Application of the EBS NRS nanobeam in thin-film magnetism

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EBS-Workshop on Nuclear Resonance Scattering

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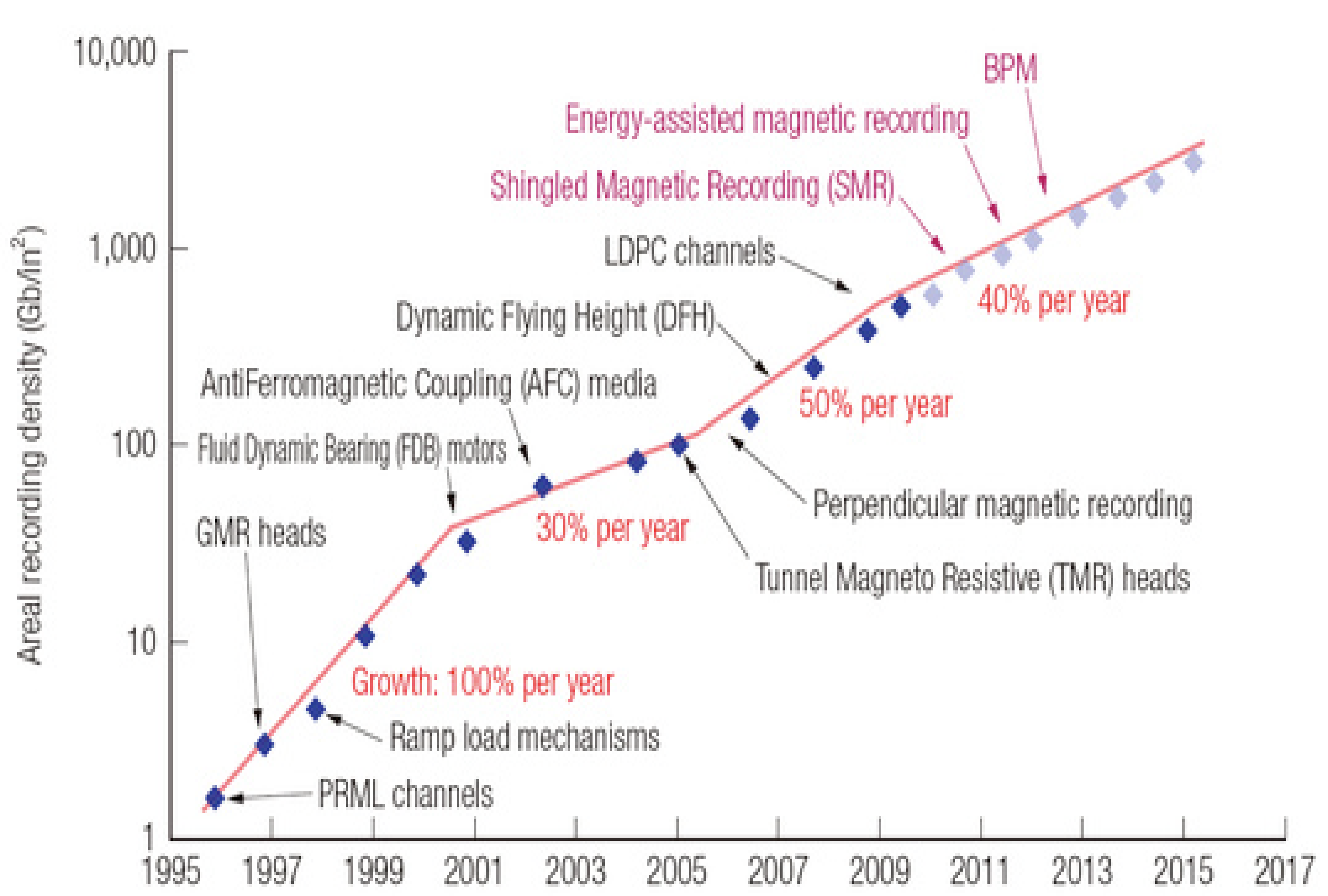
Outline

- Motivation
- Feasibility of NRS scanning magnetic microscopy with nanobeams
- Domain transformations in antiferromagnetically coupled multilayers
- Evolution of magnetism on a curved nano-surface
- Applications at grazing incidence
- Conclusions

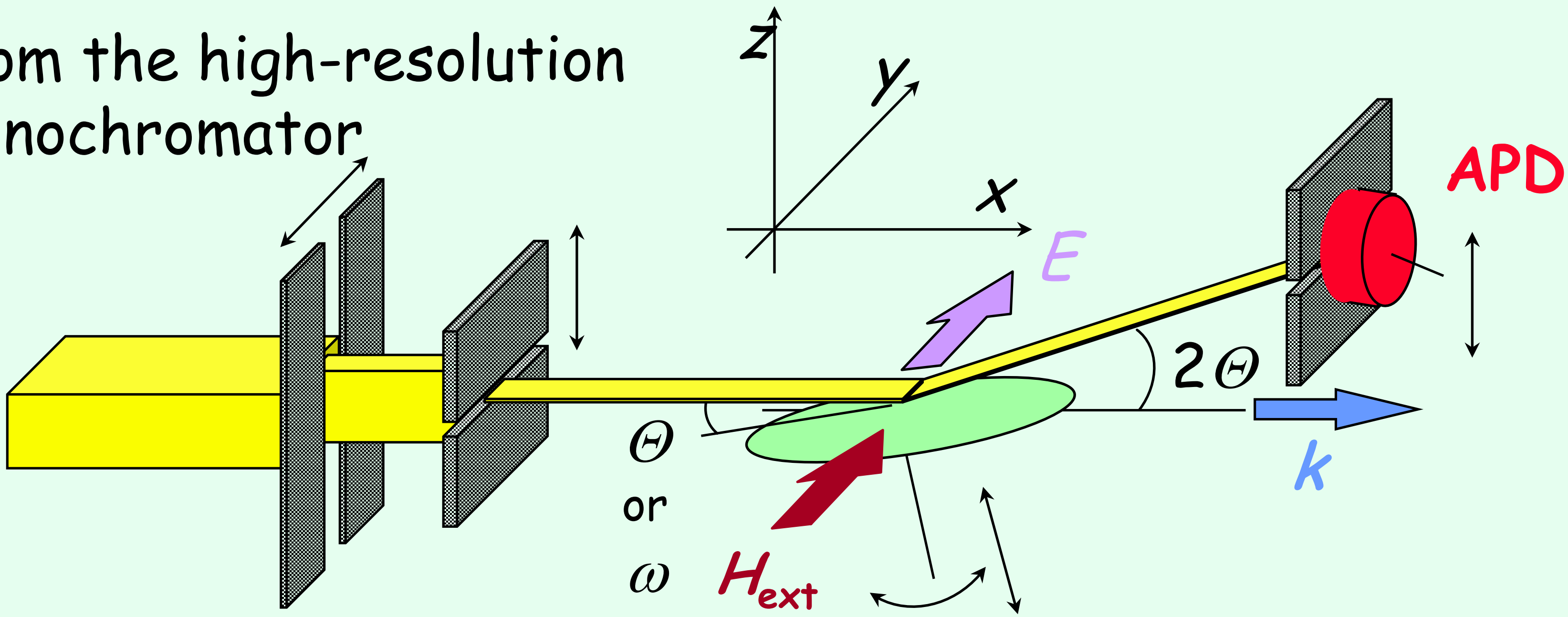
Motivation

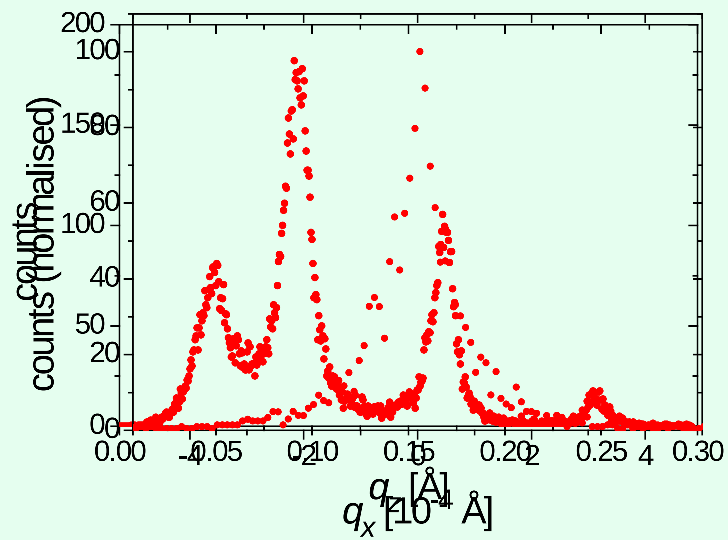


10,000
1,000
100
10
1
Areal recording density (Gb/in^2)
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
BPM
Energy-assisted magnetic recording
Shingled Magnetic Recording (SMR)
LDPC channels
40% per year
Dynamic Flying Height (DFH)
AntiFerromagnetic Coupling (AFC) media
50% per year
Fluid Dynamic Bearing (FDB) motors
Perpendicular magnetic recording
GMR heads
30% per year
Tunnel Magneto Resistive (TMR) heads
Growth: 100% per year
Ramp load mechanisms
PRML channels

Arrangement of an SMR experiment

from the high-resolution monochromator





$\Theta/2\Theta$-scan: q_z-scan

ω-scan: q_x-scan

$d = 2\pi/q_z$

$\xi = 1/\Delta q_x$

Motivation

- Off-specular SMR yields information in the reciprocal (momentum) space only so that no individual objects in the direct space can be identified.
- In case of ^{57}Fe SMR, the method is practically limited to the correlation length range of about 200 nm to 2 µm.
- Is there a chance to see thin-film magnetic phenomena in this range in the direct space using the EBS NRS nanobeam?

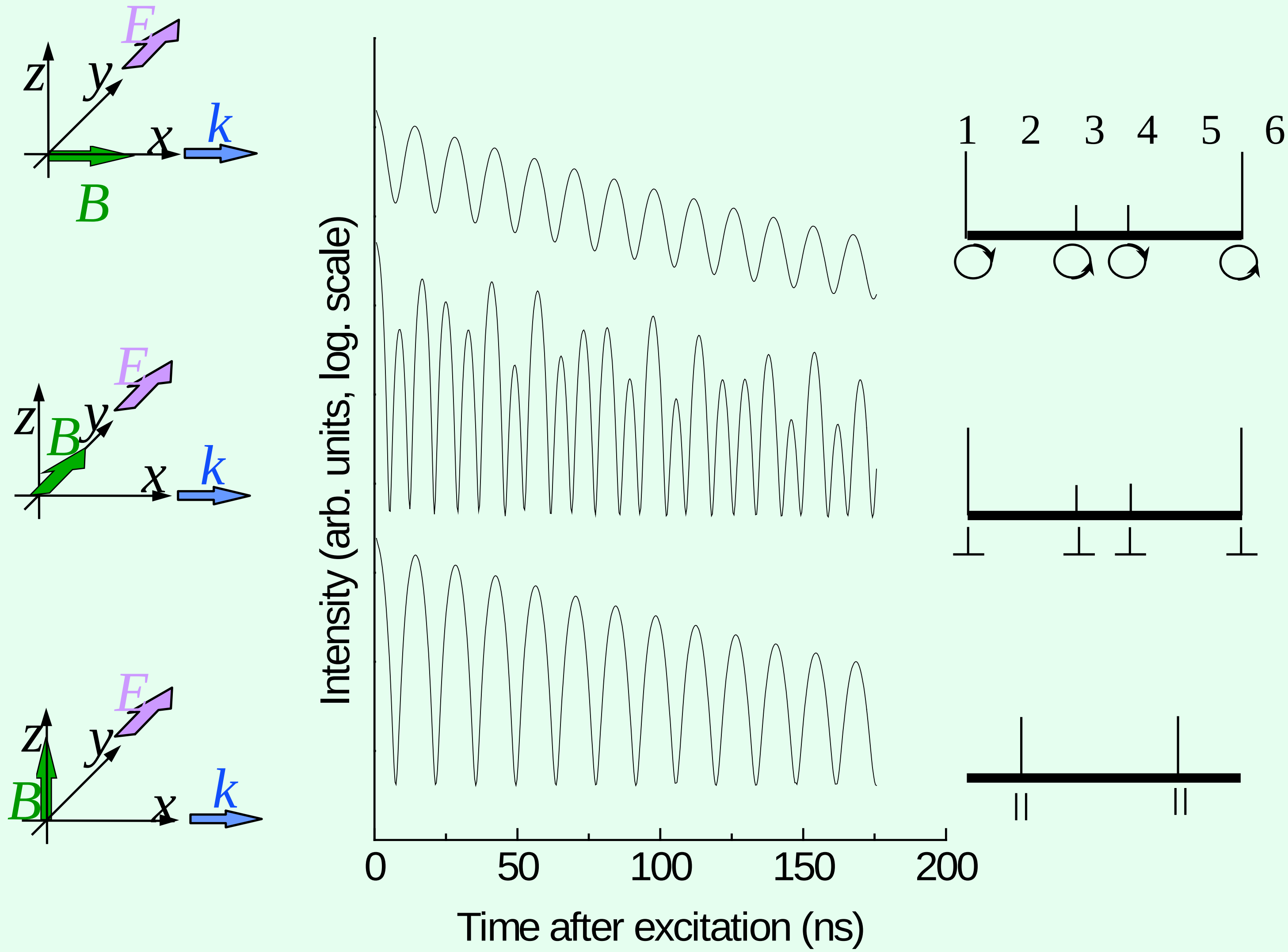
Feasibility of the approach

- Forward scattering in thin films: is it possible at all?
- Electronic absorption: for low-Z substrates may be low enough.

Substrate material	Transmission of 500 μm thickness for 14.41 keV
SiO_2 (quartz)	0.4093
MgO	0.3873
α-Al_2O_3 (sapphire)	0.3097
Si	0.2469
$BaTiO_3$	2.8×10^{-7}

- Effective thickness for ^{57}Fe: $\lambda = 46\, t\,[\mathrm{nm}]\, f$

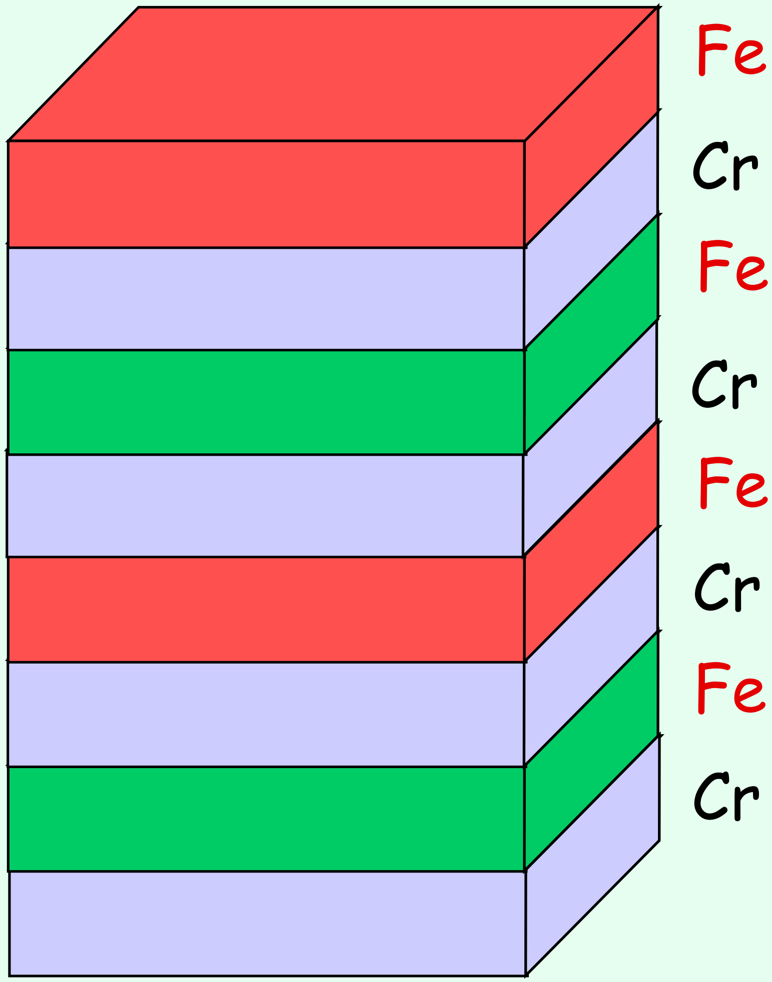
Feasibility: contrast of the hyperfine field direction (Smirnov figures)



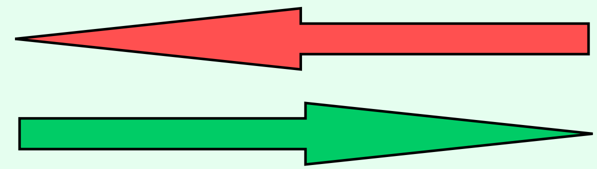
Feasibility: contrast of the hf field direction

- Hyperfine field in the *y*-*z* plane: contrast between B$\|y$ and B$\|z$ in linearly polarized light.
- Hyperfine field along the *x* axis: contrast between B$\uparrow\uparrow x$ and B$\uparrow\downarrow x$ in circularly polarized light.

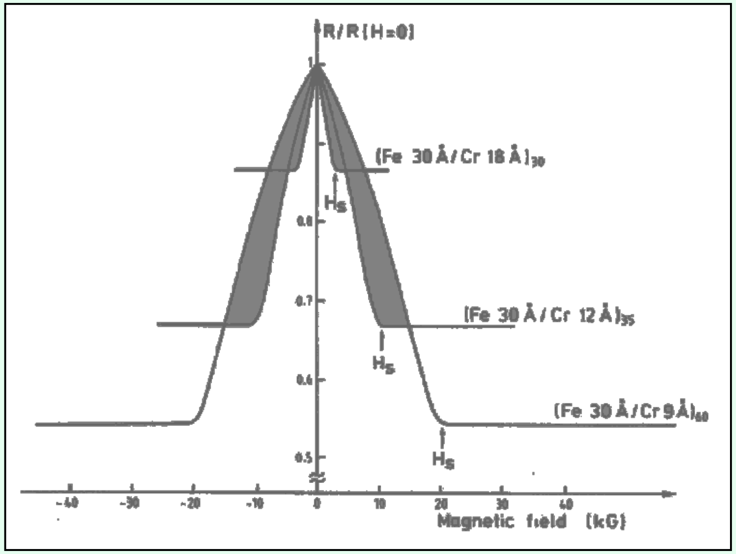
Antiferromagnetically coupled Fe/Cr multilayer



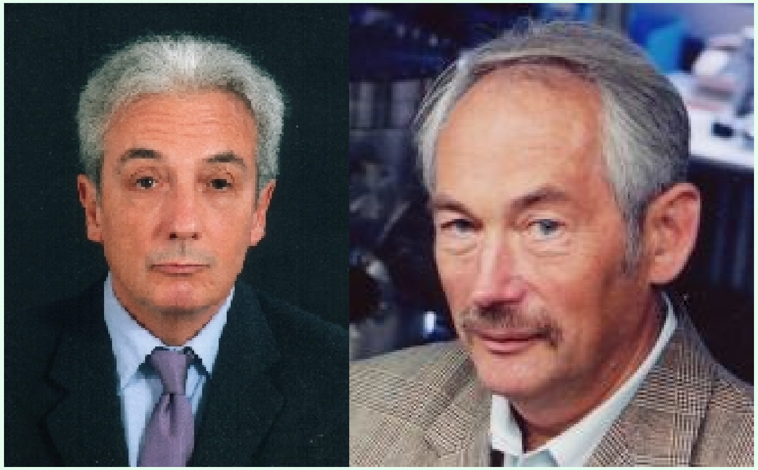
Layer magnetisations:



Giant magnetoresistance

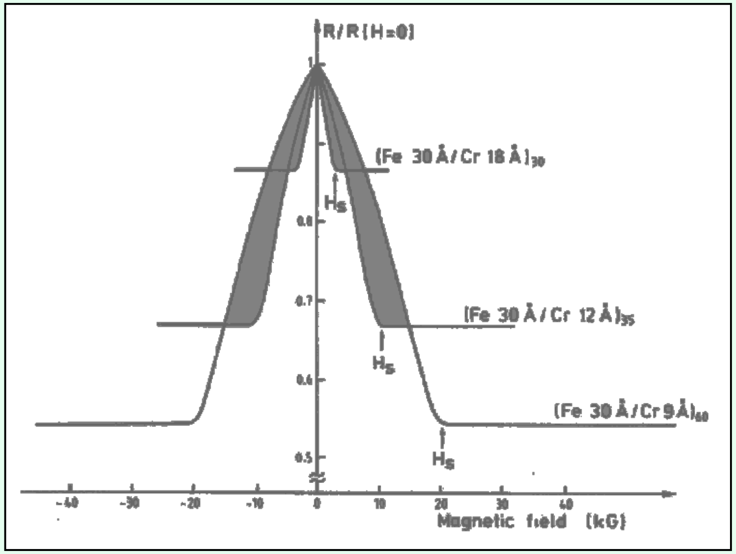


Antiferromagnetically coupled Fe/Cr multilayer

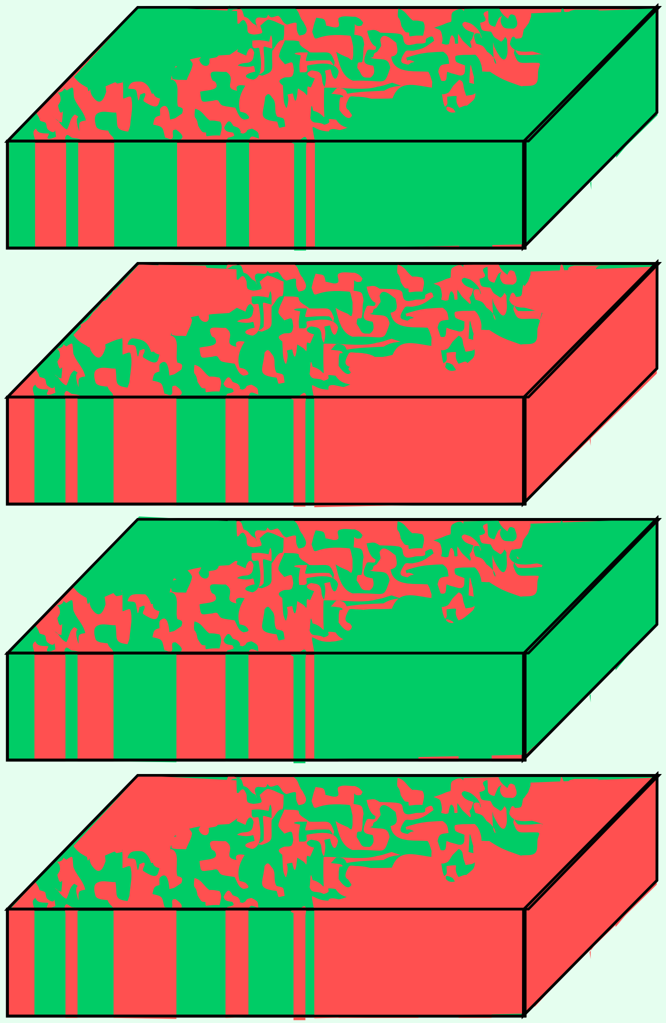


A. Fert and P. Grünberg
Nobel Prize in physics, 2007

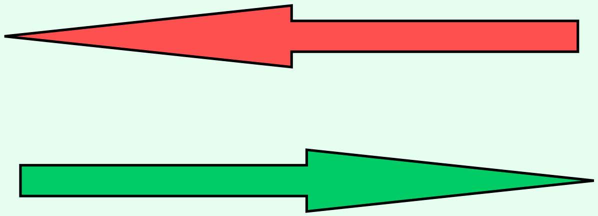
Giant magnetoresistance



Patch domains in AF-coupled multilayers

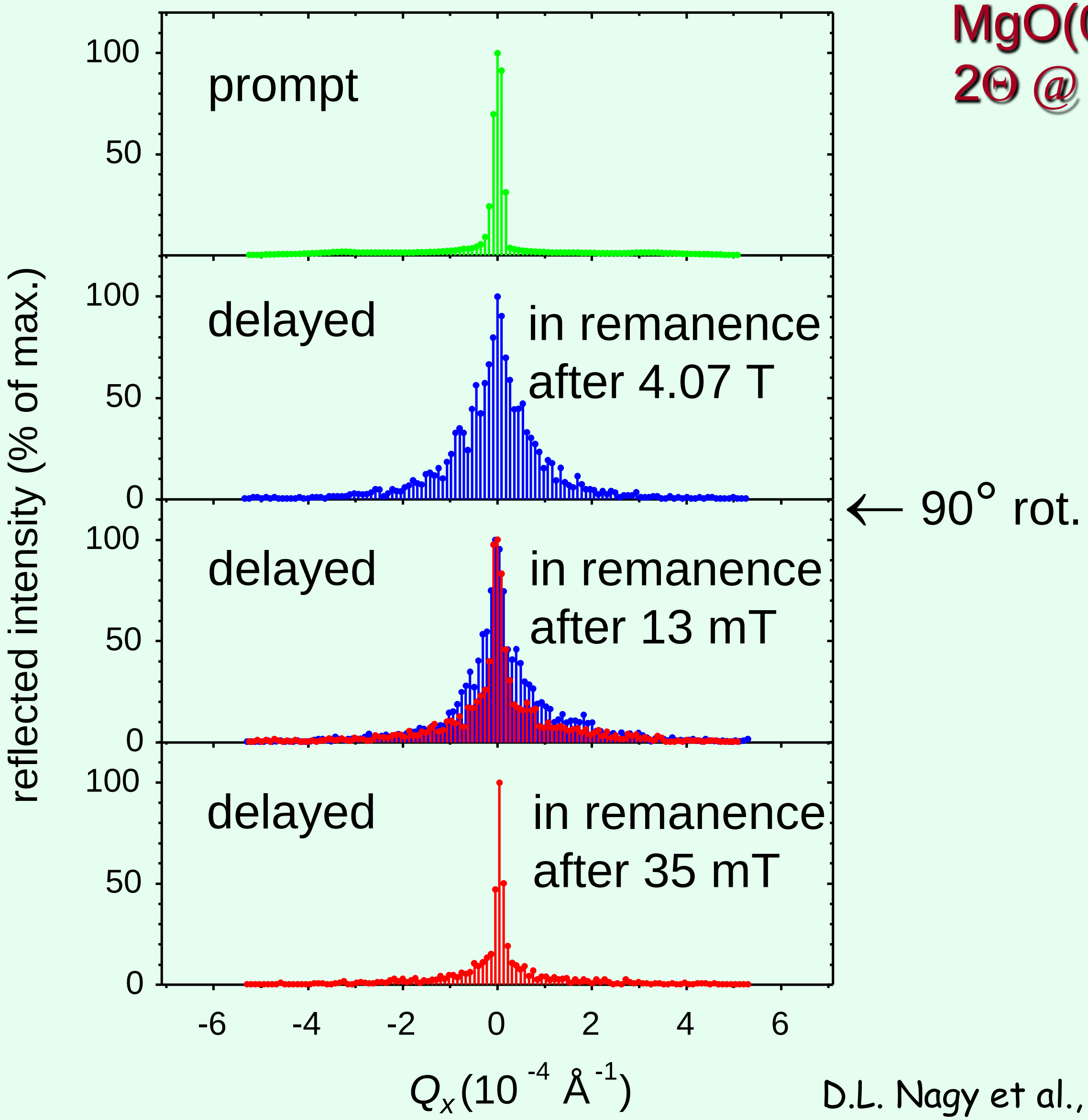


Layer magnetisations:



The 'magnetic field lines' are shortcut by the AF structure → the stray field is reduced → no 'ripple' but 'patch' domains are formed.

Spin-flop-induced domain coarsening (SMR)



$MgO(001)[^{57}Fe(26Å)/Cr(13Å)]_{20}$

2Θ @ AF reflection, easy axis

Correlation length:

$\xi = 1/\Delta Q_x$

Delayed photons before the spin flop

$\xi = 1000$ nm

Delayed photons after the spin flop

$\xi_1 > 5000$ nm

$\xi_2 = 1000$ nm

D.L. Nagy et al., PRL **88**, 157202 (2002).

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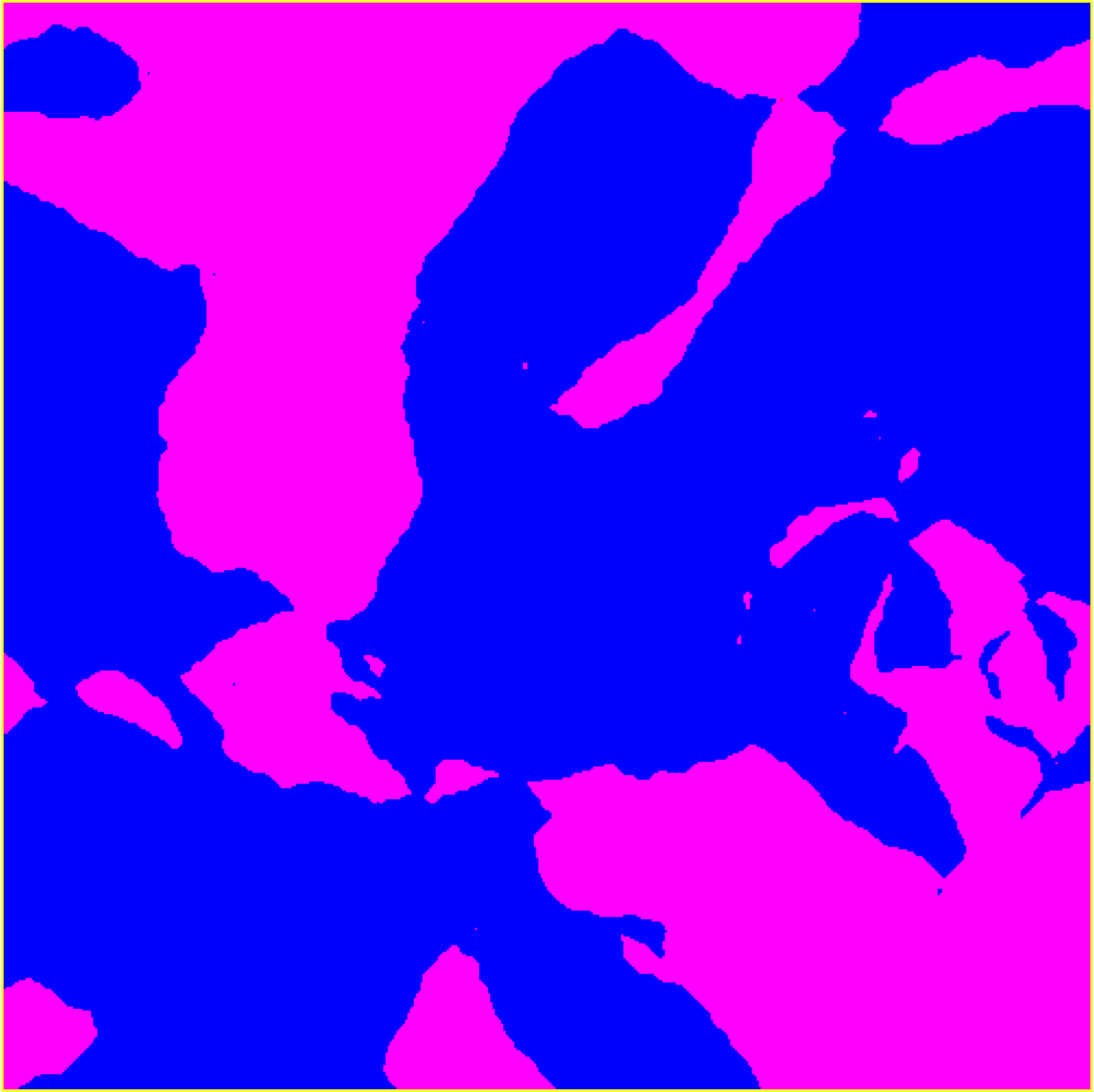
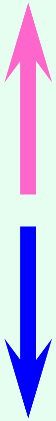
Domain coarsening during spin flop





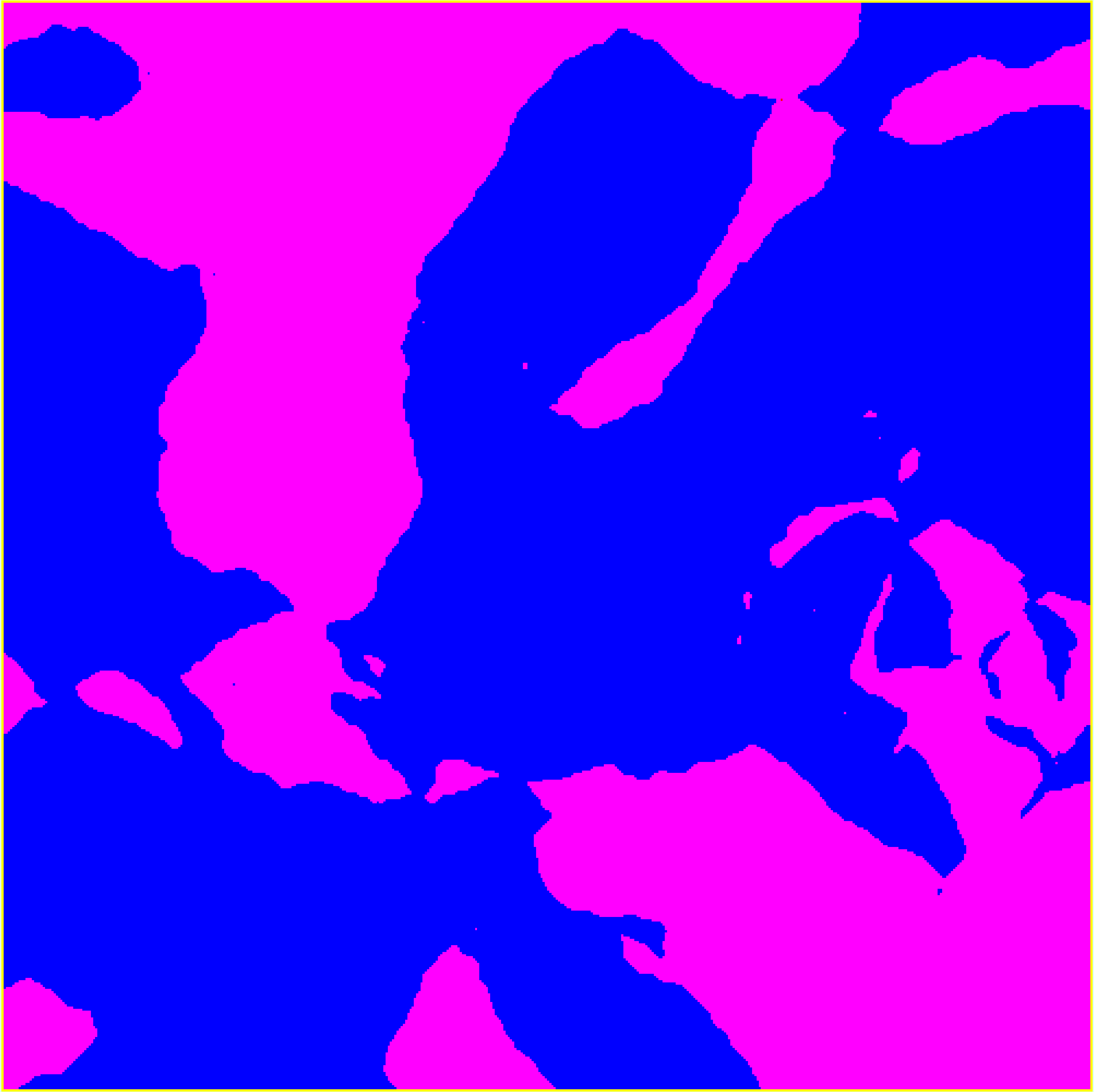
What can we see from domain coarsening?

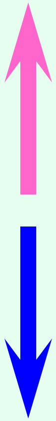
- No contrast between ← and →
  The initial picture is homogeneous. ☹
- No contrast between ↑ and ↓
  The final picture is homogeneous. ☹
- The intermediate pictures show the step-by-step progress of the spin flop and the creation of the large domains. ☺
- Can we still have a contrast between domains of the same alignment but opposite direction of the layer magnetization?

What can we see from domain coarsening?

- To have a contrast between hyperfine fields of opposite direction, photons of circular polarization are needed → insert a $\lambda/4$ phase-retarder plate!
- AF-coupled domains still have both directions of the hyperfine field → the sample should be prepared by marking every second layer with the resonant isotope ^{57}Fe.
- To have a **k**-parallel (i.e. *x*-parallel) component of layer magnetization, the sample should be tilted (e.g. by 45°) around the *z*-axis.

Domain coarsening during spin flop



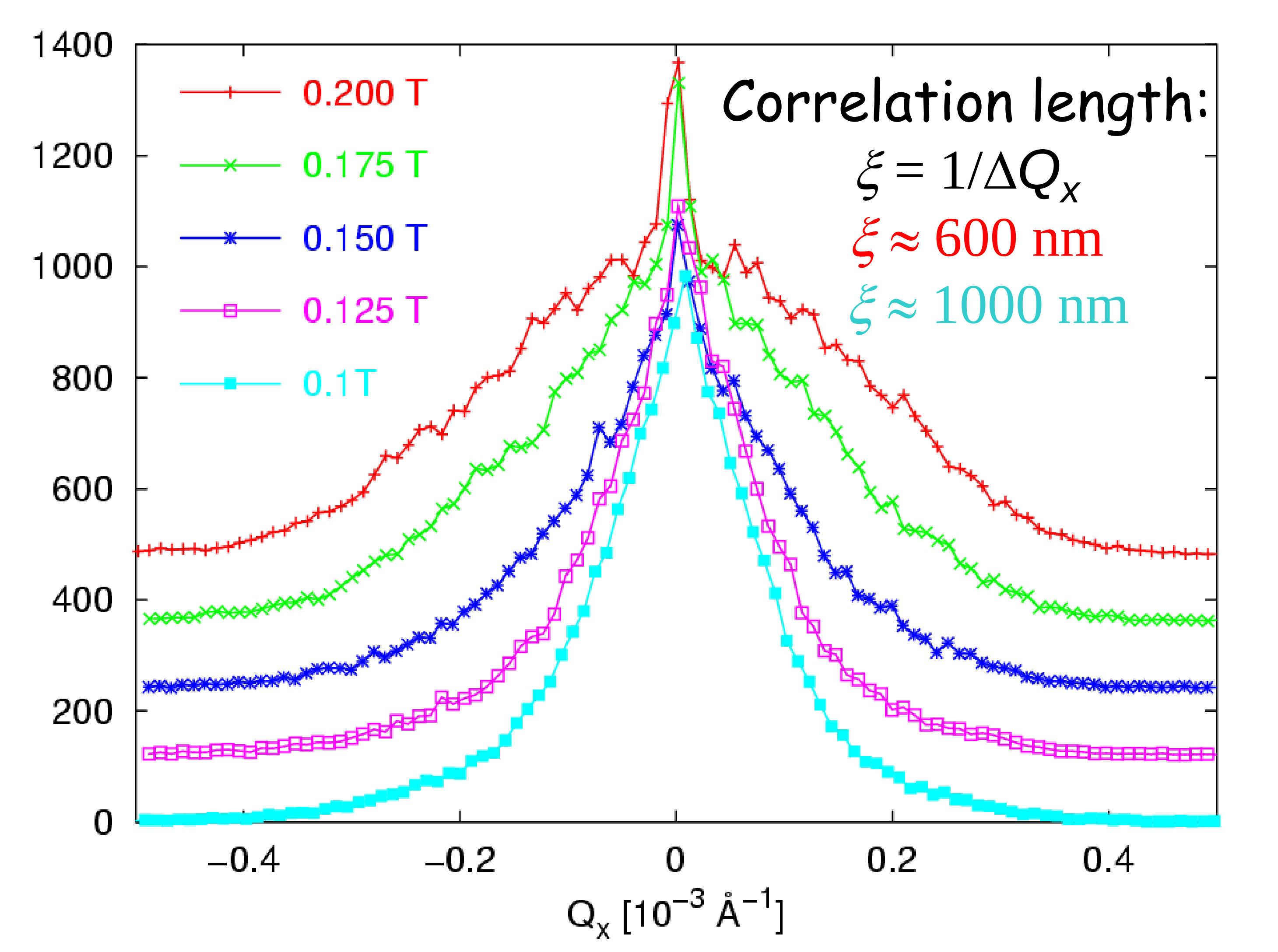


From saturation to remanence: the domain ripening

- In decreasing field the domain-wall angle and, therefore, the domain-wall energy as well as its surface density is increasing.
- In order to decrease the surface density of the domain-wall energy, the multilayer spontaneously increases the average size of the patch domains ('ripening').
- The spontaneous domain growth is limited by domain-wall pinning (coercivity).

Domain ripening: off-specular SMR

$MgO(001)[^{57}Fe(26Å)/Cr(13Å)]_{20}$
2Θ @ AF reflection, hard axis



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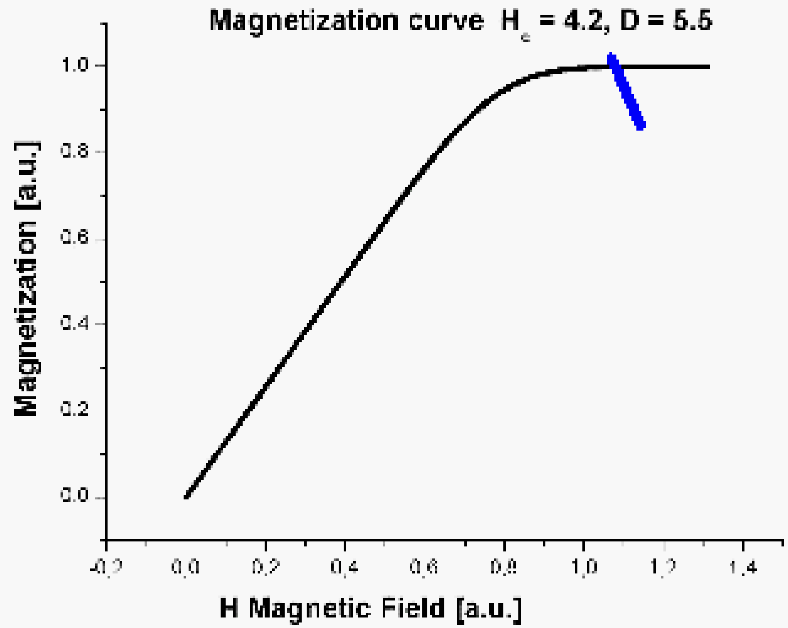
Domain formation and ripening



Domain pattern

Autocorrelation

Domain ripening at $H_c = 4.2$, $D = 5.5$

What can we see from domain ripening?

- To have a contrast between hyperfine fields of opposite direction, photons of circular polarization are needed $\rightarrow$ insert a $\lambda/4$ phase-retarder plate!
- AF-coupled domains still have both directions of the hyperfine field $\rightarrow$ the sample should be prepared by marking every second layer with the resonant isotope ^{57}Fe.
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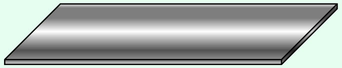
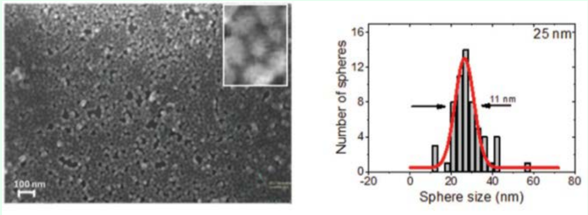
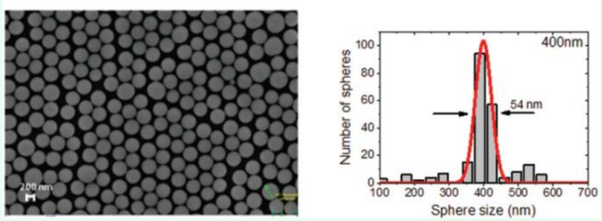
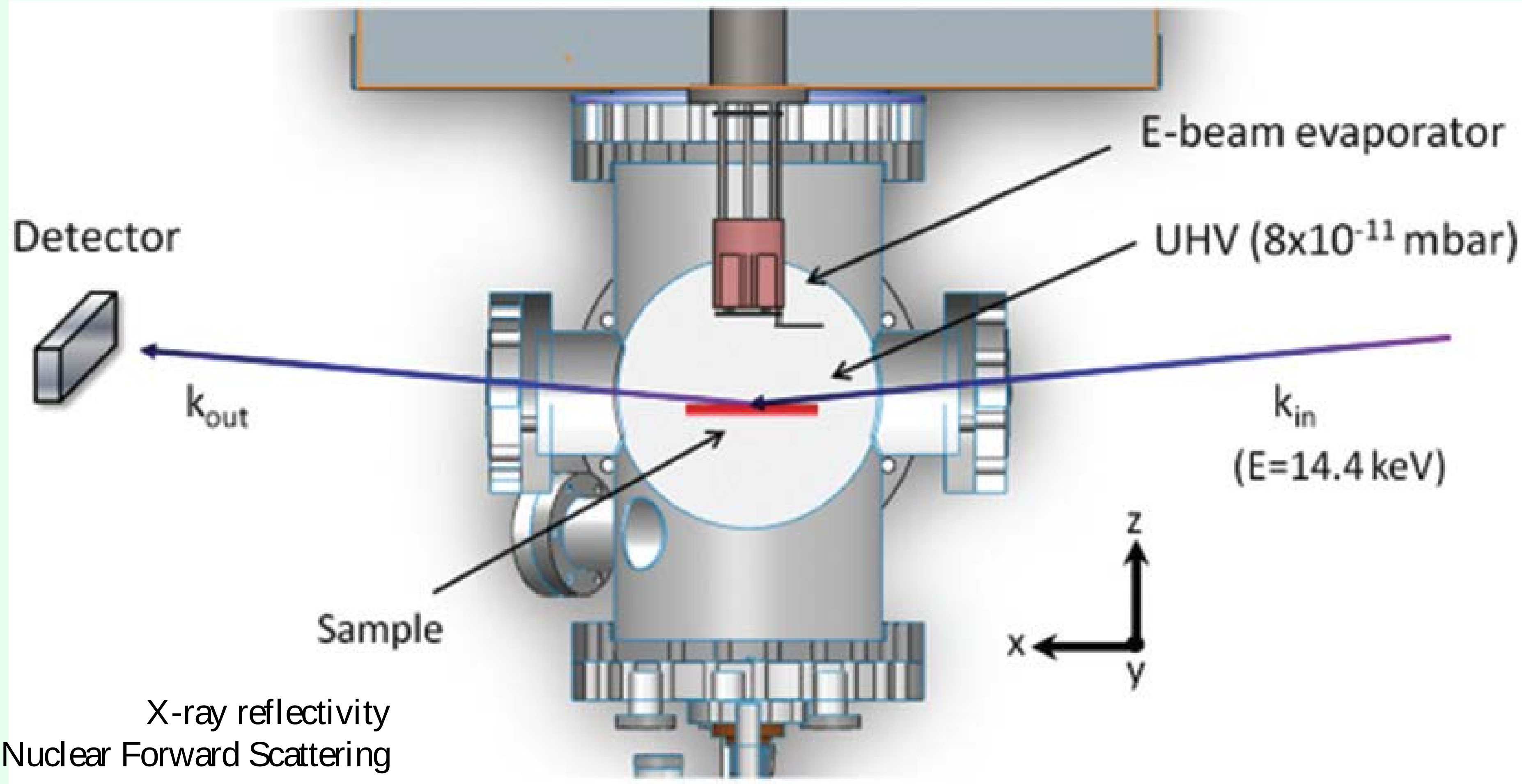
Evolution of magnetism on a curved nanosurface

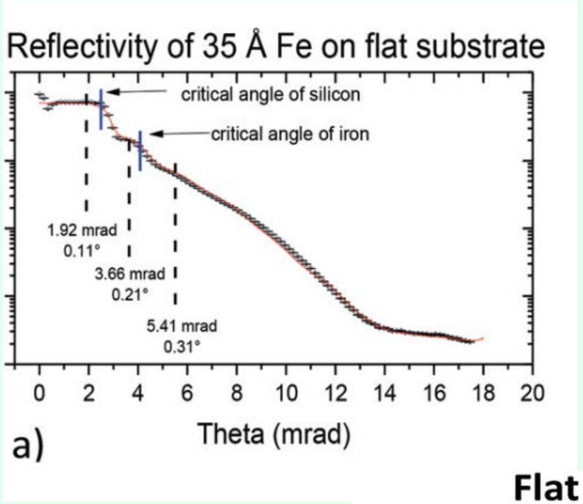


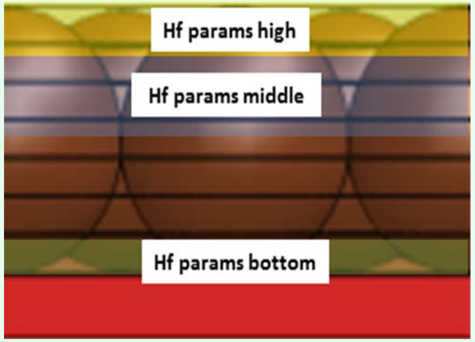


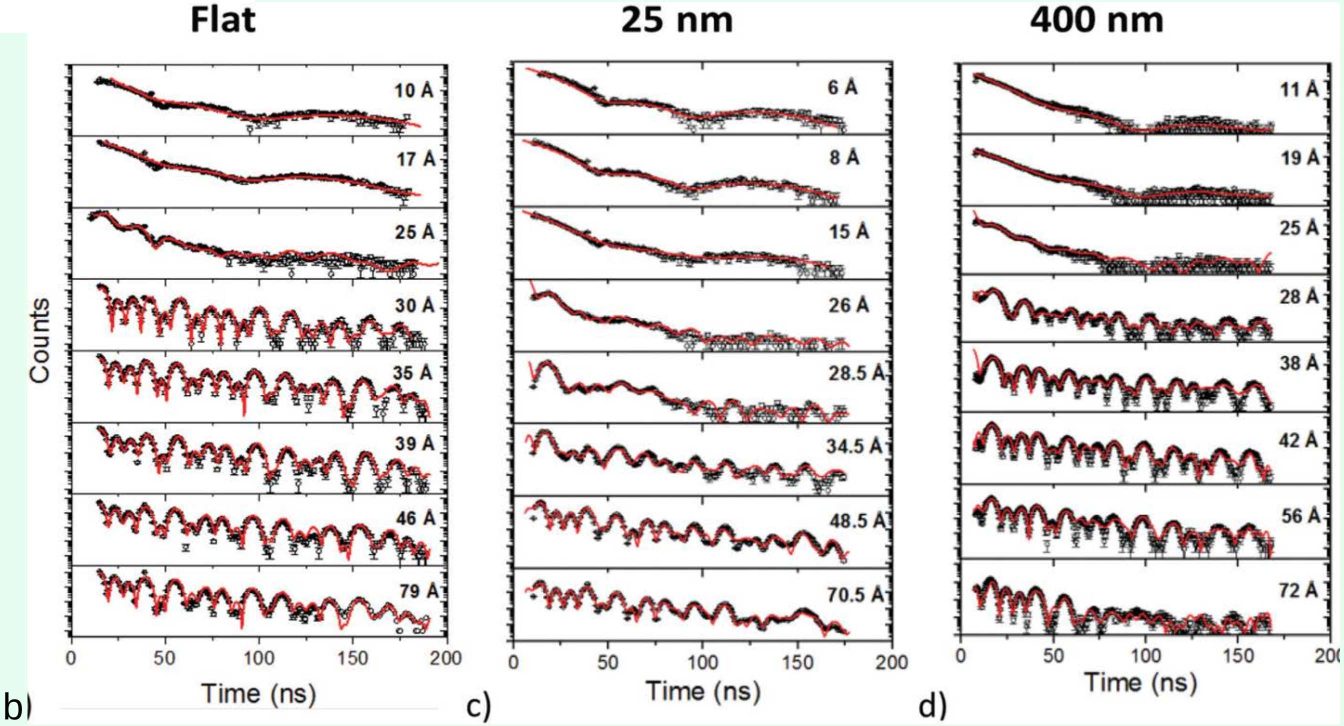




Evolution of magnetism on a curved nanosurface







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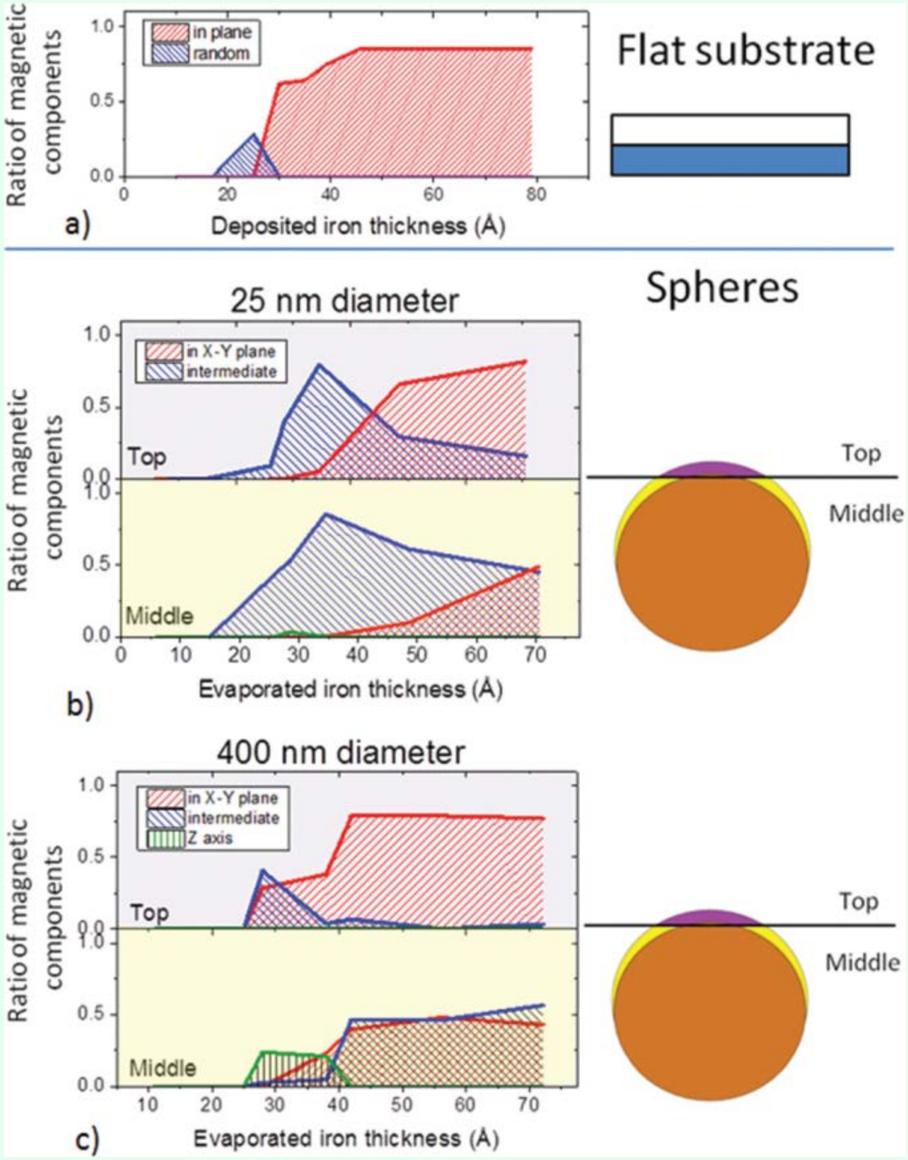
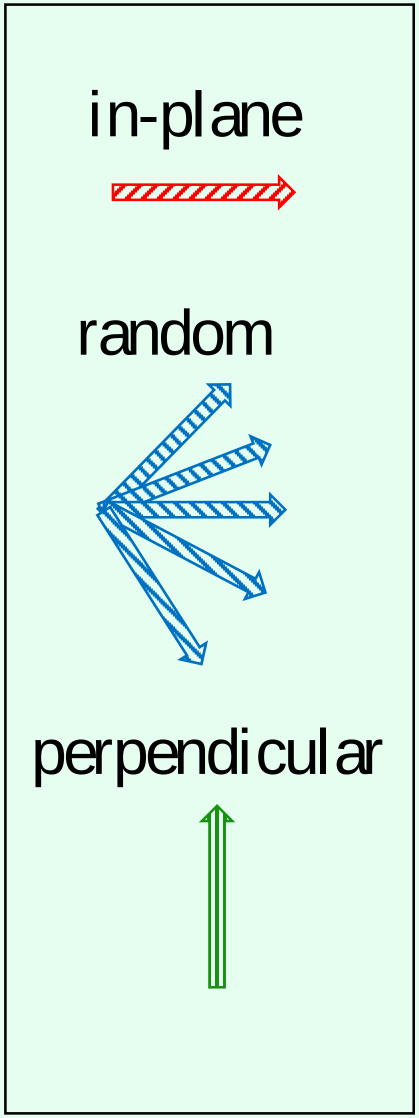
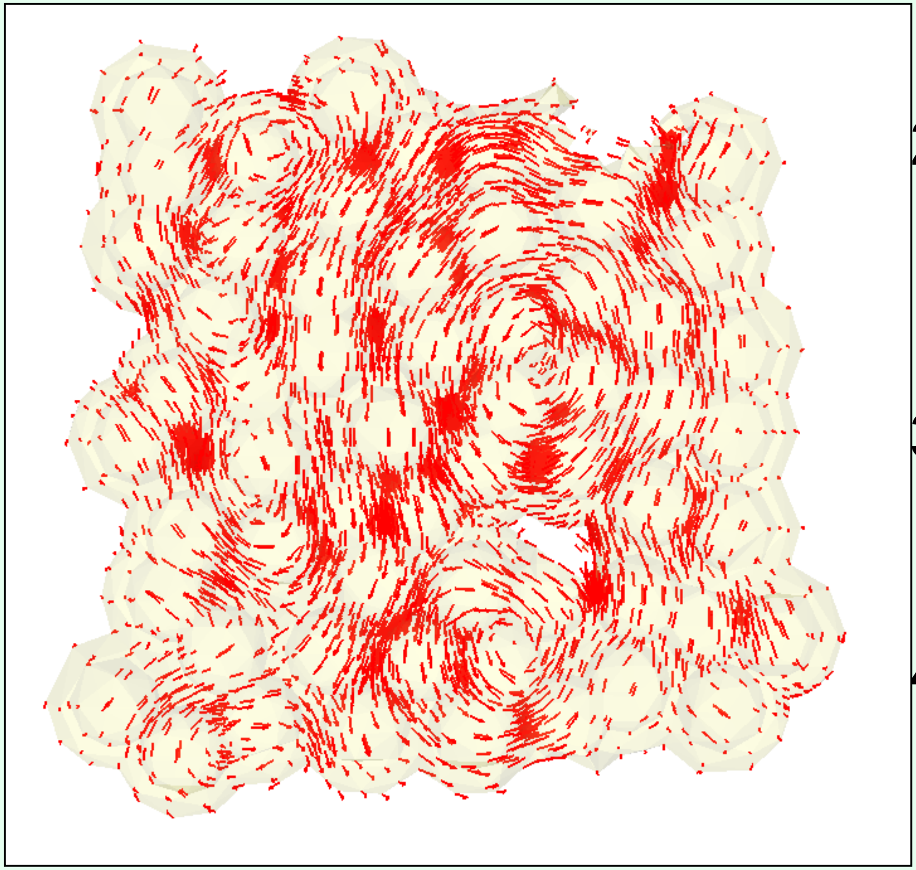
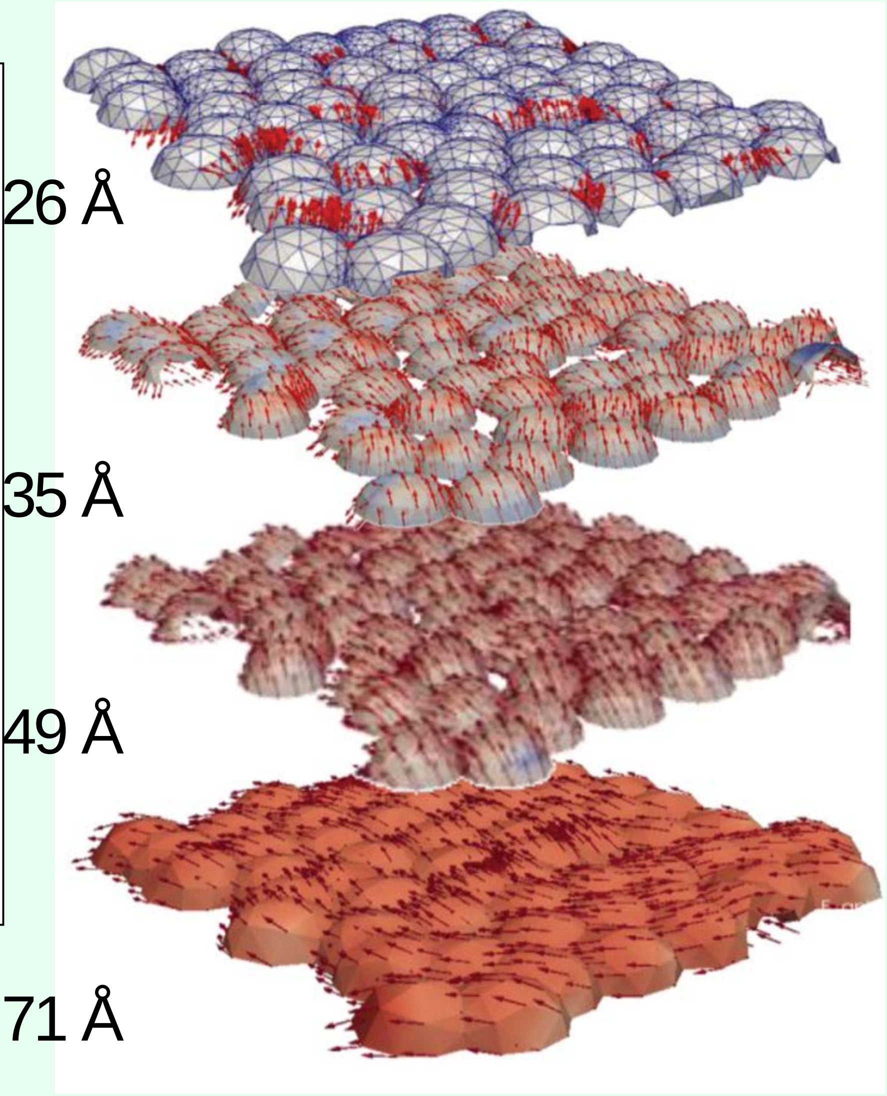




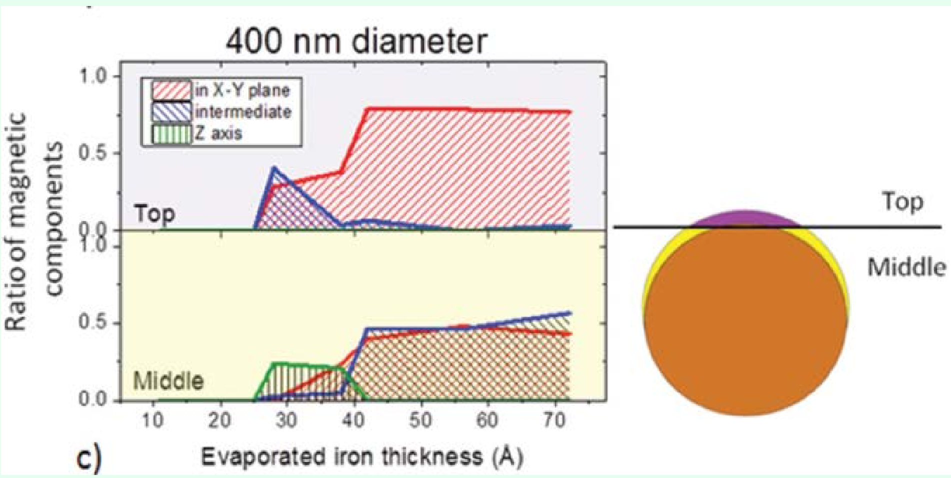
Evolution of magnetism on a curved nanosurface



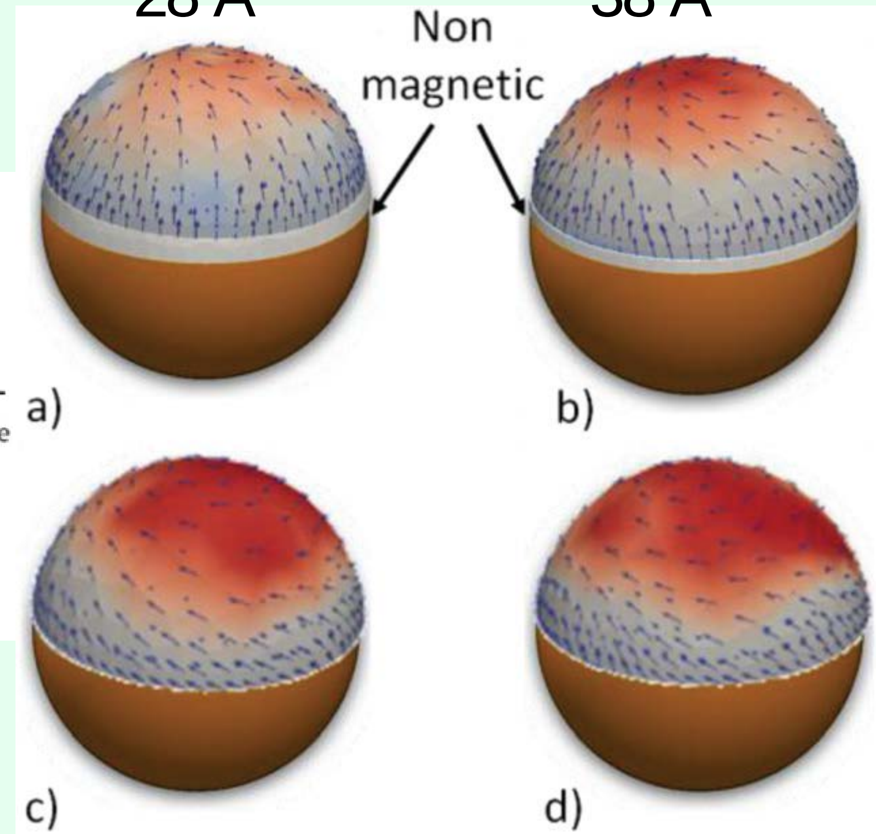
Micromagnetic simulation



Evolution of magnetism on a curved nanosurface



28 Å 38 Å



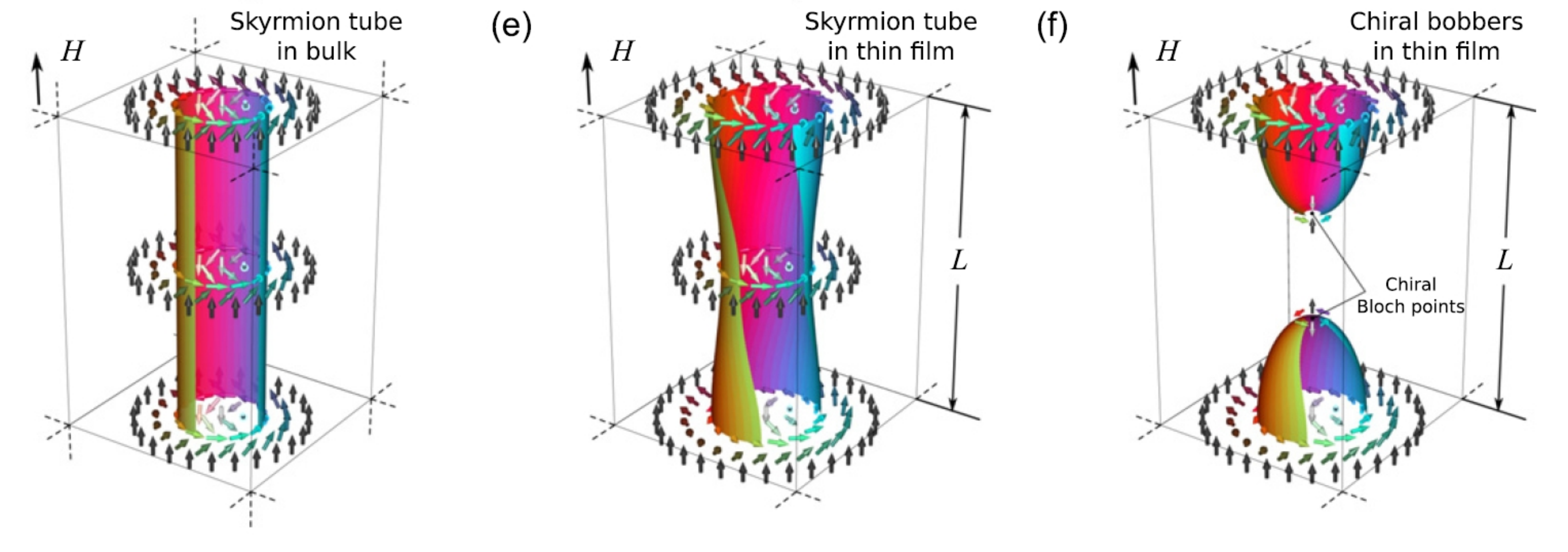
42 Å 72 Å

Si substrate/nanosphere: OK

5–50 nm ^{57}Fe: may be OK

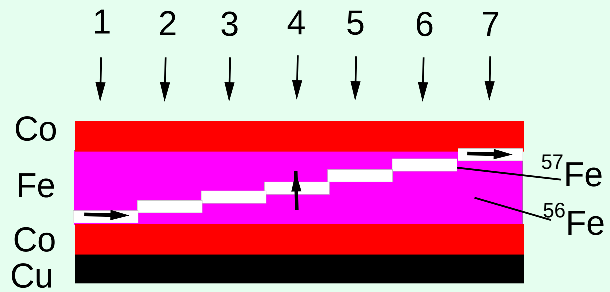
D. Merkel et al., Nanoscale, **7**, 12878 (2015).

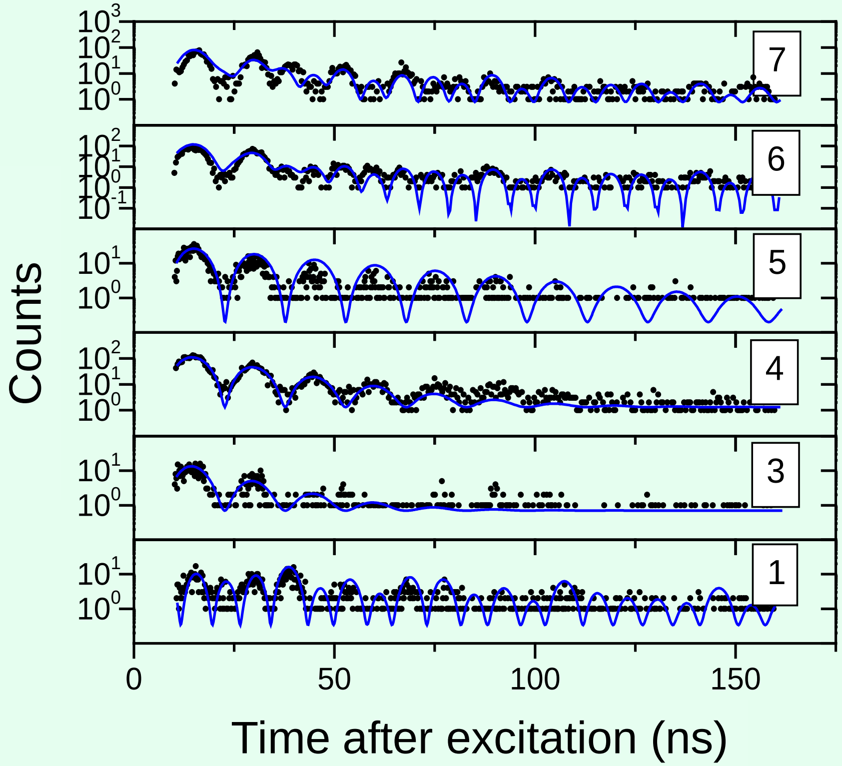
Skyrmions in thin films?



F.N. Rybakov et al, New J. Phys. **18,** 045002 (2016).

Improved lateral resolution using the non-focussed 50 μm beam at grazing incidence





Monolayer resolution can be achieved by using the resonant isotope marker technique.

In a Co/Fe(7ML)/Co trilayer, the magnetisation of the Fe layers at the Co/Fe interface is parallel while that of the internal Fe layers is perpendicular to the plane.

C. Carbone et al, ESRF Highlights **1999**, 60 (1999).

Acknowledgements…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Thank you for your attention!