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Nicolas Biziere, D Reyes, T L Wade, D Wolf, B Warot-Fonrose, S Sturm, A  
Lubk, C Gatel

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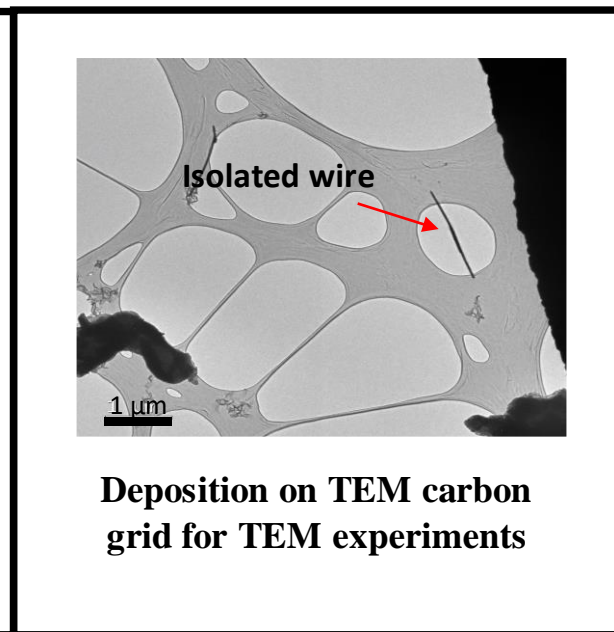
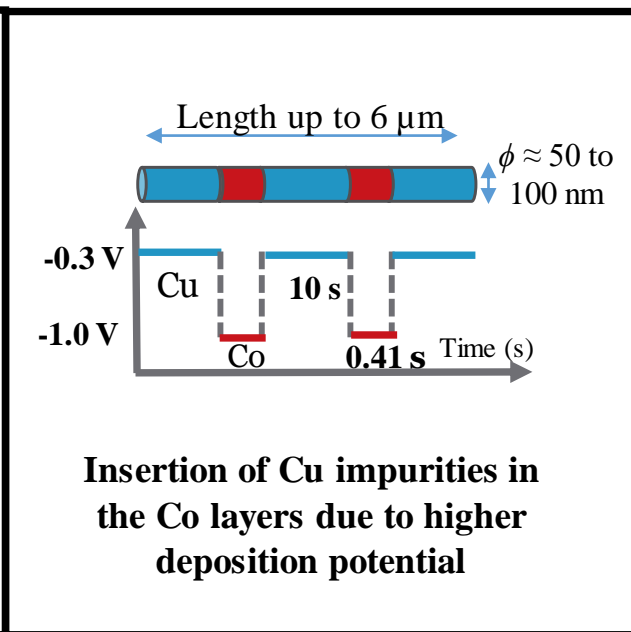
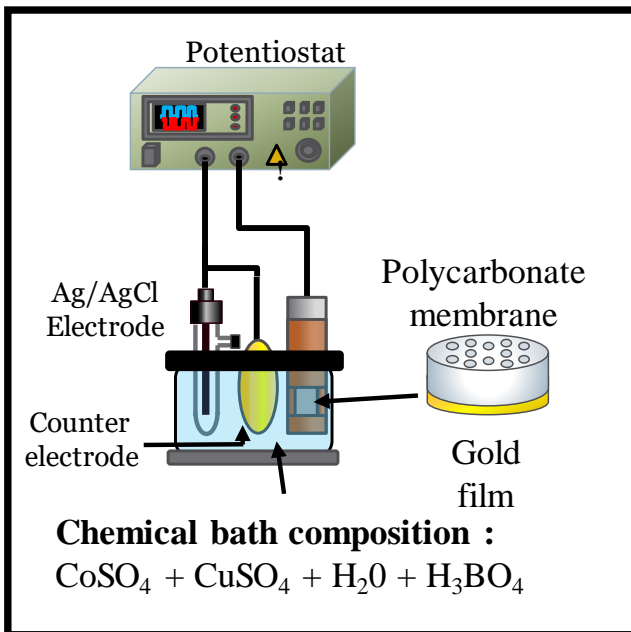
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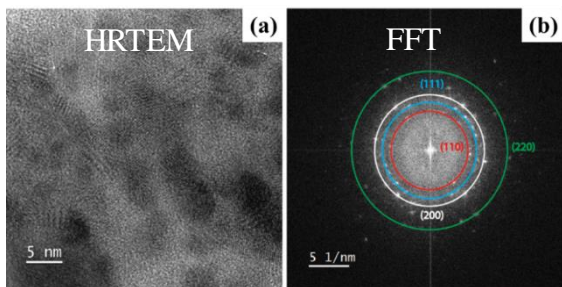
# Micromagnetism of Co/Cu multi-layered nanocylinders observed by electron holography

**N. Biziere**<sup>1</sup>, D. Reyes<sup>1</sup>, T.L. Wade<sup>3</sup>, D. Wolf<sup>3</sup>, B. Warot-Fonrose<sup>1</sup>, S. Sturm<sup>3</sup>,  
A. Lubk<sup>3</sup>, C. Gatel<sup>1</sup>

1. CEMES CNRS-UPR 8011, 31055 Toulouse, France
2. Laboratoire des Solides Irradiés, Ecole Polytechnique, CNRS, CEA, Université Paris Saclay, 91128 Palaiseau, France
3. Leibniz Institute for Solid State and Materials Research Dresden, 01069 Dresden, Germany

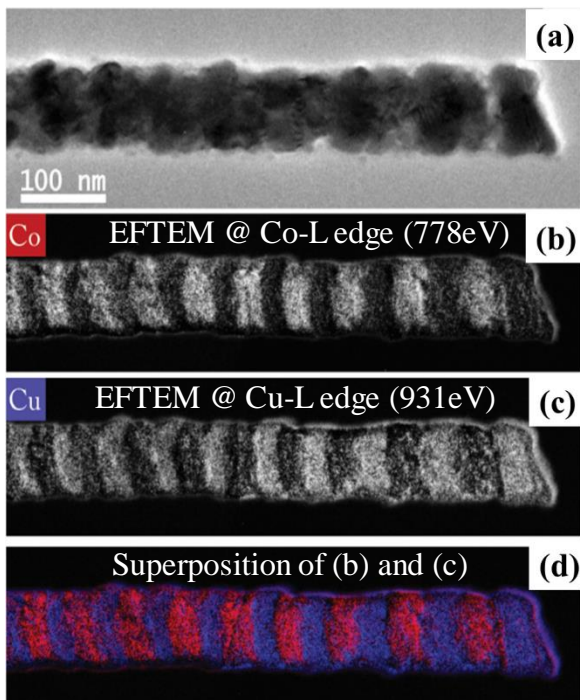
- Interest of template synthesis for magnetic multilayers :
  - ⇒ easiness to modify the thickness of the layers
  - ⇒ nice playground for micromagnetism studies
  - ⇒ potential for spin torque nano-oscillators connected in series?





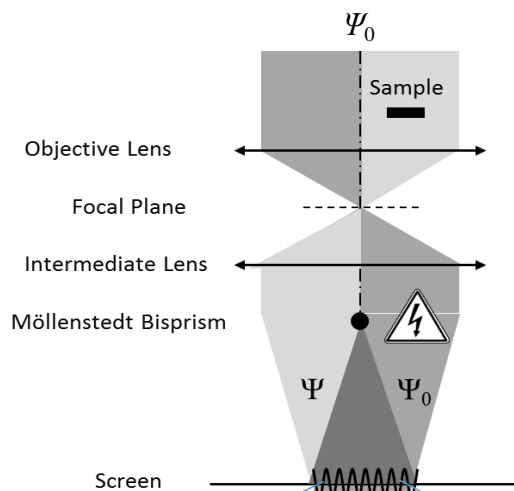
## High Resolution TEM (HREM)

- random distribution of Co and Cu polycrystals.
- grain mean size of  $7 \pm 2$  nm
- fcc phases for Co and Cu (as expected)



## Chemical analysis by Energy Filtered Transmission Electron Microscopy (EFTEM)

- Classical TEM imaging does not allow distinguishing between Co and Cu layers
- EFTEM images at the Co and Cu energy edges reveal the position of the different layers.
- Variations of diameter and thickness along the wire
- Averaged tilt angle  $\approx 20^\circ$  from wire axis and up to  $45^\circ$



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

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

Incident beam

After the sample

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

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

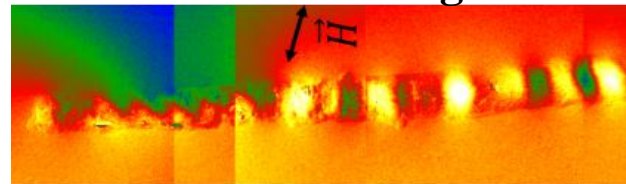
Electrostatic part

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

Magnetic part

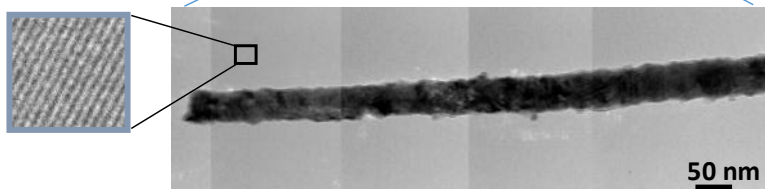
$$\phi_{Mag} = -\frac{e}{\hbar} \int B_{\perp}(x,z) dx dz$$

Phase shift image



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

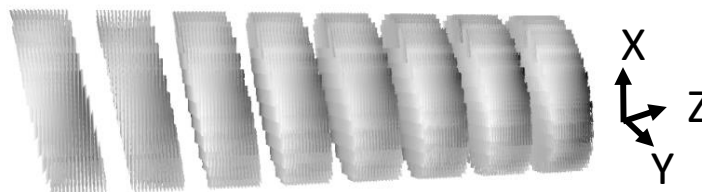
⇒ *Need for micromagnetic simulations and phase shift reconstruction to recover the full 3D magnetic state*



- OOMMF simulations of magnetic remanent states after saturation // or  $\perp$  to the wire axis
- Calculation of magnetic induction  $\vec{B}$  and reconstruction of electron phase shift  $\phi_{Mag}$  image :

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

Cell size  $2 \times 2 \times 2 \text{ nm}^3$   
From 1 to 20 layers of Co

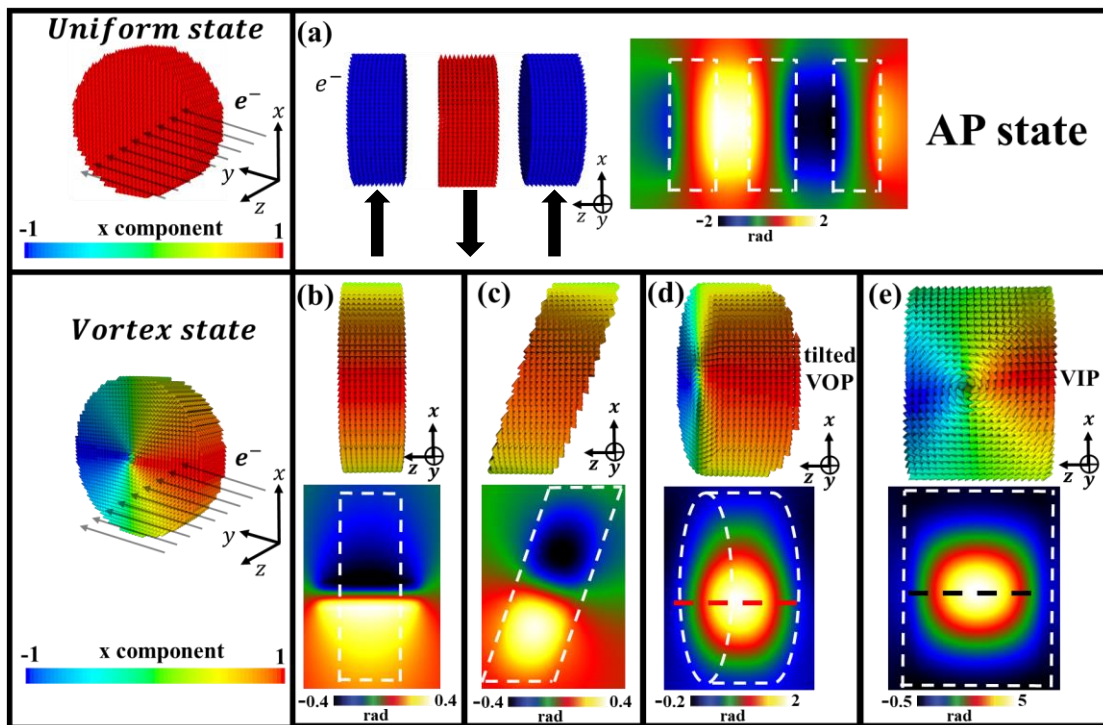


*Use of CALMIP parallel computing center of Toulouse, France*

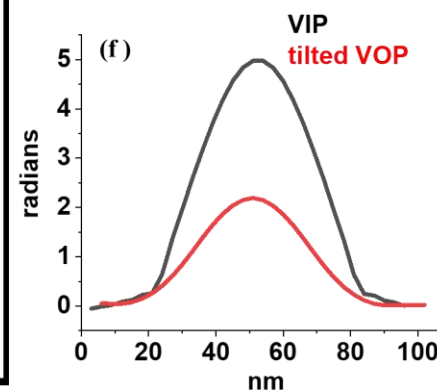
## Difficulty : high number of geometrical and magnetic inputs !

- Geometry extrapolated from EFTEM : layers tilted around Y and X axis (**more complex geometry than a simple disk!**)
- Adjustable magnetic parameters :
  - $\mu_0 M_s = 1.5 \text{ T}$  (obtained from other measurements)
  - exchange value  $A \approx 22 \cdot 10^{-12} \text{ J/m}$  (bulk =  $30 \cdot 10^{-12} \text{ J/m}$ )
  - **uniaxial crystal anisotropy field  $H_k$  because of polycrystals** (value  $K_u$ , direction  $\theta_{HK}$ ) with  $K_u$  between  $100$  and  $200 \cdot 10^3 \text{ J/m}^3$  (bulk =  $400 \cdot 10^3 \text{ J/m}^3$ )

$\Rightarrow$  **Values lower than bulk because of Cu impurities in Co**

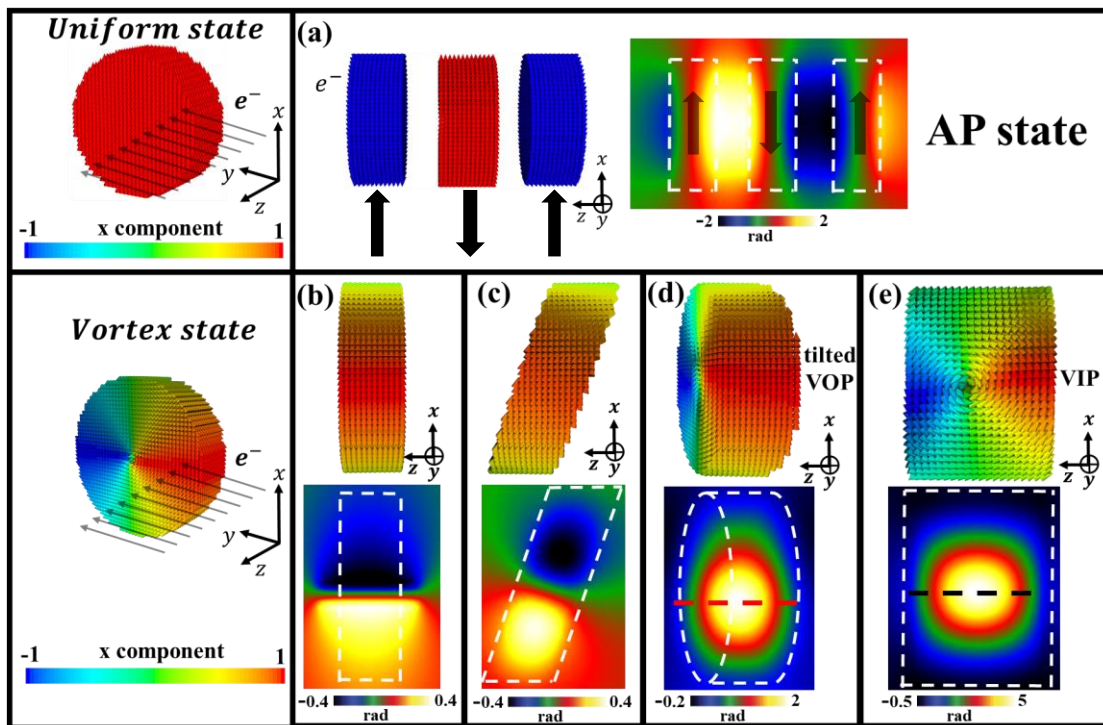


Direction of  $e^-$  beam =  $y$

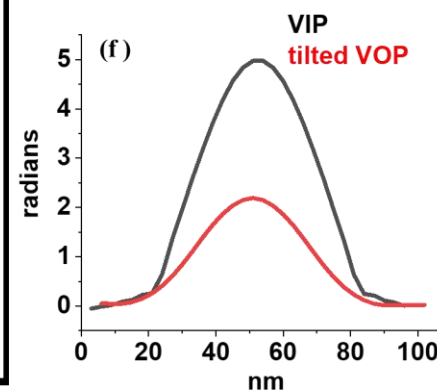


- Phase shift images depend on magnetic states and geometry of the layers.
- **Problem** : different magnetic states “look” similar because of the layer geometry

*⇒ need for qualitative and quantitative analysis of the images*



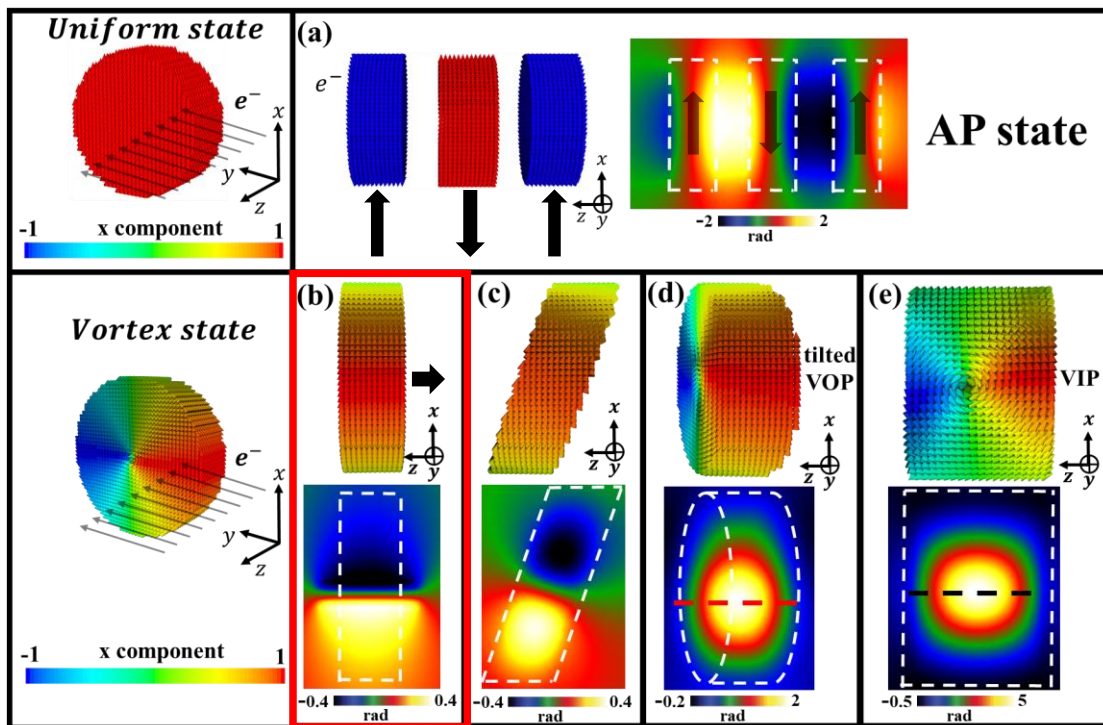
Direction of  $e^-$  beam =  $y$



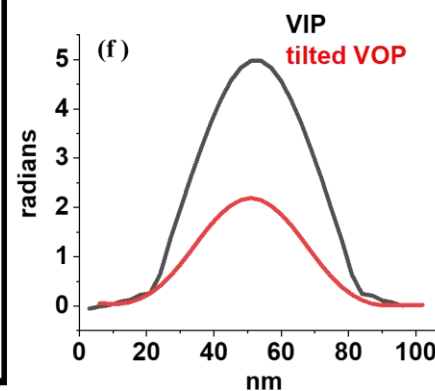
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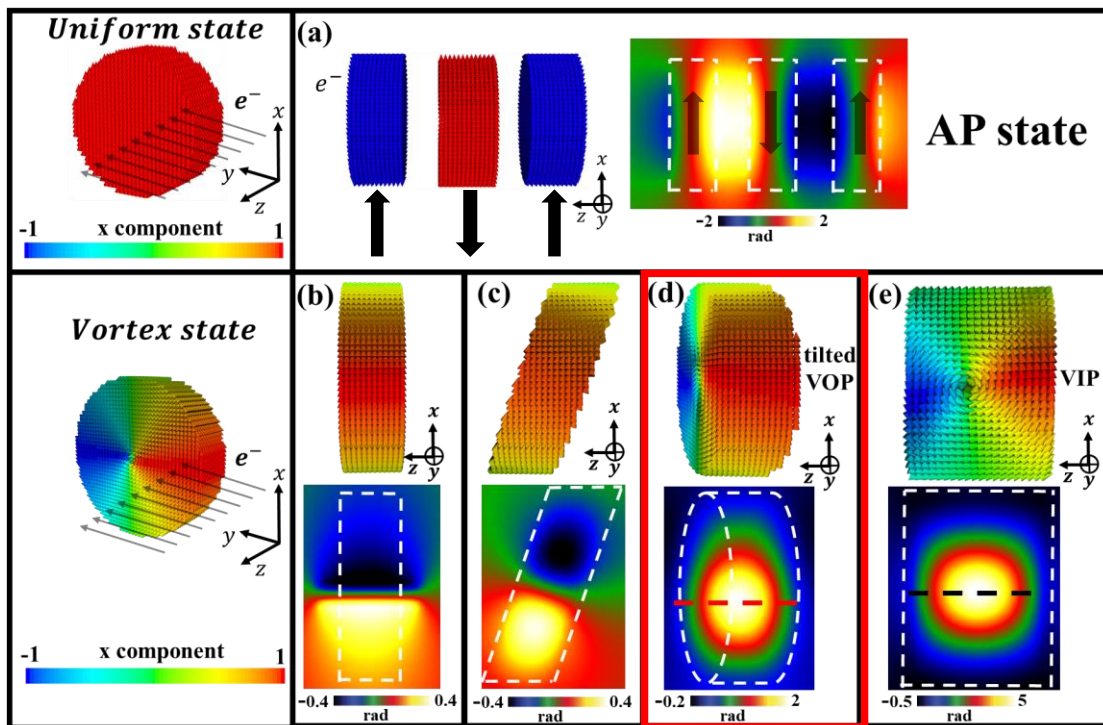


Direction of  $e^-$  beam =  $y$

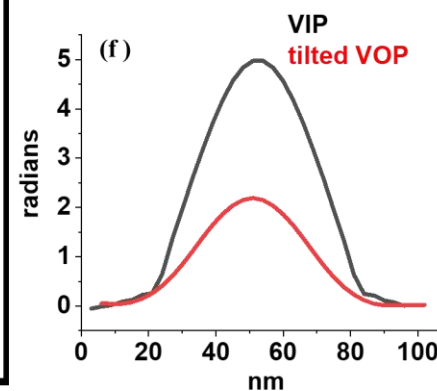


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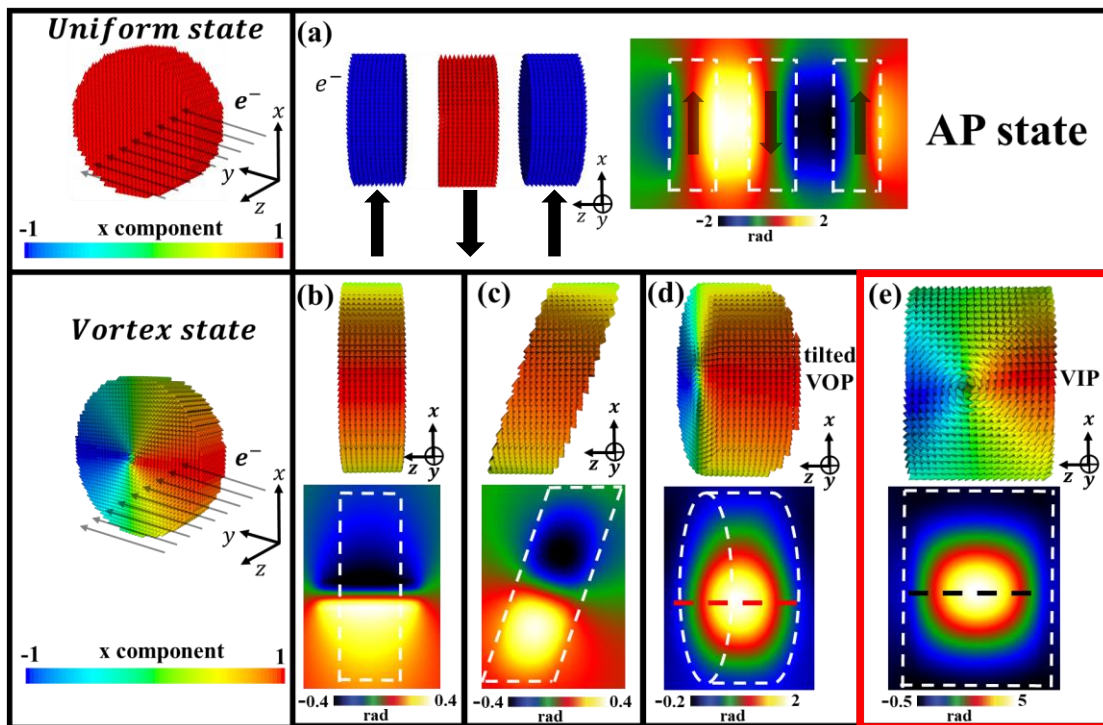


Direction of  $e^-$  beam =  $y$

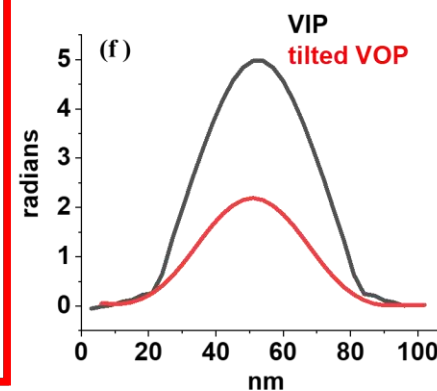


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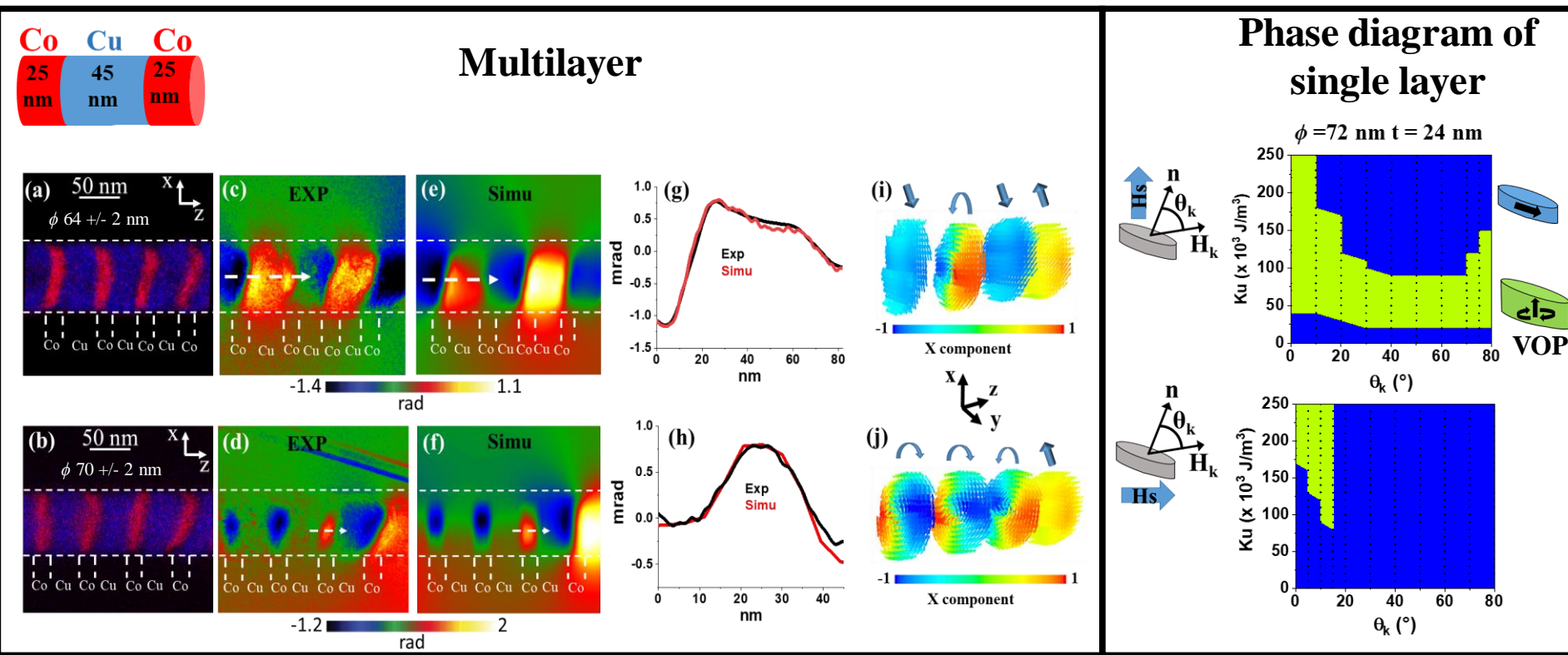


Direction of  $e^-$  beam =  $y$

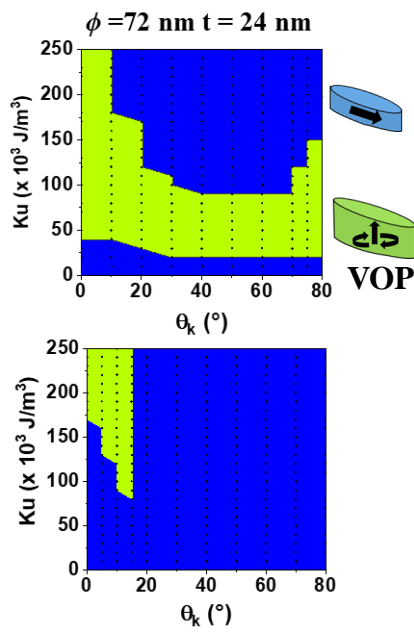


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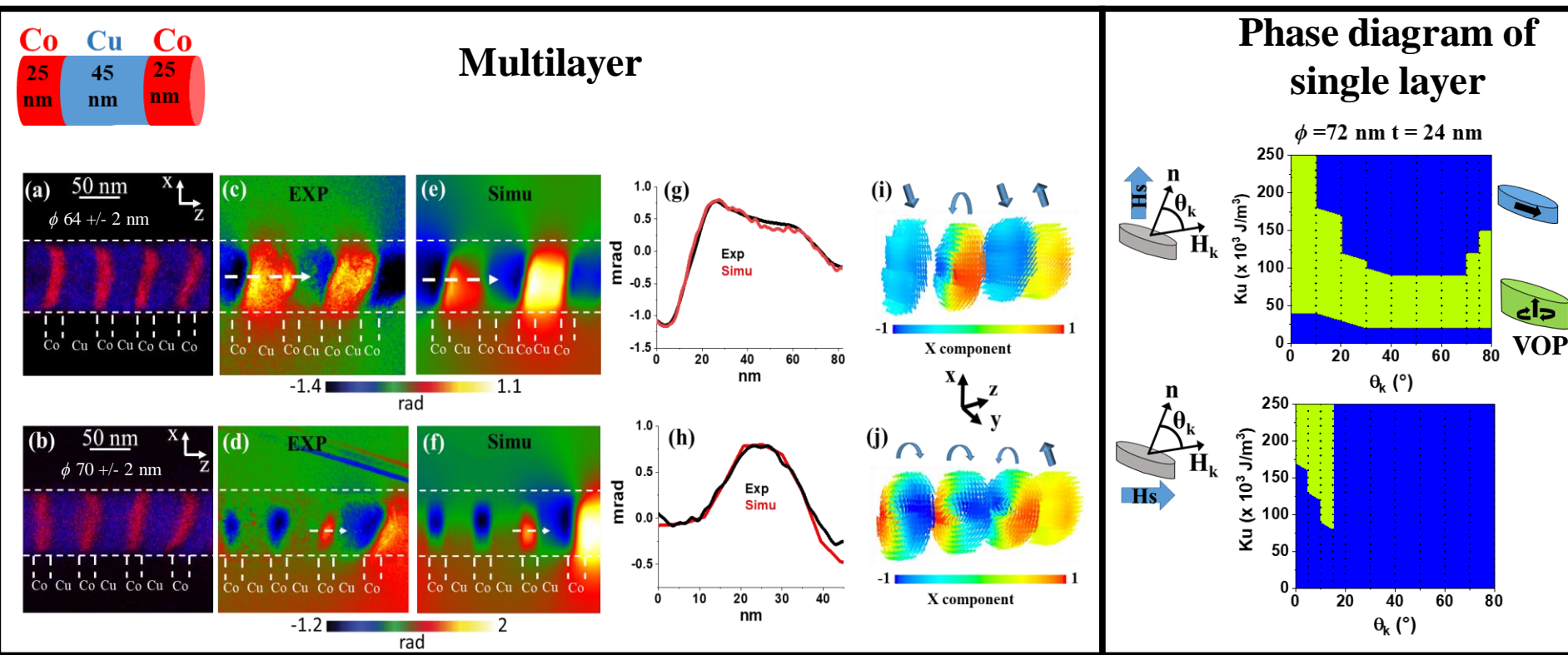


## Phase diagram of single layer



- No effect of saturation field  $H_s$  on the remanent states of multilayers
- $\approx 60\%$  of layers in antiparallel (AP) states and  $\approx 40\%$  in vortex states (VOP).

*N. Biziere et al., J. Appl. Phys. 126, 163906 (2019)*

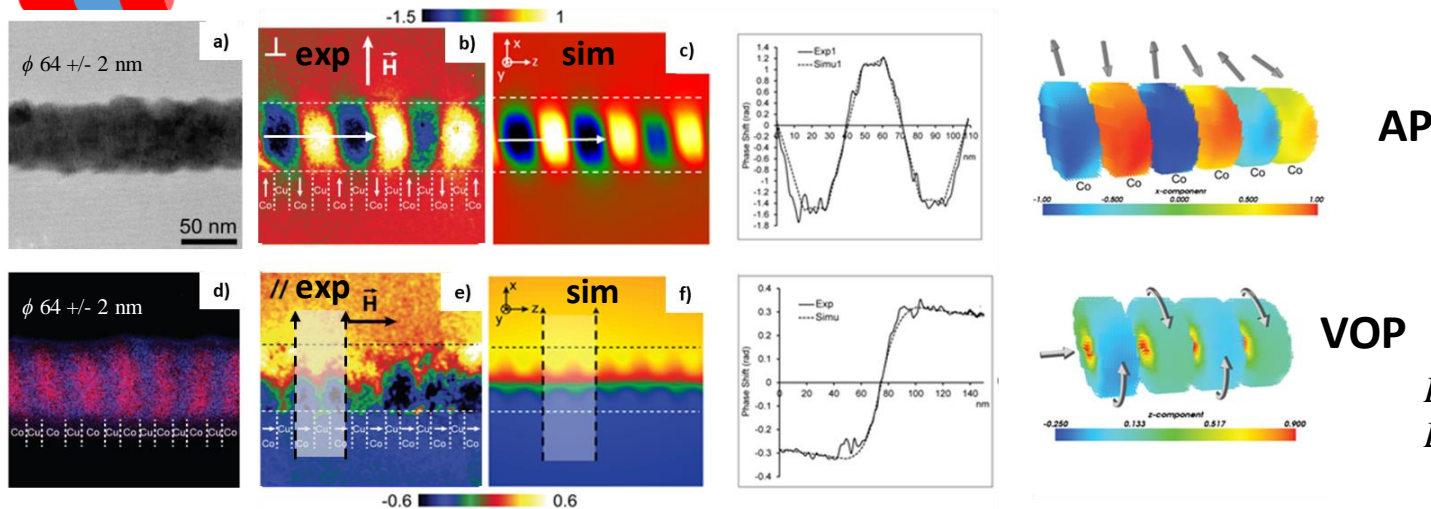


- No effect of saturation field  $H_S$  on the remanent states of multilayers
- $\approx 60\%$  of layers in antiparallel (AP) states and  $\approx 40\%$  in vortex states (VOP).
- Simulations on 20 layers show that :
  - Anti parallel states are stable whatever  $H_S$  if  $\theta_k \geq 20^\circ$
  - vortex states are stable whatever  $H_S$  only if  $\theta_k \leq 20^\circ$

*N. Biziere et al., J. Appl. Phys. 126, 163906 (2019)*

$\Rightarrow$  significant of a preferential orientation of  $H_k$  toward the wire axis ?

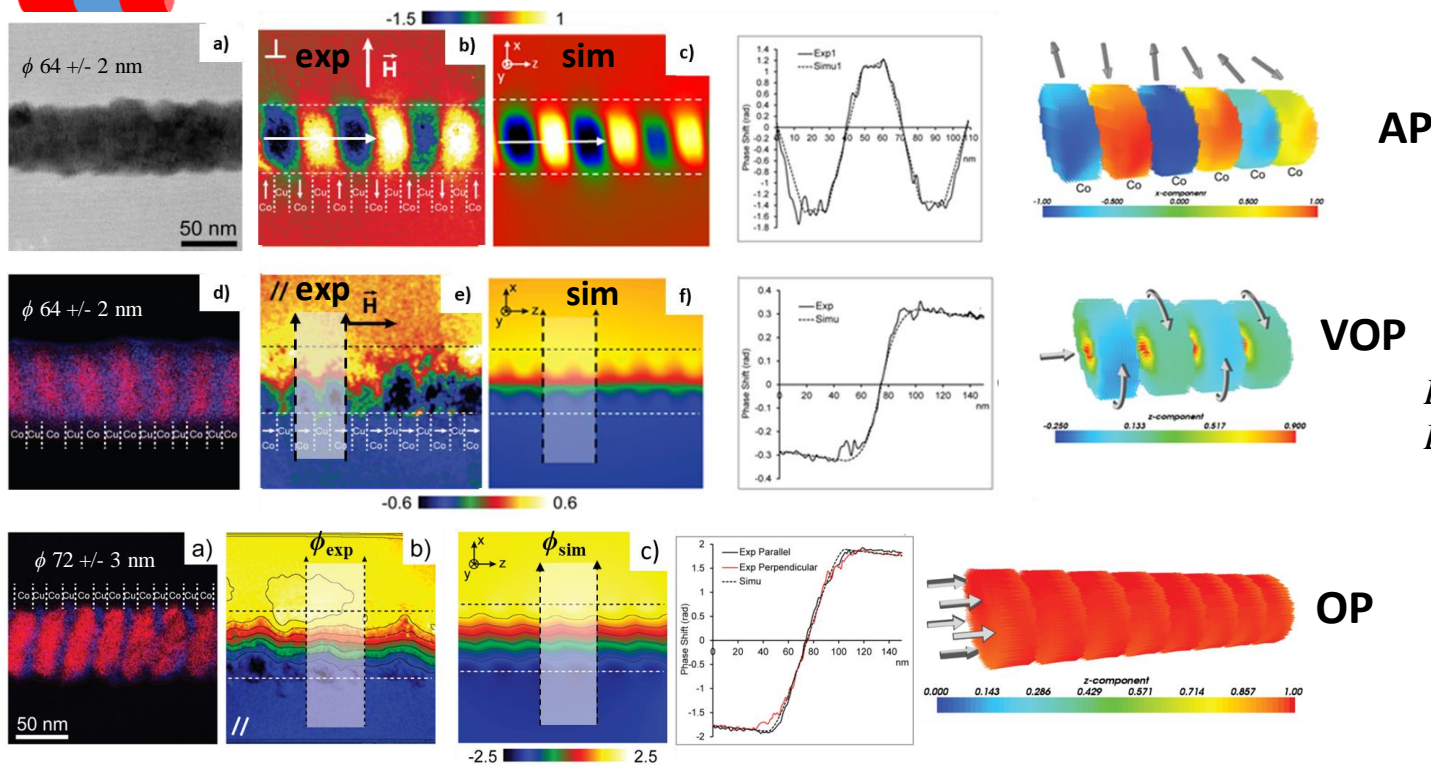
Co Cu Co  
25 nm 15 nm 25 nm



*D. Reyes et al., Nano Lett. 16, 1230, 2016.*

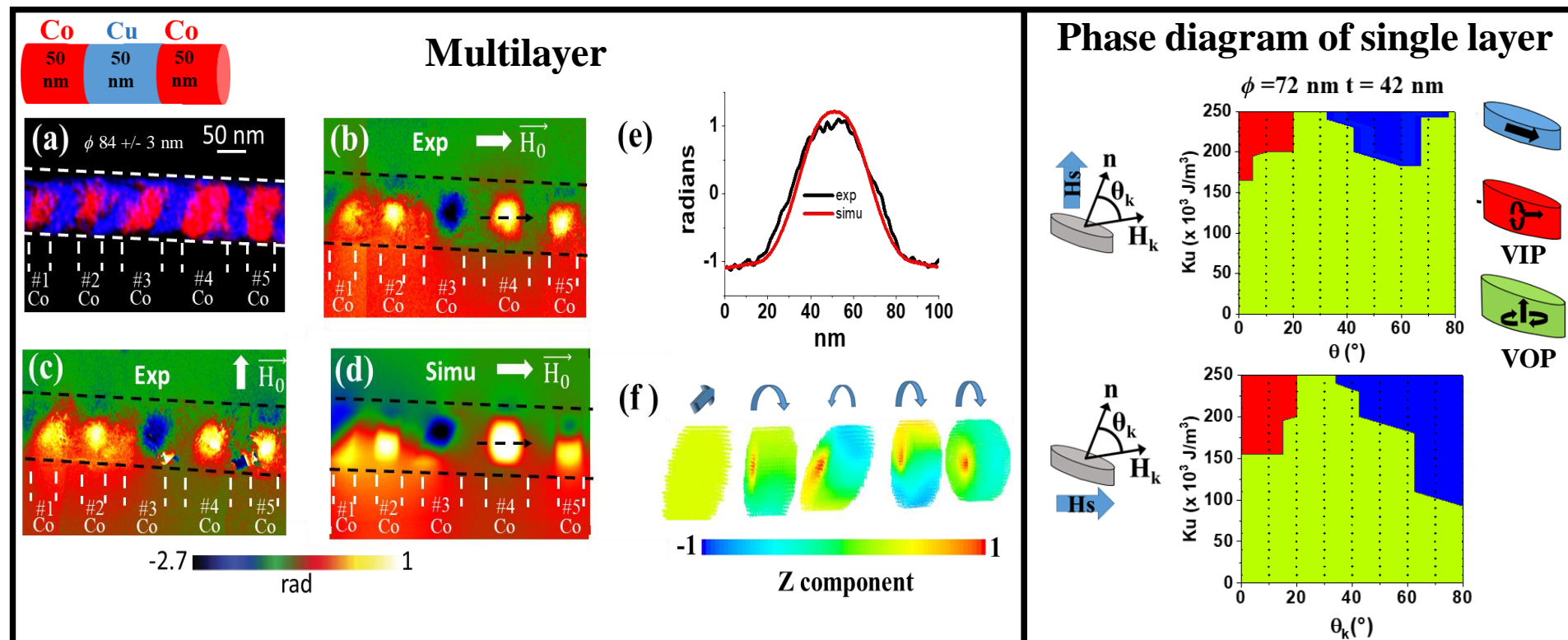
- 70% of the layers show AP configuration whatever  $H_s$  :  **favored by stronger dipolar coupling**
- 20% of layers switch between AP and VOP states when rotating  $H_s$  (only possible if  $H_k$  close from the normal of the layers).

Co Cu Co  
25 nm 15 nm 25 nm



*D. Reyes et al., Nano Lett. 16, 1230, 2016.*

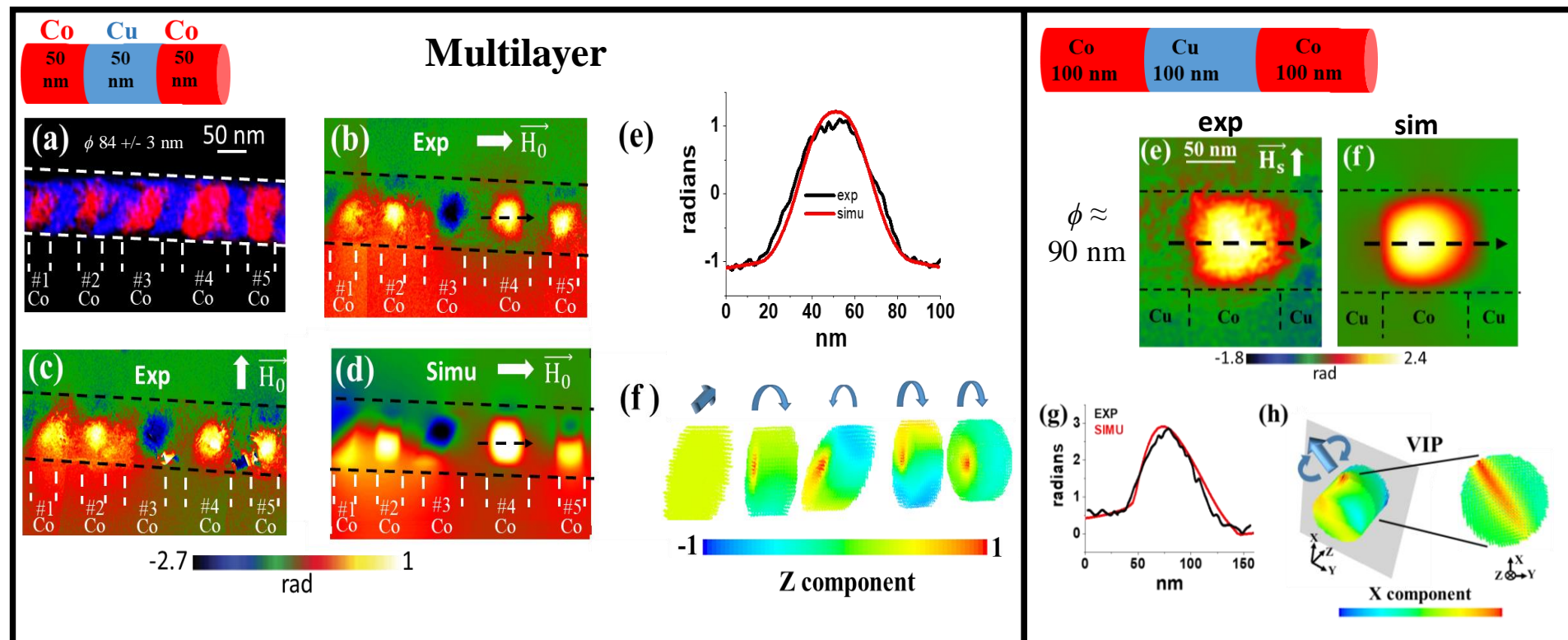
- 70% of the layers show AP configuration whatever  $H_s$  : favored by stronger dipolar coupling
- 20% of layers switch between IP and VOP states when rotating  $H_s$  (only possible if  $H_k$  close from the normal of the layers).
- 10% of out of plane state (OP) whatever  $H_s$  : impossible without dipolar coupling



*N. Biziere et al., J. Appl. Phys. 126, 163906 (2019)*

- No effect of  $H_s$  and 95% of vortex states (VOP state, with access to chirality for tilted layers)
- Simulations on multilayers show that VIP states disappear for Co<sub>50 nm</sub>/Cu<sub>50 nm</sub> because of dipolar coupling

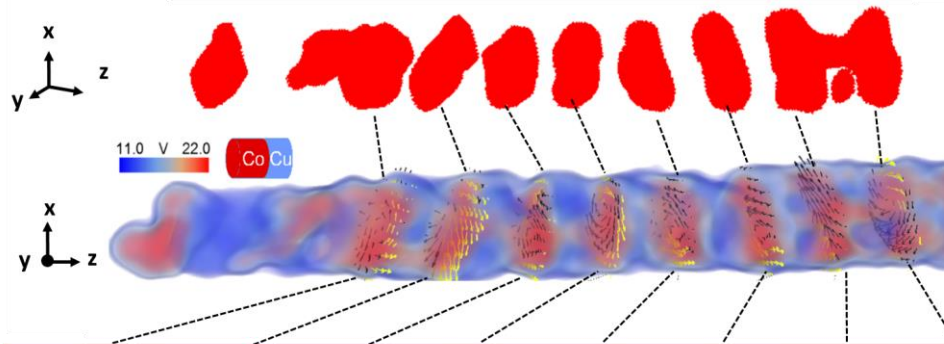




N. Biziere et al., *J. Appl. Phys.* 126, 163906 (2019)

- No effect of  $H_s$  and 95% of vortex states (VOP state, with access to chirality for tilted layers)
- Simulations on multilayers show that VIP states disappear for Co<sub>50 nm</sub>/Cu<sub>50 nm</sub> because of dipolar coupling
- VIP states observable for very thick Co layers with diameter  $\geq 80$  nm

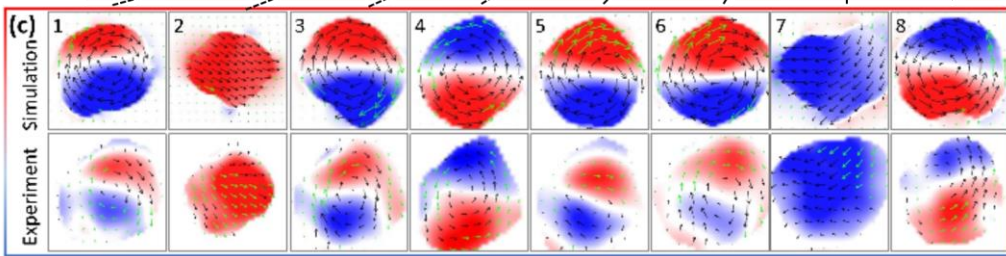
- **Principle of 3D holographic vector field electron tomography** : numerical reconstruction of 3D geometry and B field components of a nano-object via multiple tilted holograms



Implementation in OOMMF of the layer shape



Electrostatic potential of  $\text{Co}_{25\text{ nm}}/\text{Cu}_{15\text{ nm}}$  nanowire (spatial resolution 7 nm)



← Simulated B field with OOMMF

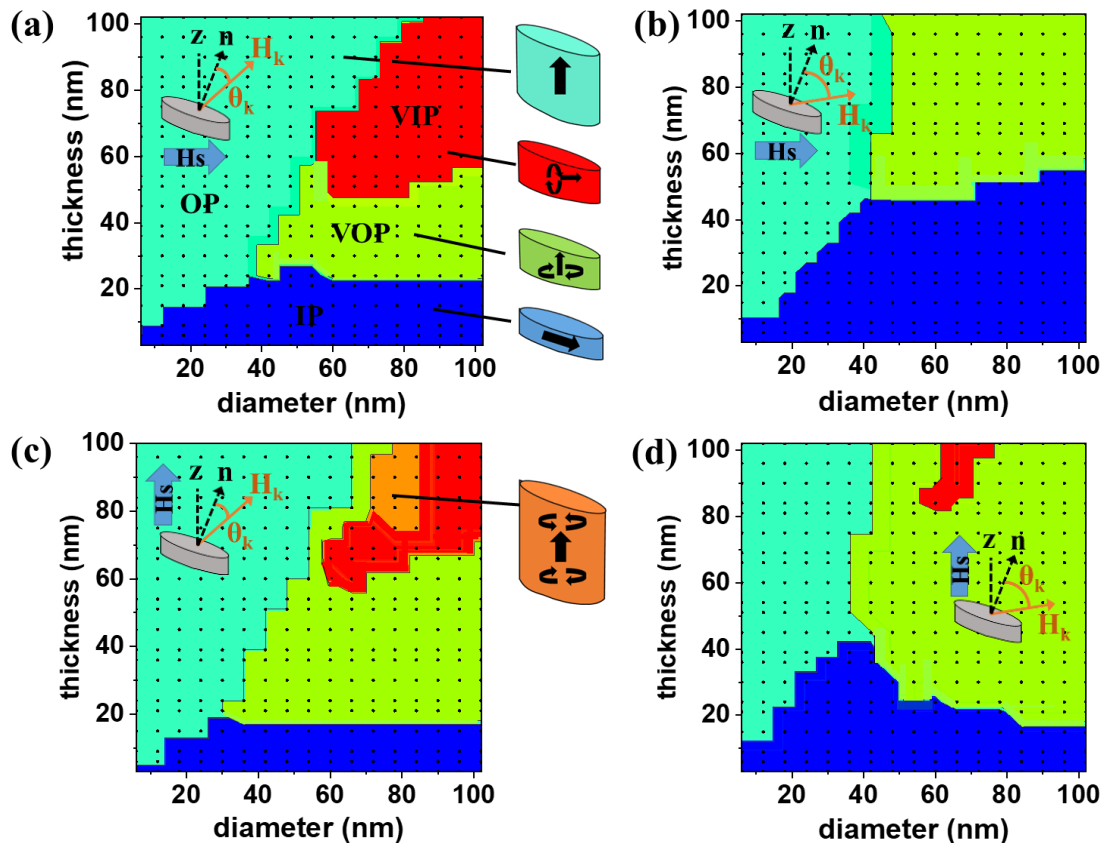
← Experimental B field recovered from 3D tomography

*D. Wolf et al., Communications Physics 2, 87, 2019.*

- Preliminary results : quantitative agreement but calculated induction overestimated (10-20%)
- Interest : removing geometrical uncertainties allow focusing on magnetic parameters of individual layers

- Due to reduced magnetic constants as compared to bulk, electrodeposited Co layers show multiple remanent states as a function of aspect ratios.
  - Inter layer dipolar coupling favors antiparallel coupling of the layers but also allows transition between uniform and vortex states.
- ⇒ For spin torque oscillators : possibility to obtain two different working frequencies at remanence by switching the direction of the saturation field.
- Drawback : the control of the electrodeposition conditions must be improved in order to use it in a reproducible way!

***Thank you !***

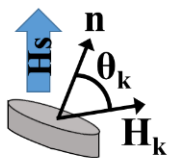


Magnetic parameters :

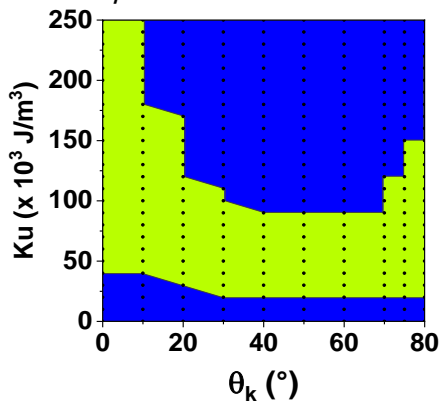
- $\mu_0 M_s = 1.5 \text{ T}$  (bulk = 1.7 T)
- Exchange value  $A = 22 \cdot 10^{-12} \text{ J/m}$  (bulk =  $30 \cdot 10^{-12} \text{ J/m}$ )
- $K_u = 130 \cdot 10^3 \text{ J/m}^3$

$\Rightarrow$  Values lower than bulk because of Cu impurities in Co

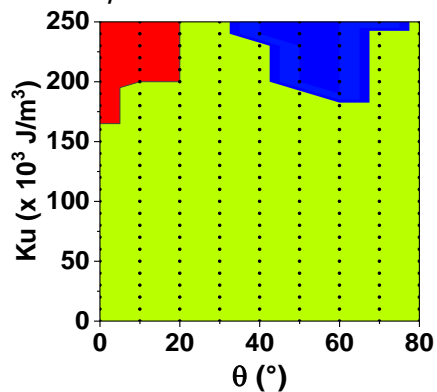
- 4 different states can be expected depending on aspect ratio
- Strong impact of  $H_k$  and  $H_s \Rightarrow$  possibility to get information on  $H_k$  by changing  $H_s$



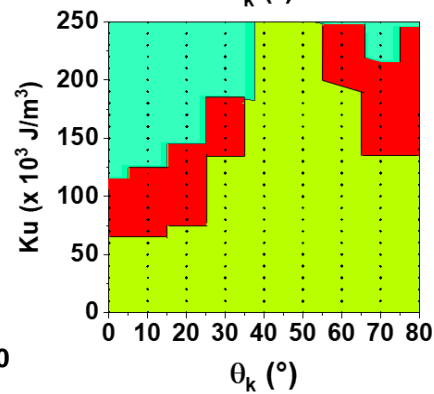
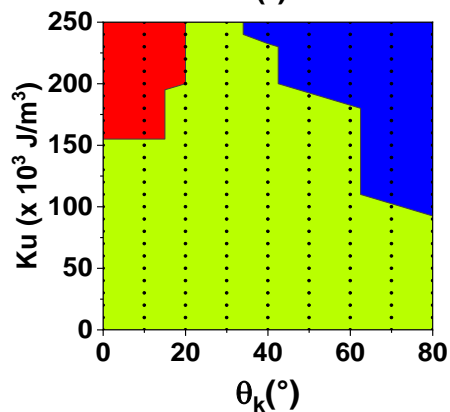
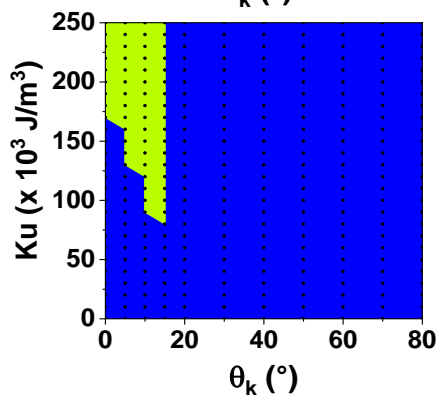
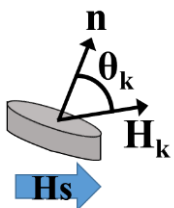
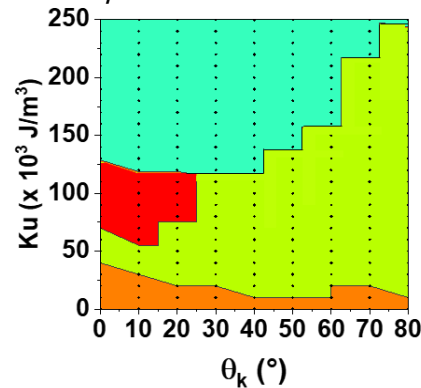
$\phi = 72 \text{ nm } t = 24 \text{ nm}$

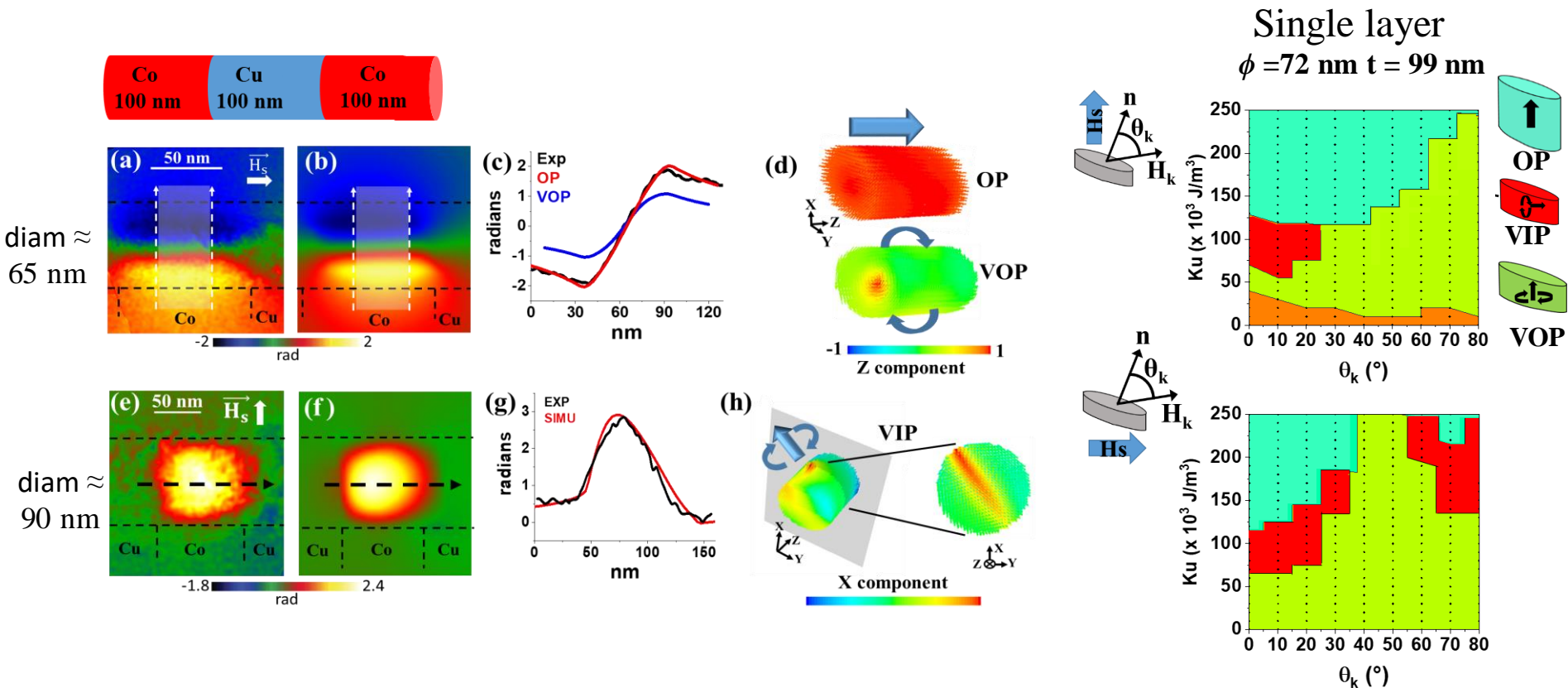


$\phi = 72 \text{ nm } t = 42 \text{ nm}$



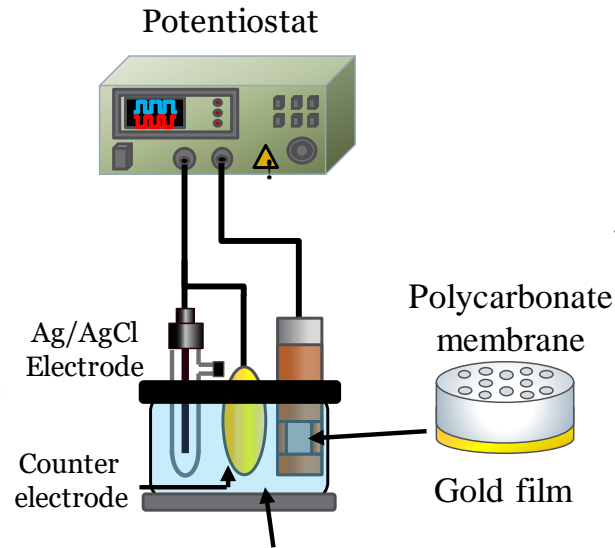
$\phi = 72 \text{ nm } t = 99 \text{ nm}$



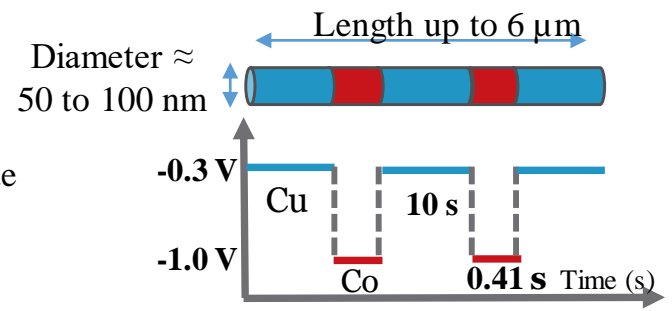


- No statistical analysis but seem that  $H_s$  has no effect.
- For diameters  $\leq 70$  nm, the dipolar coupling avoid vortex states and uniform sates (OP) aligned with the wire axis become the most stable ones for both direction of  $H_s$ .
- For large diameter ( $\approx 90$  nm) vortex states with the core perpendicular to the wire axis (VIP) become the most stable for both direction of  $H_s$

Polycarbonate Membrane



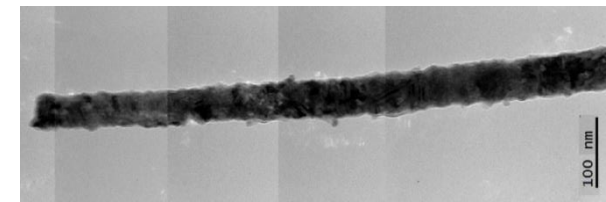
**Chemical bath composition :**  
 $\text{CoSO}_4 + \text{CuSO}_4 + \text{H}_2\text{O} + \text{H}_3\text{BO}_4$



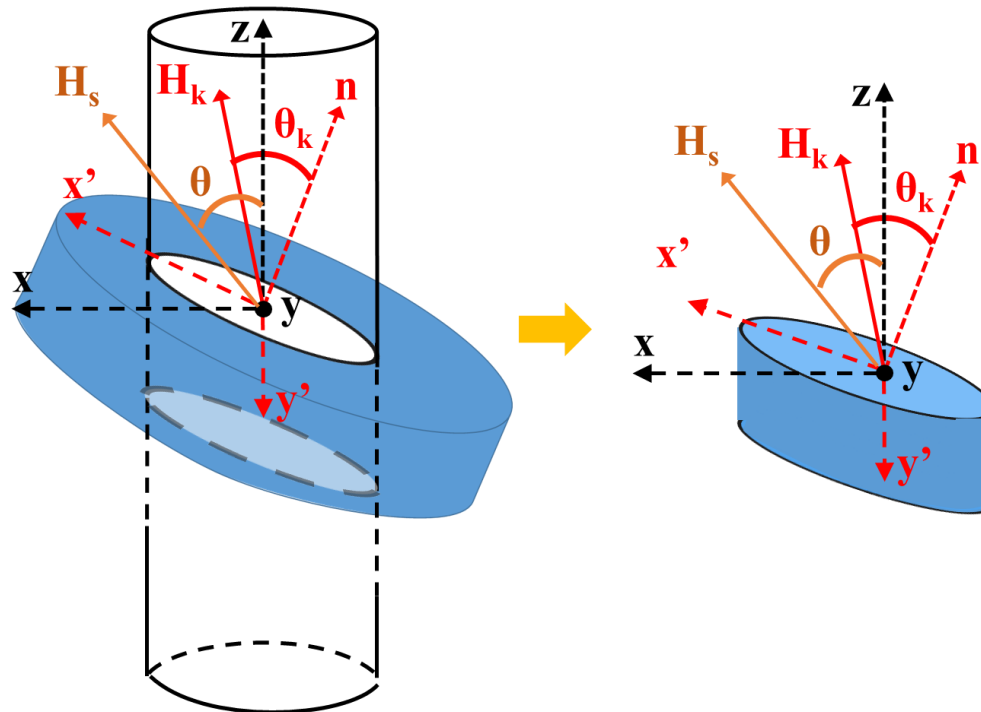
**Insertion of Cu impurities in the Co layers due to higher deposition potential**

Expected thickness Co/Cu (nm/nm)	Measured thickness Co/Cu (nm/nm)	Measured diameter (nm)
25/15	24 +/- 4 / 14 +/- 8	65 +/- 10
25/45	22 +/- 5 / 46 +/- 14	74 +/- 7
50/50	42 +/- 13 / 46 +/- 17	68 +/- 8
100/100	90 +/- 24 / 110 +/- 44	69 +/- 10

TEM analysis







**Layers like nanocylinders with tilted surfaces.**