Magnetic Force Microscopy

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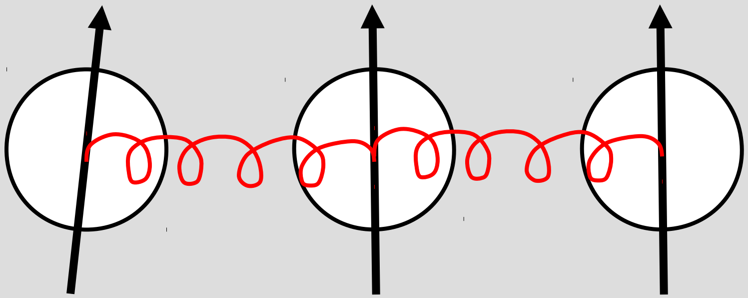
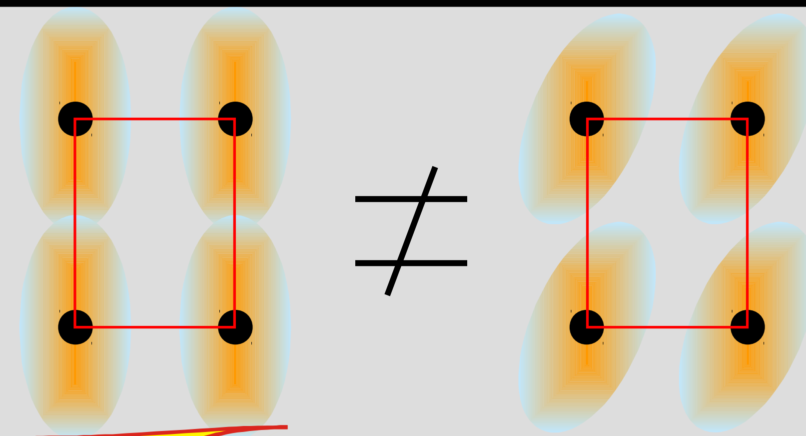
http://neel.cnrs.fr

Echange energy

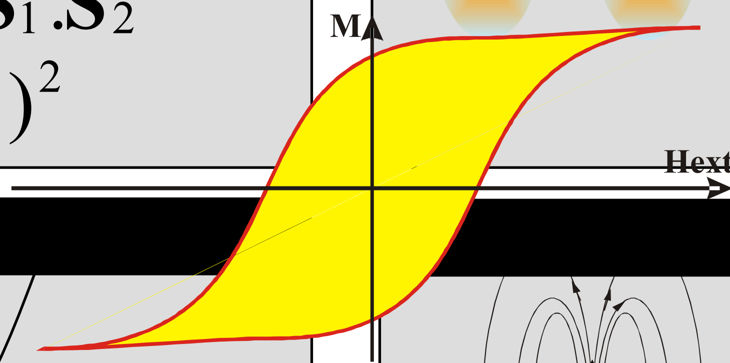


$$E_{\mathrm{Ech}} = -J_{1,2}\,\vec{\mathbf{S}}_1 . \vec{\mathbf{S}}_2$$
$$= A(\nabla\theta)^2$$

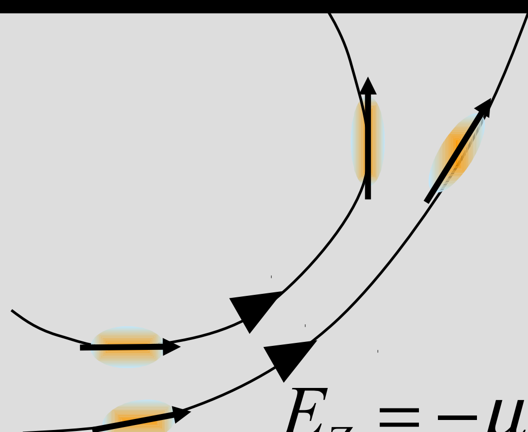
Magnetocrystalline anisotropy energy



$$E_{\mathrm{mc}} = K\sin^2(\theta)$$

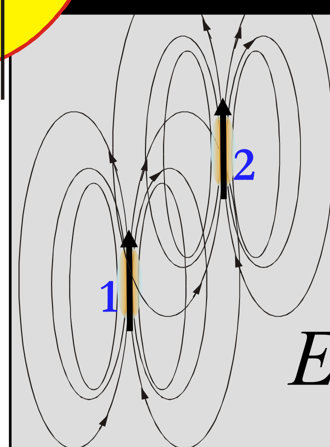


Zeeman energy (enthalpy)



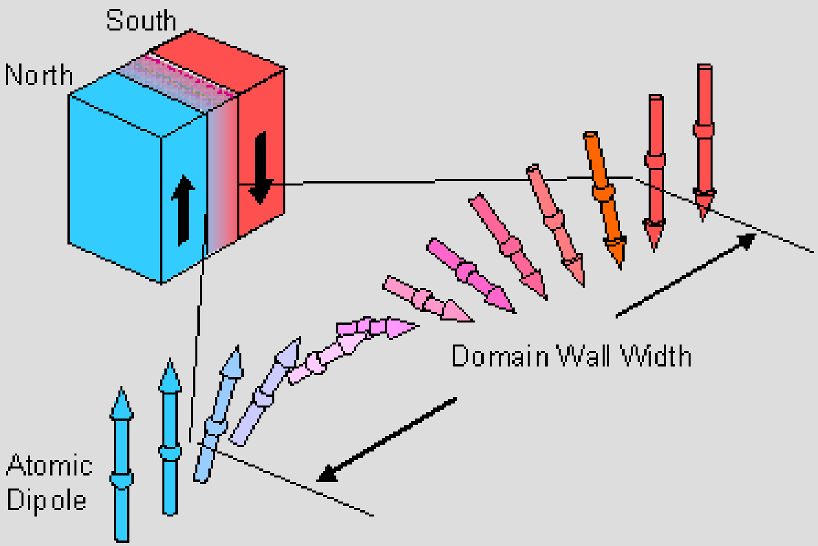
$$E_{\mathrm{Z}} = -\mu_0 \vec{\mathbf{M}}_{\mathrm{S}} . \vec{\mathbf{H}}$$

Dipolar energy



$$E_{\mathrm{d}} = -\frac{1}{2}\mu_0 \vec{\mathbf{M}}_{\mathrm{S}} . \vec{\mathbf{H}}_{\mathrm{d}}$$

Typical length scale: Bloch wall width λ_B



$$e = A(d\theta / dx)^2 + K \sin^2\theta$$

Exchange → J/m

Anisotropy → J/m^3

Numerical values

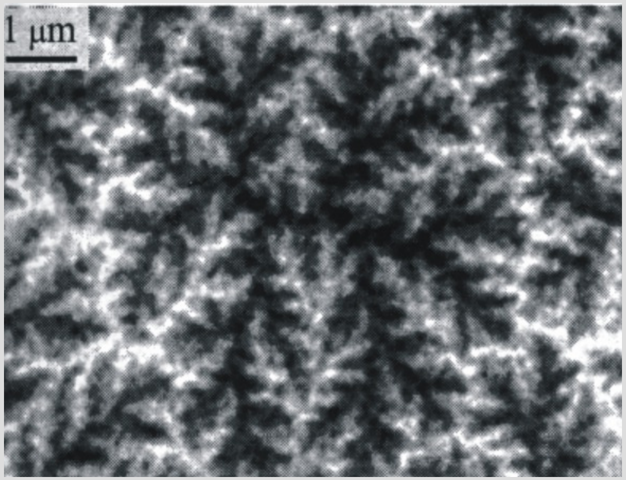
$$\lambda_B = \pi\sqrt{A/K}$$

λ_B = 2 - 3 nm → $\lambda_B \geq$ 100 nm

Hard — Soft

Bulk material

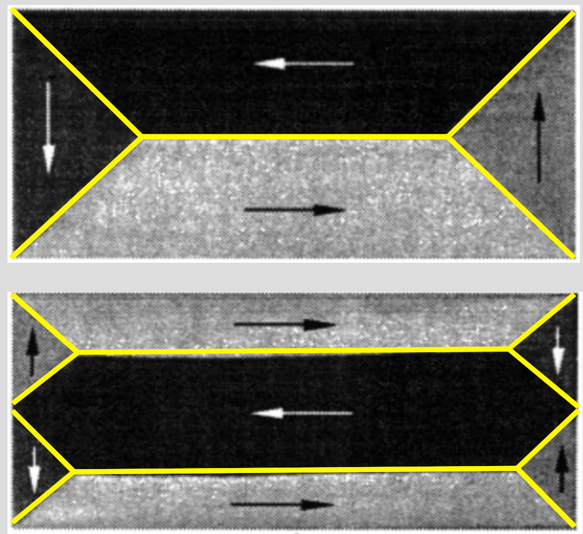
Numerous and complex magnetic domains



Co(1000) crystal – SEMPA
A. Hubert, *Magnetic domains*

Mesoscopic scale

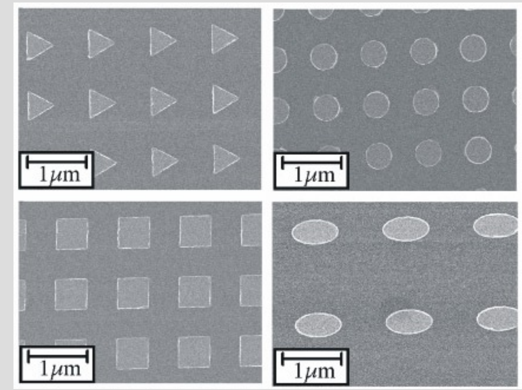
Small number of domains, simple shape

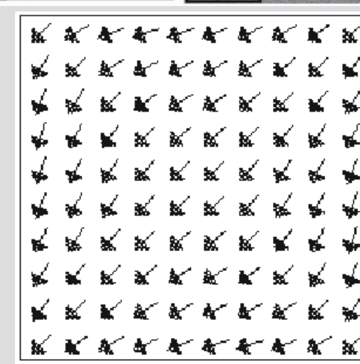


Microfabricated dots
Kerr magnetic imaging
A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain





R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1 (2000)

Nanomagnetism ~ mesoscopic magnetism

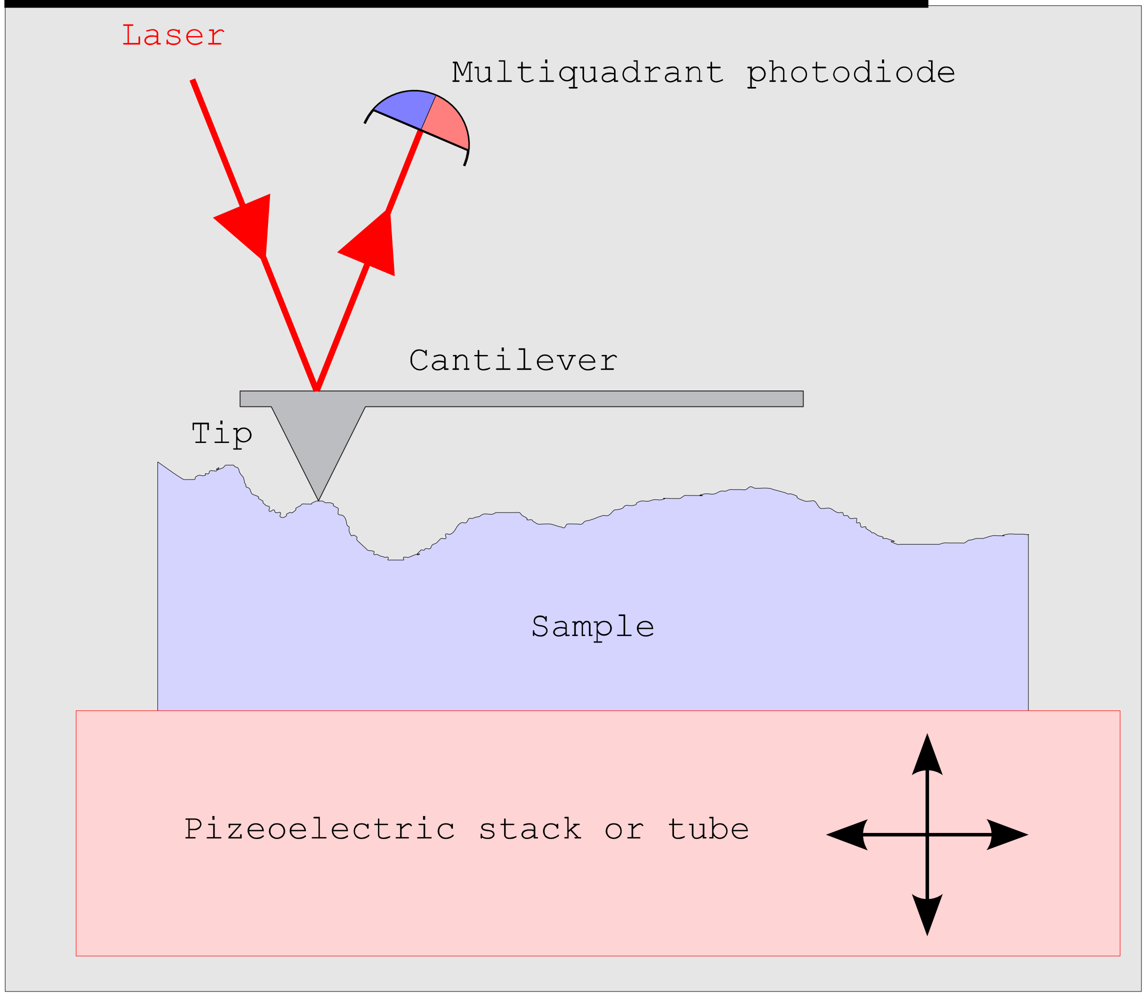
What information may be sought

- Distribution of magnetization in sample
- Direction & magnitude
- Depth resolution
- Elemental resolution
- Lateral resolution
- Time resolution

Conditions and environment

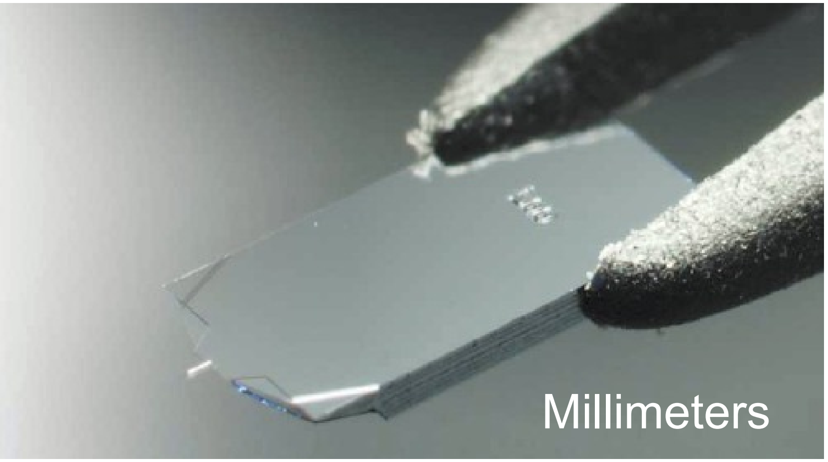
- Temperature
- Magnetic field
- Electrical current, light etc.
- Additional microscopies

Key elements of an Atomic Force Microscope (AFM)

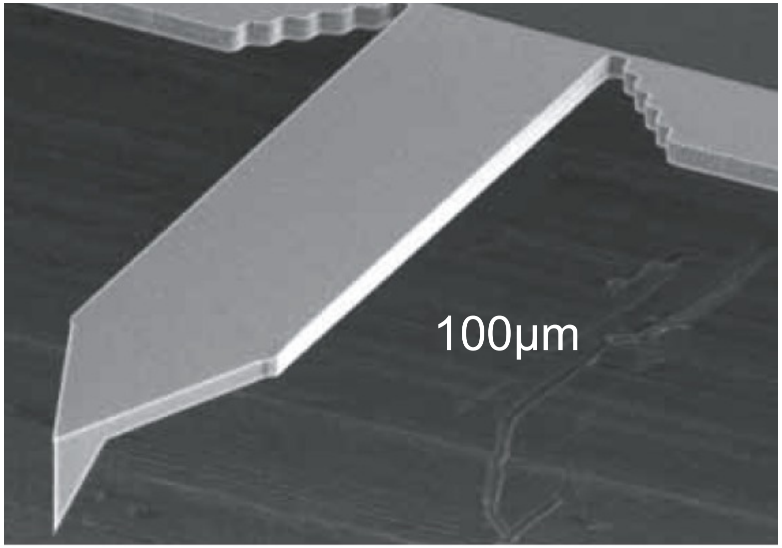


⇨ Measures forces (vertical and lateral) between sample and tip

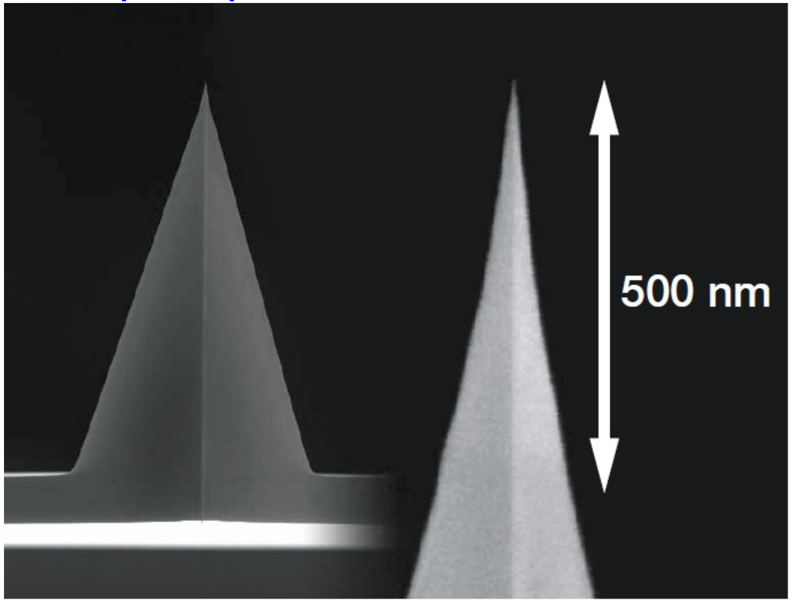
Chip – Batch fabrication



Cantilever



Full tip + apex



- ⇨ Price 10-200€/tip
- ⇨ Radius of curvature ≈ 5nm

Images : Olympus catalog (http://www.olympus.co.jp/probe)

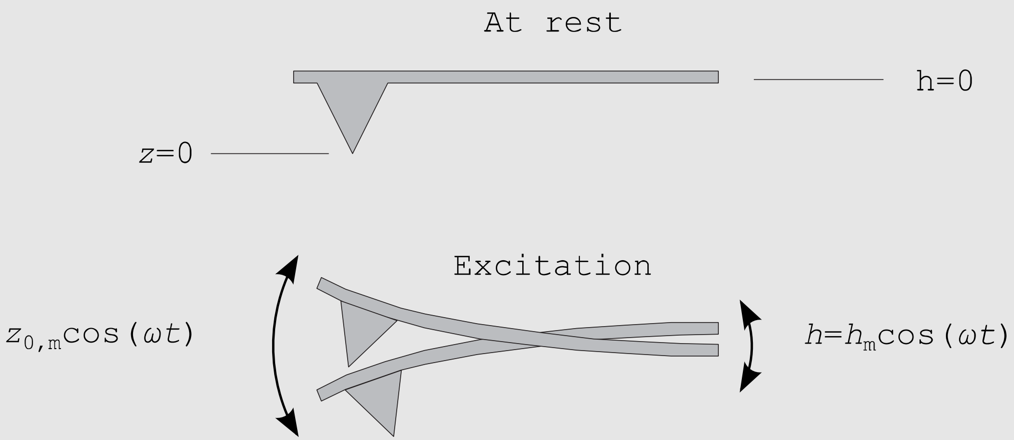
Measures

- Topography
- Mechanical properties
- Electric properties
- Piezoelectric properties
- Long-range forces (electrostatic, magnetic)
- Micromanipulation & fabrication

Modes of operation

- Static (deflection)
  - When contact is needed : electric, friction etc.
- Dynamic (cantilever oscillation)
  - Less damage to sample and tip
  - More sensitive

Mechanical excitation of cantilevers



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

m	Inertia
Γ	Damping
k	Spring
$F(z,t)$	External force

Notations

Seek solutions for $F=0$ $\quad z(t)=z_0 e^{j\omega t}$

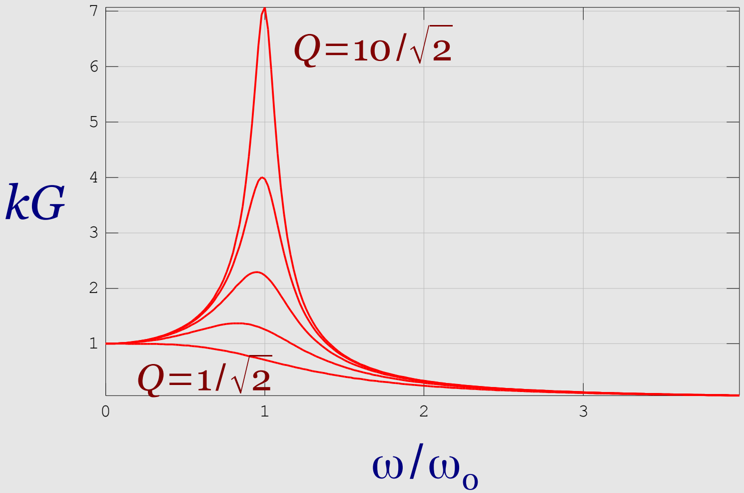
Reference angular velocity $\quad \omega_0=\sqrt{\dfrac{k}{m}}$

Quality factor $\quad Q=\dfrac{\sqrt{k\,m}}{\Gamma}$

⇨ Transfert function

$$H=\frac{z}{F}=\frac{1}{k}\,\frac{1}{-\left(\frac{\omega}{\omega_0}\right)^2+\frac{j}{Q}\left(\frac{\omega}{\omega_0}\right)+1}$$

Gain



$$G=|H|=\frac{1}{k}\frac{1}{\sqrt{\left[1-\left(\frac{\omega}{\omega_0}\right)^2\right]^2+\frac{1}{Q^2}\left(\frac{\omega}{\omega_0}\right)^2}}$$

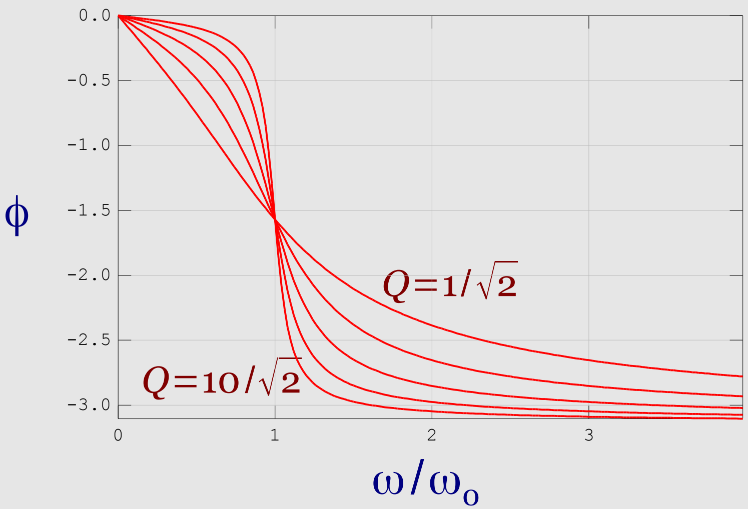
Peak at : $\omega_r=\omega_0\sqrt{1-\frac{1}{2Q^2}}$

$$kG(0)=1$$

$$kG(\omega_r)=Q$$

$$kG(\infty)=0$$

Dephasing



$$\cos\phi=\frac{1-\left(\frac{\omega}{\omega_0}\right)^2}{\sqrt{\left[1-\left(\frac{\omega}{\omega_0}\right)^2\right]^2+\frac{1}{Q^2}\left(\frac{\omega}{\omega_0}\right)^2}}$$

$$\phi(0)=0$$

$$\phi(\infty)=-\pi$$

Q>>1

$$\omega_r\approx\omega_0$$

$$\phi(\omega_r)\approx-\pi/2$$

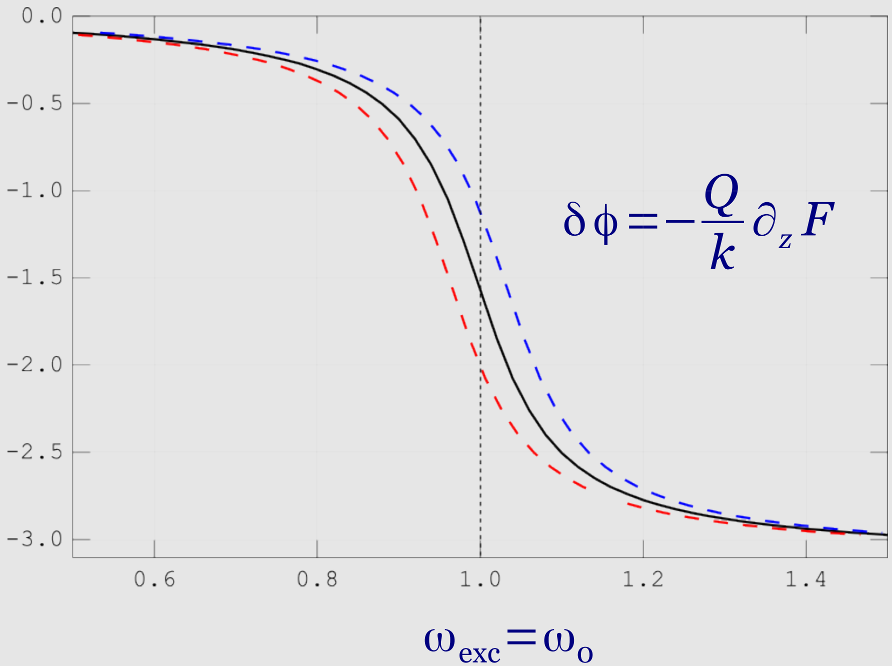
$$\frac{\Delta\omega_r}{\omega_0}\approx\frac{\sqrt{3}}{Q}$$

Tip-sample interaction treated as perturbation

$$m\ddot{z}+\Gamma\dot{z}+kz=F(z) \quad \text{with} \quad F(z)=F(z_o)+(z-z_o)\partial_z F$$

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

Phase shift



Attractive force

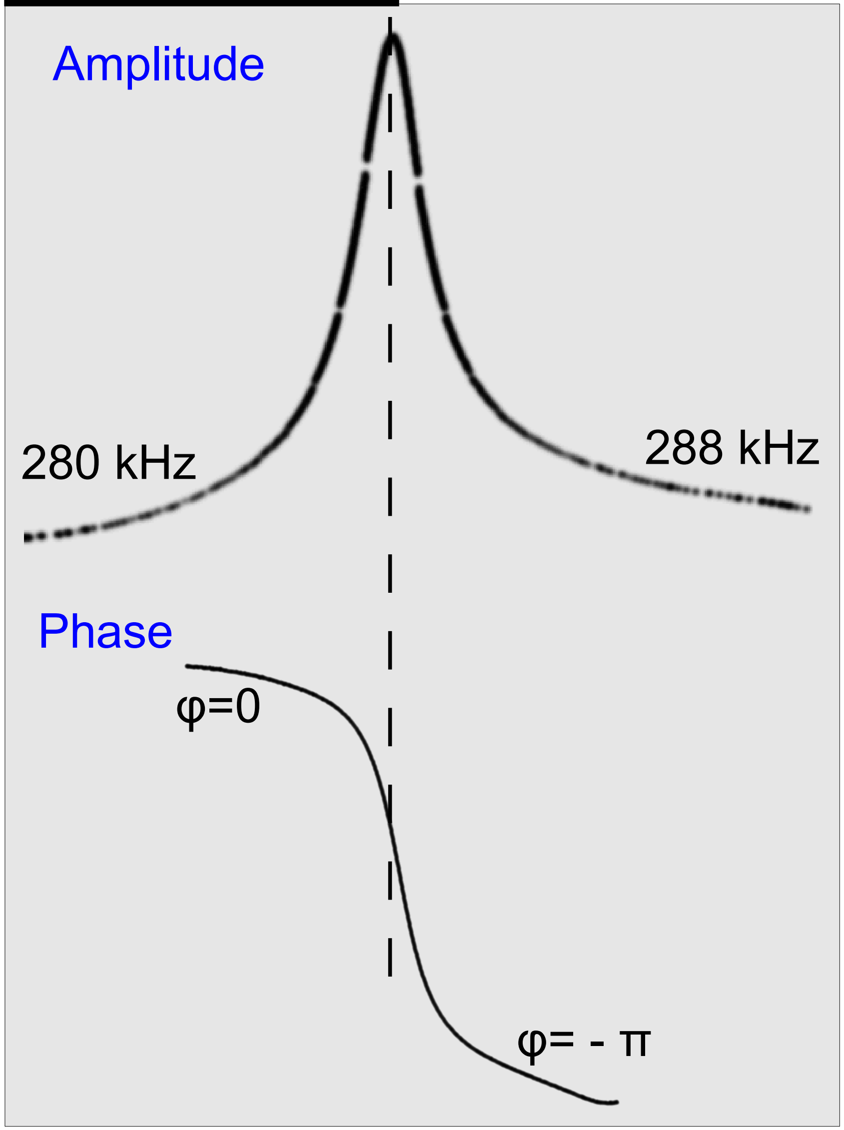
⇨ Red shift

Repulsive force

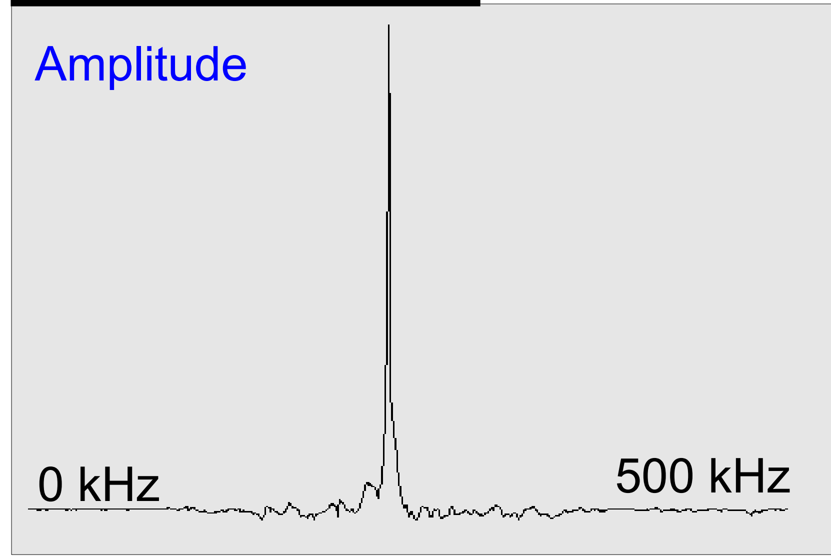
⇨ Blue shift

Forces monitored through phase shift

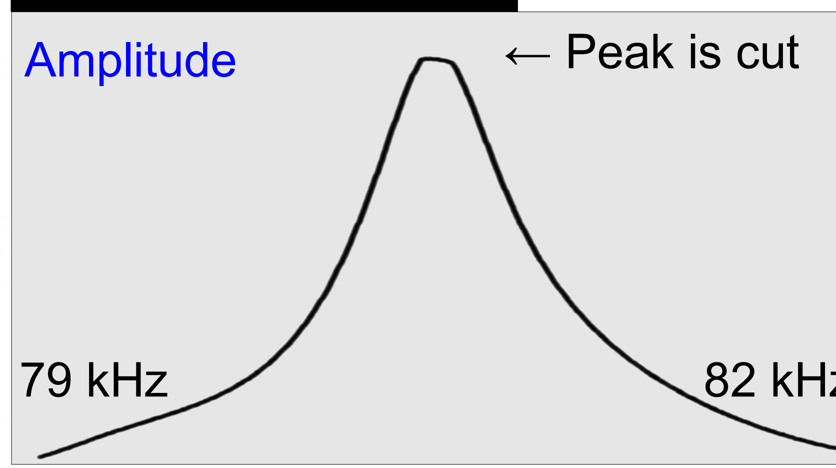
Resonance spectrum



Full resonance spectrum

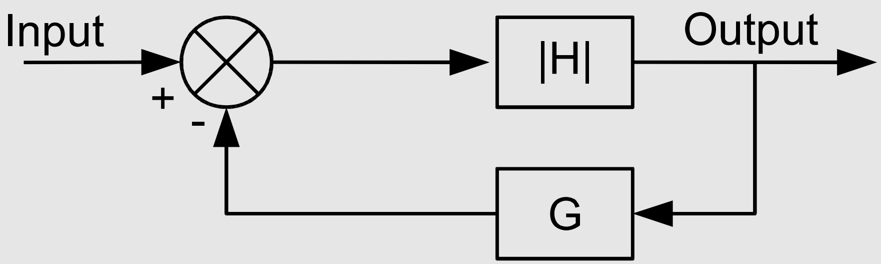


Resonance in tapping mode

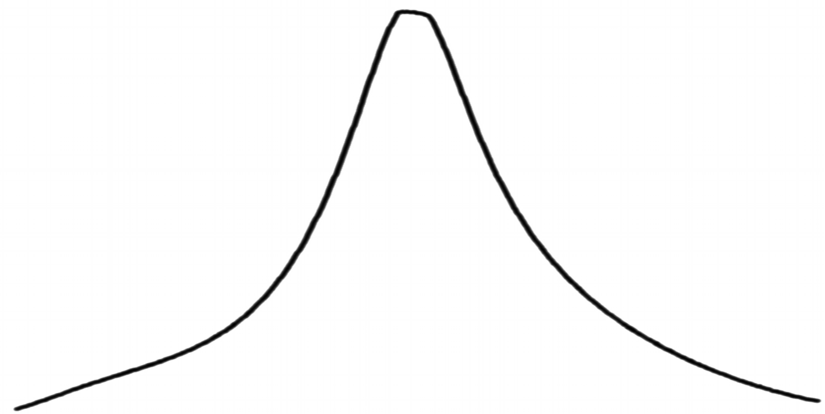


Close-loop operation

Feedback signal and setpoint: amplitude

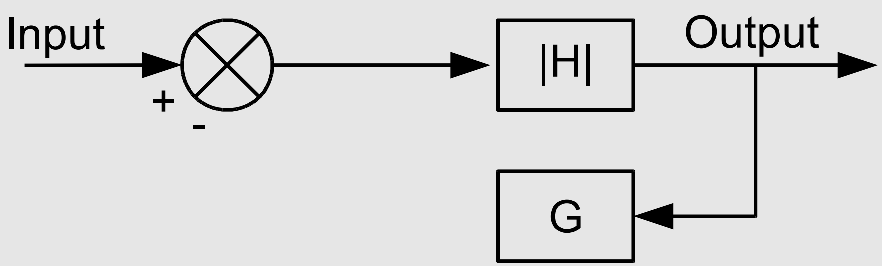


⇨ Map at constant force

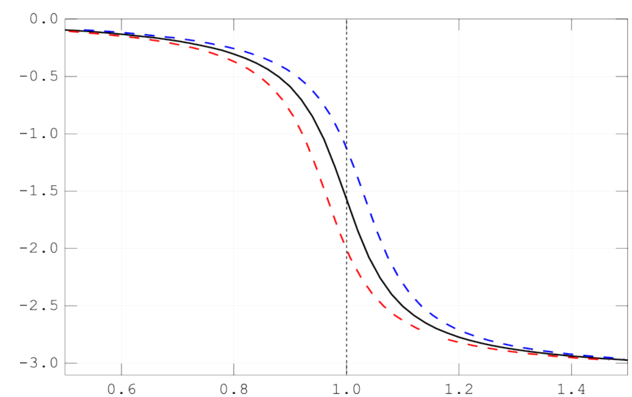


⇨ Ex : map = topography with setpoint on the amplitude

Open-loop operation



⇨ Map The force along a predefined trajectory (plane, lift-height etc.)

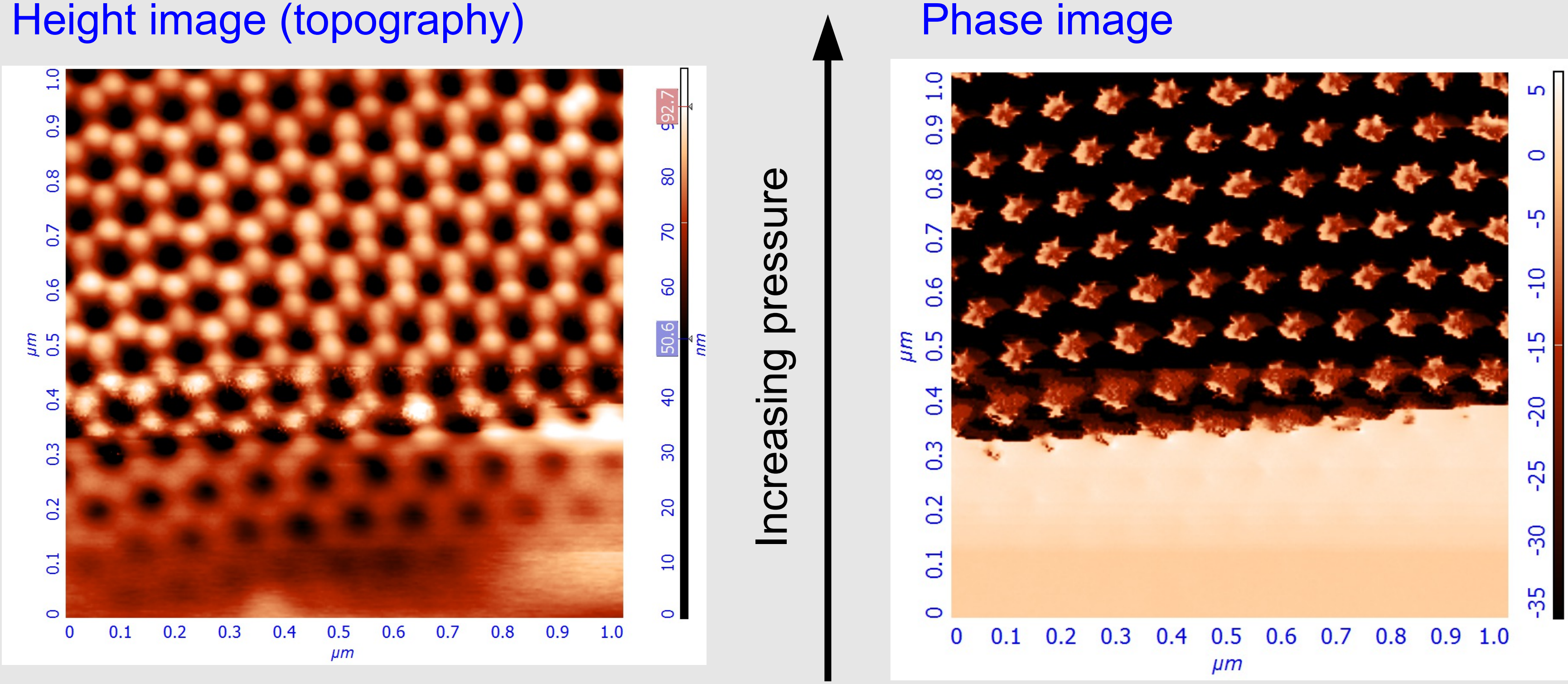


⇨ Ex : map = magnetic stray field above sample

Images

Height image (topography)

Phase image

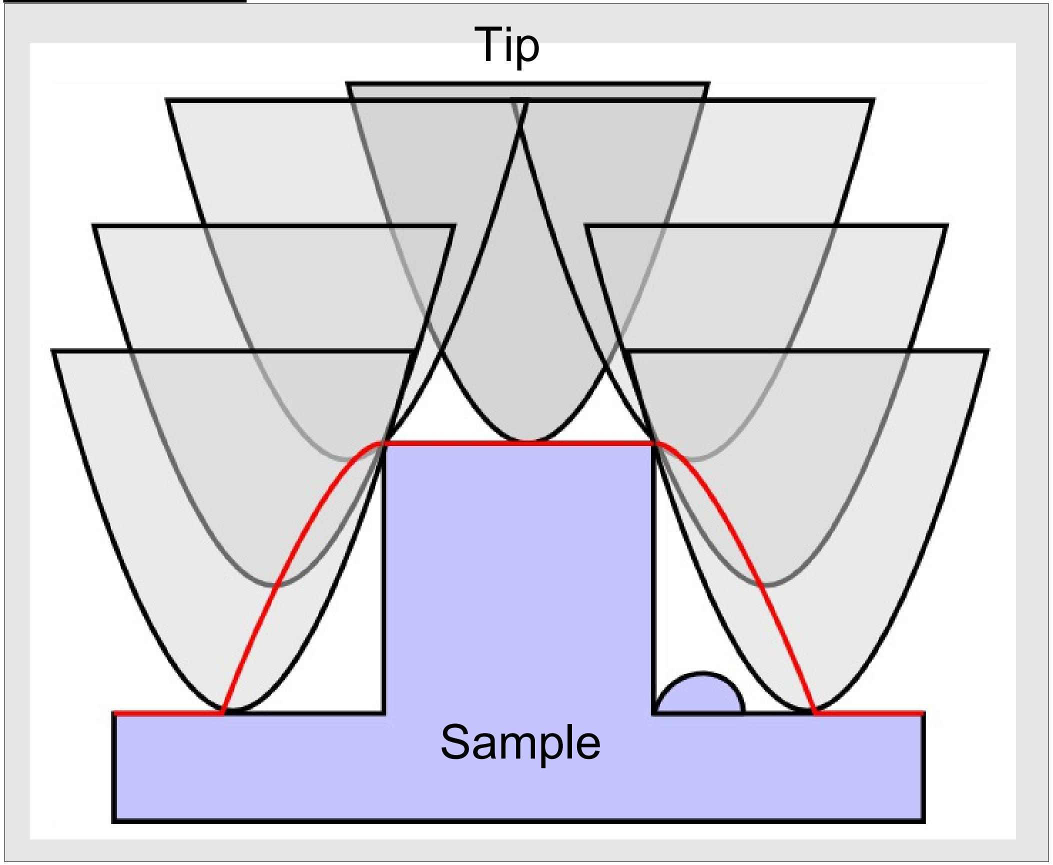


To notice

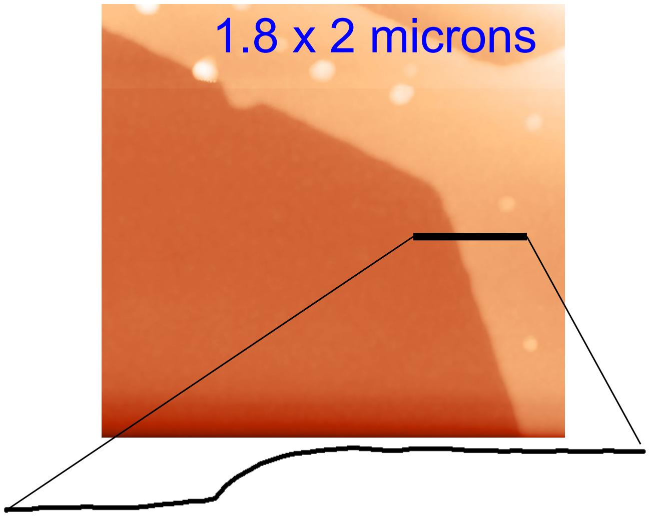
- Non-contact part (bottom of image)
- Phase does not reflect topography
- Noise and phase depend on set point

Sample : self-organized Anodized Alumina (synthesis L. Cagnon, Institut Néel)

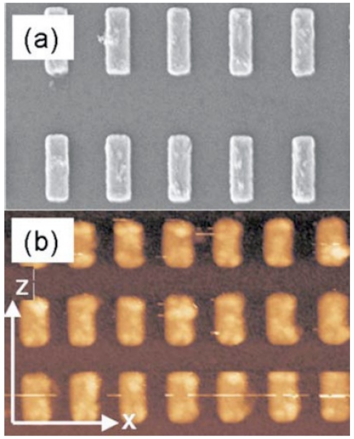
Schematics



Examples



Sample : M. Miron (Spintec)
Lithography : S. Pizzini (Néel)

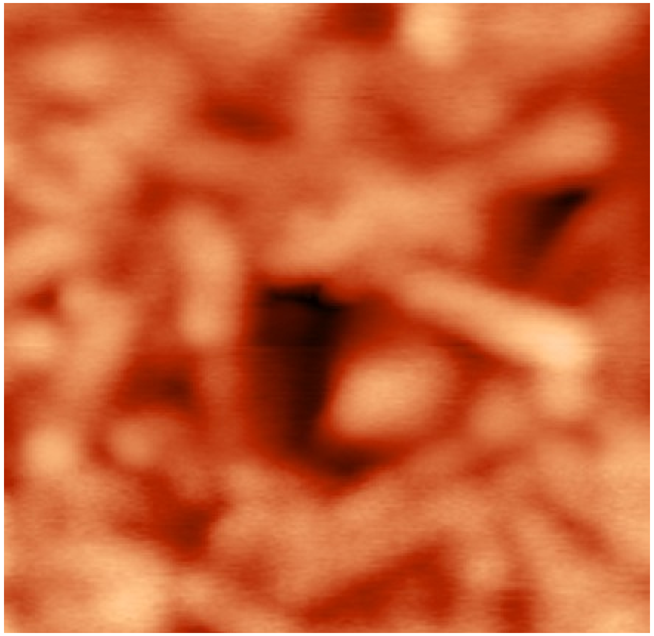


S. Y. Suck et al., APL95, 162503 (2009)

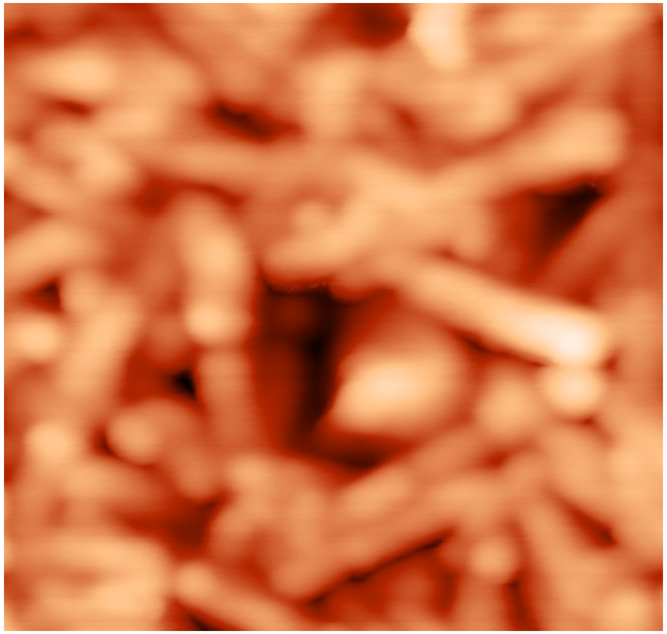
Notice

- Lateral (base) size is over-estimated with AFM
- Shading, not convolution (no true retrieval possible)
- Tips are less sharp for MFM due to magnetic coating

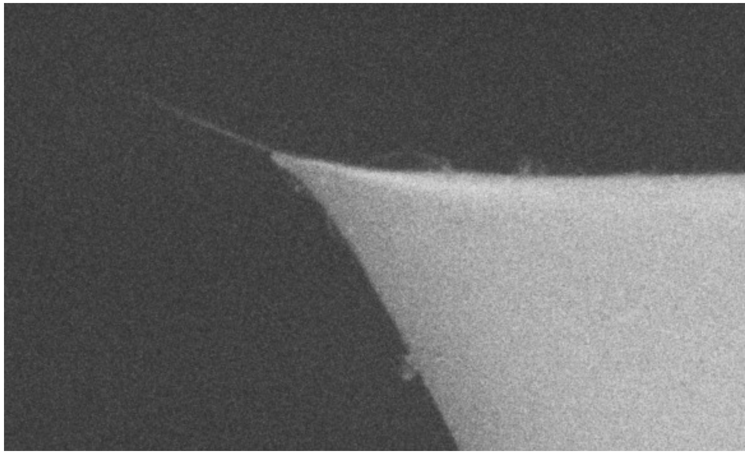
ZIP disk, 400x400 nm



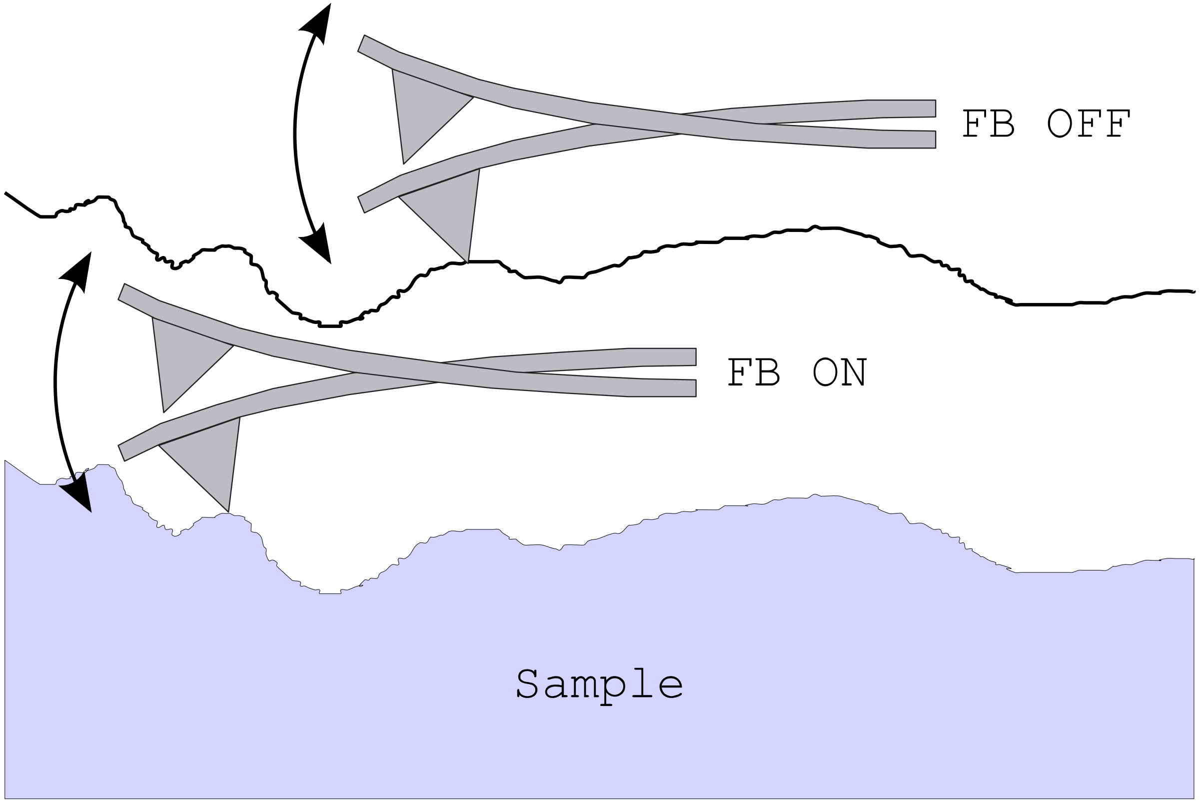
Usual tip

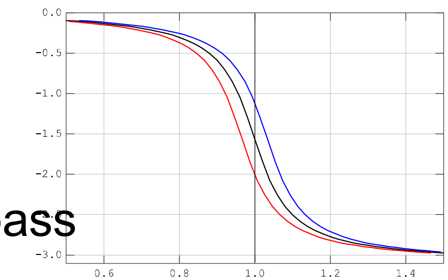


SWCNT tip



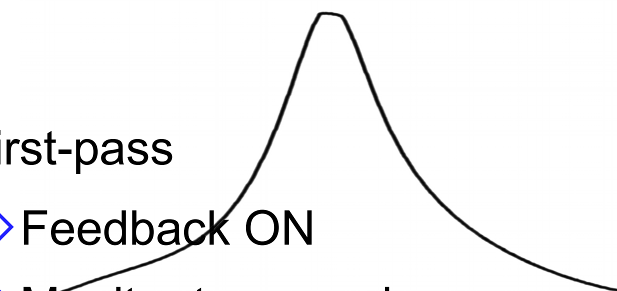
Tip : A. M. Bonnot (Institut Néel)





Second pass

- Monitor long-range forces (magnetic, electrostatic)



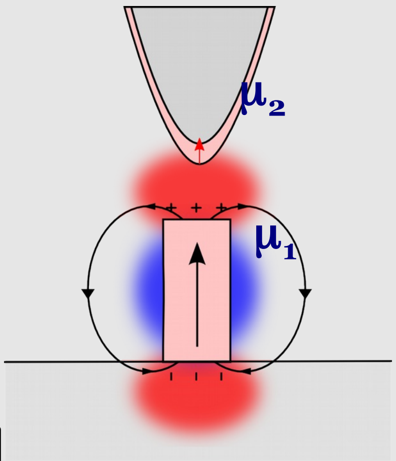
First-pass

- Feedback ON
- Monitor topography (height) and any other signal (phase etc.)

Calculate energy with magnetic dipoles

Magnetic field arising from a magnetic dipole

$$H_d(\mathbf{r}) = \frac{\mu_0}{4\pi r^3}\left[\frac{3(\boldsymbol{\mu}_1.\mathbf{r})\mathbf{r}}{r^2} - \boldsymbol{\mu}_1\right]$$



$$\Rightarrow \mathbf{F}_2(\mathbf{r}) = -\nabla E_{1,2} = \mu_0 \nabla(\mathbf{H}_d.\boldsymbol{\mu}_2)$$

$$\mathbf{F}_2(\mathbf{r}) = -\nabla \mathcal{E}_{1,2}$$ with $$\boxed{\mathcal{E}_{1,2} = -\mu_0 \boldsymbol{\mu}_2.\mathbf{H}_d}$$

Calculate energy with magnetic dipoles

Analogy with electrostatics thanks to $\mathrm{div}(\mathbf{H}_d) = -\mathrm{div}(\mathbf{M})$

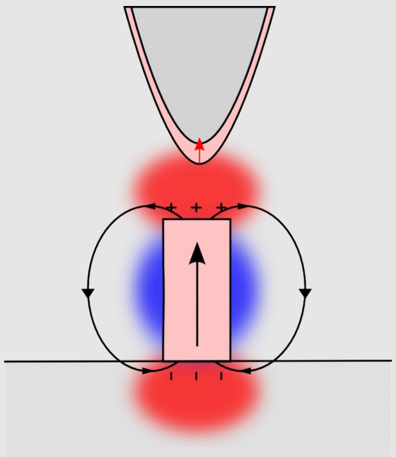
$$\mathbf{H}_d(\mathbf{r}) = M_s\left(-\iiint_{\text{space}} \frac{\mathrm{div}[\mathbf{m}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi\|\mathbf{r}-\mathbf{r}'\|^3}\mathrm{d}^3 r' + \iint_{\text{sample}} \frac{[\mathbf{m}(\mathbf{r}').\mathbf{n}(\mathbf{r}')].(\mathbf{r}'-\mathbf{r})}{4\pi\|\mathbf{r}-\mathbf{r}'\|^3}\mathrm{d}^2 r'\right)$$

$\rho(\mathbf{r}) = -M_s \mathrm{div}[\mathbf{m}(\mathbf{r})]$ Volume charges

$\sigma(\mathbf{r}) = M_s \mathbf{m}(\mathbf{r}).\mathbf{n}(\mathbf{r})$ Surface charges

$$\boxed{\mathcal{E}_{1,2} = \mu_0 \sigma.\varphi}$$ with $$\mathbf{H}_d = -\nabla\varphi$$

Tip is a dipole

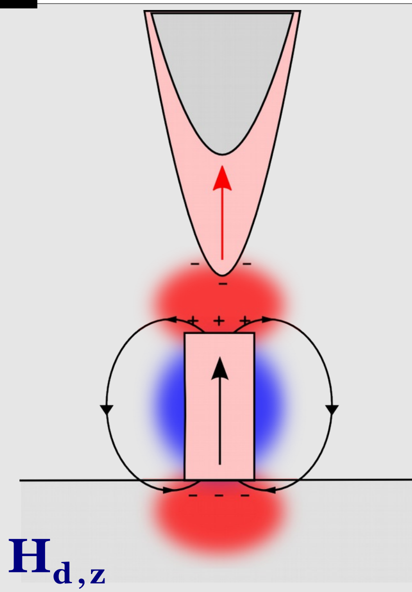


$$\mathcal{E}_{1,2} = -\mu_0 \boldsymbol{\mu}_2 . \mathbf{H}_d$$

$$\mathcal{E}_{1,2} = -\mu_0 (\mu_x . H_{d,x} + \mu_y . H_{d,y} + \mu_z . H_{d,z})$$

⇨ $$\delta\phi = \frac{Q}{k} \mu_0 \mu_i \partial_z^2 H_{d,i}$$

Tip is a monopole



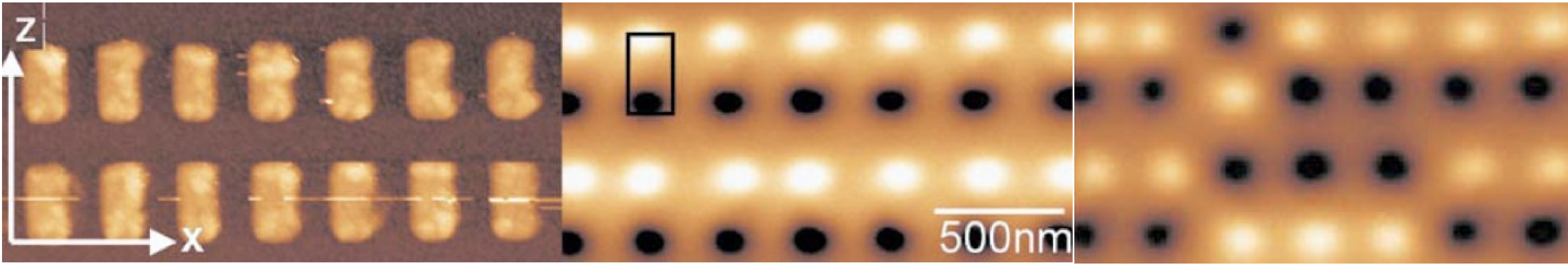
$$\mathcal{E}_{1,2} = \mu_0 \sigma . \varphi$$

$$\mathbf{F}_z = -\mu_0 \sigma \mathbf{H}_{d,z}$$

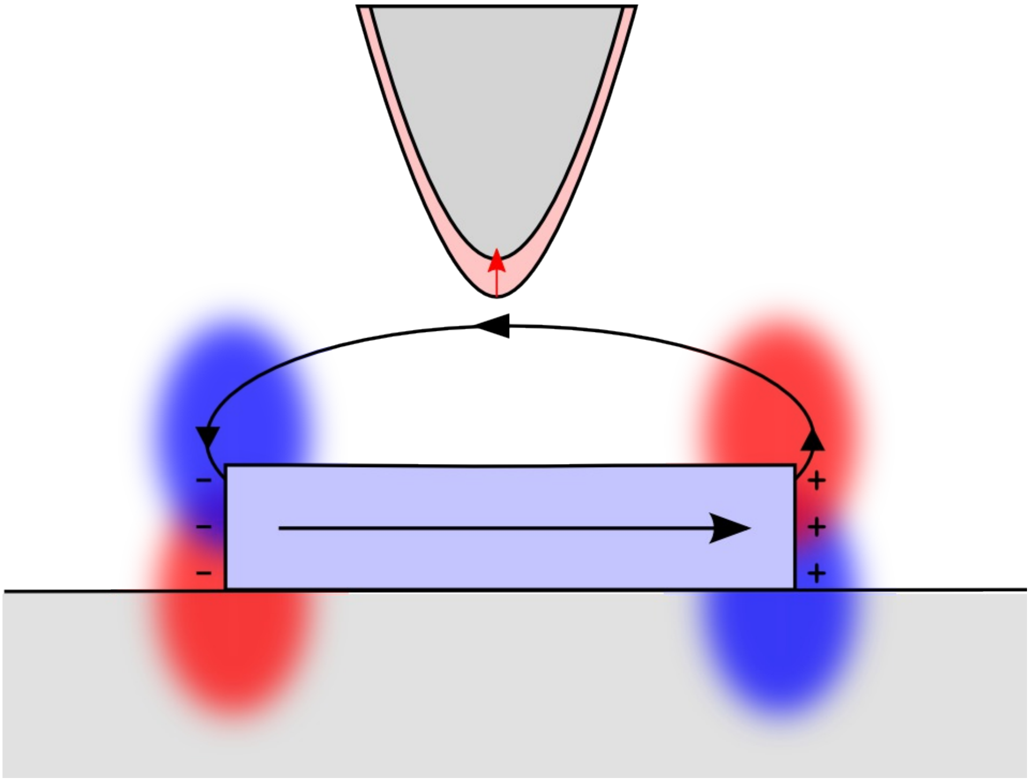
⇨ $$\delta\phi = \frac{Q}{k} \mu_0 \sigma \partial_z H_{d,z}$$

- In practice, a combination of both models is best suited (dipole is more important)
- MFM is sensitive to some derivative(s) of the stray field from the sample
- MFM may be sensitive to in-plane field, depending on the tip moment.

Topography | MFM, saturated | MFM, partly reversed

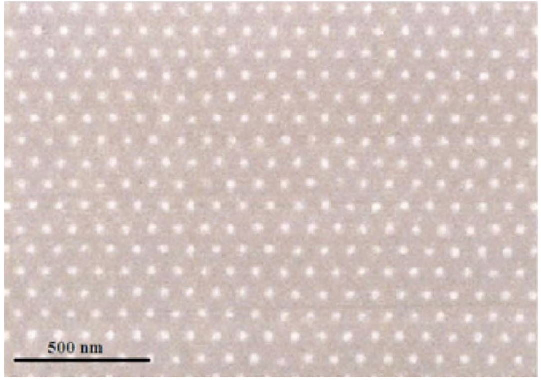


S. Y. Suck et al., APL95, 162503 (2009)

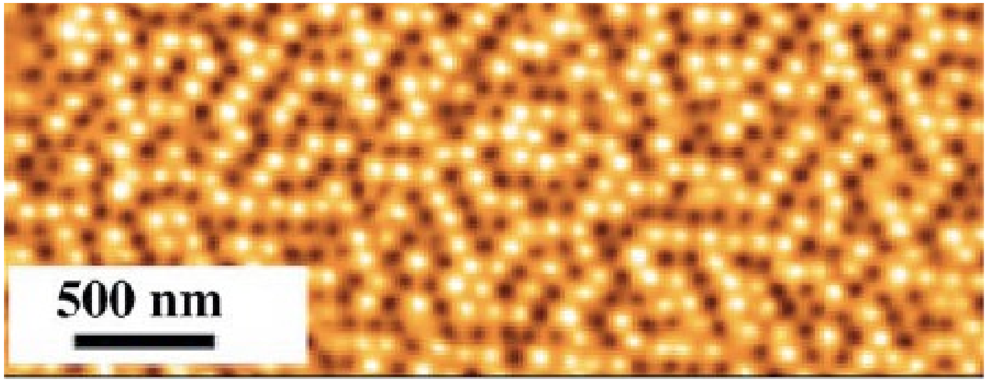


Single-domain in-plane magnetized dots appear as dipoles

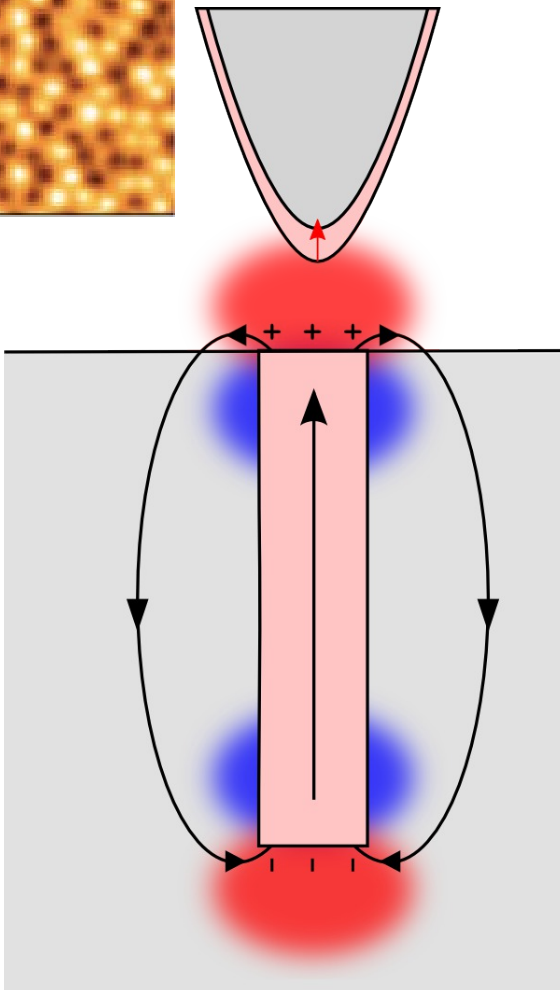
Structure (SEM)



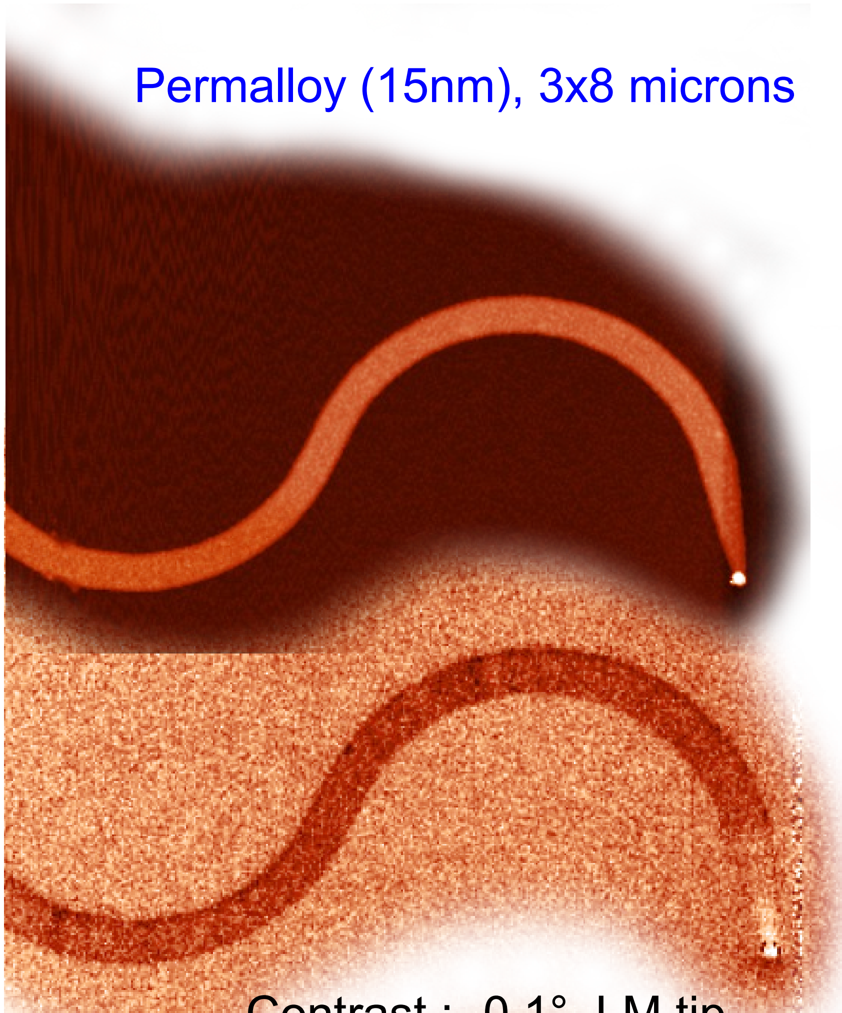
MFM, partly reversed



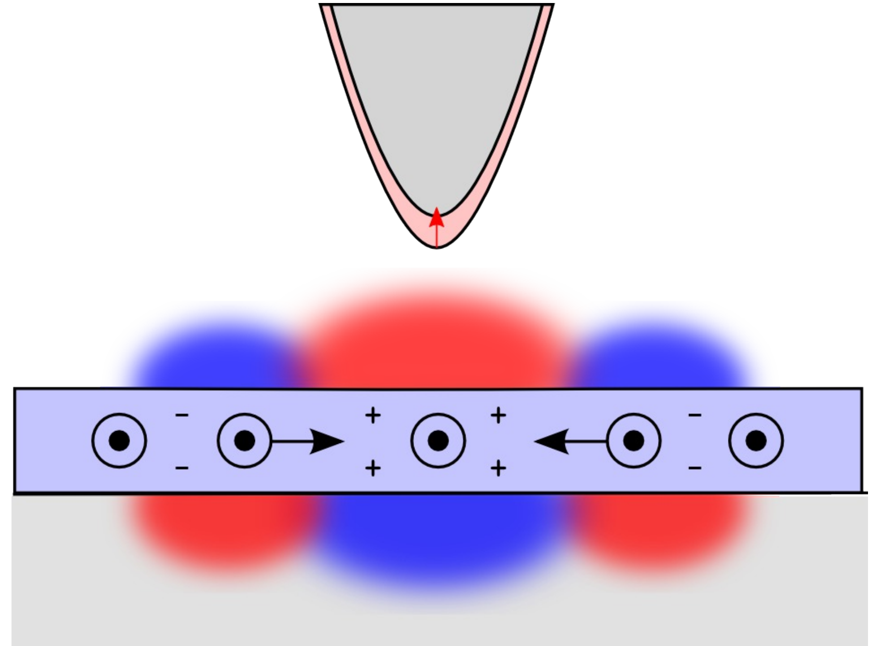
T. Wang et al., APL 92, 192504 (2008)



↳ Single-domain out-of-plane magnetized dots appear as monopoles



Lithography : S. Pizzini (Institut Néel)
Imaging : Z. Ishaque (Institut Néel)

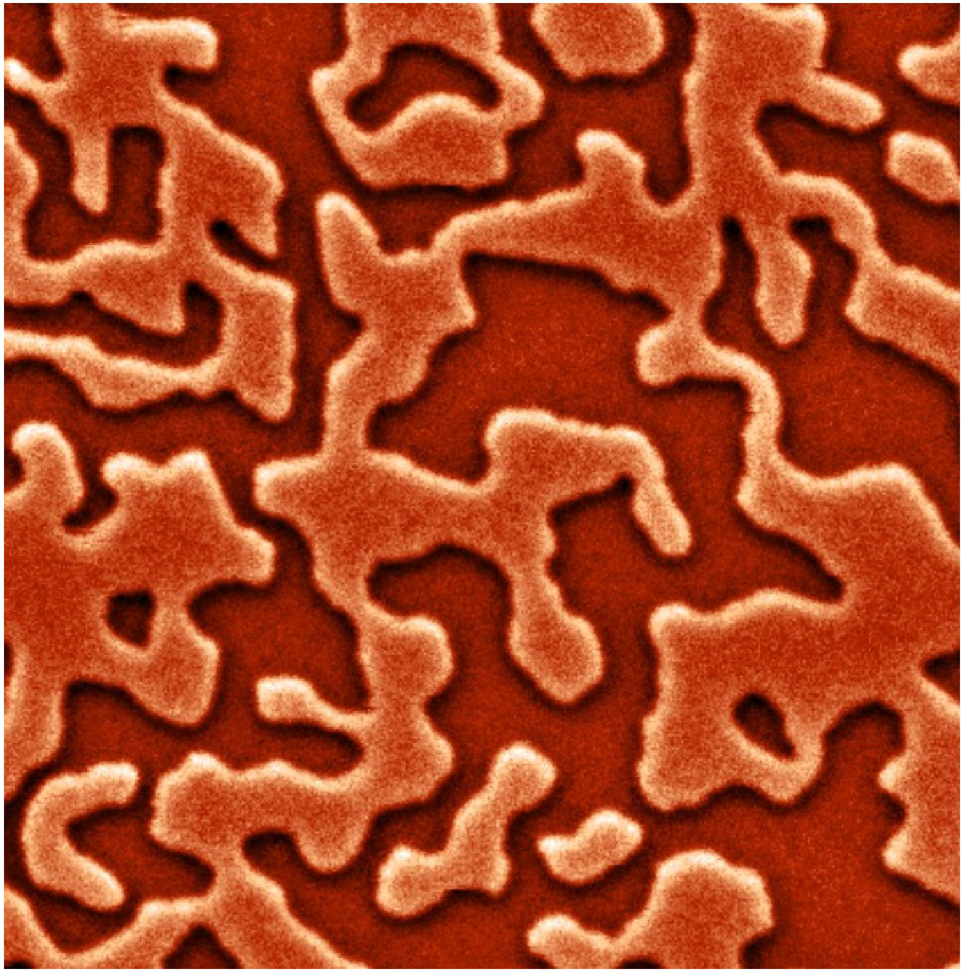


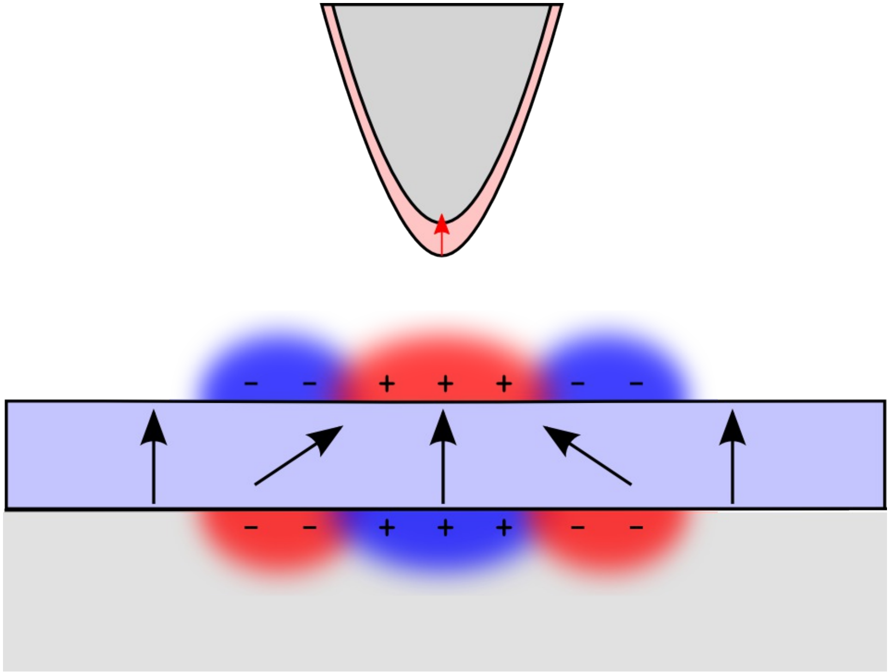
Principle :

1. Stray field magnetizes sample
2. Sample is non -uniform → stray field
3. Tip measures sample's stray field

- It is a DOMAIN contrast
- Interaction is ALWAYS attractive : red shift
- Contrast is proportionnal to the square of the tip moment

FePt (4nm), 5x5 microns





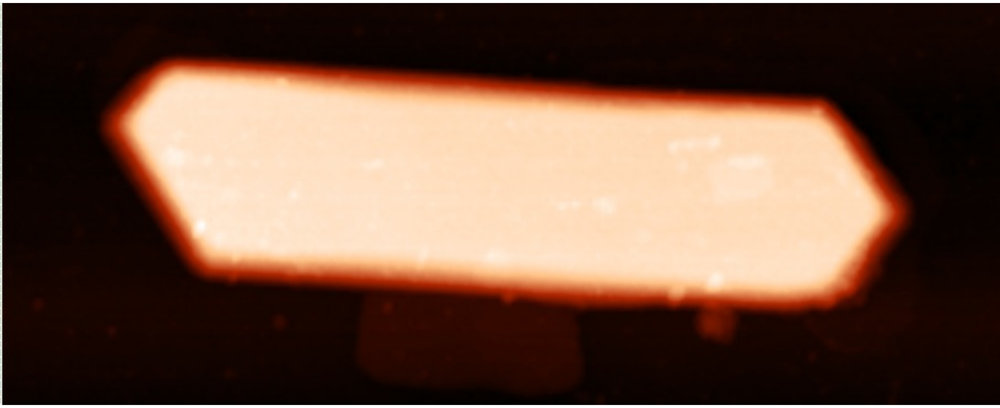
↳ It is a DOMAIN contrast
↳ The direction of magnetization is deduced

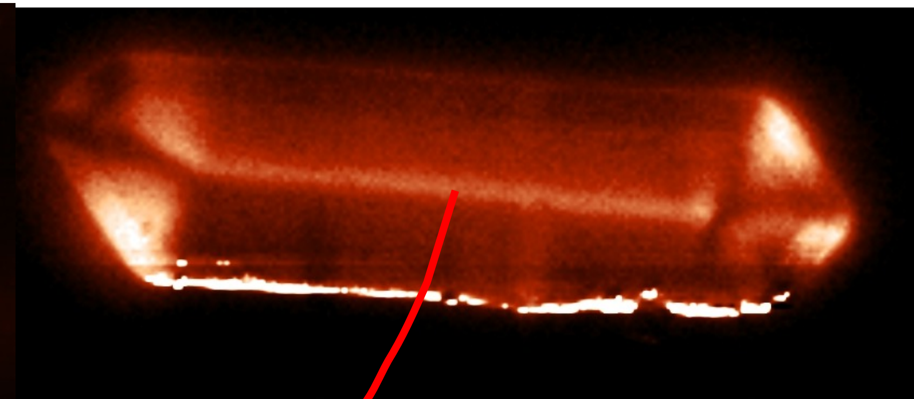
Sample : A. Marty (CEA-Grenoble)
Imaging : M. Darques (Institut Néel)

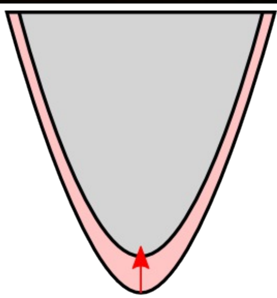
Contrast : ±0.4°, LM tip

Quantitative analysis :
L. Belliard et al., J. Appl. Phys. 81, 3849 (1997)

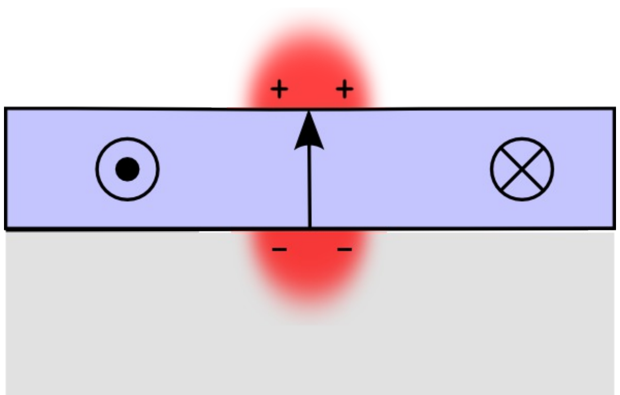
Fe dot (25nm), 2.5x1 microns

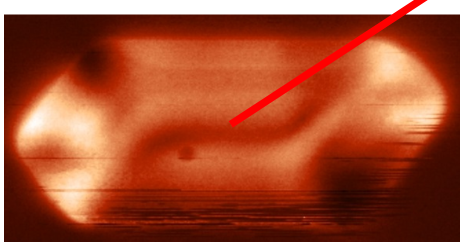




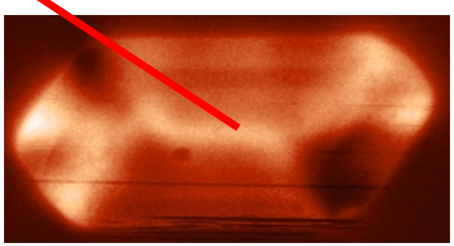


- Contrast is MONOPOLAR
- Informs about the <u>polarity</u> of the wall core



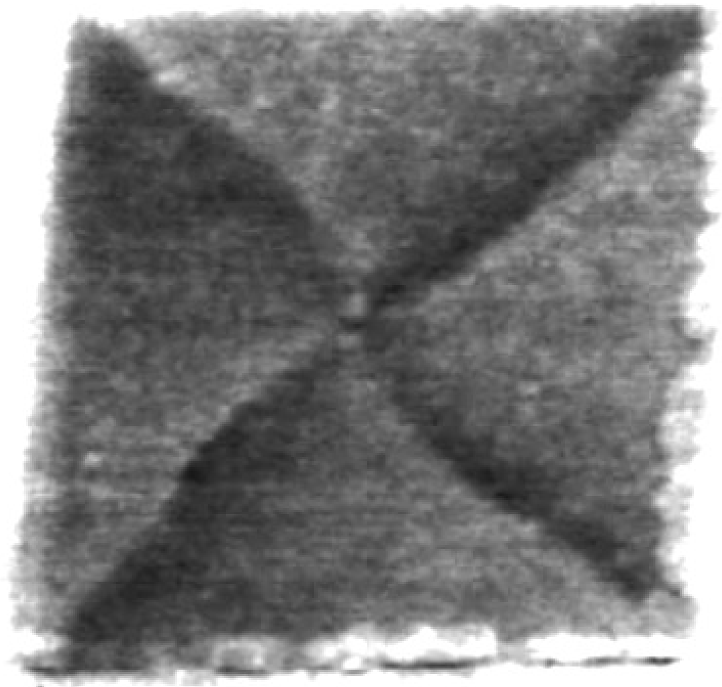


Down core



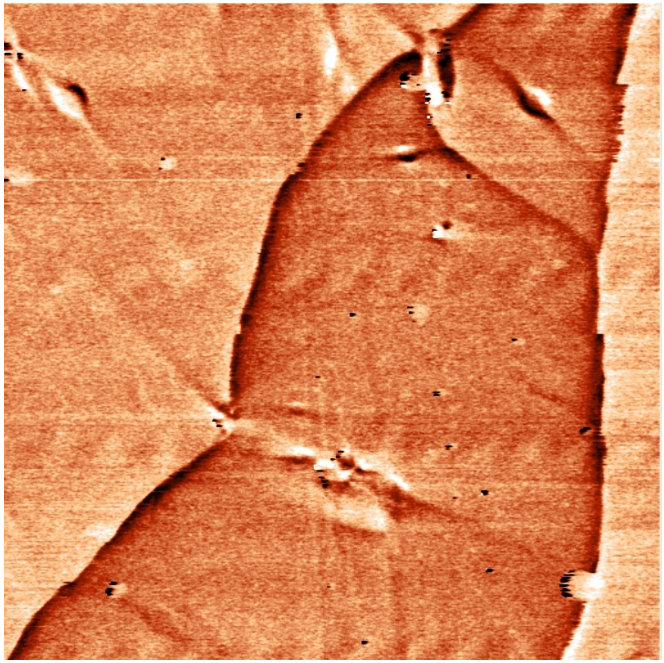
Up core

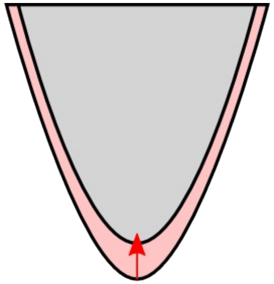
Permalloy dot (16nm)
2x2 microns

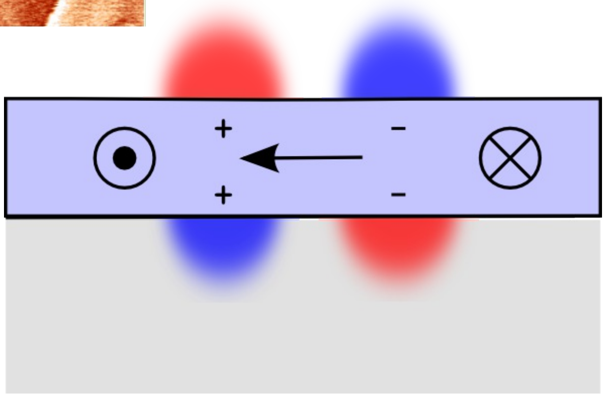


J. M. Garcia et al., APL 79, 656 (2001)

Permalloy film (20nm)
10x10 microns

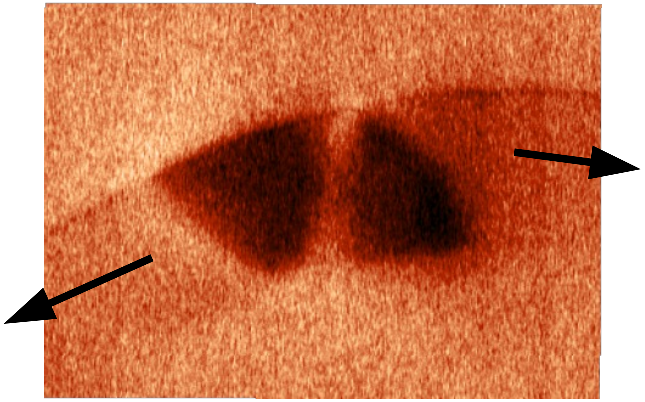




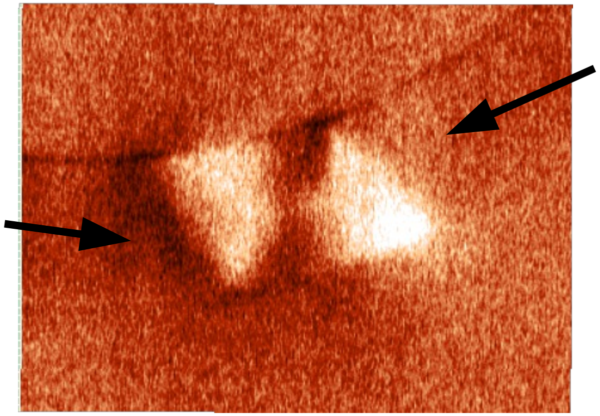


- Néel wall give rise to DIPOLAR contrast
- Informs about the chirality of the wall core

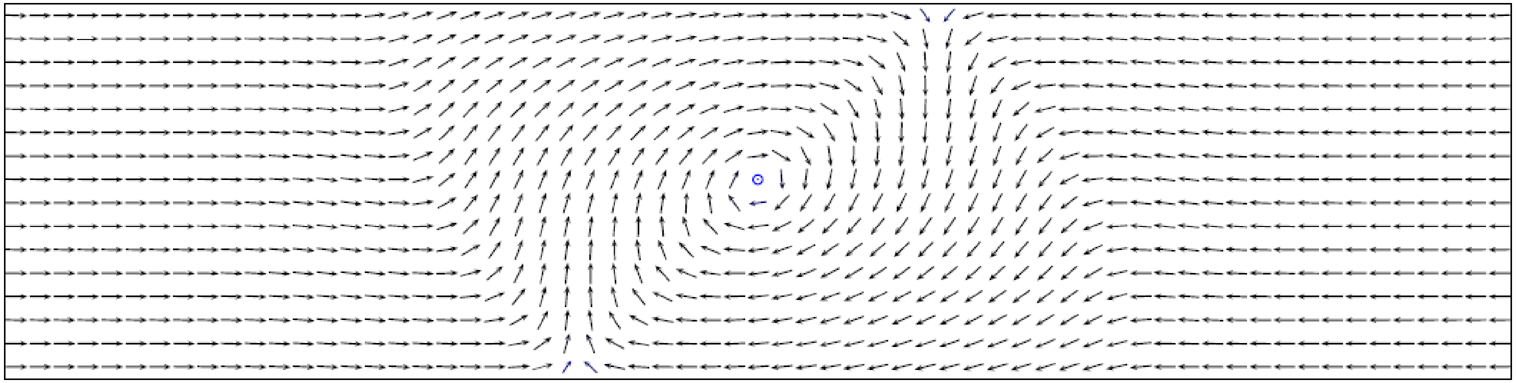
Permalloy stripes (15nm), 250nm wide



Contrast : ±0.3°, tip 5nm CoCr



Known as vortex domain-wall

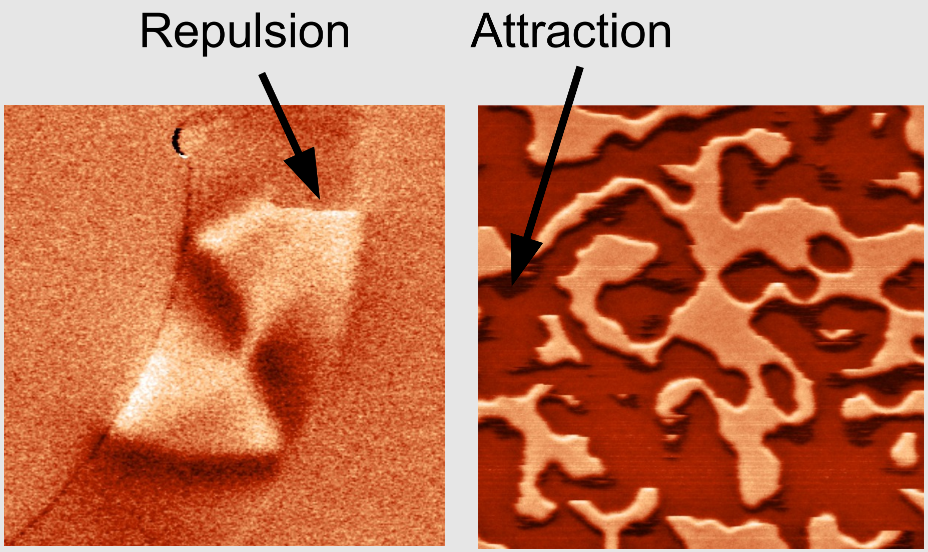


R. McMichael and M. Donahue, IEEE Trans. Magn. 33, 4167 (1997)

↳ Walls in in-plane magnetized stripes → MONOPOLAR
↳ Contrast informs about head-to-head ot tail-to-tail

Tips influencing samples

Moderate



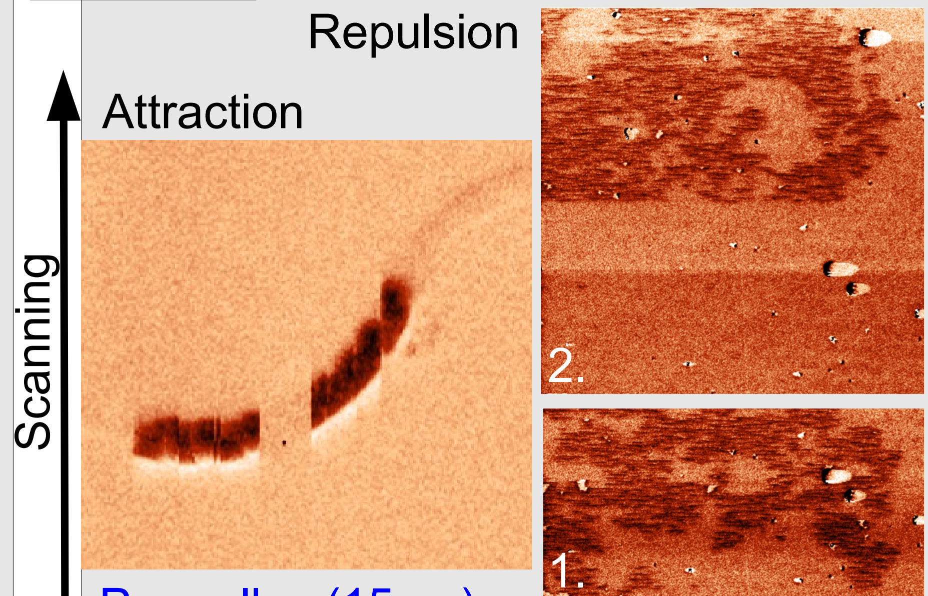
Permalloy (15nm)
500nm wide

Sample : S. Pizzini
Imaging : Z. Ishaque

FePt (4nm)
Image 5 microns

Sample : A. Marty
Imaging : M. Darques

Moderate



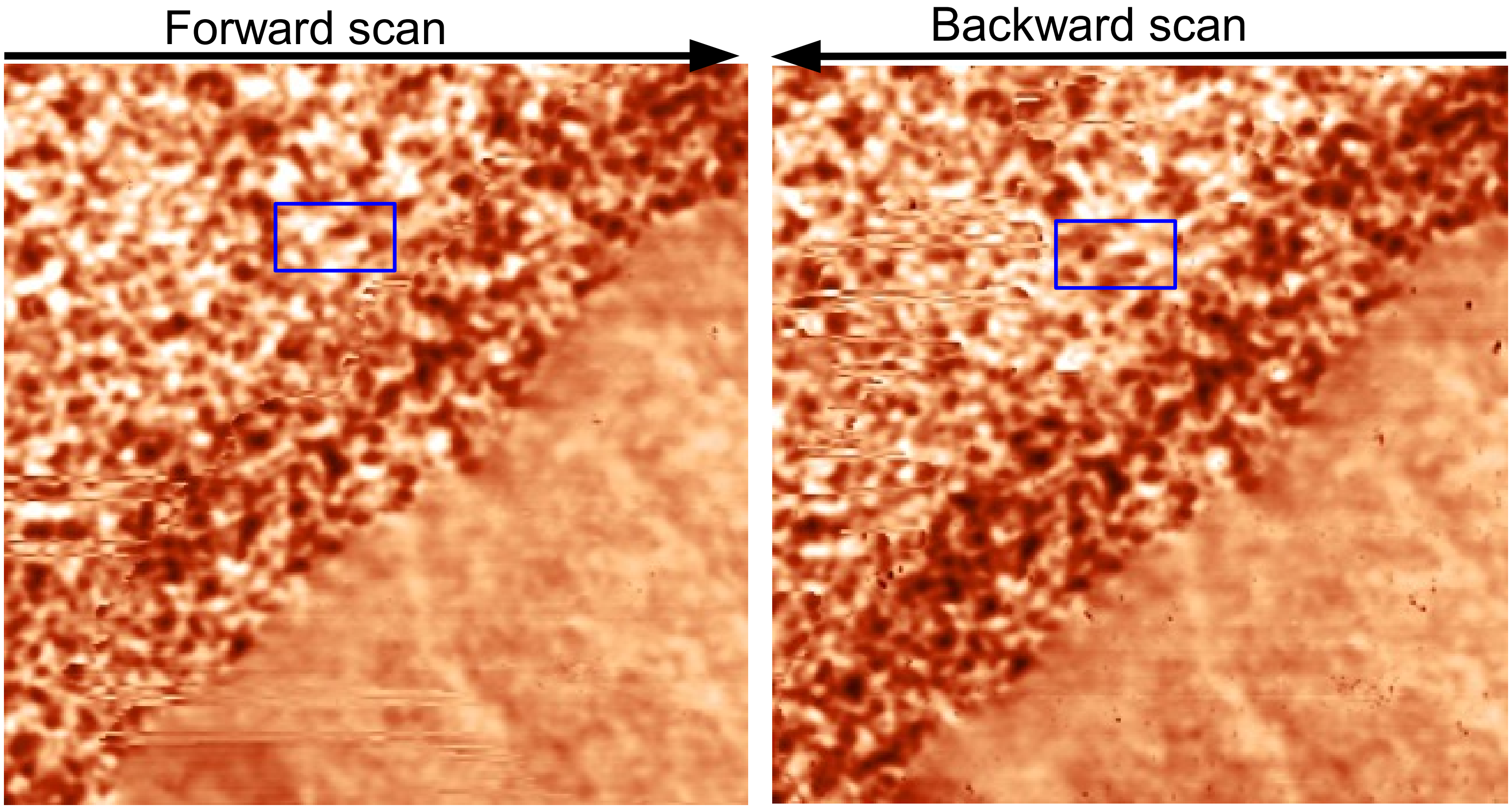
Permalloy (15nm)
500nm stripes

Sample : S. Pizzini
Imaging : Z. Ishaque

Co (0.6nm)/
graphene (20 mic)

C. Dieudonné

- Repeat measurement and/or change scanning direction
- Low-coercive samples require low-moment tips
- Commercial 'low-moment' may not be low enough



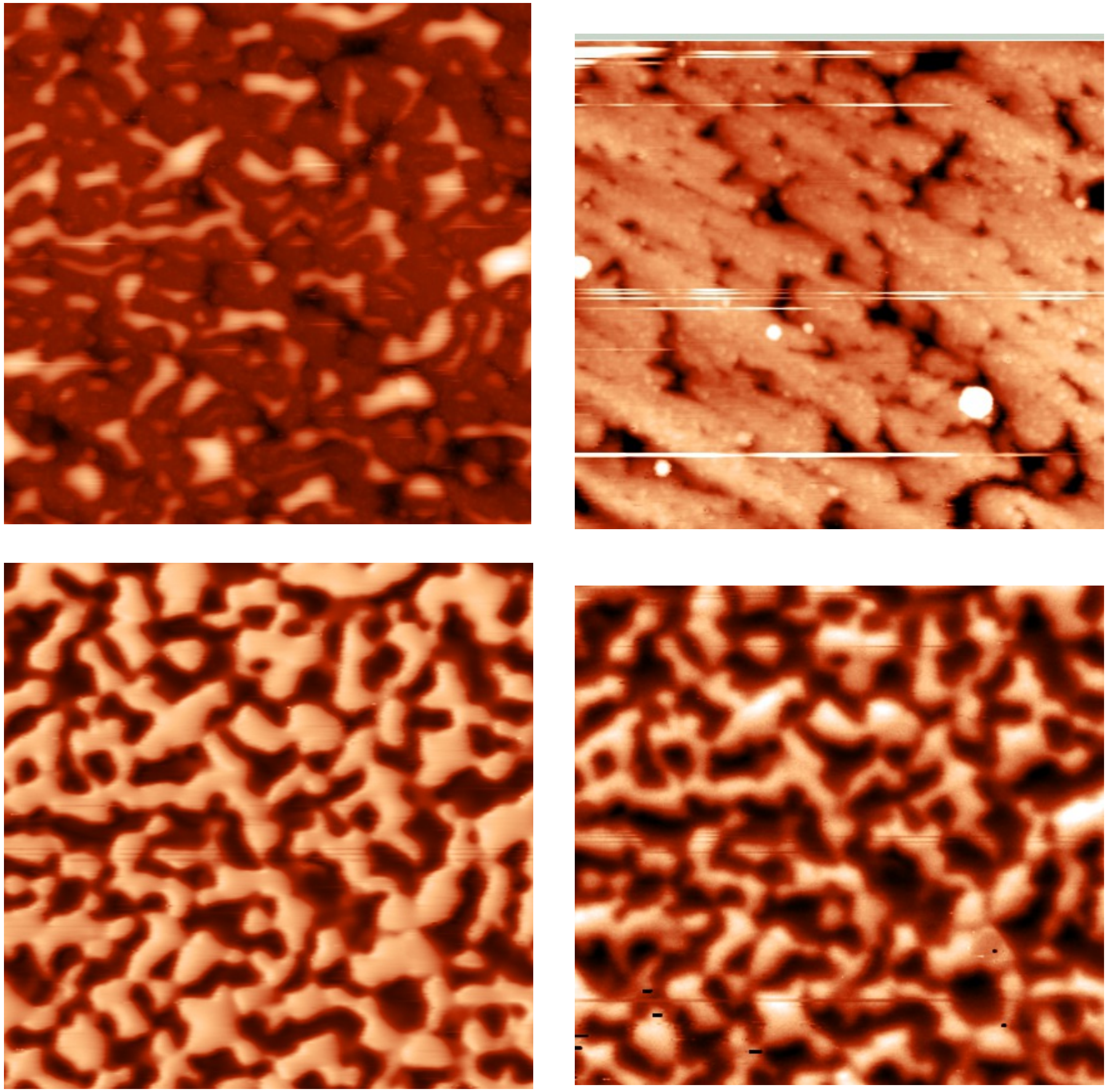
FePt thick film

G. Ciuta (Institut néel)

↳ Moment of tip reverses during scan
↳ Permanent magnet → Choose high-coercivity tips (eg Asylum)

NdFeB thick film

Soft cantilever (70kHz) | Stiff cantilever (300kHz)

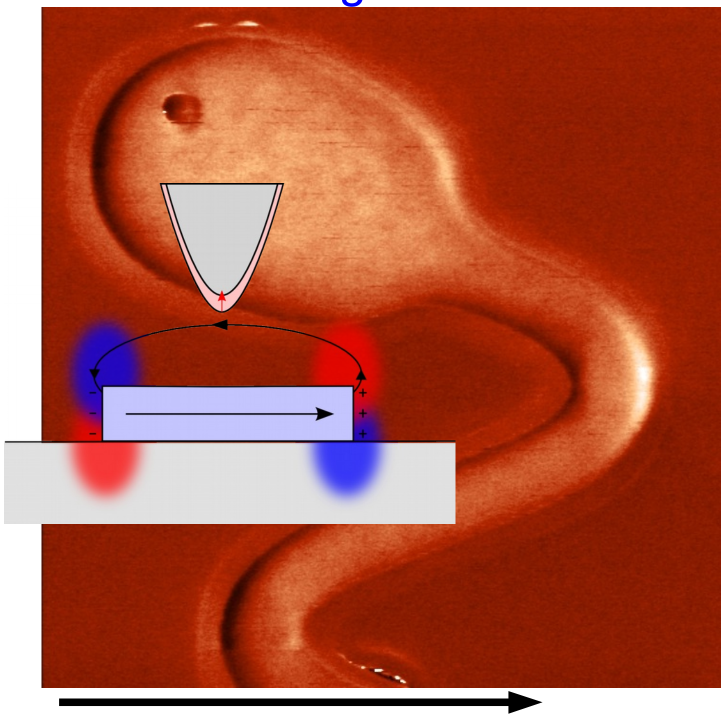


Contrast : ±20° | Contrast : ±0.5°

- Cantilever repeled for tip and sample opposite
- 'Attractive' domains are over-dominant in the image
- 'Repulsive' domains lack of resolution
- Use stiff cantilever for permanent magnets

Sample : G. Ciuta (Institut néel)

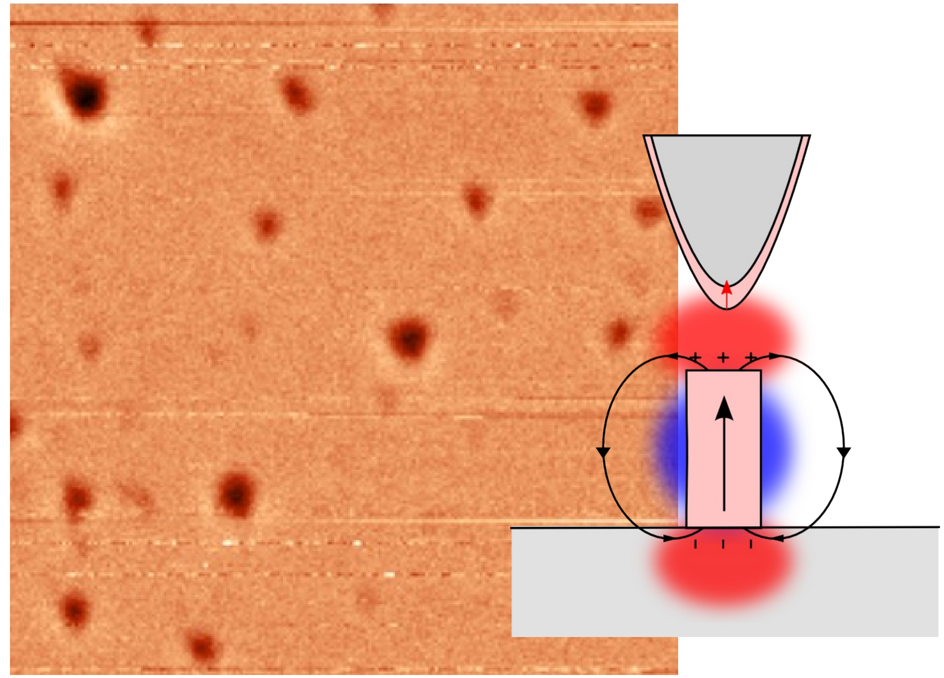
Co(5)\Cu(5)\Py(15nm)
5 microns image



In-plane field (30mT)

Sample : A. Masseboeuf (CEA-Grenoble)

Agglomerated Fe3O4
superparamagnetic particles



Out-of-plane field (400mT)

Sample : K. Aissou (LCPO , Bordeaux)

➯ Coercive field of usual tips of the order of 50mT

Moment

Normal moment for most samples (30-50nm CoCr)

Low moment, or even :

Superparamagnetic or ultra-low moment

⇨ Low-coercivity samples

⇨ Increased resolution

⇨ At the expense of sensitivity

Cantilever

Normal stifness ('force modulation') → resonance at 70kHz

Large stifness

⇨ High stray-field samples (typically permanent magnets)

⇨ At the expense of sensitivity

Tip sharpness

Normal resolution (50nm)

Sharp tips (resolution 25nm), expense :

⇨ Commercial and/or spacial fabrication (FIB etc.)

⇨ Loss of sensitivity

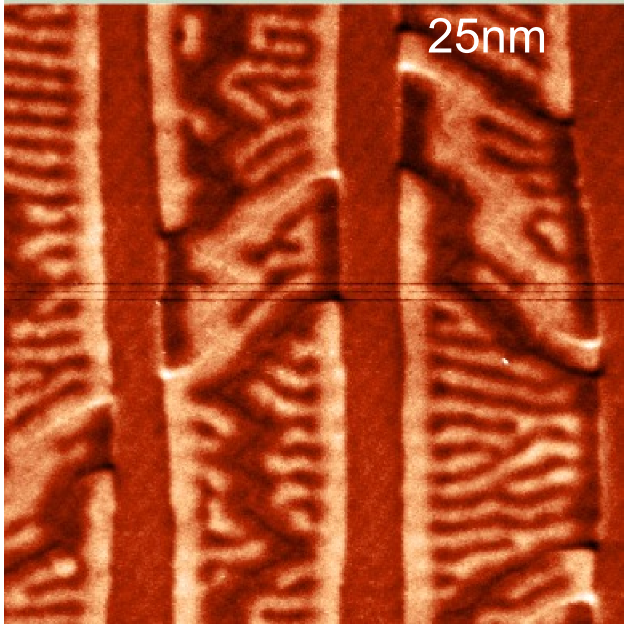
Coercivity

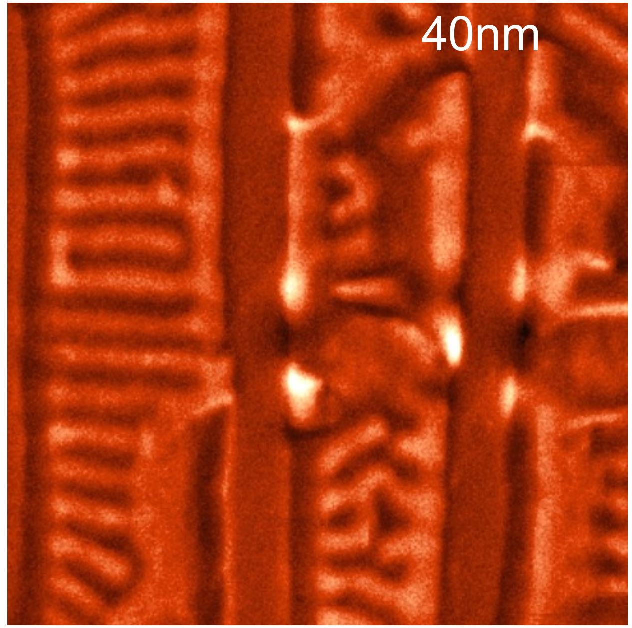
Normal (30-70mT)

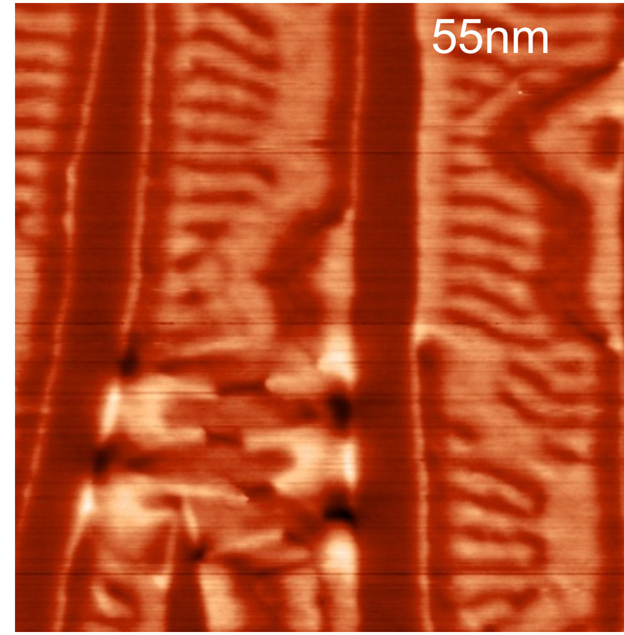
High coercivity (eg Asylum)

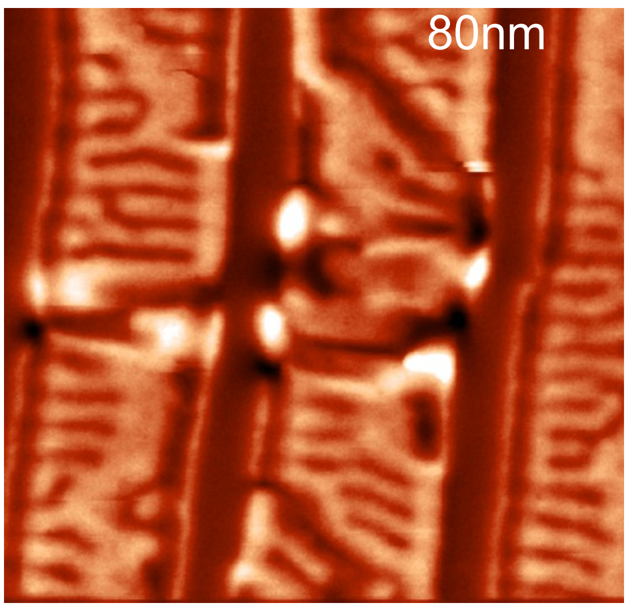
⇨ High stray-field samples (typically permanent magnets)

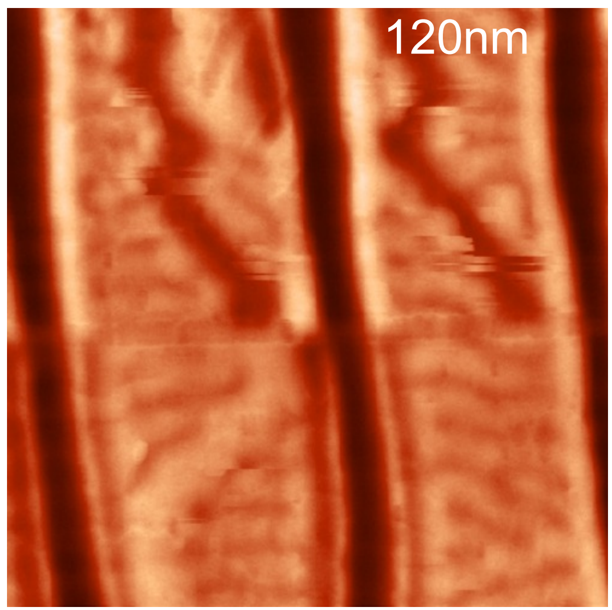
⇨ At the expense of cost





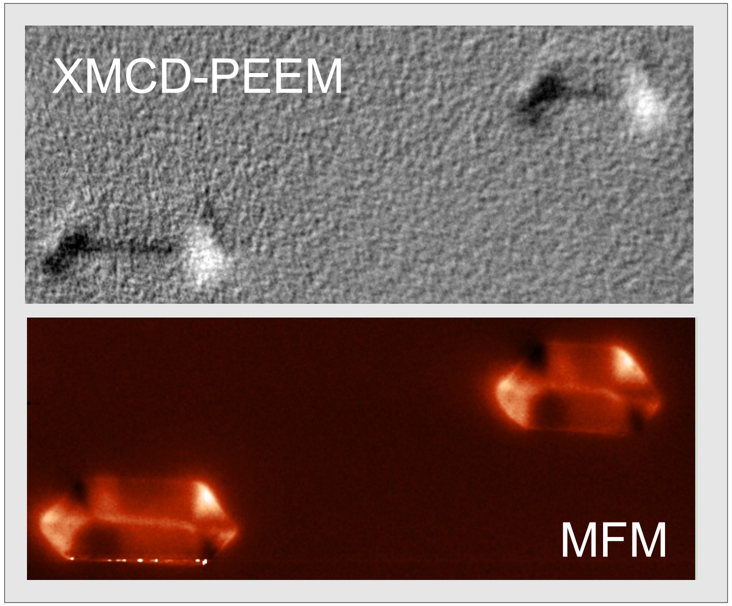


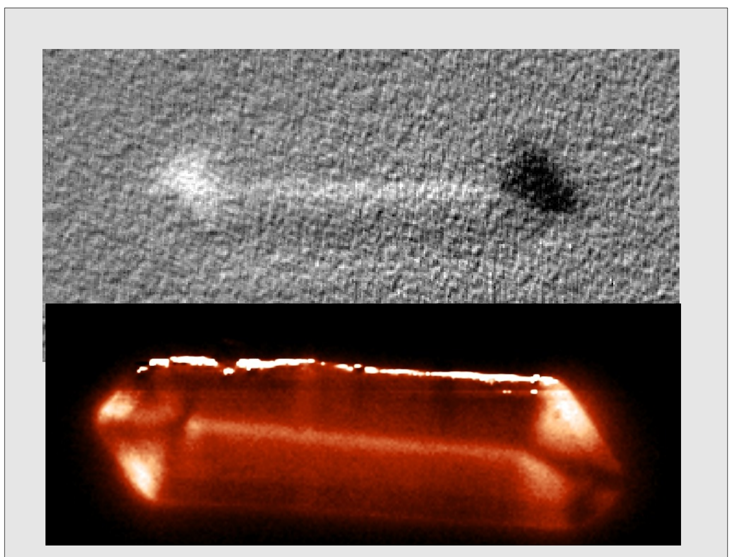


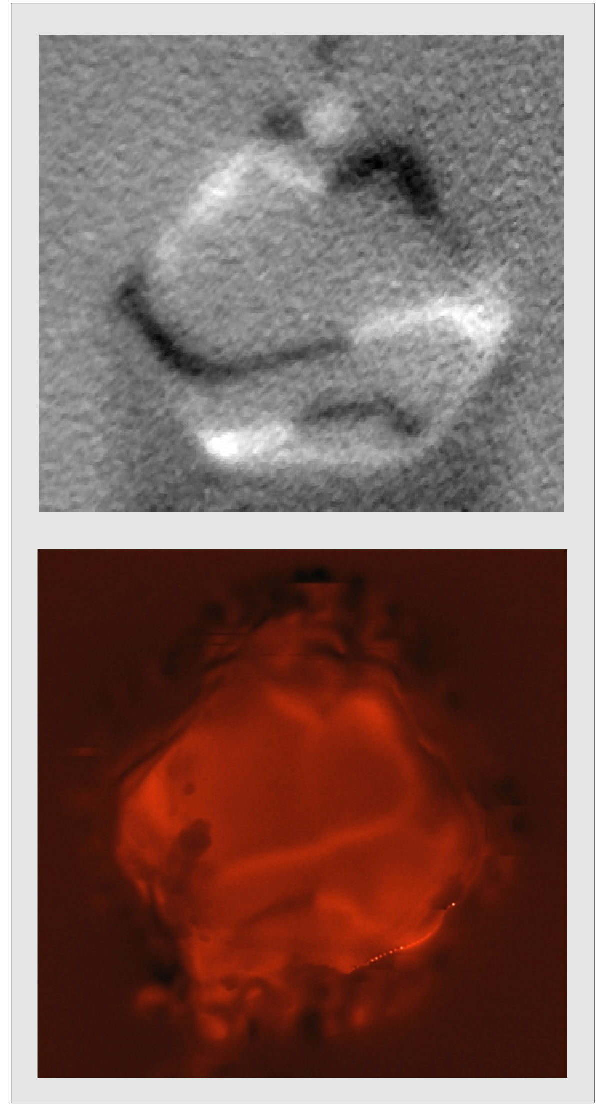


- Compare tips !
- Use identical sample and imaging parameters

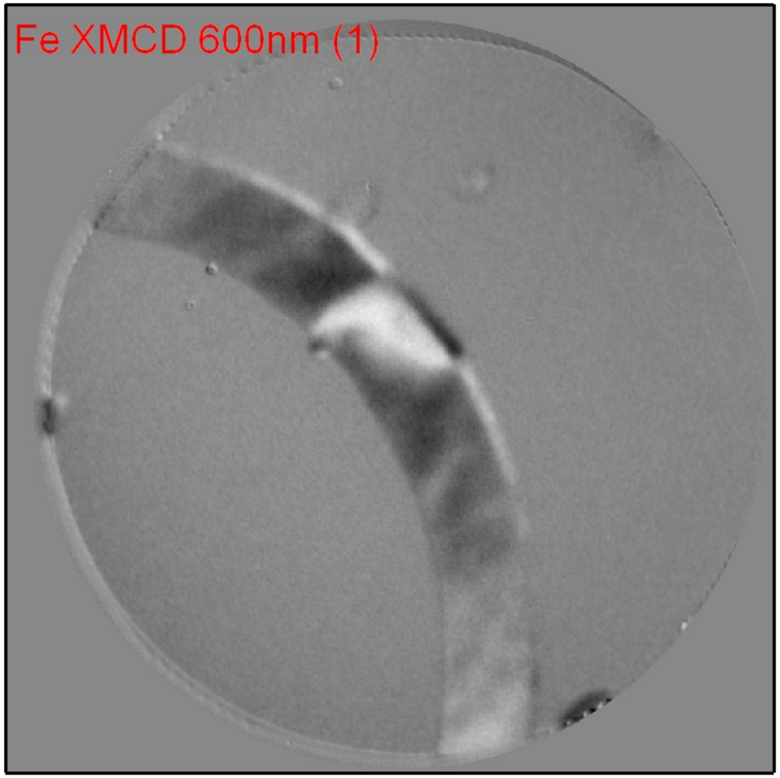
Sample : MnAs(001)
R. Belkhou (Soleil)


XMCD-PEEM
MFM

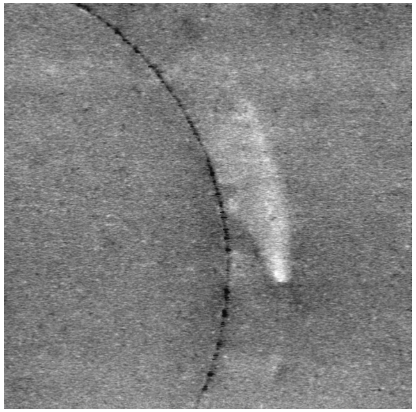




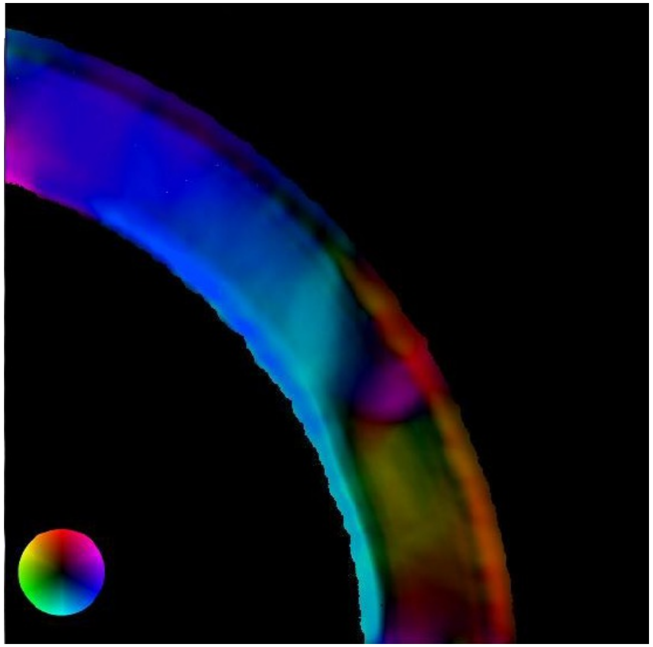
XMCD-PEEM



MFM



Lorentz



Some references

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A. Hubert, R. Schäfer, Magnetic domains, Springer (1999)

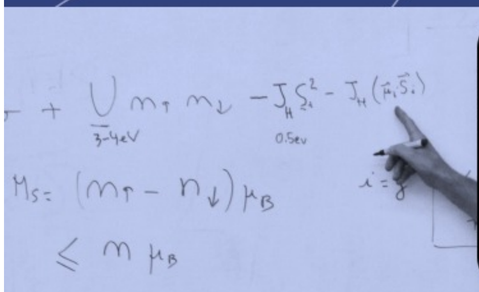
Repository of the European School on Magnetism : http://esm.neel.cnrs.fr
See 2005 School : « New experimental approaches to Magnetism »

Why we DO need 'SOLEIL'

EUROPEAN SCHOOL ON MAGNETISM 2011

TIME-DEPENDENT PHENOMENA IN MAGNETISM

Aug 22nd - Sep. 2nd 2011
Targoviste - Romania



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Scope

The European School on Magnetism (ESM) is a joint action of the European Community of Magnetism, organized in cooperation with JEMS conference (Joint European Magnetic Symposia). ESM aims at providing young scientists with a thorough insight in the fundamentals of magnetism up to its most modern aspects.

Like previous editions of ESM, the 2011 School is based on a broad series of fundamental lectures, before focusing on a special topic. The topic selected for 2011, time-dependent phenomena in magnetism, covers a wide range of phenomena from