
Magnetic states in Co/Cu multi-layered nano-wires observed by electron holography

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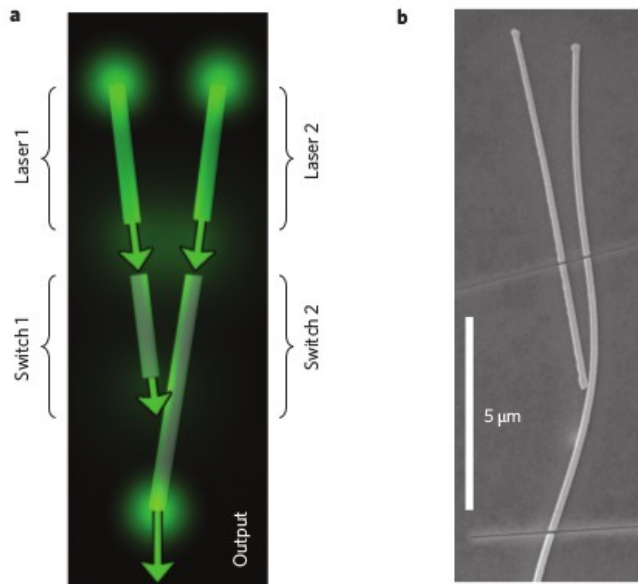
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³*LSI, École Polytechnique, Palaiseau, France*

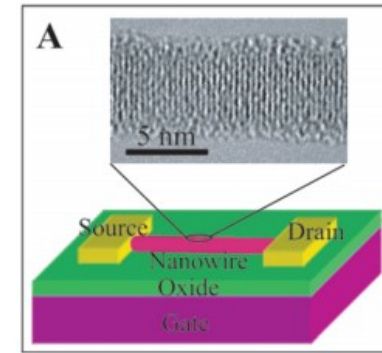
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Nanowires are considered as building blocks for the next generation of electronics, photonics, sensors and energy applications.



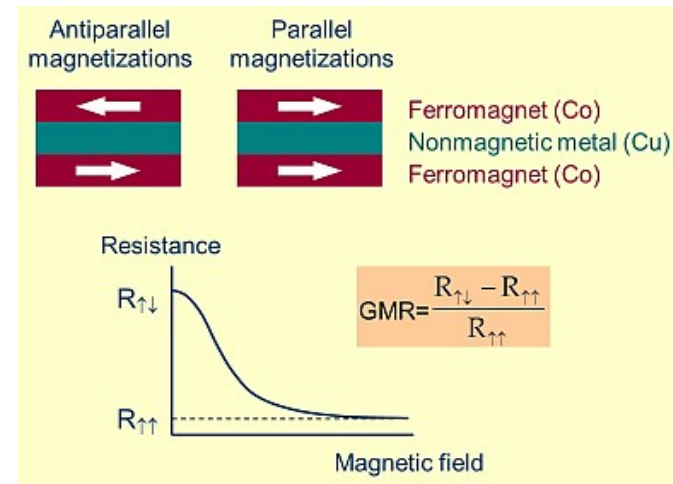
CdS nanowires, acting like a NAND gate

Brian Piccione, *Nature nanotechnology*, 7, 640–645 (2012)



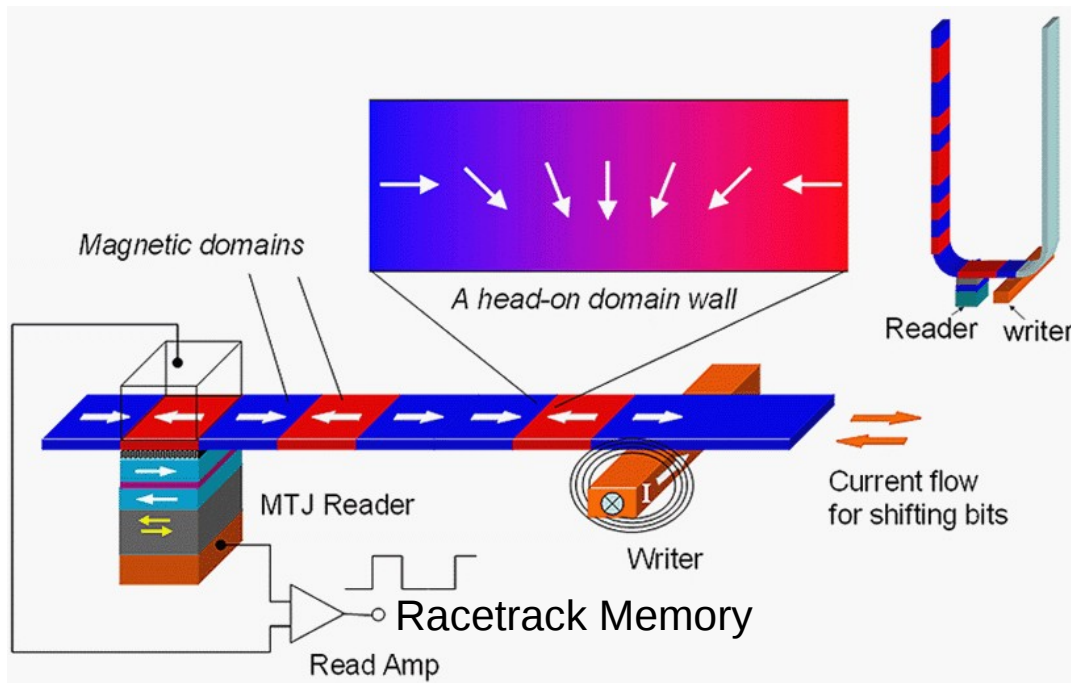
FET with SiNW nanowire

Yi Cui et al, *Nano Lett.*, Vol. 3, No. 2, 2003



Magneto-resistance

E.Y.Tsymbal et al, 3rd Joint Magnetism Workshop, 1999



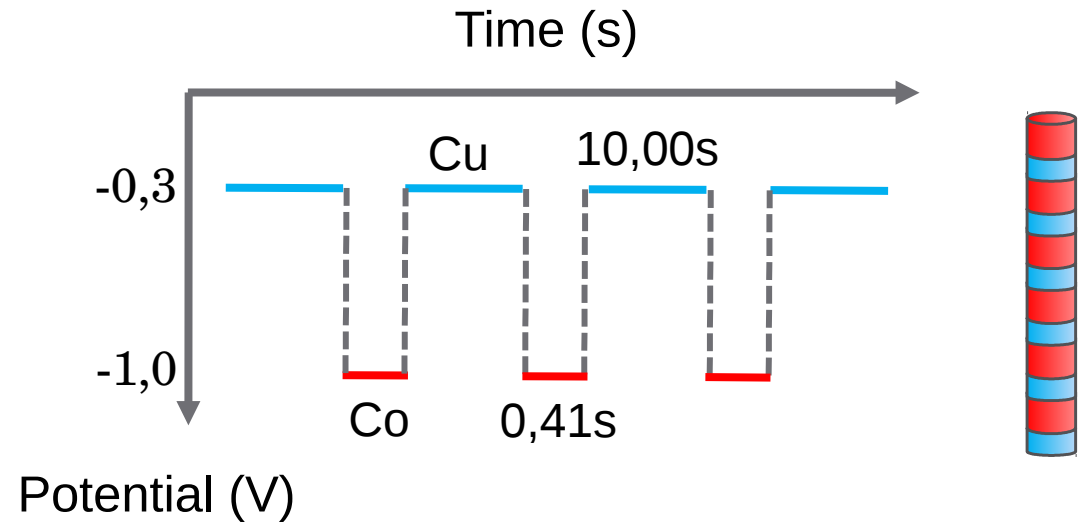
Nano-oscillators

Increase spin transfer induced RF power

Zhu, *Proceedings of the IEEE* Vol. 96, 11, 2008

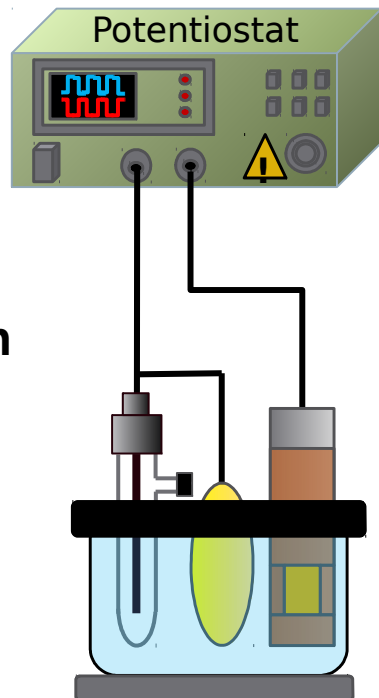
Electro-deposition:

- “Easy”
- Less expensive
- Good quality
- Large nanowires

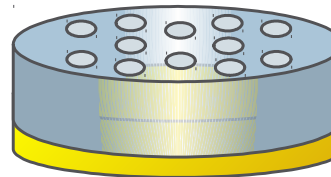


Pulsed electro-deposition

Reference
Electrode
Ag/AgCl



Polycarbonate
Membranes
Pore size 30nm



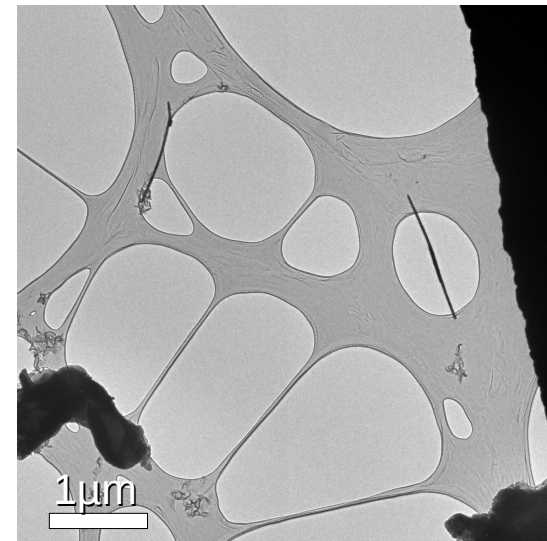
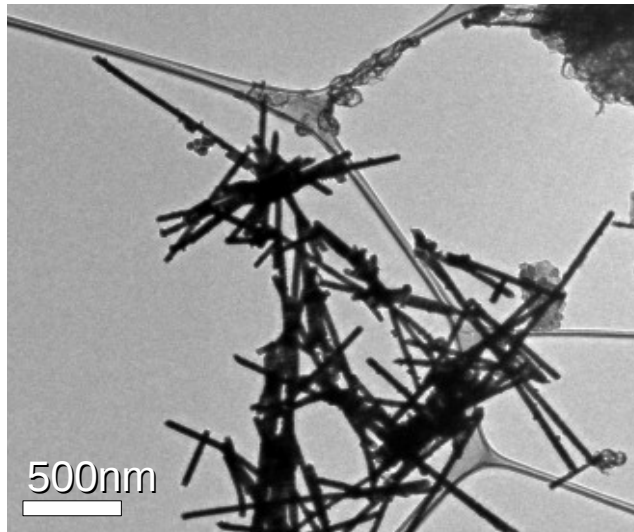
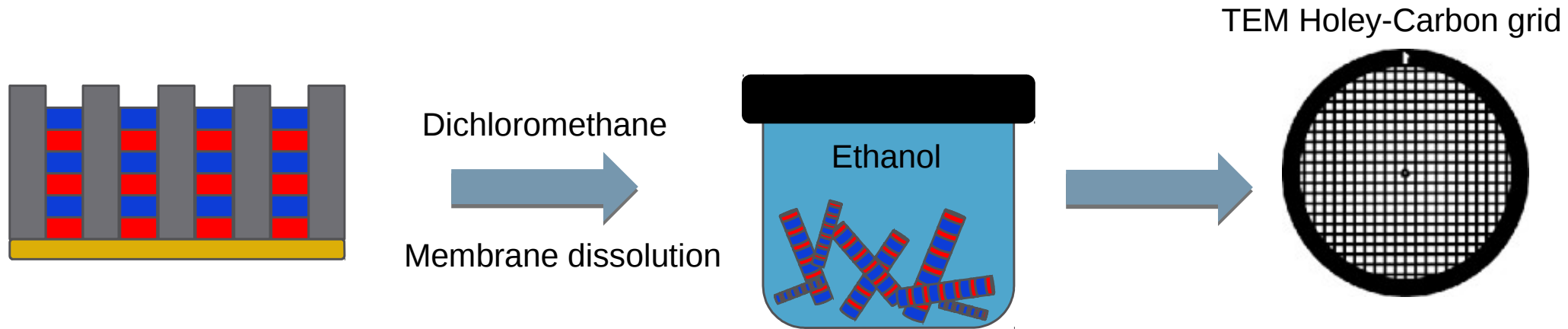
Solution

0,43 mol/L $\text{CoSO}_4 \cdot \text{H}_2\text{O}$

0,01 mol/L CuSO_4

0,58 mol/L H_3BO_4

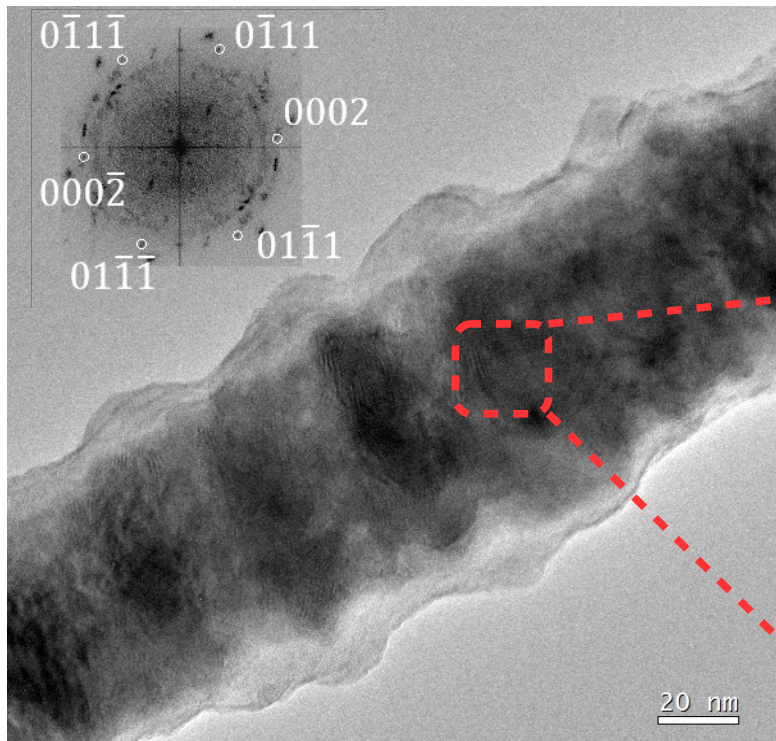
Sample preparation



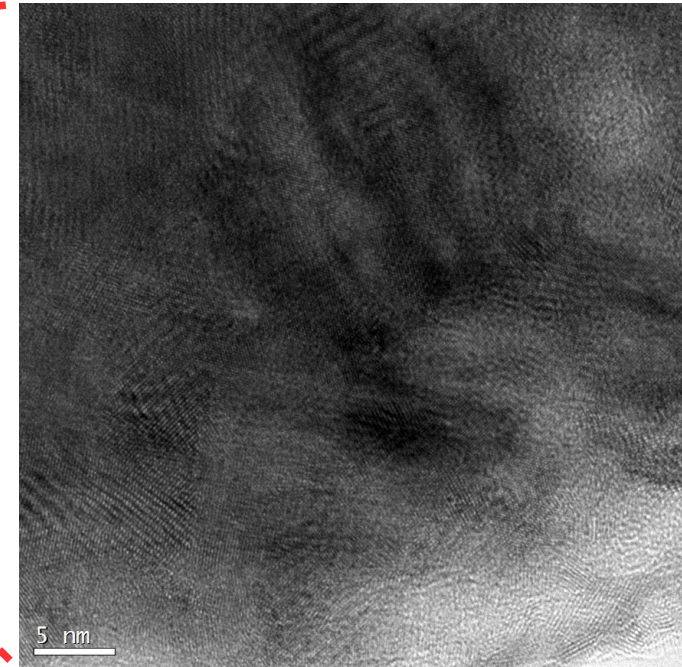
Polycrystalline with texture

Co HCP and FCC

Cu FCC

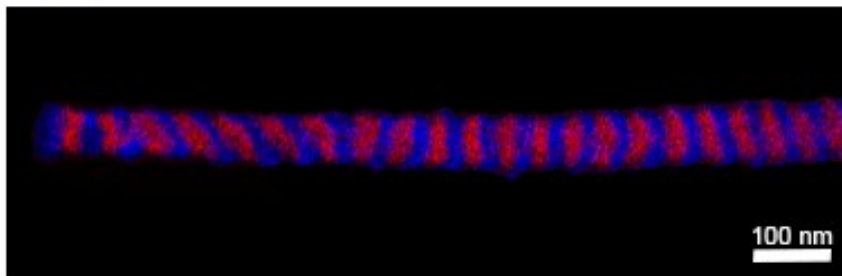
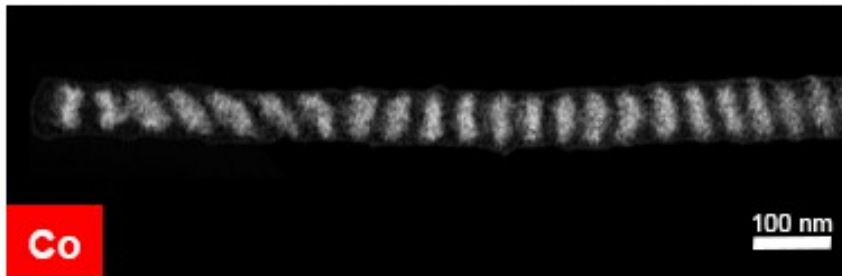
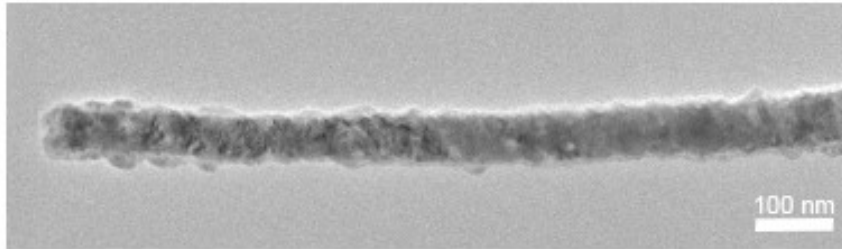


In the texture we could identify the c axis of the Co HCP $\pm 20^\circ$ respect the axis wire



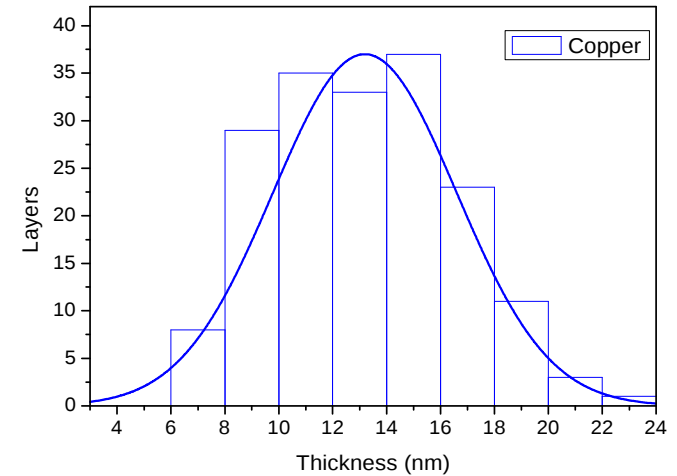
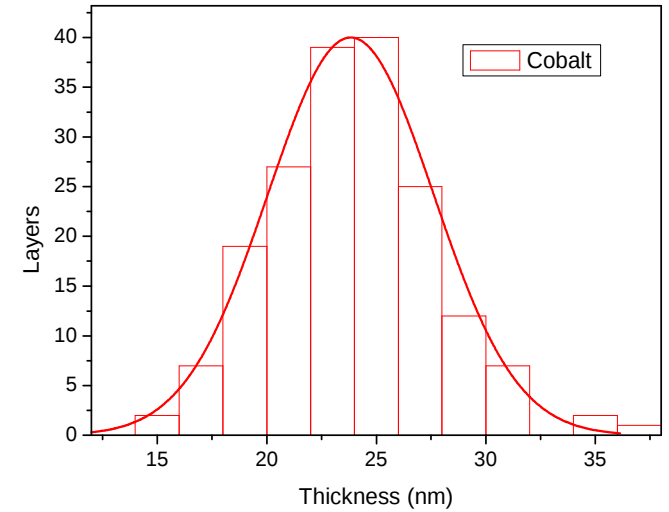
Diameters between 55nm and 80nm

Grain size ~ 7 nm



$\bar{t}_{Co} = 24 \text{ nm}$
 $\sigma_{Co}^2 = 4 \text{ nm}$

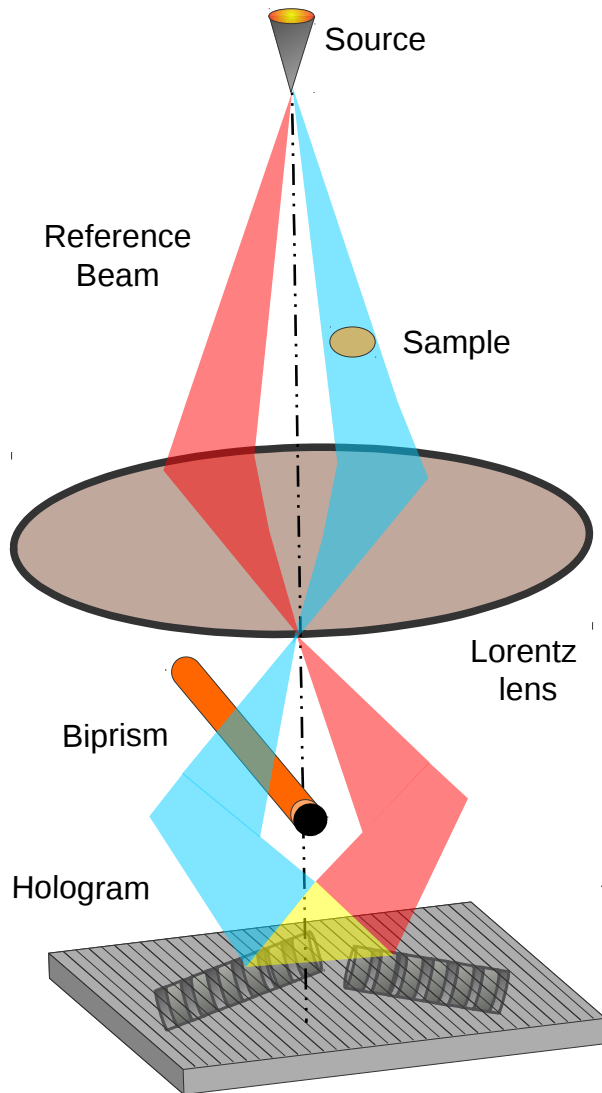
$\bar{t}_{Cu} = 14 \text{ nm}$
 $\sigma_{Cu}^2 = 4 \text{ nm}$



15% of **Cu** inside the **Co** layers
 Measured by EELS profiles

GIF Tridien (0,7 eV)

Off-axis Electron Holography



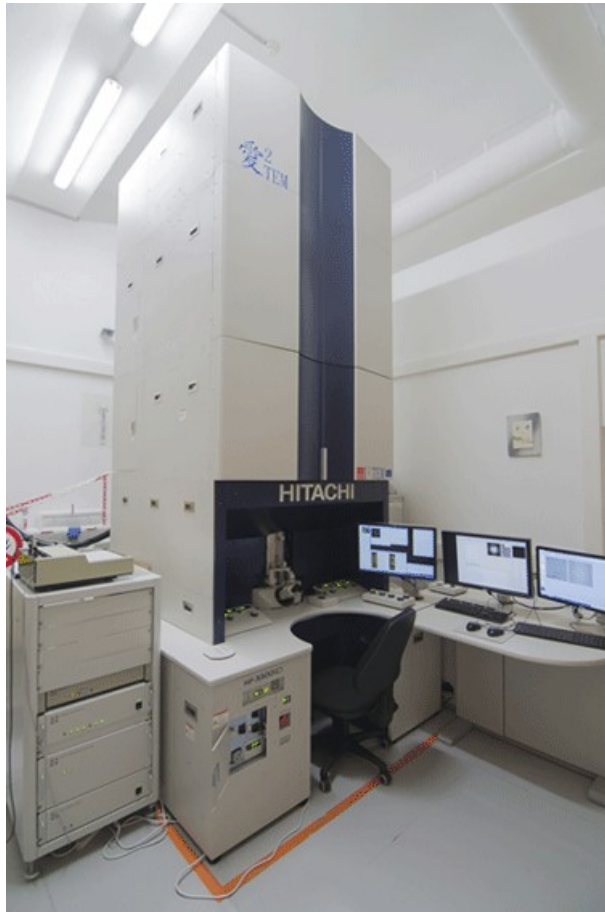
The phase of an electron wave that passed through a specimen will be changed by different factors. The change due to the electromagnetic field is given by:

$$\Phi(x) = C_E \int V(x, z) - \frac{e}{\hbar} \iint B_{\perp}(x, z) dx dz$$

Mean inner potential (MIP): $\Phi^E(x) = C_E \int V(x, z)$

Magnetic contribution: $\Phi^M = -\frac{e}{\hbar} \iint B_{\perp}(x, z) dx dz$

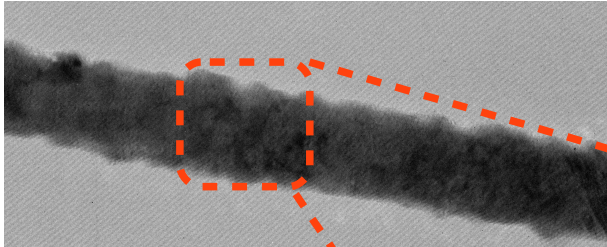
Off-axis Electron Holography



Hitachi HF3300C I2TEM

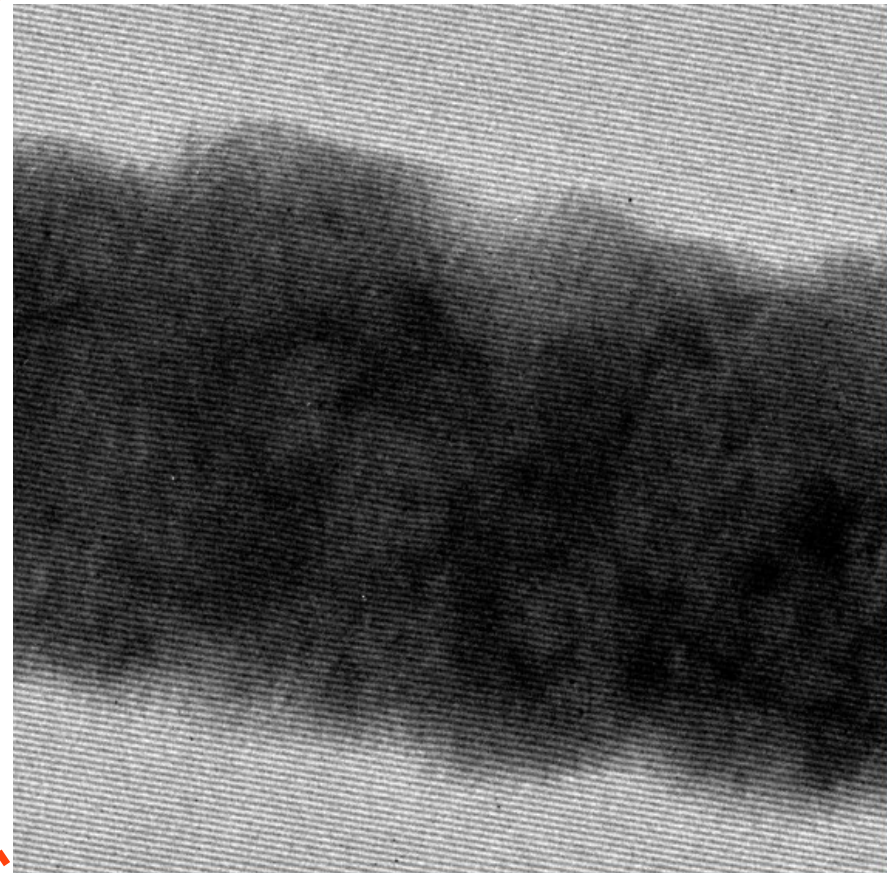
- ⦿ Cold FEG 300kV
- ⦿ Specially designed to perform electron holography and in-situ experiments: two goniometers
- ⦿ Lorentz mode: free magnetic field
- ⦿ Aberration corrector dedicated to the Lorentz mode (spatial resolution < 0.5 nm)
 - ⦿ Larger field of view
- ⦿ Four rotatable electrostatic biprisms:
 - ⦿ No Fresnel fringes

Hologram

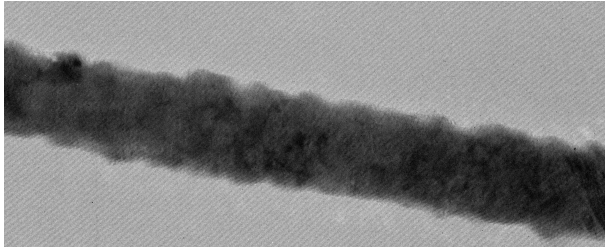


Phase shift extraction:

The fringes shift are proportional to the phase shift



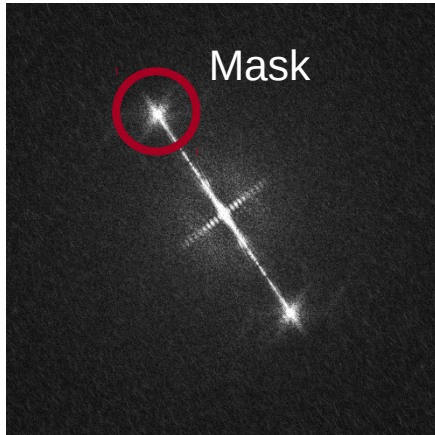
Hologram



Phase shift extraction:

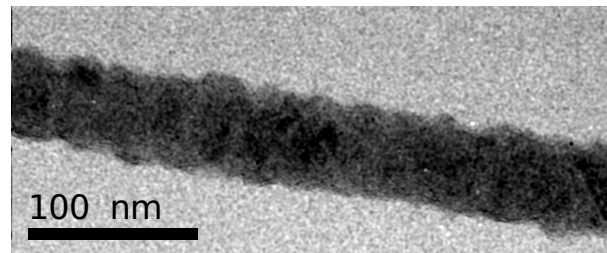
The fringes shift are proportional to the phase shift

FFT

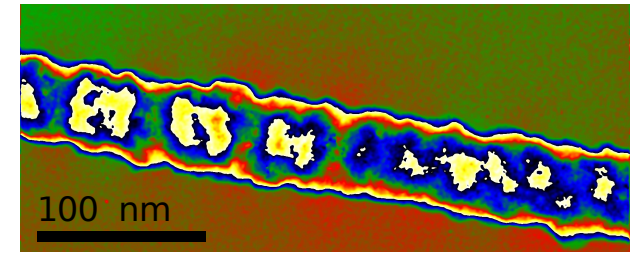


FFT⁻¹

Amplitude image



Phase image

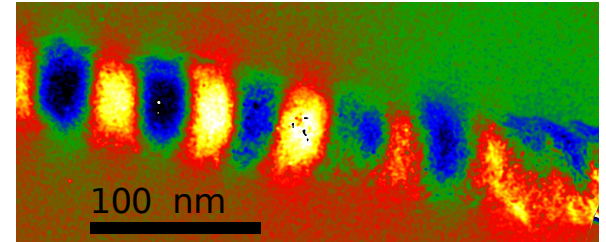
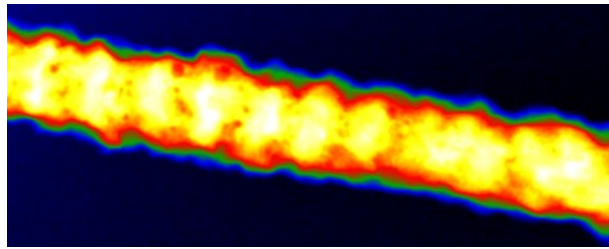
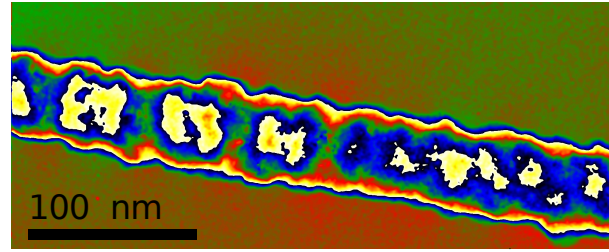
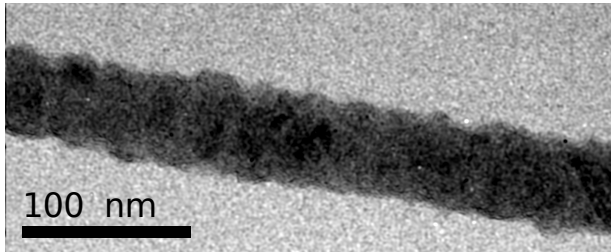


But the phase image

$$\Phi(x) = C_E \int V(x, z) - \frac{e}{\hbar} \iint B_{\perp}(x, z) dx dz$$

We need to separate the different components!

$$\Phi(x) = C_E \int V(x, z) - \frac{e}{\hbar} \iint B_{\perp}(x, z) dx dz$$

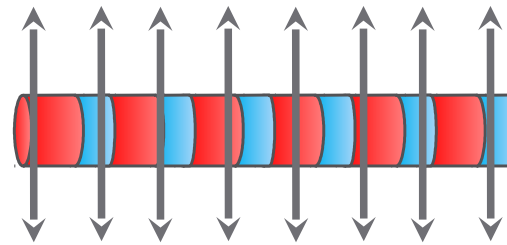
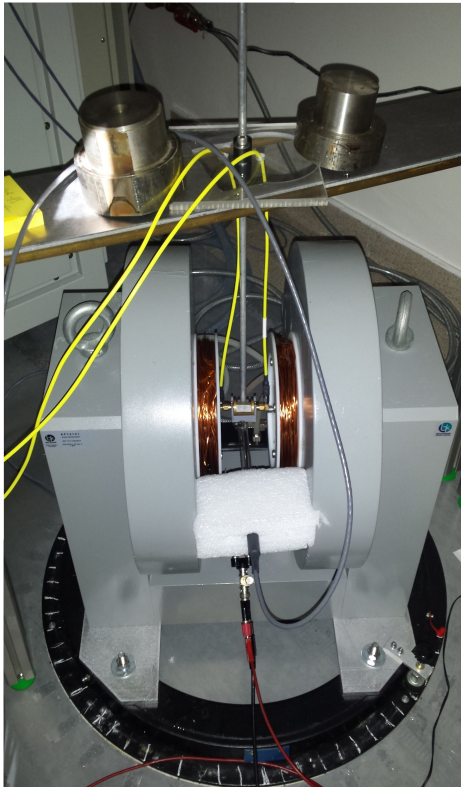


$$\Phi^E(x) = C_E \int V(x, z)$$

$$\Phi^M = -\frac{e}{\hbar} \iint B_{\perp}(x, z) dx dz$$

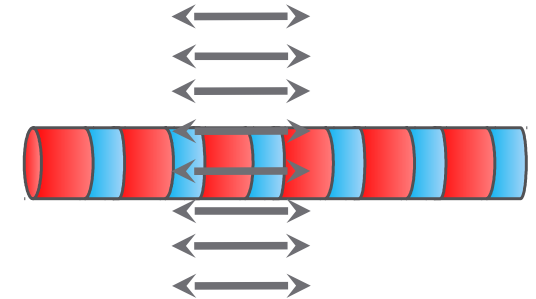
We need to record many holograms for each sample

Configurations

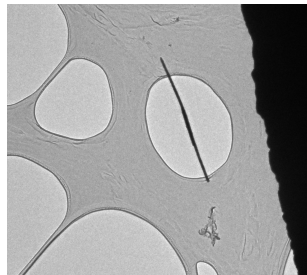


Perpendicular

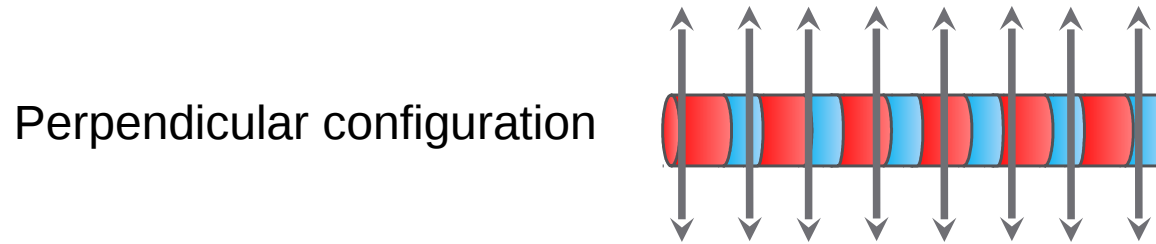
$$\|\vec{H}\| = 1,3T$$



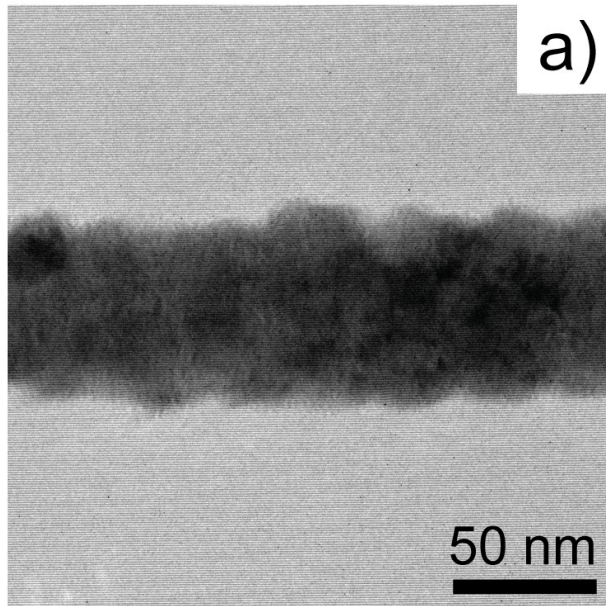
Parallel



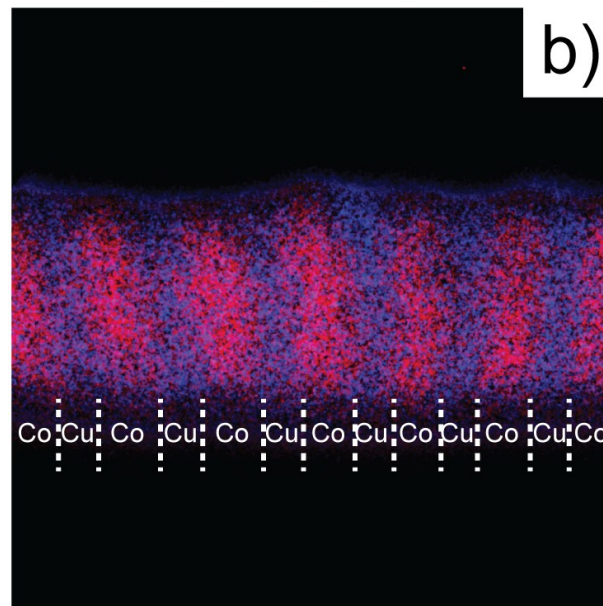
The same nanowire in the two configurations!



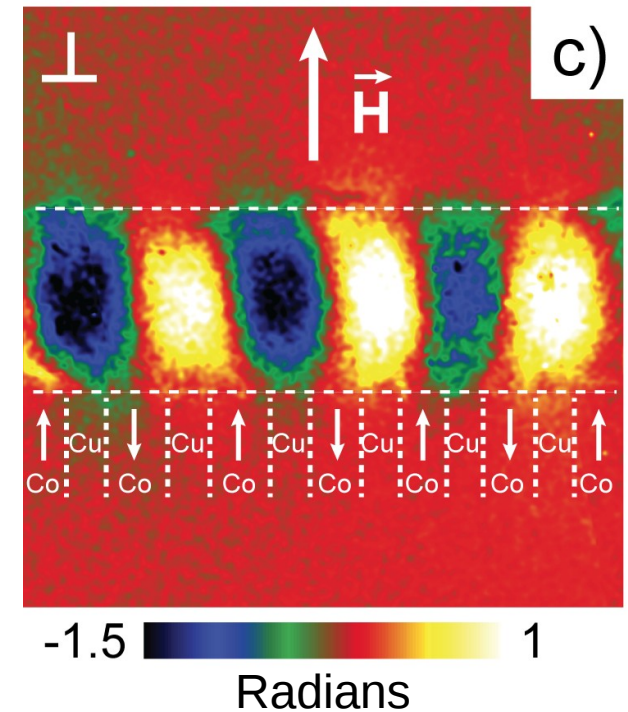
Hologram



EFTEM map



Magnetic phase image



Magnetic induction in two different directions

- Electron holography is sensible to the in plane components
- Integration over the observation direction: Inductions lines are a projection on the plane
- Allow to know the magnetic states in a 3D configuration

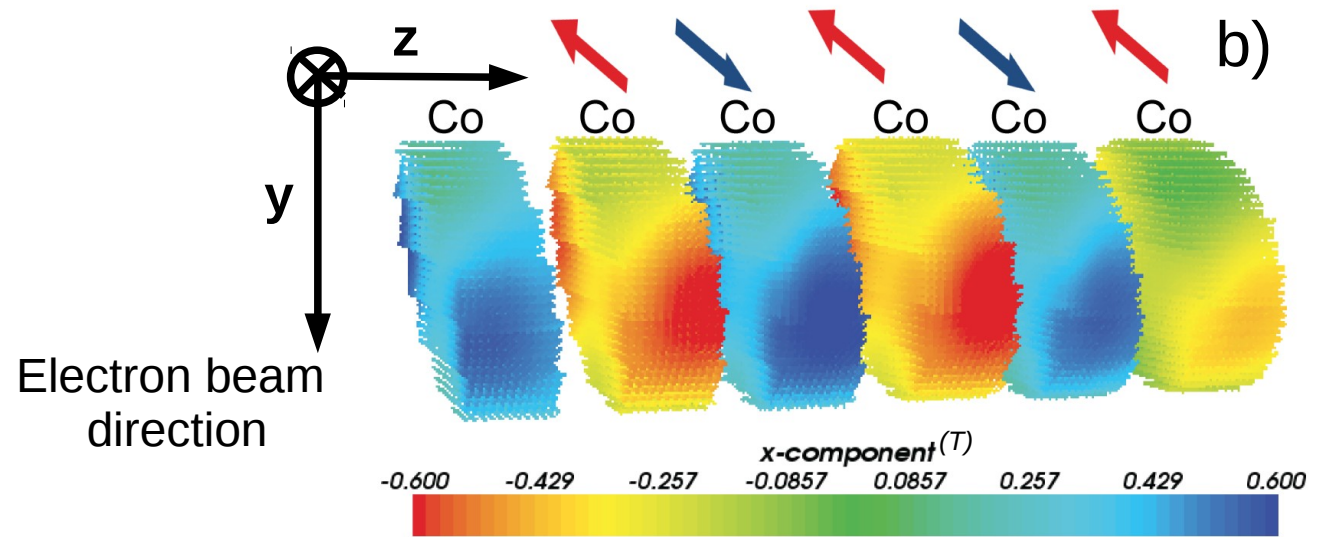
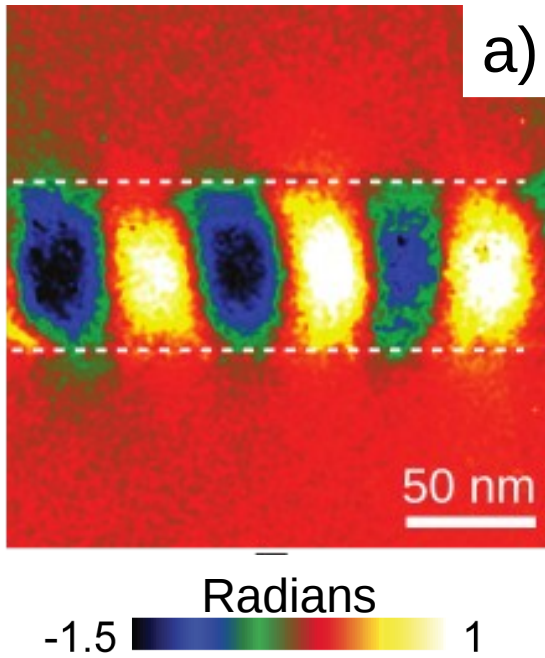


3D Micro-magnetic simulations

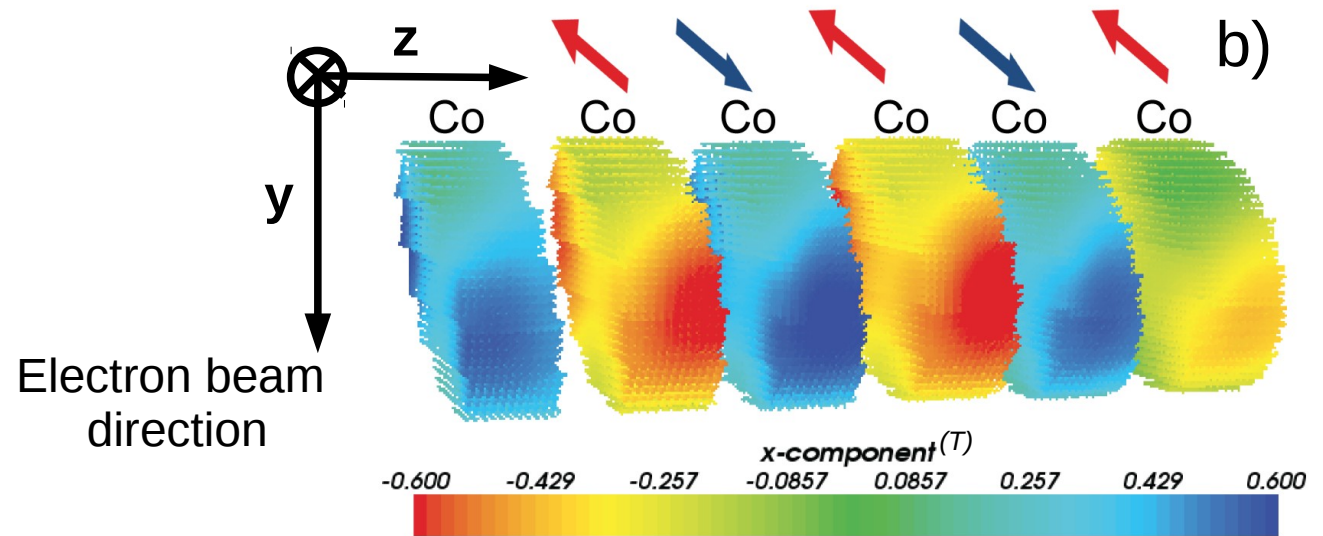
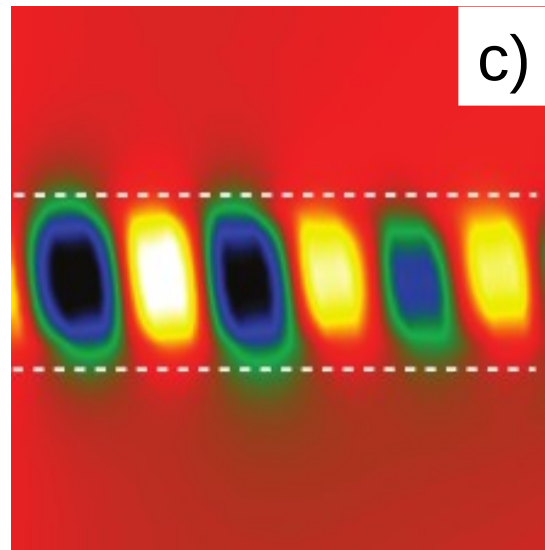
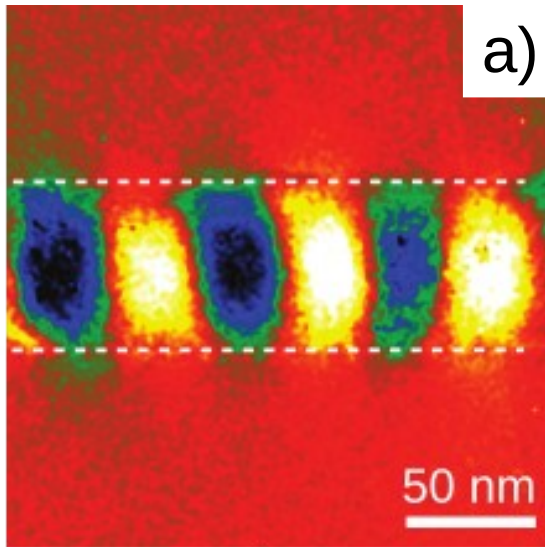


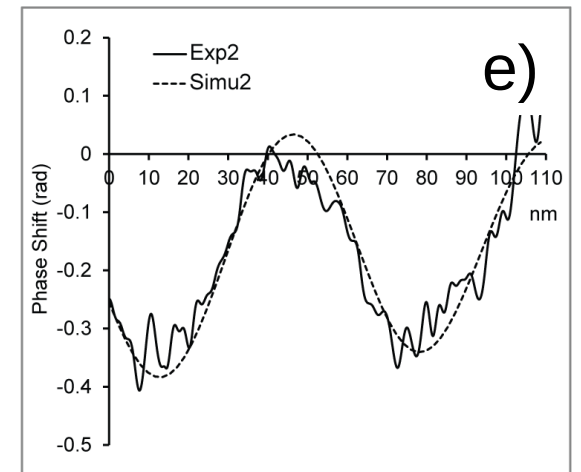
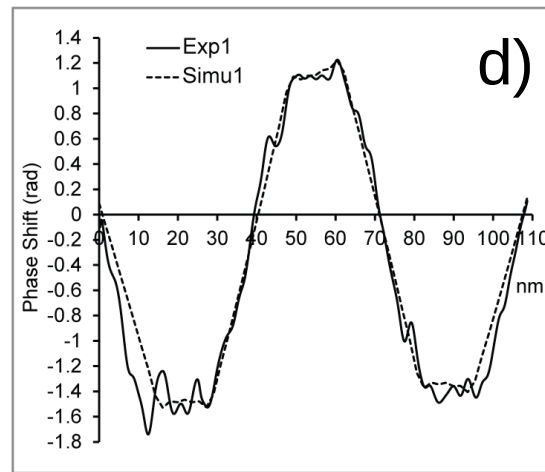
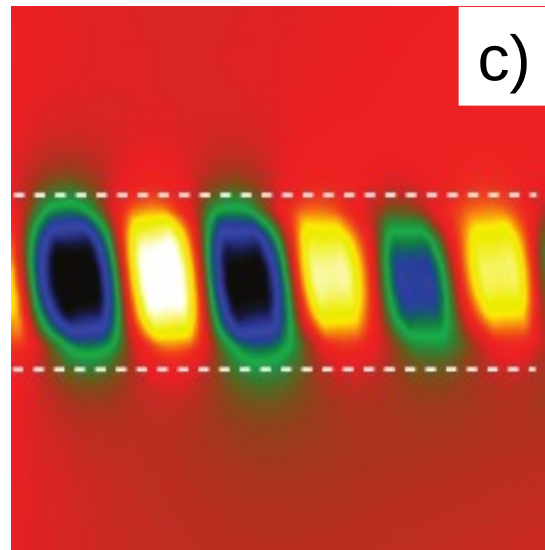
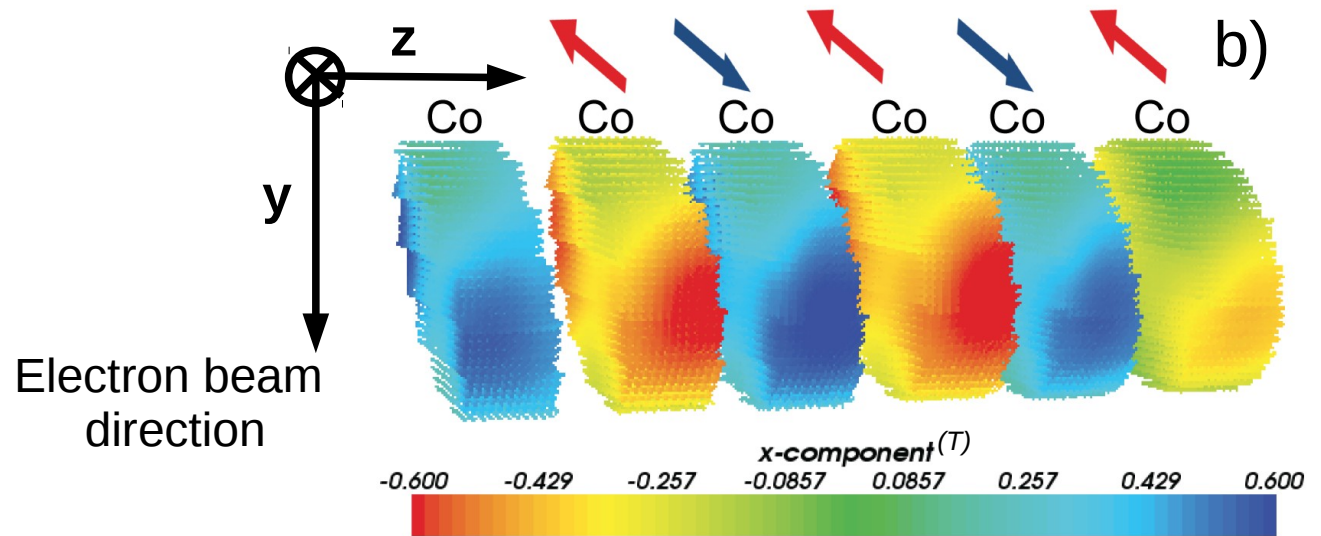
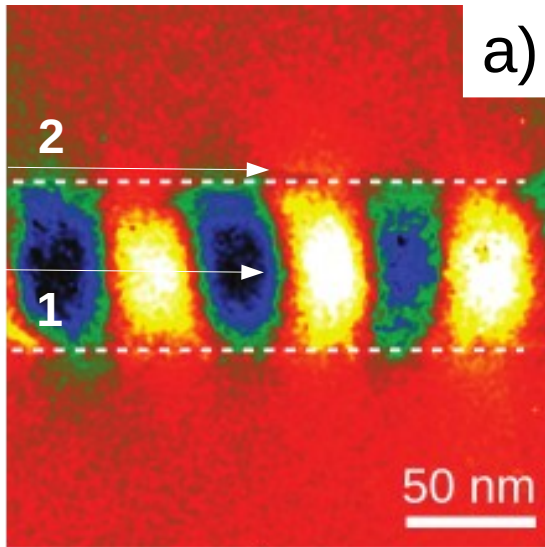
Simulations taking account of:

- Structural parameters
- Chemical information
- Magnetic parameters

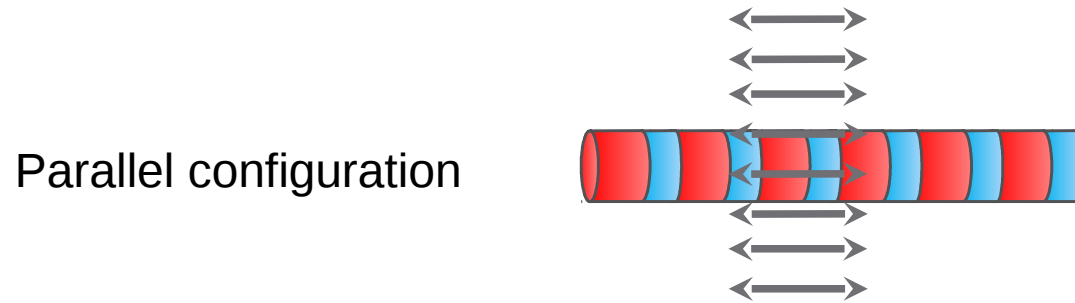


Anti-parallel coupling





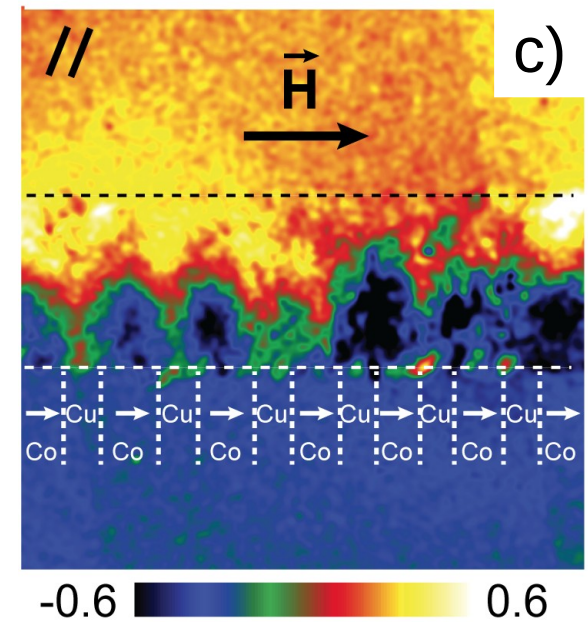
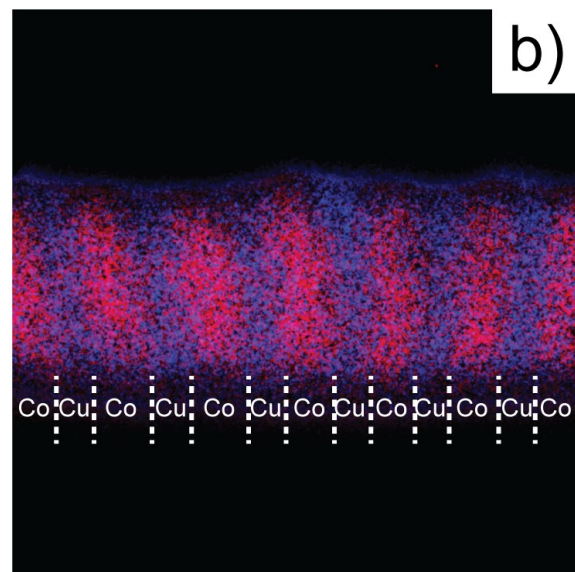
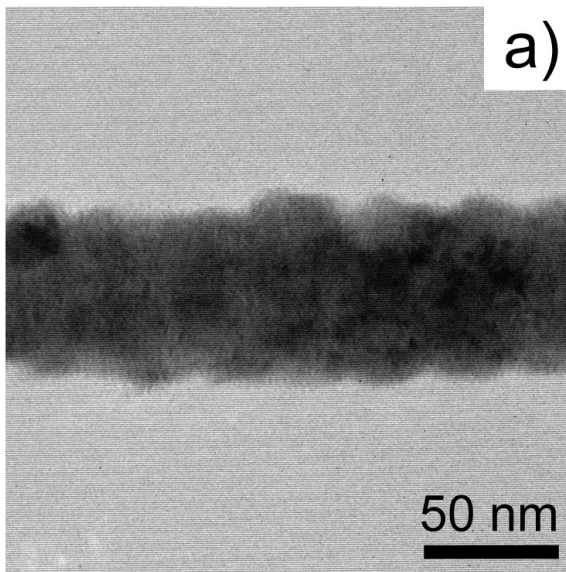
Qualitative and quantitative agreement!



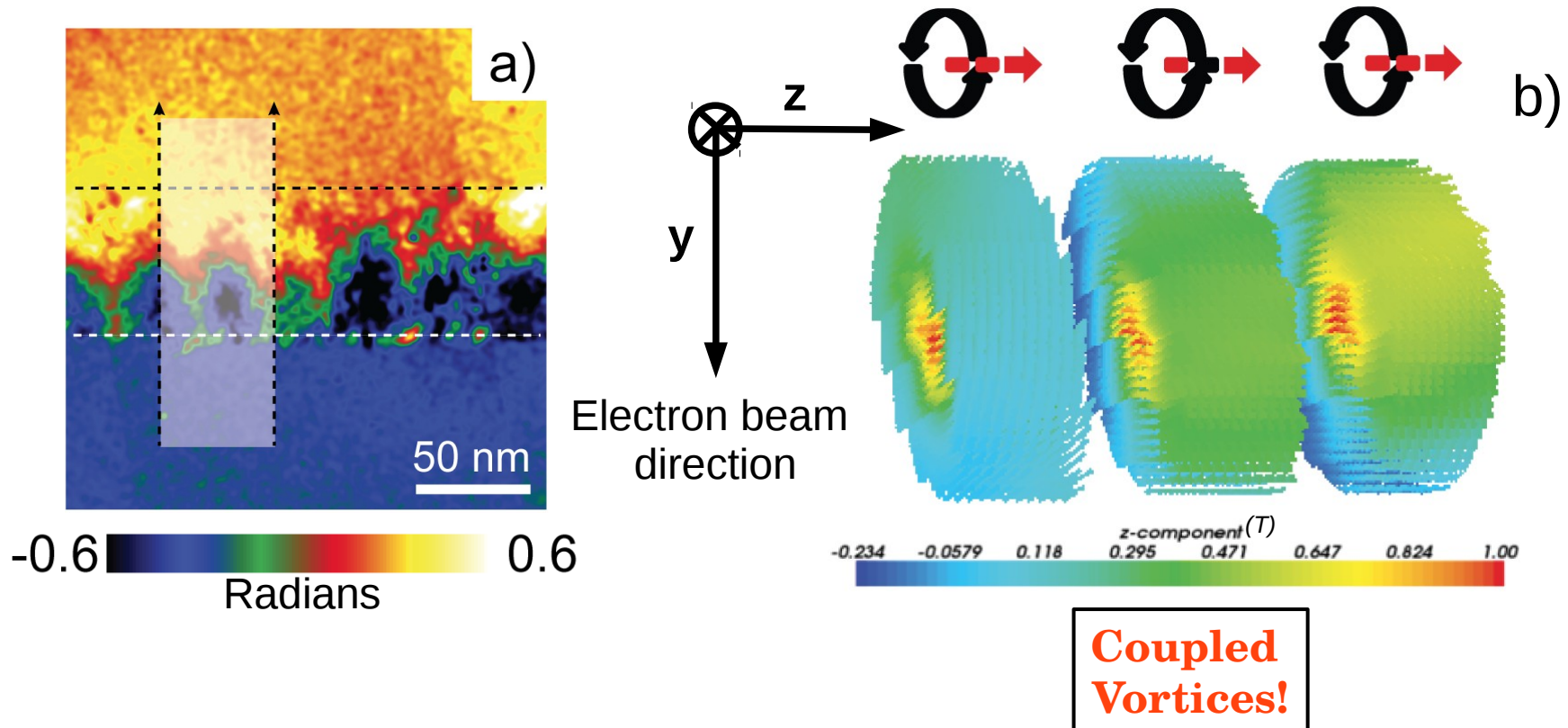
Hologram

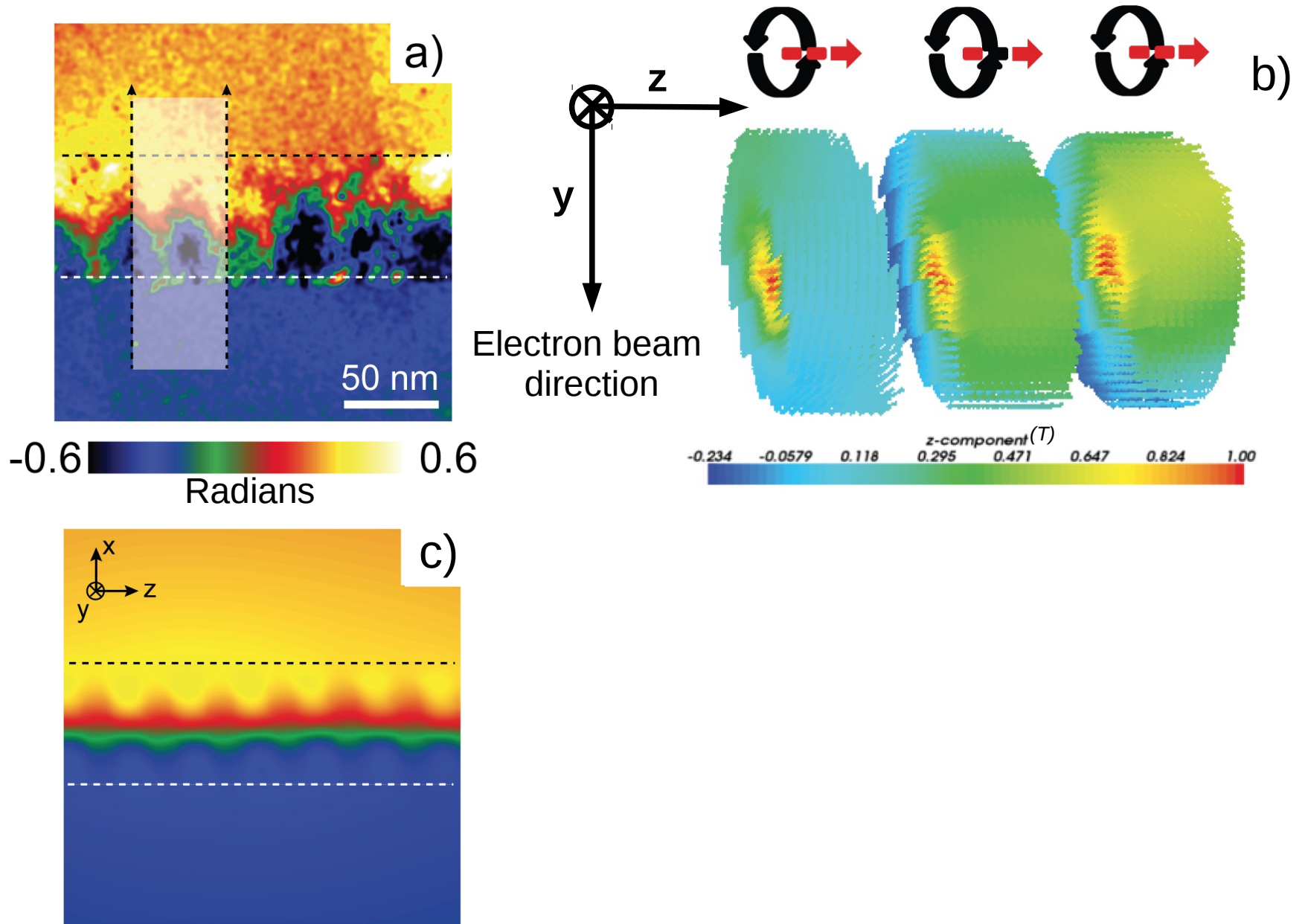
EFTEM map

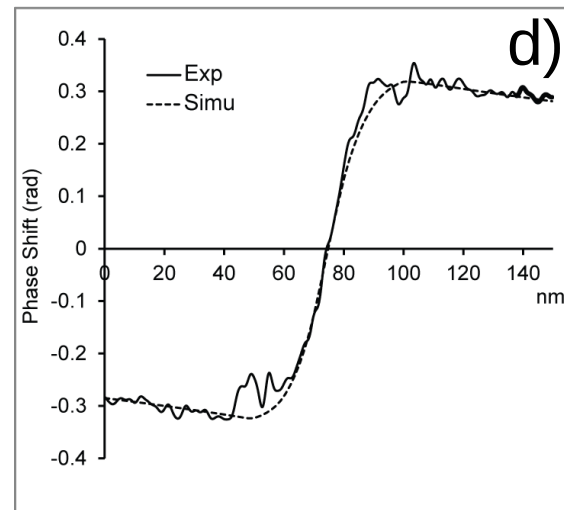
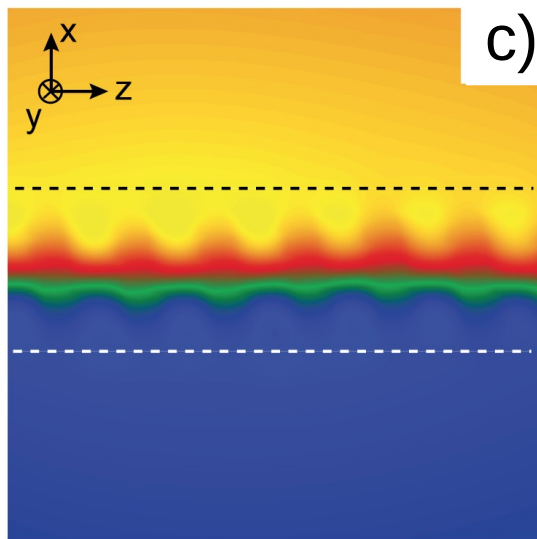
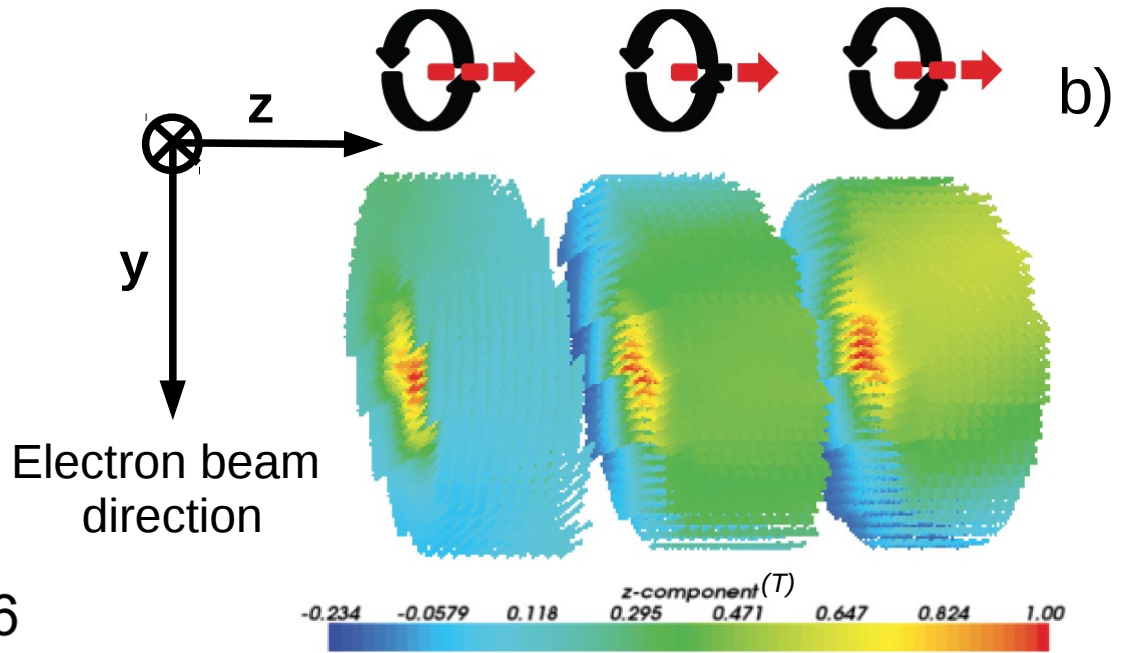
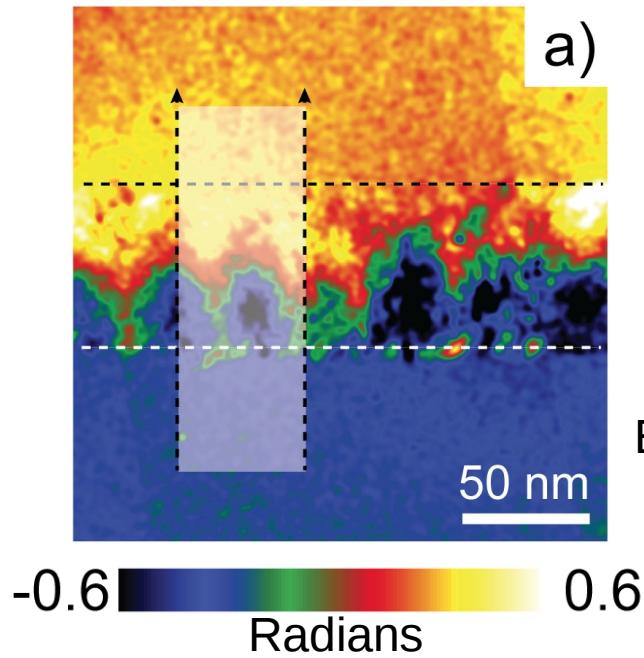
Magnetic phase image

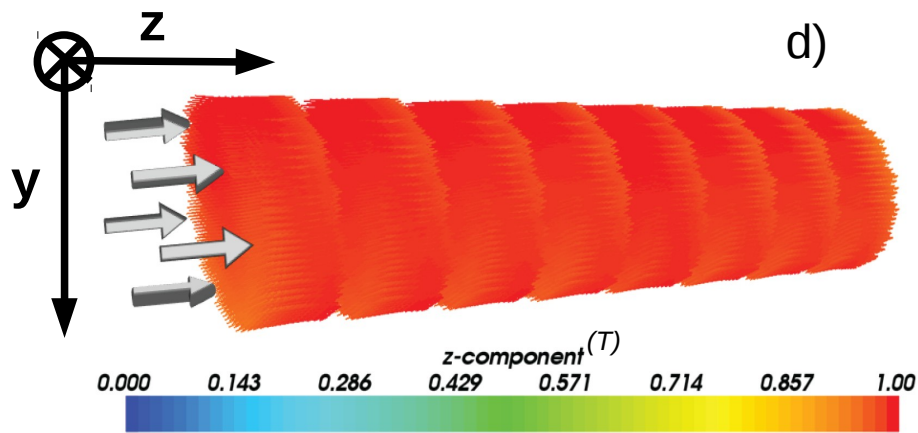
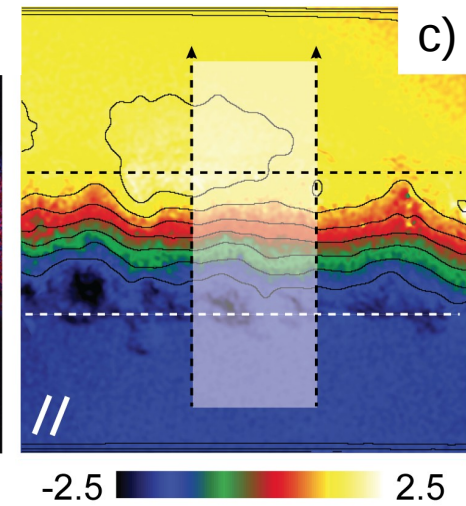
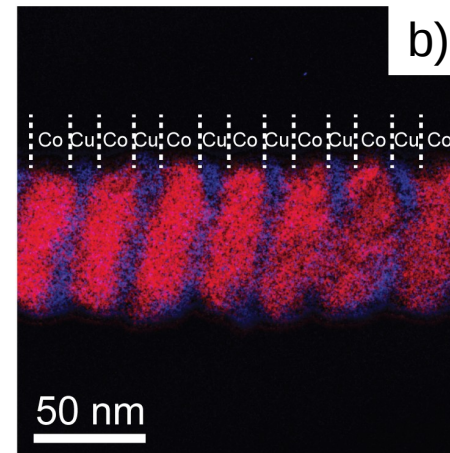
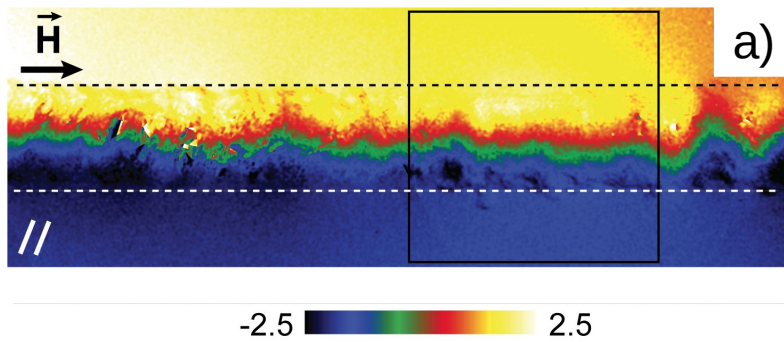


Magnetic induction parallel to the axis wire

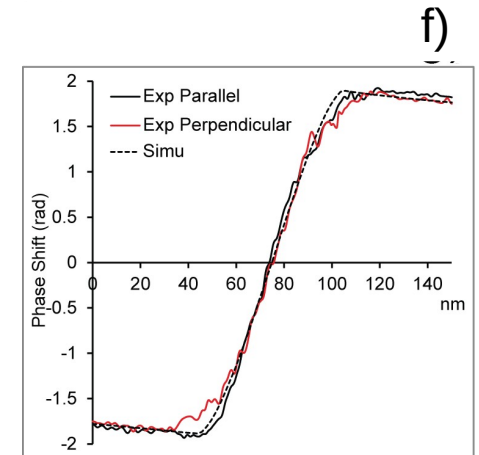
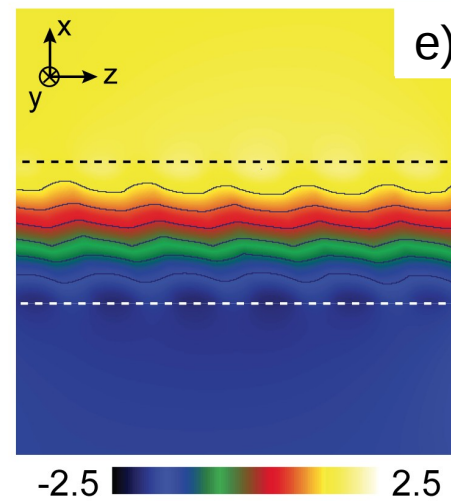
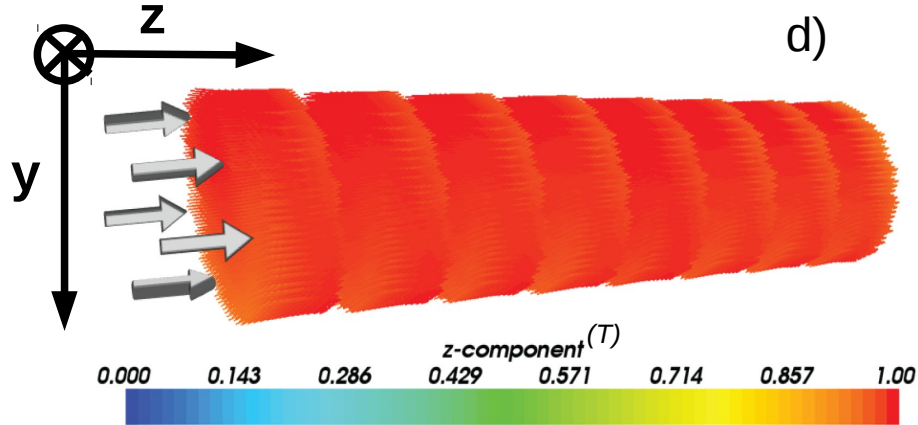
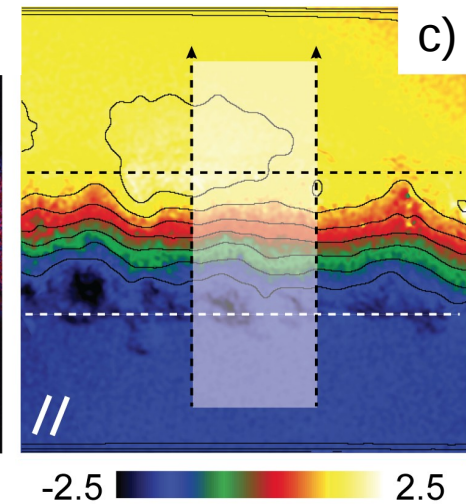
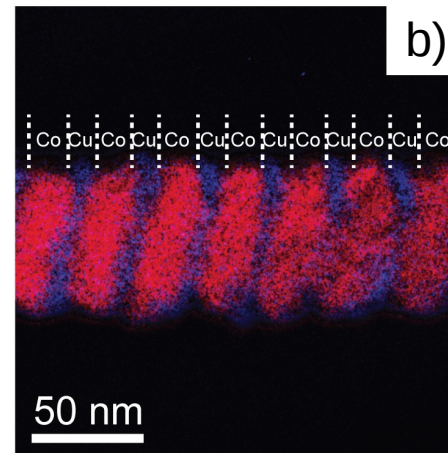
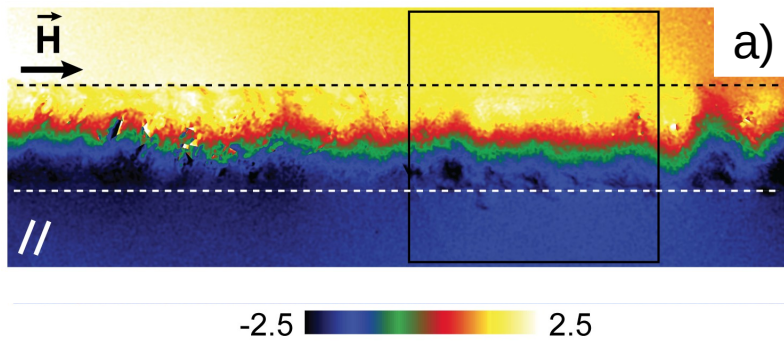




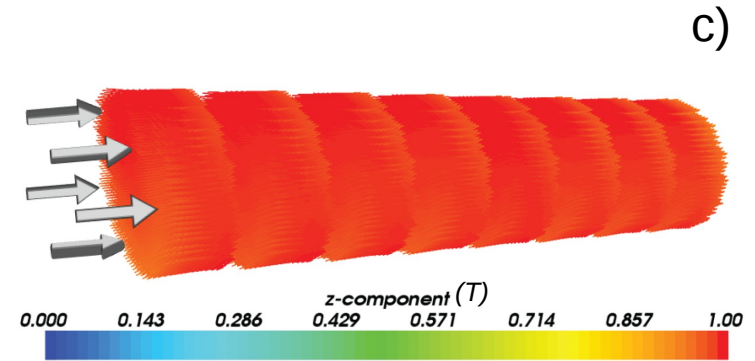
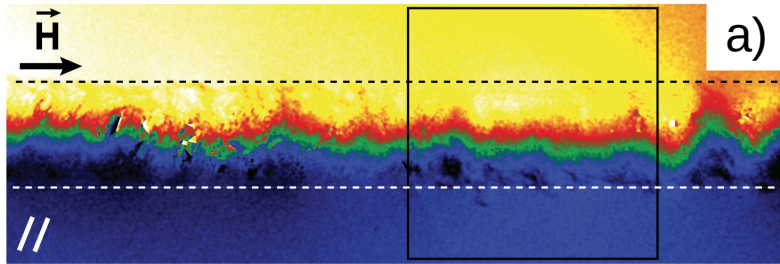




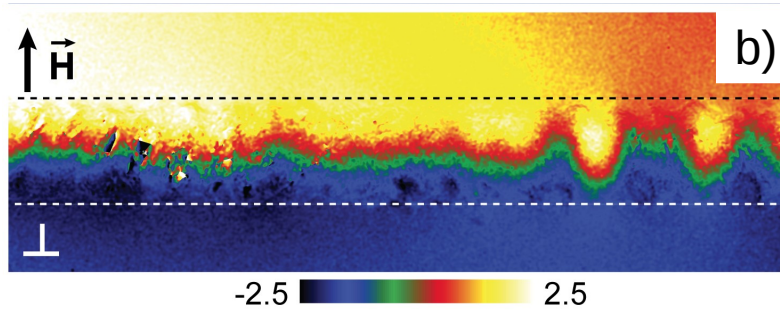
**Mono domain
State**



Parallel configuration

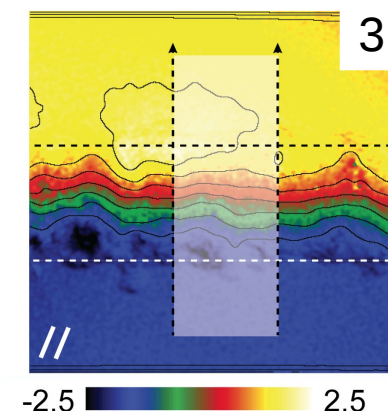
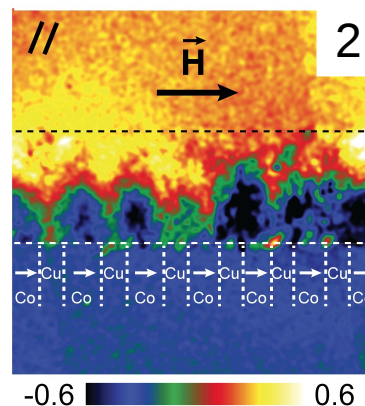
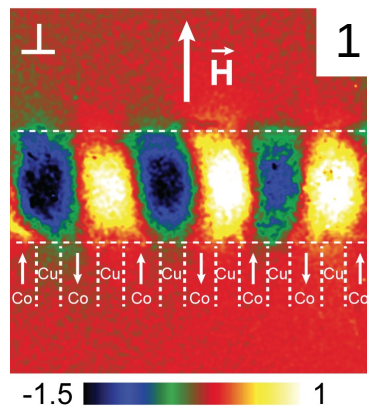


Perpendicular configuration



**Mono domain
State for both
Configurations!**

- We have produced Cu/Co multi-layered nanowires by electro-deposition with a good quality.
- The first study of the local magnetic states in Cu/Co with this resolution.
- Quantitative and local study combining structural, chemical, magnetic (electron holography) properties and 3D simulations
- We performed a systematic study of isolated nanowires with a spatial resolution no more of 2 nm by electron holography revealing 3 main configurations:



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- The French national project NASSICS (ANR12-JS10-008 01)
- The French National Research Agency under the "Investissement d'Avenir" program reference No. ANR-10-EQPX-38-01
- The authors acknowledge the "Conseil Regional Midi-Pyrénées" and the European FEDER for financial support within the CPER program
- This work was performed using HPC resources from CALMIP (Grant 2015-1428)

