Off-specular synchrotron Mössbauer and polarised neutron reflectometry in studying domain structure of antiferromagnetic multilayers

D.L. Nagy[1], L. Bottyán[1], B. Croonenborghs[2], L. Deák[1], B. Degroote[2], J. Dekoster[2], H.J. Lauter[3], V. Lauter-Pasyuk[4, 5], O. Leupold[6], M. Major[1,2], J. Meersschaut[2], O. Nikonov[3,4], A. Petrenko[4], R. Rüffer[6], J. Swerts[7], E. Szilágyi[1], K. Temst[7], A. Vantomme[2]

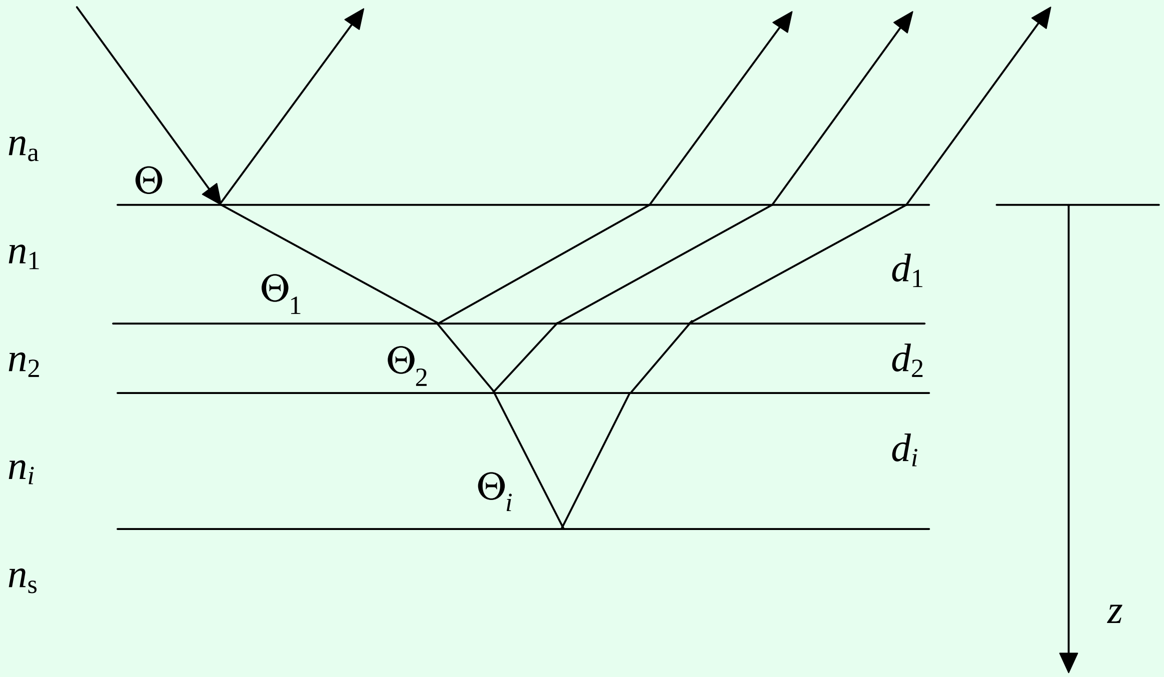
[1] *KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary*
[2] *K.U. Leuven, Instituut voor Kern- en Stralingsfysica, Leuven, Belgium*
[3] *Institut Laue–Langevin, Grenoble, France*
[4] *Joint Institute for Nuclear Research, Dubna, Russia*
[5] *Technische Universität München, Garching, Germany*
[6] *European Synchrotron Radiation Facility, Grenoble, France*
[7] *K.U. Leuven, Laboratorium voor Vaste-Stoffysica en Magnetisme, Leuven, Belgium*

Magnetic Multilayers as Seen by Photons and Neutrons
KFKI CMRC Workshop, Budapest, 6-9 December, 2001

Outline

- Synchrotron Mössbauer reflectometry, polarised neutron reflectometry; specular and off-specular (diffuse) scattering
- Field-history dependence of the domain size in antiferromagnetically coupled multilayers
- Domain formation and ripening
- The bulk-spin-flop transition in coupled multilayers
- Spin-flop-induced domain coarsening
- Conclusions

Neutron, X-ray and Mössbauer reflectometry



Relation between scattering amplitude and index of refraction:

$$n = 1 + \frac{2\pi\ N}{k^2} f$$

Neutron reflectometry: the scattering amplitudes

$$f_n = f_n^{nuc} + f_n^{mag}$$

isotope-specific scattering length

$$f_n^{mag} = \pm b$$

+ for neutron spin parallel to magnetisation

– for neutron spin antiparallel to magnetisation

for neutron spin perpendicular to magnetisation:
spin-flip scattering!

X-ray and Mössbauer reflectometry: the scattering amplitudes

$$f_{\mathrm{ph}}(E) = f_{\mathrm{ph}}^{\mathrm{el}} + f_{\mathrm{ph}}^{\mathrm{nuc}}(E)$$

$$f_{\mathrm{ph}}^{\mathrm{el}} = Zr_0 + i\delta$$

$\propto$ electron density

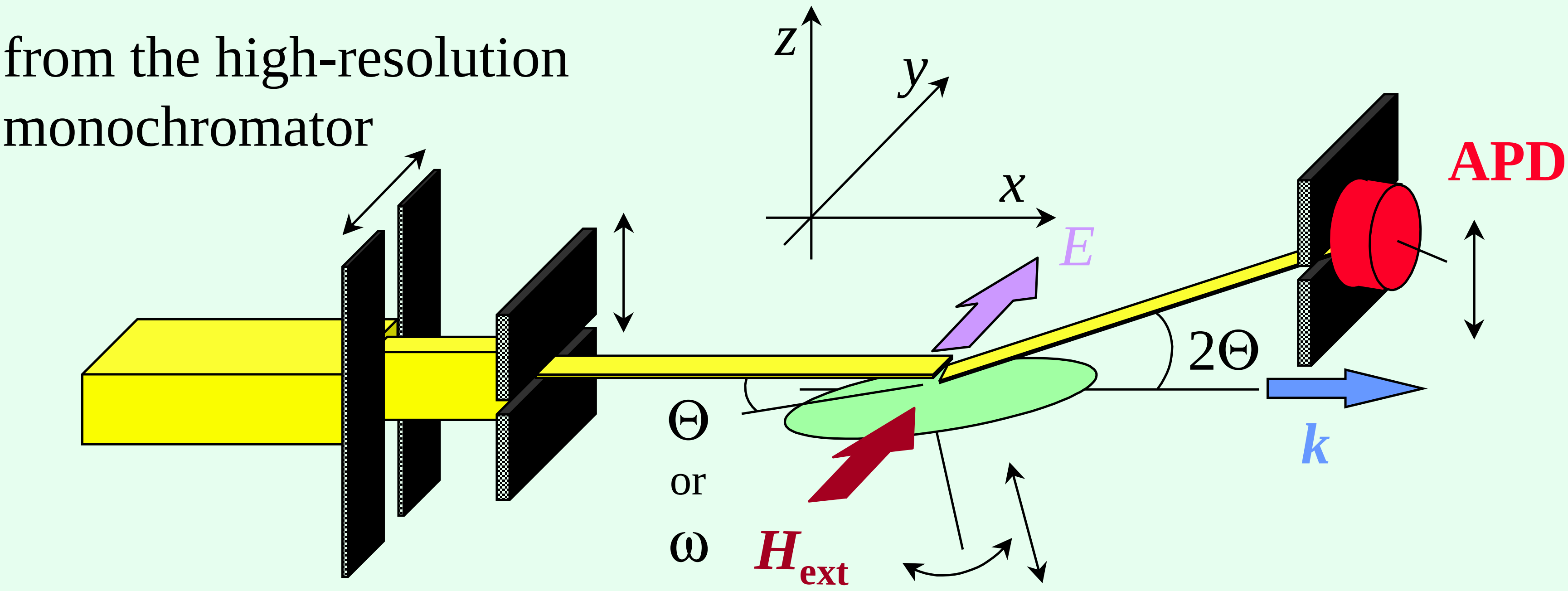
photoabsorption

hyperfine matrix elements

$$f_{\mathrm{ph}}^{\mathrm{nuc}}(E) = \frac{kV}{hc} f_{\mathrm{LM}} \frac{1}{2I_{\mathrm{g}}+1} \sum_{\alpha,\beta} \frac{|a_{\alpha\beta}|}{E - (E_\alpha - E_\beta) + i\frac{\Gamma}{2}}$$

hyperfine energies

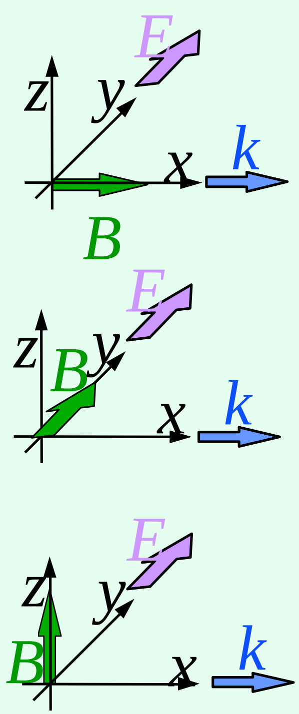
Arrangement of an SMR experiment

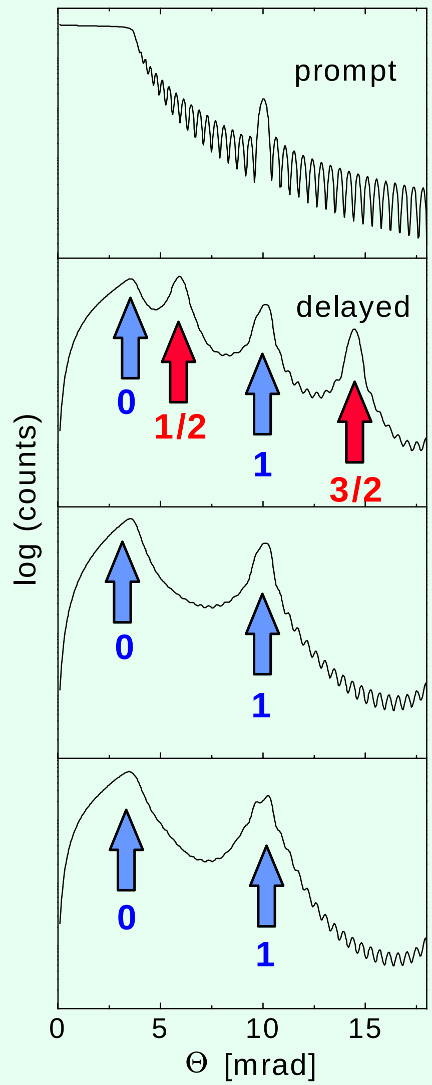


Θ/2Θ-scan: q_z-scan

ω-scan: q_x-scan

Antiferromagnetic reflections in SMR and the direction of the layer magnetisation (Θ/2Θ-scan)





Domains in a Fe/Cr/Fe trilayer

M. Rührig et al., Phys. Stat. Sol. (a) **125,** 635 (1991).

M. Rührig, Theses, 1993.

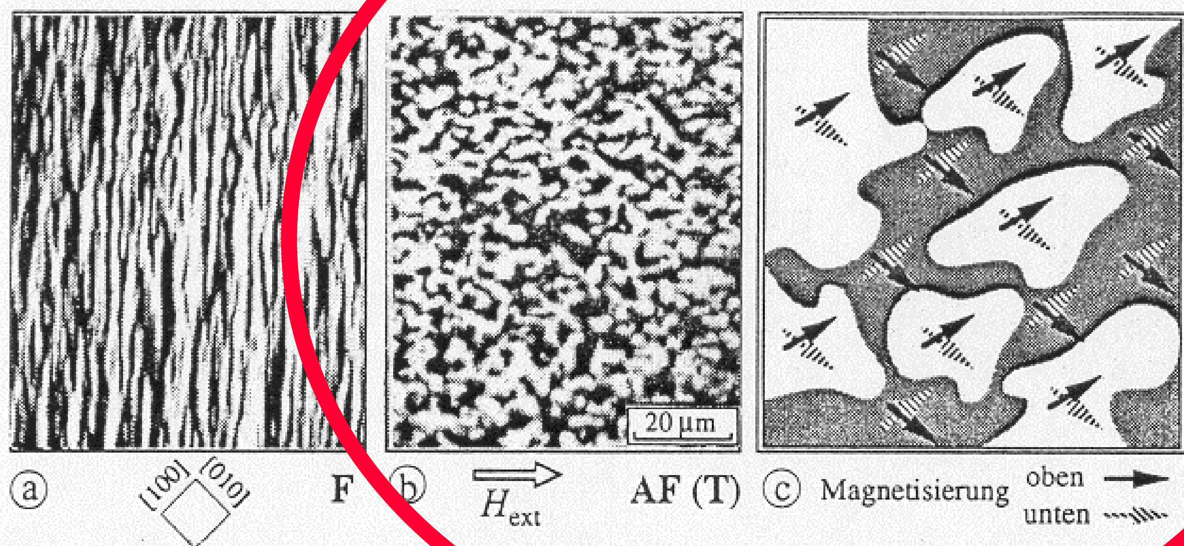
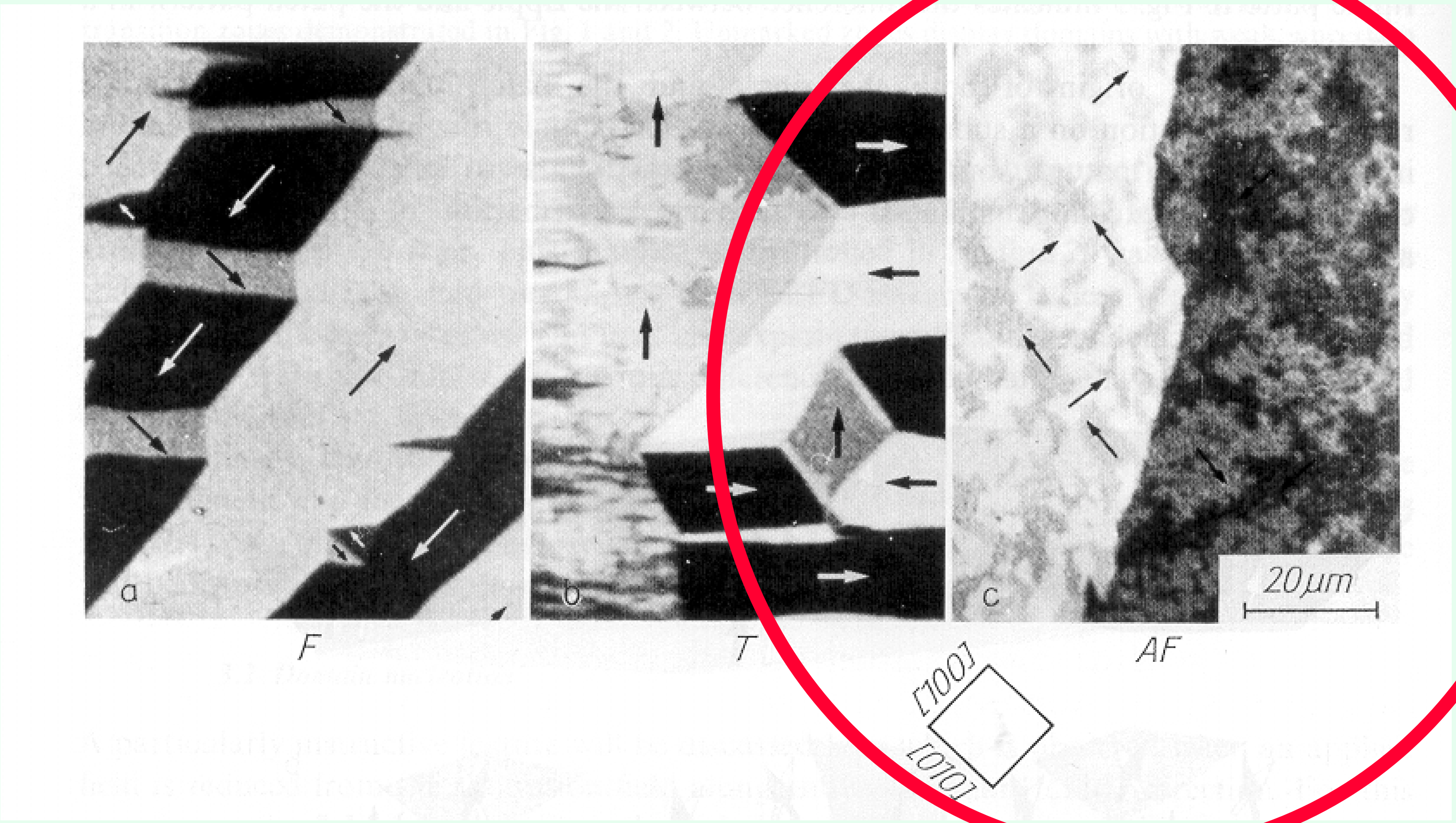


Abb. 3.5 Domänenkeimbildung in ferromagnetisch- und antiferromagnetisch gekoppelten Zonen der einkristallinen Keilprobe aus der Sättigung in schwerer Richtung kommend. Für *F*-gekoppelte Bereiche findet man wie in Einfachschichten eine ausgeprägte *Ripplebildung*, die in Remanenz zu einem stark anisotropen Domänenmuster führt (ⓐ). Im *AF*-Gebiet dagegen beobachtet man ein isotropes fleckenartiges Keimbildungsmuster (ⓑ), da dort die bevorzugte Antiparallelstellung der Magnetisierung der beiden Schichten eine Kompensation der transversalen Komponente der Magnetisierung bewirkt (ⓒ). Das Fleckenmuster wird auch in den Übergangszonen gefunden (s. unten). (ⓐ und ⓑ aus [3.9])

Domain growth in low field: Kerr microscopy

M. Rührig et al., Phys. Stat. Sol. (a) **125,** 635 (1991).



Domain growth on field reversal: magnetoresistance noise in a Co/Cu multilayer

H.T. Hardner et al., Appl. Phys. Lett **67,** 1938 (1995).

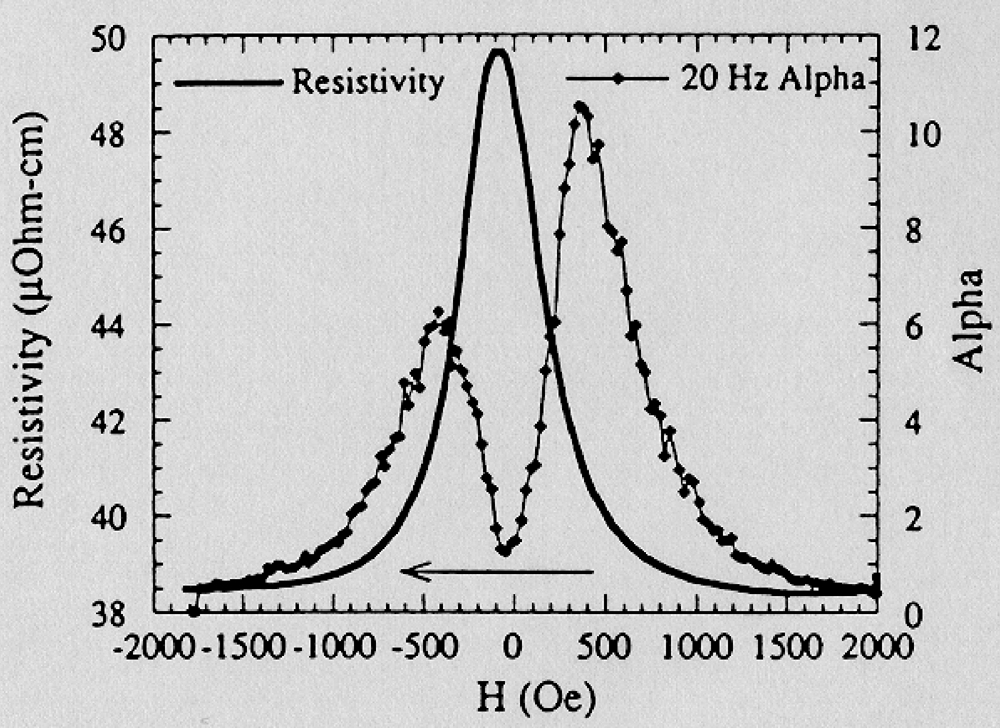
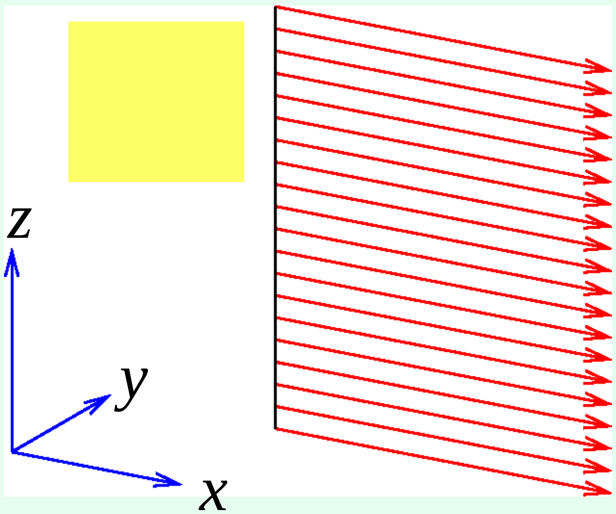


FIG. 1. The dimensionless noise parameter α(20 Hz) and resistivity as a function of field for sample 2 (Co/Cu 10 Å/21 Å×39 layers).

Domain growth: what is the mechanism?

- The driving force of domain coarsening is the small domain-wall energy.
- But: this is not enough to understand the diversity of the observed coarsening phenomena.

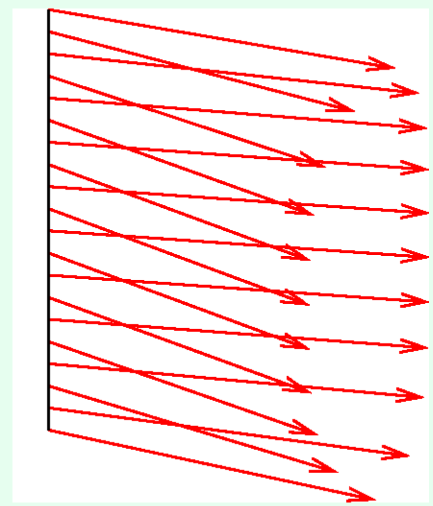
Antiferromagnetic multilayer leaving magnetic saturation



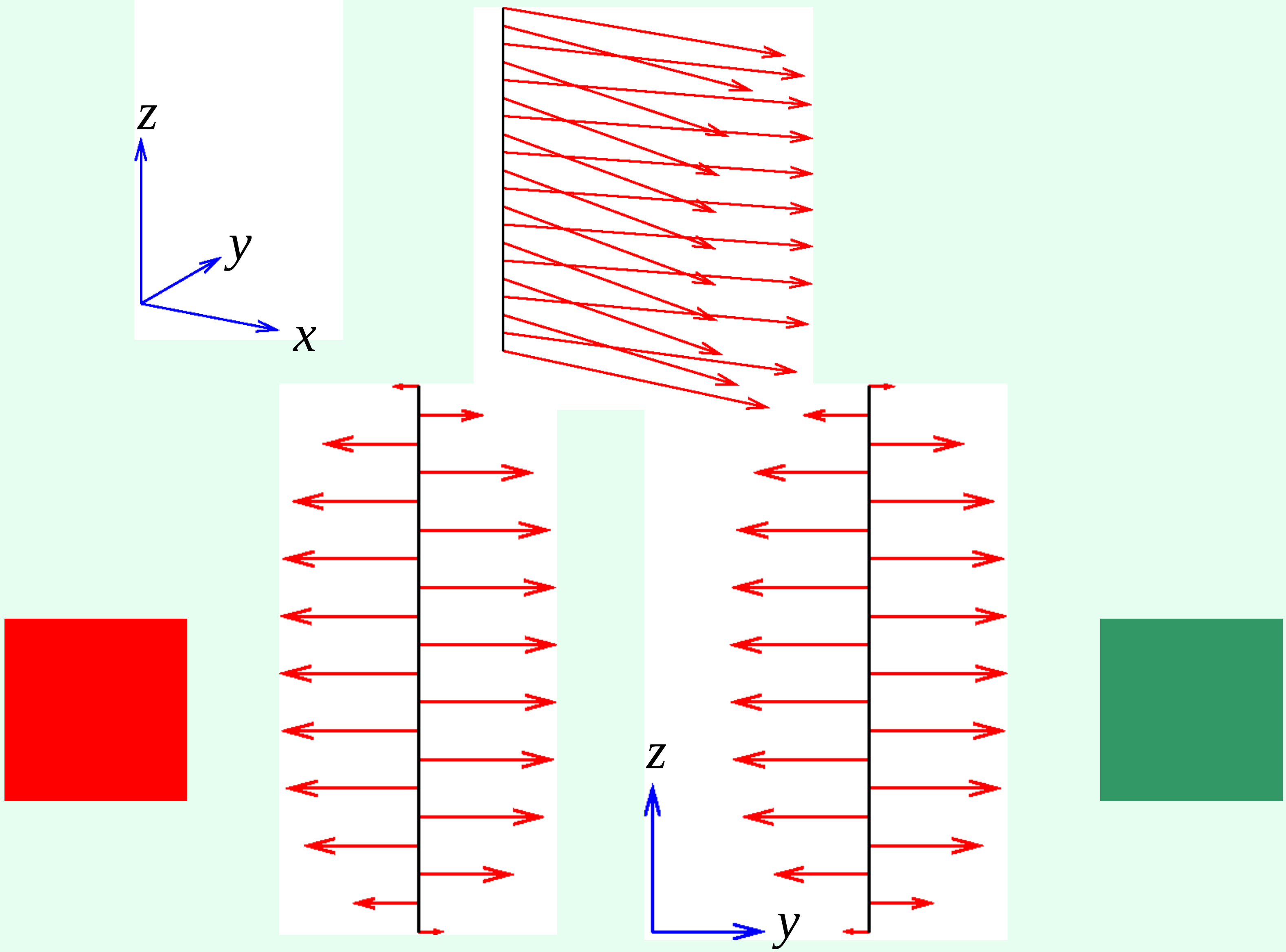
$\mathbf{H} \parallel x$

$H > H_{sat}$

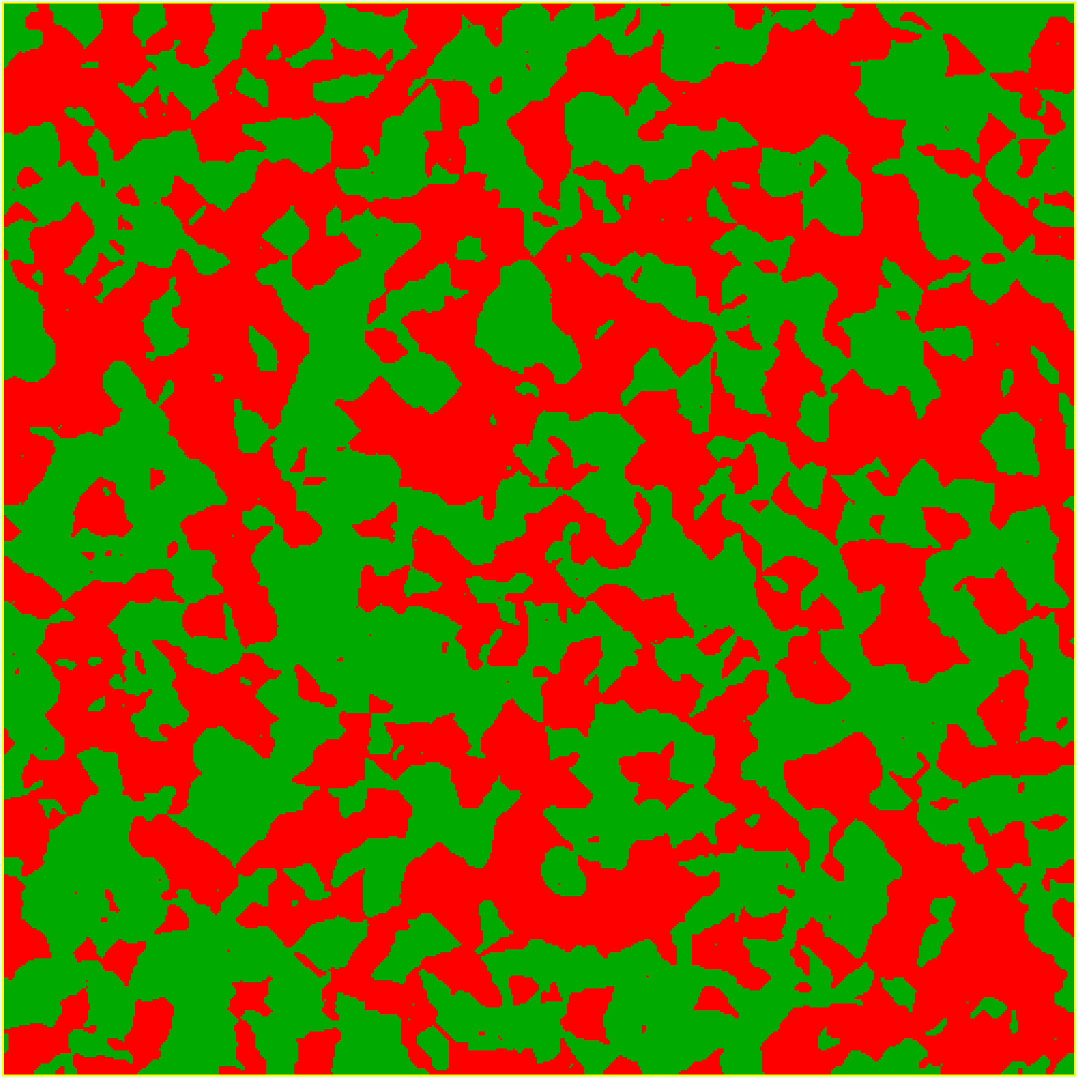
$H = 0.95\ H_{sat}$

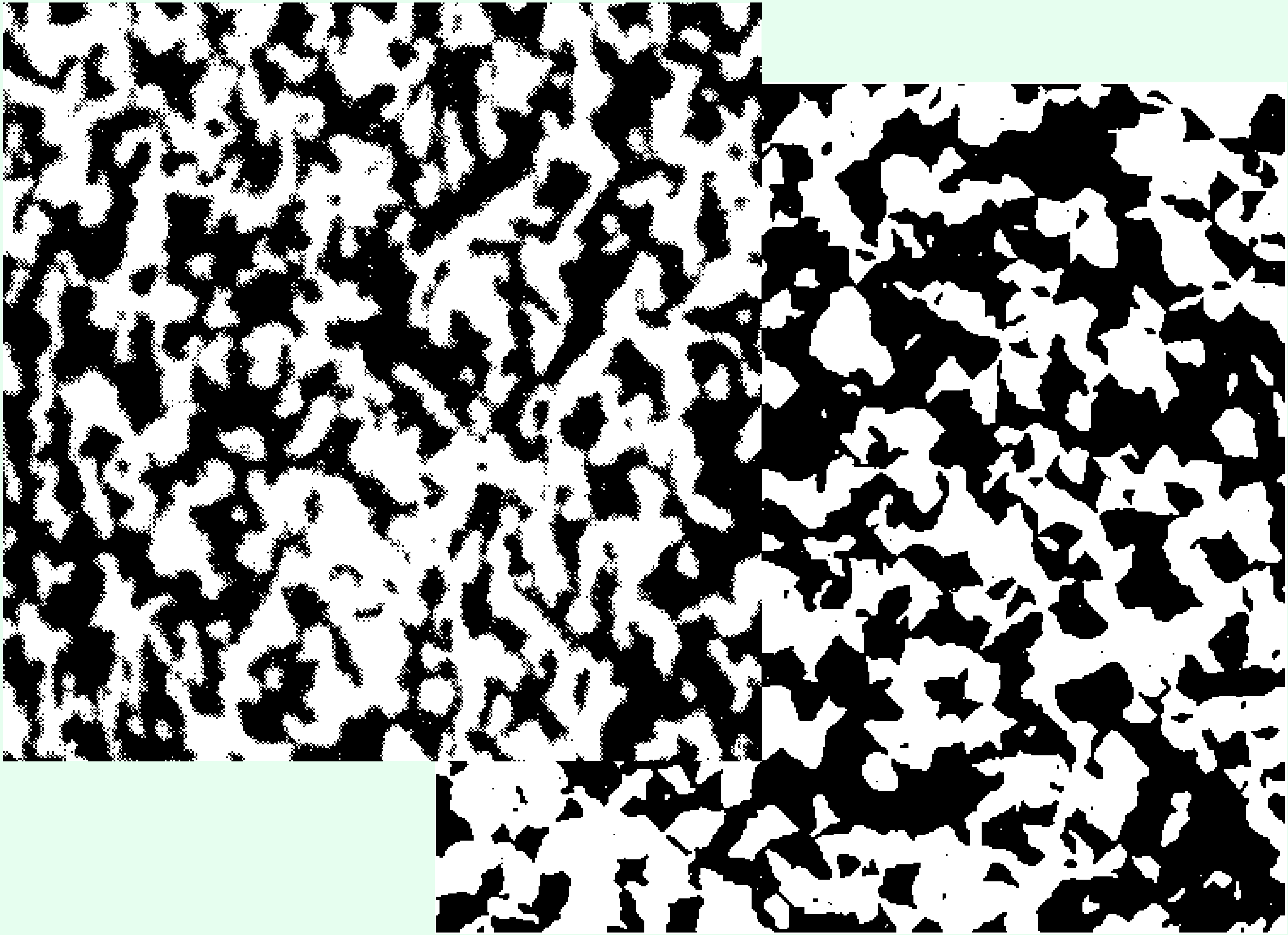


Formation of two kinds of domains



Domain formation on leaving saturation





From saturation to remanence: the domain ripening

- The correlation length of the domains immediately after their formation is equal to the lateral structural correlation length of the multilayer (terrace length, ≤ 50 nm). Still, in remanence we observe μm-size domains. Why?

- The driving force of the spontaneous change of the domain size in decreasing field is the domain-wall energy. The sign of the size change depends on the scaling law of the domain-wall density:

  inclusions ($\propto \xi$) $\Rightarrow$ decreasing domain size
  chessboard ($\propto 1/\xi$) $\Rightarrow$ increasing domain size

Domain ripening: the final state

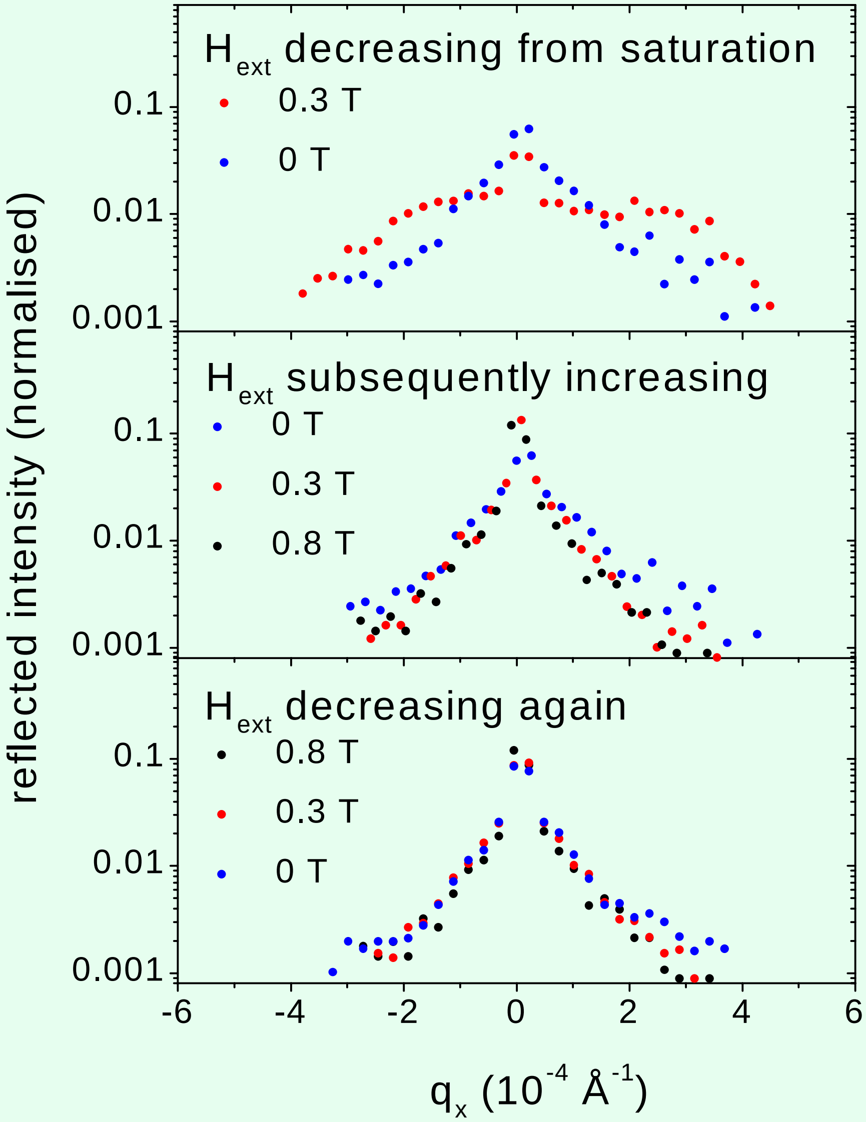
- The correlation length $\xi = 2.6\ \mu\text{m}$ of the primary domains in remanence is determined by the domain-wall-energy-driven and coercivity-limited spontaneous growth (ripening). Ripening takes place when the applied magnetic field is decreased from the saturation region to zero.
- Critical domain size after ripening:
  with the domain-wall width

$$\xi_c = \frac{\dfrac{A_{\text{ex}}\pi^2}{l} + \dfrac{lK}{4}}{2\pi M \mu_0 H_{\text{c}}}$$

$$l = (\pi/2)(A_{\text{ex}} t_{\text{Fe}}/J)^{1/2}$$

for 2 Oe < H_{c} < 30 Oe:
0.6 μm < ξ_{c} < 8.4 μm

Domain ripening: SMR



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

Decreasing the field and having left the saturation region, the AF peak appears with increasing intensity. In H_{ext} = 0.3 T the domain size is $\xi \approx$ 500 nm.

On decreasing the field to 0, the domain size increases to ξ = 2.6 μm.

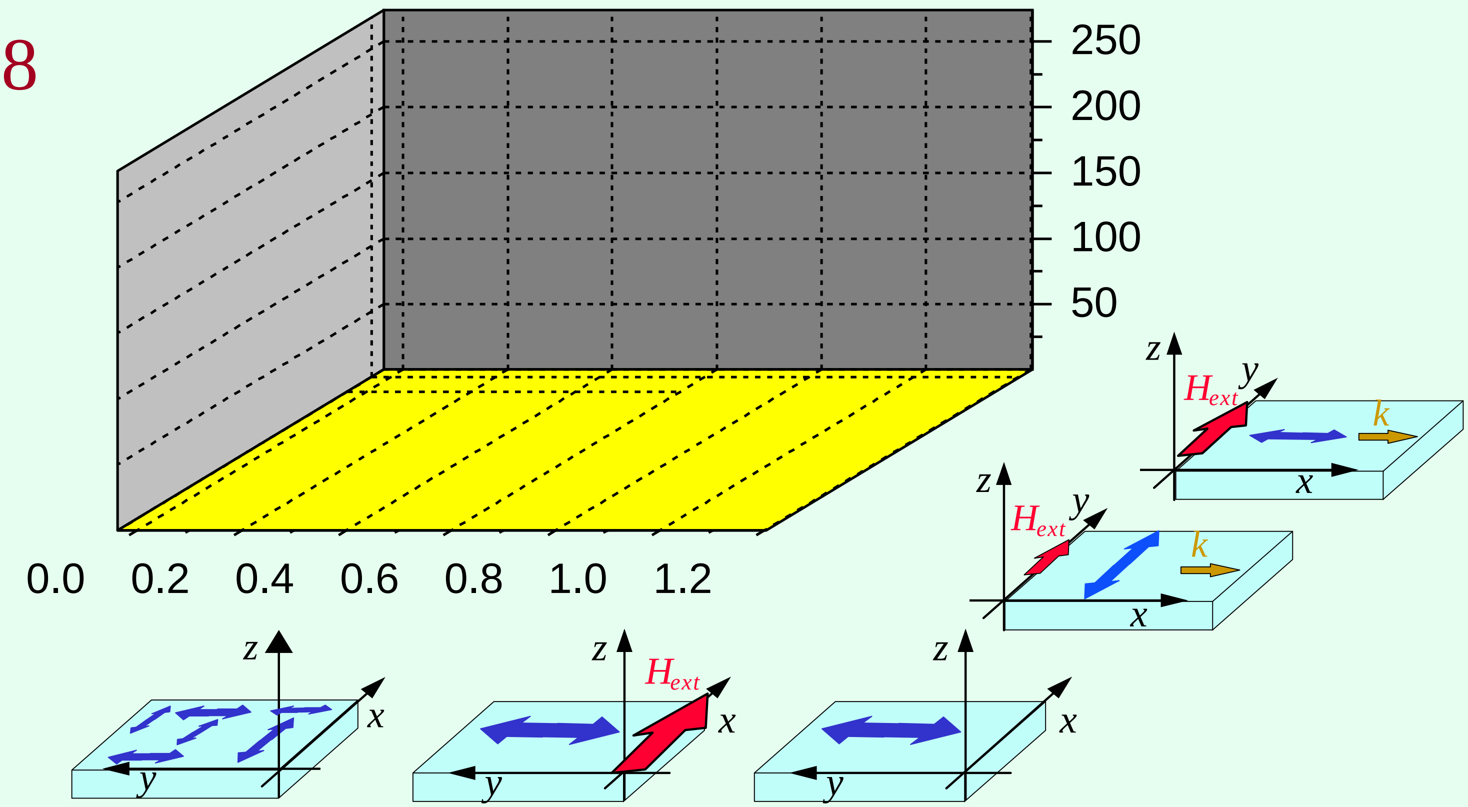
Domain ripening is an irreversible process: the domain size no longer changes in increasing or decreasing field.

Formation of very large domains (coarsening)

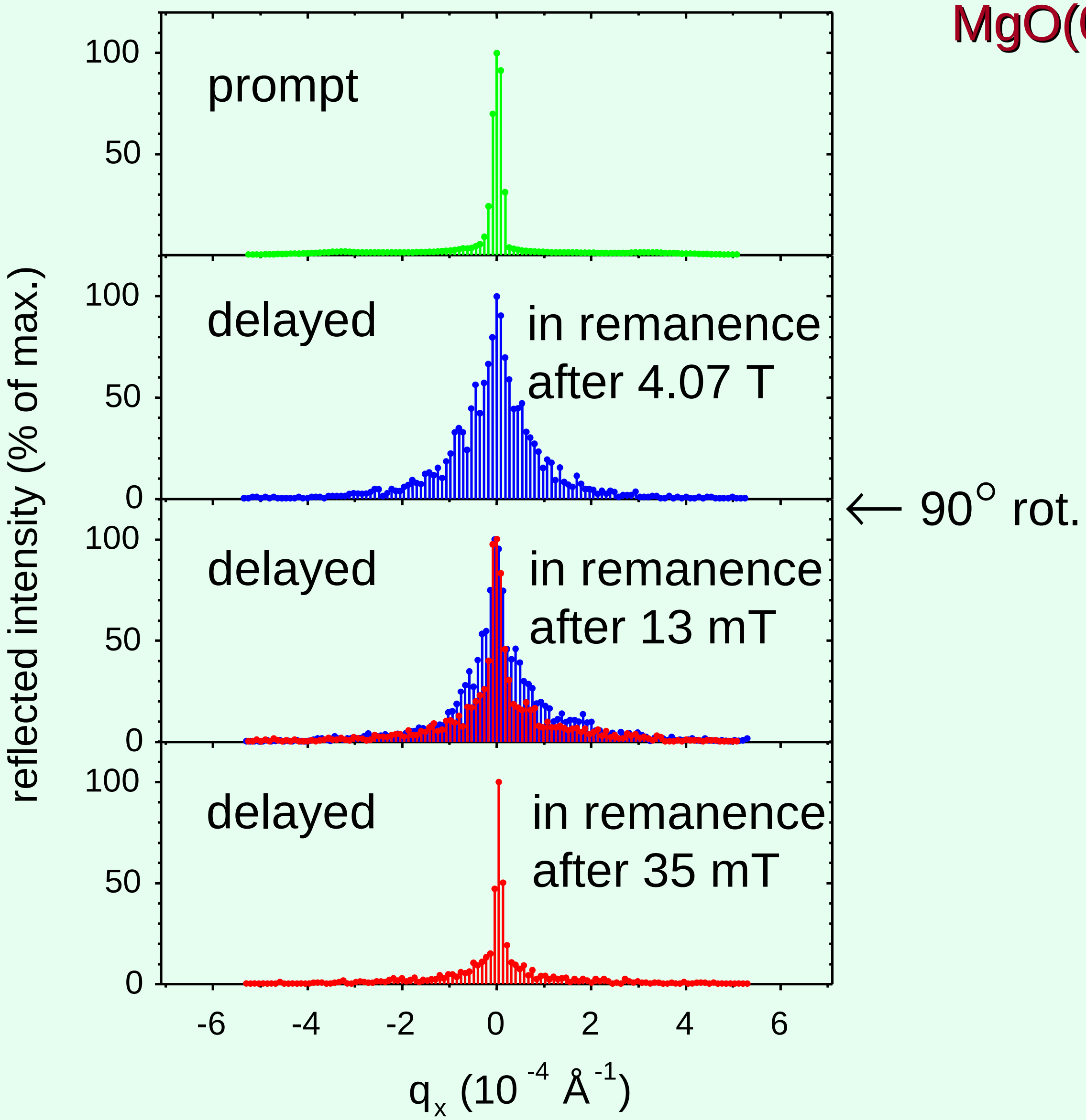
- After ripening, the domain size in remanence is expected to be always about 500 nm … 5 μm.
- This is not the case! The domain size is a complicated function of the magnetic prehistory. Under favourable conditions, even much larger domains (up to mm?) may be formed. Why?

Bulk spin flop in an epitaxial MgO(001)[$^{57}Fe(26Å)/Cr(13Å)]_{20}$ multilayer

ESRF
ID18



Spin-flop-induced domain coarsening (SMR)



MgO(001)[^{57}Fe(26Å)/Cr(13Å)]$_{20}$

2Θ @ AF reflection

Correlation length:

$\xi = 1/\Delta q_x$

Delayed photons before the spin flop

$\xi = 2.6\ \mu m$

Delayed photons after the spin flop

$\xi_1 > 16.5\ \mu m$

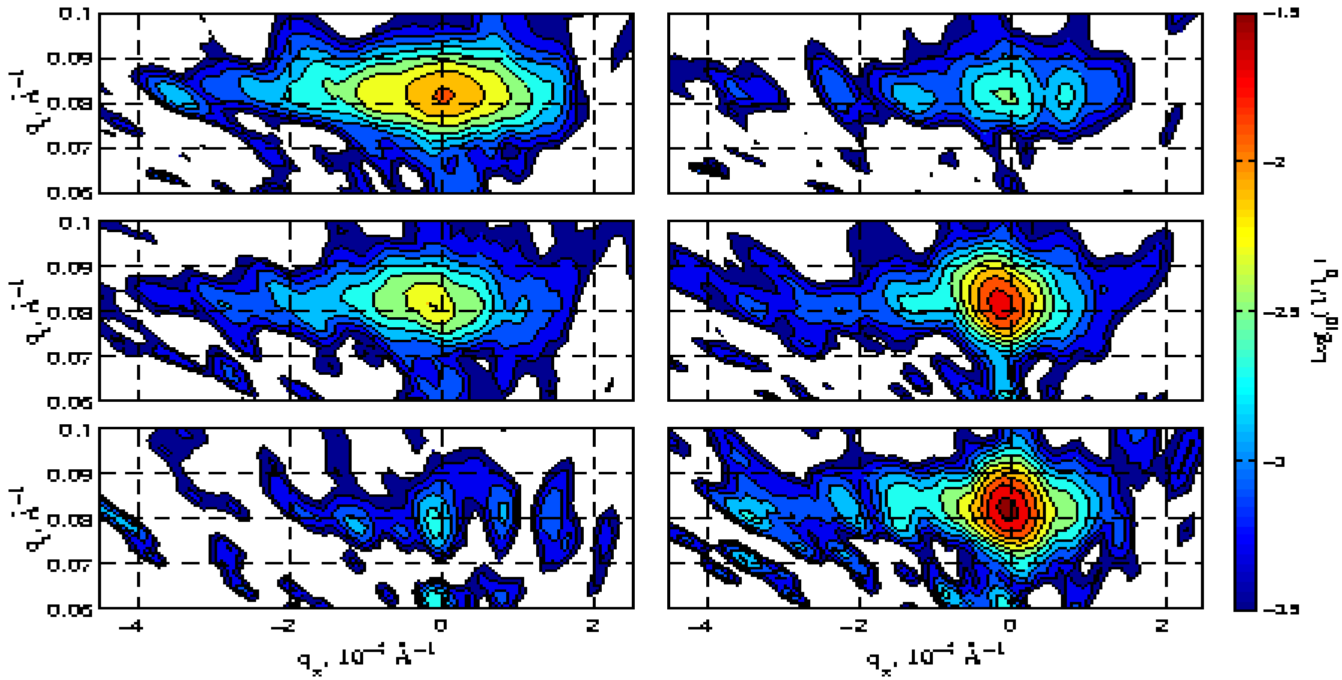
$\xi_2 = 2.6\ \mu m$

ESRF

ID18

Spin-flop induced domain coarsening (PNR)

MgO(001)[^{57}Fe(26Å)/Cr(13Å)]$_{20}$



7 mT

14.2 mT

35 mT

non-spin-flip scattering
p || M

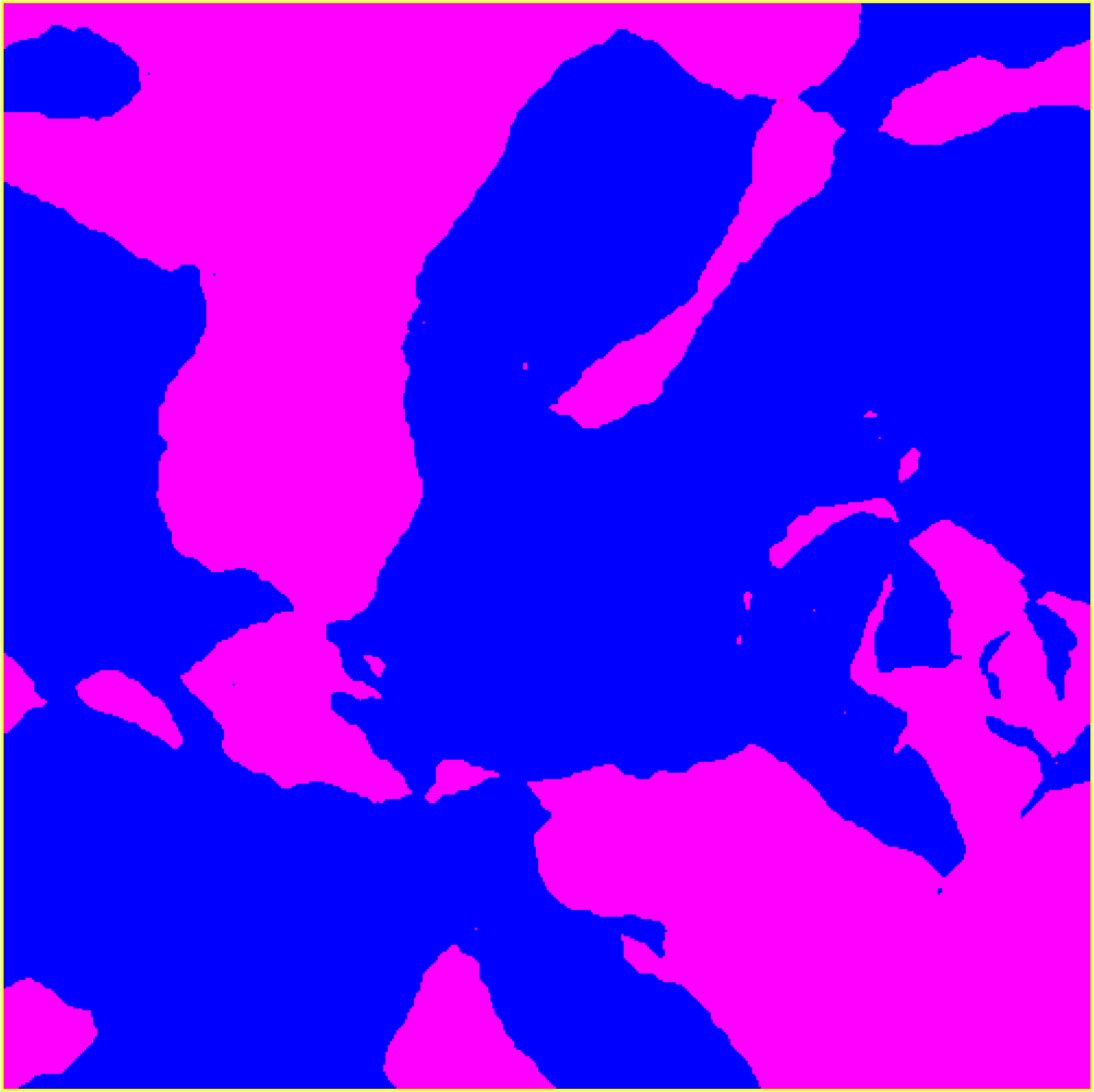
spin-flip scattering
p ⊥ M

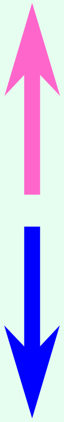
JINR
Dubna
SPN-1

Domain coarsening on spin flop

- Coarsening on spin flop is an explosion-like 90-deg flop of the magnetization annihilating primary 180-deg walls. It is limited neither by an energy barrier nor by coercivity. Consequently, the correlation length of the secondary patch domains ξ may become comparable with the sample size.

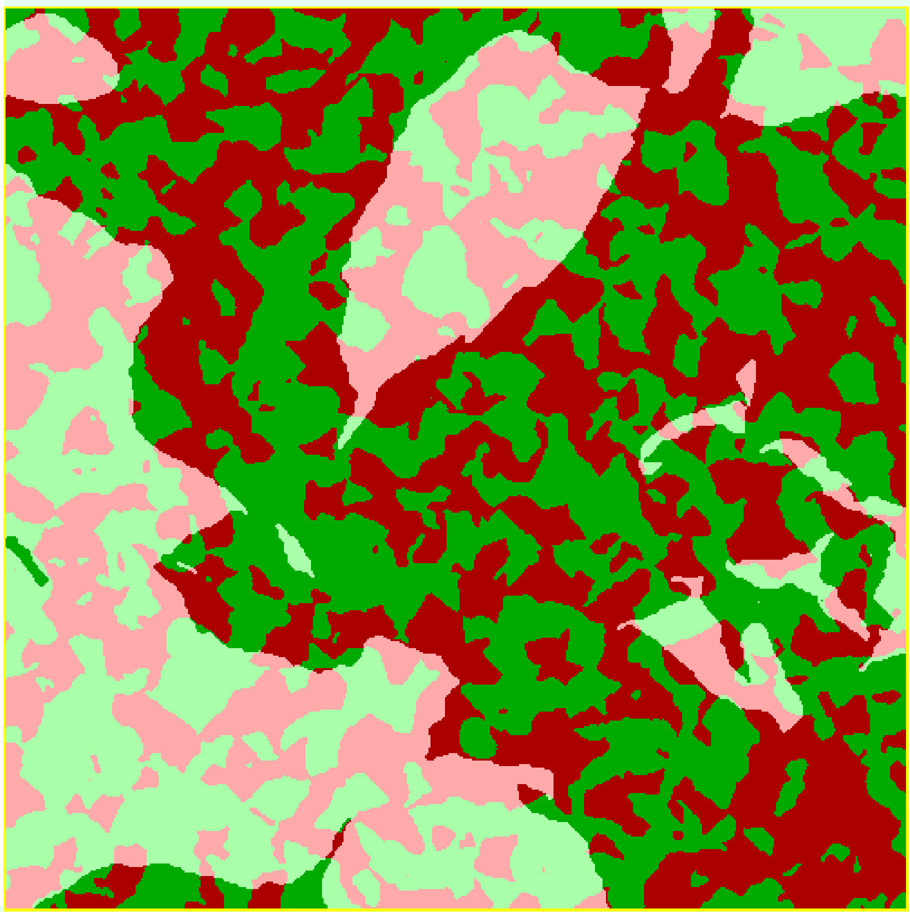
Domain coarsening during spin flop

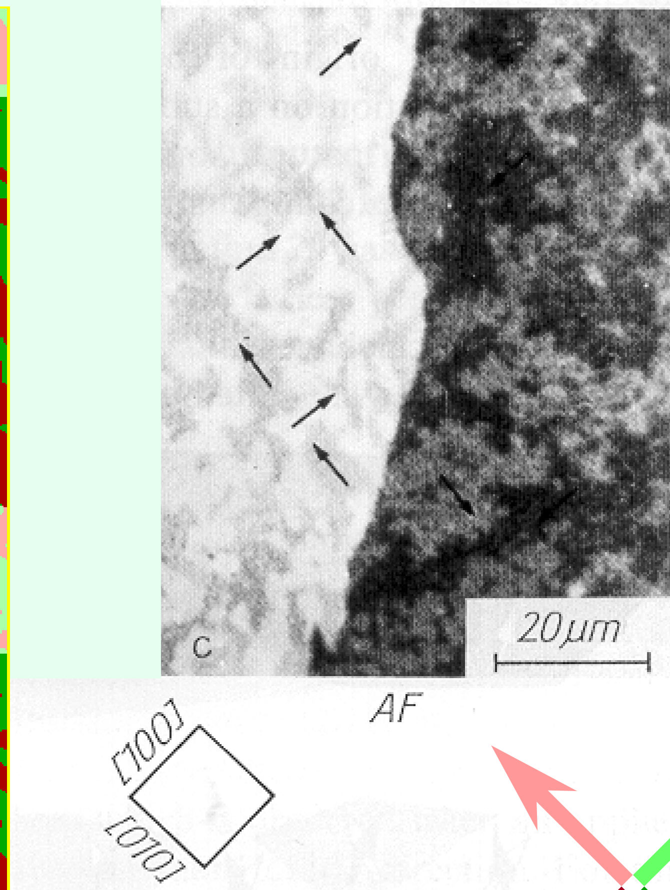


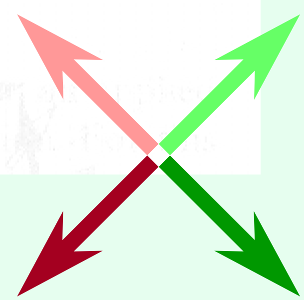


Domain coarsening on hard-direction field decreased to zero

M. Rührig et al., Phys. Stat. Sol. (a) **125,** 635 (1991).







Conclusions

- Off-specular synchrotron Mössbauer reflectometry and polarised neutron reflectometry are efficient tools of studying antiferromagnetic domains in coupled multilayers. The diffuse scattering width is inversly proportional to the correlation length.
- The native domains formed in AF-coupled multilayers upon leaving the saturation region with decreasing field are nanodomains the average size of which is determined by the structural correlation length (e.g., the terrace length).

Conclusions

- The domain-wall-energy-driven spontaneous growth of domains in magnetic field decreasing from saturation (ripening) is limited by domain-wall pinning (coercivity). Ripening results in microdomains.
- The spin flop results in domain coarsening ("millidomains" are formed).
- The condition for coarsening is the equilibrium of the Zeeman energy with the anisotropy energy. It is only this unstable state that permits the minute domain-wall energy to radically shape the domain structure.