Intermag 2015, Beijing

Temperature dependence of the exchange bias properties in polycrystalline $BiFeO_3$ / $Ni_{80}Fe_{20}$

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[2]Groupe nanomatériaux — CEMES-CNRS , Toulouse, France.
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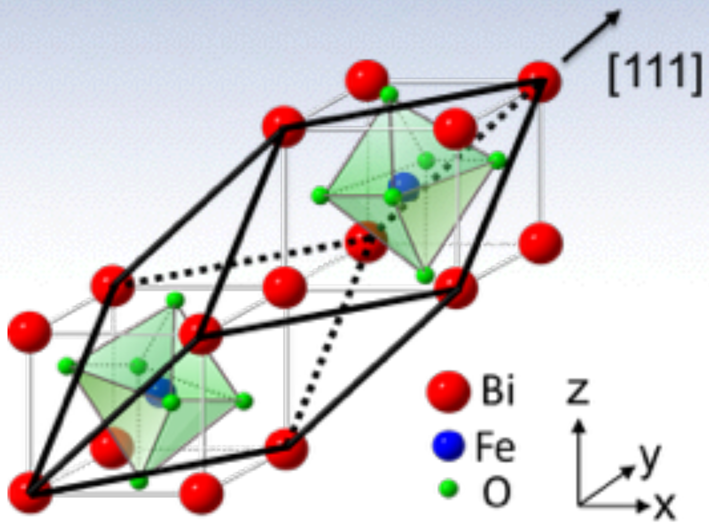

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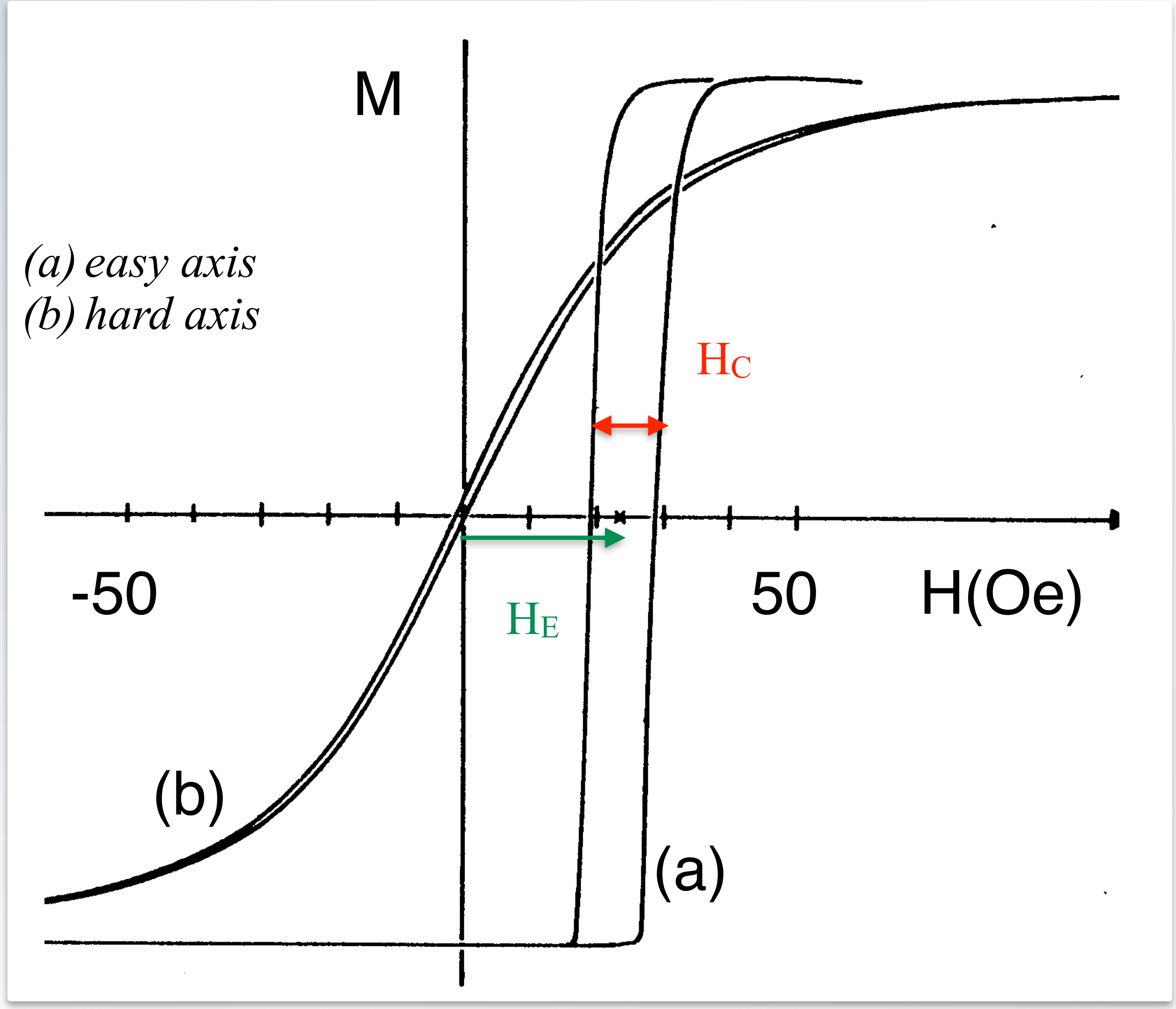
Exchange coupling

F/AF exchange coupling discovered by Meiklejohn and Bean (1956)[1].

➡ used to pin the magnetization direction in GMR or tunnel junction.



$Fe_{50}Mn_{50}$(25nm)/$Ni_{80}Fe_{20}$ (40nm)/SiO_2 [2]

➡ produce a characteristic shifted hysteresis cycle

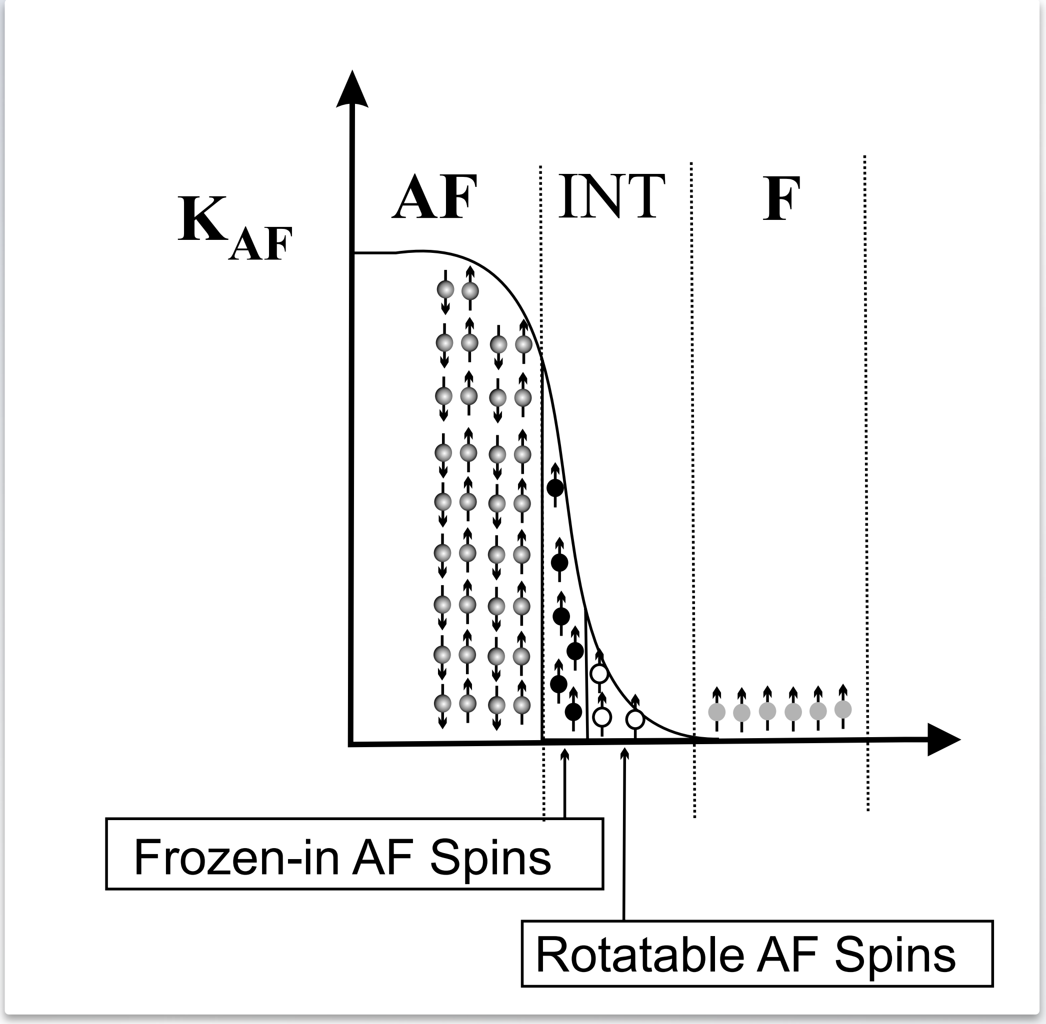
➡ higher coercive field

[1] W. H. Meiklejohn and C. P. Bean. *Phys. Rev.* **102**, 1413 (1956).

[2] R. Coehoorn. "Novel Magnetoelectronic Materials and Devices : Exchange Anisotropy / Stoner-Wohlfarth model". 2001.

Exchange coupling — Spin glass model

Spin glass model [3]: disordered frustrated interfacial spins.



Protocols to probe the thermally activated interface:

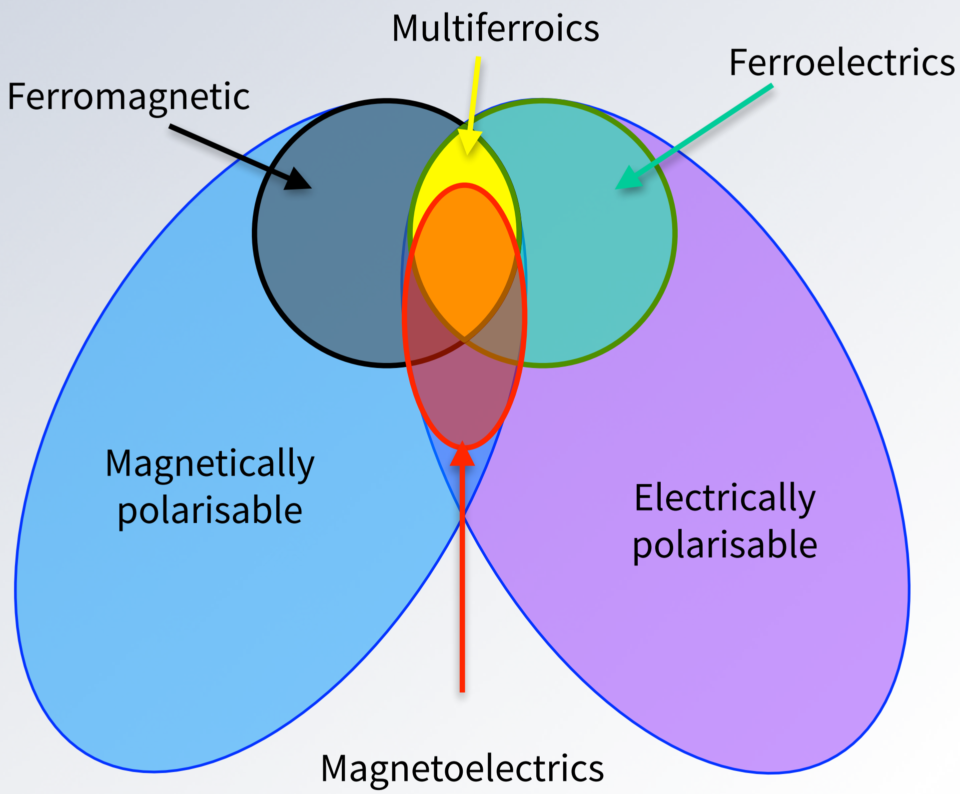
➡ Temperature loop measurements after field cooling.
➡ Training effect study.
➡ …

Difficulties to separate the different contributions to exchange bias.

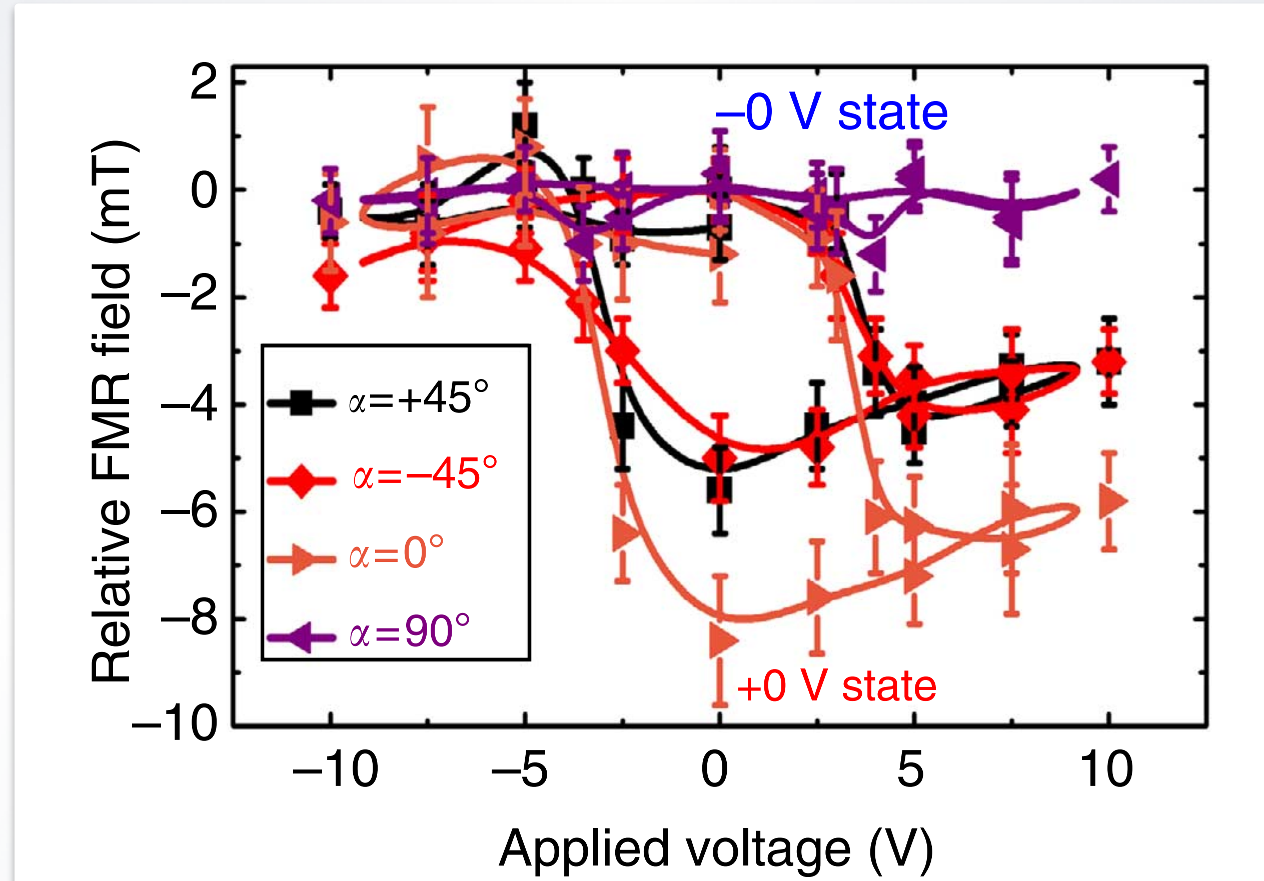
[3] F. Radu, A. Westphalen, et al. *Journal of Physics: Condensed Matter*, **18**, L29 (2006).

Multiferroics / Magnetoelectrics

Schematic of multiferroic and magnetoelectric materials [4, 5].



Electric control of the pinning direction [6].



CoFe(2.5nm) / BFO (200nm)

- $BiFeO_3$ is a canted antiferromagnetic of type G.

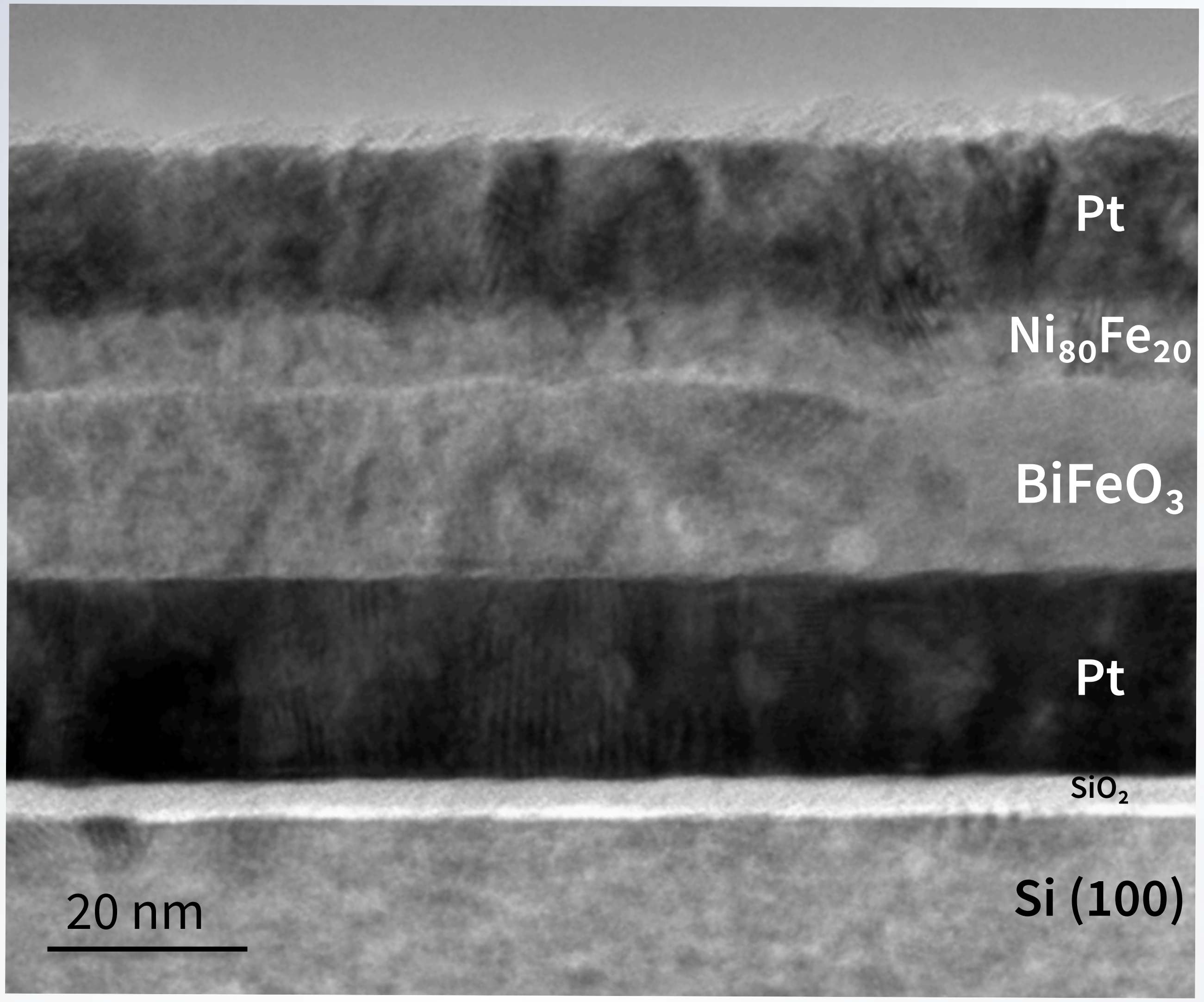
Curie temperature	$T_C \sim 1143K$	
Néel temperature	$T_N \sim 643K$	[7]

[4] W. Eerenstein, N. D. Mathur, and J. F. Scott. *Nature*, **442**, 759 (2006).
[5] L. W. Martin and R. Ramesh. *Acta Materialia*, **60**, 2449 (2012).
[6] Z. Zhou, M. Trassin, et al. *Nature Communications*, **6**, 6082 (2015).
[7] R. T. Smith, G. D. Achenbach, et al. *J. Appl. Phys.* **39**, 70 (1968).

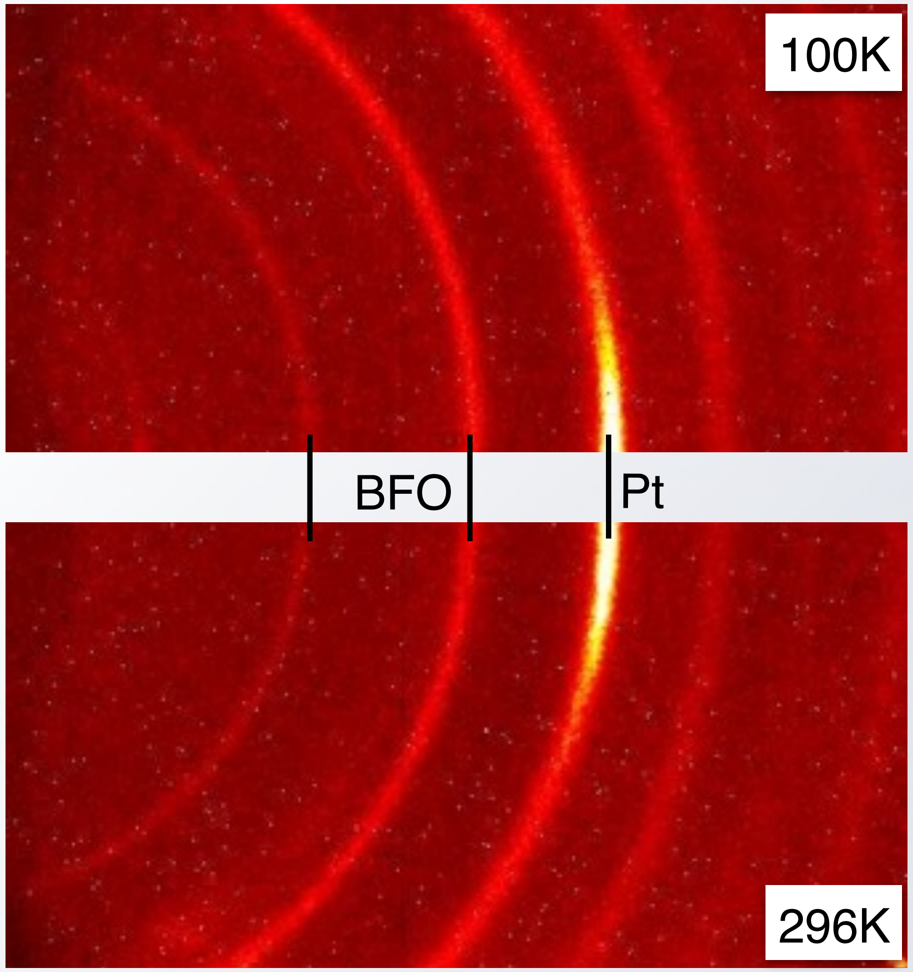
NiFe/BiFeO_3 bilayer

Samples grown by RF sputtering under static in-plane magnetic field, and annealed to crystallize the BiFeO_3 multiferroic phase [8, 9].

Coupling study depending on t_{BFO} thickness (0nm, 29nm, 85nm, 177nm).



TEM cross-section for t_{BFO} = 29nm.



Conventional XRD between 77K and 300K

➡ continuous FM layer

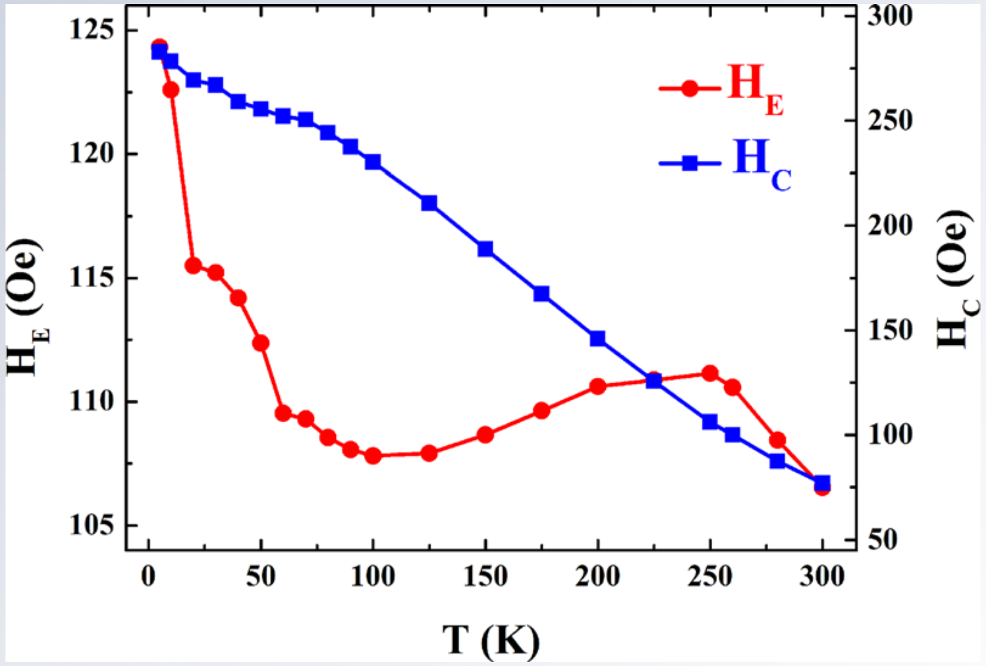
➡ high roughness (~15nm RMS for 177nm BFO)

➡ polycrystalline BFO

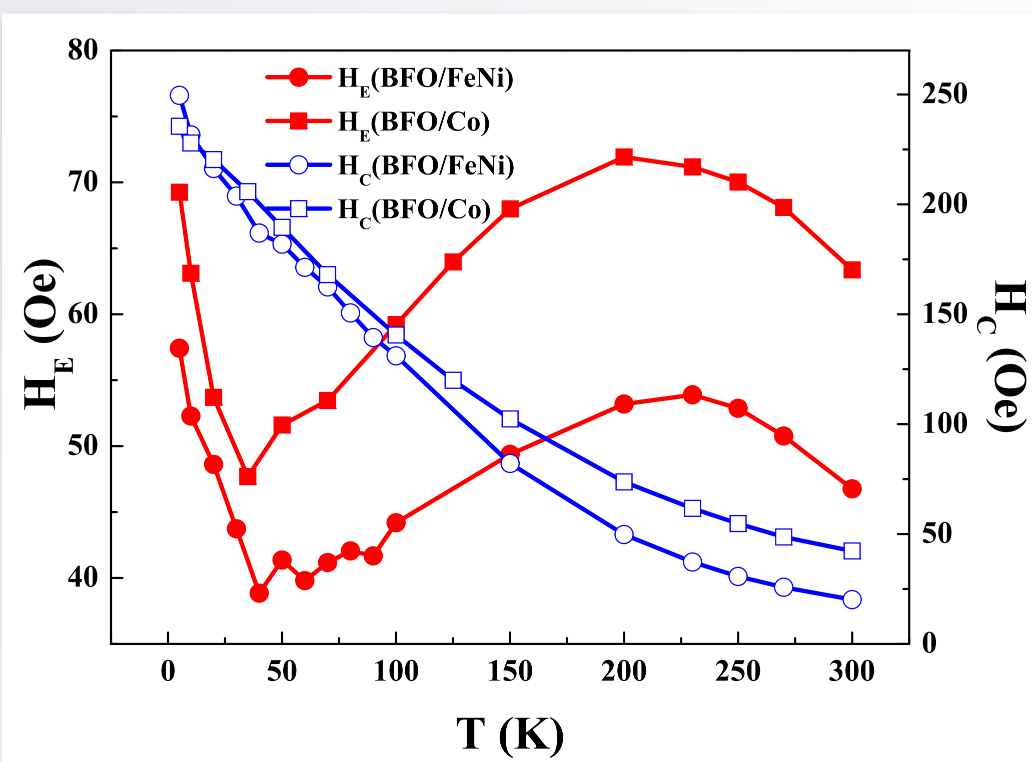
[8] T. Hauguel, S. P. Pogossian, et al. *J. Appl. Phys.* **110**, 073906 (2011).
[9] T. Hauguel, S. P. Pogossian, et al. *J. Appl. Phys.* **112**, 093904 (2012).

Temperature evolution (SQUID)

After field cooling along deposition field, loop measurements at different temperatures.

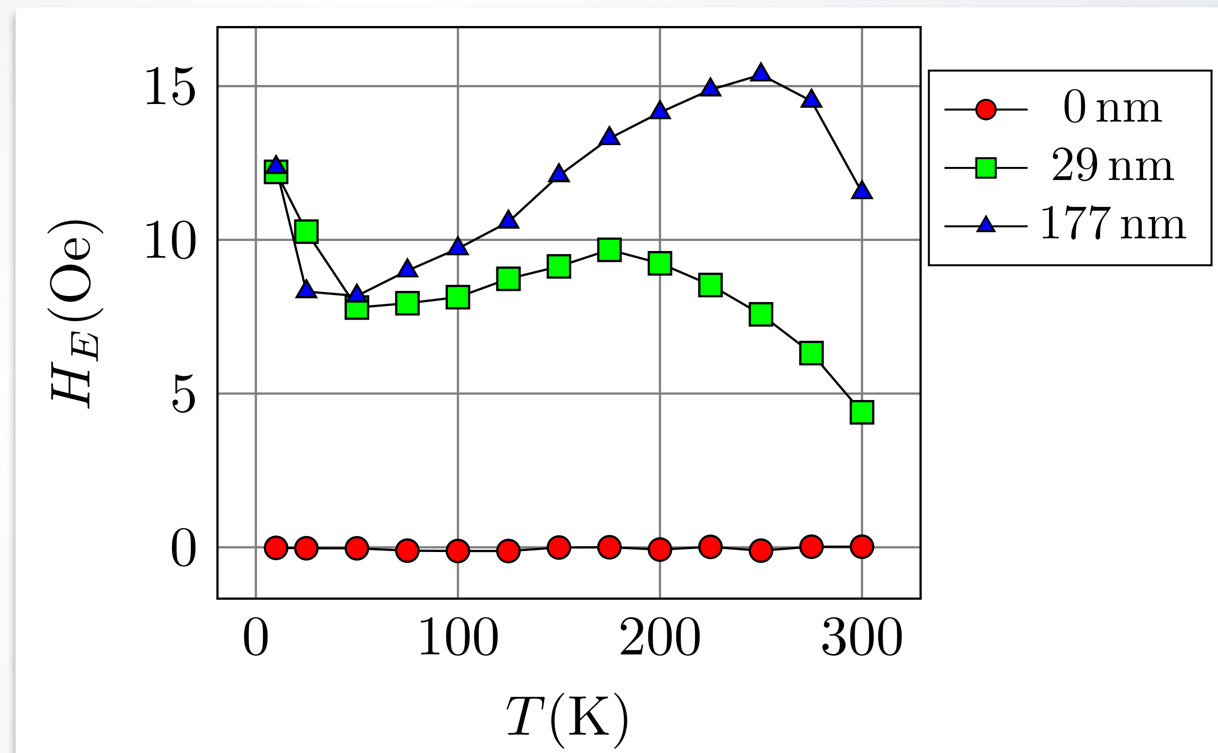


Epitaxial Co (4nm) / BFO (80nm) [10]



Polycrystalline Py(3.6 nm)/BFO(40nm) and Co(4nm)/BFO(40nm) [11]

Non-monotonic H_E(T) observed in BFO/F systems.



Polycrystalline Py(10nm)/BFO

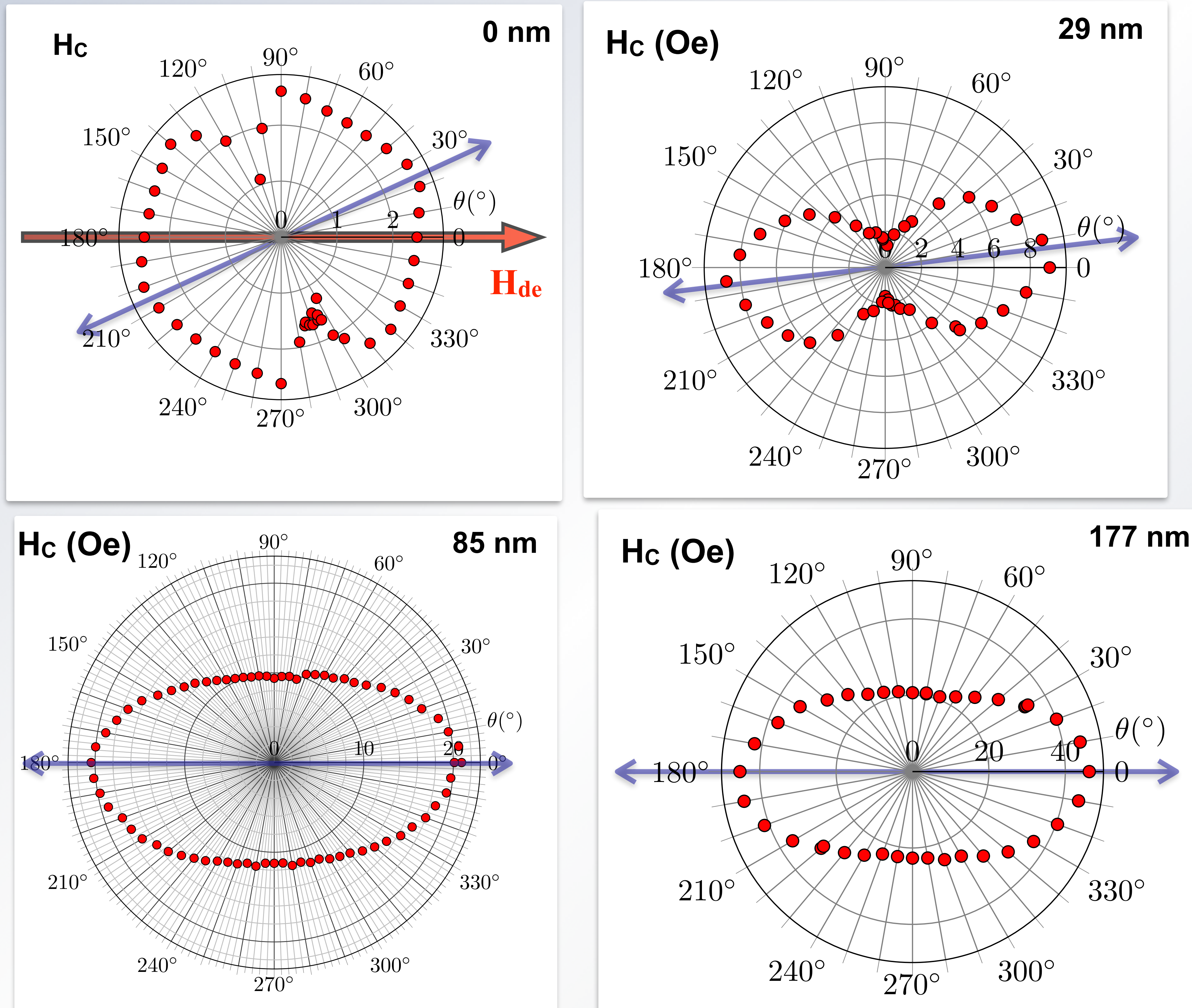
Physical origin of non-monotonic H_E(T)?

- thermal dependence of FE domains
- reconfiguration of the anisotropy axis

[10] M. C. He, B. You, et al. *J. Appl. Phys.* **117**, 17C745 (2015).
[11] X. Xue, X. Yuan, et al. *Eur. Phys. J. B*, **86**, 121 (2013).

Azimuthal behavior (VVSM)

- Azimuthal coercive field with BFO thickness.



➡30° misaligned growth induced anisotropy axis for Pt/Py/Pt.

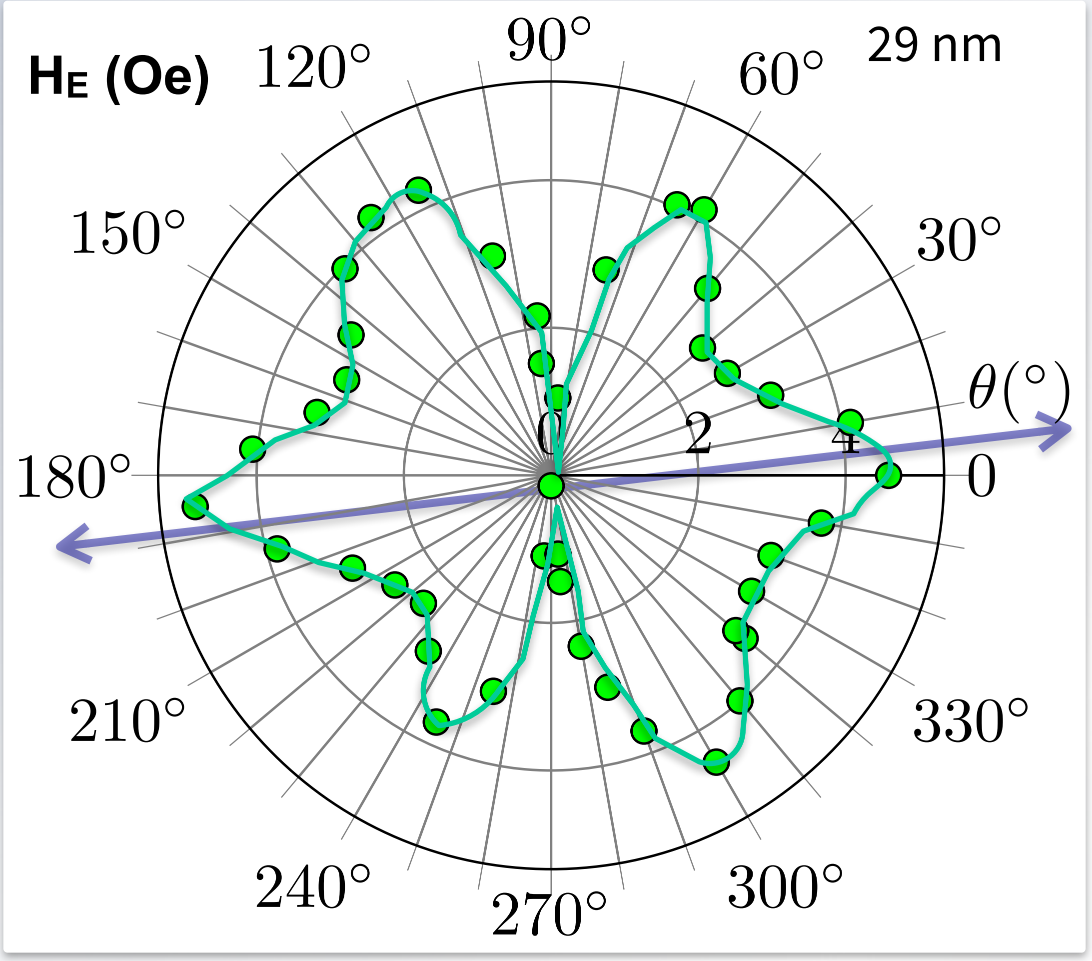
➡Dispersion of anisotropy

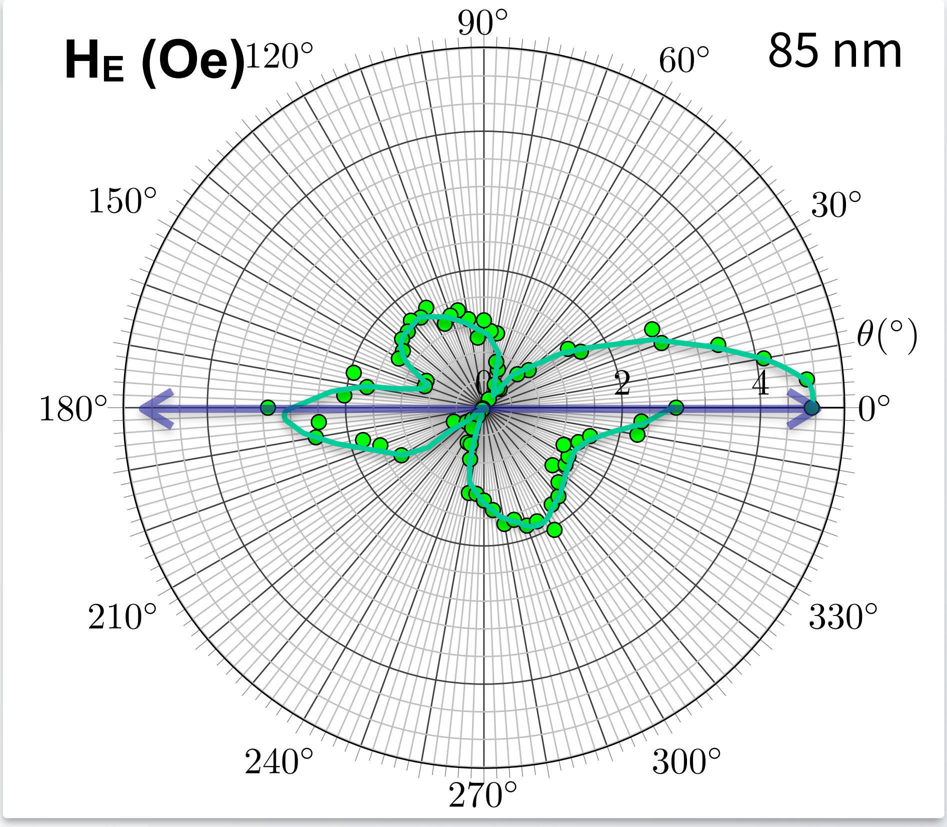
➡Realignment of uniaxial axis with t_{BFO}.

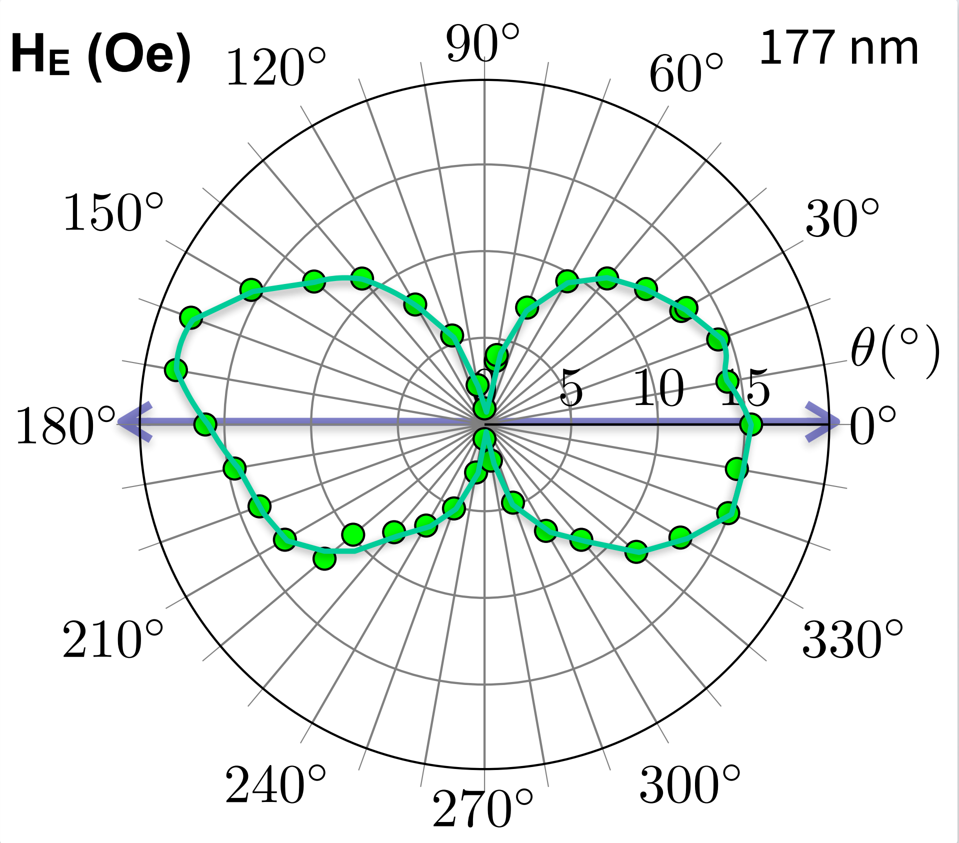
➡Uniaxial anisotropy induced by the AF for thick sample.

Azimuthal behavior (VVSM)

- Azimuthal coercive field with BFO thickness.





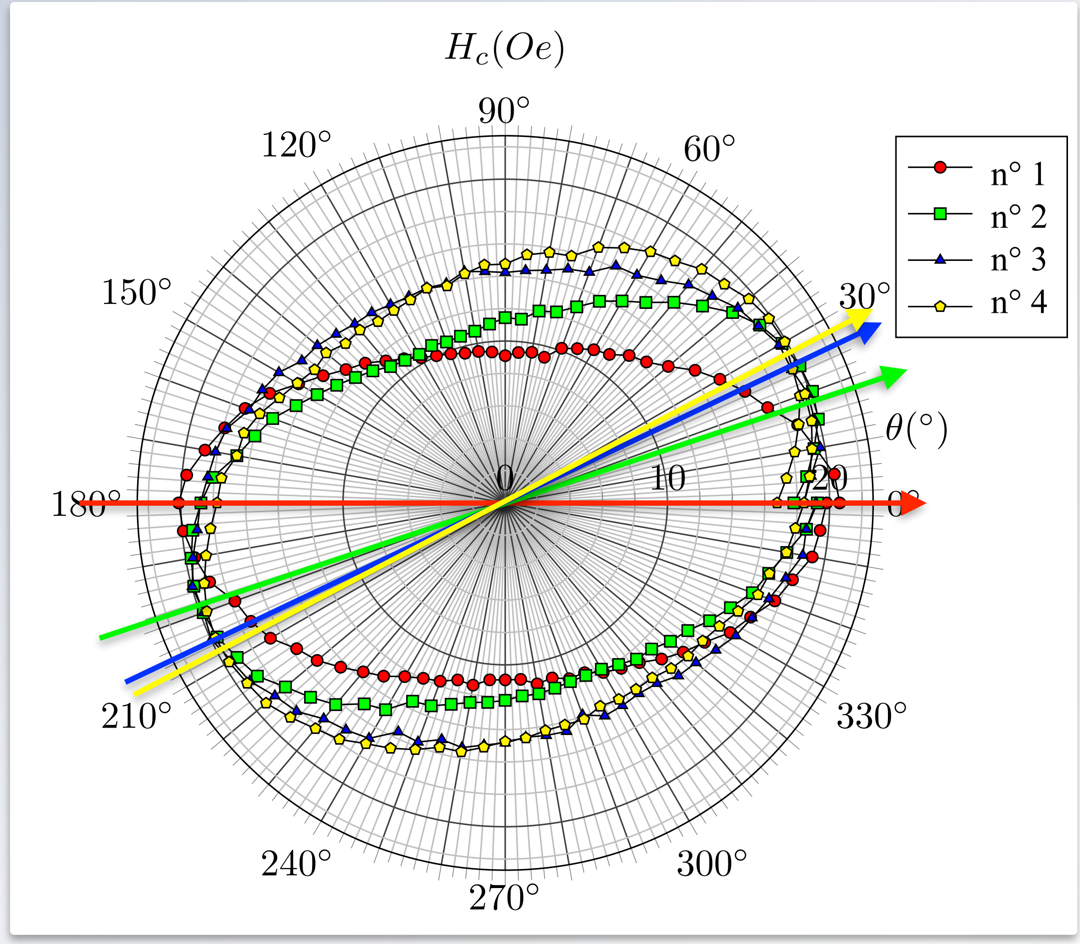


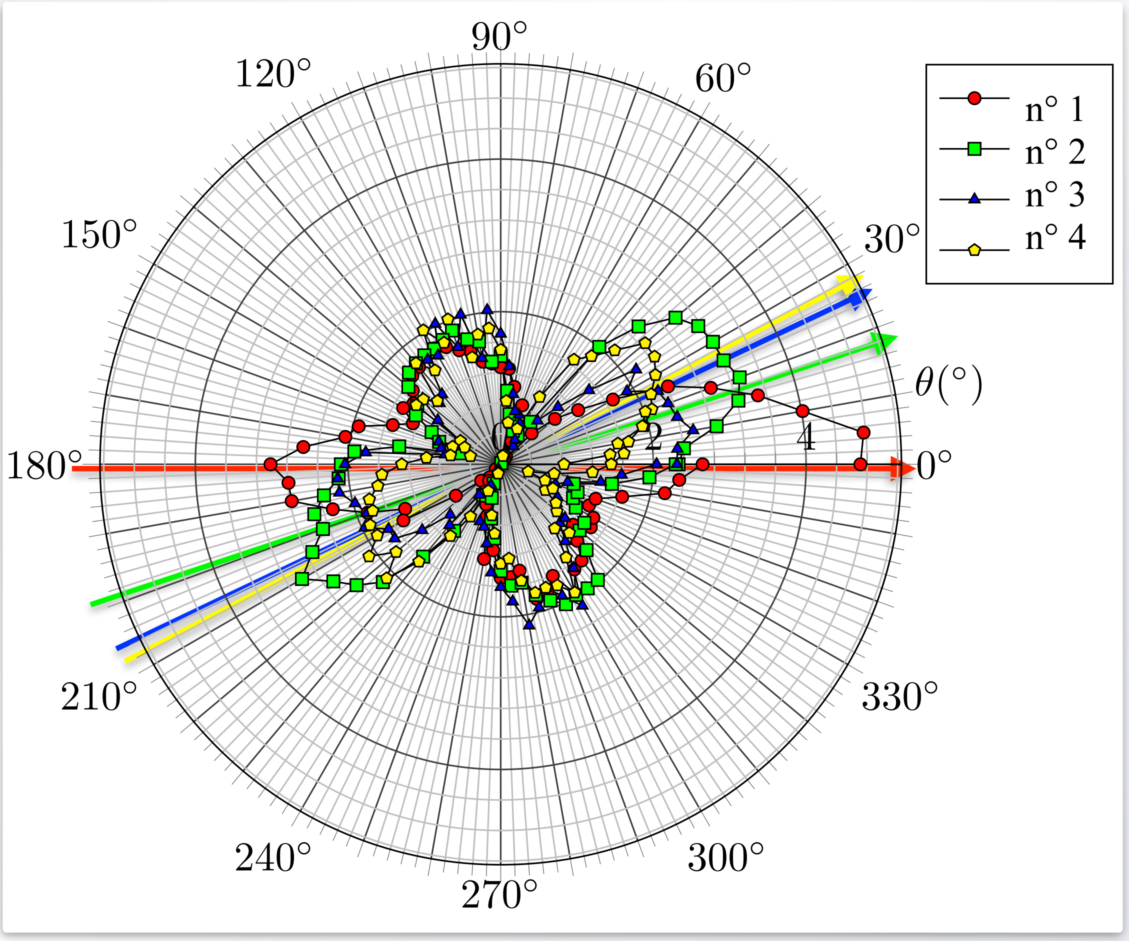
➡ Change in symmetry: misalignment of K_F and K_{AF} axis.

➡ Instability of the exchange bias after deposition.

Azimuthal training

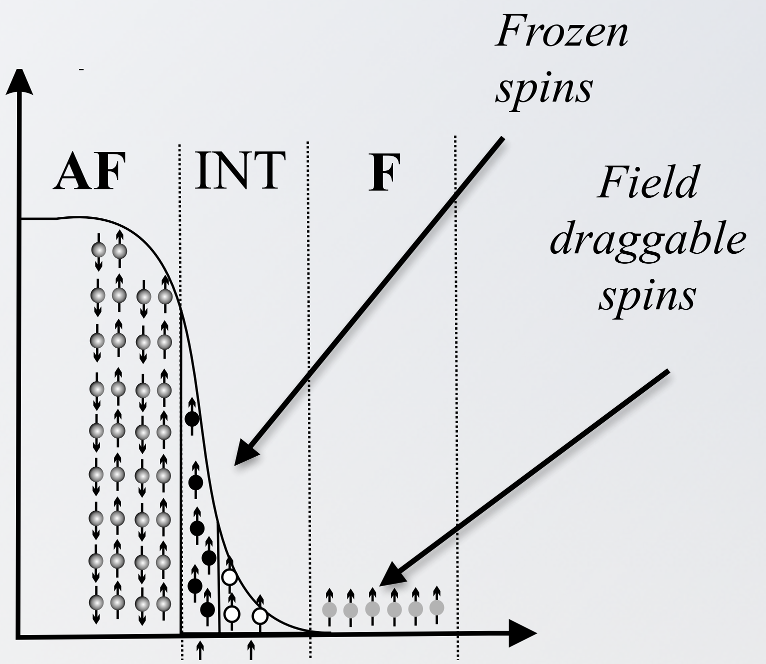
- Successive azimuthal rotation measurements for t_{BFO} = 85 nm.





➡Azimuthal training, stable after 4 rotational hysteresis.

➡Unusual behavior, can be explained using spin-glass model.



Conclusion

- Unusual azimuthal training after deposition, showing a spin reorganization at the F/AF interface.
- A phenomenon overlooked (so far): the training effect on the misalignment of exchange bias systems.
- Temperature dependence misalignments as a novel explanation for understanding and driving temperature dependent exchange bias properties in F/BFO.

Thank you

References

[1] W. H. Meiklejohn and C. P. Bean. *Phys. Rev.* **102**, 1413 (1956).

[2] R. Coehoorn. ``Novel Magnetoelectronic Materials and Devices : Exchange Anisotropy / Stoner-Wohlfarth model''. 2001.

[3] F. Radu, A. Westphalen, et al. *Journal of Physics: Condensed Matter*, **18**, L29 (2006).

[4] W. Eerenstein, N. D. Mathur, and J. F. Scott. *Nature*, **442**, 759 (2006).

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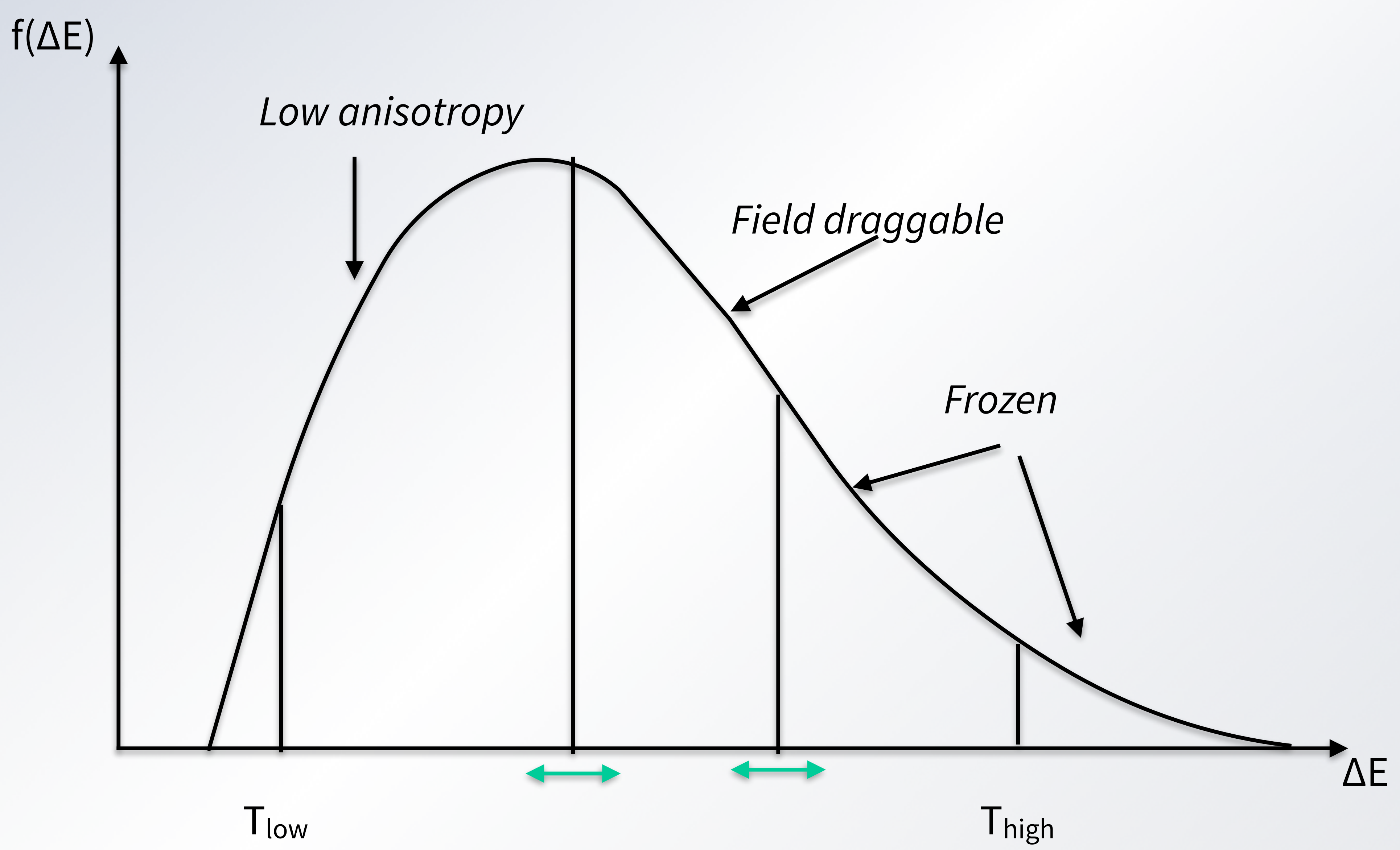
[9] T. Hauguel, S. P. Pogossian, et al. *J. Appl. Phys.* **112**, 093904 (2012).

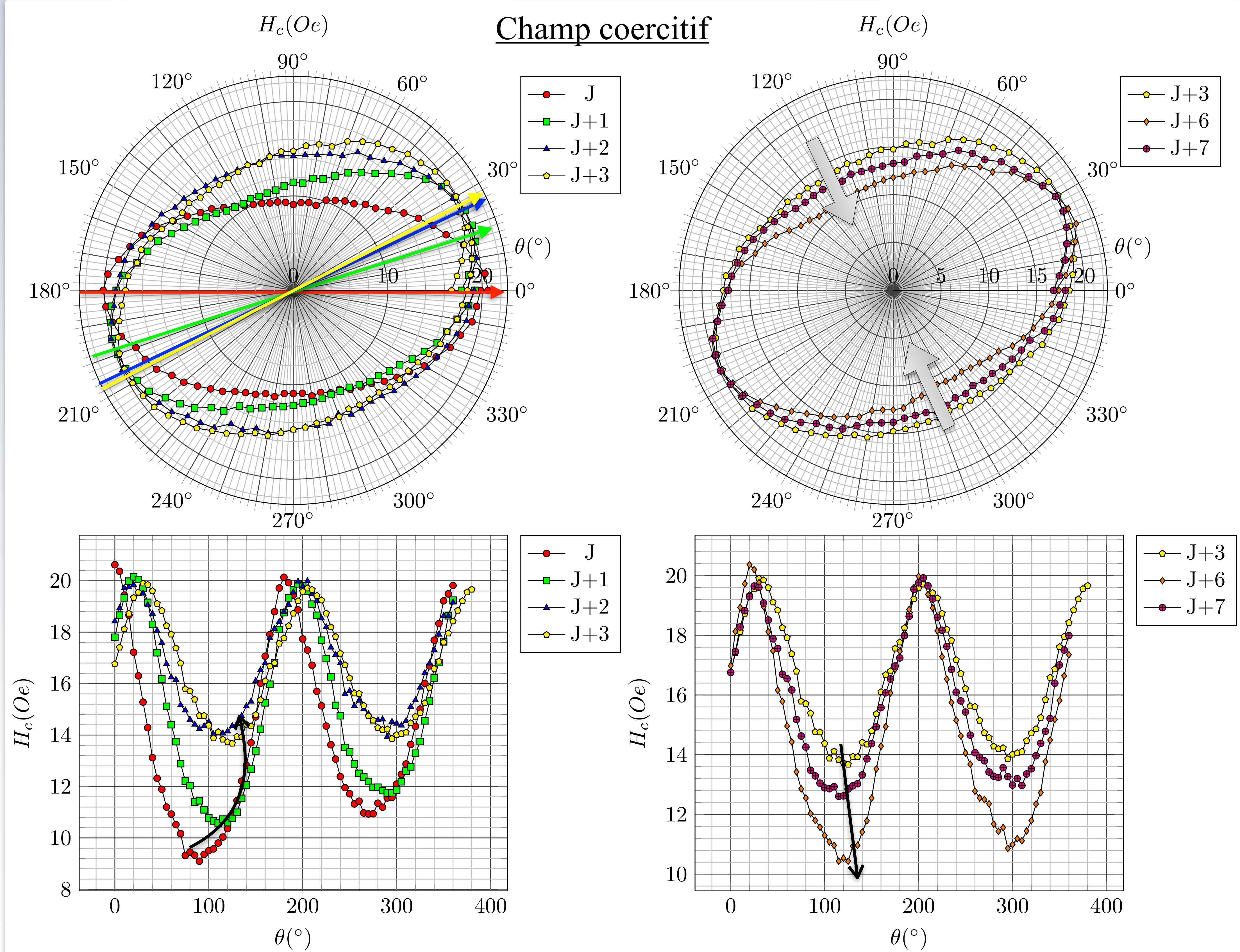
[10] M. C. He, B. You, et al. *J. Appl. Phys.* **117**, 17C745 (2015).

[11] X. Xue, X. Yuan, et al. *Eur. Phys. J. B*, **86**, 121 (2013).

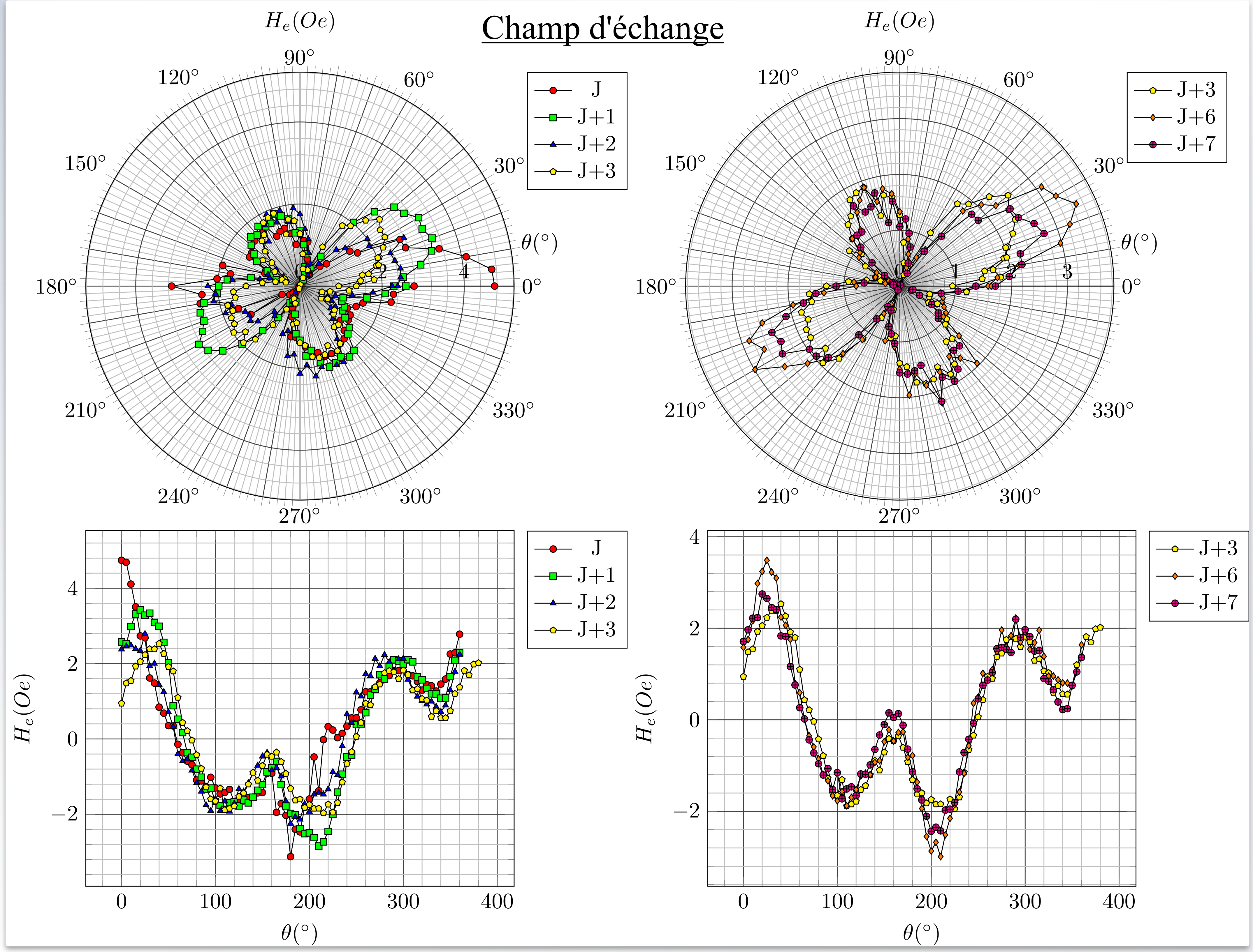


f(ΔE)
Low anisotropy
Field draggable
Frozen
ΔE
T low
T high

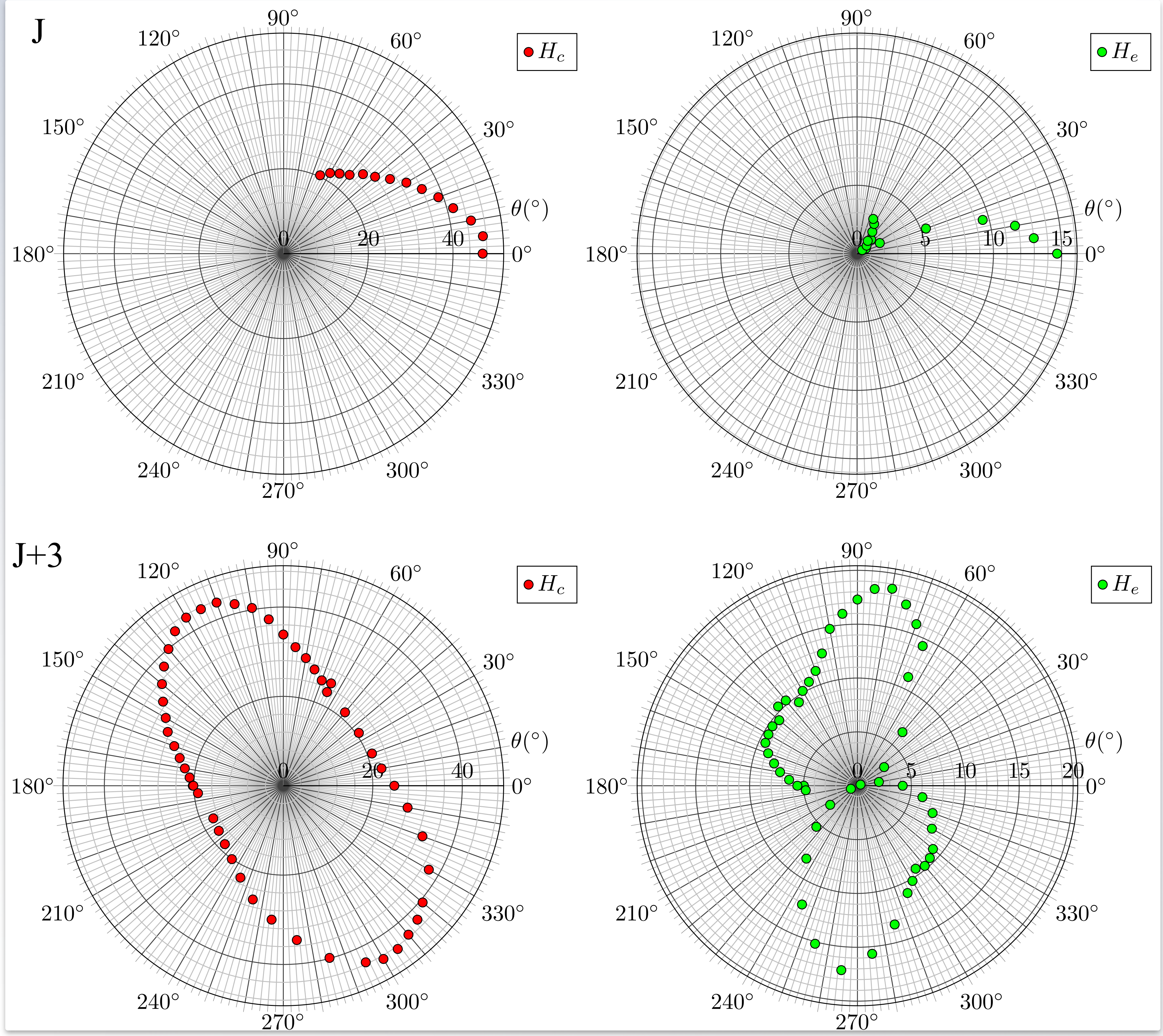
Effet de Trainage



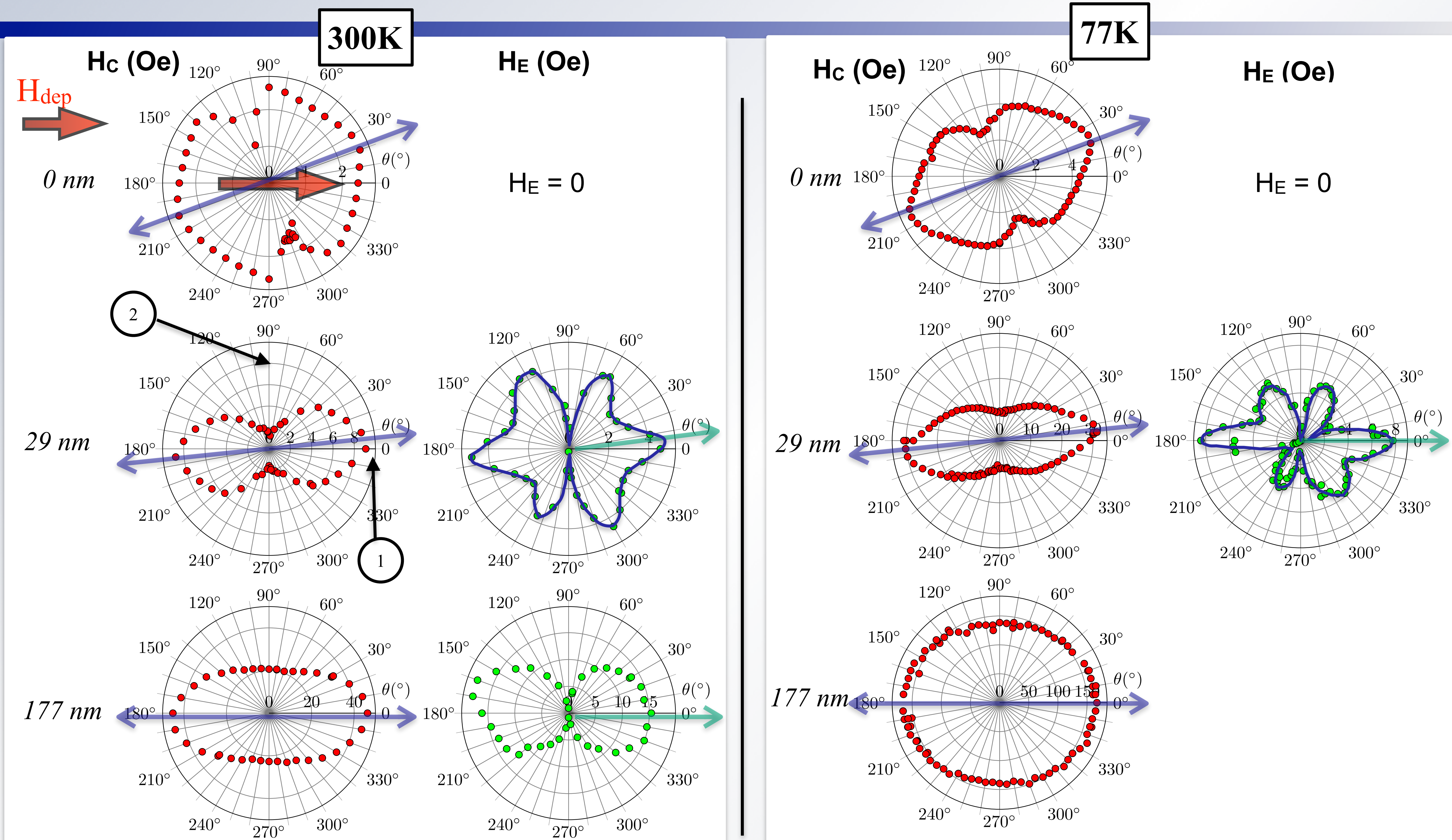
Effet de Trainage



Mesures magnétiques (VVSM)



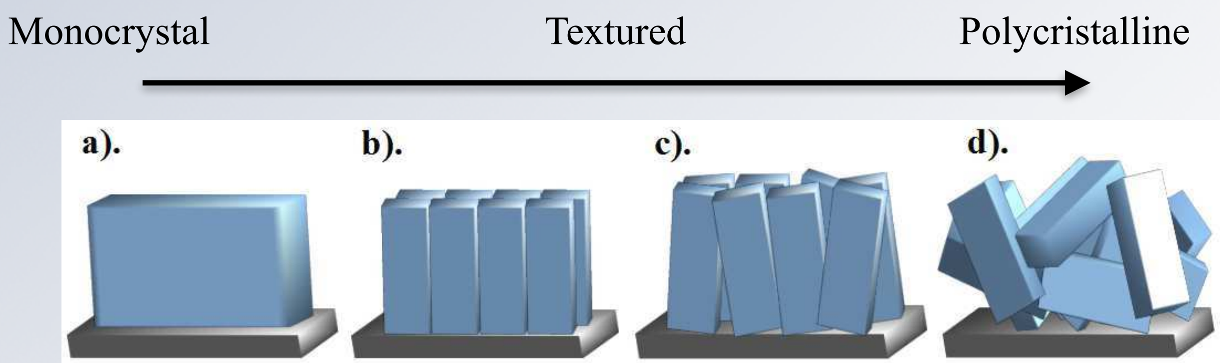
Mesures magnétiques (VVSM)



XRD

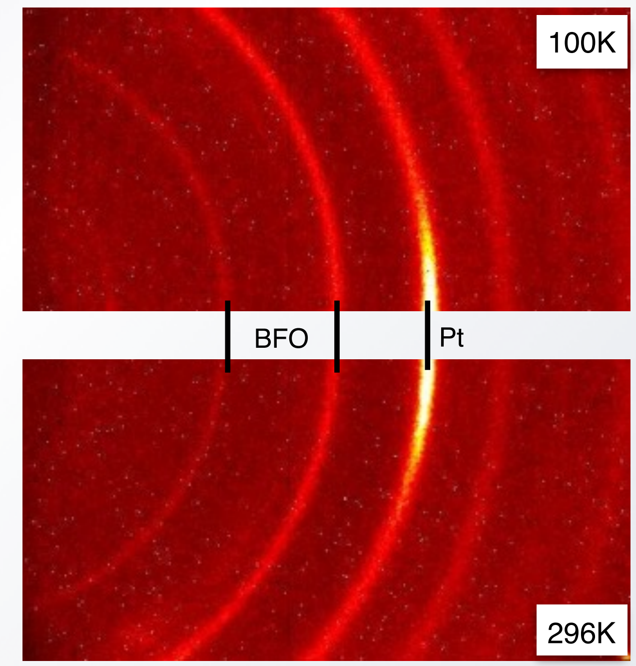
Structure

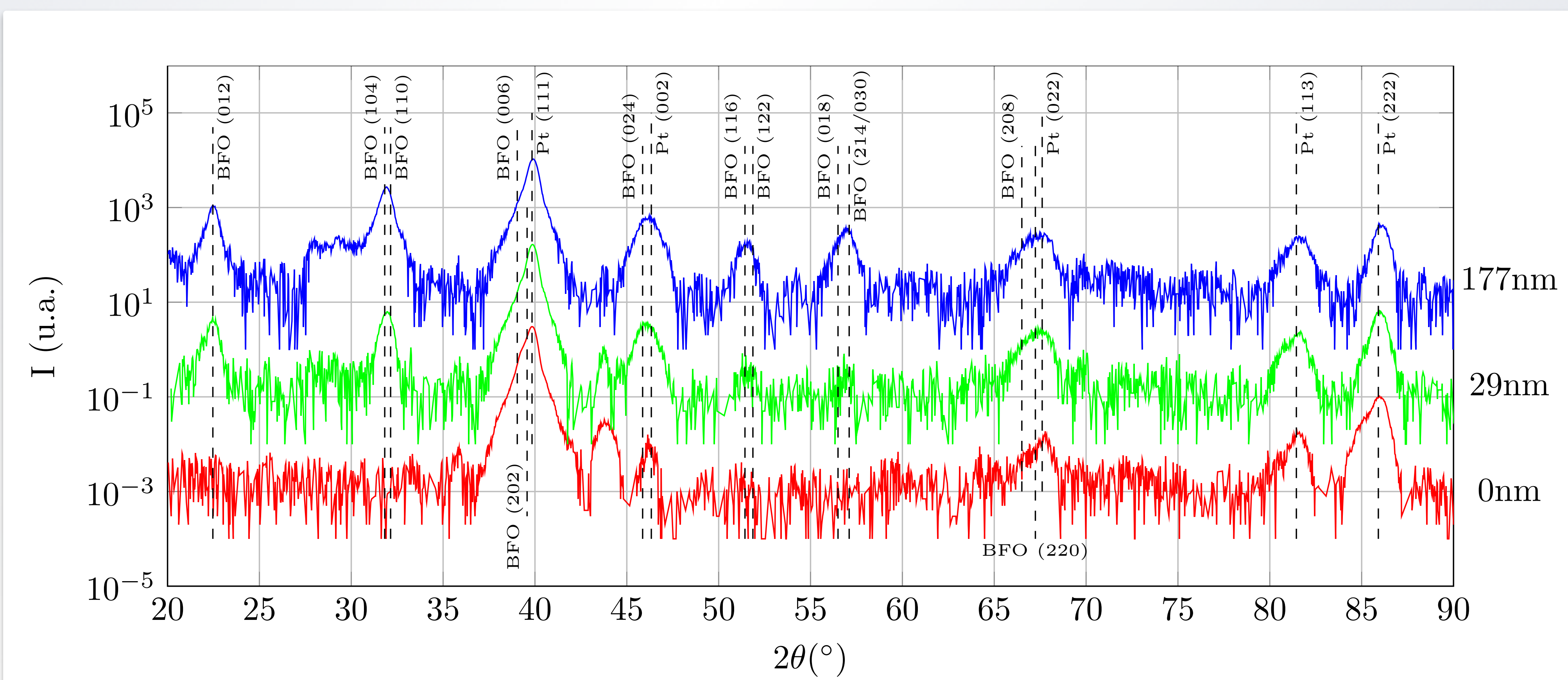
Polycristalline multiferroic α phase, with no parasitic phase.



The platinum buffer is textured, with a angular dispersion of 15°.

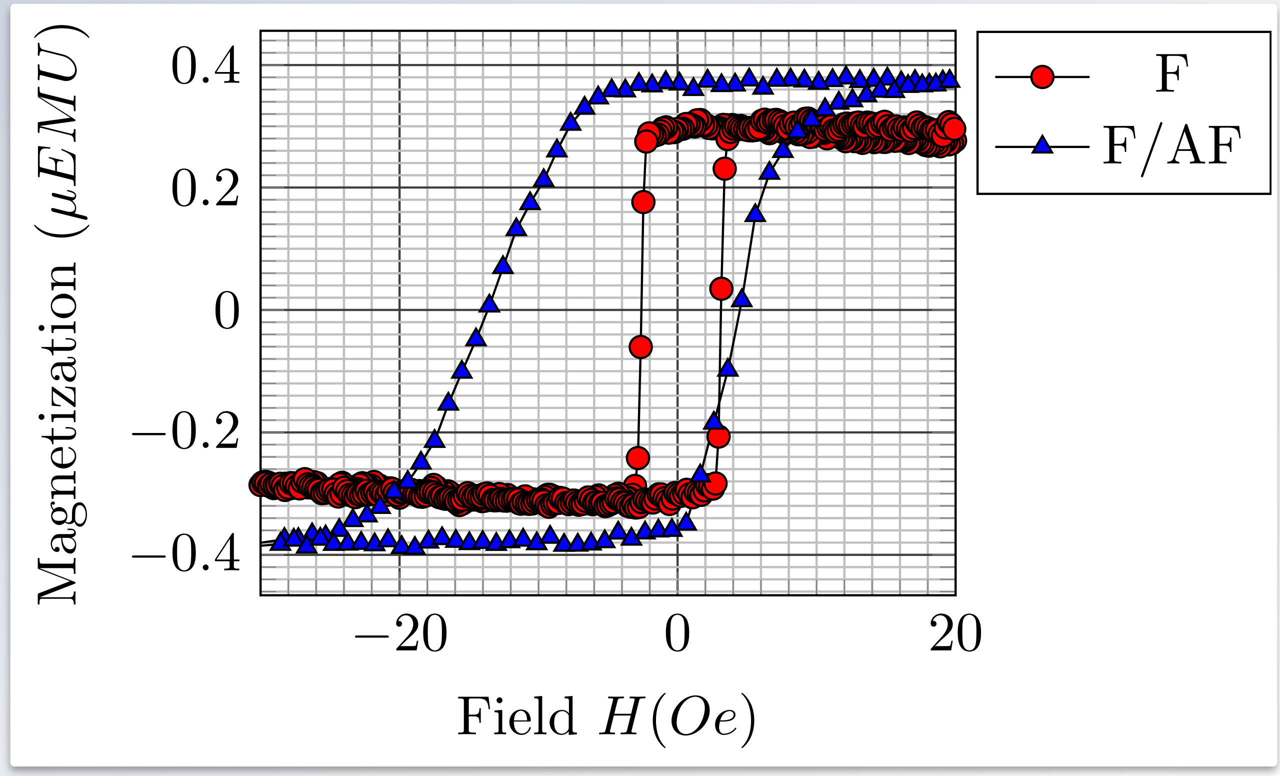
Temperature stability of the phase

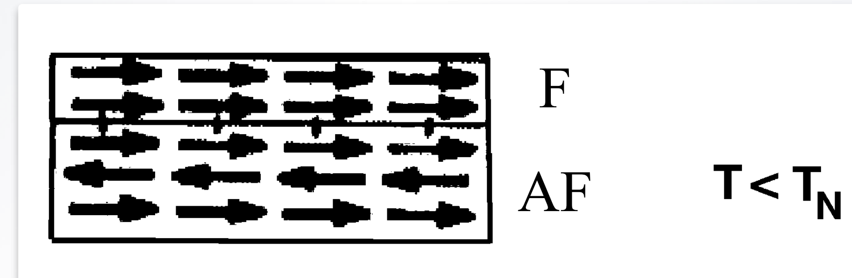




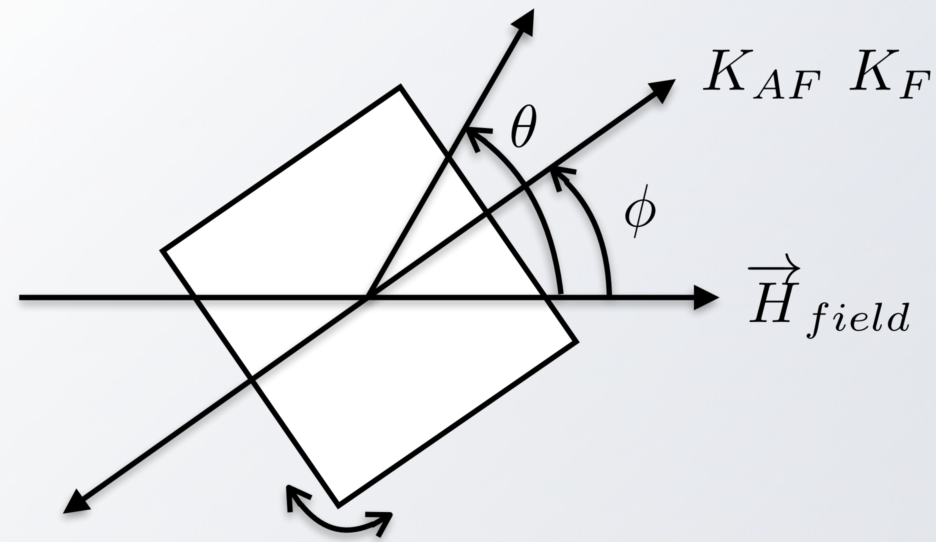
Exchange coupling

Exchange coupling discovered by Meiklejohn and Bean (1956).





Exchange bias in nanostructures, J. Nogués et al., *Physics Reports (2005 Dec 1)* ***422****: 65-117.*



Energy expression based on Stoner-Wolhfarth model.

$$E = \boxed{-\mu_0 H M_F V_F \cos(\theta)} + \boxed{K_F V_F \sin(\theta - \phi)} - \boxed{J_{eb} \frac{V_F}{t_F} \cos(\theta - \phi)}$$

Zeeman interaction — *uniaxial anisotropy* — *unidirectional anisotropy*

Magnetization	M_F
Anisotropies	K_F, K_{AF}
F volume	V_F
F thickness	t_F
Exchange surface energy	J_{eb}

New Magnetic Anisotropy
Meiklejohn, W. H.; Bean, C. P.
Phys. Rev. (1957 Feb 1) ***105*** *(3): 904-913.*

Exchange bias
Nogués, J.; Schuller, Ivan K.
Journal of Magnetism and Magnetic Materials (1999 Feb 1) ***192****: 203-232.*