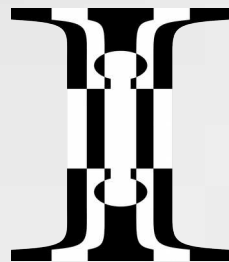


# *Electron Microscopy & Micro-magnetism*

## Micromagnetic Objects and dynamical imaging



Christophe Gatel  
*Aurélien MASSEBOEUF*  
Etienne Snoeck  
Martin Hýtch  
Bénédicte Warot  
Florent Houdellier

*Interferometry  
Instrumentation  
& In situ*

*for Electron Microscopy*

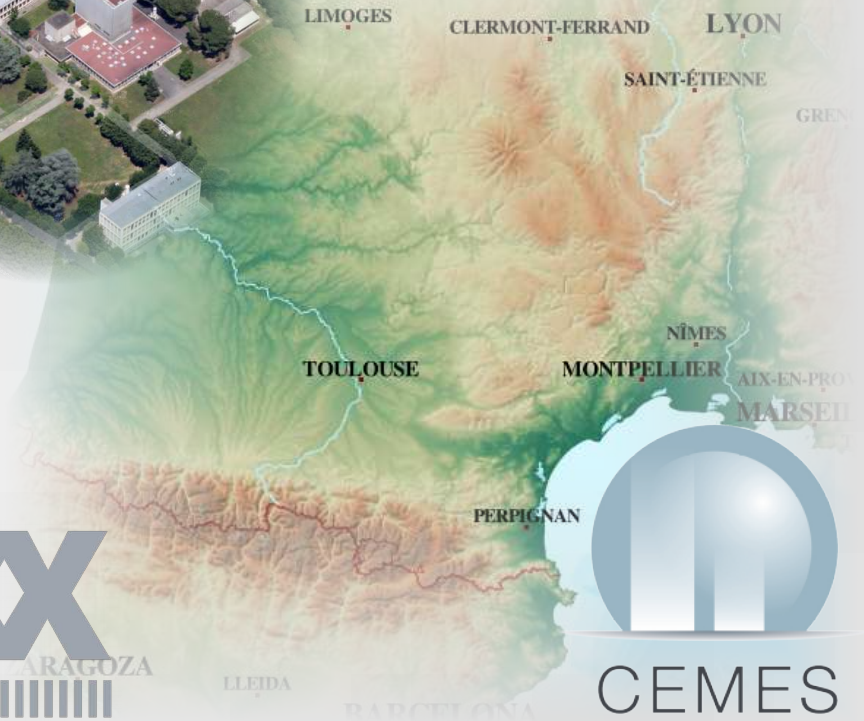
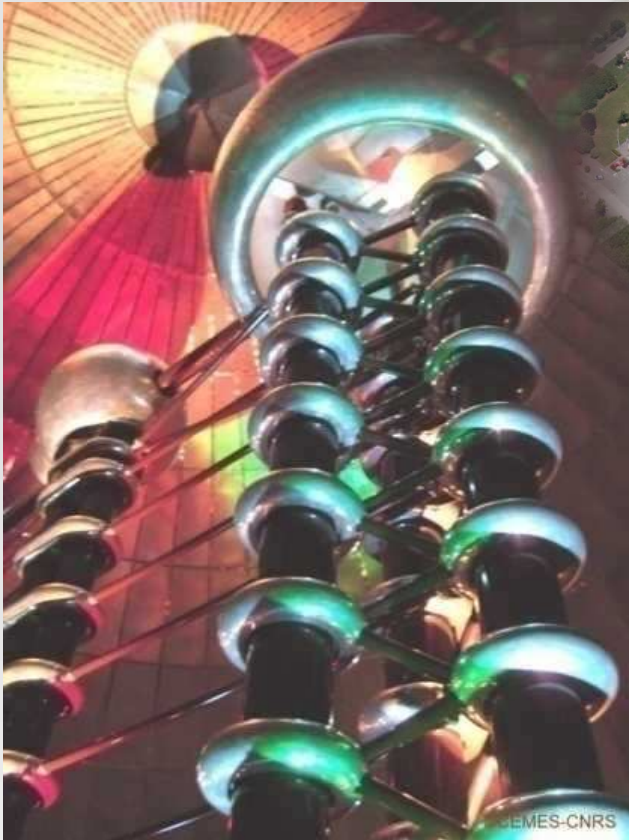


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Oct. 2017

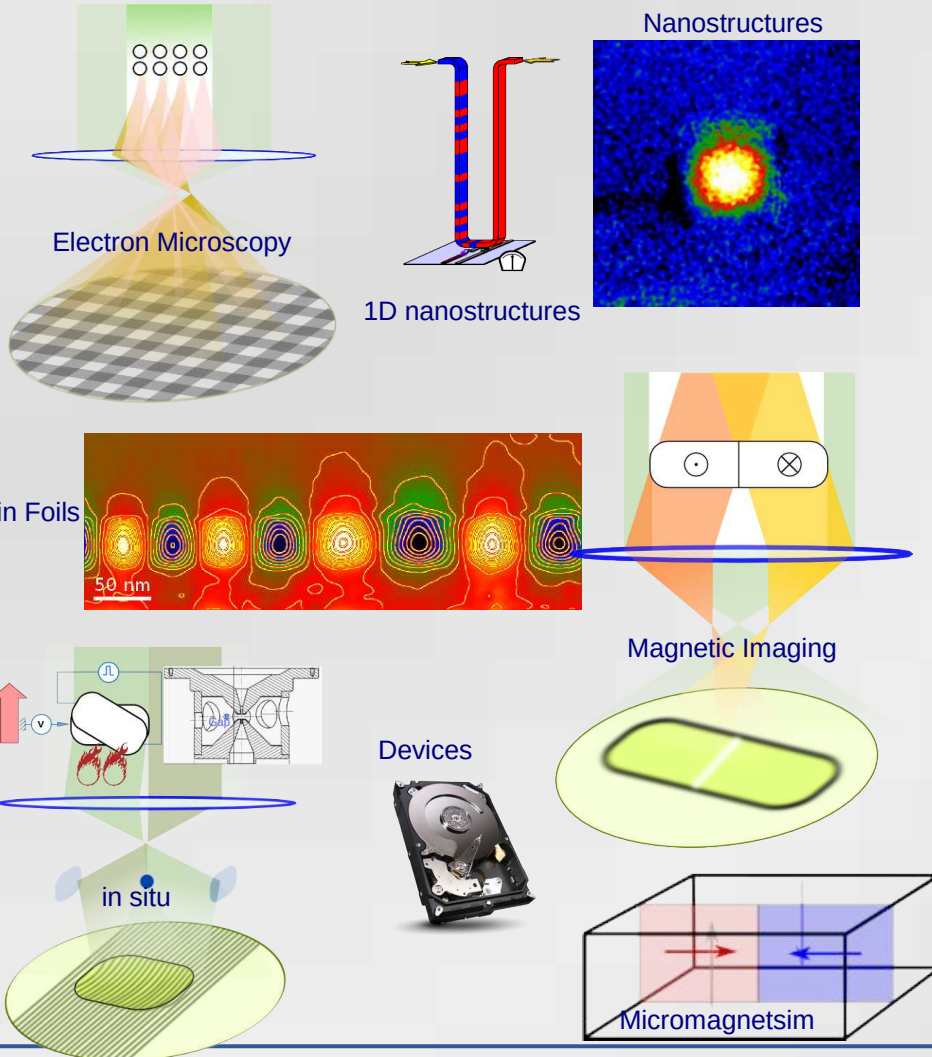


# Electron Microscopy & Micro-magnetism

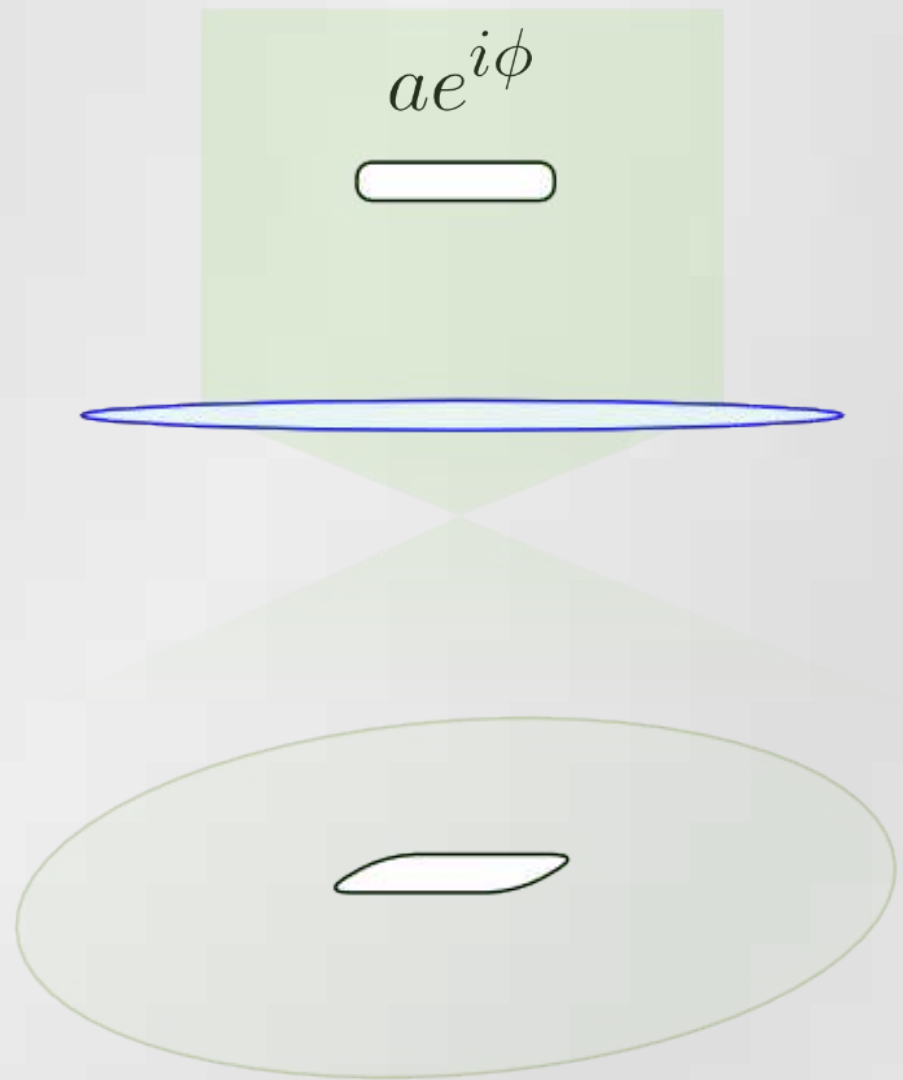
## Micromagnetic Objects and dynamical imaging



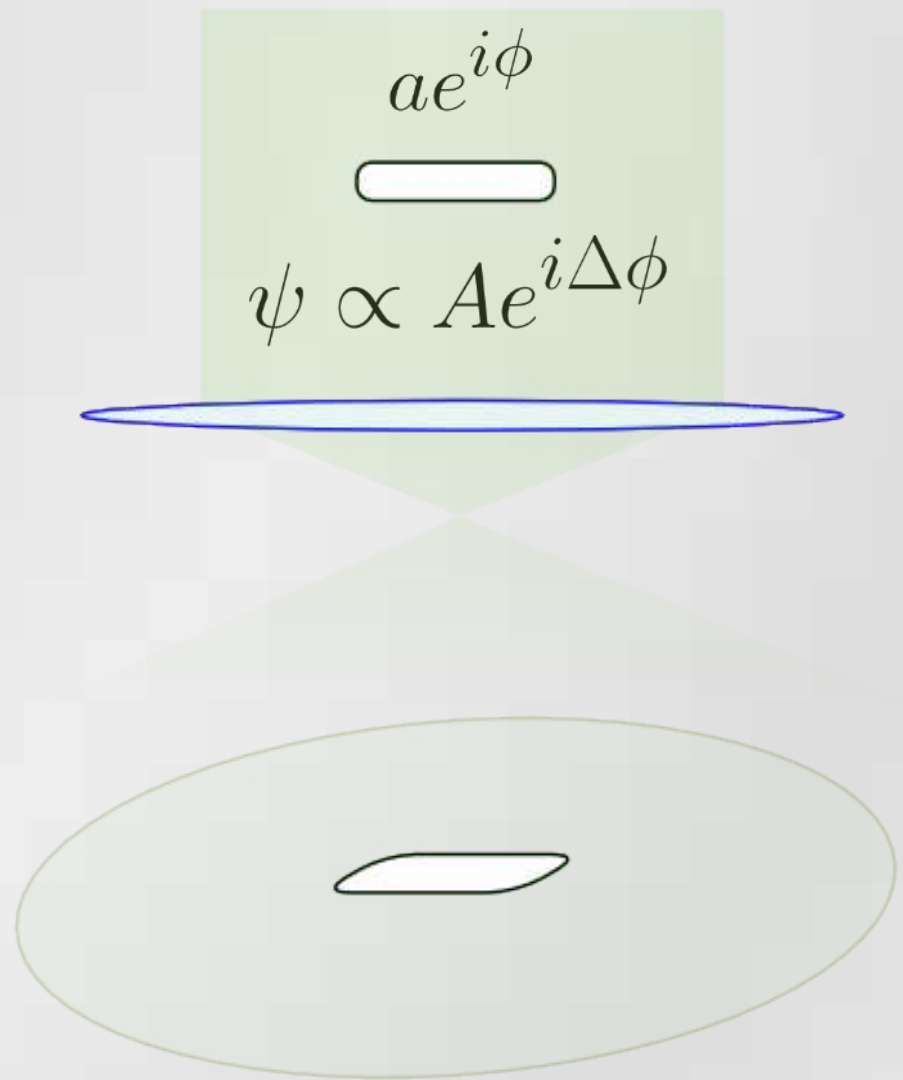
# Electron Microscopy & Micro-magnetism



**Transmission Electron Microscopy :  
Interferometry & In Situ  
For micromagnetic studies**







$$ae^{i\phi}$$



$$\psi \propto Ae^{i\Delta\phi}$$

$$T_\mu = A_\mu e^{-\alpha_\mu} e^{i\chi_\mu}$$

$$\Psi = \psi \circledast T_\mu$$



$$ae^{i\phi}$$



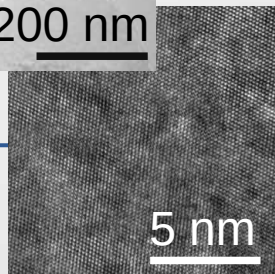
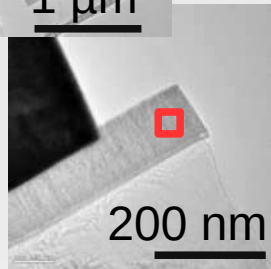
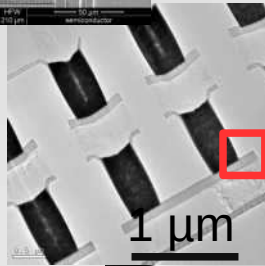
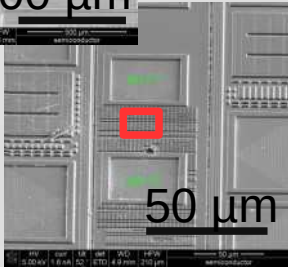
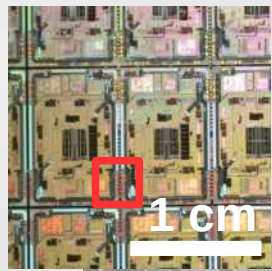
$$\psi \propto Ae^{i\Delta\phi}$$

$$T_\mu = A_\mu e^{-\alpha_\mu} e^{i\chi_\mu}$$

$$\Psi = \psi \circledast T_\mu$$



$$I \propto \|\Psi\|^2 \propto A^2$$



$$ae^{i\phi}$$



$$\psi \propto Ae^{i\Delta\phi}$$

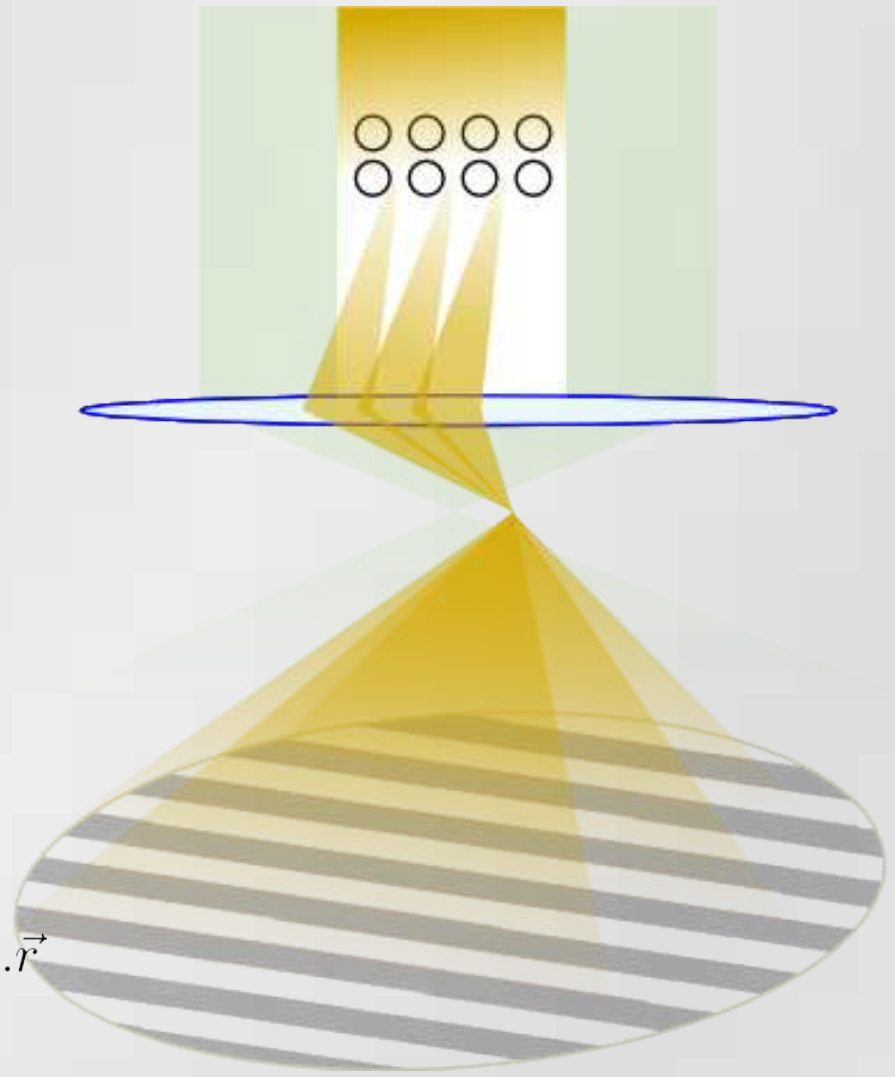
$$T_\mu = A_\mu e^{-\alpha_\mu} e^{i\chi_\mu}$$

$$\Psi = \psi \otimes T_\mu$$



$$I \propto \|\Psi\|^2 \propto A^2$$

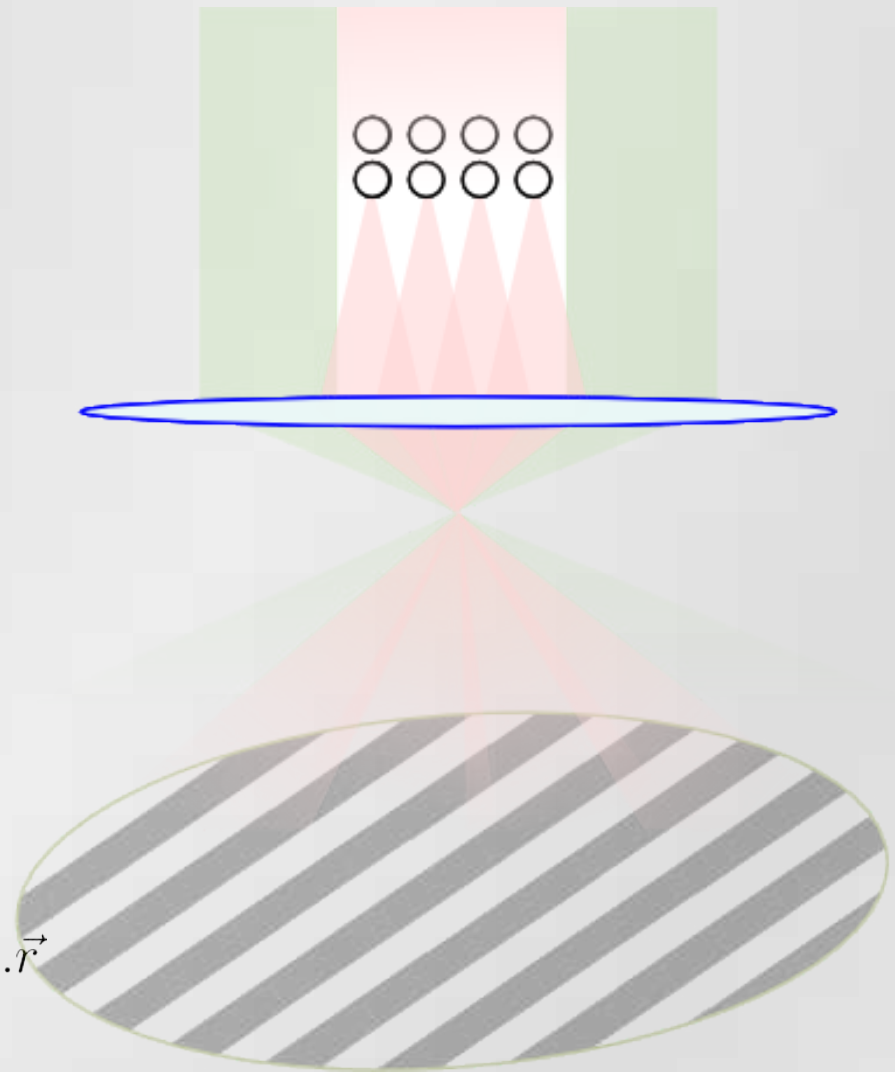
$$\Psi = \sum_g \tilde{\Psi}_g \cdot e^{2i\pi\vec{g}\cdot\vec{r}}$$



$$I \propto \sum_g \sum_{g'} \tilde{\Psi}_g \tilde{\Psi}_{g'}^* \cdot e^{2i\pi(\vec{g}-\vec{g}')\cdot\vec{r}}$$

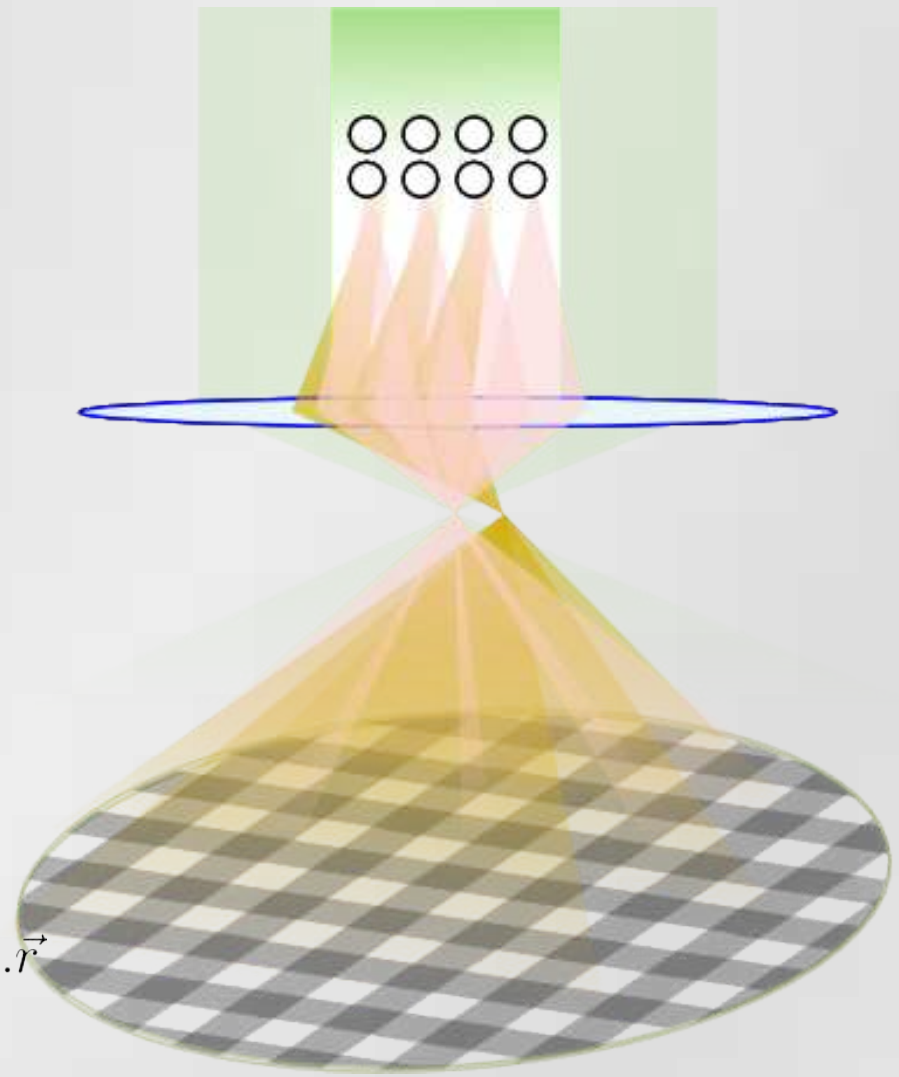


$$\Psi = \sum_g \tilde{\Psi}_g \cdot e^{2i\pi\vec{g}\cdot\vec{r}}$$



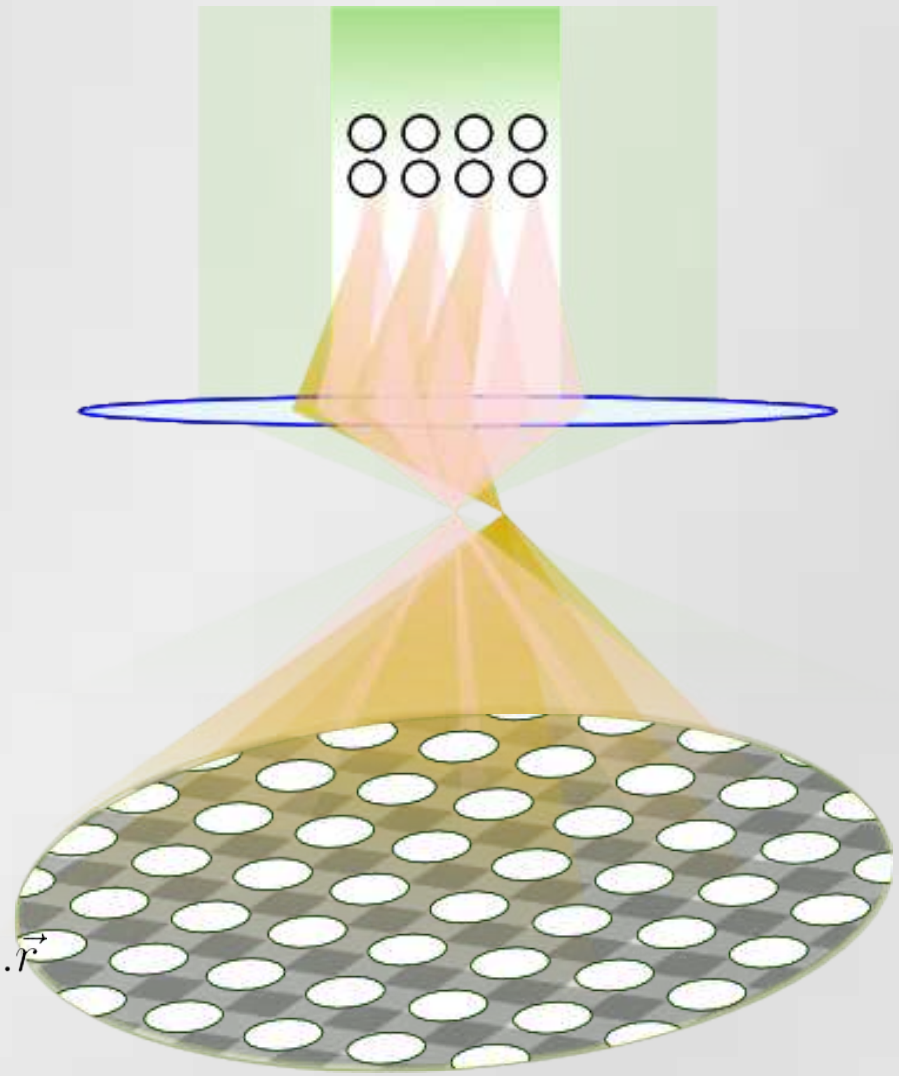
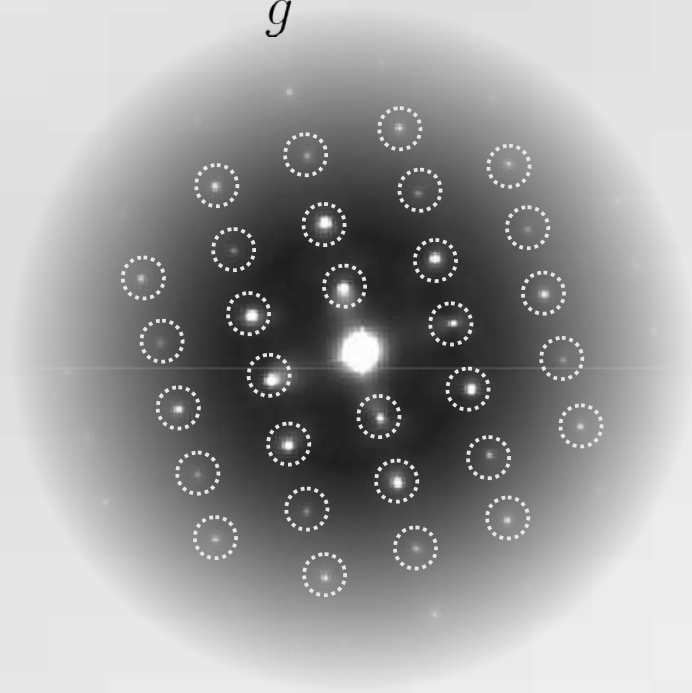
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$$\psi \propto Ae^{i\Delta\phi}$$

How to improve signal ?

$$T_\mu = A_\mu e^{-\alpha_\mu} e^{i\chi_\mu}$$

$$\Psi = \psi \circledast T_\mu$$



$$I \propto \|\Psi\|^2 \propto A^2$$

$$ae^{i\phi}$$



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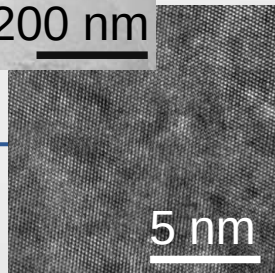
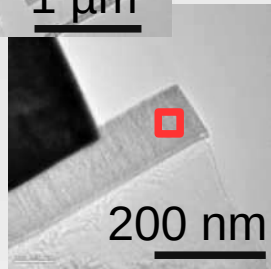
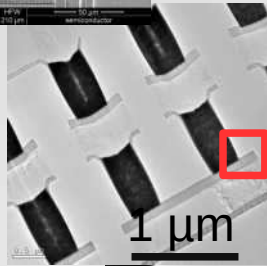
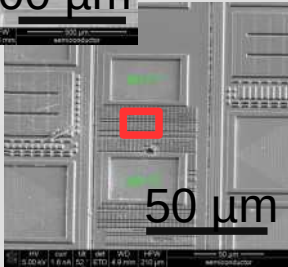
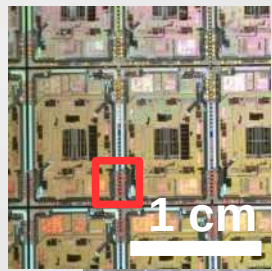
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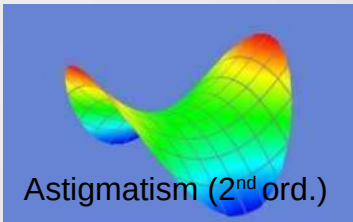


$$ae^{i\phi}$$

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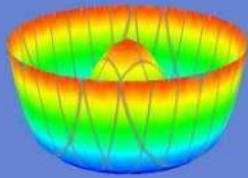

$$T_\mu = A_\mu e^{-\alpha_\mu} e^{i\chi_\mu}$$

$$\Psi = \psi \otimes T_\mu$$

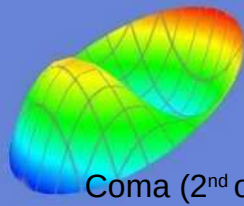

$$I \propto \|\Psi\|^2 \propto A^2$$



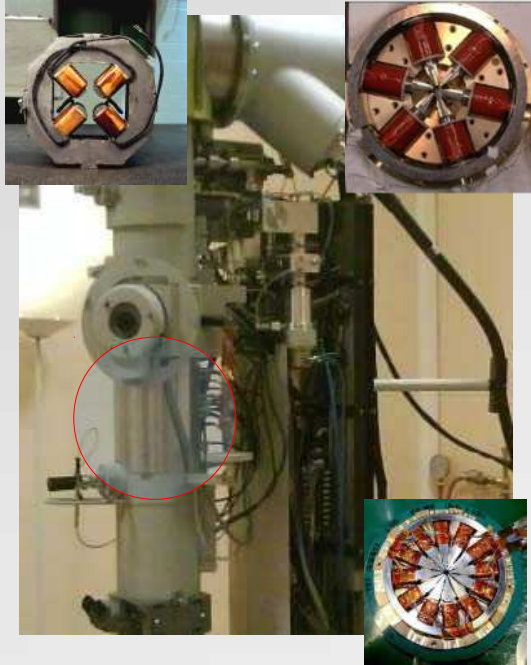
Astigmatism (2<sup>nd</sup> ord.)



Spheric (3<sup>rd</sup> ord.)



Coma (2<sup>nd</sup> ord.)



$$ae^{i\phi}$$


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$$\psi \propto Ae^{i\Delta\phi}$$

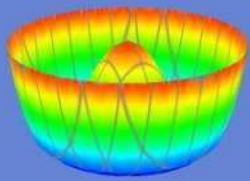
$$T_\mu = A_\mu e^{-\alpha_\mu} e^{i\chi_\mu}$$

$$\Psi = \psi \circledast T_\mu$$

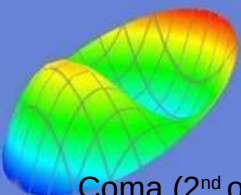
$$I \propto \|\Psi\|^2 \propto A^2$$



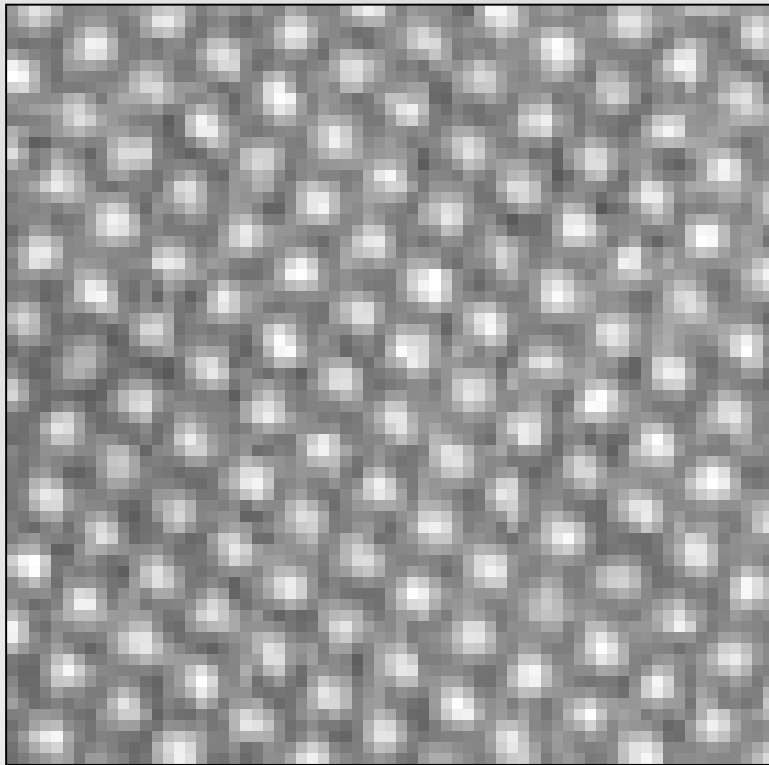
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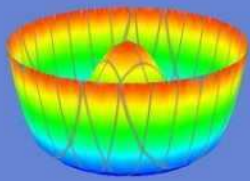
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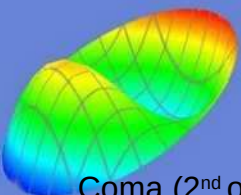

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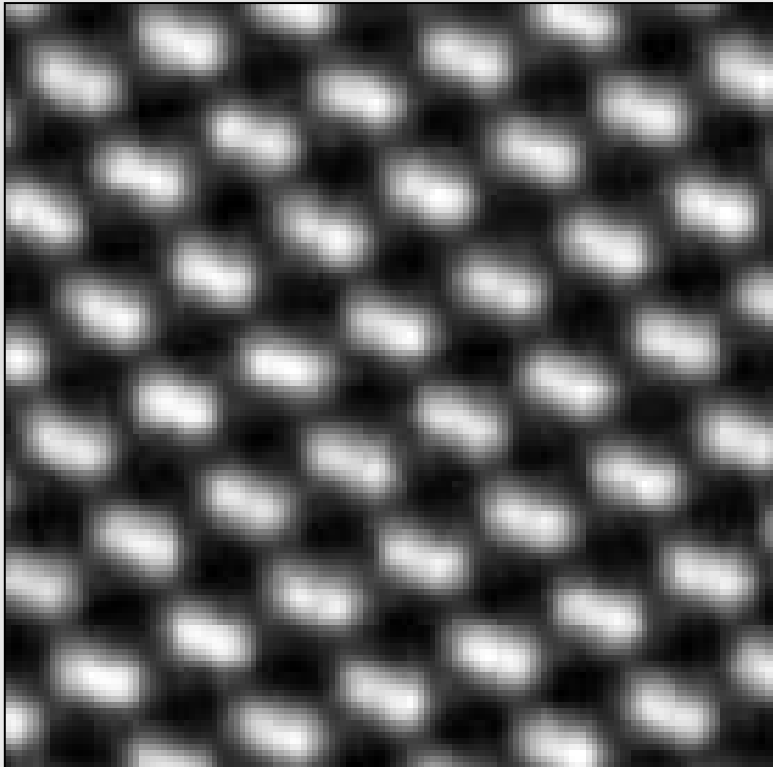
Astigmatism (2<sup>nd</sup> ord.)




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Coma (2<sup>nd</sup> ord.)




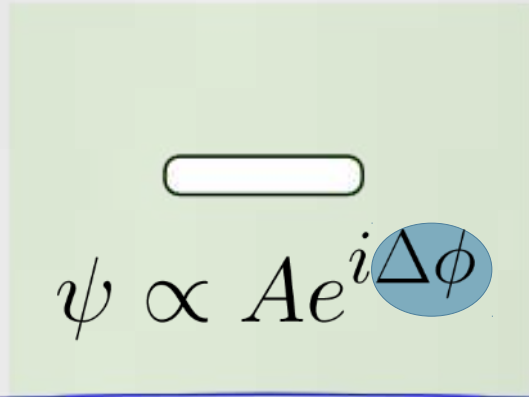
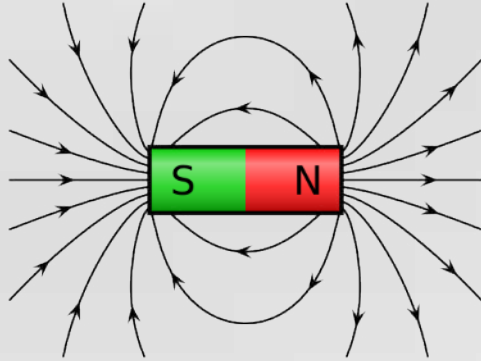
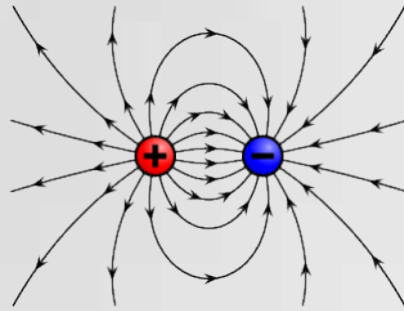
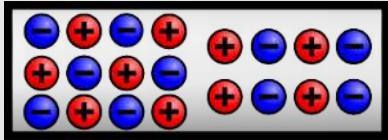

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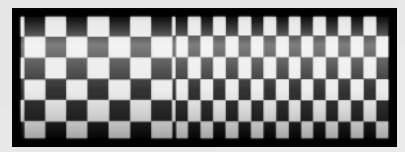
$$\Psi = \psi \circledast T_\mu$$


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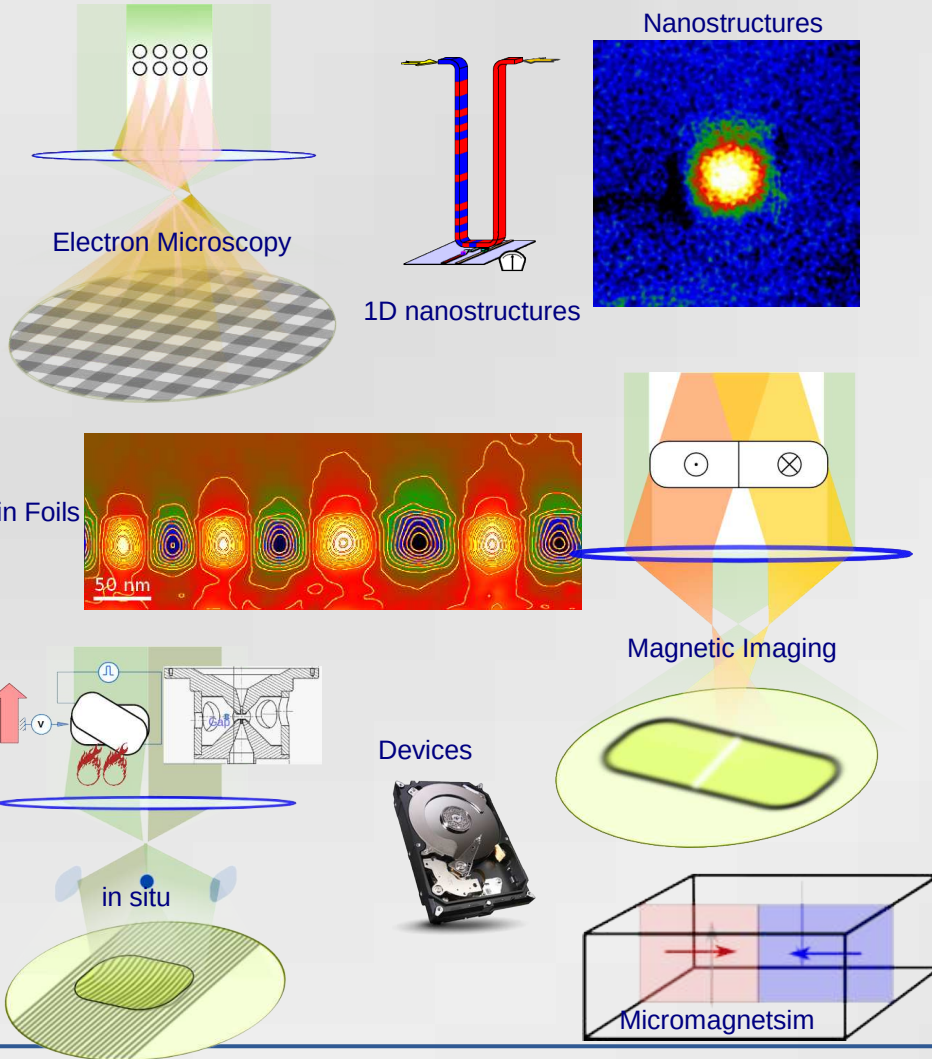
$$\Delta\phi = C_E \int_{-\infty}^{\infty} V dz - \frac{e}{\hbar} \int_{-\infty}^{\infty} A_z dz$$

Aharonov-Bohm effect



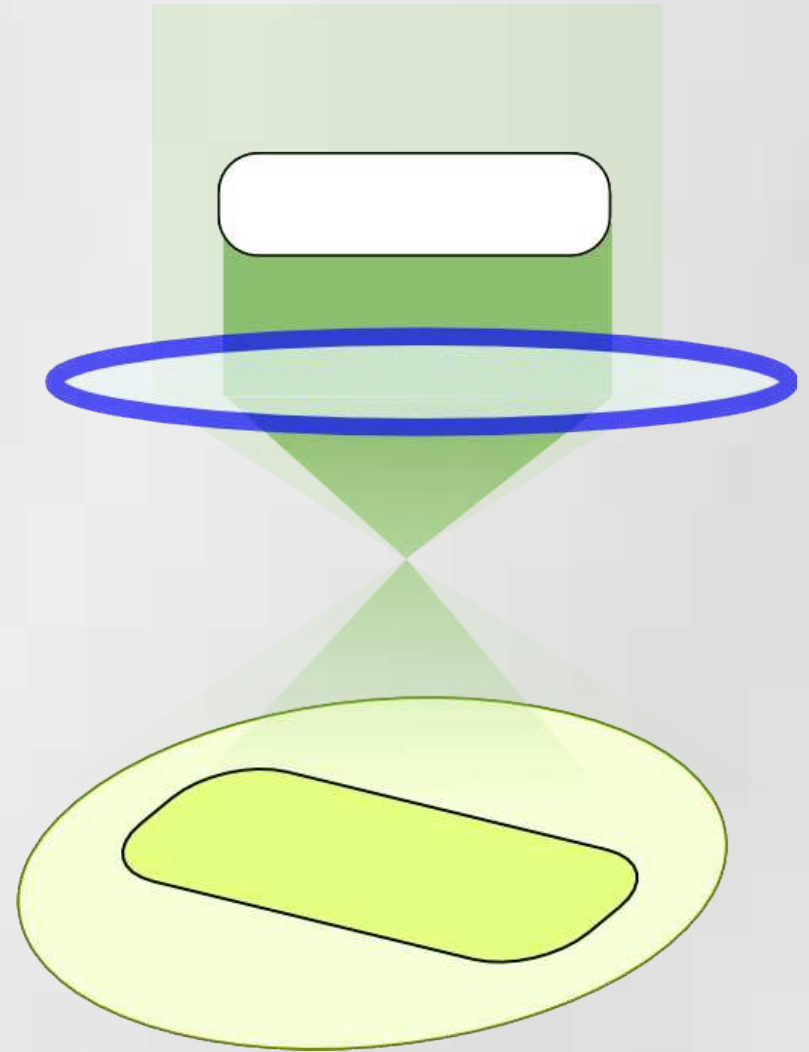
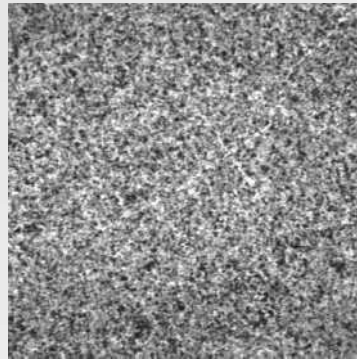


# Electron Microscopy & Micro-magnetism



**Transmission Electron Microscopy :**  
**Interferometry & In Situ**  
**For micromagnetic studies**

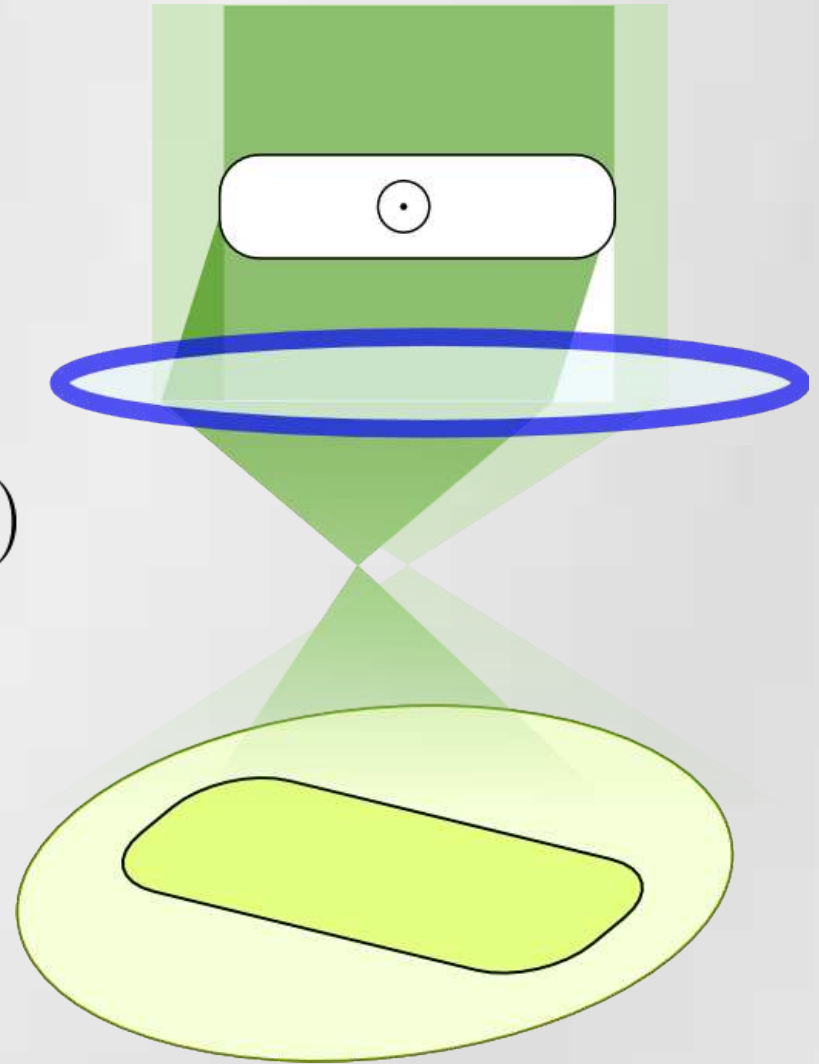
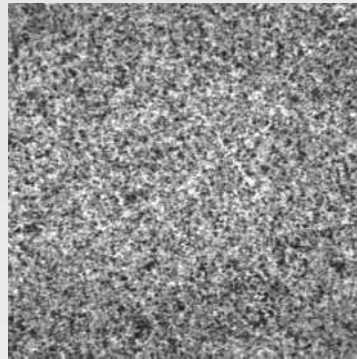
# *Electron Interferometry :*



# Electron Interferometry :

Lorentz Force :

$$\vec{F} = q(\vec{v} \wedge \vec{B})$$



Lorentz deflection angle  $\sim \mu\text{rad}$

(Bragg angle  $\sim \text{mrad}$ )

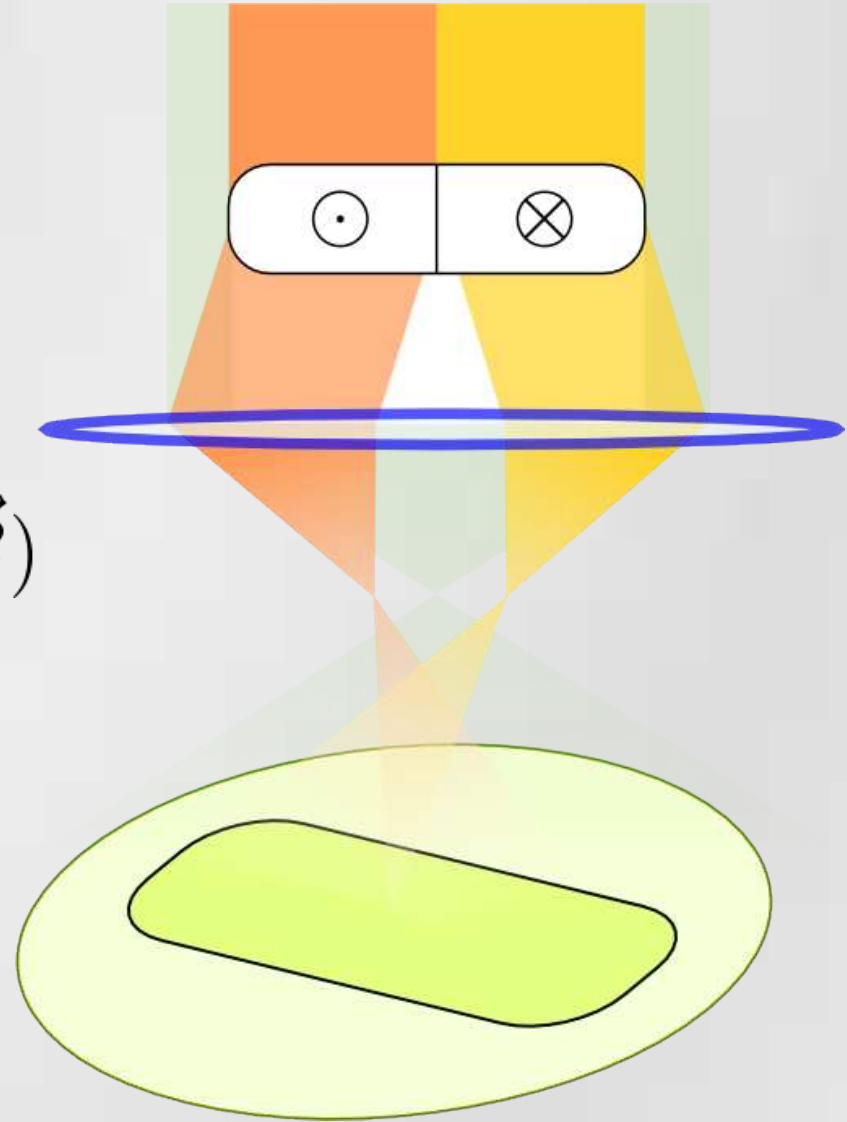
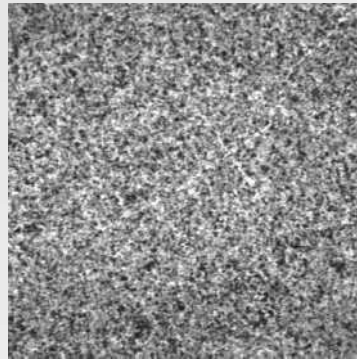
Strasbourg  
Oct. 2017

# Electron Interferometry :

Fresnel imaging  
« In-line Holography »

Lorentz Force :

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Oct. 2017



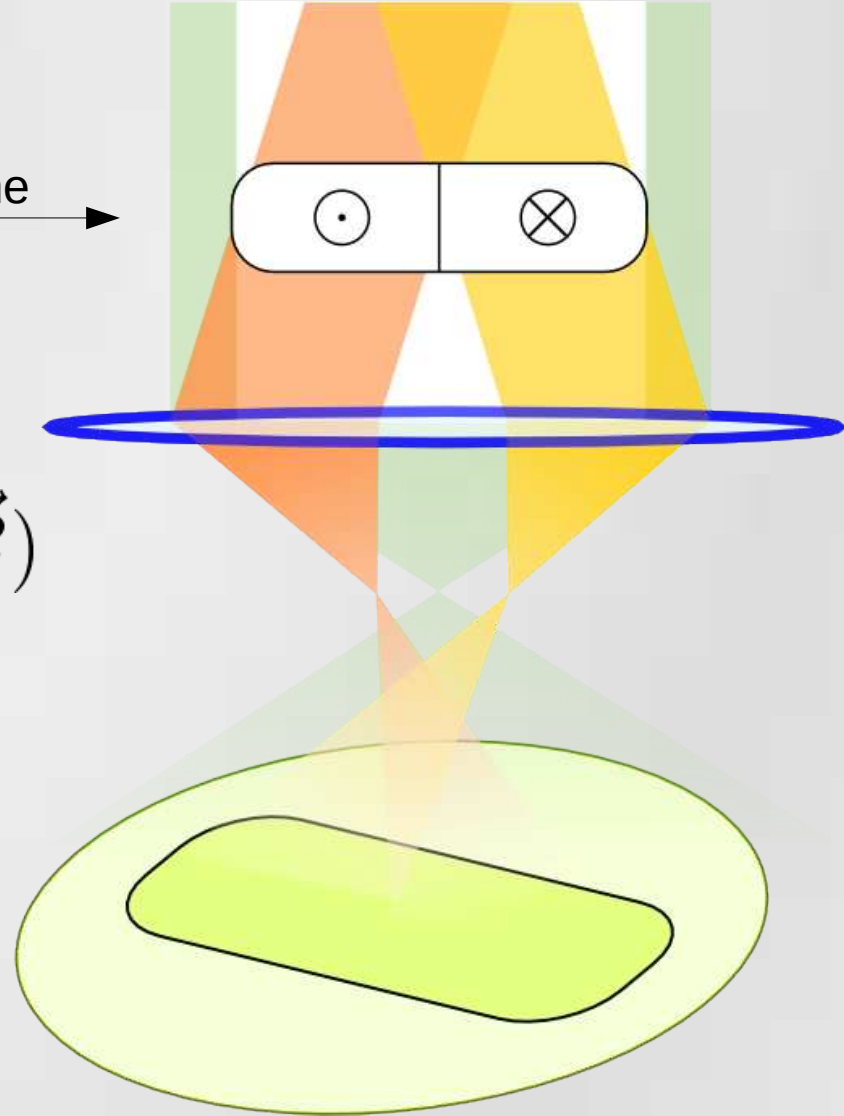
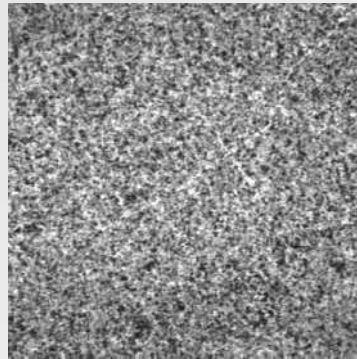
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Fresnel imaging  
« In-line Holography »

Image Plane →

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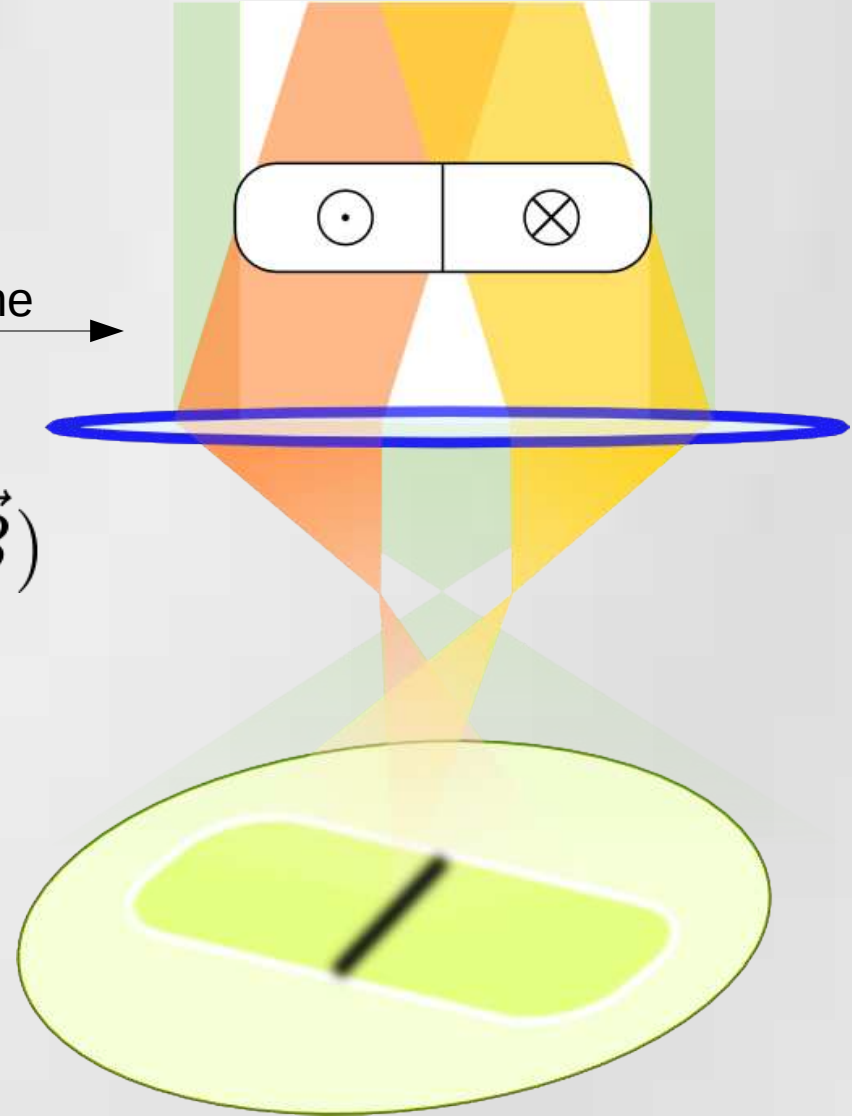
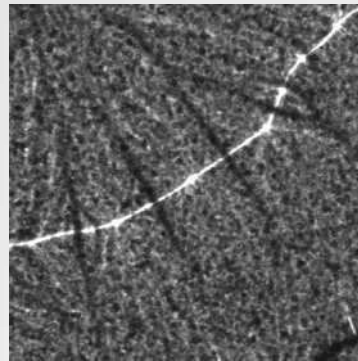


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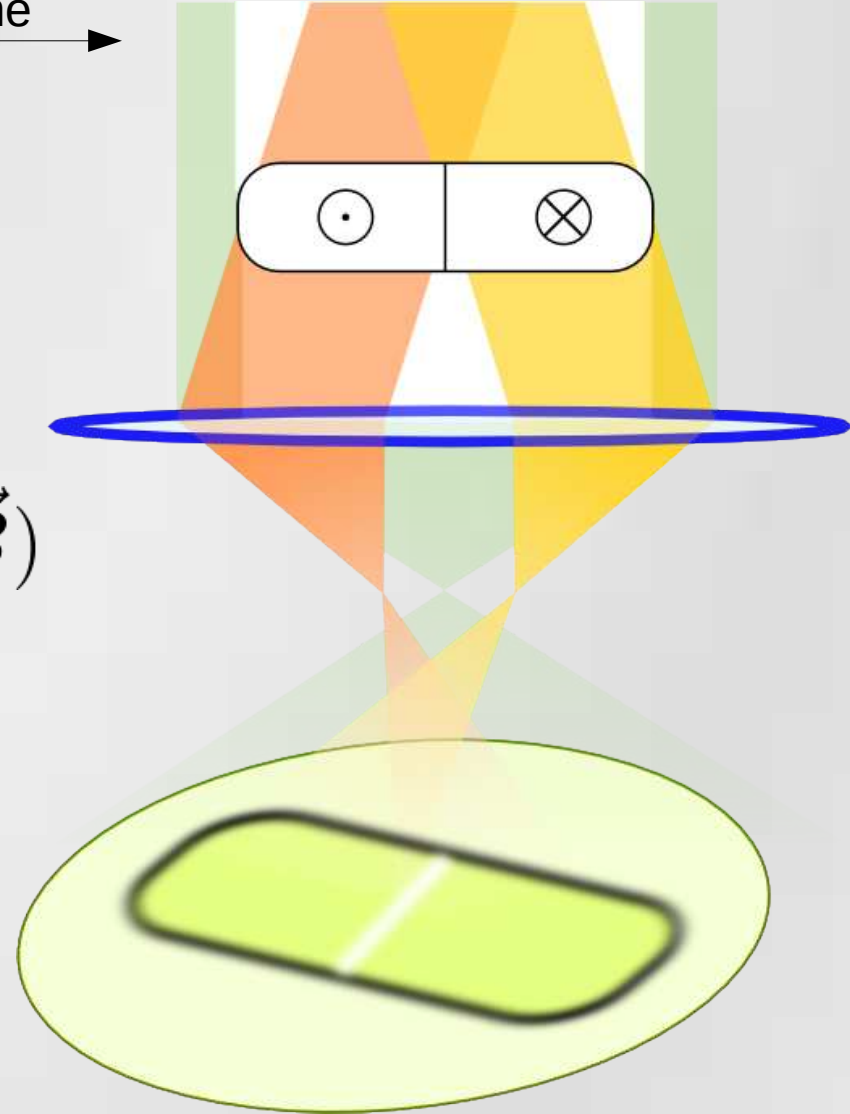




# Electron Interferometry :

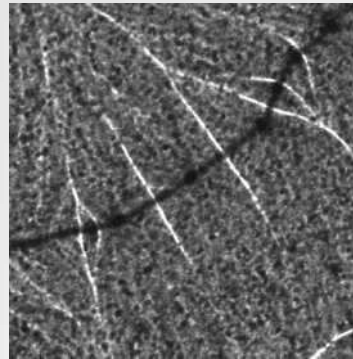
Fresnel imaging  
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Image Plane →



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# Electron Interferometry :

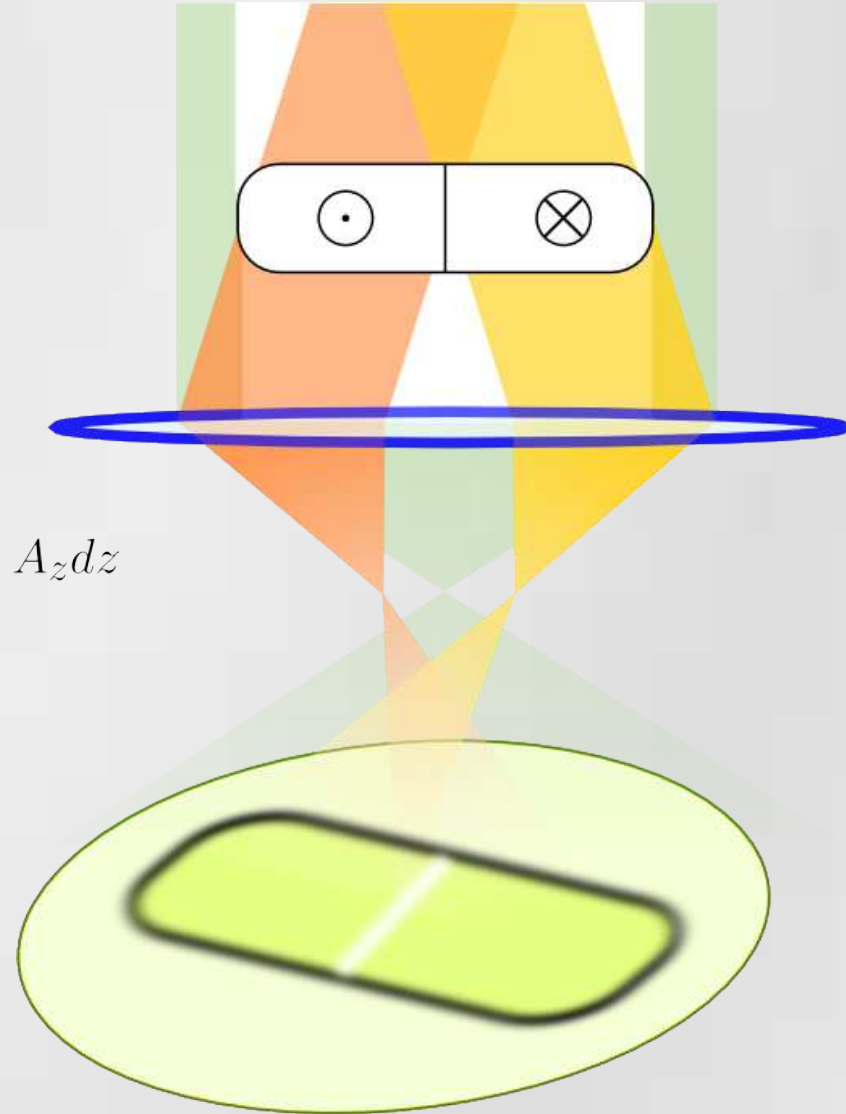
Fresnel imaging  
« In-line Holography »

Phase Reconstruction :

$$\frac{2\pi}{\lambda} \frac{\partial}{\partial z} I(x, y, z) = -\nabla_{x,y} \cdot (I(x, y, z) \nabla_{x,y} \phi_s(x, y, z))$$

Aharonov-Bohm

$$\Delta\phi = C_E \int_{-\infty}^{\infty} V dz - \frac{e}{\hbar} \int_{-\infty}^{\infty} A_z dz$$



Lorentz deflection angle  $\sim \mu\text{rad}$

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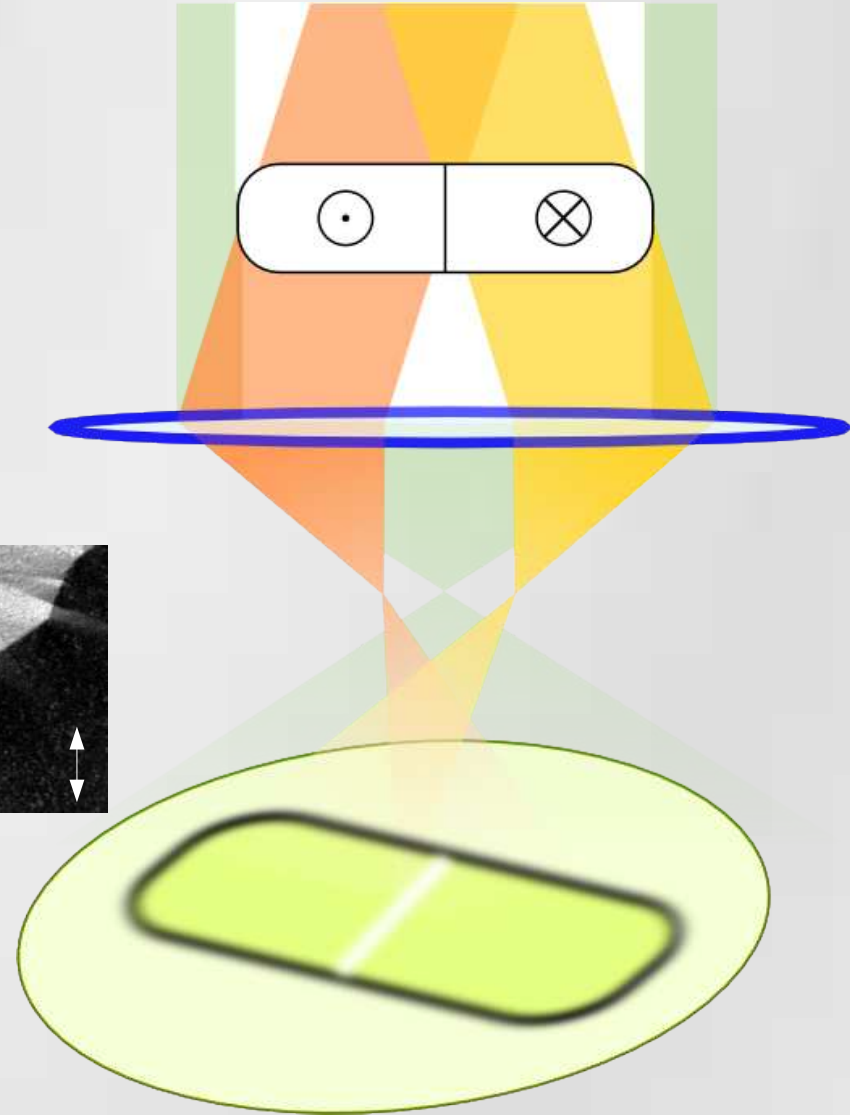
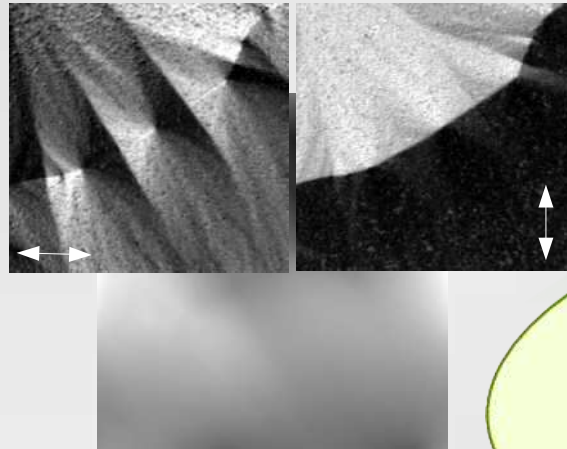


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Fresnel imaging  
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Strasbourg  
Oct. 2017



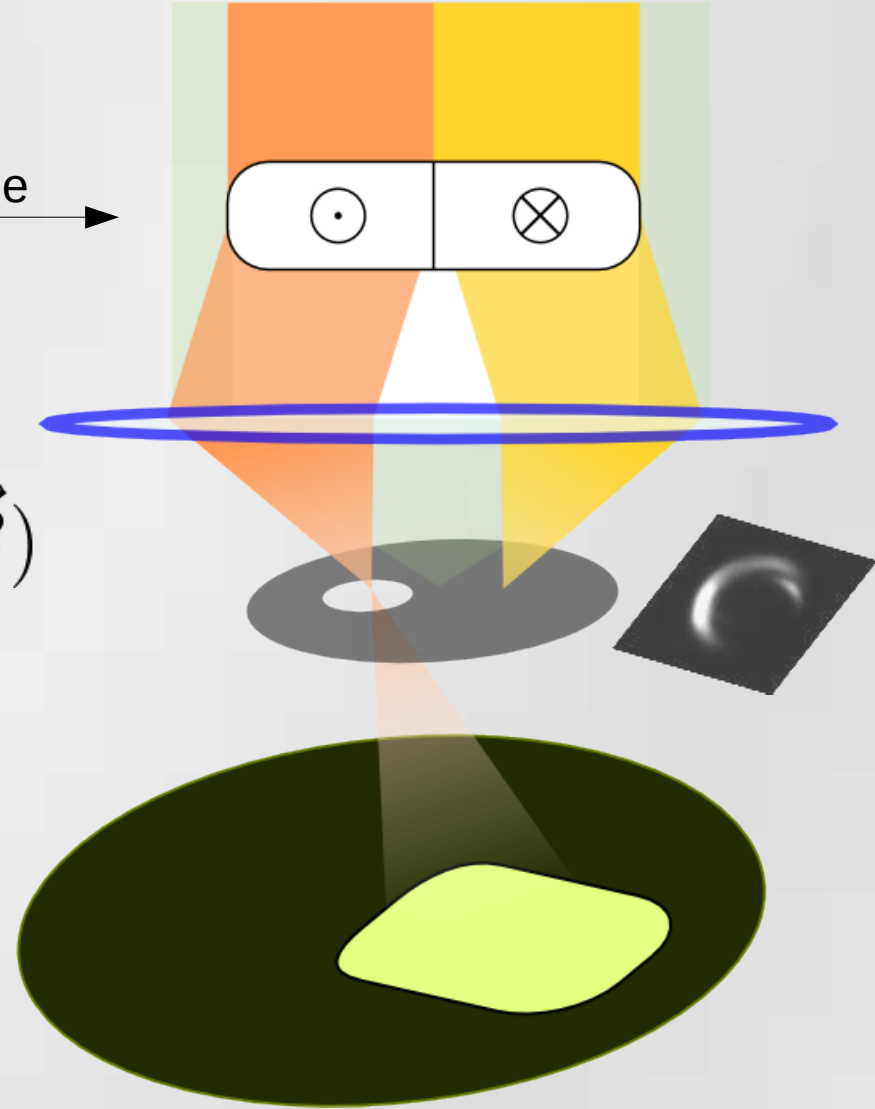
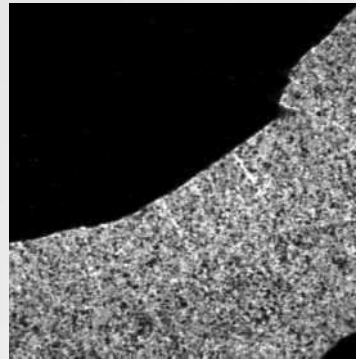
# Electron Interferometry :

Foucault imaging  
« Differential Phase Contrast »

Image Plane →

Lorentz Force :

$$\vec{F} = q(\vec{v} \wedge \vec{B})$$



Lorentz deflection angle  $\sim \mu\text{rad}$

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Strasbourg  
Oct. 2017



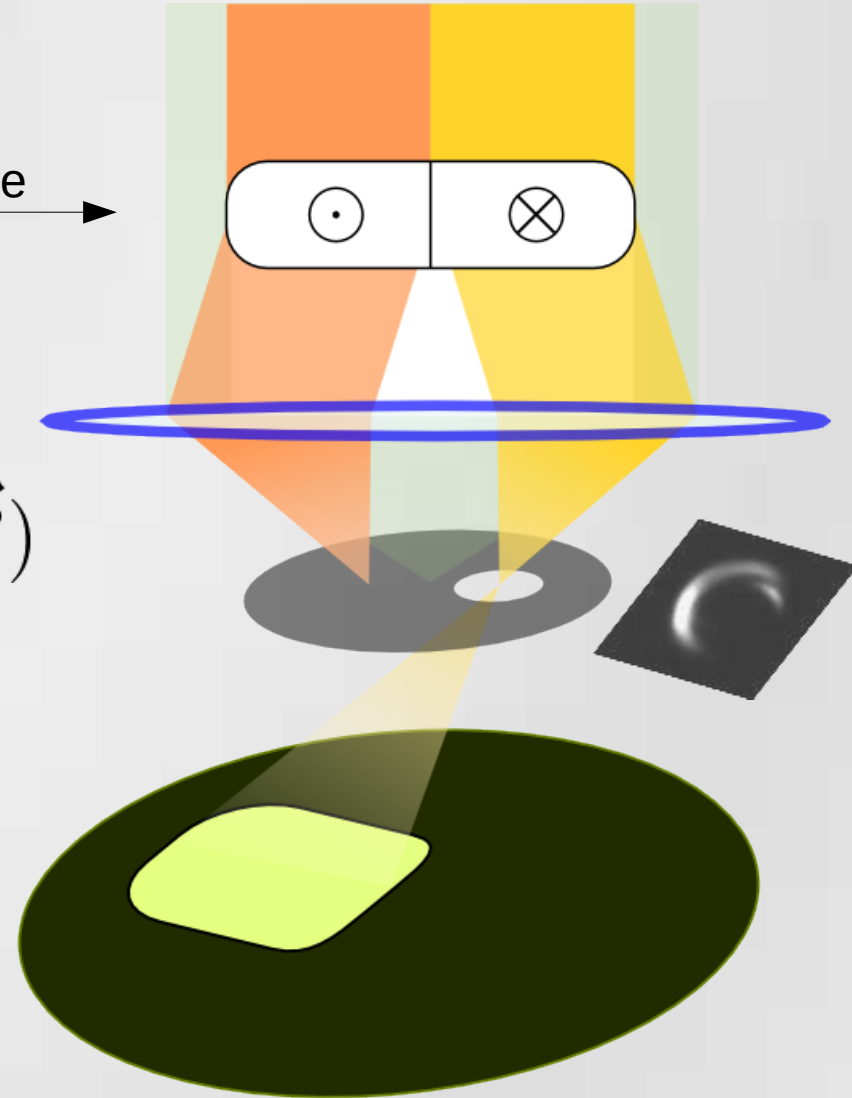
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Foucault imaging  
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Image Plane →

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Strasbourg  
Oct. 2017



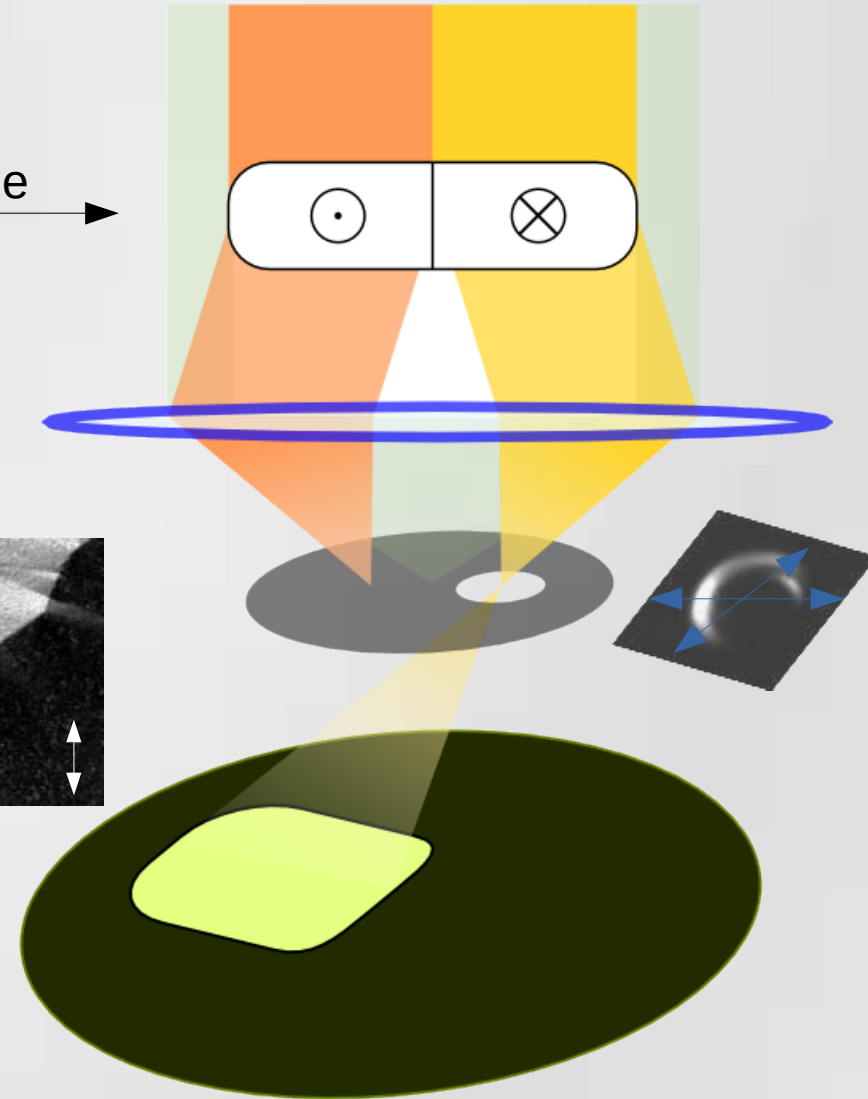
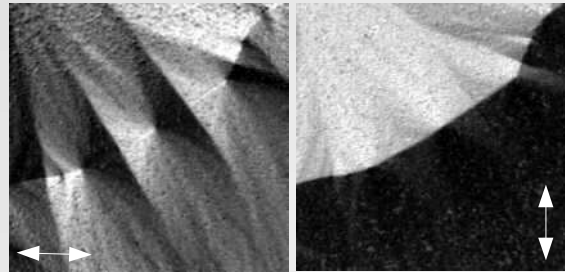
# Electron Interferometry :

Foucault imaging  
« Differential Phase Contrast »

Magnetic Deflection Reconstruction :

Image Plane →

Lorentz Force :



Lorentz deflection angle  $\sim \mu\text{rad}$

(Bragg angle  $\sim \text{mrad}$ )

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Oct. 2017

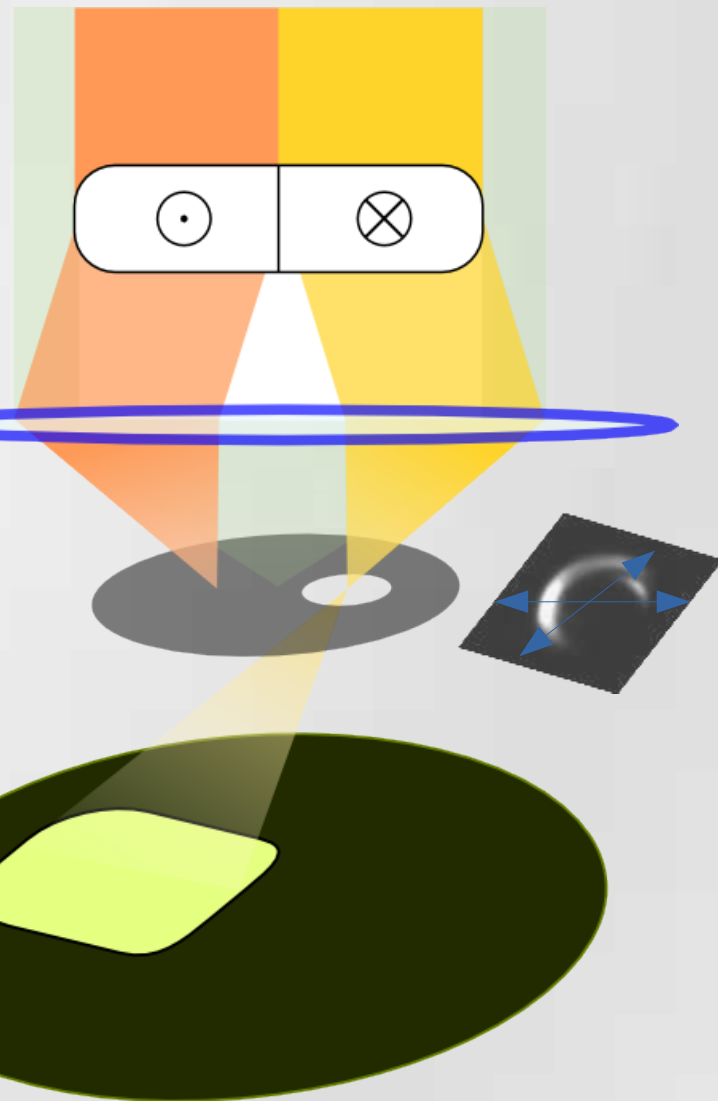


# Electron Interferometry :

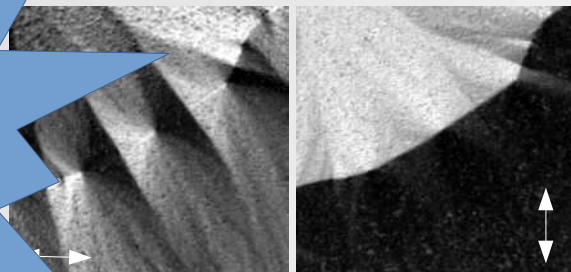
Magnetic Deflection Reconstruction :

Foucault imaging  
« Differential Phase Contrast »

Image Plane



Lorentz Force :



Also available  
in STEM

Lubk, A., et J. Zweck.

« Differential phase contrast: An integral perspective ».

Physical Review A 91, n° 2 (2015): 023805

Chapman, J. N., Batson, P. E., Wadell, E. M. & Ferrier, R. P.

Direct determination of magnetic domain-wall profiles by differential phase-contrast electron microscopy.

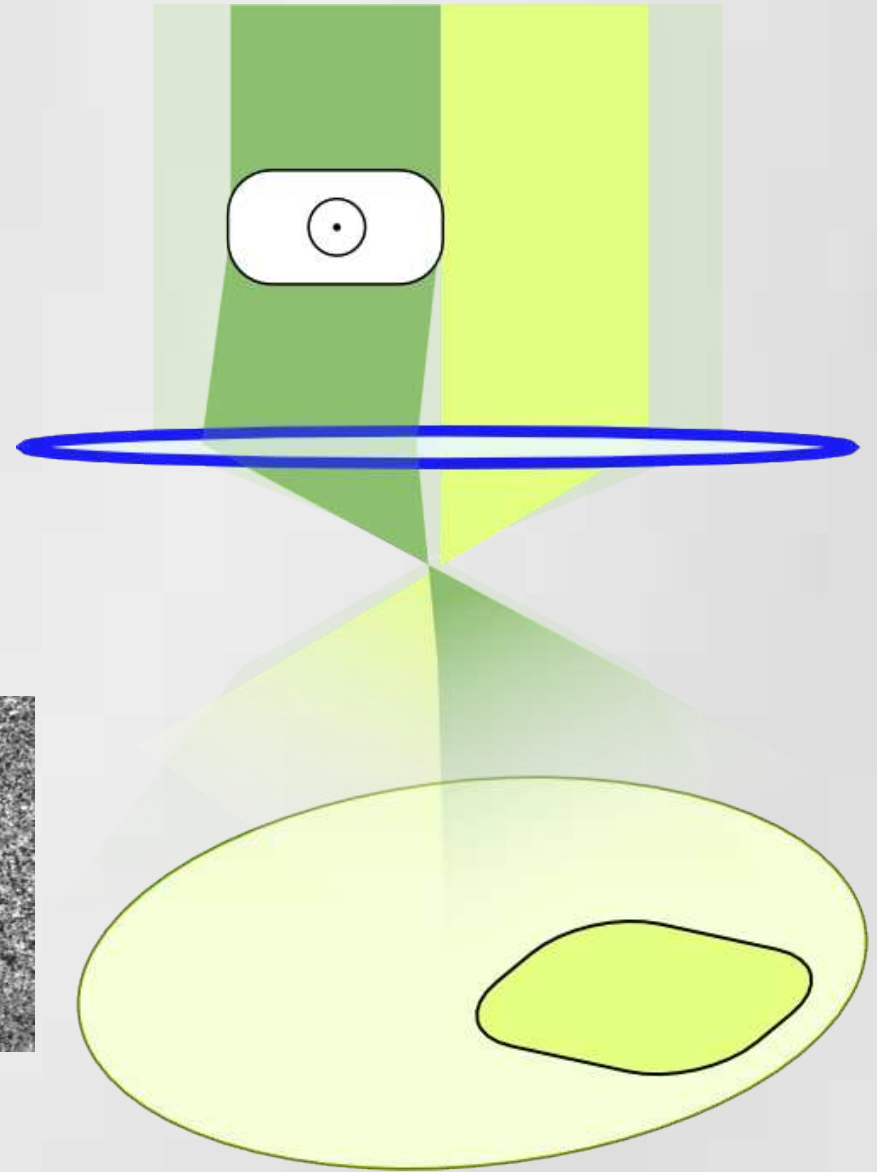
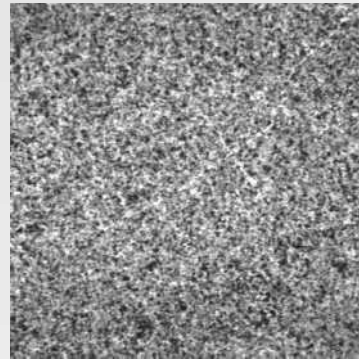
Ultramicroscopy 3, 203–214 (1978).

Strasbourg  
Oct. 2017



# Electron Interferometry :

## Out-of-Axis Holography

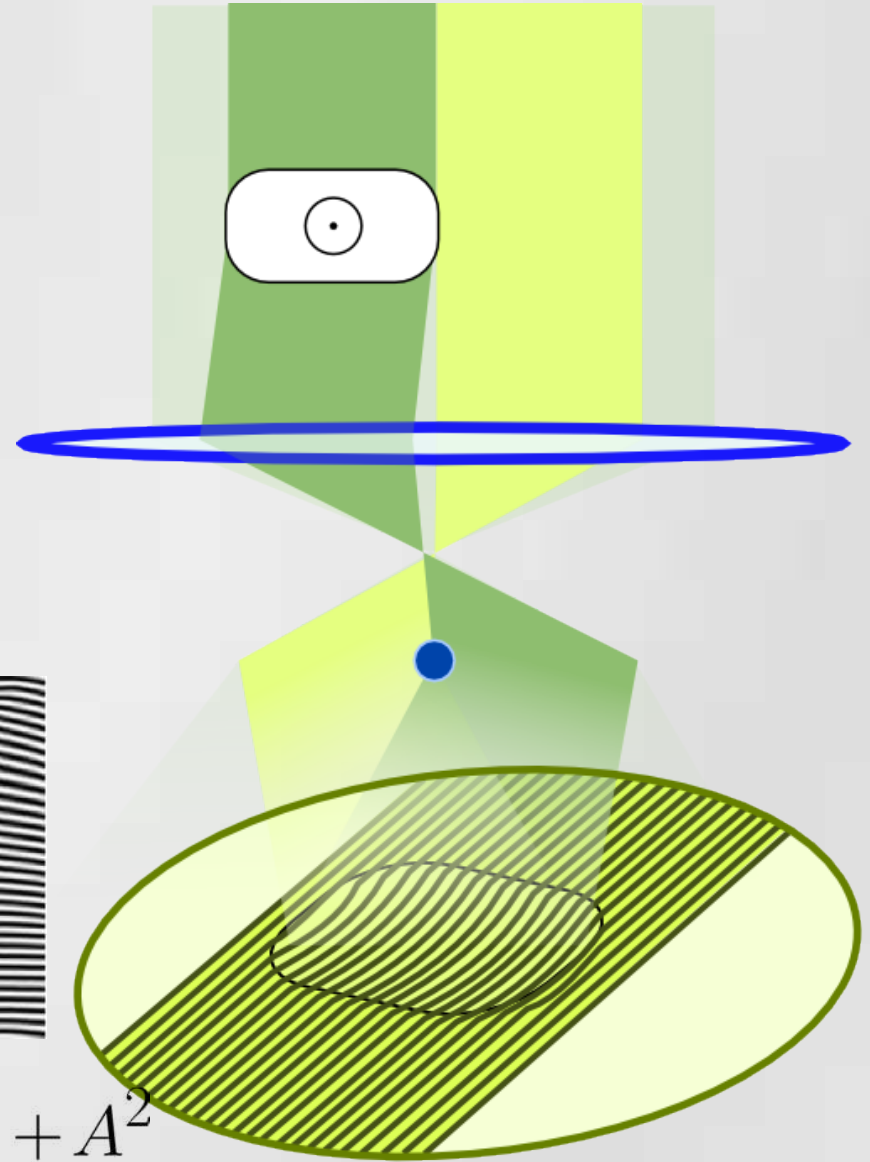


$$I \propto \|\Psi\|^2 \propto A^2$$



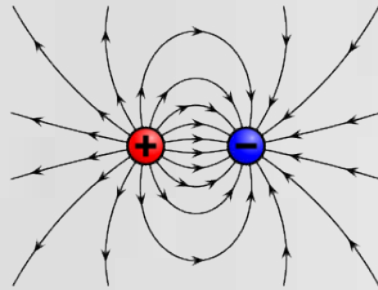
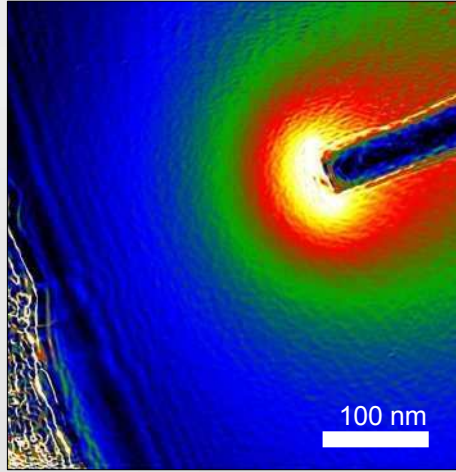
# Electron Interferometry :

## Out-of-Axis Holography



Phase Reconstruction :

$$I \propto \left\| \Psi + ae^{i\phi} \right\|^2 \propto a^2 + \cos(\Delta\phi) + A^2$$



**Phase images :**

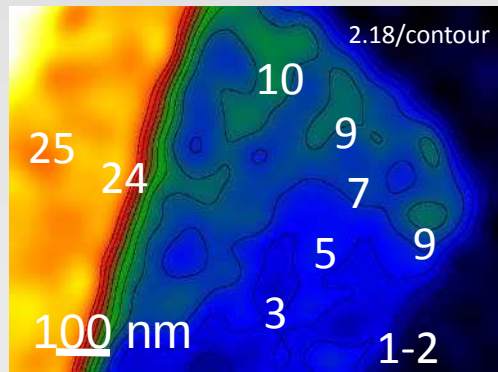
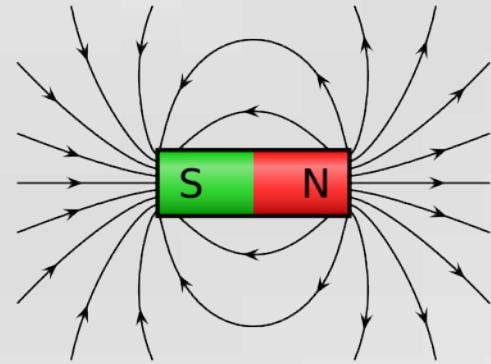
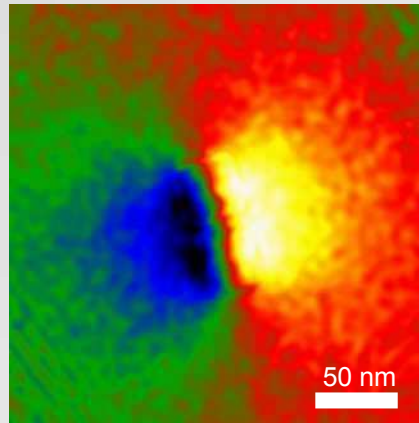
- Images in Temperature Scale
- $\vec{B}$  sensitivity ( $\perp // \vec{V}_e$ )
- Quantified in radian  
(link with  $\lambda$ ,  $e$  and  $\hbar$ )
- Contain both

**Magnetic *AND* Electrostatic**

=> separation routines

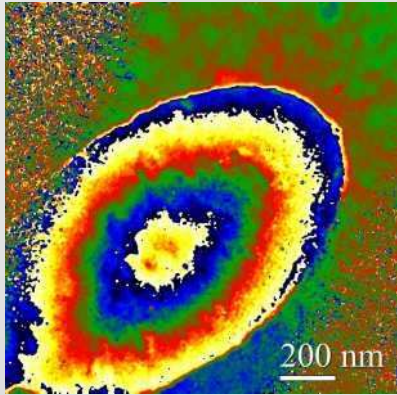
- Isophase  $\Leftrightarrow$  Magnetic flux
- Projected information

=> values in nm.T

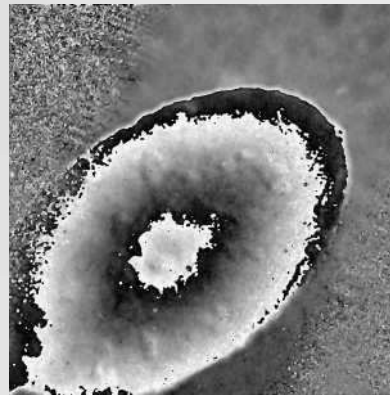


$$\Delta\phi = C_E \int_{-\infty}^{\infty} V dz - \frac{e}{\hbar} \int_{-\infty}^{\infty} A_z dz$$

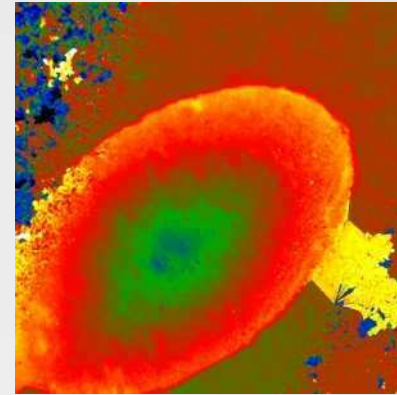
Various Phase representation



Phase (raw)  
(temperature scale)



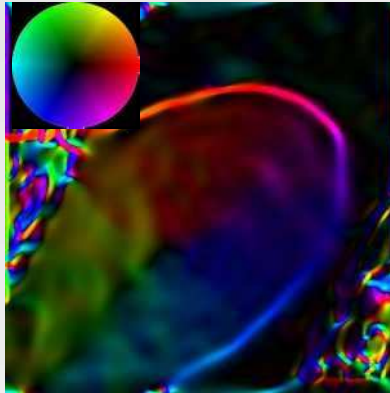
Phase (raw)  
(greyscale)



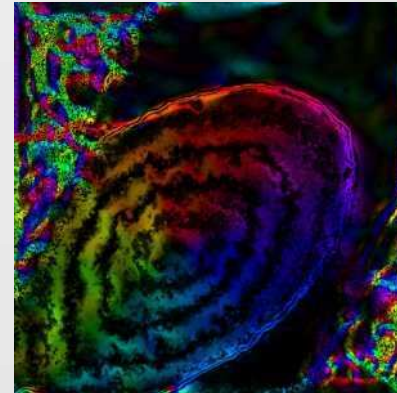
Phase Unwrap  
(temperature scale)



Phase Cosine

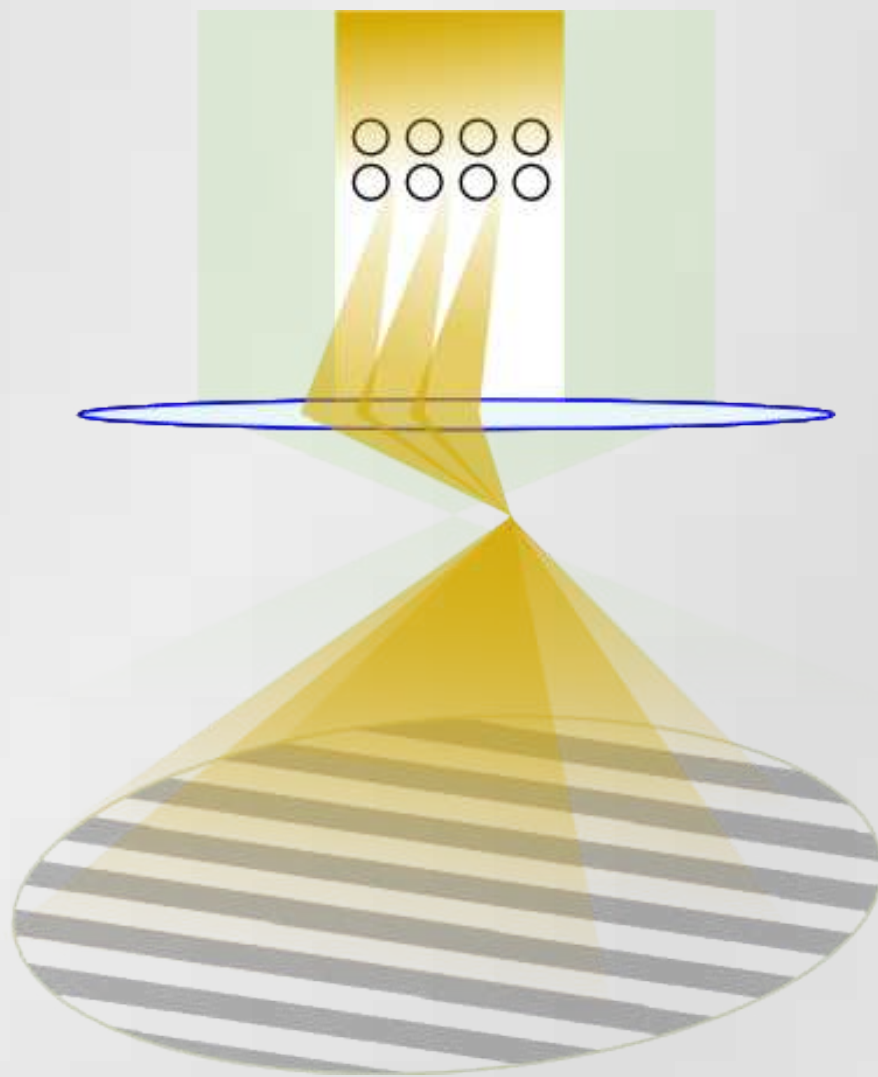
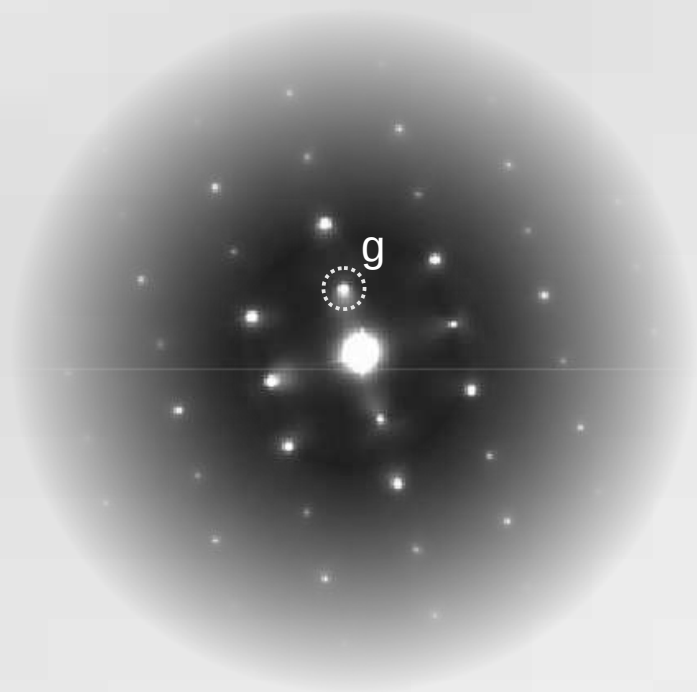


Induction Map  
(Phase gradients - Colour wheel)



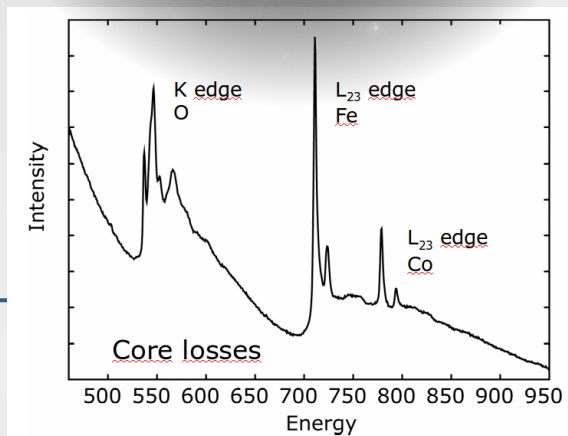
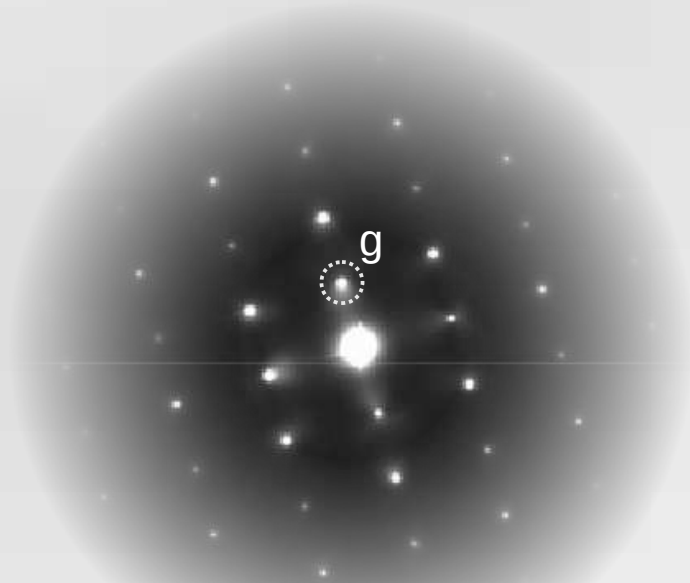
Map x Cosine

# Electron Dichroism :

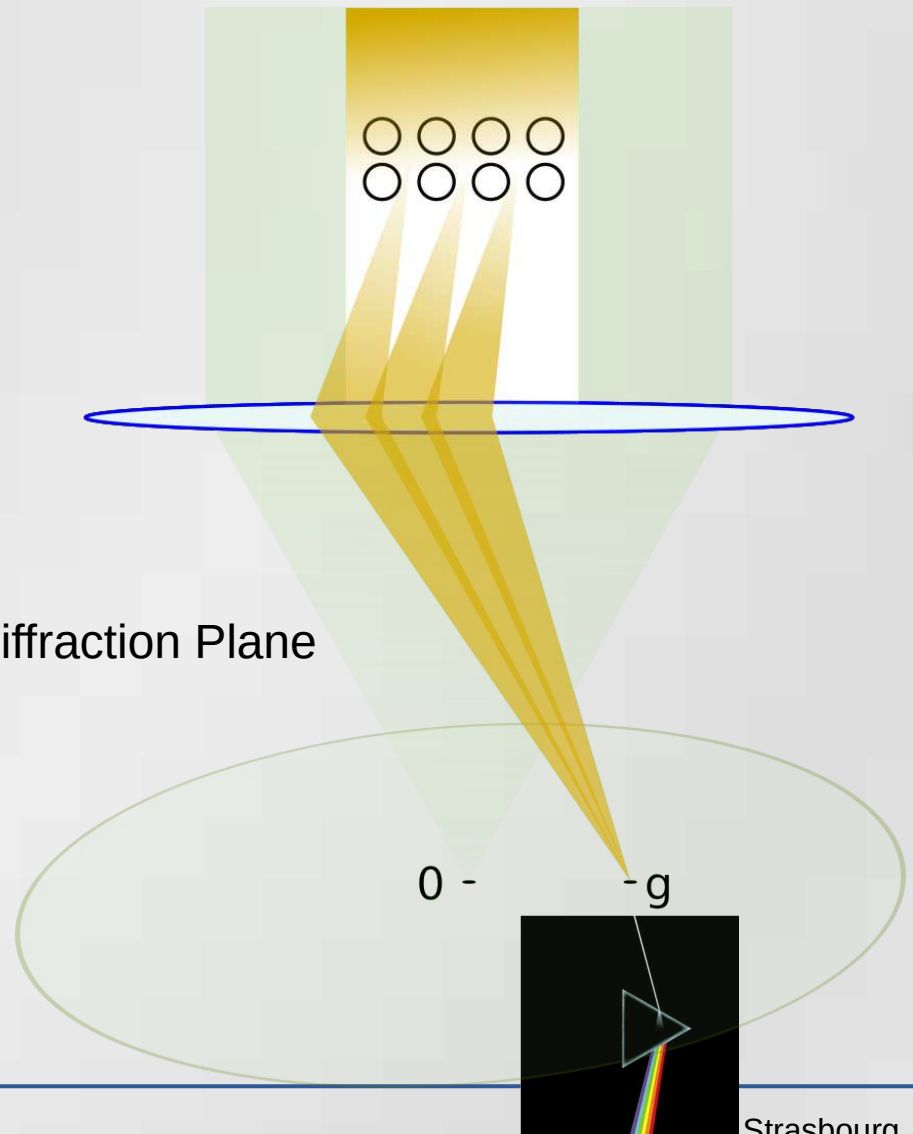




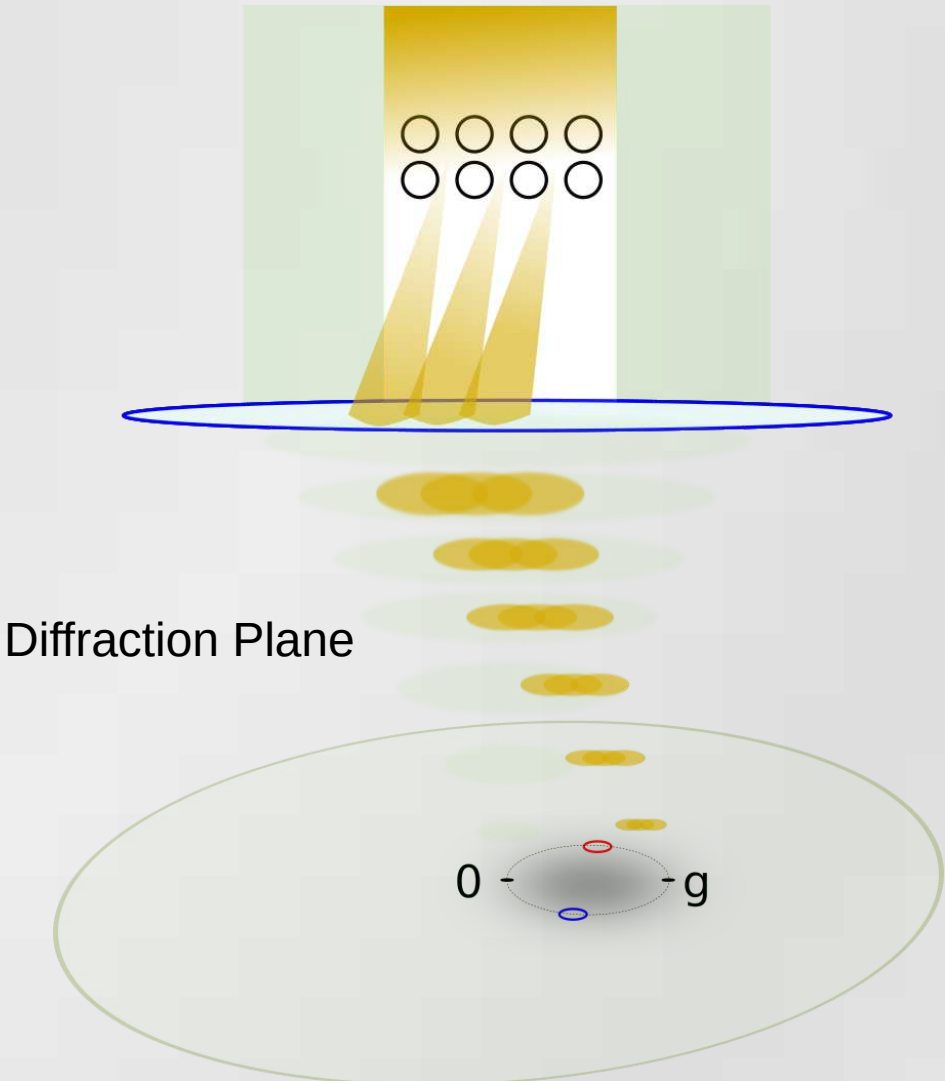
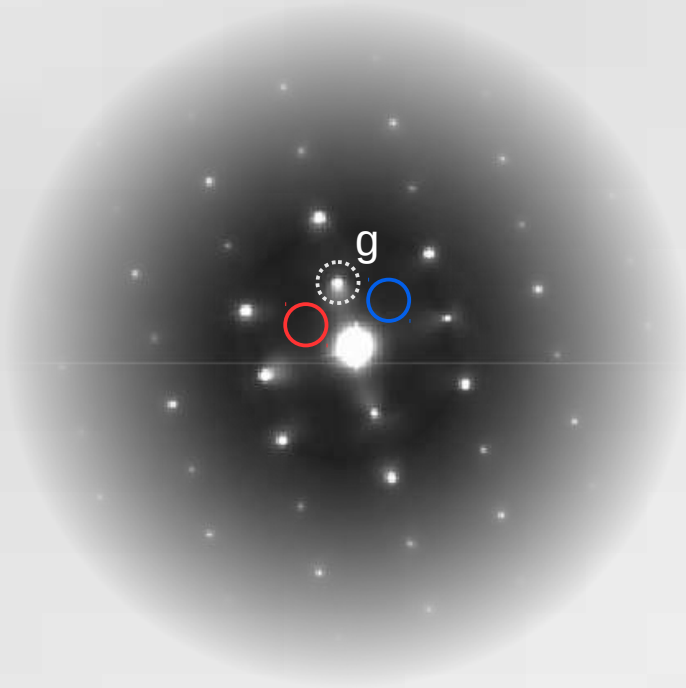
# Electron Dichroism :

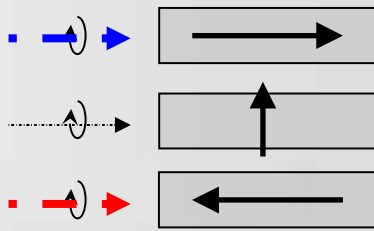


Diffraction Plane



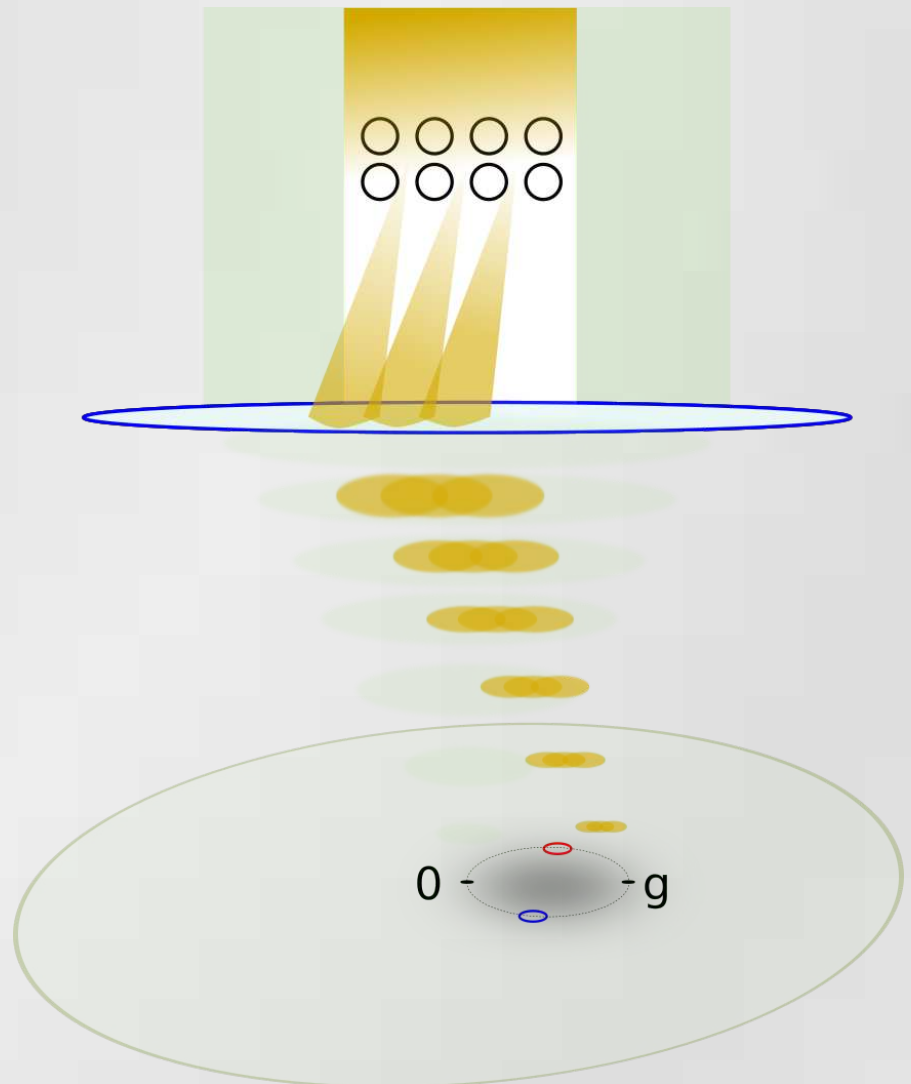
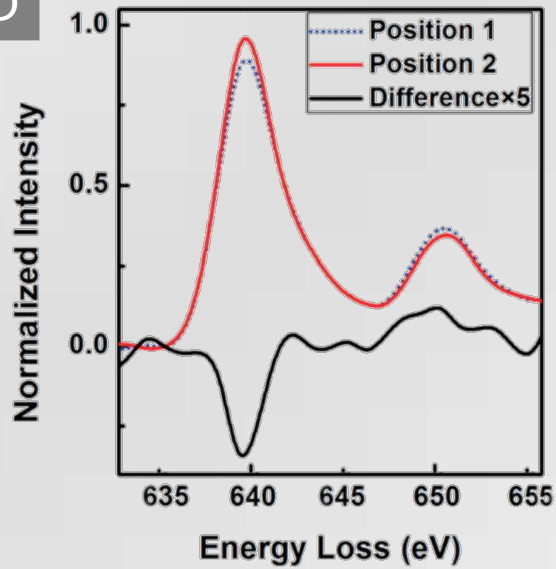
# Electron Dichroism :





XMCD

EMCD

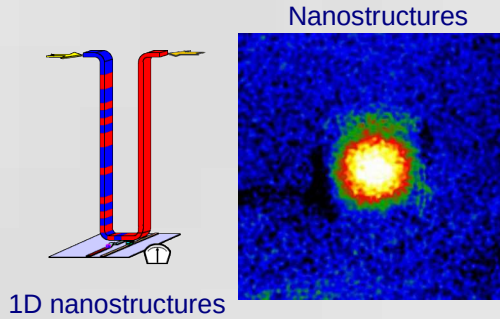
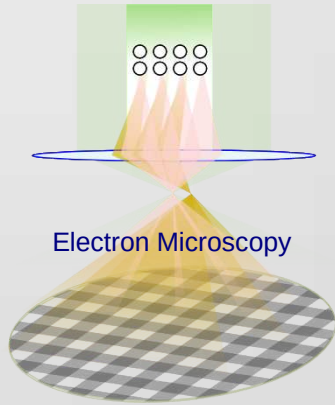


$m_l/m_s$	Hard axis [0001]	Intermediate axis [ $\bar{1}100$ ]	Easy axis [11 $\bar{2}0$ ]
EMCD	$0.06 \pm 0.04$	$0.08 \pm 0.04$	$0.09 \pm 0.04$
XMCD			$0.03 \pm 0.01^a$
DFT	0.005	0.008	0.008

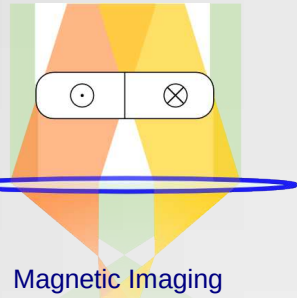
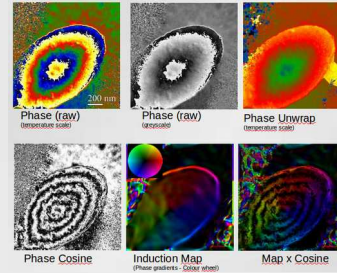
<sup>a</sup>Reference [8].



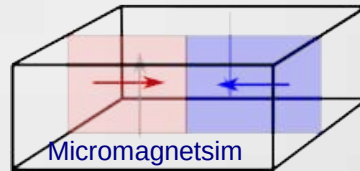
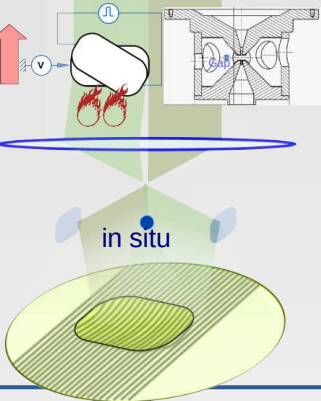
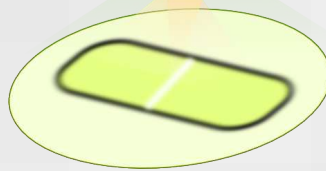
# Electron Microscopy & Micro-magnetism



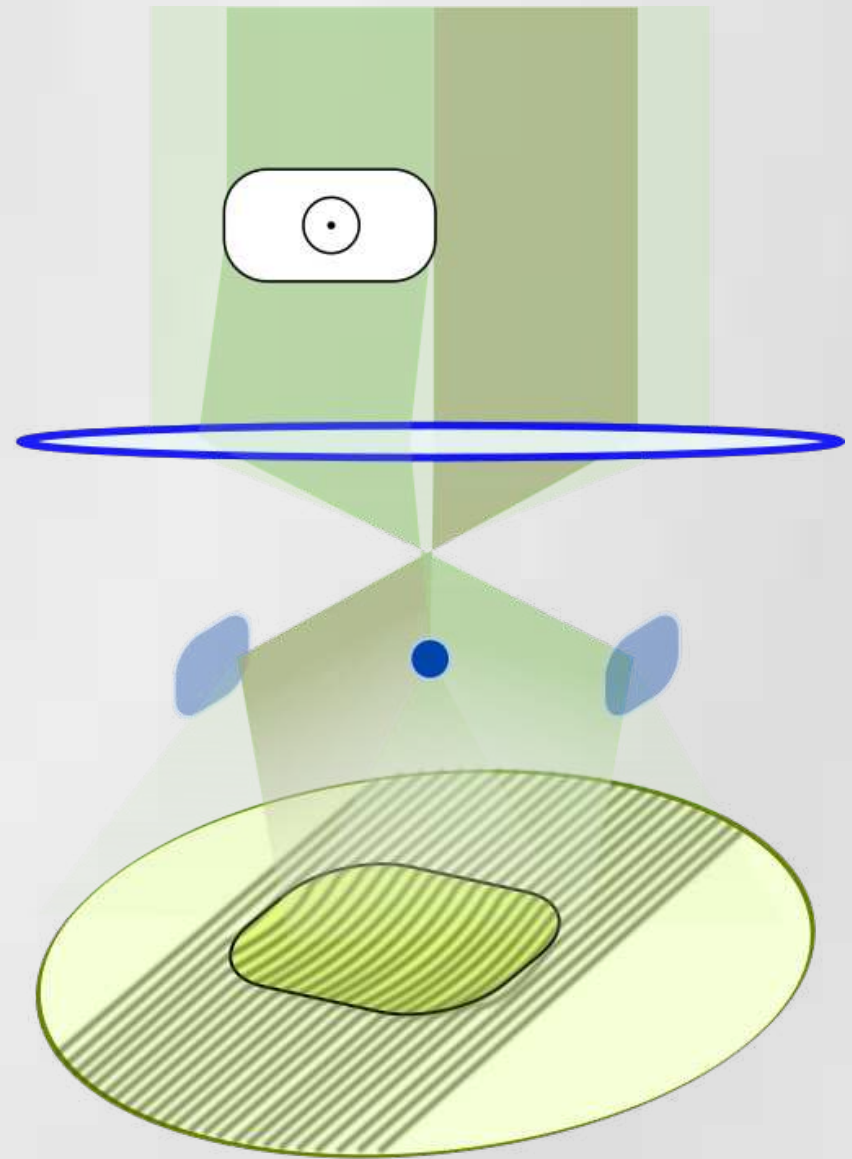
## Phase Image



## Devices

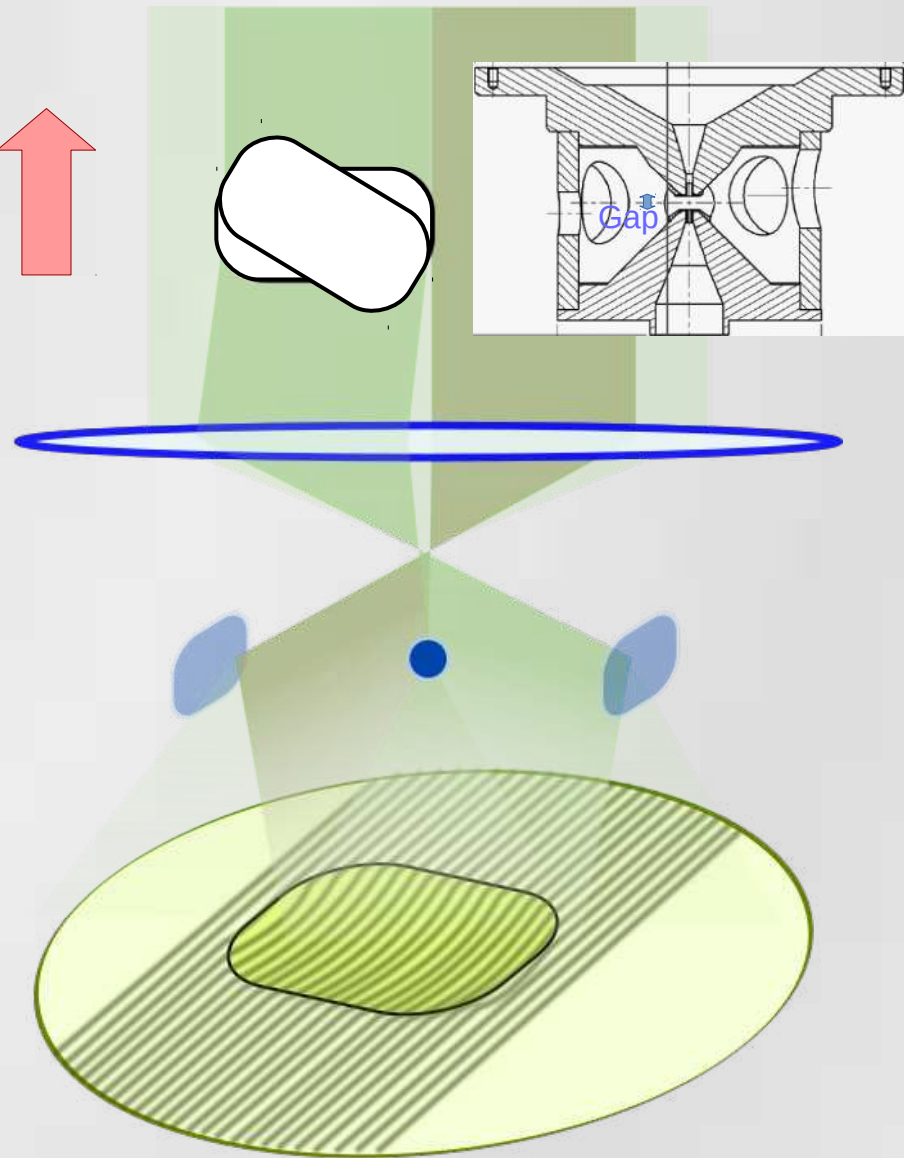
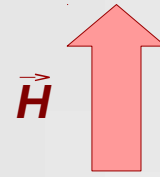


# *In situ & Dynamical Imaging*



## ***Magnetisation :***

- Magnetic Field up to 2 / 3 Tesla  
=> few 100 mT while imaging
- Magnetisation along  $e^-$  trajectory
- Tilting the sample for in-plane



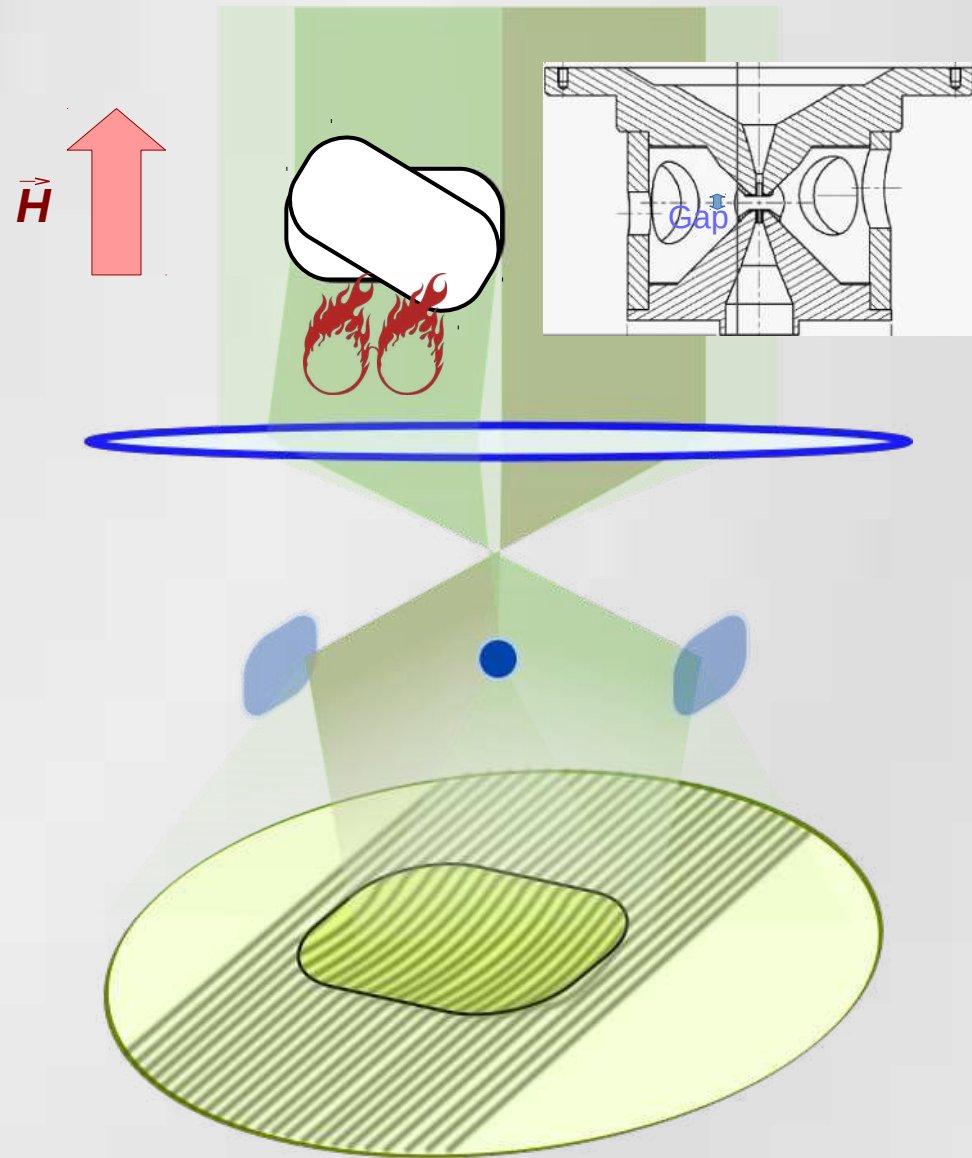
*Doggy Bag*

**Magnetisation :**

- Magnetic Field up to 2 / 3 Tesla  
=> few 100 mT while imaging
- Magnetisation along  $e^-$  trajectory
- Tilting the sample for in-plane

**Temperature :**

- Need for dedicated sample holder
  - « Easy » : -100°C to ~ 300°C
  - « Tricky » : 70 K ... 800 °C
  - « Dedicated » : few K .... 1500°C



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**Temperature :**

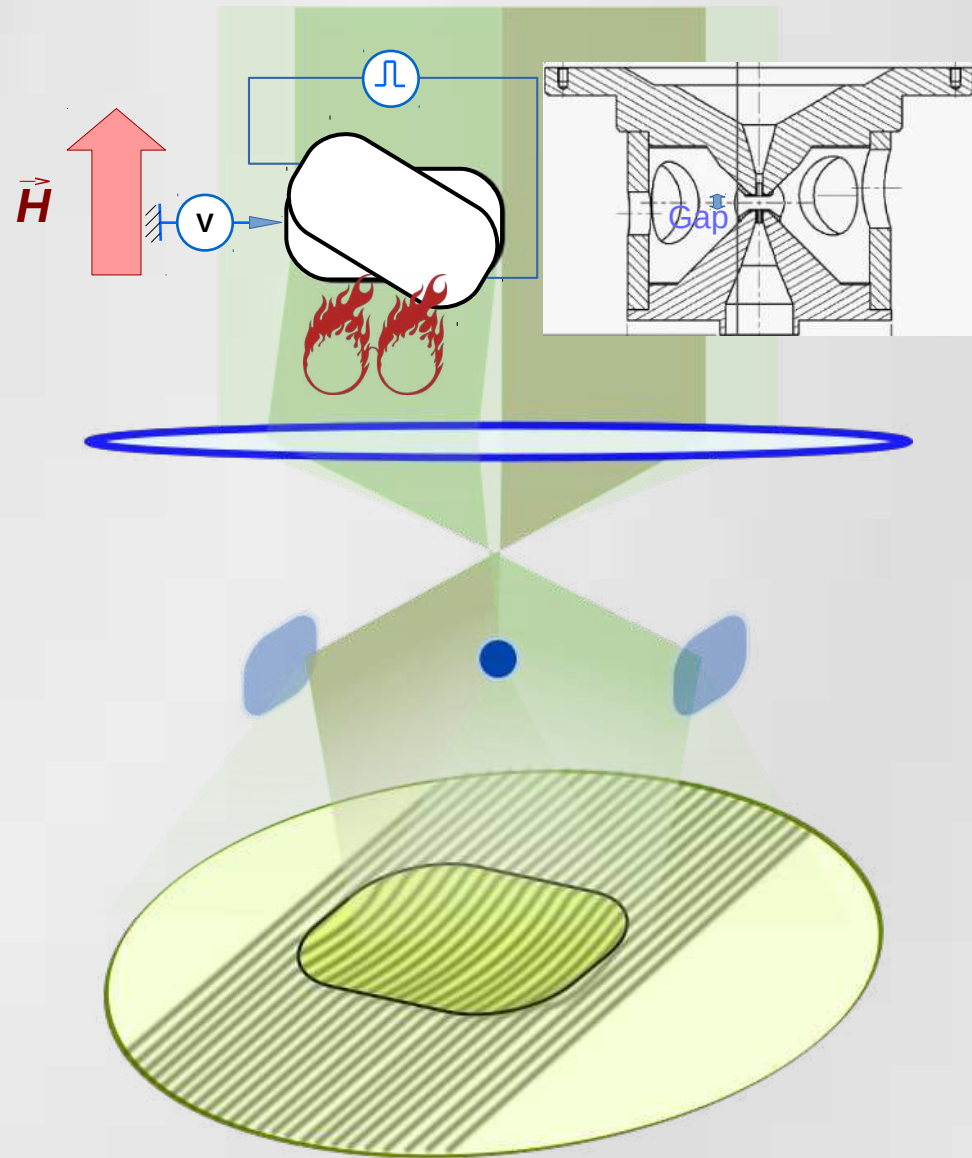
- Need for dedicated sample holder
  - « Easy » : -100°C to ~ 300°C
  - « Tricky » : 70 K ... 800 °C
  - « Dedicated » : few K .... 1500°C

**Biasing:**

- => Sample holder with up to 10 connexions
- => Nanofab with electron transparency
- => Careful of heating
- => High Frequency is the key !

**« STM » probing:**

Local biasing or stress  
Developping new tools with magnetic coils

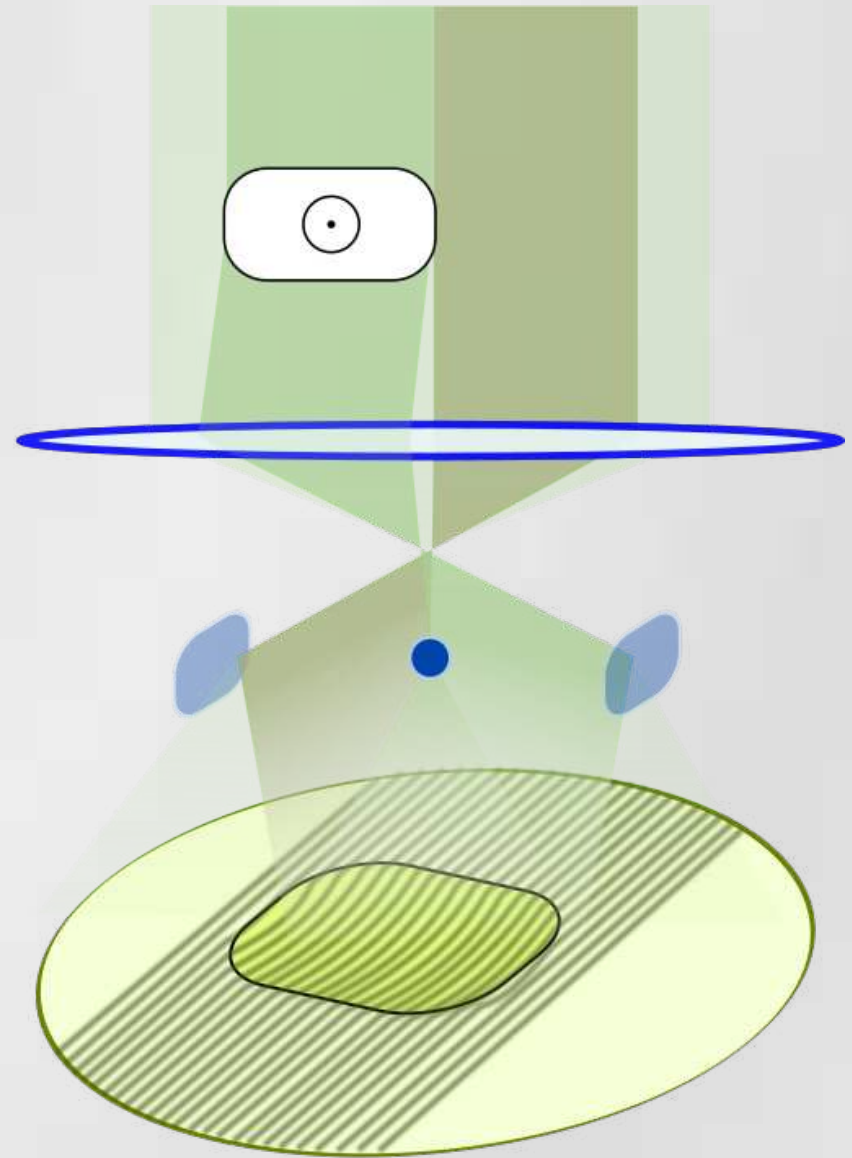




# Dynamic :

## Conventiounal TEM

- CCD response  
=> Range of **10 ms** in 4kx4k (Standard ~100 ms)
- Live imaging  
=> Fresnel (easy) or Holo (tricky)



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### Conventiounal TEM

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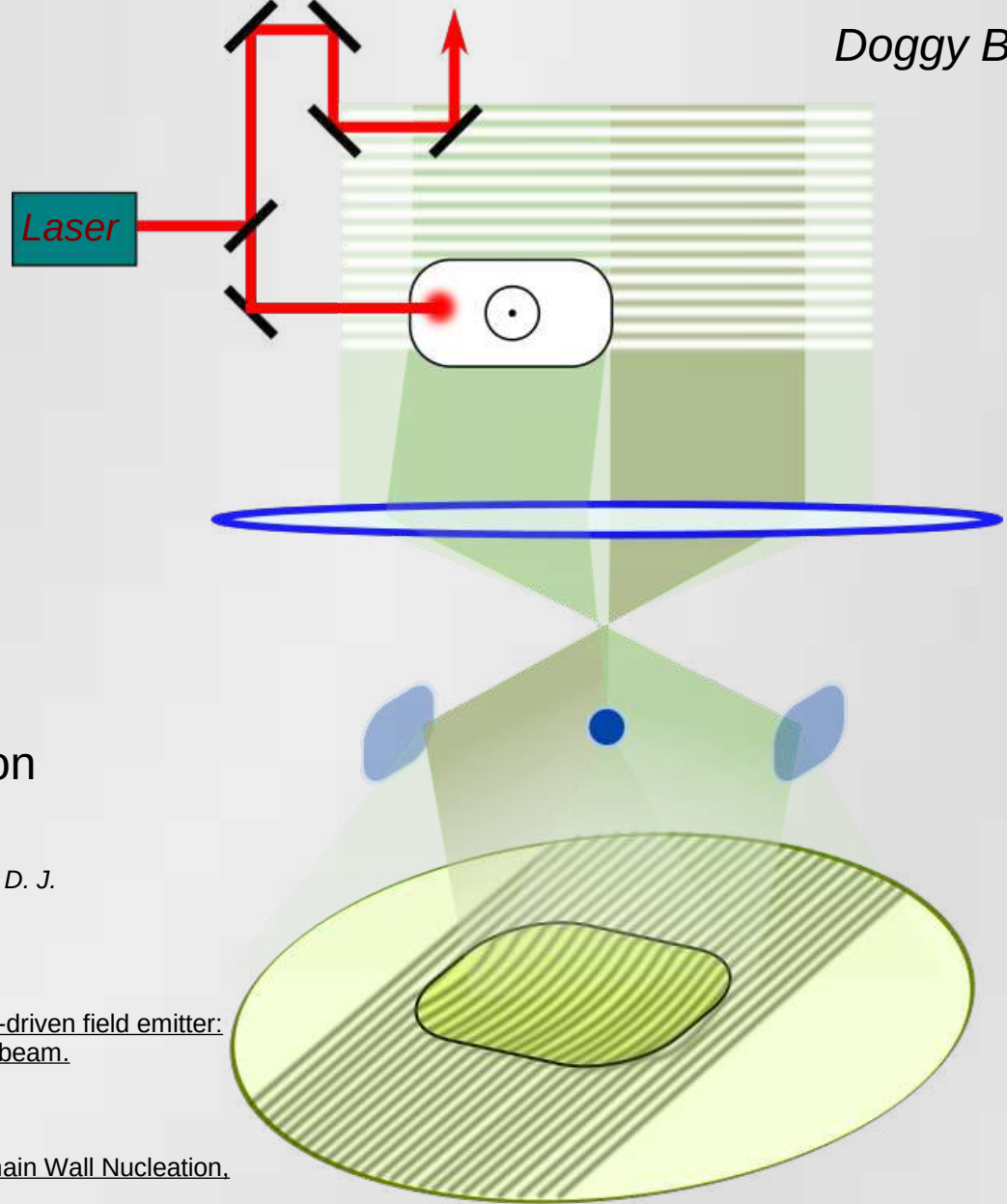
### Ultrafast-TEM

- Pump Probe or One shot  
=> Range of **fs**
- Up to now only laser excitation  
=> Still need a really complex set-up

Schliep, K. B., Quarterman, P., Wang, J.-P. & Flannigan, D. J.  
Picosecond Fresnel transmission electron microscopy.  
Appl. Phys. Lett. 110, 222404 (2017)

Feist, A. et al.  
Ultrafast transmission electron microscopy using a laser-driven field emitter:  
Femtosecond resolution with a high coherence electron beam.  
Ultramicroscopy 176, 63–73 (2017)

Park, H. S., Baskin, J. S. & Zewail, A. H.  
4D Lorentz Electron Microscopy Imaging: Magnetic Domain Wall Nucleation,  
Reversal, and Wave Velocity.  
Nano Lett. 10, 3796–3803 (2010).





## Dynamic :

### Conventionnal TEM

- CCD response

=> Range of **10 ms** in 4kx4k (Standard ~100 ms)

- Live imaging

=> Fresnel (easy) or Holo (tricky)

### Ultrafast-TEM

- Pump Probe or One shot

=> Range of **fs**

- Up to now only laser excitation

=> Still need a really complex set-up

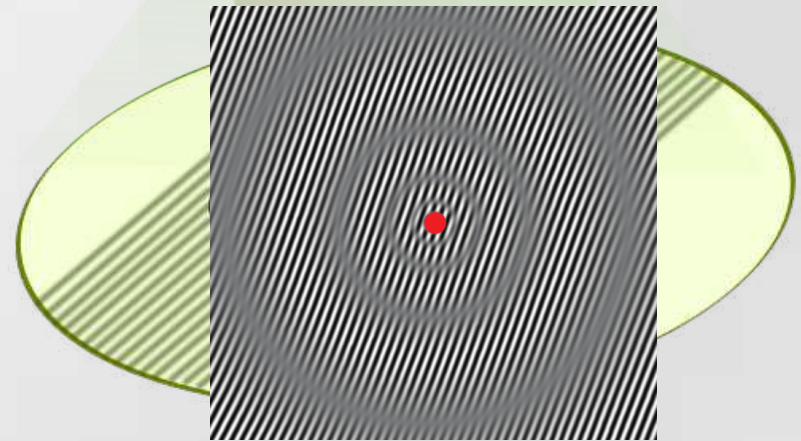
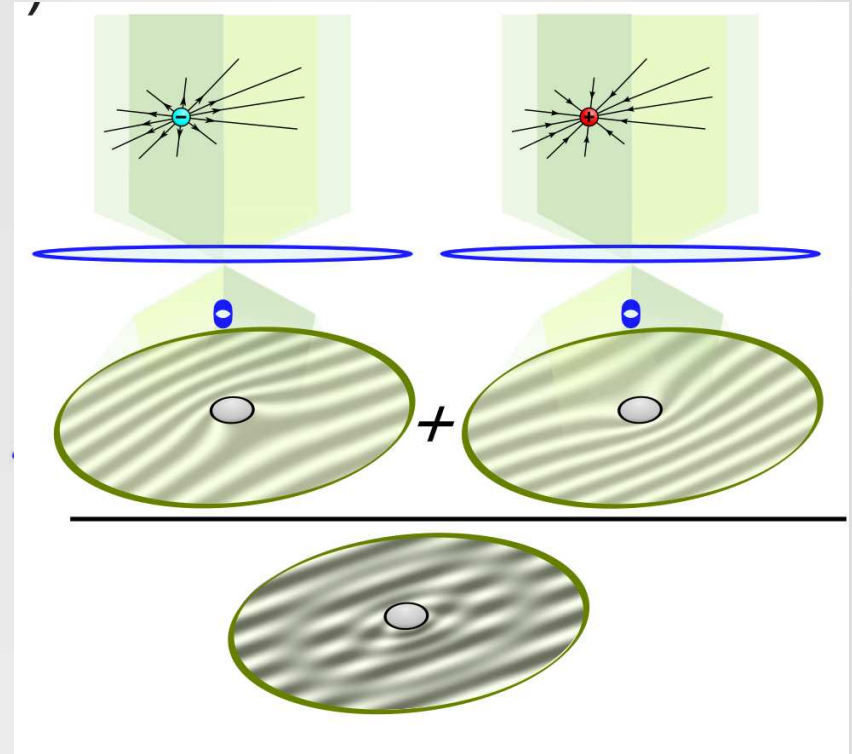
### Holographic Interferometry

- Frequential analysis

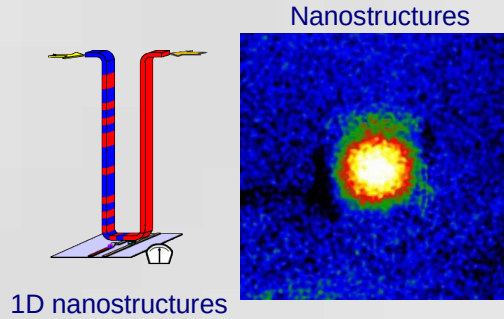
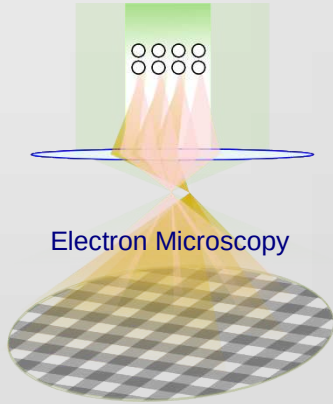
=> Range of **GHz**

- Possibility of adding a Probe part

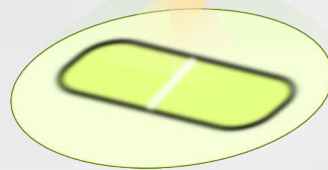
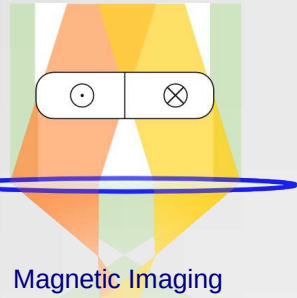
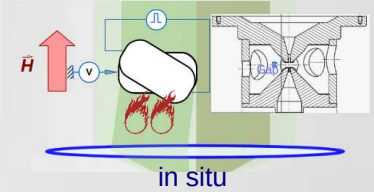
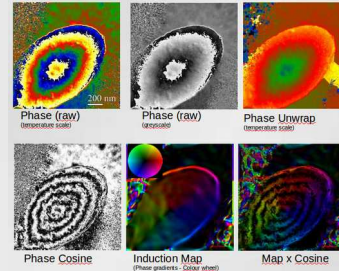
=> Chopping (Stroboscopic)



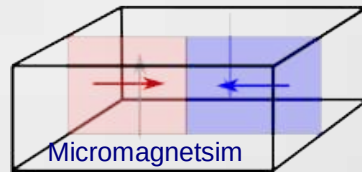
# Electron Microscopy & Micro-magnetism



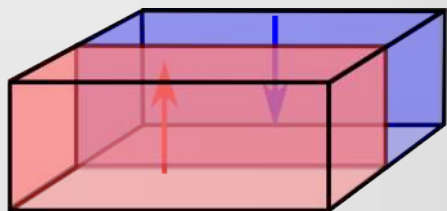
## Phase Image



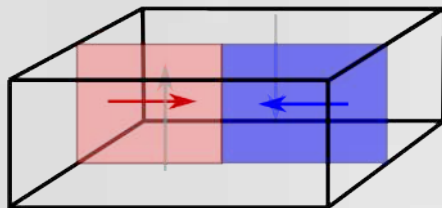
## Devices



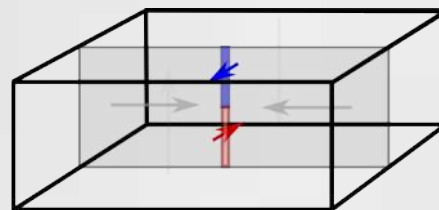
# *Micromagnetic Objects and dynamical imaging*



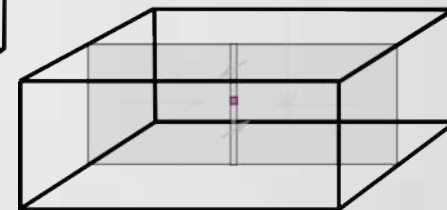
3D – Domains



2D – Domain Walls

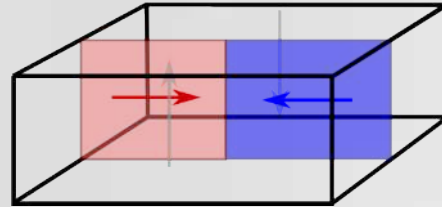


1D – Bloch lines

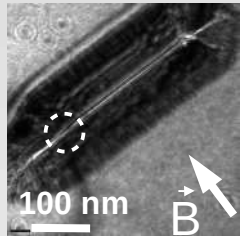
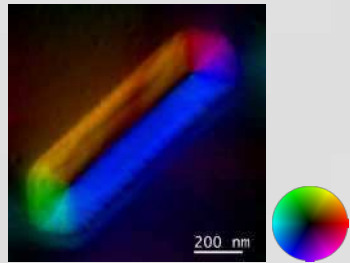


0D – Bloch points

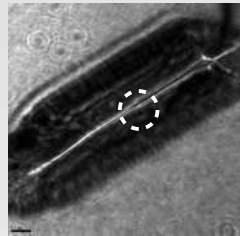
# Micromagnetic Objects and dynamical imaging



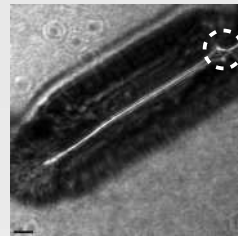
2D – Domain Walls



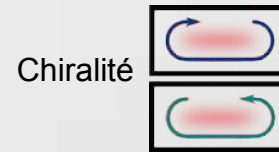
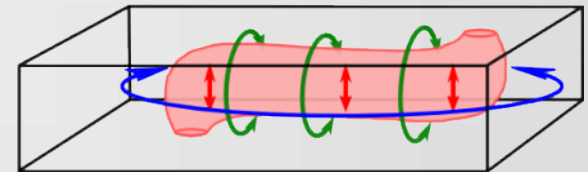
70 mT



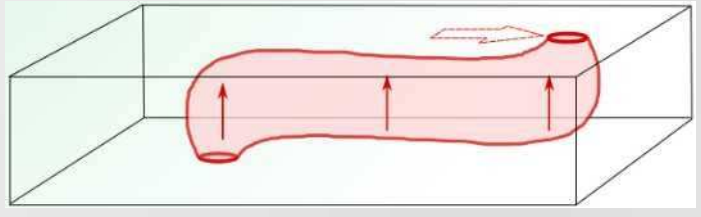
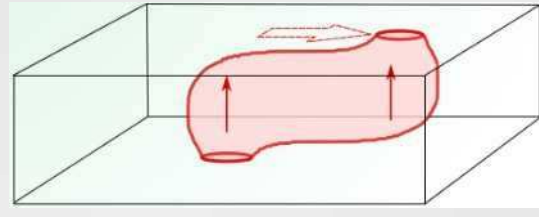
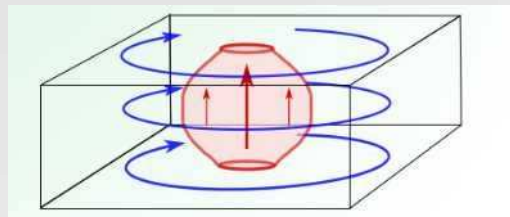
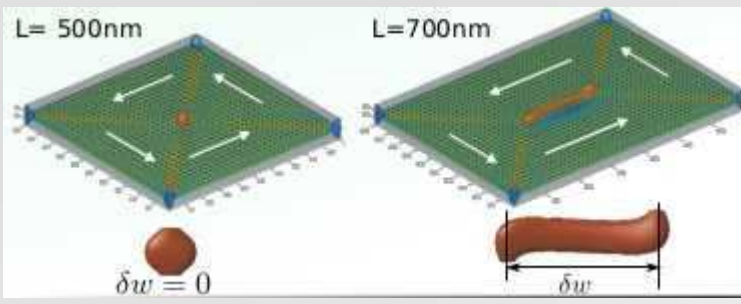
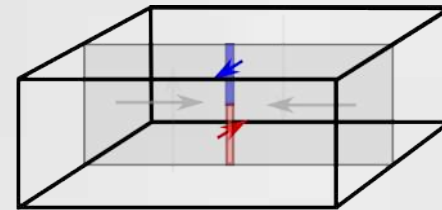
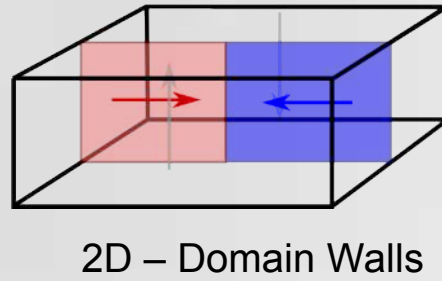
78 mT



85 mT

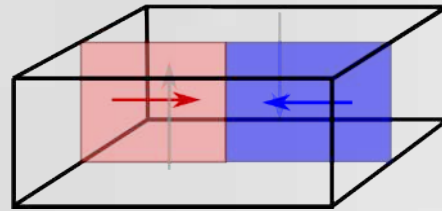


# Micromagnetic Objects and dynamical imaging

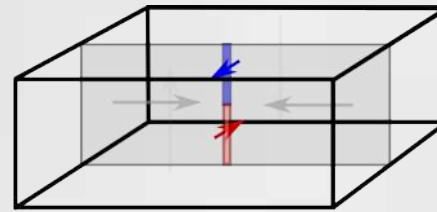




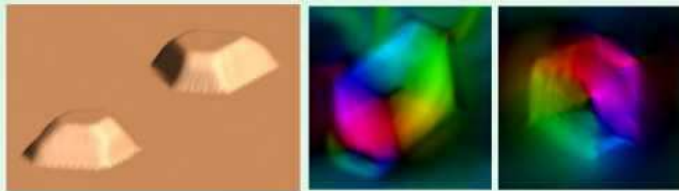
# Micromagnetic Objects and dynamical imaging



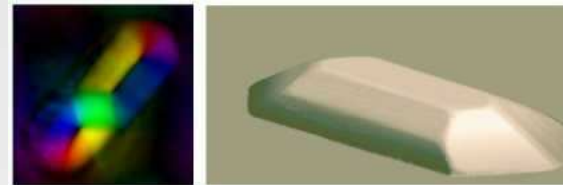
2D – Domain Walls



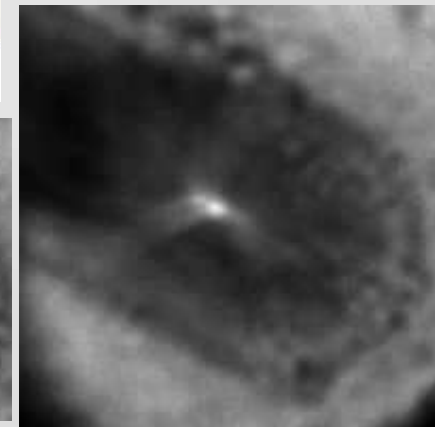
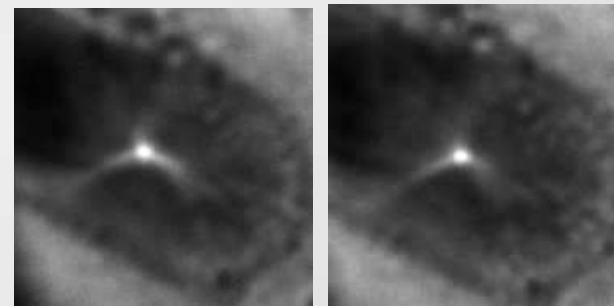
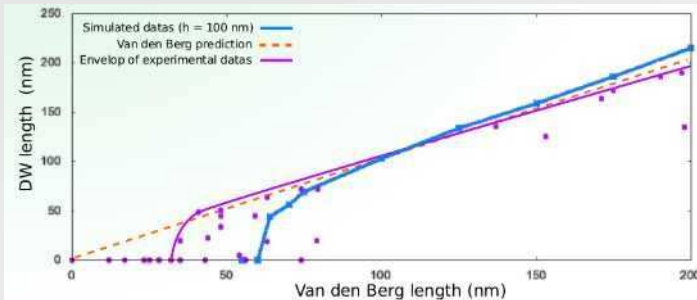
1D – Bloch lines



Cristalline Co dots

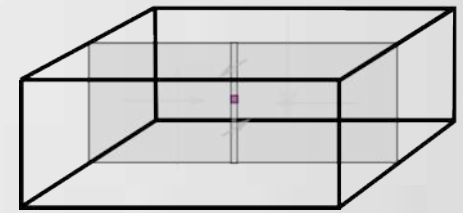
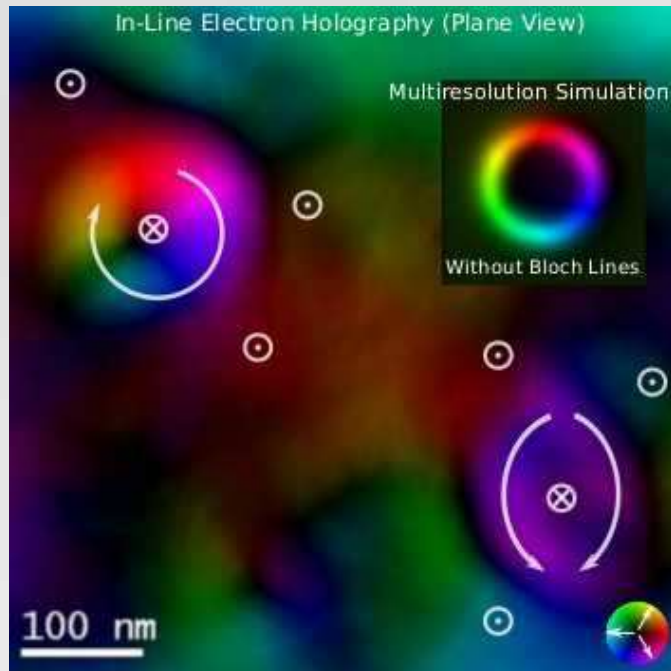


Cristalline Fe dots

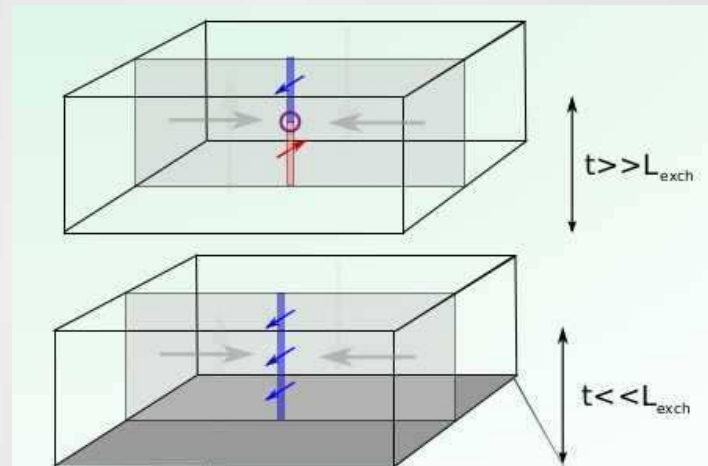




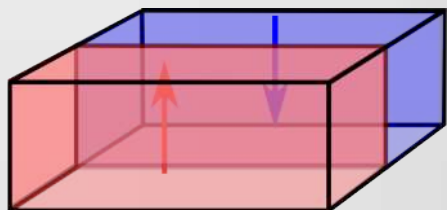
# Micromagnetic Objects and dynamical imaging



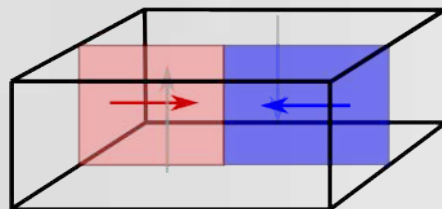
0D – Bloch points



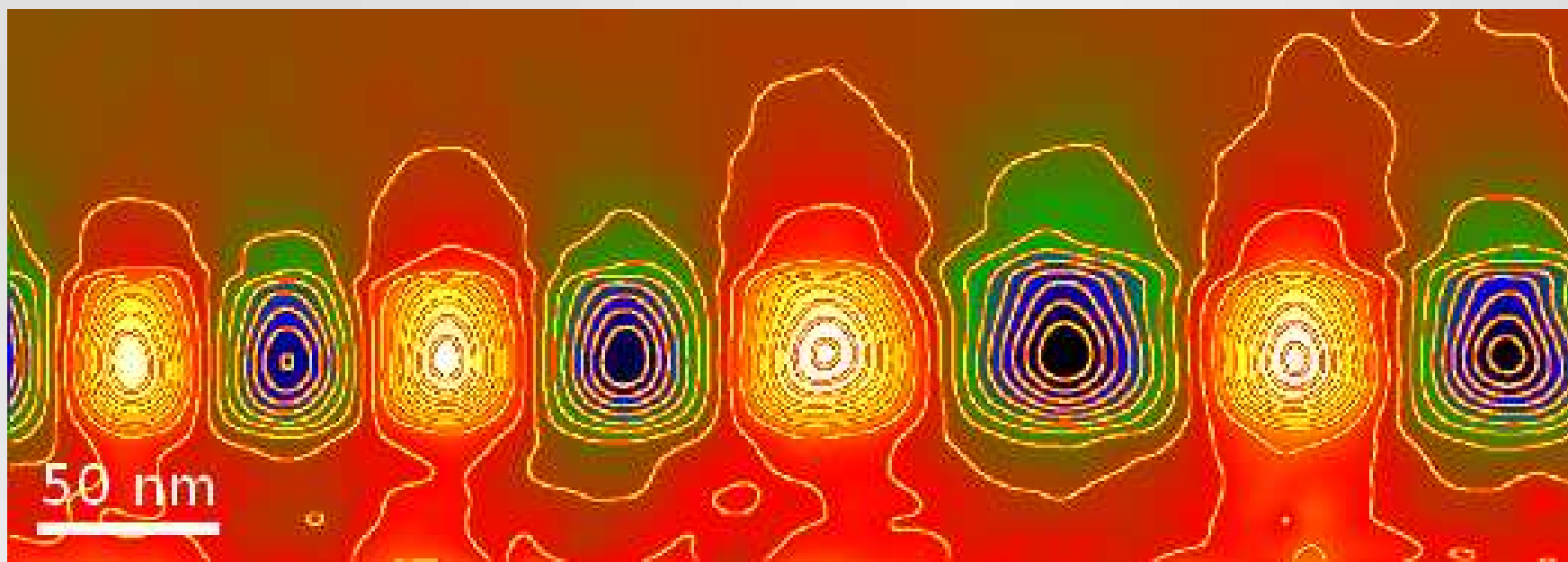
## Micromagnetic Objects and dynamical imaging



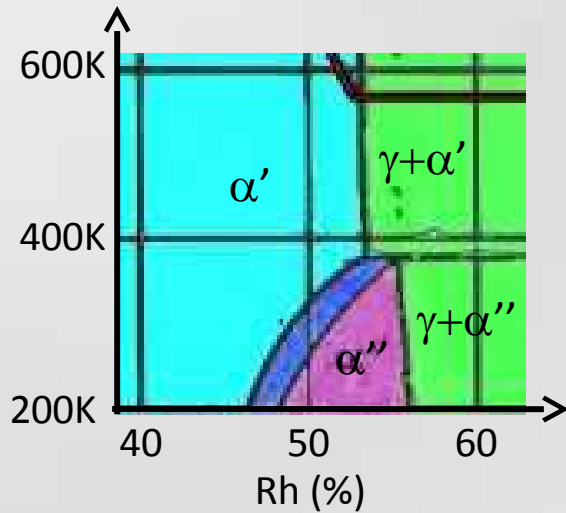
3D – Domains



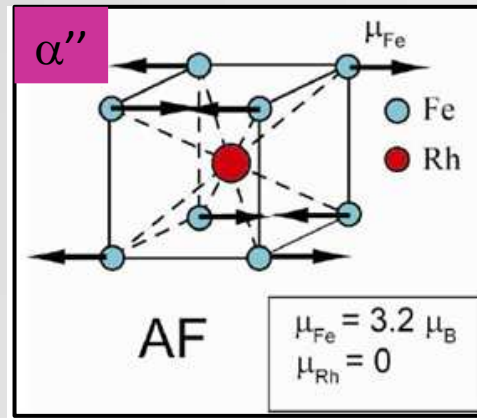
2D – Domain Walls



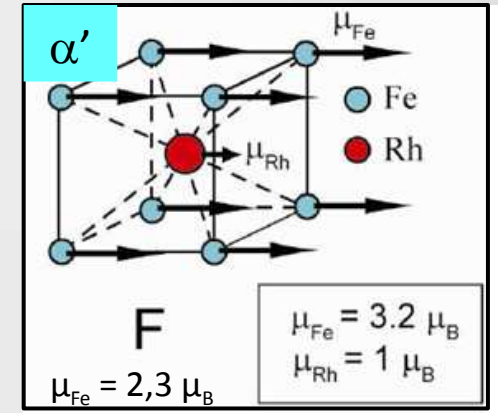
# Magnetic transition



Ordered bcc structure ( $B_2$ )

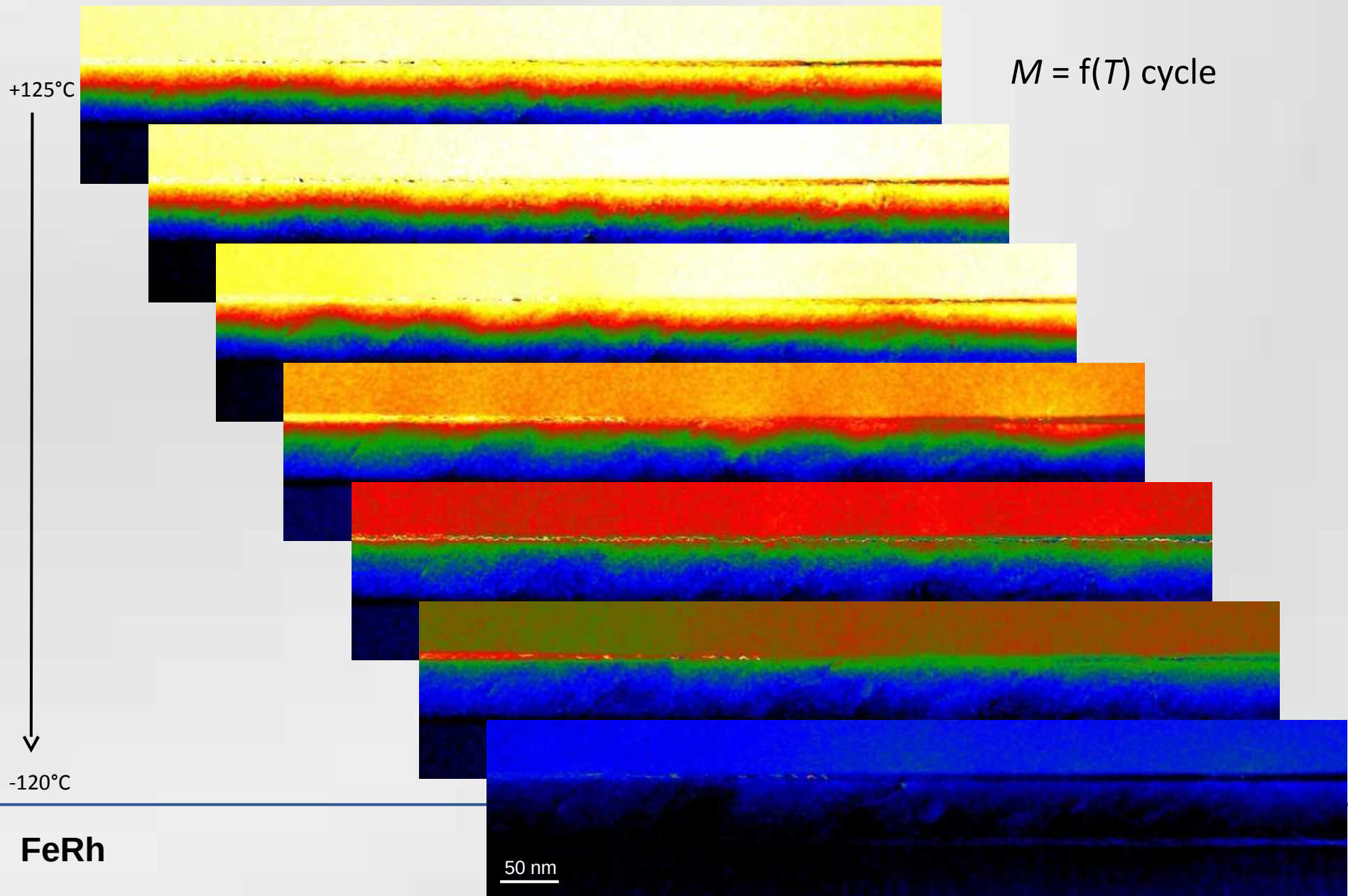


$Fe_{0.5}Rh_{0.5} : a_{AF} = 0.2987 \text{ nm}$

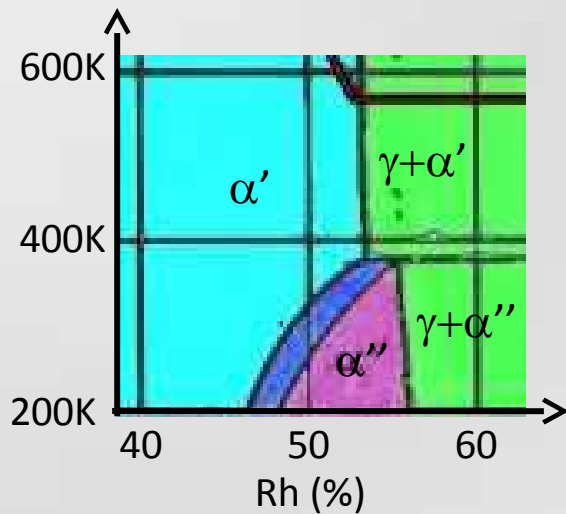


$a_F = 0.2997 \text{ nm}$

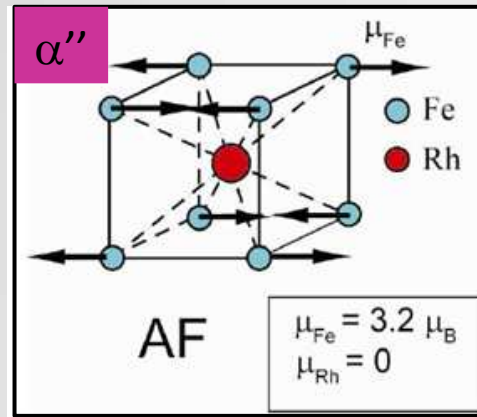
**Thin Foils and in-situ**



# Magnetic transition

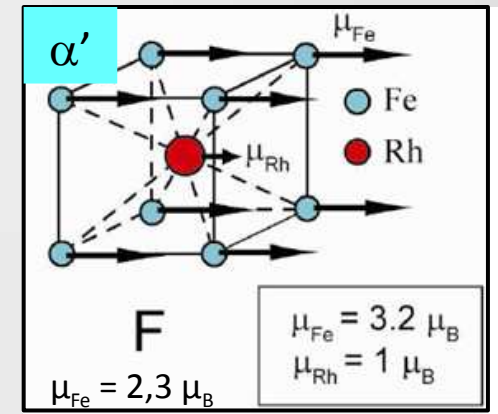


Ordered bcc structure ( $B_2$ )

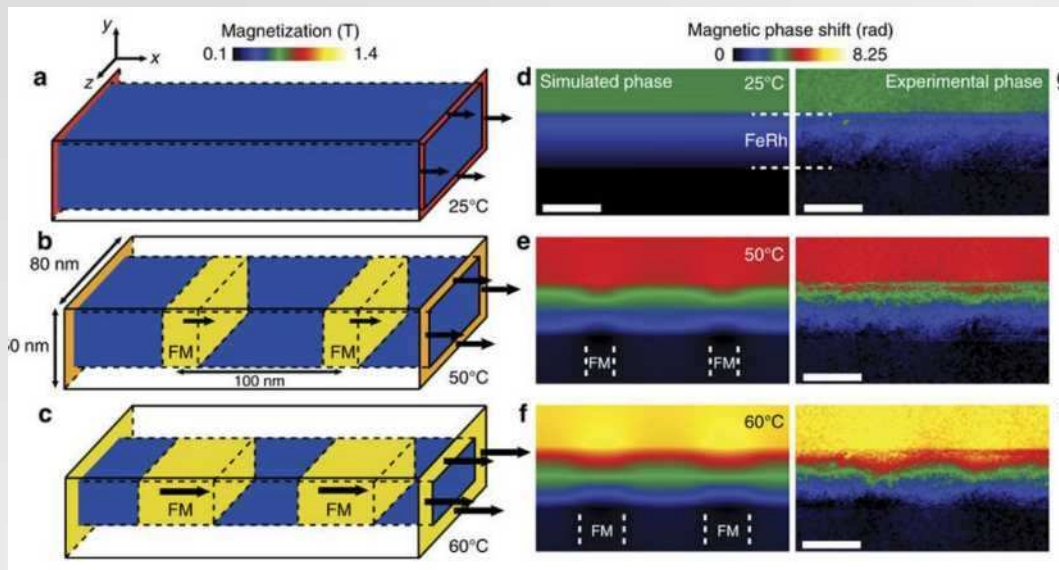


$Fe_{0.5}Rh_{0.5} : a_{AF} = 0.2987 \text{ nm}$

# Out-of-Axis Holography

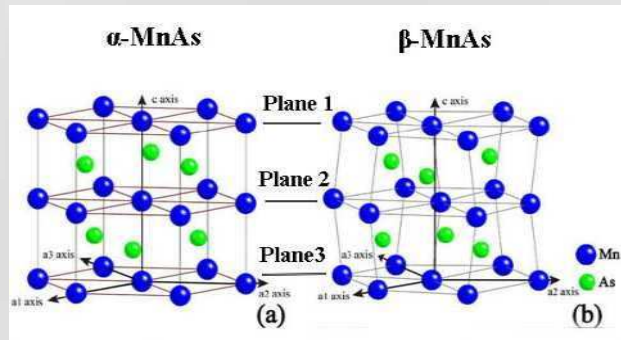


$a_F = 0.2997 \text{ nm}$



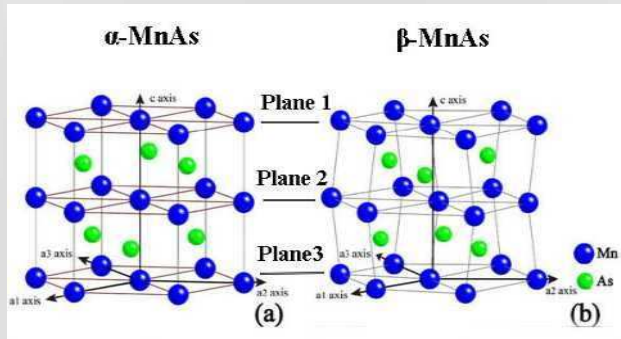
Temperature	$\phi_{Mag}$ (rad)	$B_x$ (T.nm)
+125°C (F state)	8.1	107 ( $\pm 6$ )
-120°C (AF state)	1.9	25 ( $\pm 10$ )



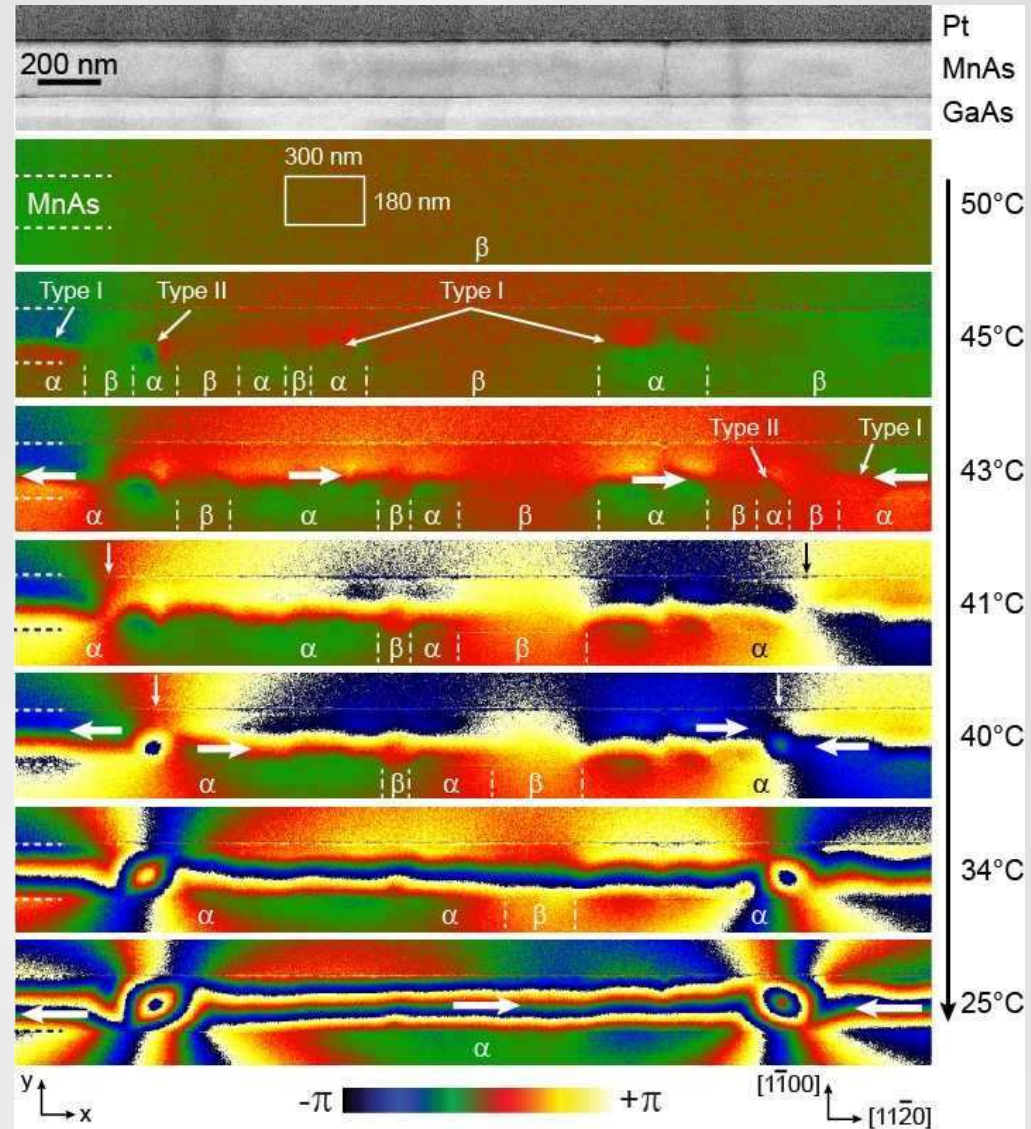


Ferromagnetic (FM)    Paramagnetic (PM)



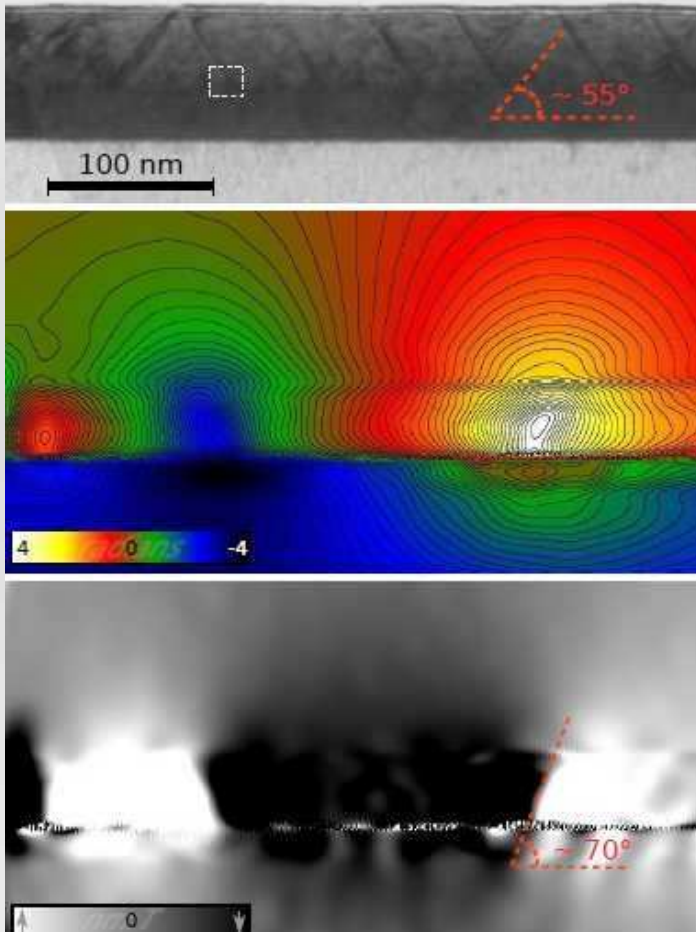


Ferromagnetic (FM)    Paramagnetic (PM)

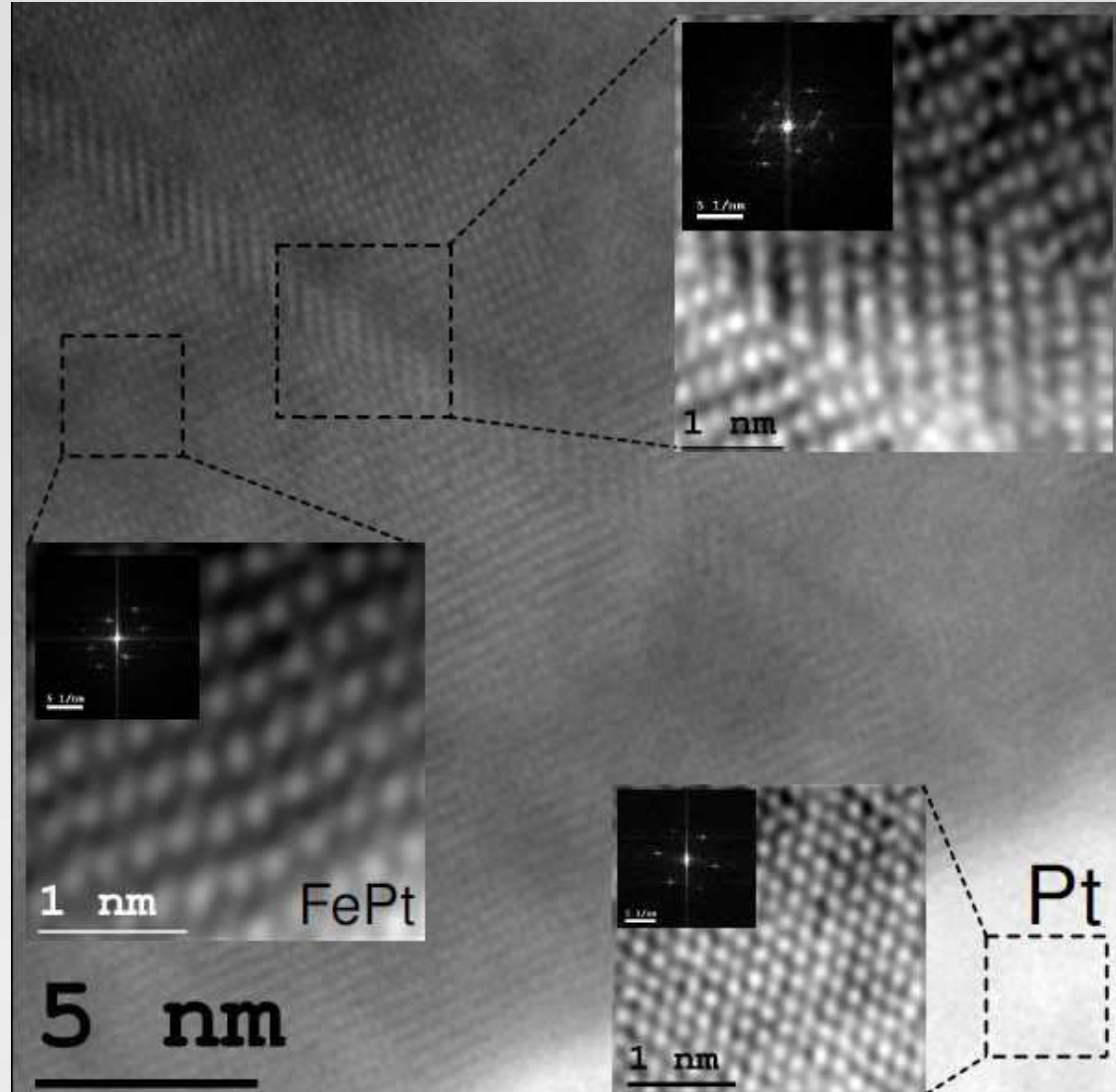
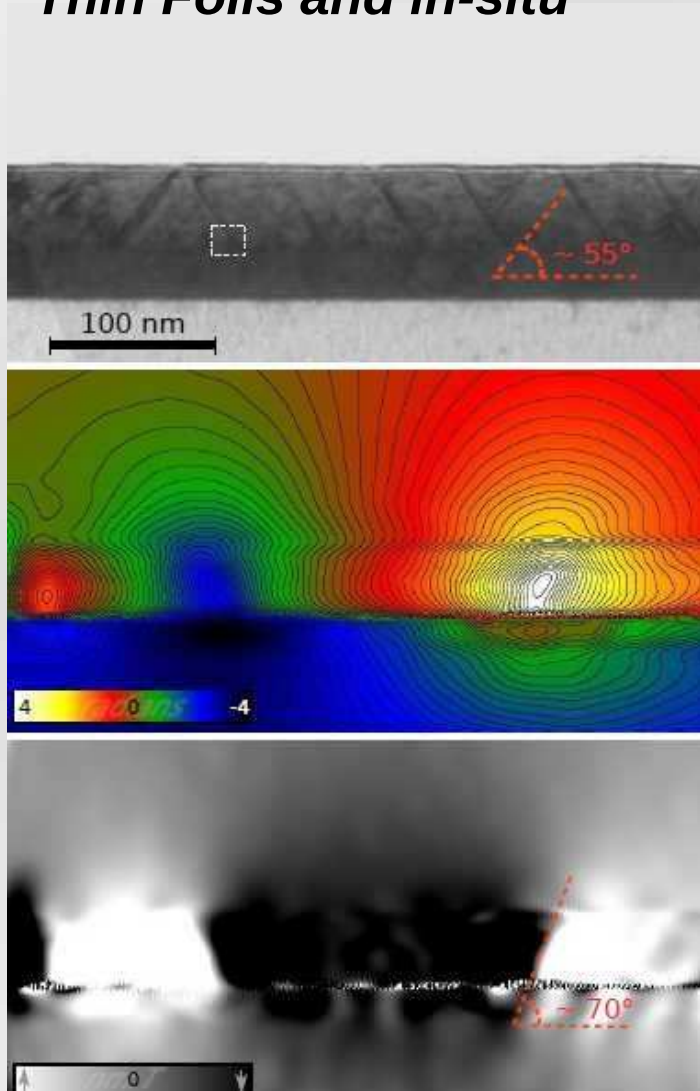


Temperature	$\phi_{Mag}$ (rad)	$B_x$ (T.nm)	$\mu_0 M$ (T)
23°C (FM)	15.6	57 ( $\pm 4$ )	0.7 ( $\pm 0.1$ )
50°C (PM)	0	0 ( $\pm 1$ )	0 ( $\pm 0.02$ )

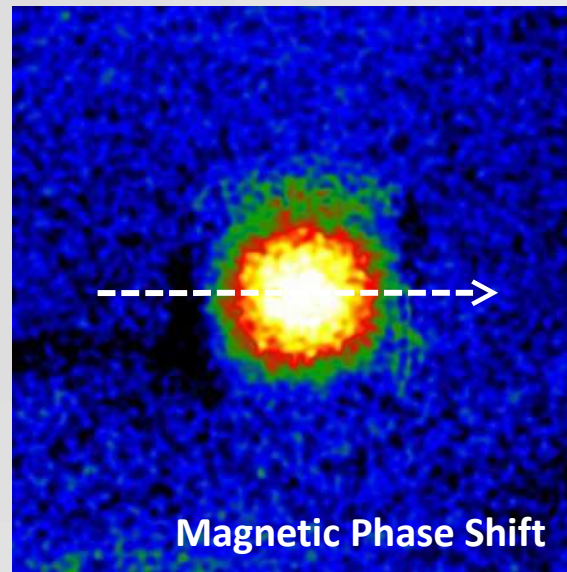
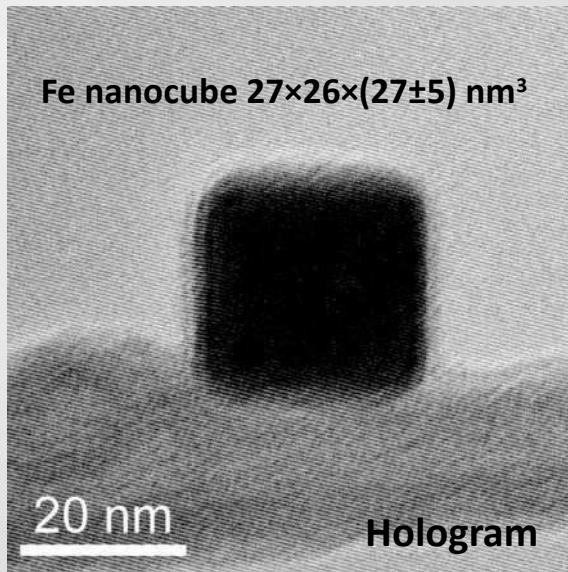
### Thin Foils and in-situ

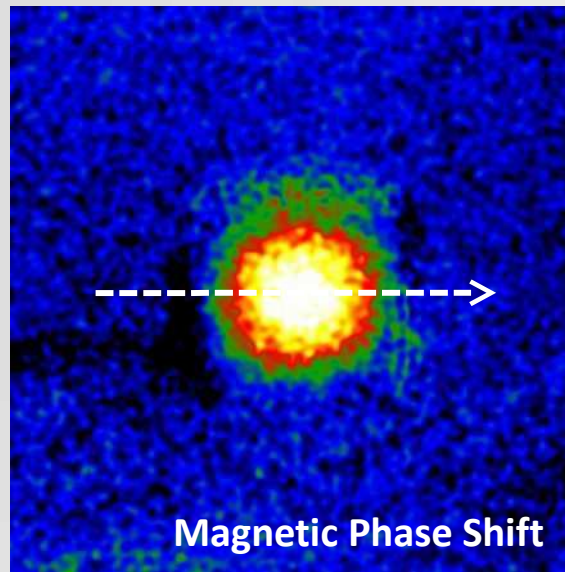
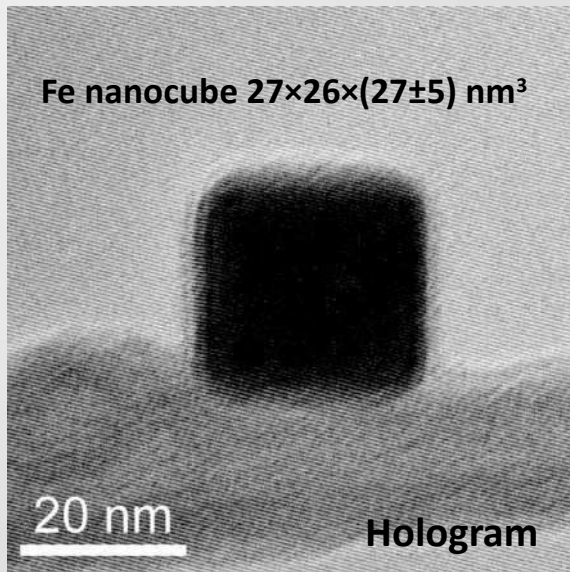


Thin Foils and in-situ









**Sensitivity :**

- Use of Phase sensitivity
  - « Easy »  $> 1 \text{ rad}$
  - « Tricky »  $< 100 \text{ mrad}$
  - « Dedicated »  $< 10 \text{ mrad}$

$1 \text{ rad} \iff 6.5 \cdot 10^{-16} \text{ Wb}$

$\iff 1/\pi \Phi_0$

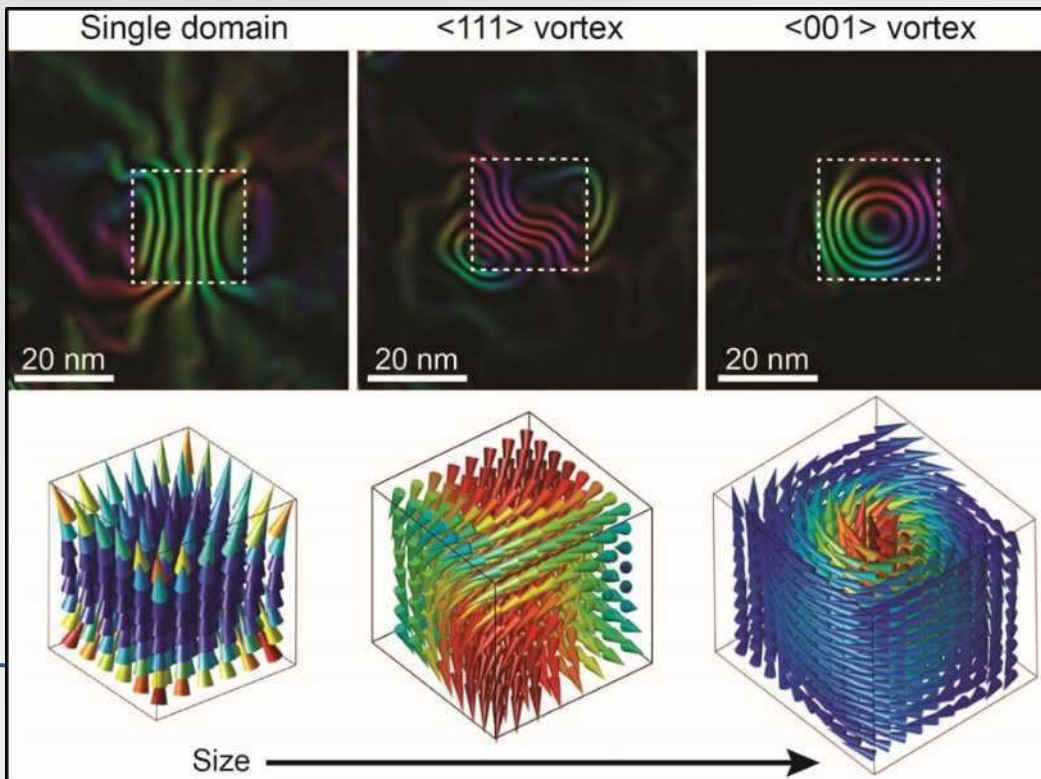
$\iff 658 \text{ T} \cdot \text{nm}^2$

$1 \text{ rad/nm} \iff 5.6 \cdot 10^4 \mu_B$

$17 \mu\text{rad} \cdot \text{nm}^{-1} \iff 1 \mu_B$

10 nm of Fe ( $\mu_0 M_s \sim 2 \text{ T}$ )

$\parallel$   
Phase gradient of 30 mrad/nm





(PtCoIr)<sub>5</sub> => 4nm de Co (anisotropie) perpendiculaire

Doggy Bag

### Sensitivity :

- Use of Phase sensitivity
  - « Easy » > 1 rad
  - « Tricky » < 100 mrad
  - « Dedicated » < 10 mrad

1 rad <=> 6.5 10<sup>-16</sup> Wb

<=> 1/π Φ<sub>0</sub>

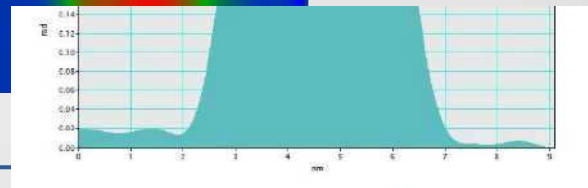
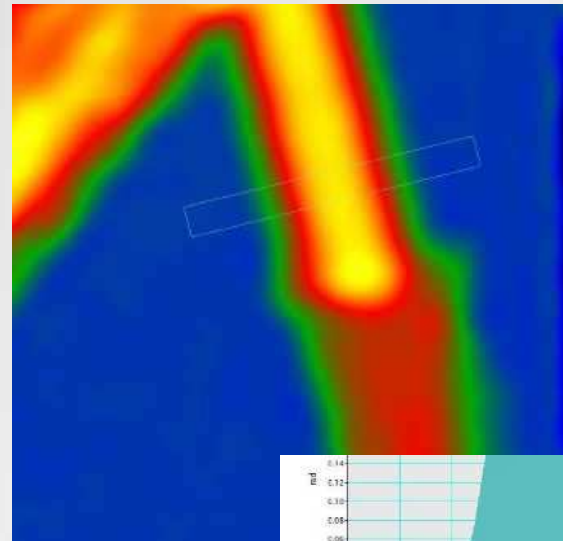
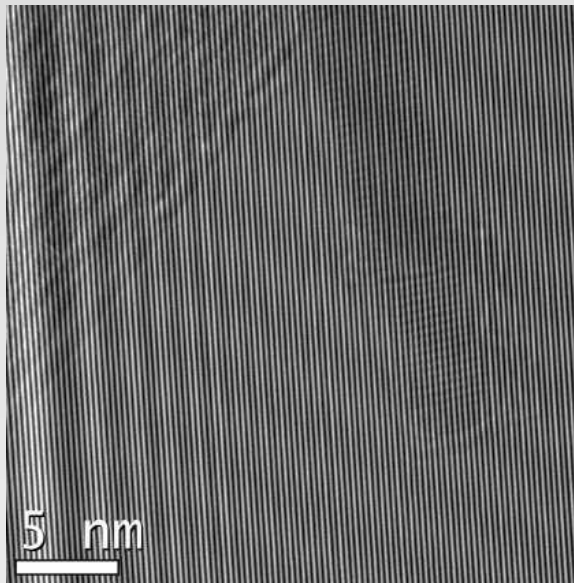
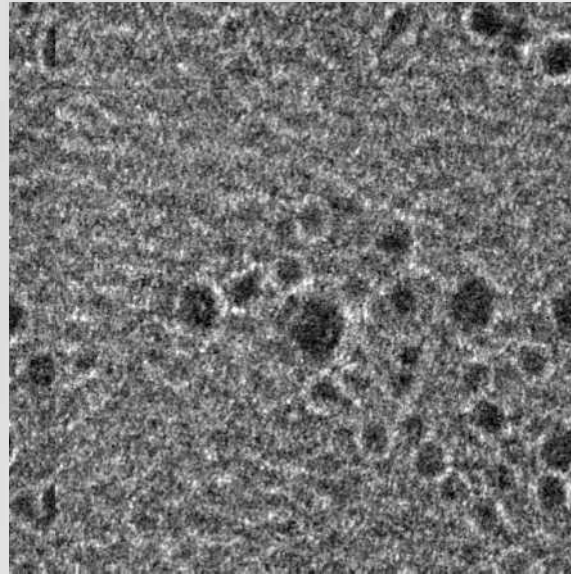
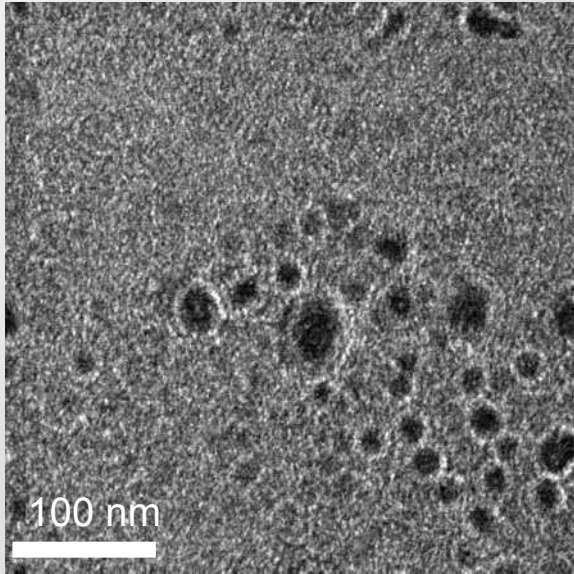
<=> 658 T.nm<sup>2</sup>

1 rad/nm <=> 5.6 10<sup>4</sup> μ<sub>B</sub>

17 μrad.nm<sup>-1</sup> <=> 1 μ<sub>B</sub>

10 nm of Fe (μ<sub>0</sub>M<sub>s</sub> ~ 2 T)

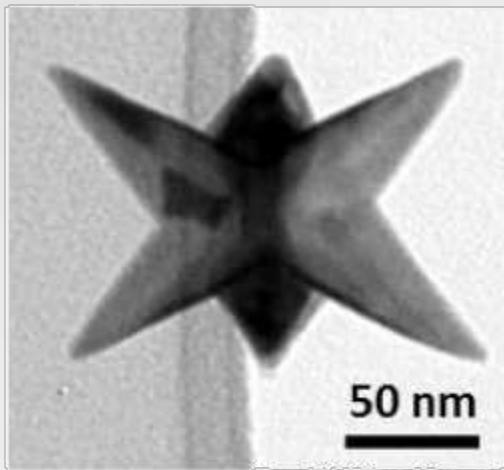
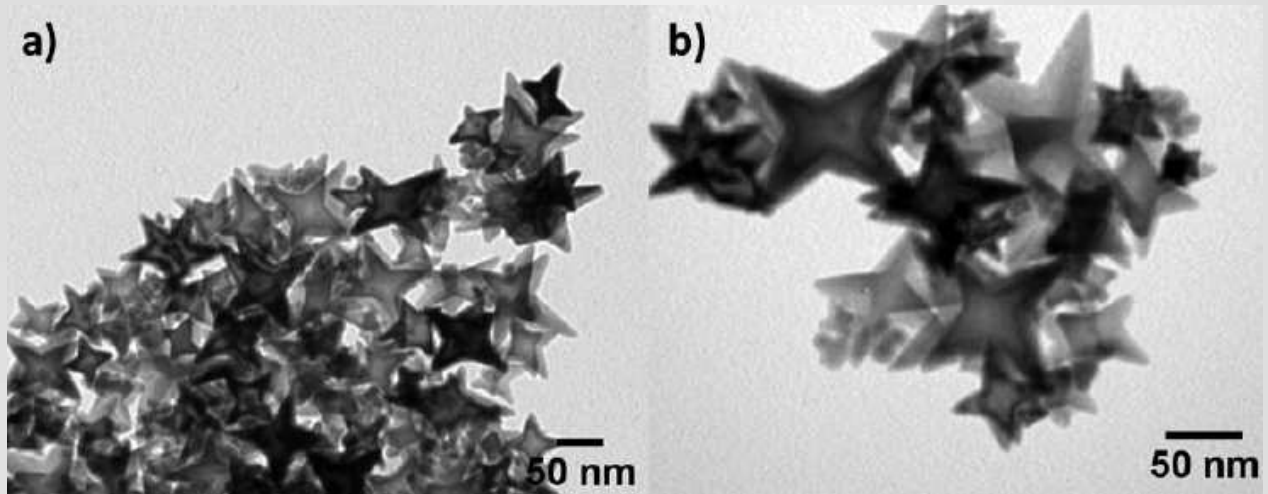
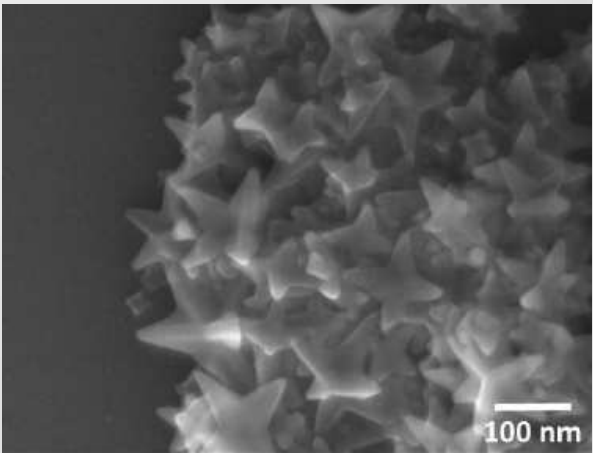
||  
Phase gradient of 30 mrad/nm



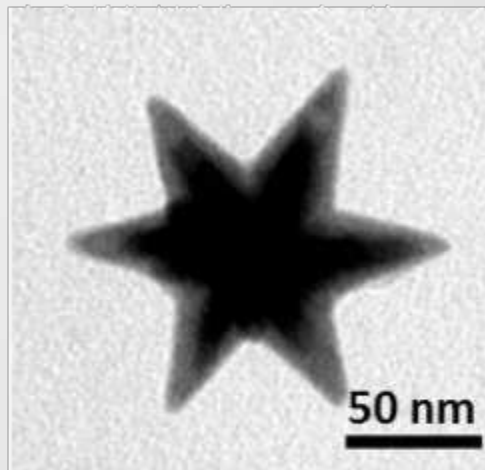
Ni@DWNT → Nanowire ~3 nm in diameter under 2 T

Masseboeuf. et al.  
Unpublished...

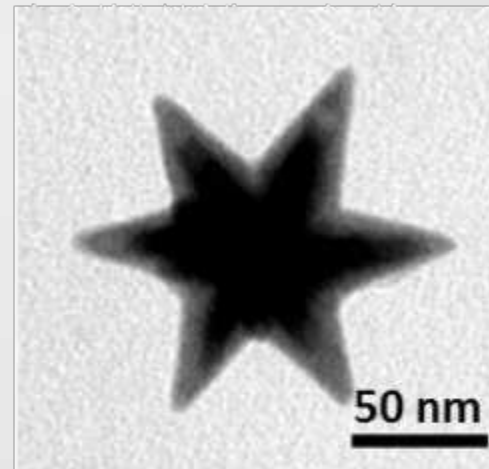
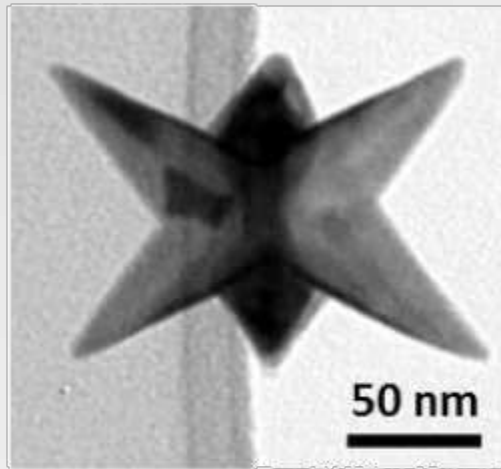
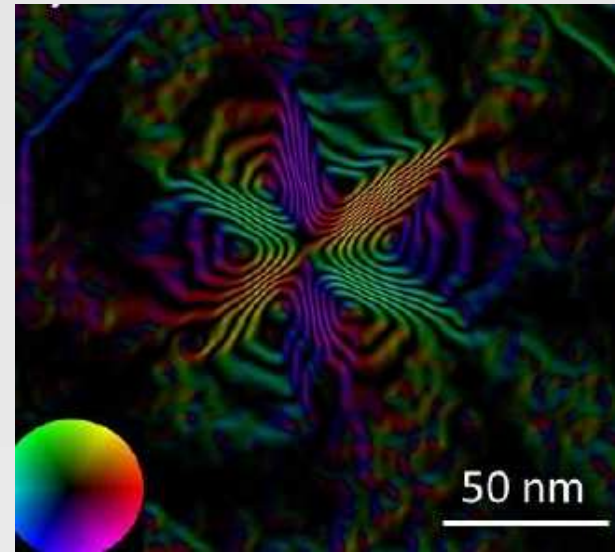
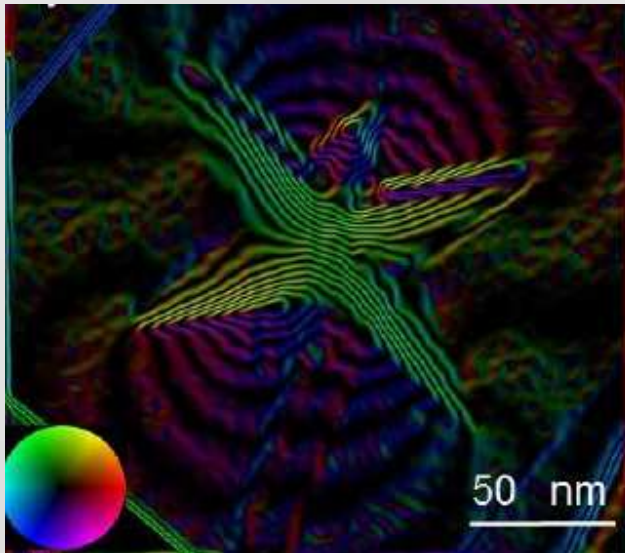




$\langle 110 \rangle$



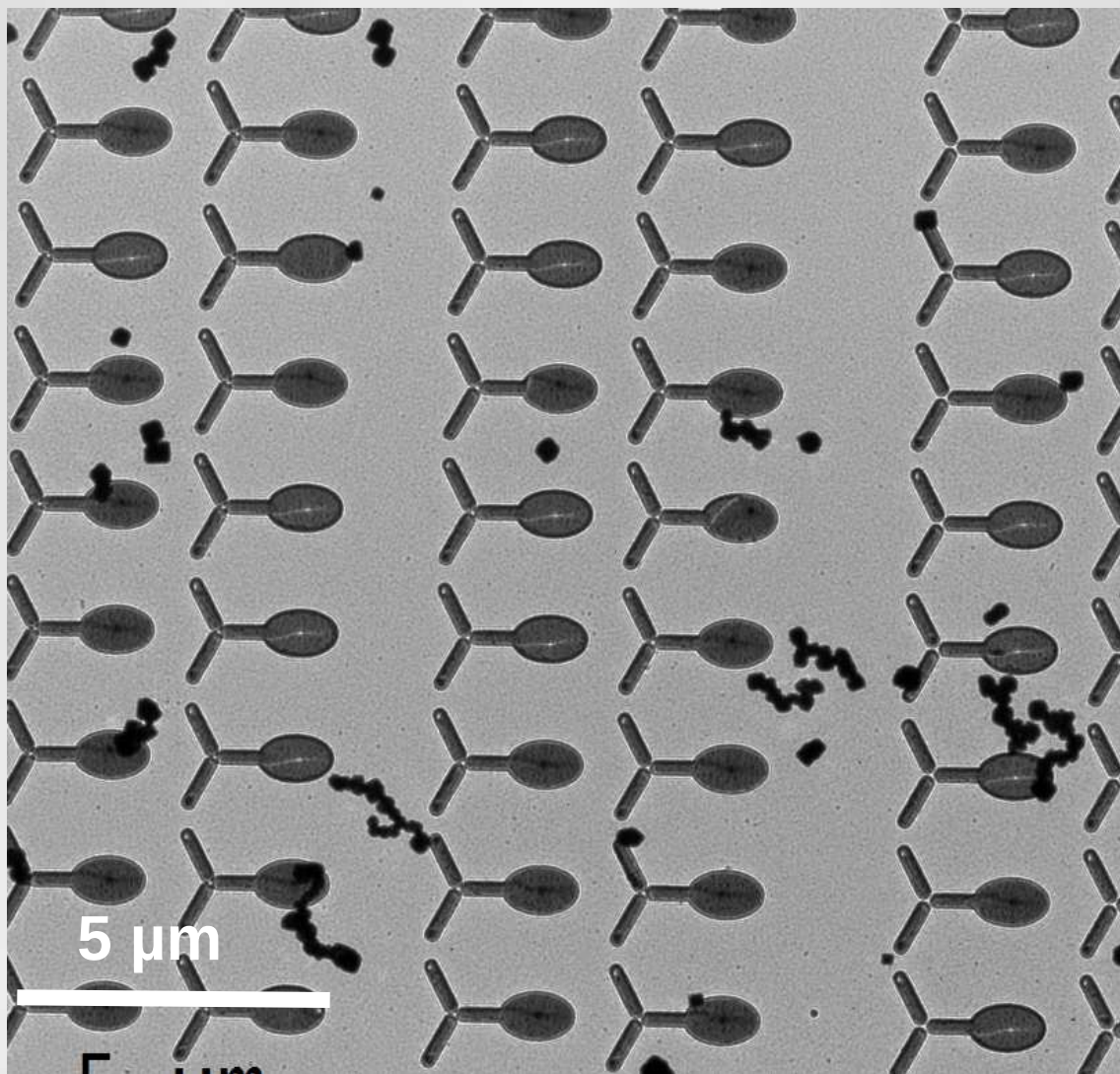
$\langle 111 \rangle$



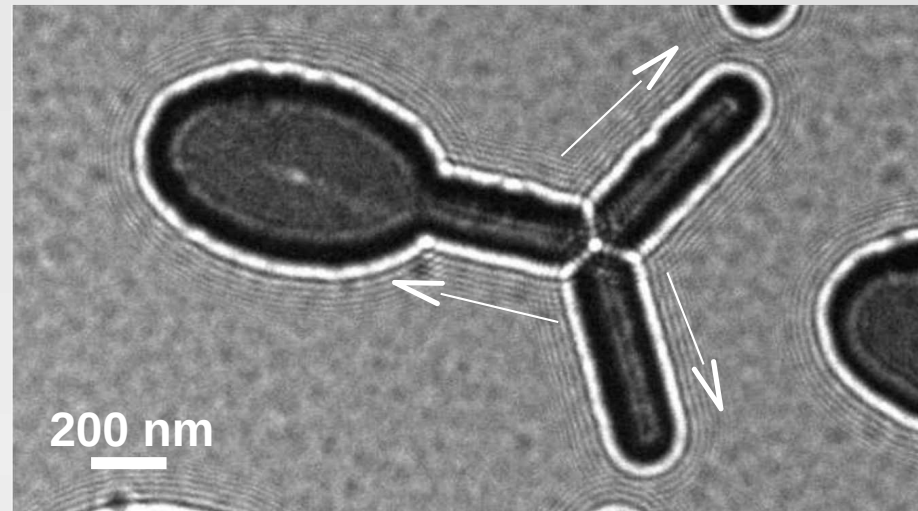
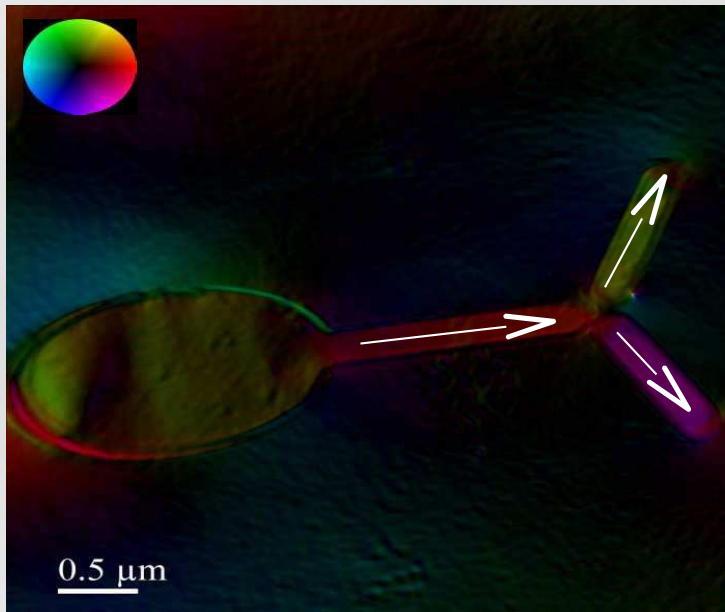
$\langle 110 \rangle$

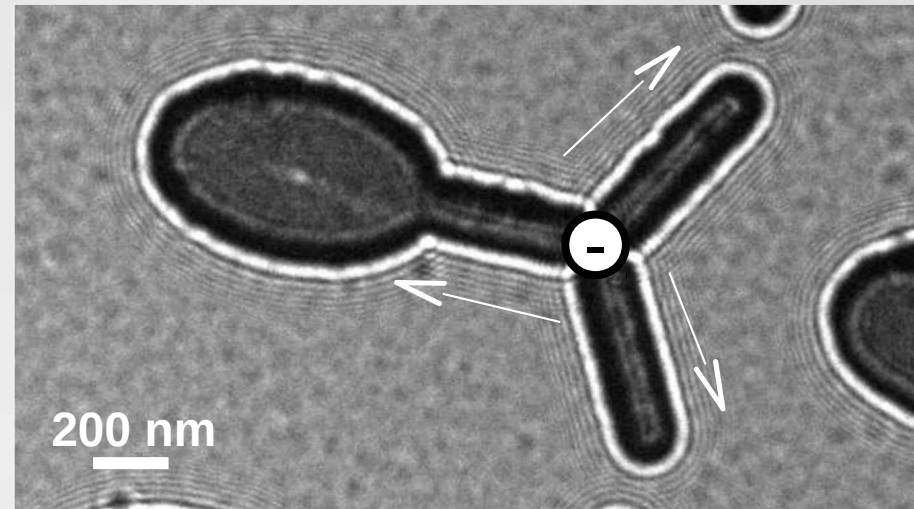
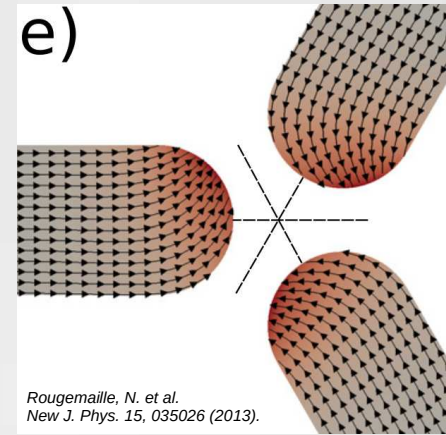
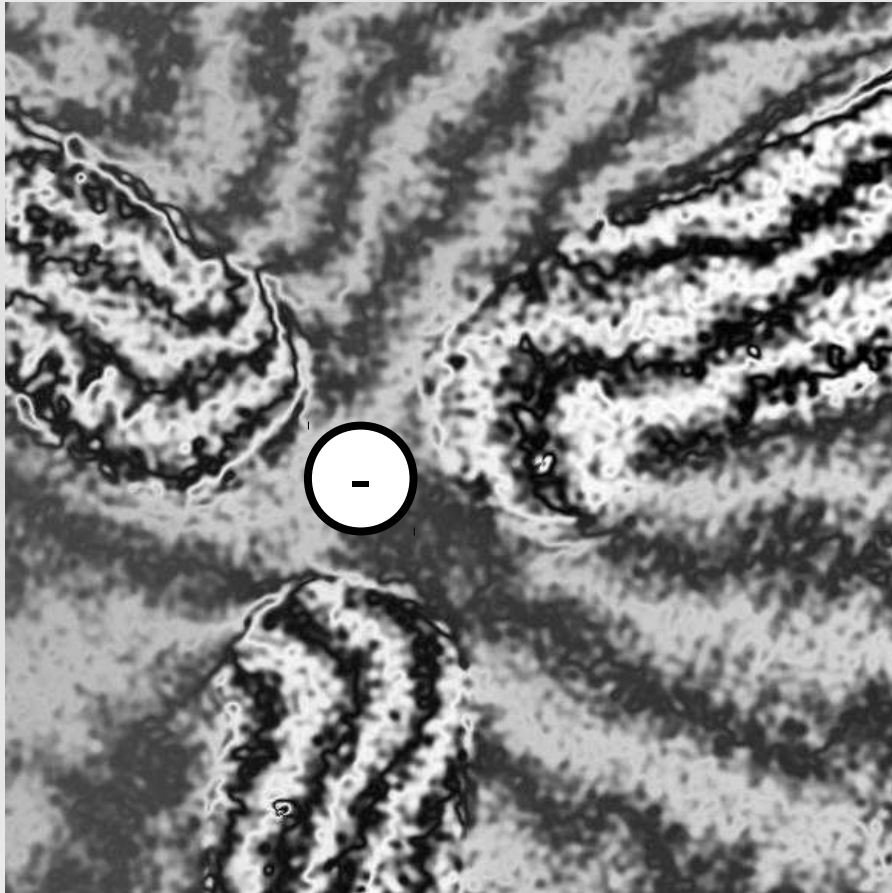
$\langle 111 \rangle$

# Magnetic Frustration



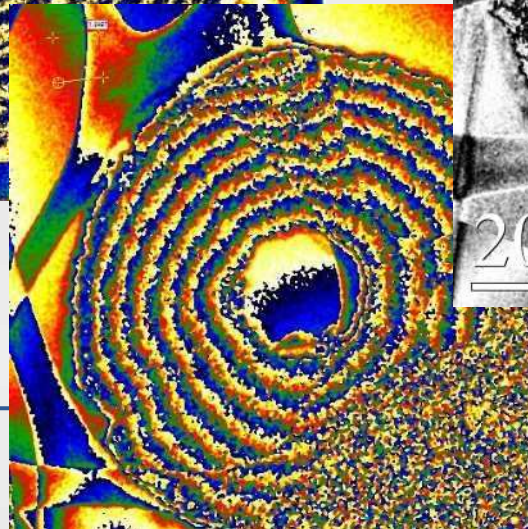
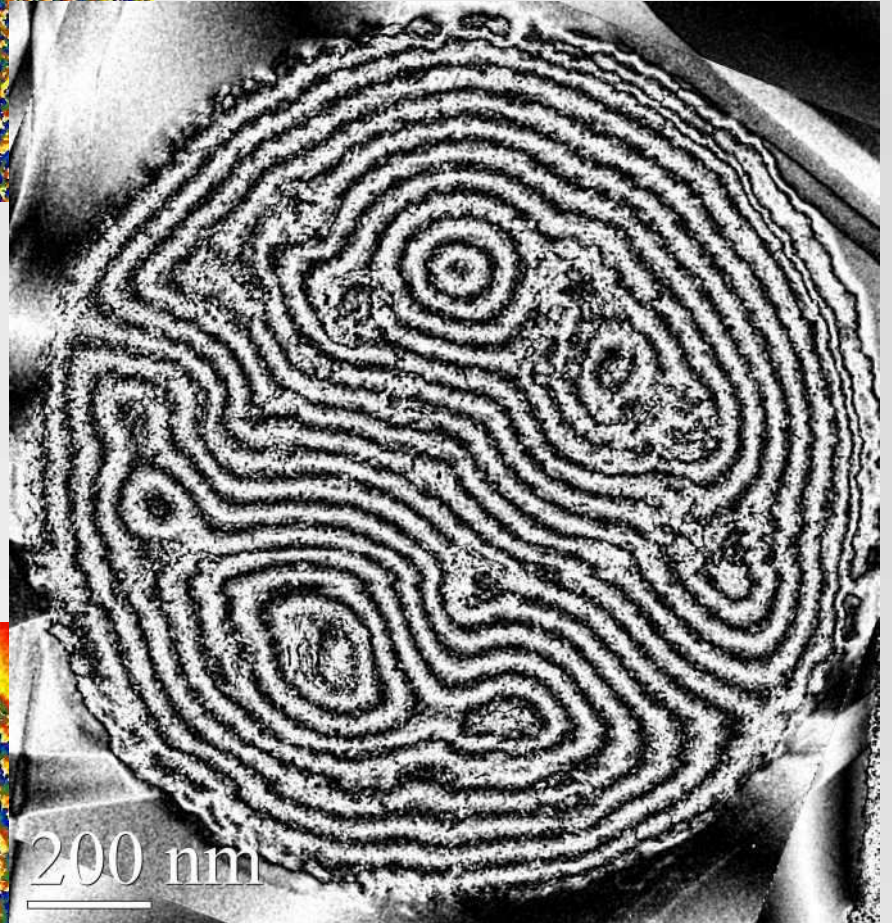
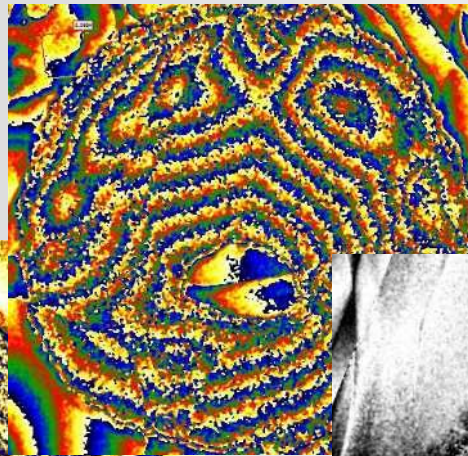
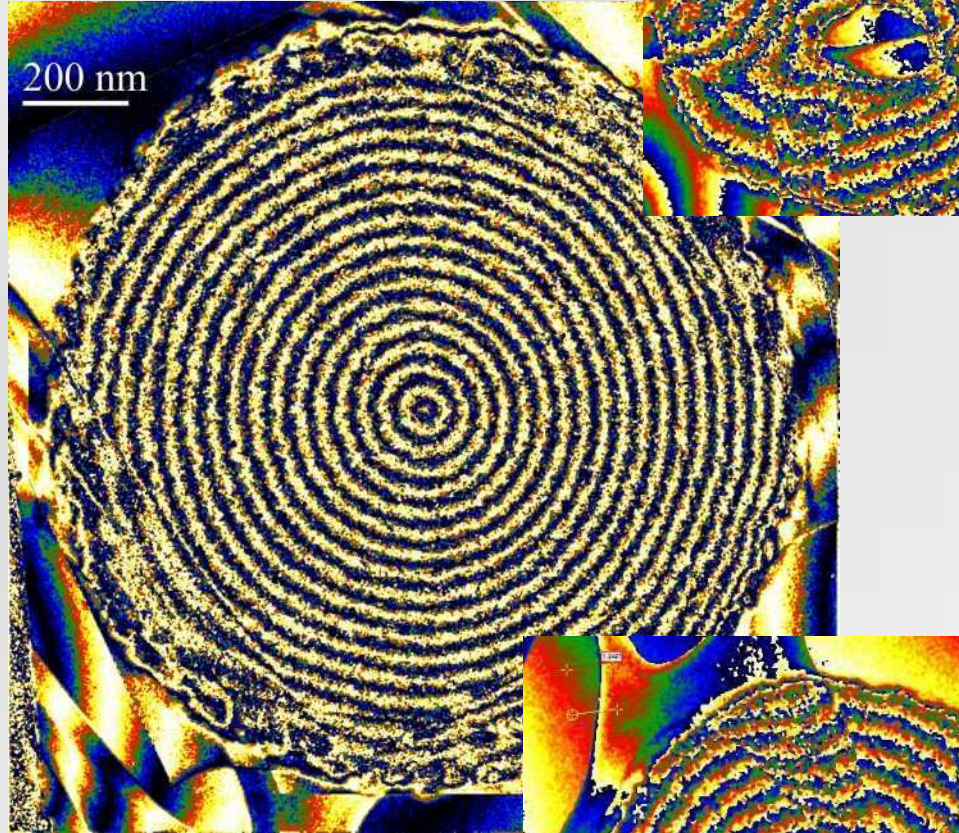








Py « microparticles vortices »  
for cell apoptosis



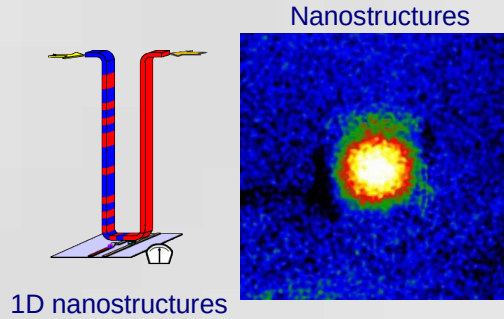
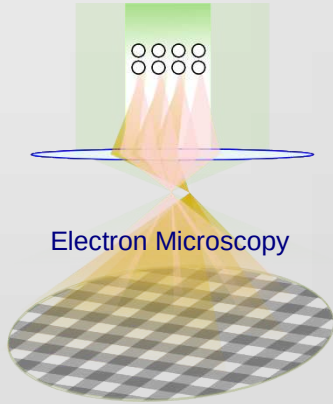


## Out-of-Axis Holography

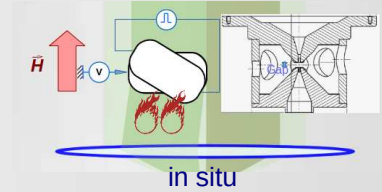
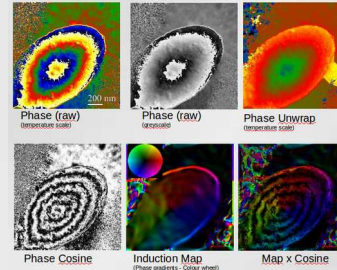
## Fresnel imaging « In-line Holography »

★★★★★	~ 1 nm	<i>Spatial Resolution</i>	~ 10 nm	★★★★★
★★★★★	~ 1 μm	<i>Field of View</i>	~ 100 μm	★★★★★
★★★★★	~ 10 nm.T	<i>Sensitivity</i>	~ 1 nm.T	★★★★★
★★★★★	~ 1 s	<i>Dynamic</i>	~ 0,1 s	★★★★★
★★★★★	Optical align <sup>t</sup>	<i>Versatility</i>	Just defocus !	★★★★★
★★★★★	Direct	<i>Quantification</i>	Need simul or big treat.	★★★★★
★★★★★	FEG, biprism, align <sup>t</sup> ...	<i>Implementation</i>	Just Low Mag !	★★★★★

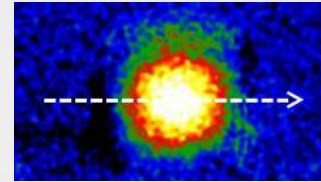
# Electron Microscopy & Micro-magnetism



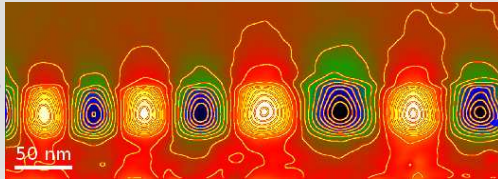
## Phase Image



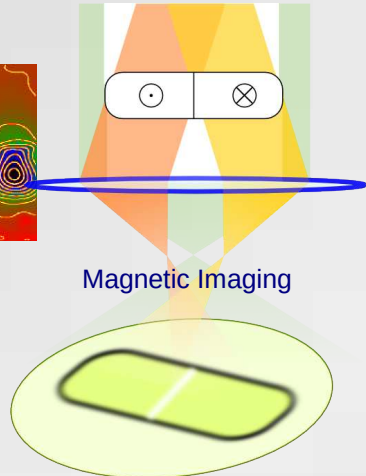
## Phase sensitivity



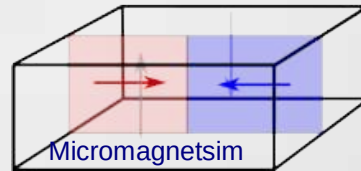
Thin Foils



## Magnetic Imaging



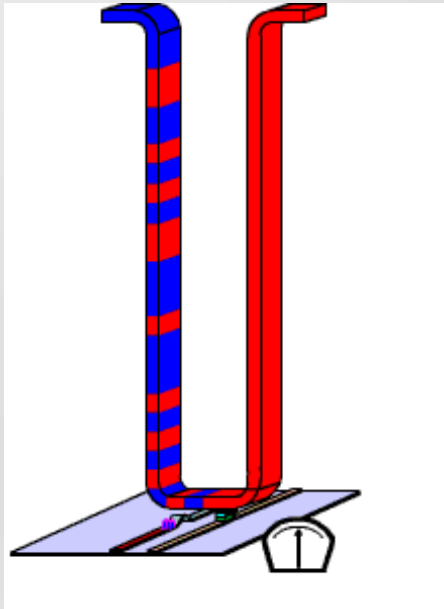
Devices



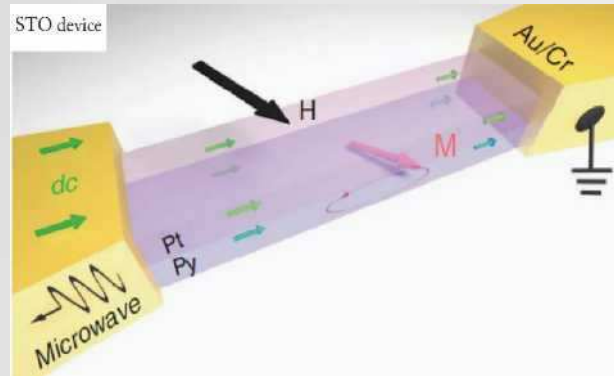
## Out-of-Axis vs In-Line

★★★★★	Spatial Resolution	★★★★★
★★★★★	Field of View	★★★★★
★★★★★	Sensitivity	★★★★★
★★★★★	Dynamic	★★★★★
★★★★★	Versatility	★★★★★
★★★★★	Quantification	★★★★★
★★★★★	Implementation	★★★★★

# Nanowires and domain walls



→ Magnetic Racetrack Memory  
Stuart Parkin. *Science* 320 (2008)



→ Nanowire spin torque oscillator  
Z. Duan et al., *Nat. Commun.* (2014)

=> Nucleation

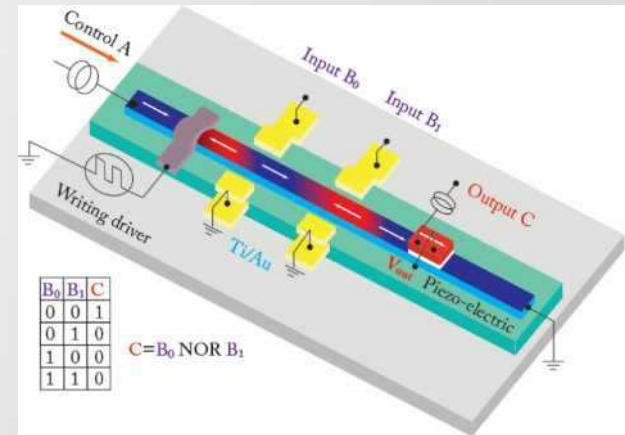
=> Pinning

=> Velocity

=> Stripes

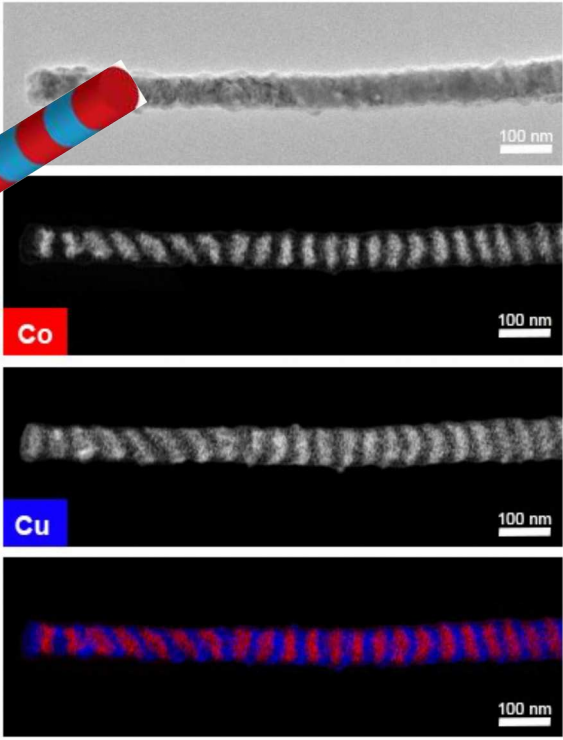
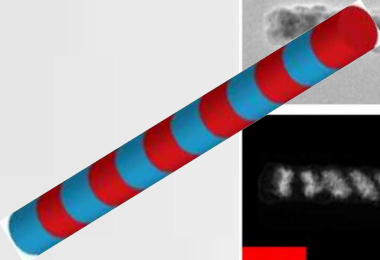
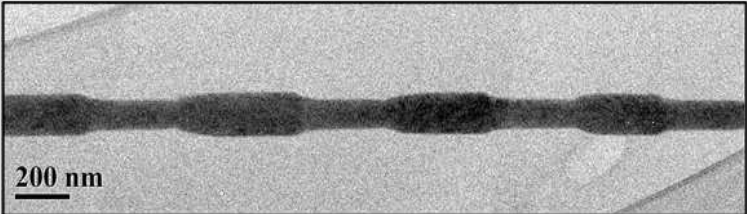
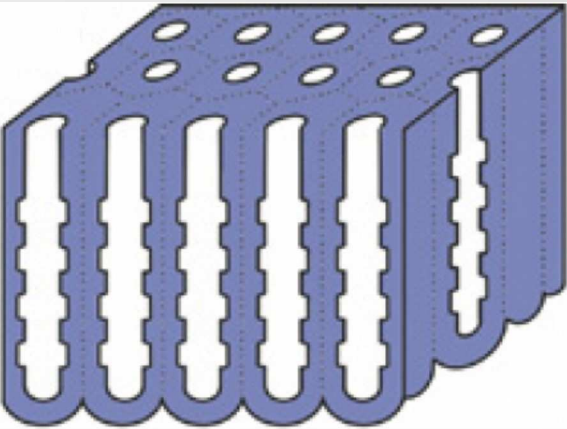
=> Wires

=> Tubes

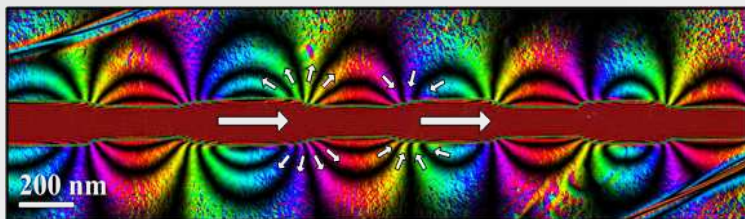
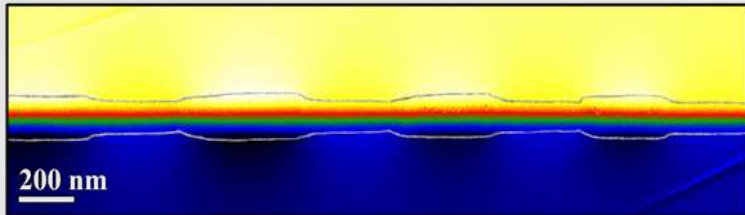
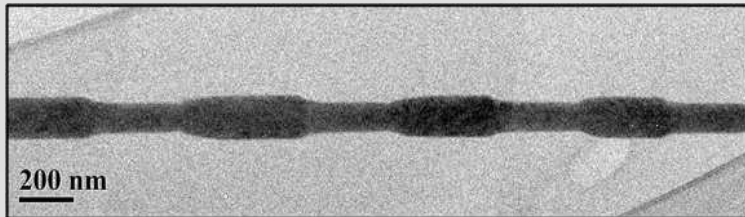
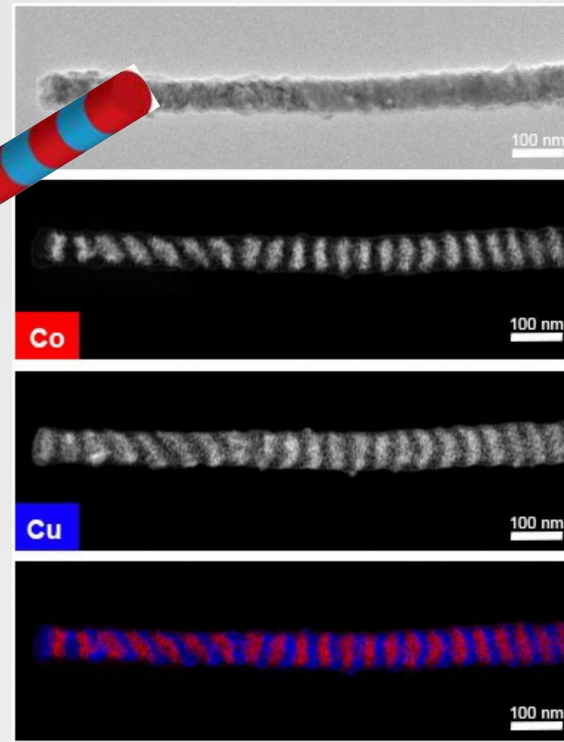
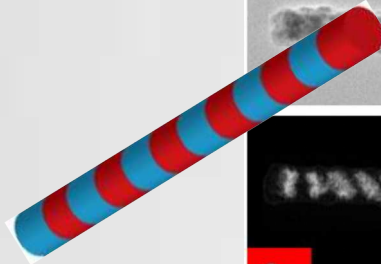
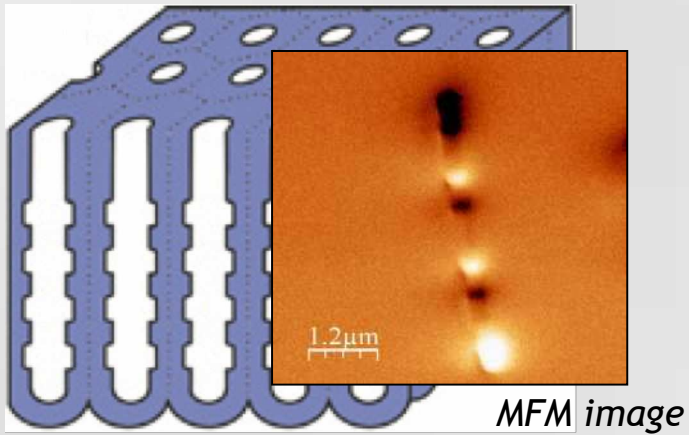


→ NOR gate by strain controlled magnetic domain wall propagation  
N. Lei et al., *Nat. Commun.* (2013)

# Nanowires and domain walls



# Nanowires and domain walls



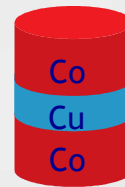
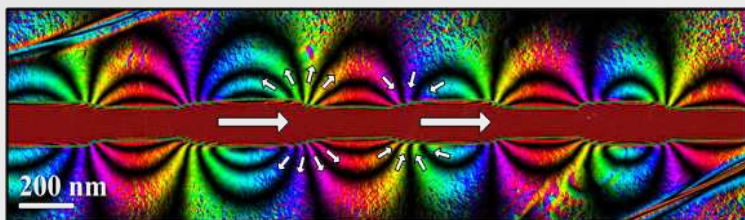
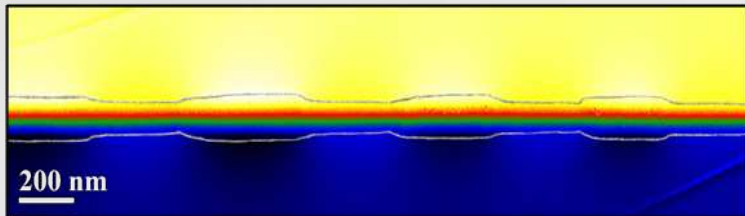
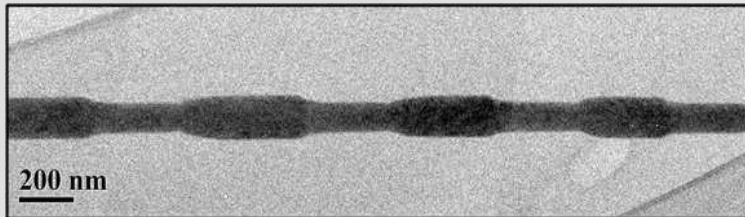
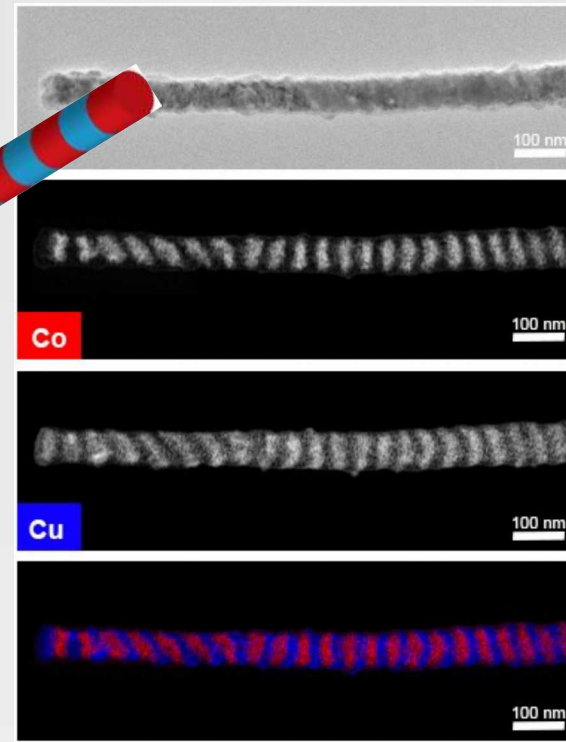
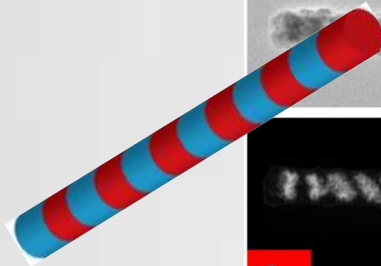
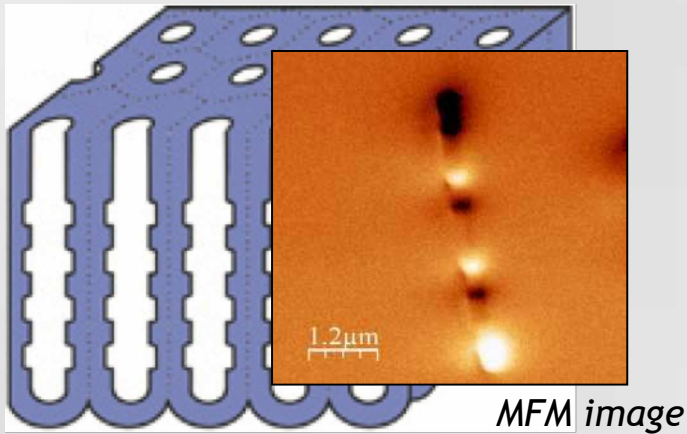
Rodríguez, L. A. et al.  
Quantitative Nanoscale Magnetic Study of Isolated Diameter-Modulated FeCoCu Nanowires.  
ACS Nano 10, 9669–9678 (2016).

Strasbourg  
Oct. 2017

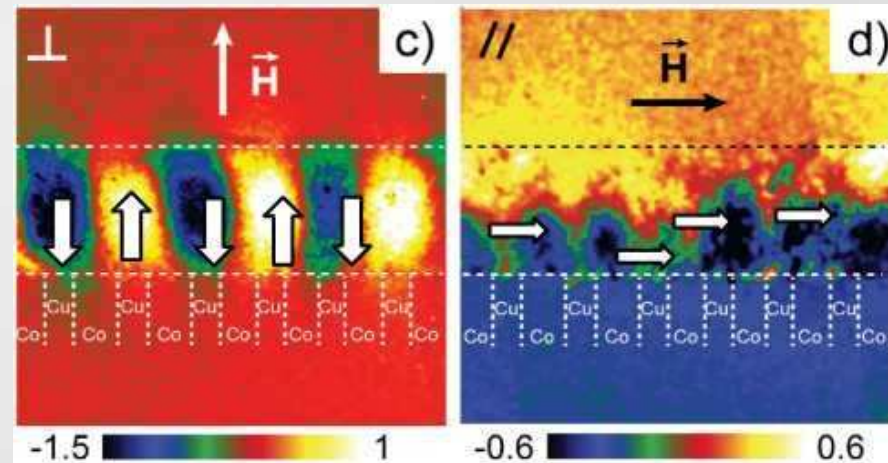




# Nanowires and domain walls



25 nm  
15 nm



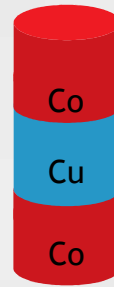
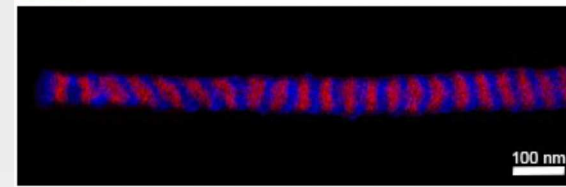
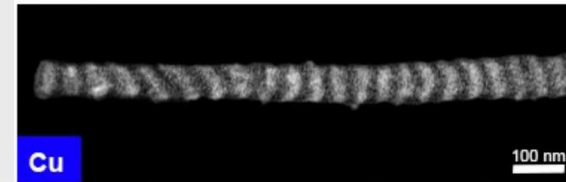
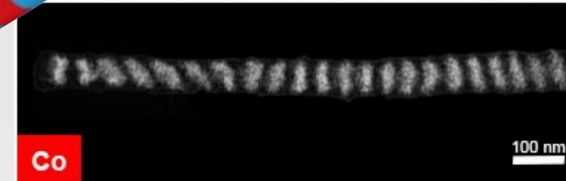
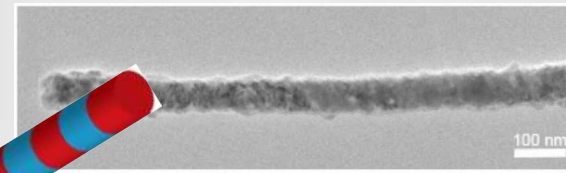
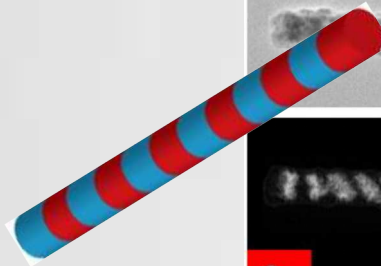
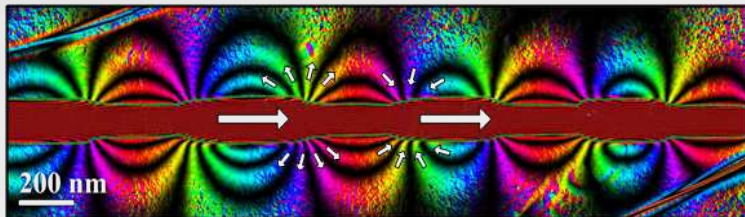
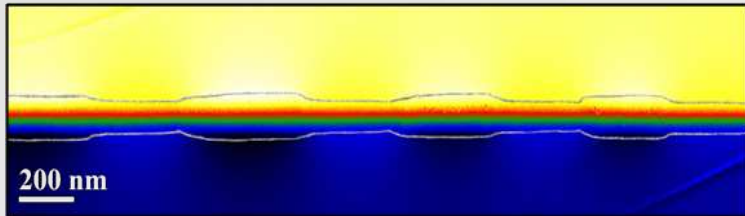
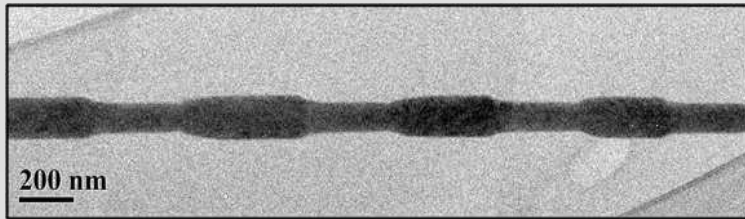
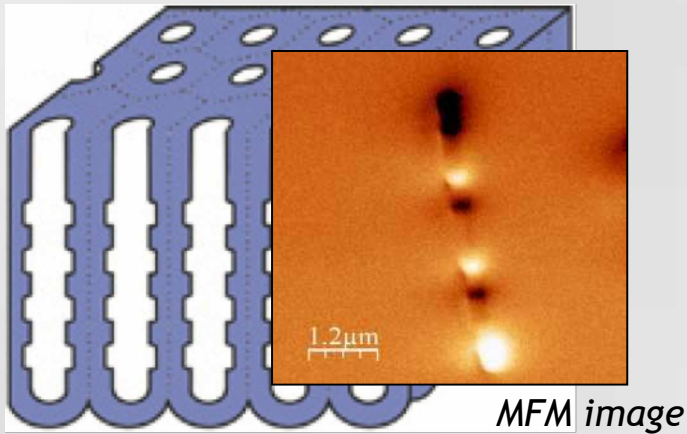
Reyes, D., Biziere, N., Warot-Fonrose, B., Wade, T. & Gatel, C.  
Magnetic Configurations in Co/Cu Multilayered Nanowires: Evidence of Structural and Magnetic Interplay.  
Nano Lett. 16, 1230–1236 (2016).

Strasbourg  
Oct. 2017



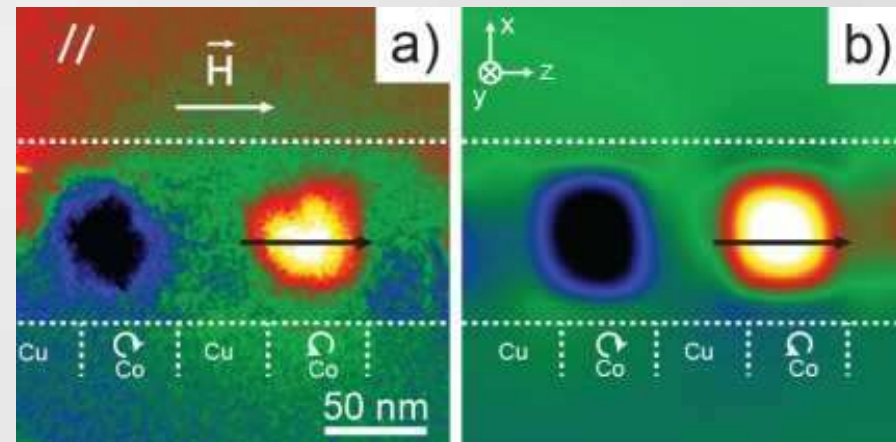


# Nanowires and domain walls



50 nm

50 nm

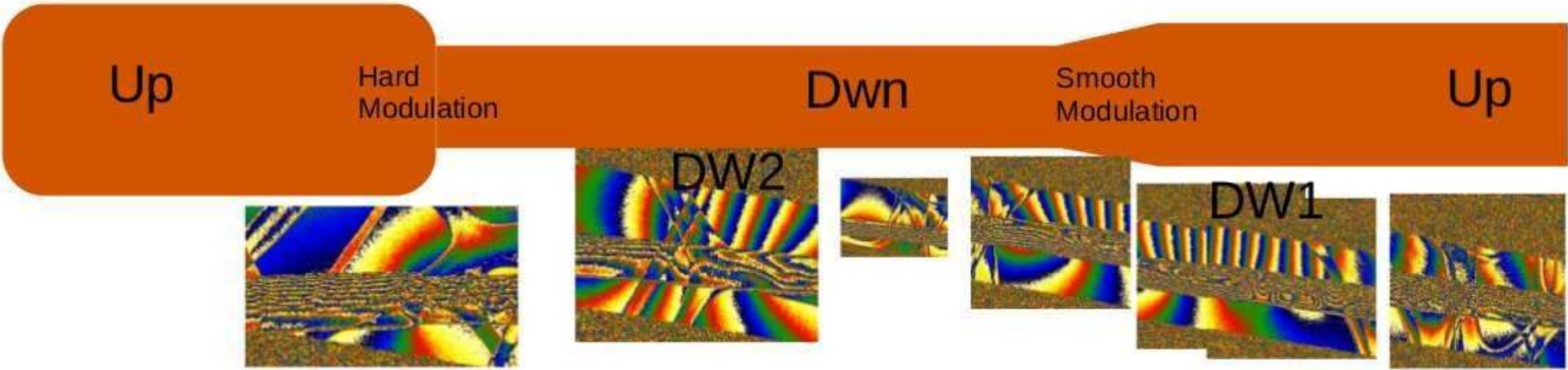
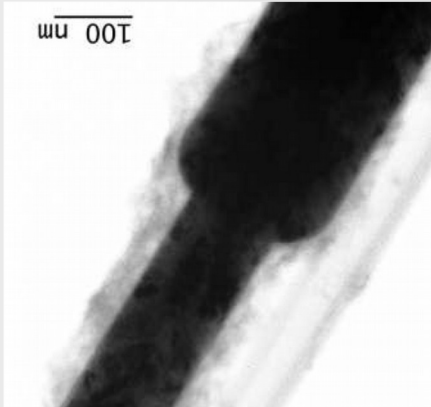


Reyes, D., Biziere, N., Warot-Fonrose, B., Wade, T. & Gatel, C.  
Magnetic Configurations in Co/Cu Multilayered Nanowires: Evidence of Structural and Magnetic Interplay.  
Nano Lett. 16, 1230–1236 (2016).

Strasbourg  
Oct. 2017



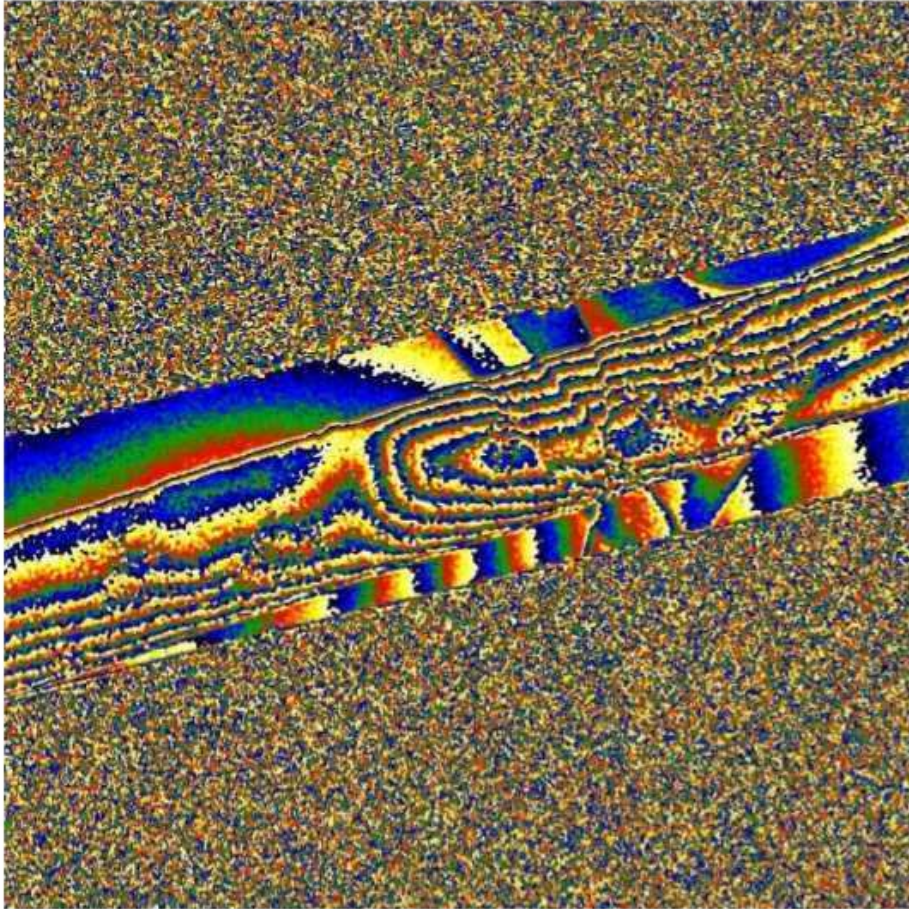
# Nanowires and domain walls



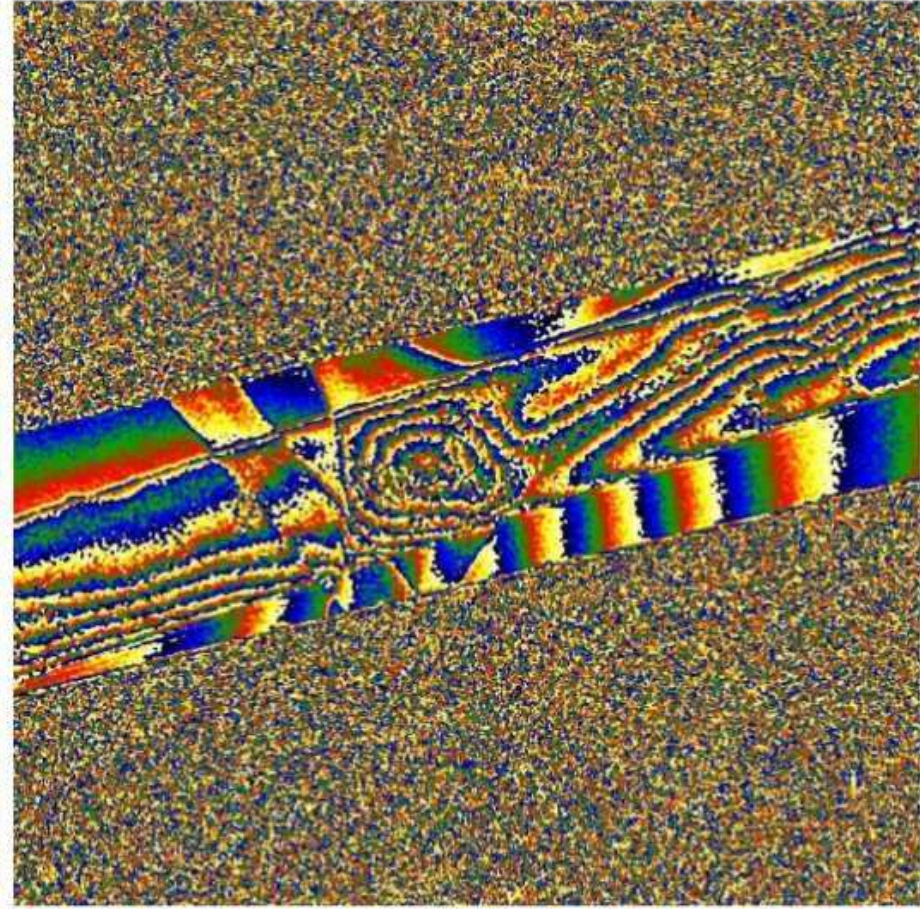


# *Nanowires and domain walls*

Pinning @ 5,62 mT

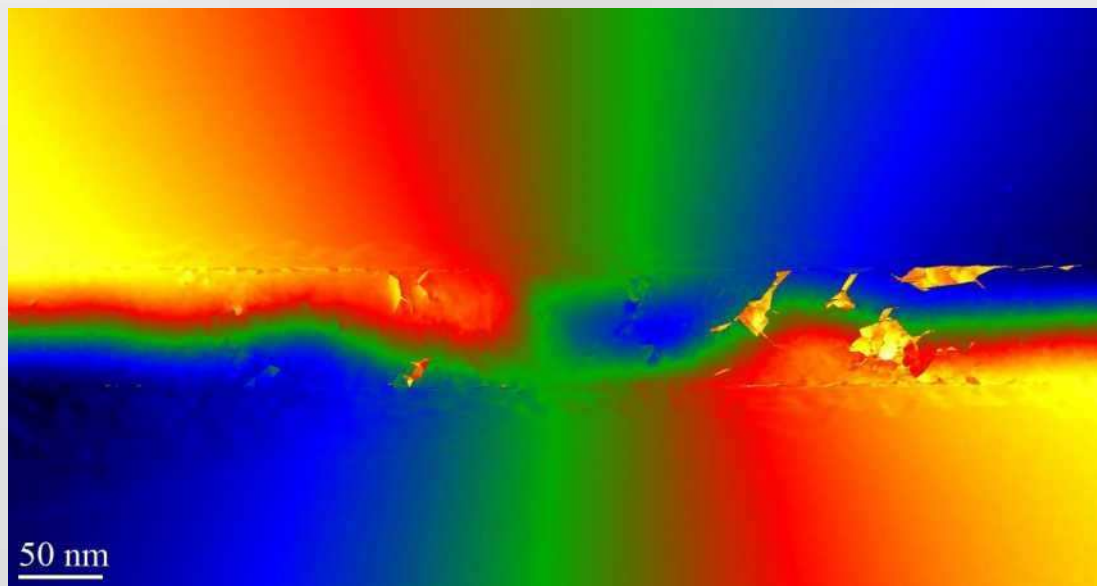


Struct change @ 8mT

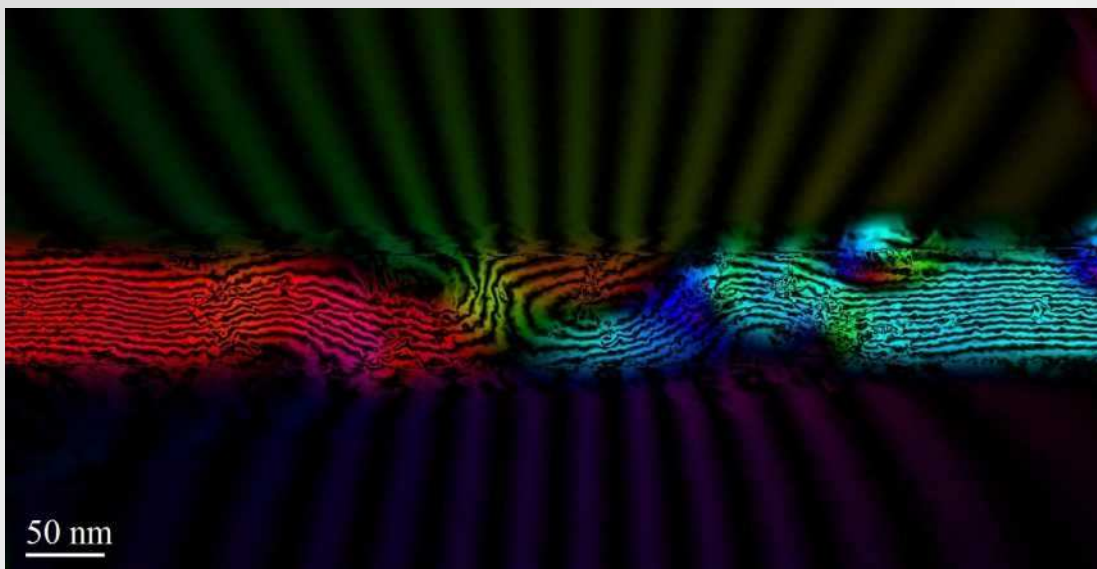




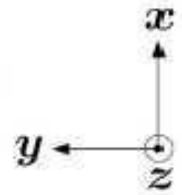
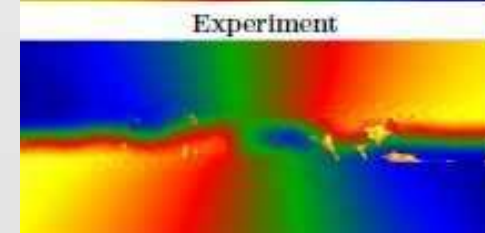
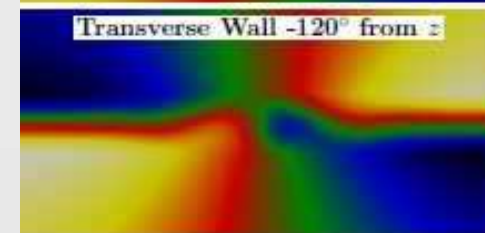
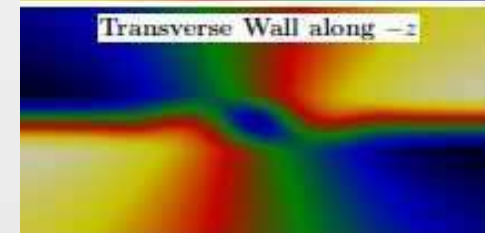
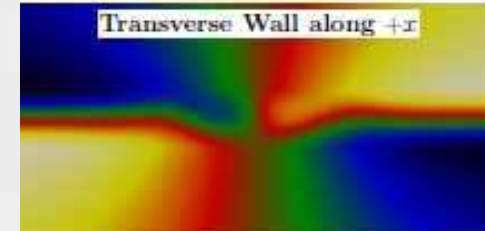
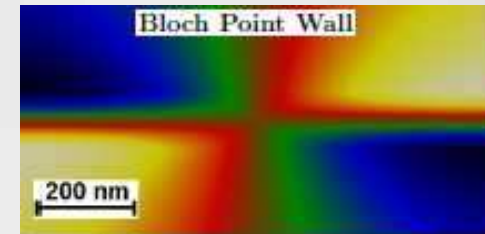
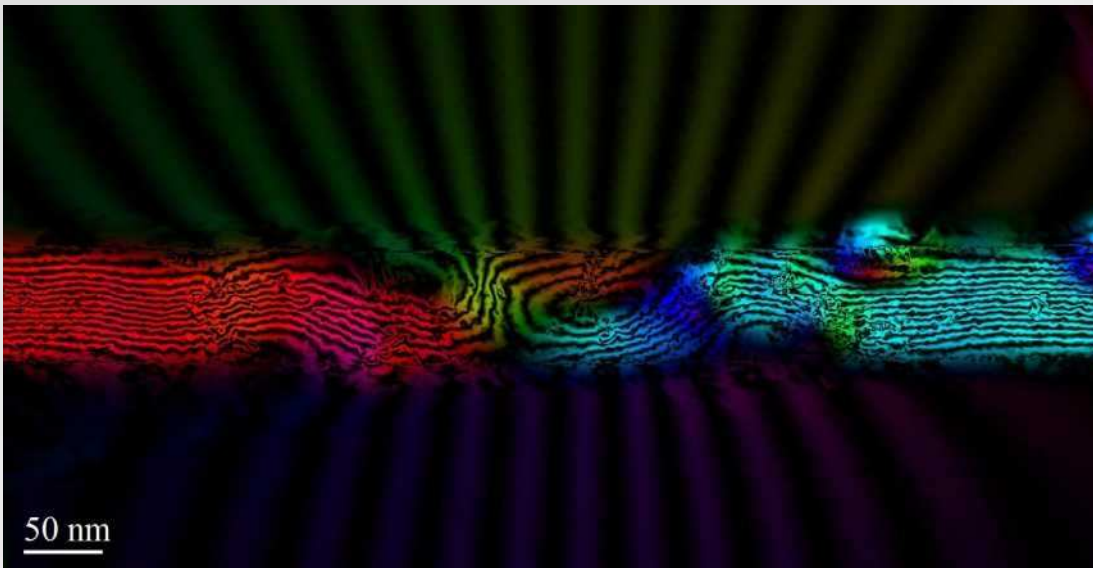
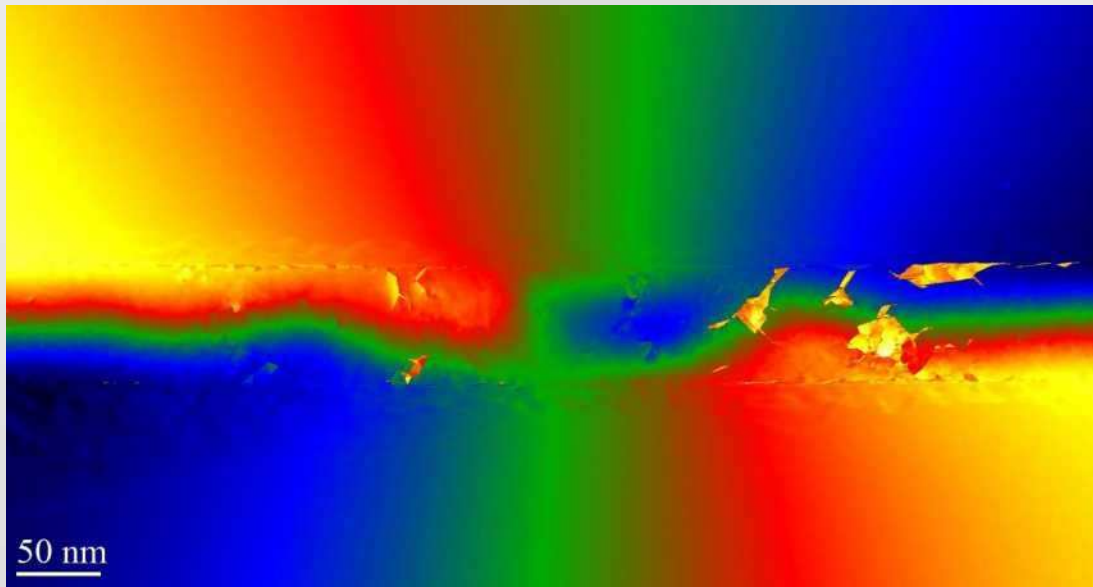
## Nanowires and domain walls



Looking for the  
Bloch Point Wall...



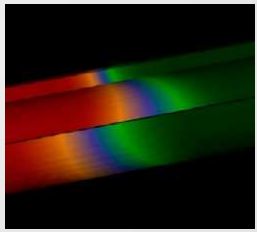
# Nanowires and domain walls



beam  $\parallel z$

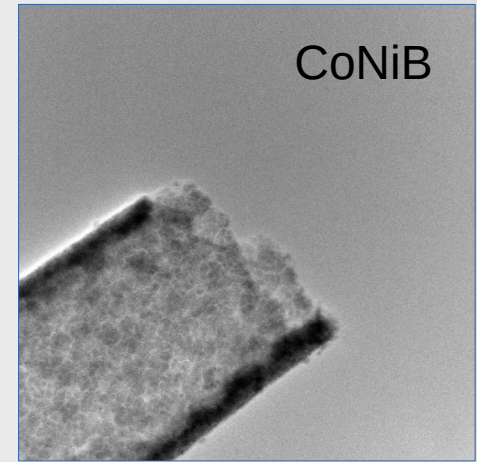
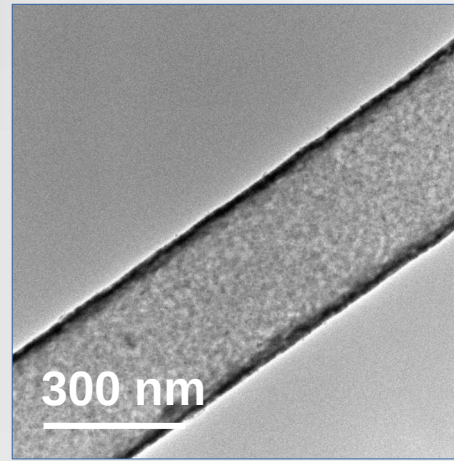


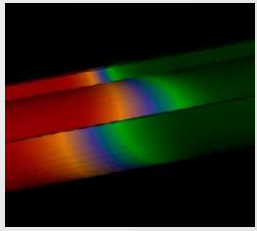




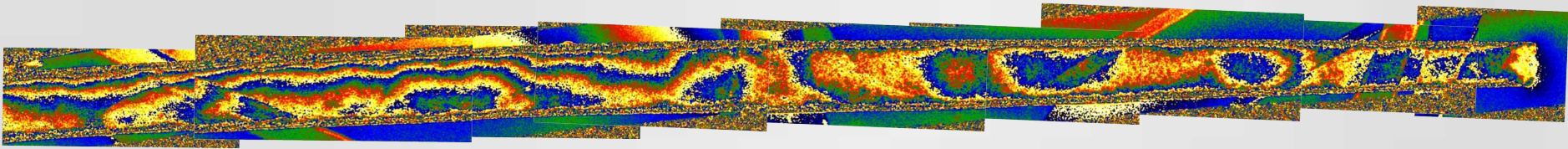
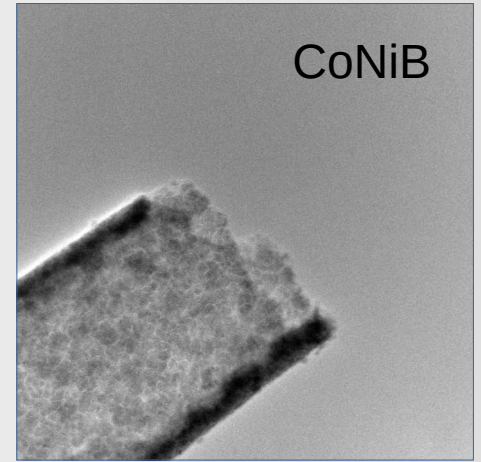
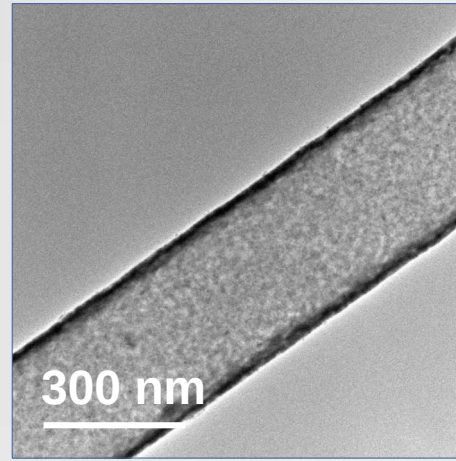
# Magnetic Nanotubes

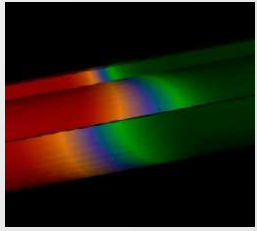
Hertel, R.  
Journal of Physics: Condensed Matter  
28, 483002 (2016).



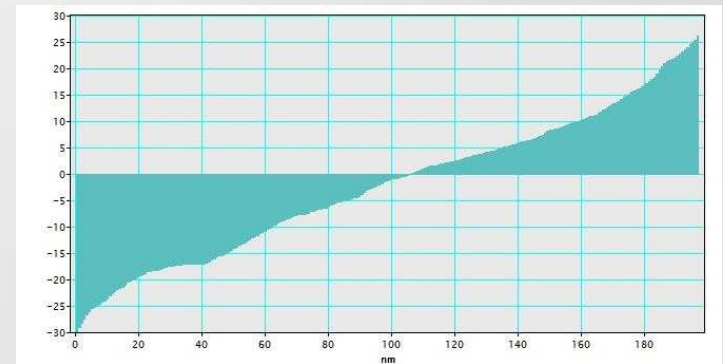
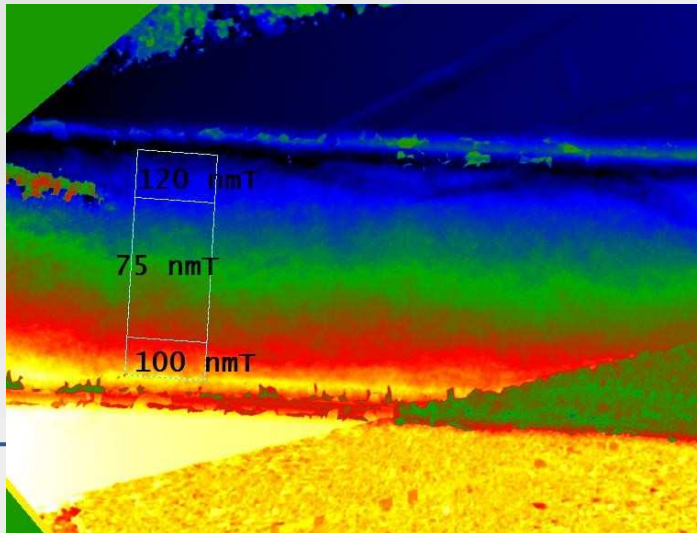
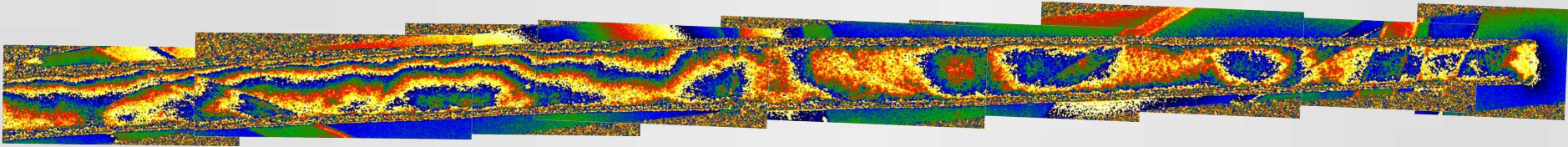
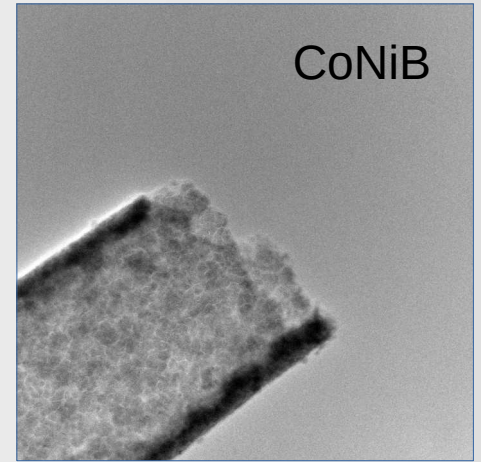
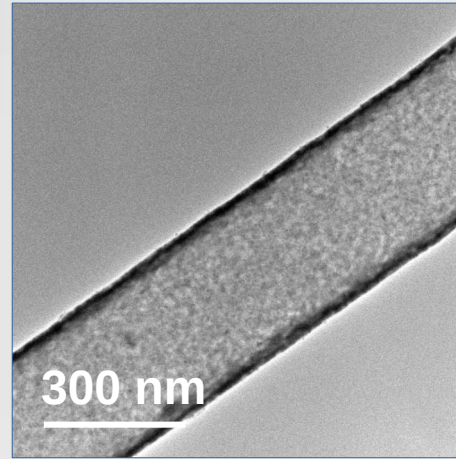


# Magnetic Nanotubes

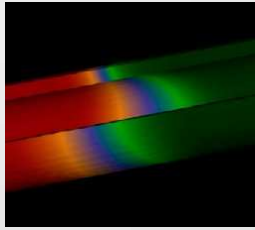




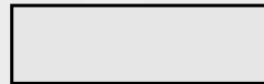
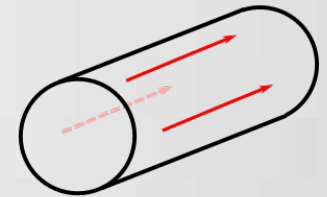
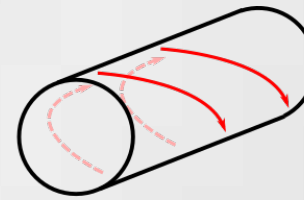
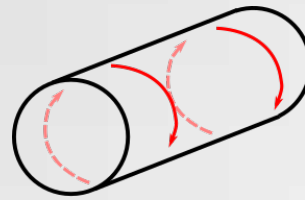
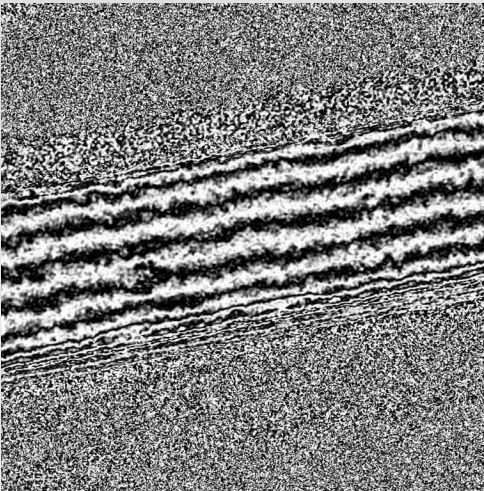
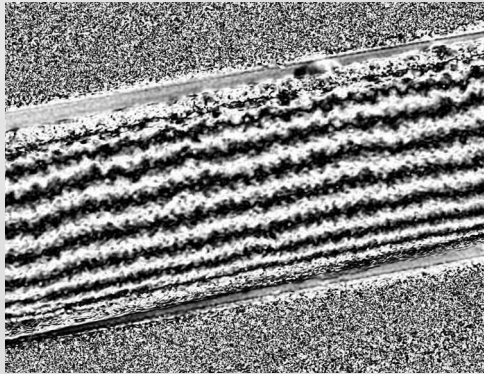
# Magnetic Nanotubes



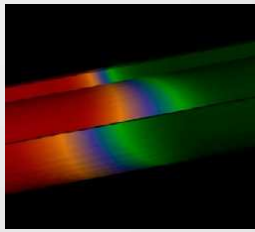




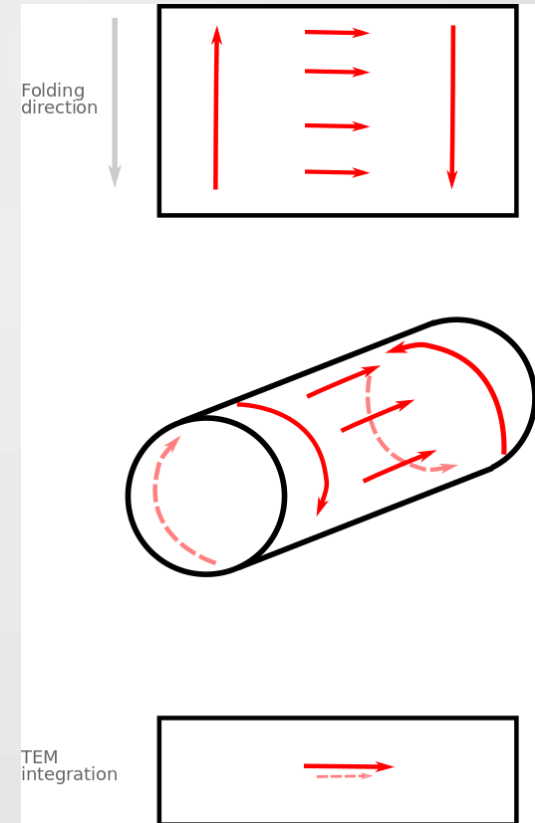
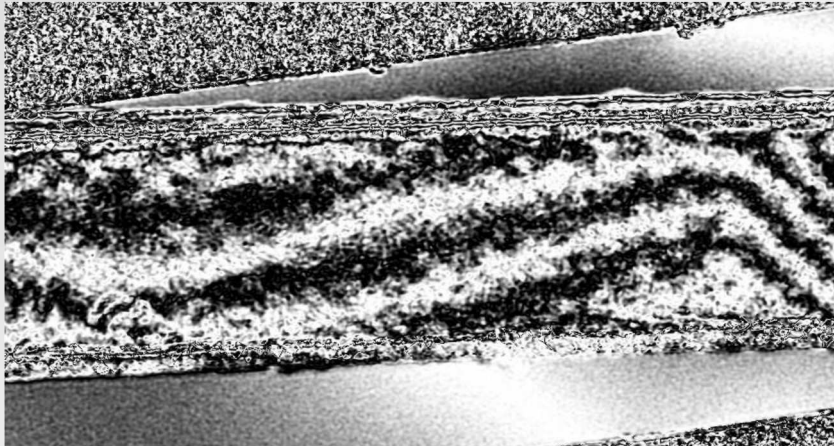
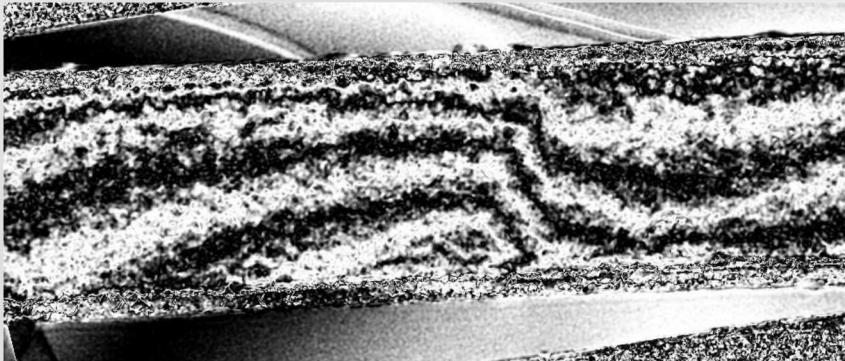
# Magnetic Nanotubes

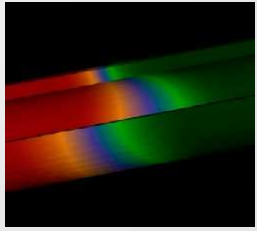




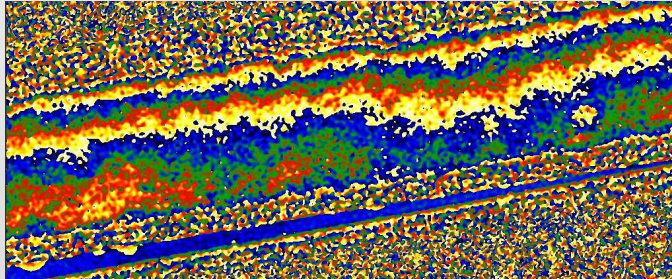


# Magnetic Nanotubes

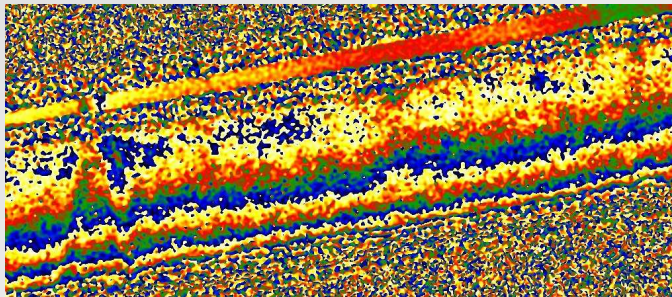




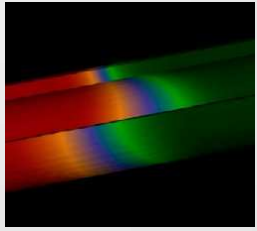
# *Magnetic Nanotubes*



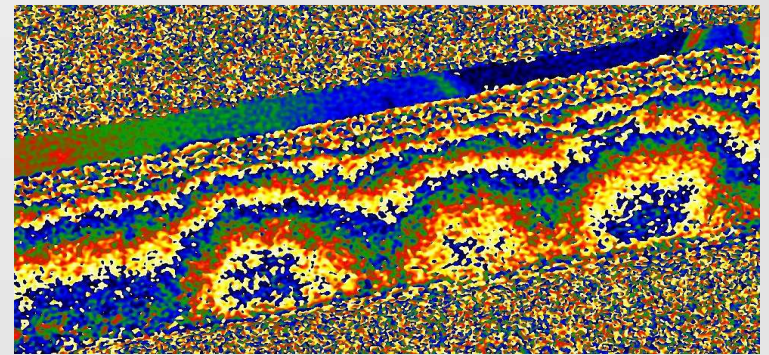
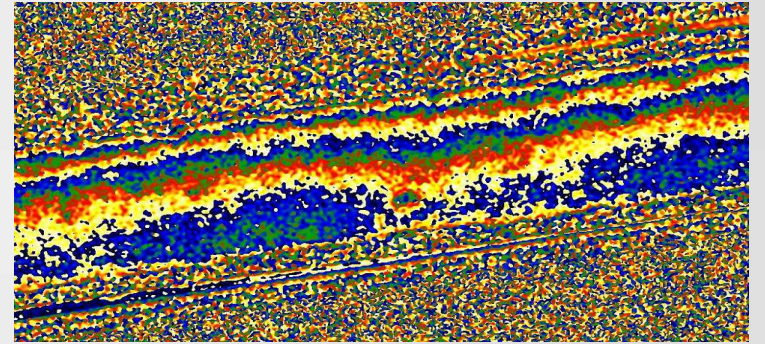
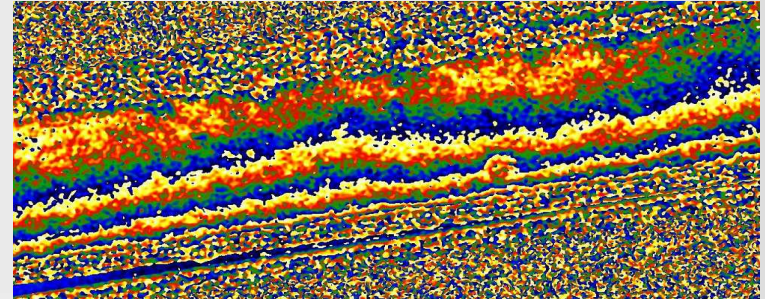
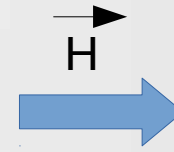
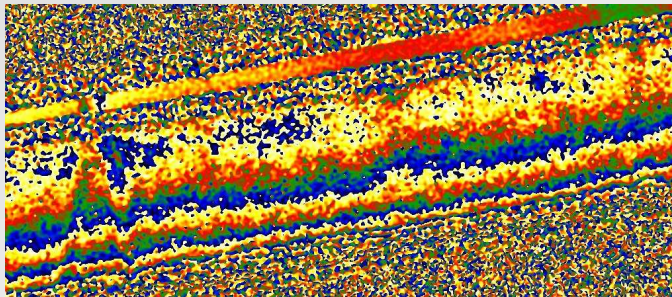
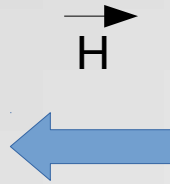
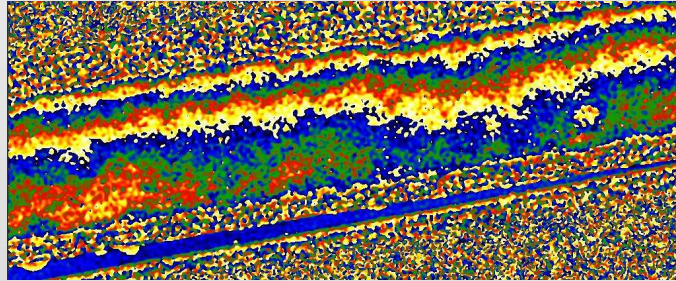
$\rightarrow$   
H





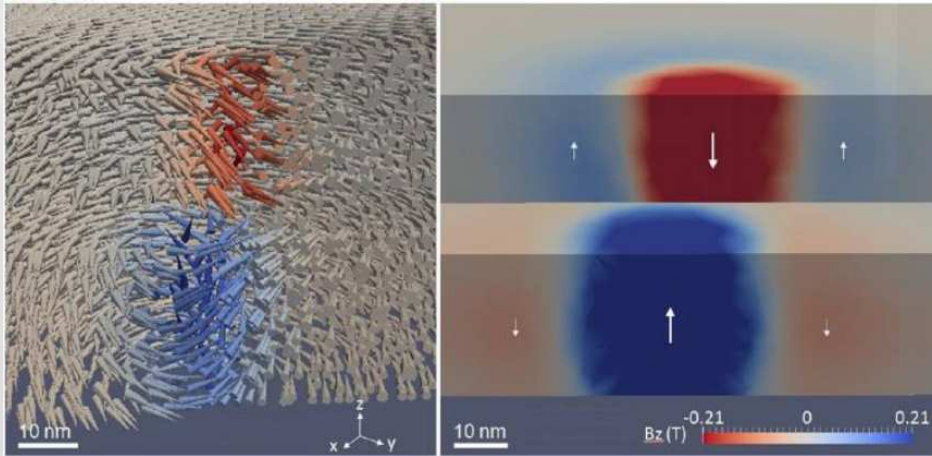


# Magnetic Nanotubes

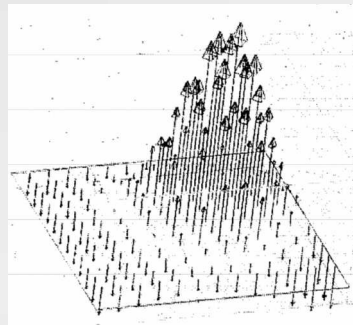




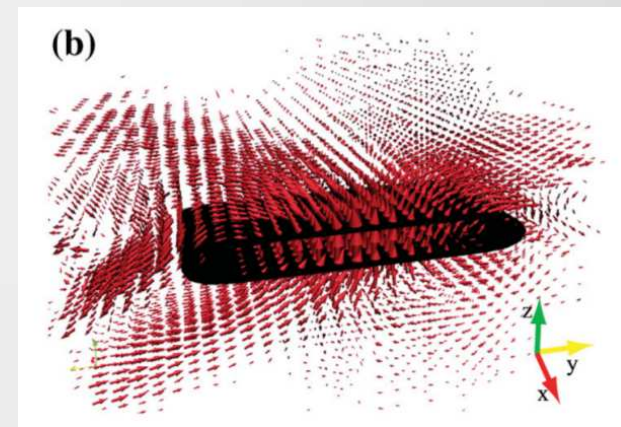
# Vectorial Tomography



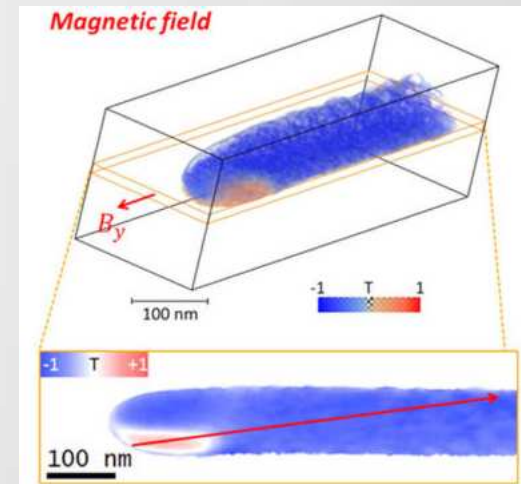
Tanigaki, T. et al.  
Nano Lett. 15, 1309–1314 (2015)



Lai, G. et al.  
Journal of Applied Physics 75, 4593–4598 (1994)



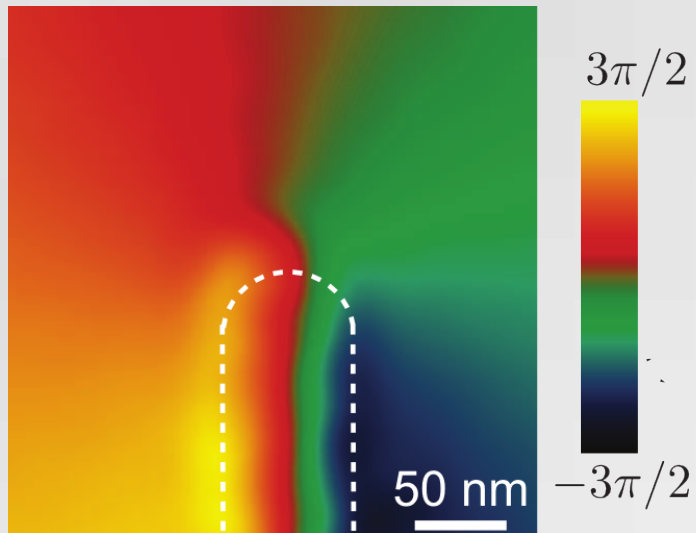
Phatak, C., Petford-Long, A. K. & De Graef, M.  
Phys. Rev. Lett. 104, 253901 (2010).



Wolf, D. et al.  
Chem. Mater. 27, 6771–6778 (2015)

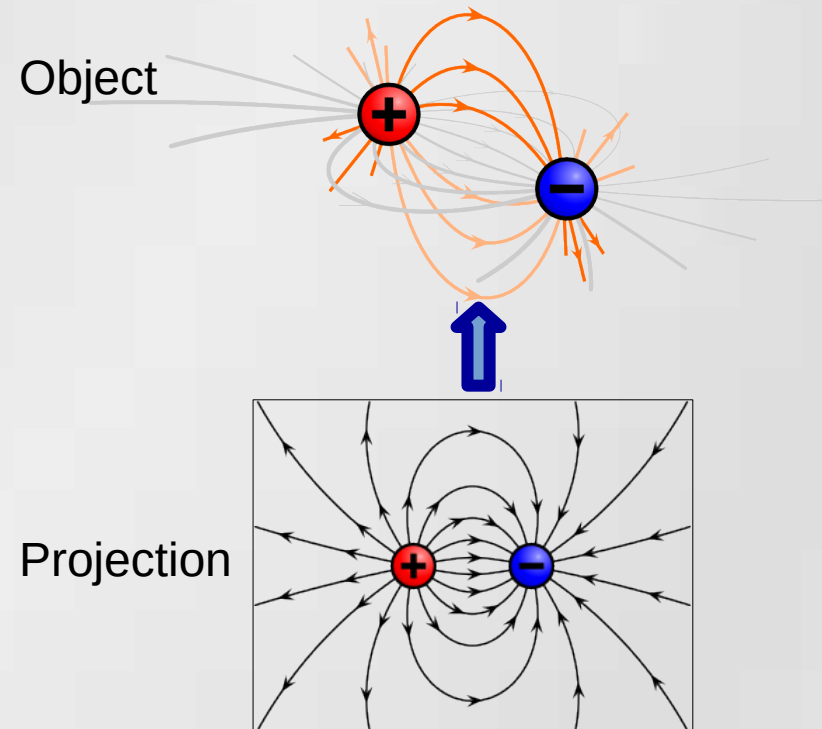


# Vectorial Tomography



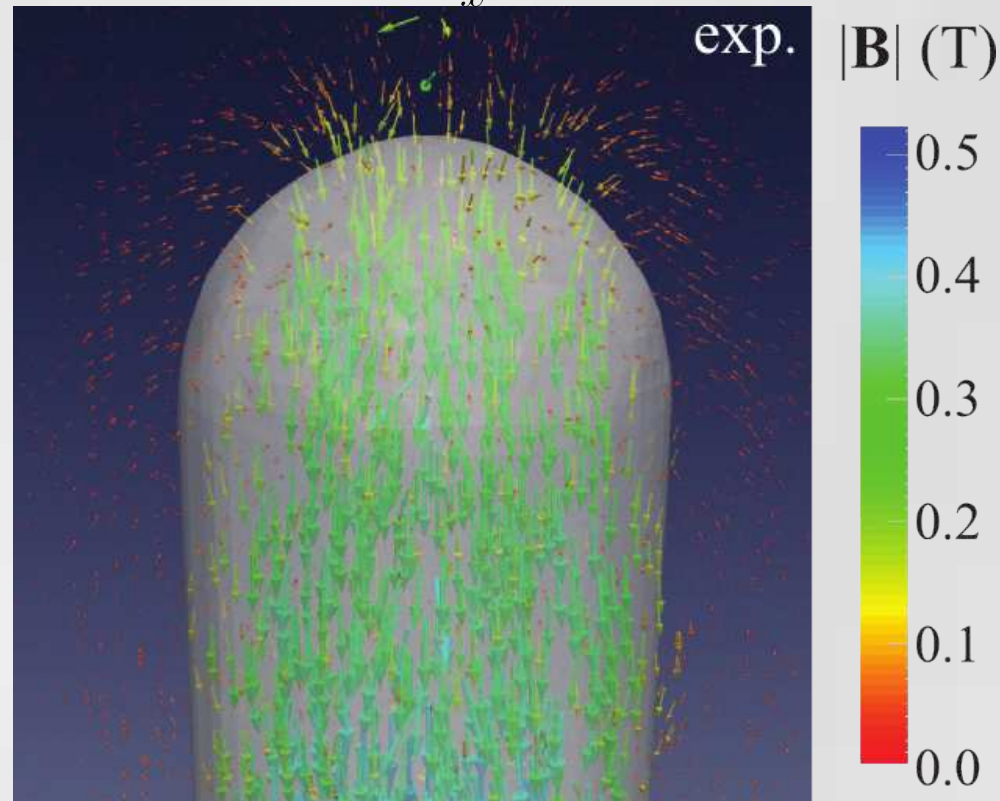
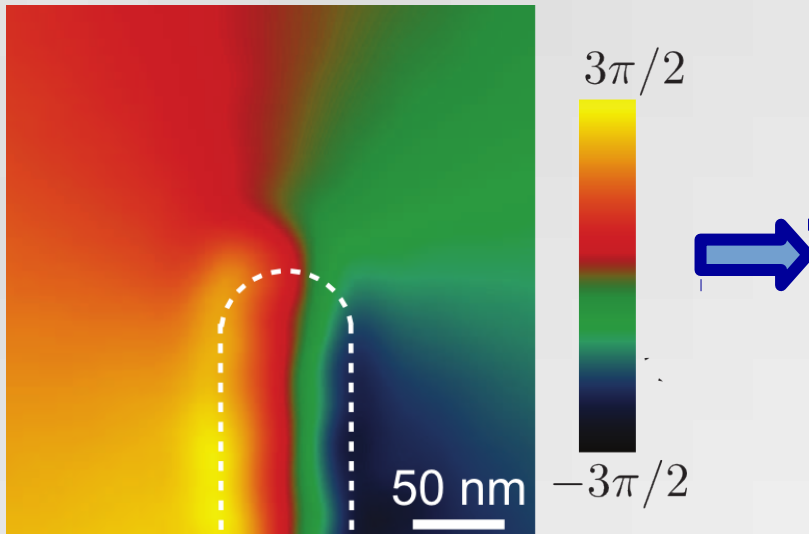
## Abel Transform

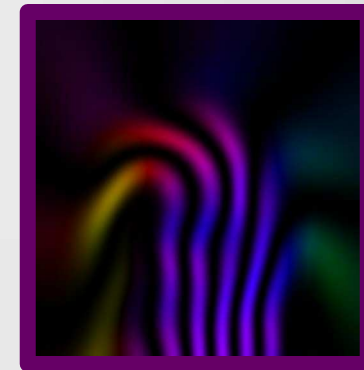
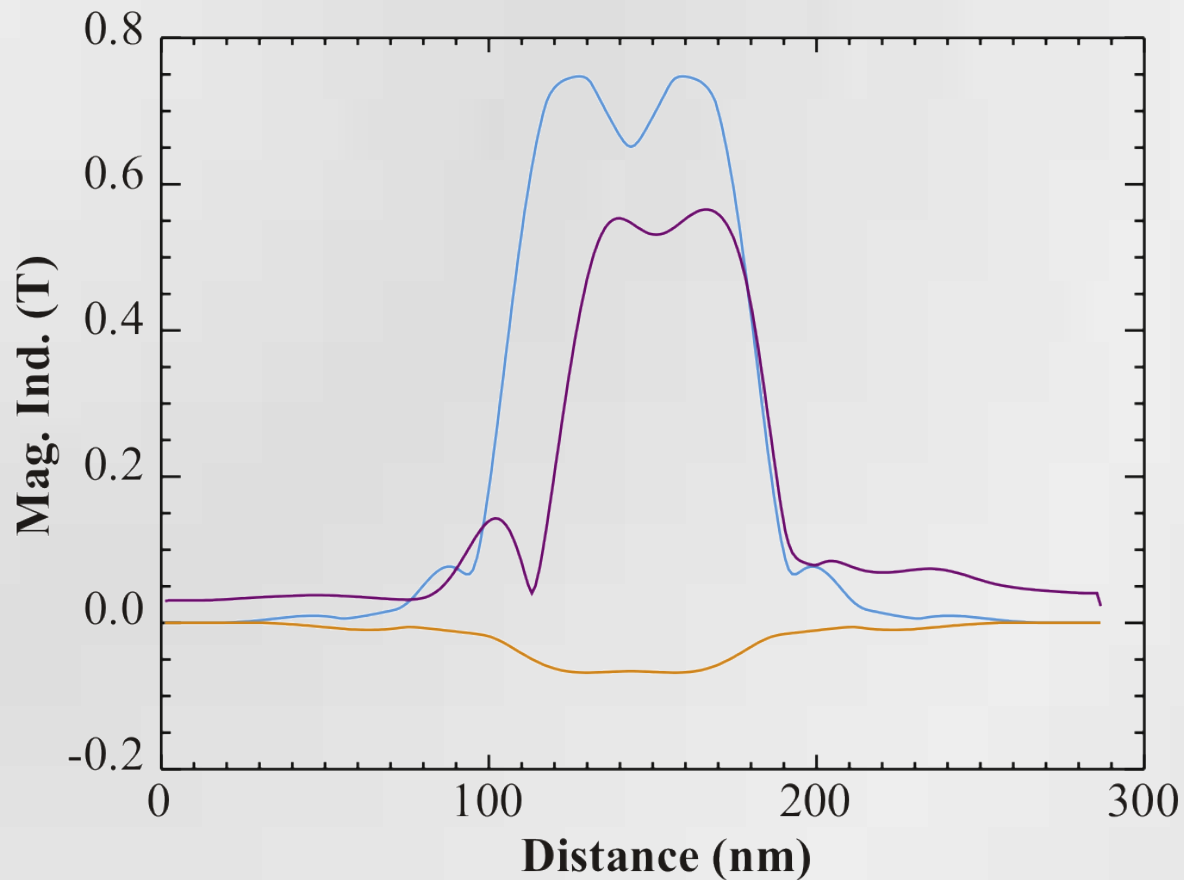
$$F(x, y) = 2 \int_x^\infty \frac{f(\rho, y) \rho}{\sqrt{\rho^2 - x^2}} d\rho$$



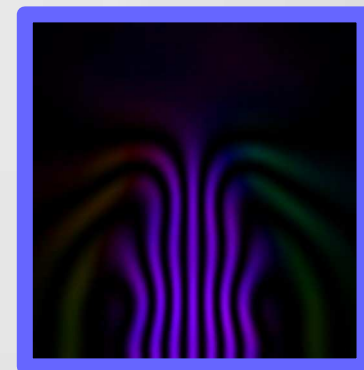
# Abel Transform

$$F(x, y) = 2 \int_x^\infty \frac{f(\rho, y) \rho}{\sqrt{\rho^2 - x^2}} d\rho$$





Projected



Mid-NW



Above-NW

$$\mu_0 M_S = 0,7 \text{ T}$$

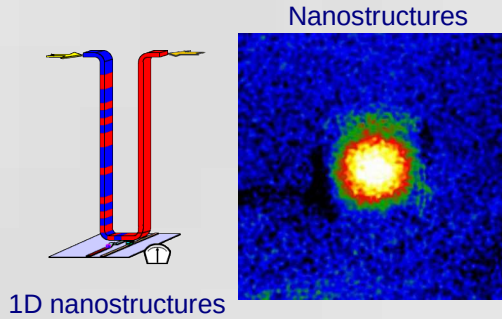
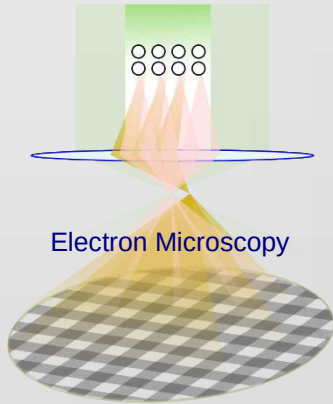
Biziere, N. et al.  
*Nano Lett.* **13**, 2053–2057 (2013)

Phatak, C. et al.  
 Quantitative 3D electromagnetic field determination of 1D nanostructures from single projection.  
*Ultramicroscopy* 164, 24–30 (2016)

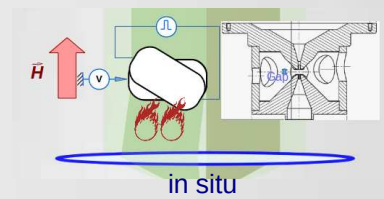
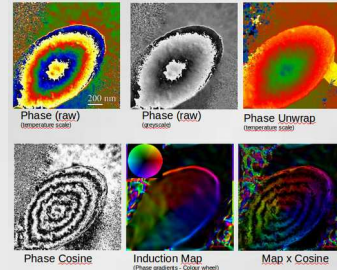
Strasbourg  
 Oct. 2017



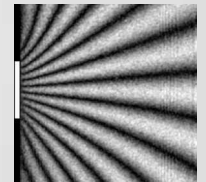
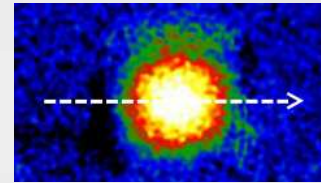
# Electron Microscopy & Micro-magnetism



## Phase Image



## Phase sensitivity

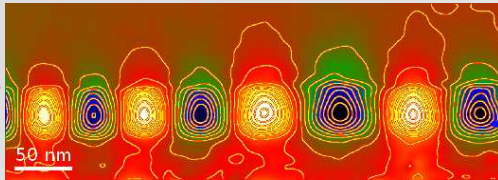


New Techniques

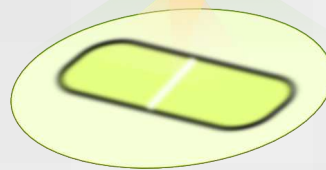
## Out-of-Axis vs In-Line

★★★★★	Spatial Resolution	★★★★★
★★★★★	Field of View	★★★★★
★★★★★	Sensitivity	★★★★★
★★★★★	Dynamic	★★★★★
★★★★★	Versatility	★★★★★
★★★★★	Quantification	★★★★★
★★★★★	Implementation	★★★★★

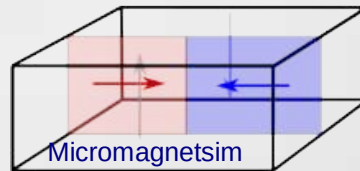
Thin Foils



## Magnetic Imaging



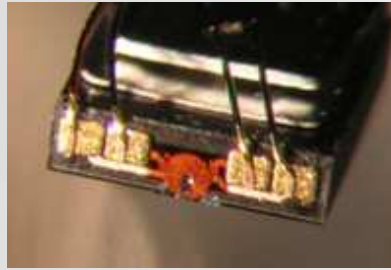
Devices



in situ

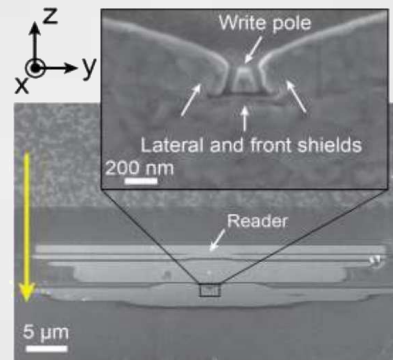
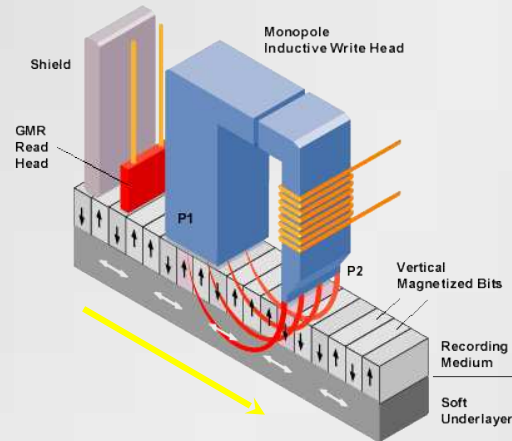


# Devices

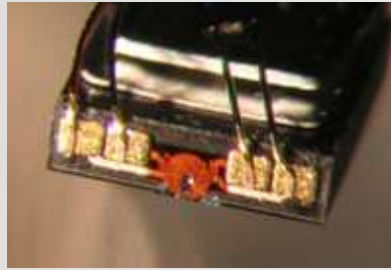


« A hard drive head is like a spaceship flying at a speed of Mach 2, 10 cm above the ground, counting grass by stalk packages of 10, over a field as big as Ireland. »

John Chapman

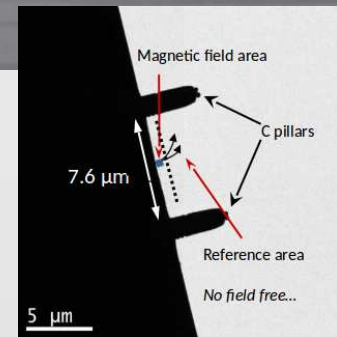
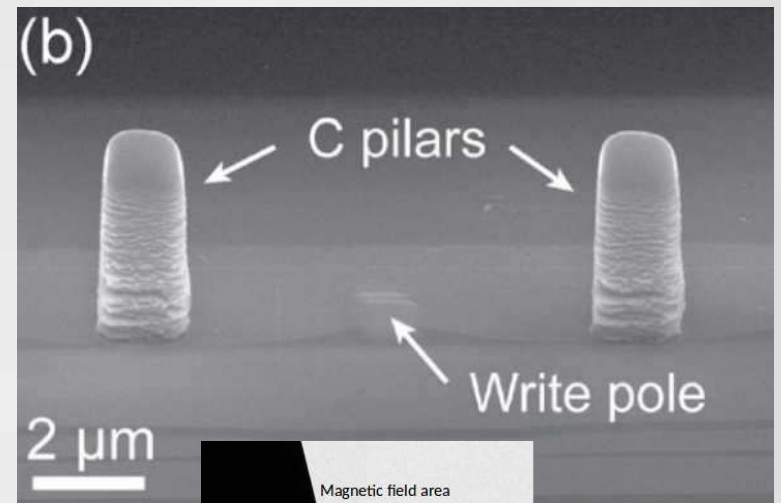
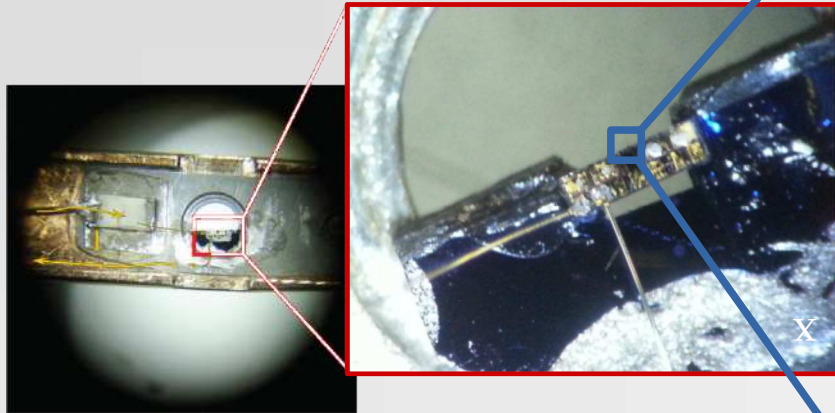


# Devices

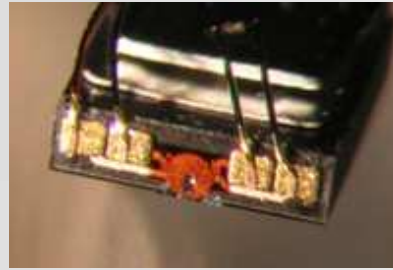


« A hard drive head is like a spaceship flying at a speed of Mach 2, 10 cm above the ground, counting grass by stalk packages of 10, over a field as big as Ireland. »

John Chapman



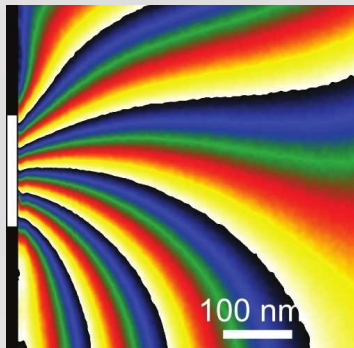
# Devices



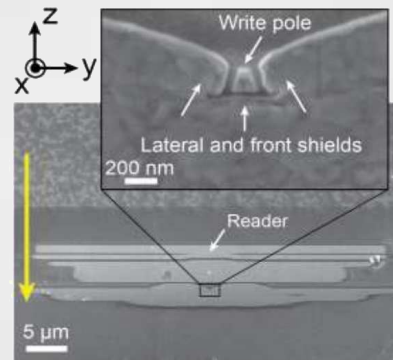
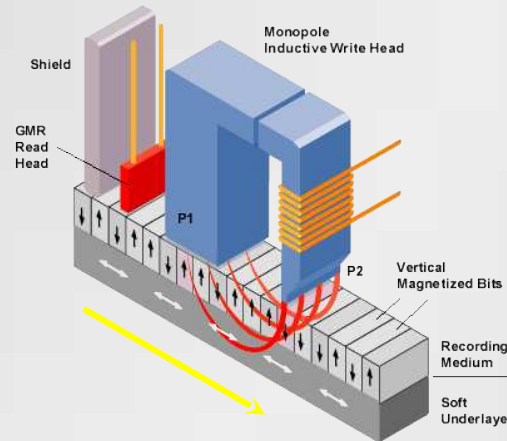
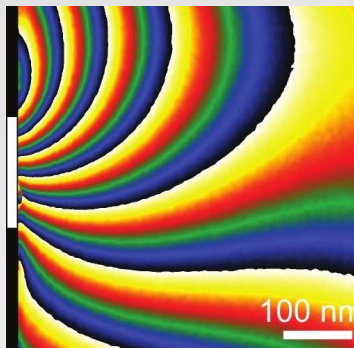
« A hard drive head is like a spaceship flying at a speed of Mach 2, 10 cm above the ground, counting grass by stalk packages of 10, over a field as big as Ireland. »

John Chapman

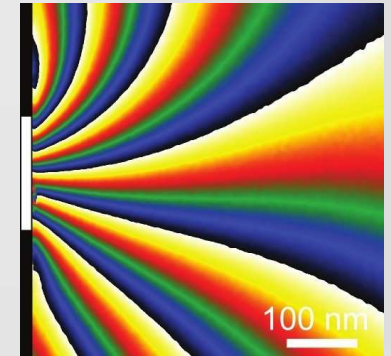
+60 mA



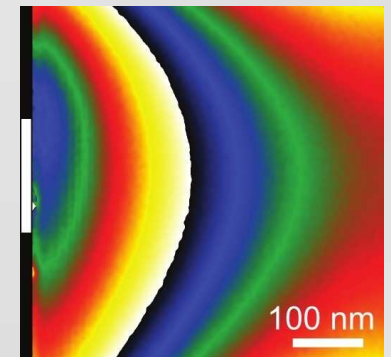
-60 mA



SUM

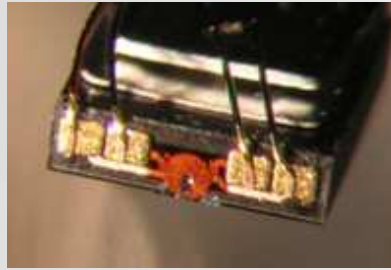


DIFF





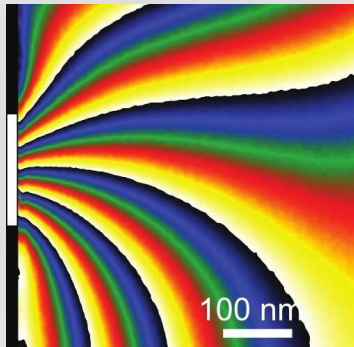
# Devices



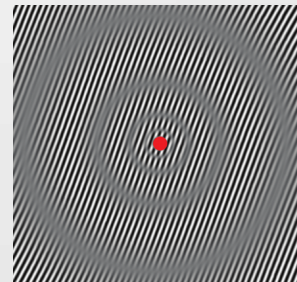
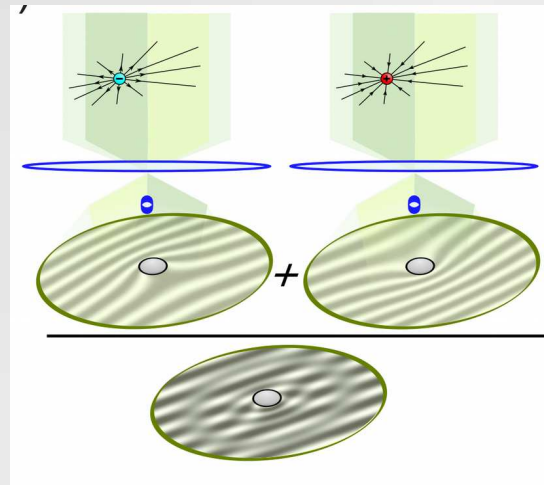
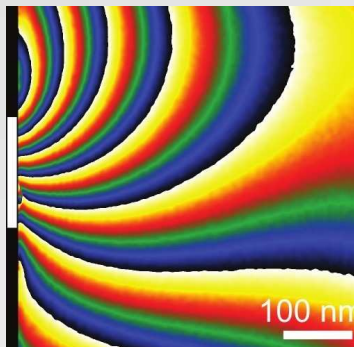
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John Chapman

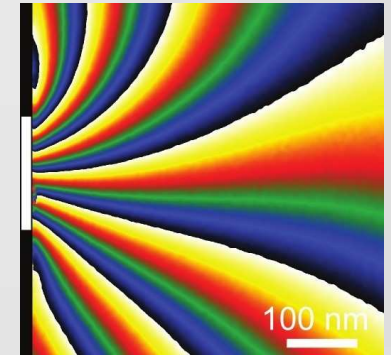
+60 mA



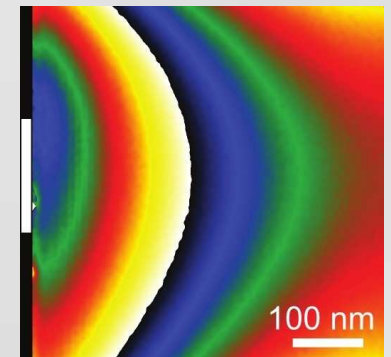
-60 mA



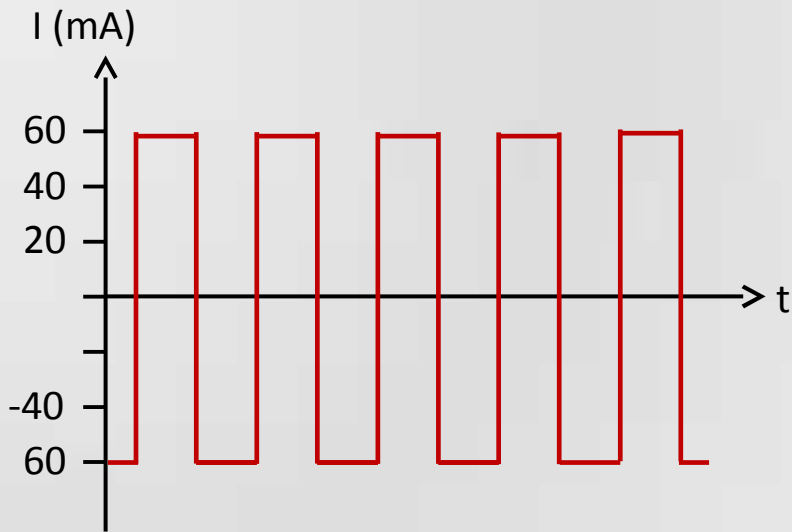
SUM



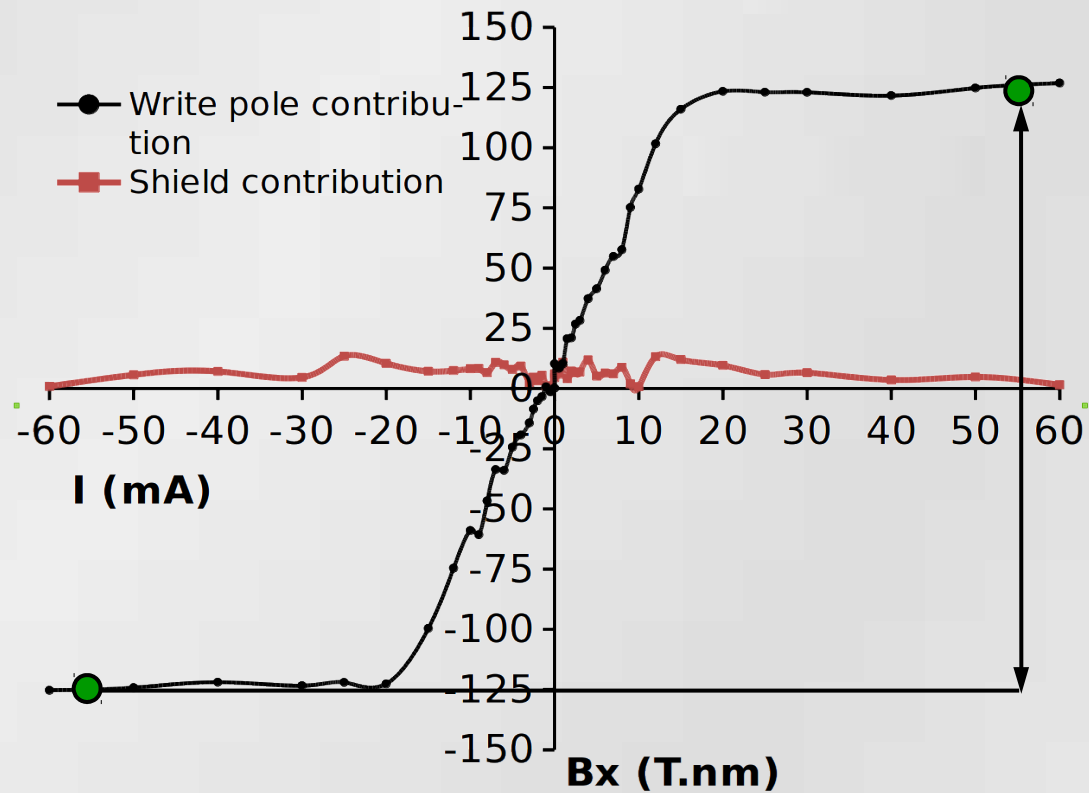
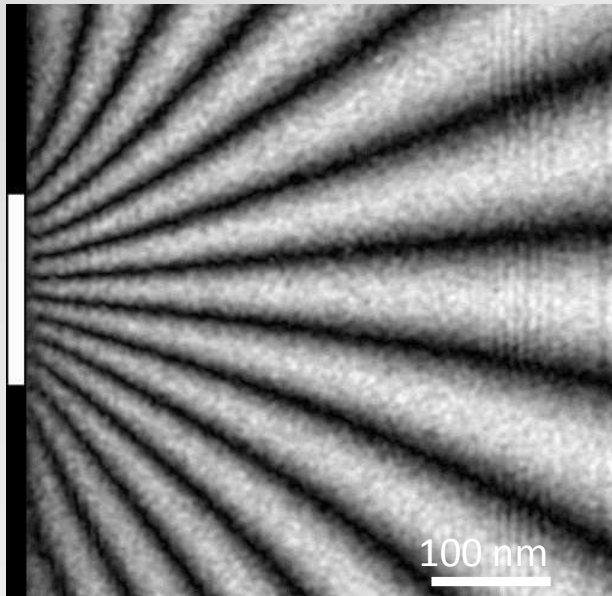
DIFF

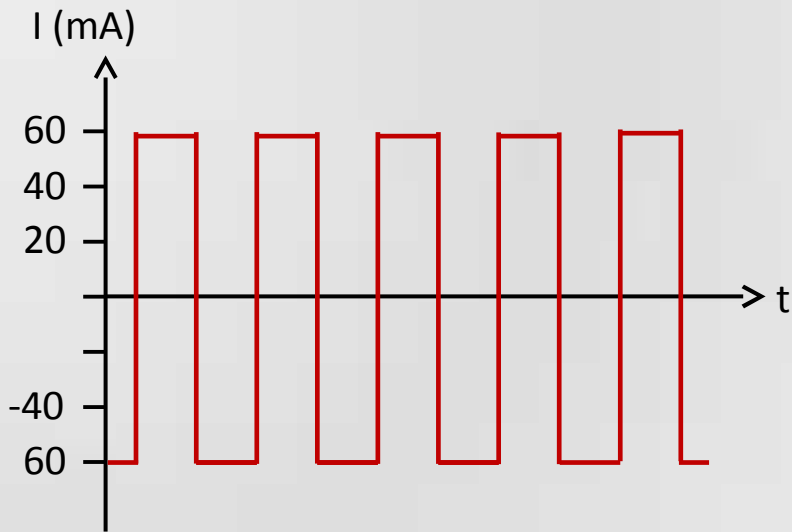






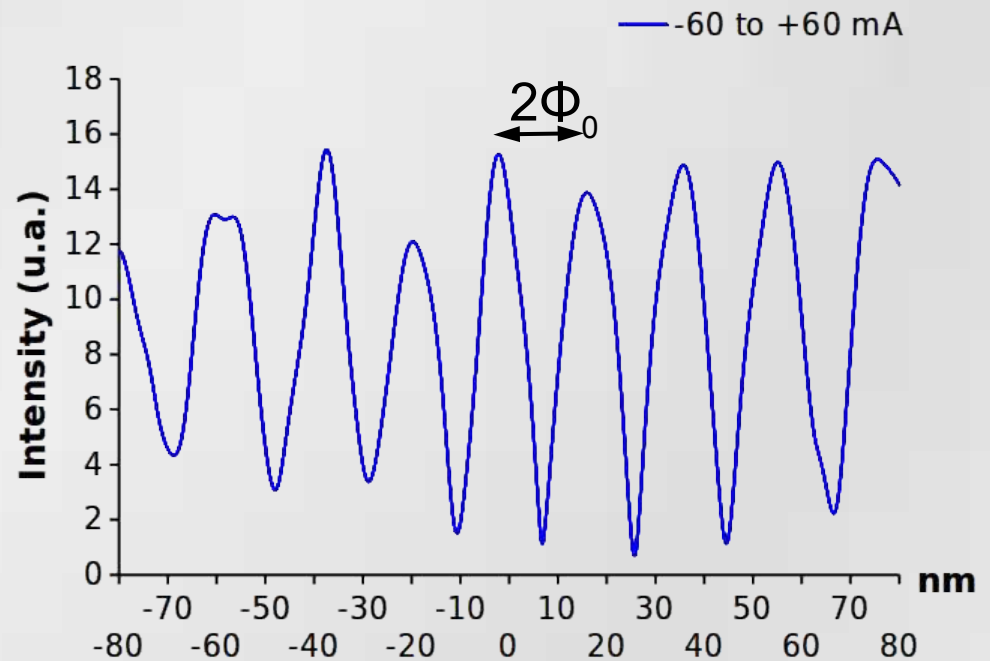
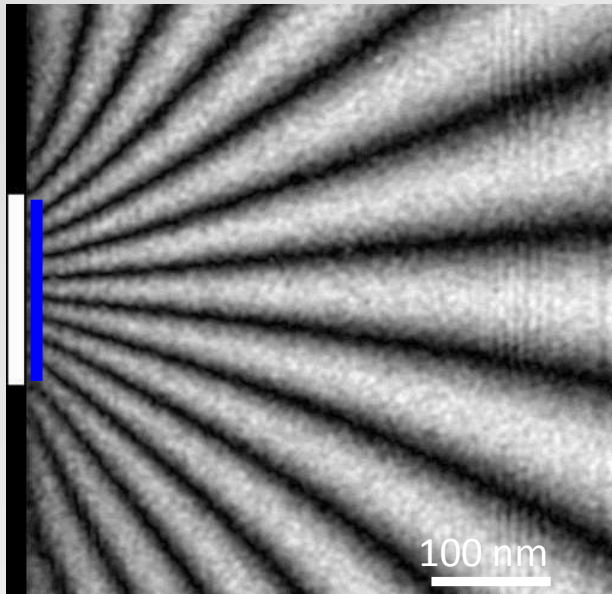
$25 \Phi_0 \iff 260 \text{ T.nm}$   
 (pole extension of 200 nm)

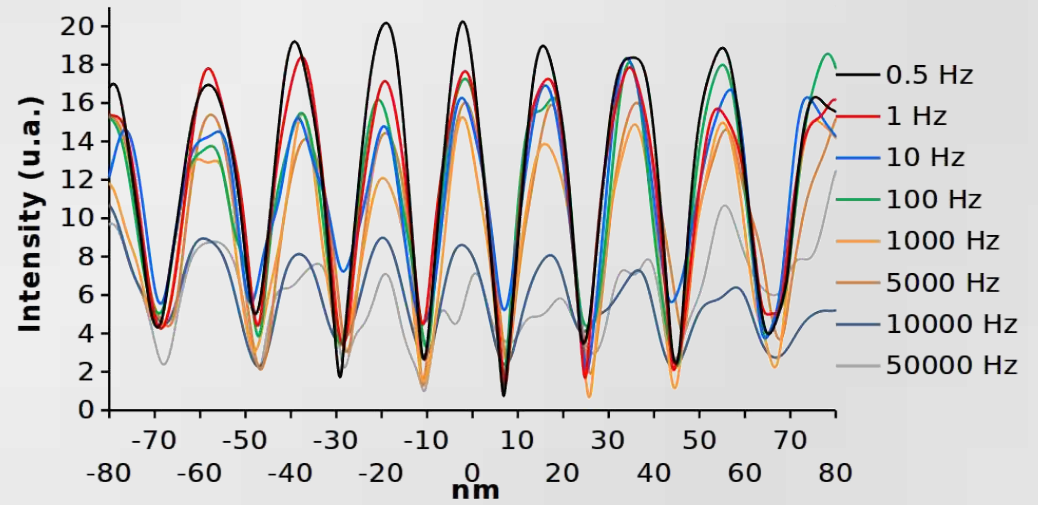
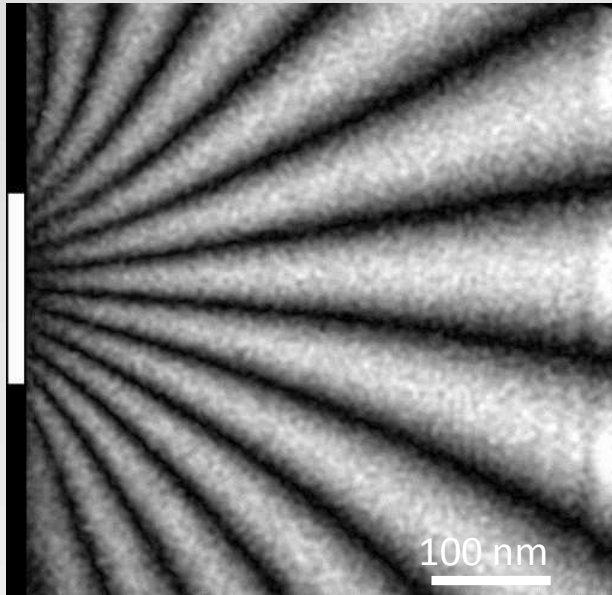
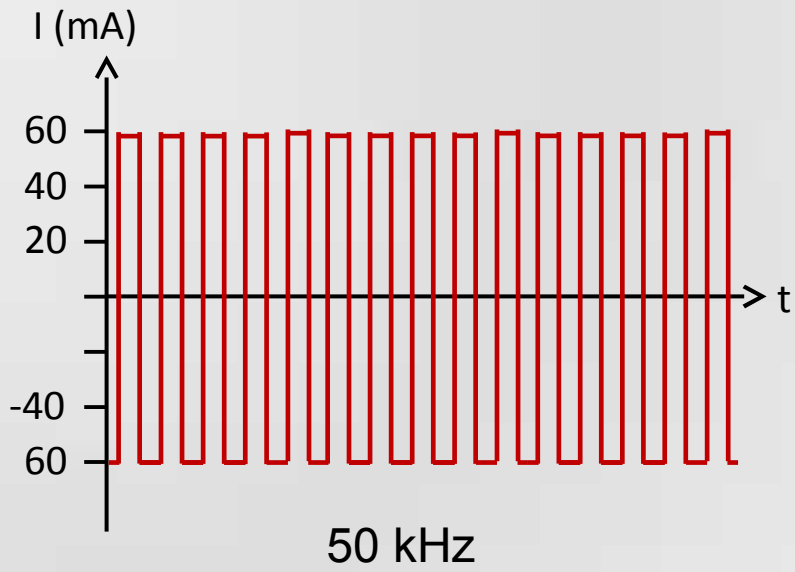




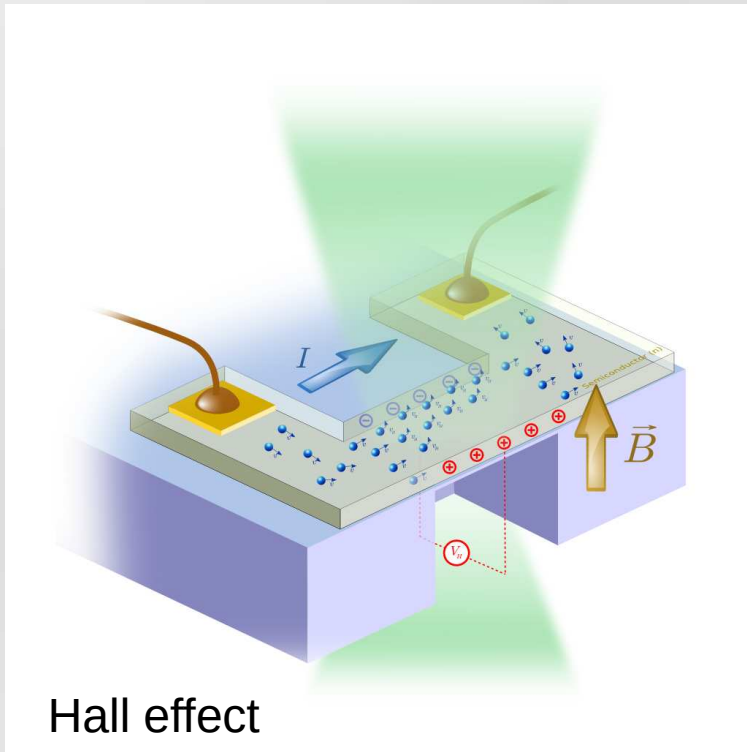
$25 \Phi_0 \iff 260 \text{ T.nm}$   
 (pole extension of 200 nm)

$0,11 \Phi_0 / \text{nm} \iff 235 \text{ T.nm}$

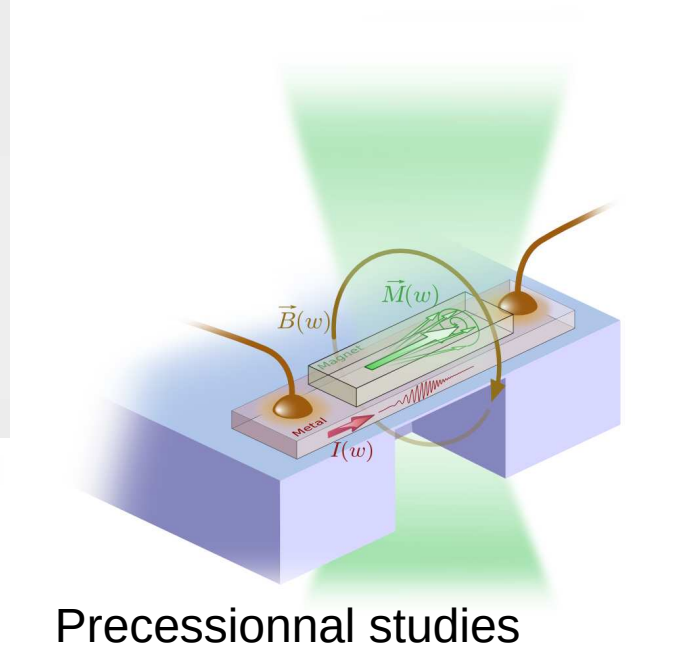
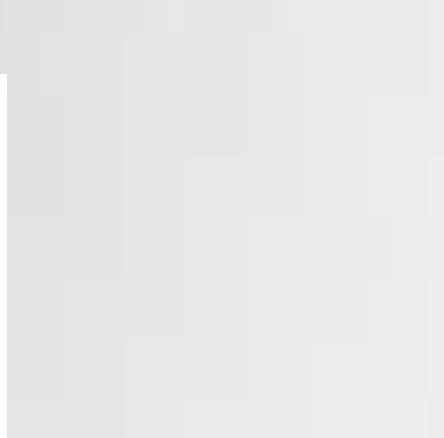




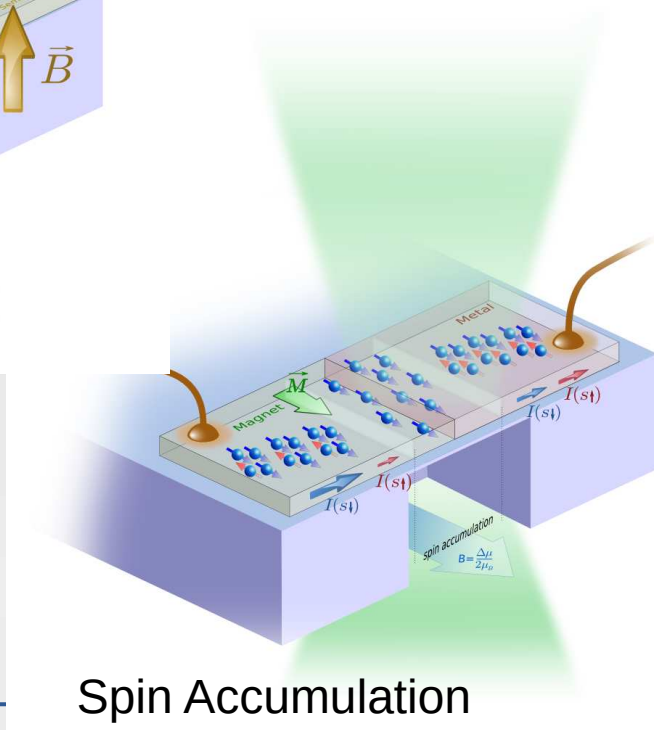
# Devices



Hall effect



Precessional studies



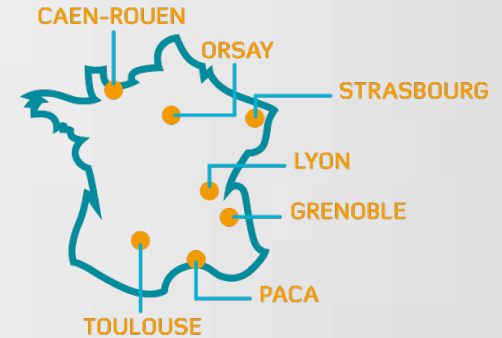
Spin Accumulation



**Merci**

**French network**

<http://www.metsa.fr/>



**Apply for  
electron beam time**

**European network (under renewal)**

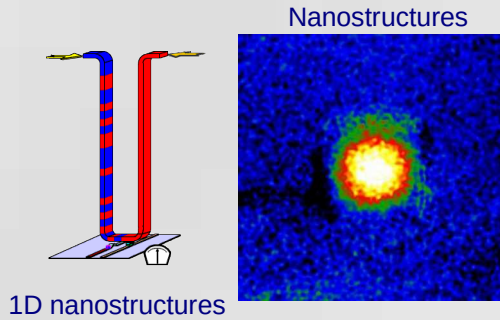
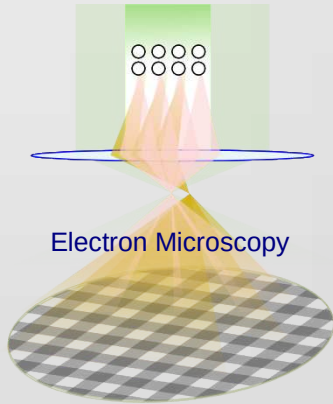
<http://esteem2.eu/>



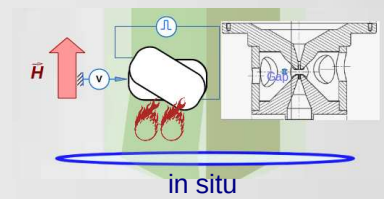
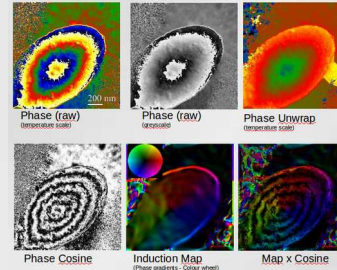
Strasbourg  
Oct. 2017



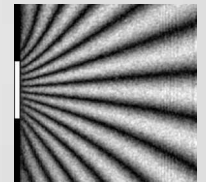
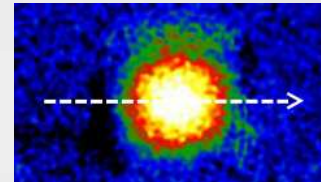
# Viel mal merci fer ehri Uffmerksamkeit



## Phase Image



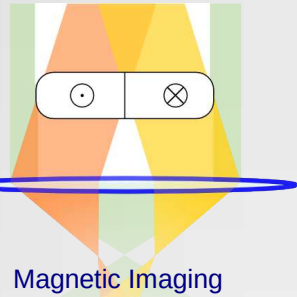
## Phase sensitivity



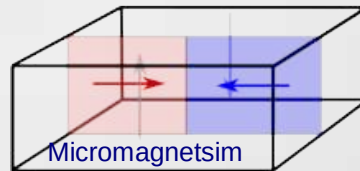
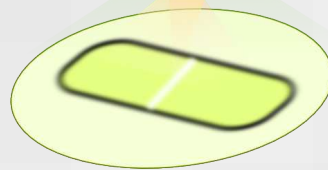
New Techniques

## Out-of-Axis vs In-Line

★★★★★	Spatial Resolution	★★★★★
★★★★★	Field of View	★★★★★
★★★★★	Sensitivity	★★★★★
★★★★★	Dynamic	★★★★★
★★★★★	Versatility	★★★★★
★★★★★	Quantification	★★★★★
★★★★★	Implementation	★★★★★

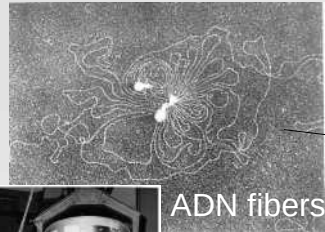


## Devices

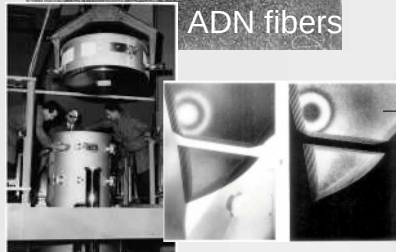


# CEMES

1957 – Opening of LOE *(by Gen. De Gaulle)*



1958 – 1,5 MeV microscope



1970 – 3 MeV microscope

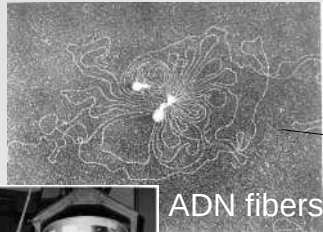
1980 – 1,6 MeV cold-cathode STEM



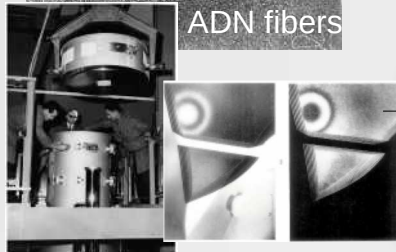


# CEMES

1957 – Opening of LOE *(by Gen. De Gaulle)*



1958 – 1,5 MeV microscope



1970 – 3 MeV microscope

1980 – 1,6 MeV cold-cathode STEM



1989 – CEMES





# ***CEMES***

2004 – First commercial  
Cs-Corrected microscope



# CEMES

2004 – First commercial  
Cs-Corrected microscope



2012 – I2TEM



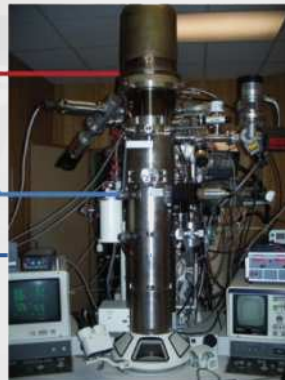
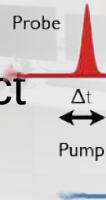
# CEMES

2004 – First commercial  
Cs-Corrected microscope



2012 – I2TEM

... – the femtoTEM project





# CEMES

*CEMES in 2017*

7 TEM's - *open for users and external (networks)*

2 FIB's - *« nano Swiss Army knife »*

Scanning Probes  $\mu$  - *dedicated*

Clean Room Facility - *« PicoLab »*





# ***CEMES***

*CEMES in 2017*

Staff :

200 persons (~ 120 permanents)

7 Research Groups & 3 Technical Clusters



# CEMES

*CEMES in 2017*

Staff :

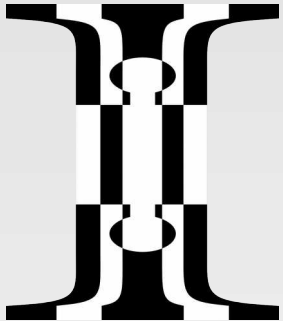
200 persons (~ 120 permanents)

7 Research Groups & 3 Technical Clusters

## I3EM

(hosted by C. Gatel)

Christophe Gatel  
Florent Houdellier  
Martin Hýtch  
Aurélien Masseboeuf  
Etienne Snoeck  
Bénédicte Warot



# ***Emerging Techniques***

***Cylindrically Symetric Vectorial Field Tomography (VFET)***

***Dynamical Holographic Moirés (DHM)***

***Electron Magnetic Circular Dichroism (EMCD)***

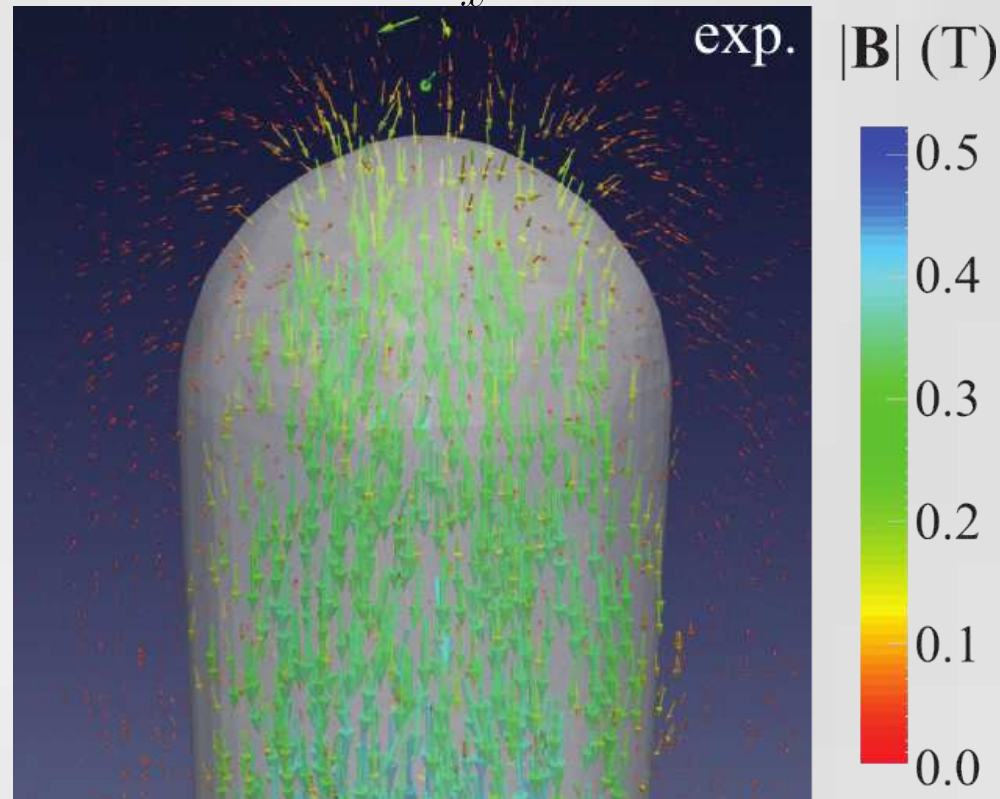
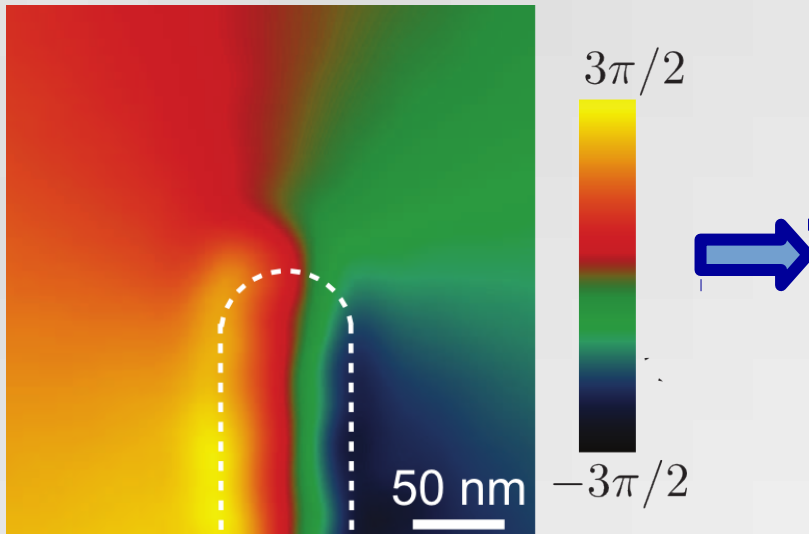
***Charge Counting***

***UltraFast Electrom Microscopy (UEM)***

# Abel Transform

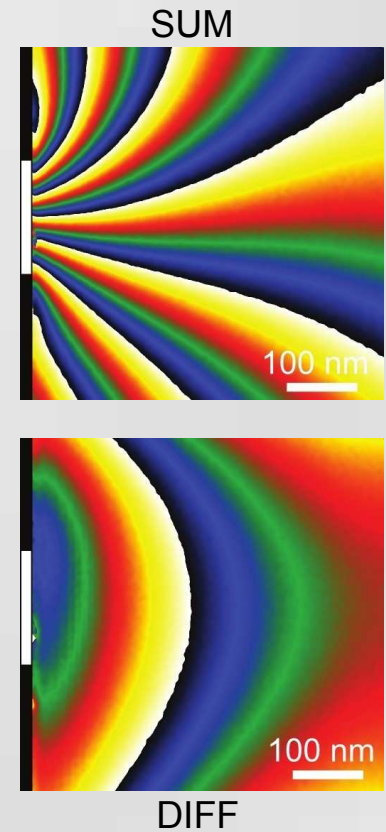
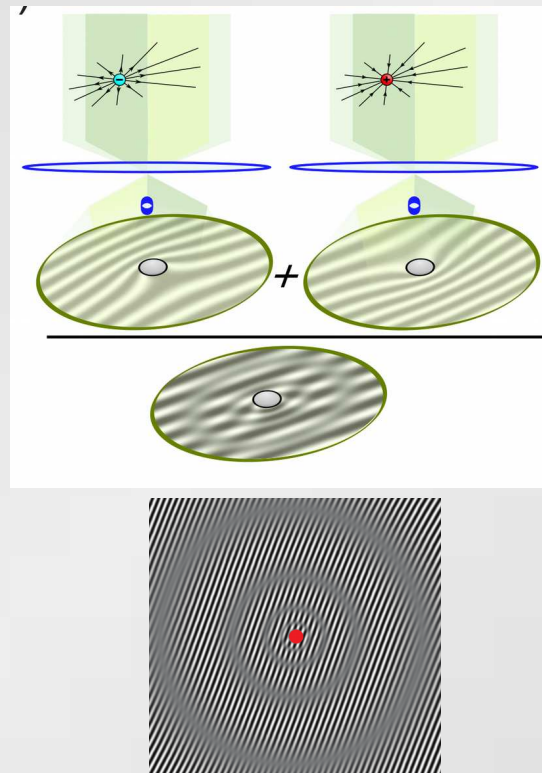
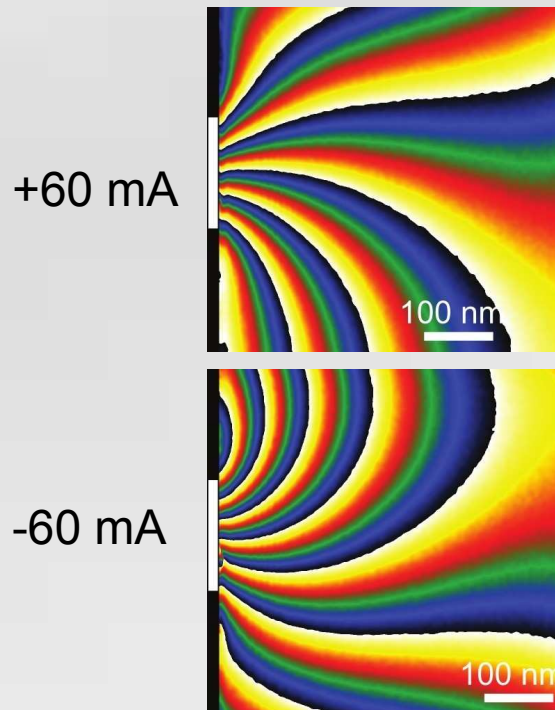
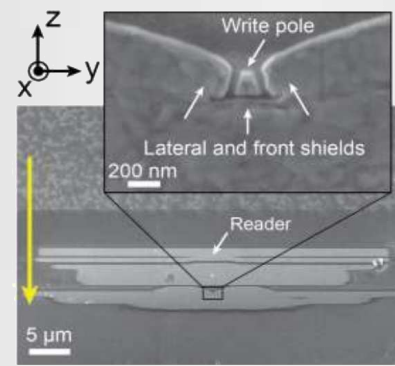
## Cylindrically Symmetric Vectorial Field Tomography (VFET)

$$F(x, y) = 2 \int_x^\infty \frac{f(\rho, y) \rho}{\sqrt{\rho^2 - x^2}} d\rho$$

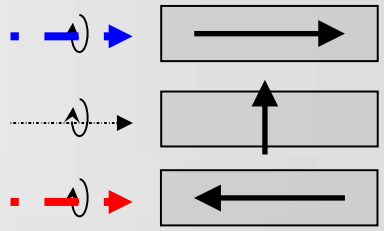




# Dynamical Holographic Moirés (DHM)

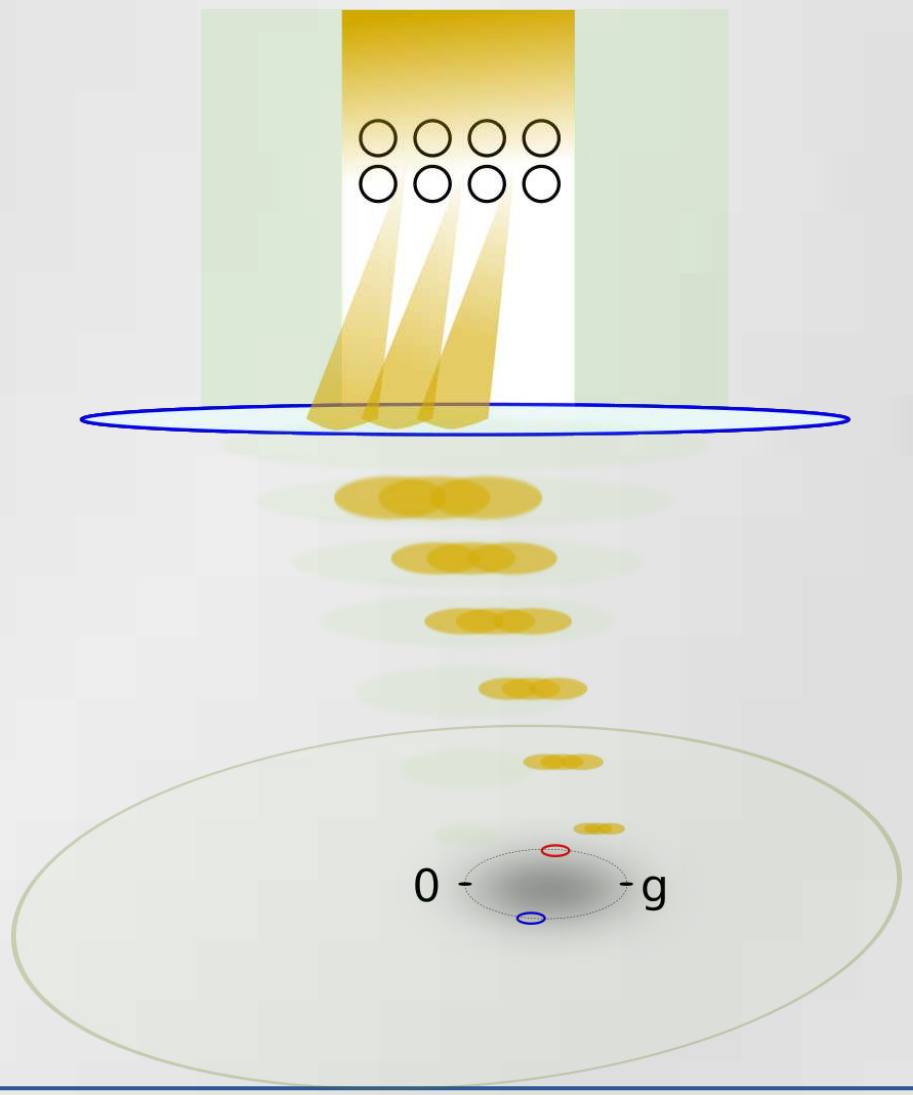
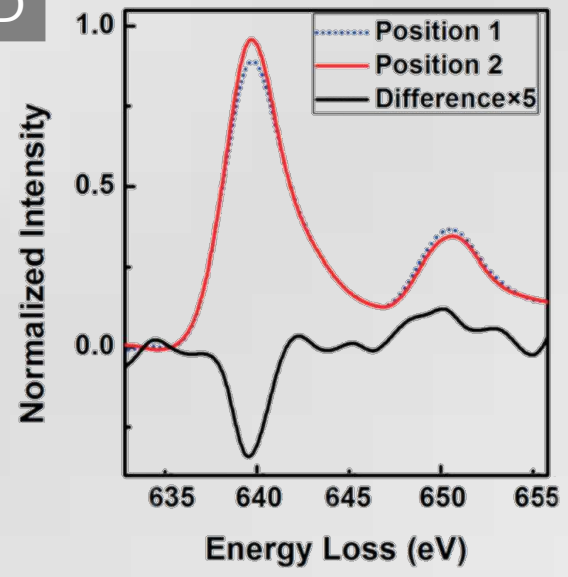


# Electron Magnetic Circular Dichroism (EMCD)



XMCD

EMCD

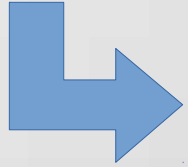


$m_l/m_s$	Hard axis [0001]	Intermediate axis [1100]	Easy axis [1120]
EMCD	$0.06 \pm 0.04$	$0.08 \pm 0.04$	$0.09 \pm 0.04$
XMCD			$0.03 \pm 0.01^a$
DFT	0.005	0.008	0.008

<sup>a</sup>Reference [8].

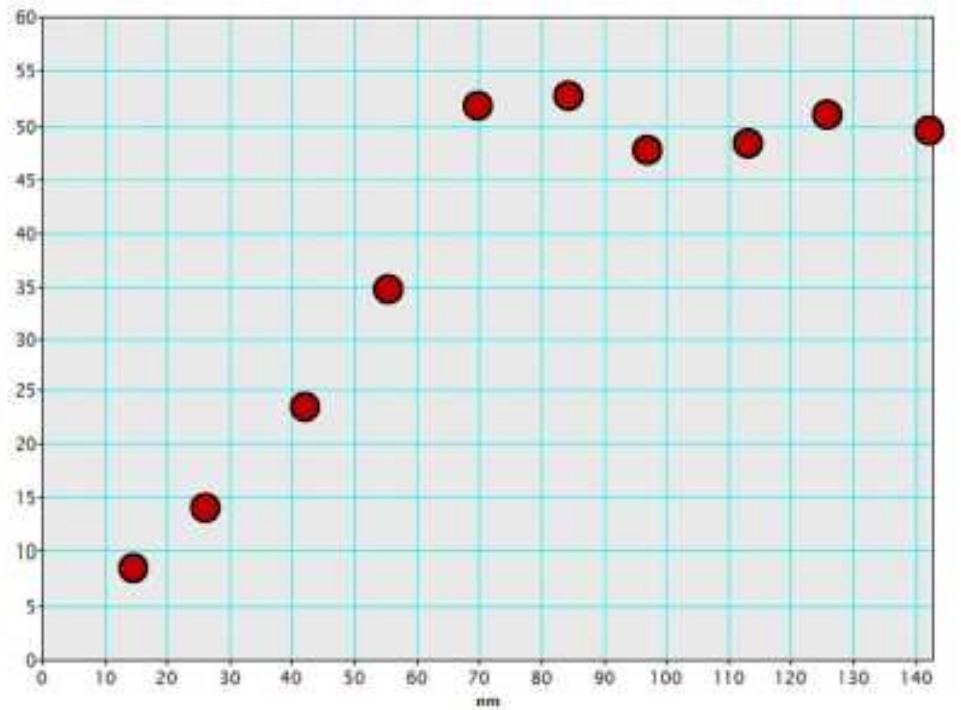
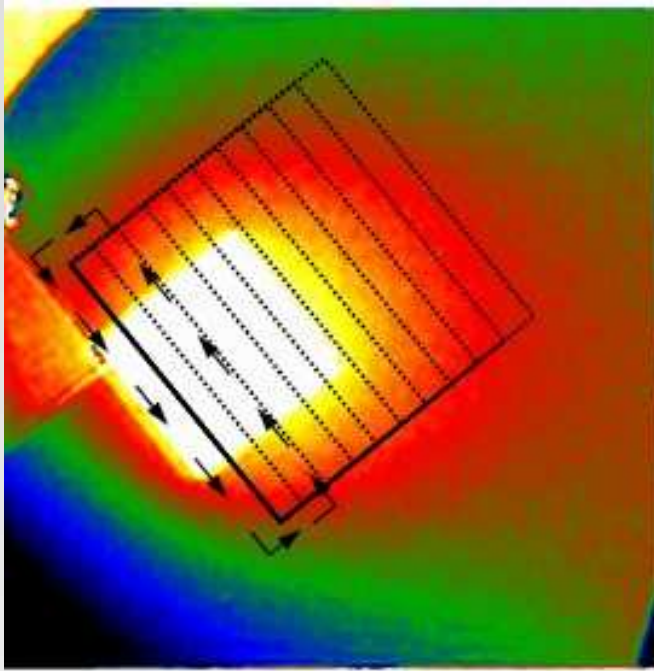
## Charge Counting

$$\Delta\phi = C_E \int_{-\infty}^{\infty} V dz - \frac{e}{\hbar} \int_{-\infty}^{\infty} A_z dz$$

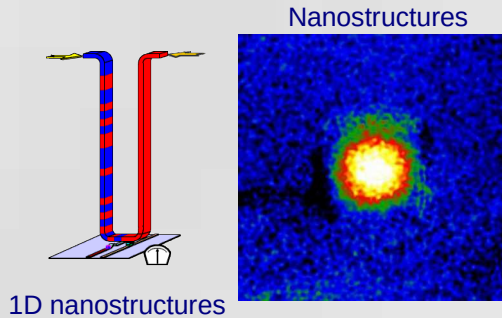
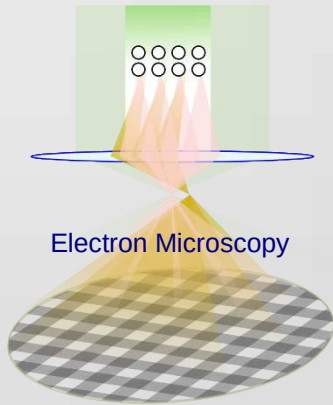


Gauss Theorem :

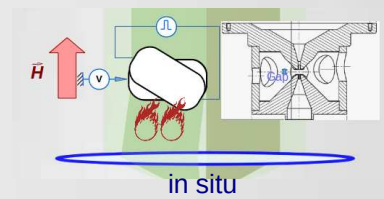
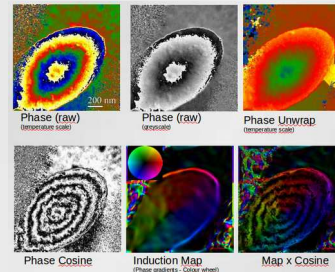
$$Q = -\frac{\epsilon_0}{C_E} \oint_C \nabla \phi_{Elec}(\mathbf{r}) \cdot \mathbf{e}_n dl$$



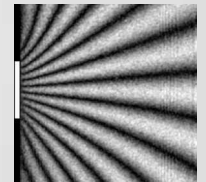
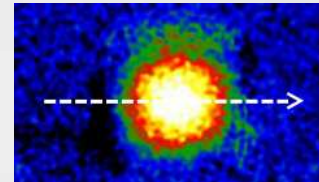
# Electron Microscopy & Micro-magnetism



## Phase Image



## Phase sensitivity

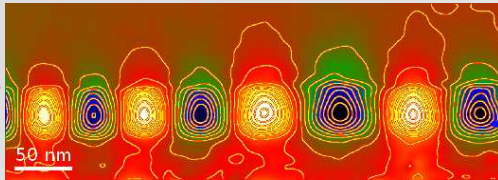


New Techniques

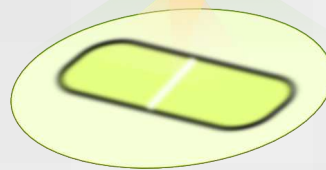
## Out-of-Axis vs In-Line

★★★★★	Spatial Resolution	★★★★★
★★★★★	Field of View	★★★★★
★★★★★	Sensitivity	★★★★★
★★★★★	Dynamic	★★★★★
★★★★★	Versatility	★★★★★
★★★★★	Quantification	★★★★★
★★★★★	Implementation	★★★★★

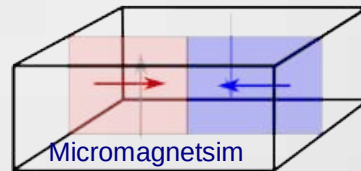
Thin Foils



## Magnetic Imaging



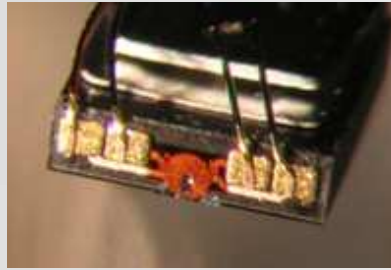
Devices



in situ

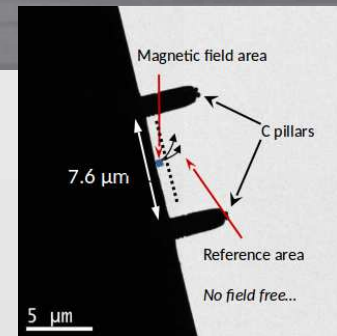
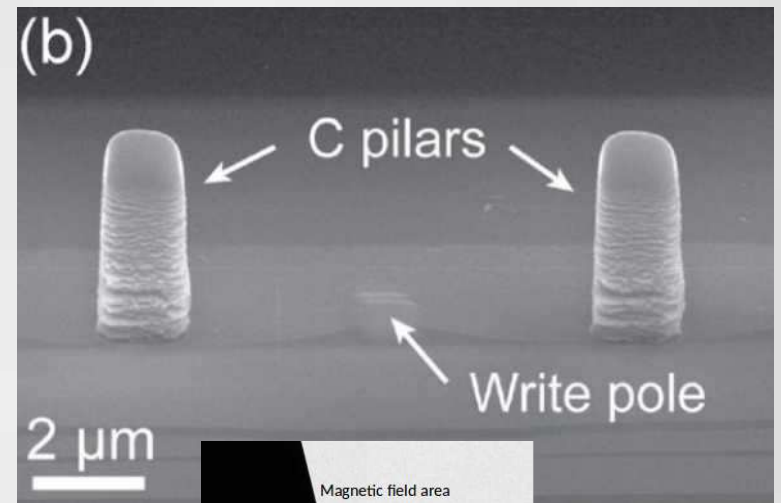
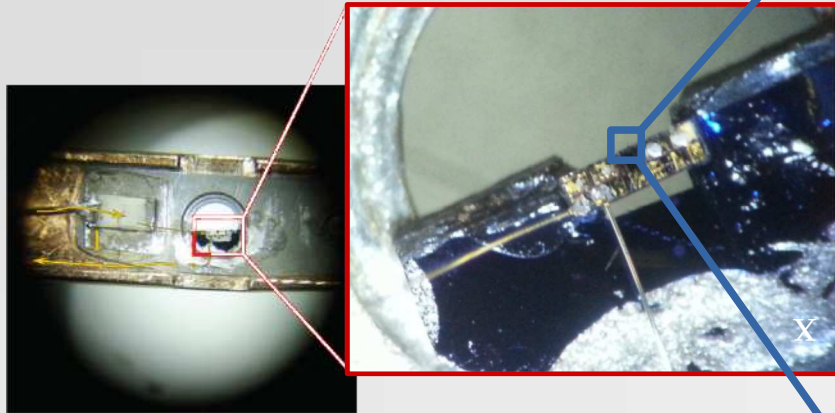


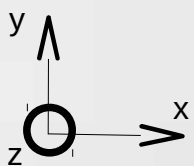
# Devices



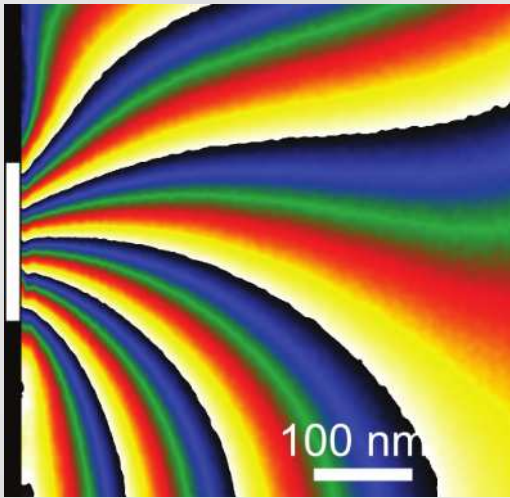
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John Chapman

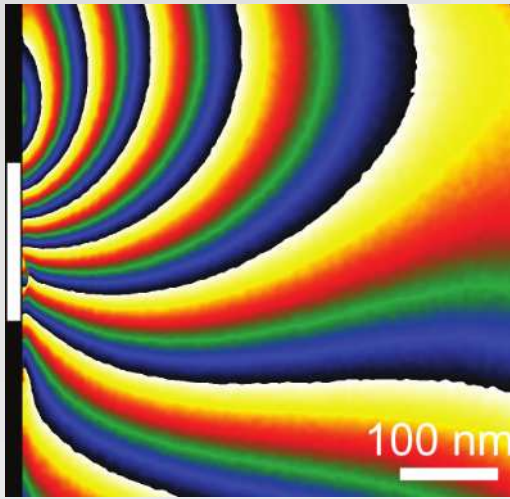


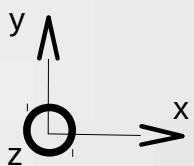


+60 mA

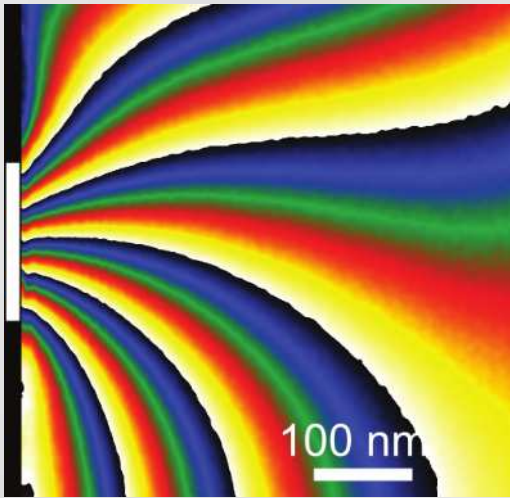


-60 mA

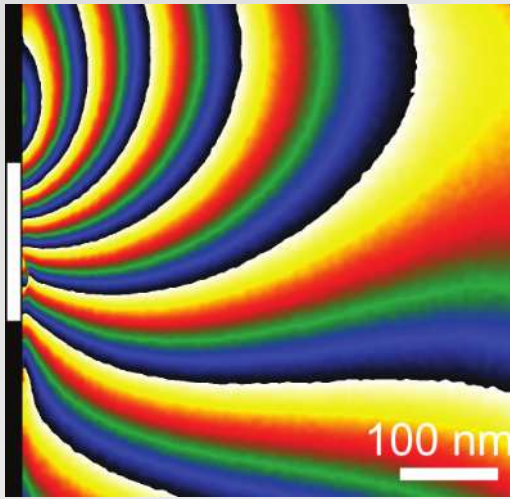




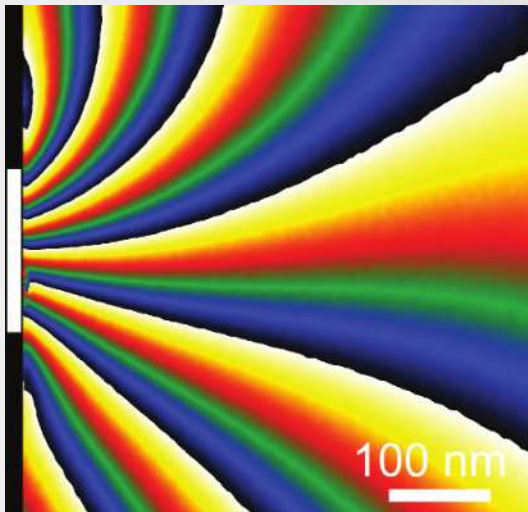
+60 mA



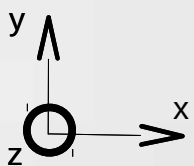
-60 mA



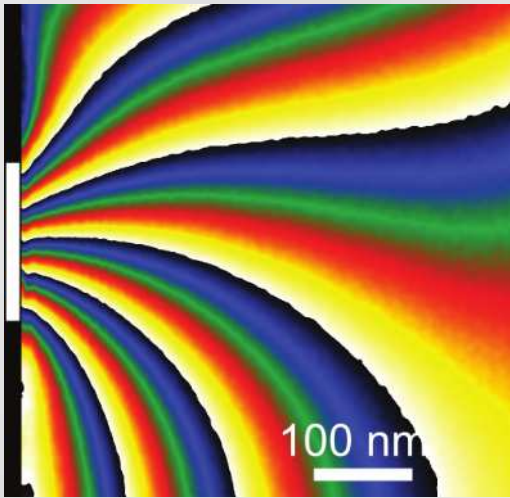
$\Delta$



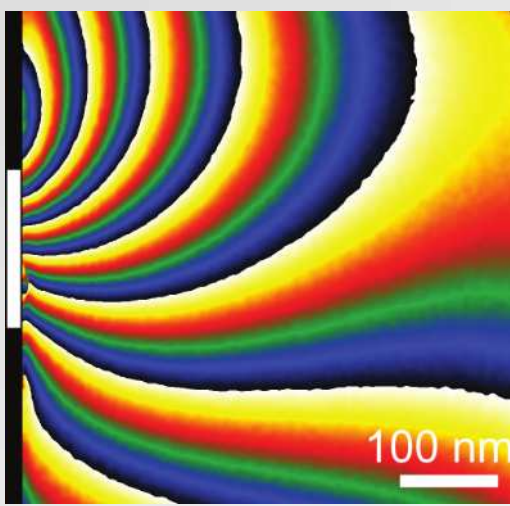
Magnetic Pole contribution



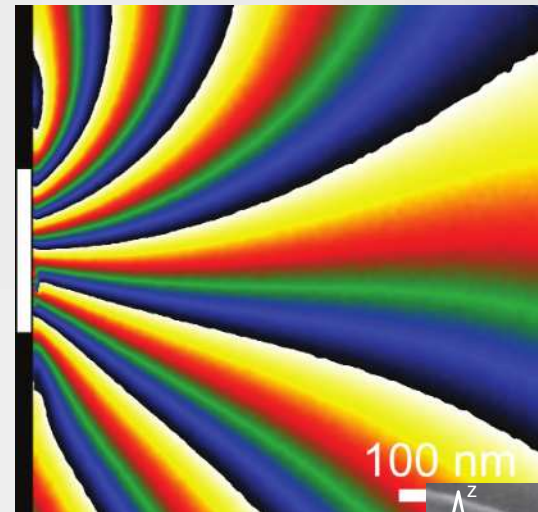
+60 mA



-60 mA



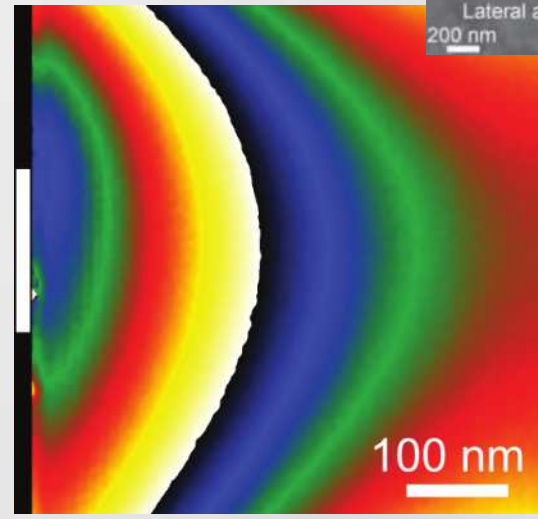
$\Delta$



Magnetic Pole contribution

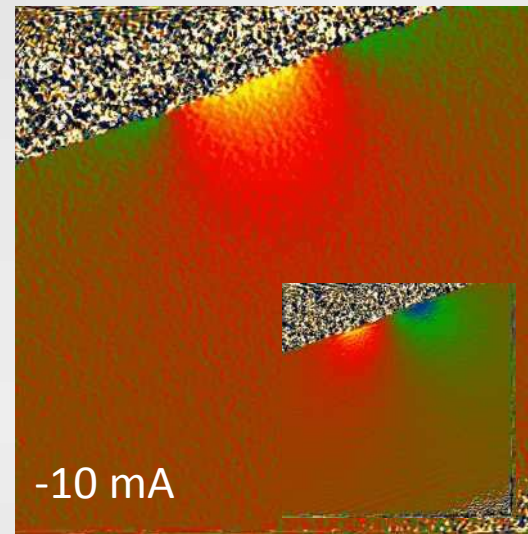
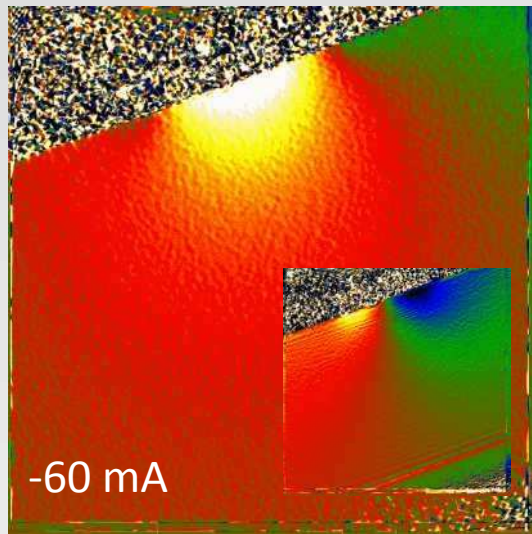
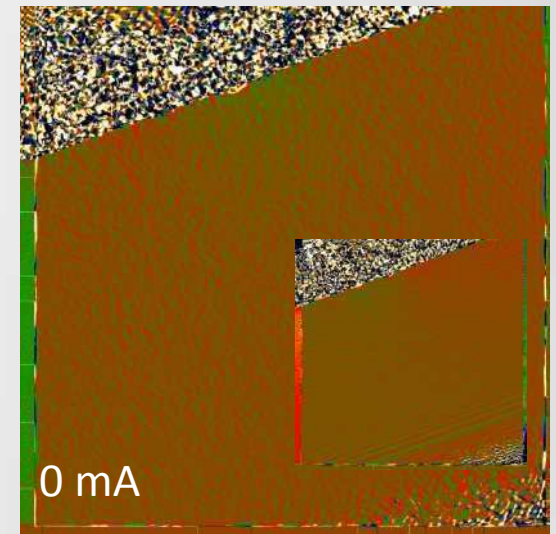
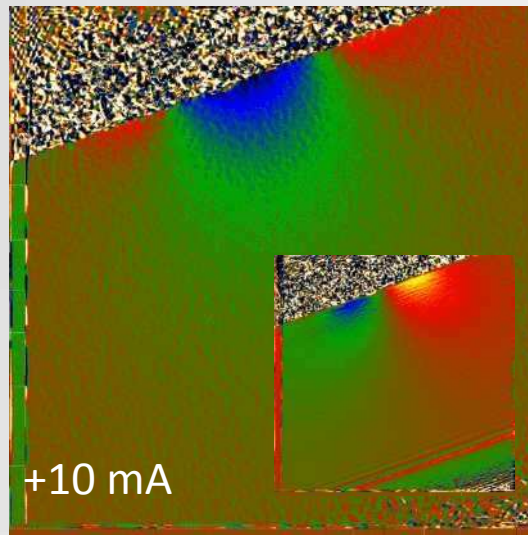
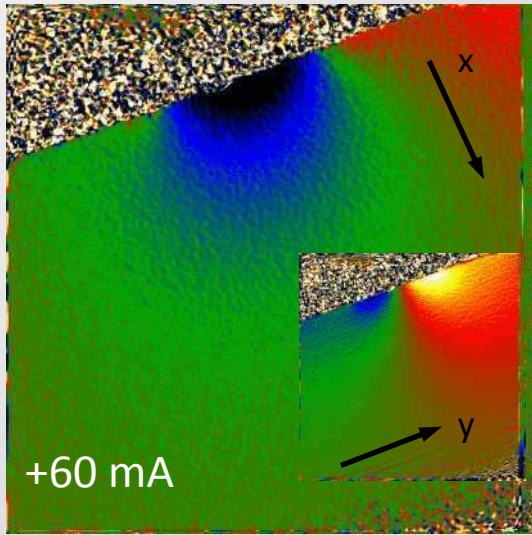


$\Sigma$

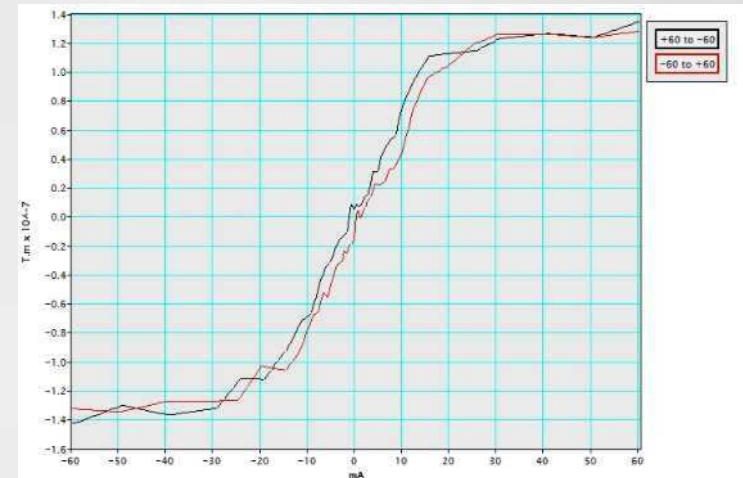
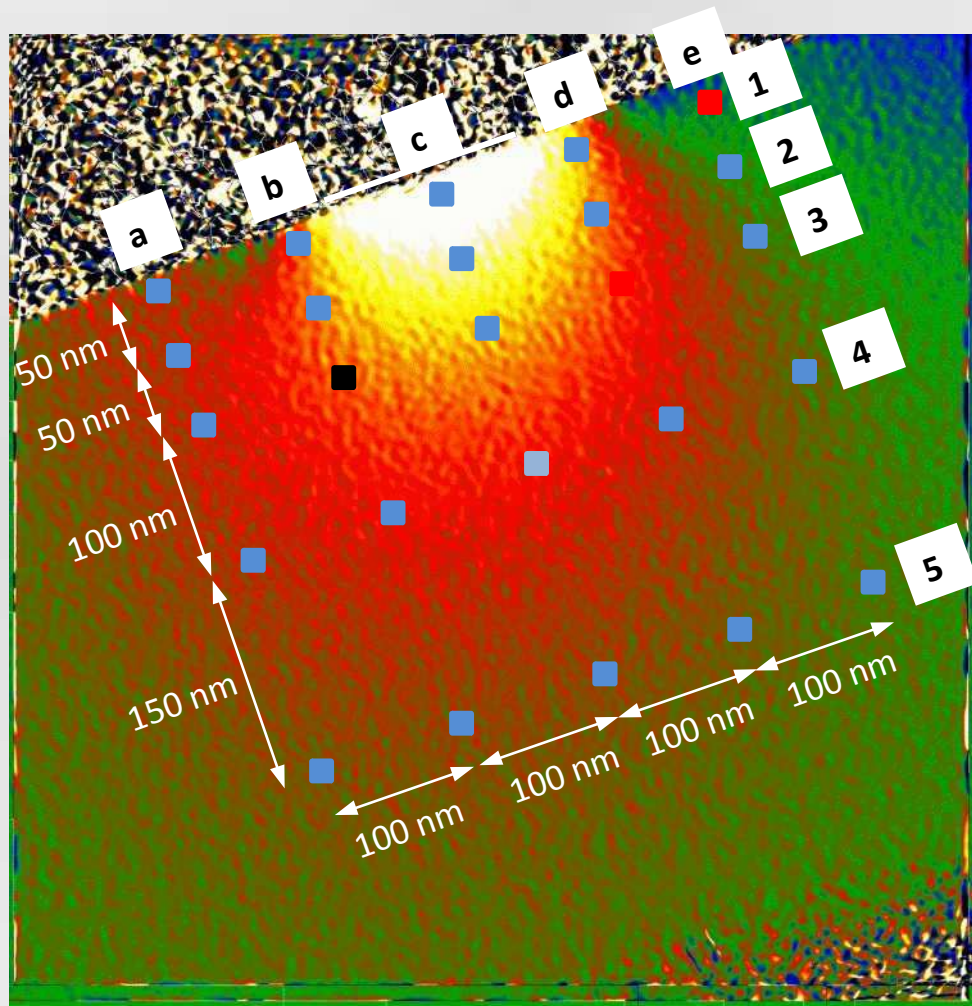


Magnetic Shield contribution





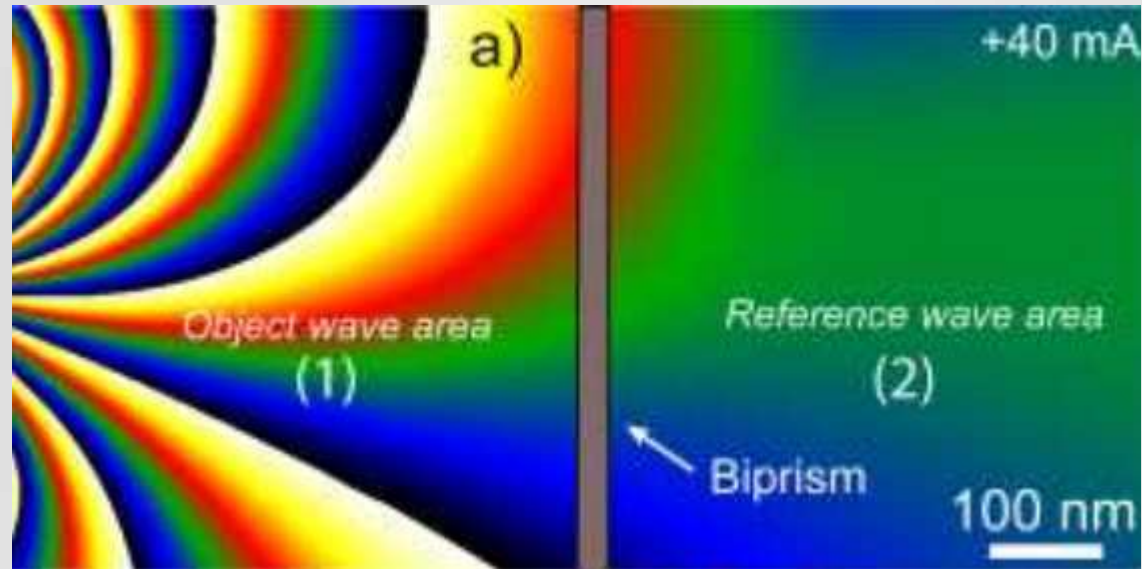
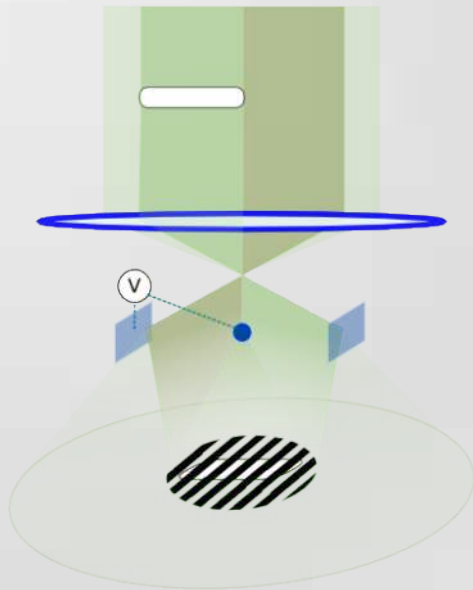
Quantitative data :



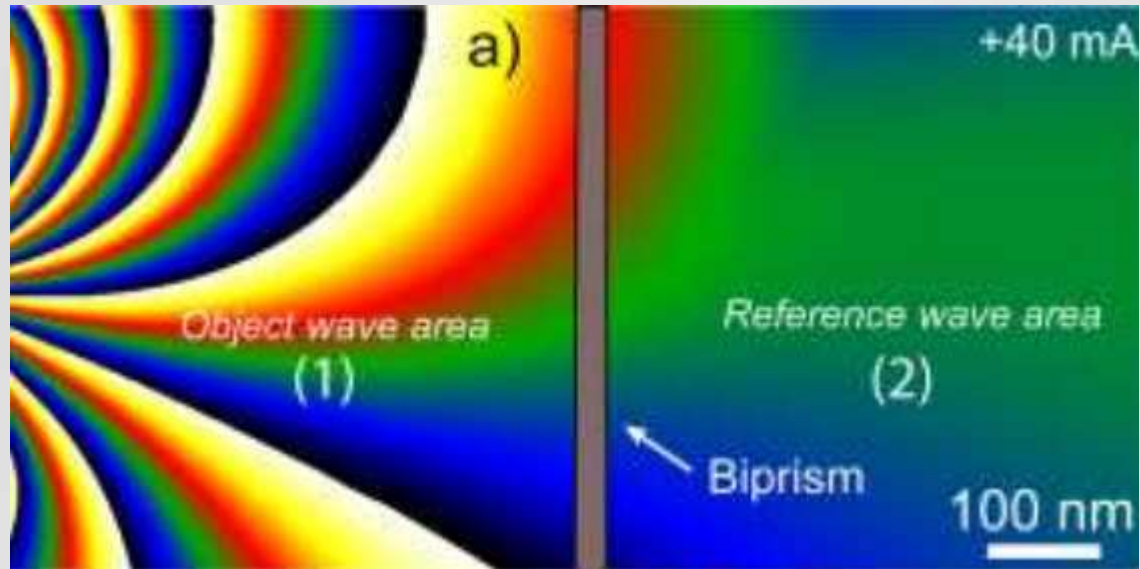
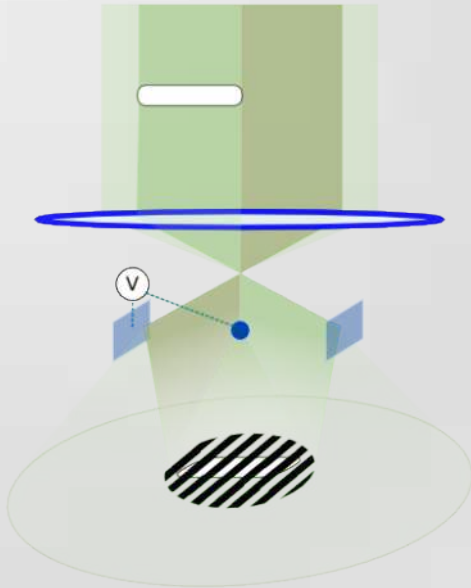
Example : Hysteresis of X-comp. in C2



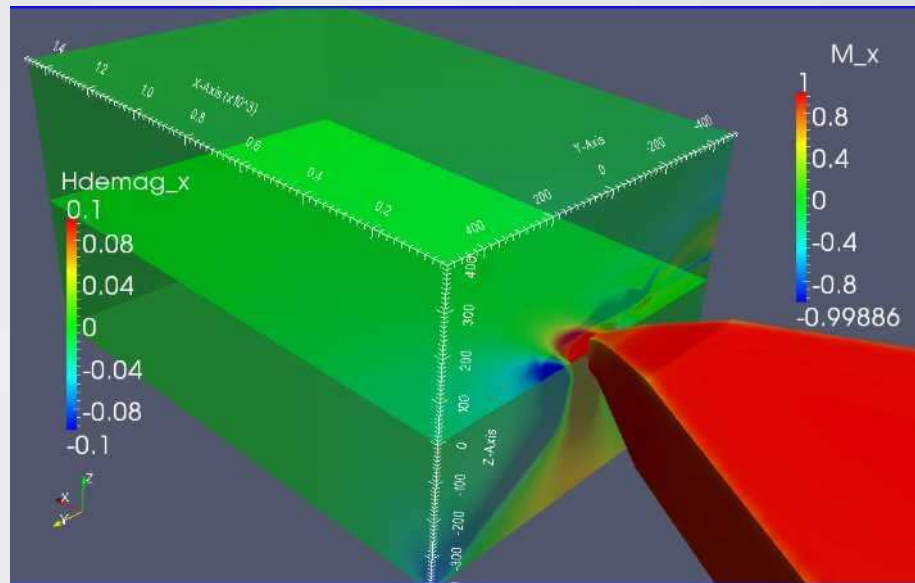
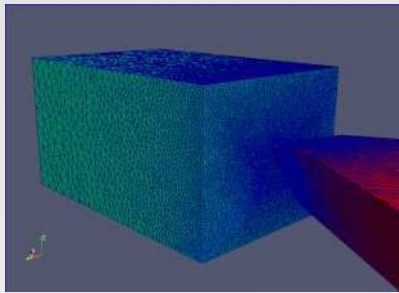
# Quantitative data : The « Disturbed Reference » problem



# Quantitative data : Reference problem



## Finite Element Modeling





# Quantitative data : Magnetic flux measurement

