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School on Pulsed Neutrons: Characterization of Materials

15 - 26 October 2007

Surfaces and Thin Films

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23. October 2005

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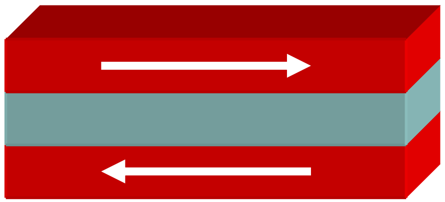
School on Pulsed Neutron Sources
Trieste - Italy, 15 - 26 October 2007

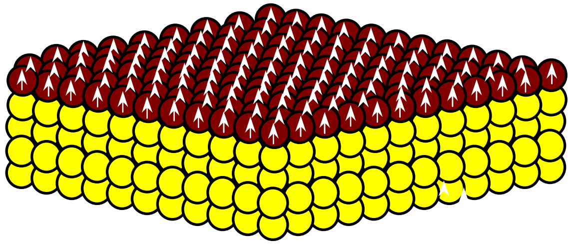
Surfaces, Interfaces and Thin Films

For fundamental properties in the area of magneto- and spintronics

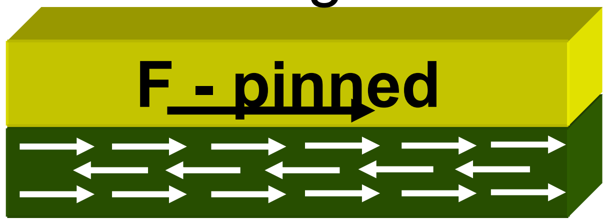
GMR heterostructures



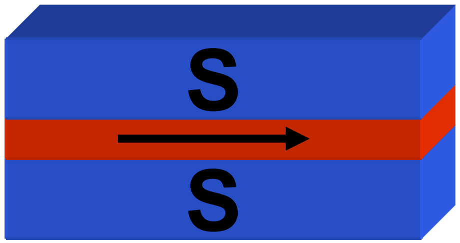
Magnetic films



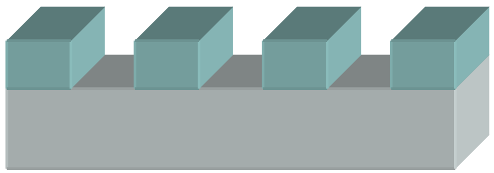
Exchange bias



Proximity effects
and tunneling



Lateral structures



Content

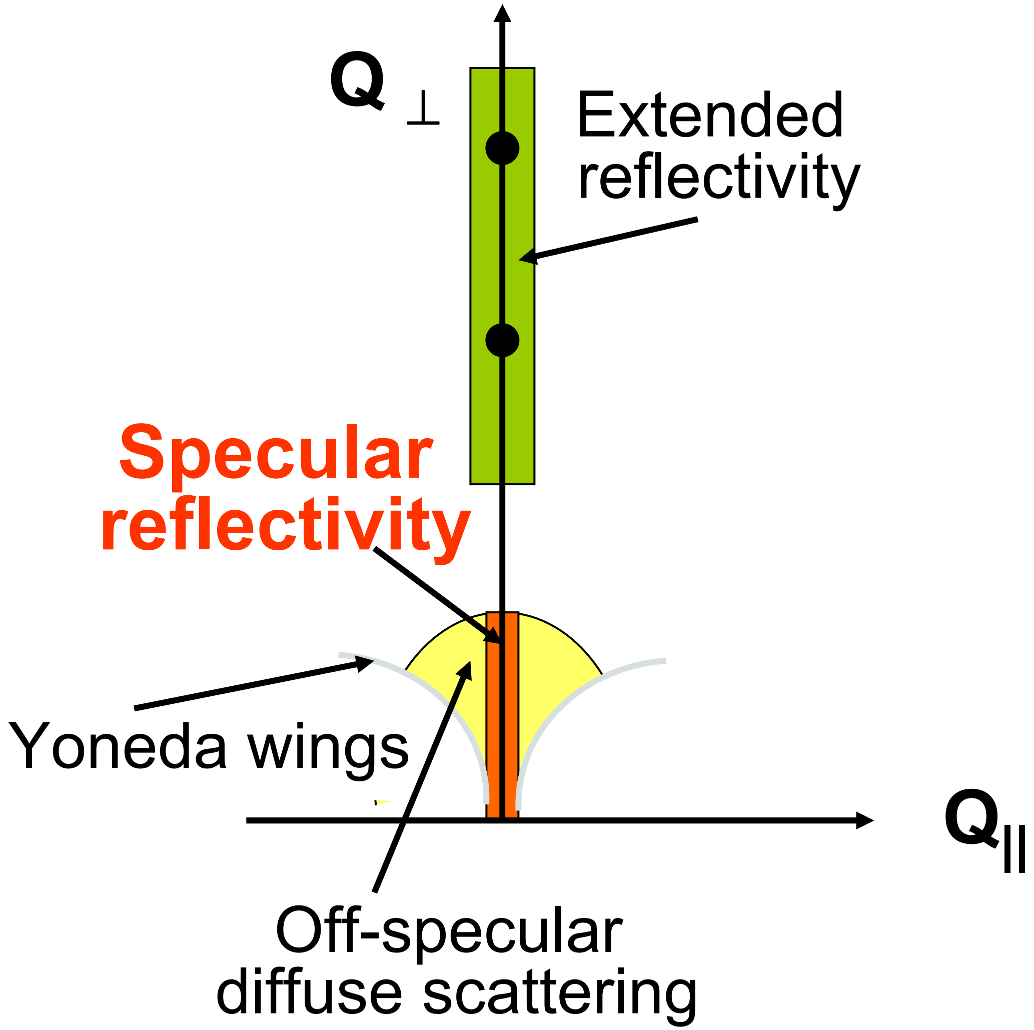
1. **X-ray reflectivity**
2. **Neutron reflectivity**
3. **Polarized neutron reflectivity (PNR)**

- Methods
- Instrumentation
- Examples

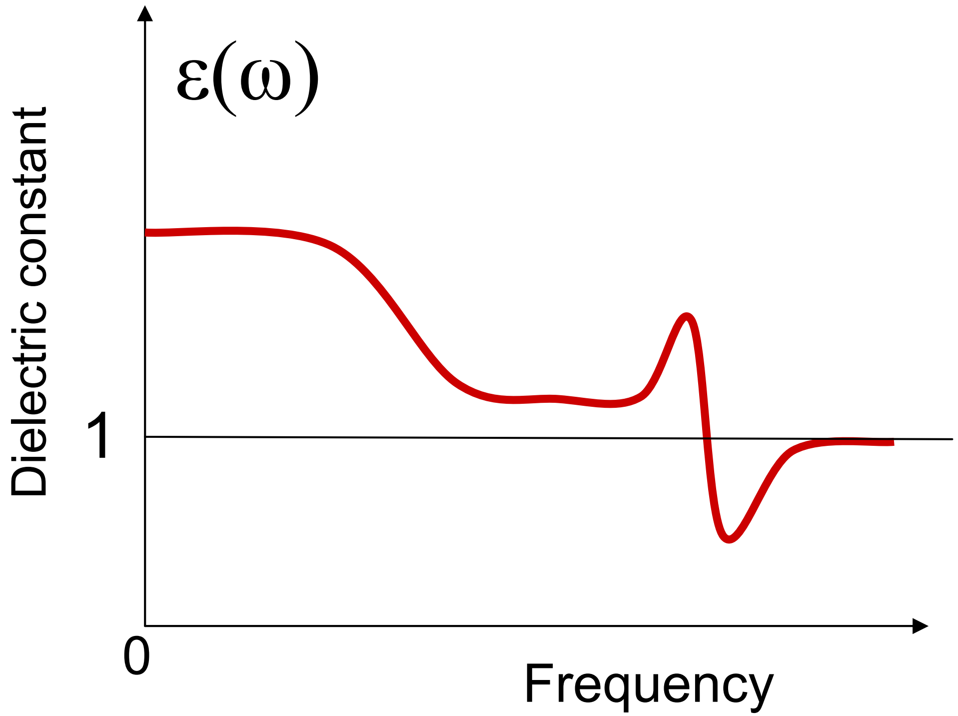
4. **Case study: do we still need neutrons?**

1. X-ray and neutron reflectivity

Specular reflectivity basics



Index of refraction for EM waves



$$\sqrt{\varepsilon(\omega)} = n(\omega) = \text{fractive index} \Rightarrow \text{optics}$$

X-ray refractive index

Refractive Index:

$$n^2(\omega) = 1 + \frac{4\pi\rho_A e^2}{m_e} \sum_i \frac{f_i}{\omega_i^2 - \omega^2 + i\gamma}$$

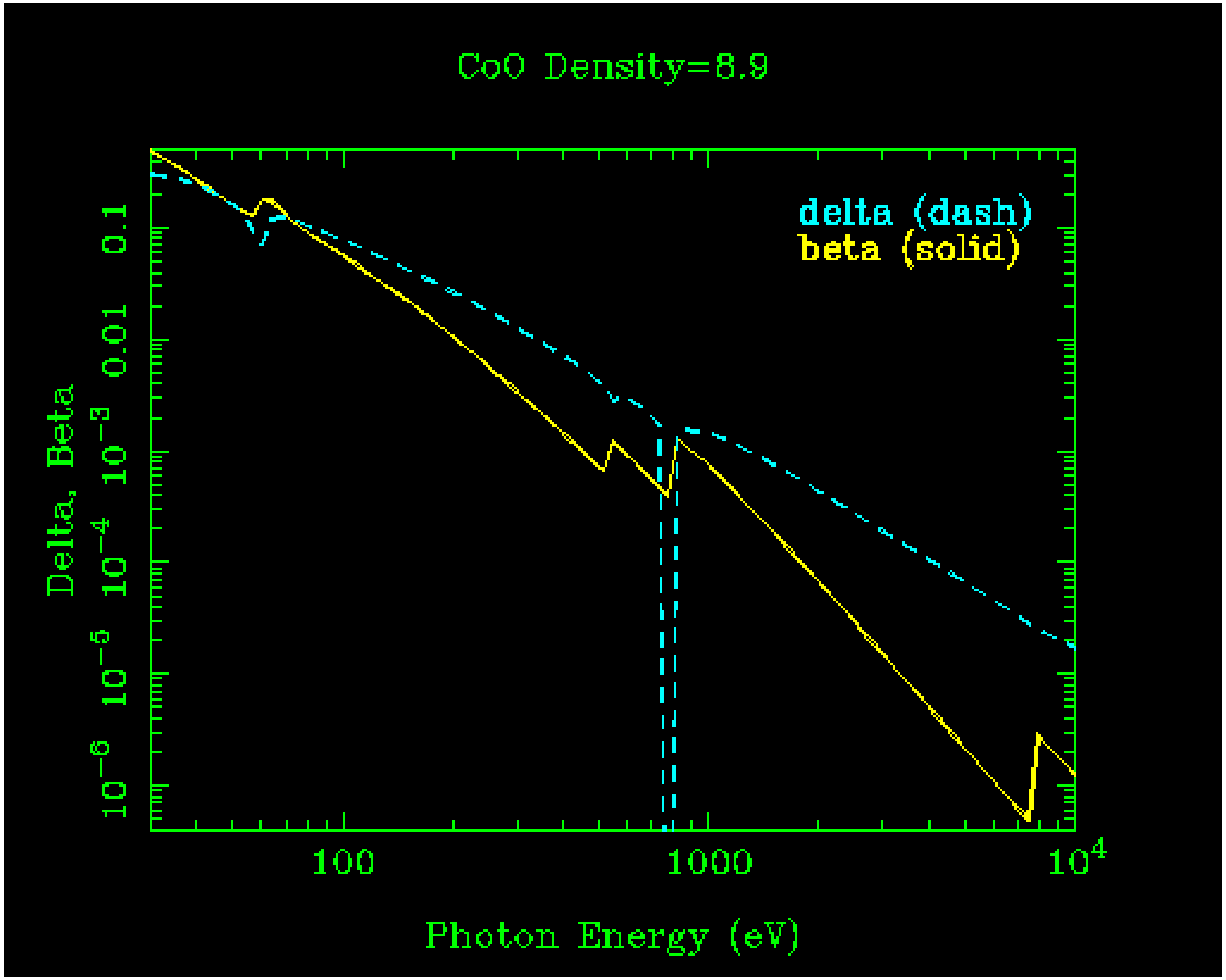
For x-ray's, the refractive index is always smaller than 1:

$$n(\lambda) = 1 - \frac{r_0}{2\pi} \rho_e \lambda^2$$
$$\approx 1 - 10^{-5} < 1$$

Adding dispersion and absorption correction:

$$n(Q_z) = 1 - \frac{2\pi r_0}{k_0^2} \rho_A [f(Q_z) + \Delta f] - \frac{i\mu}{2k_0}$$
$$= 1 \qquad - \delta \qquad - i\beta$$
$$\cong 1 \qquad - \qquad 10^{-5} \qquad < \qquad 1$$

Plot of δ and β for CoO



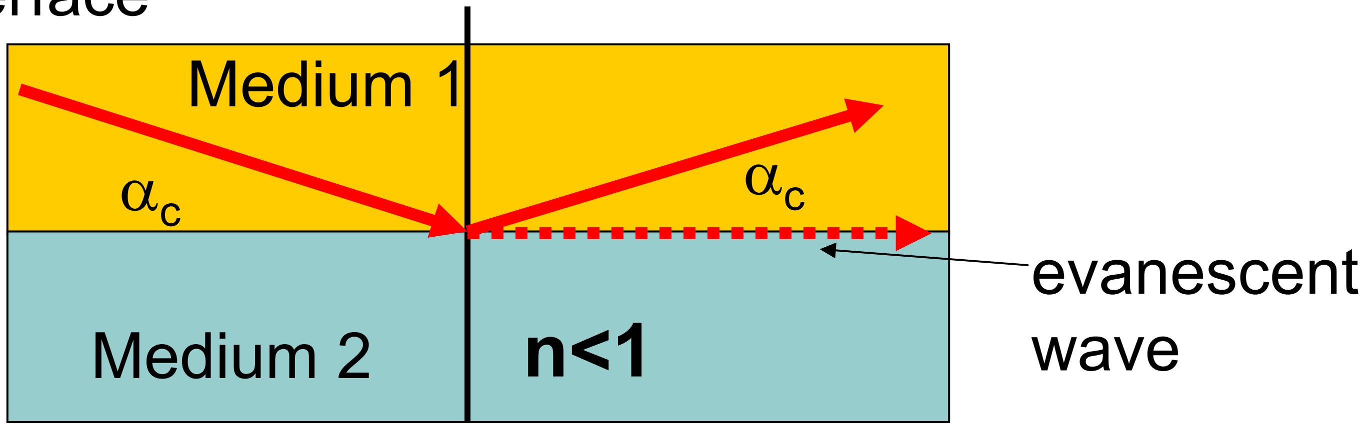
http://www-cxro.lbl.gov/optical_constants/getdb2.html

Critical angle for total reflection

Since n < 1, total reflection occurs at:

$$\frac{\cos\alpha_c}{\cos 0} = \cos\alpha_c = n$$

For all angles $\alpha < \alpha_c$ the wave can not penetrate into the medium, but at α_c there is an evanescent wave travelling along the interface



Critical Scattering Vector

Scattering vector is defined as:

$$Q = \frac{4\pi}{\lambda}\sin\alpha = 2k\sin\alpha$$

Accordingly the critical scattering vector is:

$$Q_c = \frac{4\pi}{\lambda}\sin\alpha_c = 2k\sqrt{1-\cos^2\alpha_c} = \sqrt{4k^2(1-n^2)}$$

$$\cong \sqrt{4k^2 2\delta} = \sqrt{16\pi r_0 \rho_e}$$

$$Q_c \propto \sqrt{\rho_e}$$

The critical scattering vector is no more a function of the wavelength. It is entirely determined by the property of the material and in particular by the electron density ρ_e.

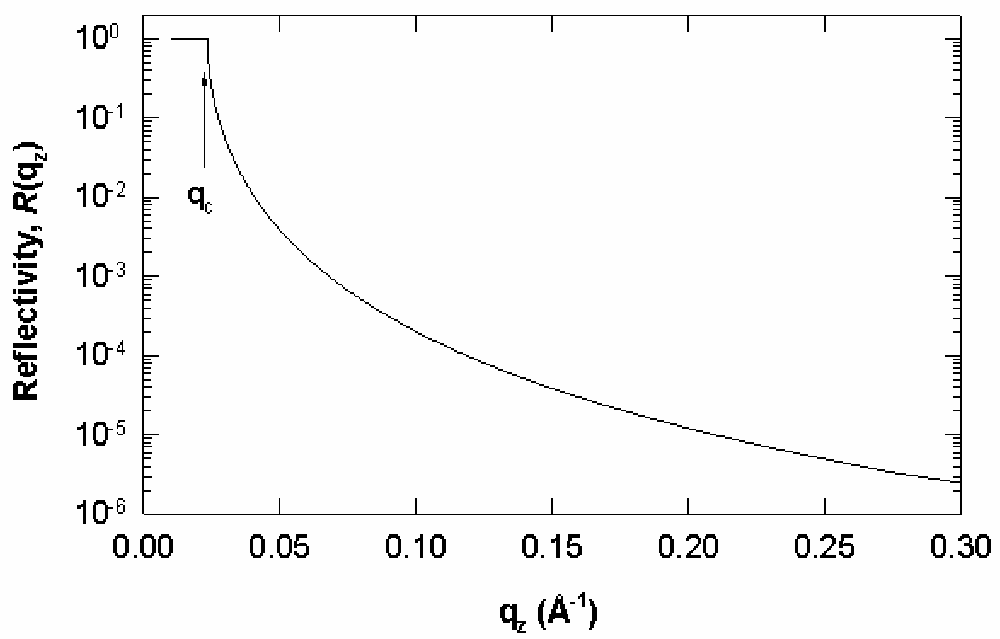
Fresnel reflectivity

For $Q_z < Q_c$: $R = 1$,

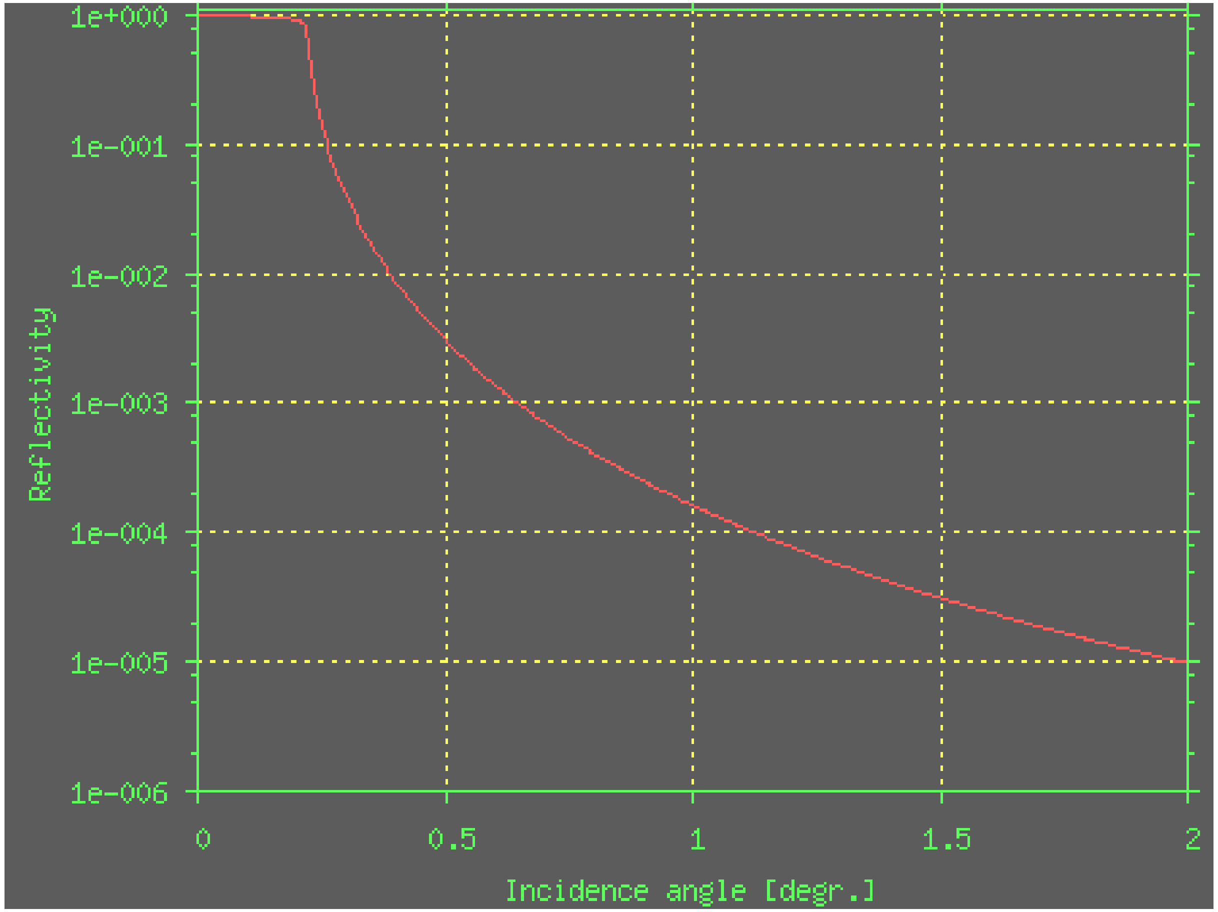
For $Q_z > Q_c$: $R = R_f$

The reflectivity drops with Q^4, for scattering vectors $Q >> Q_c$.

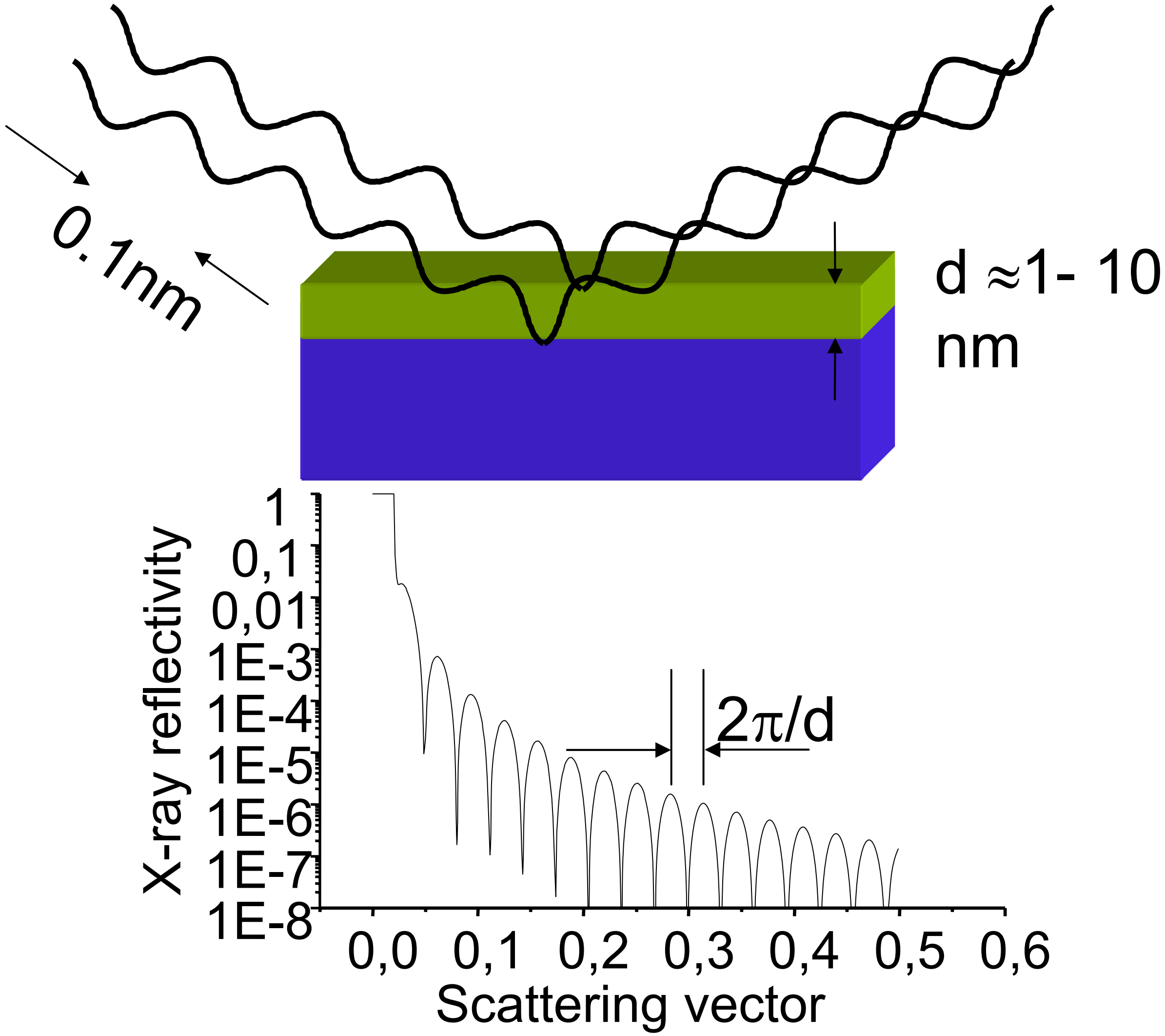
This applies for perfectly flat interfaces.



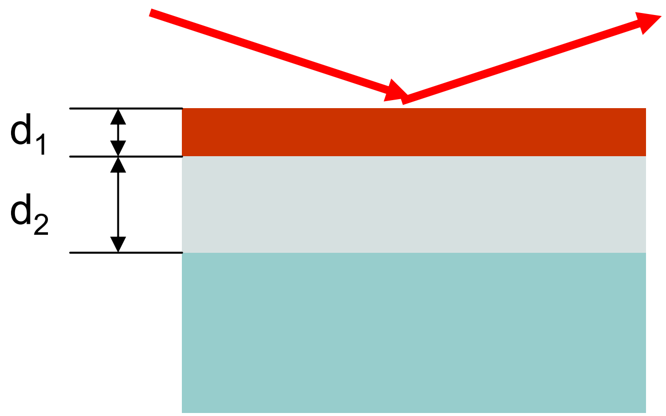
Fresnel reflectivity for Si

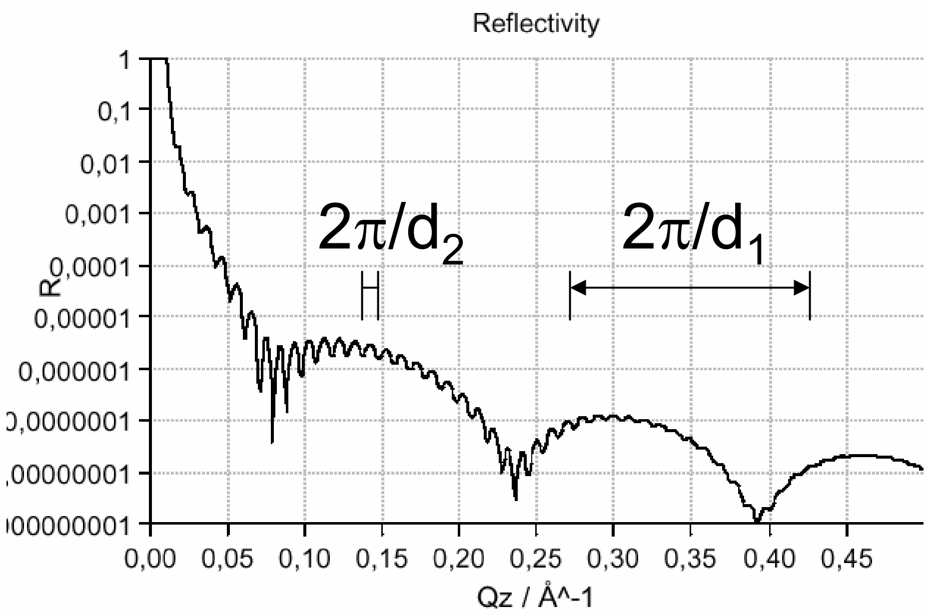


Reflectivity from a thin layer: Kiessig fringes

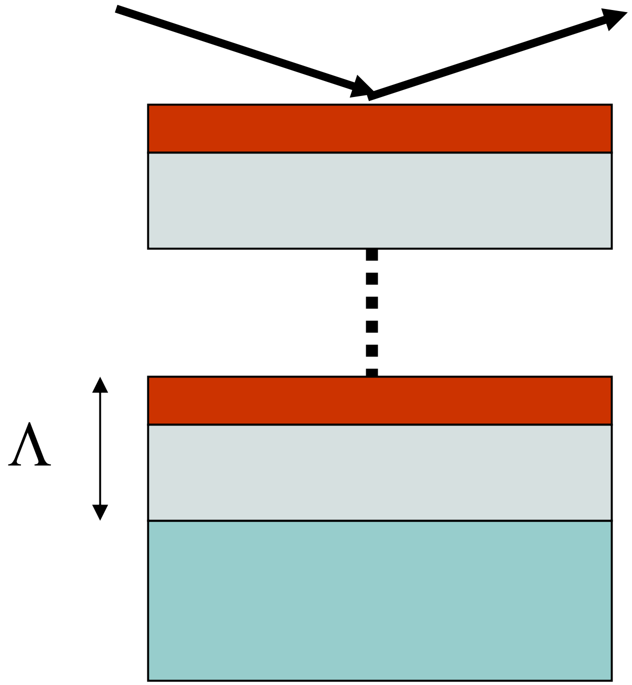


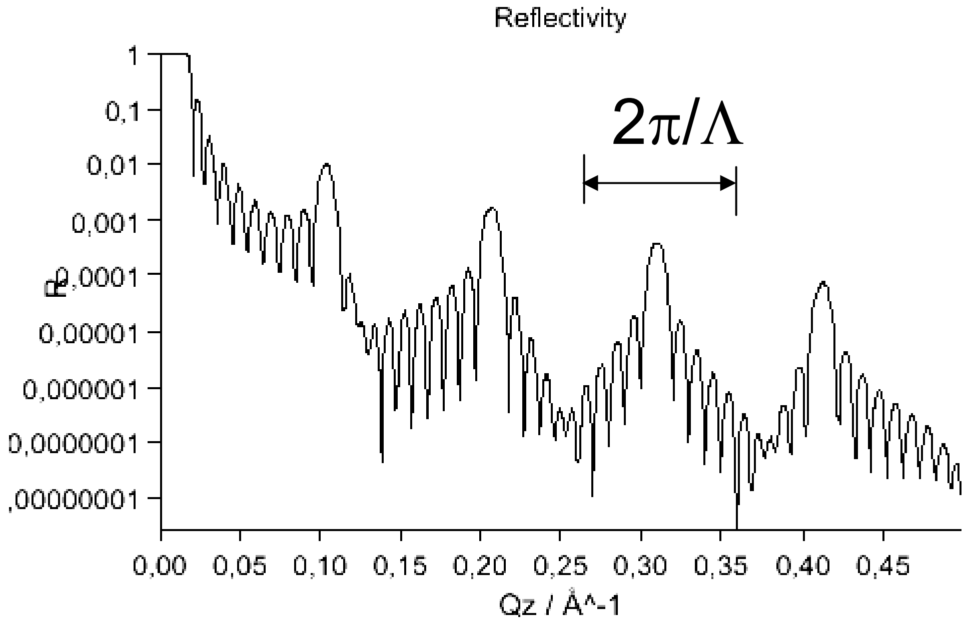
Reflectivity from a double layer





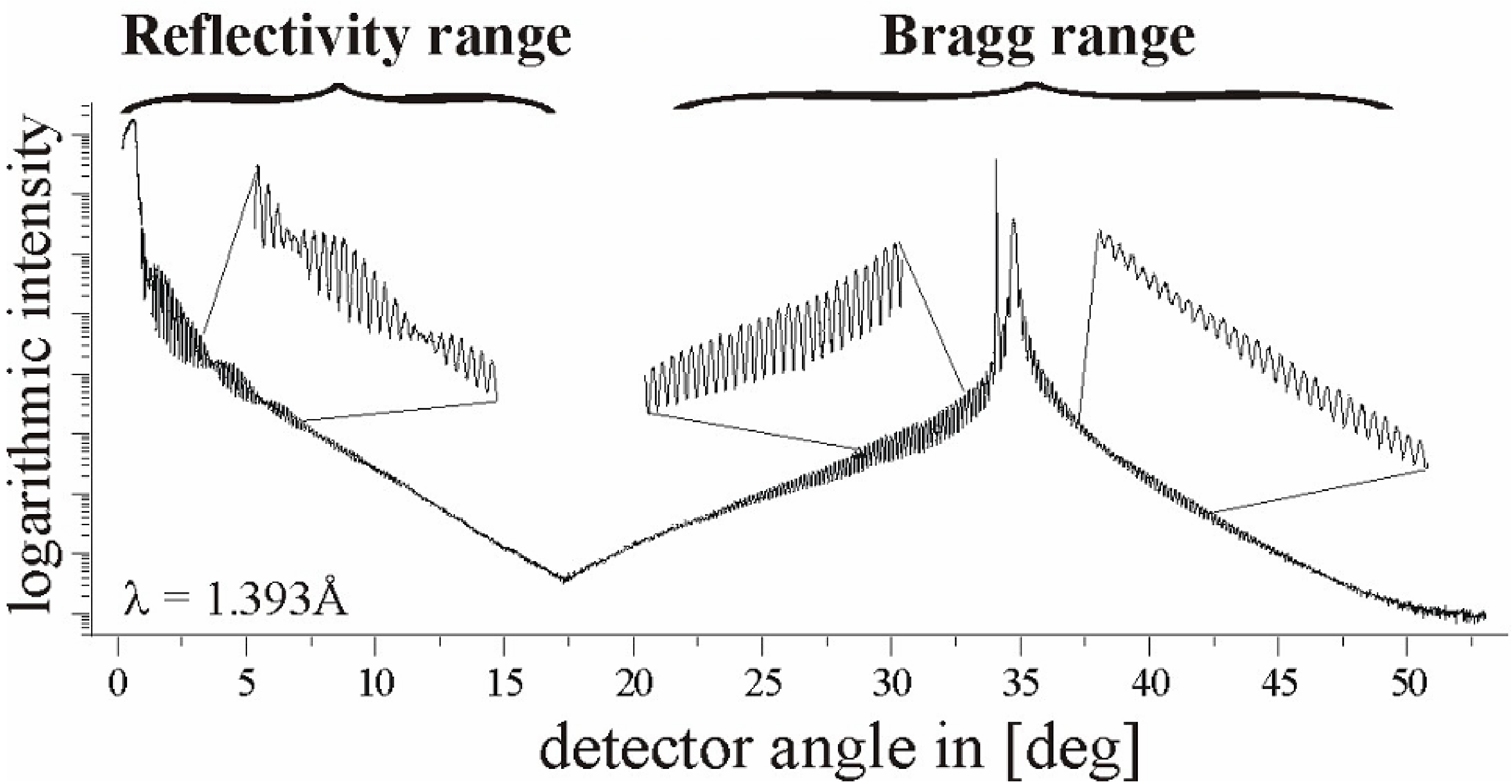
Reflectivity from a multilayer



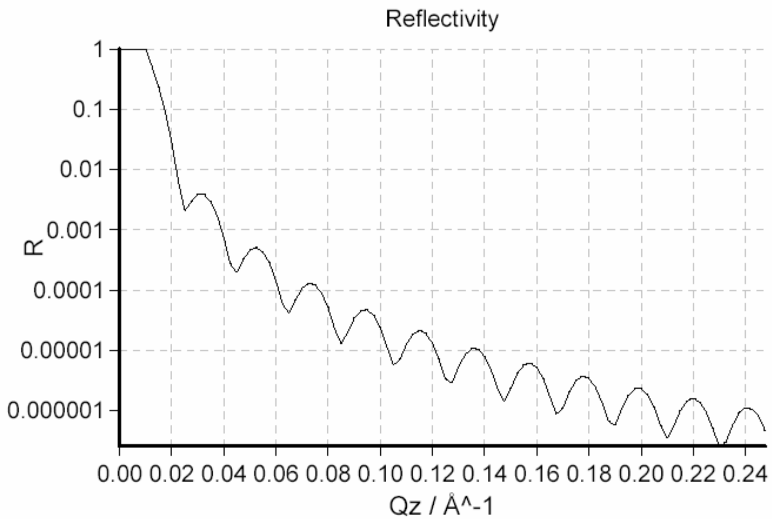


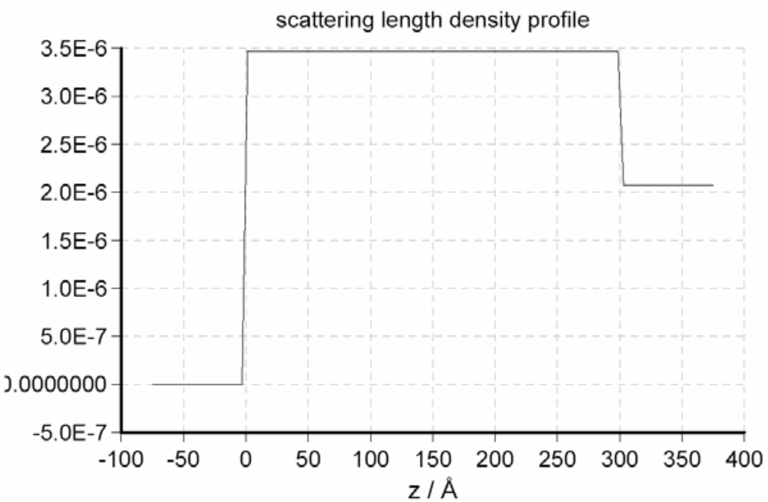
$$Q_l = \sqrt{Q_c^2 + l^2 \left(\frac{2\pi}{\Lambda} \right)^2}$$

Reflectivity and Bragg range



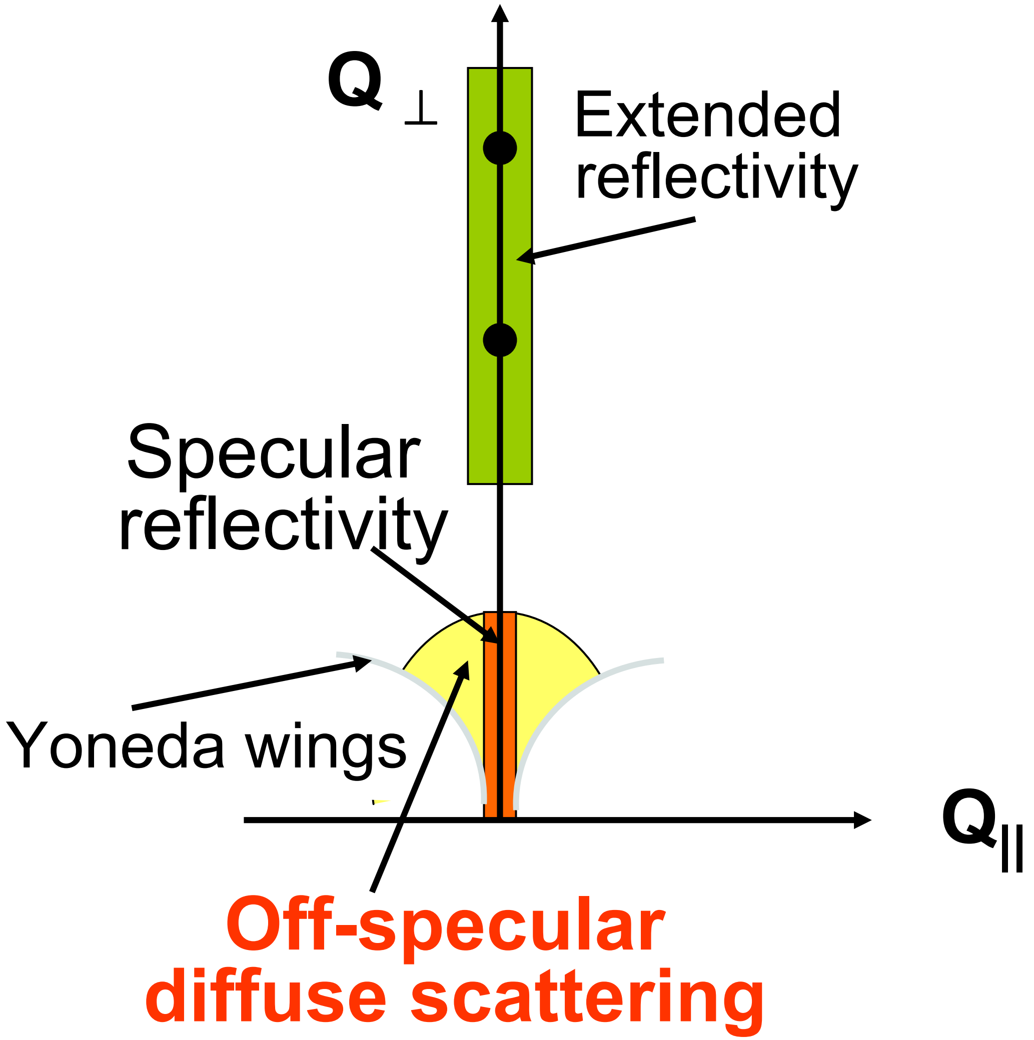
Electron density profile from reflectivity data



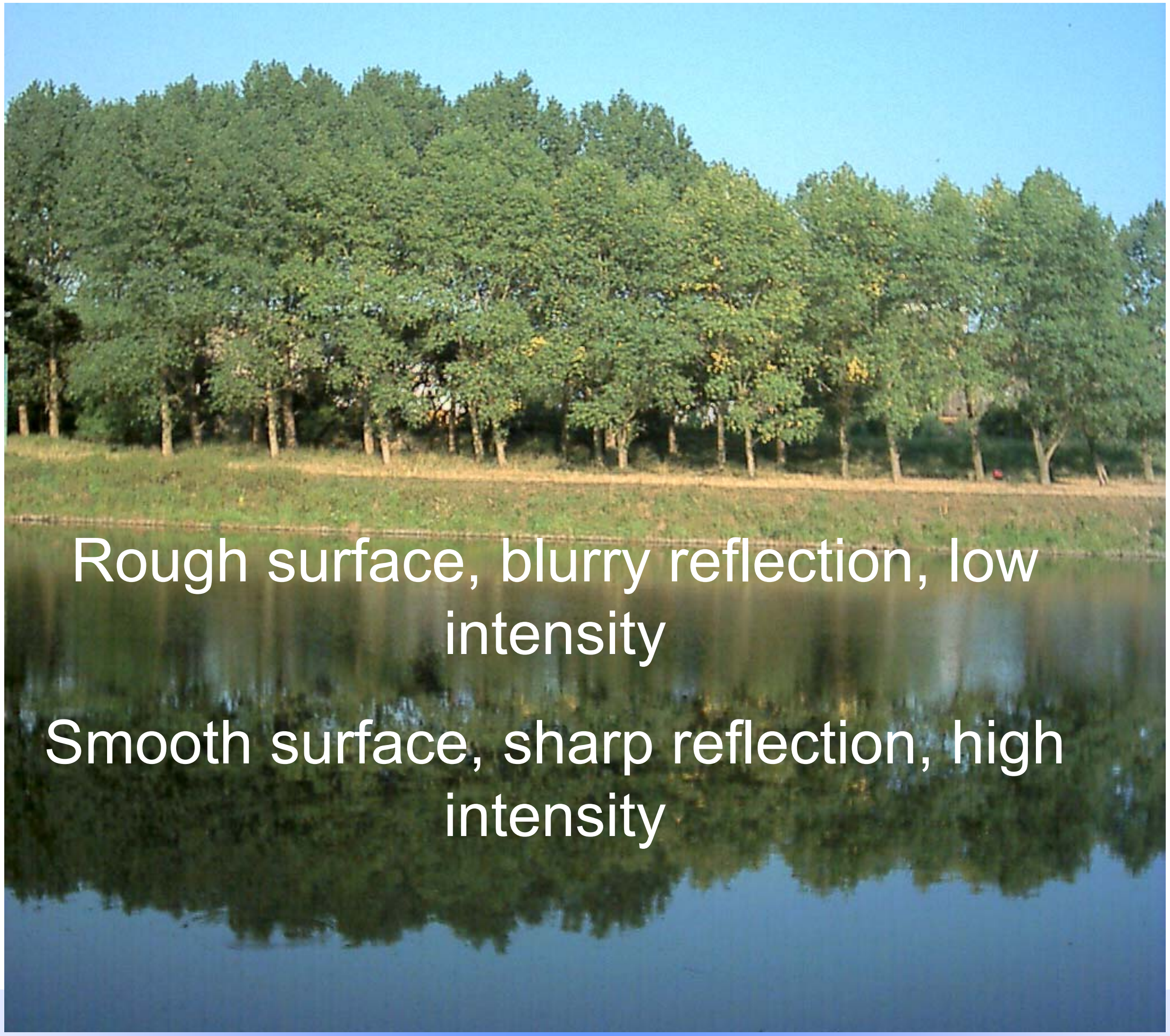


Back transformation from reflectivity data to electron densities and thickness profiles is the ultimate goal. However, the back transformation is not always uniquely possible.

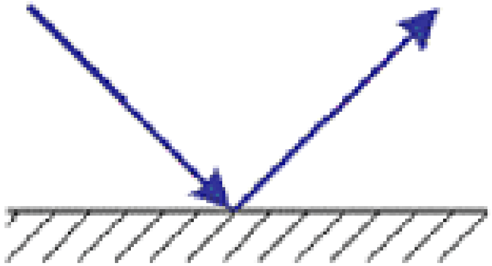
Reflectivity with surface roughness



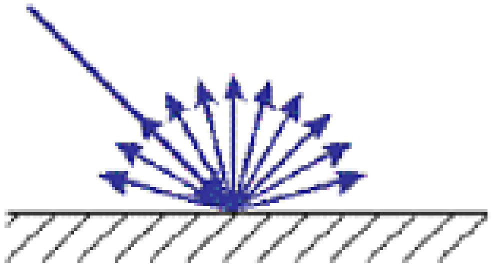
Smooth and rough surfaces



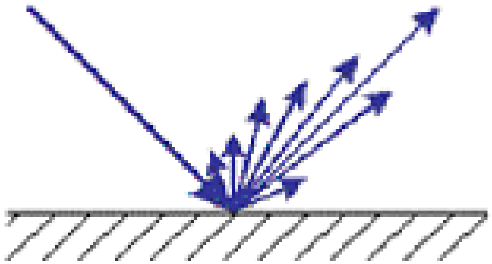
Off-specular scattering from rough interfaces



Perfectly specluar surface,
100% reflection, mirror image



Perfectly rough surface,
100% diffuse scattering, projector wall



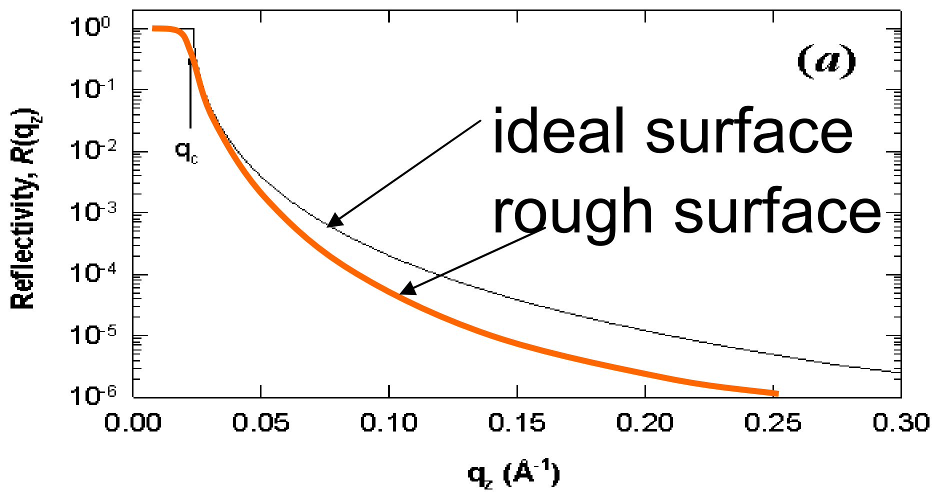
Partially reflecting and scattering from rough surface

Reflectivity of rough surface

Master formular yields for a Gaussian roughness a damped Fresnel reflectivity:

$$R(Q_z) = R_F(Q_z)\exp(-Q_z^2\sigma^2)$$

$R_F(Q_z)$ is the Fresnel reflectivity of the ideal surface. Roughness adds a damping factor, similar to the Debye-Waller factor:



Diffuse Scattering

Scattering function in the Born approximation:

$$S(\vec{Q}) = \int \langle \rho(0)\rho(R) \rangle e^{i\vec{Q}\bullet\vec{R}} d^3R$$

Pair correlation function:

$$G(\vec{R}) = \Big\langle \big(\rho(0) - \langle \rho(0) \rangle\big)\big(\rho(\vec{R}) - \langle \rho(\vec{R}) \rangle\big) \Big\rangle$$

$$= \langle \rho(0)\rho(\vec{R}) \rangle - \langle \rho(0) \rangle \langle \rho(\vec{R}) \rangle$$

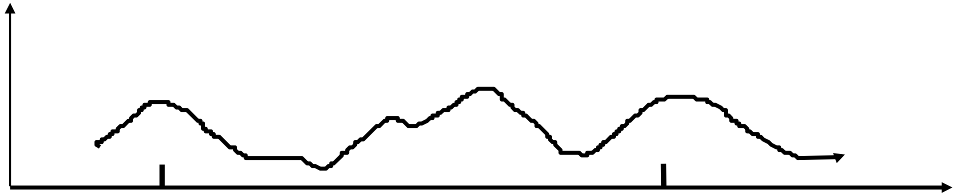
$$= \langle \rho(0)\rho(\vec{R}) \rangle - \langle \rho(0) \rangle^2$$

Inserting:

$$S_{tot}(\vec{Q}) = \underbrace{\langle \rho(0) \rangle^2 \int e^{i\vec{Q}\bullet\vec{R}} d^3R}_{\textbf{Specular Reflection}} + \underbrace{\int C(\vec{R}) e^{i\vec{Q}\bullet\vec{R}} d^3R}_{\textbf{Diffuse Scattering}}$$

$$= S_{spec}(\vec{Q}) + S_{diff}(\vec{Q})$$

Height-height correlation function



Height-height correlation function for a single self-affine, fractal surface:

$$C(R) = \langle z(0)z(R) \rangle = \sigma^2 \exp[-(R/\xi)]^{2h}$$

σ = rms roughness

ξ = cut-off length:

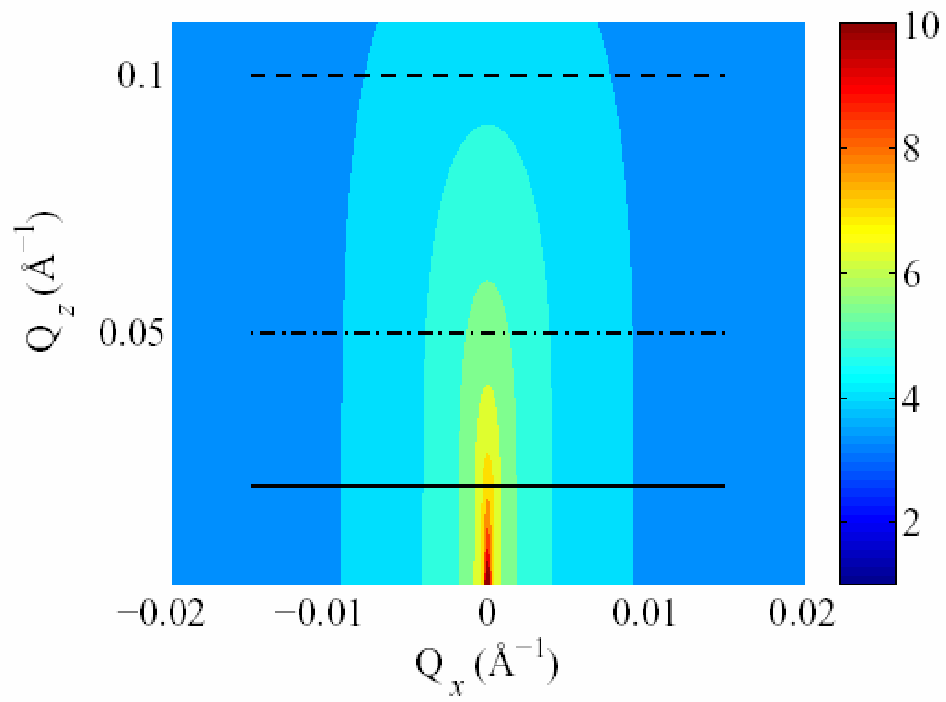
for $R > \xi$, interface appears smooth,

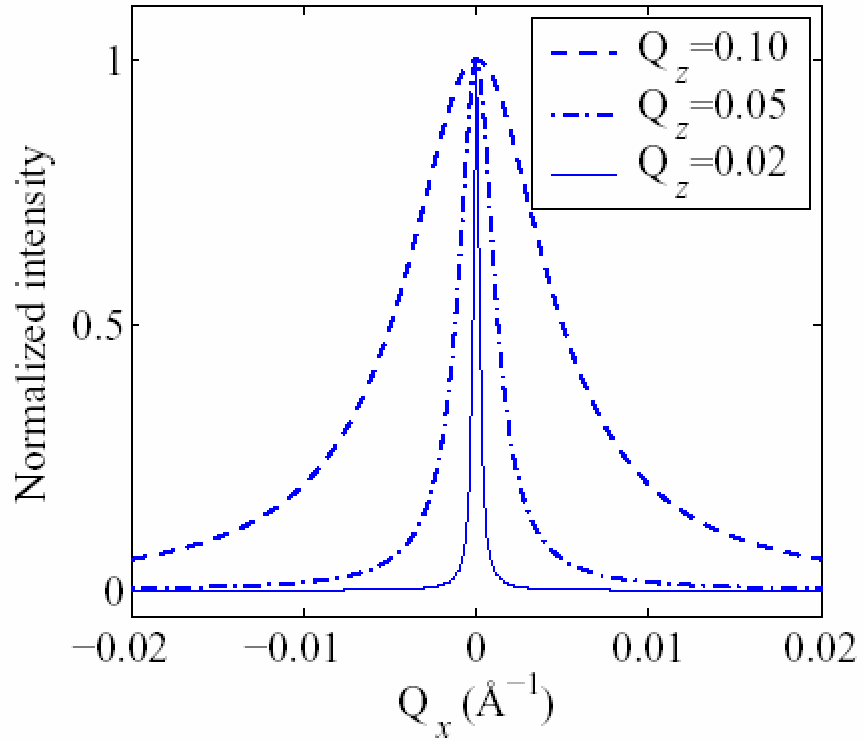
for $R < \xi$, interface appears rough, fractal behavior

$$S_{diff}(\vec{Q}) = \frac{\exp(-Q_z^2\sigma^2)}{Q_z^2} \times \int [\exp(Q_z^2 C(R)) - 1] \exp(iQ_{\parallel} R) d^2 R$$

S.K. Sinha, E.B. Sirota, S. Garoff, and H.B. Stanley, Phys. Rev. B 38 2297 (1988)

Specular and off-specular scattering

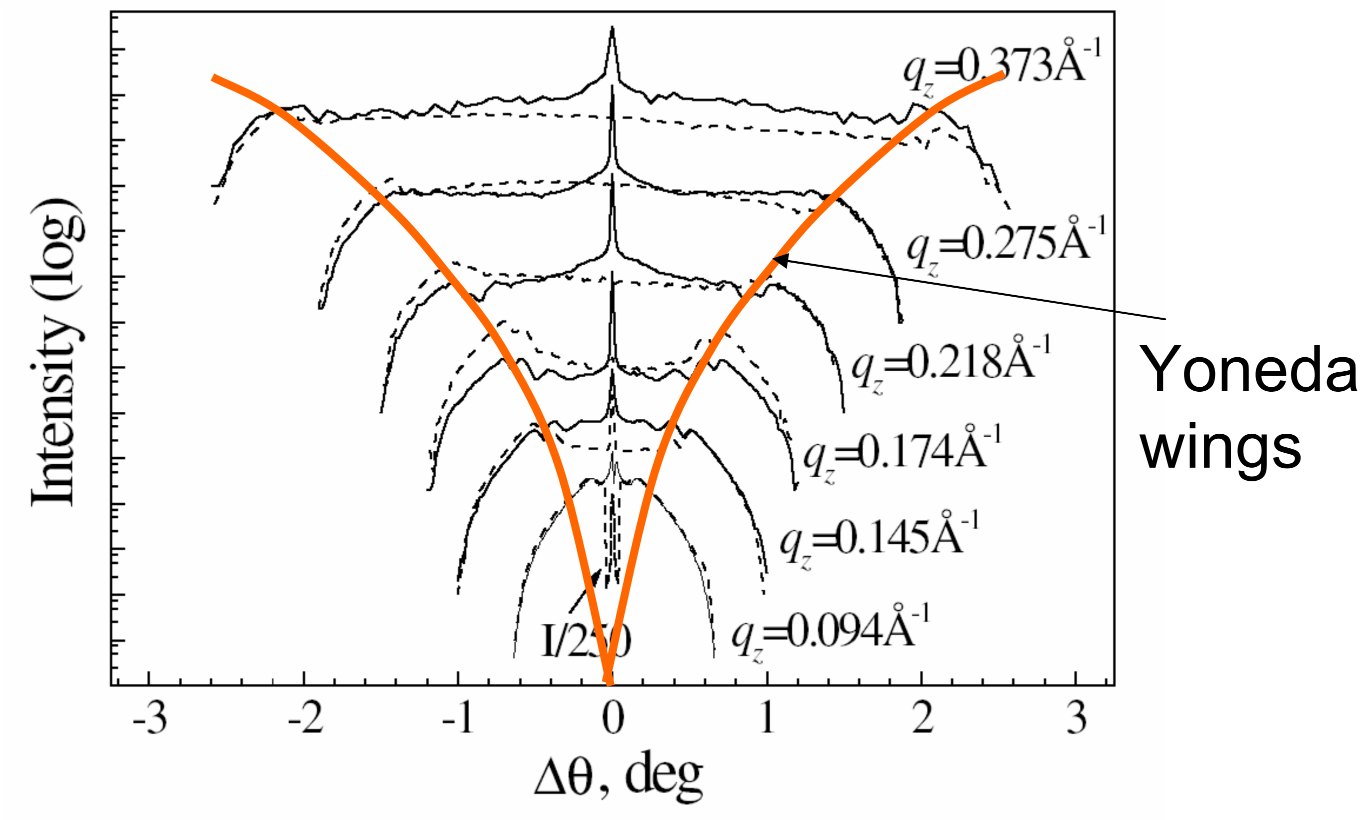




J. Als-Nielsen and Des McMorrow, Wiley, 2001

Transverse scans

Transverse scan from an FePt film on GaAs



A. Nefedov et al. J. Phys.: Condens. Matter **14,** 12273 (2002)

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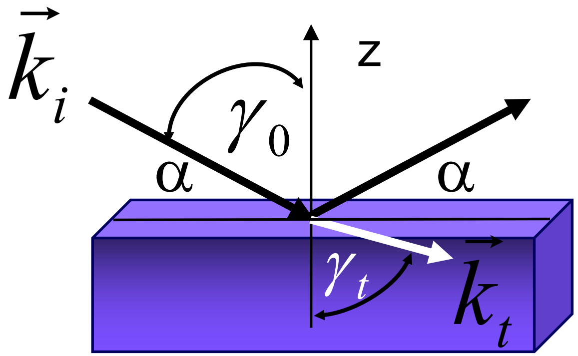
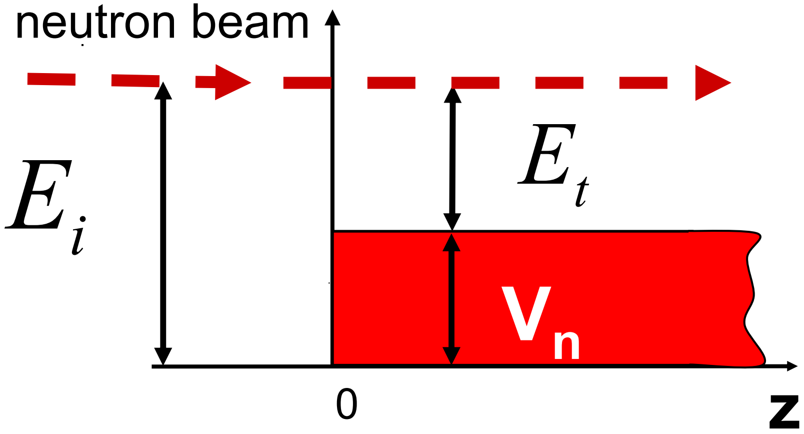
Refractive index for neutrons

Snell's law for specular reflection:



$$n = \frac{\sin\gamma_0}{\sin\gamma_t} = \frac{|\vec{k}_t|}{|\vec{k}_i|}$$

QM potential step for the z-component of the kinetic energy:



Nuclear potential:

$$V_n = \frac{2\pi\hbar^2}{m} N_A b_{coh}$$

Combining both

$$n^2 = \frac{\sin^2 \gamma_0}{\sin^2 \gamma_t} = \frac{\left|\vec{k}_t\right|^2}{\left|\vec{k}_i\right|^2} = \frac{E_t}{E_i} = \frac{E_i - V_n}{E_i} = 1 - \frac{4\pi}{k_i^2} N_A b_{coh}$$

N_A = nuclei number density

b_{coh} = coherent scattering length of nuclei A

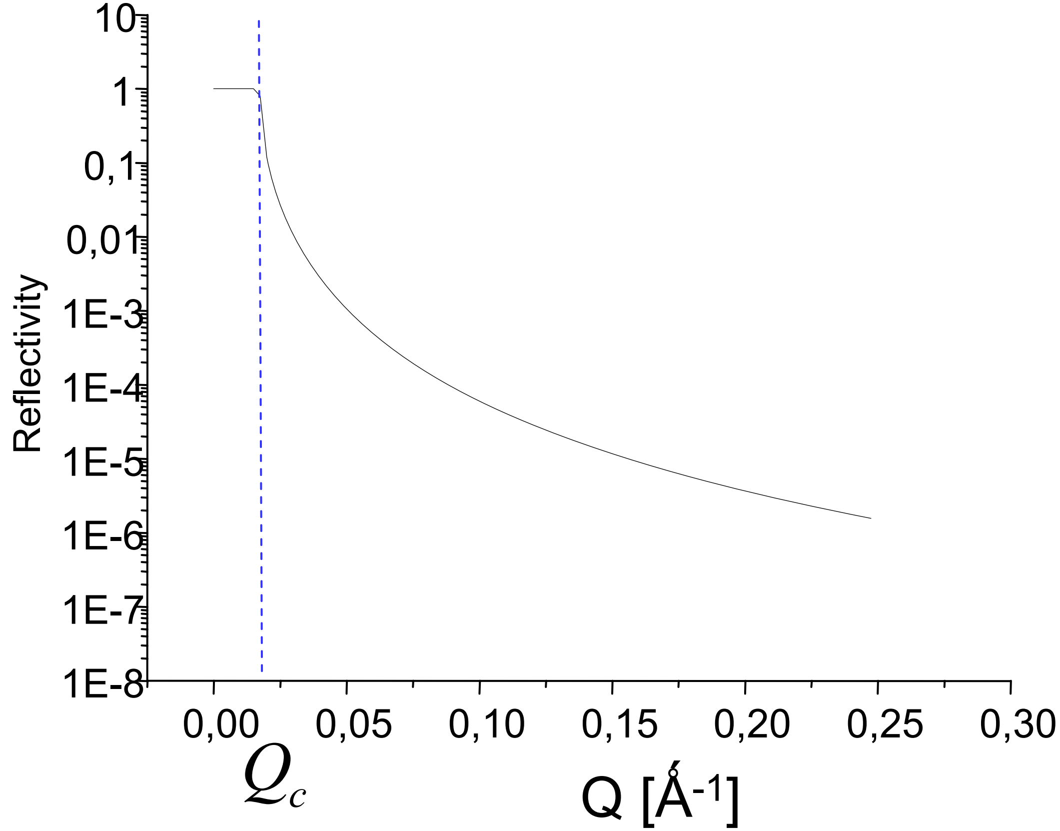
Notice that n ≤ 1, only for $b_{coh} \geq 0$

Total reflection only for $b_{coh} \geq 0$

$$Q_c = \frac{4\pi}{\lambda} \sin \alpha_c = \sqrt{4k^2 (1 - n^2)} = \sqrt{16\pi N_A b_{coh}}$$

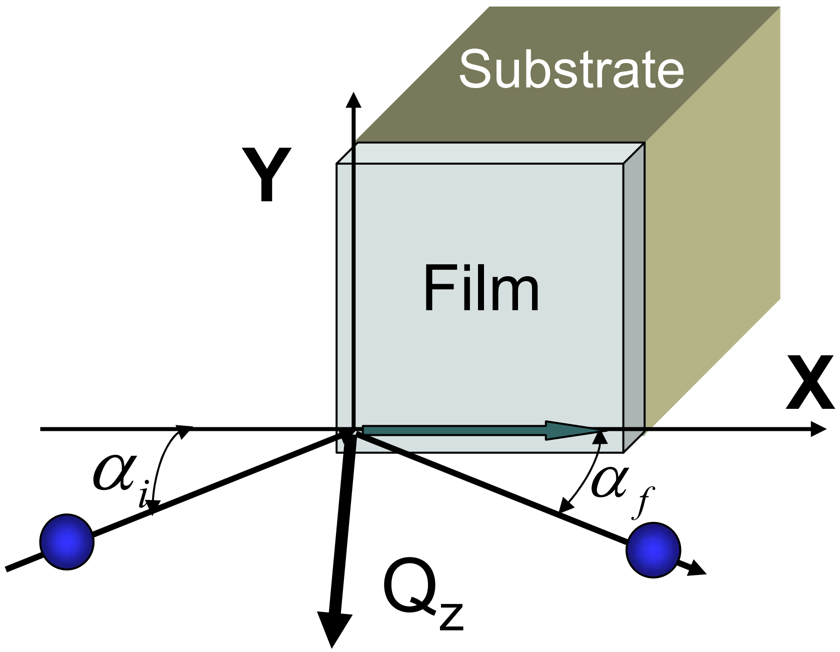
$$Q_c \propto \sqrt{N_A b_{coh}}$$

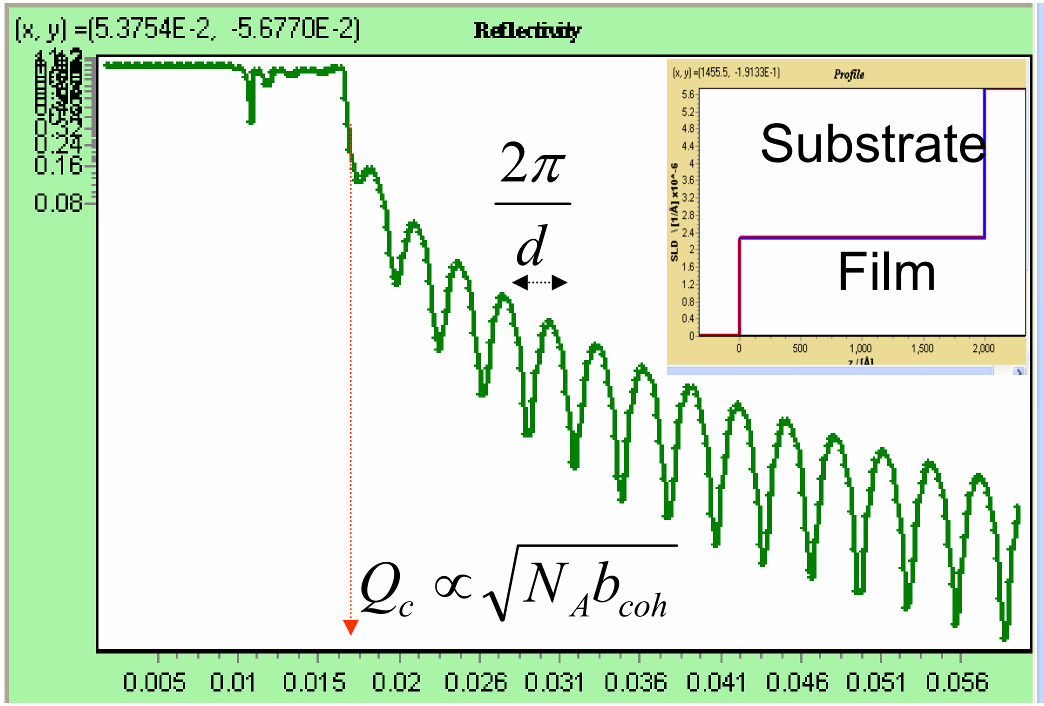
Example:
Neutron reflectivity from a non-magnetic, infinite thick and flat sample



For $Q_z < Q_c$: R = 1, only for b >0, i.e. for coherent scattering length.

Neutron Reflectivity





- ❖Film thickness
- ❖Interface roughness
- ❖Density profiles

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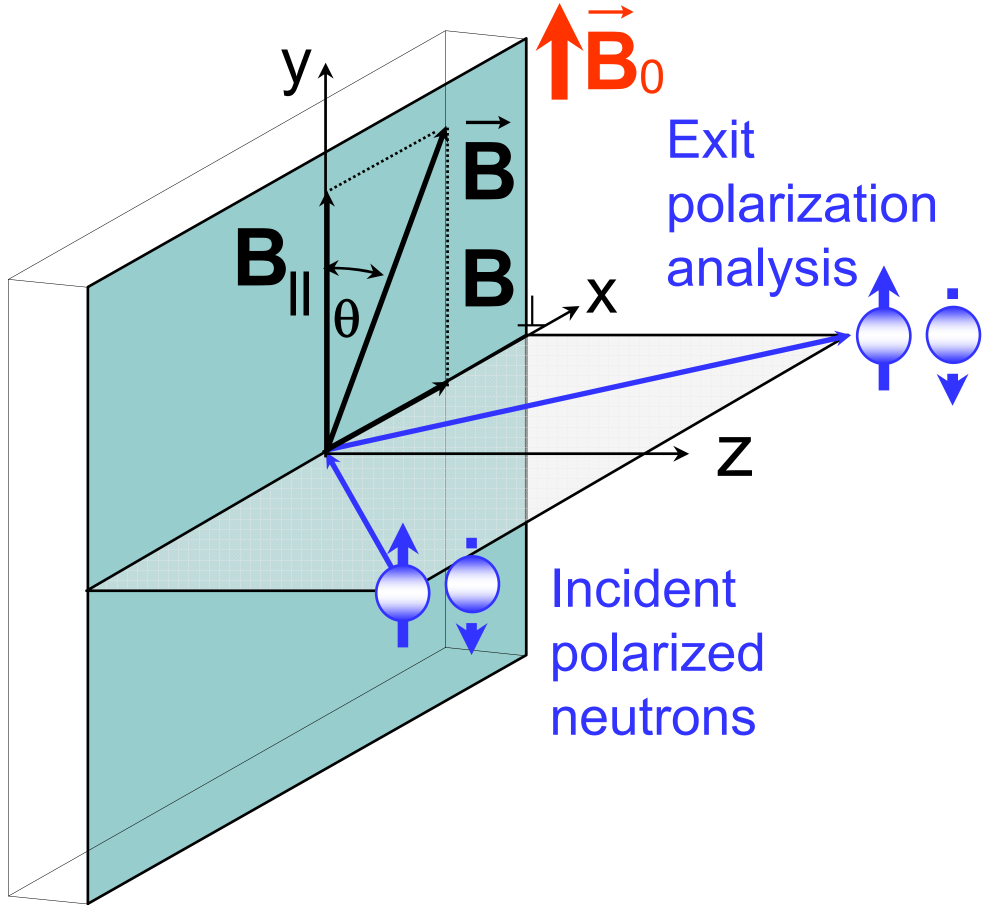
Polarized Neutron Reflectivity: The four cross-sections



$$\vec{B} = \left(B_{\perp}, B_{||}, 0\right)$$

Four cross sections:

$R^{+,+}$ $R^{-,-}$ $R^{+,-}$ $R^{-,+}$

$R^{\pm,\pm}$: Reflectivities

Quantum mechanical description of the scattering process

1D optical potential:

$$V = \underbrace{\frac{2\pi\hbar^2}{m} N_A b}_{\text{nuclear part}} - \underbrace{\vec{\mu}\cdot\vec{B}}_{\text{magnetic part}}$$

N_A: atomic number density

b: coherent neutron scattering length

$\vec{\mu}$: neutron magnetic momentum

$$\boxed{\vec{\mu} = \gamma\mu_N\hat{\sigma}}$$

μ_N: nuclear magneton

γ= -1.913: gyromagnetic ratio

$\hat{\sigma}$: Pauli spin operator

Schrödinger equation:

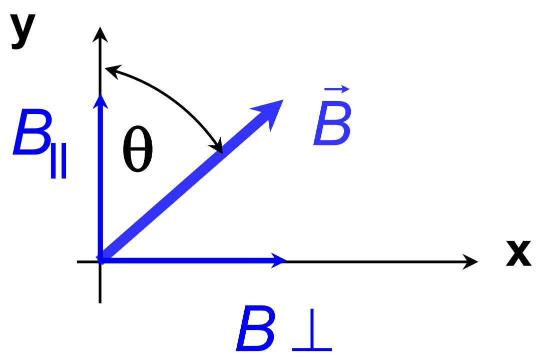
$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V\right]\Psi(z) = E\Psi(z)$$

$$\sigma_\perp = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix};\quad \sigma_{||} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix};\quad \sigma_z = \begin{pmatrix} 0 & -\mathbf{i} \\ \mathbf{i} & 0 \end{pmatrix}$$

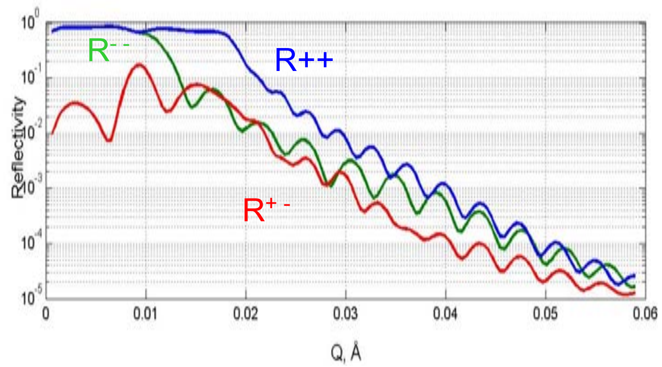
Polarized Reflectivity

- Non-Spin-Flip (NSF)

$$R^{\pm,\pm} = \underbrace{\frac{1}{2}\left(|r_+|^2 + |r_-|^2\right)}_{nuclear} \pm \underbrace{\frac{1}{2}\left(|r_+|^2 - |r_-|^2\right)\mathbf{cos}\,\theta}_{magnetic}$$



$$\Rightarrow \quad R^{+,+} - R^{-,-} = \left(|r_+|^2 - |r_-|^2\right)\mathbf{cos}\,\theta \propto B_{||}$$



- Spin-Flip (SF)

$$R^{\pm,\mp} = \frac{1}{4}|r_+ - r_-|^2\,\mathbf{sin}^2\,\theta \propto B_{\perp}{}^2$$

$r_\pm$: reflection amplitudes

Reflectivity and Asymmetry

$$R^{+} = R^{++} + R^{+-}$$

$$R^{-} = R^{--} + R^{-+}$$

$$R^{+} - R^{-} = R^{++} - R^{--}$$

$$R^{+} + R^{-} = R^{++} + R^{--} + R^{+-} + R^{-+}$$

- Spin Asymmetry

$$SA = \frac{R^{+} - R^{-}}{R^{+} + R^{-}} = \frac{R^{++} - R^{--}}{R^{++} + R^{--} + R^{+-} + R^{-+}}$$

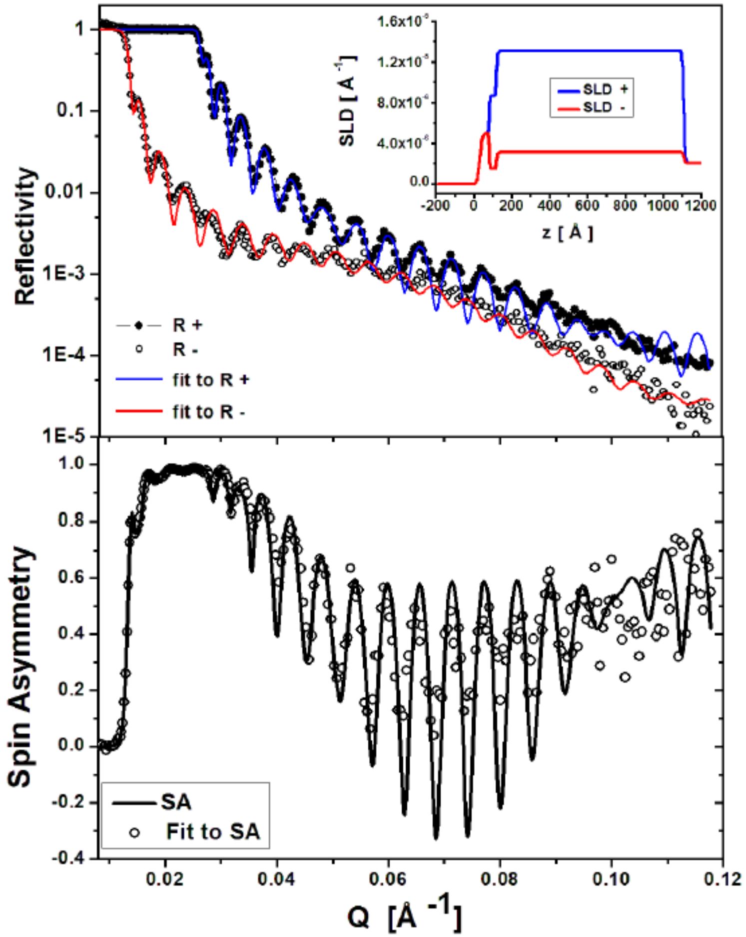
Reflectivity and Asymmetry of single Fe - layer

Reflectivities **:**

R^+ *and* R^-

Spin Asymmetry **:**

$$SA = \frac{R^+ - R^-}{R^+ + R^-}$$



F. Radu et al.

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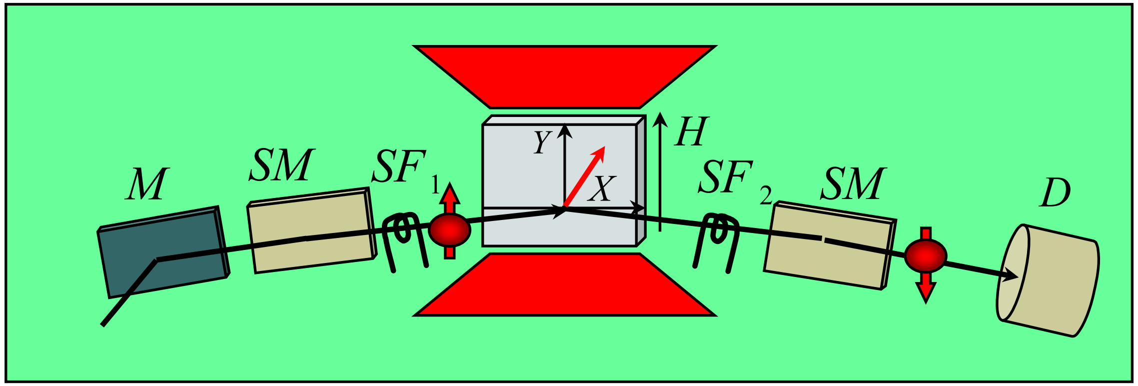
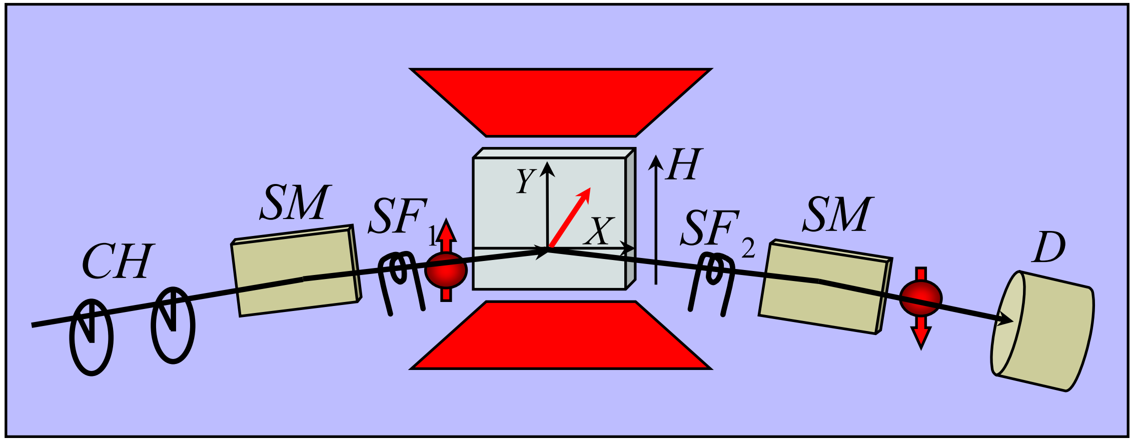
Instrumention: two types

- Angle dispersive
- monochromatic beam
- scanning of θ

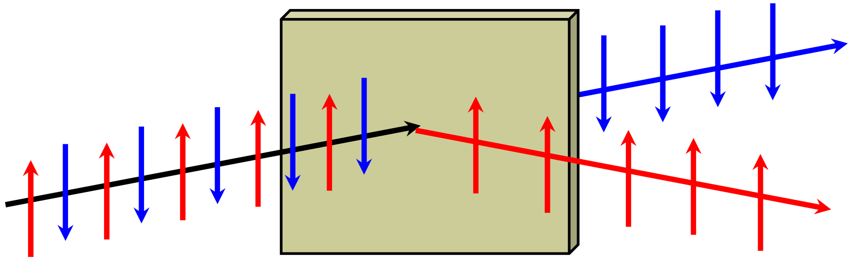


- Wavelength dispersive
- White beam
- TOF method,
- fixed θ

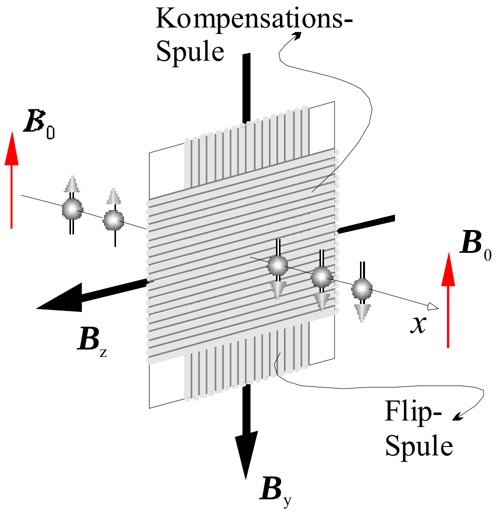


Polarizer, analyzer, spin flipper

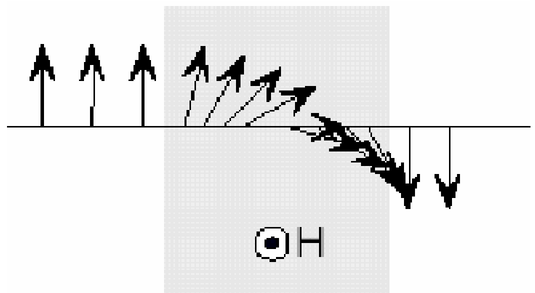
transmission supermirror:



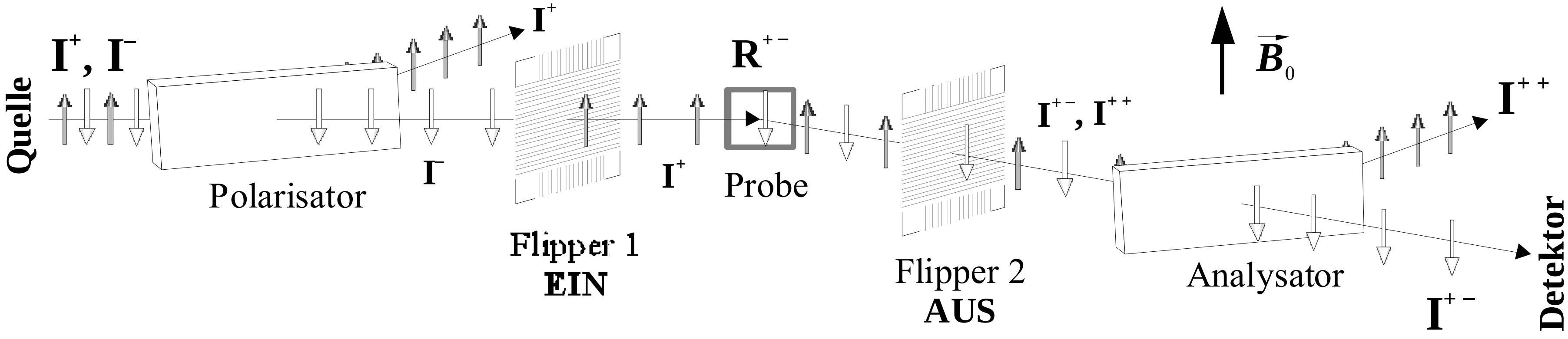
Mezei spin-π neutron–flipper



Adiabatic spin rotation



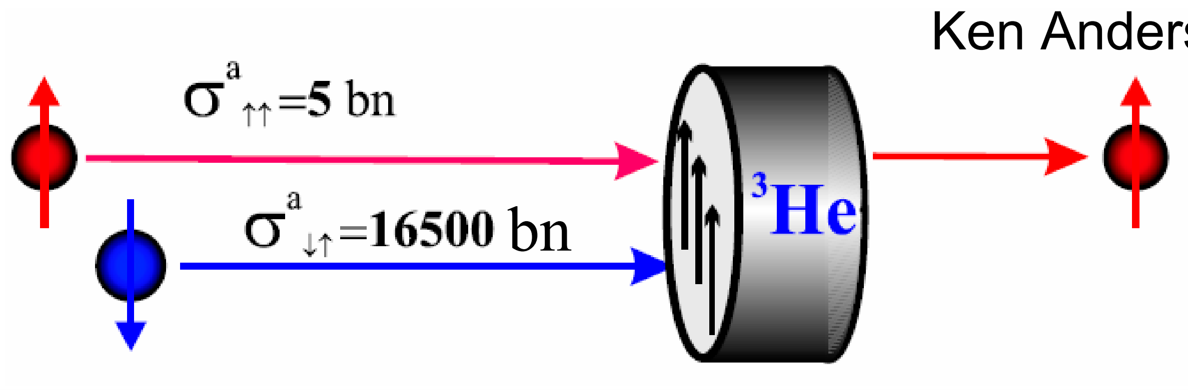
Schematics: neutron reflectometer with complete polarization analysis

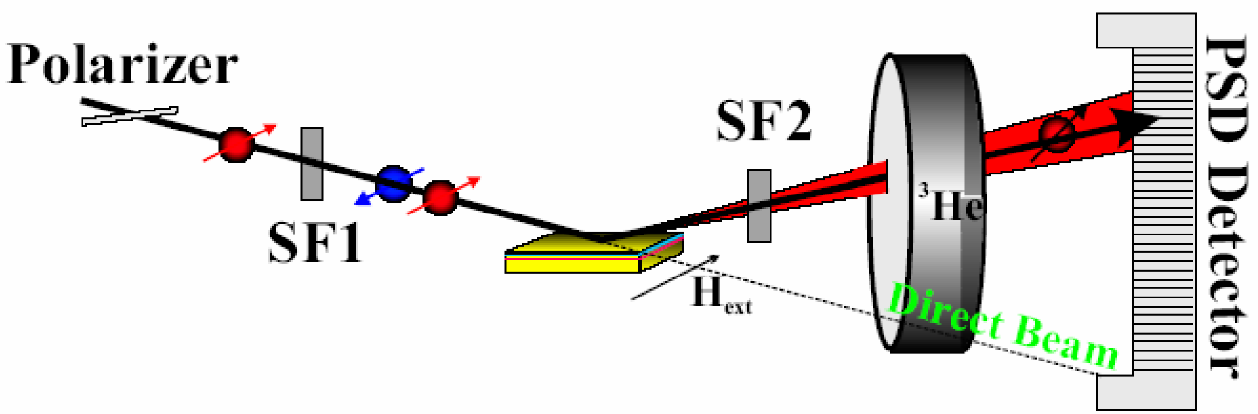


This part is identical for angle dispersive and wavelength dispersive instruments

^{3}He Spin-Filter for the spin analysis of diffuse scattering

Ken Anderson, ILL

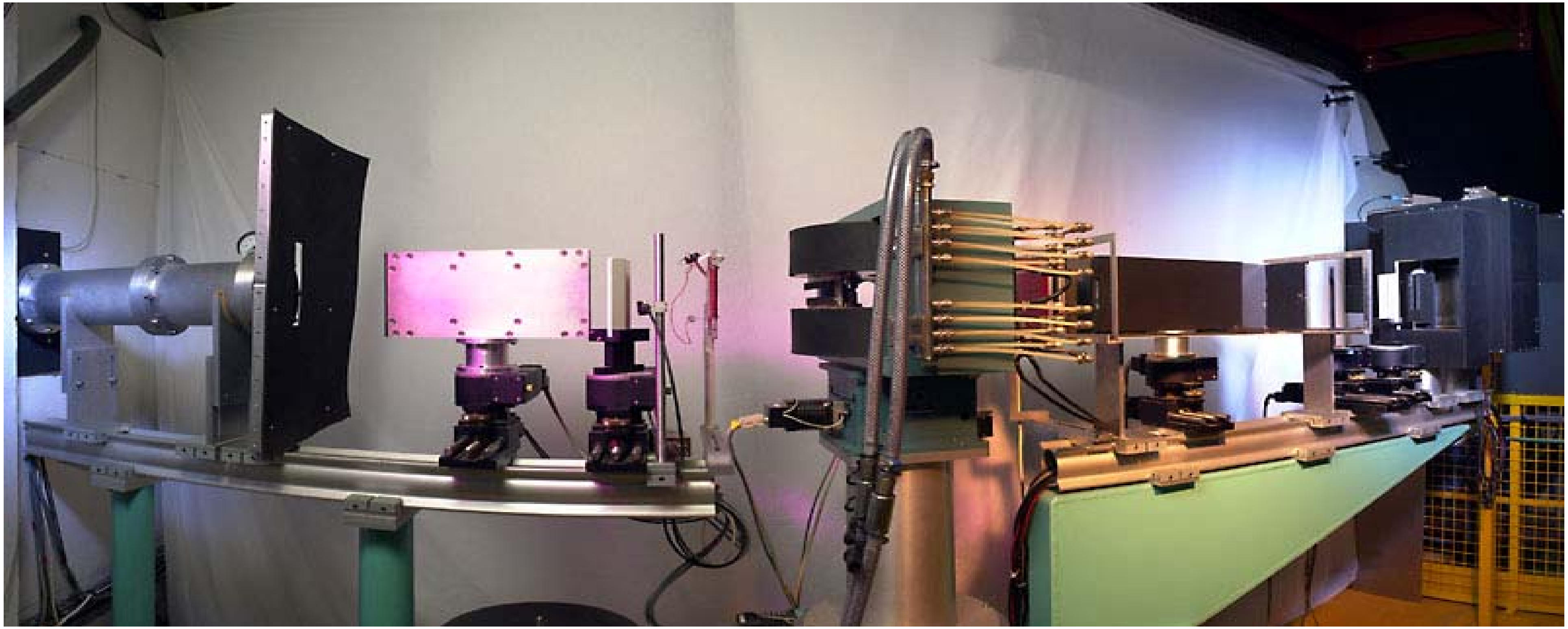




^{3}He spin-filter technique is very useful for the polarization analysis of off-specular scattering. Compared to solid-state analyzer, the spin-filter covers a wider angular range and is free of small angle scattering.

The ADAM Reflectometer at the ILL

Polarizer-SM | Front flipper | Sample in magnet | Back flipper | Analyzer-SM | Detector



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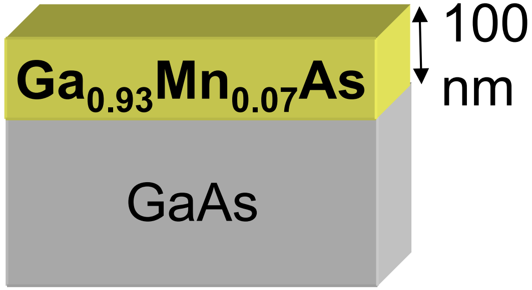
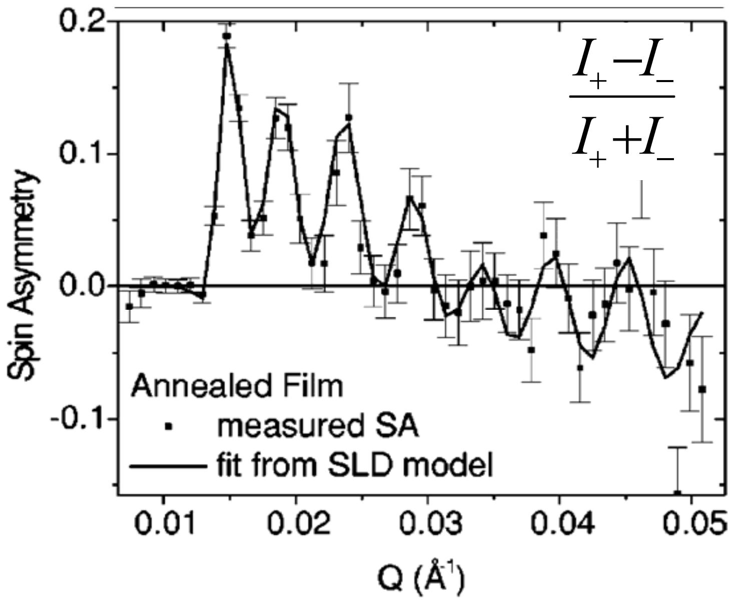
Nuclear and magnetic density profile in (GaMn)As

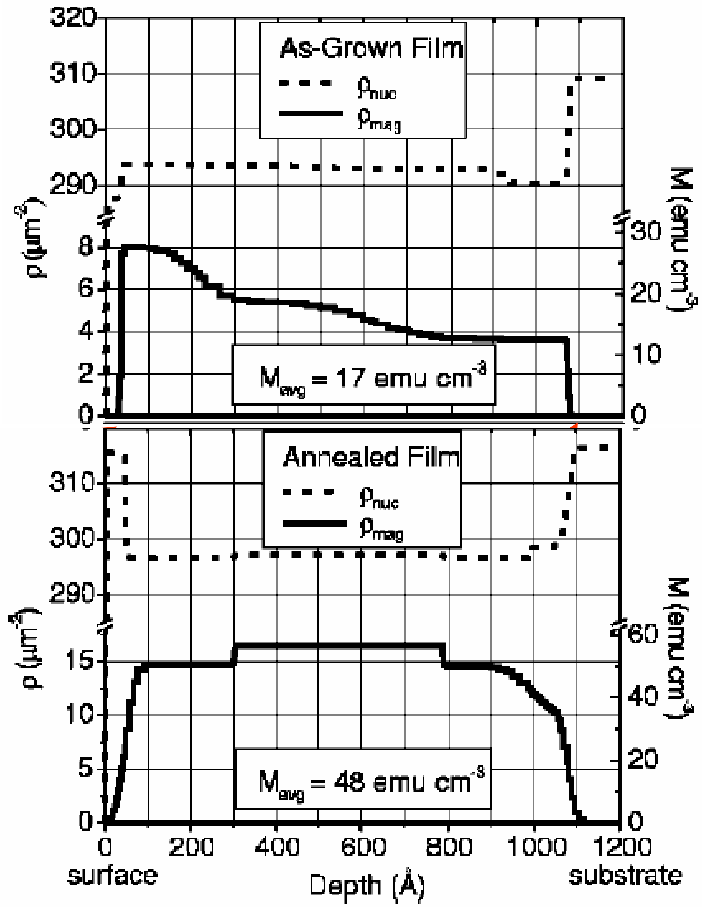


before annealing

after annealing at 280°C for 1 h

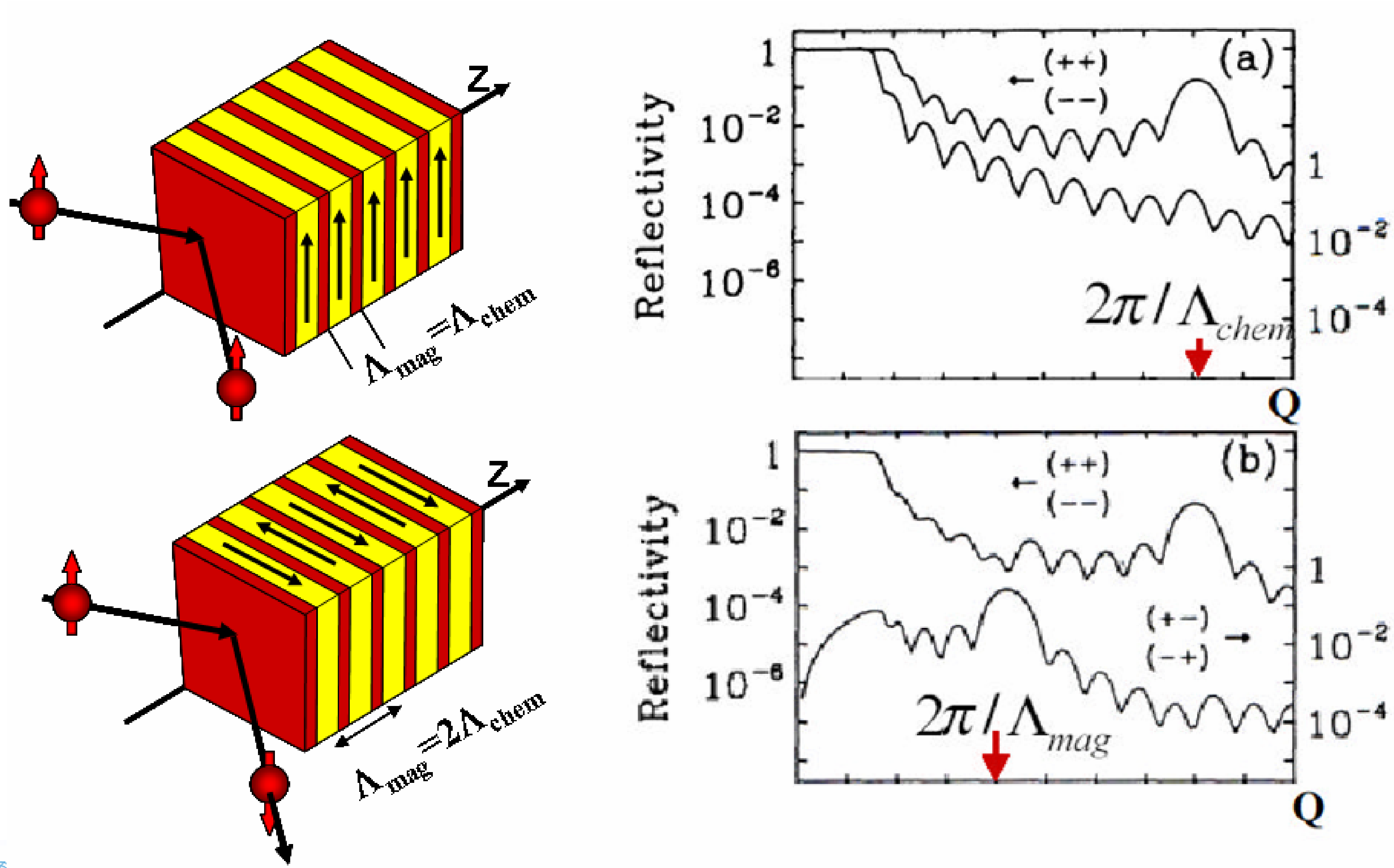
Spin asymmetry



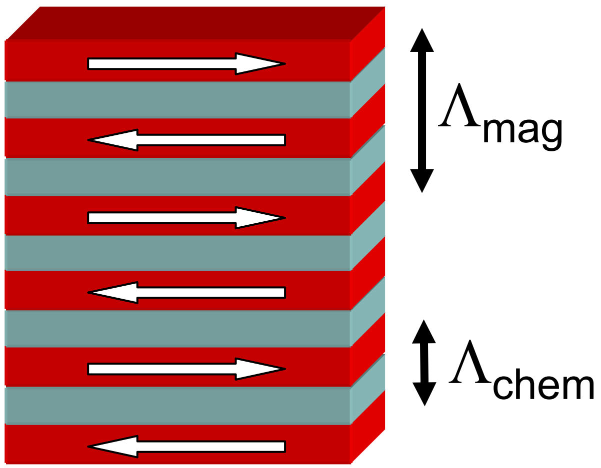


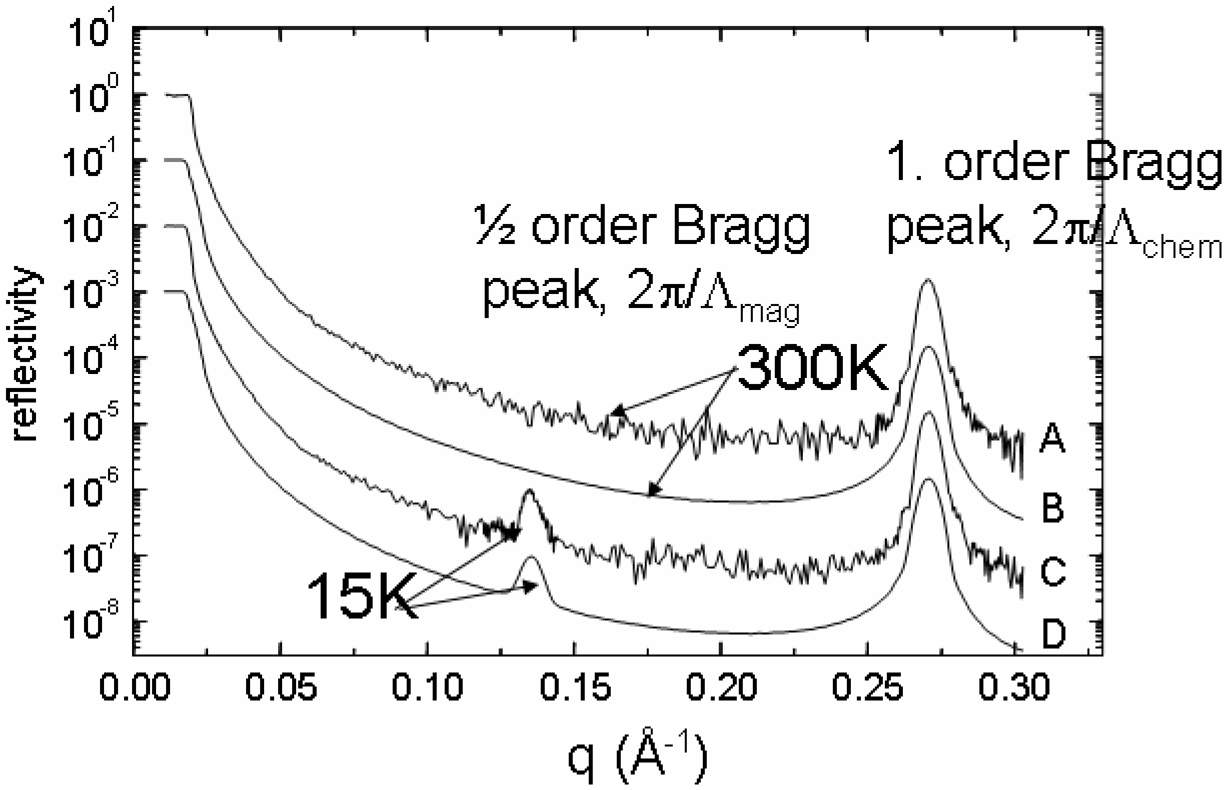
B.J. Kirby et al. Phys. Rev. B **69** (2004) 081307

PNR from model-spinstructures in magnetic multilayers



AF case: NR of Fe(2ML)/V(13ML) above and below T_N = 100K



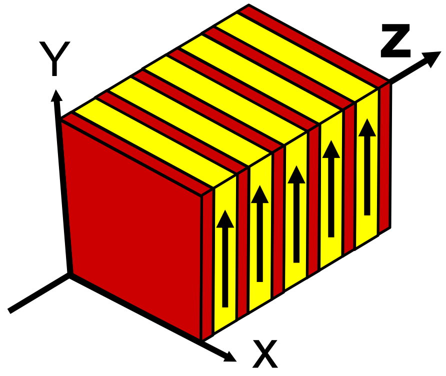


Antiferromagnetic coupling below the Néel temperature
Intensity = M^2

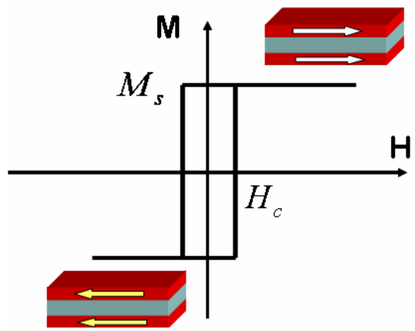
V. Leiner, K. Westerholt, A. M. Blixt, H. Zabel and B. Hjörvarsson: Physical Review Letters, **91**, 037202 (2003)

Three steps to FM sample analysis

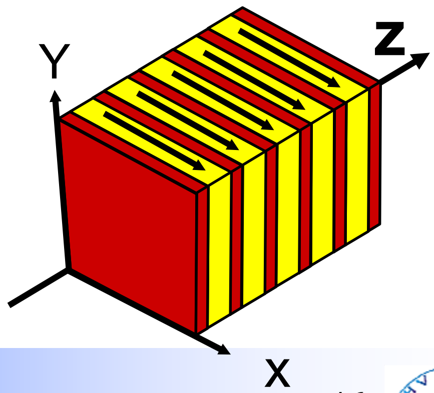
1. Align sample with easy axis parallel to Y-axis



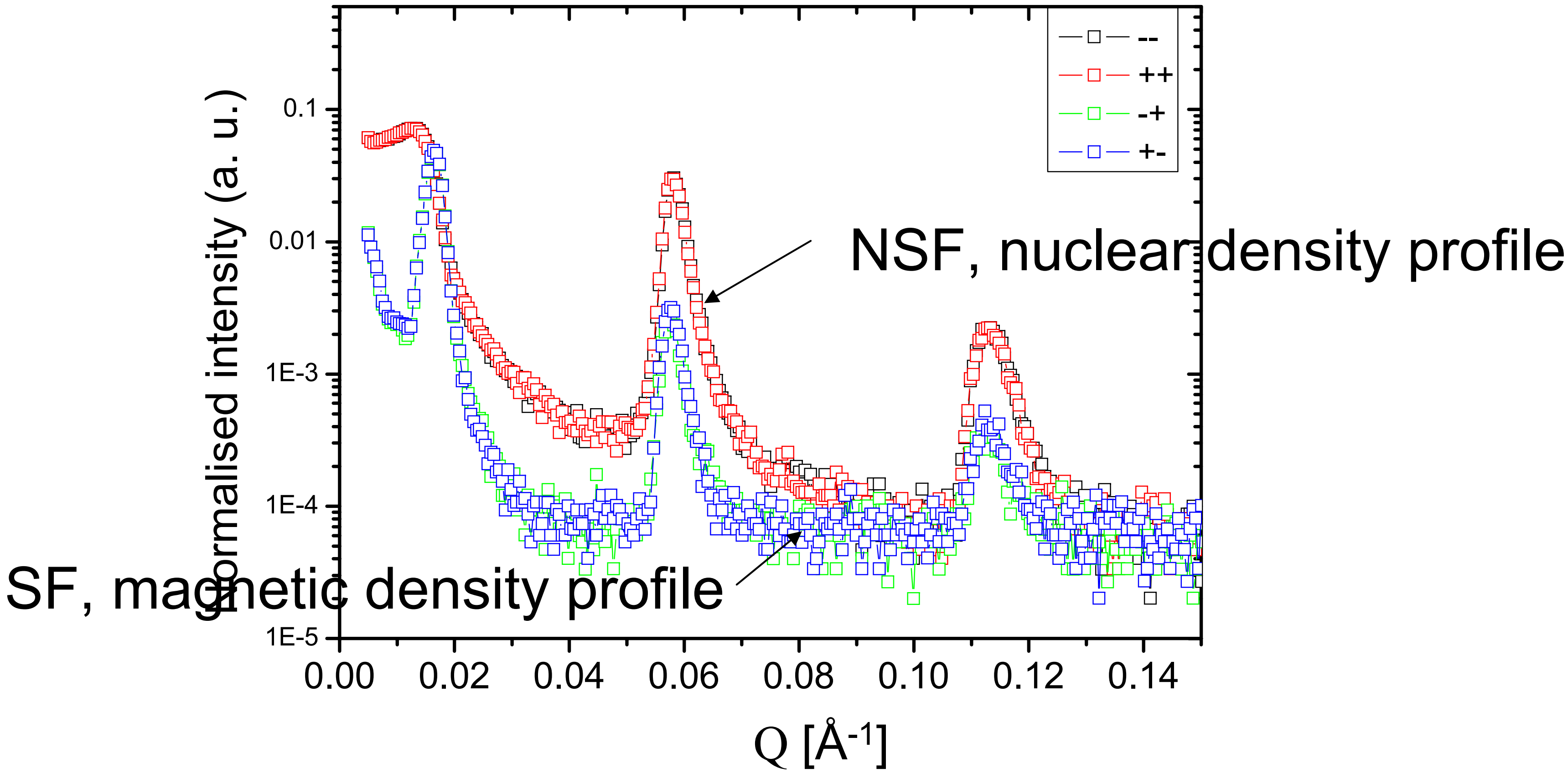
2. Go to saturation and then back to remanence



3. Rotate sample in remanence by 90°. Now the NSF reflectivity is only nuclear, and the SF reflectivity is only magnetic.



PNR in remanence



Nuclear and magnetic density profiles have the same periodicity but different shape.

M. Vadala, K. Zhernenkov, M. Wolff, H. Zabel, August 2006, ADAM reflectometer

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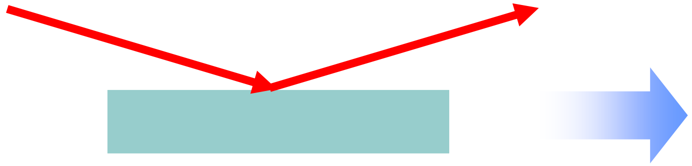
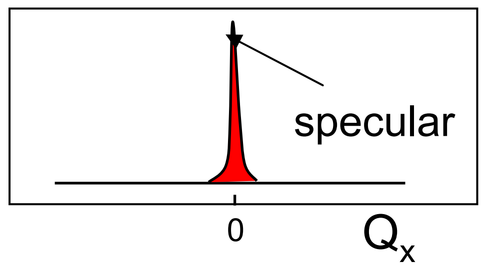
Transverse reflectivity

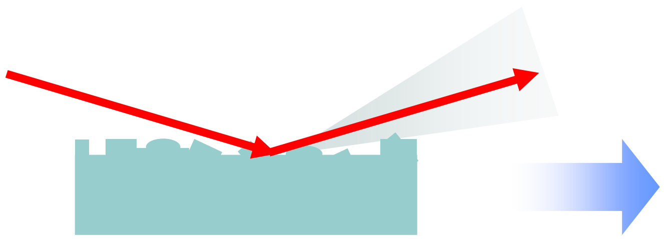
Transverse scan

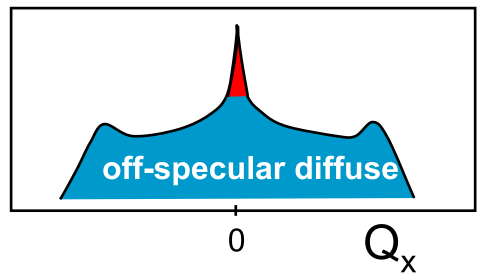
Flat film:
Specular



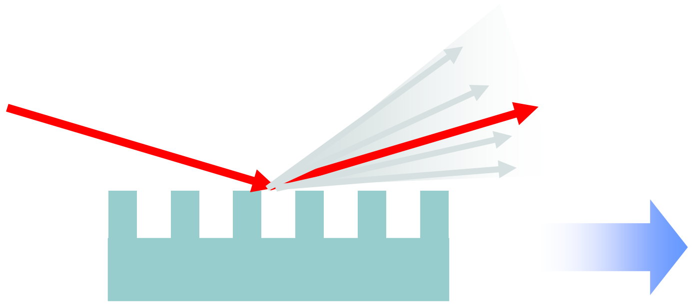


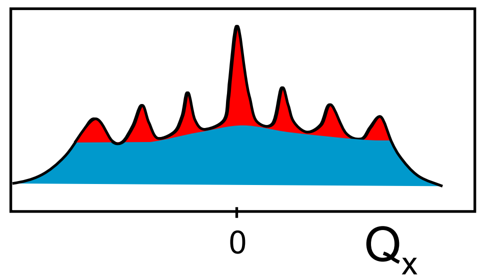
Rough surface:
Specular + Diffuse



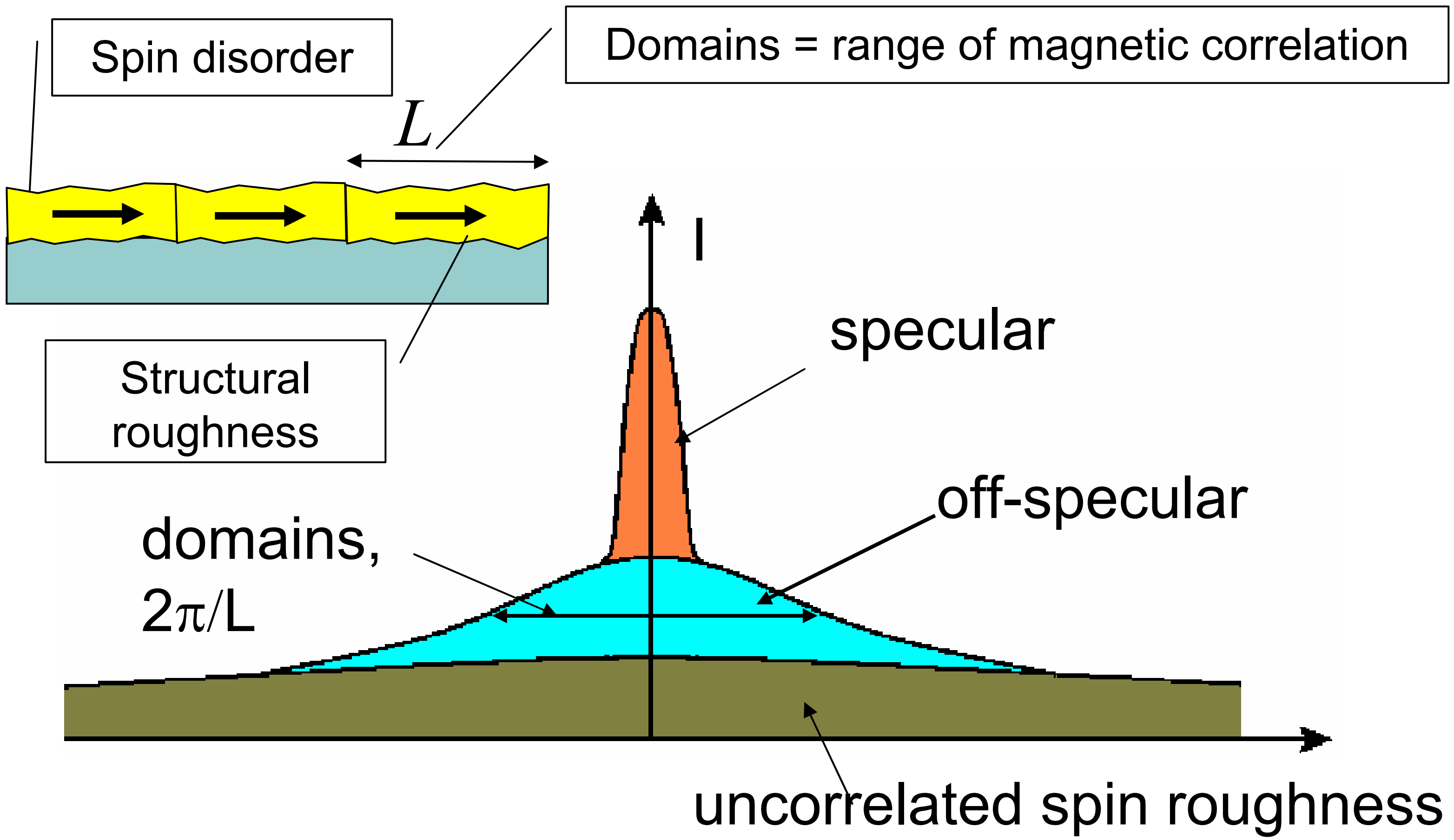


Lateral periodic pattern:
Diffuse + Bragg

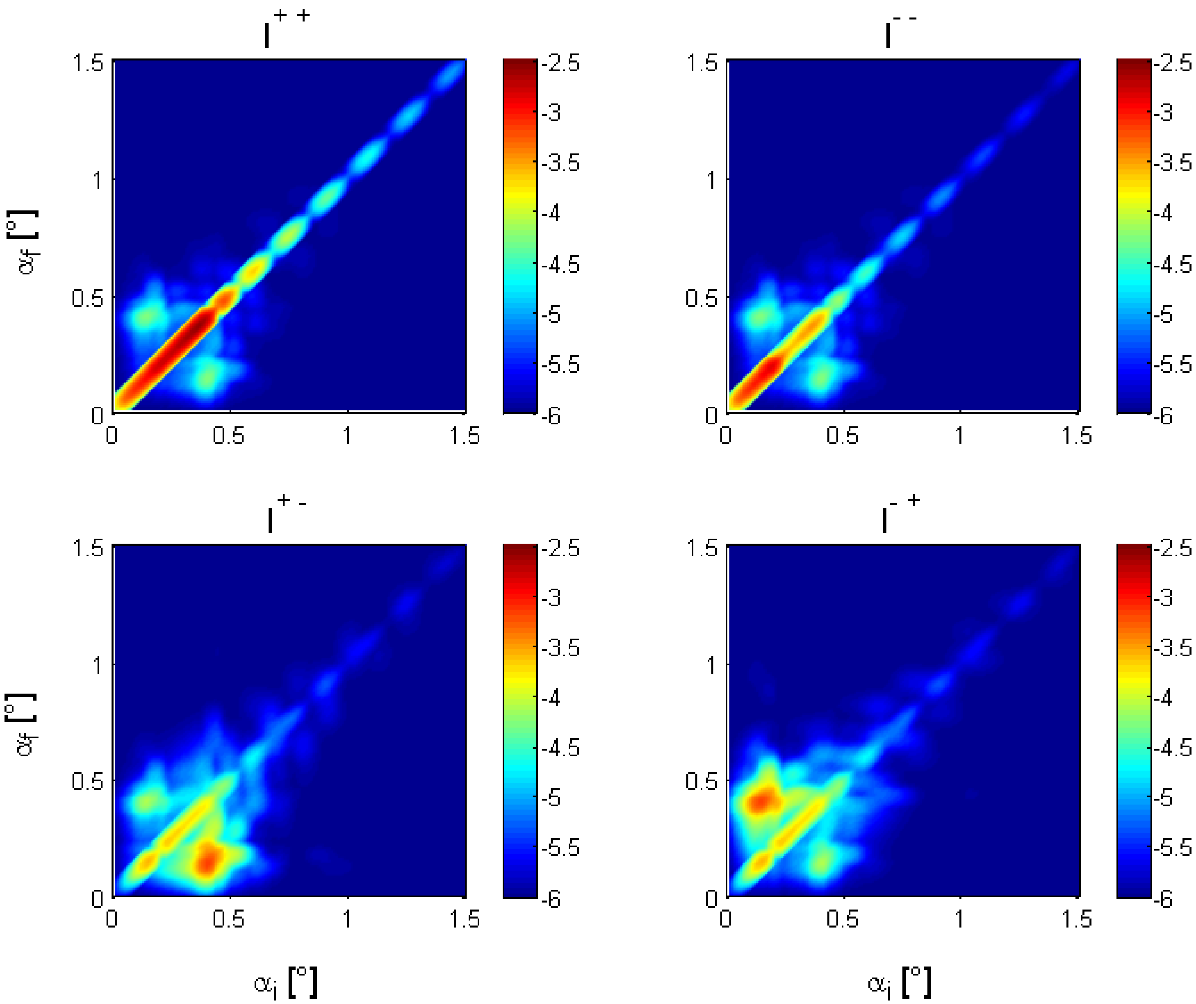




Types of magnetic roughness

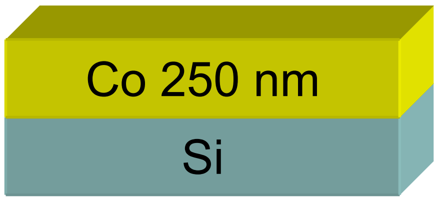


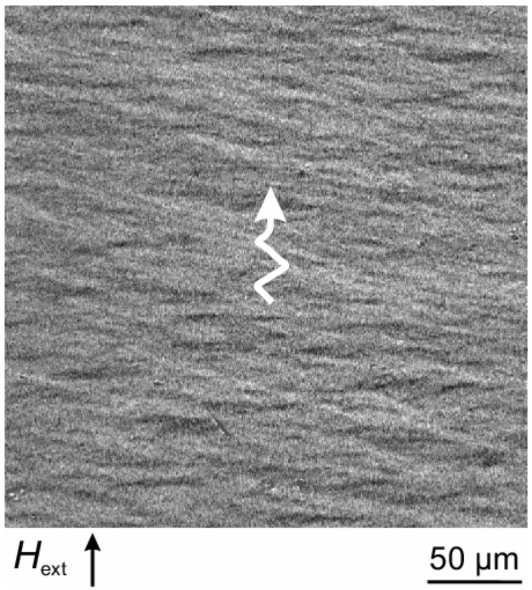
Domain size: 1 μm (´<< L_c)

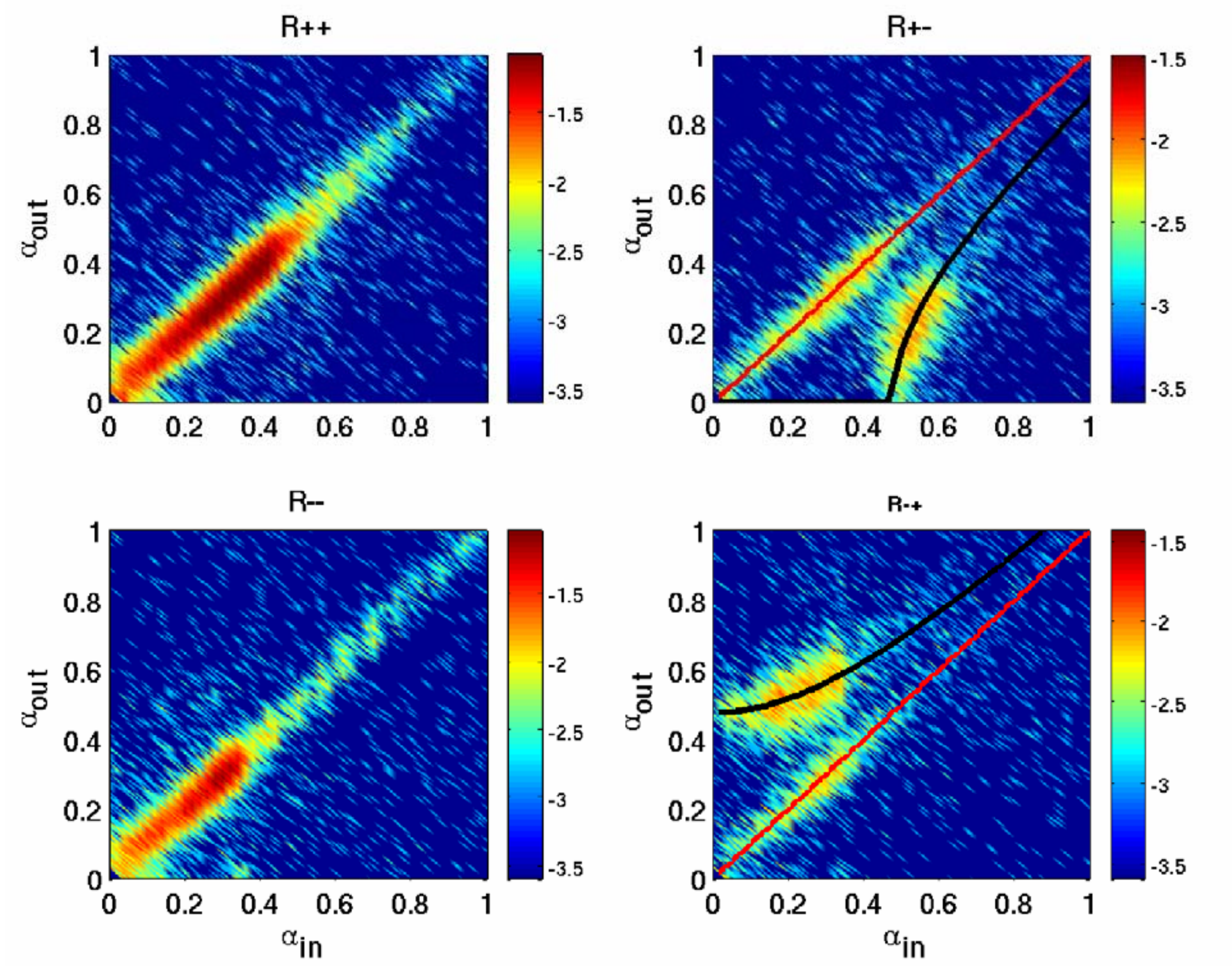


Simulations from B.P. Toperberg

Single ferromagnetic film in the domain state

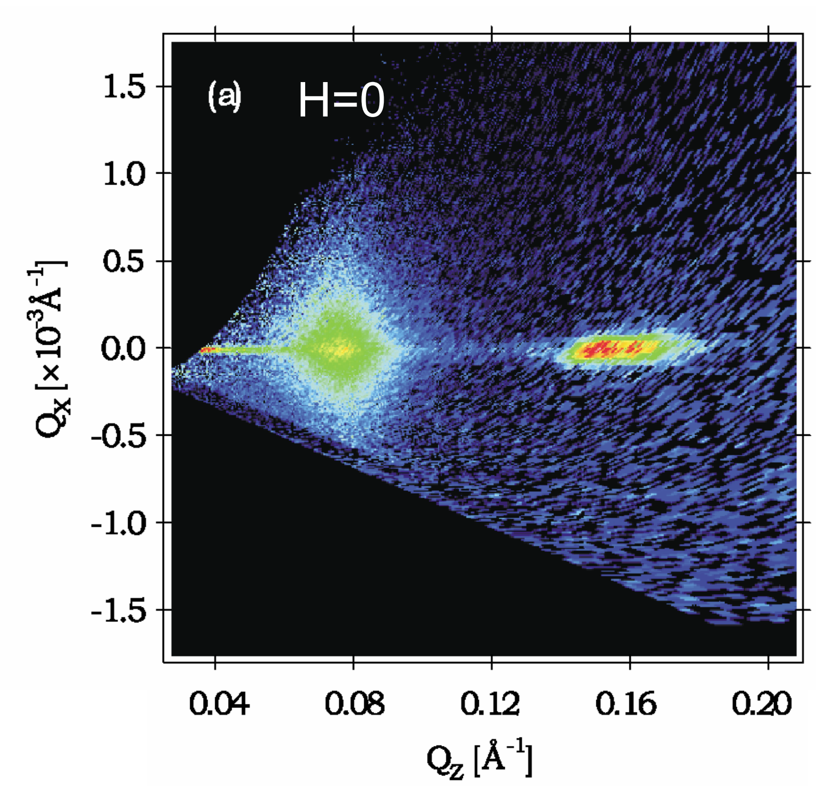


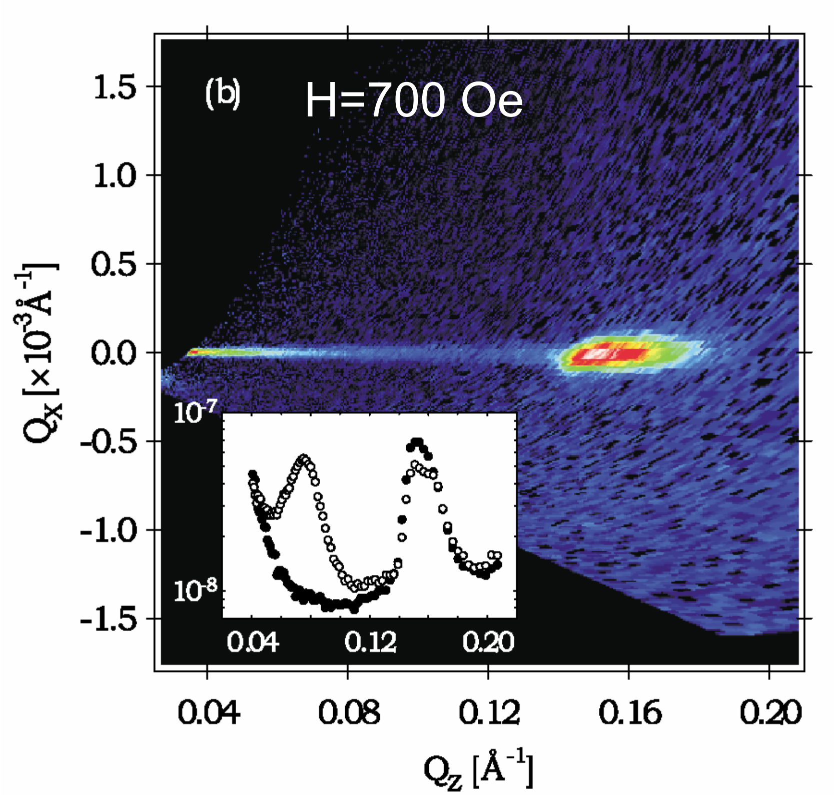




F. Radu et al. J. Phys.: Condens. Matter 17 (2005) 1711

Magnetic roughness in Co/Cu superlattices

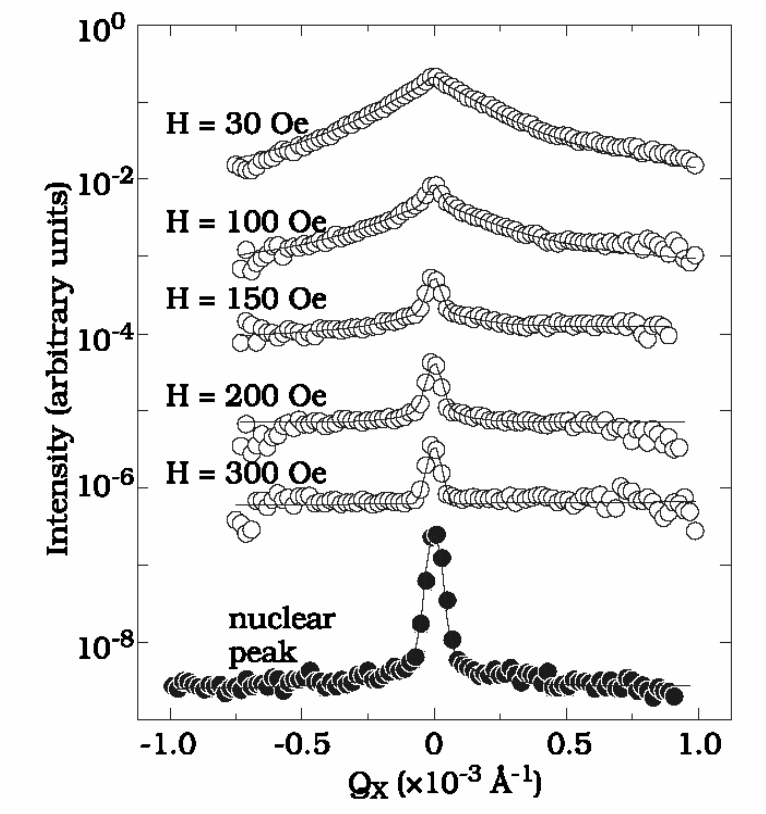




- ½ order AF peak, only diffuse peak ⇒ small domain size
- weak out-of-plane correlation, gradient in periodicity

S. Langridge, J. Schamlian, C.H. Marrows, D.T. Dekadjevi, B.J. Hickey, PRL **85**, 4964 (2000).

Transverse scans across half-order AF peak



$$S_{Diff}(Q) = DW \int d^2\vec{r} e^{i\vec{Q}_{\parallel}\cdot\vec{r}} [s + m + sm]$$

s = structural roughness

m =domain distribution roughness

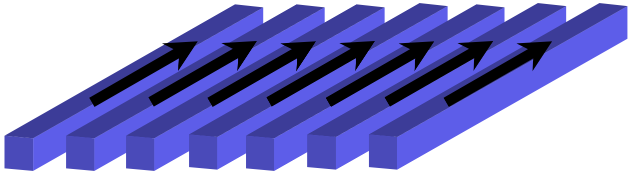
sm =cross term contains magnetic roughness

Diffuse scattering due to:

- domain size distribution
- orientational domain distribution
- Lorentzian profile changes into Gaussian profile with increasing domain size
- Diffuse scattering diminishes in high fields

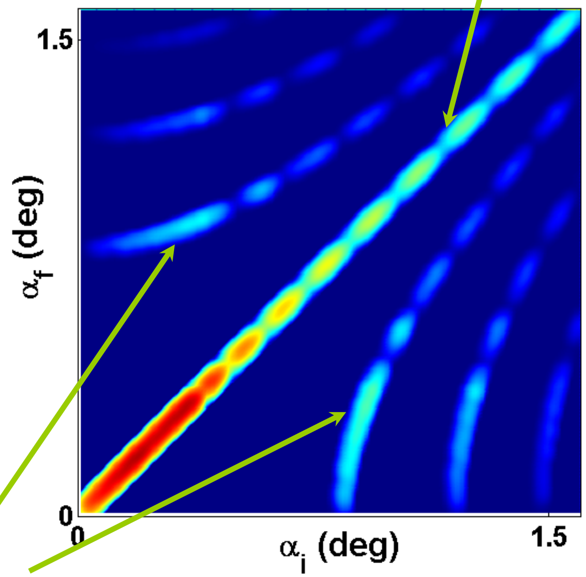
Content

PNR from patterned films



Specular reflectivity

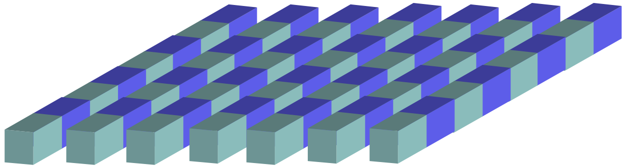
Simulation:



Bragg reflections

Courtesy K. Theis-Bröhl, Bochum

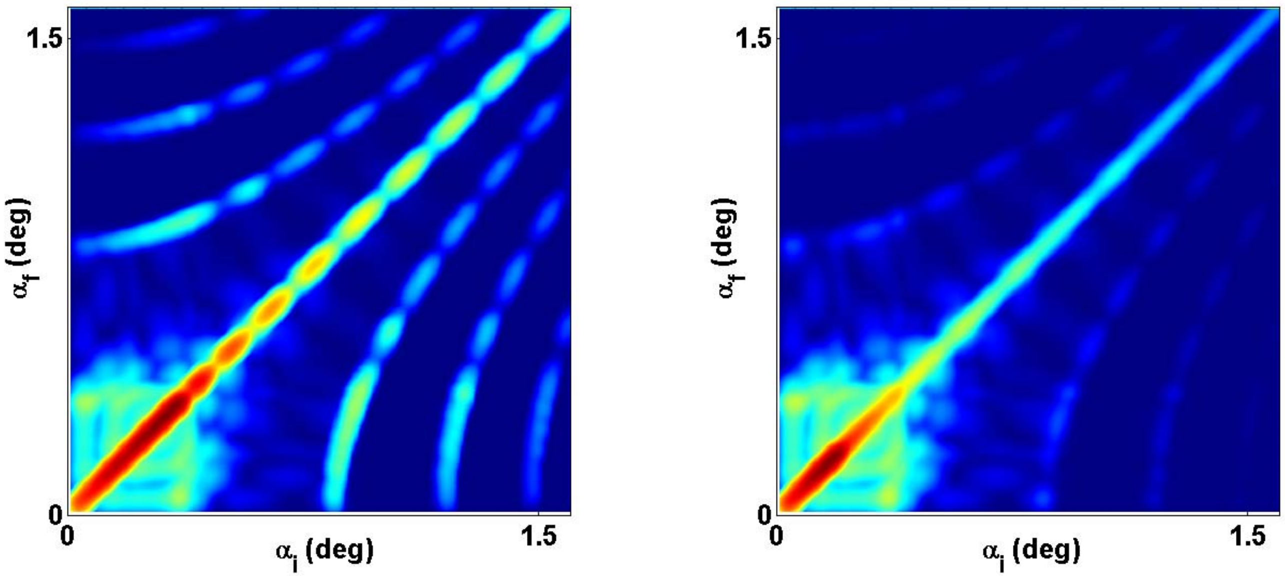
PNR from patterned films: domains



Non-spin-flip channels

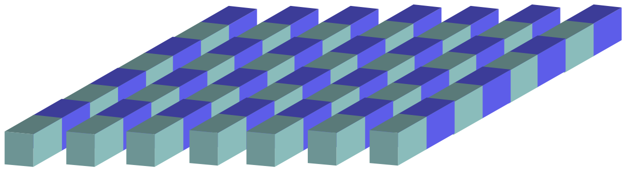
Simulation:

R^{++} R^{--}



Courtesy K. Theis-Bröhl, Bochum

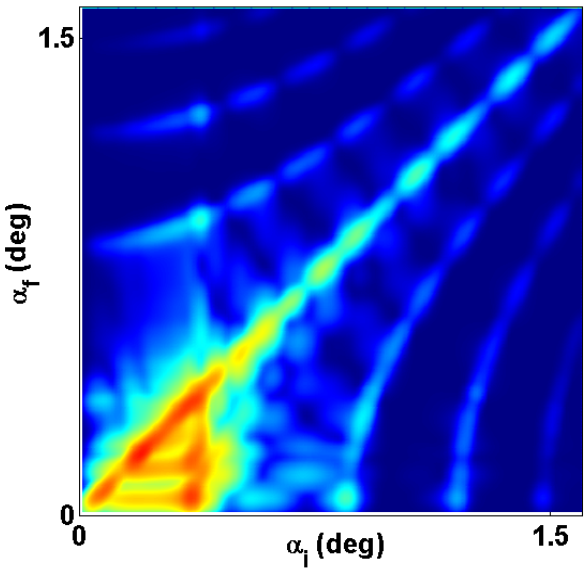
PNR from patterned films: domains



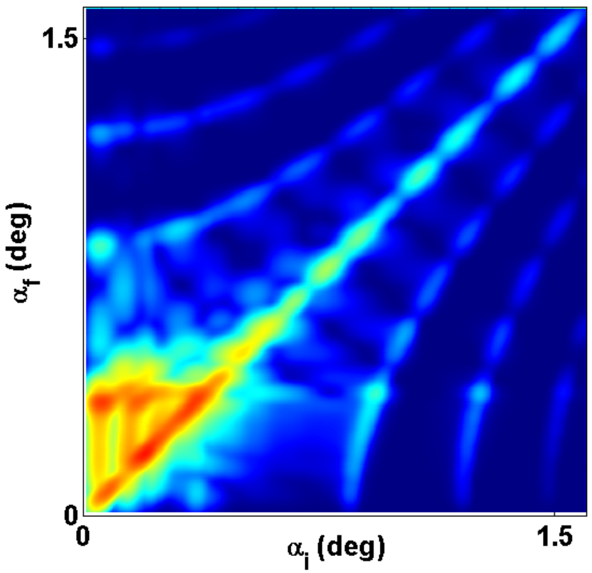
Spin-flip channels

Simulation:

R^{+-}

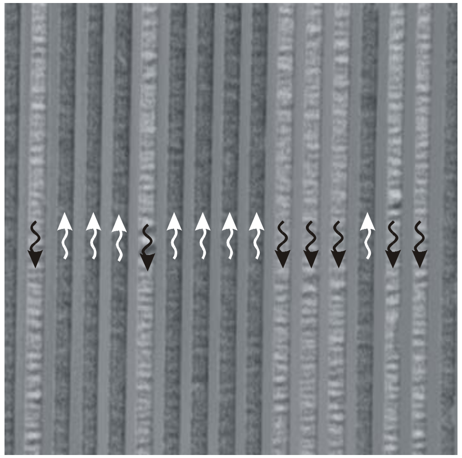


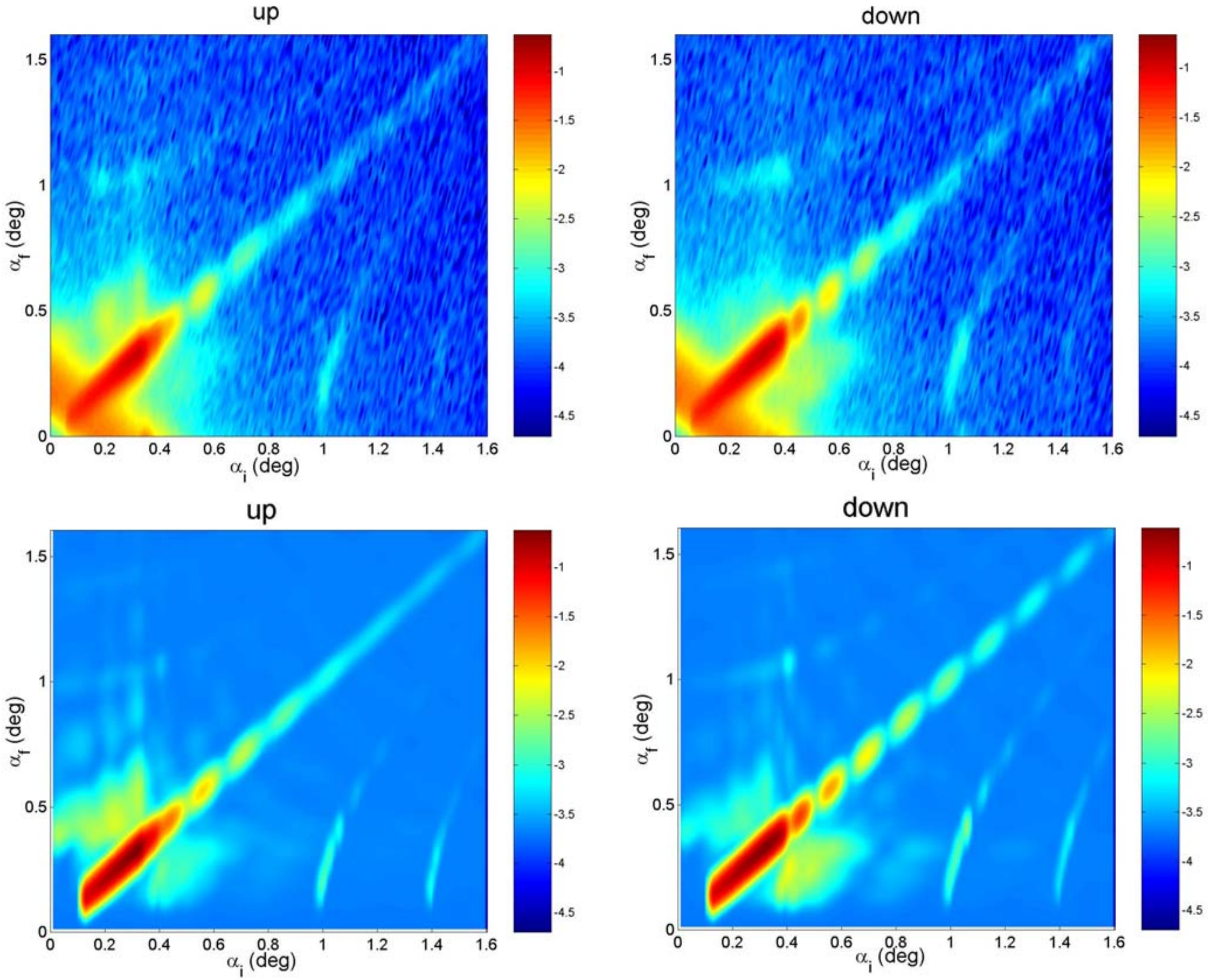
R^{-+}



Reciprocal space map from a stripe array

Experiment:

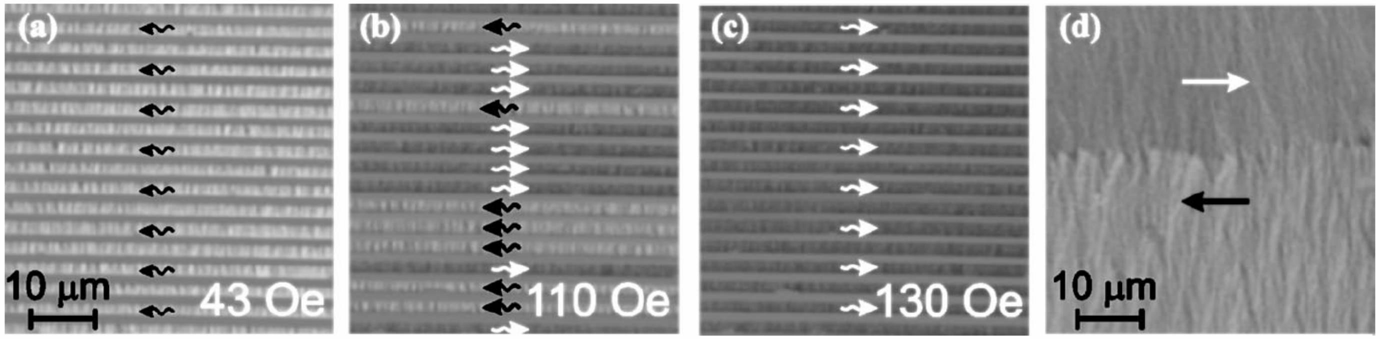




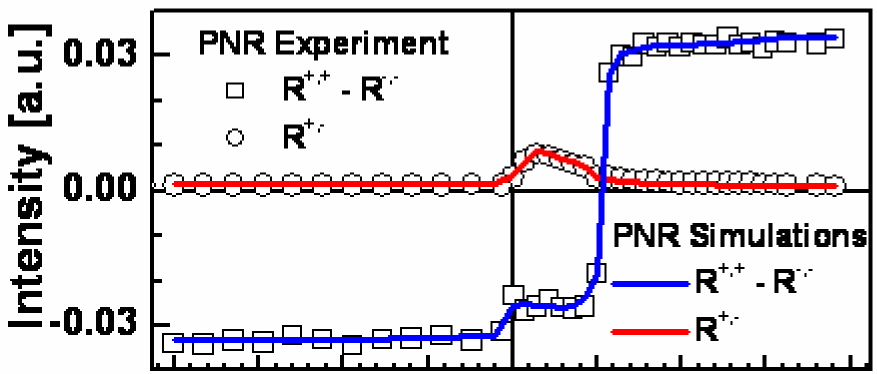
Simulation:

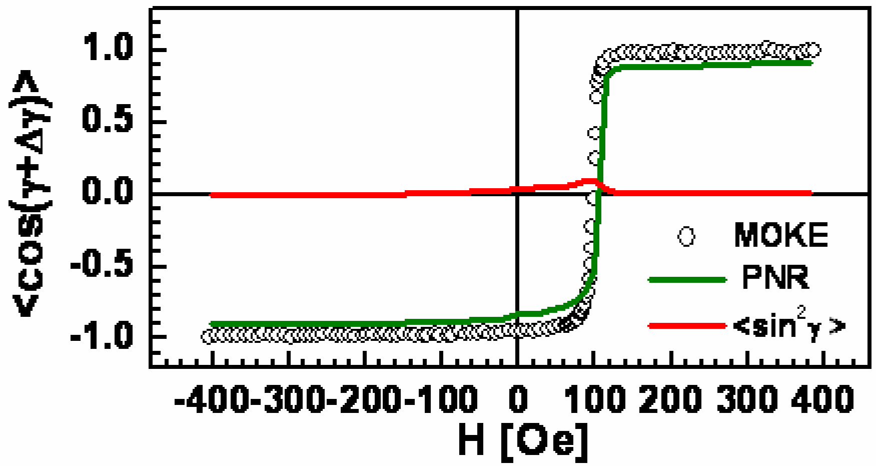
K. Theis-Bröhl, et al. Phys. Rev. B **68**, 184415 (2003).

Magnetization reversal parallel to stripes



Average hysteresis and quantitative determination of fluctuations

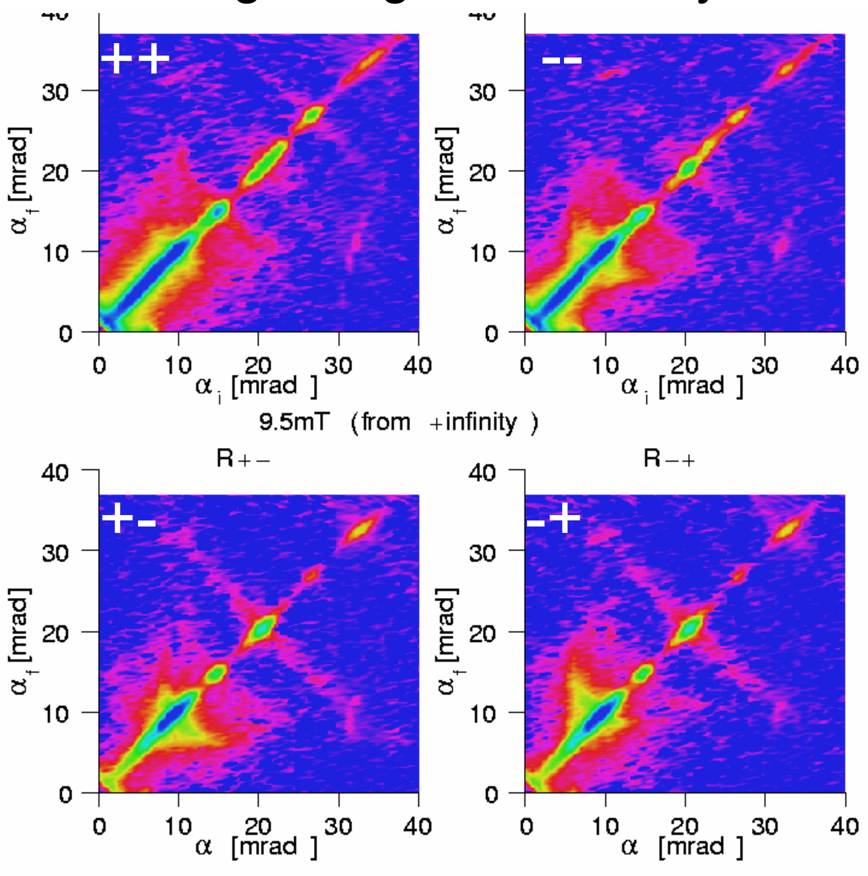


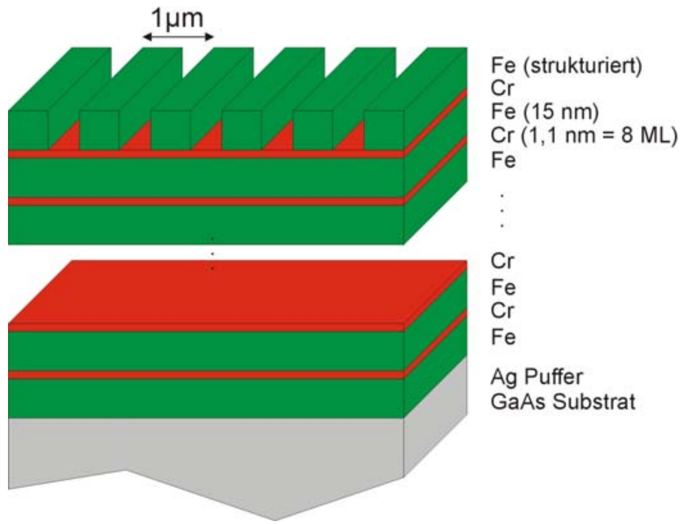


K. Theis-Bröhl, et al. Phys. Rev. B **71**, 020403(R) (2005).

Laterally structured Fe/Cr multilayer

- **Fe stripes on AF-Fe/Cr ML** Λ=1 μm
  Ziegenhagen et al., Physica B **335** (2003) 50





<u>Maps:</u>

- specular PNR
  (half- and full-order peaks)
- off-specular diffuse scattering
- Bragg sheets
- first-order lateral Bragg diffraction

Measurements @ FRJ2, HADAS

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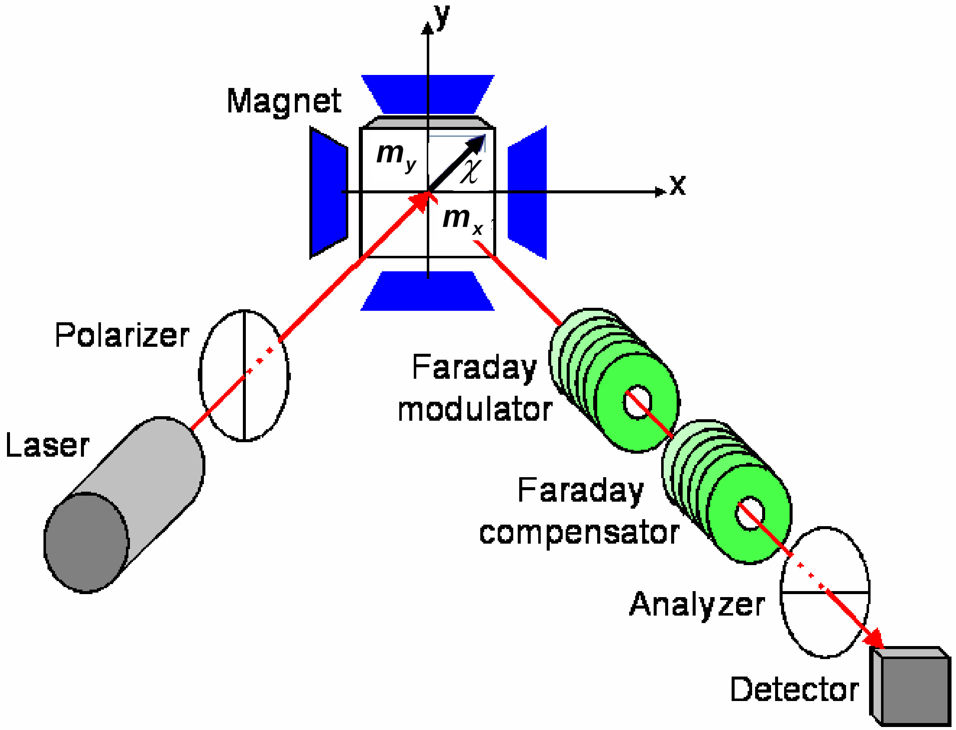
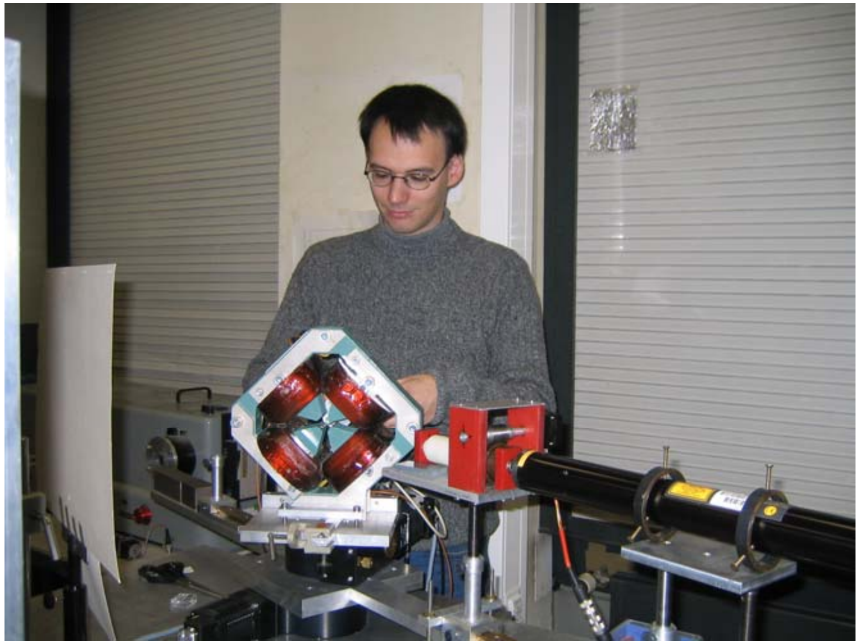
4. Case study: do we still need neutrons?

Analytical tools

- Magneto-optic Kerr effect (MOKE):
  Vector – magnetometry
- Polarized neutron reflectivity (PNR):
  Vector – magnetometry
  + depth resolution
- X-ray resonant magnetic scattering (XRMS):
  Vector – magnetometry
  + depth resolution
  + element selectivity
  + time resolution

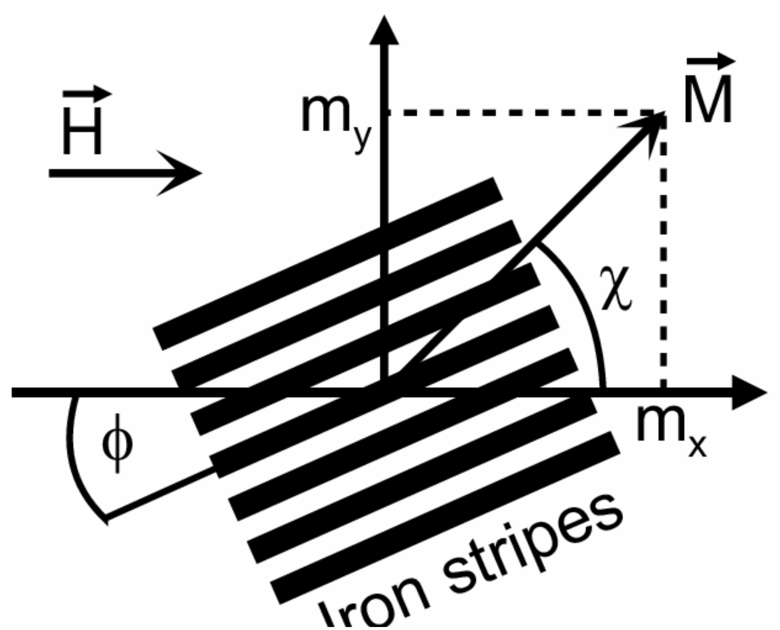
Longitudinal vector - MOKE





Kerr angle
$$\theta_K^x \sim m_x = |\vec{m}| \cos\chi$$
$$\theta_K^y \sim m_y = |\vec{m}| \sin\chi$$

Vector-MOKE



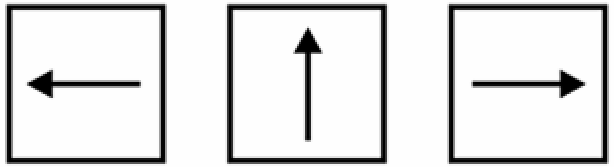
$$\frac{m_x}{m_y} = \frac{\cos\chi}{\sin\chi} = \frac{\theta_K^x}{\theta_K^y}$$

$$\chi = arc\cot\left(\frac{\theta_K^x}{\theta_K^y}\right)$$

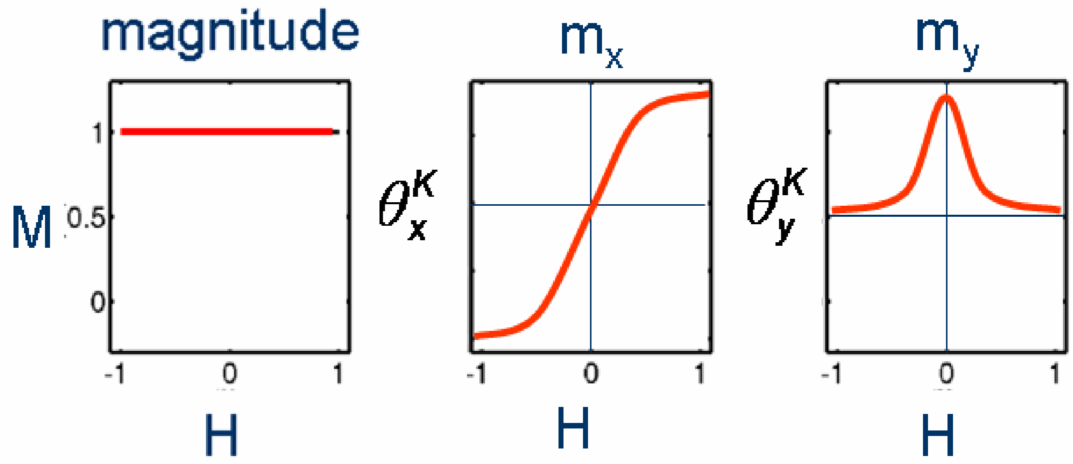
$$\frac{\left|\vec{M}\right|}{\left|\vec{m}\right|_{x,sat}} = \frac{\theta_K^x}{\theta_K^{x,sat}}\frac{1}{\cos\chi}$$

Two limiting cases

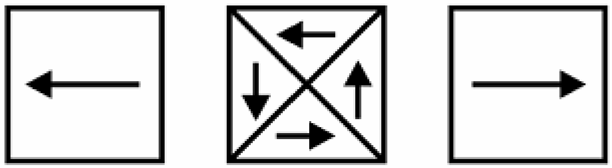
Coherent rotation:



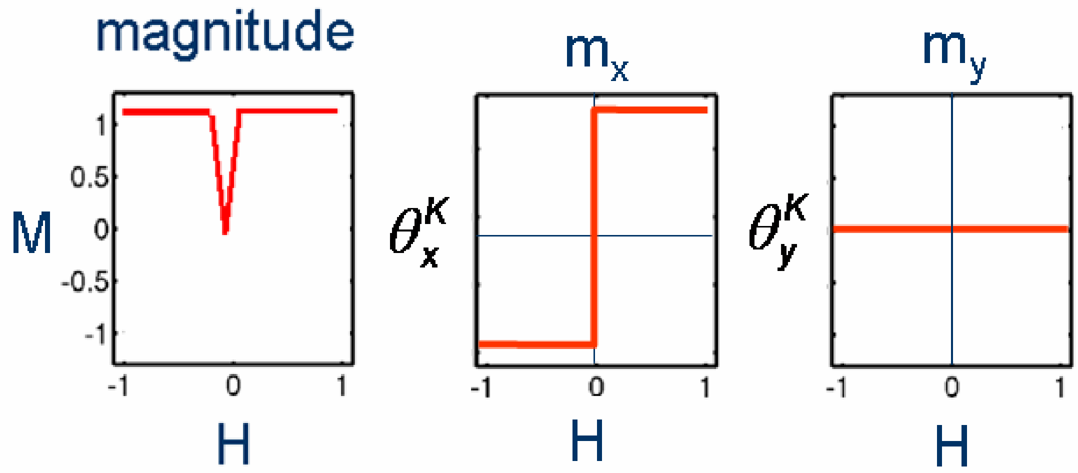
$$m_x = -1 \qquad = 0 \qquad = +1$$
$$m_y = 0 \qquad = +1 \qquad = 0$$



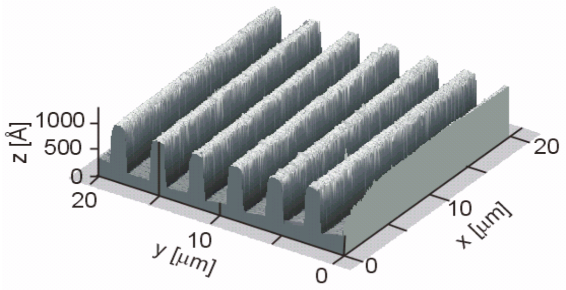
Domain formation:

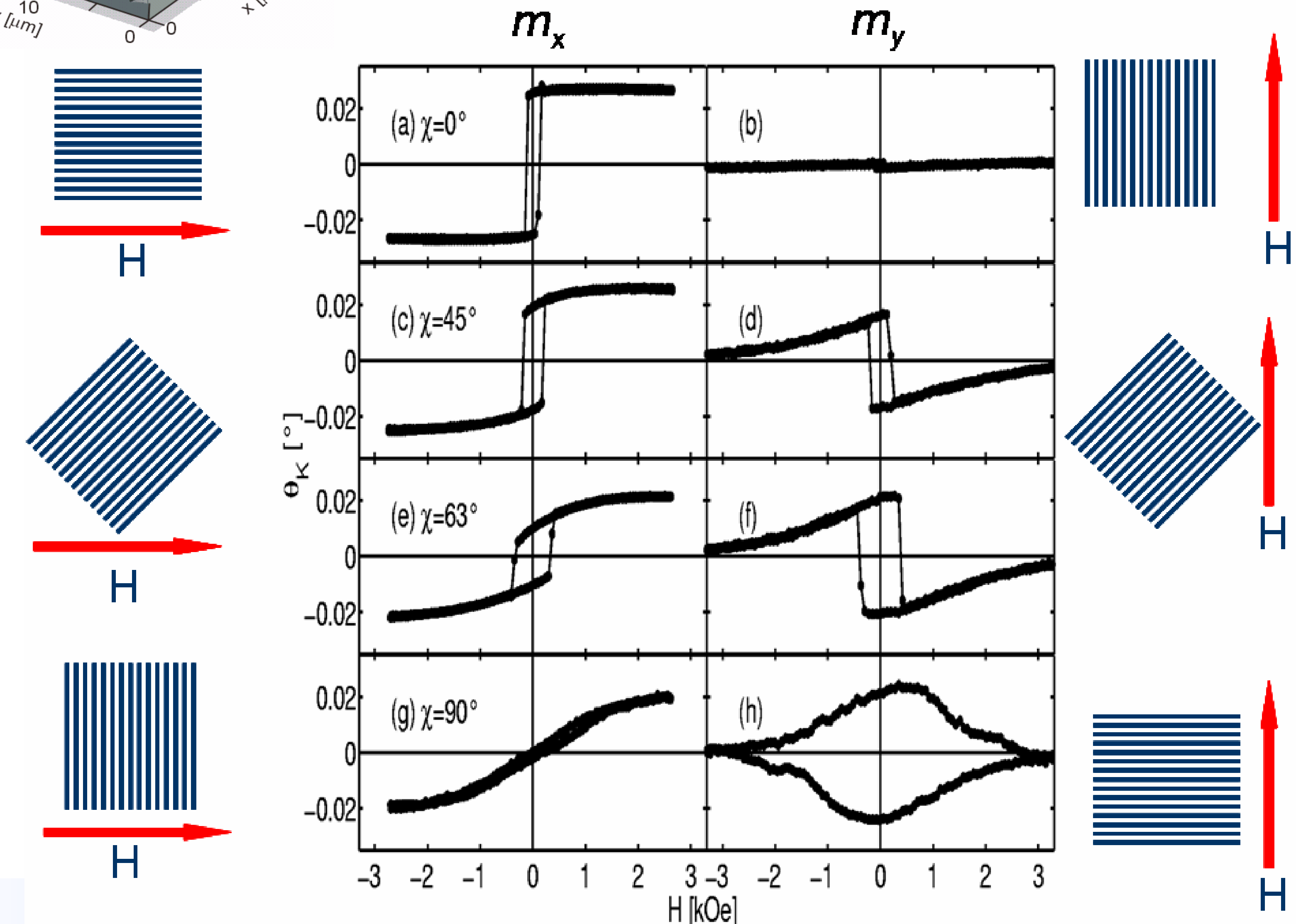


$$m_x = -1 \qquad = 0 \qquad = +1$$
$$m_y = 0 \qquad = 0 \qquad = 0$$



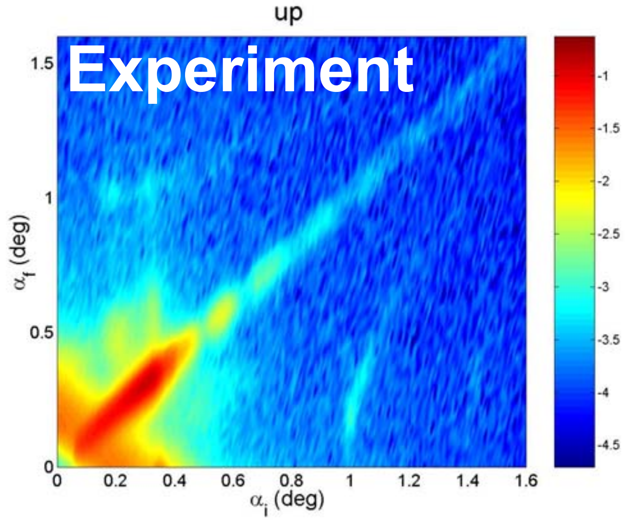
Magnetization reversal in a stripe array

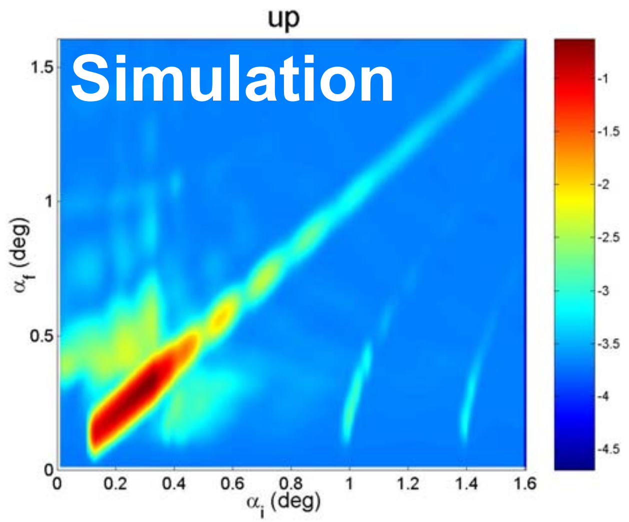




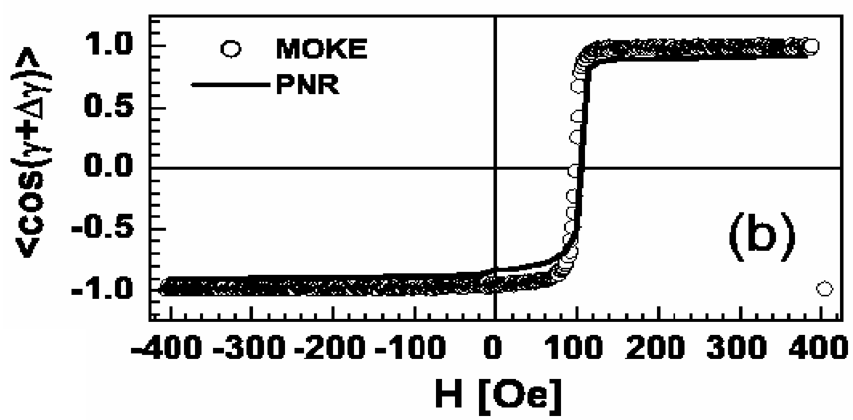
T. Schmitte, et al. PRB **67**, 184415 (2003)

Magnetization reversal of a stripe array

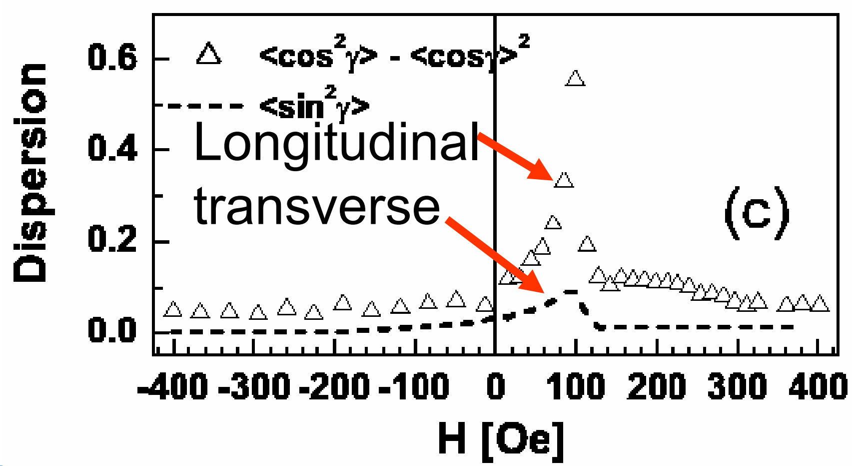




Normal component || H:

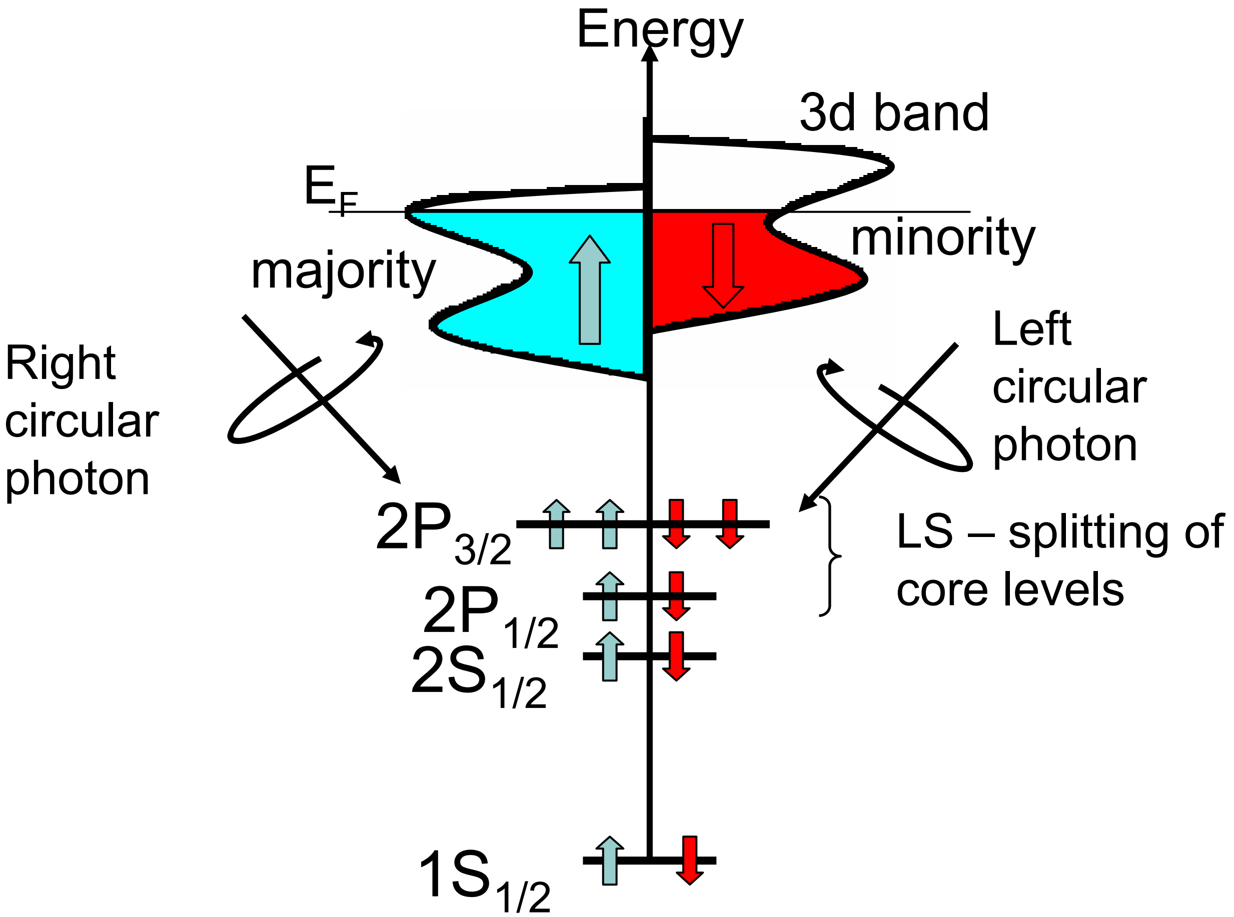


Fluctuations:



K. Theis-Bröhl et al. Phys. Rev. B 71 (2005) 020403

MCD for ferromagnetic metals



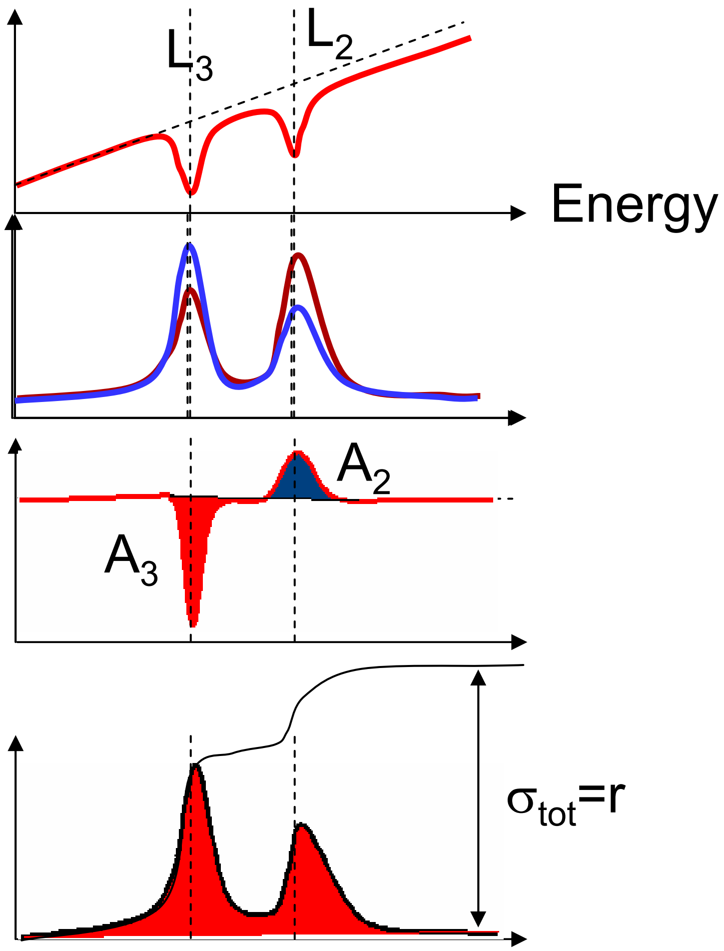
MCD for ferromagnetic metals

Transmission

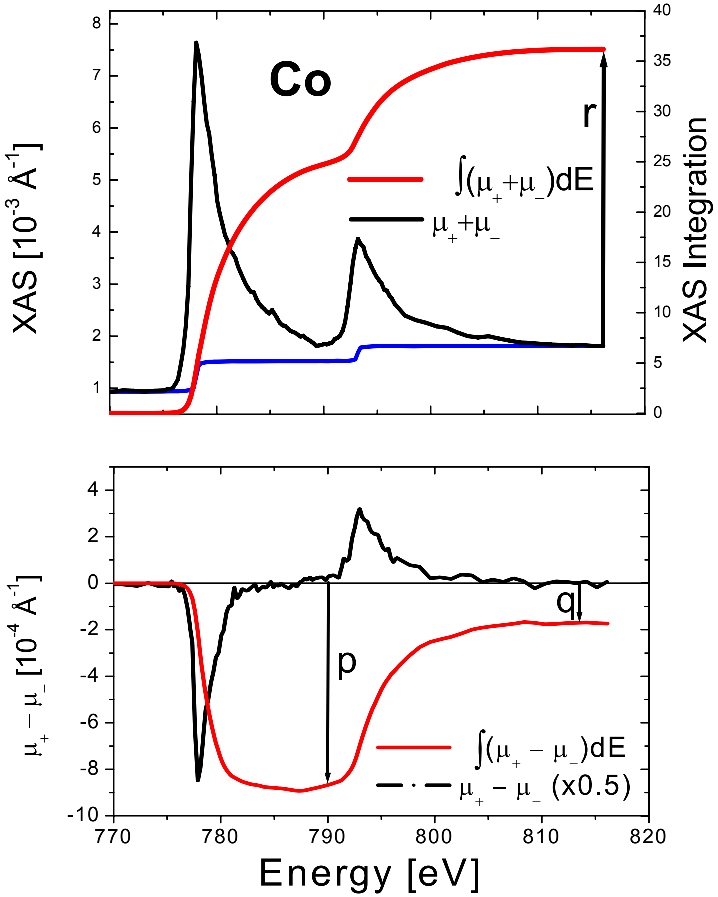
Absorption for right
circular polarisation

Difference signal, MCD

Total absorption, σ_{tot}



Spin and orbital moments from sum rules

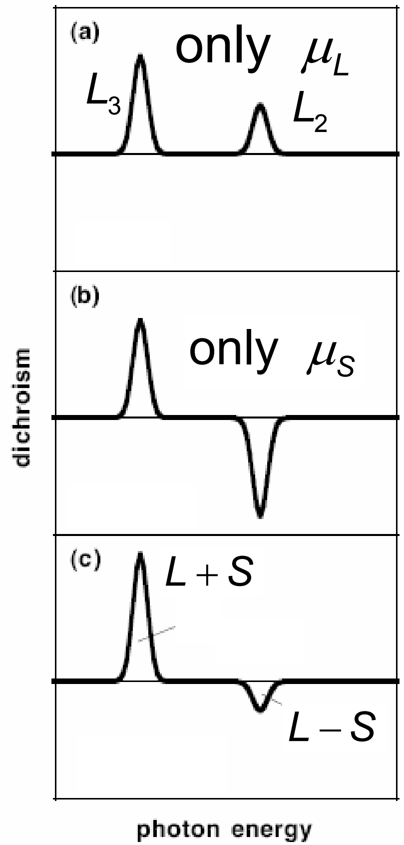


$$m_{\text{orb}}[\mu_B/\text{atom}] = -\frac{4qh}{3r}$$

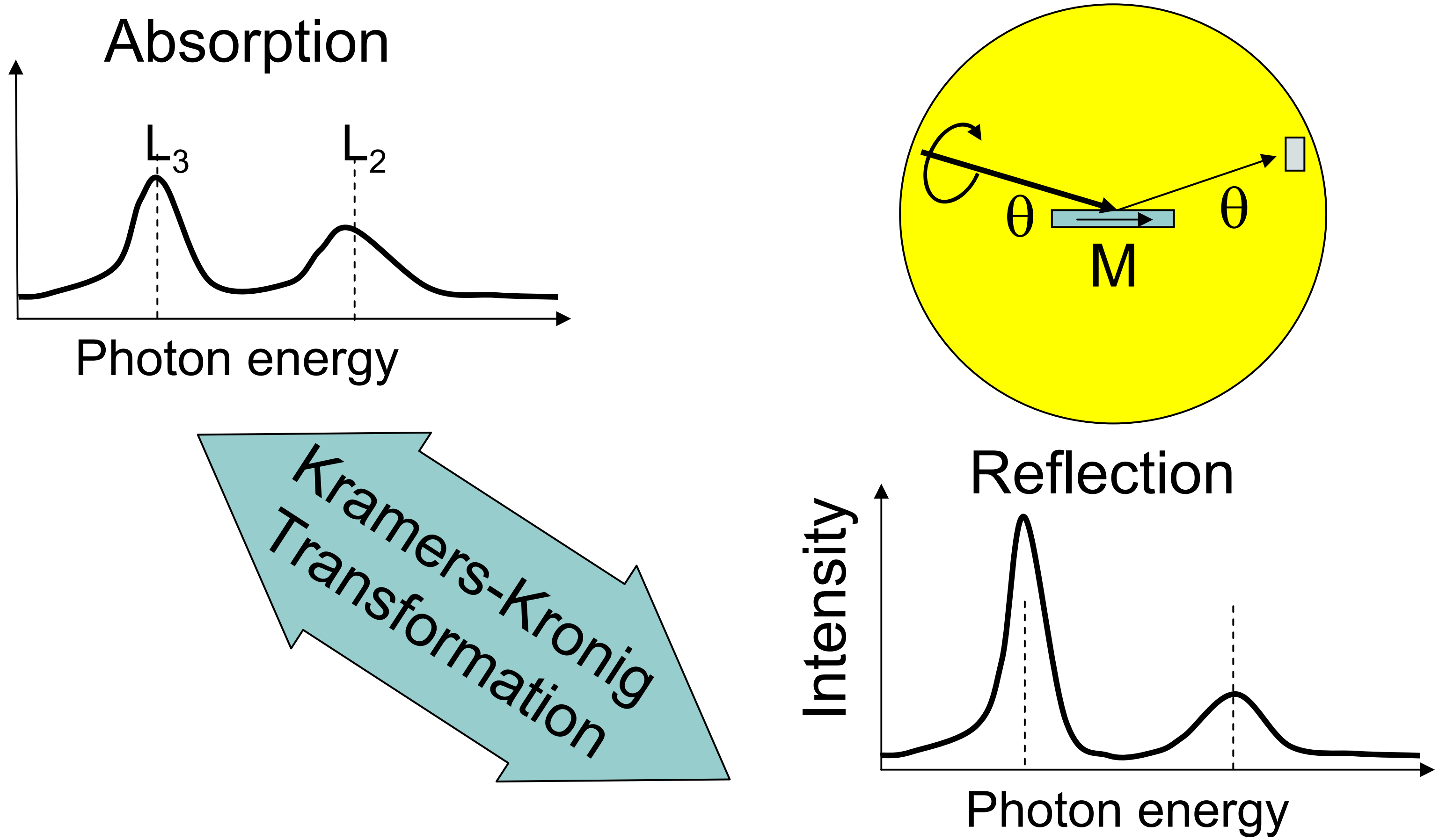
$$m_{\text{spin}}[\mu_B/\text{atom}] = -\frac{(6p-4q)h}{r}$$

$$\Rightarrow \frac{m_{\text{orb}}}{m_{\text{spin}}} = \frac{2q}{9p-6q}$$

$$h = (10-3d)$$



From absorption to reflection



X-ray magnetic scattering (XRMS)

$$f = \left(\mathbf{e}_f^* \cdot \mathbf{e}_i\right)\left\{-r_e Z + \frac{3}{8\pi}\lambda\left[F_1^1 + F_{-1}^1\right]\right\}$$

Charge scattering (non-resonant and resonant)

$$+\mathrm{i}\left(\mathbf{e}_f^* \times \mathbf{e}_i\right)\cdot \hat{\mathbf{m}}\frac{3}{8\pi}\lambda\left[F_1^1 - F_{-1}^1\right]$$

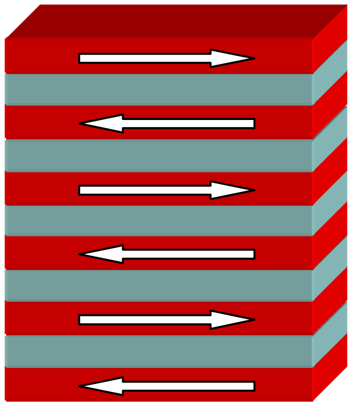
1st order in **M** → Circular Dichroism

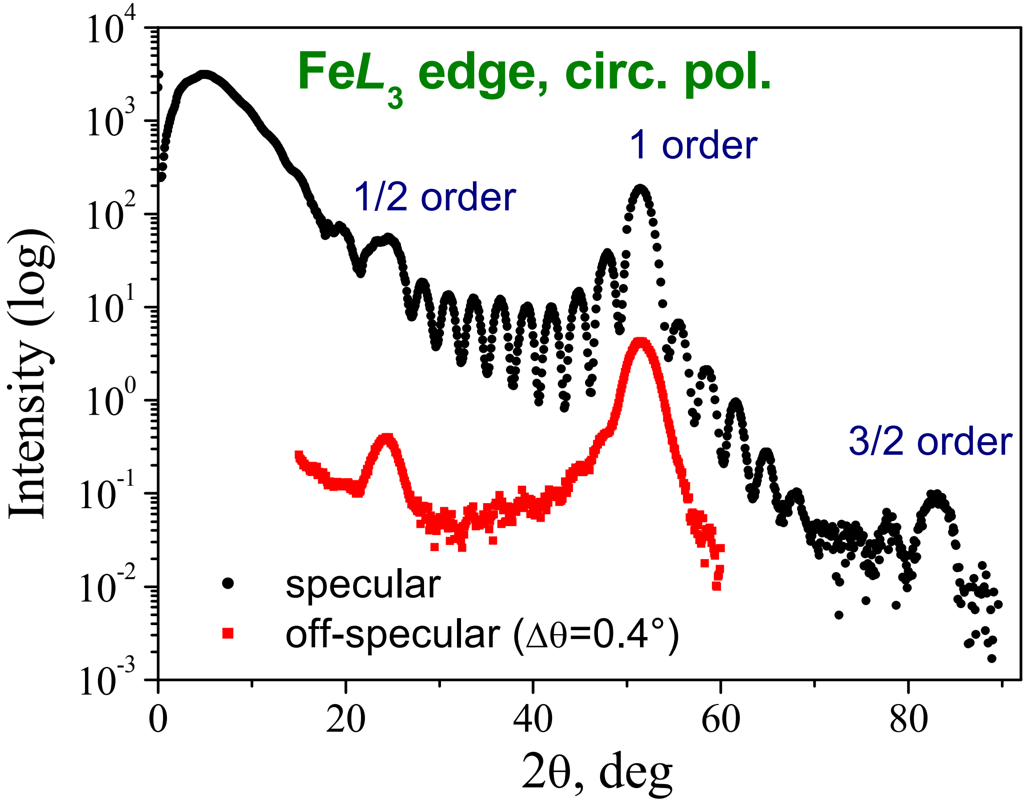
$$+\left(\mathbf{e}_f^* \cdot \hat{\mathbf{m}}\right)\left(\mathbf{e}_i^* \cdot \hat{\mathbf{m}}\right)\frac{3}{8\pi}\lambda\left[2F_0^1 - F_1^1 - F_{-1}^1\right]$$

2nd order in **M** → Linear Dichroism

Resonant magnetic scattering

Fe/Cr superlattices: resonant magnetic scattering

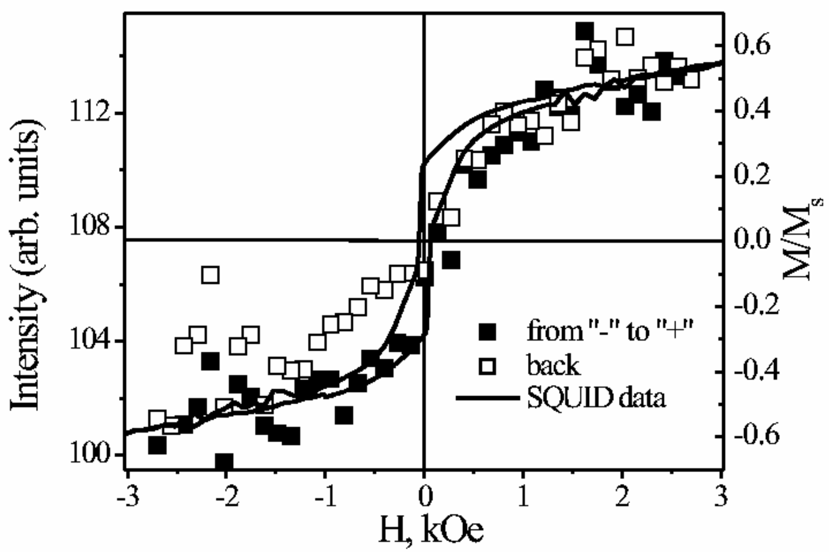




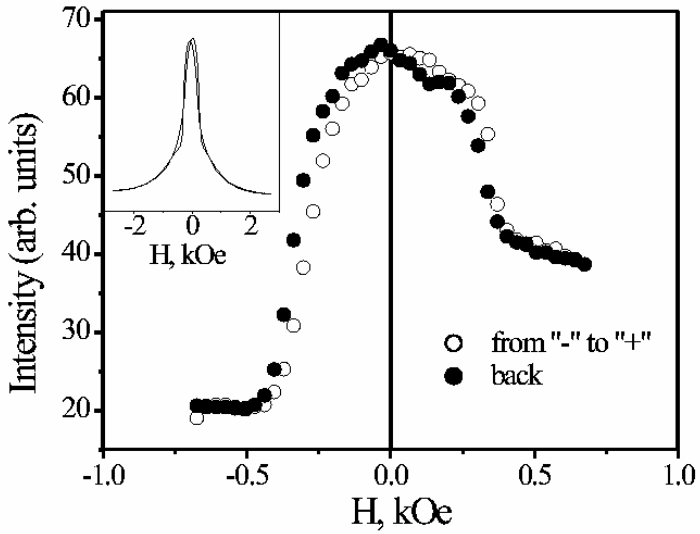
A.Nefedov, J. Grabis, A. Bergmann, F. Radu and H. Zabel, Superlattices and Microstructures, **37**, 99 (2005)

Fe/Cr superlattices: hysteresis

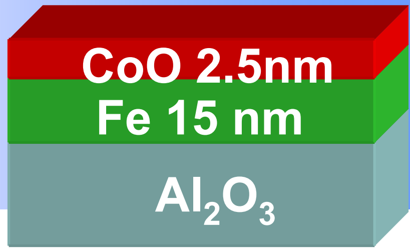
FM-hysteresis loop at
1. order peak, circular pol



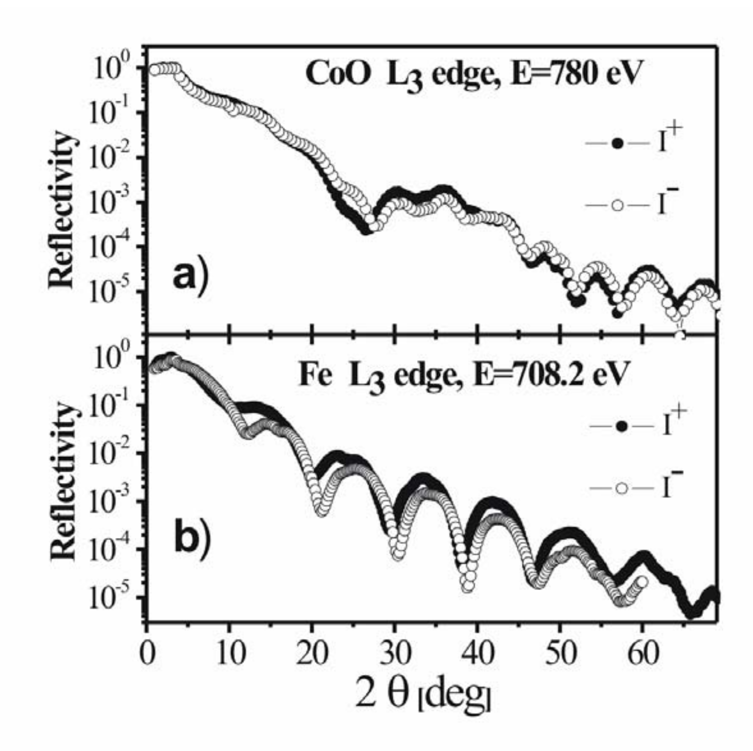
AFM-hysteresis loop at
1/2 order peak, linear pol



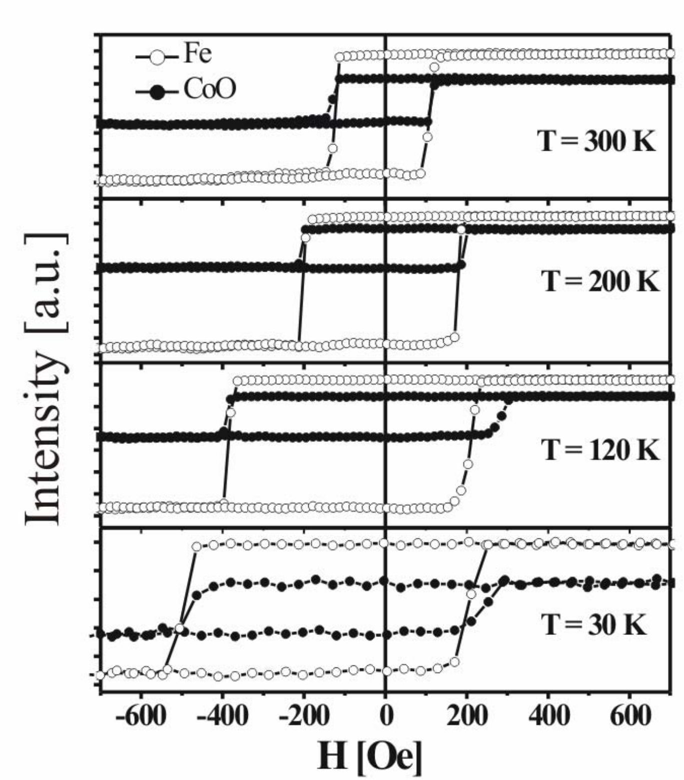
Element specific reflectivities and hysteresis of EB system



XRMS after field cooling
in H_{FC} = + 2 kOe at 30 K



Hystereses



$T > T_N$

$T < T_N < T_B$

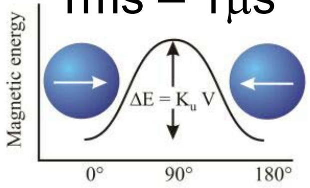
$T_N > T > T_B$

$T < T_B$

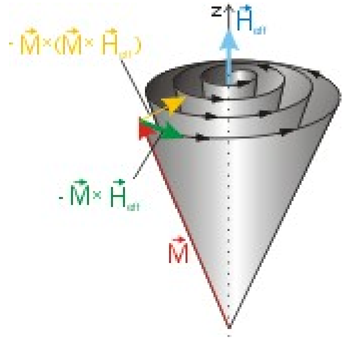
F. Radu, et al. JMMM 300 (2006) 206

Time scales in magnetic materials

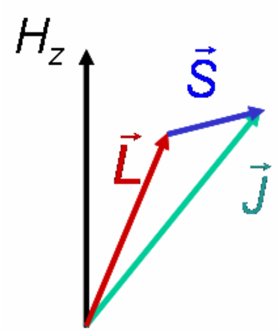
Thermal activations 1ms – 1μs



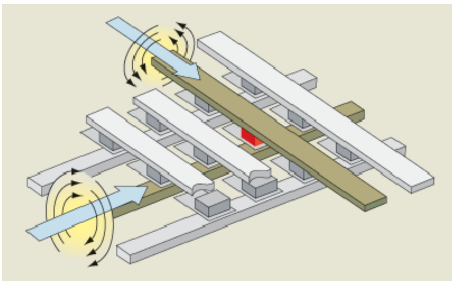
Spin-lattice relaxation and damping ~ 100ps



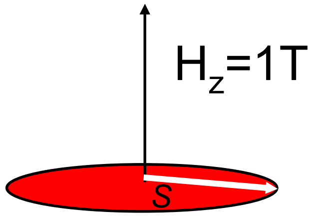
SL-coupling ~ 100fs



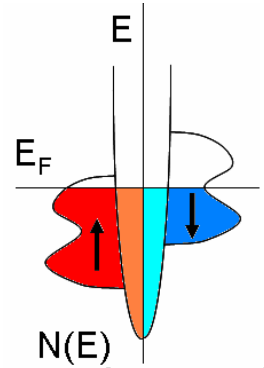
1μs 1ns 1ps 1fs



Domain nucleation + propagation ~ 1 ns

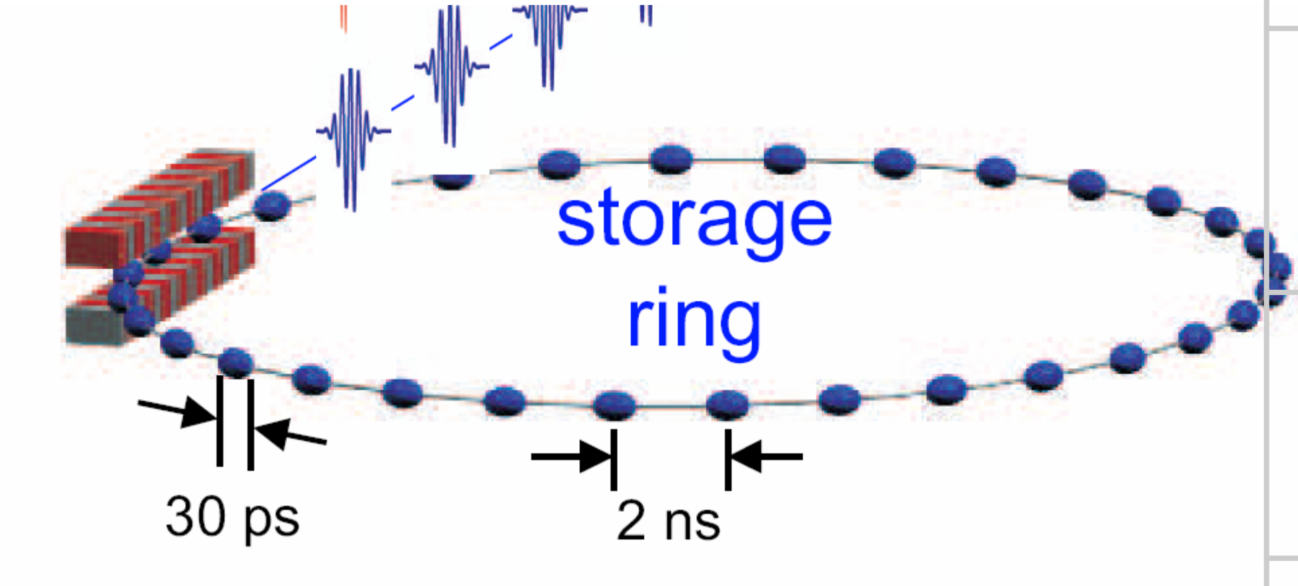


Spin precession ~ 10 ps



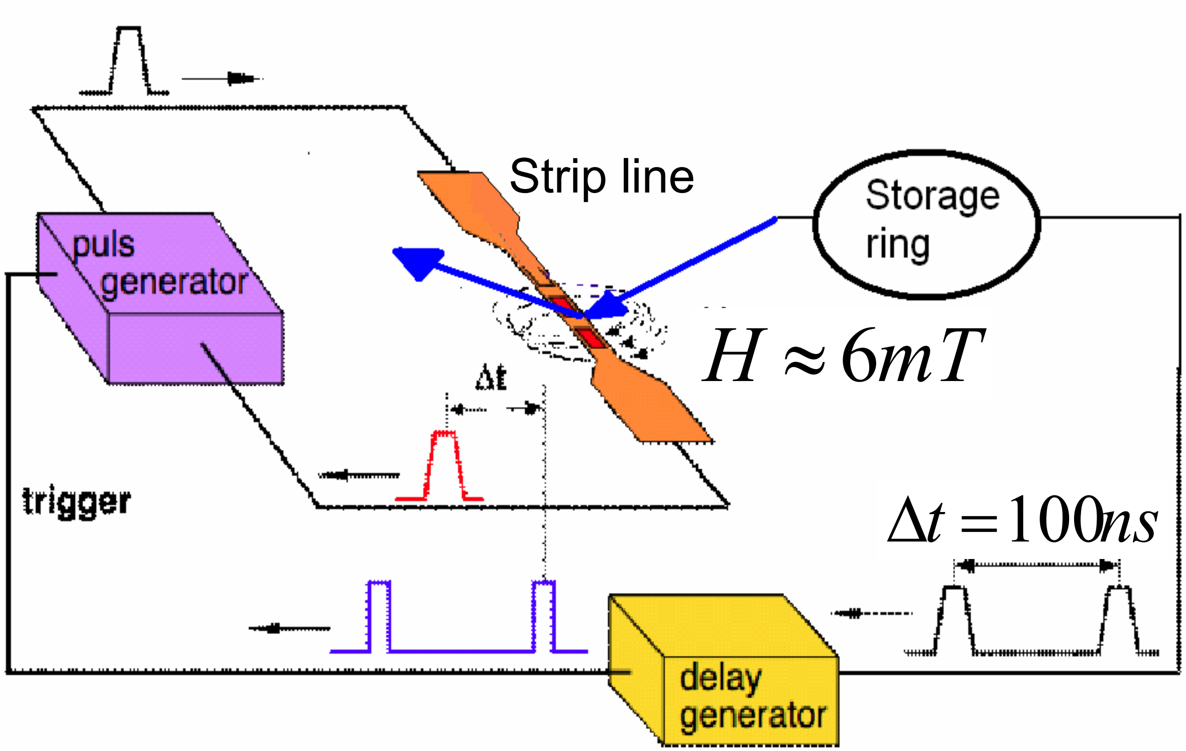
Exchange interaction ~ 1fs

Time resolved reversal XRMS



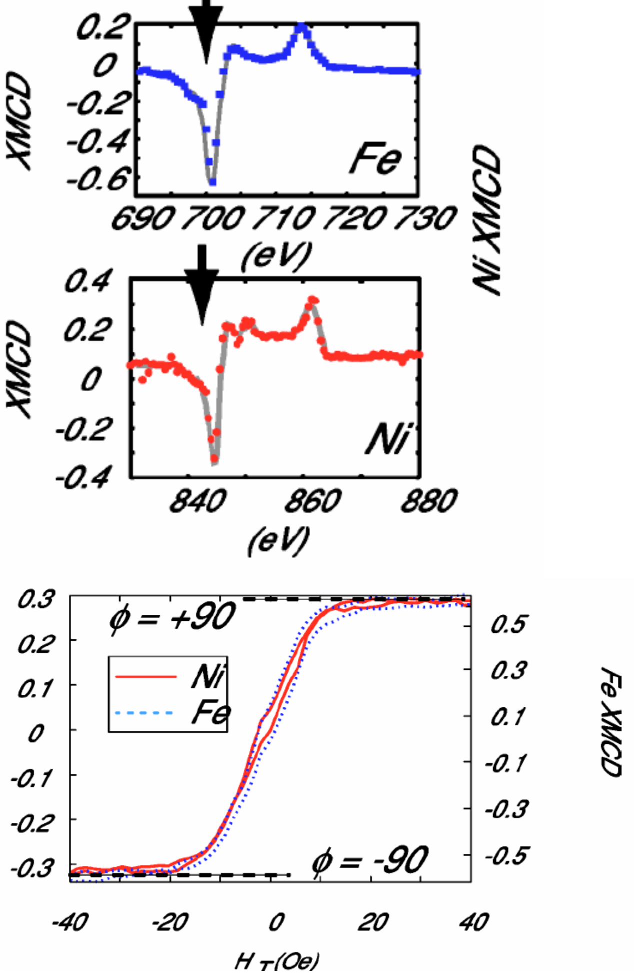
	BESSY low **α**
pulse width	30 ps
repeat time	2 ns
n_{bunch} current	400 0.5 μA

Time domain: pump probe technique

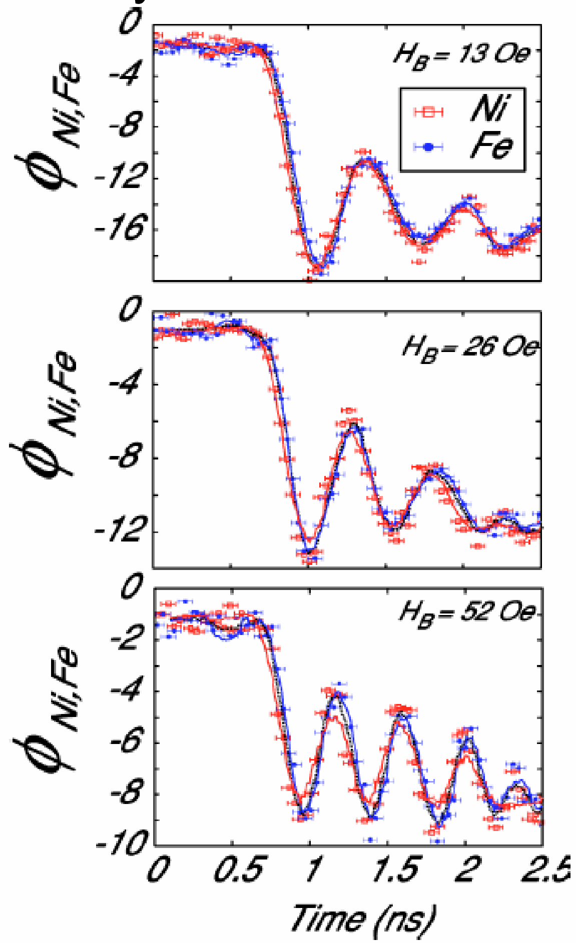


Precessional dynamics of elemental moments in a ferromagnetic alloy

Statics



Dynamics TR-XMCD



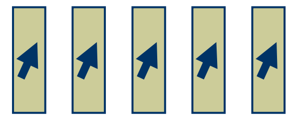
W. E. Bailey et al. PRB 70 (2004) 172403

Summary: uses of PNR

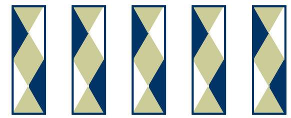
- Layer resolved magnetization vector
- Magnetization profile independent of structural/chemical profile
- Absolute moment evaluation not obscured by substrate effects
- Distinction between different types of magnetization reversal
- High field measurements
- Domain distribution, domain sizes, domain walls
- Ferro- and antiferromagnetic structures
- Non-collinear magnetism
- Magnetic correlation lengths

Topics for PNR studies

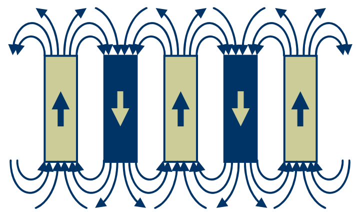
- **Quantitative vector magnetometry**



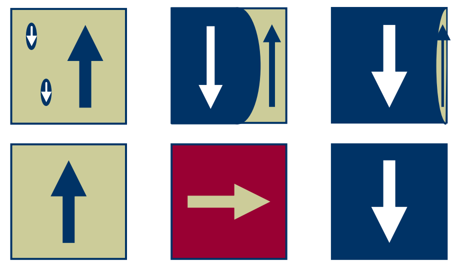
- **Domain configurations**



- **Interactions between elements**



- **Details of remagnetization**
  - **domain nucleation/ wall movement**
  - **vs. rotation**



Literature

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- *C. Fermon, F. Ott, A. Menelle*, „Neutron Reflectometry“ in X-Ray and Neutron Reflectivity: Prinziples and Applications, J. Daillant, A. Gibaud (Eds.), Lecture Notes in Physics, Springer, 1999.
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- *H. Zabel*, Materials Today, **8** (2006) 42

Advantages and disadvantages: XRMS

- 🙂 High flux and large *q*
- 🙂 Element specific
- 🙂 Distinguish L and S
- ☹ Cross sections not known
- ☹ Indirect probe of the magnetisation
- ☹ Measure interference term between charge and magnetism
- 🙂 Time resolved experiments
- ☹ Penetration depth

Thank you for your attention