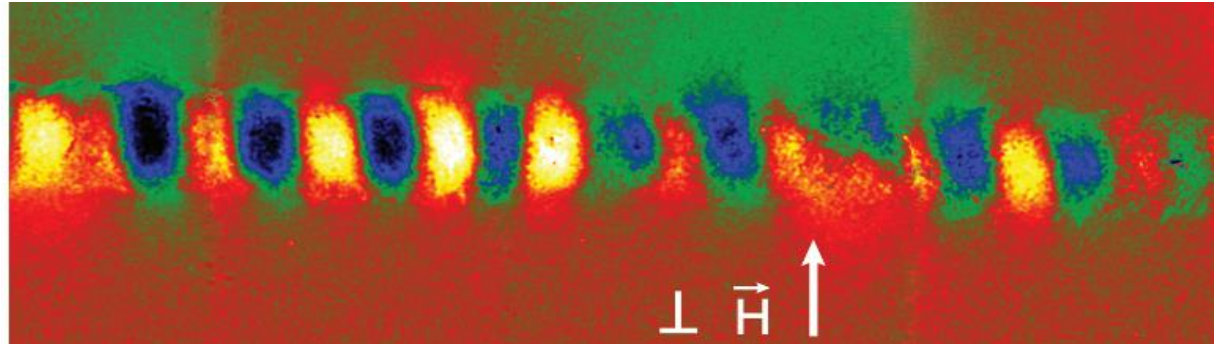


Micromagnetic study of magnetic states in Co/Cu multilayered cylinders observed by electron holography

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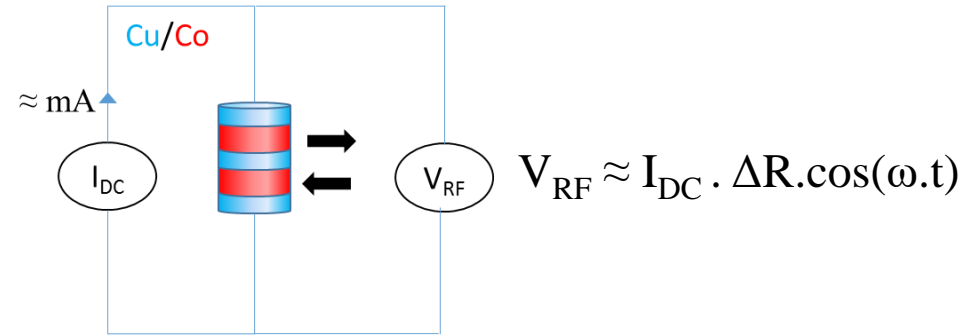


M²OZART Workshop on Nanomagnetism, Zaragoza Spain

Motivations

Why (still!) studying multi-layered systems?

- Spin torque nano-oscillators : injection of a DC current in a magnetic nanostructure to get a microwave voltage.



- Microwave power depends on the number of layers connected in series : **interest for magnetic nano-multilayers**
- The frequency of V_{RF} depends on the magnetic state of the layers

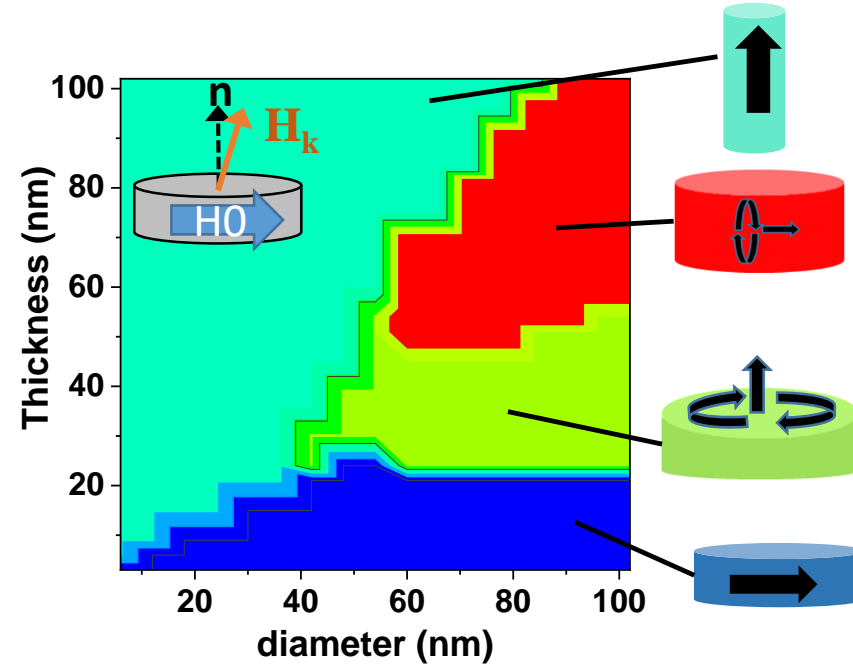
Experimental interest :

nice playground for advanced electron holography experiments and nanomagnetism !

Example of a single layer phase diagram

Remnant states depends on :

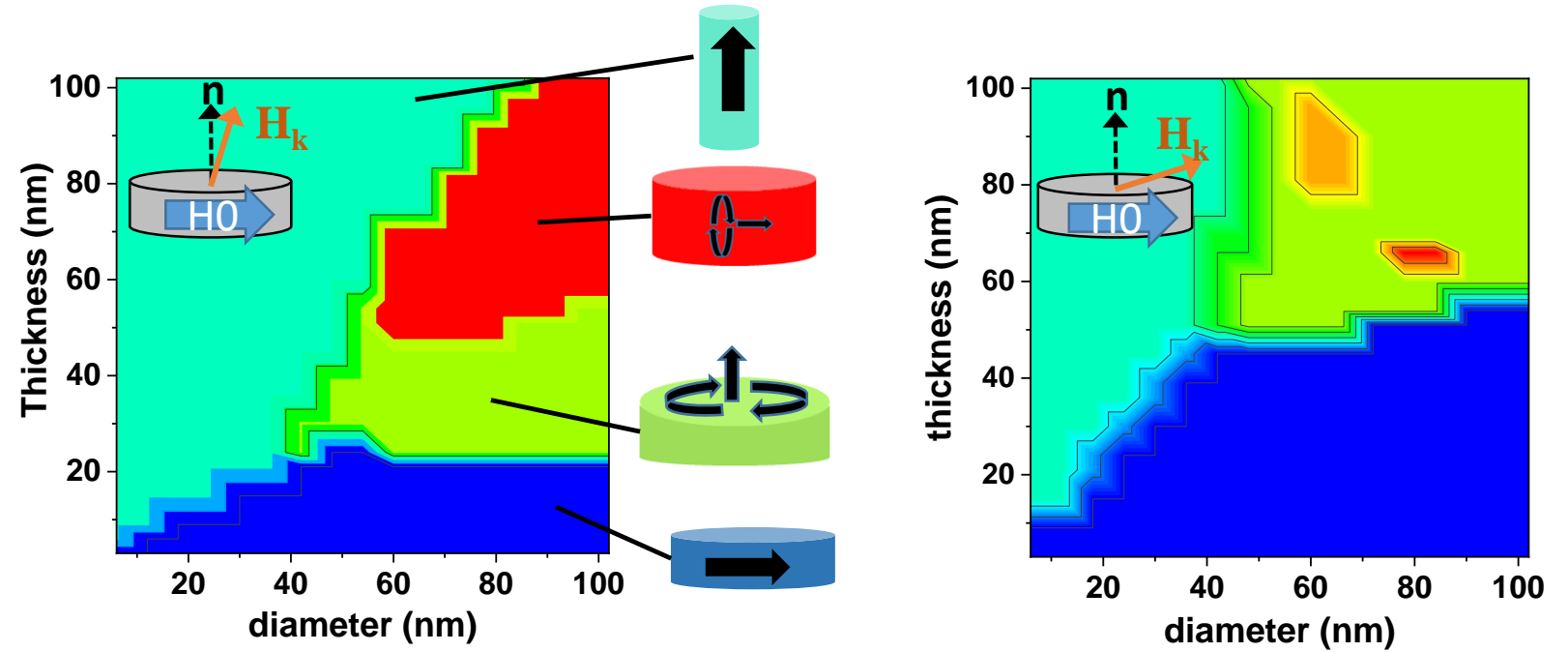
- Shape anisotropy



Example of a single layer phase diagram

Remnant states depends on :

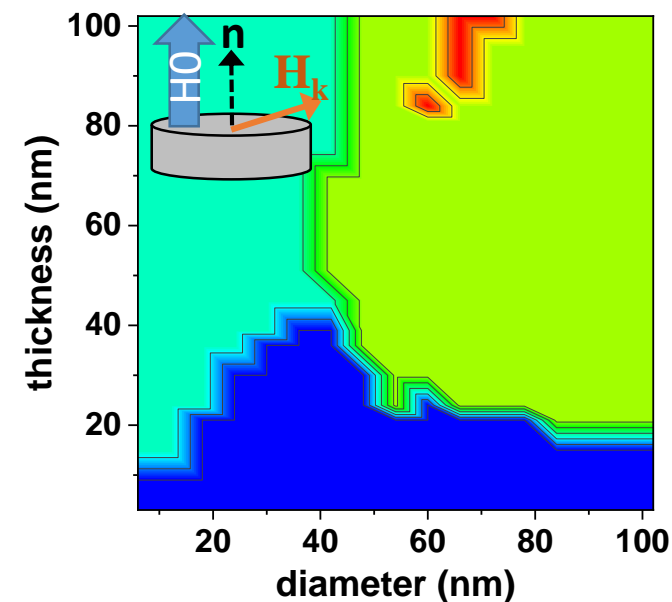
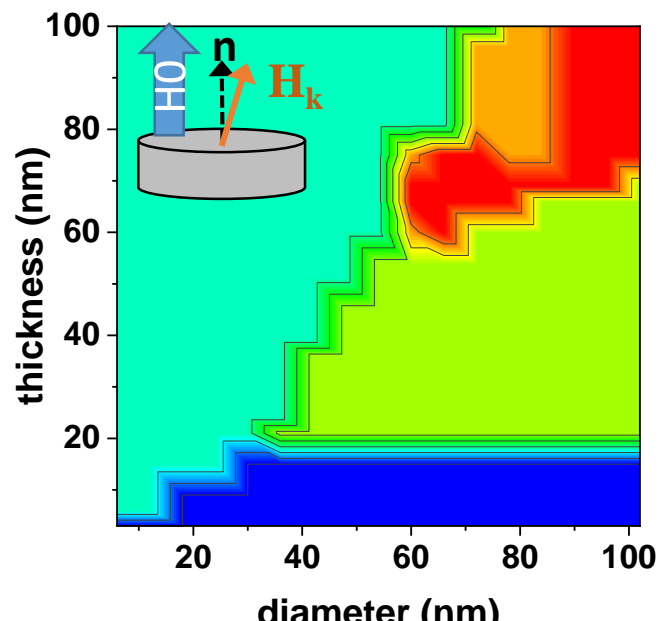
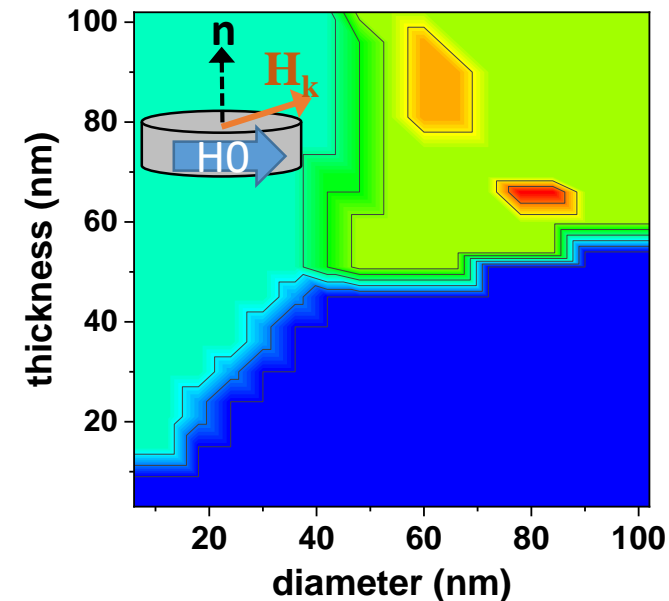
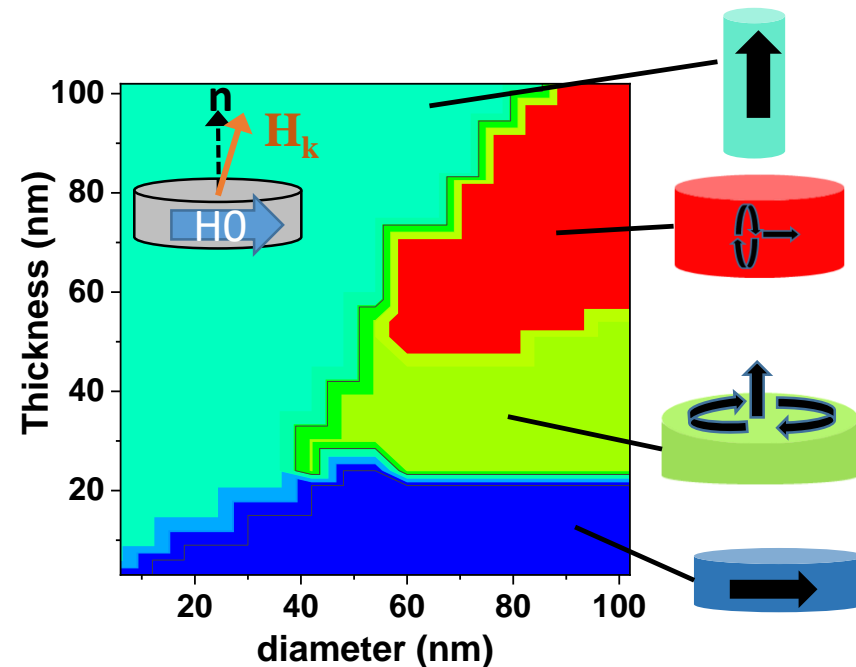
- Shape anisotropy
- Crystal anisotropy



Example of a single layer phase diagram

Remnant states depends on :

- Shape anisotropy
- Crystal anisotropy
- Direction of saturation field H_0
- Dipolar coupling between layers for multilayers

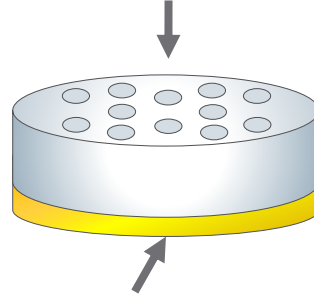


Growth of nanowires (in collaboration with T. Wade LSI –Palaiseau)

Electrodeposition:

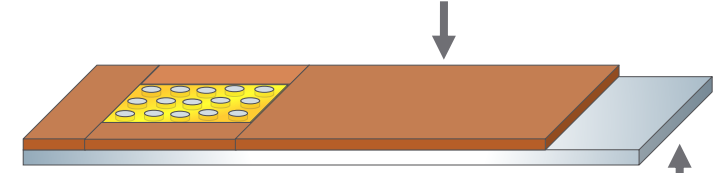
- “Easy”
- “Cheap”
- Control of length

Polycarbonate membrane



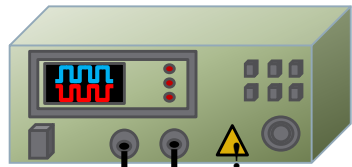
Thin film of gold

Kapton tape

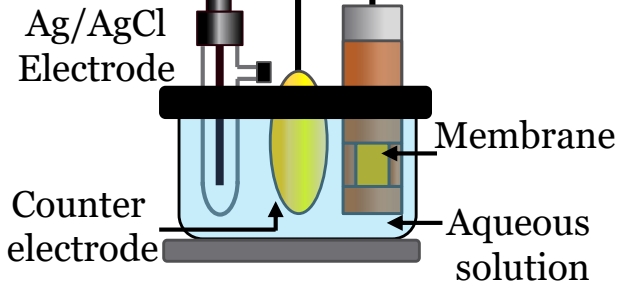


Metal piece (Al)

Potentiostat



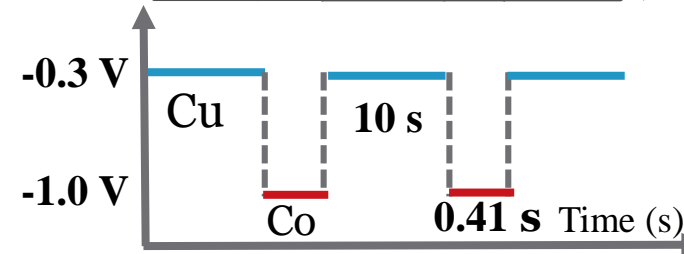
Chemical bath composition :
 $\text{CoSO}_4 + \text{CuSO}_4 + \text{H}_2\text{O} + \text{H}_3\text{BO}_4$



Length up to $6 \mu\text{m}$

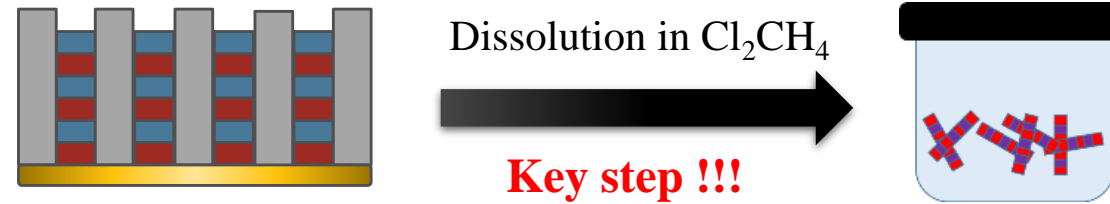


Diameter from 50 to 100 nm

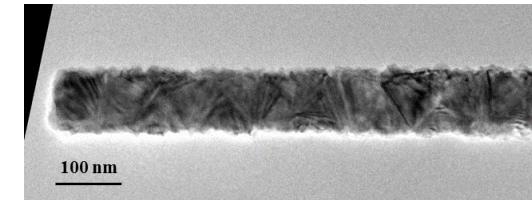
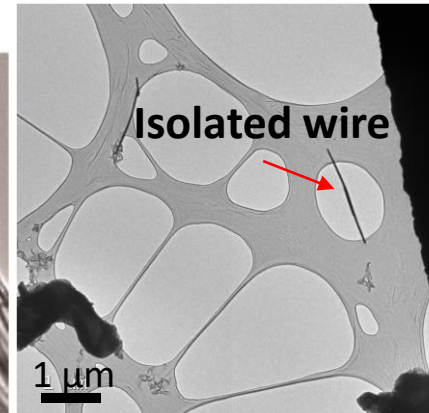
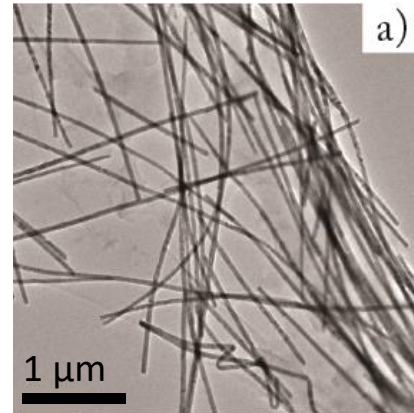


Co-deposition of Cupper in the Cobalt layers !

Growth of nanowires (in collaboration with T. Wade LSI –Palaiseau)



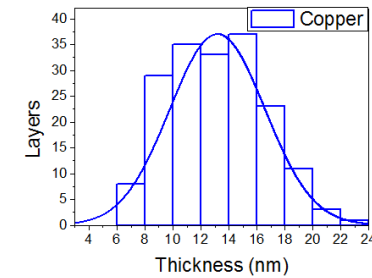
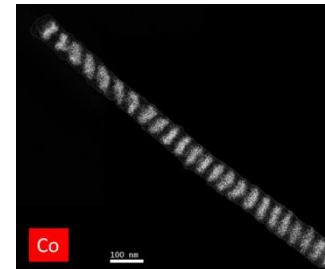
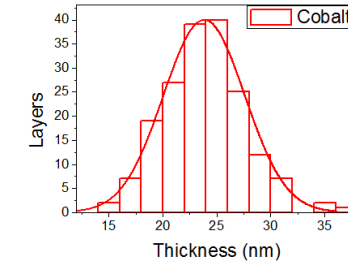
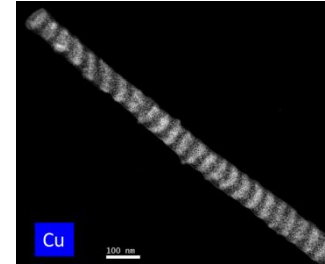
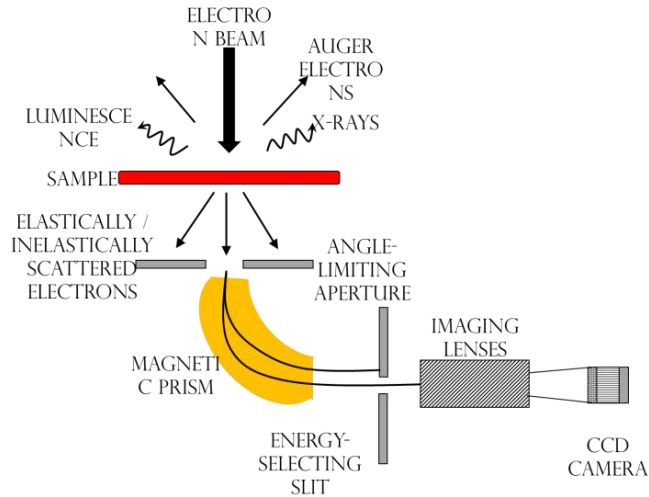
Deposition on
TEM carbon grid



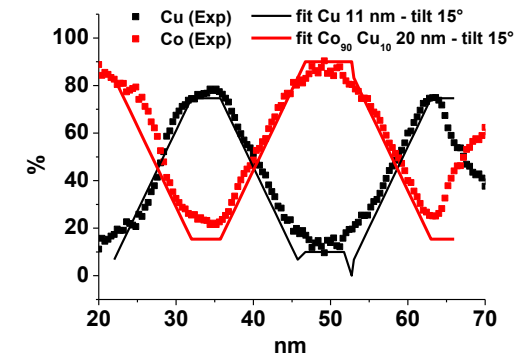
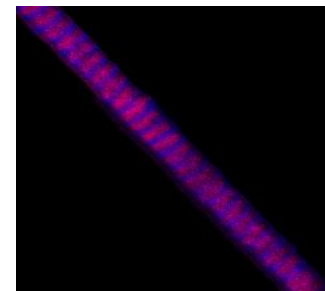
- Polycrystalline nano-cylinders with mean diameter of 50, 80 or 110 nm
- Hundreds of nanowires on a TEM grid

Structural and chemical analysis

- Method : Energy Filtered Transmission Electron Microscopy (**EFTEM**) and Electron Energy Loss Spectroscopy (**EELS**)

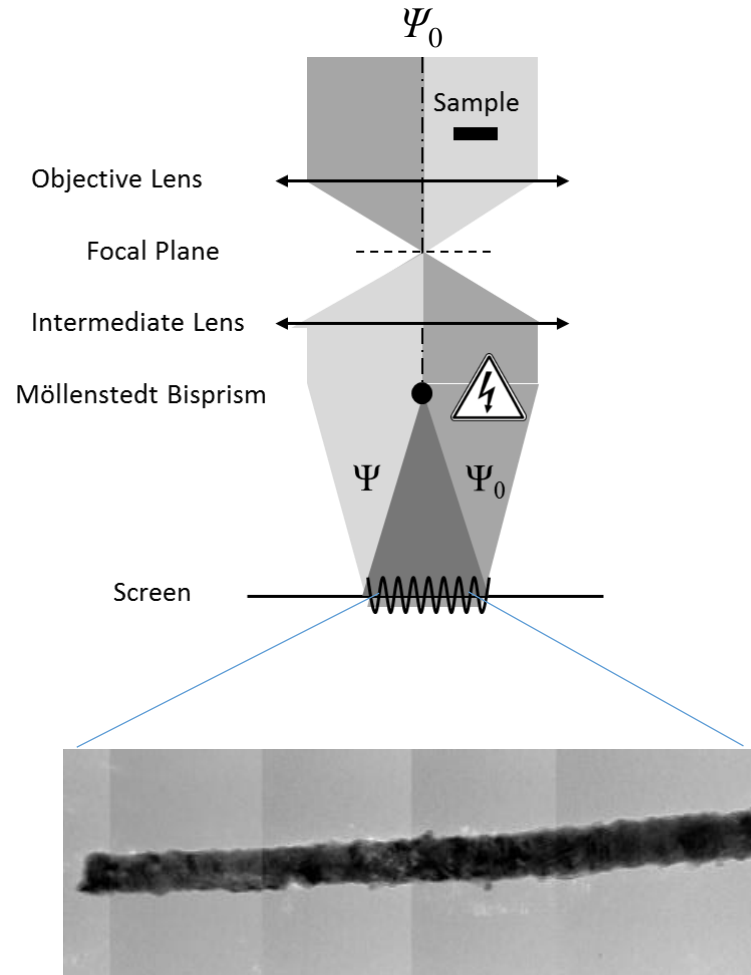


- $\approx 15\%$ of Cu impurities in Co
- Average tilt angle of the layers $\approx 15^\circ$
- Diameters : between 55 et 80 nm
- Average thicknesses :
 - Co 25 nm
 - Cu 14 nm



Magnetic state observation

- Method : Electron Holography



$$\Psi_0 = \exp(i\mathbf{k}\cdot\mathbf{r})$$

$$\Psi(\mathbf{r}) = A_S(\mathbf{r}) \exp i((\mathbf{k}\cdot\mathbf{r}) + \phi_S(\mathbf{r}))$$

Incident beam

After the sample

The information about magnetization is in $\phi_S(\mathbf{r})$

$$\phi_S(x) = \phi_{\text{elec}}(x) + \phi_{\text{Mag}}(x)$$

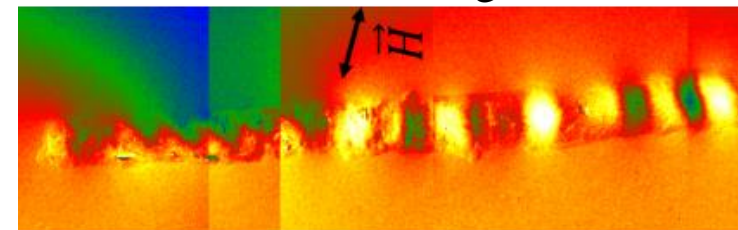
Electrostatic part

$$\phi_{\text{elec}}(x) = C_E \int V(x,y,z) dz$$

Magnetic part

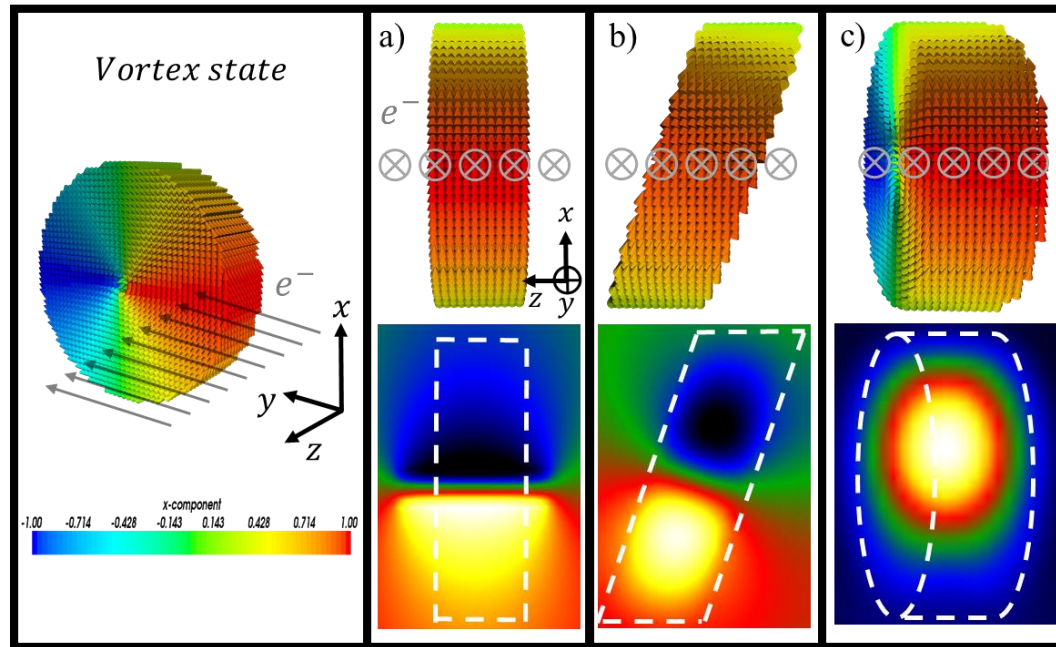
$$\phi_{\text{Mag}}(x) = -\frac{e}{\hbar} \int B_{\perp}(x,z) \cdot dx \cdot dz$$

Phase shift image



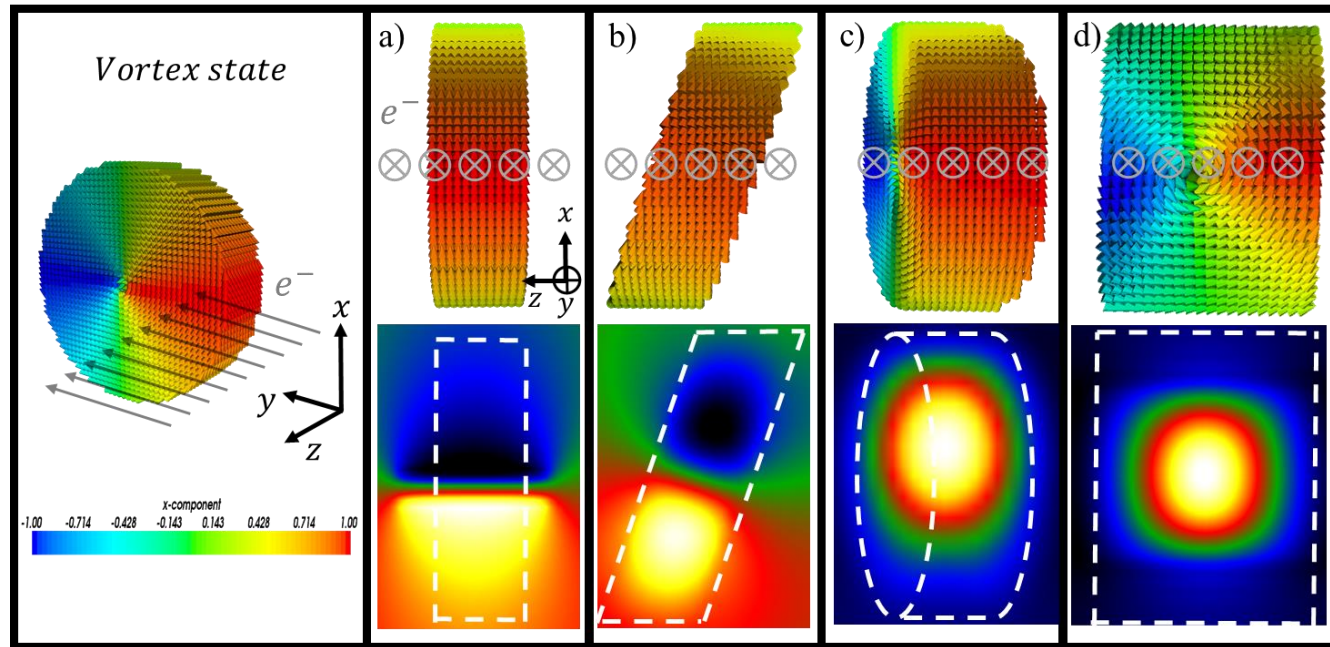
- Integration of \mathbf{B} along the electron path
- \Rightarrow Sensitive to in plane components of \mathbf{B}
- \Rightarrow **2D projection of the 3D magnetic state**

Illustration of the 2D projection problem



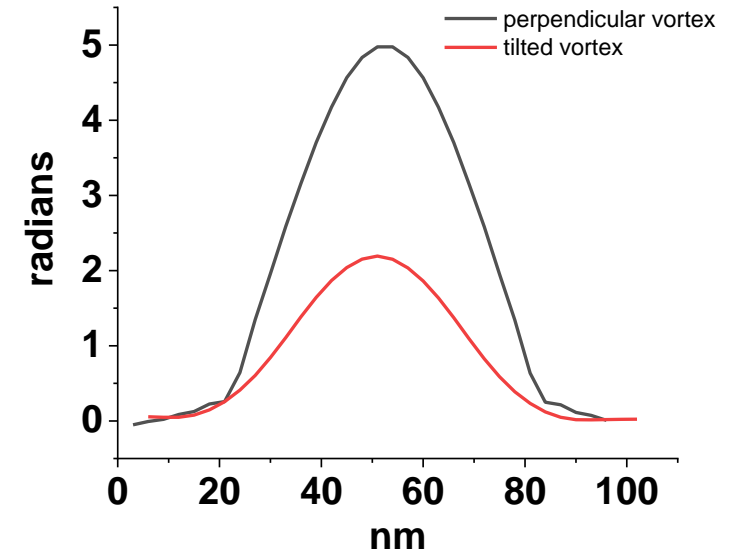
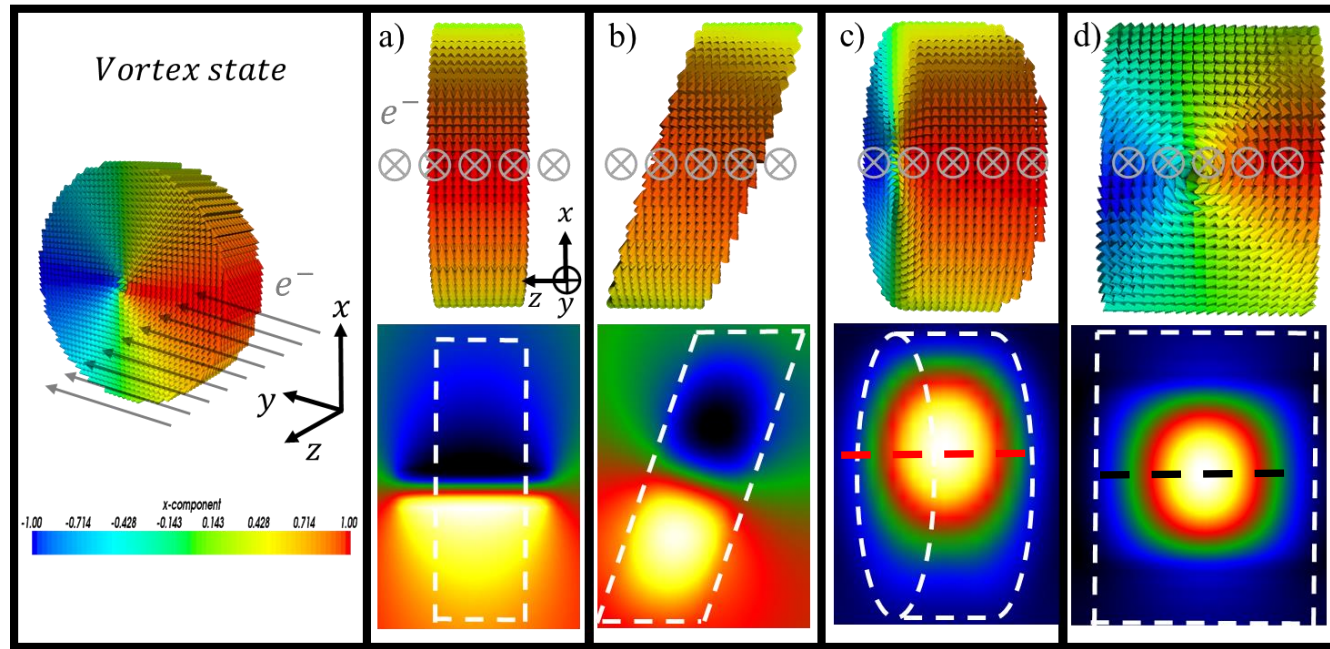
- **Extrinsic** parameter : the orientation of the layers with respect to the e^- direction

Illustration of the 2D projection problem



- **Extrinsic** parameter : the orientation of the layers with respect to the e^- direction
- **Intrinsic** parameters : magnetic properties and dimensions of the layers.

Illustration of the 2D projection problem



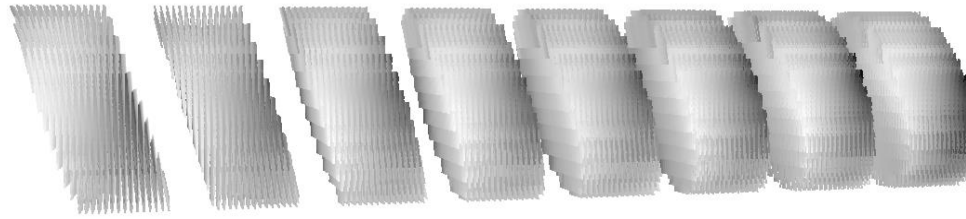
- **Extrinsic** parameter : the orientation of the layers with respect to the e^- direction
- **Intrinsic** parameters : magnetic properties and dimensions of the layers.

Need for qualitative AND quantitative characterization

Magnetic state simulation and electronic phase reconstruction

- Simulation of remanent state after saturation at $\mu_0 H = 1.3\text{T}$ in +X or +Z ($\pm 10^\circ$) : 3D OOMMF freeware
(CALMIP parallel computing center of Toulouse, France)

- Calculation of magnetic phase : $\vec{B} = \mu_0 (\vec{M} + \vec{H}_D) \Rightarrow \phi_{Mag} = -\frac{e}{\hbar} \iint \mathbf{B}_\perp(x, z) \cdot d\mathbf{x} \cdot dz$



Up to 20 bilayers of Co/Cu

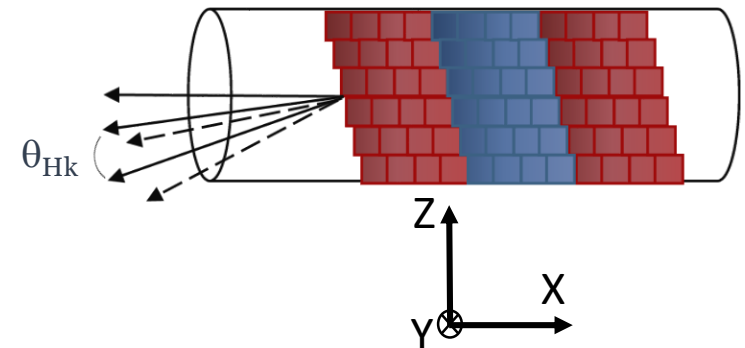
Cell size $2 \times 2 \times 2 \text{ nm}^3$

Universe size $500 \times 500 \times 1100 \text{ nm}^3$

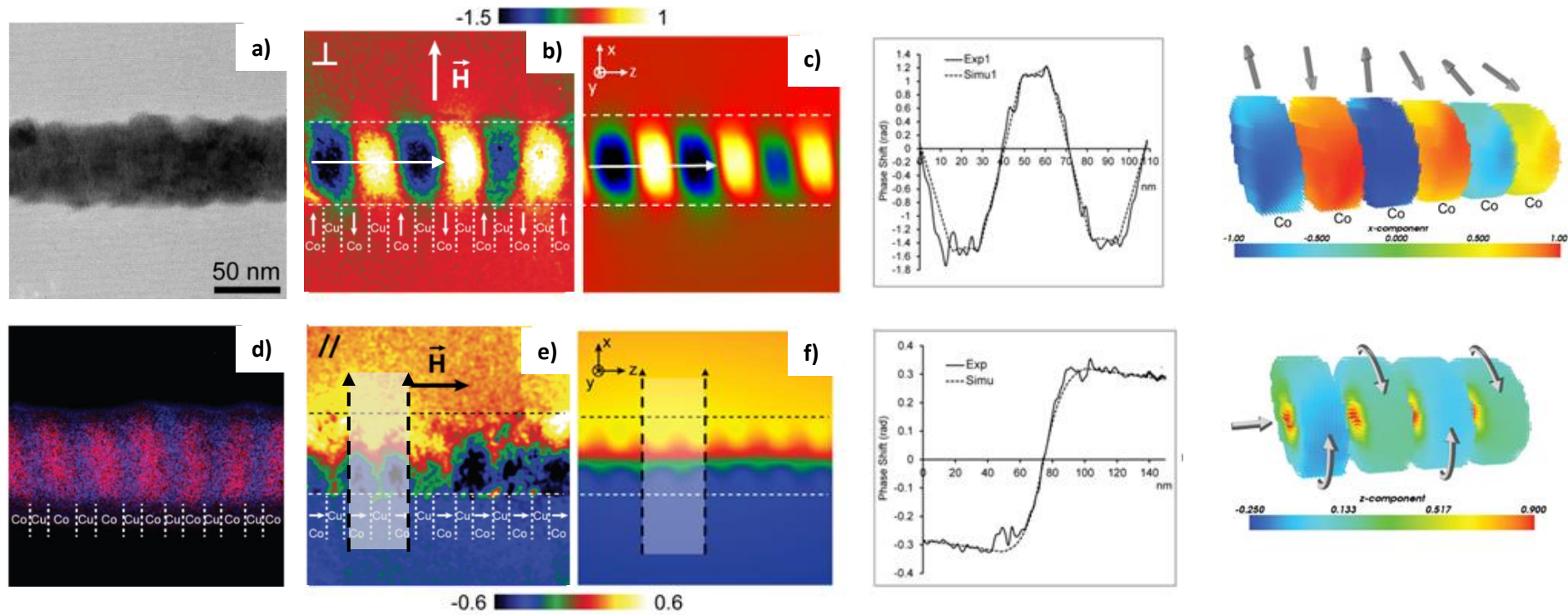
Simulation time : up to few days

Difficulty : high number of geometrical and magnetic inputs !

- Starting point for geometry : implementation of average parameters obtained by EELS/EFTEM
- Magnetic parameters :
 - $\mu_0 M_s = 1.5 \text{ T}$ as starting point
 - uniaxial crystal anisotropy field H_k
 - adjustable parameters : anisotropy field H_k (value, direction θ_{Hk}) and exchange value A



Remanent magnetic states in $\text{Co}_{25\text{ nm}}/\text{Cu}_{15\text{ nm}}$ ($\phi \approx 70\text{ nm}$)

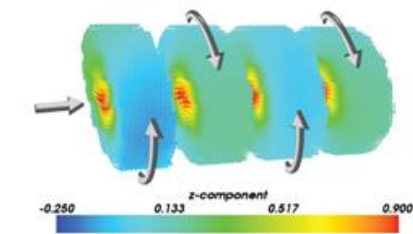
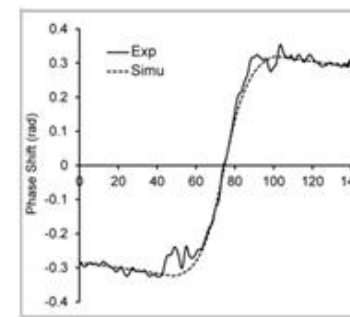
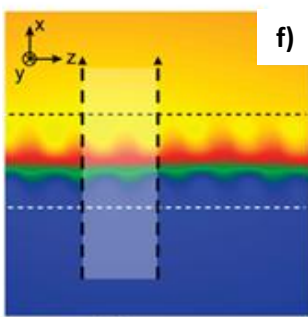
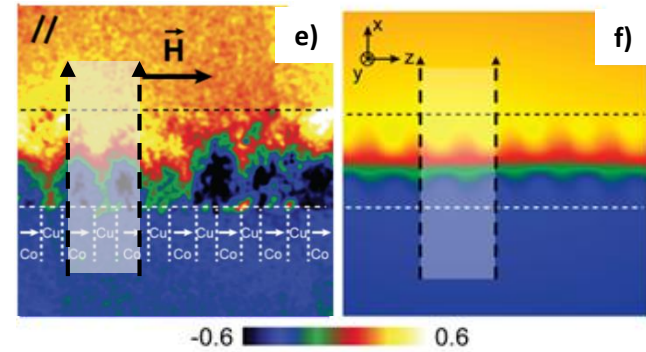
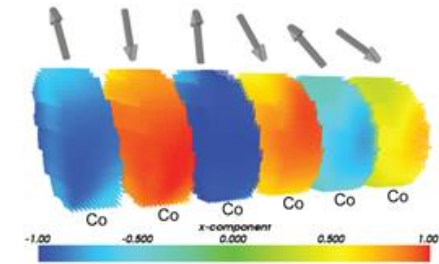
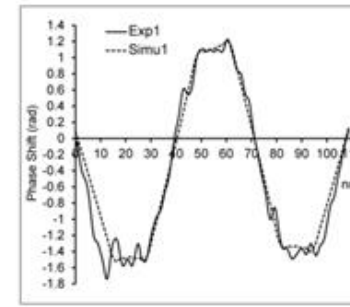
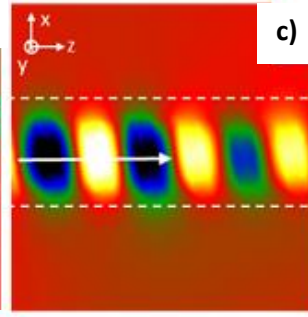
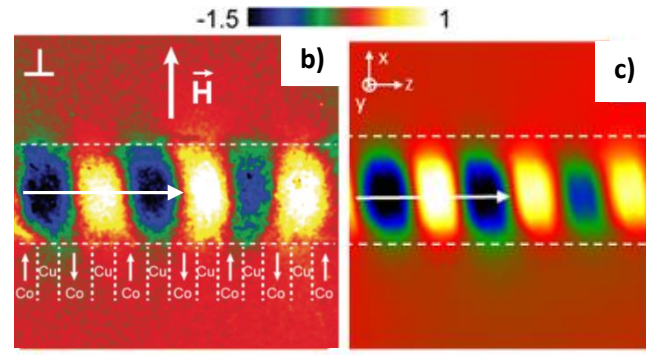
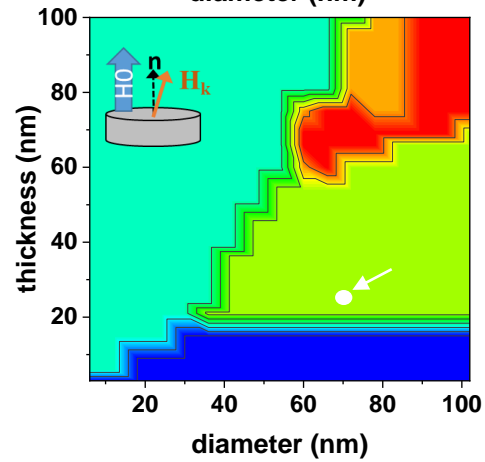
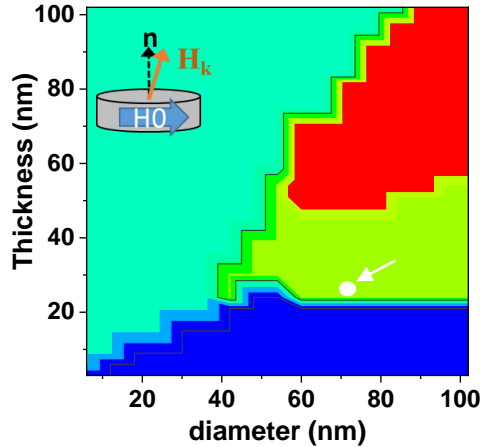


Quantitative agreement between simulation and experiment for :

- $\mu_0 M_s = 1.5\text{ T}$ (bulk = 1.7 T)
- Exchange value = $22 \cdot 10^{-12}\text{ J/m}$ (bulk = $30 \cdot 10^{-12}\text{ J/m}$)
- $\mu_0 H_k = 0.15\text{ T}$ (bulk = 0.6 T) and randomly distributed at 20° from the normal of the Co layers

Values much lower than bulk !
Presence of Cu impurities + grains

Remanent magnetic states in $\text{Co}_{25\text{ nm}}/\text{Cu}_{15\text{ nm}}$ ($\phi \approx 70\text{ nm}$)



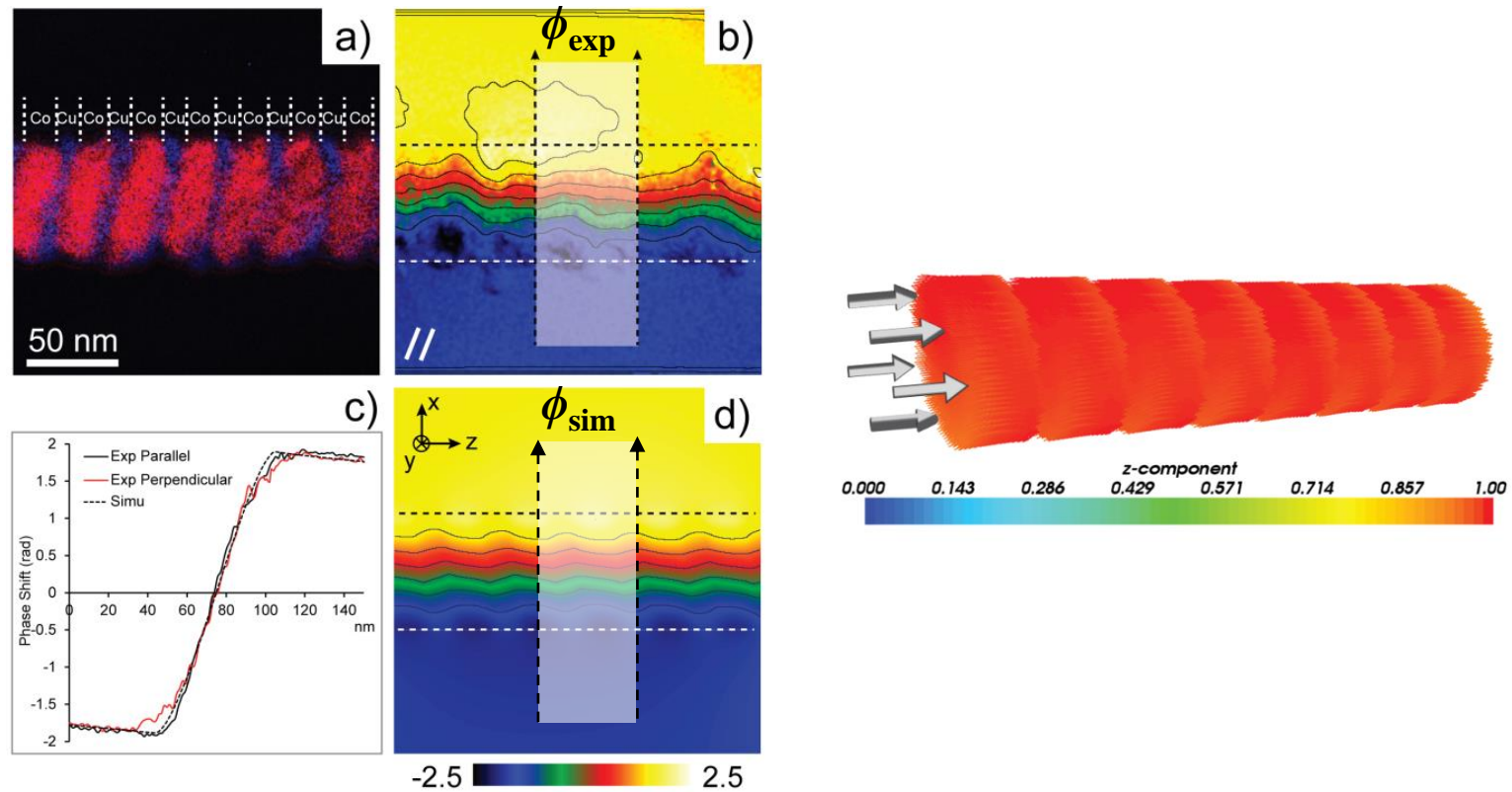
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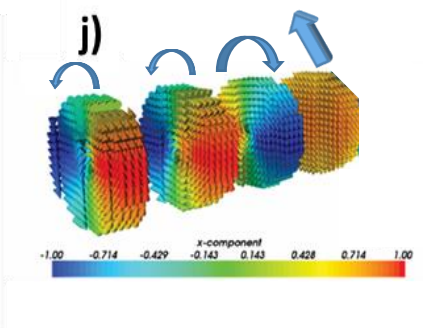
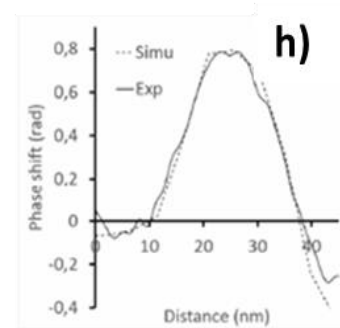
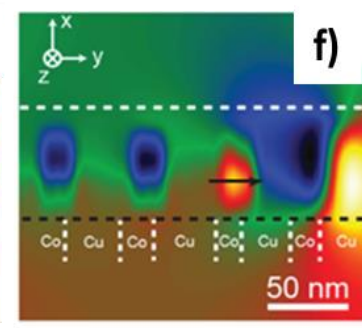
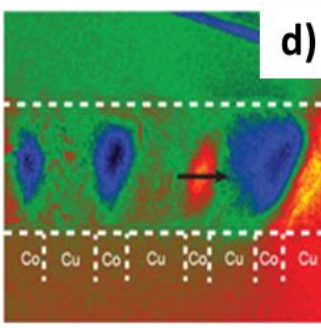
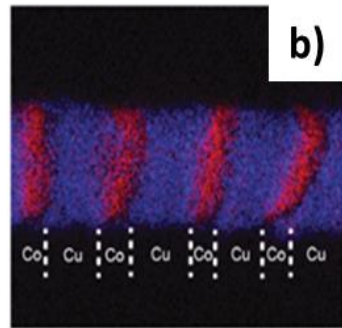
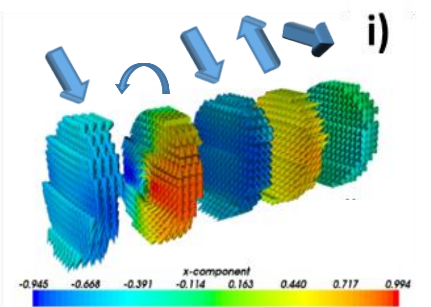
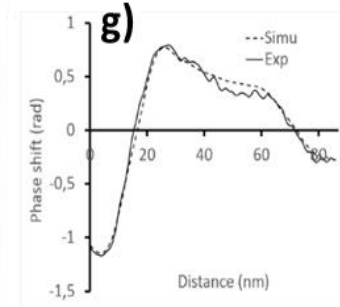
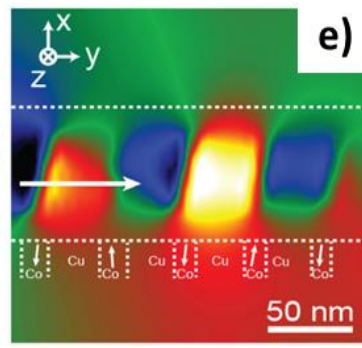
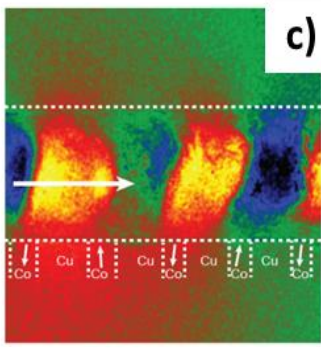
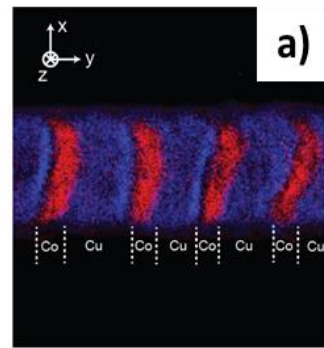
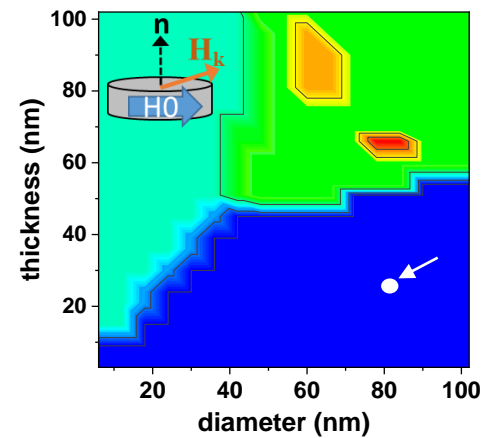
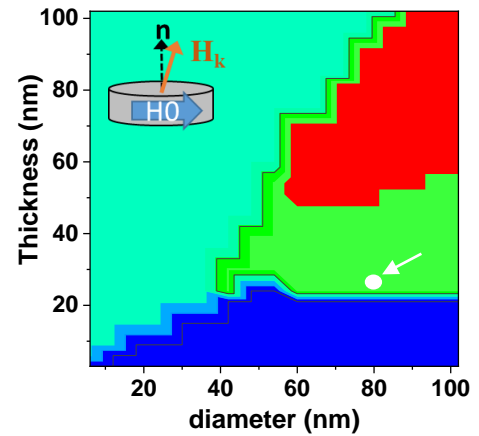
Dipolar coupling allows for the transition between the two magnetic states

Remanent magnetic states in $\text{Co}_{25\text{ nm}}/\text{Cu}_{15\text{ nm}}$ ($\phi \approx 70\text{ nm}$)



- Third configuration : mono-domain like state with magnetization along the wire axis
- Can be simulated by considering $\mu_0 H_k > 0.3\text{ T}$ and randomly distributed within 20° from the normal of the Co layers

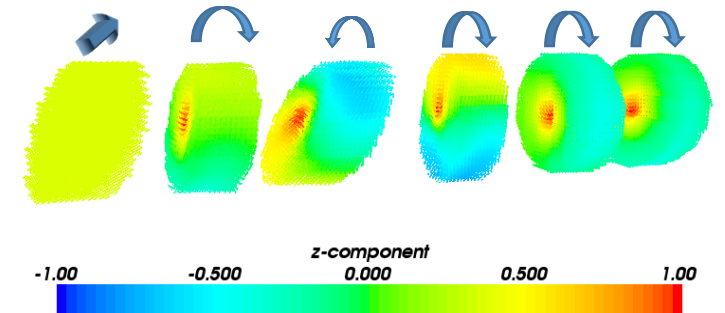
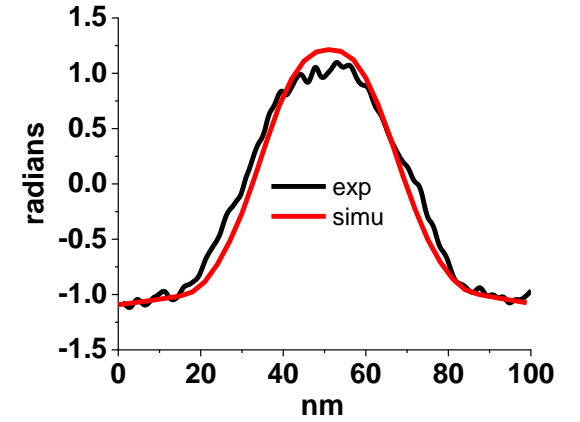
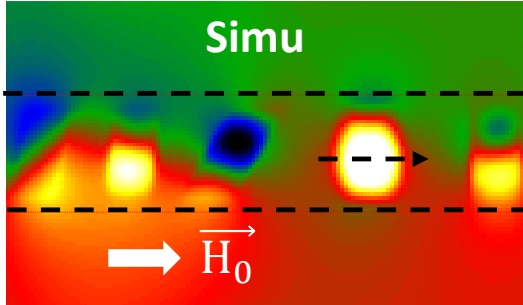
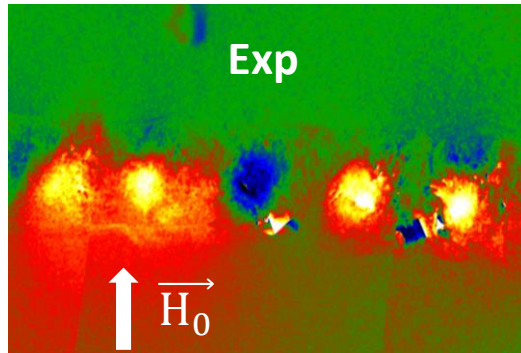
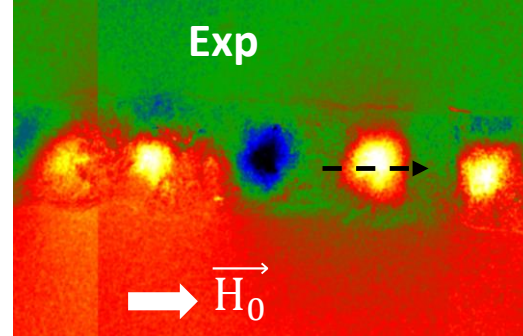
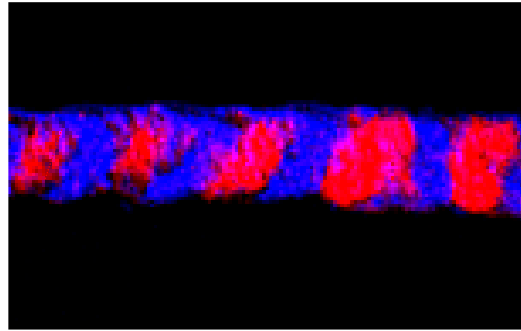
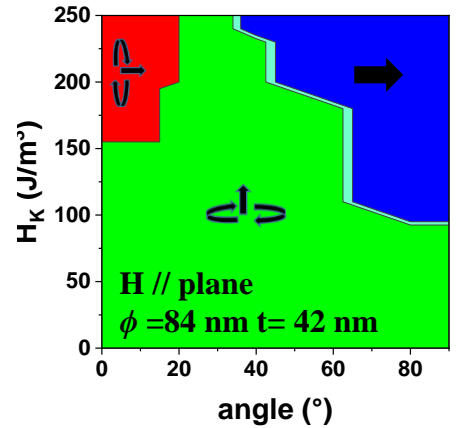
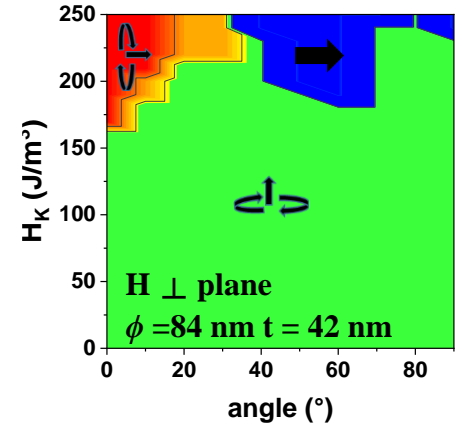
Effect of interlayer spacer : $\text{Co}_{25\text{ nm}}/\text{Cu}_{45\text{ nm}}$ ($\phi \approx 80\text{ nm}$)



The decrease of dipolar coupling prevents from :

- transitions between different states when changing H_0
- formation of monodomain like states

Effect of aspect ratio : $\text{Co}_{45 \text{ nm}}/\text{Cu}_{50 \text{ nm}}$ ($\phi \approx 80 \text{ nm}$)



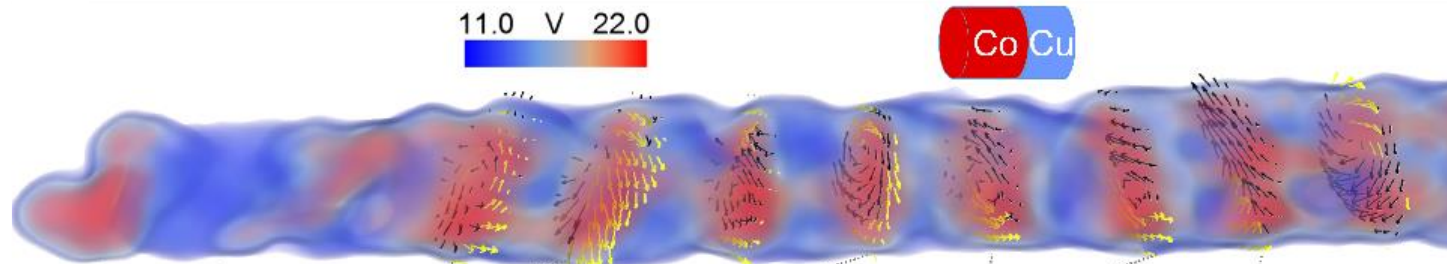
- Increasing the Co aspect ratio ≥ 0.5 leads to mainly vortices states as expected for single layer

Huge difficulty to simulate because of unknown structural inputs :
 \Rightarrow need for 3D tomography!

Contribution of 3D tomography to nanomagnetism

(collaboration D. Wolf and A. Lubk, Institute for Solid State Research, Dresden Germany)

- Principle of tomography : numerical reconstruction of 3D geometry and induction components of a nano-object via multiple tilted holograms

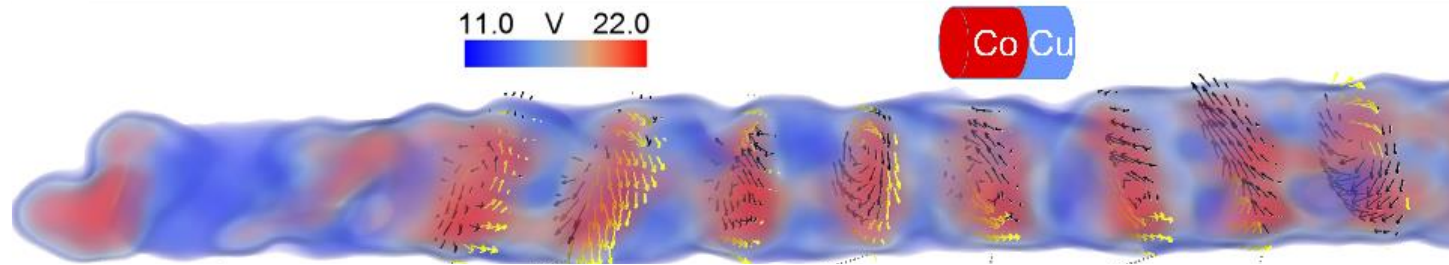


Mean inner potential of $\text{Co}_{25 \text{ nm}}/\text{Cu}_{15 \text{ nm}}$

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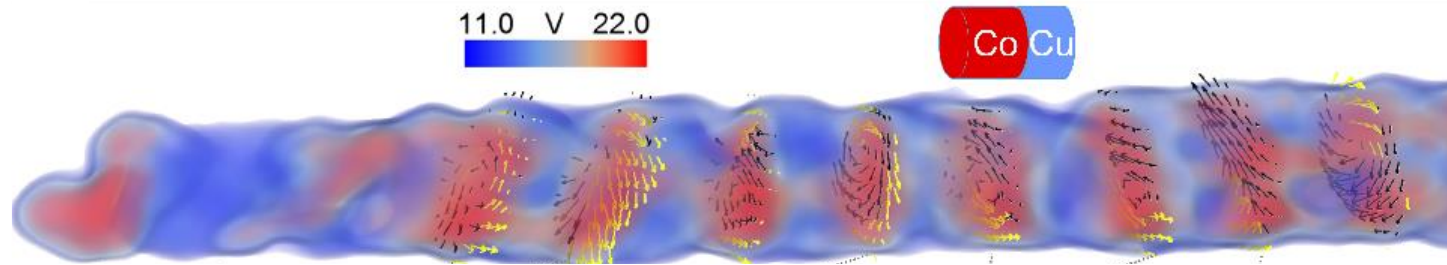


Implementation of exact
shape in OOMMF

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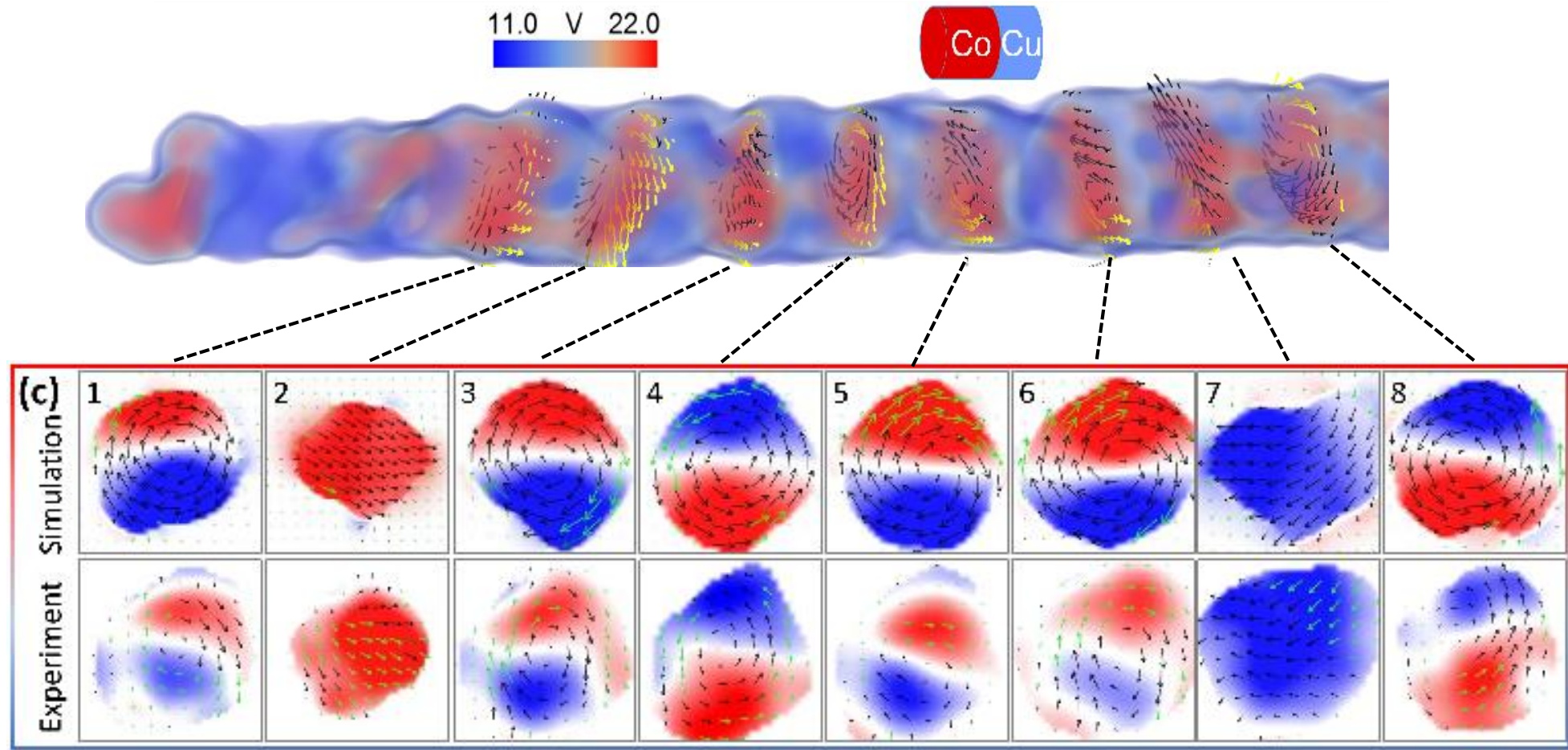
Implementation of exact
shape in OOMMF



3D tomography allows to reveal
more complex geometries than
expected !

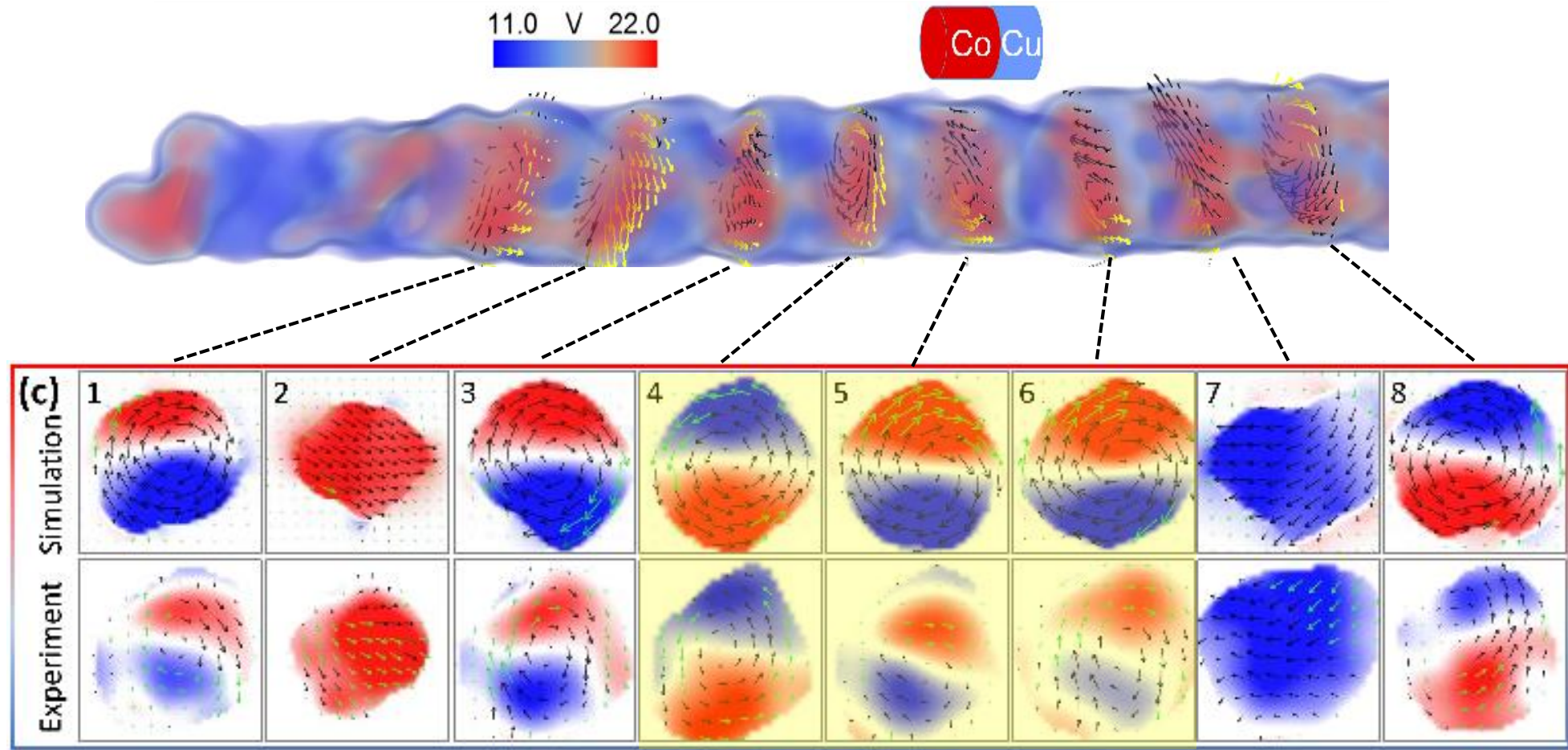
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Contribution of 3D tomography to nanomagnetism

(collaboration D. Wolf and A. Lubk, Institute for Solid State Research, Dresden Germany)



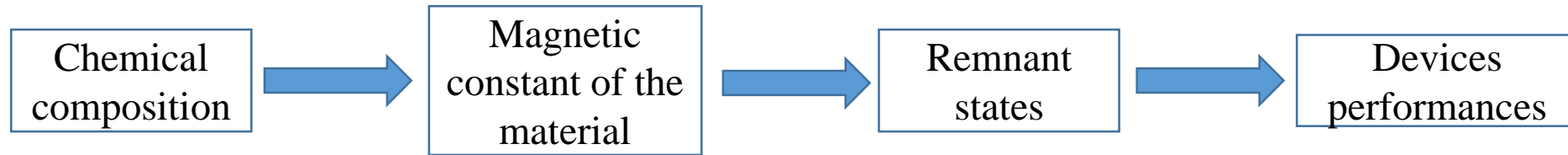
Very thin layers down to 15 nm : exchange decreased by 40 % as compared to other layers to enter a vortex!

Conclusion

- For small Cu thickness, dipolar coupling allows for transition between different remnant states

⇒ Interest for spin torque oscillators with multiple working frequencies.

- For large Cu thickness or high aspect ratio of Co, remnant states are defined by intrinsic properties of the layers



- 3D tomography opens new possibility for nanomagnetism studies :

⇒ avoids geometrical uncertainties

⇒ allows for much better description of magnetic states and reverse engineering of magnetic parameters for each layer