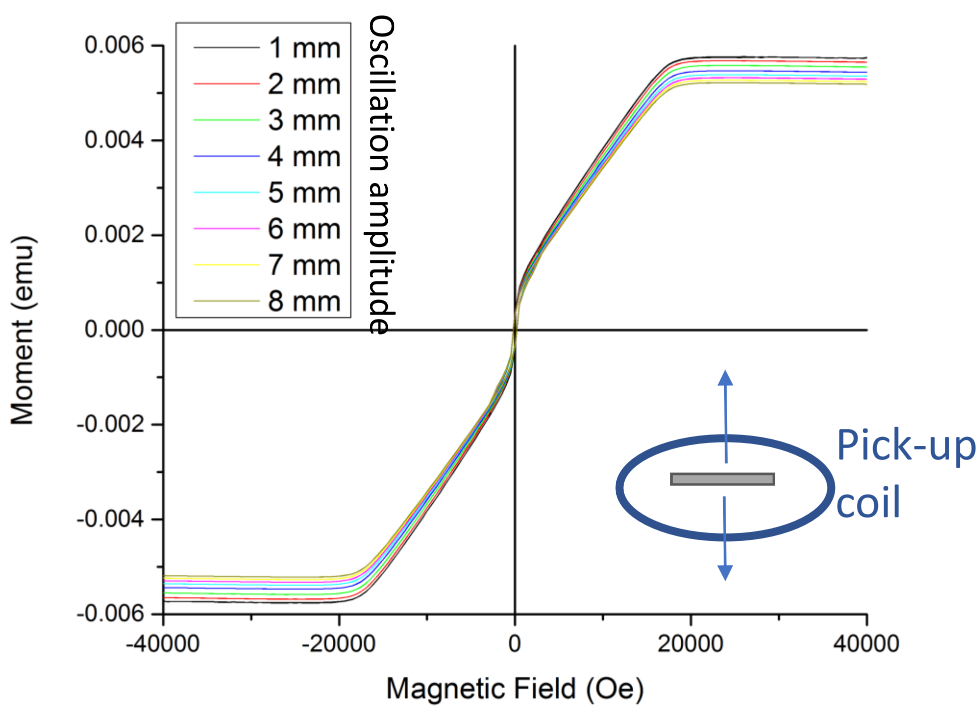
Experimental limiting factors : sample geometry

Final Lock-in voltage =
Gain x Moment x Sample geometry factor x Coil geometry factor x Amplitude x Frequency

Film in-plane



Film out-of-plane

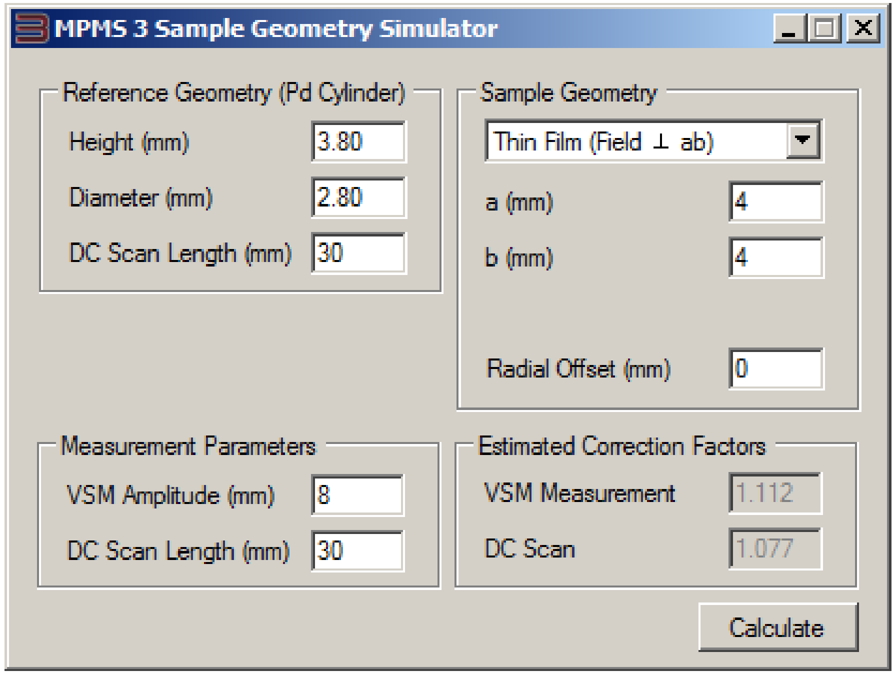


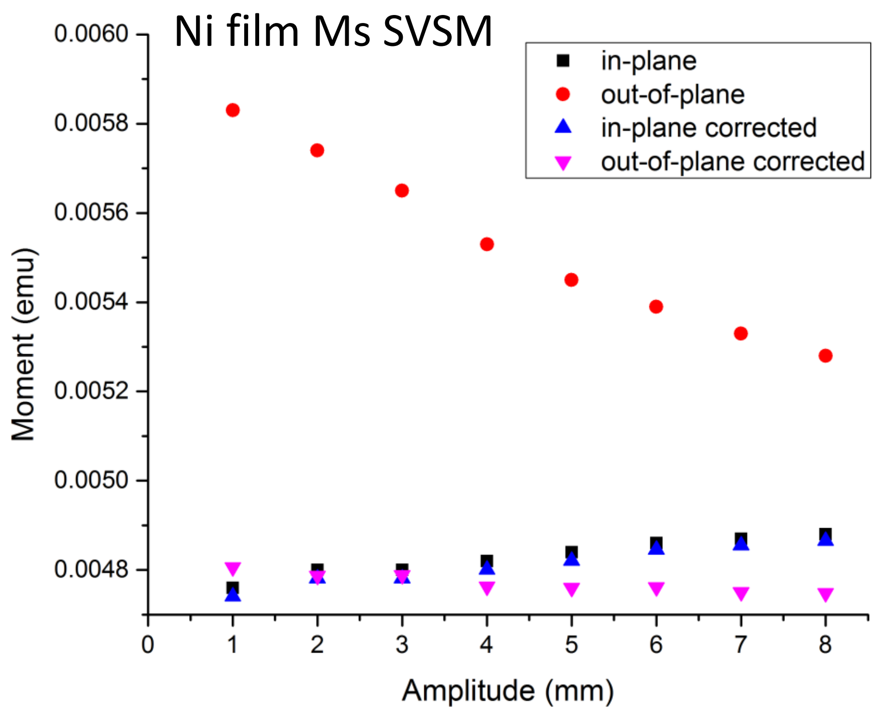
Example of a **thin film sample geometry** effect for SQUID VSM
(4 mm x 4 mm x 200 nm Ni film on silicon)

Experimental limiting factors : sample geometry

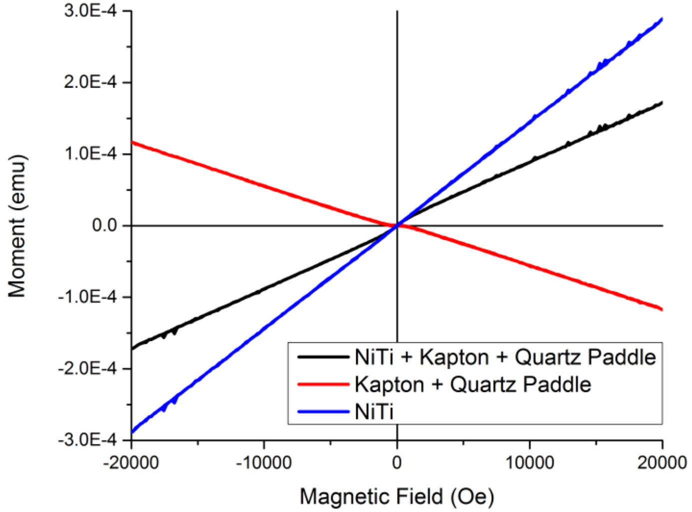
Final Lock-in voltage =
Gain x Moment x Sample geometry factor x Coil geometry factor x Amplitude x Frequency

QD Software : Corrected Moment = Measured Moment / Correction Factor





Experimental limiting factors : background



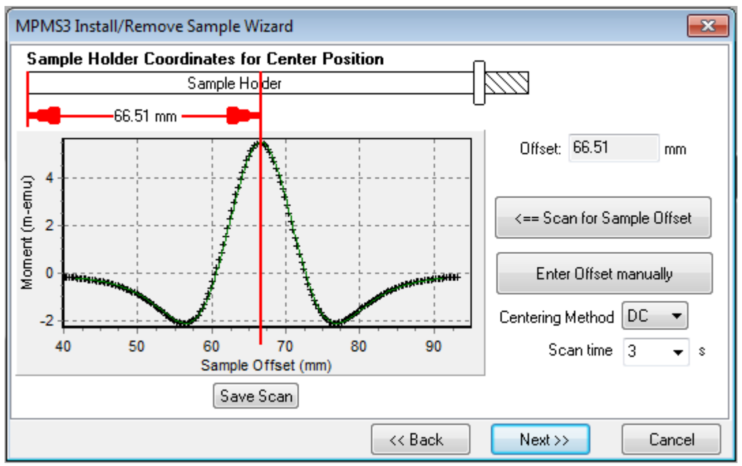
Final Lock-in voltage =

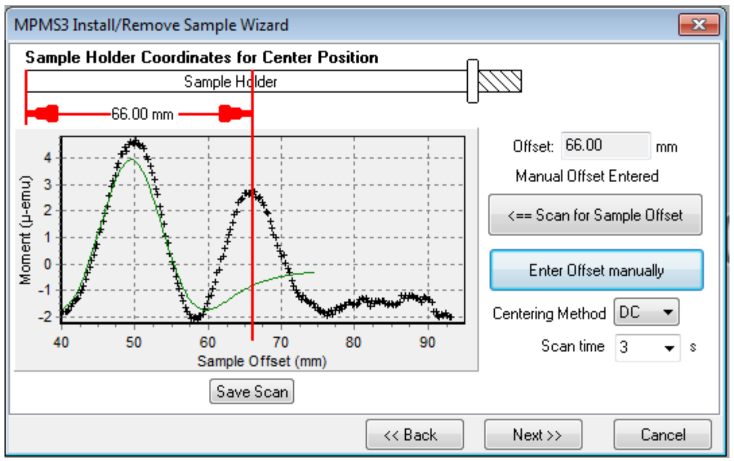
Gain x Moment x Sample geometry factor x Coil geometry factor x Amplitude x Frequency

contains any magnetic signal from the environment (background)

Here, same piece of Kapton tape and sample holder measured without the sample to obtain background signal.

But it can be worst… and if you don't check, you don't find out

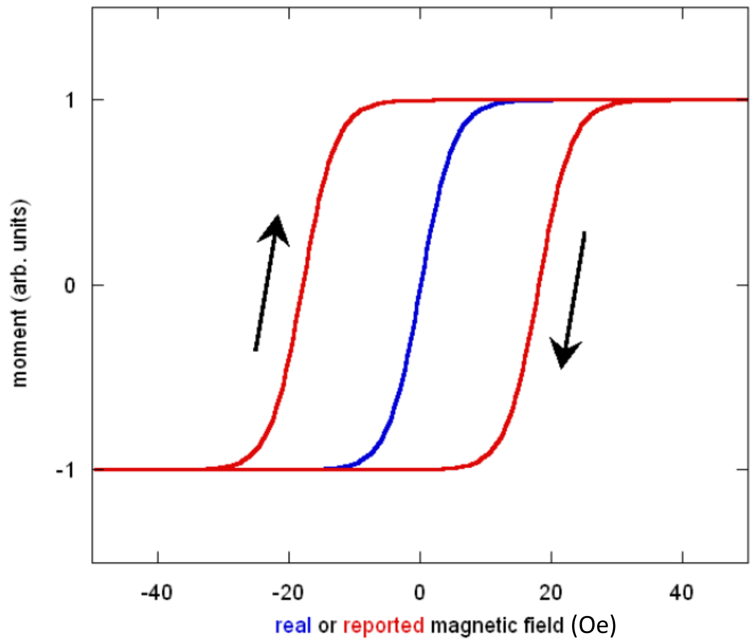


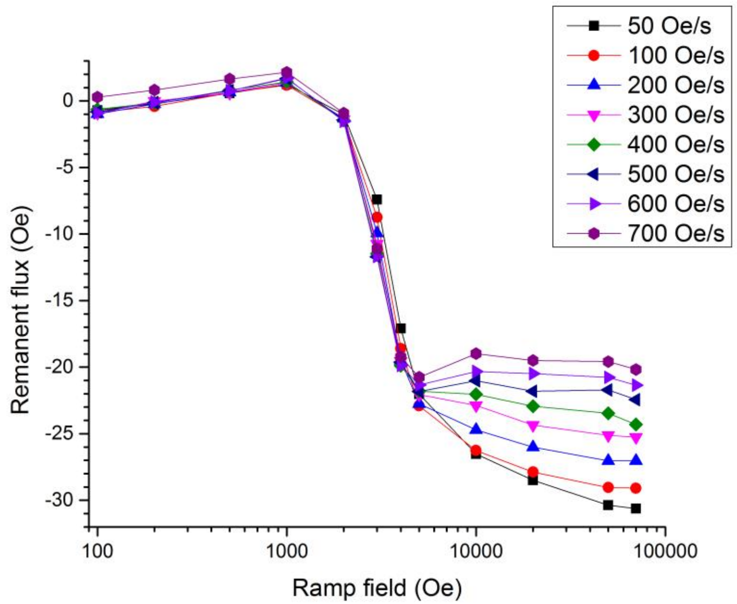


In the case of a non-uniform background signal, the software is still trying to fit the curve whatever the curve is.

Experimental limiting factors : trapped field

The superconductive magnet can have trapped flux especially when the magnet has been loaded at fields larger ~0,5 T

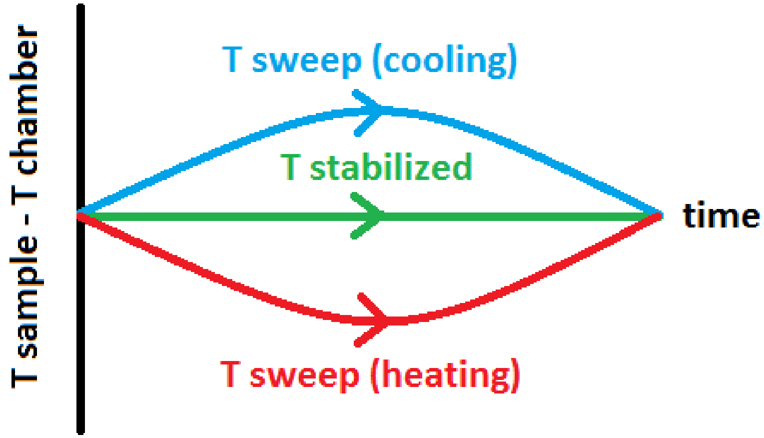


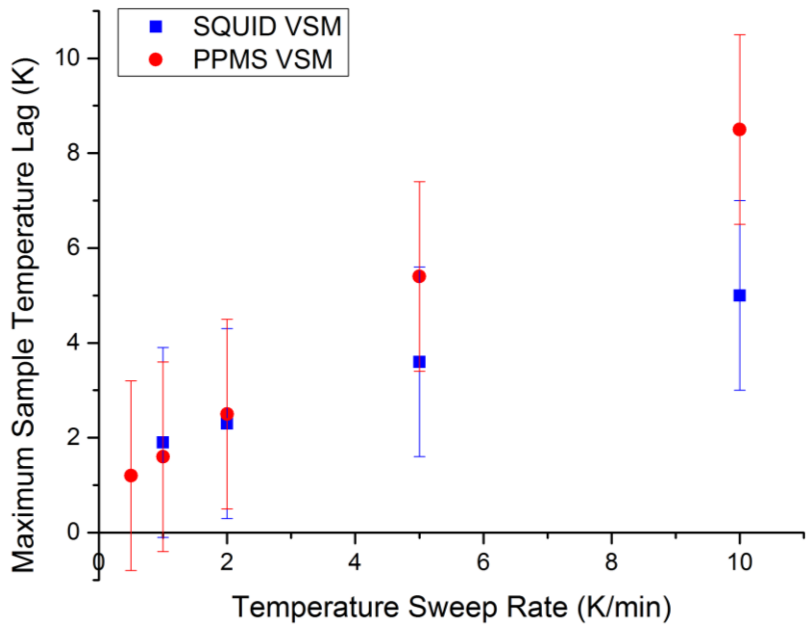


The System does not measure the actual field. The reported field is calculated based on the current placed in the magnet.

Experimental limiting factors : temperature

When measuring while temperature is sweeping, there will be thermal lag between the measured and the actual sample temperature.





Don't sweep faster than 3K/min even if your tool can go 20K/min

Outline

I. Few preliminary details about the sample environment

➡ Magnetic field, Temperature

II. Static macroscopic magnetometry techniques

➡ VSM, SQUID, **Torque, MOKE, XMCD**

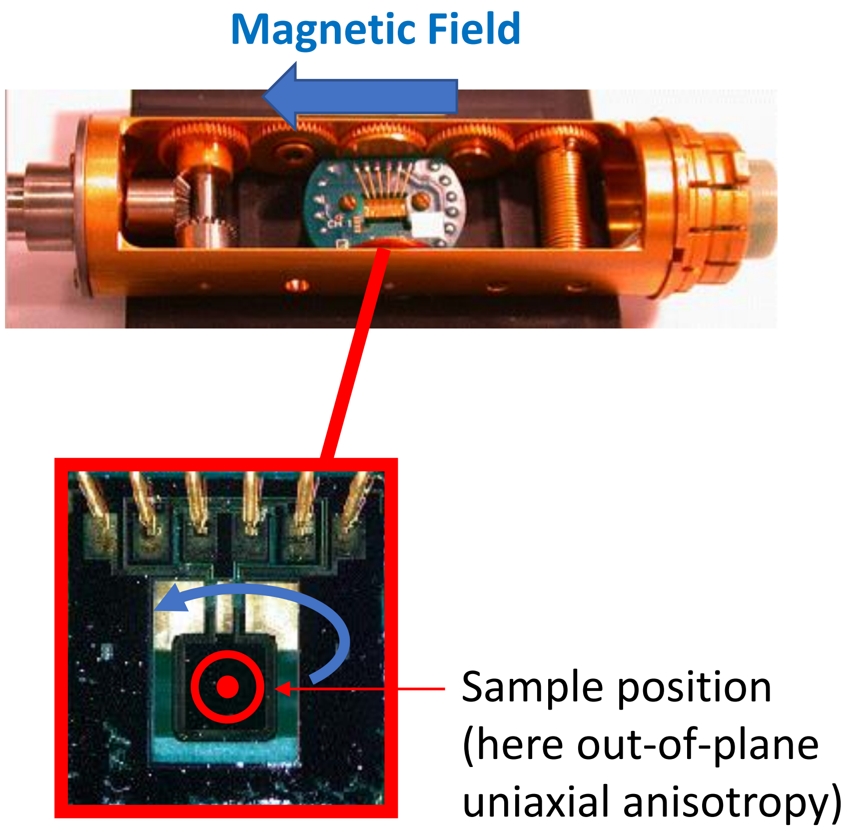
III. AC macroscopic magnetometry techniques

➡ AC susceptometry

IV. Imaging techniques

➡ Scanning probe microscopies, Photon-out

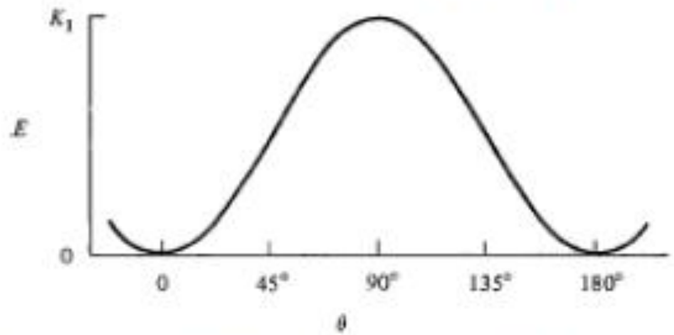
Torque magnetometry



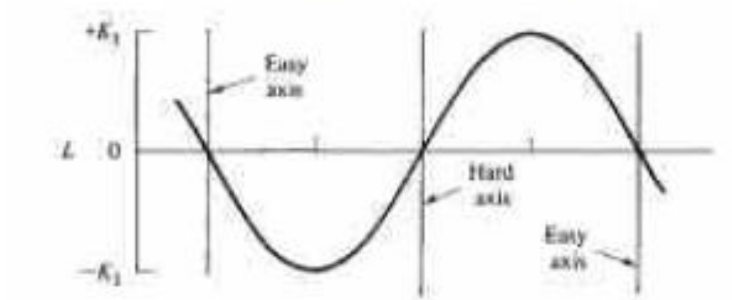
Torque measured via piezoelectricity

$$Torque: \quad \tau = \vec{M} \times \vec{B} = -\frac{dE}{d\theta}$$

Uniaxial anisotropy $E_a = K_1 \sin^2\theta$

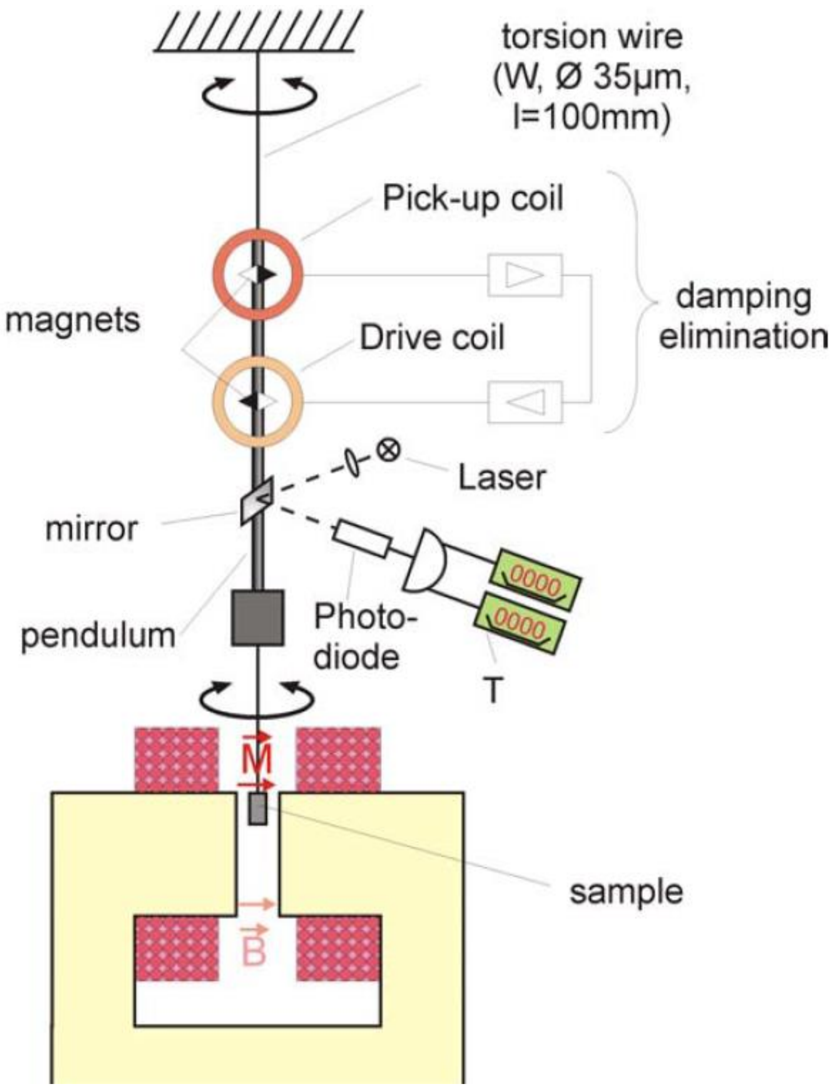


Torque $-dE_{tot}/d\theta = -dE_a/d\theta = -K_1 \sin 2\theta$



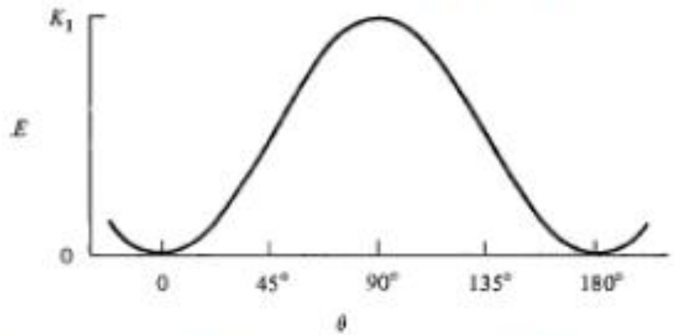
https://www.youtube.com/user/QuantumDesignUSA

Torque magnetometry

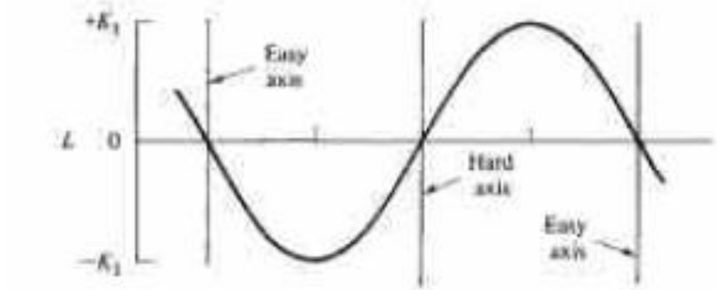


$$Torque: \quad \tau = \vec{M} \times \vec{B} = -\frac{dE}{d\theta}$$

Uniaxial anisotropy $E_a = K_1 \sin^2\theta$

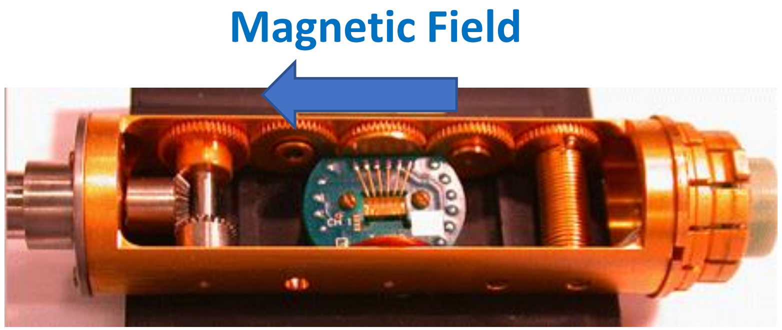


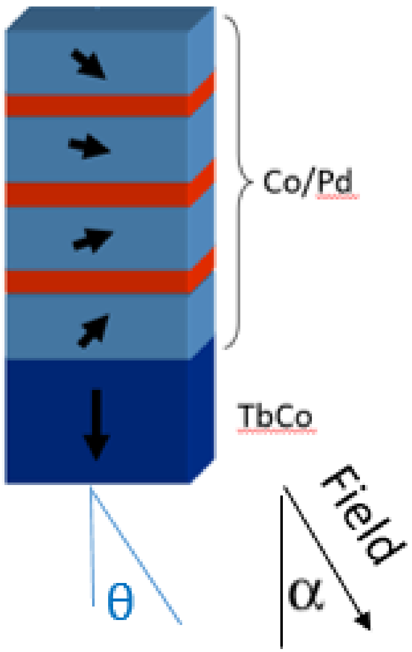
Torque $-dE_{tot}/d\theta = -dE_a/d\theta = -K_1 \sin 2\theta$



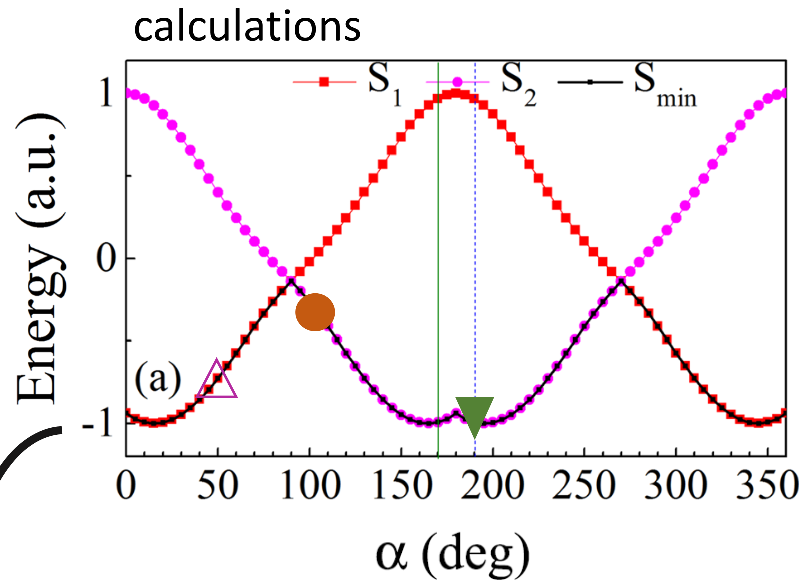
Bergholz, Elmers, Gradmann, PRL 63,566 (1989) / Appl. Phys. A 51, 255 (1990)

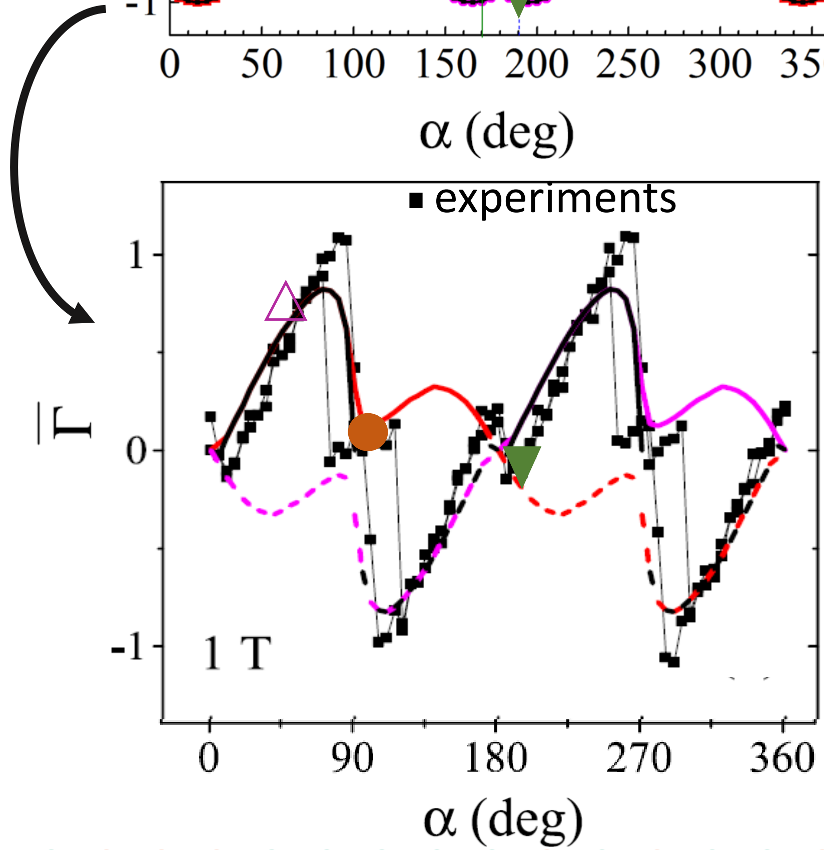
Torque magnetometry : non-uniform configuration





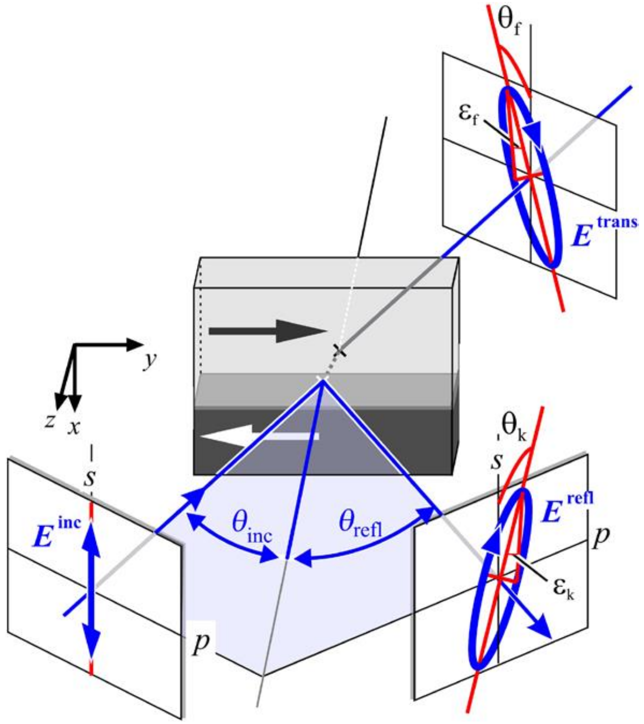
$$Torque\ \tau = \frac{dE}{d\alpha}$$





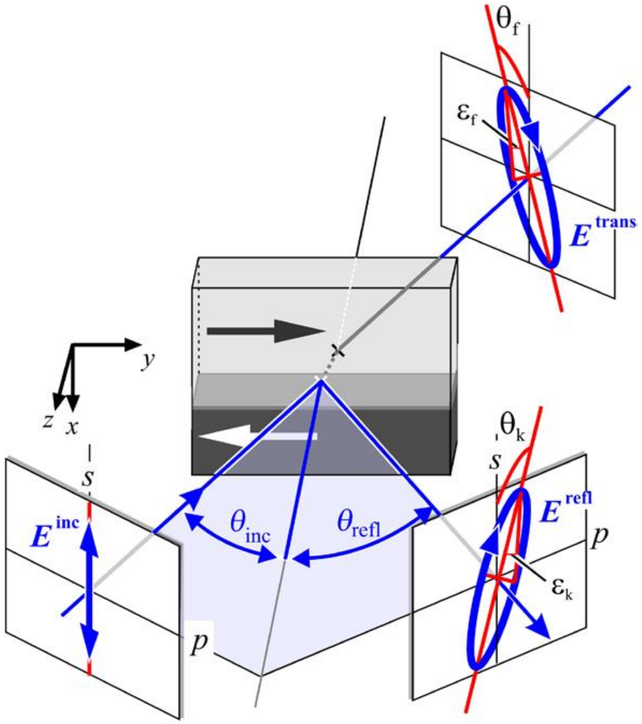
P. Vallobra, JAP 120, 013903 (2016)

Magneto-optical Kerr effect magnetometry



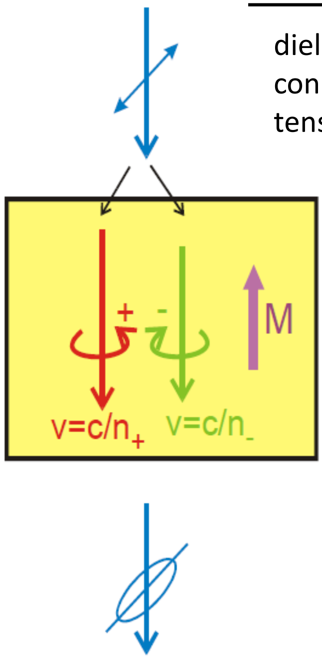
M. Faraday (1846), J. Kerr (1877)

Magneto-optical Kerr effect magnetometry



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

Classical description



dielectric conductivity tensor

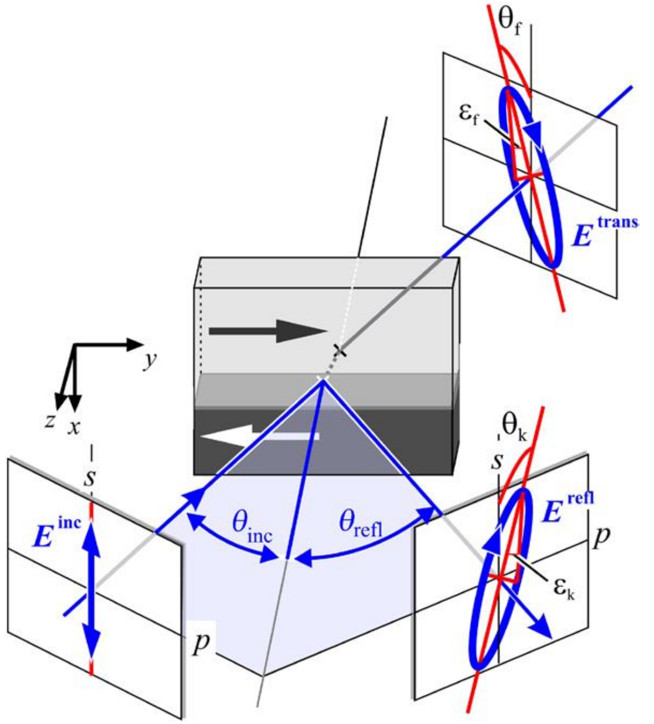
$$\overleftrightarrow{\sigma} = \begin{bmatrix} \sigma_0 & -\sigma_1 m_z & 0 \\ \sigma_1 m_z & \sigma_0 & 0 \\ 0 & 0 & \sigma_0 \end{bmatrix}$$

diagonalization

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

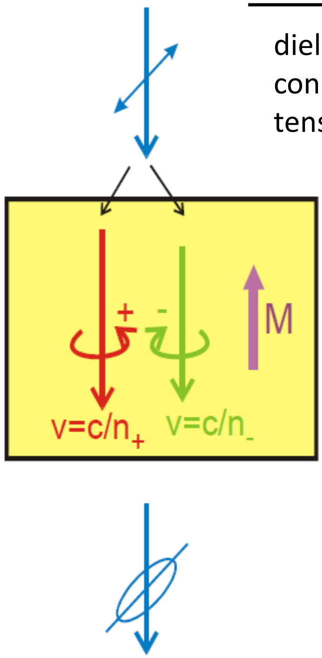
$$n_\pm(\omega) = \sqrt{1 + \frac{4\pi i}{\omega}\sigma_\pm(\omega)}$$

Magneto-optical Kerr effect magnetometry



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

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

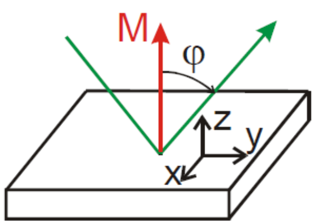
$$n_\pm(\omega) = \sqrt{1 + \frac{4\pi i}{\omega}\sigma_\pm(\omega)}$$

More generally : 3 useful configurations

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

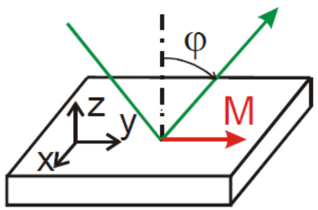
Polar Kerr effect (PMOKE)

M ⊥ sample surface



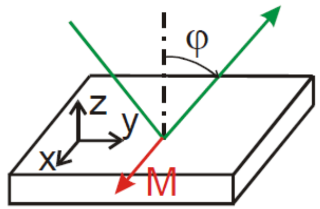
Longitudinal Kerr effect (LMOKE)

M || plane of incidence



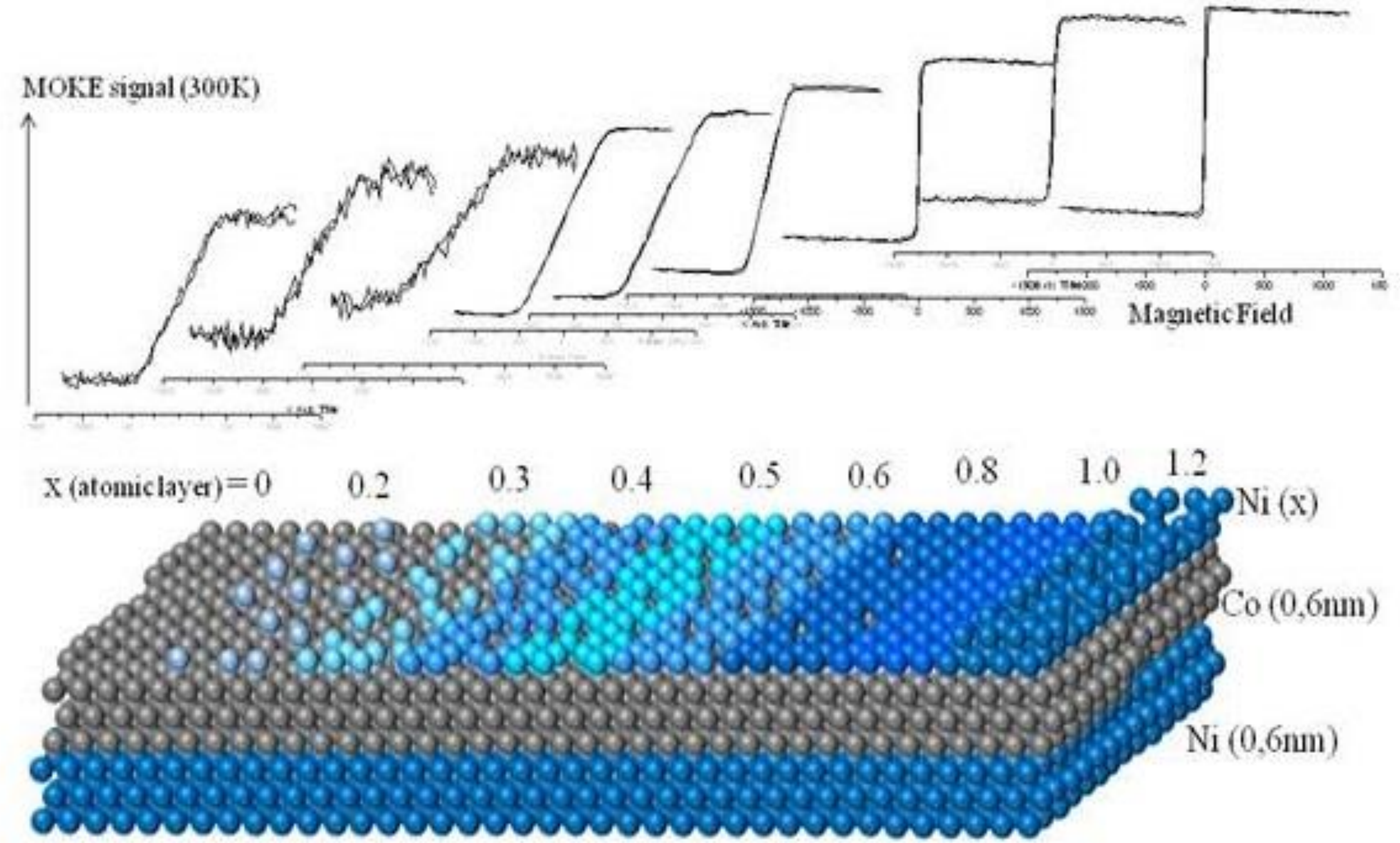
Transversal Kerr effect (TMOKE)

M ⊥ plane of incidence



MOKE example : sensitive to surfaces

Example : study of magnetic anisotropy in multilayer thin film Ni(0.6nm)/Co(0.6nm)/Ni(x)

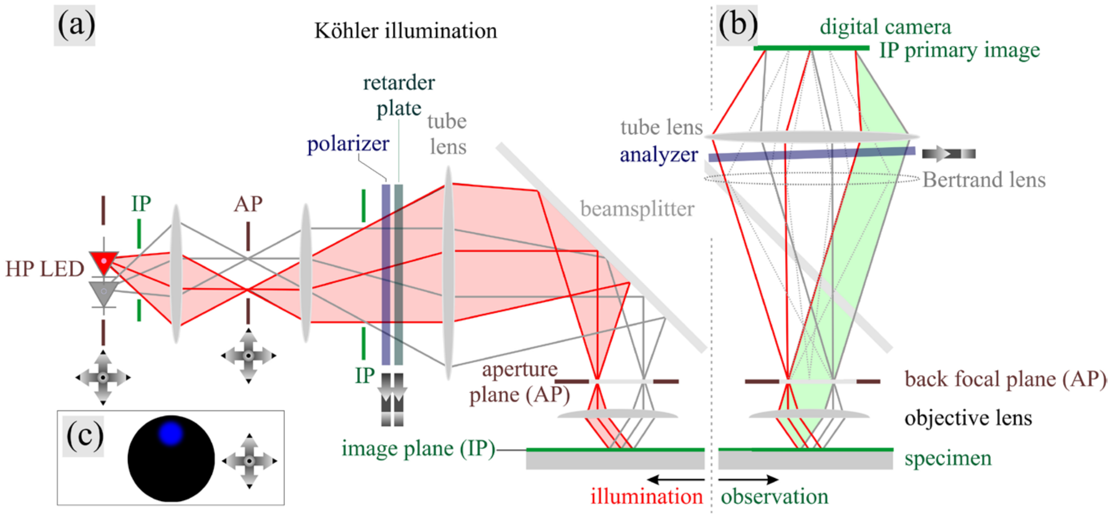


Applied magnetic field

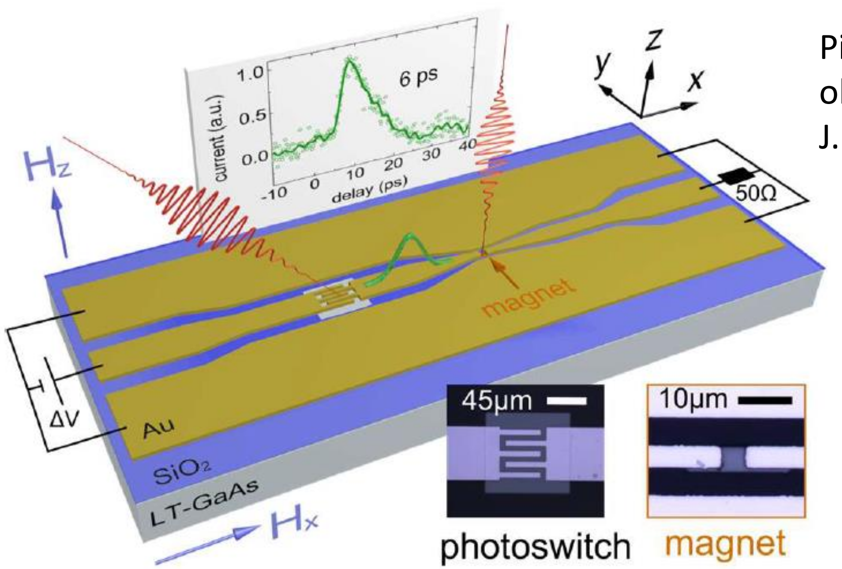
MOKE is only sensitive to about 20-50 nm thickness at the materials surface

MOKE magnetometry : imaging and dynamics

MOKE can be focused and so it can be used to perform magnetic microscopy



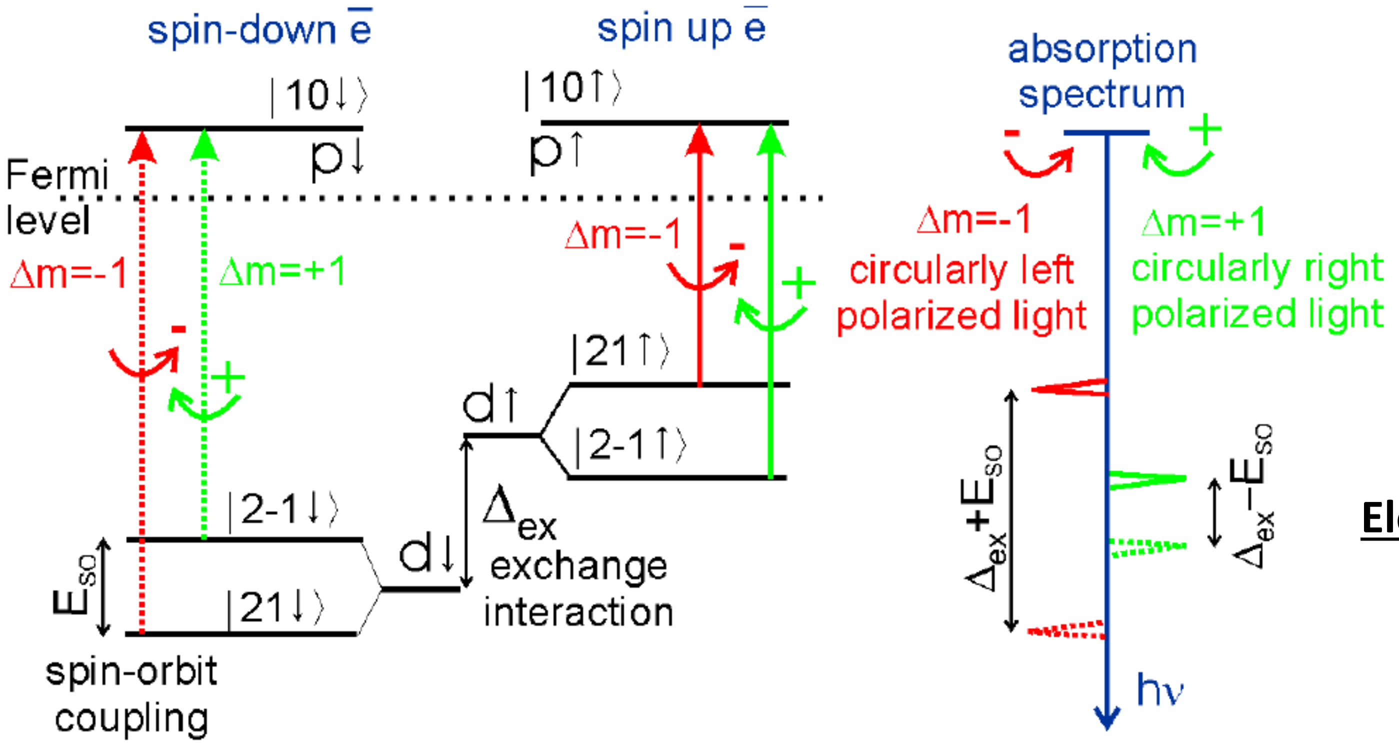
Laser can be pulsed so that MOKE can be used to probe magnetic changes at different timescales down to femtosecond



Picosecond SOT switching observed by MOKE
J. Gorchon arXiv:1912.01377

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

MOKE magnetometry : microscopic model



⇒ Both spin orbit coupling and exchange are necessary for MO activity

Hulme, Proc. R. Soc. London **A135**, 237 (1932)

Bruno, PRB **53**, 9214 (1995)

Transition energy ≈ eV

Electron (l, m, s) transition rules :

- Energy : $E_f - E_i = \hbar\omega$

  (absorbed photon energy = difference between final and initial state)

- Electron spin : Δs=0

  (spin of electron is preserved for electric dipole transitions)

- Orbitum momentum : Δl=±1

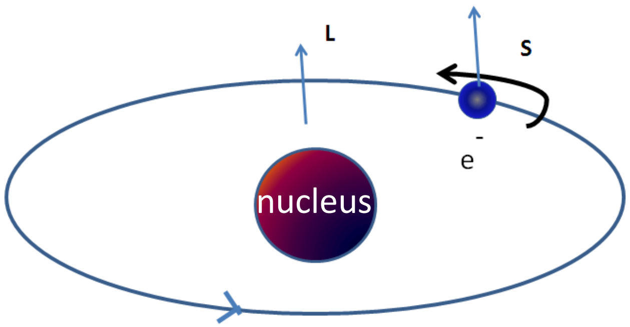
  (photon has angular momentum 1ħ). Therefore only s↔p, p↔d etc. are allowed

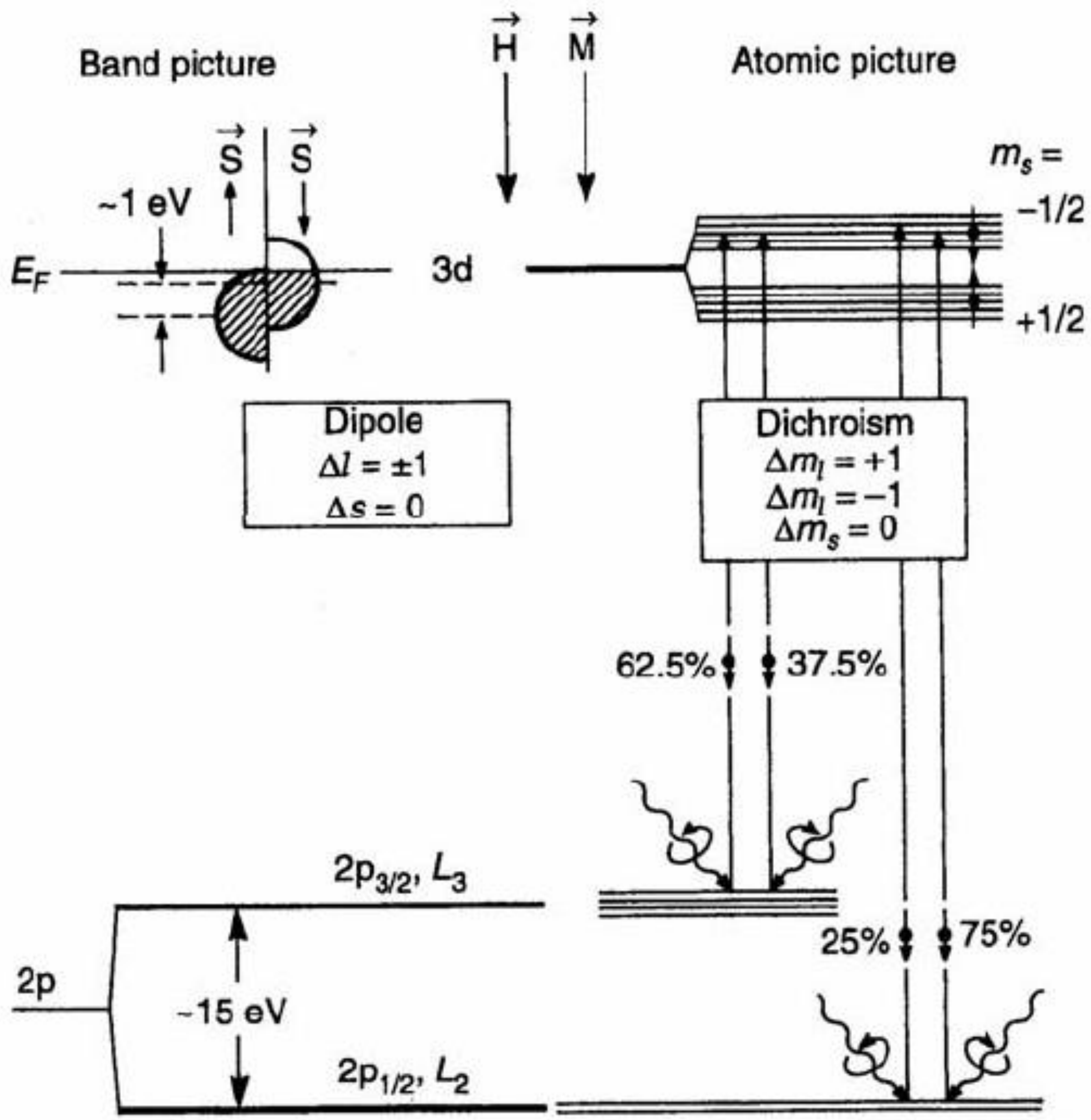
- Orbital momentum along z-axis : Δm=±1

  (determines if photon is right/left polarized)

P. Bruno, PRB 53, 9214 (1996)

X-ray magnetic circular dichroism (XMCD)



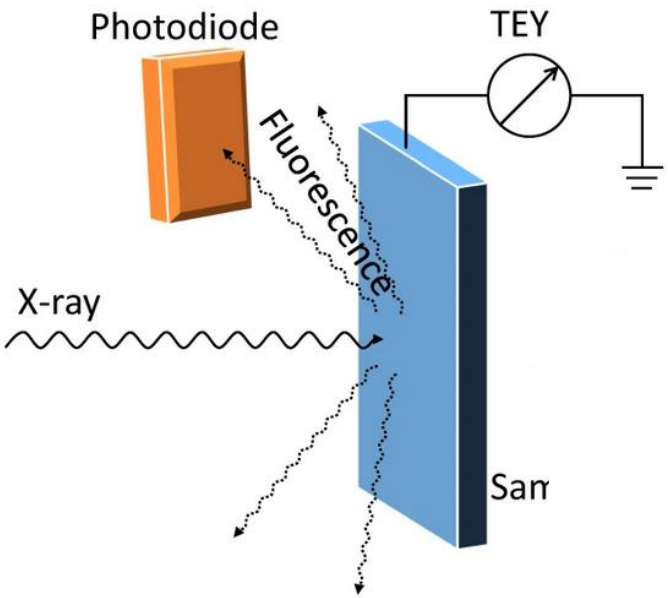


- **XMCD disentangles spin and orbital magnetic moment**

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

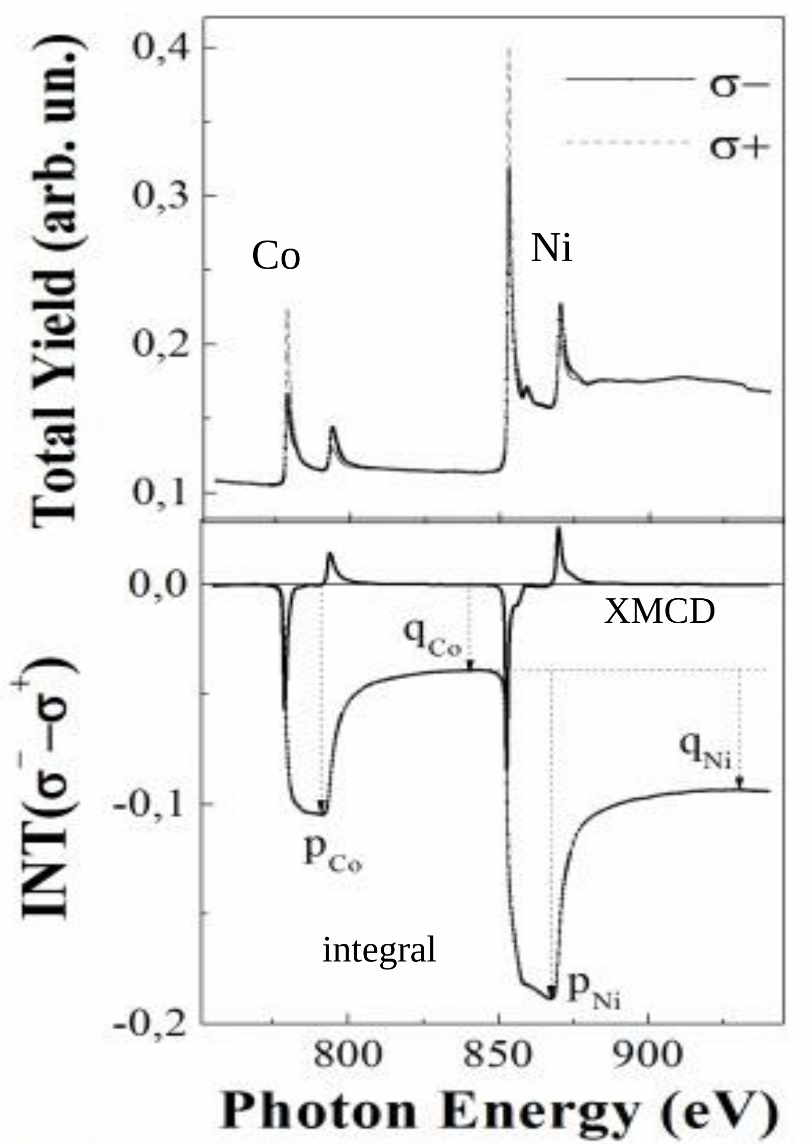
- **XMCD requieres to work in synchrotron to get enough X-ray flux (700 - 900 eV for Fe,Co,Ni)**

X-ray magnetic circular dichroism (XMCD)



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

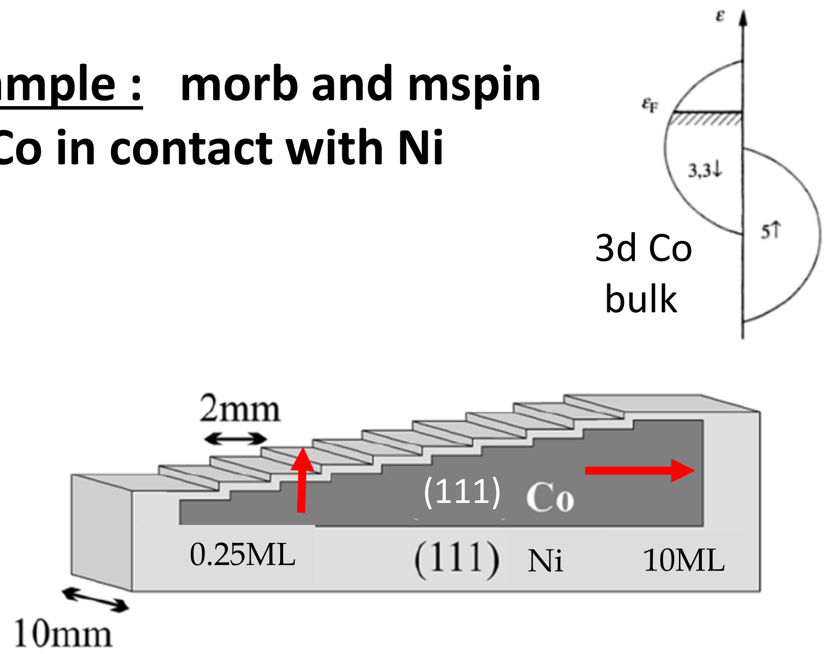
$$m_{\text{orb}} = \langle L_z\rangle \frac{\mu_B}{\hbar} = n_h \cdot \left(\frac{2q}{3r}\right)\mu_B$$

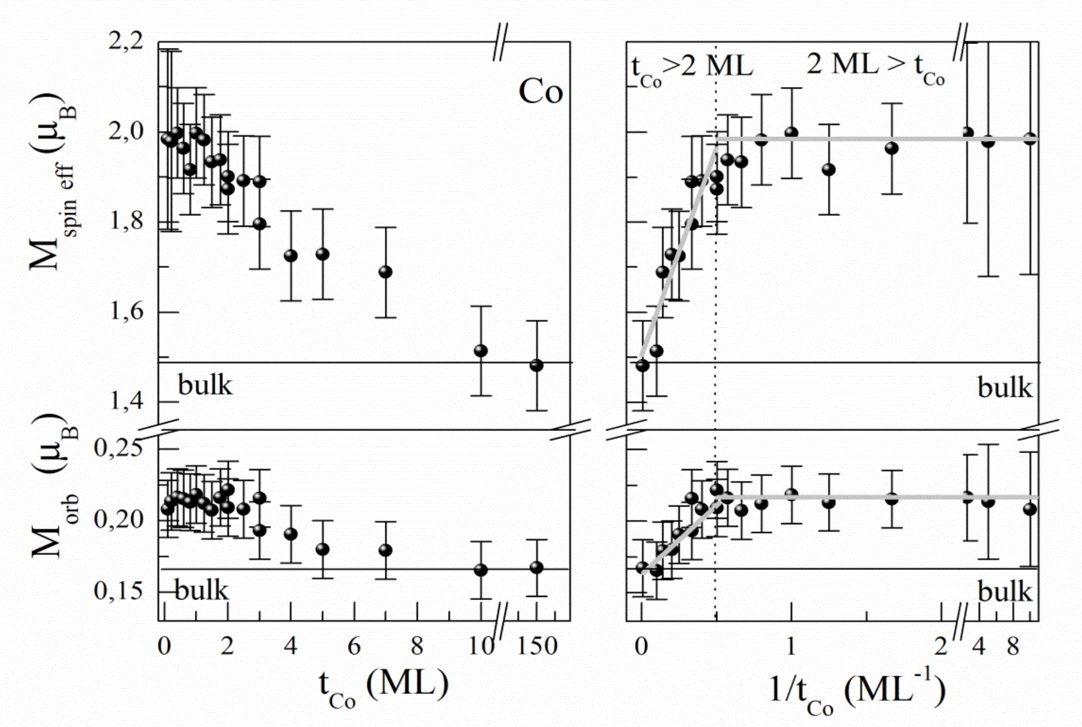


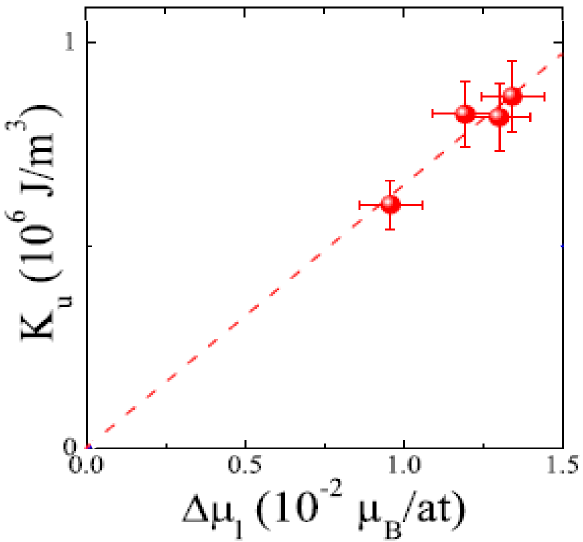
« Surface » sensitive technic (< 50 nm)

Example of XMCD data

Example : morb and mspin of Co in contact with Ni







1) Co Spin and orbital moments are affected by the Co/Ni interface electronic hybridizations

2) The macroscopic anisotropy constant is proportional to the anisotropy of orbital moment

$$K_u = A \frac{\xi N}{4V} \frac{\Delta \mu_l}{\mu_B}$$

S. Andrieu, PRMater 2, 064410 (2018)

Outline

I. Few preliminary details about the sample environment

➡ Magnetic field, Temperature

II. Static macroscopic magnetometry techniques

➡ VSM, SQUID, Torque, MOKE, XMCD

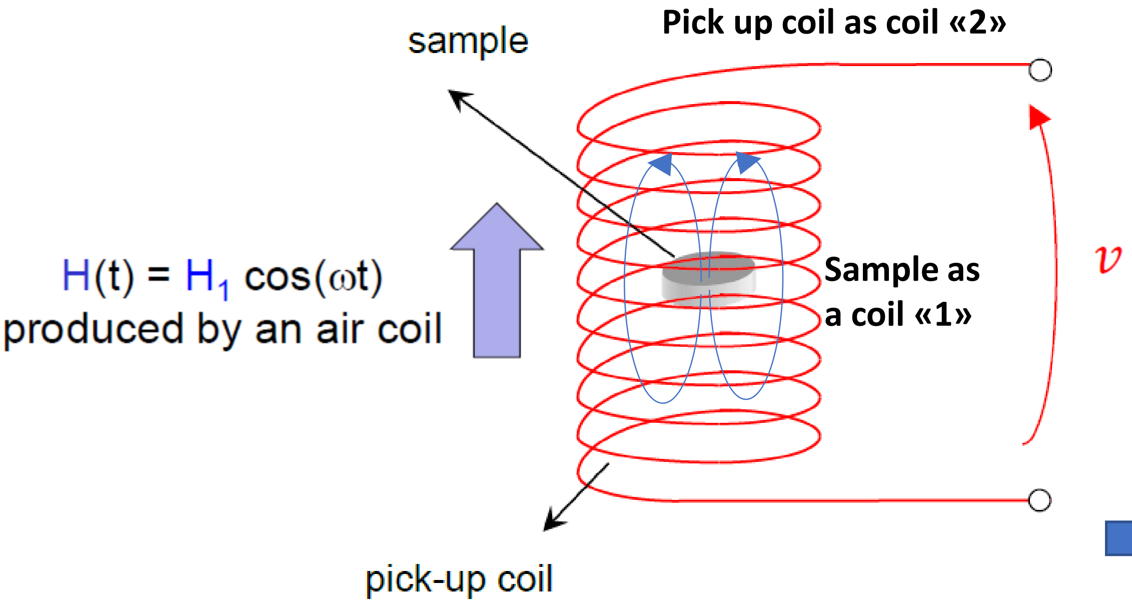
III. AC macroscopic magnetometry techniques

➡ **AC susceptometry**

IV. Imaging techniques

➡ Scanning probe microscopies, Photon-out

AC susceptometry : measure of susceptibility χ



$$\Phi_2 = \int \vec{B}_{12}\, d\vec{S}_2 = M_{12}.I_1 \qquad \vec{g}_{21} = \frac{\vec{B}_{21}}{I_2}$$

$$\Phi_1 = \int \vec{B}_{21} d\vec{S}_1 = \vec{B}_{21}\,\vec{S}_1 = M_{21}.I_2 = \vec{g}_{21} I_2 \vec{S}_1$$

$$M_{12} = M_{21} = \vec{g}_{21}\vec{S}_1$$

$$\Phi_2 = M_{12}\, I_1 = \vec{g}_{21}\vec{S}_1\, I_1 = \vec{g}_{21}.\vec{m}_1$$

Faraday's law

$$v = -\frac{\partial \phi_2}{\partial t} = -g_{21}\frac{\partial m_1}{\partial t}$$ avec $\overline{H}_1 = H_1\,[e^{j\omega t}]$, $\overline{M}_1 = M_1\,[e^{j\omega t}]$

Here the sample does not move

$$v = \left(\frac{1}{\alpha}\right) V\, f\, H_1\, \chi$$

Proportionnality factor: $\frac{1}{\alpha}$; Sample volume: V; Excitation frequency: f; Sample susceptibility: χ

M. Nikolo, Am. J. Phys., 63, 57 (1995)

Coil sets in a PPMS

Frequency range 0.1Hz-1kHz
AC amplitude 0.01 à 1 mT

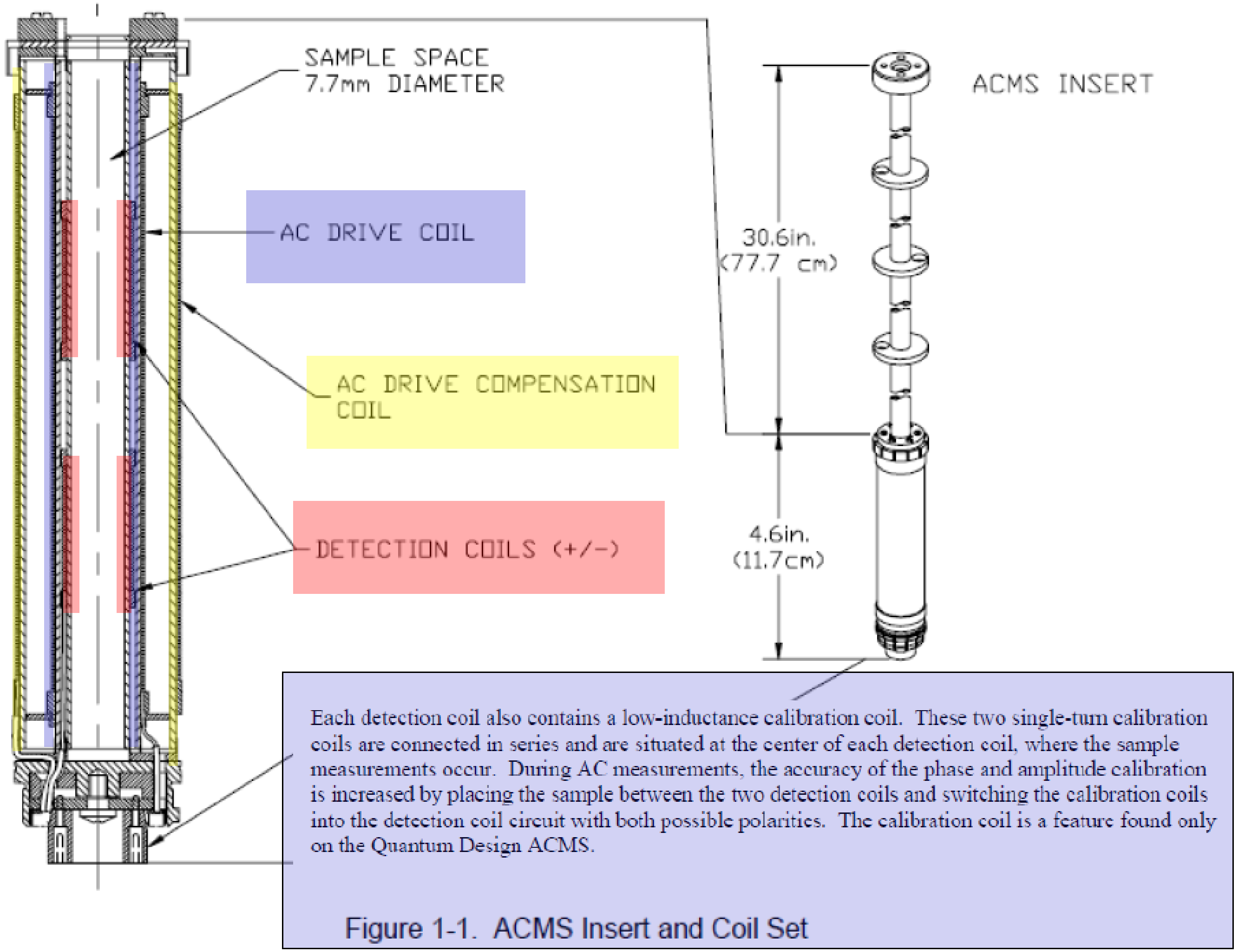


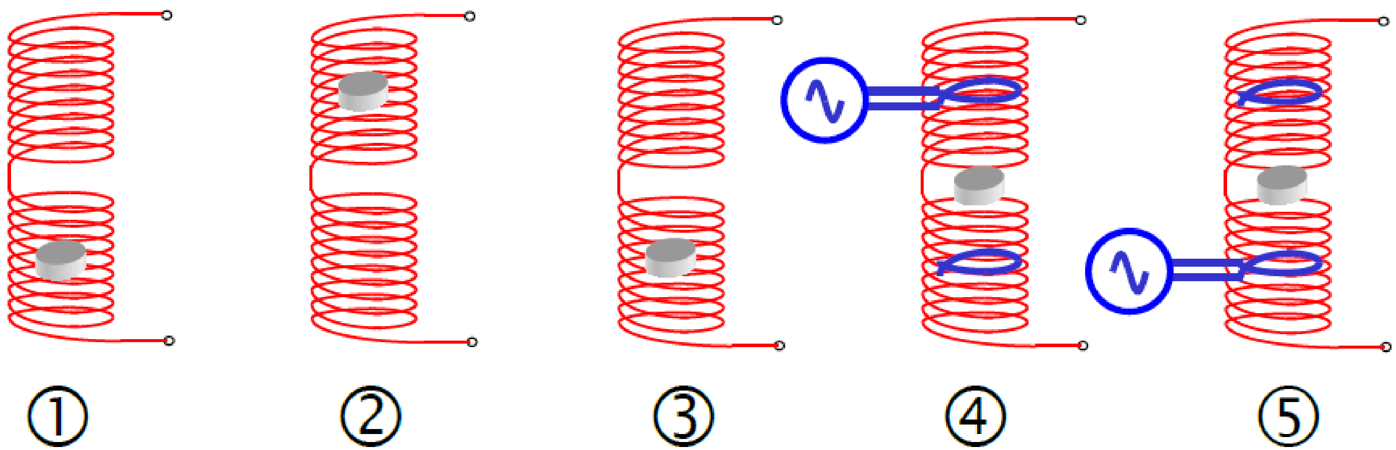
Figure 1-1. ACMS Insert and Coil Set

Physical Property Measurement System AC Measurement System Option User's Manual

Measurement method in a PPMS

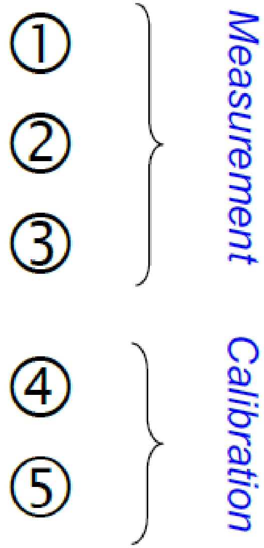
2 coils in opposite current direction to cancel applied H(t) and to be sensitive to the sample

$V = (V_1 - V_2) / 2$



By default, the sample undergoes a five-point measurement process that utilizes the calibration coil to increase measurement accuracy. The first reading is made with the sample positioned in the center of the bottom detection coil. Then the sample is positioned in the center of the top detection coil, and then in the center of the bottom coil again. During all three readings, the signals from the detection coil array are amplified, low-pass filtered, and digitized by an analog-to-digital converter (A/D). These signals are stored as waveform blocks in the data buffer. All 128 buffer points are used to record each response waveform. The points are fitted and compared to the driving signal to determine the real and imaginary components of the response when the sample is in the center of each detection coil. (Imaginary components are in phase with the driving signal and real components are 90° out of phase with the driving signal.) Subtracting one reading from the other gives a sample vector in the complex plane.

When the bottom-top-bottom coil readings are complete, the sample is placed at the center of the detection coil array so that it is between the two detection coils. Two more readings are taken with the calibration coil switched into the detection circuit with opposing polarities. The real and imaginary components of each response waveform are obtained by again fitting the data and comparing it to the driving signal. The two calibration readings are subtracted to yield a calibration vector in the complex plane. Subtracting the two calibration readings subtracts out the sample signal, leaving only environmental and instrumental factors that affect the reading.

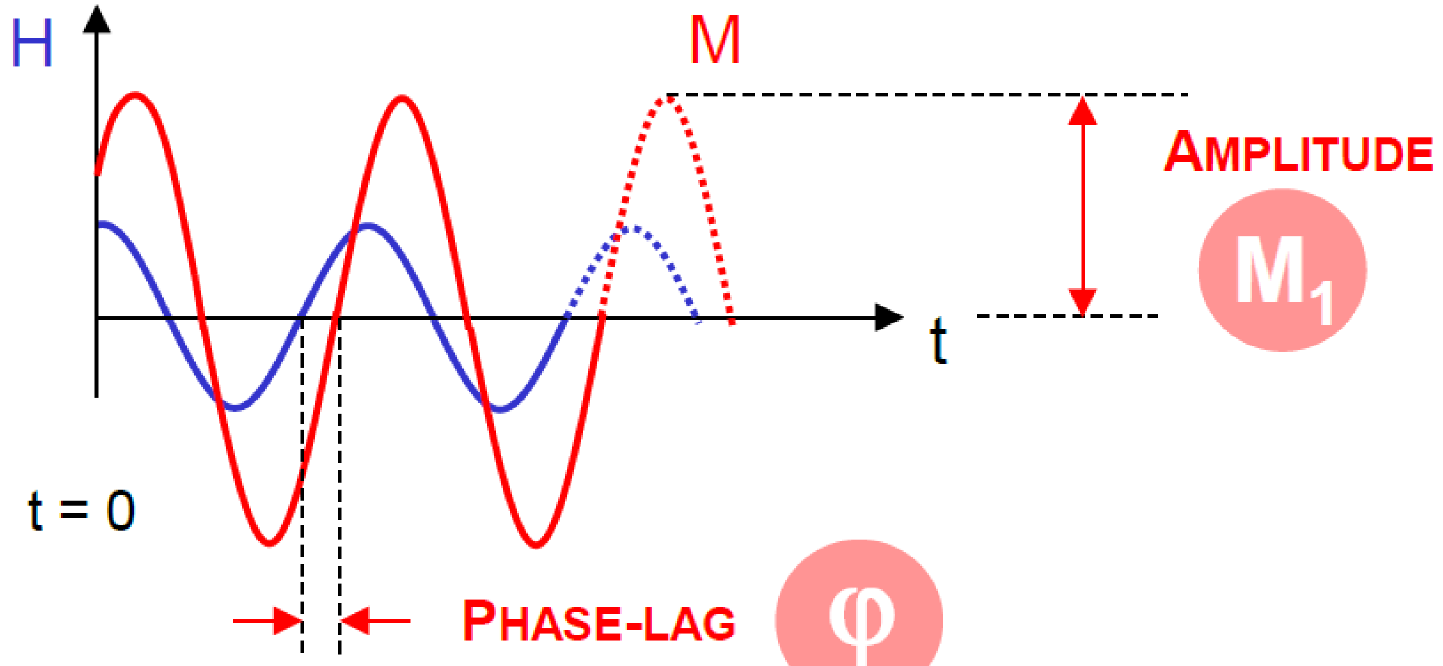


Physical Property Measurement System AC Measurement System Option User's Manual

AC susceptometry equations

$H(t) = H_1 \cos(\omega t)$

$[\ \omega = 2\pi f\ ]$



$M(t) = M_1 \cos(\omega t - \varphi)$

$= \underbrace{M_1 \cos(\varphi)}_{M'} \cos(\omega t) + \underbrace{M_1 \sin(\varphi)}_{M''} \sin(\omega t)$

! Important remarks !

- M(t) is assumed to follow a sinewave
- Physics dictates that M'' should be ≥ 0

⇒ $\overline{M}_1 = M_1 [\ e^{j\omega t}\ ]$ with $\overline{\chi}_1 = \overline{M}_1 / H_1 = \chi' - j\,\chi''$

AC susceptometry equations

When M(t) is assumed to follow a pure sinewave (i.e. only one « fundamental » signal at one frequency ω) the complex AC susceptibility reads:

$$\chi_1 = \chi = \chi' - j\,\chi''$$

In-phase component (χ')

Out-of-phase component (χ'')

χ' is related to magnetic energy **stored in the material**

$\chi' < 0$ for diamagnetic mat.

$\chi' > 0$ for paramagnetic mat.
ferromagnets
anti-ferromagnets
ferrimagnets
etc.

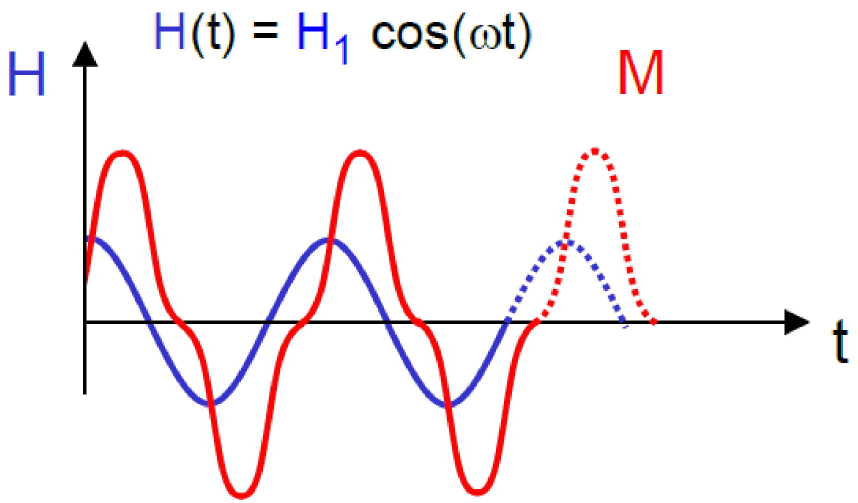
χ'' is related to magnetic energy **converted into heat**

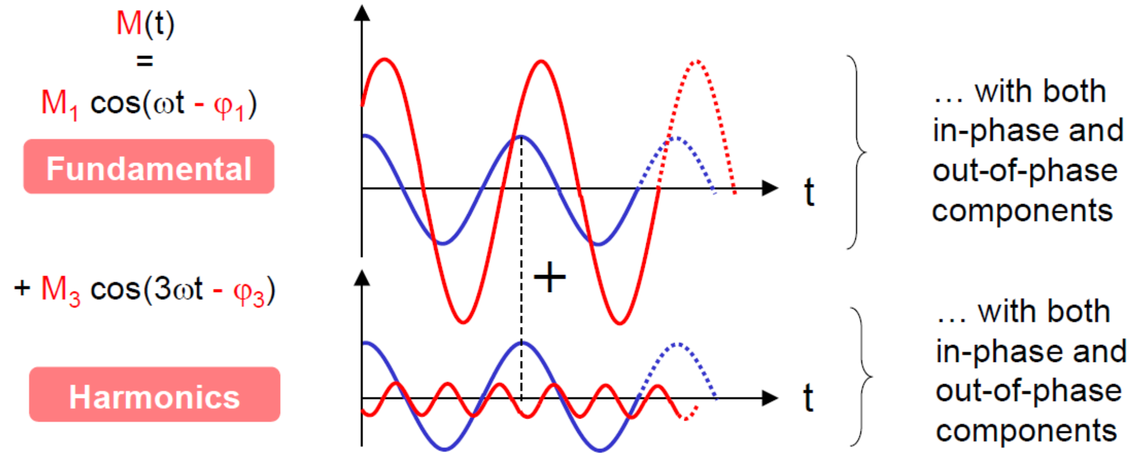
If there are no losses:
$\chi'' = 0$

If there are magnetic losses
$\chi'' > 0$

AC susceptometry equations

Most of the time M does not linearly vary with H :





BUT M(t) is still a periodic signal of the same period as the AC field.
Therefore, thanks to the Fourier theorem, M(t) reads

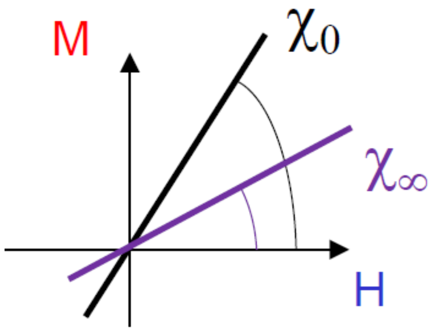
$$M(t) = H_1 \sum_{n=1}^{\infty} \left(\chi'_n \cos(n\omega t) + \chi''_n \sin(n\omega t) \right)$$

<u>If M(t) is a pure sinewave</u> : χ'_1 and χ''_1 only $\rightarrow$ χ' (= χ'_1) and χ'' (= χ'_1)
<u>If M(t) is distorted</u> : $\rightarrow$ the harmonic susceptibilities might be $\neq 0$

➢ Harmonics originate from the **<u>non-linearity</u>** of the M-H process

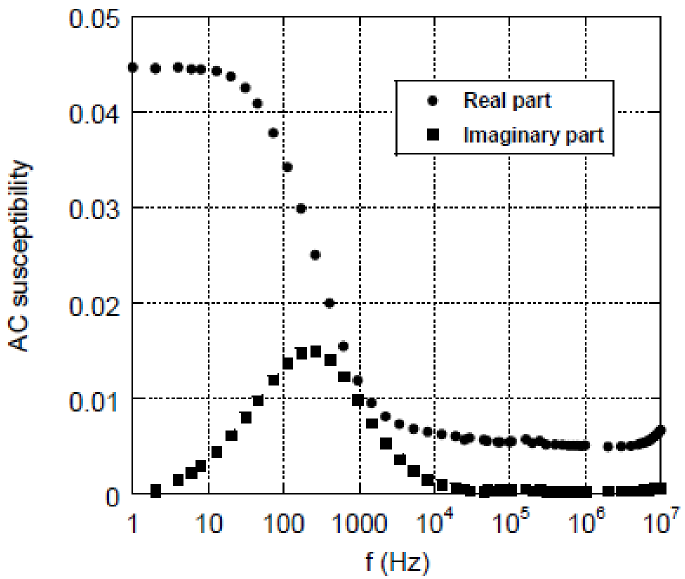
Examples of AC susceptometry data

To characterize Bownian relaxation of nanoparticles



We assume a Debye-type relaxation:

$$\chi = \chi_\infty + \frac{\chi_0 - \chi_\infty}{1 + j\omega\tau}$$



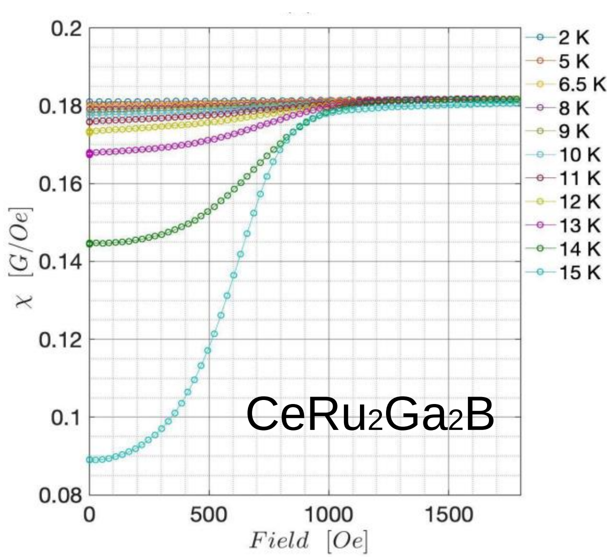
$$\chi' = \chi_\infty + \frac{\chi_0 - \chi_\infty}{1 + \omega^2\tau^2}$$

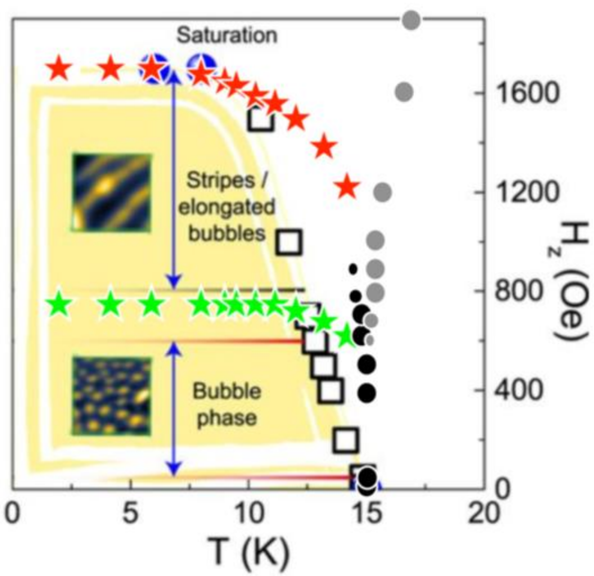
$$\chi'' = \frac{\omega\tau(\chi_0 - \chi_\infty)}{1 + \omega^2\tau^2}$$

$\chi'_n = 0$ and $\chi''_n = 0$

No harmonics

To find transition between 2 magnetic configurations





Outline

I. Few preliminary details about the sample environment

➡ Magnetic field, Temperature

II. Static macroscopic magnetometry techniques

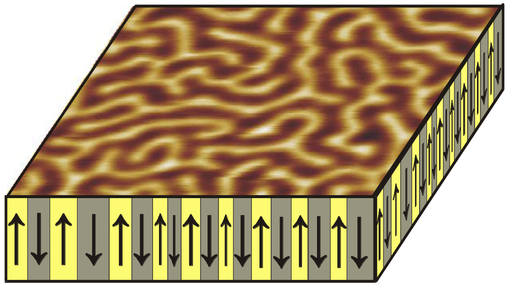
➡ VSM, SQUID, Torque, MOKE, XMCD, Photo-emission spectroscopy

III. AC macroscopic magnetometry techniques

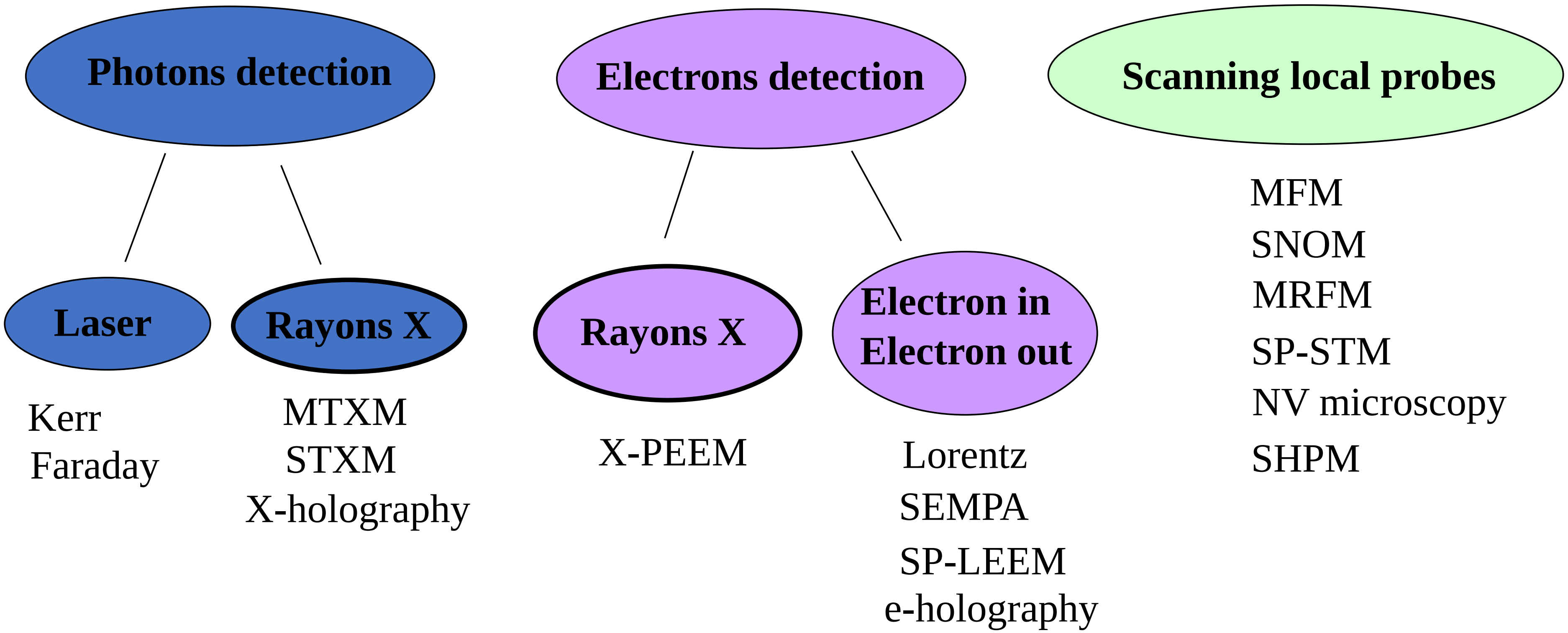
➡ AC susceptometry, FMR

IV. Imaging techniques

➡ **Scanning probe microscopies, Photon-out, Electron-out**



microscopy techniques : a rough map



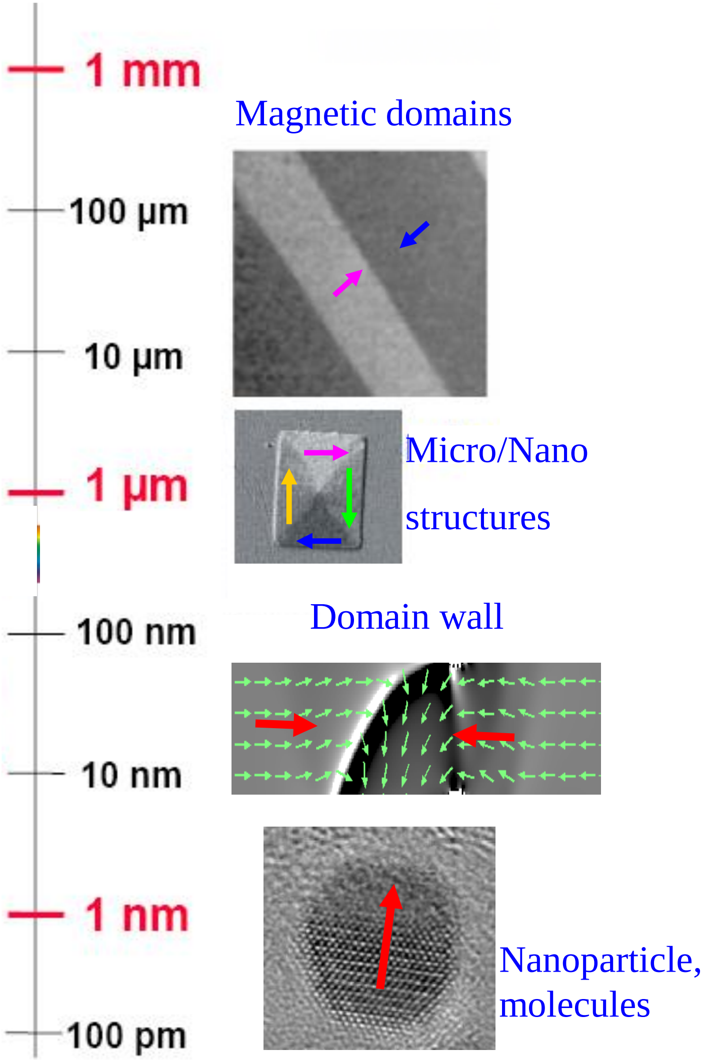
NV = NV center of diamond probe
MFM = magnetic force microscopy
MRFM = magnetoc resonance force microscopy
MTXM = magnetic transmission X-ray microscopy
SEMPA = scanning electron microscopy with polarization analysis
SNOM = scanning near field optical microscopy

SP-LEEM = spin polarized low energy electron microscopy
SP-STM = spin polarized scanning tunneling microscopy
STXM = scanning transmission X-ray microscopy
X-PEEM = X-ray photoemission electron microscopy
SHPM = scanning all probe microscopy

Which technics fits your need ?

The 1st parameter to check may be the size of your object…

Spatial scale

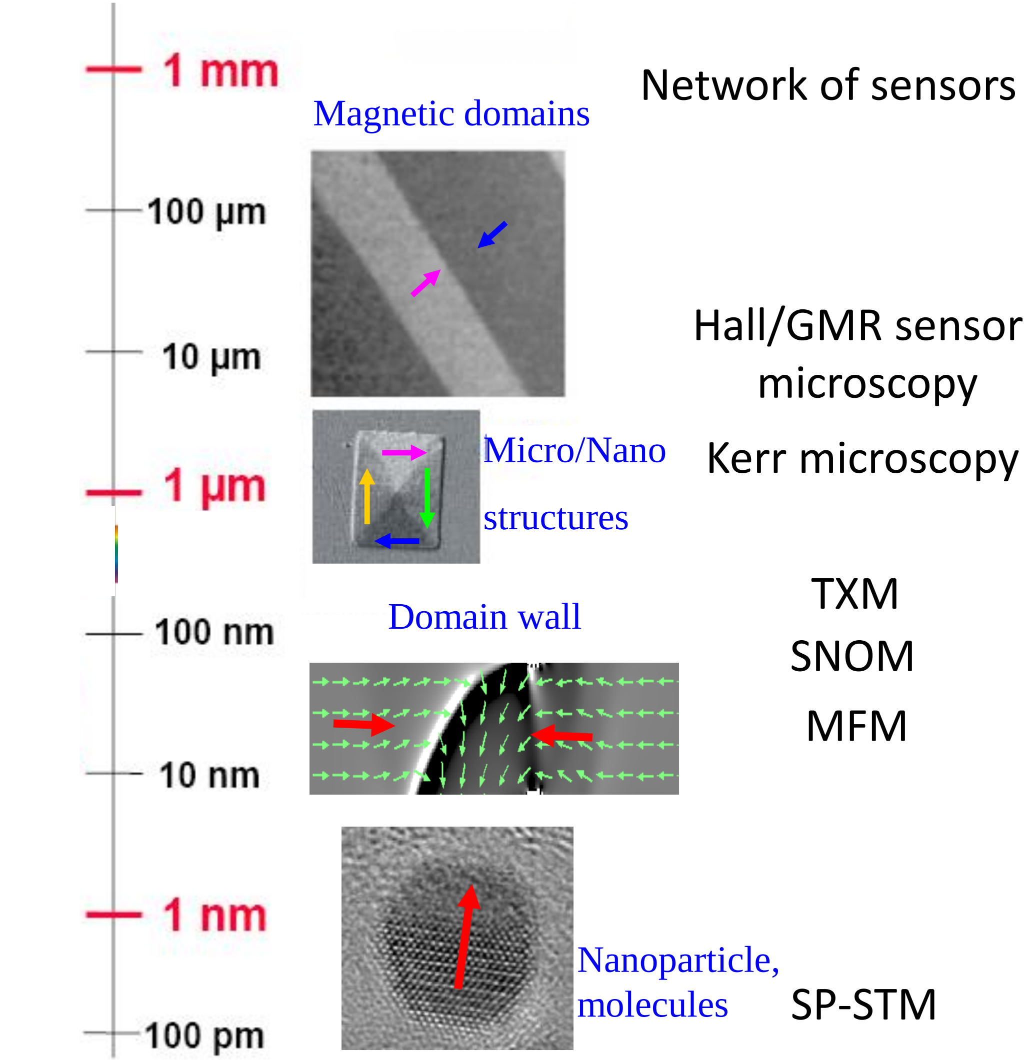


Which technics fits your need ?

The 1st parameter to check may be the size of your object…

Spatial scale

Microscopy techniques

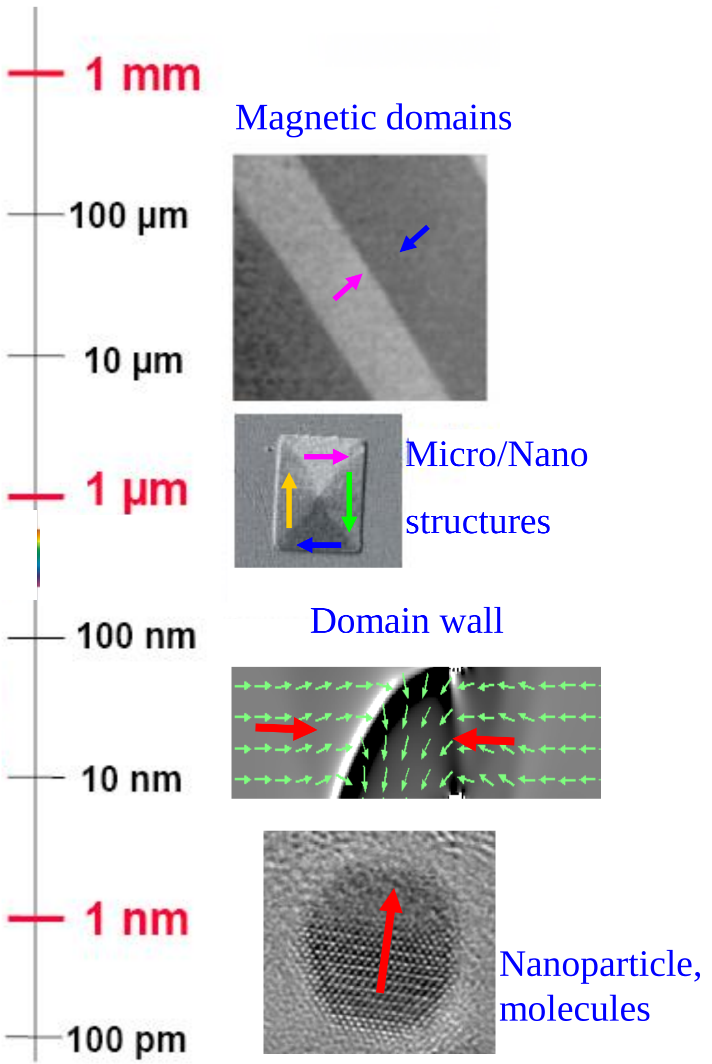


Technique	Probed Quantity	Spatial Resolution	Temporal Resolution	Info. Depth	Comments
Lorentz Microscopy	stray field + sample induction	10 nm	1 ns	sample average	Thin samples, Quantitative info. with differential phase contrast microscopy.
Electron Holography	stray field + sample induction	5 nm	10 ms	sample average	Quantitative info. through mathematical image reconstruction.
SEMPA	magneti-zation	20 nm	700 ps*	1 nm	Quantitative info., Long acquisitions, UHV required.
SP-STM	magneti-zation	atomic	120 ps*	surface	UHV required, Usually low temperature, Long acquisitions.
MFM	stray field	10-100 nm	low	1000 nm	Potentially invasive, Long acquisitions, Few sample requirements.
TXM	magneti-zation	25 nm	50 ps	sample average	Synchrotron technique, Quick overview images.
STXM	magneti-zation	25 nm	50 ps	sample average	Synchrotron technique, High repetition rates.
PEEM	magneti-zation	25 nm	50 ps	5 nm	Synchrotron technique, Discharges possible due to high potential.

R.M. Reeve *et al.*, arXiv:1806.07767v2

Which technics fits your need ?

Spatial scale



… But you also need to check other criteria…

	Sp-STM	MFM	NV	BEMM	SEMPA	SPLEEM	TEM	XMCD -PEEM	XMCD-microscopy (Fresnel ZP)
Resolution	<1nm	15nm	5-10 nm	1-5nm	10nm	10nm	1-2nm	25nm → 10nm	15nm
Sensitivity	High	Med	High	Med	Med	High	Low	High	High
In-field	YES	Limited	Limited	YES	local	No?	Limited	No?	YES
Versatile*	No	YES	Yes	No	Yes	UHV	Limited	Yes	Limited
Dynamics	No	No	No	No	No	No	New	Yes	Yes
Element-sensitive	Limited	No	No	No	No	Limited	Limited	Yes	Yes
Probes	m_i	$\mathbf{H}_d$	$\mathbf{H}_d$	m_i	$\mathbf{m}$	$\mathbf{m}$	$m_{x,y}$	m_k	m_k

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?

Outline

I. Few preliminary details about the sample environment

- Magnetic field, Temperature

II. Static macroscopic magnetometry techniques

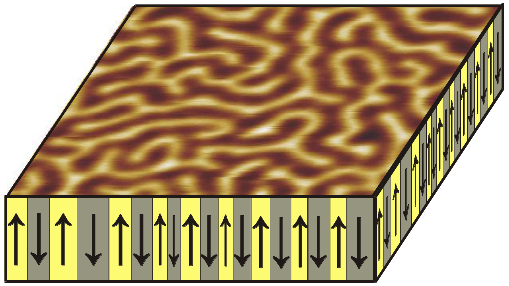
- VSM, SQUID, Torque, MOKE, XMCD

III. AC macroscopic magnetometry techniques

- AC susceptometry, FMR

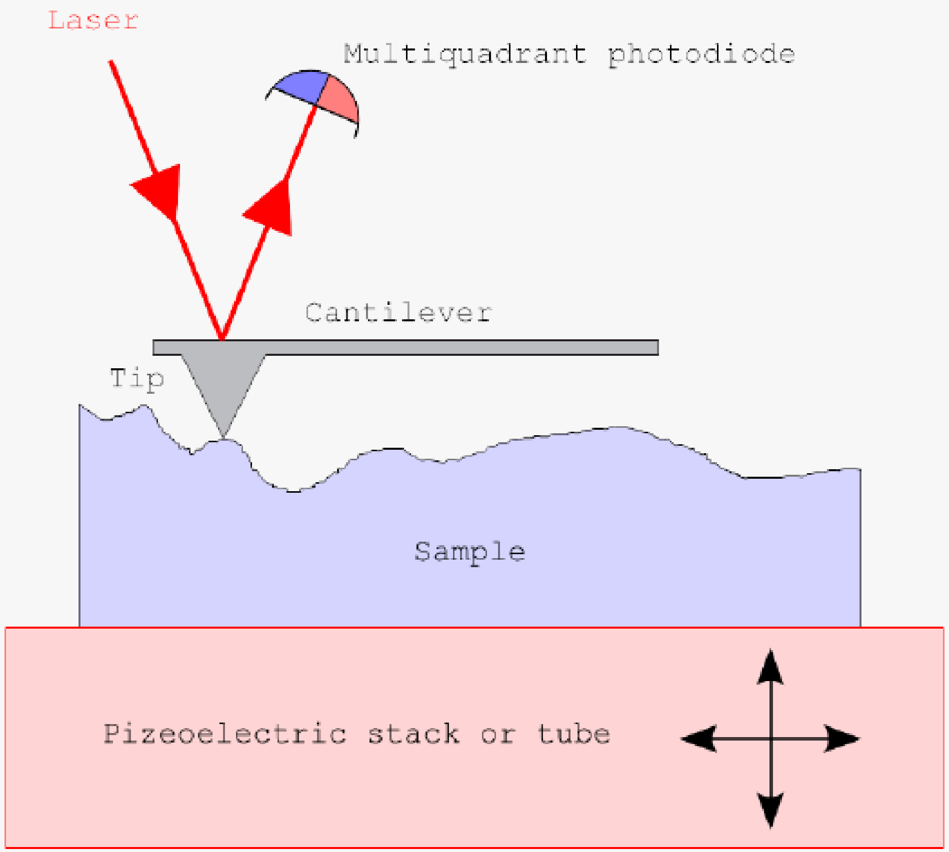
IV. Imaging techniques

- **Scanning probe microscopies**, Photon-out



Magnetic force microscopy

The Atomic Force Microscope (AFM)



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

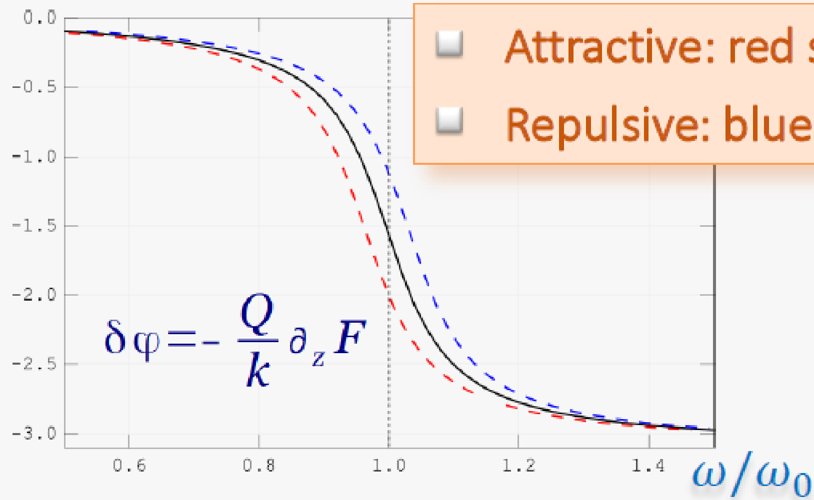
The cantilever as an oscillator

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

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

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

Probing forces with the phase shift



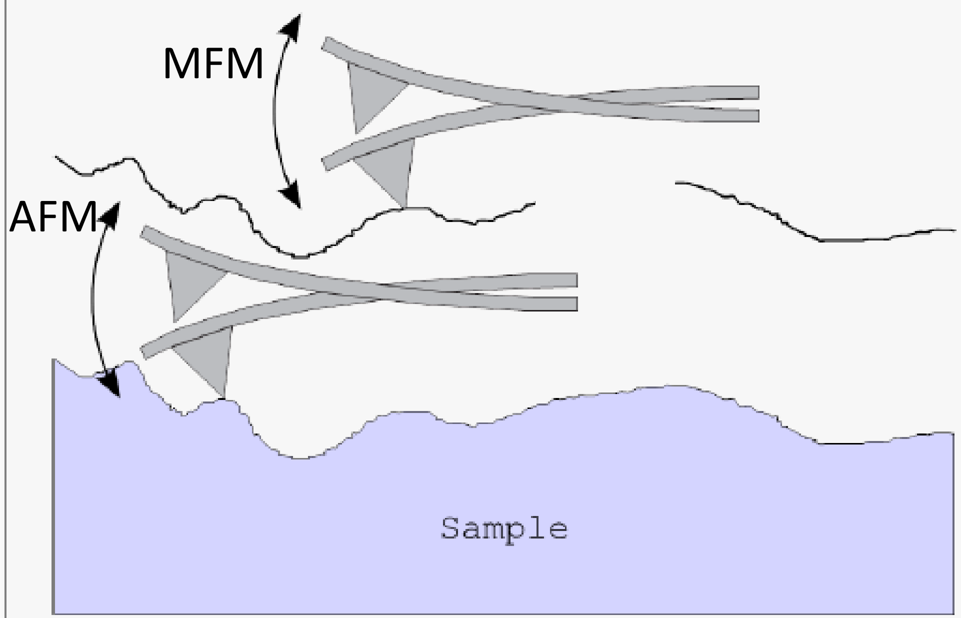
$$\delta\varphi=-\frac{Q}{k}\partial_z F$$

- Attractive: red shift
- Repulsive: blue shift

AFM characterizes topography

Magnetic force microscopy (MFM)

MFM : two-pass technique

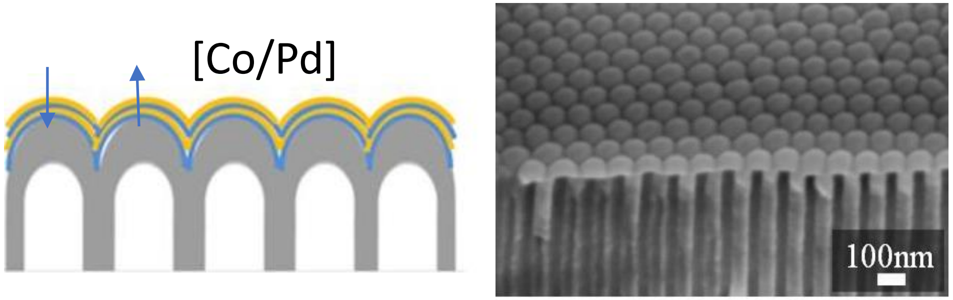


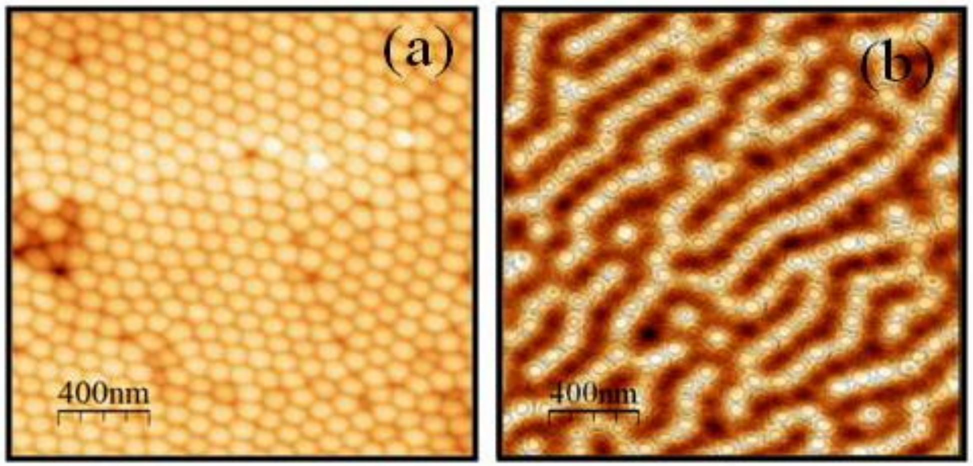
- First pass: measure topography
- Second pass: measure magnetism

NB: other measurement modes exist

Y. Zhu Ed., Modern techniques for charact-erizing magnetic materials, Springer (2005)

Example: magnetic domain configuration of [Co/Pd] multilayer on patterned substrate





L. Piraux et al., APL 101, 013110 (2012)

Magnetic force microscopy : criteria

What is measured?

- Stray field?
- Indirect?
- Hardly quantitative

Environmental conditions

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

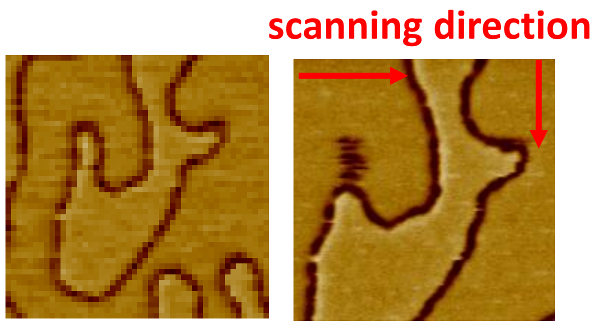
Which specifications?

- Depth resolution: surface/volume
- Lateral resolution: 25-50nm
- Sensitivity: medium (1nm thickness)
- Time/Spectral resolution: slow

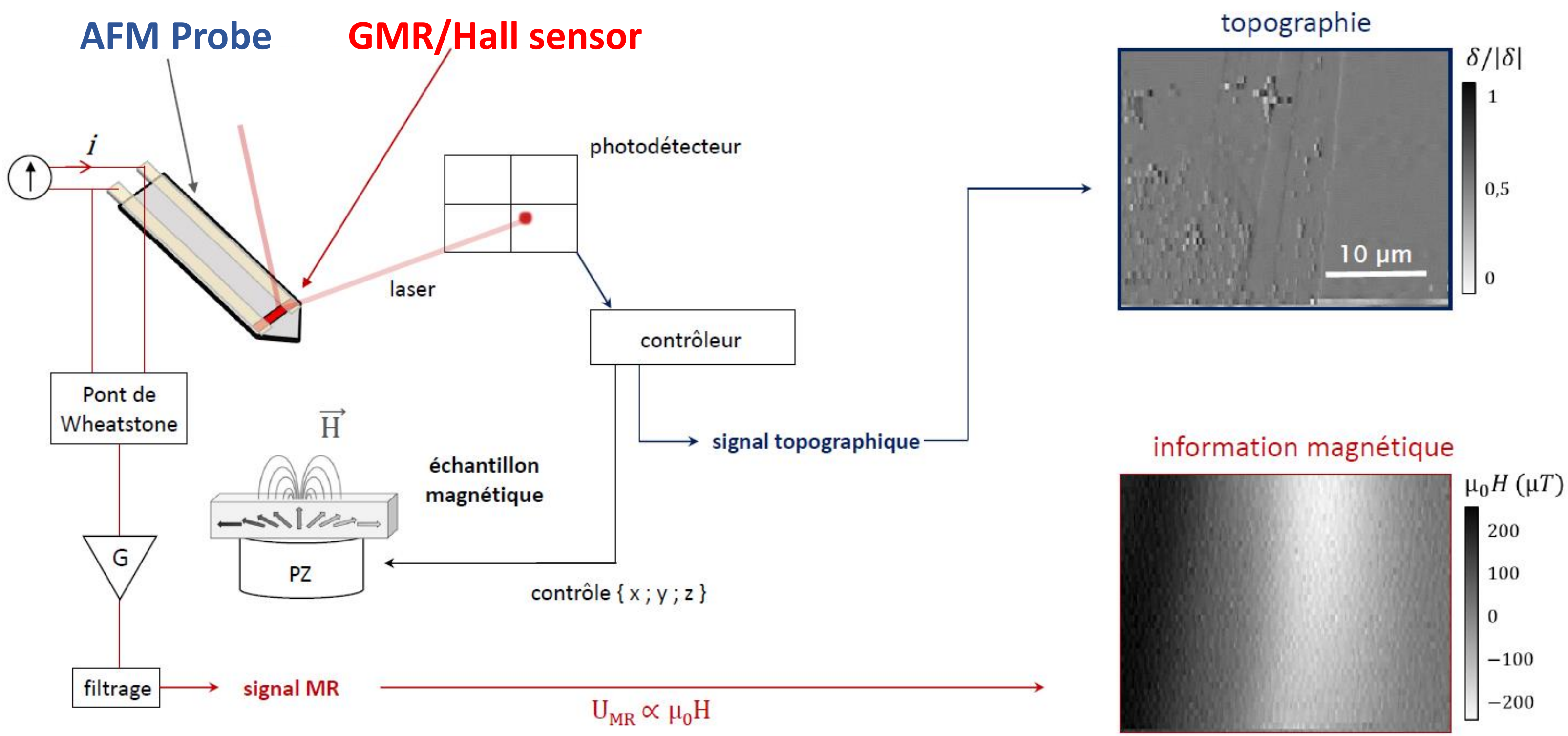
Versatility

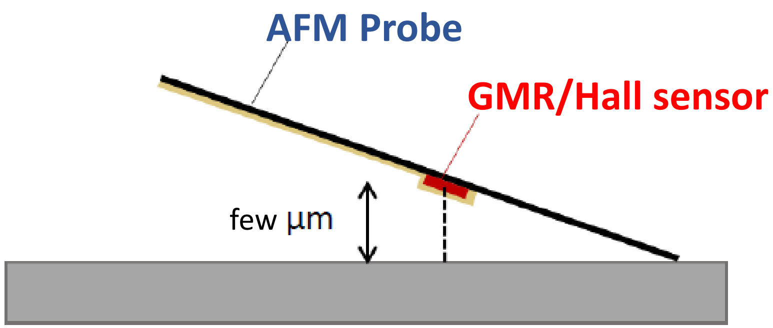
- No sample preparation needed
- Time per measurement: few mn
- Ex situ
- In-lab, cheap
- May influence sample

Tip-sample interactions can impact the magnetic configuration of your sample



Scanning GMR/Hall probe microscopy



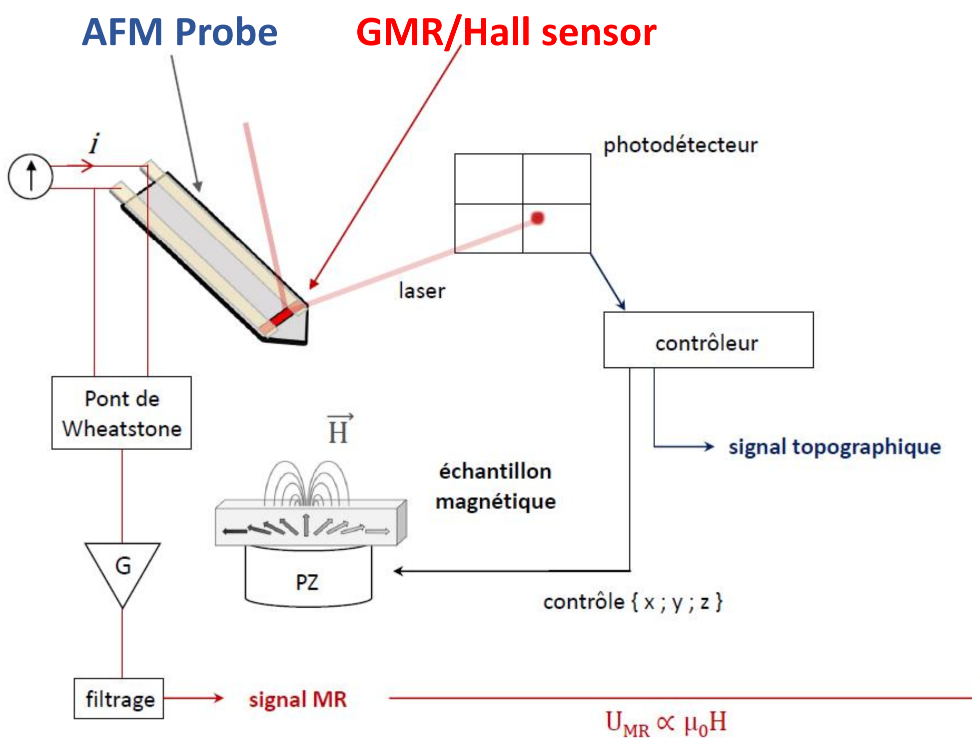


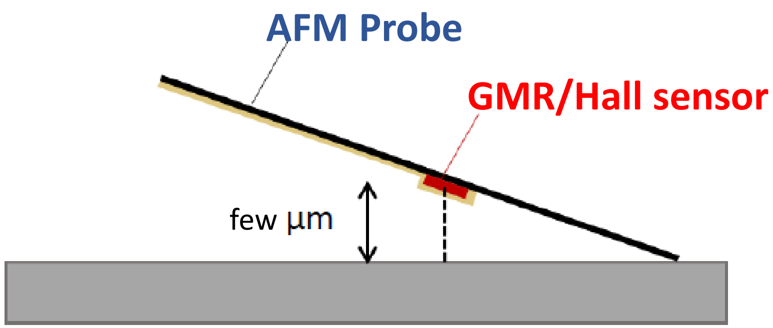
Advantage : To get a direct access to magnetic field instead of its second derivative as in MFM

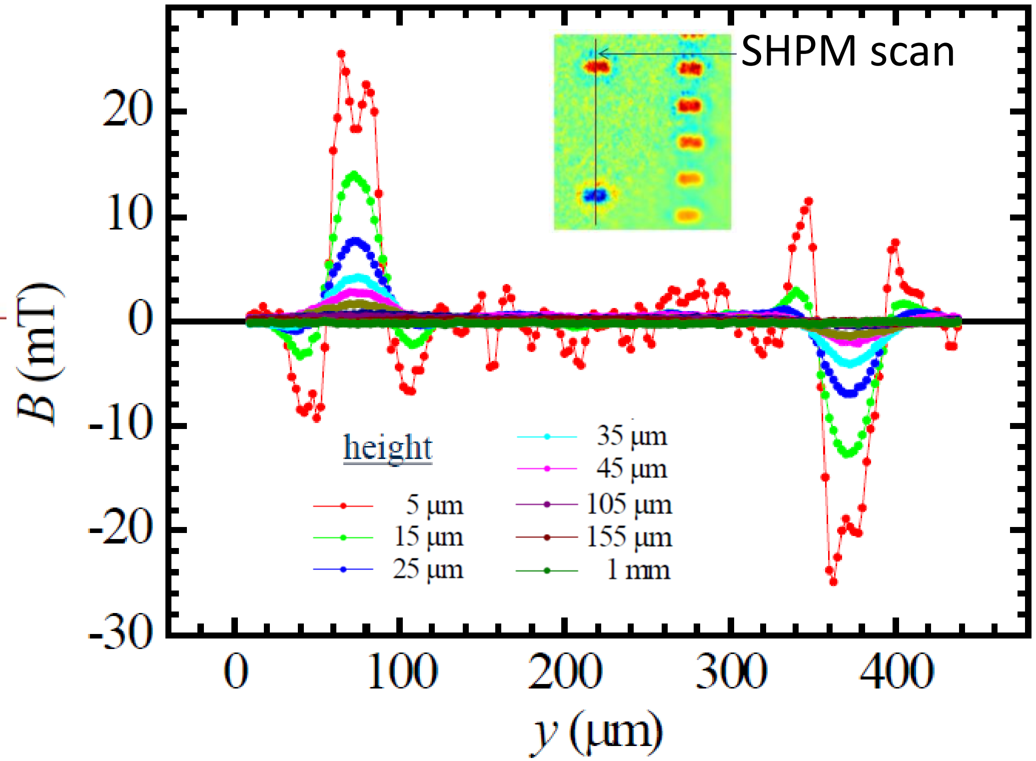
J. Moulin (phD thesis 2020)

Scanning GMR/Hall probe microscopy

<u>Advantage :</u> To get a direct access to magnetic field instead of its second derivative as in MFM

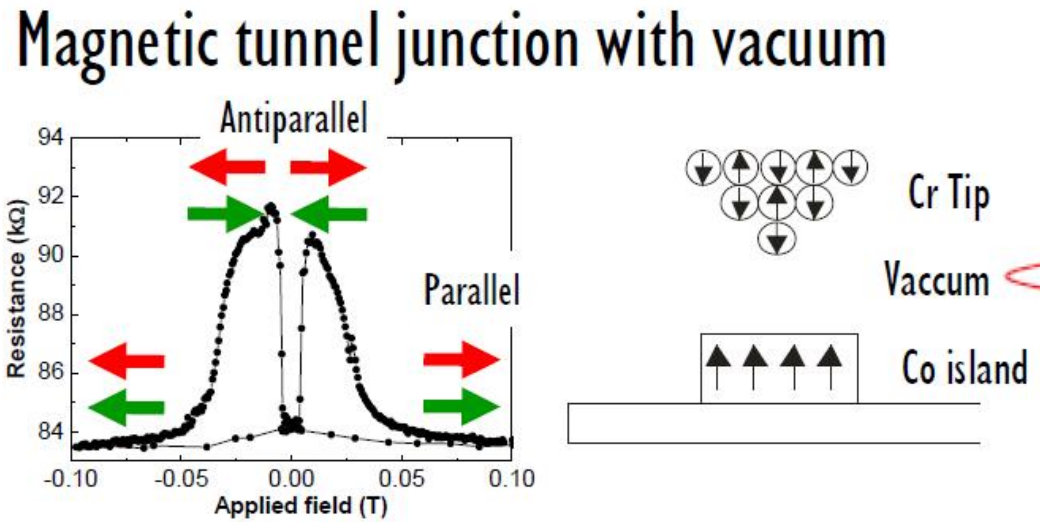


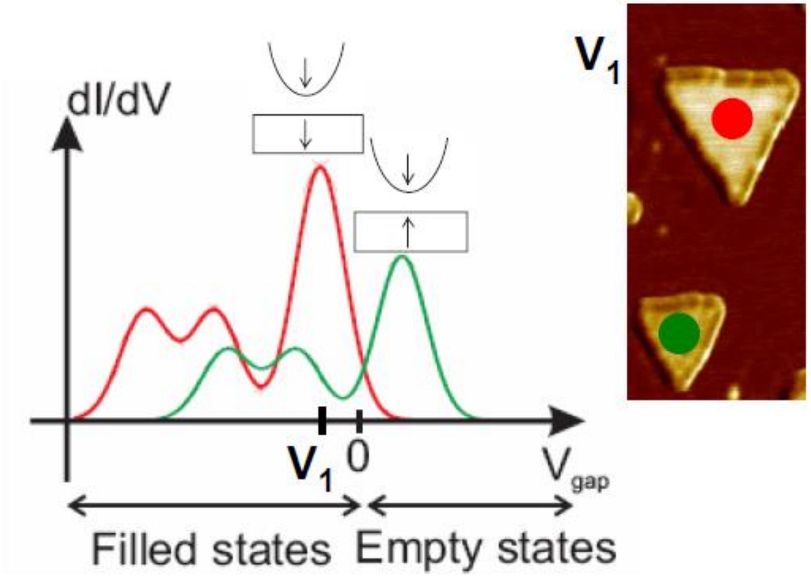


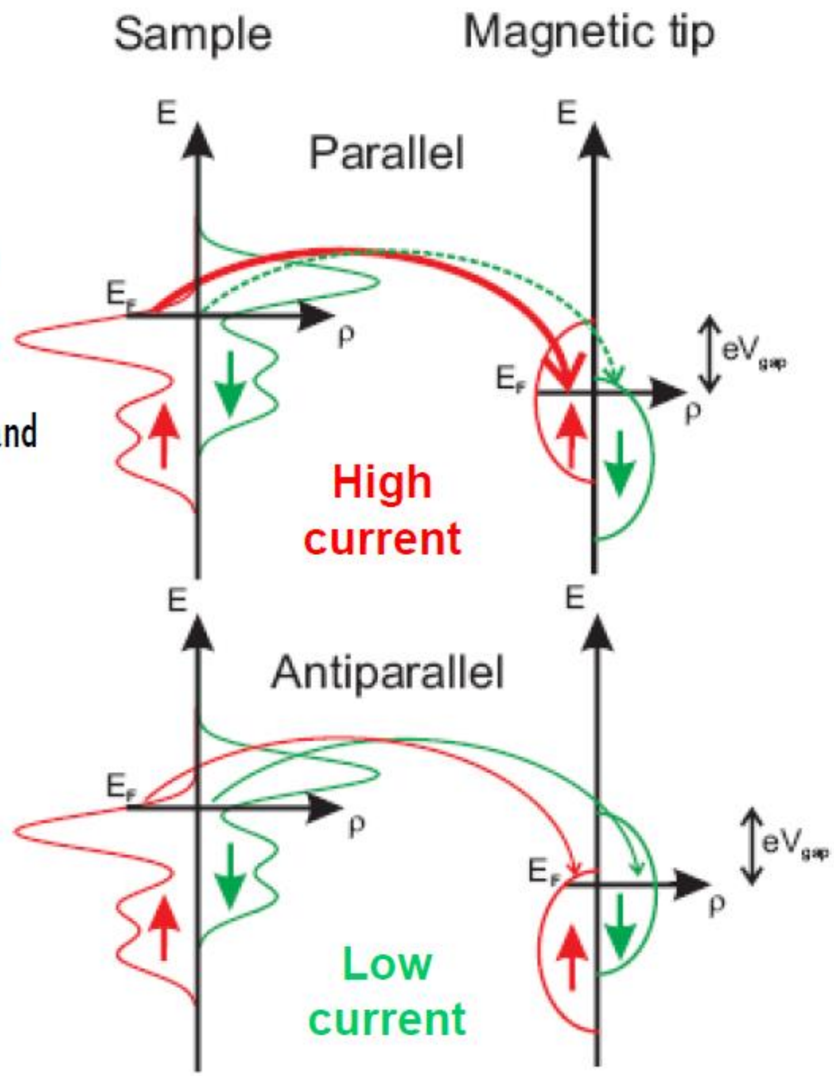


K. Hasselbach (internal com., 2014)

Spin-polarized Scanning Transmission Microscope







Bode, Getzlaff, Wiesendanger, Phys. Rev. Lett. 81, 4256 (1998).

Wulfhekel, Kirschner, Appl. Phys. Lett. 75, 1944 (1999).

Spin-polarized Scanning Transmission Microscope

What is measured? ✓
- Related to magnetization and element
- Indirect? ✓
- Not quantitative

Environmental conditions
- Low temperature only ✓
- Field: magnetic field ✓
- Light ✓

Which specifications? ✓
- Magnetization: 3D
- Depth resolution: surface.
- Lateral resolution: atom
- Sensitivity: high
- Time/Spectral resolution: emerging

Versatility ✓
- Ultra-high vacuum and single crystal
- Time per measurement: minutes
- Mid-scale in-lab.

Outline

I. Few preliminary details about the sample environment

➡ Magnetic field, Temperature

II. Static macroscopic magnetometry techniques

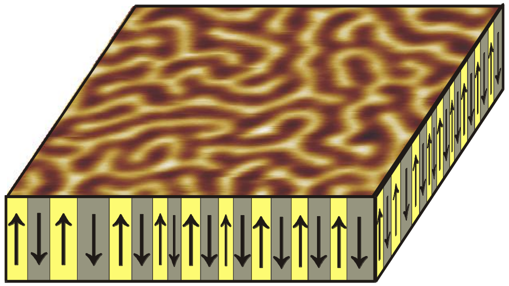
➡ VSM, SQUID, Torque, MOKE, XMCD

III. AC macroscopic magnetometry techniques

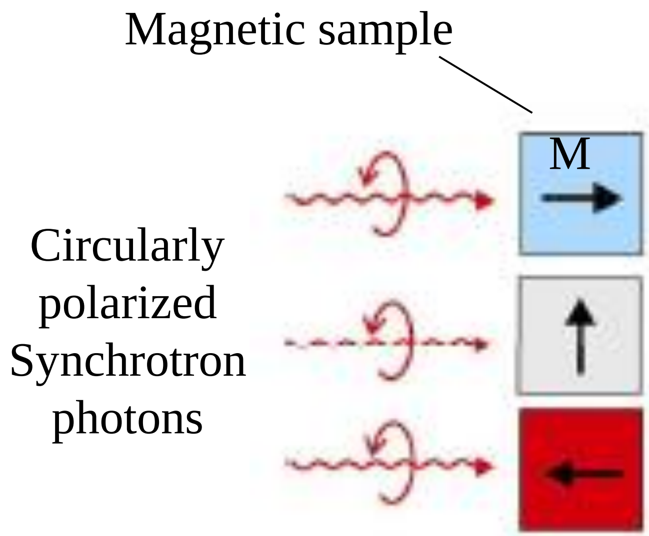
➡ AC susceptometry

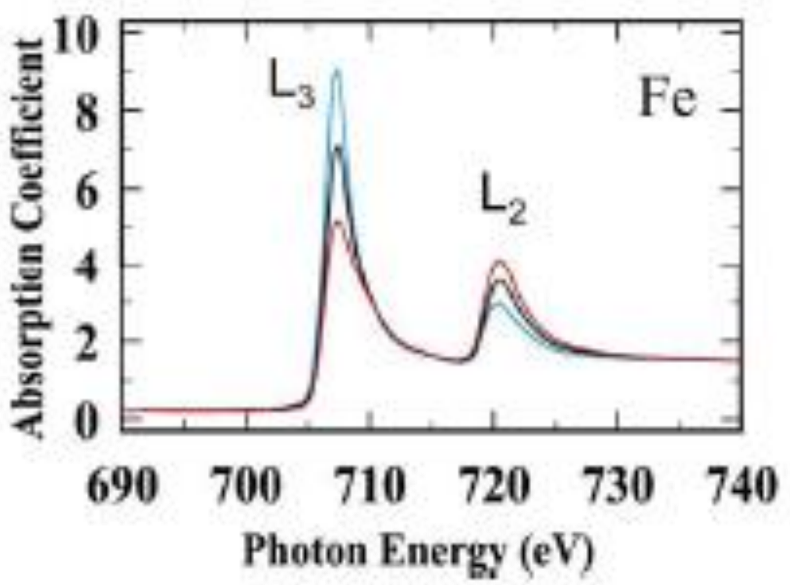
IV. Imaging techniques

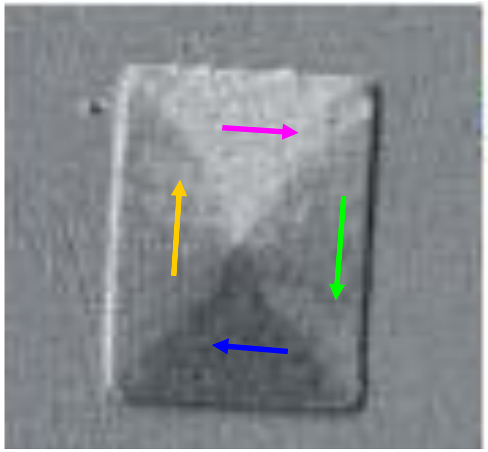
➡ Scanning probe microscopies, **Photon-out**



Using XMCD contrast to image







X-ray absorption depends on the angle of incidence regarding to the magnetic moment direction

=> **Magnetic contrast**

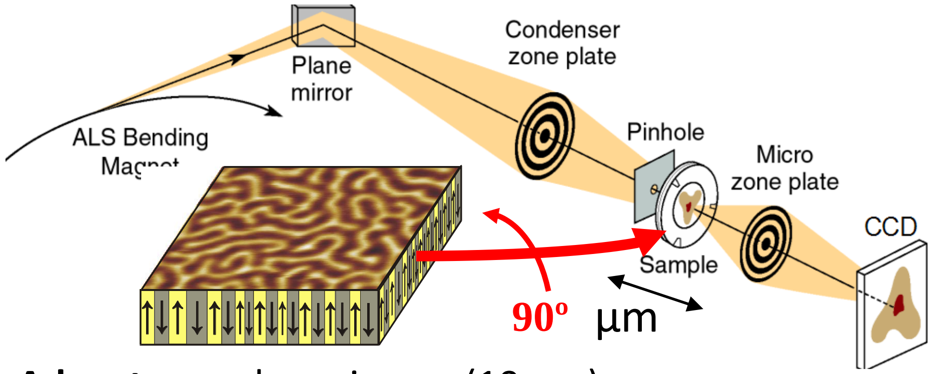
BONUS : Absorption depends on electronic transitions

=> **Chemical selectivity**

X-ray miscroscopy

Transmission X-ray microscopy (TXM)

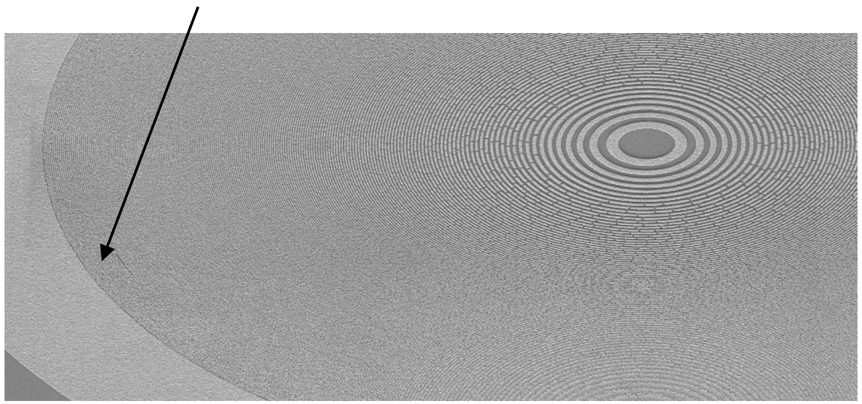
(ALS, SLS, BESSY II, ANKA)



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

Disadvantages : mostly 300K, small field, lenses

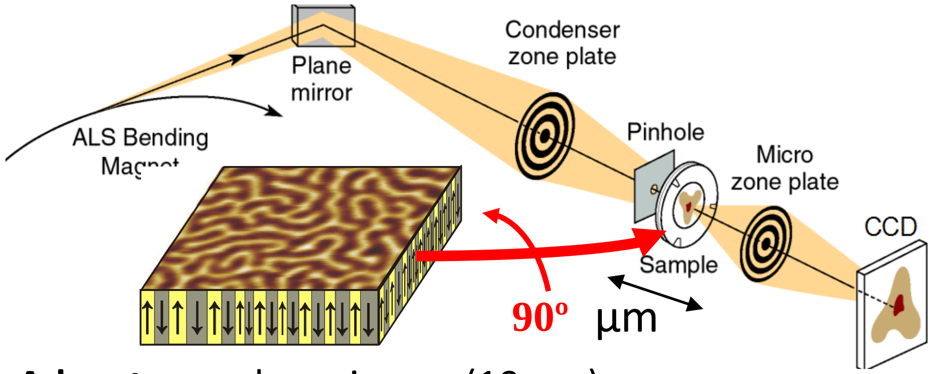
Distance between 2 circles => resolution (here 15 nm)



X-ray miscroscopy

Transmission X-ray microscopy (TXM)

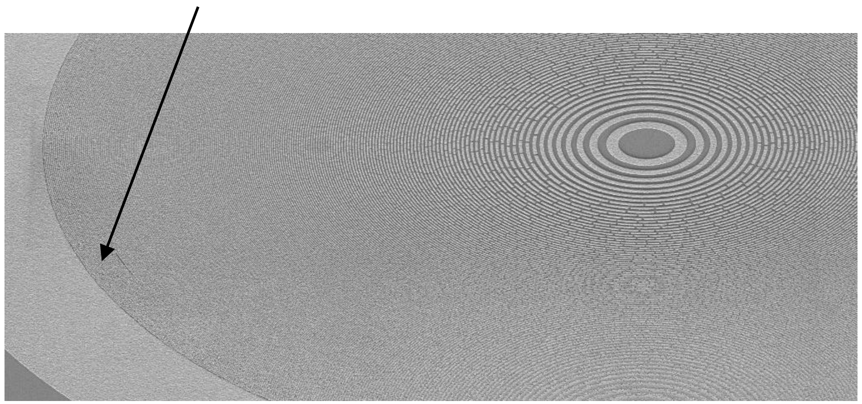
(ALS, SLS, SOLEIL, BESSY II, ANKA)



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

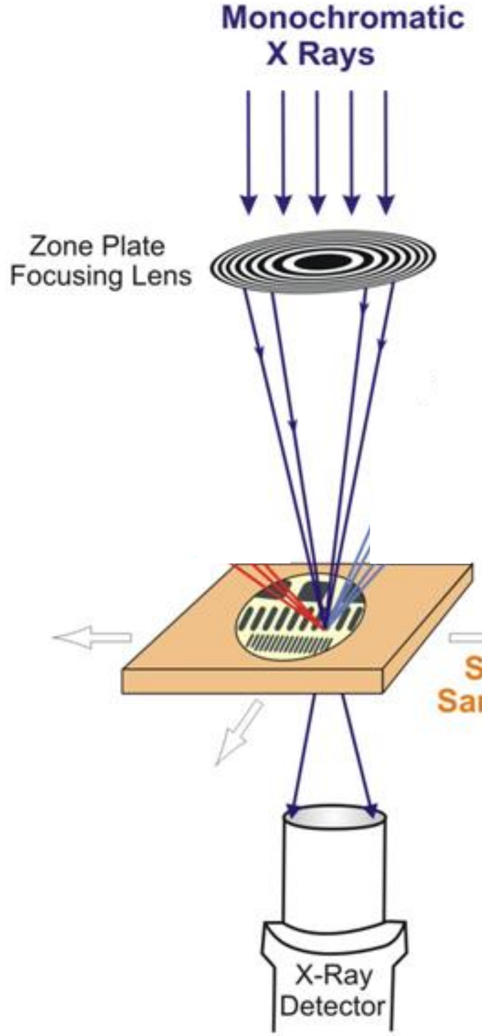
Disadvantages : mostly 300K, small field, lenses

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



Scanning TXM

(ALS, SSRL, SLS, Soleil)



Still 50 ps time resolution and 25 nm resolution

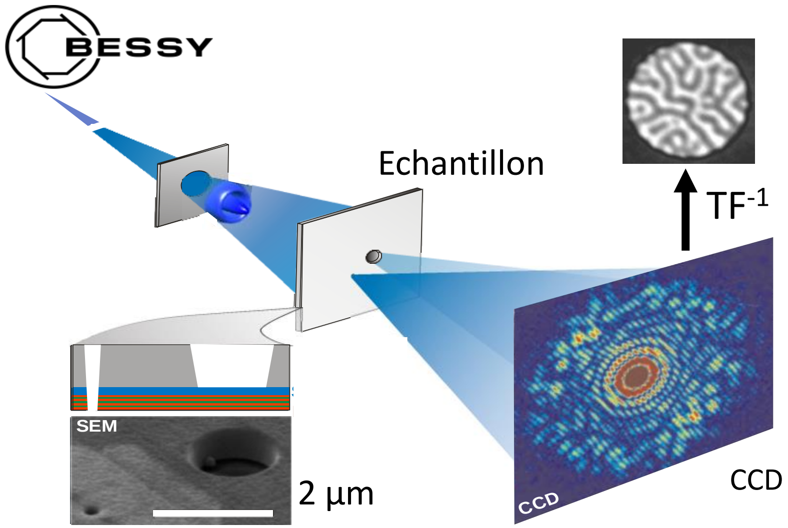
BUT Only one lense

AND Scanning

=> More flux locally

X-ray miscroscopy

X-ray Holography

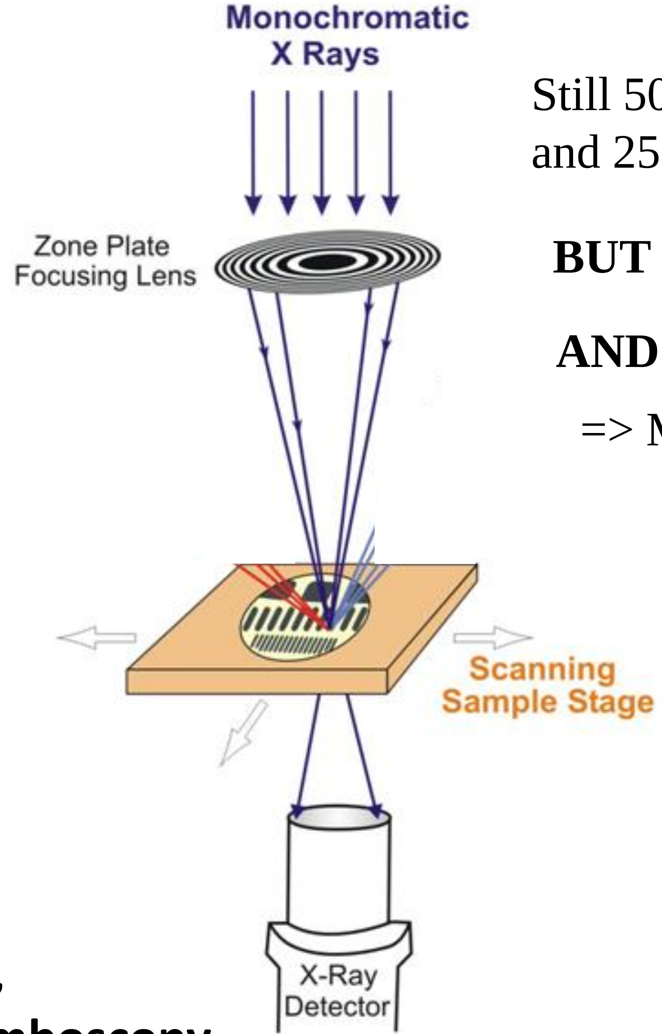


Advantage : 400K-10K, more space around the sample

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

Scanning TXM

(ALS, SSRL, SLS, Soleil)



Still 50 ps time resolution and 25 nm resolution

BUT Only one lense

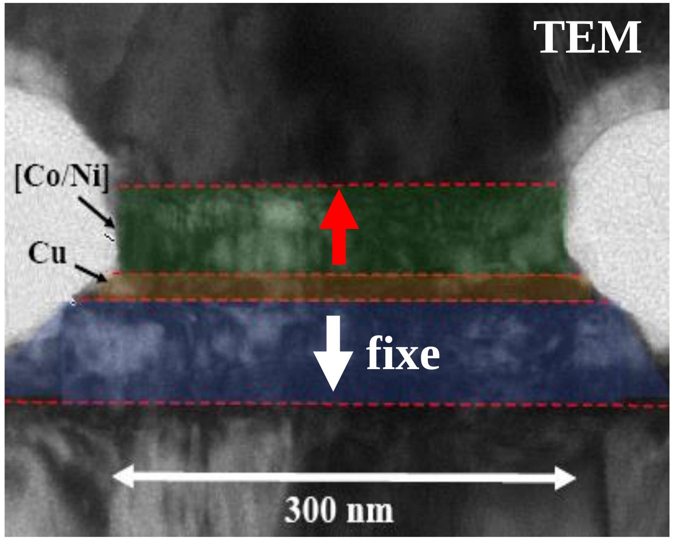
AND Scanning

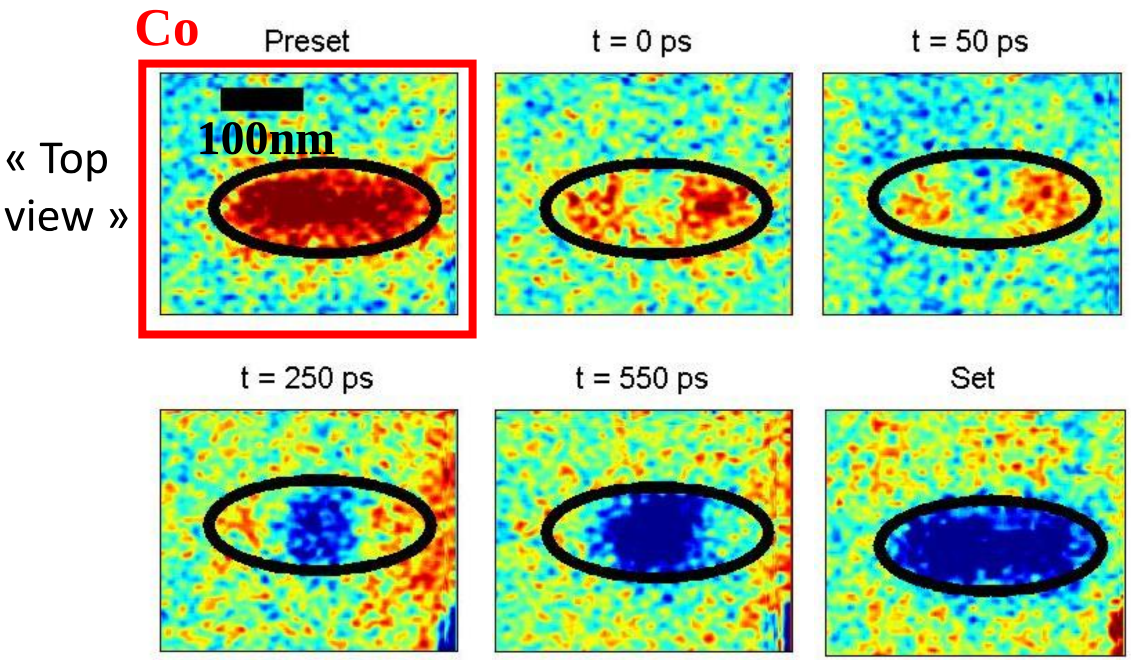
=> More flux locally

**Dynamics in MTXM, STXM,
Holography requieres stromboscopy**

Example : STT-induced switching by STXM

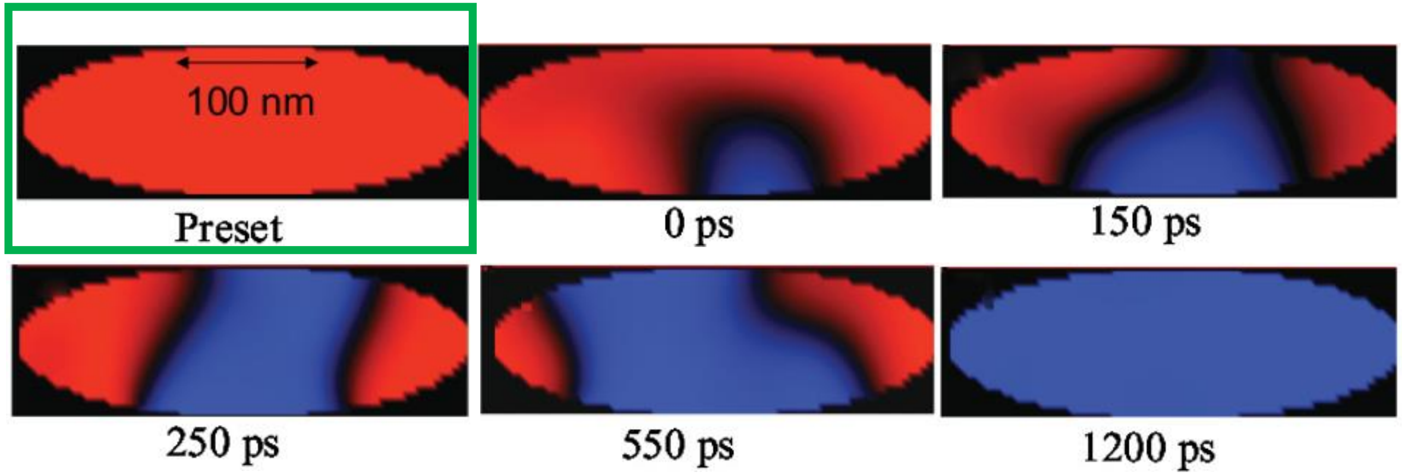
t=0ps





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

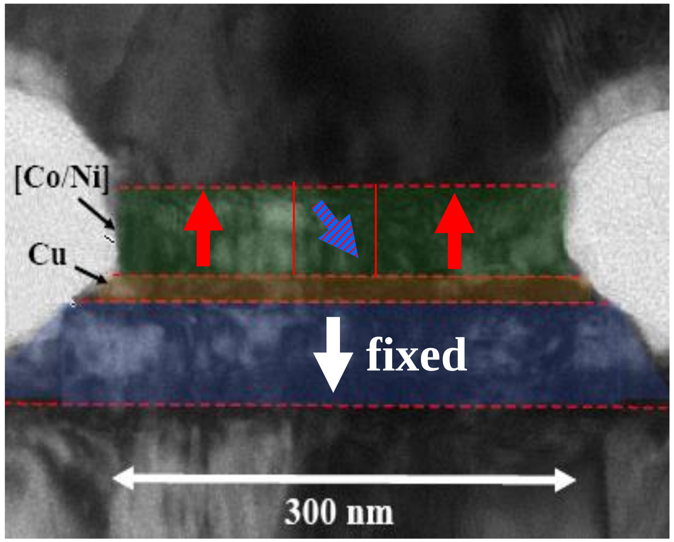
Micromagnetic simulation (Scheinfein code)



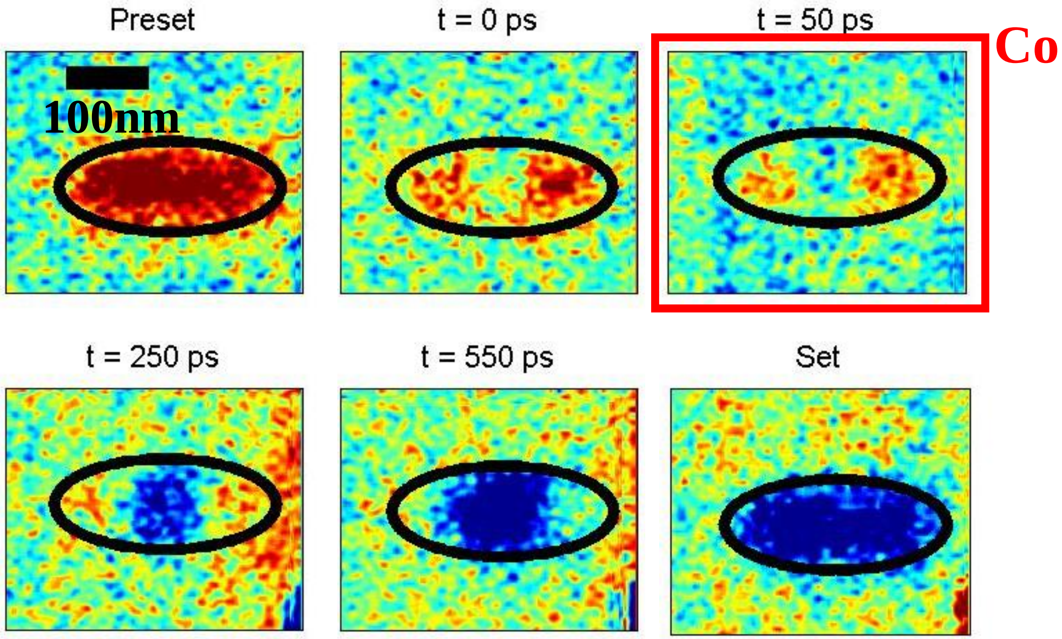
D.P. Bernstein et al., PRB(R) 83, 180410 (2011)

Example : STT-induced switching by STXM

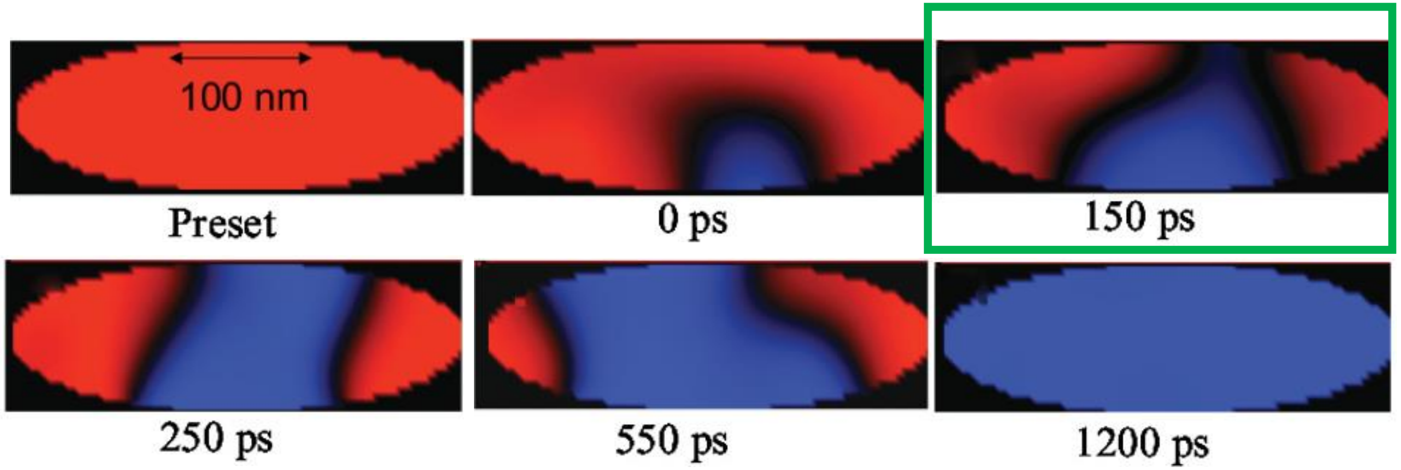
t=50ps



Excitation : Current pulsed at t=0ps



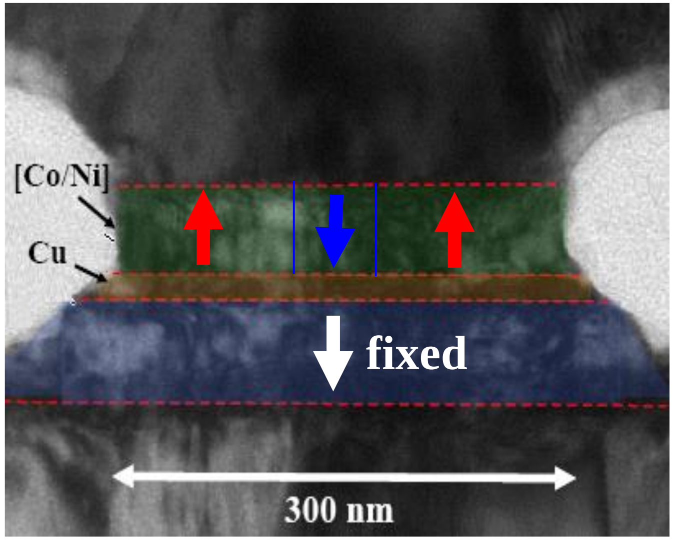
Micromagnetic simulation
(Scheinfein code)

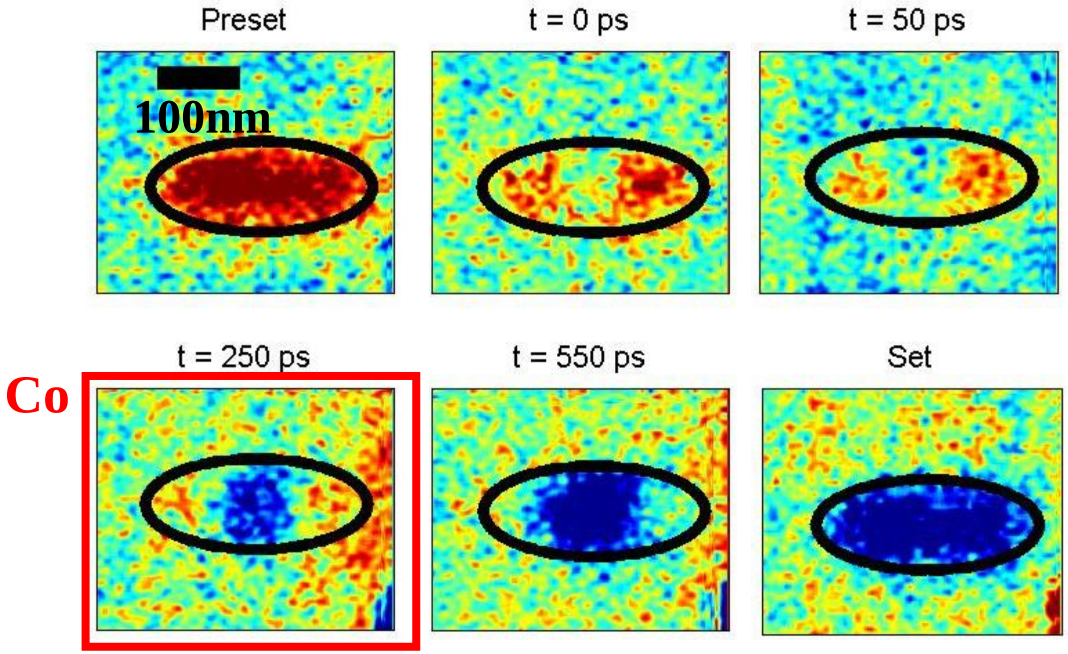


D.P. Bernstein et al., PRB(R) 83, 180410 (2011)

Example : STT-induced switching by STXM

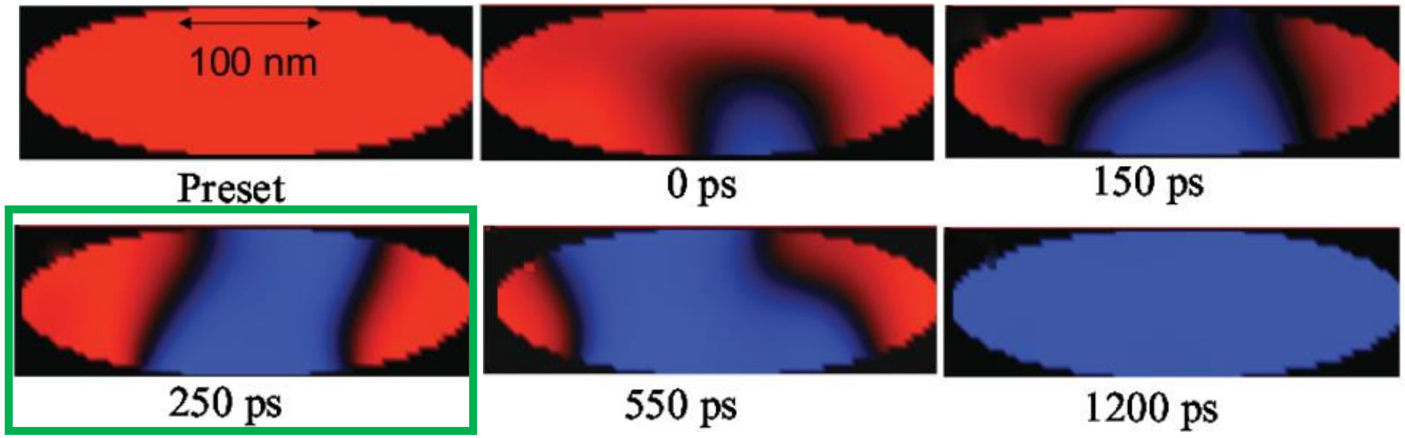
t=250ps





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

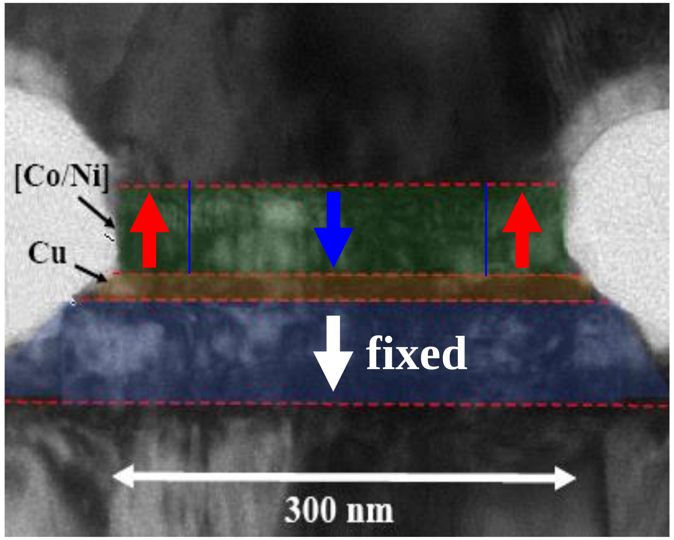
Micromagnetic simulation (Scheinfein code)



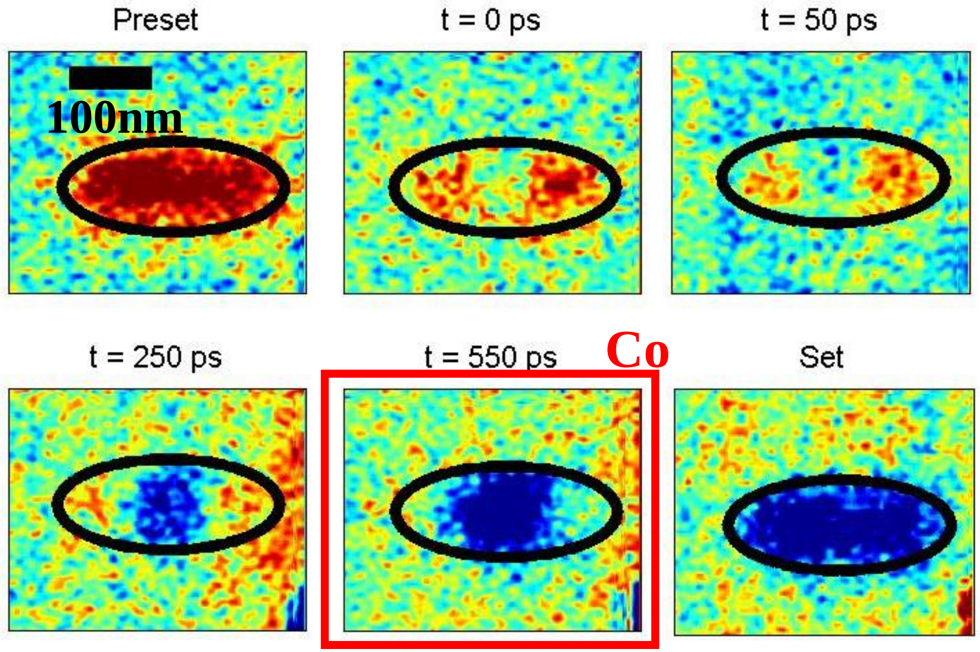
D.P. Bernstein et al., PRB(R) 83, 180410 (2011)

Example : STT-induced switching by STXM

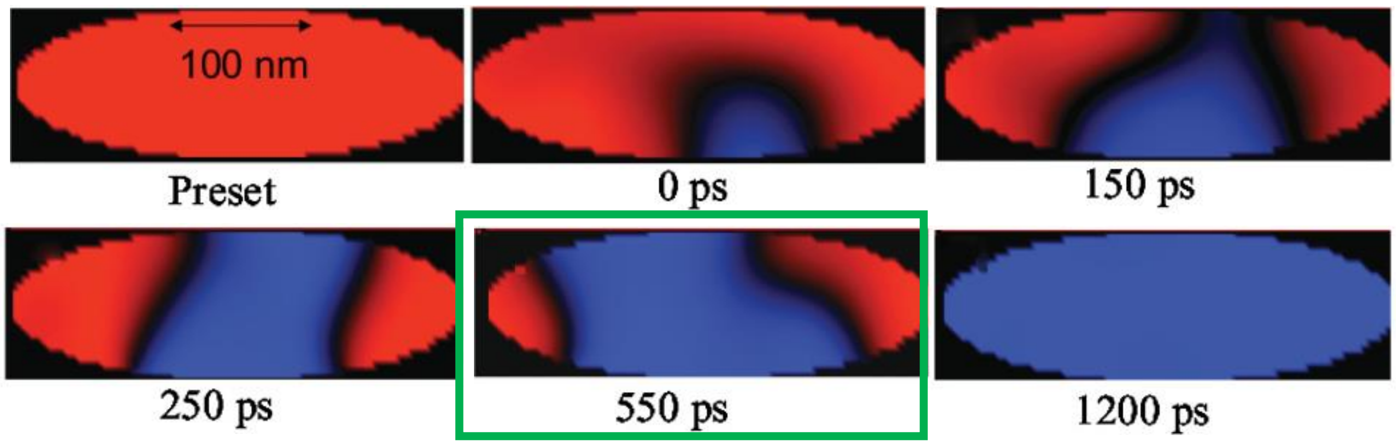
t=550ps



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

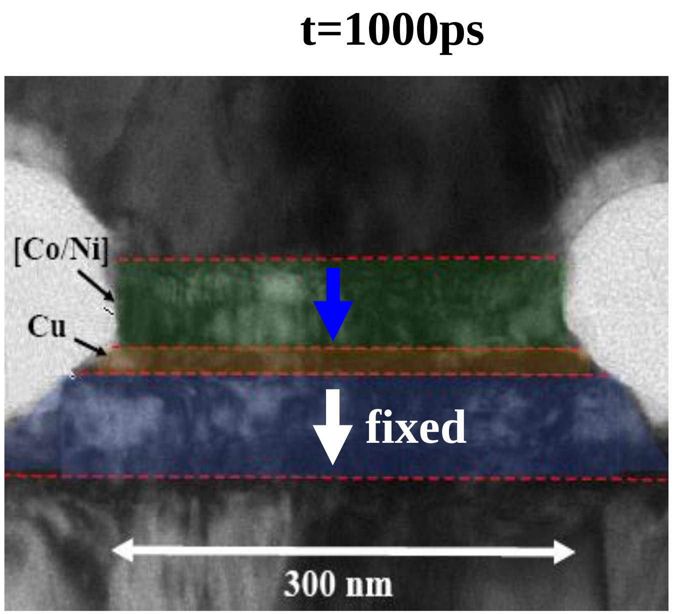


Micromagnetic simulation
(Scheinfein code)

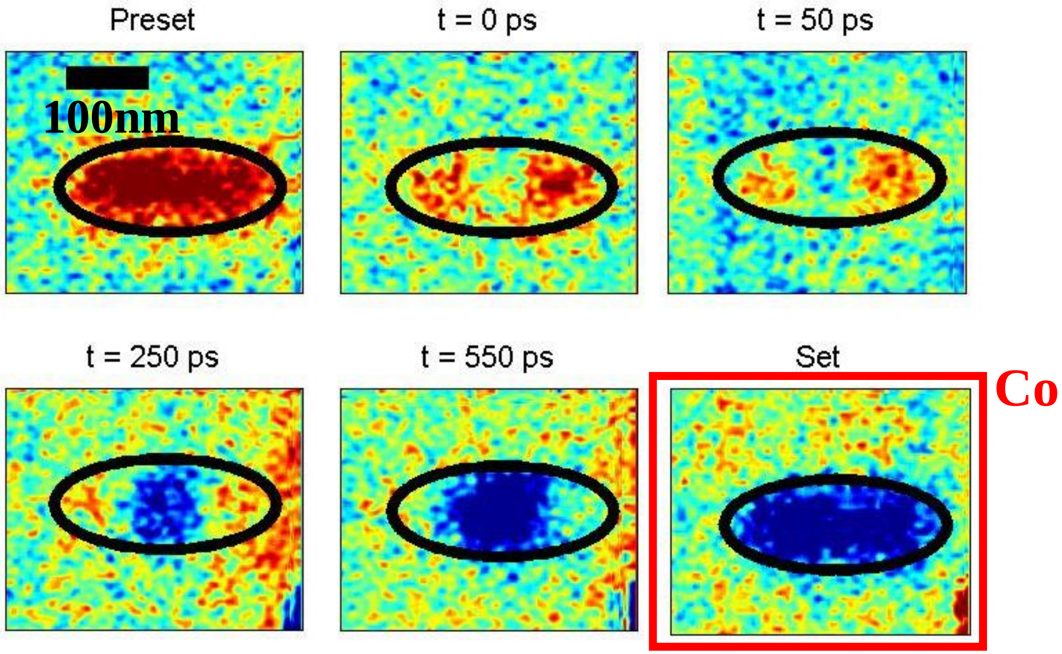


D.P. Bernstein et al., PRB(R) 83, 180410 (2011)

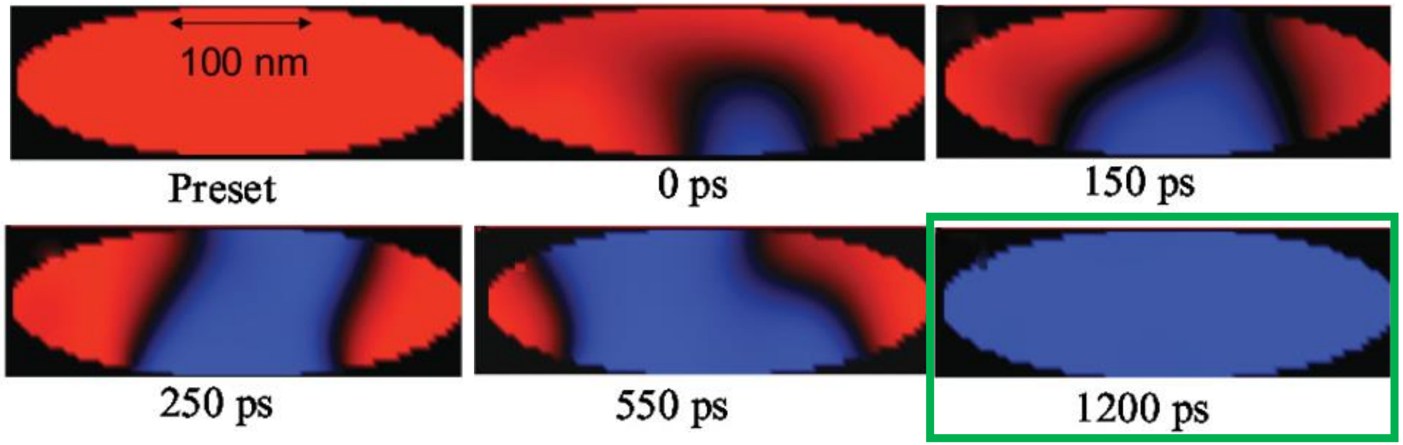
Example : STT-induced switching by STXM



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



Micromagnetic simulation
(Scheinfein code)



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

X-ray microscopy : criteria

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

Magnetic measurement : Summary

e-ESM, an online higher-education Magnetism event

I. Few preliminary details about the sample environment

➡ Magnetic field, Temperature

II. Static macroscopic magnetometry techniques

➡ VSM, SQUID, Torque, MOKE, XMCD

III. AC macroscopic magnetometry techniques

➡ AC susceptometry

IV. Imaging techniques

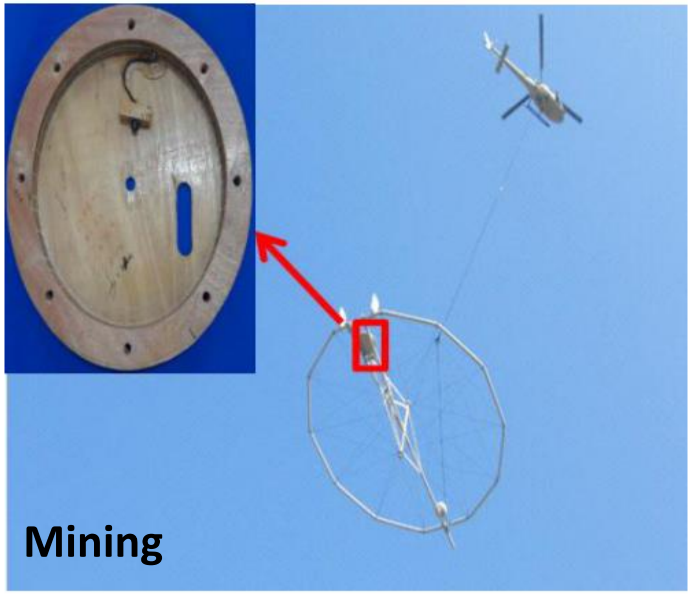
➡ Scanning probe microscopies, Photon-out

CONCLUSION :

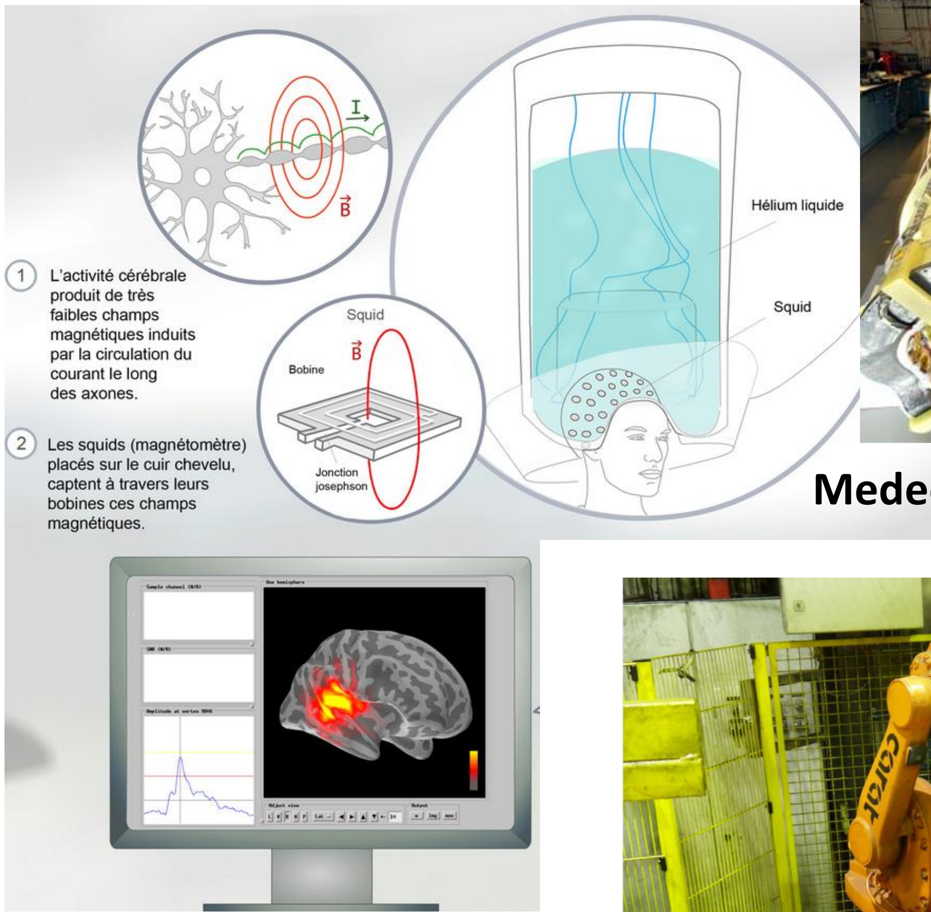
Know your tool box and you will find the **rigth** tool**S** to answer your need

Magnetometers are not only lab tools

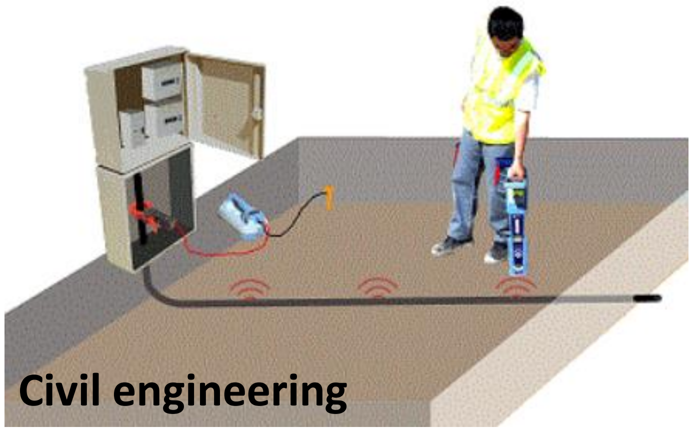
Here I focused on material characterization in lab but magnetometers can be used in many ways



Mining



Medecine



Civil engineering

Metallurgy

Few references

SQUID R.L. Fagaly Review of Scientific Instruments **77**, 101101 (2006)

M. Buchner et al. J. Appl. Phys. **124**, 161101 (2018);

D.-X. Chen,et al., REVIEW OF SCIENTIFIC INSTRUMENTS **82**, 045112 (2011)

VSM S. Foner, Review of Scientific Instruments 30, 548 (1959)

V. Lopez, Review of Scientific Instruments 89, 034707 (2018)

Torque S. Brialmont et al. , Rev. Sci. Instrum. 90, 085101 (2019)

AC susceptometry M. Nikolo, Am. J. Phys., 63, 57 (1995)

F. Gömöry, Supercond. Sci. Technol. 10 (1997) 523

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

Magnetic Imaging R.M. Reeve et al. arXiv:1806.07767v2

W. Kuch, Book "Magnetism: A Synchrotron Radiation Approach", p275-320 (2006)

And many more at : **http://magnetism.eu/esm/repository-topics.html**

THE EUROPEAN SCHOOL ON MAGNETISM