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Polarized neutron reflectivity for the exploration of magnetic nanostructures.

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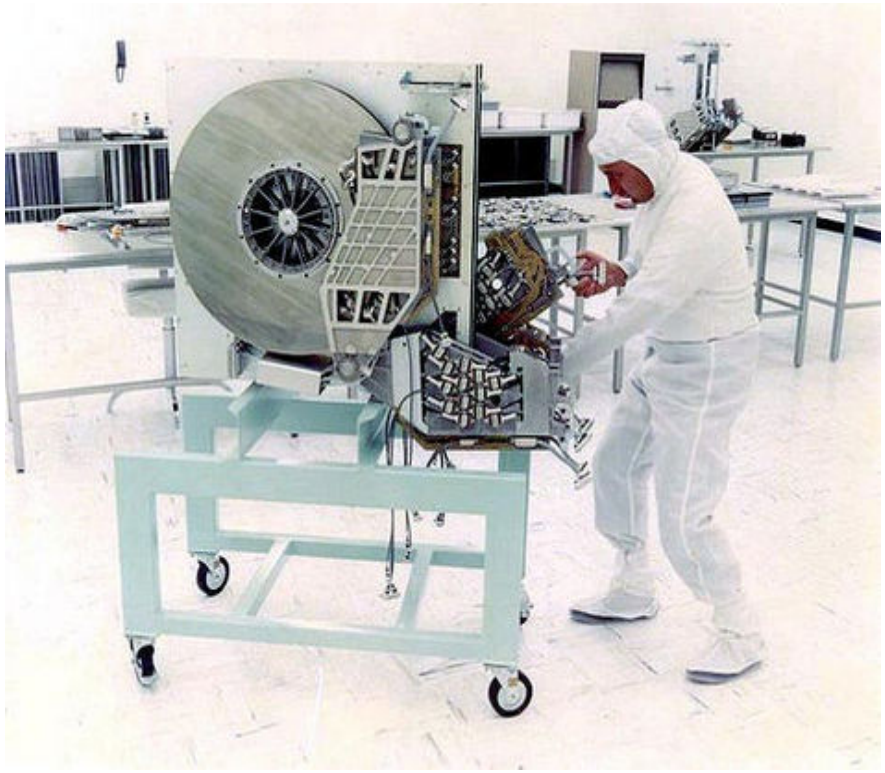
ESS Science Meeting, Brussels, September 14th 2017

Size does matter! Ex.: hard disk

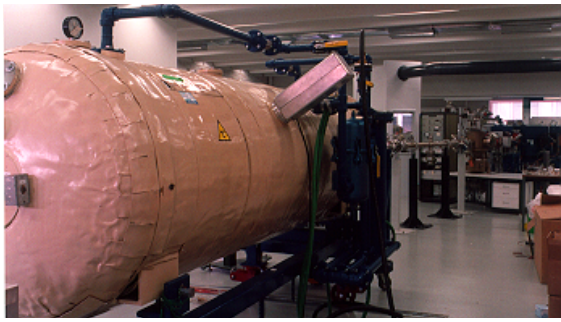


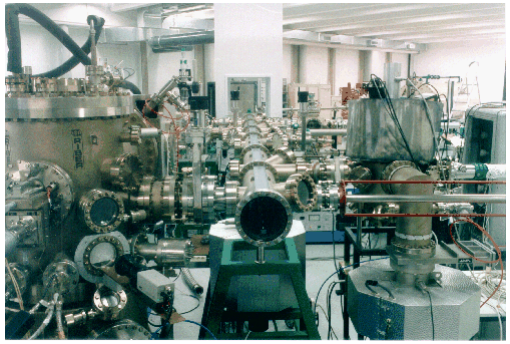
Anno 1975

Anno 2017

Progress is strongly rooted in fundamental studies of nanomagnetism, interfacial effects and dynamics!

Ion and Molecular Beam Laboratory





Leuven Isotope Separator

Switch Magnet

Implantation chamber

High-current Separator

RBS/C chamber

Pelletron accelerator

RF

Soft landing

Oxide MBE

STM

MBE

Cluster source

MBE

AES

Multi function chamber

SNICS

CEMS

UHV system

SPIRIT

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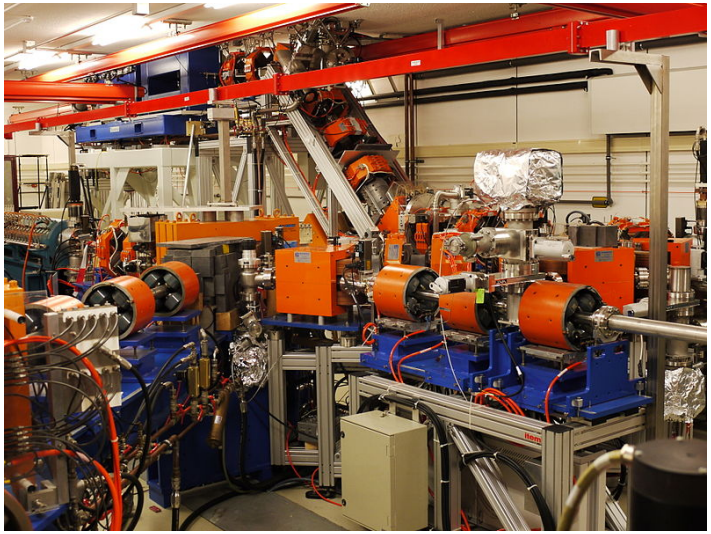
http://fys.kuleuven.be/iks/nvsf/experimental-facilities/experimental-facilities-home

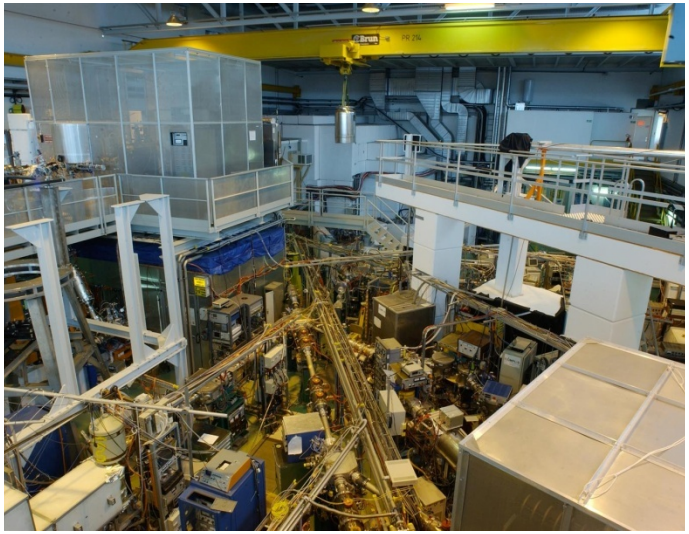
Complementarity with LSF

Complementary approach :
experiments at international large-scale facilities
for neutrons, muons, photons and radioactive ions

ESRF and ILL, Grenoble



FELIX Nijmegen



ISOLDE, CERN

MLZ (Munich), HZB (Berlin), PSI (Villigen), DESY-Petra (Hamburg), BESSY (Berlin), APS (Argonne)…

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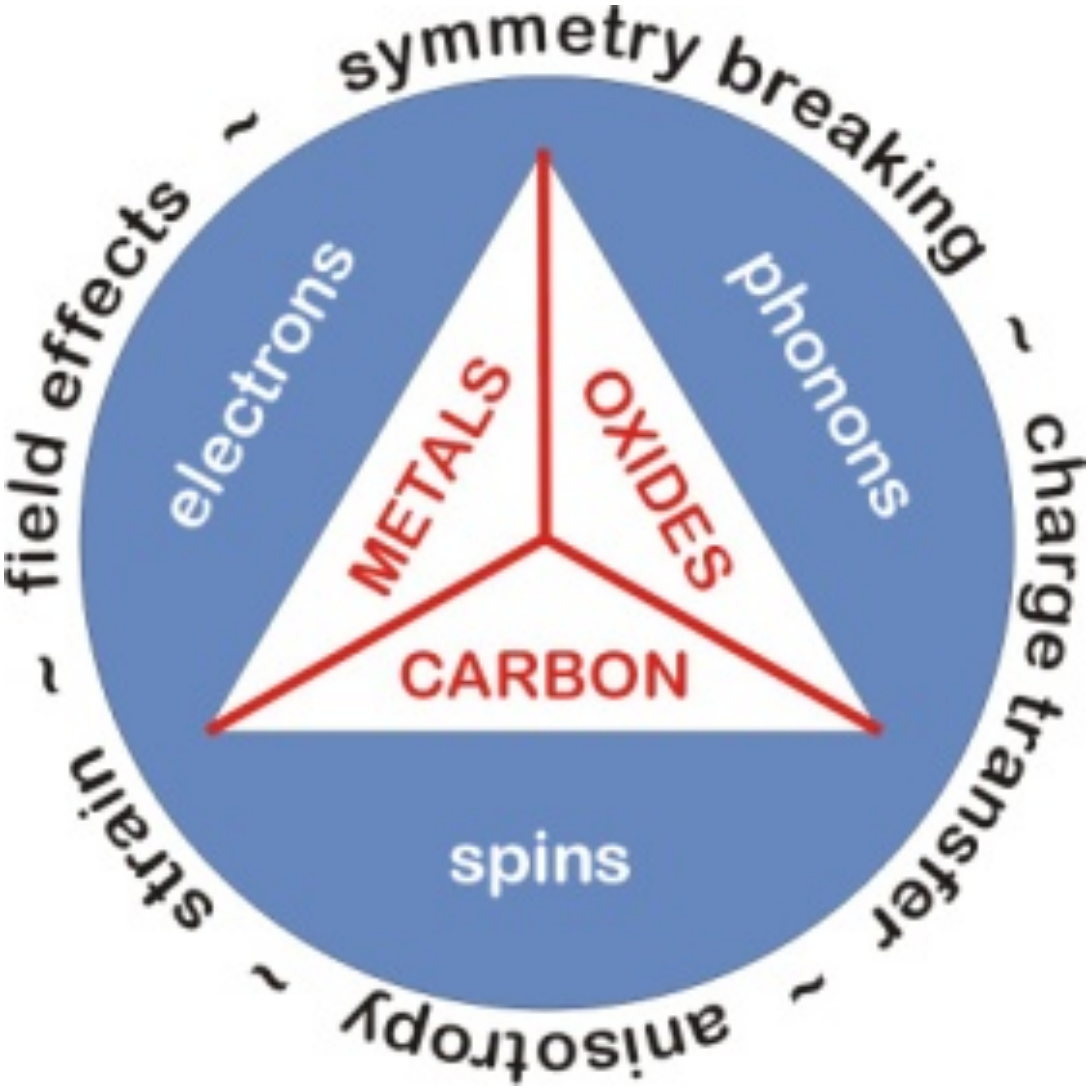
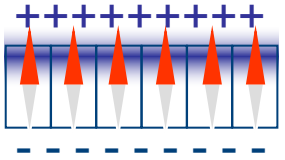

symmetry breaking
charge transfer
anisotropy
strain
field effects
electrons
phonons
spins
METALS
OXIDES
CARBON

General framework and trends

→ **interface-driven effects** in ‘hybrid’ magnetic structures

Confrontation of different order parameters



ferromagnet/antiferromagnet (exchange bias)
strong/weak anisotropy (exchange spring)
ferroelectric/ferromagnet (‘composite’ multiferroic)
superconductor/ferromagnet (proximity effect)
dilute magnetic semiconductor/ferromagnet
topological insulator/ferromagnet
…

→ resolve interaction at relevant length scale
correlate with structure/chemistry of interface

Fundamental research but close link to applications!

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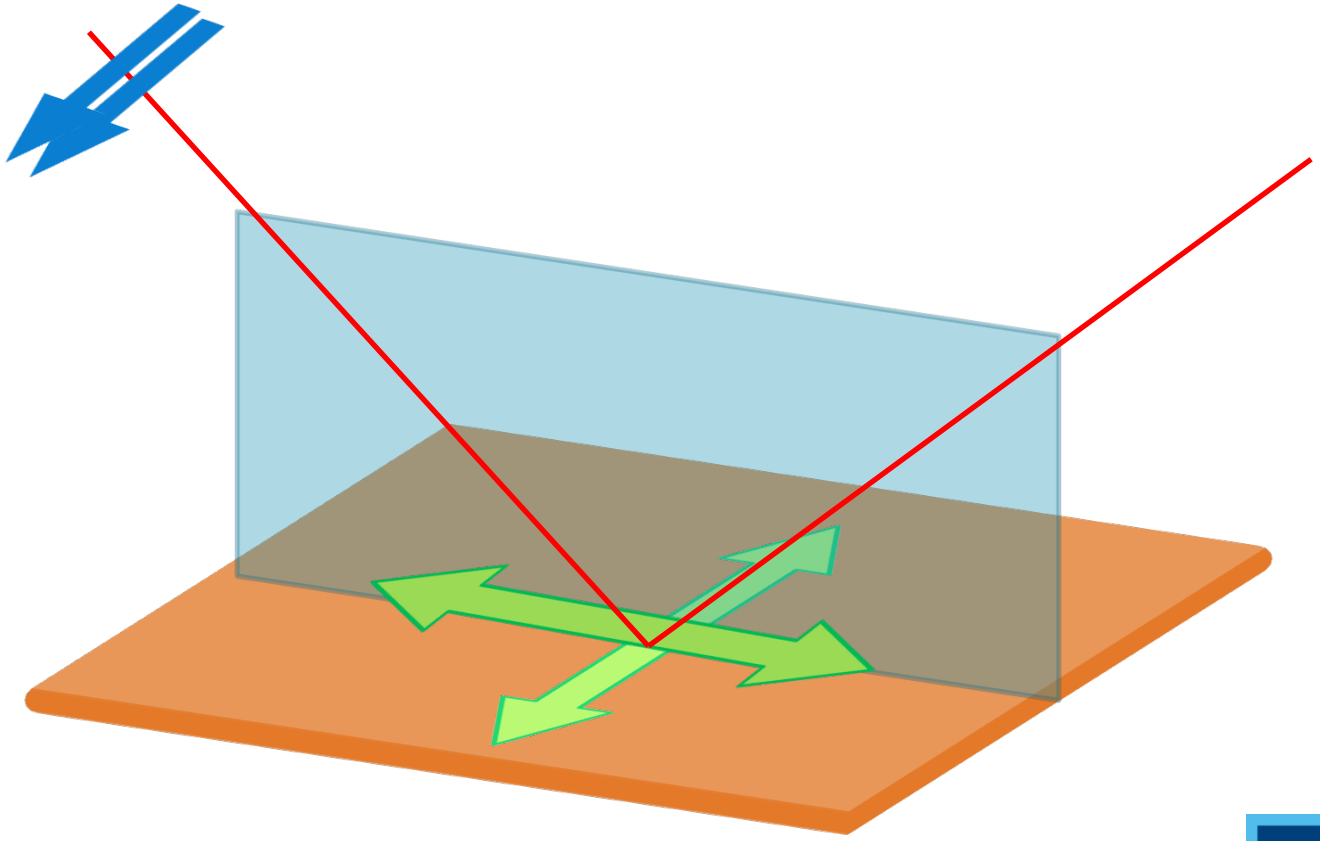
PNR: two fundamental interactions

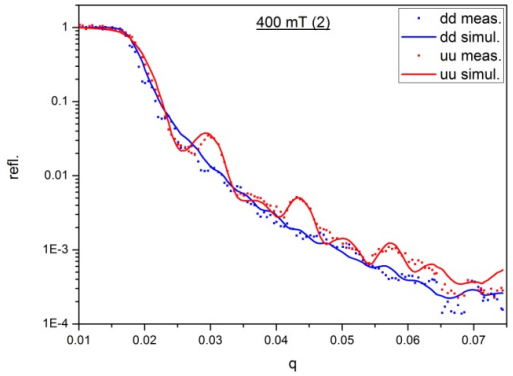
Non Spin Flip interaction:
Neutron spin // magnetization

Spin Flip interaction:
Neutron spin ⊥ magnetization



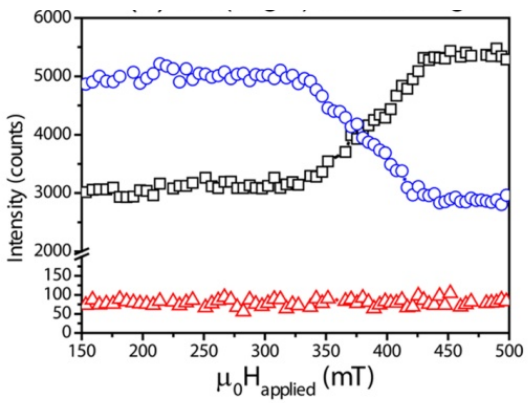
PNR: key to asymmetry in reversal mechanism in EB systems
M.R. Fitzsimmons, P. Yashar, C. Leighton, I.K. Schuller, J. Nogués, C.F. Majkrzak, J.A. Dura, PRL **84**, 3986 (2000); F. Radu et al., PRB 67, 134409 (2003)

Polarized neutron reflectivity (PNR)



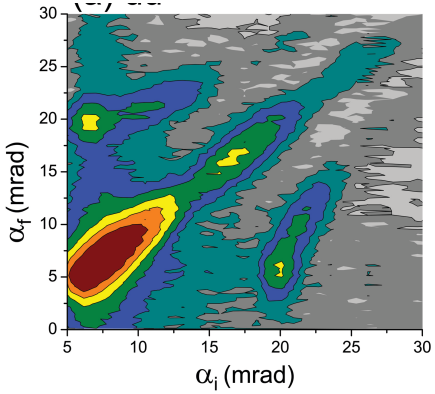
Specular reflectivity scan at fixed field

Magnetic depth profile



Magnetic field scan at fixed angle

Magnetic reversal mechanism



Reciprocal space map at fixed field

In-plane magnetic correlations

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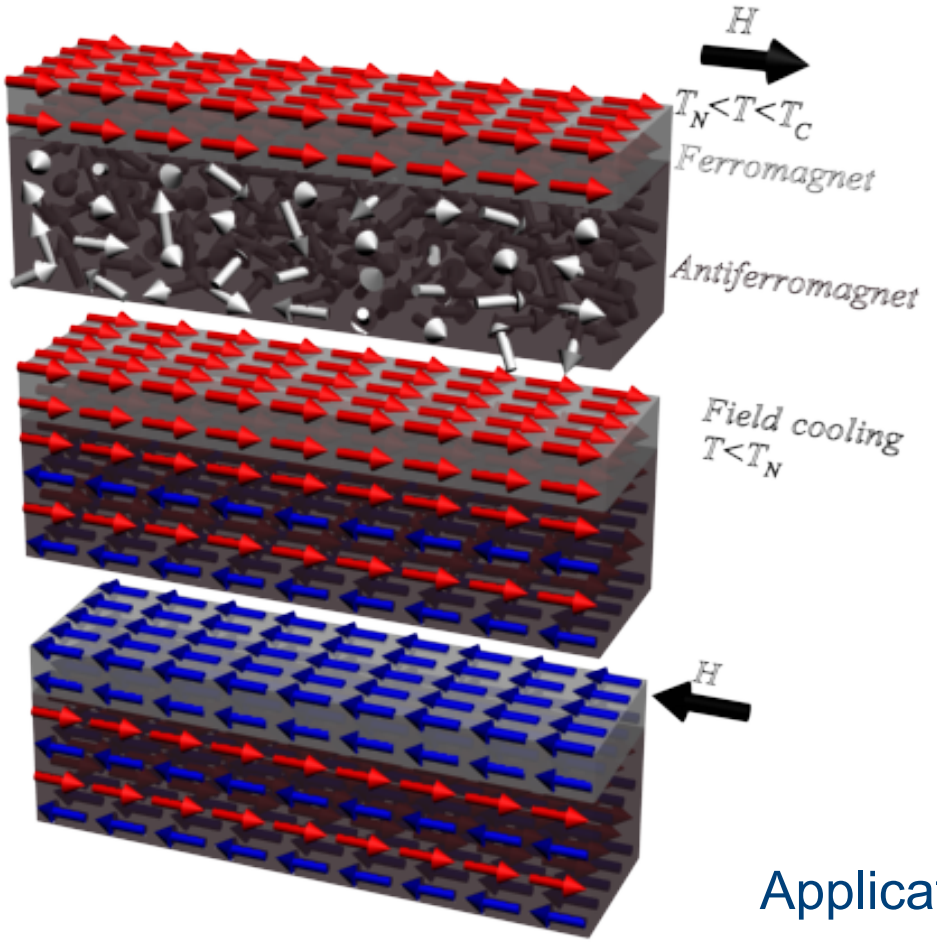
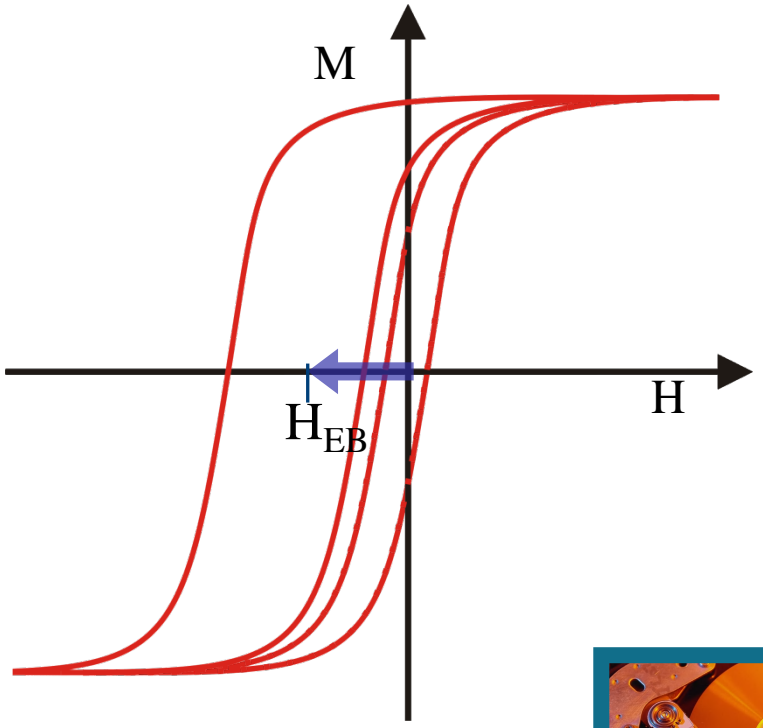
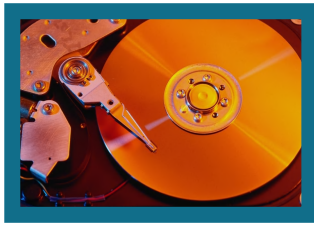
See also V. Lauter et al. in e.g. PRL 89, 167203 (2002); PRB 83, 174418 (2011)

Exchange bias effect





Application: spin valve, sensors…

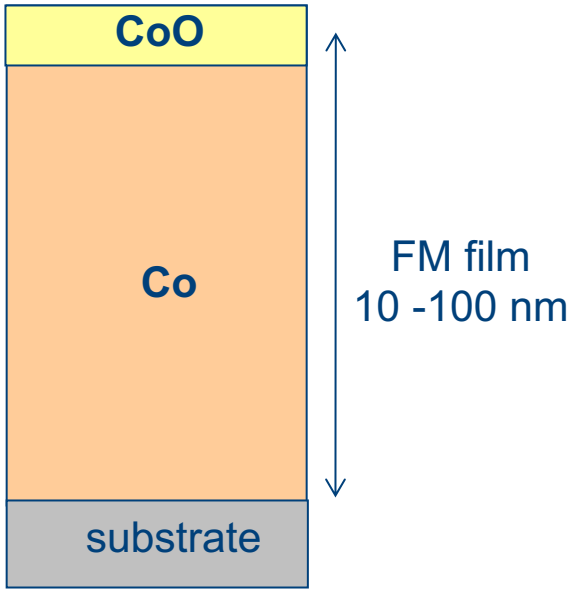


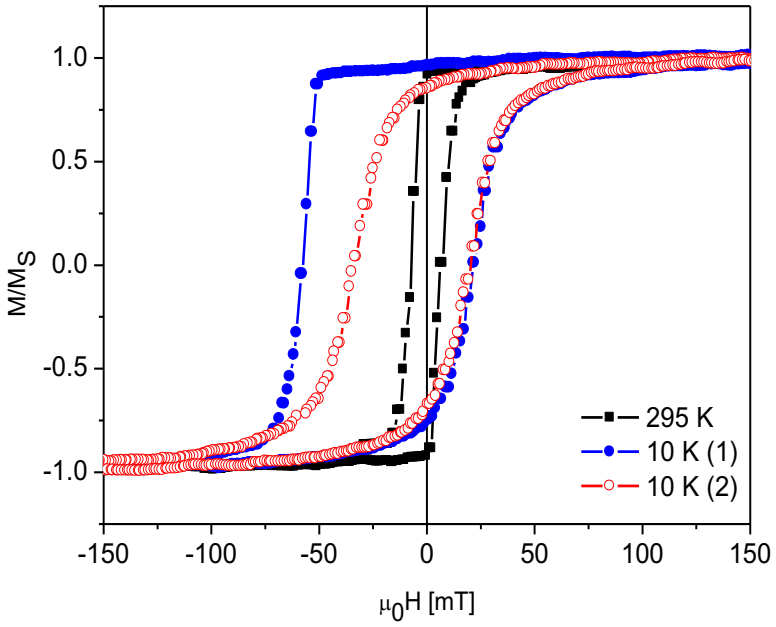
W. H. Meiklejohn and C. P. Bean, Phys. Rev. **102**, 1413 (1956)
J. Nogués and Ivan K. Schuller, JMMM 192 (1999)
F. Radu and H. Zabel, Springer Tracts Mod. Phys. 227 1743 (2007)

Exchange Bias in thin films

Bilayer exchange bias system:

- Archetypal EB system: **Co-CoO bilayers**
- CoO limited to 2-3 nm due to **self-limiting** nature of oxidation





H_E = shift
H_C = broadening

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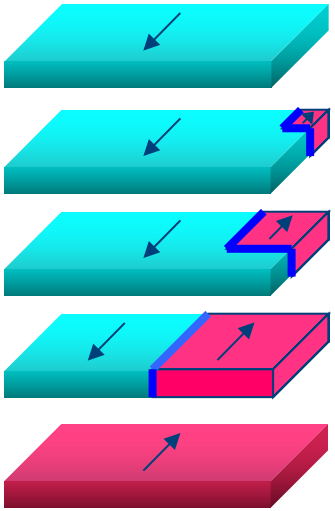
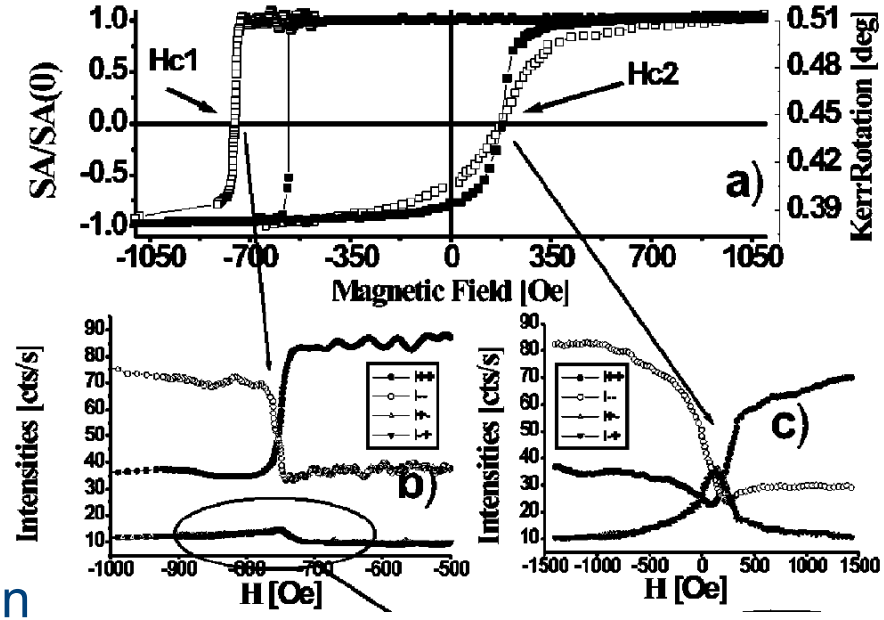
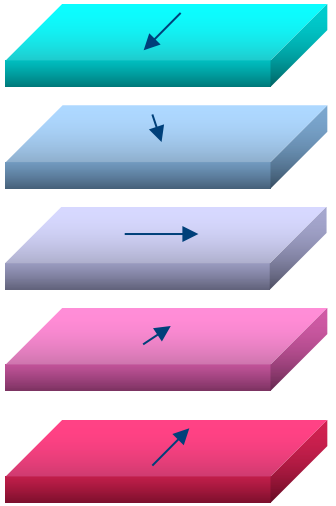
S. Brems, D. Buntinx, K. Temst, C. Van Haesendonck, F. Radu, H. Zabel, PRL 95, 157202 (2005)

Asymmetry in reversal

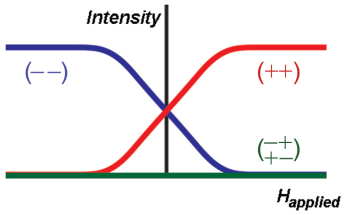
Asymmetry between 1st (domain wall nucleation and motion) and 2nd (coherent rotation) magnetization reversals by magnetic field scans in PNR



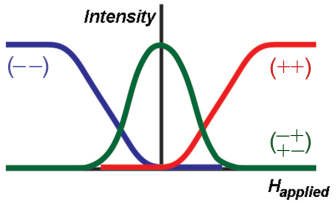




Domain wall motion



Rotation



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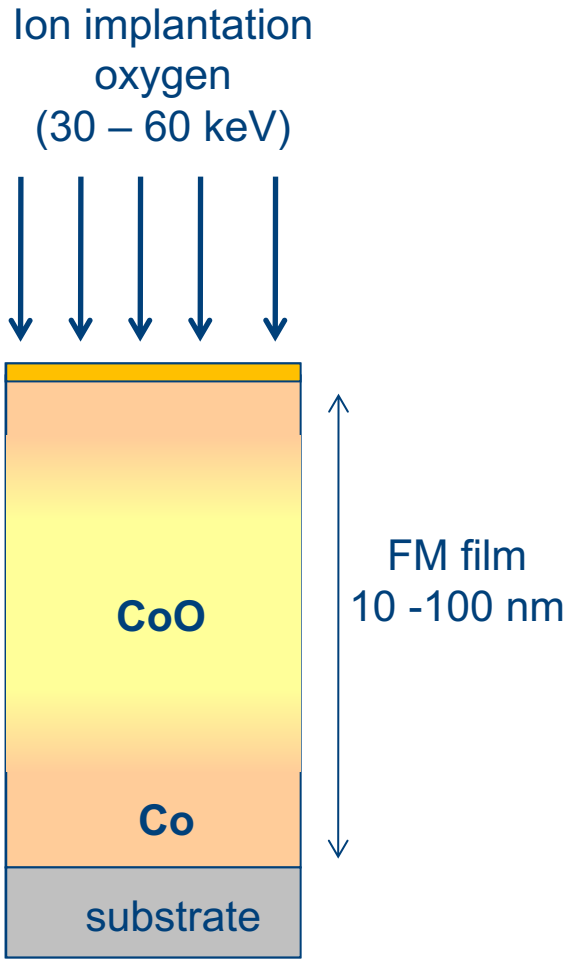
F. Radu et al., Phys. Rev. B 67, 134409 (2003)
A. Paul et al., APL 95, 092502 (2009); APL 97, 032505 (2010)

Exchange Bias by ion implantation

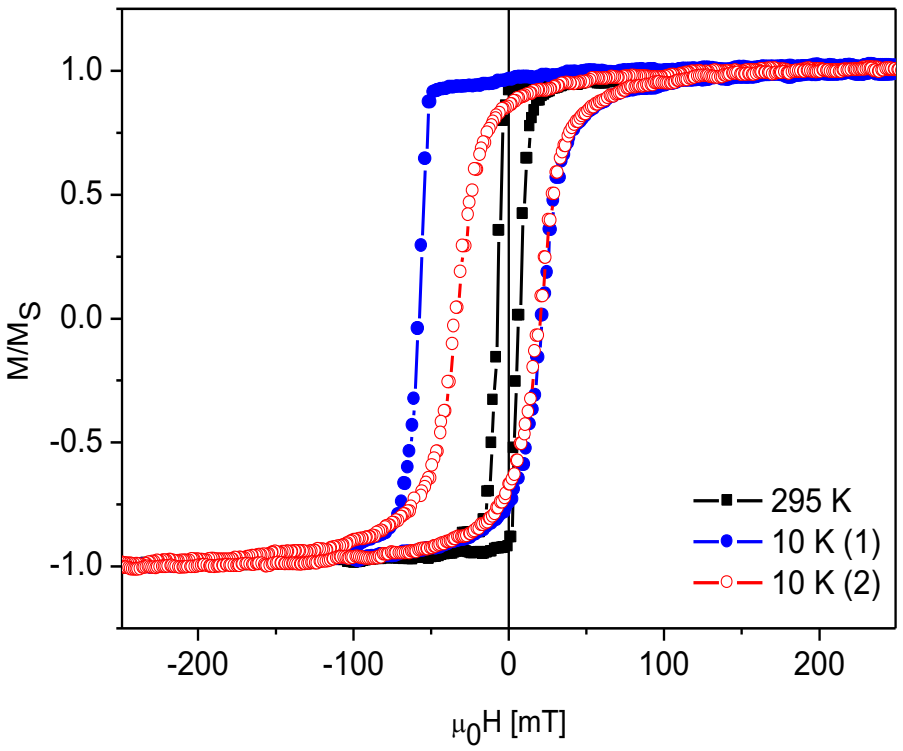


Implanted exchange bias system:

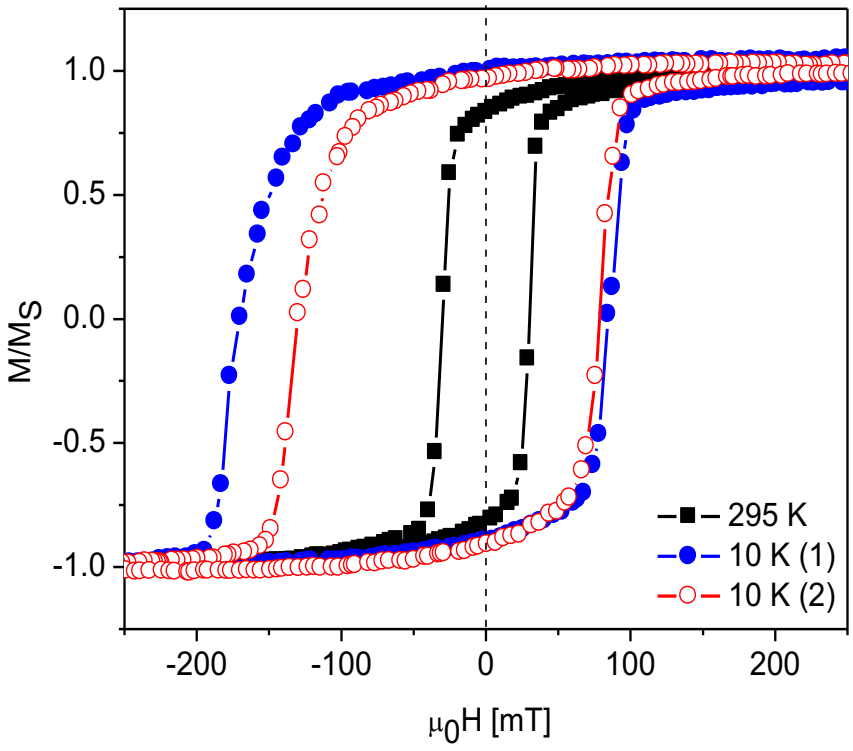
- **Overcome limited thickness** of surface oxidation
- AFM **embedded** in FM
- Up to 14 % O in Co
- Multiple **interfaces** between FM and AFM

Challenge: correlate magnetism with gradient in thin film, small area sample

EB by ion implantation vs. bilayer



Bilayer system
30 nm Co film
surface oxidation



Implanted system
100 nm Co film
$1x10^{17}$ ^{16}O at 60 keV

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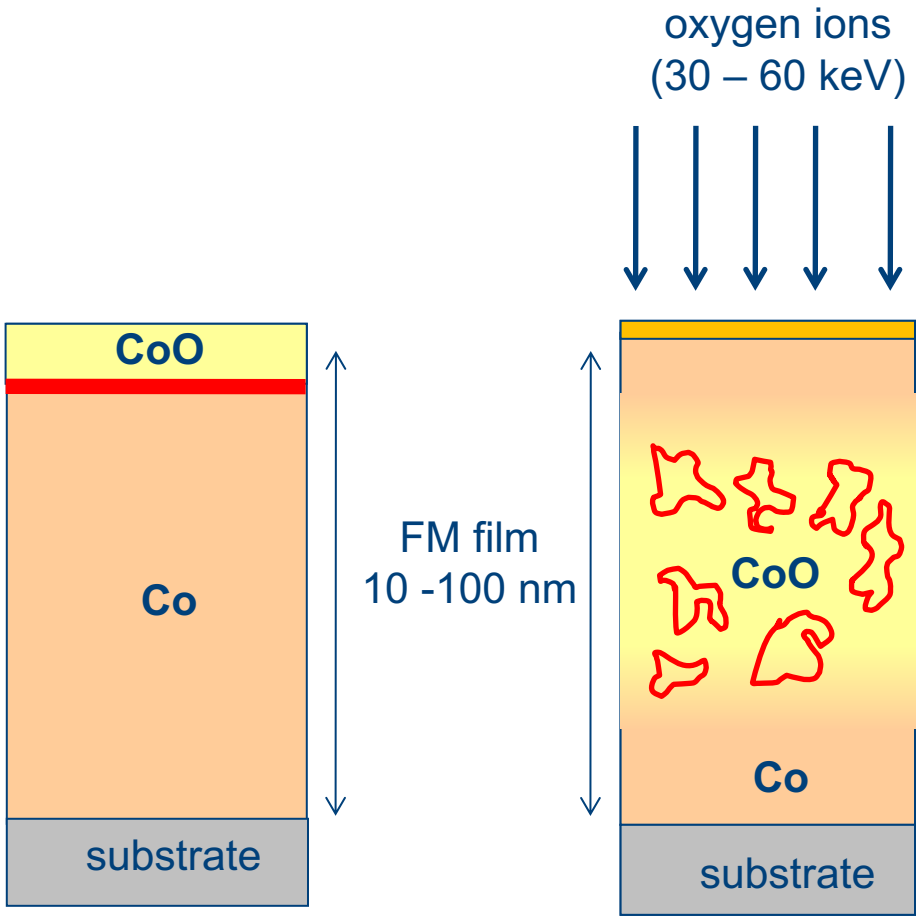
FM/AFM interface



Bilayer system: planar interface between FM and AFM

Implanted system: interface between FM and AFM distributed throughout layer

→ **magnetic depth profile? reversal mechanism ?**

→ **probe by polarized neutron reflectivity**

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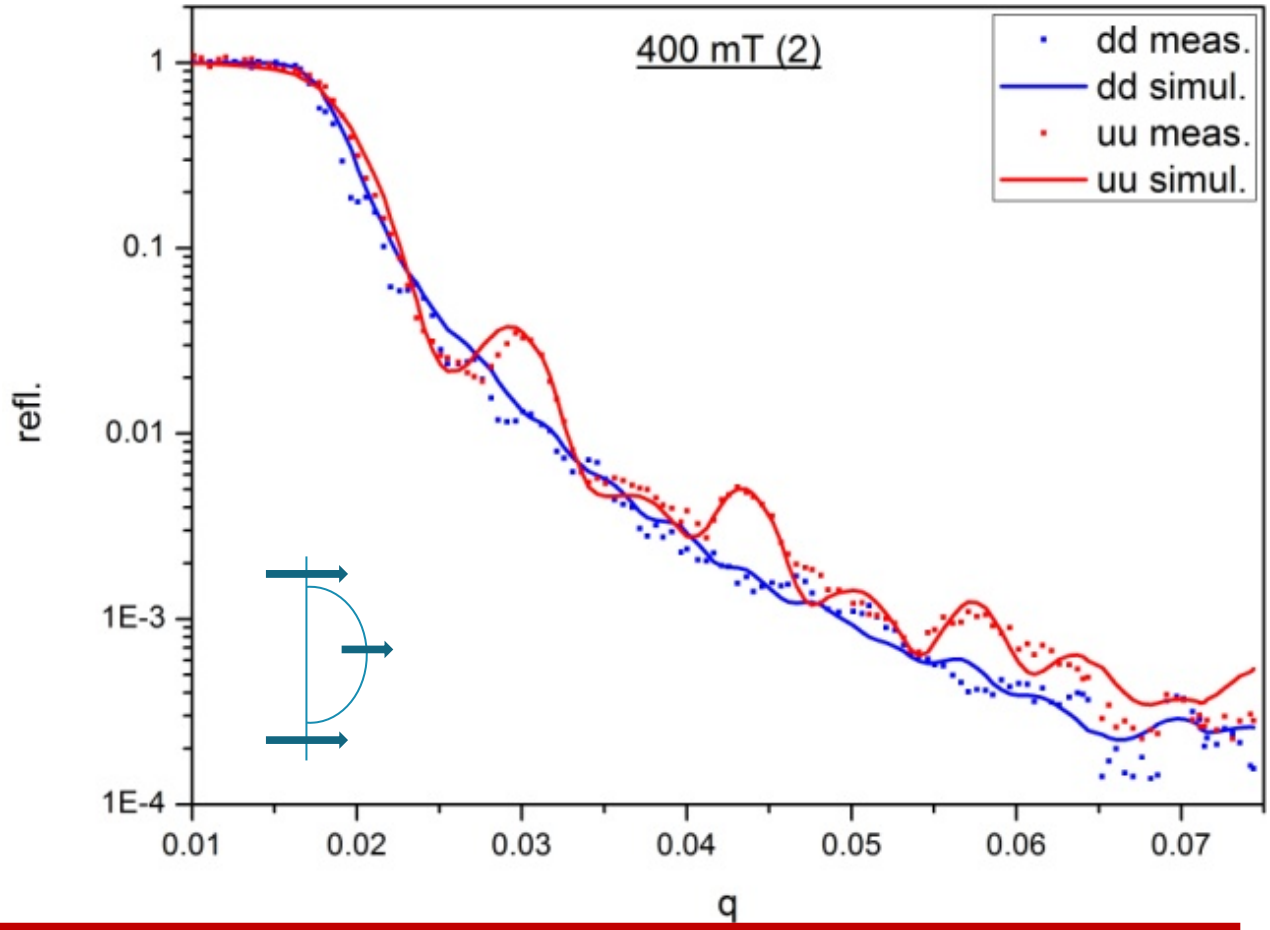
E. Menéndez et al., ACS Appl. Mater. Interfaces 5, 4320 (2013)

Magnetic depth profile



Polarized neutron reflectivity:

- **chemical depth profile (like XRR) *plus***
- **magnetic depth profile (vectorial)**

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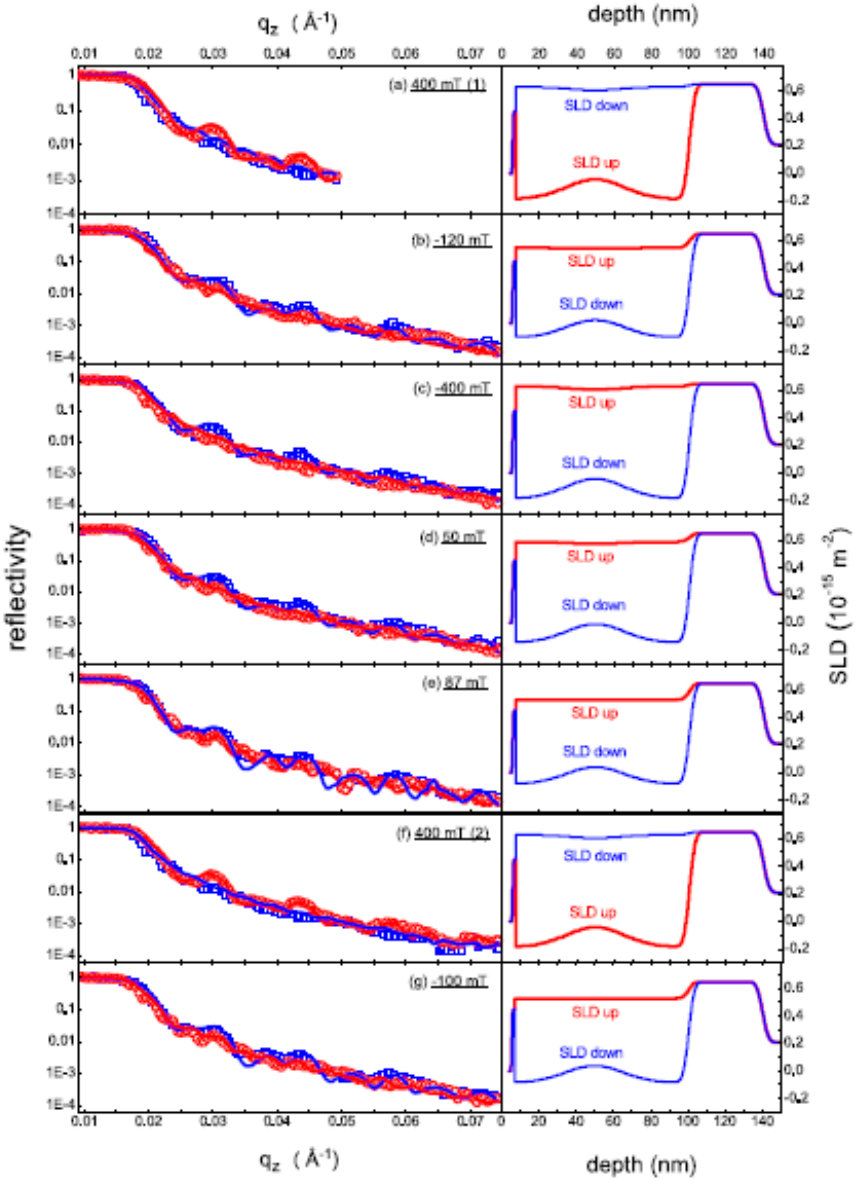
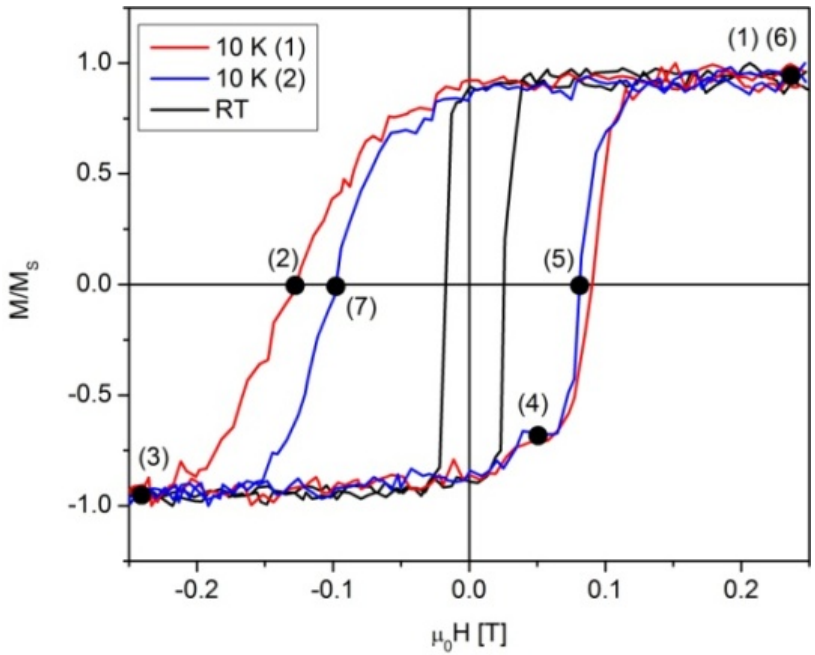
J. Demeter et al., J. Phys. D: Appl. Phys. **45,** 405004 (2012)

Magnetic depth profile





Magnetic depth profile correlates well with gaussian implantation profile

J. Demeter et al., J. Phys. D: Appl. Phys. **45,** 405004 (2012)

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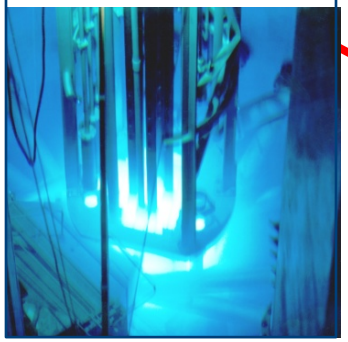
Best of both worlds: PNR and AMR

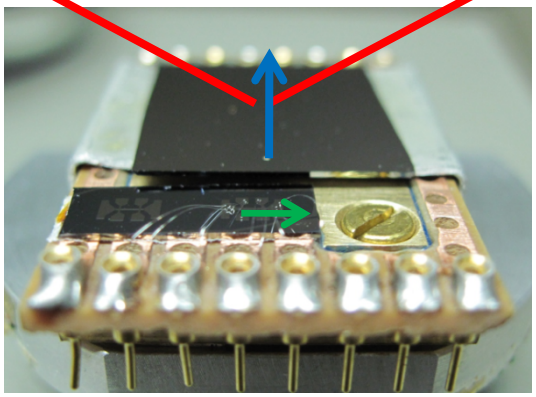
Simultaneous measurement of PNR and AMR in reflectometer

Neutron source



Detection of reflected neutrons

Neutron Beam



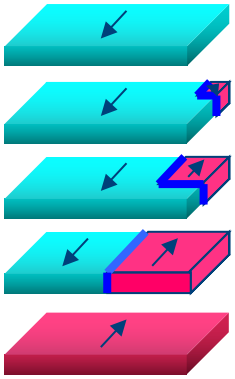
Magnetic Field

Electrical Current

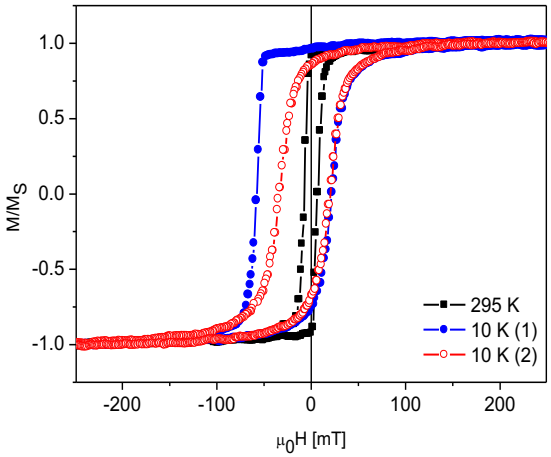
Combination PNR-AMR solves several experimental issues !

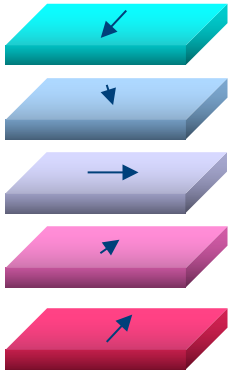
Magnetization reversal mechanism

BILAYER



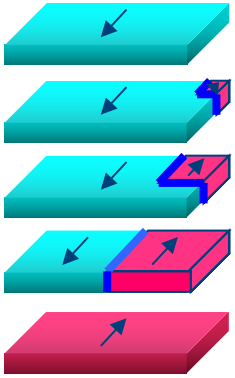
Domain wall motion



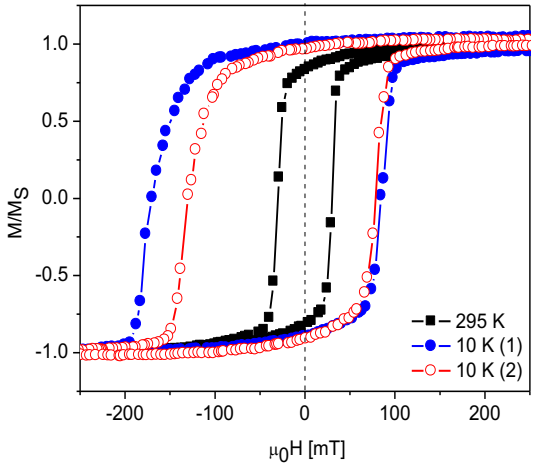


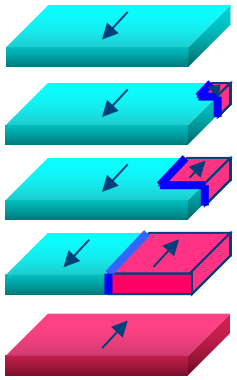
Rotation

IMPLANTED SYSTEM



Domain wall motion



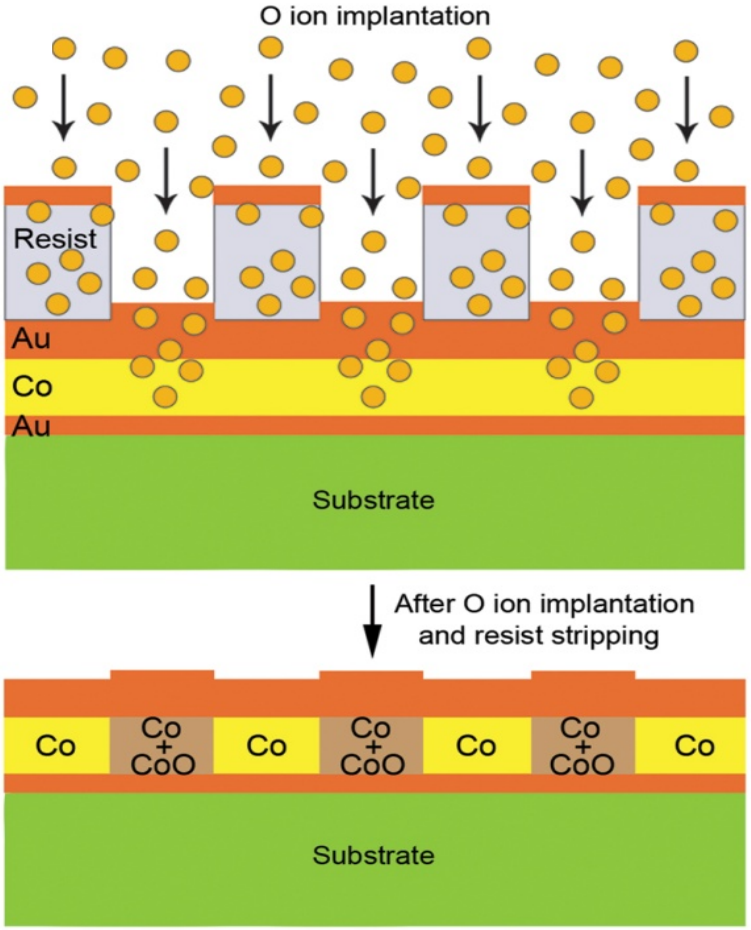


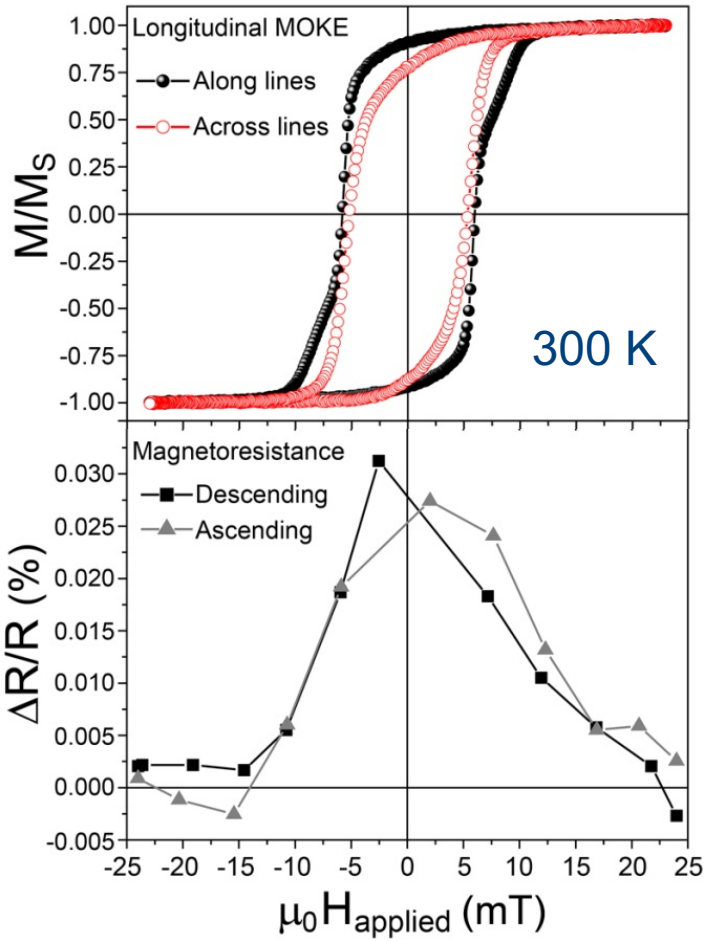
Domain wall motion

E. Menéndez et al., Phys. Rev. B 89, 144407 (2014)

Lateral patterns in 30 nm Co film

Combine ion implantation with UV-lithography





Magnetoresistance at room temperature: GMR mechanism

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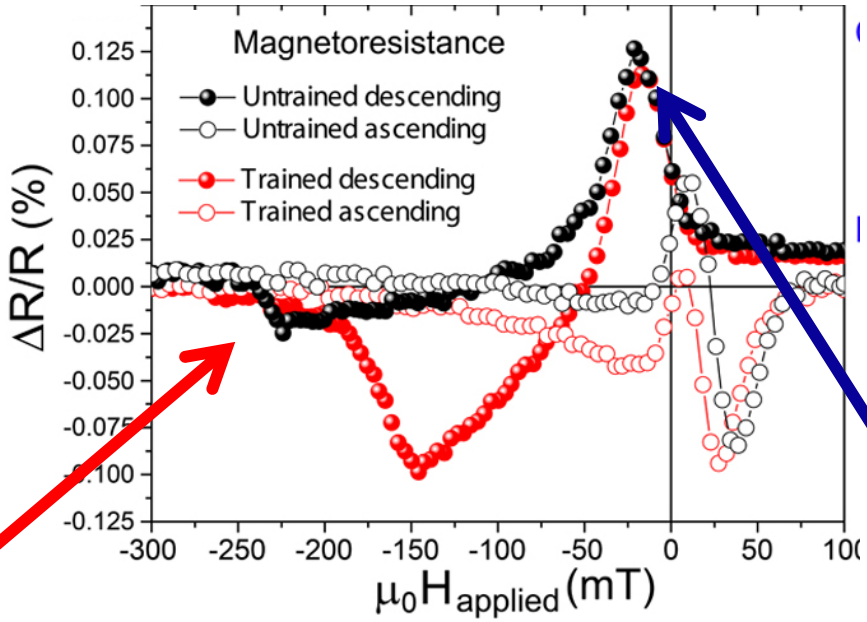
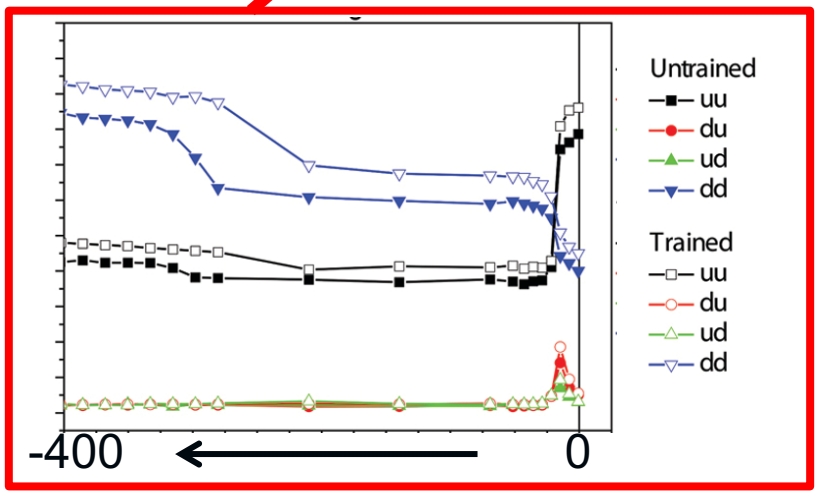
E. Menéndez et al., Small (2016) – collaboration with UGent

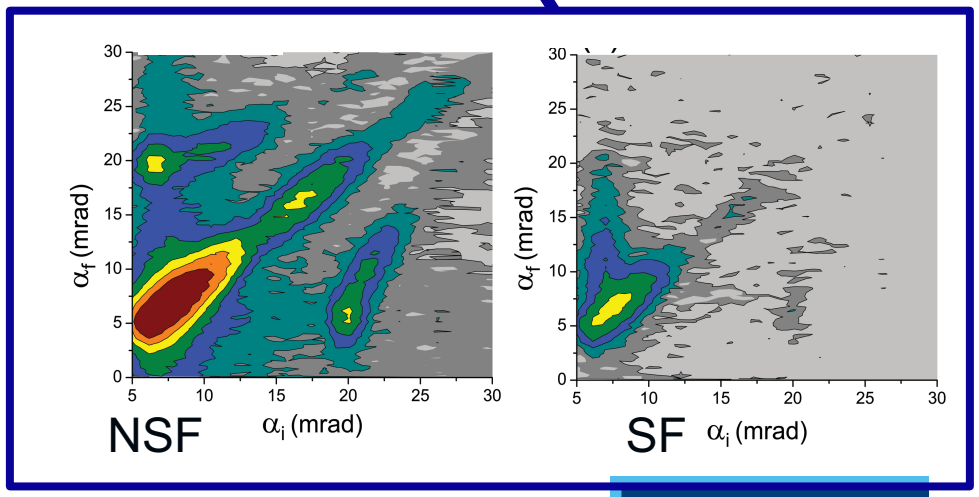
Low temperature magnetoresistance



Domain walls in implanted areas (AMR)

Lateral pattern of domain walls (GMR) at boundaries between implanted and non-implanted areas





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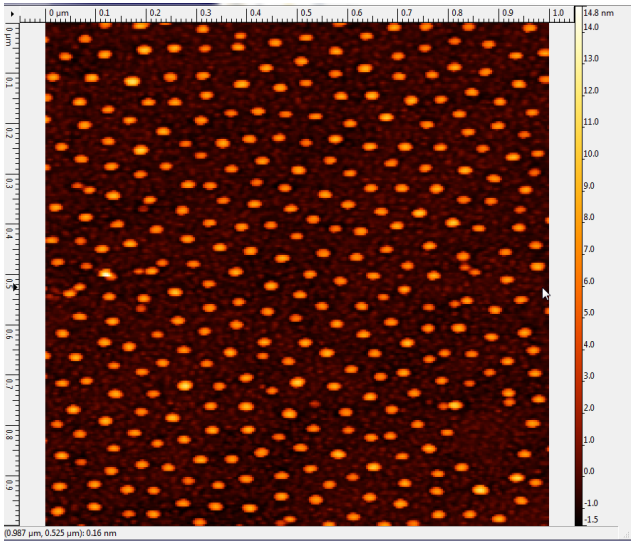
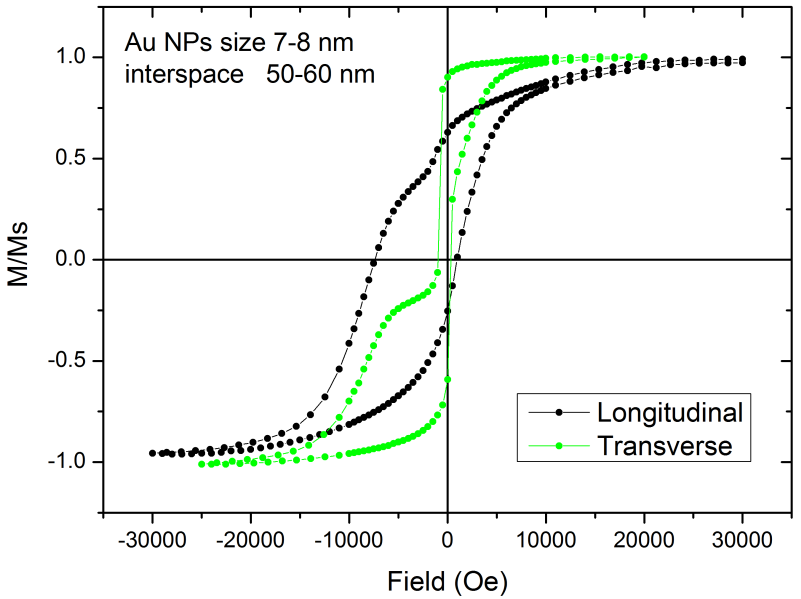
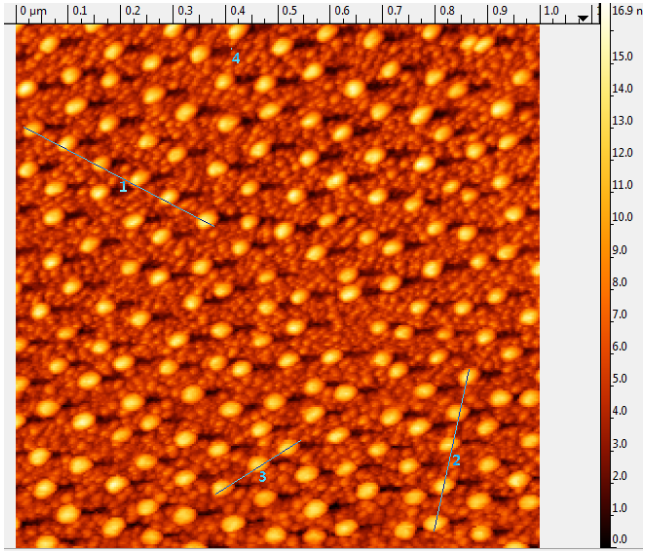
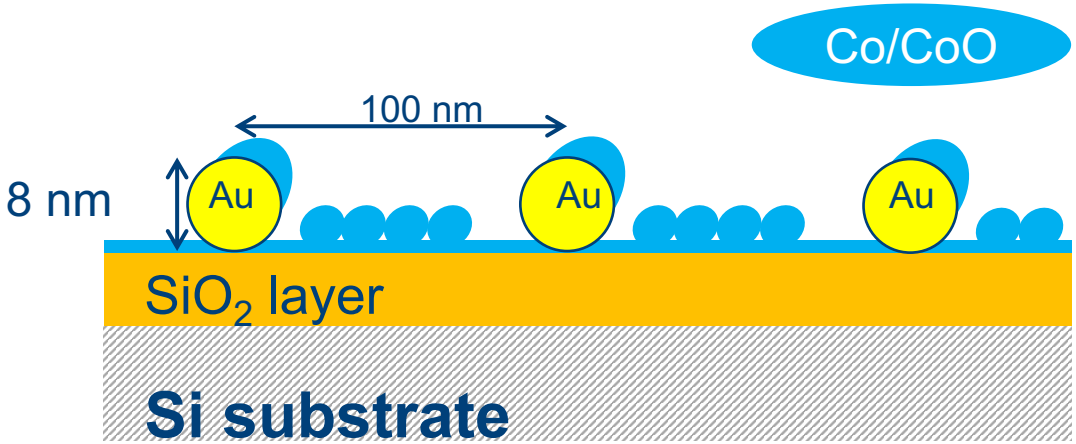
Nanotemplate patterns









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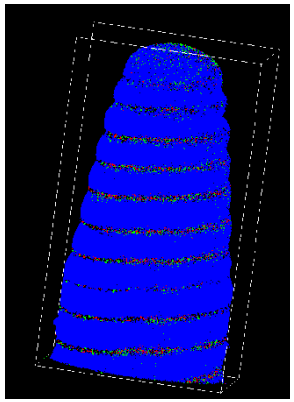
Collab. with H.-G. Boyen, UHasselt

The future: wish list

- magnetic fields with precise control
- 2-axis sample holder (azimuthal)
- combination with magnetotransport
- ability to apply electric fields
- 1K – 1000 K temperature range
- Easy switching (unpolarized/polarized, GISANS)

- measuring small samples (5 mm x 5 mm)
- ‘plug and play’ sample holders
- treatment of off-specular data

- further development of MBE/TEM (APT?)



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Collaborators

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- **Thiago Dias, Julian Geshev**
  Instituto de Física, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil
- **José Francisco Lopez-Barbera, Josep Nogués**
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  ICREA-Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain
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  NIST Center for Neutron Research, Gaithersburg, Maryland, USA

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